Daya Bay Neutrino Summer School
1-9 July 2017

SUPERNOVA IN ASTROPARTICLE PHYSICS
(II)

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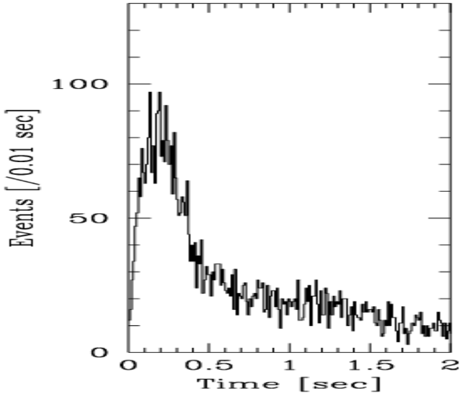
FUTURE SN NEUTRINO OBSERVATIONS

What have we learnt? What can we learn?

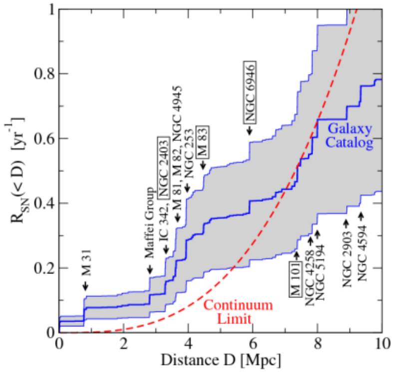
 SN 1987A	 Future supernova
General confirmation of core-collapse paradigm (total energy, spectra, time scale)	• Detailed test by high-statistics signal • Detection of unexpected features
No unexpected energy-loss channel: Restrictive limits on axions, large extra dimensions, right-handed neutrinos (couplings, mixings, dipole moments), Majorons, light SUSY particles, …	Should be generally confirmed (low-statistics signal enough), but uncertainty dominated by theory (processes in a dense nuclear medium)
Nothing useful about absolute m_ν	Short time variation of signal
• Nothing useful about oscillations • Hints that flavor dependence of spectra indeed is not large	Neutrino mass hierarchy (with luck)

NEUTRINO DETECTION METHODS



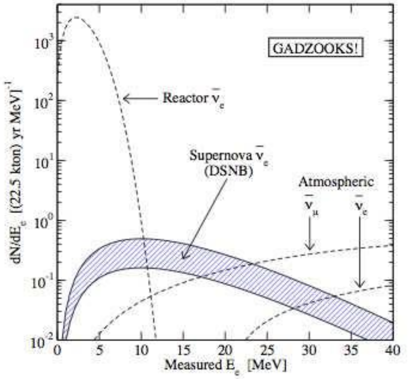
- Milky-Way SN

  Excellent statistics (10^4 events for 10 kpc)
  High-sensitivity to explosion scenario
  1 SN ~ 40 years



- SNe in nearby galaxies

  Few to 10 neutrinos per SN, but requires a Mton-class detector
  1 SN ~ year



- Diffuse Supernova Neutrino Background (DSNB)

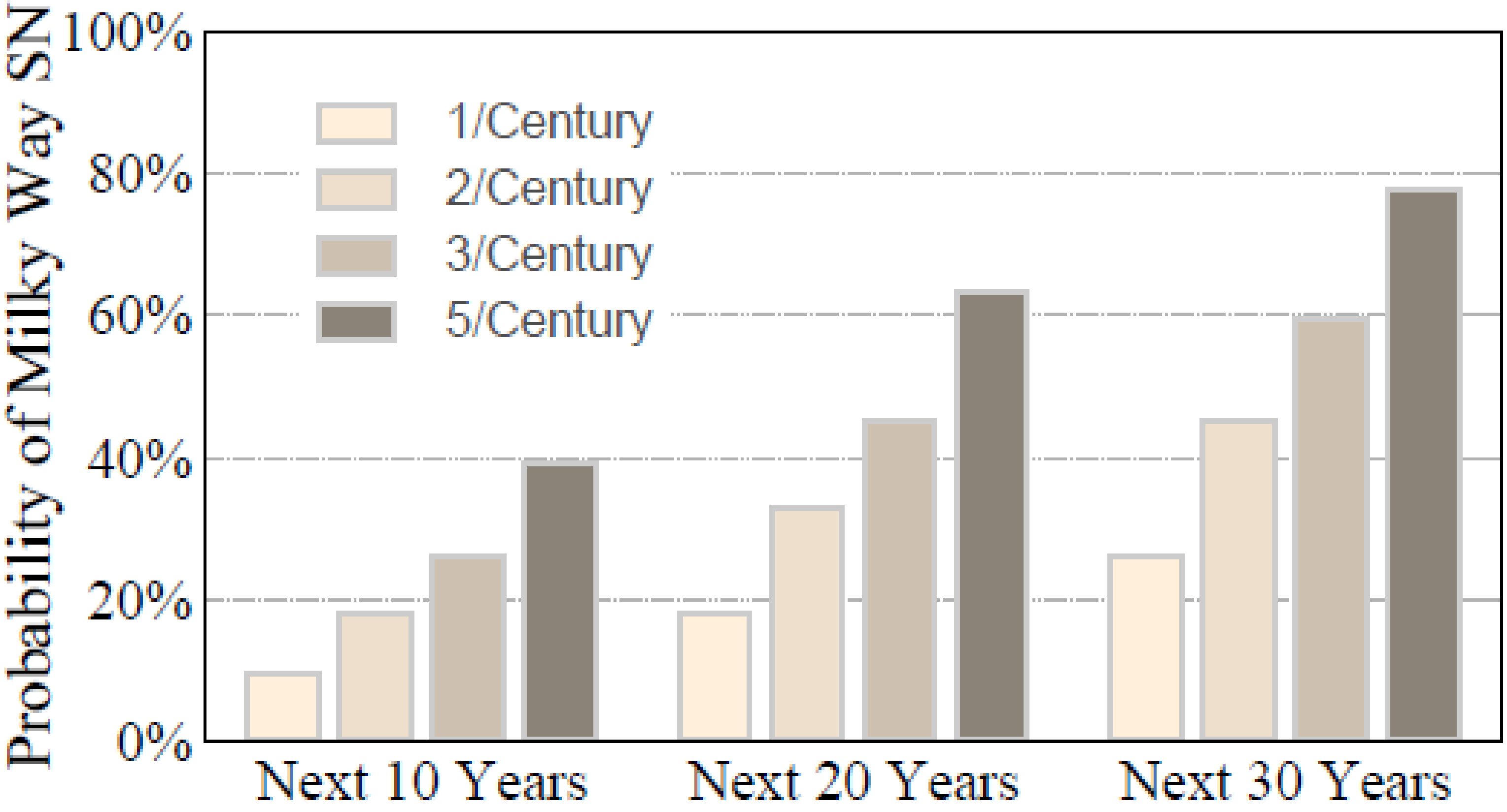
  Neutrinos from all past core-collapse SNe; emission is averaged, no timing or direction
  (faint) signal is always there

What could we see “tomorrow”?

SN 20XXA !

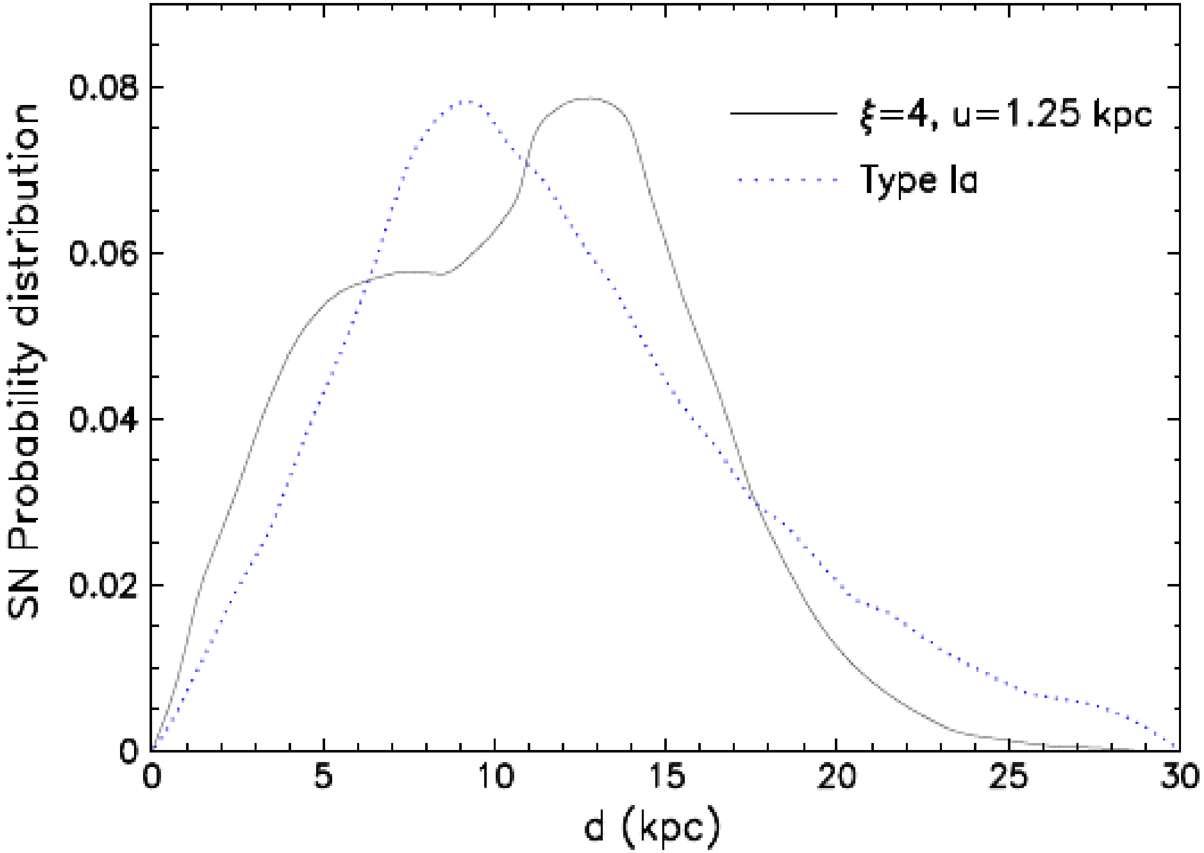
PROBABILITY OF MILKY-WAY SN

[Kistler, Yuksel, Ando, Beacom & Suzuki, 0810.1959]



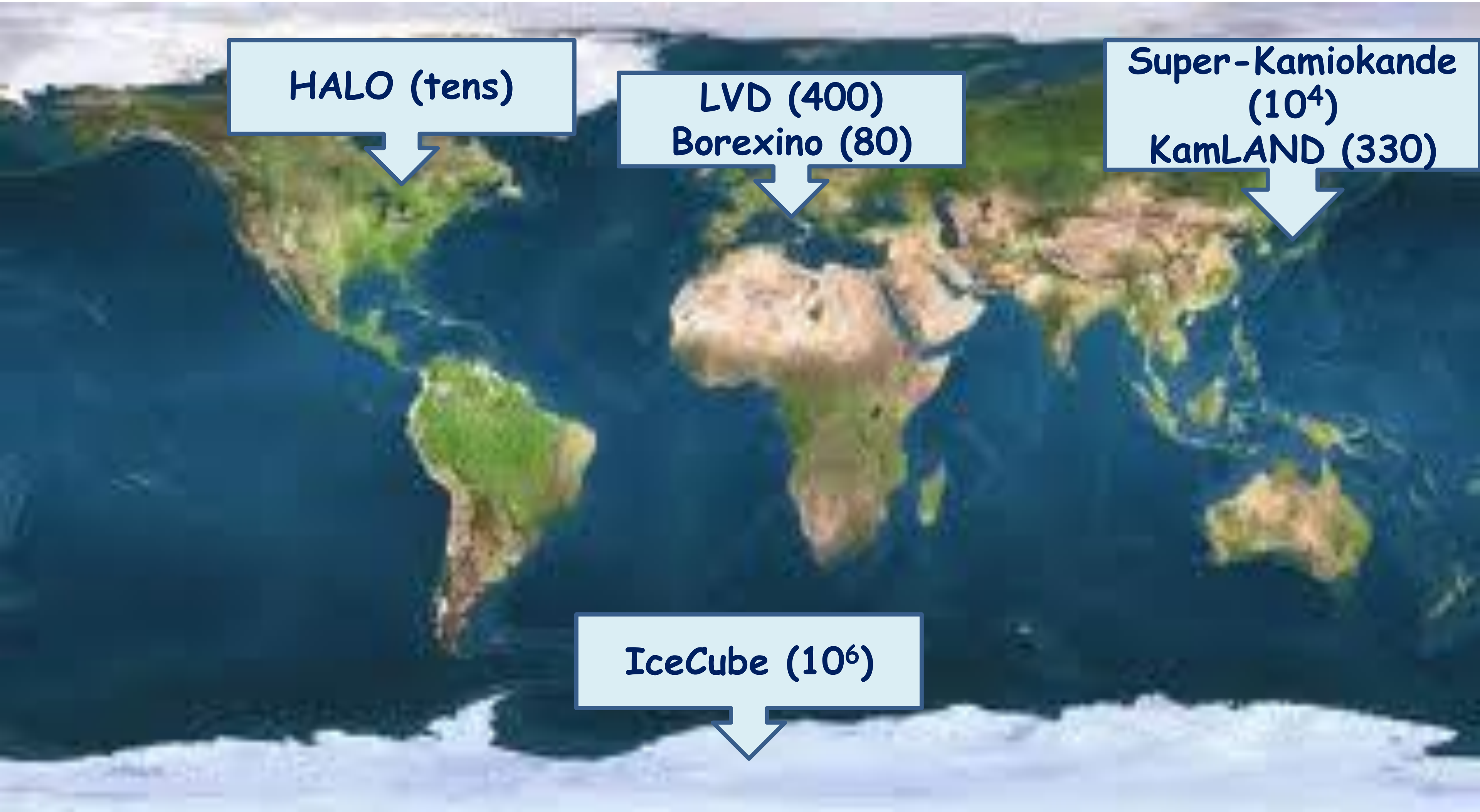
GALACTIC SUPERNOVA DISTANCE DISTRIBUTION

[<u>A.M.</u>, Raffelt, Serpico, astro-ph/ 0604300]



Average distance 10.7 kpc, rms dispersion 4.9 kpc
(11.9 kpc and 6.0 kpc for SN Ia distribution)

Large Detectors for Supernova Neutrinos



HALO (tens)

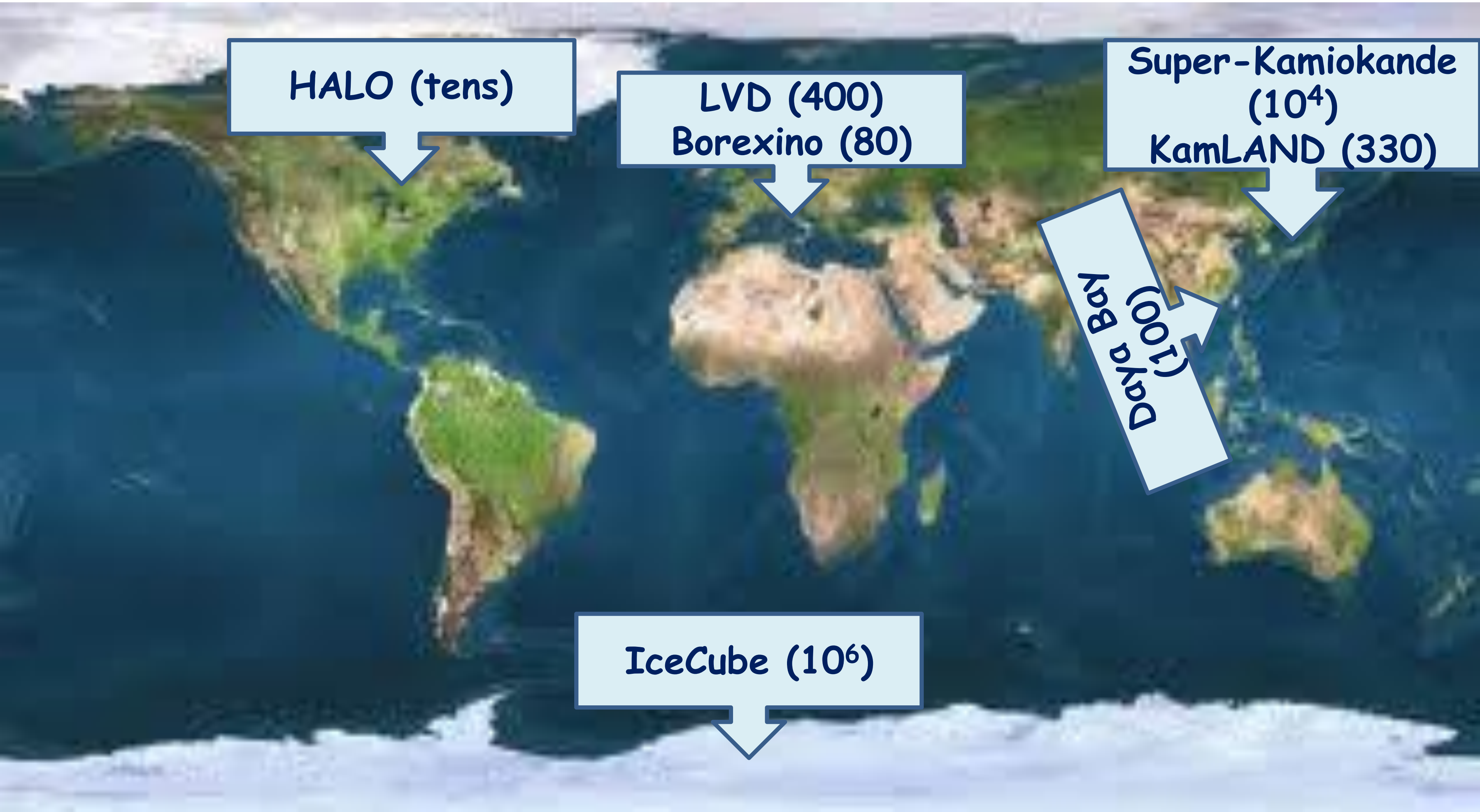
LVD (400)
Borexino (80)

Super-Kamiokande
(10^4)
KamLAND (330)

IceCube (10^6)

In brackets events for a "fiducial SN" at distance 10 kpc

Large Detectors for Supernova Neutrinos



HALO (tens)

LVD (400)
Borexino (80)

Super-Kamiokande (10^4)
KamLAND (330)

Daya Bay (100)

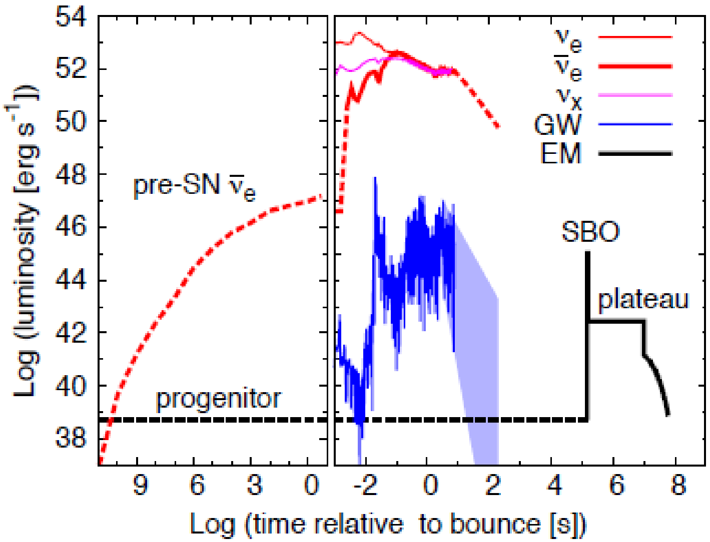
IceCube (10^6)

In brackets events for a "fiducial SN" at distance 10 kpc

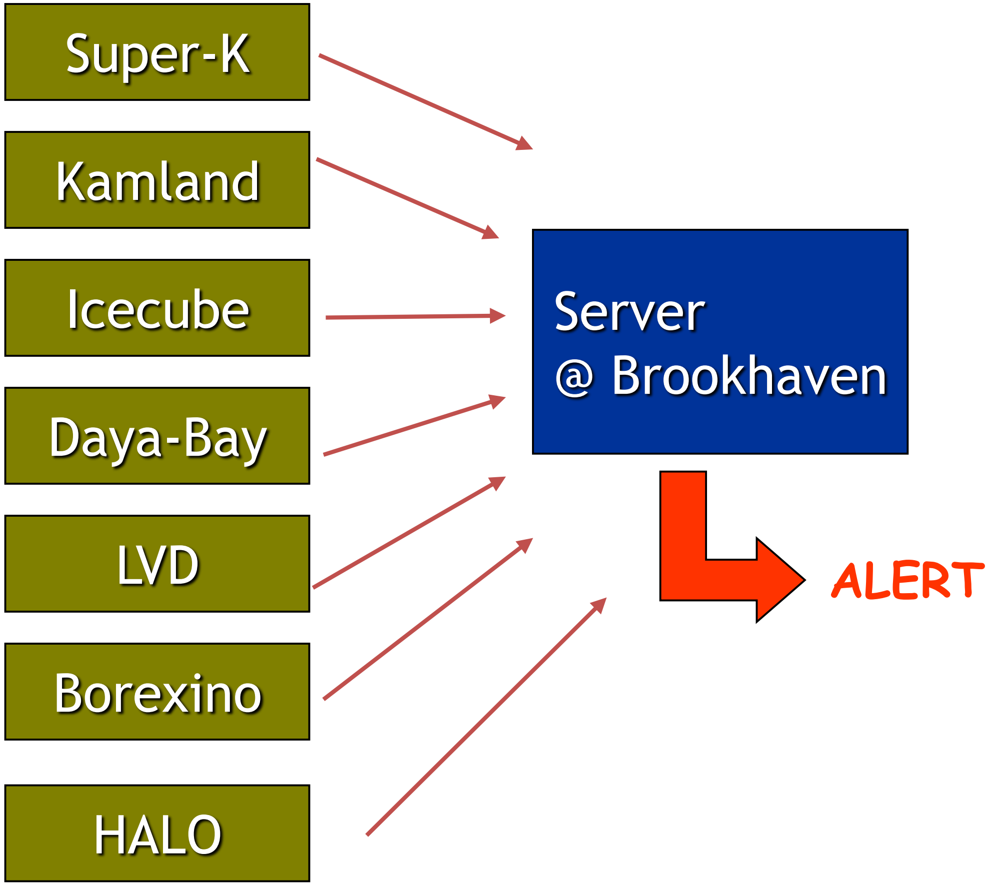
SUPERNOVA EARLY WARNING SYSTEM (SNEWS)

[P.Antonioli et al., astro-ph/0406214]

Neutrinos several hours before light



Neutrino observations can alert astronomers several hours in advance to a SN. To avoid false alarms, require alarm from at least two experiments



Super-K

Kamland

Icecube

Daya-Bay

LVD

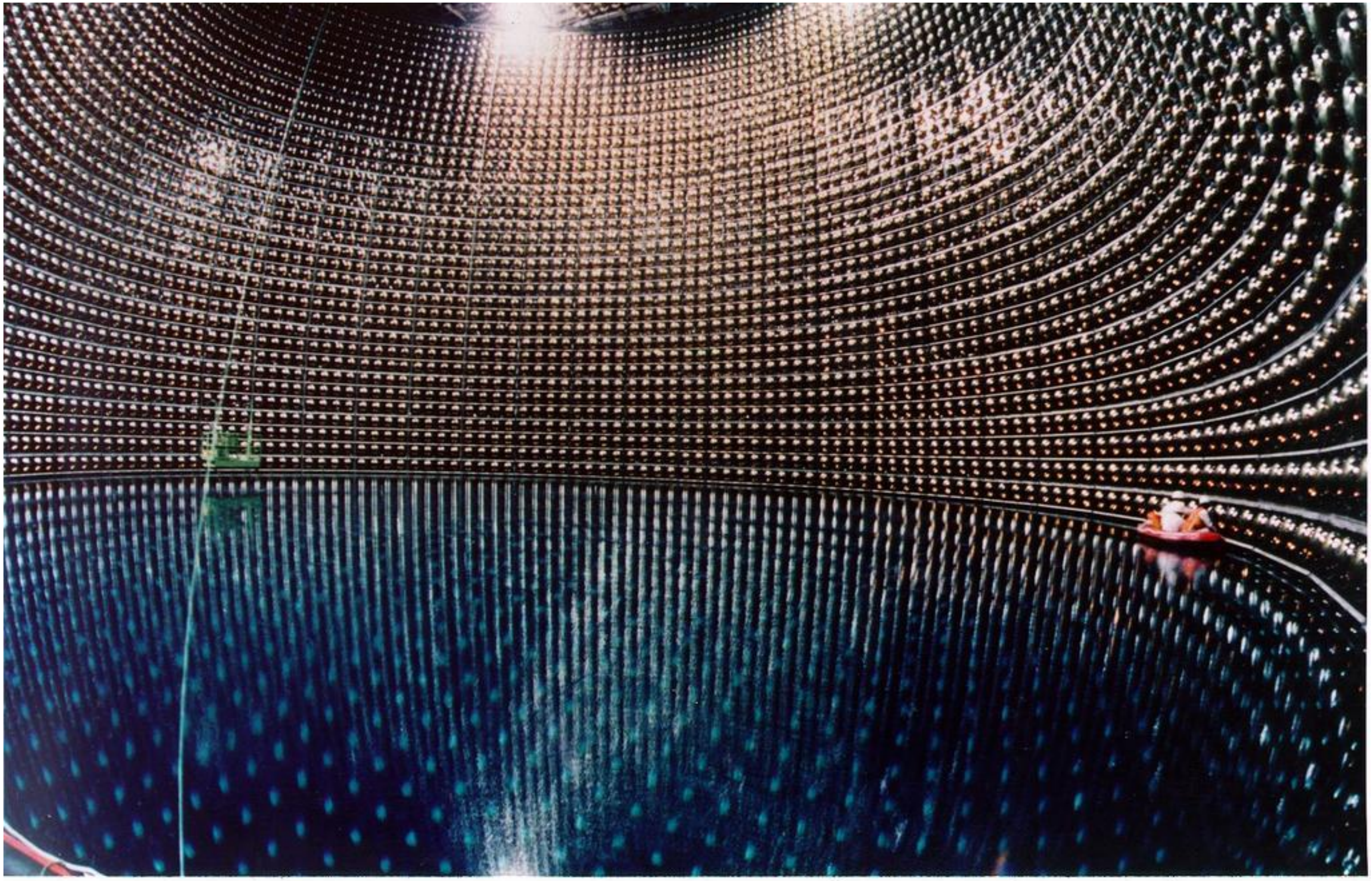
Borexino

HALO

Server
@ Brookhaven

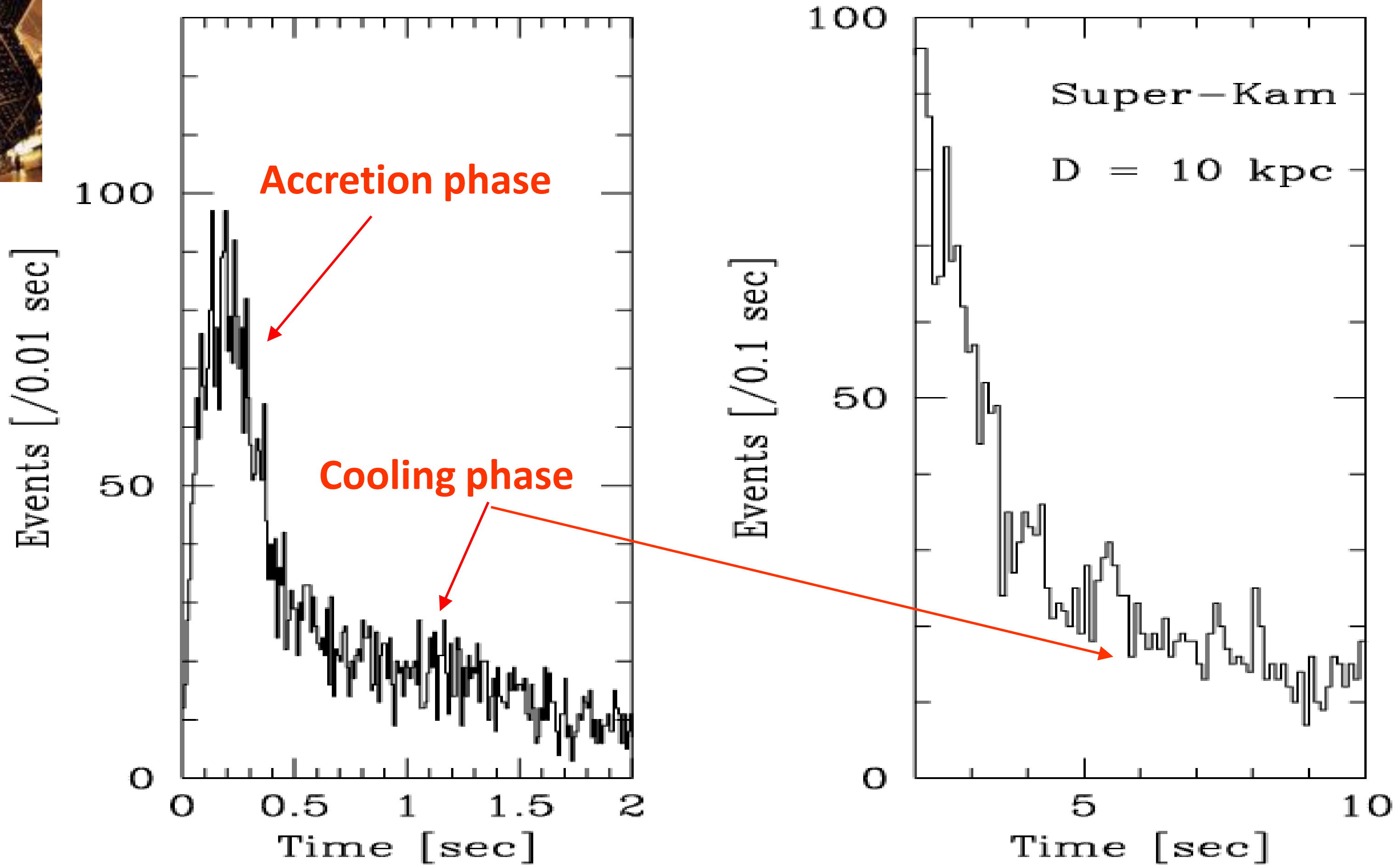
ALERT

SUPER-KAMIOKANDE DETECTOR



SK is a cylindrical tank containing 50000 ton of light water surrounded by photomultipliers, located underground in the Kamioka mine in Japan.

Simulated Supernova Signal at Super-Kamiokande



Accretion phase

Cooling phase

Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model

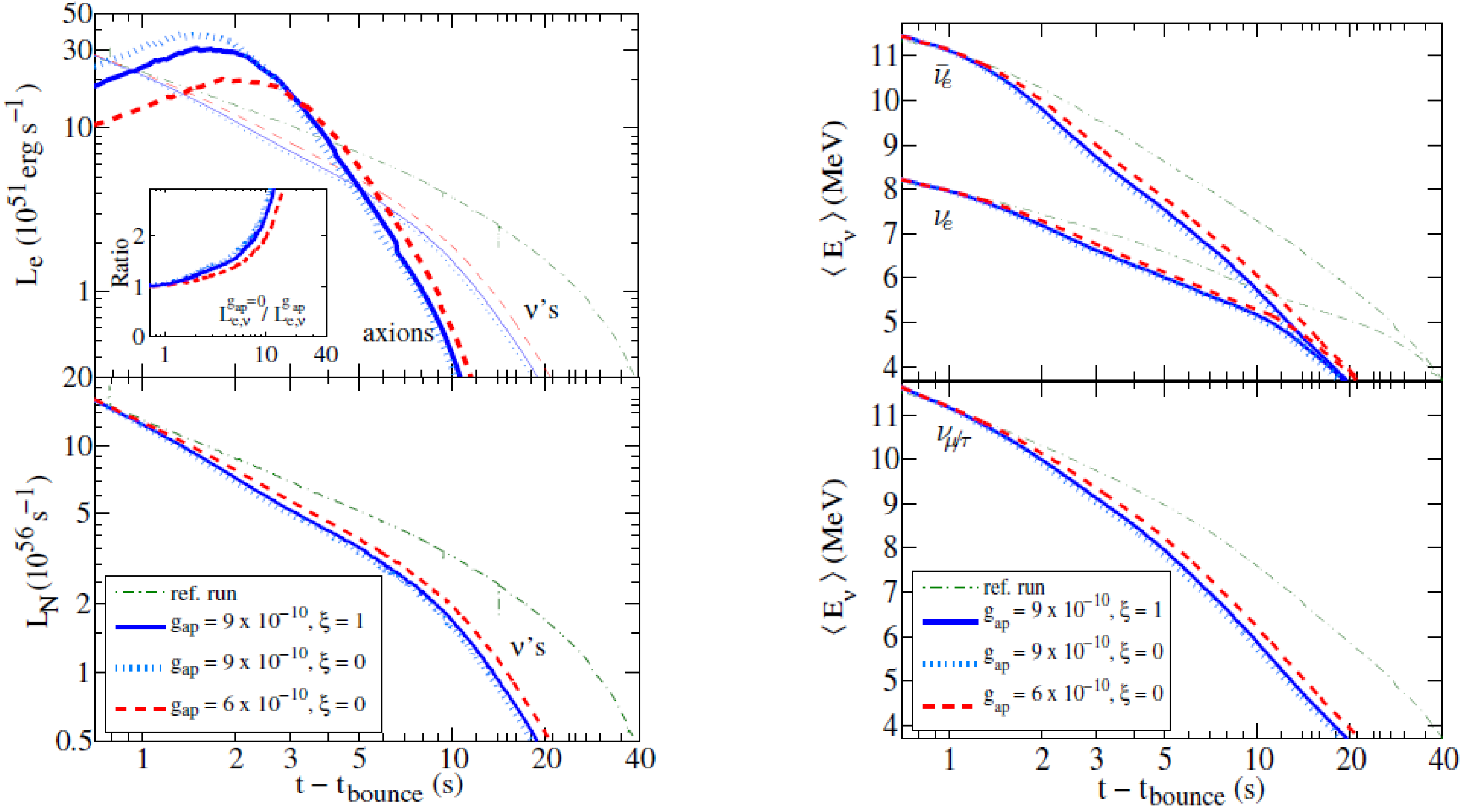
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

A REAPPRISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

[Fischer, Chakraborty, Giannotti *A.M.* , *Payez & Ringwald, 1605.08780*]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



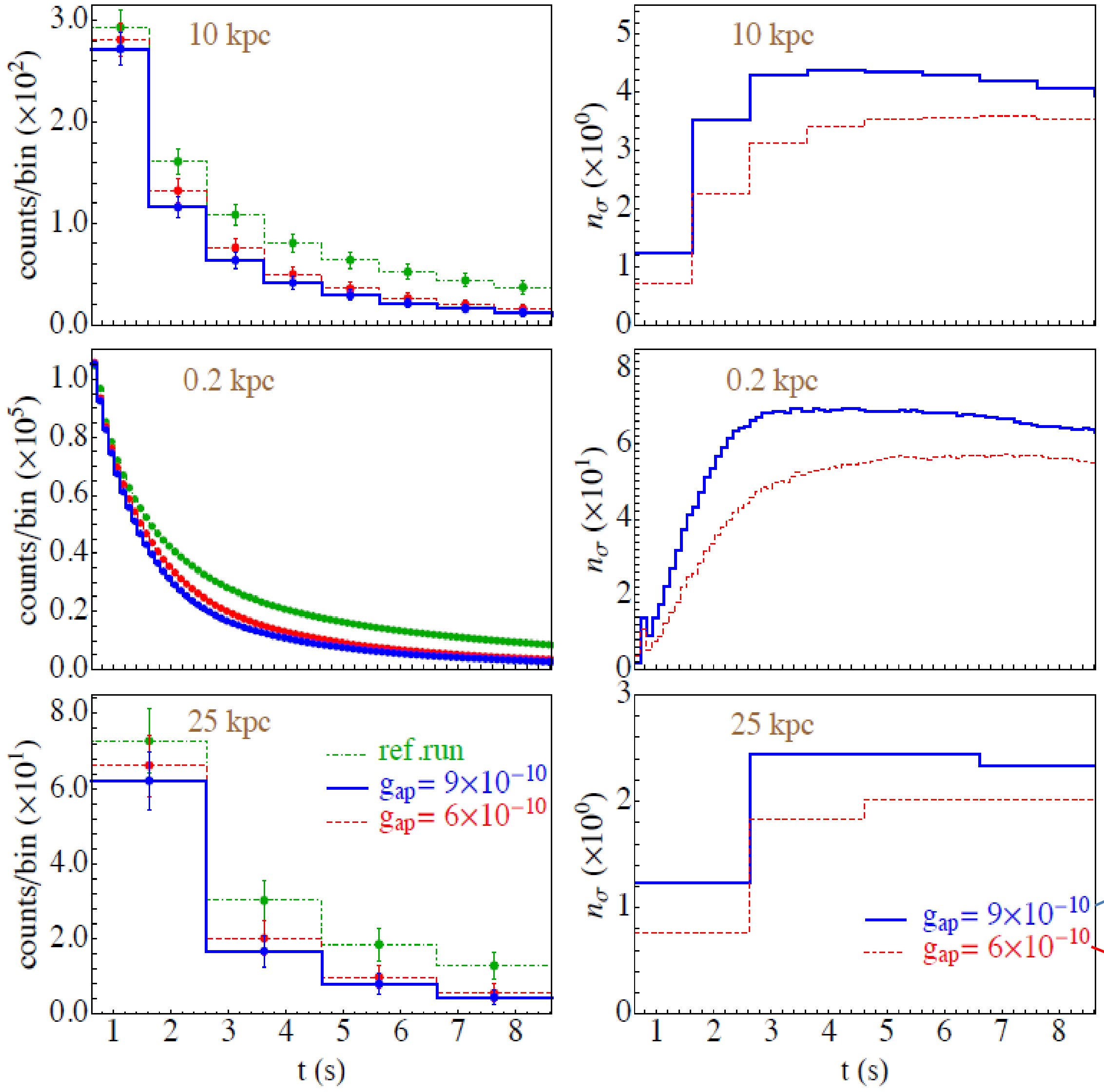
(a) Energy and number luminosities

(b) Average neutrino energies

KSVZ hadronic axion model (g_{an} =0)

IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande



(~ GC)

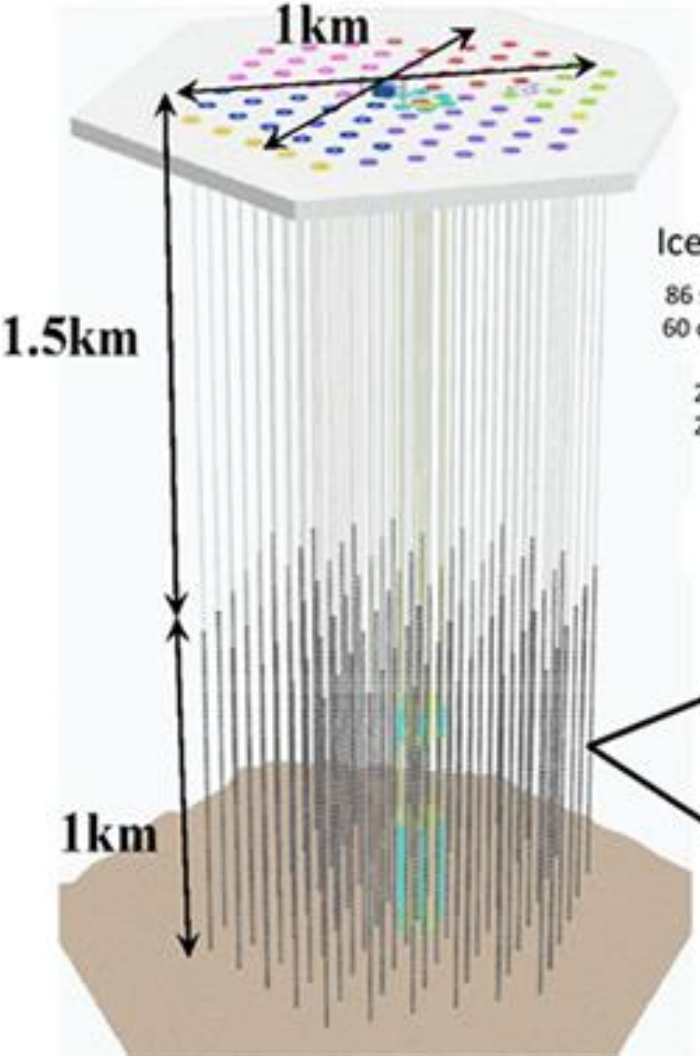
(Betelgeuse)

$m_a = 3 \times 10^{-2}\ eV$,
$f_a = 4.8 \times 10^8 GeV$

$m_a = 8 \times 10^{-2}\ eV$,
$f_a = 7.3 \times 10^8 GeV$

ICECUBE NEUTRINO TELESCOPE AT SOUTH POLE

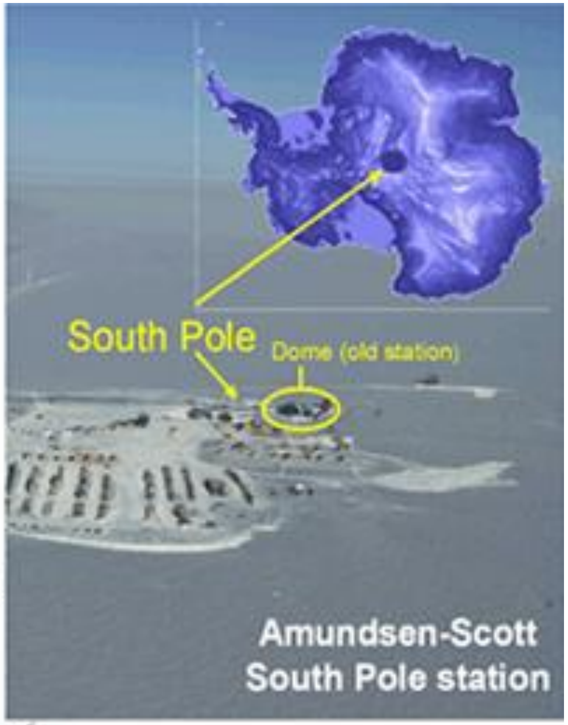
The IceCube Neutrino Telescope



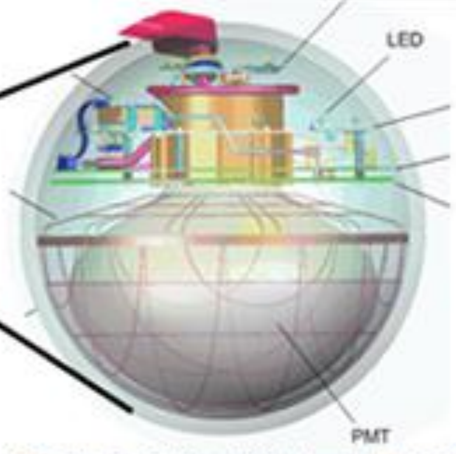
IceCube Array

86 strings including 8 DeepCore strings
60 optical sensors on each string

2004:	Project Start	1 string
2011:	Project completion	86 strings



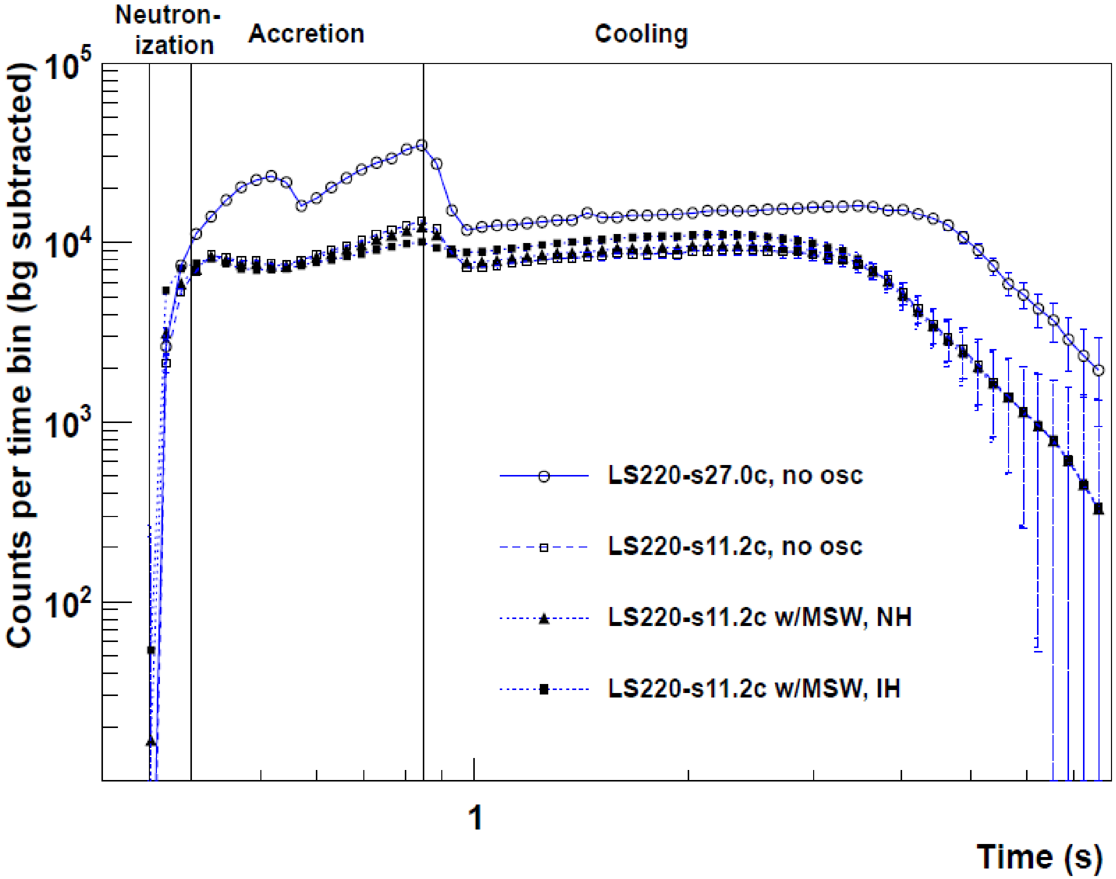
5160 optical sensors



Digital Optical Module (DOM)

SN NU SIGNAL IN ICECUBE

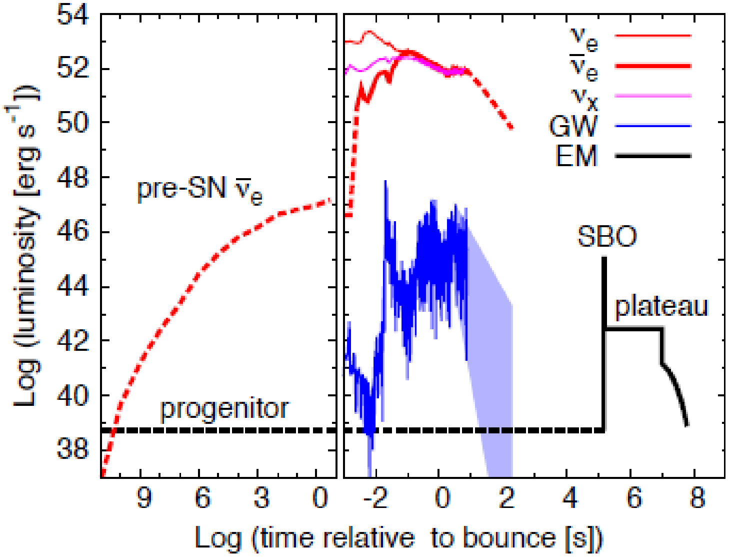
[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



High statistics reconstruction of the nu light curve. Possible to distinguish the different post-bounce phases.

MILLISECOND BOUNCE TIME RECONSTRUCTION

External trigger for GW search



ICECUBE

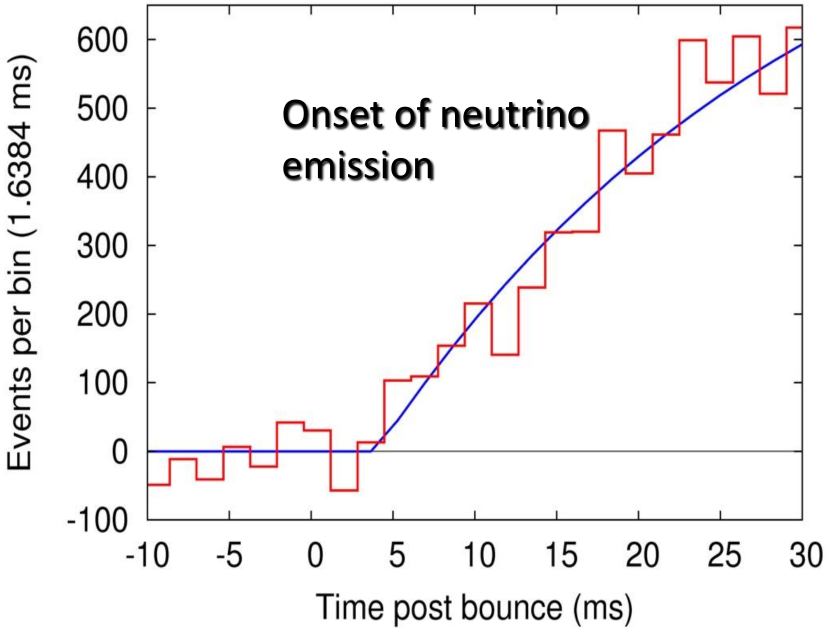
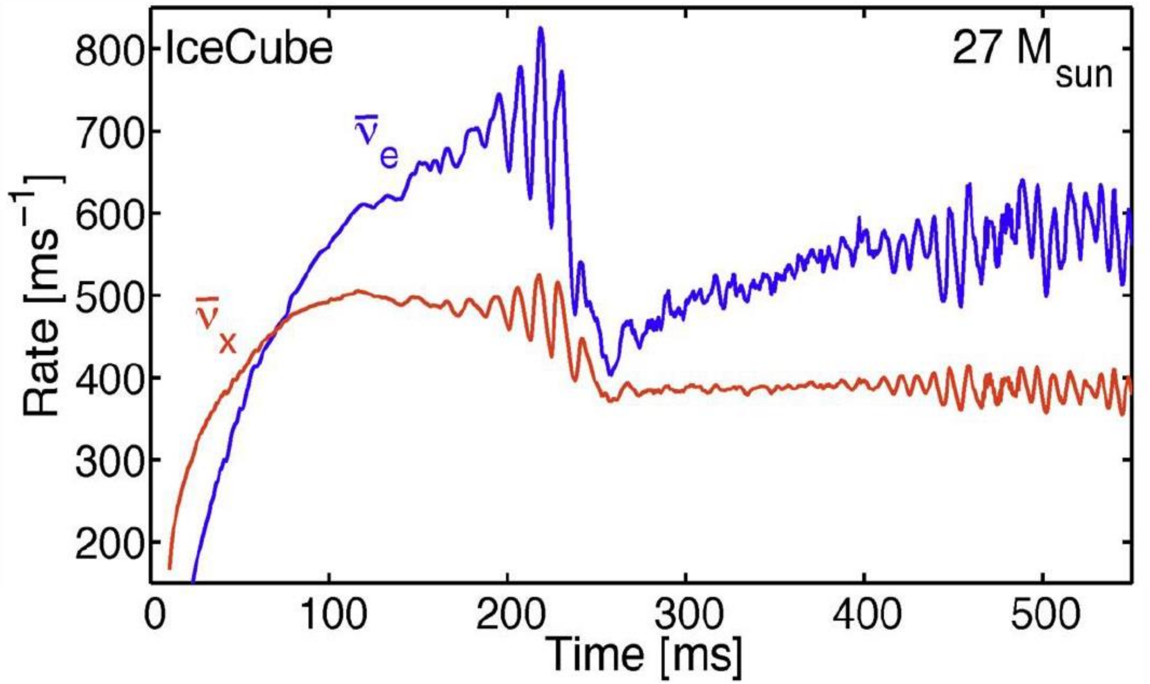


FIG. 1: Typical Monte Carlo realization (red histogram) and reconstructed fit (blue line) for the benchmark case discussed in the text for a SN at 10 kpc.

[Halzen & Raffelt, arXiv:0908.2317]

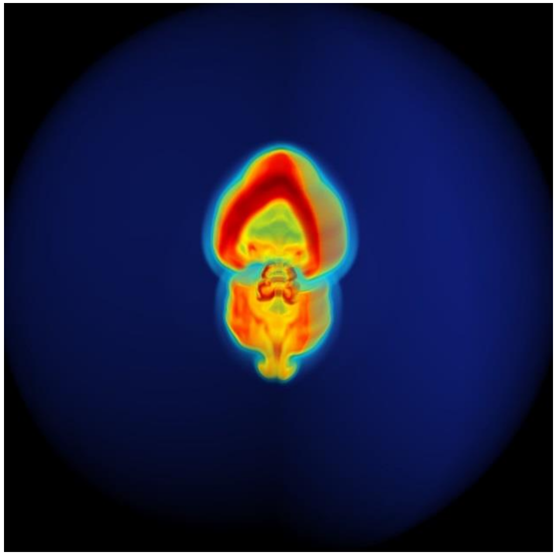
Possible also in Super-K
[see Pagliaroli, Vissani, Coccia & Fulgione arXiv:0903.1191]

SHORT TIME VARIATIONS IN SN ν SIGNAL



Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936

Convective motions lead to large-amplitude oscillations of the stalled shock with a period of ~ 10 ms



Necessary high statistics and high time resolution

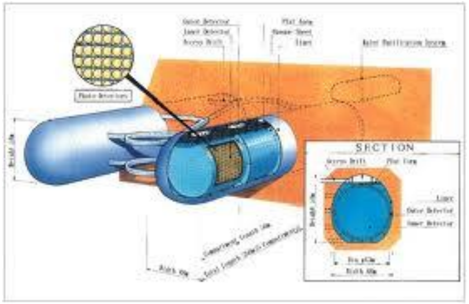
Icecube is ok!

NEXT-GENERATION DETECTORS

Mton scale water Cherenkov detectors

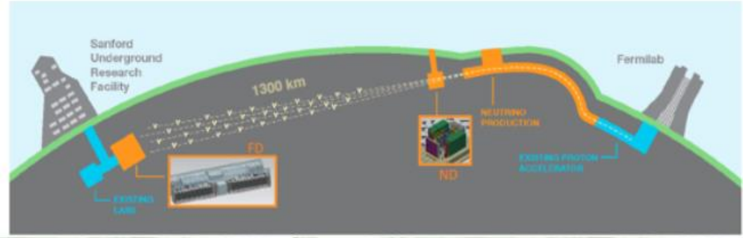
(10^5 events) $(\bar{\nu}_e)$

HYPER-KAMIOKANDE



40 kton Liquid Argon TPC

(3000 events) (ν_e)



DUNE

Dark matter detectors

DARWIN

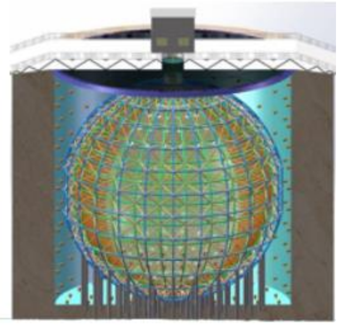
40 tons

(700 events)

$(\nu_{e,x}, \bar{\nu}_{e,x})$

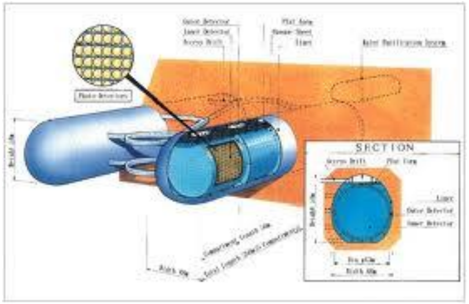
20 kton scintillator

(6000 events) $(\bar{\nu}_e)$

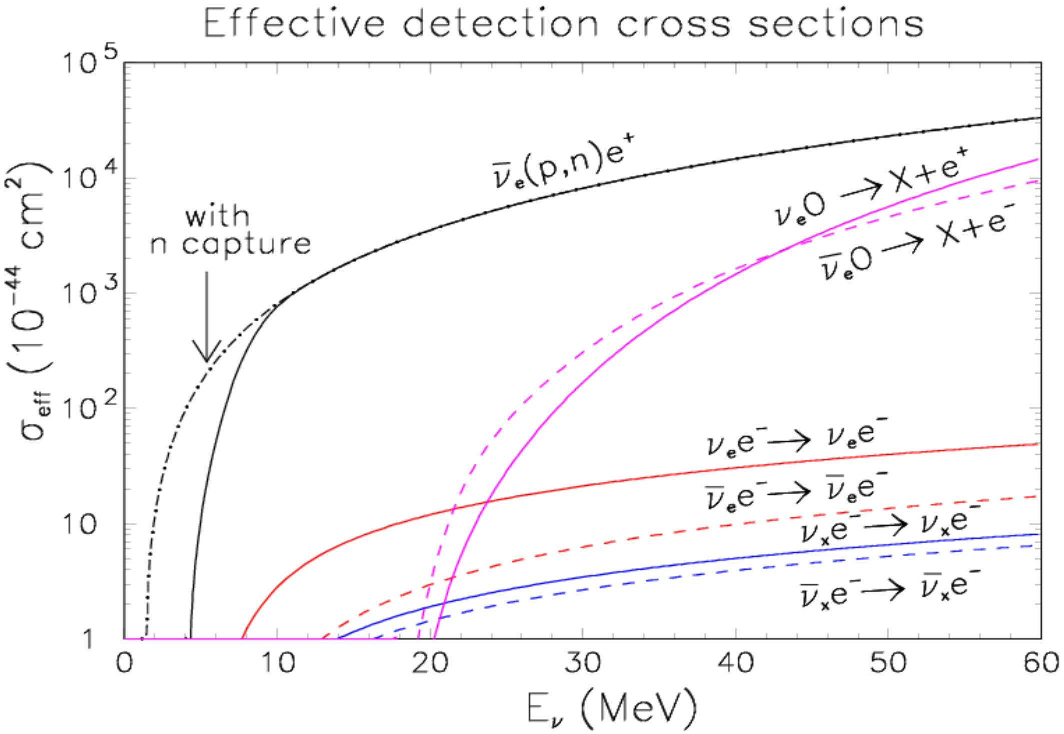


JUNO

0.4 Mton WATER CHERENKOV DETECTOR



HYPER-KAMIOKANDE



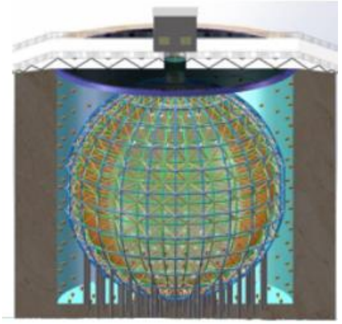
Interactions	# of events @ 10 kpc
$\bar{\nu}_e + p \rightarrow n + e^+$	2×10^5
$\overset{(-)}{\nu}_e + O \rightarrow X + e^{\pm}$	10^4
$\nu + e^- \rightarrow \nu + e^-$	10^3

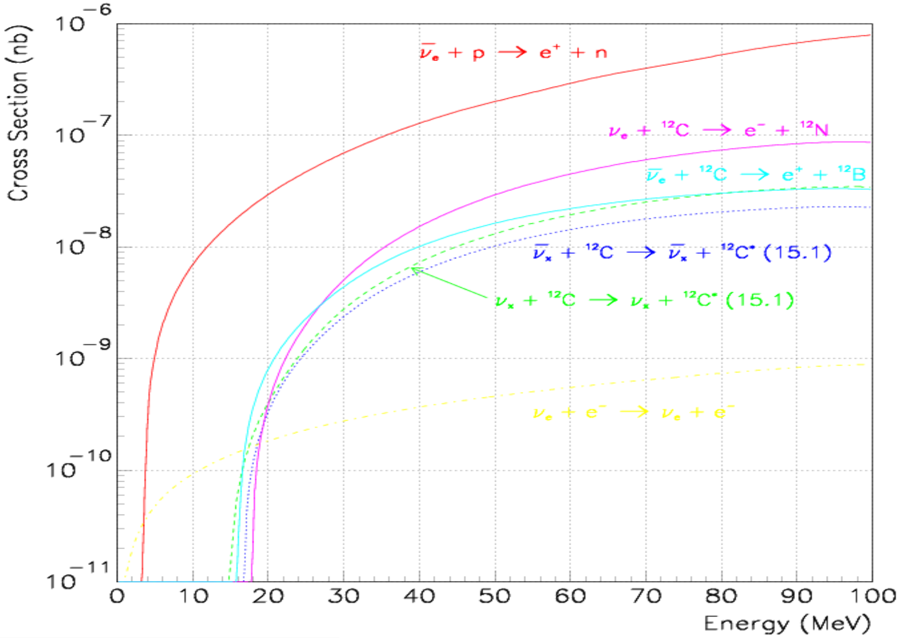
Golden channel:

Inverse beta decay (IBD) of $\bar{\nu}_e$

JUNO: 20 kton LIQUID SCINTILLATOR

JUNO





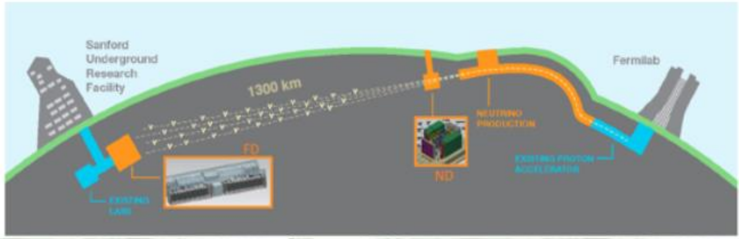
Interactions	# of events at 10 kpc
$\bar{\nu}_e + p \to n + e^+$	4.5×10^3
$\bar{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	250
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	40
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	1.5×10^3
$\nu + e^- \to \nu + e^-$	300

Golden channel:

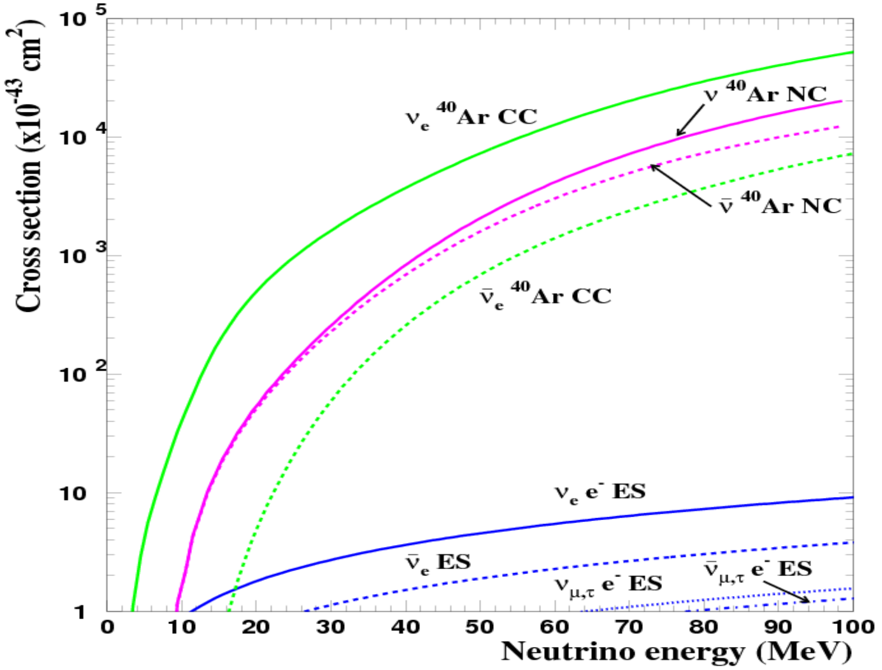
Inverse beta decay (IBD) of $\bar{\nu}_e$

Better energy resolution than a water Cherenkov

DUNE: 40 kton LIQUID ARGON TPC



DUNE



Interactions	# of events @ 10 kpc
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	1×10^4
$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$	400
$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$	1.2×10^4
$\nu + e^- \rightarrow \nu + e^-$	0.4×10^3

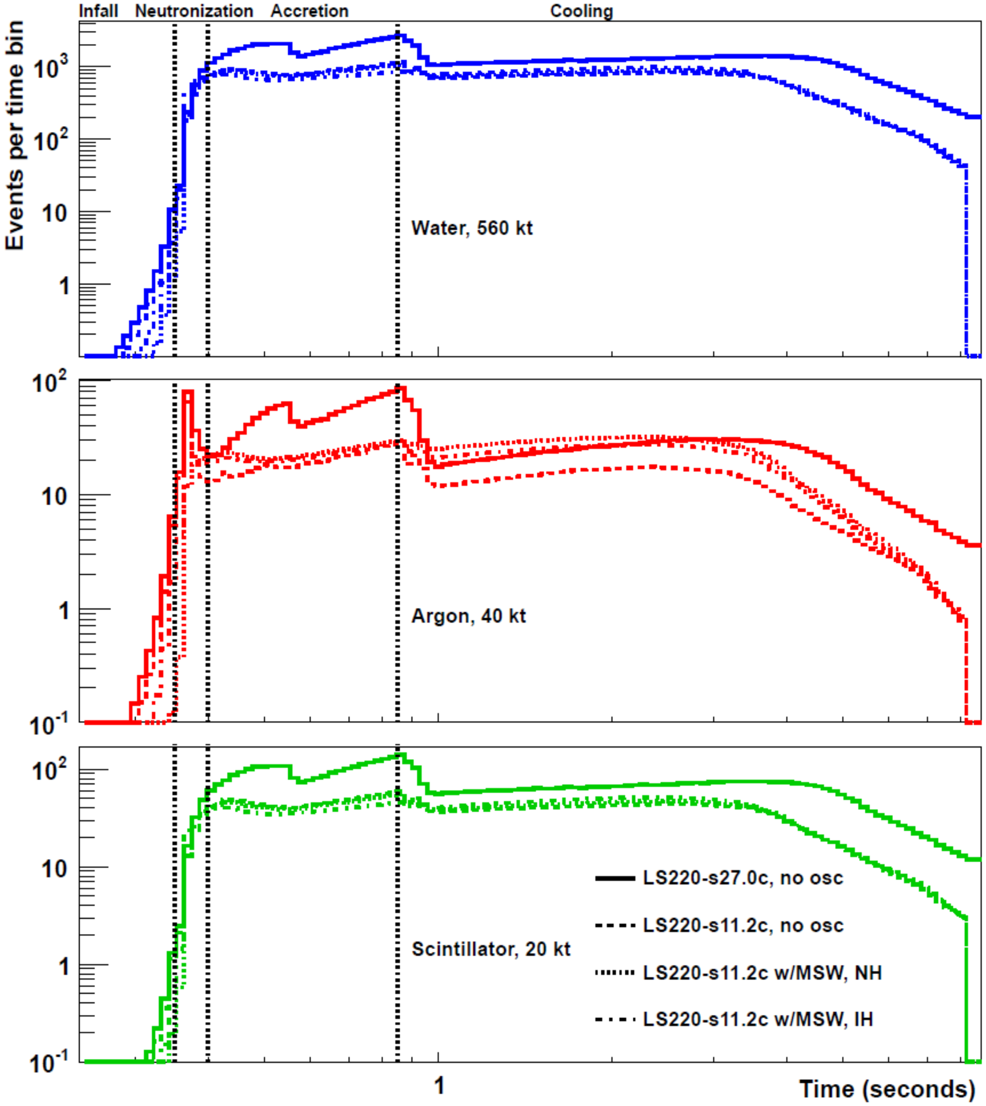
Golden channel:

ν_e *Ar CC*

Complementary to previous techniques

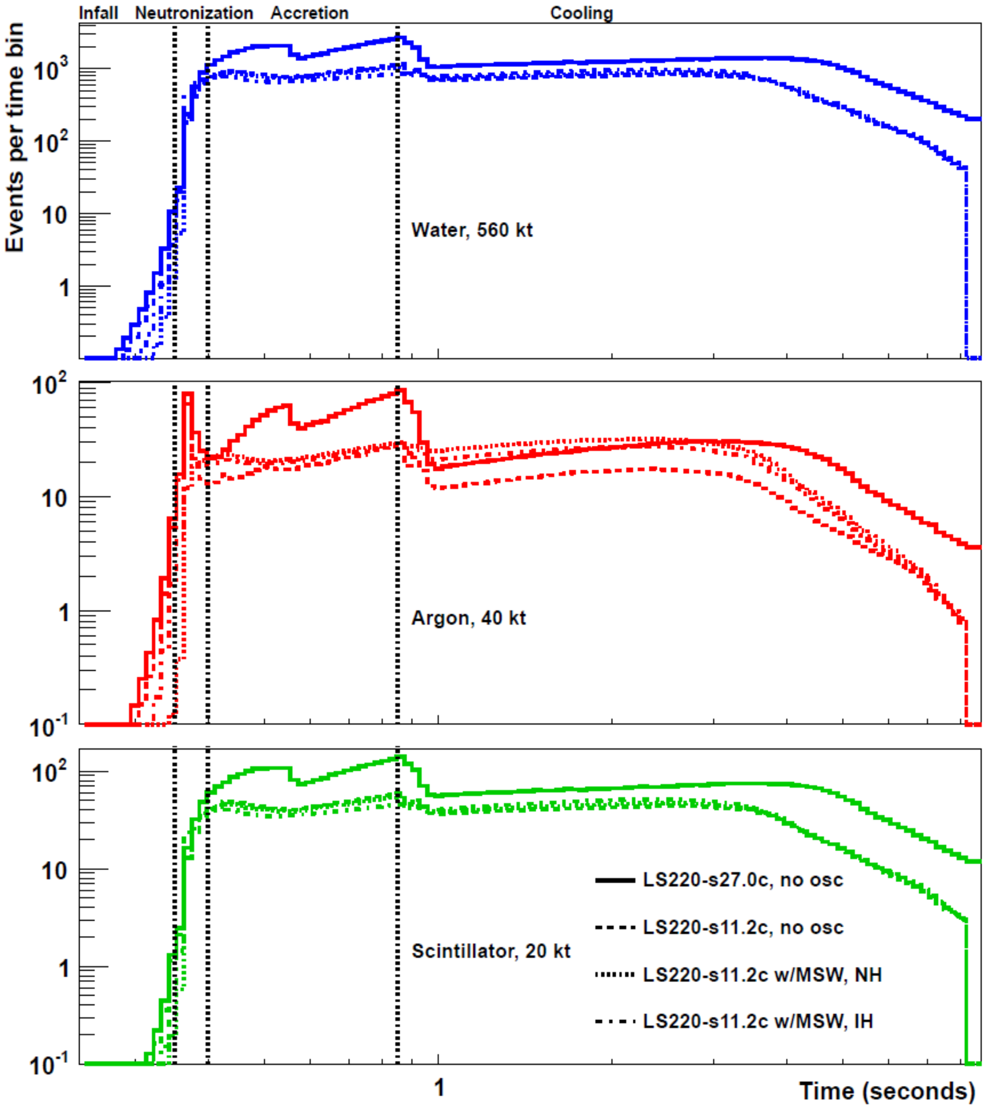
SN NU SIGNAL IN FUTURE DETECTORS

[<u>A.M.</u>, Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



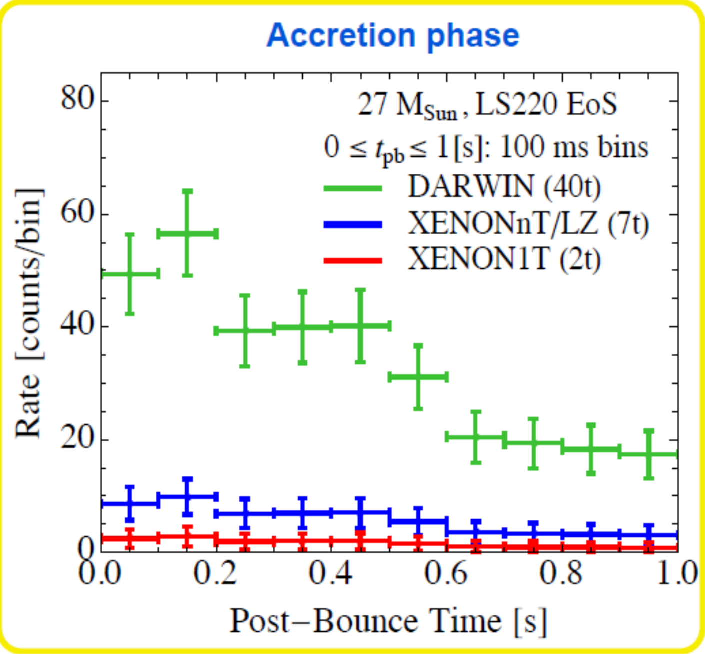
SN NU SIGNAL IN FUTURE DETECTORS

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

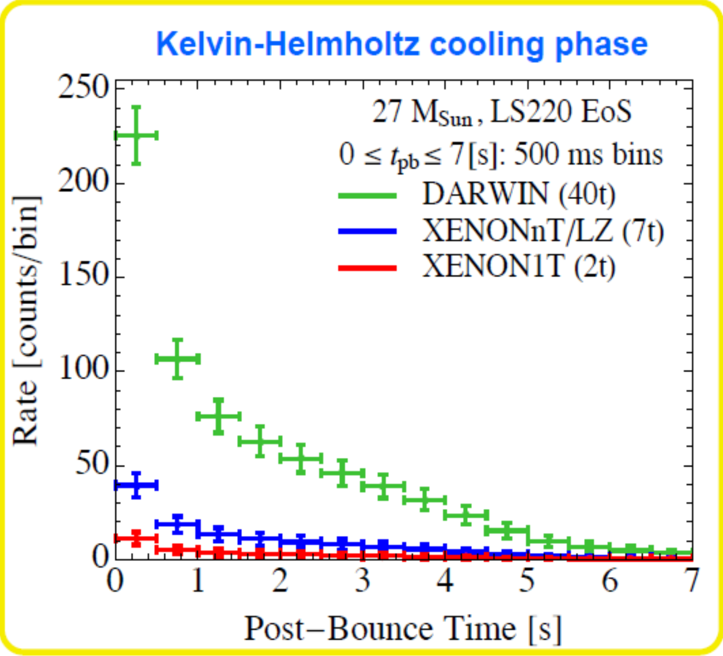


SN NU SIGNAL IN DM DETECTORS

[Lang,McCabe, Reichard, Selvi & Tamborra, arXiv:1606.09243 [astro-ph.HE]]



Accretion phase

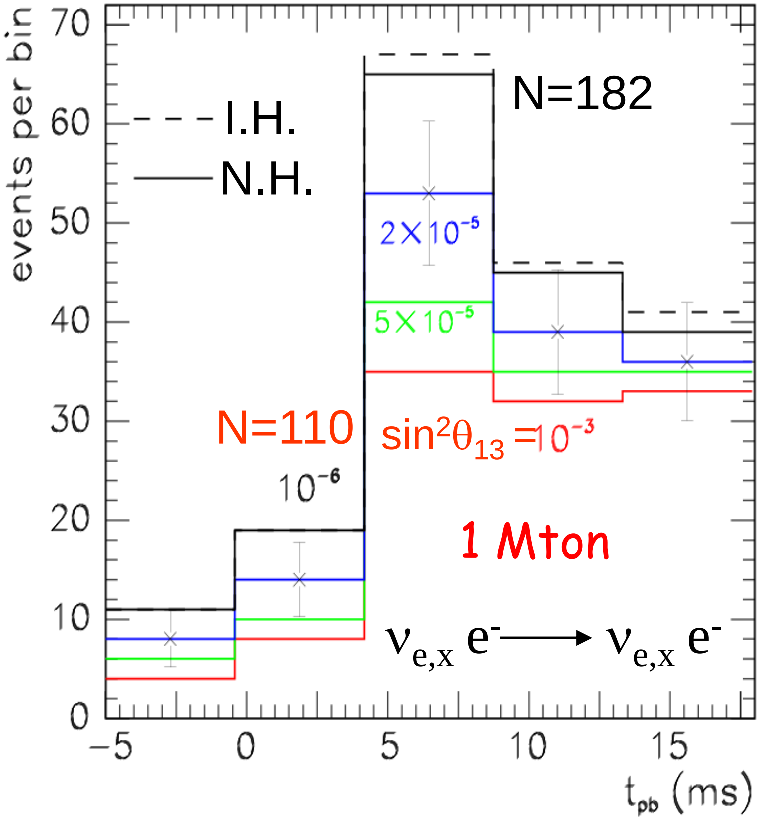


Kelvin-Helmholtz cooling phase

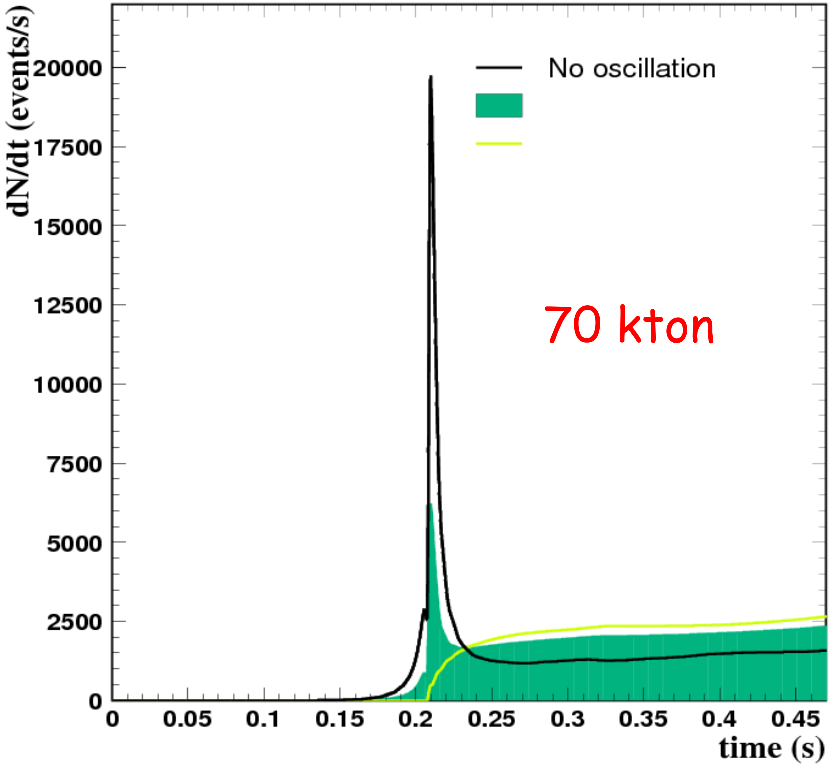
DARWIN will be able to clearly reconstruct the neutrino light-curve and to differentiate among phases of neutrino signal. Partial sensitivity with XENONnT/LZ.

NEUTRONIZATION BURST

WC



Lar TPC ν_e ^{40}Ar CC



[M.Kachelriess & R. Tomas, hep-ph/0412082]

[I.Gil-Botella & A.Rubbia, hep-ph/0307244]

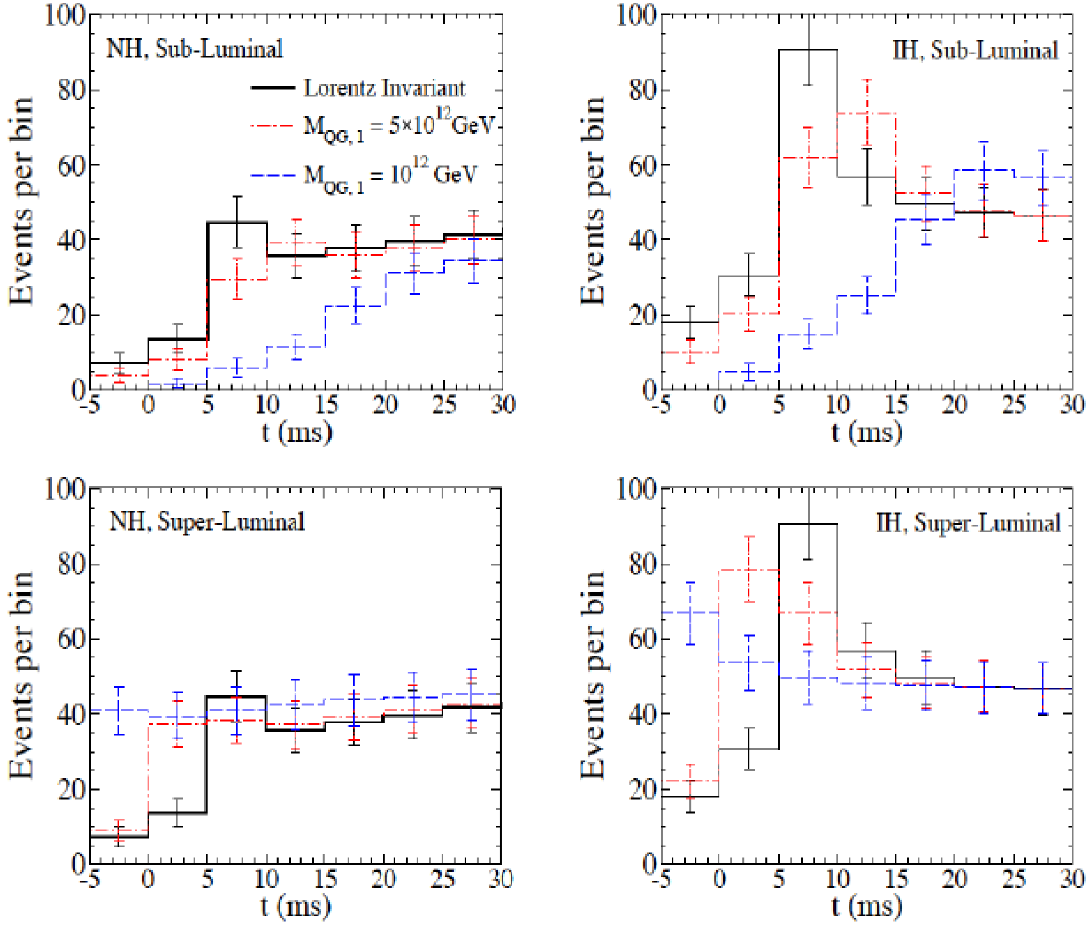
- Robust feature of SN simulations
- Possibility to probe oscillation physics during early stages of a SN
- SN distance measurement (with a precision of ~5 %): N~ $1/d^2$. Useful in case of dust oscuration.

SN Bounds on Neutrino Velocity

Violation of Lorentz invariance

[Ellis et al., 0805.0253 & 1110.4848]

$$\frac{v-c}{c} = \left(\frac{E}{M_{QG}}\right)^{\alpha}$$



The signal would be spread out and shifted in time.

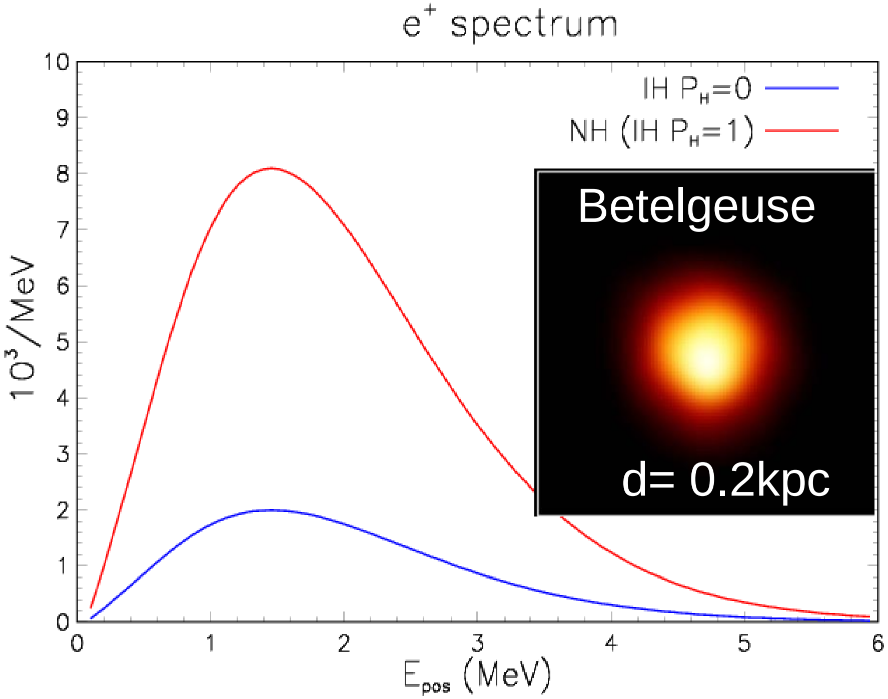
$(v-c)/c < 10^{-14}$ for linear Lorentz violation
$(v-c)/c < 10^{-8}$ for quadratic Lorentz violation

[Chakraborty, Mirizzi & Sigl, 1211.7069]

Silicon burning: SN self-alert

[A. Odrzywolek, M. Misiaszek, and M. Kutschera, astro-ph/0311012]

During the last stage of a pre-supernova star, while the Silicon core ignites, n's are produced copiously by $e^+ e^- \longrightarrow \nu \bar{\nu}$.



Detection reaction: $\bar{\nu}_e p \longrightarrow n\, e^+$

For Betelgeuse (d=0.2kpc) will be ~10^4 e^+ in NH (~2.5×10^3 in IH, P_H=0)

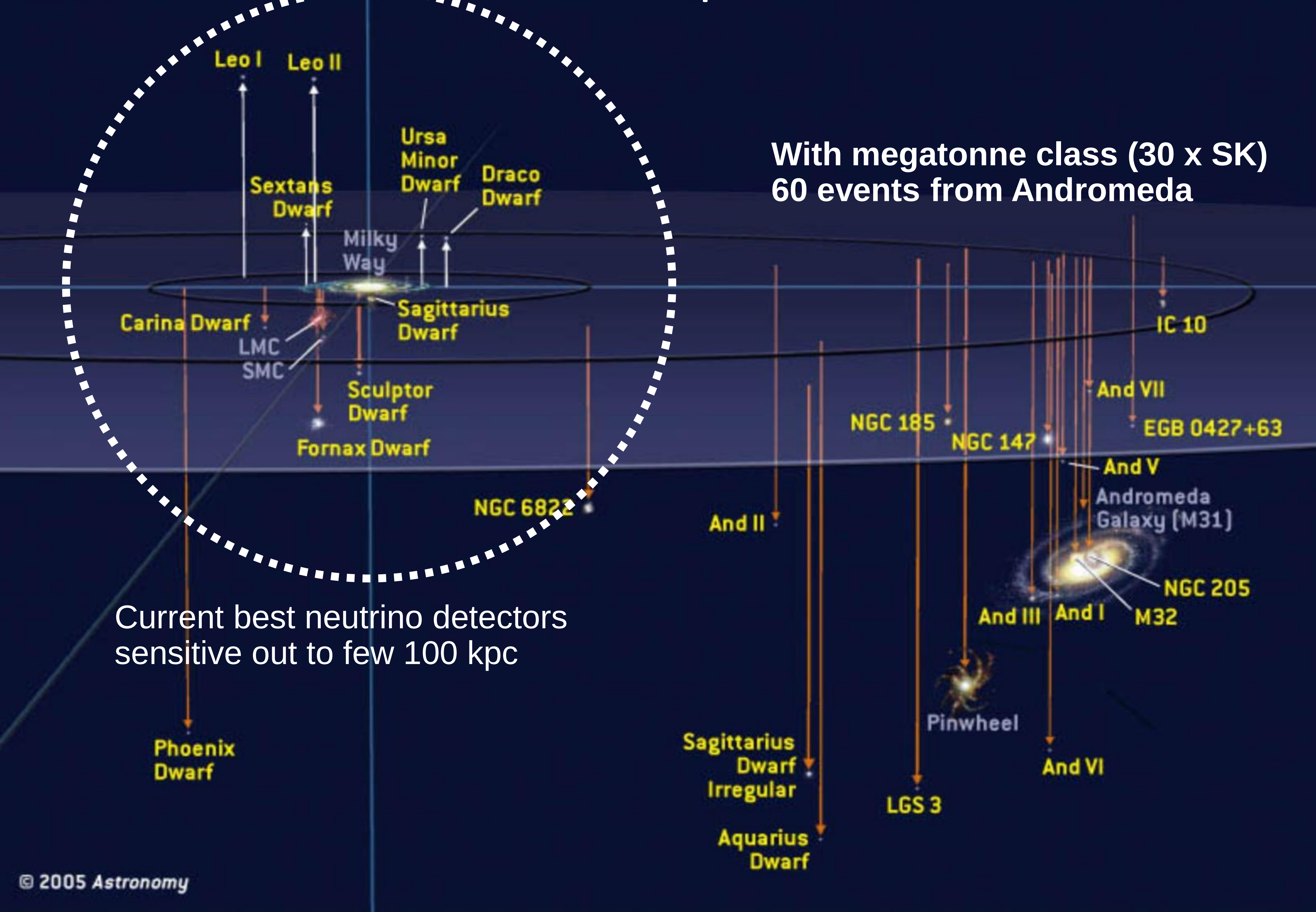
The detection of e^+ is very difficult (because of the threshold E_{TH} = 7 MeV), however ….

…. Adding gadolinium [J.F.Beacom, and M.R.Vagins, "*GADZOOKS! Antineutrino Spectroscopy with Large Water Cerenkov Detectors*", hep-ph/0309300], it would be possible to detect the associated neutron, but only for very close stars (d $\lesssim$ 2 kpc) because of the high neutron background (~2500 ev/day).

Possibility to "foresee" the SN collapse (for close by Supernovae)

NEUTRINOS FROM ALL COSMIC SUPERNAVAE

Local Group of Galaxies



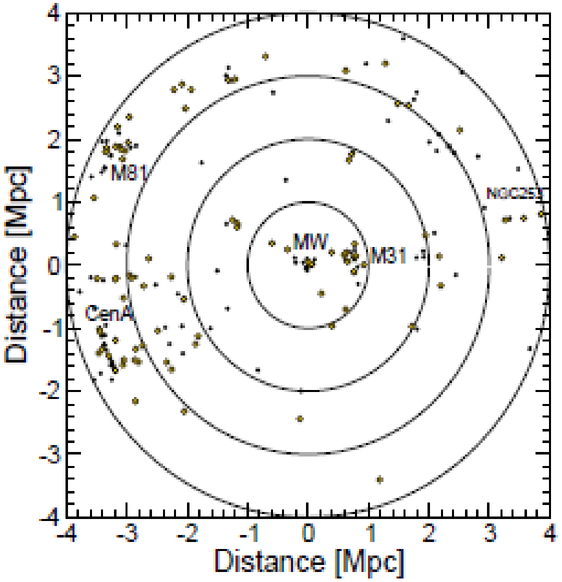
With megatonne class (30 x SK)
60 events from Andromeda

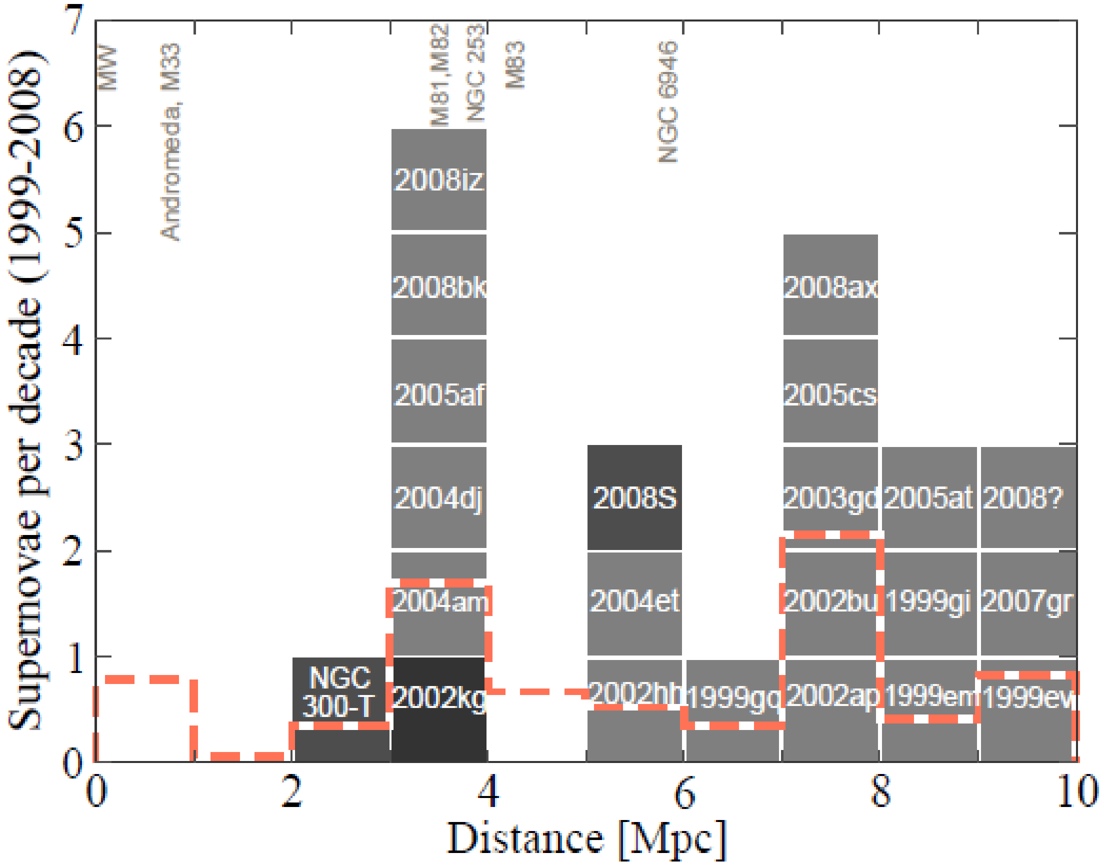
Current best neutrino detectors sensitive out to few 100 kpc

© 2005 Astronomy

OBSERVED SUPERNOVAE IN THE LOCAL UNIVERSE

[Kistler, Yuksel, Ando, Beacom & Suzuki, 0810.1959]



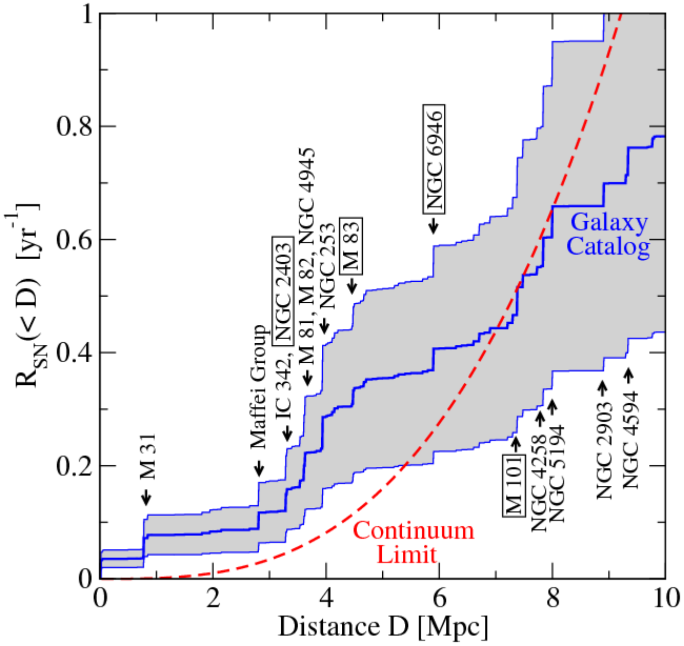


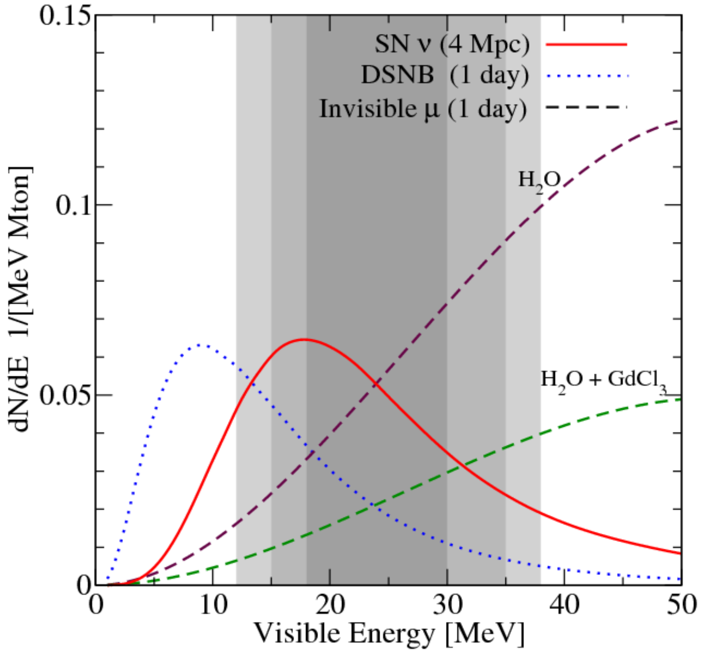
Detection of Neutrinos from Supernovae in Nearby Galaxies

[S. Ando, J. Beacom, and Y. Yuksel, astro-ph/0503321]

Mton Cherenkov

Cumulative SN rate





Reconstruction of SN neutrino spectrum by the patient accumulation of ~1 neutrino per supernova from galaxies within 10 Mpc, in which one expects at least 1(2) SN per year.

NEUTRINO EVENTS RATE FROM EXTRAGALACTIC SNe

[Kistler et al., 0810:1959]

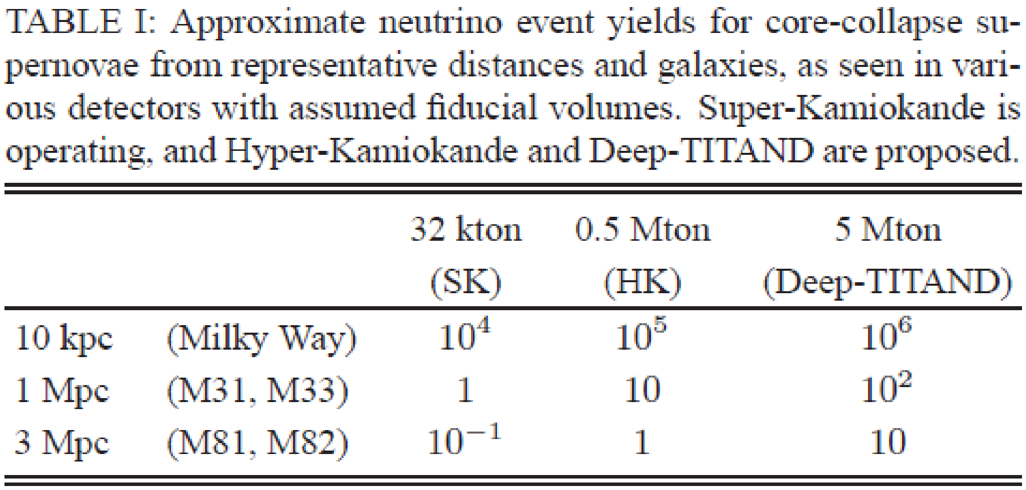


TABLE I: Approximate neutrino event yields for core-collapse supernovae from representative distances and galaxies, as seen in various detectors with assumed fiducial volumes. Super-Kamiokande is operating, and Hyper-Kamiokande and Deep-TITAND are proposed.

		32 kton (SK)	0.5 Mton (HK)	5 Mton (Deep-TITAND)
10 kpc	(Milky Way)	10^4	10^5	10^6
1 Mpc	(M31, M33)	1	10	10^2
3 Mpc	(M81, M82)	10^{-1}	1	10

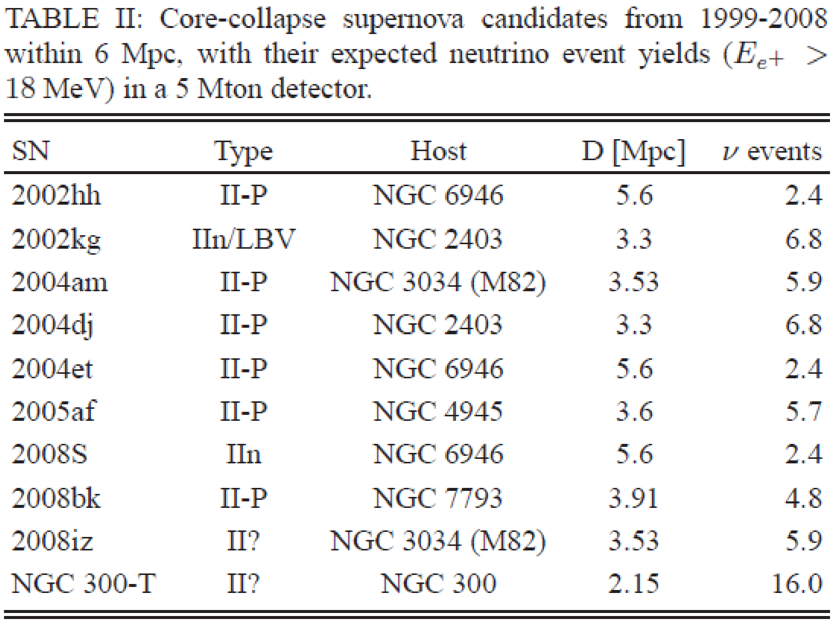
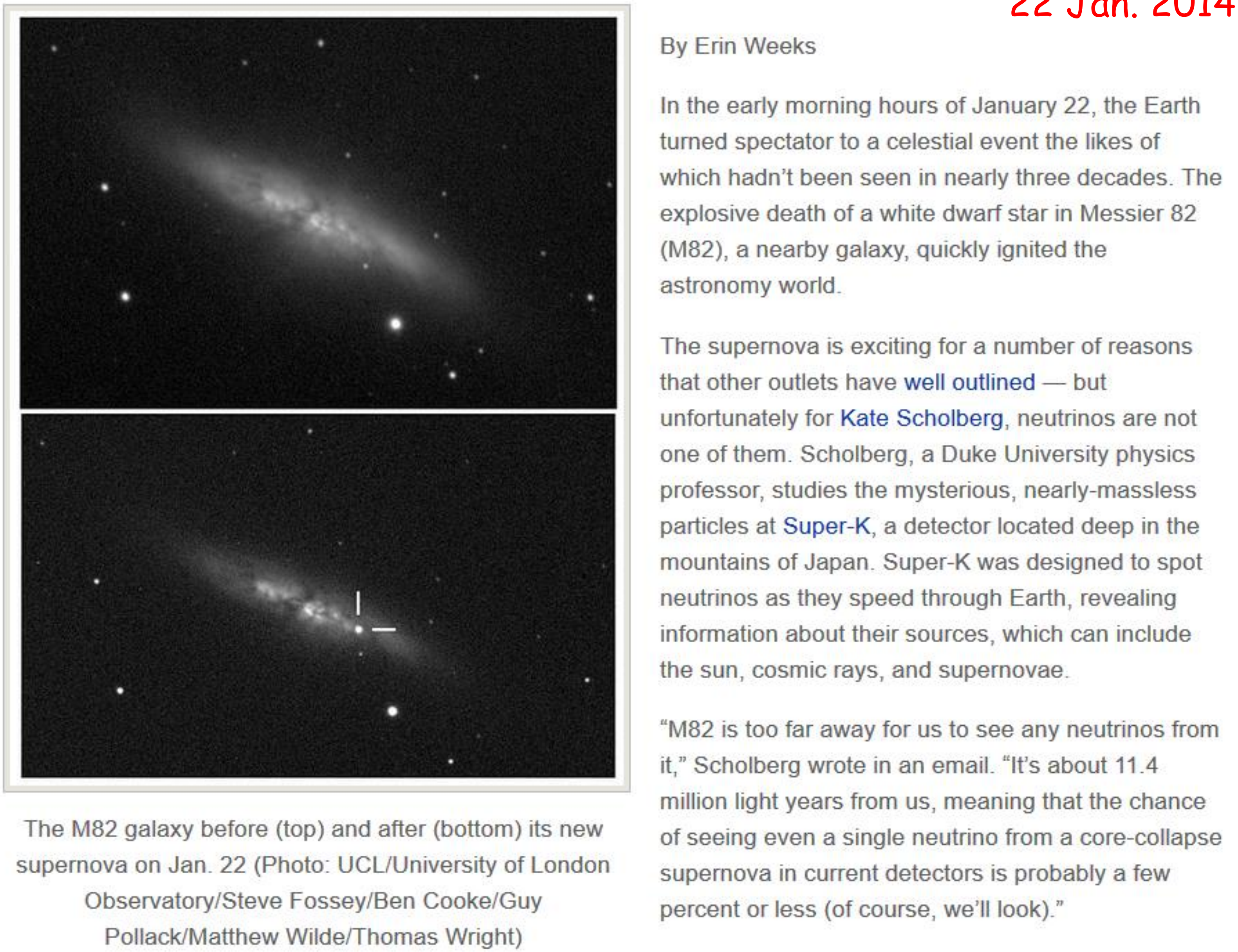


TABLE II: Core-collapse supernova candidates from 1999-2008 within 6 Mpc, with their expected neutrino event yields ($E_{e^+} > 18$ MeV) in a 5 Mton detector.

SN	Type	Host	D [Mpc]	ν events
2002hh	II-P	NGC 6946	5.6	2.4
2002kg	IIn/LBV	NGC 2403	3.3	6.8
2004am	II-P	NGC 3034 (M82)	3.53	5.9
2004dj	II-P	NGC 2403	3.3	6.8
2004et	II-P	NGC 6946	5.6	2.4
2005af	II-P	NGC 4945	3.6	5.7
2008S	IIn	NGC 6946	5.6	2.4
2008bk	II-P	NGC 7793	3.91	4.8
2008iz	II?	NGC 3034 (M82)	3.53	5.9
NGC 300-T	II?	NGC 300	2.15	16.0

Supernova Explosion in M82: Exciting, but No Neutrinos

22 Jan. 2014



The M82 galaxy before (top) and after (bottom) its new supernova on Jan. 22 (Photo: UCL/University of London Observatory/Steve Fossey/Ben Cooke/Guy Pollack/Matthew Wilde/Thomas Wright)

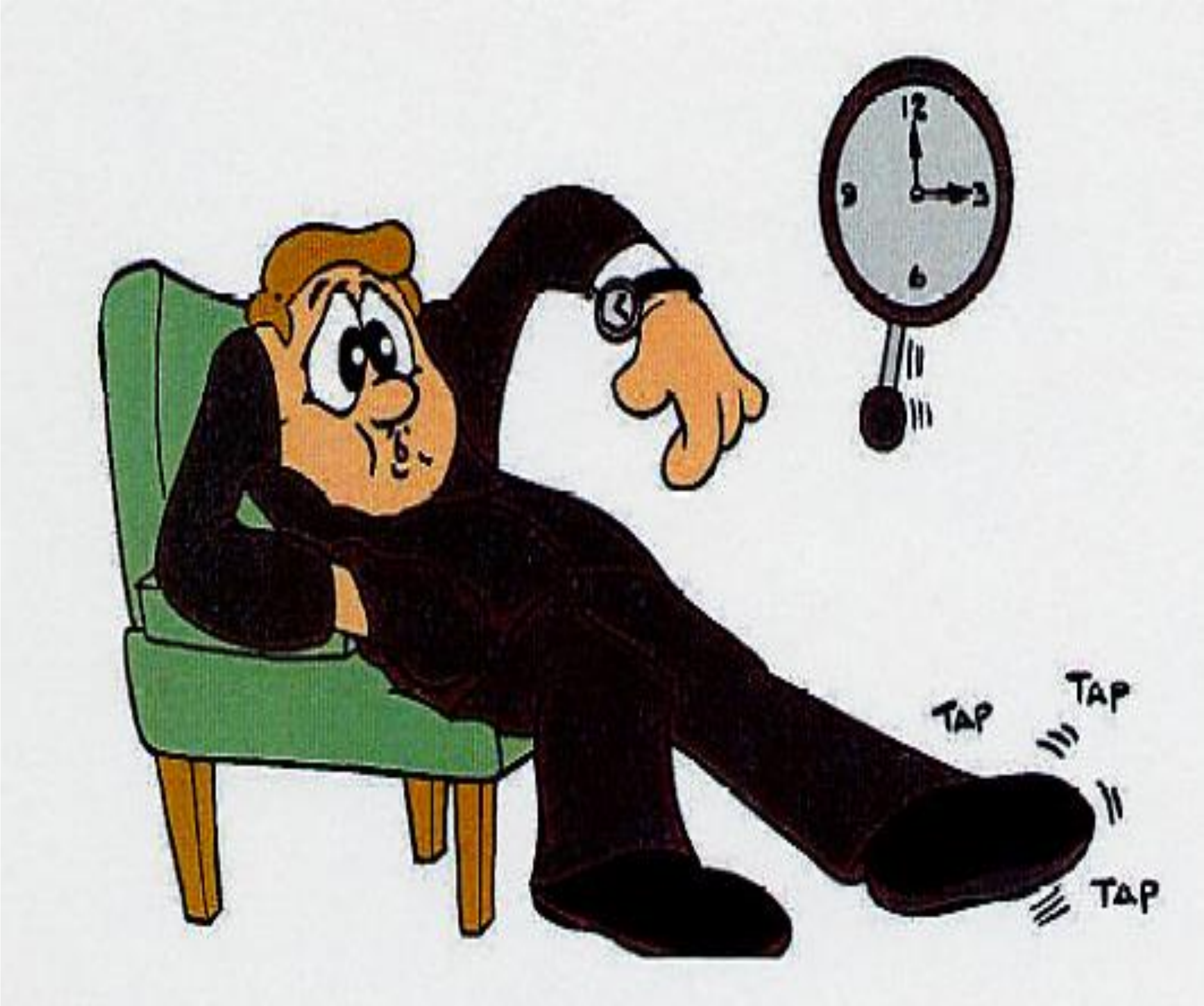
By Erin Weeks

In the early morning hours of January 22, the Earth turned spectator to a celestial event the likes of which hadn't been seen in nearly three decades. The explosive death of a white dwarf star in Messier 82 (M82), a nearby galaxy, quickly ignited the astronomy world.

The supernova is exciting for a number of reasons that other outlets have well outlined — but unfortunately for Kate Scholberg, neutrinos are not one of them. Scholberg, a Duke University physics professor, studies the mysterious, nearly-massless particles at Super-K, a detector located deep in the mountains of Japan. Super-K was designed to spot neutrinos as they speed through Earth, revealing information about their sources, which can include the sun, cosmic rays, and supernovae.

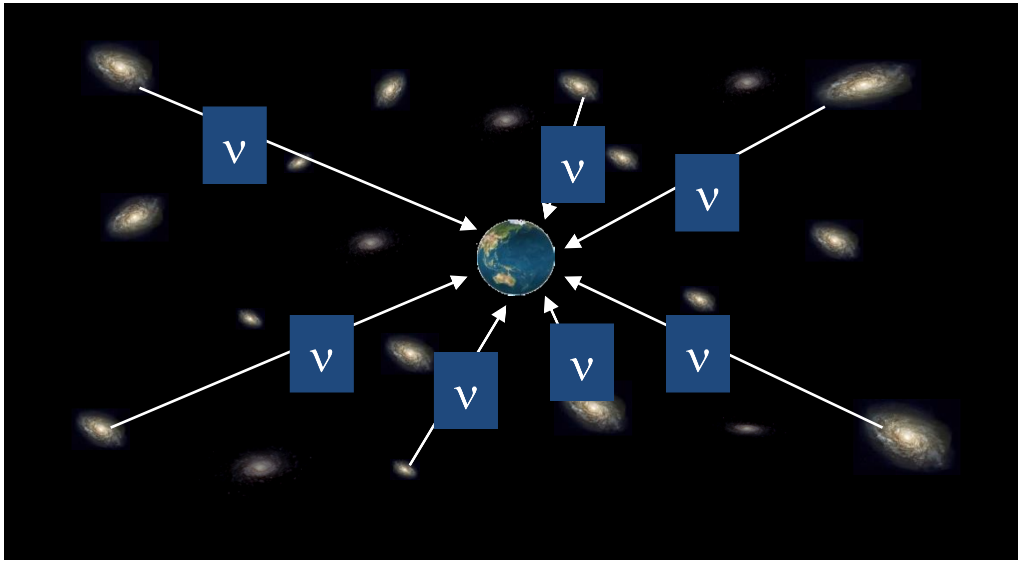
"M82 is too far away for us to see any neutrinos from it," Scholberg wrote in an email. "It's about 11.4 million light years from us, meaning that the chance of seeing even a single neutrino from a core-collapse supernova in current detectors is probably a few percent or less (of course, we'll look)."

A galactic SN explosion is a spectacular event which will produce an enormous number of detectable ν, but it is a <u>rare</u> event (~ 3/century) …



.... Conversly, there is a guaranteed ν background produced by all the past Supernovae in the Universe, but leading to much less detectable events.

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND (DSNB)



WHAT CAN WE LEARN FROM DSNB?

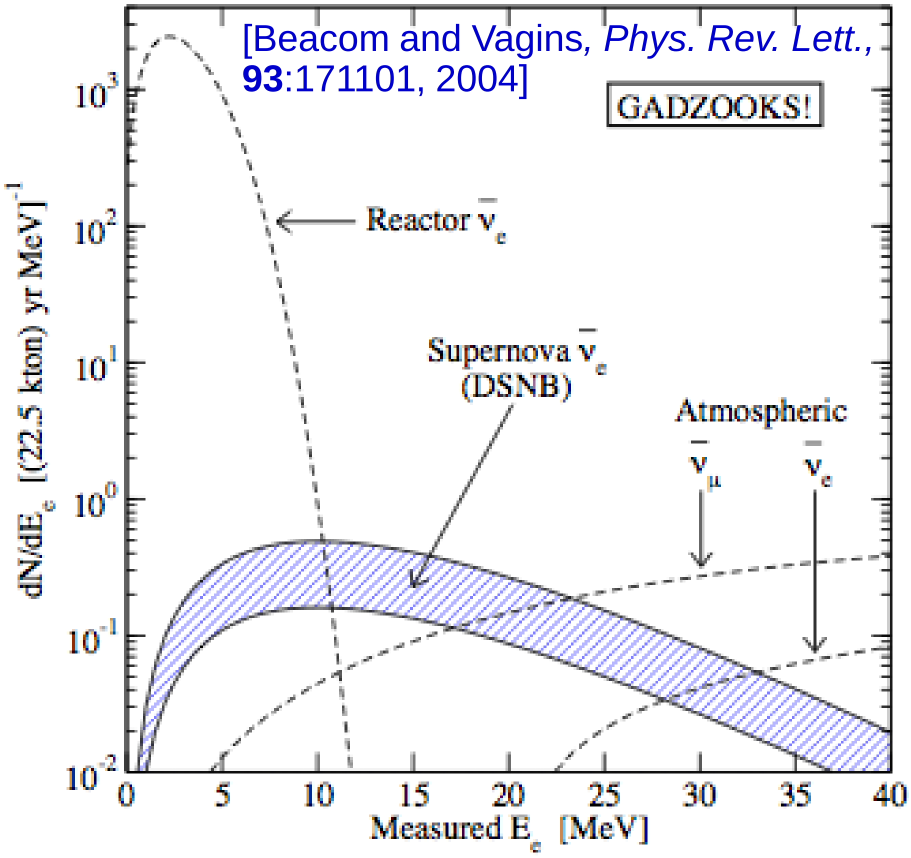
In principle, we can extract information on:

- **Star formation rate**
- **Neutrino masses and mixing parameters**
- **SN neutrino energies**

… not all at the same time, however!

(degeneracy of effects)

BACKGROUND IN SK FOR DSNB SIGNAL


[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

Below ~15–20 MeV, bkgd dominated by spallation products (made by atmospheric μ) and by reactor $\bar{\nu}_e$.

For $E_\nu \in$ [20-30] MeV, the bkg of low-energy atmospheric $\bar{\nu}_e$ is relatively small.

But, in this window, there is a large background due to “invisible” μ (i.e. below Cherenkov emission threshold) decay products, induced by low energy atmospheric ν_μ and $\bar{\nu}_\mu$.

DSNB signal should manifest as distortion of the bkg spectra.

No distortion → flux limit

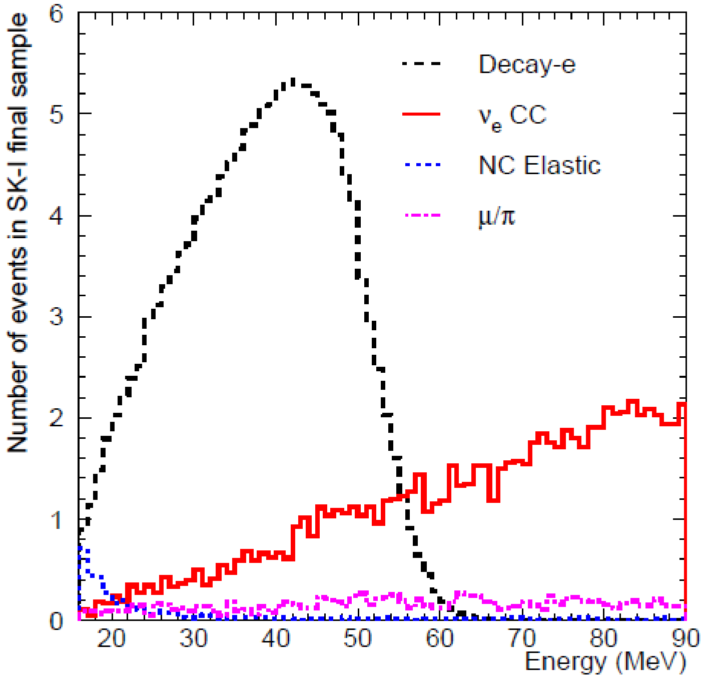


FIG. 11. Spectra of the four remaining backgrounds in the signal Cherenkov angle region with all reduction cuts applied. The ν_μ CC channel is from decay electron data; the other three are from MC. All are scaled to the SK-I LMA best fit result.

DSNB signal should manifest as distortion of the bkg spectra.

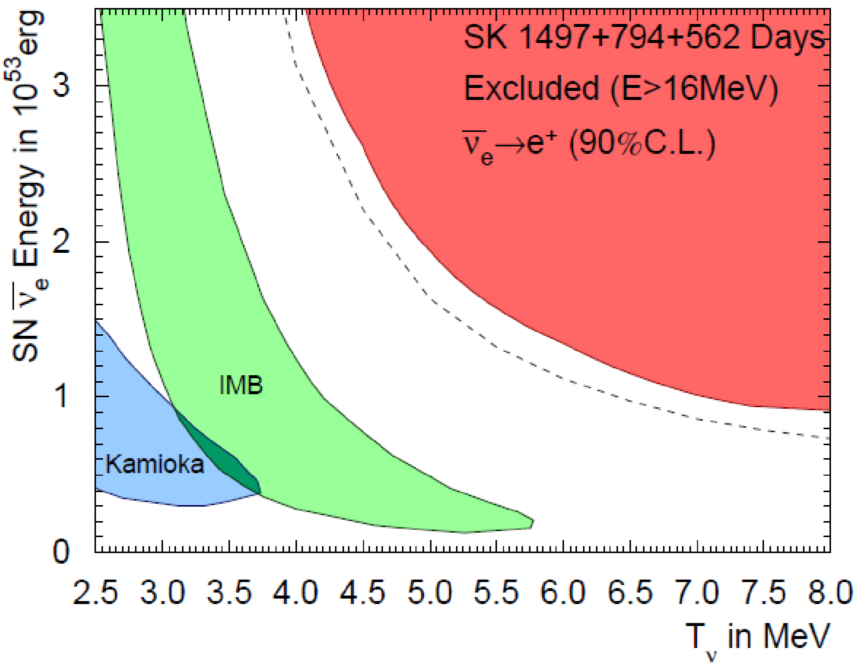
No distortion ⟶ flux limit

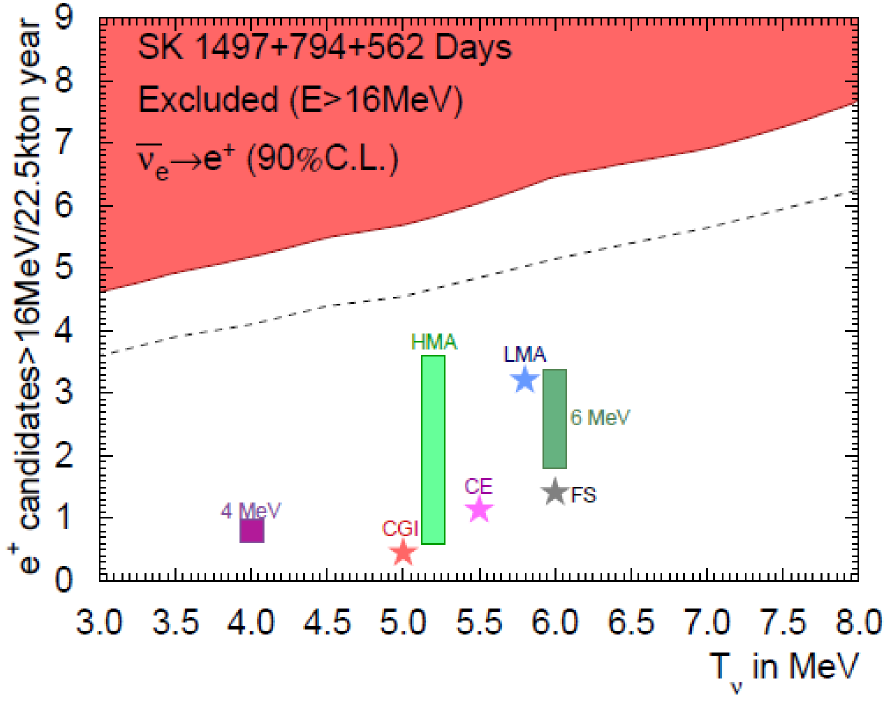
Super-Kamiokande collaboration recently investigated the DSNB flux using 2853 days of data [Bays et al., arXiV:1111:5031]. It fixed an upper bound on DSNB signal:

$$J_{\bar{\nu}_e} \leq 3\ \mathrm{cm}^{-2}\ \ \mathrm{s}^{-1}$$

SN NEUTRINO EMISSION LIMIT FROM DSNB

[Bays et al., arXiV:1111.5031, see also Vissani & Pagliaroli, 1102.0447]





The SK limit is close to the most recent theoretical predictions

… but
Super-K is background limited.

DSNB SIGNAL

The DSNB event rate spectrum, in units s^{-1} MeV^{-1}, is

$$\frac{dN_{vis}}{dE_{vis}}(E_{vis}) = \int_0^\infty [R_{SN}(z)][(1+z)\varphi[E_\nu(1+z)]][N_T\sigma(E_\nu)]\left[\left|\frac{c\,dt}{\mathrm{dz}}\right|dz\right]$$

comoving cosmic core-collapse rate, in units Mpc^{-3} yr^{-1}

average time-integrated emission per supernova, in units MeV^{-1}; redshift reduces emitted energies and compresses spectra

the number of targets X the detection cross section

Differential distance

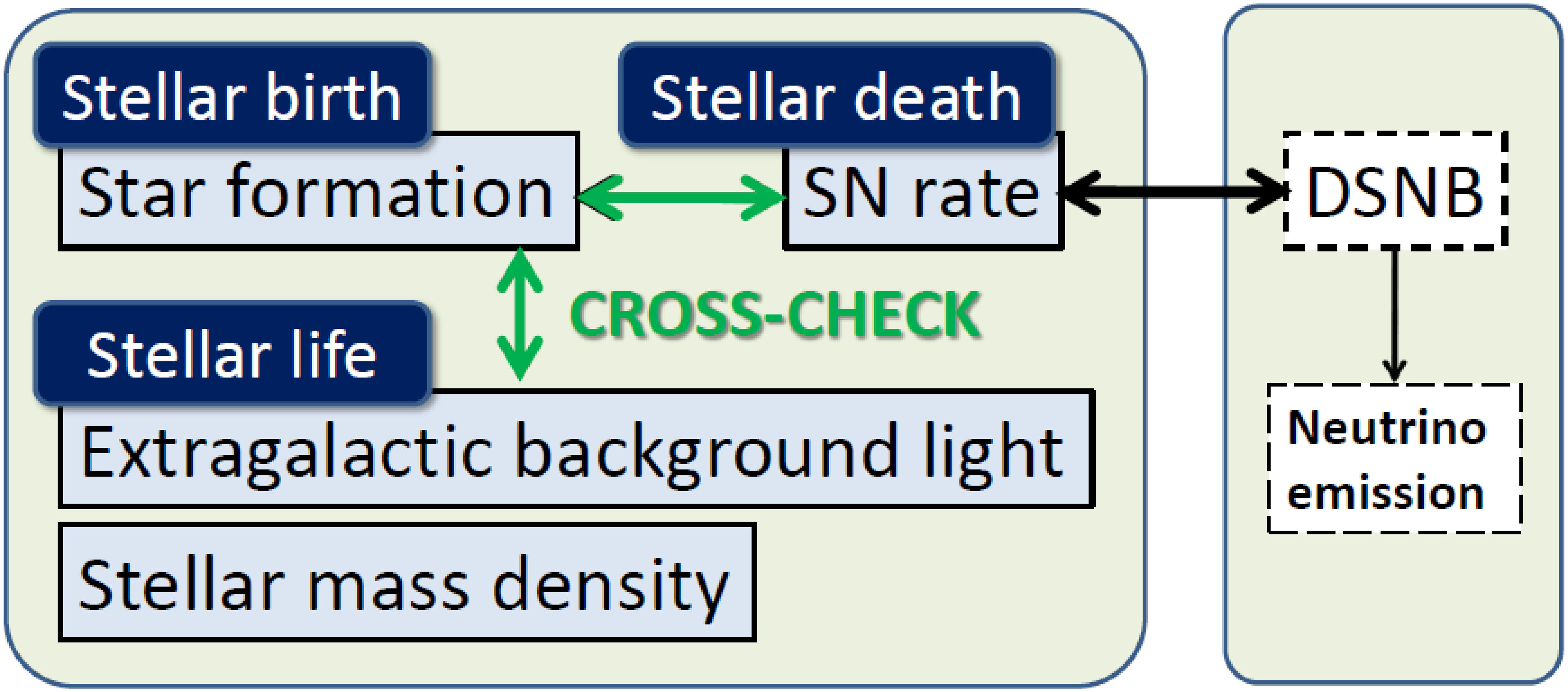
$$\left|\frac{dt}{dz}\right|^{-1} = H_0(1+z)\left[\Omega_\Lambda + \Omega_m(1+z)^3\right]^{1/2}$$

$$H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$\Omega_m = 0.3, \Omega_\Lambda = 0.7$$

Information Flow

[Totani et al. (1998), Fukugita&Kawasaki (2003), Ando (2004), Hopkins&Beacom (2006)]



Stellar birth

Star formation

Stellar death

SN rate

DSNB

Neutrino emission

CROSS-CHECK

Stellar life

Extragalactic background light

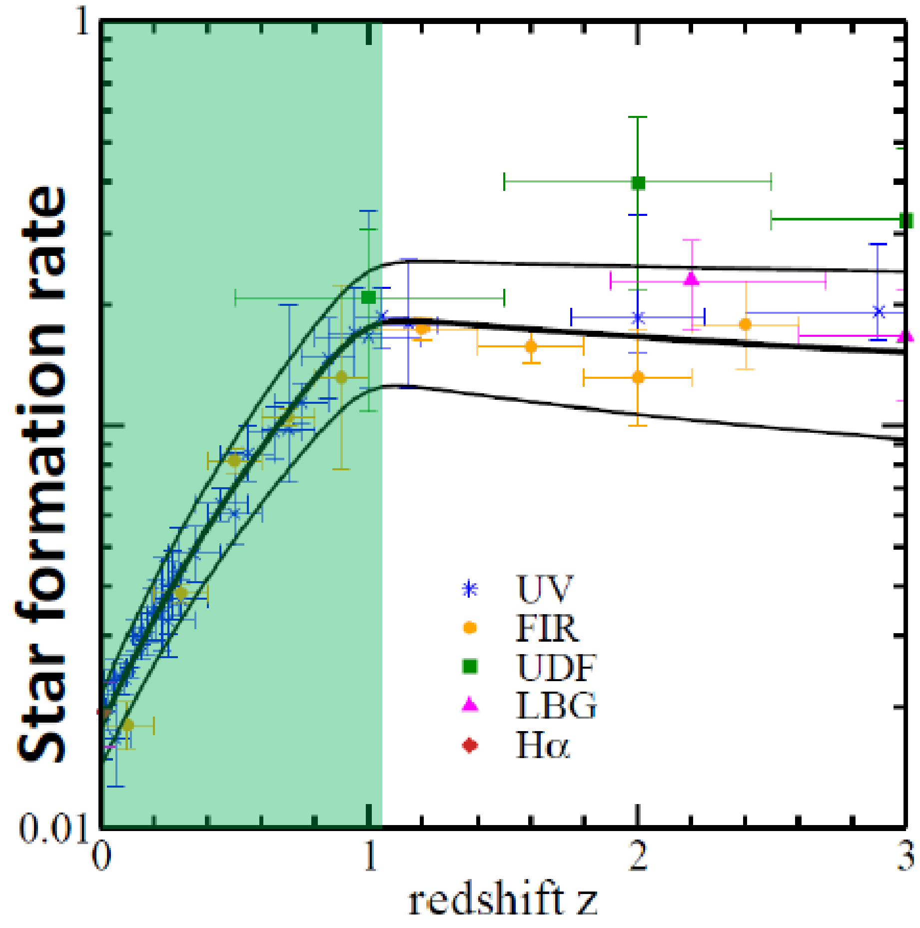
Stellar mass density

☐ ***QUESTIONS*:**

1. **When can we detect the DSNB?**
2. **Can the DSNB be used to study stellar/neutrino physics?**

Star Formation Rate

[Horiuchi et al. (2008)]



[Hopkins (2004), Hopkins&Beacom (2006), Yuksel et al. (2008)]

- ☐ **Determination**
  1. **Observe luminosity**
  2. **Calibration: stellar pop. code**
- ☐ **Sources of uncertainty**
  - ➢ **Dust correction**
  - ➢ **Stellar pop. code inputs**
    - **Star formation duration, metallicity, …**
  - ➢ **Initial mass function**
- ☐ **Different indicators are consistent to ~ 20% (at z < 1, which yields 90% of DSNB events)**

Extragalactic Background Light: Prediction

- ☐ **Non-nucleosynthesis sources (e.g., AGNs) are negligible** *[Hopkins et al. (2006)]*, **i.e., the background light acts as a calorimetric test of the star formation history.**
- ☐ **Predictions from the star formation rate:**

$$\boxed{I(\nu)} = \frac{c}{4\pi}\int_0^{z_*} \epsilon(\nu', z)\left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z.$$

$$\epsilon(\nu, z) = \int_{t_*}^{t_z} \boxed{\dot{\rho}_*(t)}\,\mathrm{d}t \int_{0.1}^{M(t')} L(\nu, M, t')\,\boxed{\phi(M)}\,\mathrm{d}M,$$

Star formation rate **Initial mass function**

Numerical values:

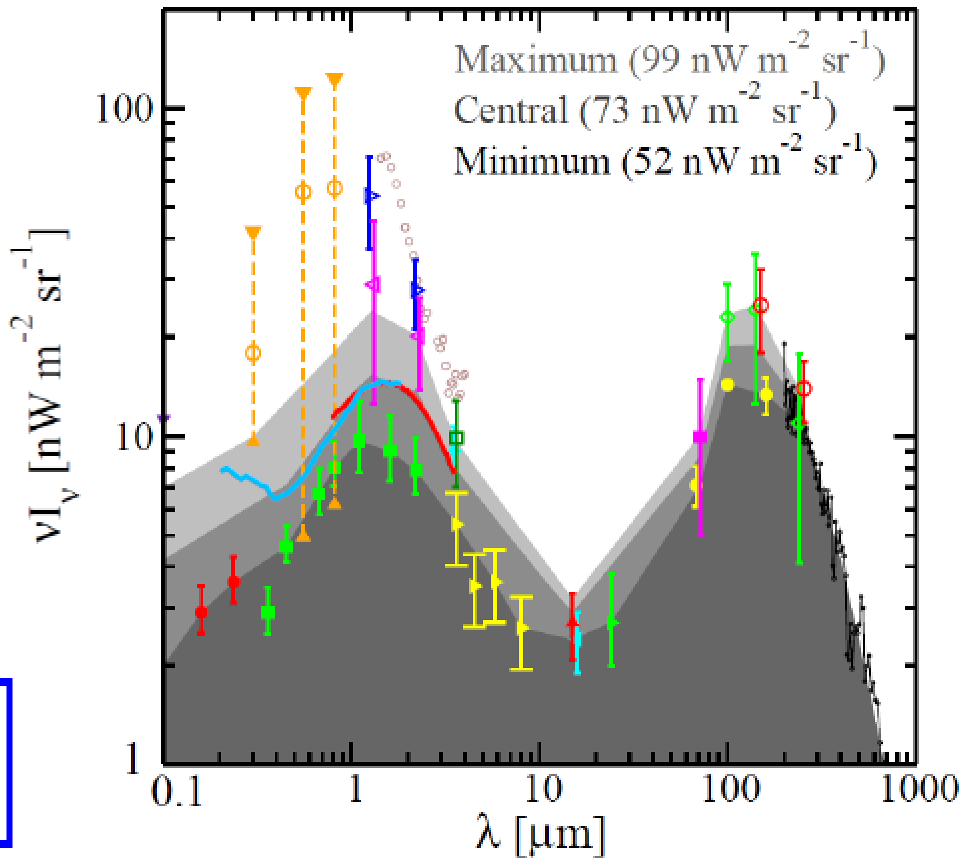
- **Salpeter IMF (-2.35, 1995) : $I_{tot} \sim 95$ nW m^{-2} sr^{-1}**
- **Kroupa IMF (-2.3, 2001) : $I_{tot} \sim 88$ nW m^{-2} sr^{-1}**
- **Baldry-Glazebrook (-2.1, 2003) IMF : $I_{tot} \sim 78$ nW m^{-2} sr^{-1}**

Extragalactic Background Light: Obs

- ☐ **Background light observations:**
  - ➢ **Upper**: goes through data error bars
    [Bernstein 2002, 2005, 2007, etc]
  - ➢ **Nominal**: respects gamma-ray constraints
    [by HESS (2006), MAGIC (2008)]
  - ➢ **Lower**: galaxy counts
    [Madau&Pozzetti (2000), etc]
- ☐ **Total background light:**

$$\boxed{73^{+26}_{-21}\ \mathrm{nW m^{-2} sr^{-1}}}$$

[Horiuchi et al. (2008)]

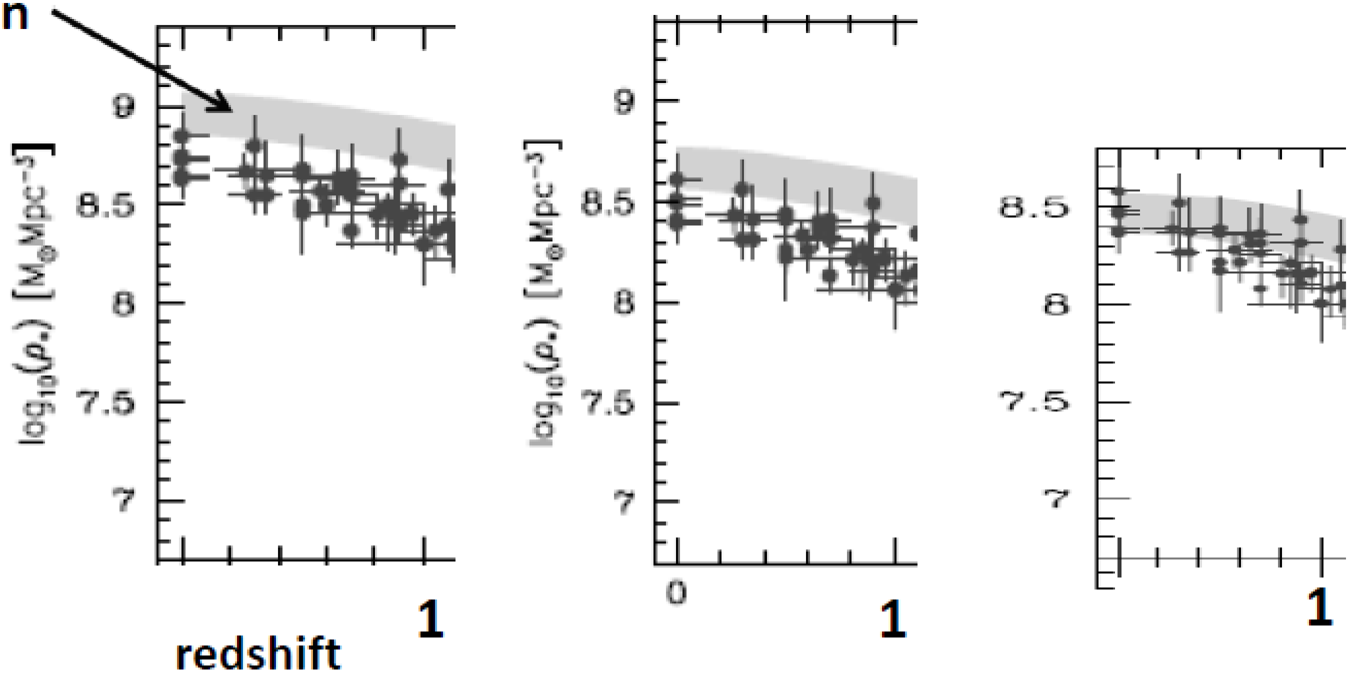


Choice of IMF

☐ **Baldry-Glazebrook IMF (2003) is a modern IMF, suggested to be the average IMF by stellar mass density studies** *[e.g., Wilkins et al. (2008)]*

Salpeter (1955) **Kroupa (2001)** **BG (2003)**

band: prediction



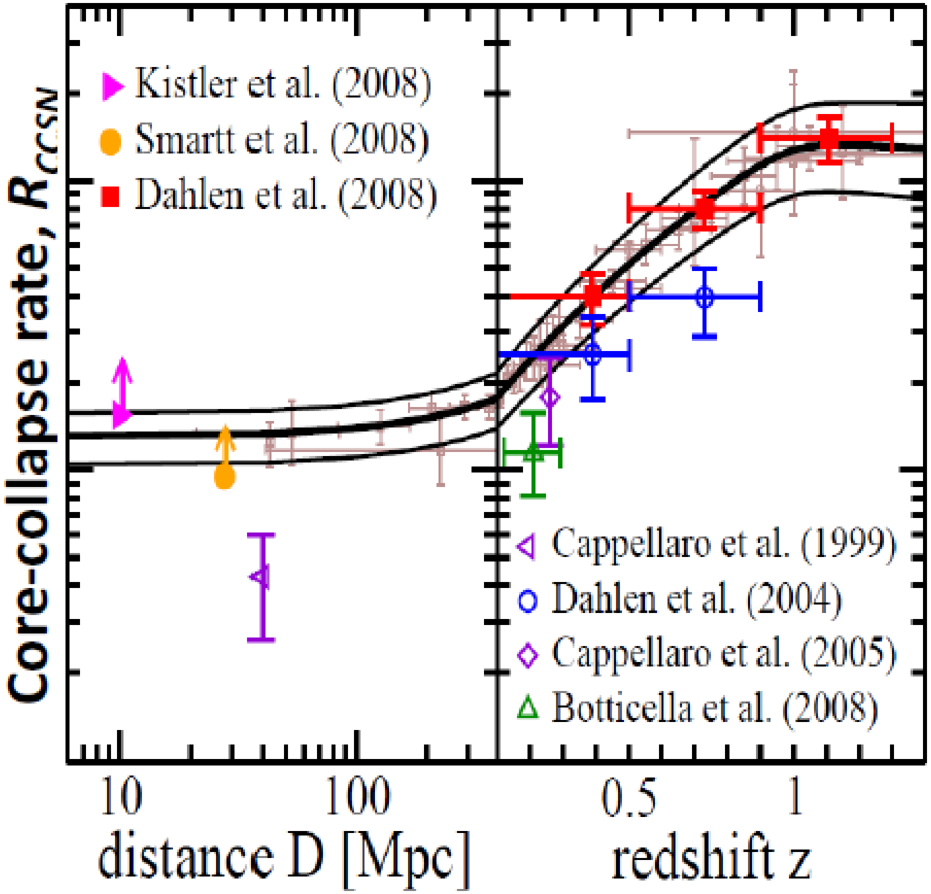
Core-Collapse Supernova Rate

- ☐ **Prediction: follows from the star formation rate**

$$\dot{\rho}_{\rm SNII}(z) = \dot{\rho}_*(z)\frac{\int_8^{50}\psi(M)dM}{\int_{0.1}^{100}M\psi(M)dM}$$

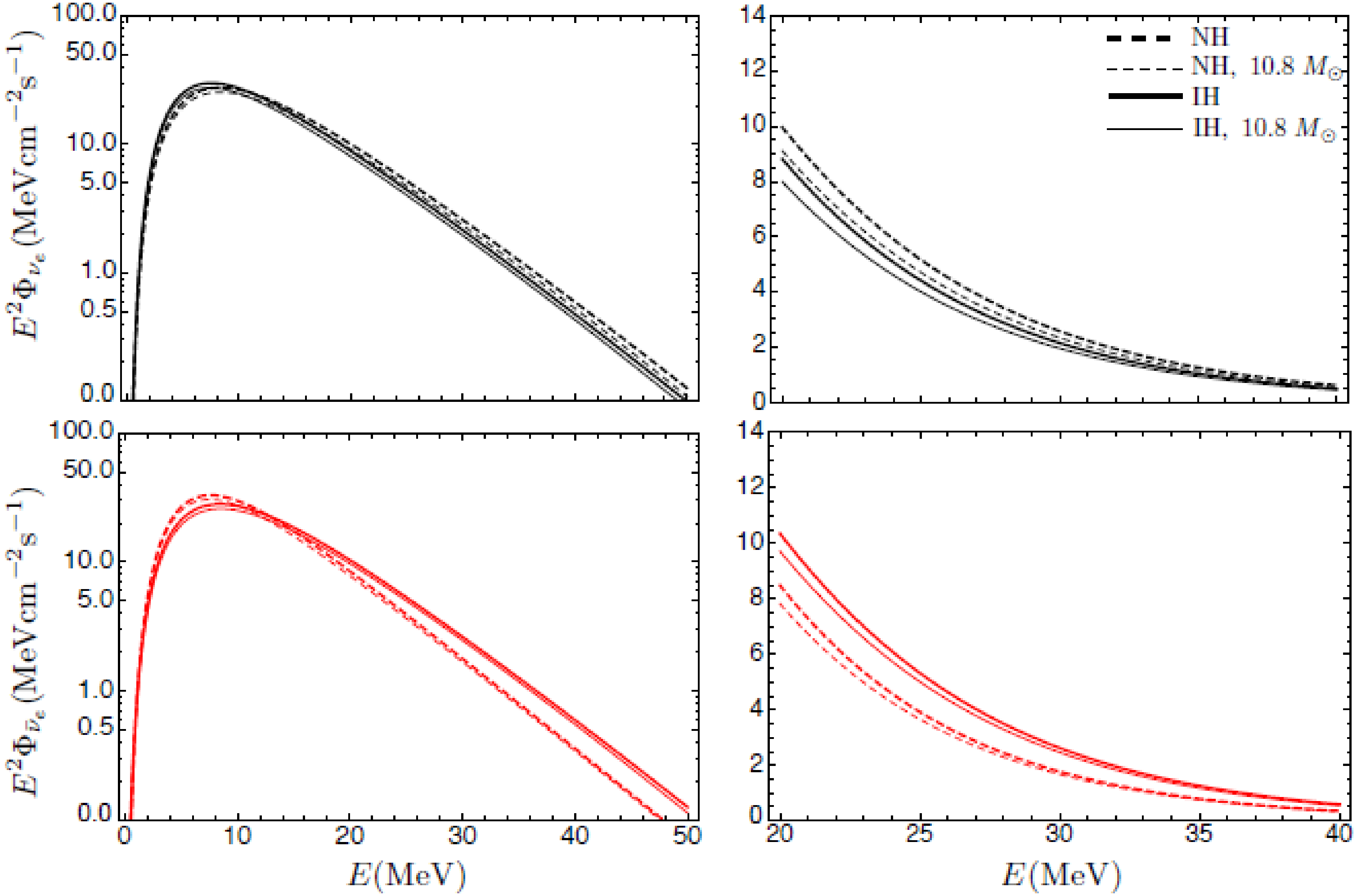
  - **M_{min}: 8.5 M_{sun} for Type II-P** *[Smartt et al. (2008)]*
  - **Almost independent of the initial mass function**
- ☐ **Observed: most likely low limits**
  - **Incompleteness**
  - **Host galaxy dust**
  - **Type Ia / CCSN ratio**

[Horiuchi et al. (2008)]



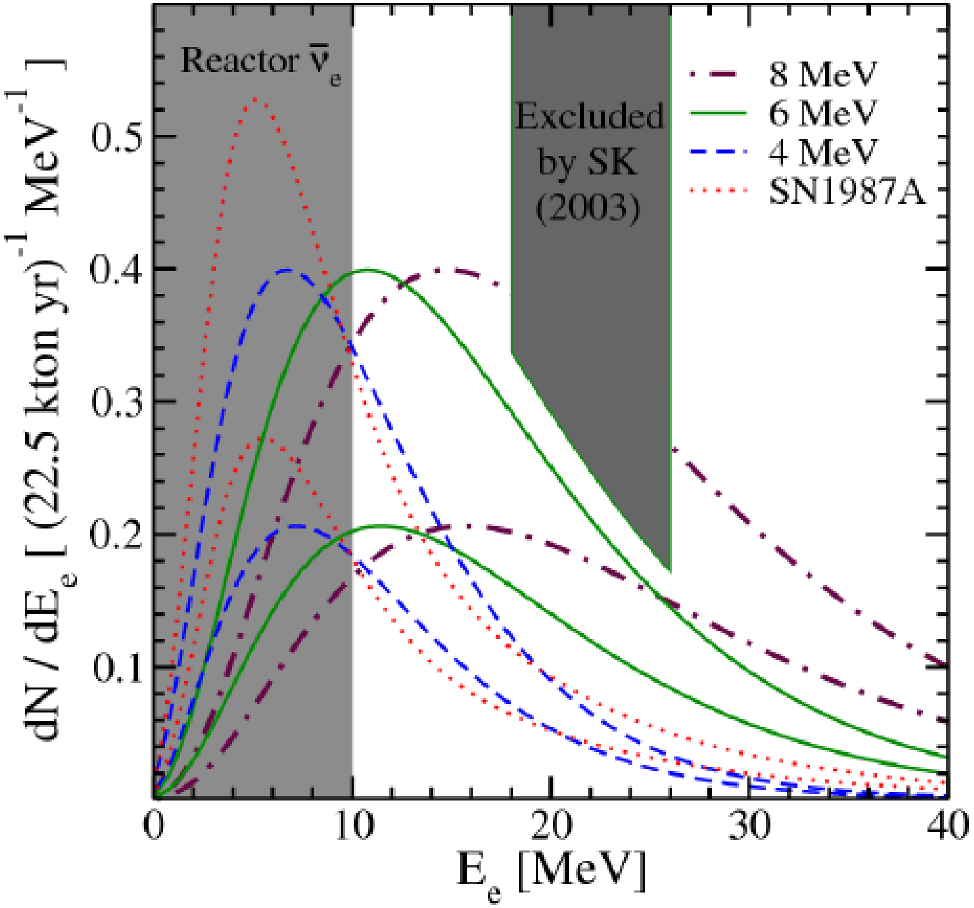
DSNB FLUX

[*Lunardini & Tamborra., arXiV:1205.6292*]



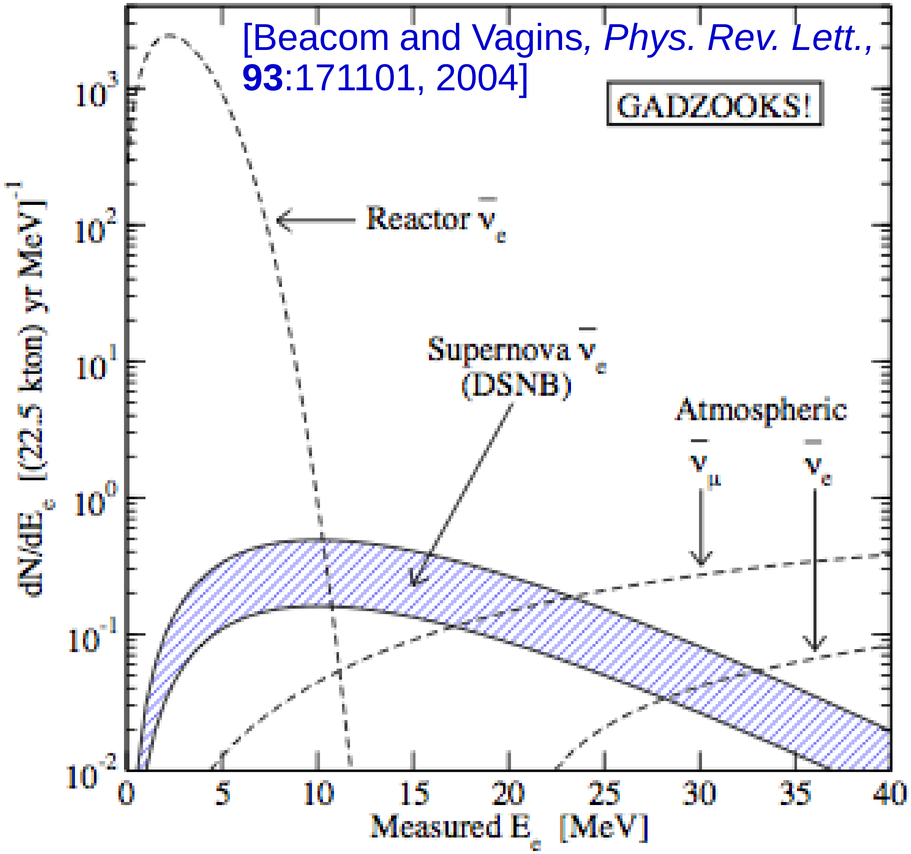
DSNB event spectrum @SK

[Horiuchi et al. (2008)]



- ☐ **Thermal spectra (T_{eff}) + uncertainty bands for R_{CCSN}**
- ☐ **SK limit:** *[Malek et al. (2003)]*
  - ➢ **Int. flux < 1.2 cm^{-2} s^{-1}**
  - ➢ **Int. event < 2 event yr^{-1}**
- ☐ **Results:**
  - ➢ **SK partially constraints T_{eff} = 8 MeV**
  - ➢ **Uncertainty band due to R_{CCSN} is not large (smaller than T_{eff} uncertainty).**

BACKGROUND IN SK FOR DSNB SIGNAL



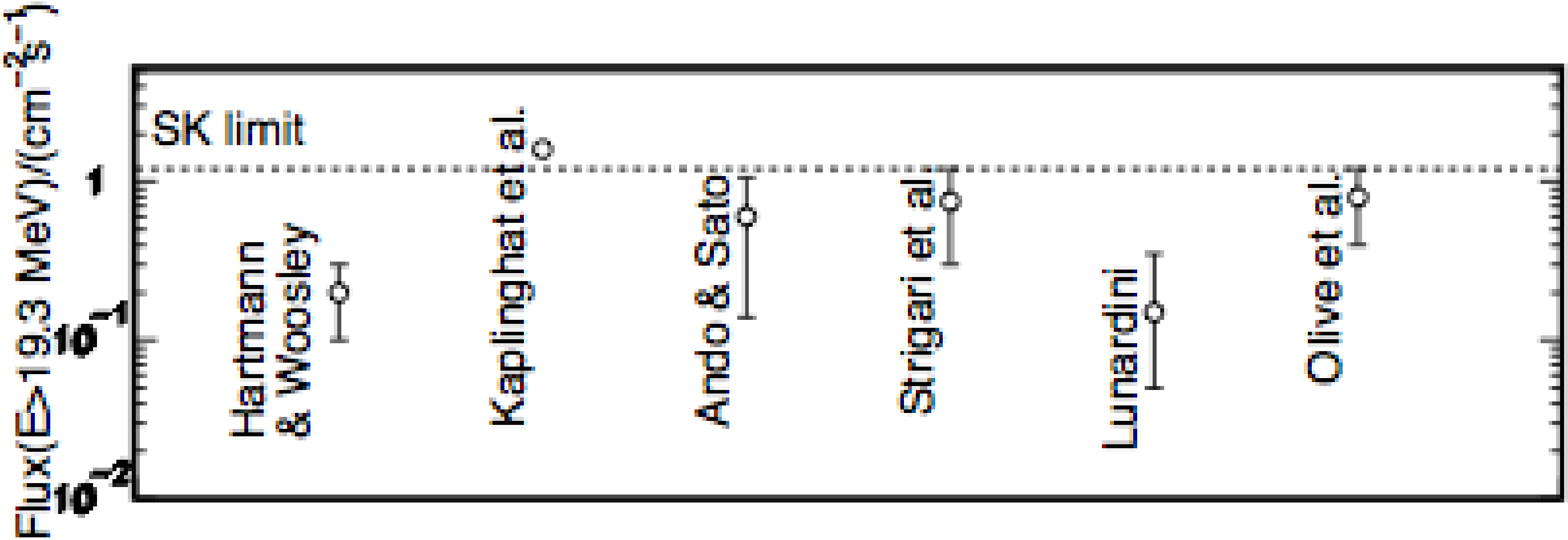
[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

Below ~15–20 MeV, bkgd dominated by spallation products (made by atmospheric μ) and by reactor $\bar{\nu}_e$.

For $E_\nu \in$ [20-30] MeV, the bkg of low-energy atmospheric $\bar{\nu}_e$ is relatively small.

But, in this window, there is a large background due to “invisible” μ (i.e. below Cherenkov emission threshold) decay products, induced by low energy atmospheric ν_μ and $\bar{\nu}_\mu$.

SK flux limit vs. DSNB flux predictions

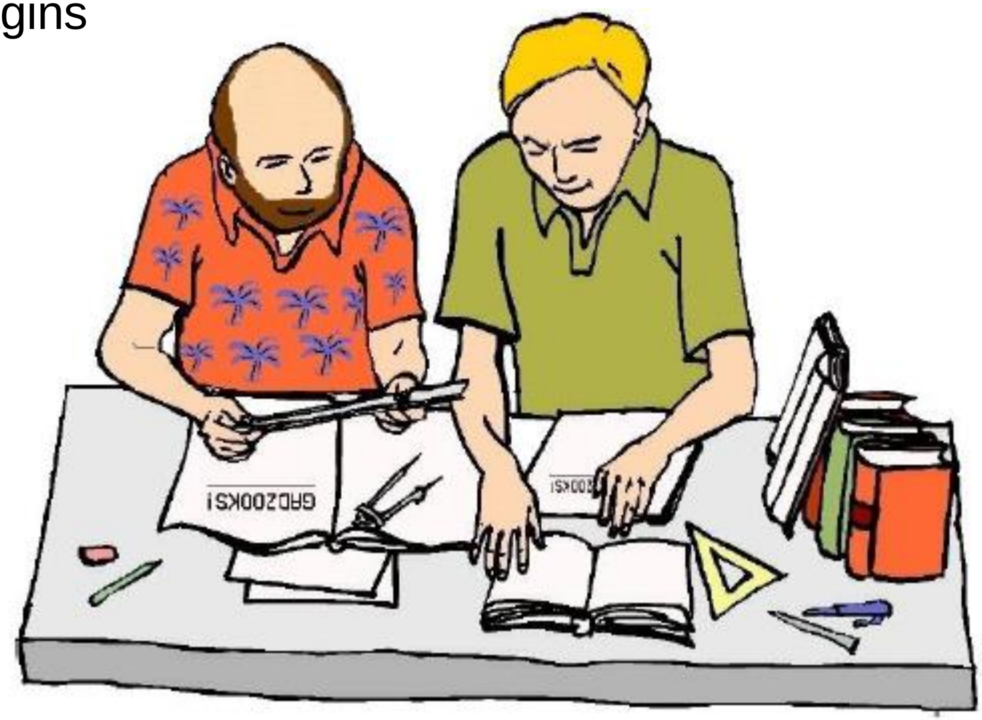


Getting very close to some… but
Super-K is background limited.

How can we identify neutrons produced by the inverse beta process (from supernovae, reactors, etc.) in really big water Cherenkov detectors?

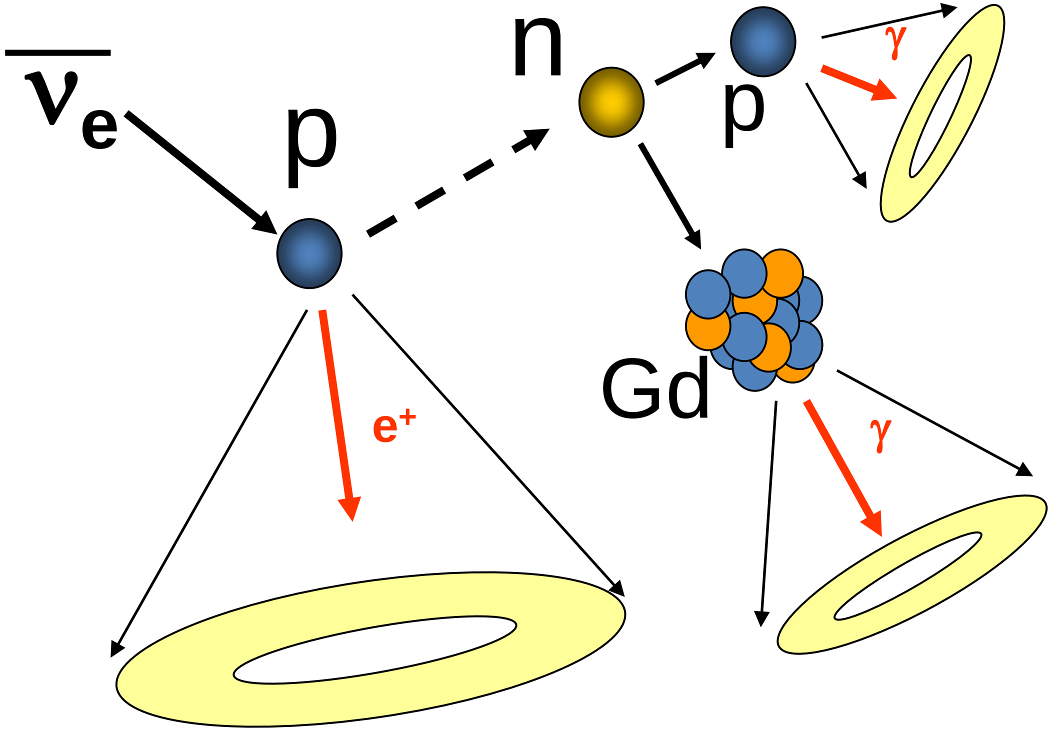
$$\overline{\nu}_e + p \longrightarrow e^+ + n$$

Slide from Mark Vagins



With this in mind, John Beacom and I wrote the original
GADZOOKS!
(Gadolinium Antineutrino Detector Zealously
Outperforming Old Kamiokande, Super!)
paper in late 2003. It was published the following year:
[Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004]

Neutron tagging in Gd-enriched WC Detector



Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV γ-ray

Possibility 2: 90% or more

$n+Gd \rightarrow \sim 8MeV\ \gamma$

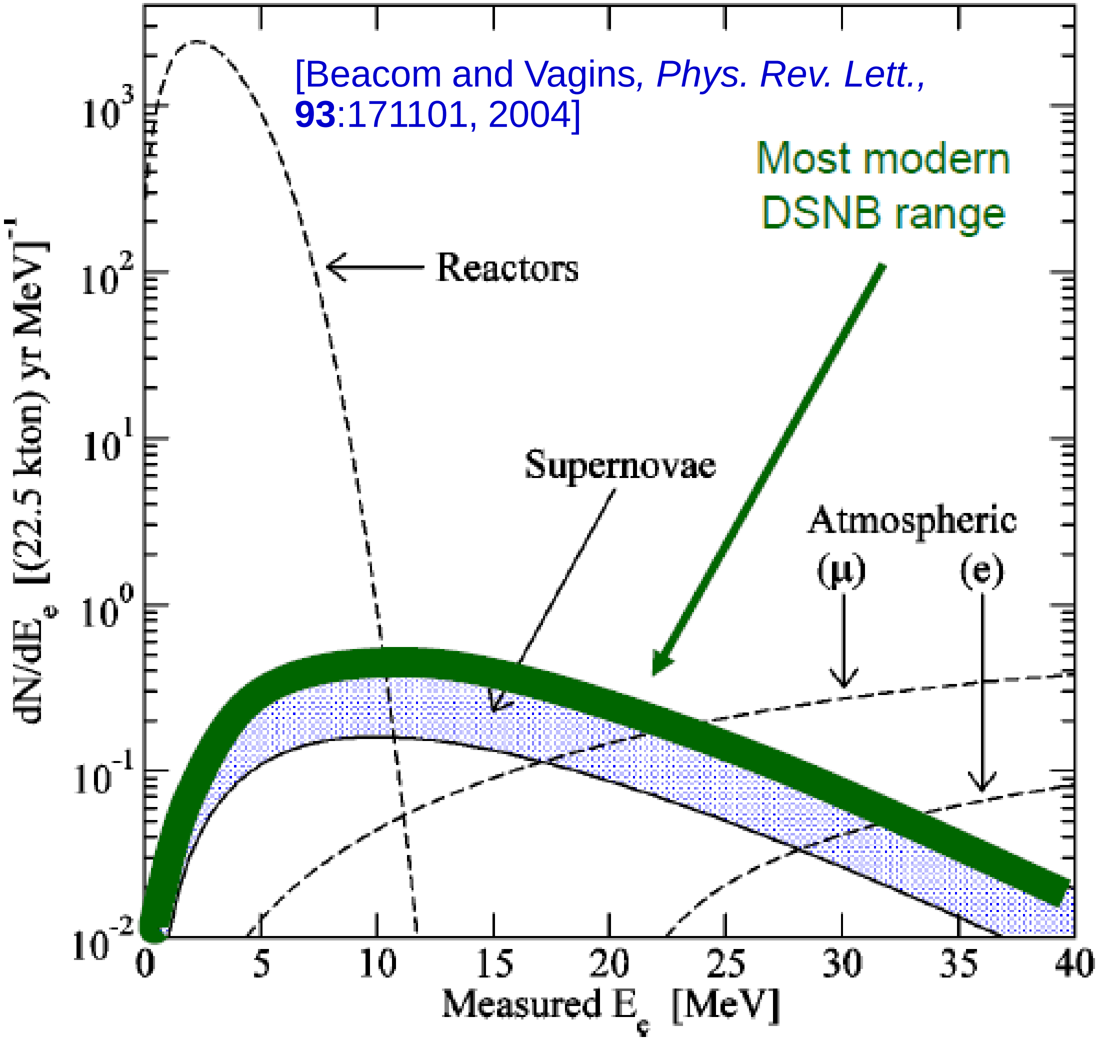
$\Delta T = \sim 30\ \mu sec$

Positron and gamma ray vertices are within ~50cm.

$\bar{\nu}_e$ can be identified by delayed coincidence.

[reaction schematic by M. Nakahata]

Here's what the coincident signals in Super-K with $GdCl_3$ or $Gd_2(SO_4)_3$ will look like (energy resolution is applied):



[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

Most modern DSNB range

$\bar{\nu}_e + p \rightarrow e^+ + n$

spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

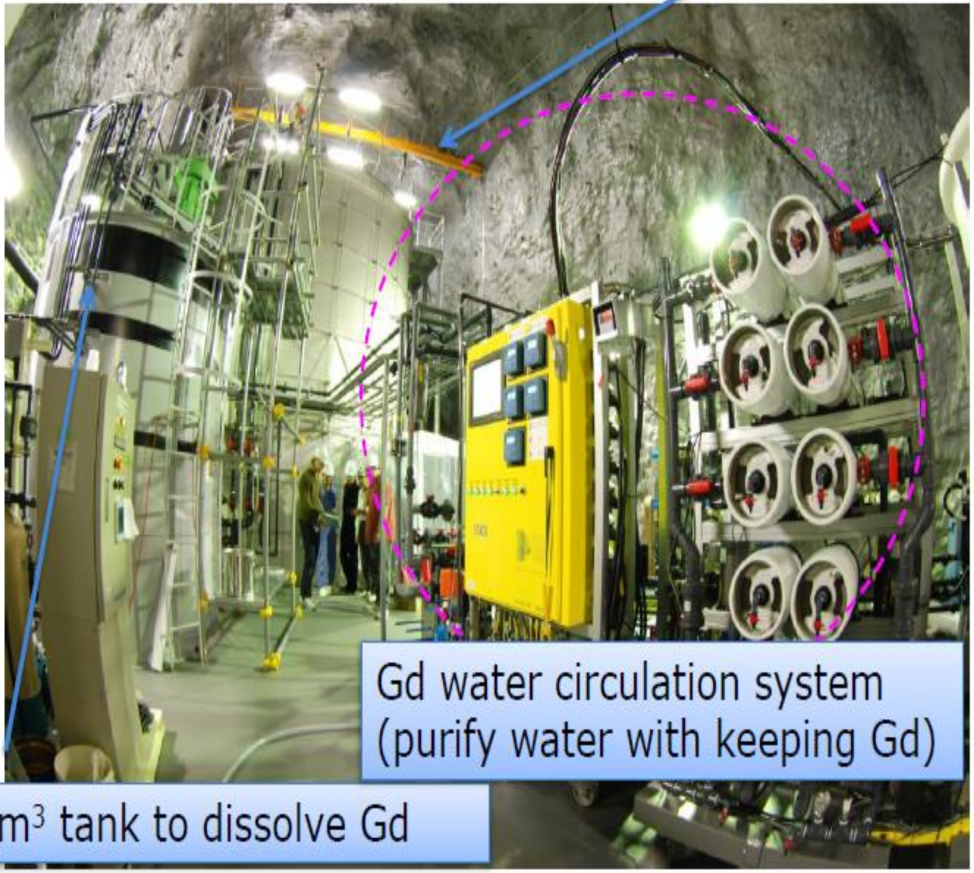
λ=~4cm, τ=~30μs

→ A few clean events/yr in Super-K with Gd

EGADS

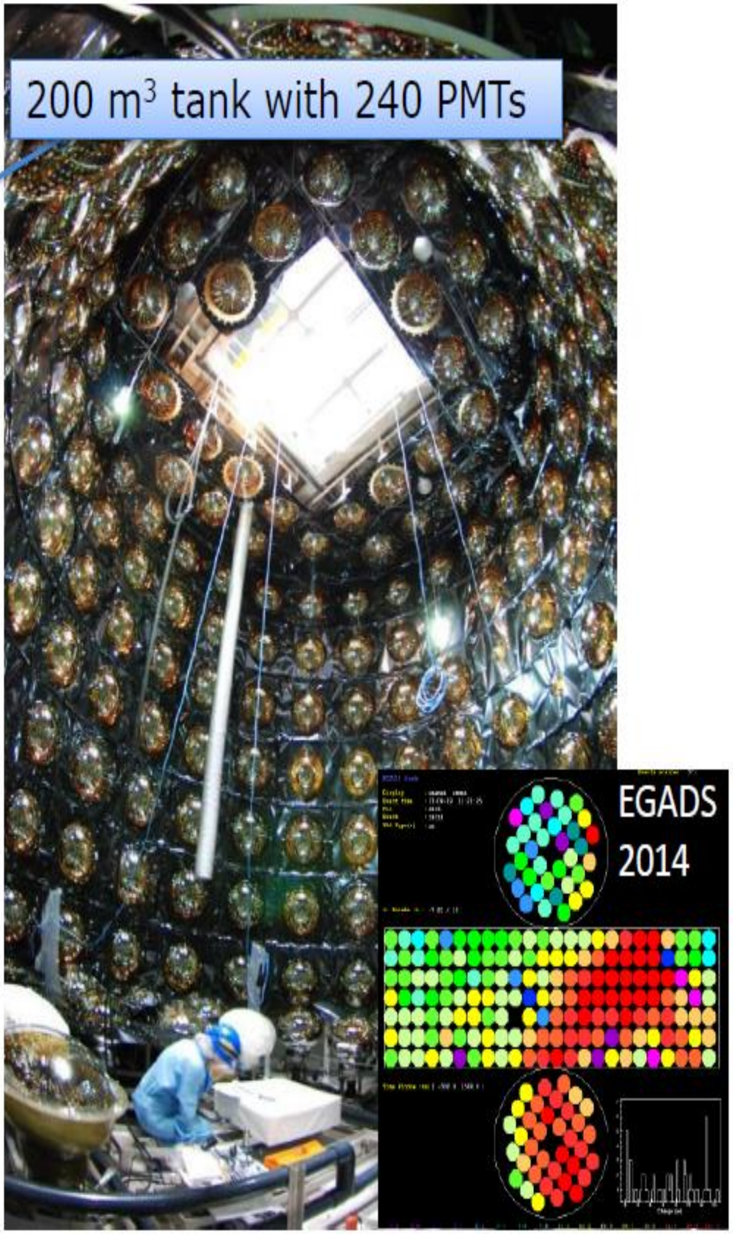
Evaluating Gadolinium's Action on Detector Systems

- To study the Gd water quality with actual detector materials.
- The detector fully mimic Super-K detector;
  SUS frame, PMT and PMT case, black sheets, etc.
- Tests for Hyper-K; 13 HPDs



Gd water circulation system (purify water with keeping Gd)

15m³ tank to dissolve Gd



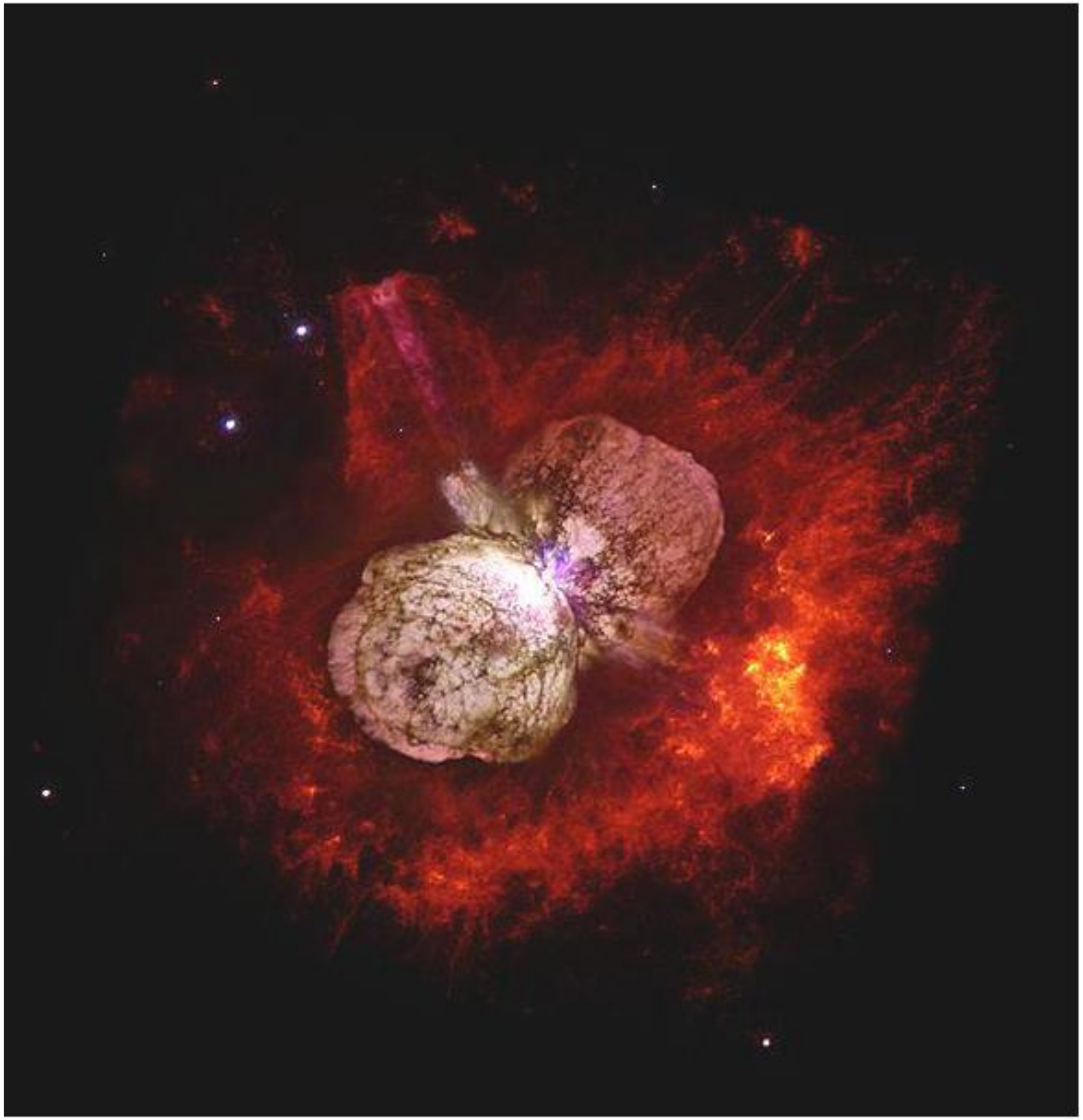
200 m³ tank with 240 PMTs

SK & T2K Joint Statement on "SK-Gd"

- Jan.30, 2016

On June 27, 2015, the Super-Kamiokande collaboration approved the SK-Gd project which will enhance neutrino detectability by dissolving gadolinium in the Super-K water.

T2K and SK will jointly develop a protocol to make the decision about when to trigger the SK-Gd project, taking into account the needs of both experiments, including preparation for the refurbishment of the SK tank and readiness of the SK-Gd project, and the T2K schedule including the J-PARC MR power upgrade. Given the currently anticipated schedules, the expected time of the refurbishment is 2018.



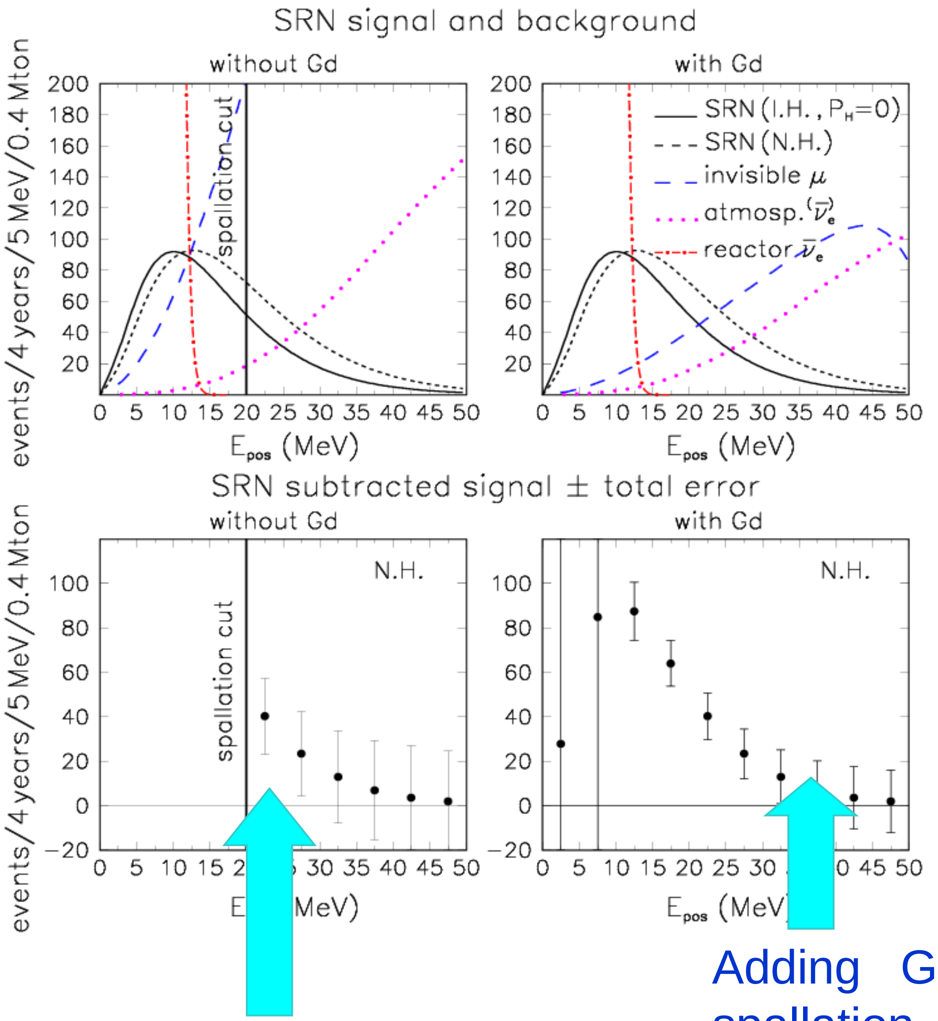
A concluding thought:

This Gd business would work great with a closer SN, too. If Eta Carinae - which has shown recent variability - happens to explode sometime in the next few years, we would expect to see ~400 tagged supernova neutrino events…

…in the Gd-loaded EGADS tank!

[G.L.Fogli, E.Lisi, A.M., and D.Montanino, hep-ph/0412046]

Mton Cherenkov



Below ~15–20 MeV, bkgd dominated by spallation products (made by atmospheric μ) and by reactor $\bar{\nu}_e$.

For $E_\nu \in$ [20-30] MeV, the bkg of low-energy atmospheric $\bar{\nu}_e$ is relatively small.

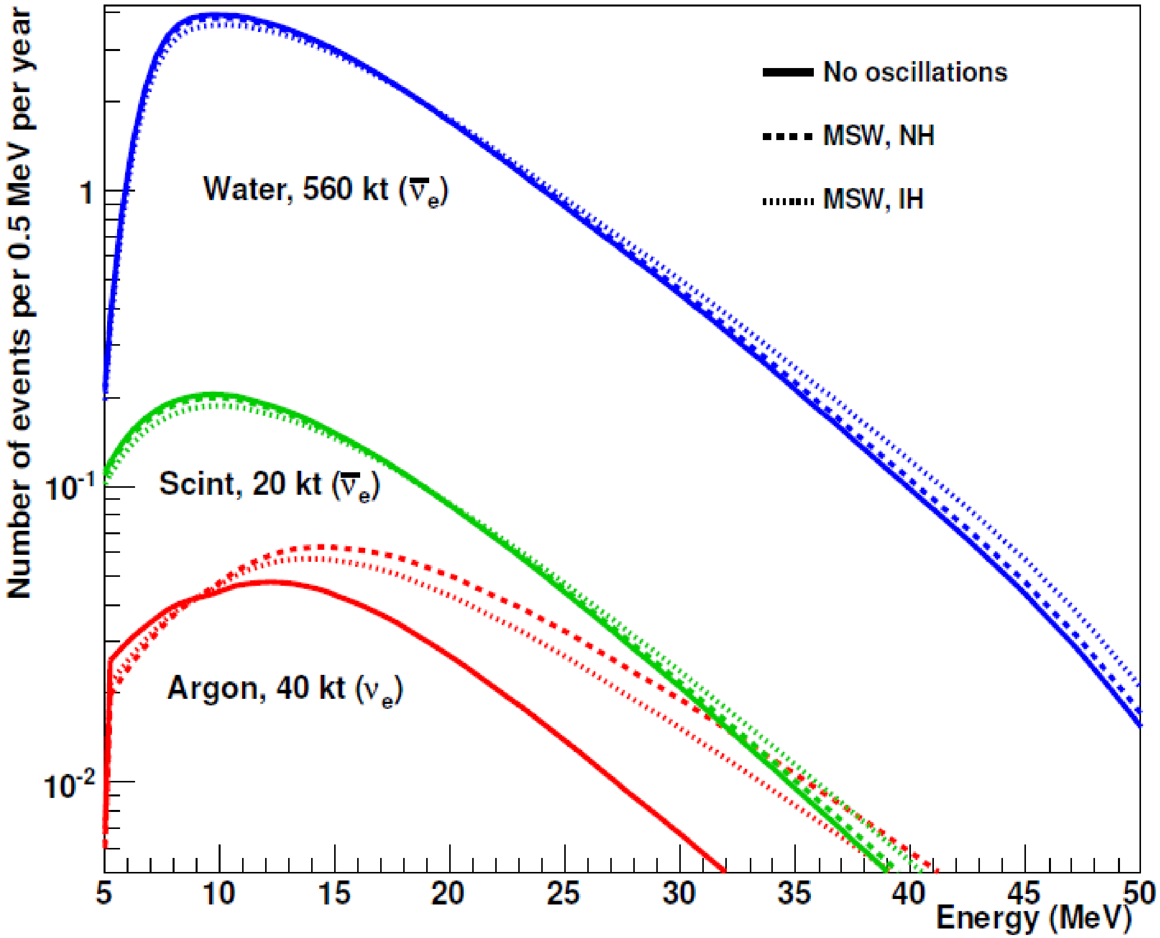
But, in this window, there is a large background due to “invisible” μ (i.e. below Cherenkov emission threshold) decay products, induced by low energy atmospheric ν_μ and $\bar{\nu}_\mu$.

A 2-3σ signal could emerge after an exposure of 4 years in a 0.4 Mton detector

Adding Gd [J.F.Beacom, and M.R.Vagins, hep-ph/0309300], spallation ~eliminated, invisible m reduced by ~5. The analysis threshold lowered. In the window $E_{pos} \in [10,20]$ MeV, after 1 year, the DSNB signal detectable at 6σ level

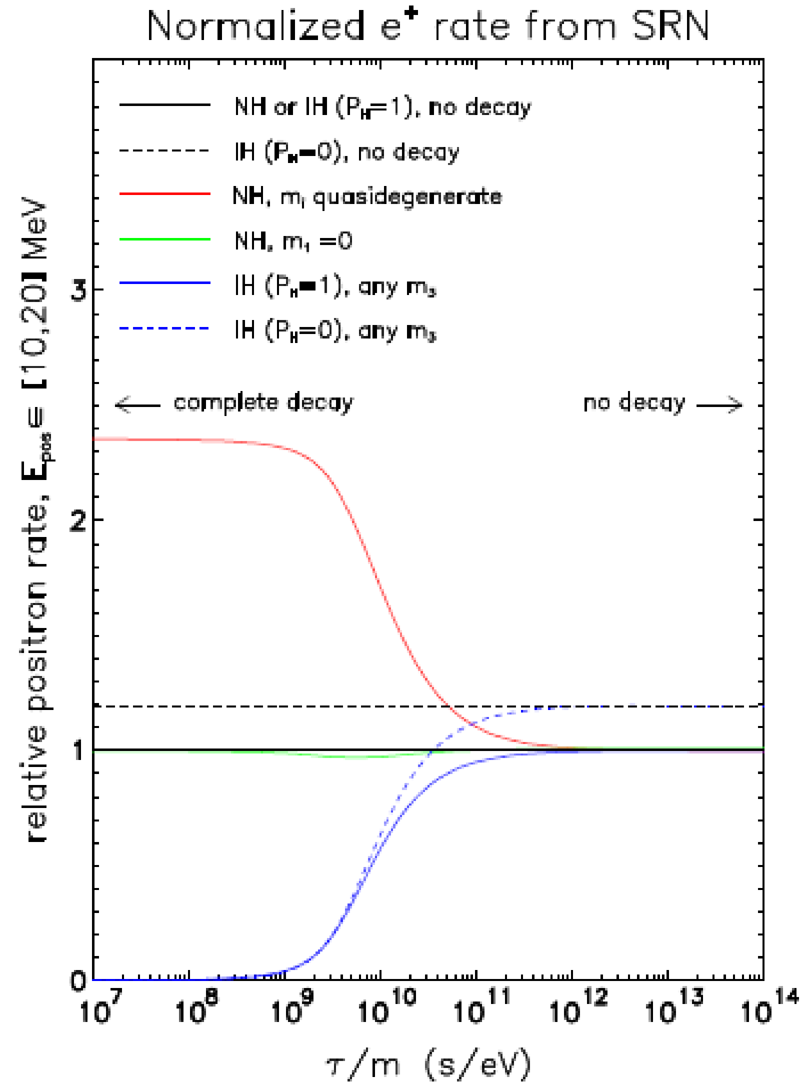
DSNB IN LARGE FUTURE DETECTORS

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]



CONSTRAINT OF NU INVISIBLE DECAY FROM DSNB

[Fogli, Lisi, A.M., Montanino, hep-ph/0401227]

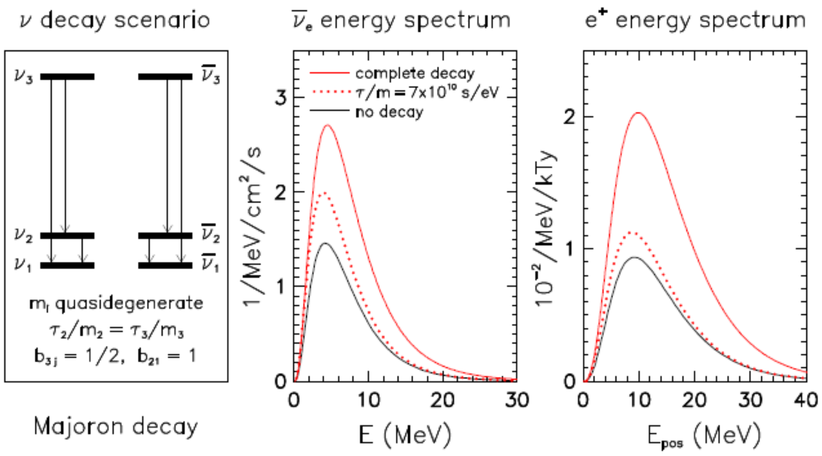


Nu decay in Majoron

$$\nu \rightarrow \nu' + \phi$$

DSNB can probe lifetimes of cosmological interest

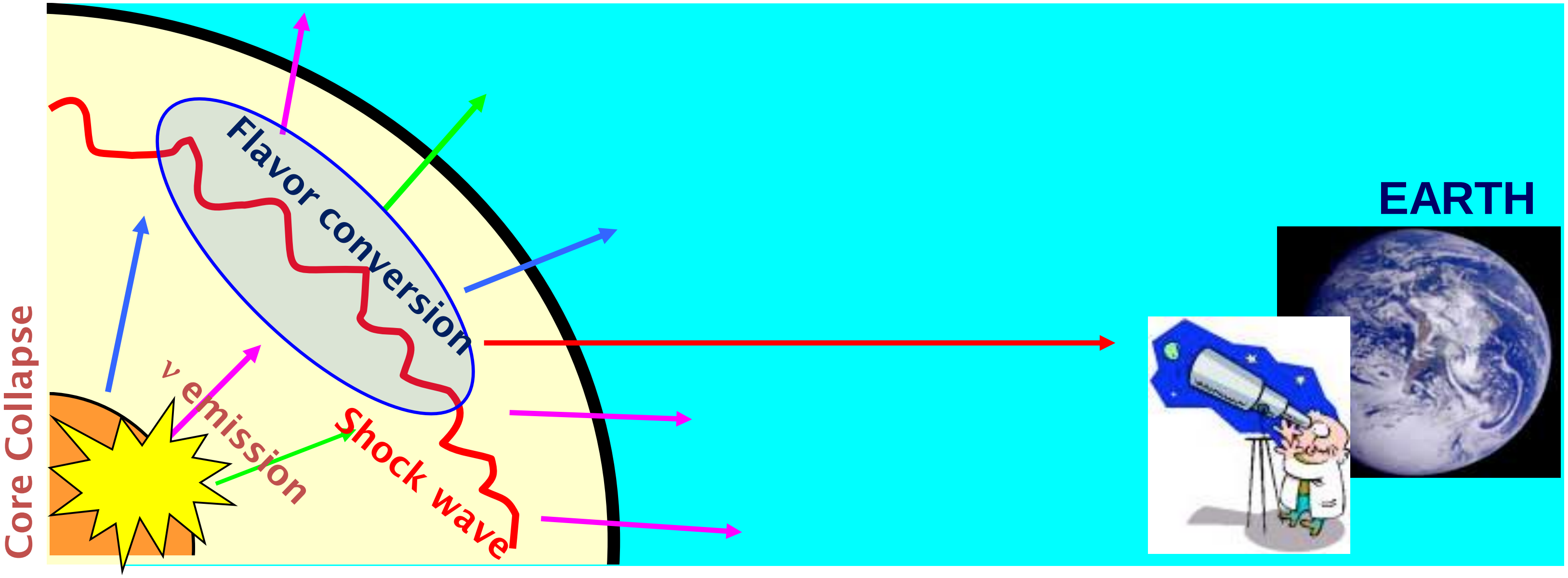
$$\frac{\tau_i E}{m_i} \leq 1/H_0$$



DSNB spectrum larger, comparable or smaller than the standard one

SN NEUTRINO FLAVOR CONVERSIONS

TYPICAL PROBLEMS IN SUPERNOVA NEUTRINOS



Production (flavor)

Propagation (mass,mixing)

Detection (flavor)

$$\left| \quad \langle \psi_i \quad \right| \qquad \int \exp(-iHt) \qquad \left| \quad \psi_f \rangle \quad \right|$$

- Simulations of SN explosion
- Initial energy spectra
- Initial time spectra

- Matter effects: shock wave,turbulences, Earth crossing, …
- Dense neutrino bkg
- New interactions
- Decays
- ………

- CC & NC interactions
- Different detectors
- Energy spectra
- Angular spectra
- Time spectra

Theory

Phenomenology

SN ν FLAVOR TRANSITIONS

The flavor evolution in matter is described by the non-linear MSW equations:

$$i\frac{d}{dx}\psi_{\nu}=\left(H_{vac}+H_{e}+H_{\nu\nu}\right)\psi_{\nu}$$

In the standard 3ν framework

- $$H_{vac}=\frac{U\ M^{2}\ U^{?}}{2E}$$

  Kinematical mass-mixing term

- $$H_{e}=\sqrt{2}G_{F}\,\mathrm{diag}(N_{e},0,0)$$

  Dynamical MSW term (in matter)

- $$H_{\nu\nu}=\sqrt{2}G_{F}\int(1-\cos\theta_{pq})\left(\rho_{q}-\bar{\rho}_{q}\right)dq$$

  Neutrino-neutrino interactions term (non-linear)

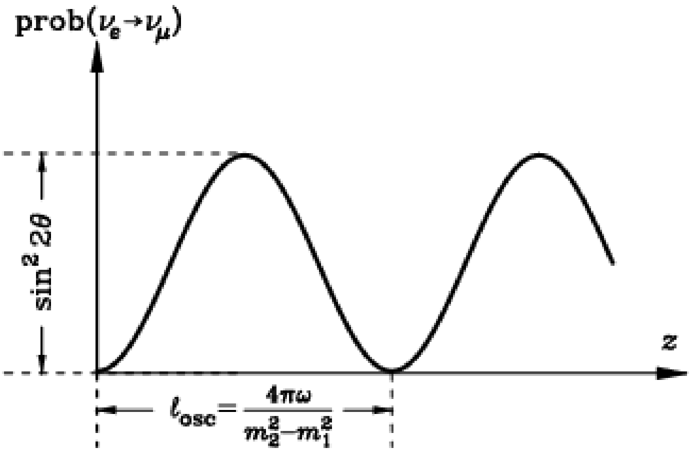
VACUUM OSCILLATIONS

- **Two flavor mixing** $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Each mass eigenstates propagates as $\mathbf{e^{ipz}}$ with $p_i = \sqrt{E^2 - m^2} \approx E - \frac{m_i^2}{2E}$

$$\left|\nu_\mu(z)\right\rangle = -\sin\theta\, e^{-ip_1 z}\left|\nu_1\right\rangle + \cos\theta\, \mathrm{e}^{-\mathrm{ip}_2 z}\left|\nu_2\right\rangle$$

- **2 ν oscillation probability** $P(\nu_e \to \nu_\mu) = \left|\left\langle \nu_\mu(z) \middle| \nu_e(0)\right\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$



Bruno Pontecorvo (1967)

Dubna 1988. Neutrino oscillations.

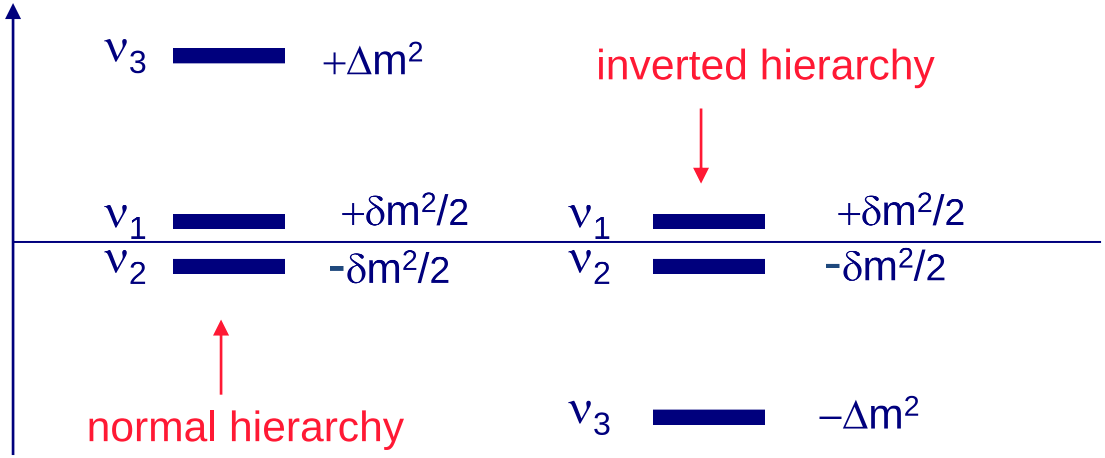
3ν FRAMEWORK

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix

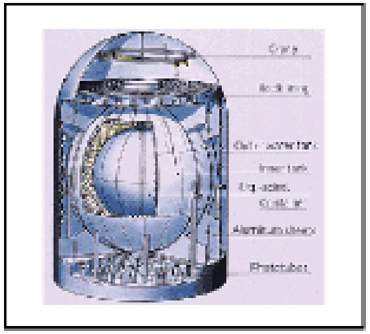
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc., δ CP phase

- **Mass-gap parameters:** $M^2 = \left(\underbrace{-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}}_{\text{“solar”}}, \underbrace{\pm\Delta m^2}_{\text{“atmospheric”}} \right)$



STATUS OF NEUTRINO OSCILLATIONS



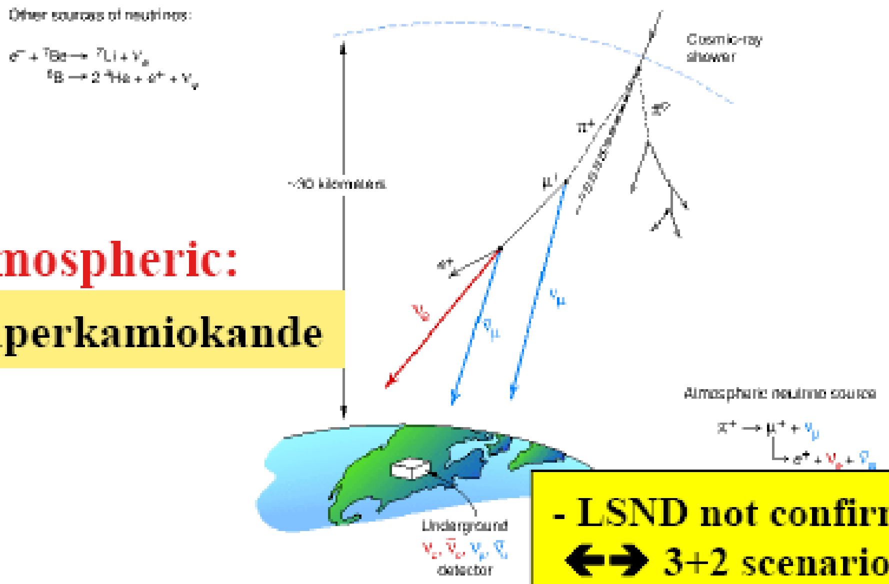
Reactors: KAMLAND

Beams: K2K ➔ MINOS
➔ OPERA

solar: **GALLEX/GNO** ➔ SK, SNO

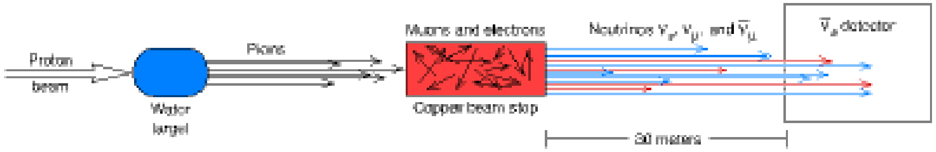
atmospheric:

Superkamiokande



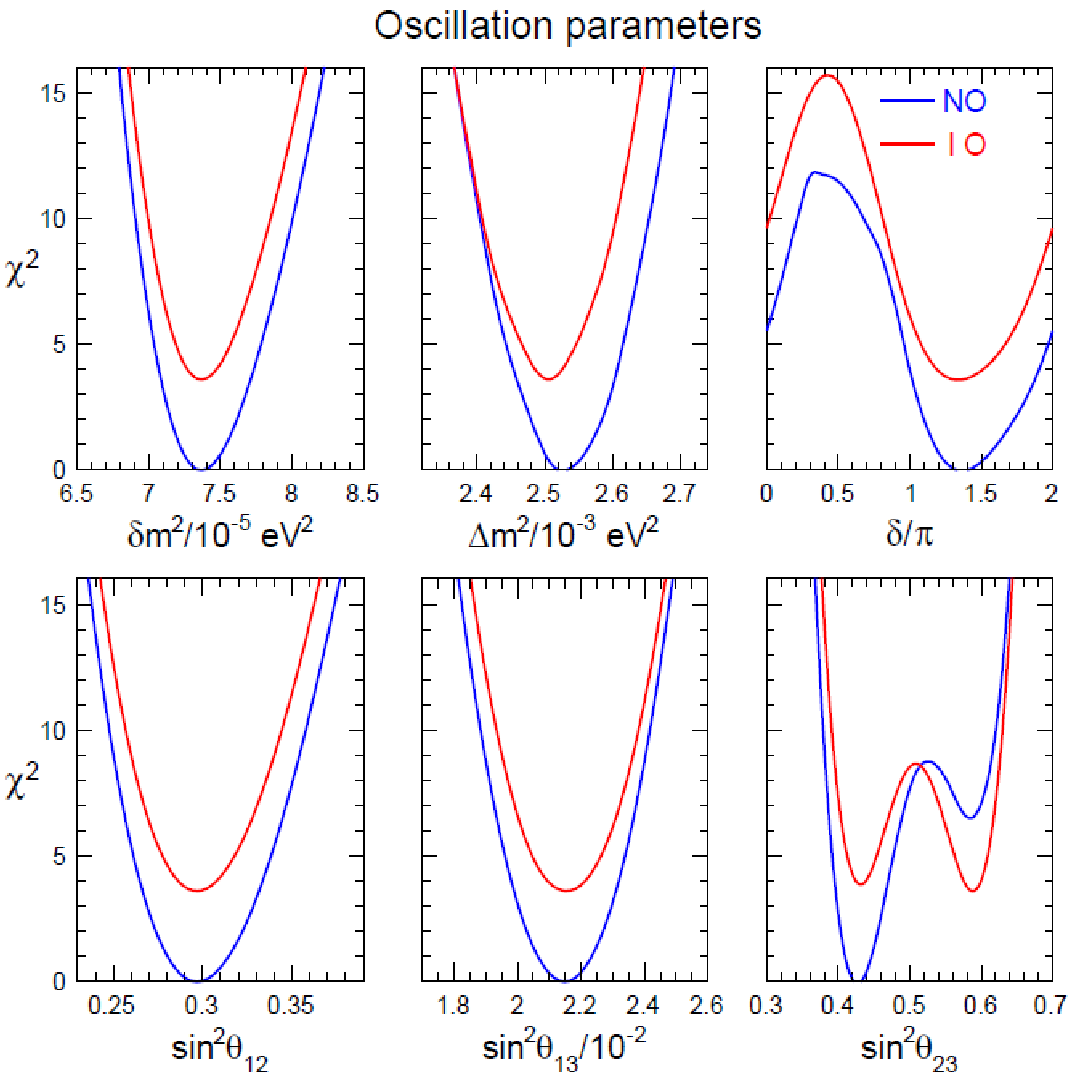
- LSND not confirmed !
↔ 3+2 scenarios?
- upturn at low E ?

LSND? ➔ MiniBooNE



GLOBAL OSCILLATION ANALYSIS (2017)

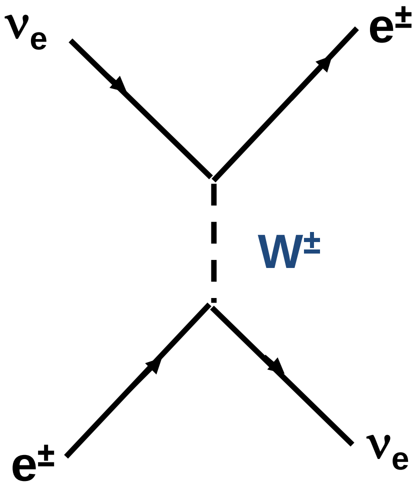
[Capozzi et al., arXiv:1703.0447]



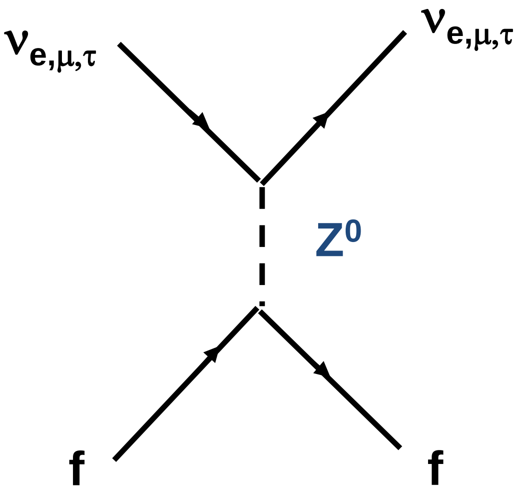
MATTER POTENTIAL

[Wolfenstein, PRD 17, 2369 (1978)]

When neutrinos propagate in a medium they will experience a shift of their energy, similar to photon refraction, due to their coherent interaction with the medium constituents



Charged current



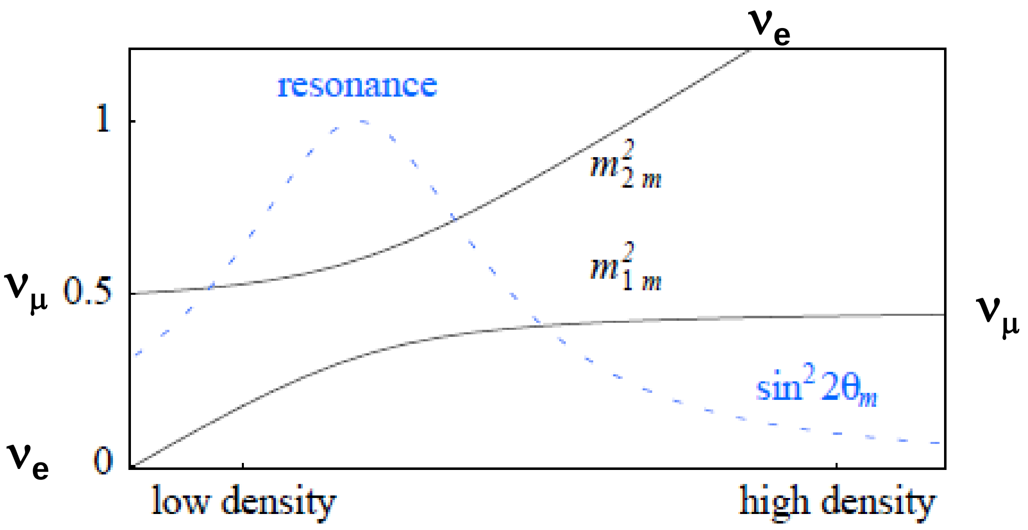
Neutral current

The difference of the interaction energy of different flavors gives an effective potential for electron (anti)neutrinos

$$\boxed{V(x) = \sqrt{2} G_F N_e}$$

net electron density

MIKHEYEV-SMIRNOV-WOLFENSTEIN (MSW) EFFECT



$$\nu_e = \cos\theta_m \nu_1 + \sin\theta_m \nu_2$$

Mixing angle in matter

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(\frac{2EV}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}}$$

ADIABATIC EVOLUTION ➡ **ν mass eingenstates remains the same for all the propagation**

- $\theta << 1, \ V >> \frac{\Delta m^2}{2E} \longrightarrow \theta_m \approx \frac{\pi}{2}, \nu_e \approx \nu_{2m}$ **Matter dominance**
- $V \approx \frac{\Delta m^2}{2E} \longrightarrow \theta_\mathrm{m} \approx \frac{\pi}{4}$ **Resonance**
- $V \approx 0 \longrightarrow \theta_\mathrm{m} \approx \theta, \nu_2 \approx \nu_\mu$ **Resonant flavor conversions**

Resonances in matter occur either for ν or for anti-ν

In the adiabatic limit is easy to describe the MSW effect. The adiabaticity implies that ν is propagating for many oscillation wavelengths. The phase information is lost

Adiabatic probabilites = classical probabilities

$$P(\nu_e \to \nu_e) = \sum_i P_m(\nu_e \to \nu_i) P(\nu_i \to \nu_e)$$

Final ν_e No crossing Rotate to mass basis

$$= (1\ \ 0) \begin{pmatrix} \cos^2\theta & \sin^2\theta \\ \sin^2\theta & \cos^2\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos^2\theta_m & \sin^2\theta_m \\ \sin^2\theta_m & \cos^2\theta_m \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Back to flavor basis Initial ν_e

$$= \sin^2\theta \sin^2\theta_m + \cos^2\theta \cos^2\theta_m = \frac{1}{2}(1 + \cos 2\theta \cos 2\theta_m)$$

If initial n_e is large $\longrightarrow$ $\cos 2\theta_m \sim -1$

And if θ small $\longrightarrow$ $P(\nu_e \to \nu_e) \simeq \frac{1}{2}(1 - \cos 2\theta) \ll 1$ Strong conversion probabilities

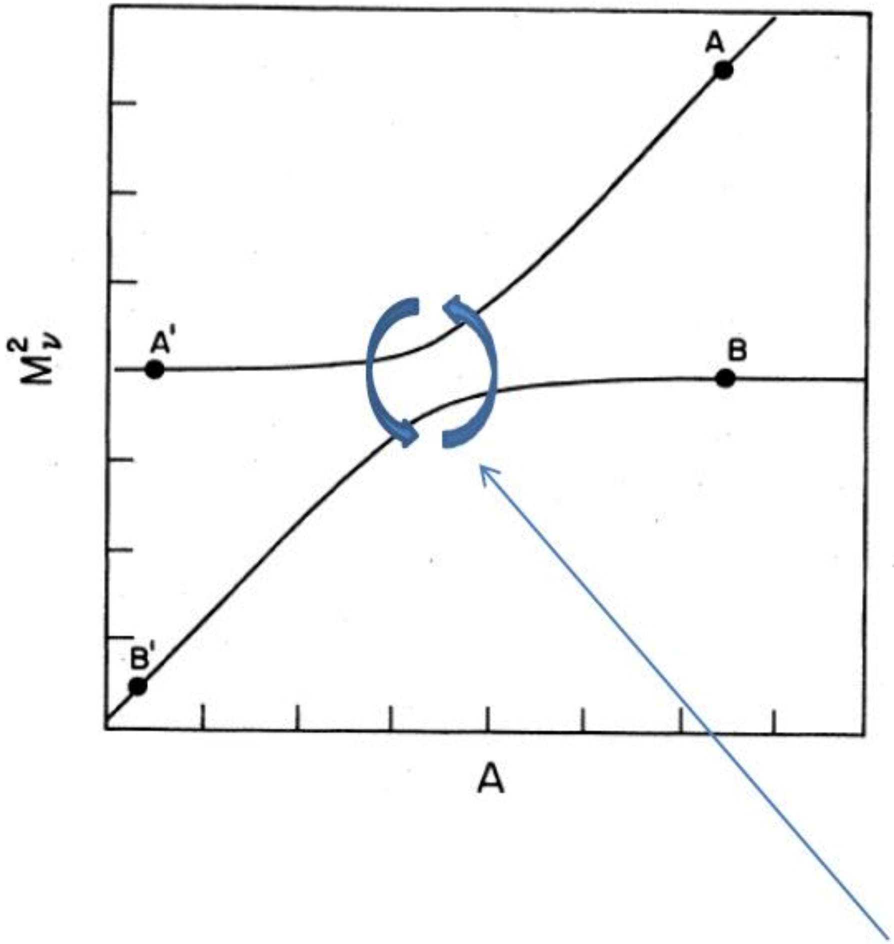
CORRECTIONS TO ADIABATIC APPROXIMATION

At the resonance there can be a violation of the adiabaticity. The corrections take form of "level crossing" where the state ν_1 can cross over ν_2 and vice-versa

This is analogous to quantum tunneling effect. This effect can be described in terms of a level crossing probability

$$P_c \equiv |\langle \nu_2(x_+)|\nu_1(x_-)\rangle|^2$$

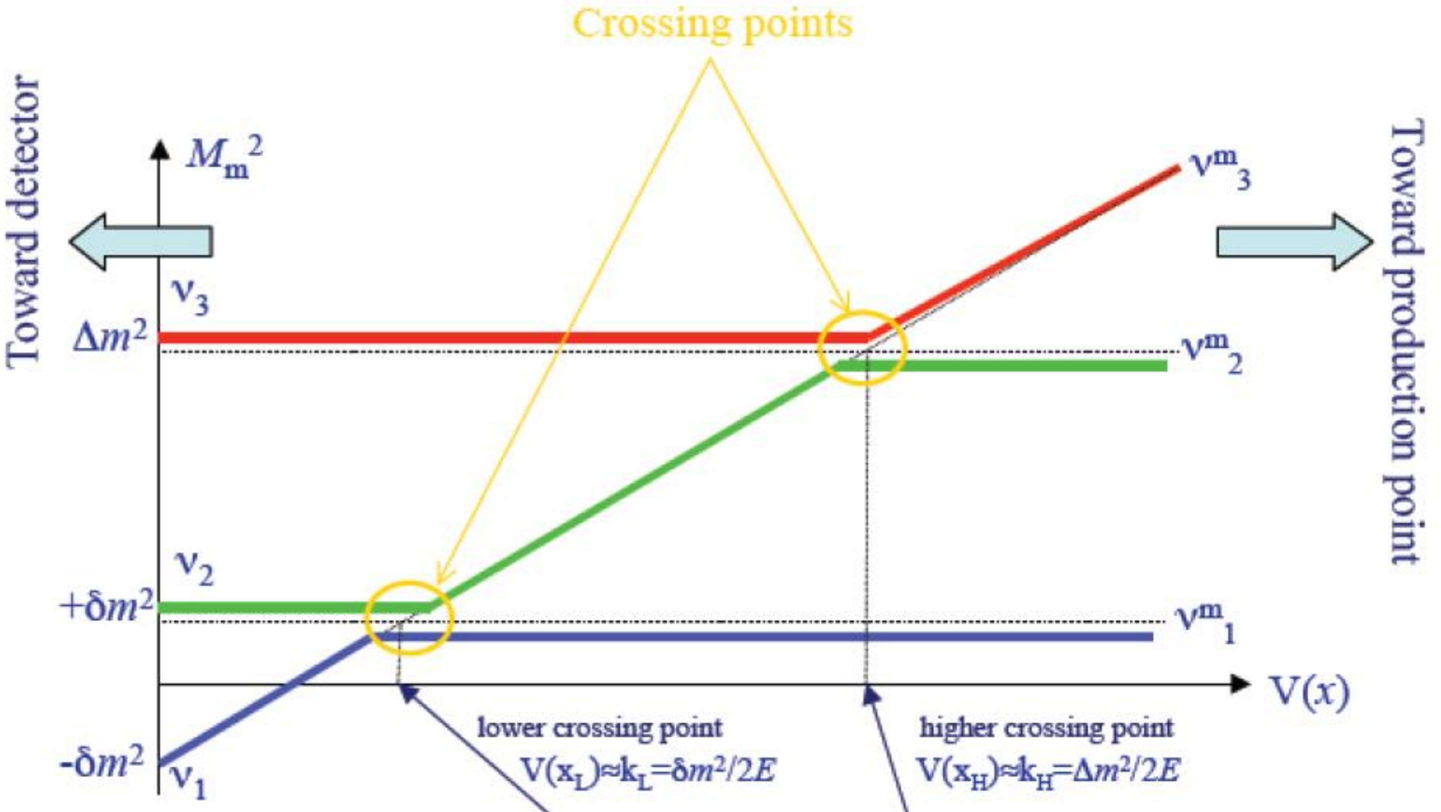
Here, $x_\pm$ refer to two faraway points on either side of the resonance position, where the adiabatic approximation is still valid. Unitarity for two flavors tells us that P_c is also the probability of crossing from ν_1 over ν_2 and $1-P_c$ is the probability for ν_1 or ν_2 to stay on the same mass eigenstate.



$$P(\nu_e \to \nu_e) = (1 \;\; 0) \begin{pmatrix} \cos^2\theta & \sin^2\theta \\ \sin^2\theta & \cos^2\theta \end{pmatrix} \begin{pmatrix} (1-P_c) & P_c \\ P_c & (1-P_c) \end{pmatrix} \begin{pmatrix} \cos^2\theta_m & \sin^2\theta_m \\ \sin^2\theta_m & \cos^2\theta_m \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$= \frac{1}{2} + (\frac{1}{2} - P_c)\cos 2\theta \cos 2\theta_m$$

THREE-FLAVOR EFFECTS



$$P_{ee} \cong [1,\ 0,\ 0]\cdot \underbrace{\begin{pmatrix} U_{e1}^2 & U_{e2}^2 & U_{e3}^2\\ U_{\mu 1}^2 & U_{\mu 2}^2 & U_{\mu 3}^2 \\ U_{\tau 1}^2 & U_{\tau 2}^2 & U_{\tau 3}^2\end{pmatrix}}_{\substack{\text{rotation to the}\\ \text{original flavor basis}}} \cdot \underbrace{\begin{pmatrix}1-P_L & P_L & 0\\ P_L & 1-P_L & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{\text{lower transition}\\ P_L=P_c(\nu^m{}_2\to\nu^m{}_1)}} \cdot \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & 1-P_H & P_H\\ 0 & P_H & 1-P_H\end{pmatrix}}_{\substack{\text{higher transition}\\ P_H=P_c(\nu^m{}_3\to\nu^m{}_2)}} \cdot \underbrace{\begin{pmatrix}\tilde U_{e1}^2 & \tilde U_{\mu 1}^2 & \tilde U_{\tau 1}^2\\ \tilde U_{e2}^2 & \tilde U_{\mu 2}^2 & \tilde U_{\tau 2}^2 \\ \tilde U_{e3}^2 & \tilde U_{\mu 3}^2 & \tilde U_{\tau 3}^2\end{pmatrix}}_{\substack{\text{rotation to eigenstates}\\ \text{in matter}\\ \text{(at the production point)}}} \cdot \begin{bmatrix}1\\0\\0\end{bmatrix}$$

=0 always adiabatic

SN NU FLUXES AFTER MSW EFFECT

- NH

$$\begin{aligned} F_{\overline{\nu}_e} &\simeq \cos^2\theta_{12} F^0_{\overline{\nu}_e} + \sin^2\theta_{12} F^0_{\nu_x} \ , \\ F_{\nu_e} &\simeq \sin^2\theta_{12} P_H F^0_{\nu_e} + (1 - \sin^2\theta_{12} P_H) F^0_{\nu_x} \end{aligned}$$

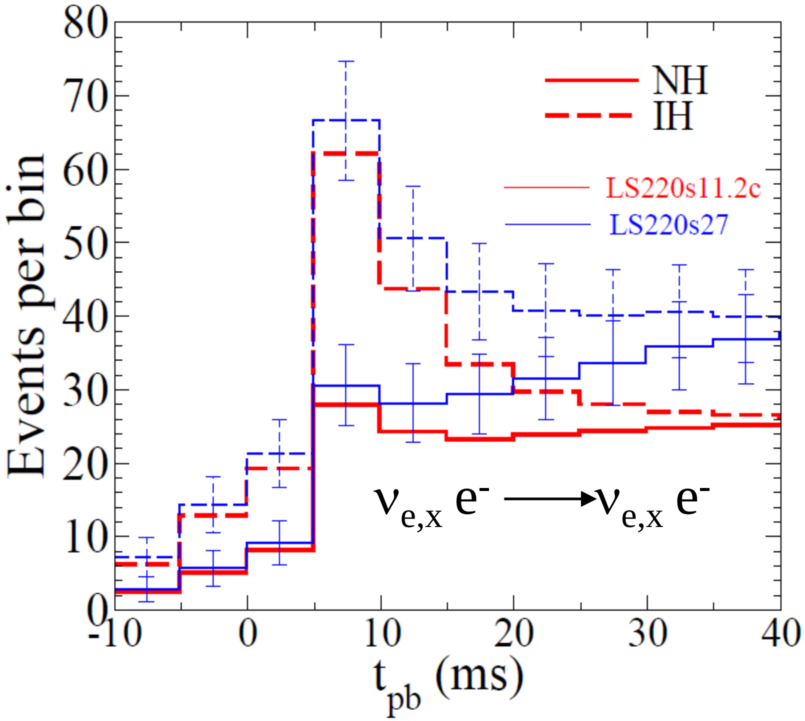
- IH

$$\begin{aligned} F_{\overline{\nu}_e} &\simeq \cos^2\theta_{12} P_H F^0_{\overline{\nu}_e} + (1 - \cos^2\theta_{12} P_H) F^0_{\nu_x} \ , \\ F_{\nu_e} &\simeq \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x} \ . \end{aligned}$$

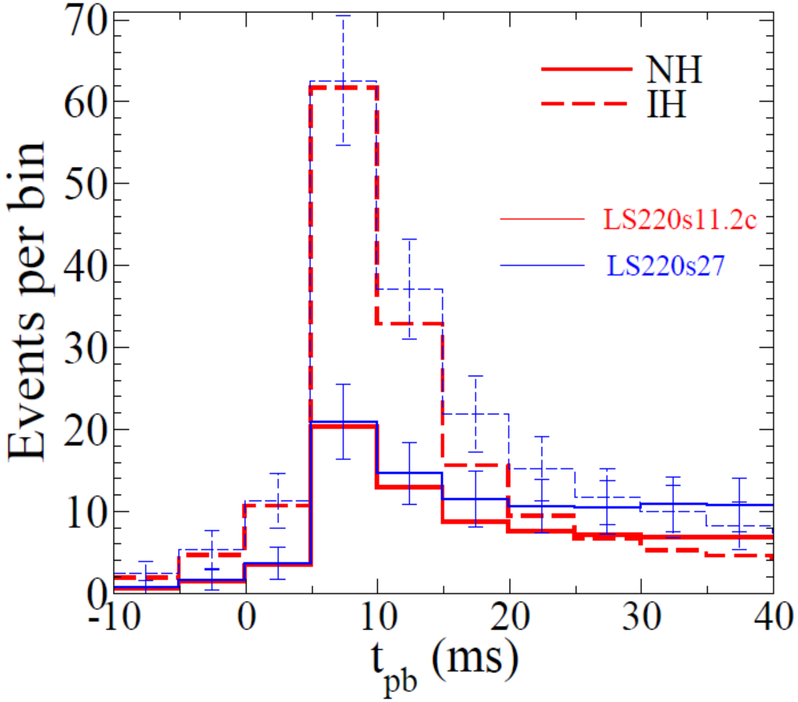
NEUTRONIZATION BURST

[A.M., Tamborra, Janka, Saviano, Scholberg et al., arXiv:1508.00785 [astro-ph.HE]]

560 kton Water Cherenkov



40 kton LAr



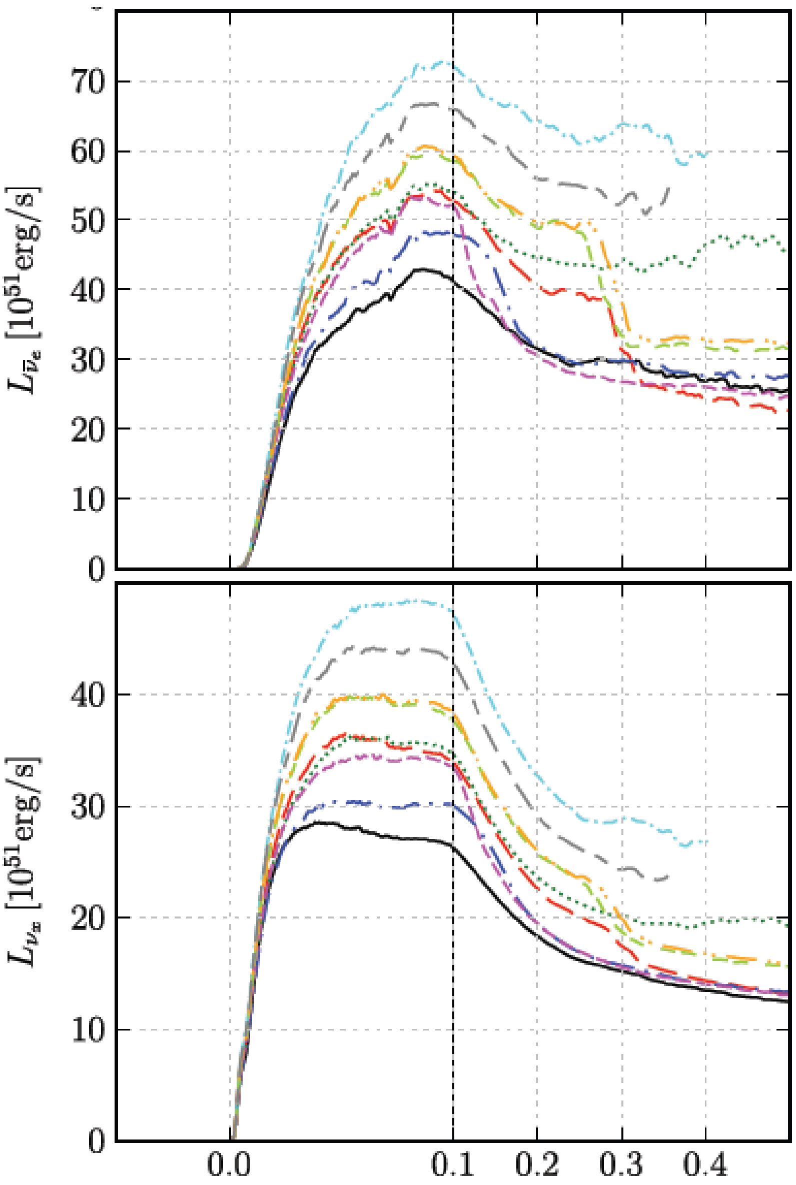
Robust feature of SN simulations

[Kachelriess et al., astro-ph/0412082, Gil-Botella & Rubbia, hep-ph0307244]

At “large” θ_{13} (like recently measured!):

- The peak is not seen → The hierarchy is normal (if one could see it...)
- The peak is seen → The hierarchy is inverted (more robust)

RISE TIME OF SN NEUTRINO SIGNAL



Garching group, 2011

- The production of $\bar{\nu}_e$ is more strongly suppressed than that of ν_x during the first tens of ms after bounce because of the high degeneracy of e and ν_e .
- The high degeneracy allows only for a low abundance of e^+, the production of $\bar{\nu}_e$ by pair annihilation and e^+ capture on neutrons is not very efficient. Moreover, since in the optical tick regime $\bar{\nu}_e$ are in chemical equilibrium with the matter, their degeneracy also blocks the phase space for the creation of $\bar{\nu}_e$ via nucleon-nucleon bremmstrahlung (which however is operative also for ν_x).
- $\bar{\nu}_e$ are produced more gradually via cc processes (e captures on free nucleons) in the accreting matter; ν_x come fastly from a deeper region

The lightcurves of the two species in the first O(100) ms are quite different.

RISE TIME ANALYSIS: HIERARCHY DETERMINATION

[see Serpico, Chakraborty, Fischer, Hudepohl, Janka & A.M., 1111.4483]

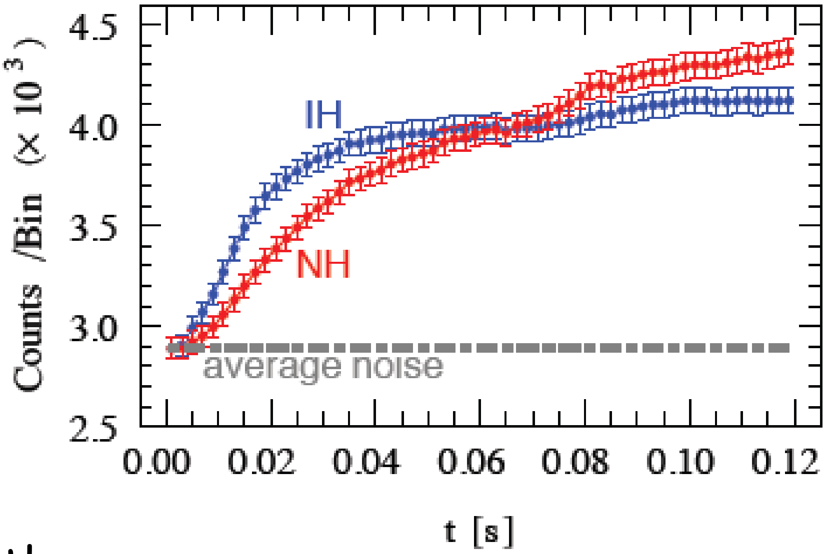
In accretion phase one has

$$F^D_{\bar{\nu}_e} = \cos^2\theta_{12} F_{\bar{\nu}_e} + \sin^2\theta_{12} F_{\bar{\nu}_x}$$ NH

$$F^D_{\bar{\nu}_e} = F_{\bar{\nu}_x}$$ IH

A high-statistics measurment of the rise time shape may distinguish the two scenarios

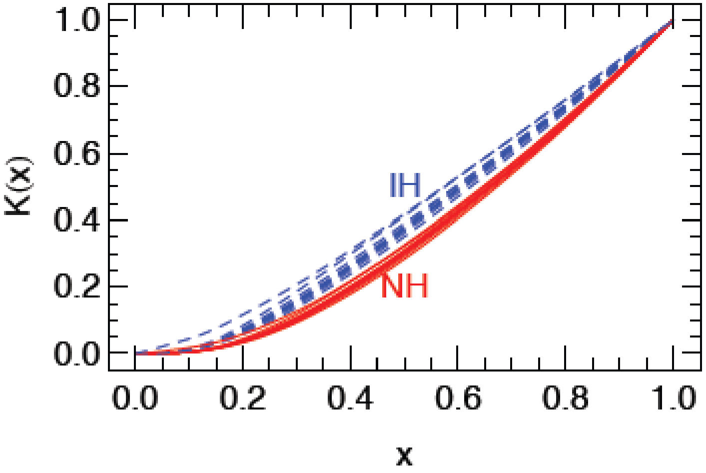
SN ν signal in Icecube



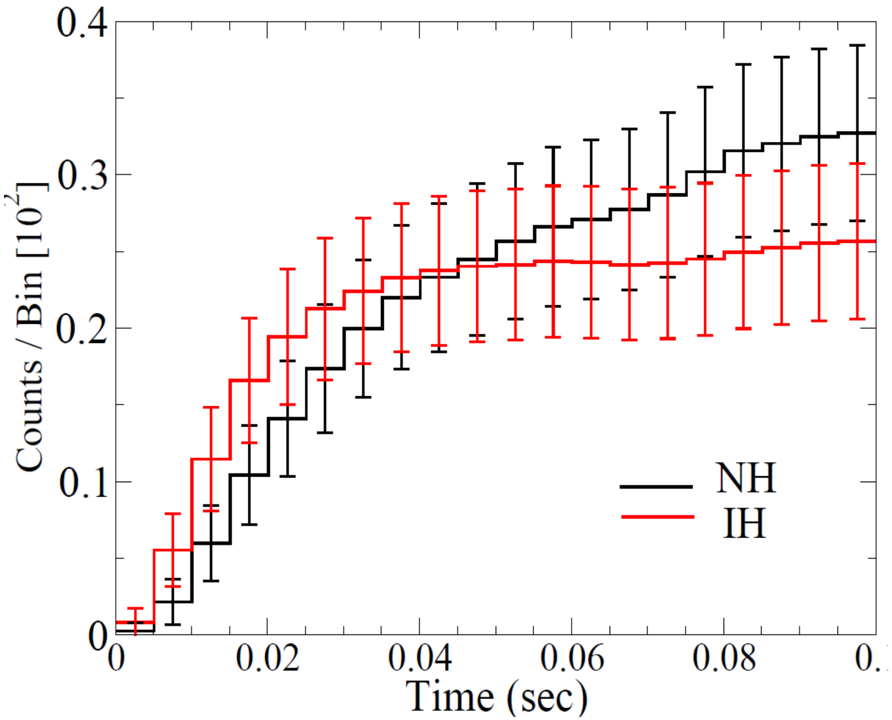
- Are the rise time shapes enough robustly predicted to be useful?

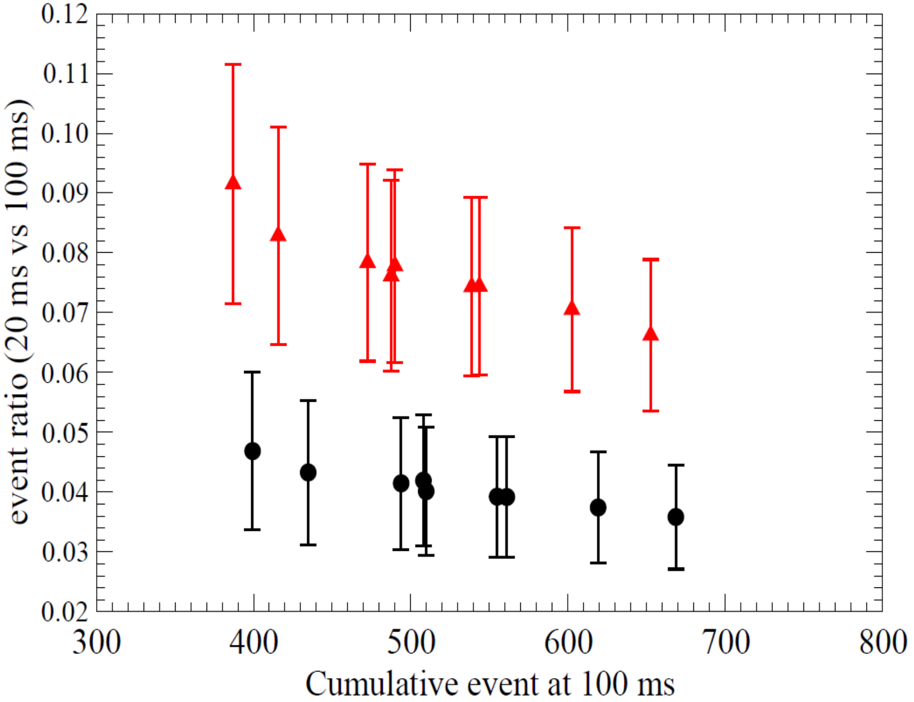
Models with state-of-the art treatment of weak physics (Garching simulations) suggest so: one could attribute a "shape" to NH and IH.

Cumulative distribution

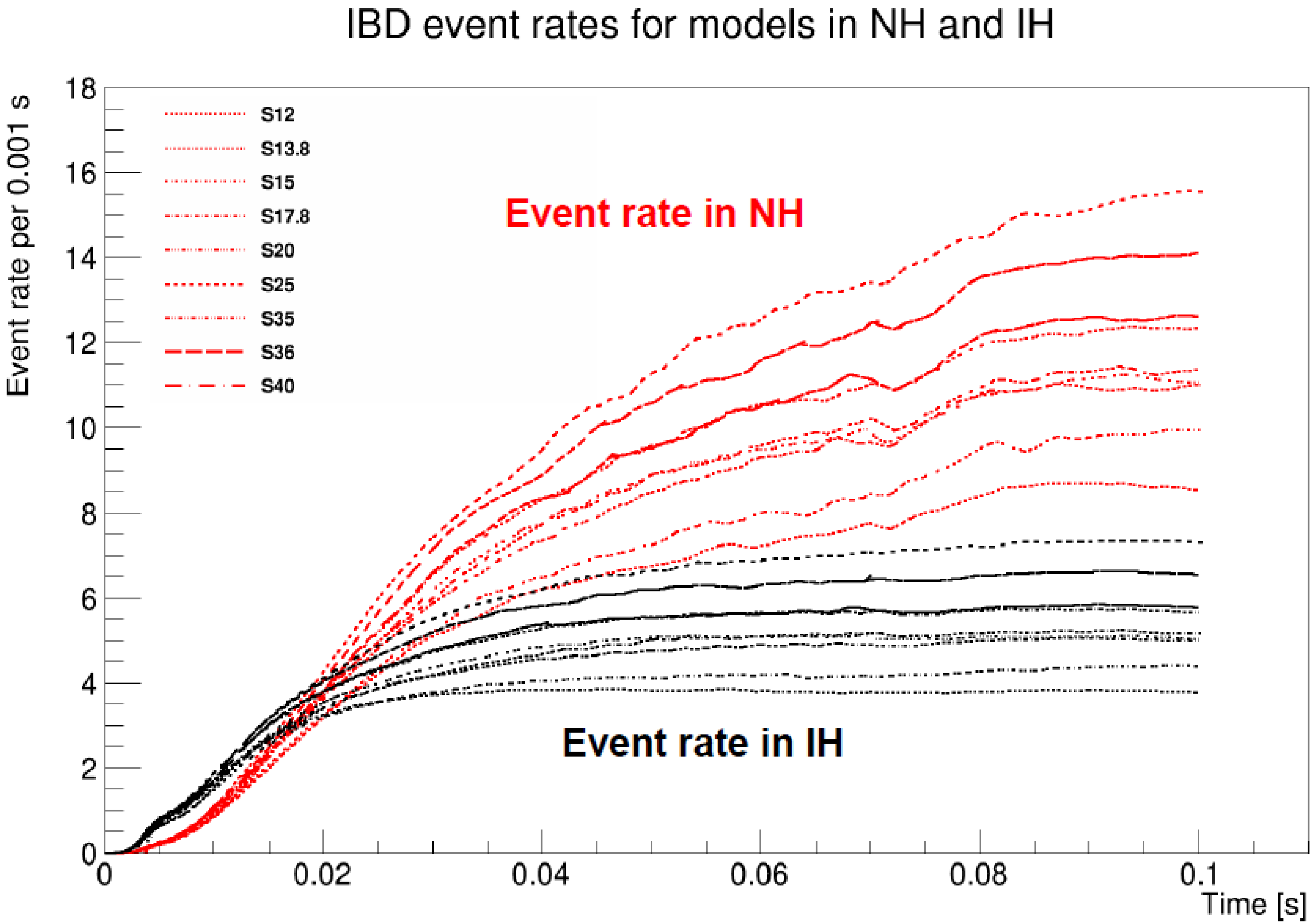


RISE TIME ANALYSIS IN LENA

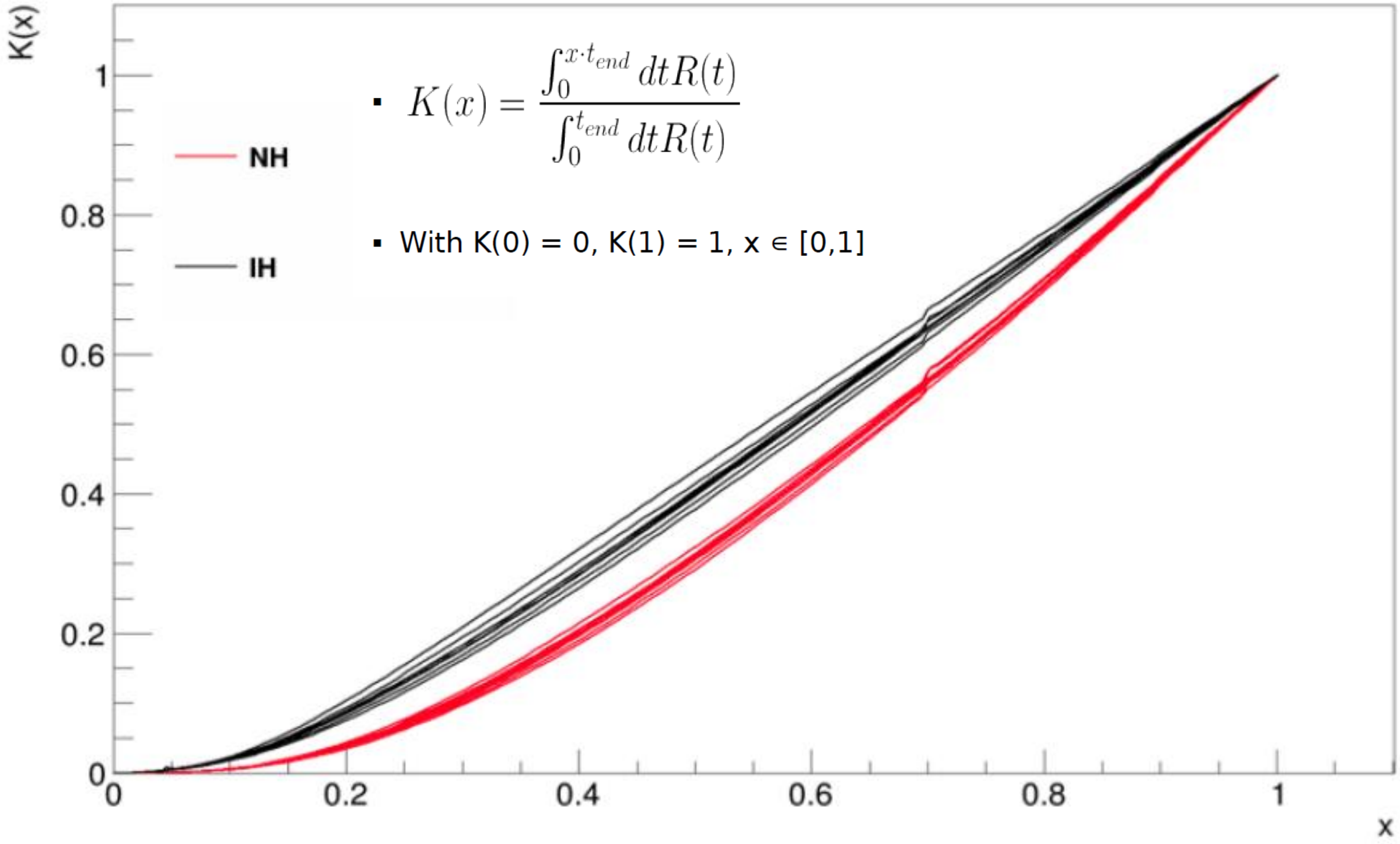




RISE TIME ANALYSIS IN LENA

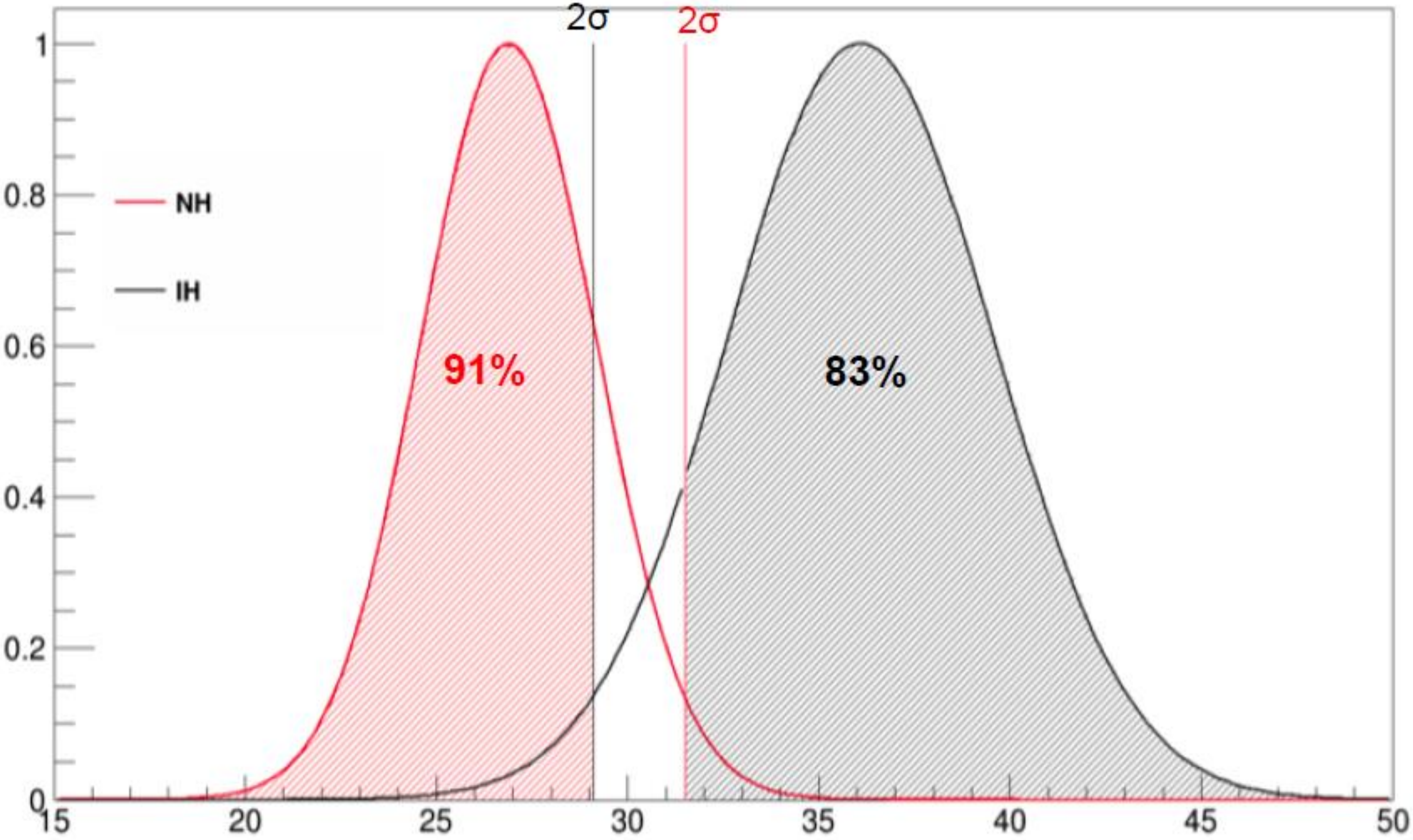


Cumulative time distributions for different models assuming NH and IH

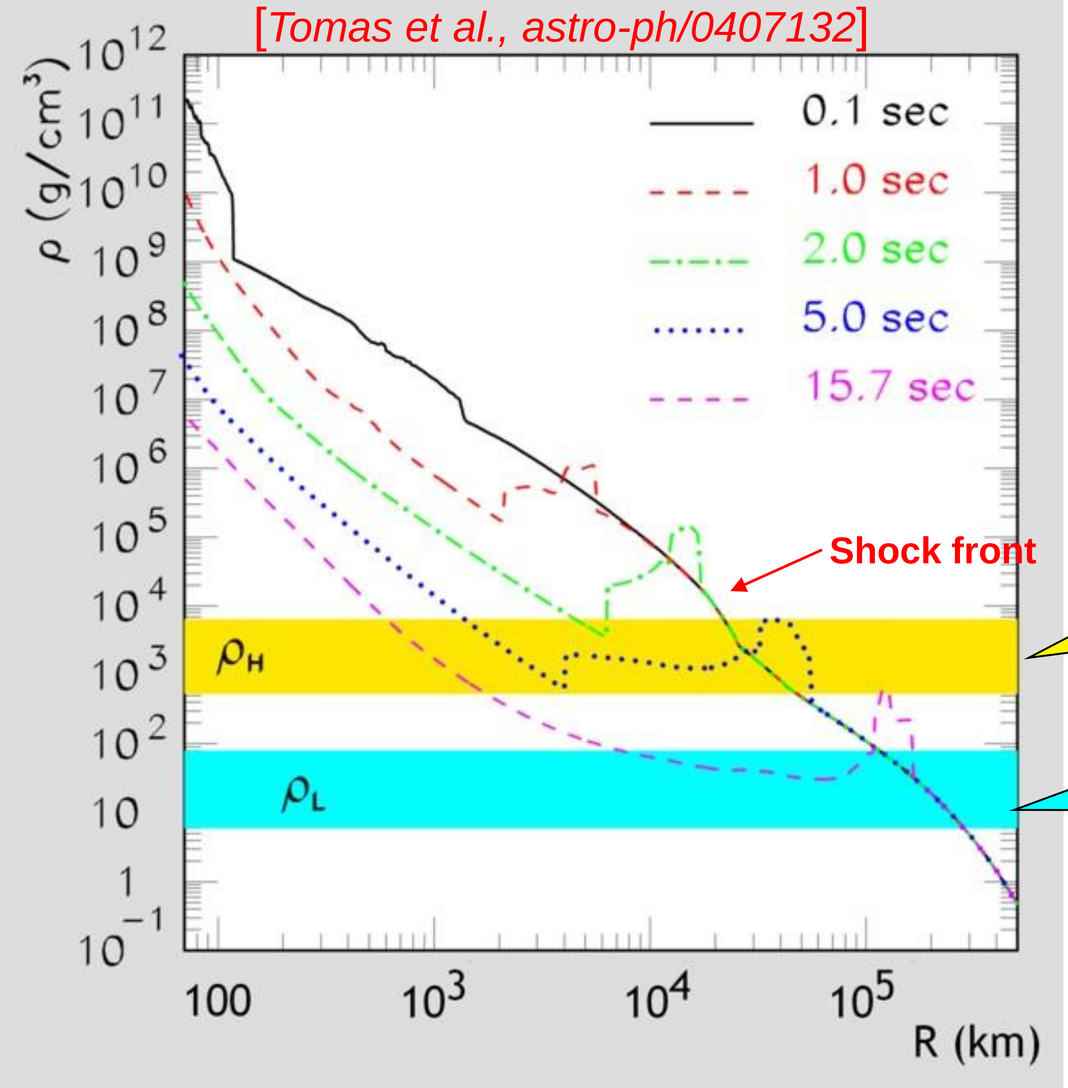


- $K(x) = \frac{\int_0^{x \cdot t_{end}} dt R(t)}{\int_0^{t_{end}} dt R(t)}$
- With K(0) = 0, K(1) = 1, x ∈ [0,1]

Distribution of cumulative event rate after 46ms



MSW MATTER EFFECT IN SN



[Tomas et al., astro-ph/0407132]

A few second after the core bounce, shock wave(s) can induce time-dependent matter effects in neutrino oscillations

[R.Schirato, and G. Fuller, astro-ph/0205390**]**

Resonance density for Δm^2_{atm}

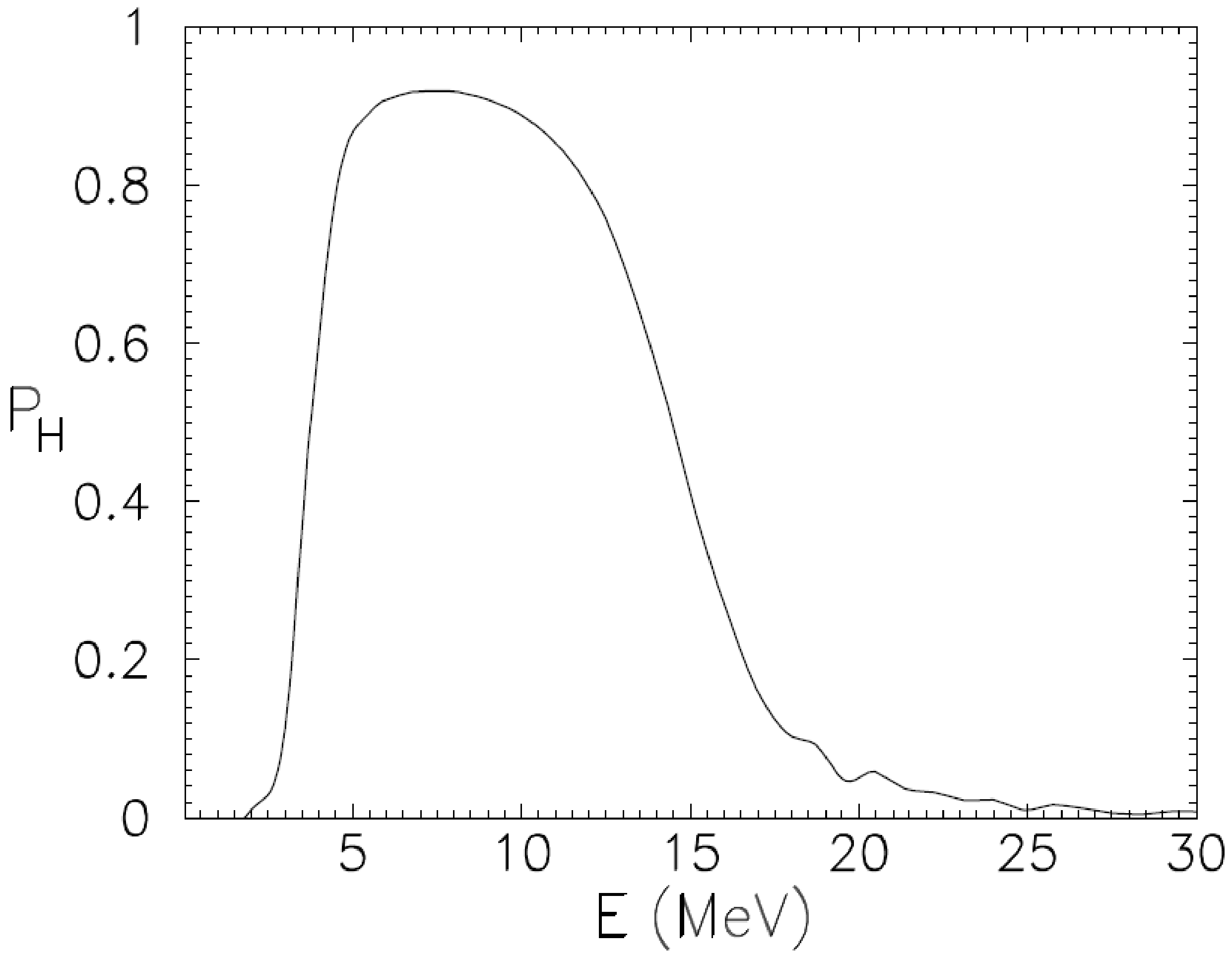
Not adiabatic along the shock front for large θ_{13}

Resonance density for Δm^2_{sol}

Always adiabatic

Neutrino oscillations as a "camera" for shock-wave propagation

CROSSING PROBABILITY ALONG THE SHOCK FRONT



The crossing probability has a typical top-hat structure, jumping from P_H~0 (adiabatic regime) to P_H~1 (extreme non-adiabatic regime) when resonance condition is satisfied along the shock-front

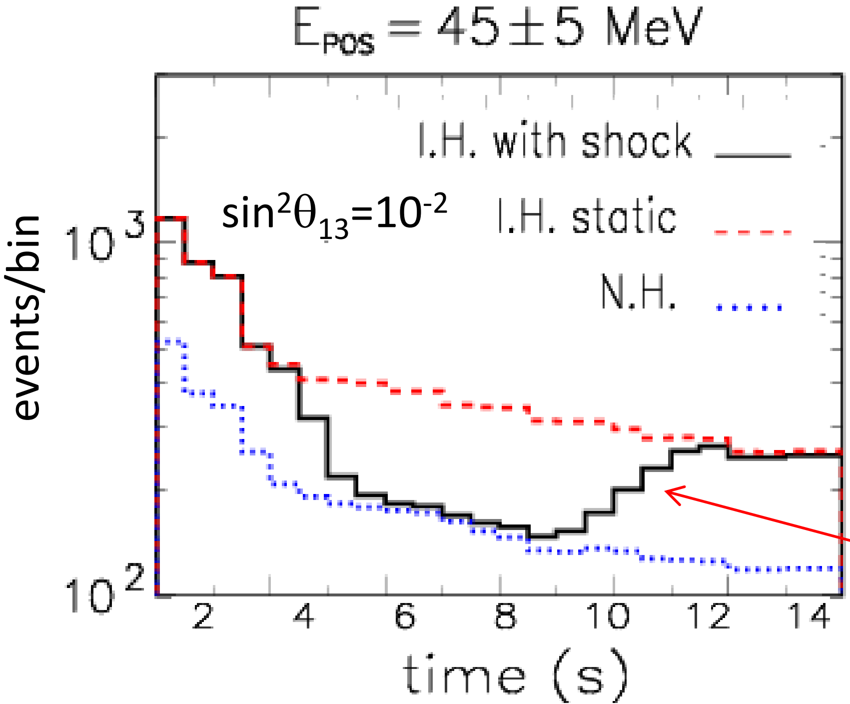
PROBING SHOCK WAVES

[see, e.g., G.L. Fogli, E.Lisi, A.M., and D. Montanino, hep-ph/0304056; G.L. Fogli, E. Lisi, A.M., and D. Montanino, hep-ph/0412046, Tomas et al., astro-ph/0407132]

0.4 Mton WC

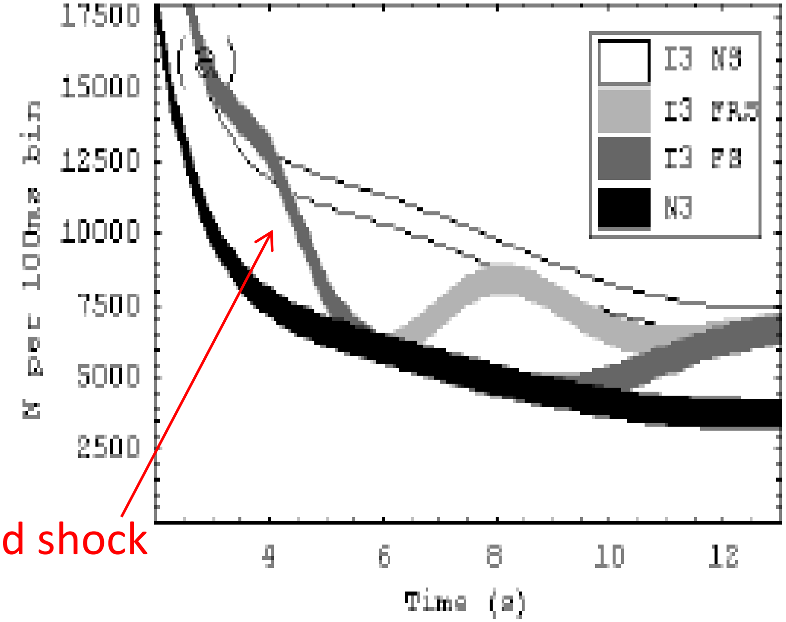
$\bar{\nu}_e + p \rightarrow n + e^+$

Icecube



[Fogli et al., hep-ph/0412046]

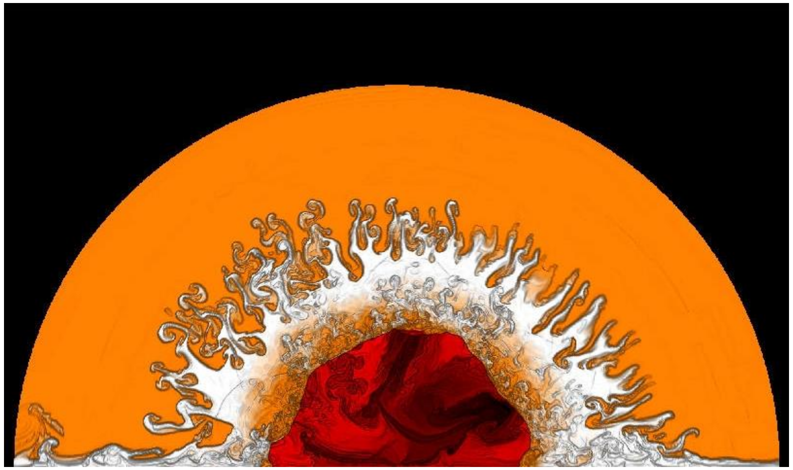
IH fwd shock



[Choubey et al, hep-ph/0605255]

In inverted hierarchy flavor conversions along the shock-waves induce non-monotonic time spectra.

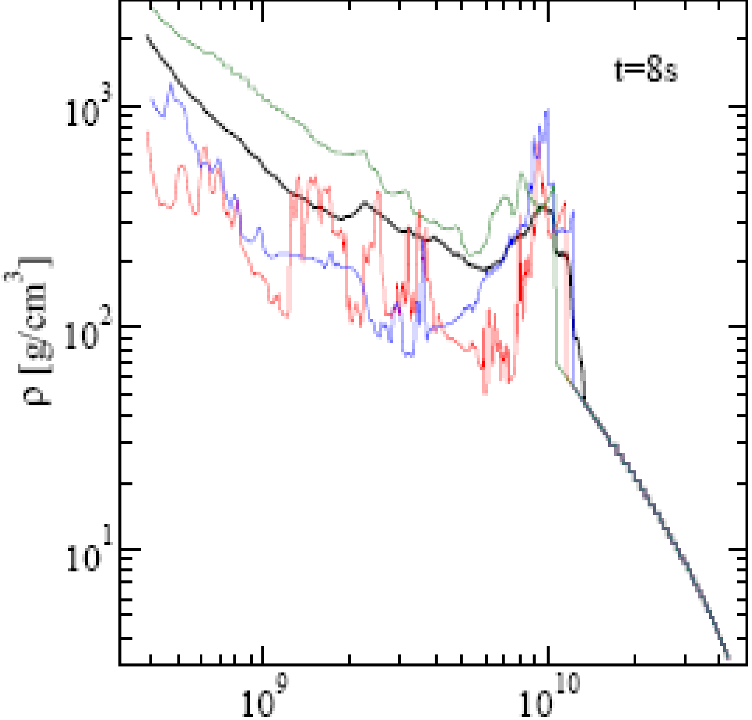
STOCHASTIC DENSITY FLUCTUATIONS



Turbulent convective motions behind the shock front create a fluctuating density field in the post-shock region. A SN neutrino "beam" might thus experience stochastic matter effects while traversing the stellar envelope.

[Fogli, Lisi, A.M. , Montanino, hep-ph/0603033; Friedland, astro-ph/0607244; Choubey, Harries, Ross, hep-ph/0703092, Kneller, 1004.1288, Kneller & Volpe, 1006.0913]

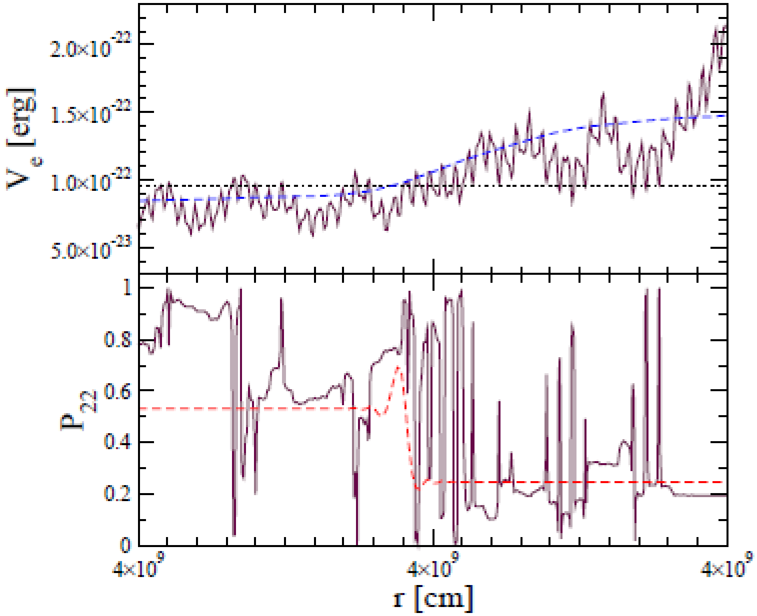
GARCHING 2D simulation



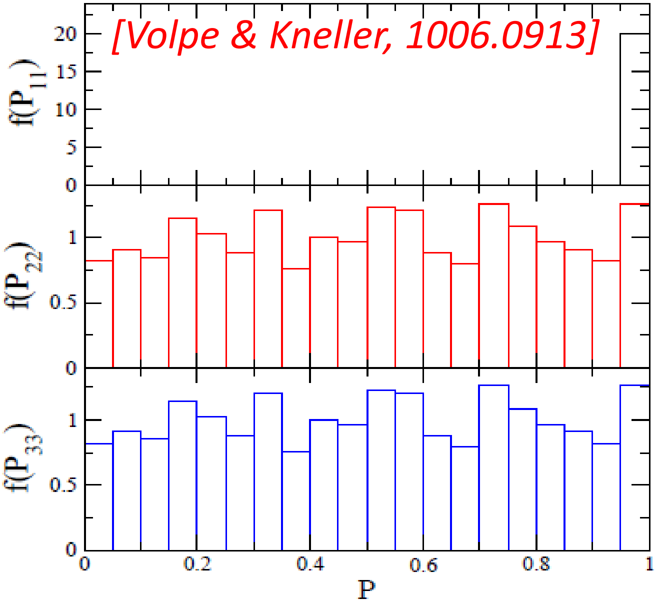
Depolarization ($\langle P_{ee} \rangle \to \frac{1}{2}$) would replace the shock-signature when turbulence is relevant

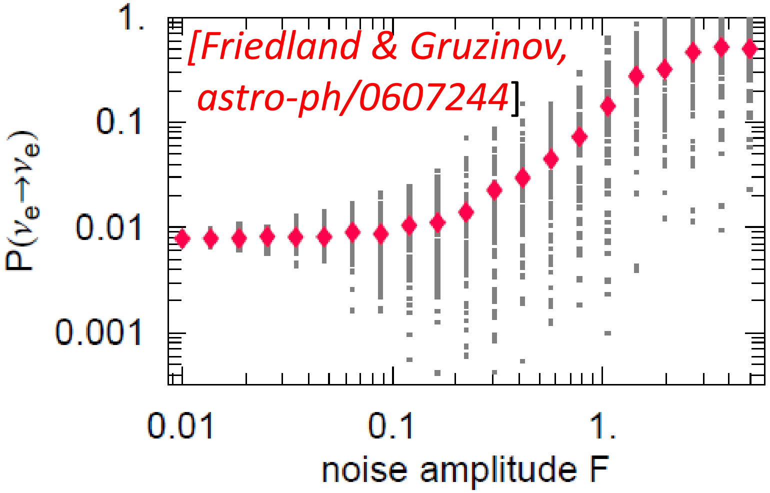
ν FLAVOR CONVERSIONS IN A TURBULENT SN

MSW multiple H-resonances



Probability distribution over many realizations of the random noise


[Volpe & Kneller, 1006.0913]


[Friedland & Gruzinov, astro-ph/0607244]

Strong fluctuations: Complete flavor depolarization : $\langle P_{ee}\rangle \rightarrow 1/2$

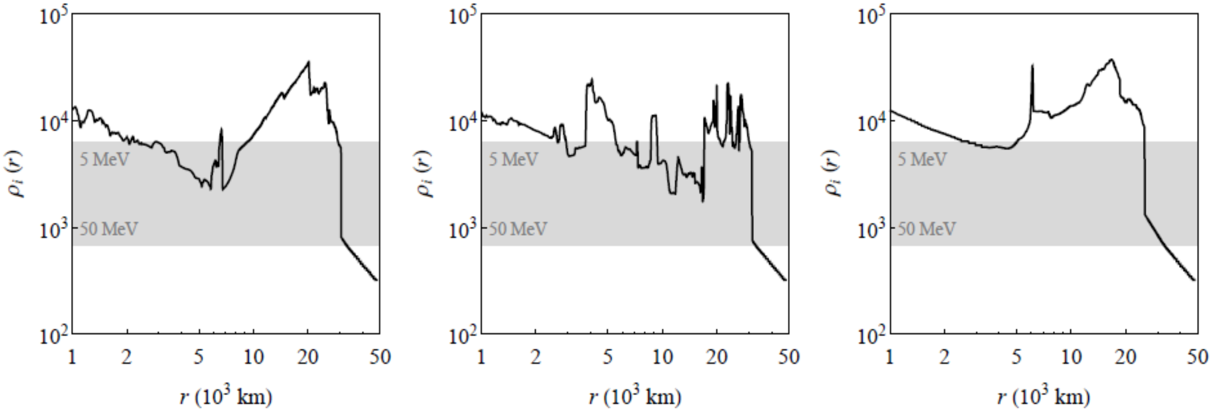
(Both resonant & off-resonant effects)

Depolarization would replace the shock-signature: SHADOW EFFECT

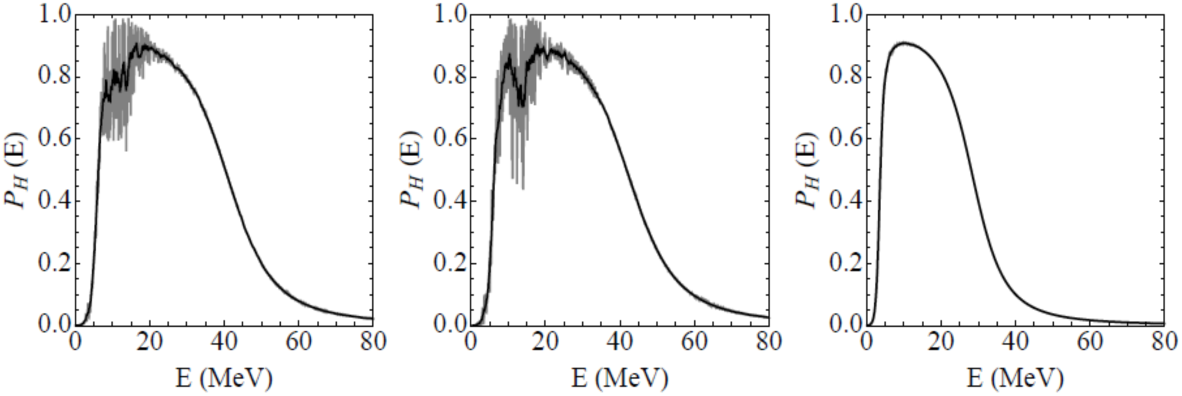
ν FLAVOR CONVERSIONS IN A 2D SN MODEL

[Borriello, Chakraborty, Janka, Lisi, A.M., 1310.7488]

Three representative lines of sight



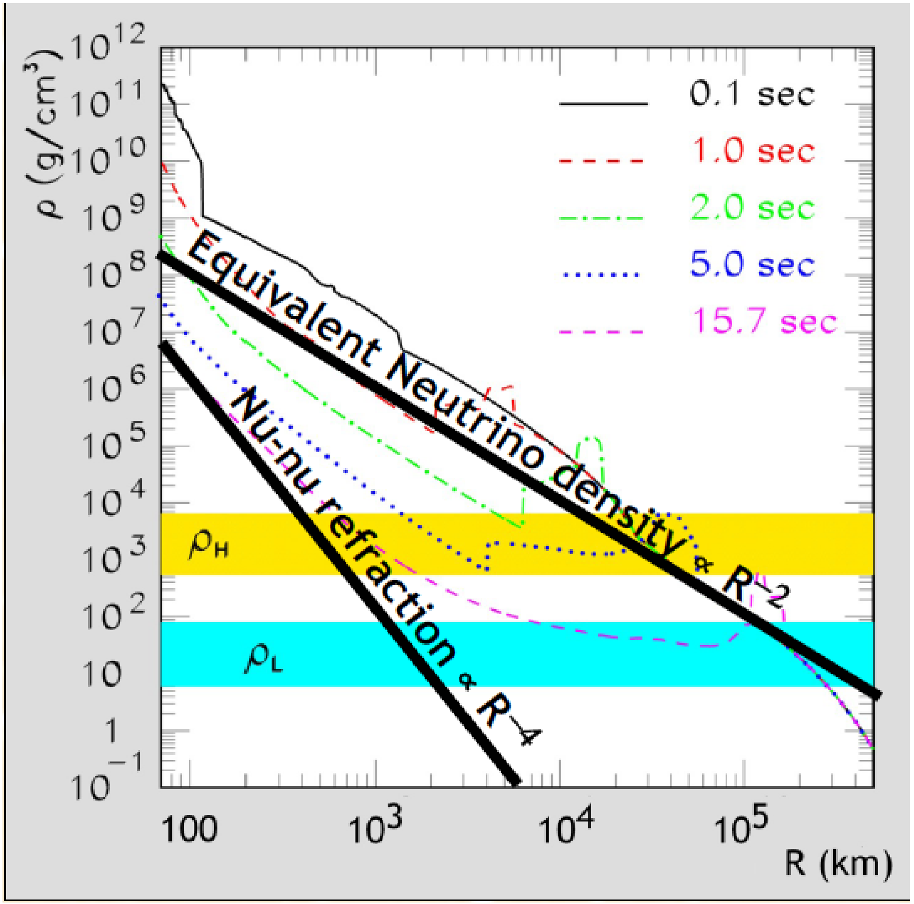
Neutrino crossing probabilities



modest damping effect

NEUTRINO-NEUTRINO INTERACTIONS

In the region just above the neutrino-sphere the neutrino density exceeds the ordinary electron background. Neutrinos themeselves form a background medium



ν–ν NC interactions important!

- Matter bkg potential

$$V = \sqrt{2} G_F N_e \quad \sim R^{-3}$$

- ν–ν potential

Multi-angle effects

$$\mu = \sqrt{2} G_F n_\nu (1 - \cos\theta_{pq}) \sim R^{-2} \times R^{-2} = R^{-4}$$

Lesson: self-interactions (μ) can induce large, non-MSW flavor change at small radii, despite large matter density V

Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

Collective Supernova Nu Oscillations since 2006

Two seminal papers in 2006 triggered a torrent of activities
Duan, Fuller, Qian, astro-ph/0511275, Duan et al. astro-ph/0606616

Balantekin, Gava & Volpe [0710.3112]. Balantekin & Pehlivan [astro-ph/0607527]. Blennow, Mirizzi & Serpico [0810.2297]. Cherry, Fuller, Carlson, Duan & Qian [1006.2175, 1108.4064]. Cherry, Wu, Fuller, Carlson, Duan & Qian [1109.5195]. Cherry, Carlson, Friedland, Fuller & Vlasenko [1203.1607]. Chakraborty, Choubey, Dasgupta & Kar [0805.3131]. Chakraborty, Fischer, Mirizzi, Saviano, Tomàs [1104.4031, 1105.1130]. Choubey, Dasgupta, Dighe & Mirizzi [1008.0308]. Dasgupta & Dighe [0712.3798]. Dasgupta, Dighe & Mirizzi [0802.1481]. Dasgupta, Dighe, Raffelt & Smirnov [0904.3542]. Dasgupta, Dighe, Mirizzi & Raffelt [0801.1660, 0805.3300]. Dasgupta, Mirizzi, Tamborra & Tomàs [1002.2943]. Dasgupta, Raffelt & Tamborra [1001.5396]. Dasgupta, O'Connor & Ott [1106.1167]. Duan, Fuller, Carlson & Qian [astro-ph/0608050, 0703776, 0707.0290, 0710.1271]. Duan, Fuller & Qian [0706.4293, 0801.1363, 0808.2046, 1001.2799]. Duan, Fuller & Carlson [0803.3650]. Duan & Kneller [0904.0974]. Duan & Friedland [1006.2359]. Duan, Friedland, McLaughlin & Surman [1012.0532]. Esteban-Pretel, Mirizzi, Pastor, Tomàs, Raffelt, Serpico & Sigl [0807.0659]. Esteban-Pretel, Pastor, Tomàs, Raffelt & Sigl [0706.2498, 0712.1137]. Fogli, Lisi, Marrone & Mirizzi [0707.1998]. Fogli, Lisi, Marrone & Tamborra [0812.3031]. Friedland [1001.0996]. Gava & Jean-Louis [0907.3947]. Gava & Volpe [0807.3418]. Galais, Kneller & Volpe [1102.1471]. Galais & Volpe [1103.5302]. Gava, Kneller, Volpe & McLaughlin [0902.0317]. Hannestad, Raffelt, Sigl & Wong [astro-ph/0608695]. Wei Liao [0904.0075, 0904.2855]. Lunardini, Müller & Janka [0712.3000]. Mirizzi, Pozzorini, Raffelt & Serpico [0907.3674]. Mirizzi & Serpico [1111.4483]. Mirizzi & Tomàs [1012.1339]. Pehlivan, Balantekin, Kajino & Yoshida [1105.1182]. Pejcha, Dasgupta & Thompson [1106.5718]. Raffelt [0810.1407, 1103.2891]. Raffelt & Sigl [hep-ph/0701182]. Raffelt & Smirnov [0705.1830, 0709.4641]. Raffelt & Tamborra [1006.0002]. Sawyer [hep-ph/0408265, 0503013, 0803.4319, 1011.4585]. Sarikas, Raffelt, Hüdepohl & Janka [1109.3601]. Sarikas, Tamborra, Raffelt, Hüdepohl & Janka [1204.0971]. Saviano, Chakraborty, Fischer, Mirizzi [1203.1484]. Wu & Qian [1105.2068]……………………….

NEUTRINO-NEUTRINO HAMILTONIAN

$$i\frac{d}{dx}\psi_{\nu}^{(i)} = \left(H_{vac} + H_{e} + \sum_{j} H_{\nu\nu}^{(ij)} \right)\psi_{\nu}^{(i)}$$

In early studies the neutrino-neutrino Hamiltonian was assumed diagonal in flavor basis: No contribution to flavor evolution!

Critical examination of this assumption by J.Pantaleone [PLB 287, 128 (1992)]

Low-energy neutral current Hamiltonian for ν-ν interactions possesses an U(N) symmetry. A diagonal $H_{\nu\nu}$ doesn't respect this symmetry.

Pantaleone proposed a modified form of $H_{\nu\nu}$ which contains non-zero off-diagonal terms

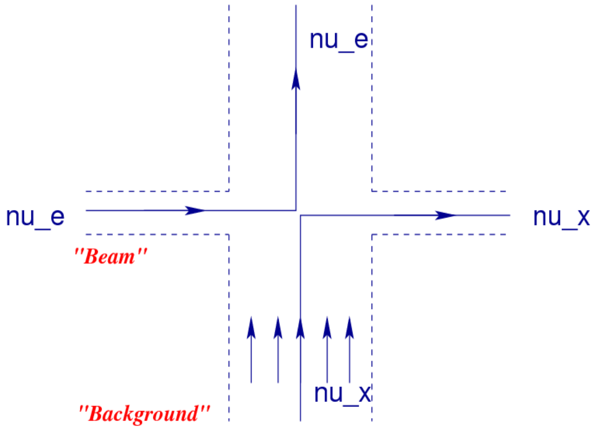
$$H_{\nu\nu} = A\begin{pmatrix} |\nu_e|^2 & \nu_e\nu_\mu^* \\ \nu_e^*\nu_\mu & |\nu_\mu|^2 \end{pmatrix}$$

It respects U(N) symmetry

$$A = \sqrt{2}G_F\left(1-\cos\theta_{ij}\right)$$

NEUTRINO FLAVOR CONVERSIONS IN A NEUTRINO BACKGROUND

Since $H_{\nu\nu}$ cannot change the *total* flavor of the system, ν-ν interactions do contribute to the flavor evolution only when the “propagating” and “background” neutrinos do exchange momenta



Momentum exchange

↓

Flavor exchange

If all the ν in the bkg are in the same flavor state $\nu_x = \cos\alpha\,\nu_e + \sin\alpha\,\nu_\mu$

$$H_{\nu\nu} \propto \frac{\sqrt{2}G_F n_2}{2}\begin{pmatrix}\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix} \Longrightarrow P(\nu_e \to \nu_\mu) \approx \sin^2 2\alpha (G_F n_2 L)^2/2$$

[Friedland & Lunardini, hep-ph/0304055]

However, one cannot distinguish btw beam and bkg. Instrinsic non-linear problem !

DENSITY MATRIX FOR THE NEUTRINO ENSEMBLE

Diagonal elements related to flavor content

$$\rho_{\alpha\alpha} = \frac{F_{\nu_\alpha}(E,r)}{F(E,r)}$$

$$\rho = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho^*_{e\mu} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{e\tau} & \rho^*_{\mu\tau} & \rho_{\tau\tau} \end{pmatrix}$$

Off-diagonal elements responsible for flavor conversions

- In 2ν scenario (Δm^2_{atm}, θ_{13}). Decompose density matrix over Pauli matrices to get the "**polarization**" (Bloch) vector **P**. Survival probability Pee =1/2(1+$\mathbf{P}_z$) . $\mathbf{P}_z$ = -1 -> Pee =0 ; $\mathbf{P}_z$ = 0 -> Pee =1/2 (flavor decoherence)

- The EOMs for the time evolution in a homogeneous medium are the Liouville equations (e.g. Early Universe)

$$i\partial_t \rho_{\mathrm{p}} = [H_{\mathrm{p}}, \rho_{\mathrm{p}}]$$

GENERAL EQUATIONS OF MOTION

[*Sigl & Raffelt, Nucl.Phys.B406:423-451,1993*]

ν

$$i\partial_t \rho_p = +\left[\frac{M^2}{2p}, \rho_p\right] + \sqrt{2}G_F\left[L, \rho_p\right] + \sqrt{2}G_F \int \frac{d^3q}{(2\pi)^3}(1-\cos\theta_{pq})\left[(\rho_q - \bar{\rho}_q), \rho_p\right]$$

$\bar{\nu}$

$$i\partial_t \bar{\rho}_p = \underbrace{-\left[\frac{M^2}{2p}, \bar{\rho}_p\right]}_{\text{vacuum oscillations}} + \underbrace{\sqrt{2}G_F\left[L, \bar{\rho}_p\right]}_{\text{usual matter effects}} + \underbrace{\sqrt{2}G_F \int \frac{d^3q}{(2\pi)^3}(1-\cos\theta_{pq})\left[(\rho_q - \bar{\rho}_q), \bar{\rho}_p\right]}_{\text{neutrino-neutrino interactions}}$$

- Vacuum oscillations

  - M^2 is the neutrino mass matrix

  - Note the opposite sign between neutrinos and antineutrinos

- Matter effects

  In normal matter, L=diag(N_{e-}-N_{e+},0,0)

- Non-linear neutrino-neutrino effects

  Relevant when ν-ν interaction energy exceeds typical vacuum oscillation frequency

$$\omega_{osc} = \frac{\Delta m^2}{2E} < \mu = \sqrt{2}G_F n_\nu \left\langle 1-\cos\theta_{pq}\right\rangle$$

EQUATIONS OF MOTION FOR TWO FLAVOR CASE

ν

$$\partial_t \vec{P}_{\vec{p}} = \overbrace{+\omega \vec{B}\times \vec{P}_{\vec{p}}}^{\text{vacuum}} + \overbrace{\lambda \vec{z}\times \vec{P}_{\vec{p}}}^{\text{matter}} + \sqrt{2}G_F \int \overbrace{\frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{pq})(\vec{P}_{\vec{q}}-\vec{\bar{P}}_{\vec{q}})\times \vec{P}_{\vec{p}}}^{\nu\text{-}\nu\text{ interactions}}$$

$\overline{\nu}$

$$\partial_t \vec{P}_{\vec{p}} = -\omega \vec{B}\times \vec{\bar{P}}_{\vec{p}} + \lambda \vec{z}\times \vec{\bar{P}}_{\vec{p}} + \sqrt{2}G_F \int \frac{d^3\vec{q}}{(2\pi)^3}(1-\cos\theta_{pq})(\vec{P}_{\vec{q}}-\vec{\bar{P}}_{\vec{q}})\times \vec{\bar{P}}_{\vec{p}}$$

- **Polarization vectors** $$\rho_p = \frac{f_p}{2}(1+\vec{\sigma}\cdot\vec{P}_p)$$
- **“Magnetic field”** $$\vec{B} = \left(\sin 2\theta_{13}, 0, \mp\cos\theta_{13}\right)$$
- **Vacuum frequency** $$\omega = \frac{\Delta m^2}{2E}$$
- **Matter potential** $$\lambda = \sqrt{2}G_F N_e$$
- **ν–ν potential** $$\mu = \sqrt{2}G_F n_\nu \left\langle 1-\cos\theta_{pq}\right\rangle$$

2.3.1 Polarization vector and neutrino oscillations

Neutrino oscillations are frequently described by a Schrödinger equation of the form

$$i\dot{\Psi} = \Omega\Psi \qquad \text{with} \qquad \Omega = p + \frac{M^2}{2p}, \tag{50}$$

with p the neutrino momentum, M the mass matrix, and Ψ a column vector with two or more flavors. For two generations, the relation between flavor and mass eigenstates is given by Eq. (22). Instead of the state vectors, however, one can work with the 2×2 density matrix in flavor space which is defined by

$$\rho_{ab} = \Psi_b^* \Psi_a, \tag{51}$$

where the indices a and b run, for example, over ν_e and ν_μ or over 1 and 2 in the mass basis. With the help of the density matrix we can find an intuitive geometric interpretation of oscillation phenomena. In addition, one can treat statistical mixtures of states, i.e. when the neutrinos are not characterized by pure states.

a) Show that the equation of motion is: $i\dot{\rho} = [\Omega, \rho] = [M^2, \rho]/2p$.

b) Write the mass matrix in the form $M^2/2p = V_0 - \frac{1}{2}\mathbf{V}\cdot\sigma$ and show, that in the flavor basis

$$V_0 = \frac{m_2^2 + m_1^2}{4p} \text{ and } \mathbf{V} = \frac{2\pi}{\omega_{\rm osc}} \begin{pmatrix} \sin 2\theta \\ 0 \\ \cos 2\theta \end{pmatrix} \text{ with } \omega_{\rm osc} = \frac{4\pi p}{m_2^2 - m_1^2}. \tag{52}$$

The vector $\mathbf{V}$ is thus rotated against the 3–axis with the angle 2θ. Has this orientation in the 1–2 plain a physical meaning?

c) Express the density matrix in terms of a polarization vector in form of $\rho = \frac{1}{2}(1+\mathbf{P}\cdot\sigma)$. Physical interpretation of its components?

d) Which property of $\mathbf{P}$ characterizes the "purity" of the state, i.e. when does the density matrix describe pure states, when maximally incoherent mixing?

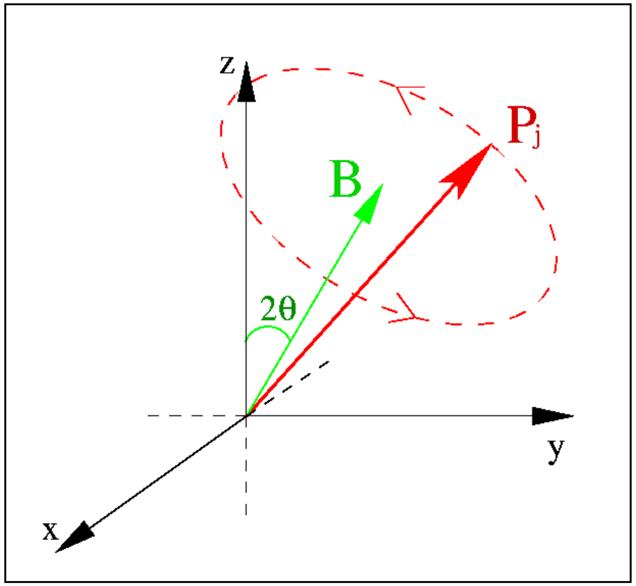
e) Show that the equation of motion is a precession formula, $\dot{\mathbf{P}} = \mathbf{V}\times\mathbf{P}$. Obtain the oscillation probability for an initial ν_e.

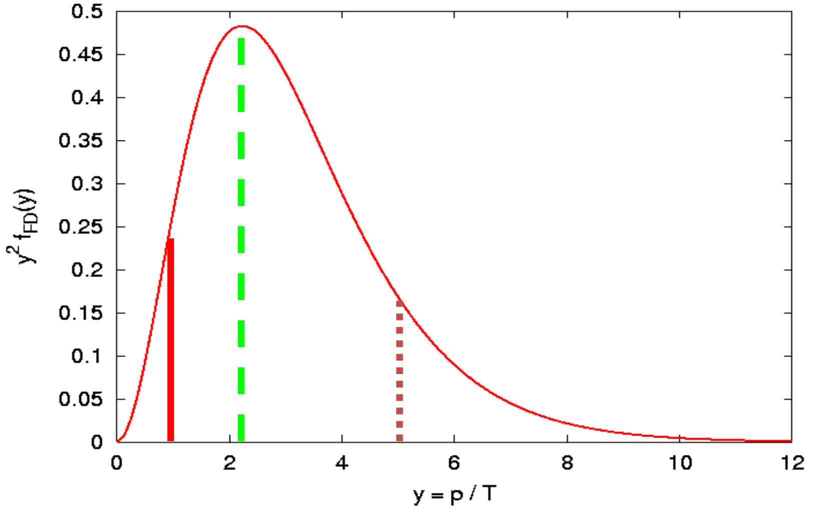
f) The energy of (non–mixed) relativistic neutrinos in a normal medium is $E = p + (m^2/2p) + V_{\rm med}$. Here $V_{\rm med}$ is given by Eq. (11). What is $\mathbf{P}$ in the medium? What is the mixing angle in the medium?

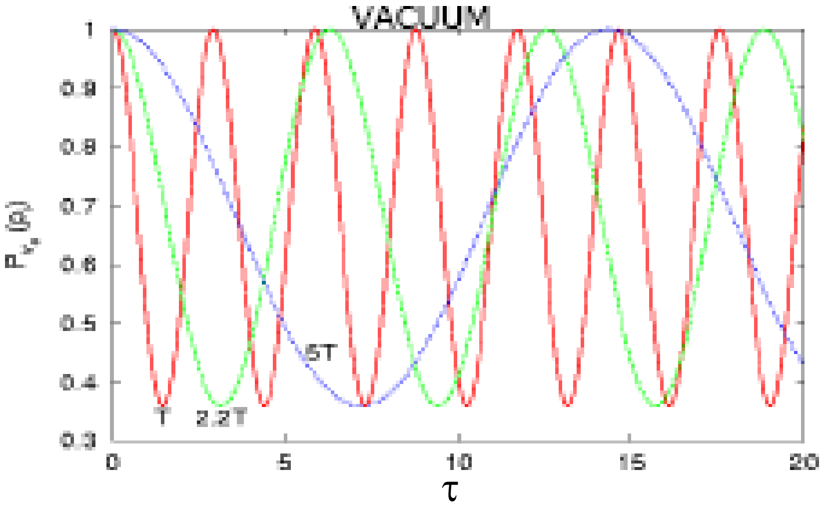
g) In a medium consisting of neutrinos (supernova, early universe) one can not distinguish between a test neutrino and a background neutrino, so that oscillations with medium effects are in general nonlinear. What is the advantage of the density matrix formalism in this situation?

VACUUM OSCILLATIONS: SPIN PRECESSION ANALOGY

$$\partial_t \vec{P}_{\vec{p}} = +\omega \vec{B} \times \vec{P}_{\vec{p}}$$







Neutrinos with a broad distribution precess with different frequencies around the external magnetic field B (in flavor space)

Kinematical decoherence in flavor space

ν-ν INTERACTIONS: SINGLE-ANGLE APPROXIMATION

The structure of neutrino-neutrino interactions contains an angular modulation

“multi angle case”

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3\vec{q}}{(2\pi)^3} \boxed{(1-\cos\theta_{pq})} (P_{\vec{q}} - \bar{P}_{\vec{q}})$$

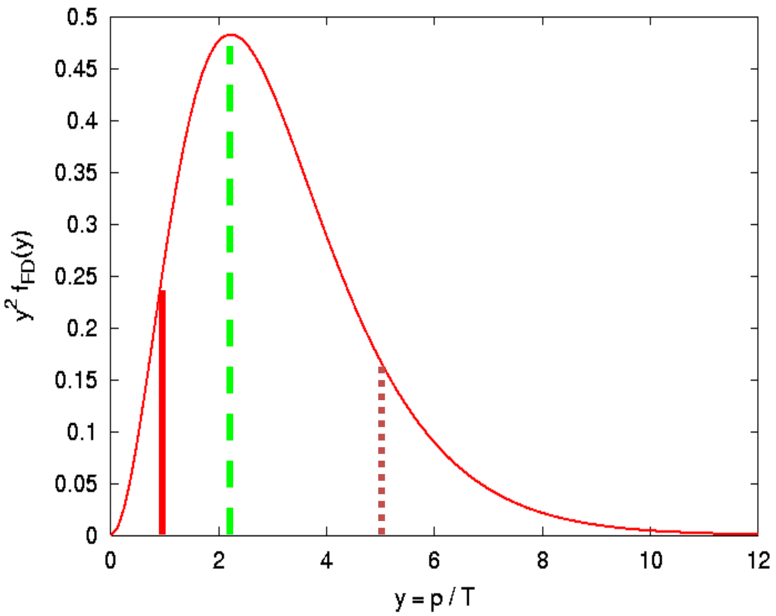
This makes very challenging the solution of the equations.

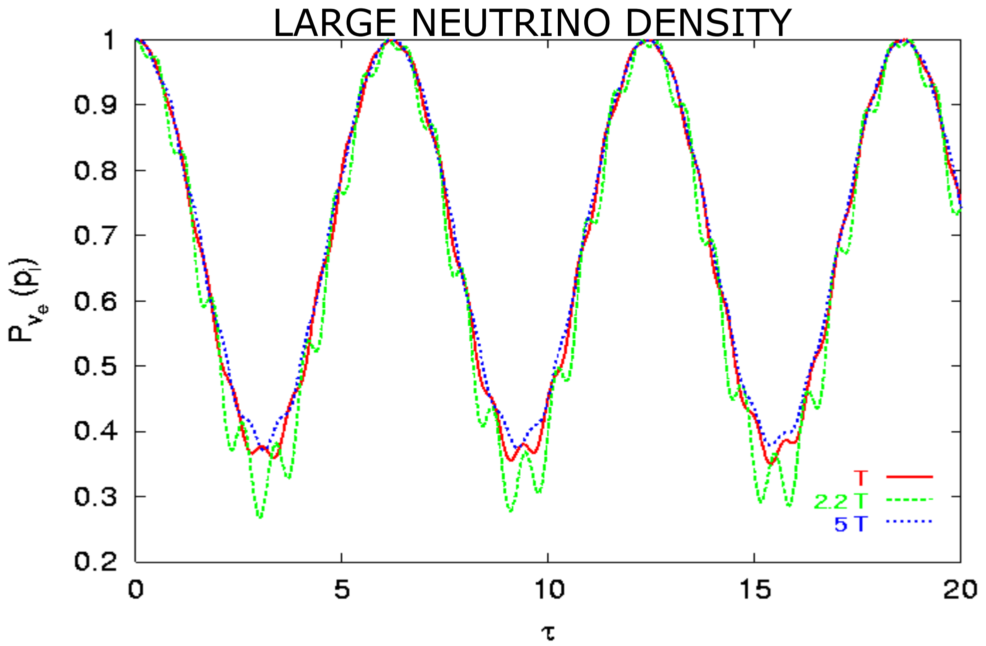
If averaged: single angle approximation

$$H_{\nu\nu} = \mu \int dq (P_q - \bar{P}_q) = \mu (P - \bar{P})$$

SYNCHRONIZED OSCILLATIONS BY NEUTRINO-NEUTRINO INTERACTIONS

$$\partial_t P_\omega = \omega B \times P_\omega + \mu P \times P_\omega$$





- $\mu >> \omega$ → All the modes lock to each other and spin-precess together, in analogy to spin-coupling in atoms

Synchronized oscillation frequency: $\omega_{sync} = \left\langle \frac{\Delta m^2}{2E} \right\rangle$

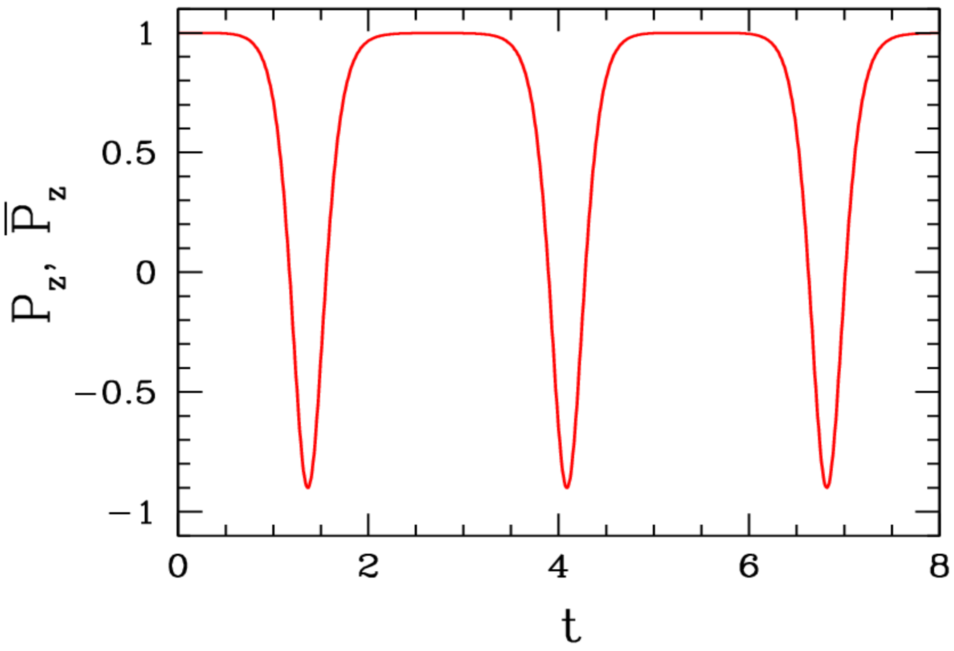
[Pastor, Raffelt, Semikoz, hep-ph/0109033]

OSCILLATIONS OF NEUTRINOS PLUS ANTINEUTRINOS IN A BOX

Equal densities of ν_e and $\bar{\nu}_e$, only one neutrino energy, $\mu \gg \omega$

$$\nu \qquad \partial_t P = +\omega B \times P + \mu(P - \bar{P}) \times P$$

$$\bar{\nu} \qquad \partial_t \bar{P} = -\omega B \times \bar{P} + \mu(P - \bar{P}) \times \bar{P}$$



In inverted hierarchy: coherent “pair conversion” $\nu_e \bar{\nu}_e \longrightarrow \nu_\mu \bar{\nu}_\mu$

With constant μ: periodic behaviour

PENDULUM IN FLAVOR SPACE

[Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695, Duan, Carlson, Fuller, Qian, astro-ph/0703776]

Neutrino mass hierarchy (and θ_{13}) set initial condition and fate

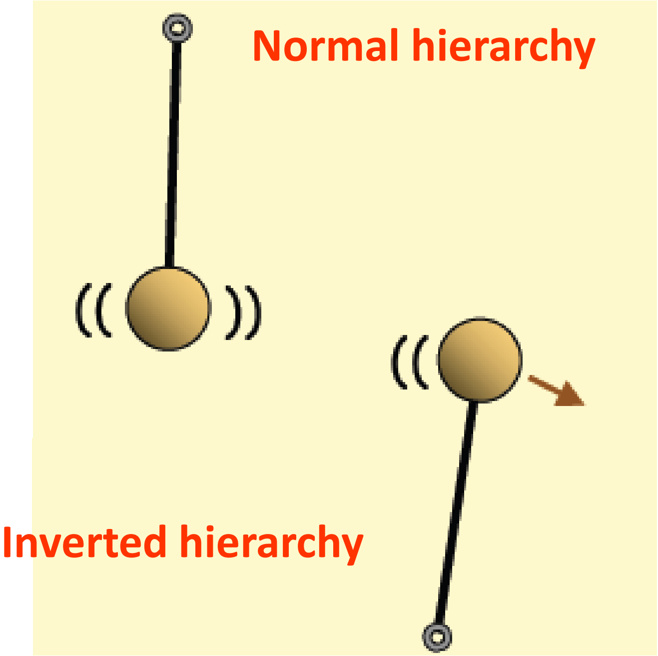
With only initial ν_e and $\overline{\nu}_e$:

- **Normal hierarchy**

  Pendulum starts in ~ downard (stable) positions and stays nearby. No significant flavor change.

- **Inverted hierarchy**

  Pendulum starts in ~ upward (unstable) positions and eventually falls down. Significant flavor changes.



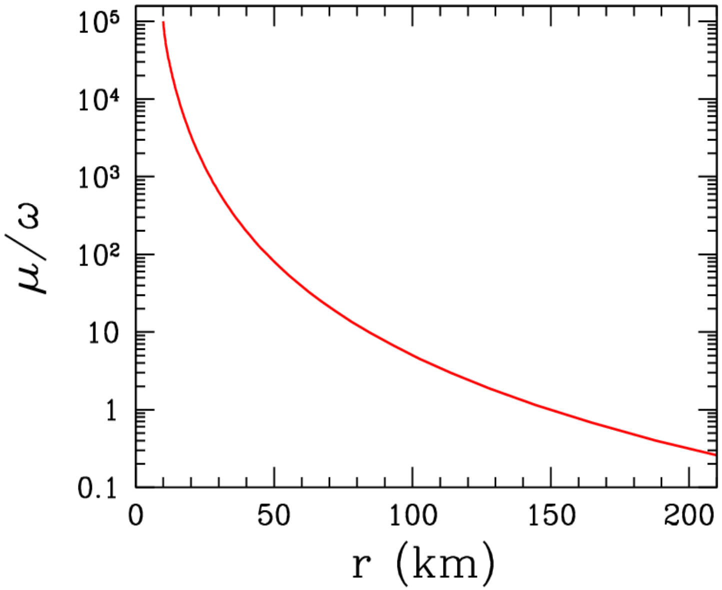
θ_{13} sets initial misalignment with vertical. Specific value not much relevant.

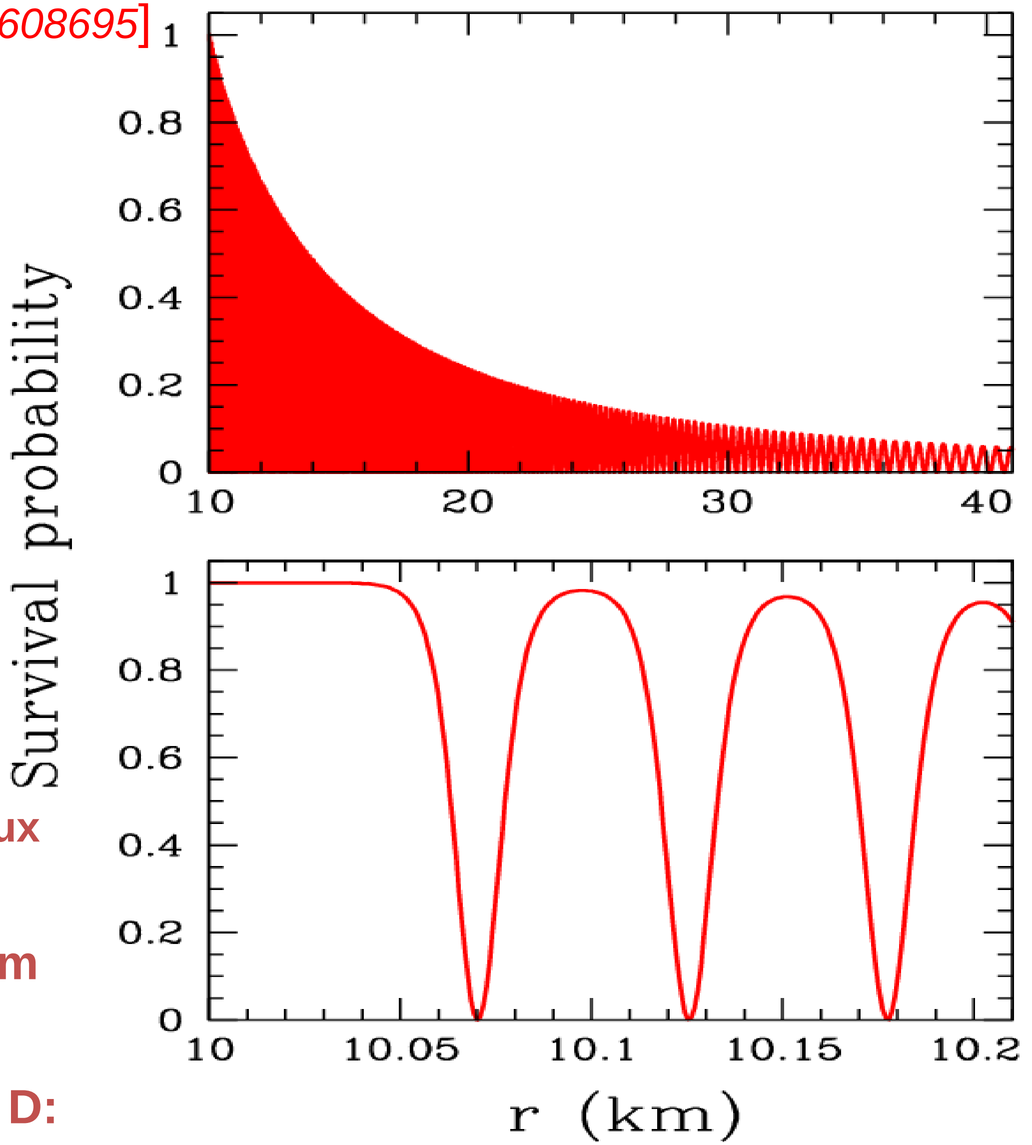
Which mass hierarchy?

With only initial ν_μ and $\overline{\nu}_\mu$ large flavor conversions in NH. The unstable case is when the initial ensemble consists of that flavor which is dominated by the heavier mass eigenstate.

SUPERNOVA CASE

[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]





- **In SN μ decreases ad r^{-4} (geometric flux diluition and ν's become more co-linear)**
- **Momentum of inertia of the pendulum $I = \mu^{-1}$ increases**
- **Conservation of angular momentum D:**

- kinetic energy ($D^2/2I$) decreases

- amplitude decreases as $\mu^{1/2}$

→ **Complete flavor conversions!**

GYROSCOPIC PENDULUM IN FLAVOR SPACE

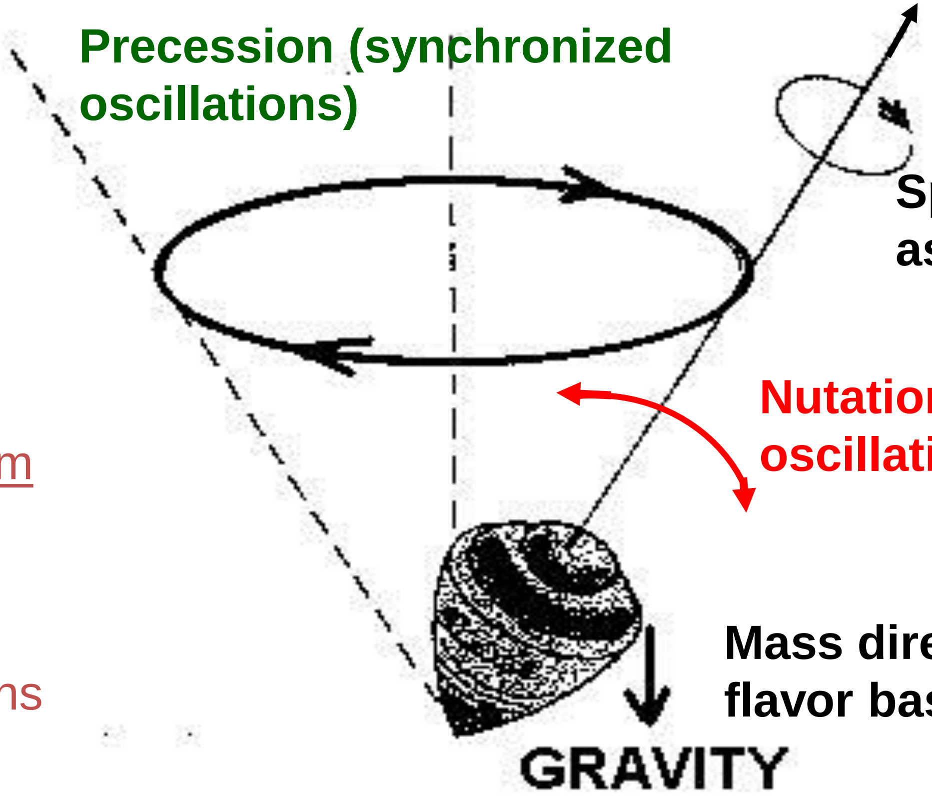
[*Hannestad, Raffelt, Sigl, Wong, astro-ph/0608695*]

Roughly speaking:

mass^{-1}: (anti)neutrino density

spin: #neutrinos - #antineutrinos

- Very asymmetric system ($n_{\nu e} >> n_{\bar{\nu} e}$)
  - Large spin
  - Almost pure precession
  - Synchronized oscillations
- Perfecly symmetric system ($n_{\nu e} = n_{\bar{\nu} e}$)
  - No spin
  - Fully pendular oscillations



Polarization vector for neutrinos plus antineutrinos

Precession (synchronized oscillations)

Spin (lepton asymmerty)

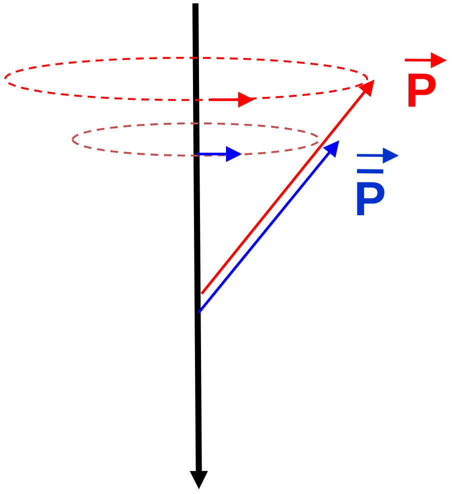
Nutation (pendular oscillations)

Mass direction in flavor basis

SYNCHRONIZED VS PENDULAR OSCILLATIONS

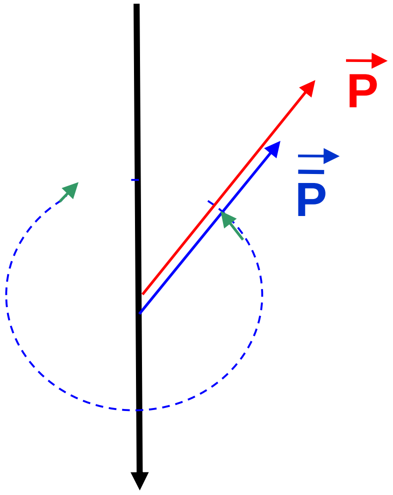
Synchronized oscillations

$$\frac{1+\alpha}{(1-\alpha)^2}\omega < \mu$$



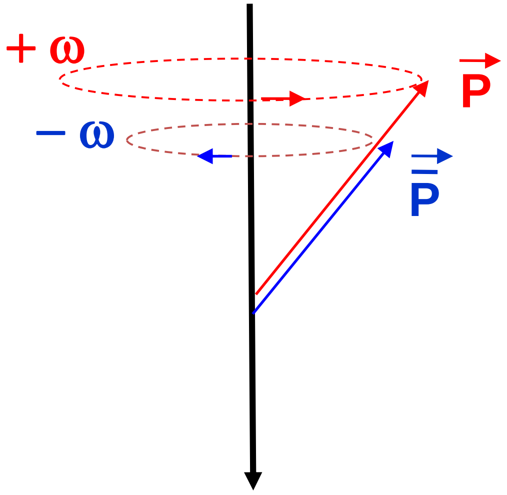
Pendular oscillations

$$\omega \ll \mu \ll \frac{1-\alpha}{(1+\alpha)^2}\omega$$



Vacuum oscillations

$$\mu \ll \omega$$

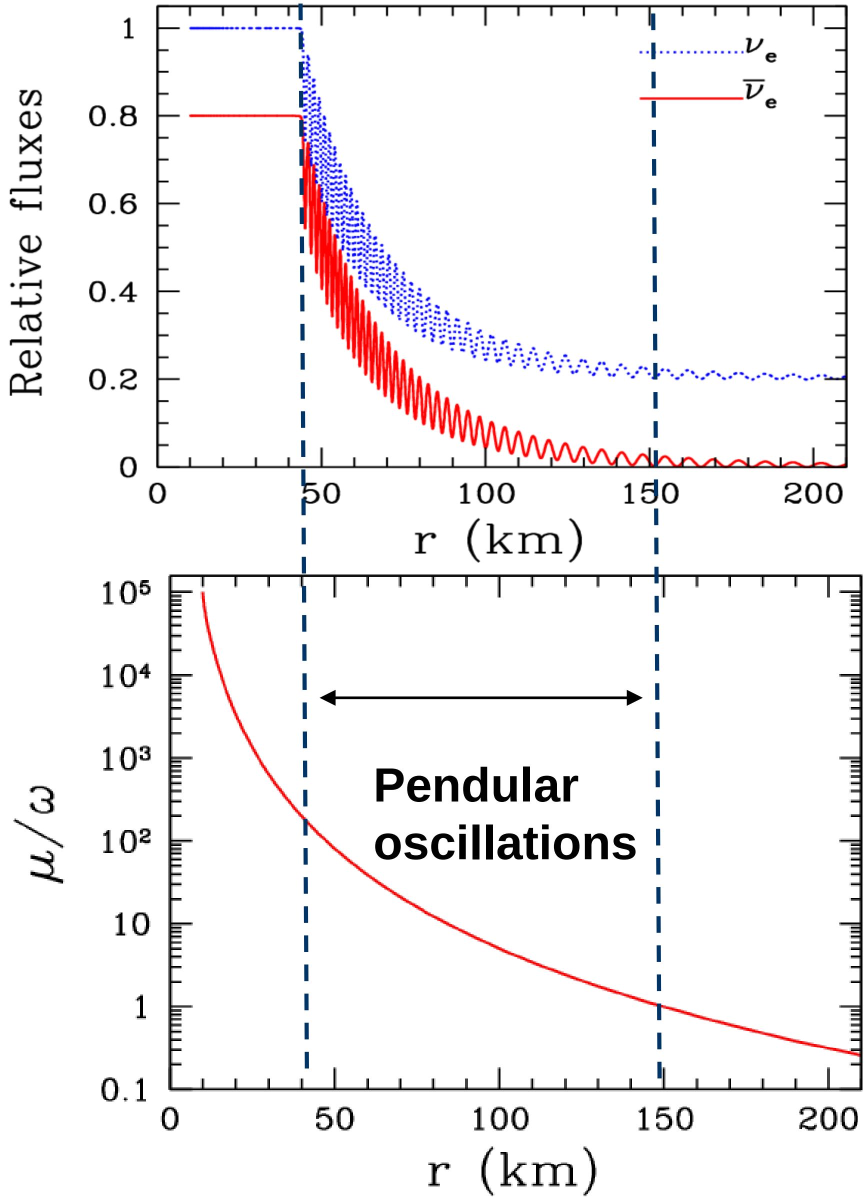


Asymmetric system,

Initially consisting of unequal numbers $n_{\bar{\nu}_e}=\alpha n_{\nu_e}$

with equal energies and $\mu=\sqrt{2}G_F n_\nu$

FLAVOR CONVERSIONS IN A TOY-SUPERNOVA



- **Assume 80% anti-neutrinos**
- **Vacuum oscillation frequency**
  ω= 0.3 km^{-1}
- **Neutrino-neutrino interaction energy at nu sphere (r=10 km)**
  μ=0.3×10^5 km^{-1}

Conservation of the flavor-lepton number

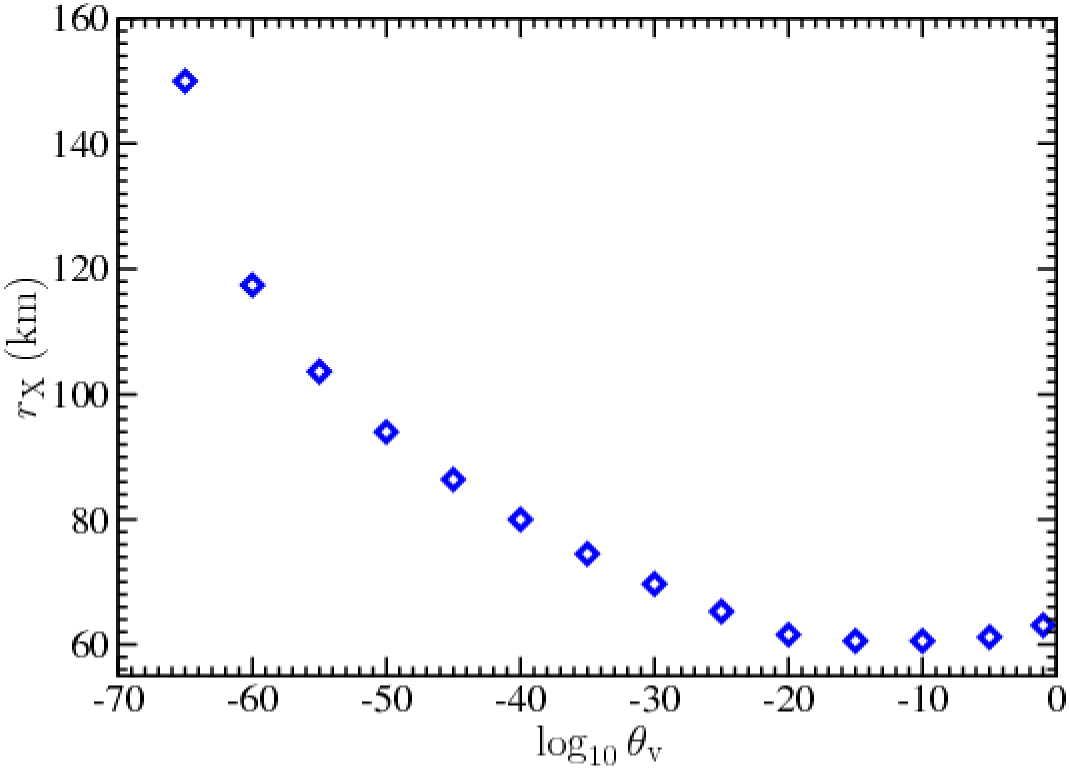
$$D_z = P_z - \bar{P}_z = const$$

Pendular conversions are pair conversions $\nu_e \bar{\nu}_e \rightarrow \nu_x \bar{\nu}_x$

COLLECTIVE OSCILLATIONS IN IH @ $\theta_{13} \rightarrow 0$

Collective flavor conversions in inverted hierarchy are expected also for $\theta_{13}\rightarrow 0$, when further MSW matter effects are negligible

[Duan, Fuller, Carlson & Qian, arXiv:0707.0290 (astro-ph)]



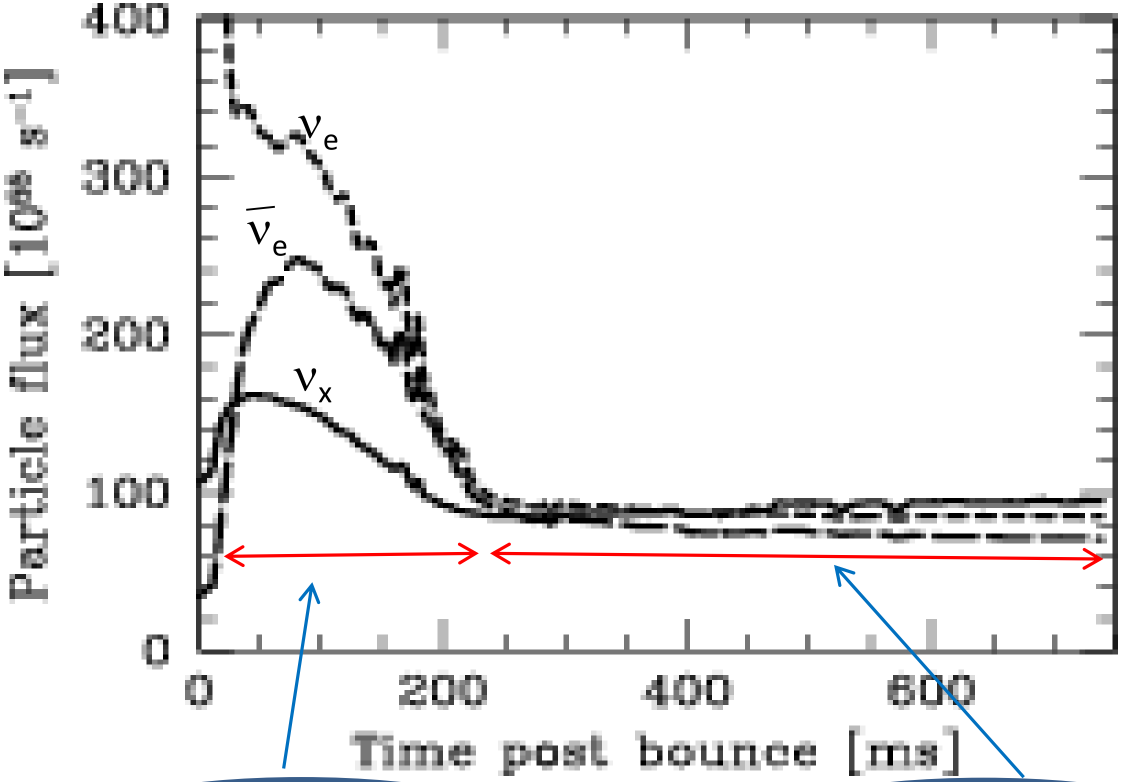
Onset radius of collective conversions

$\log_{10}\theta_{13}$

Effect logarithmically delayed when $\theta_{13}\rightarrow 0$

NEUTRINO FLUX NUMBERS

[*Raffelt et al. (Garching group), astro-ph/0303226*]



Accretion phase

$$F_{\nu e} > F_{\bar{\nu} e} > F_{\nu x}$$

Excess of ν_e due to deleponization

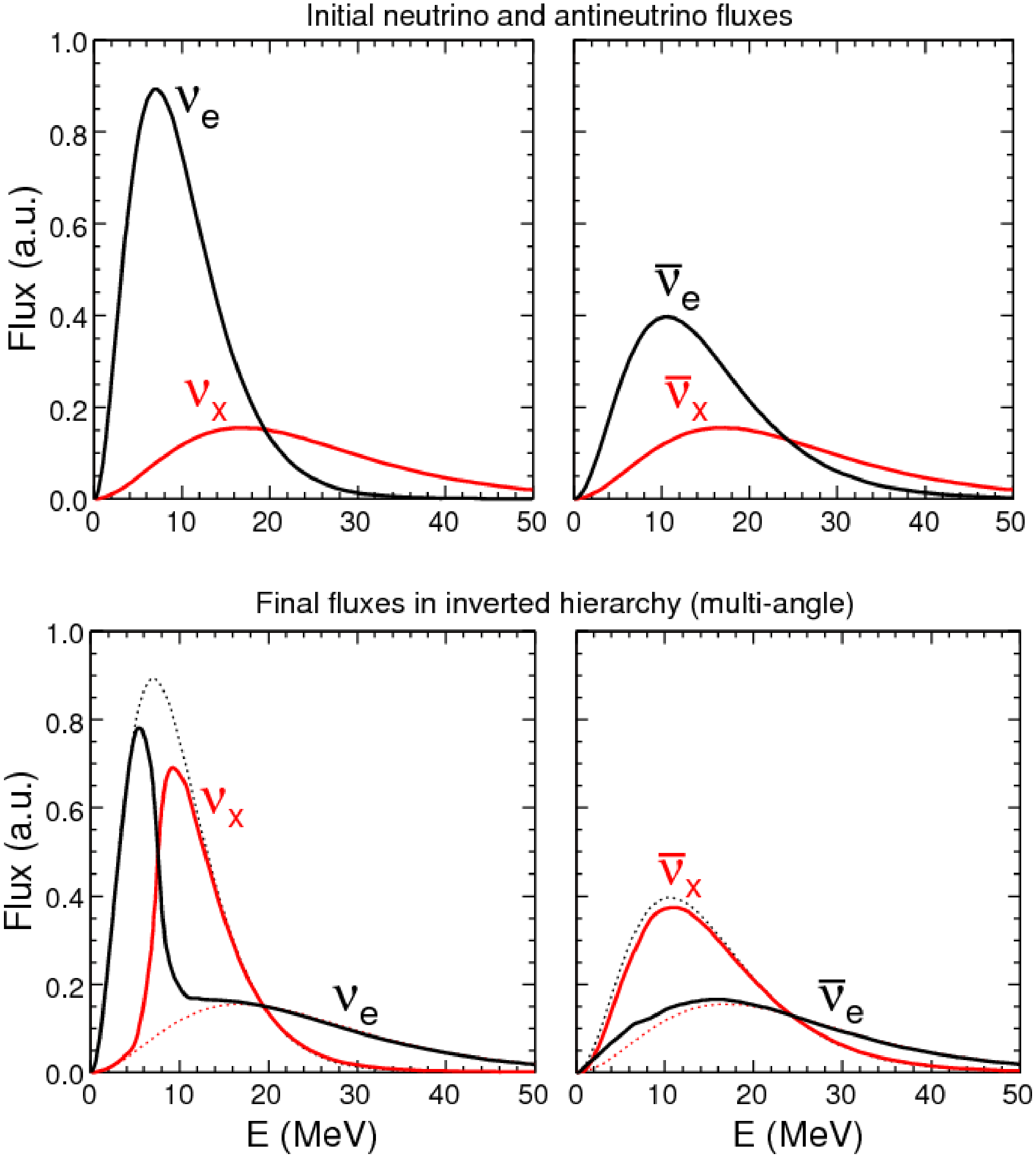
Cooling phase

$$F_{\nu x} \geq F_{\nu e} \geq F_{\bar{\nu} e}$$

Moderate flavor hierarchy, possible excess of ν_x

SPECTRAL SPLITS IN THE ACCRETION PHASE

[Fogli, Lisi, Marrone, A.M. , arXiV: 0707.1998 [hep-ph], Duan, Carlson, Fuller, Qian, astro-ph/0703776, Raffelt and Smirnov, 0705.1830 [hep-ph]]


Initial neutrino and antineutrino fluxes

Final fluxes in inverted hierarchy (multi-angle)

Initial fluxes at neutrinosphere (r ~10 km)

$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 2.4 : 1.6 : 1.0$$

(ratio typical of accretion phase)

Inverted mass hierarchy

2ν=(Δm^2, θ_{13})

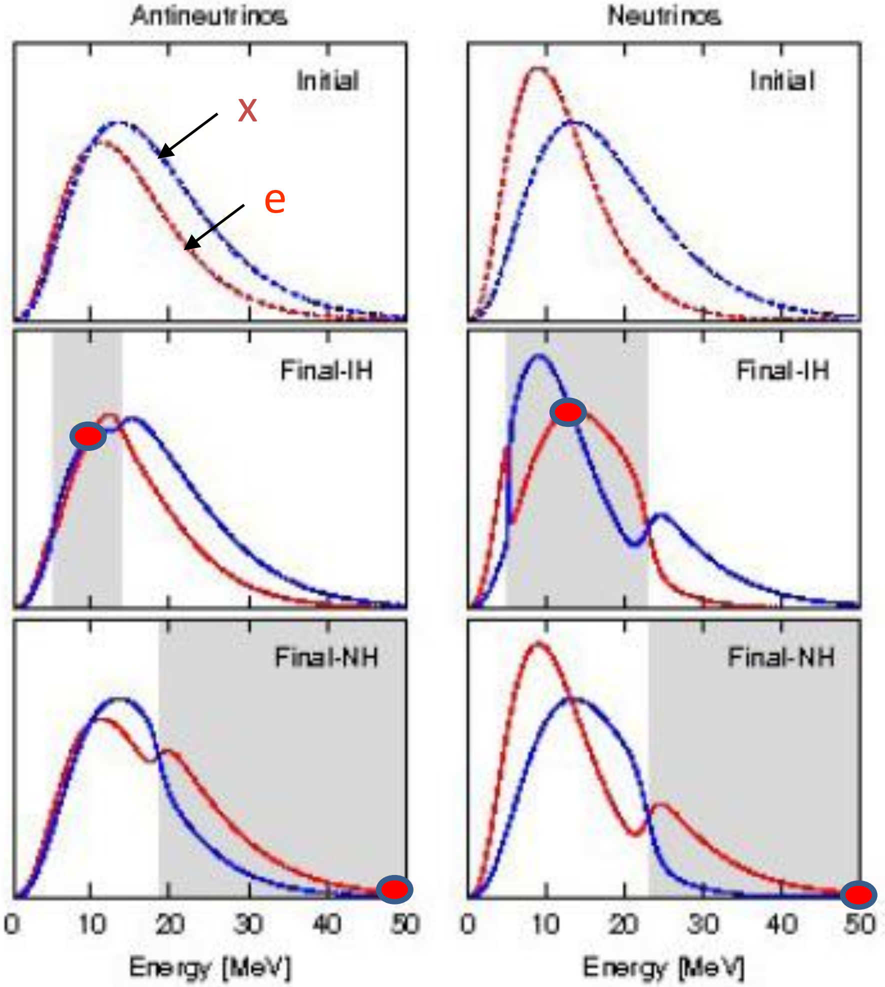
Fluxes at the end of collective effects (r ~200 km)

Nothing happens in NH

MULTIPLE SPECTRAL SPLITS IN THE COOLING PHASE

[Dasgupta, Dighe, Raffelt & Smirnov, arXiv:0904.3542 [hep-ph]]

$2\nu = (\Delta m^2, \theta_{13})$



$$F_{\nu e} : F_{\bar{\nu} e} : F_{\nu x} = 0.85 : 0.75 : 1.00$$

(possible during the cooling phase)

Splits possible in both normal and inverted hierarchy, for ν & $\bar{\nu}$!!

Splits develops around the crossing points of the spectra (expect at E=0)

$$F_{\nu e}(E_c) - F_{\nu x}(E_c) = 0$$

THREE FLAVOR EFFECTS RELEVANT IN IH

[Friedland, 1001.0996; Dasgupta, A.M., Tamborra, Tomas, 1002.2943]

MULTI-ANGLE (M.A.) EOMs FOR SN NEUTRINOS

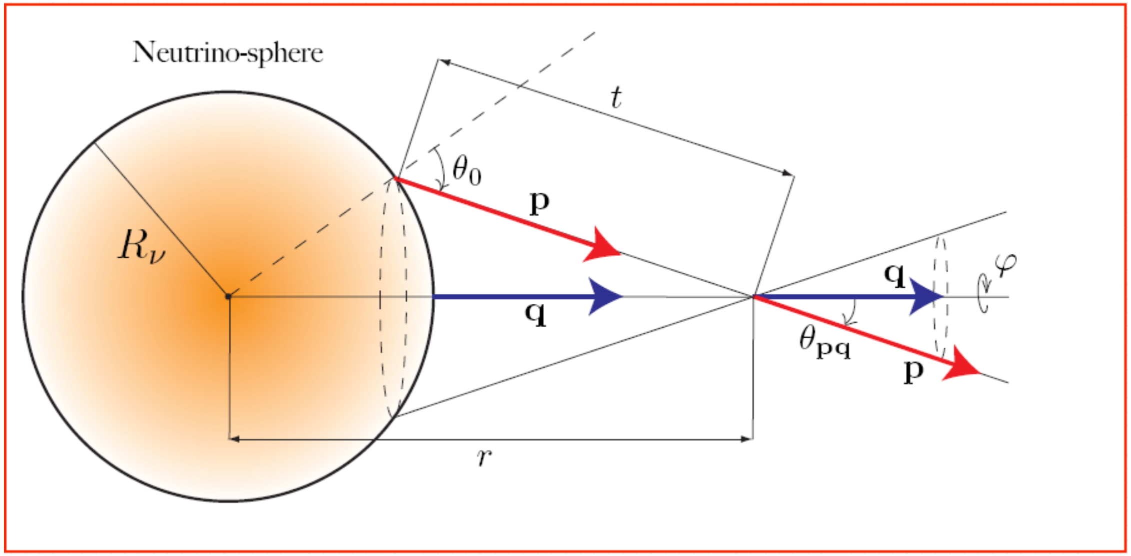
Evolution in space for ν's streaming from a SN core in quasi-stationary situation

$$i\,\vec{\mathrm{v}}_{\mathrm{p}}\cdot\vec{\nabla}_x\rho_{p,x}=\left[H(\omega,\lambda,\rho_{p',x}),\rho_{p,x}\right]$$

Liouville operator for free streaming ν

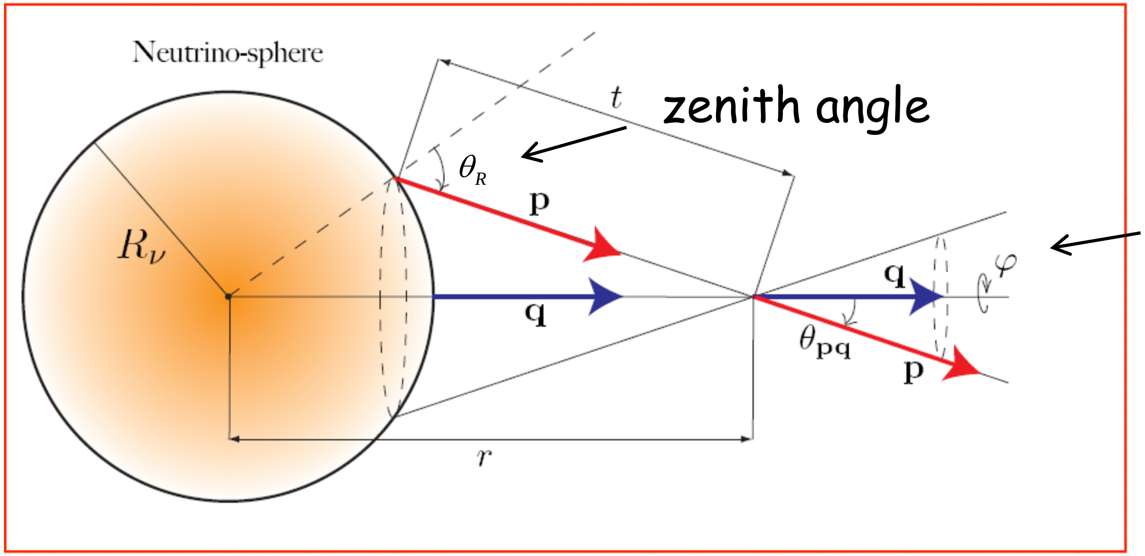
MULTI-ANGLE ν–ν HAMILTONIAN

$$H_{\nu\nu}=\sqrt{2}G_F\int d\vec{q}\,\left(1-\vec{\mathrm{v}}_{\mathrm{p}}\cdot\vec{\mathrm{v}}_q\right)\left(\rho_{q,x}-\bar{\rho}_{q,x}\right)$$



BULB MODEL

[see, e.g., Duan et al., astro-ph/0606616] → First large-scale multi-angle simulations



Azimuthal angle

- Neutrinos are emitted uniformly and (half)-isotropically from the surface of a sphere (ν-sphere), like in a blackbody.
- Physical conditions depend only on the the distance r from the center of the star (azimuthal symmetry)
- Only multi-zenith-angle (MZA) effects in terms of $u = \sin^2 \theta_R$
- Project evolution along radial direction (ODE problem) $\vec{v}_p \cdot \vec{\nabla}_x \rightarrow v_r d_r$

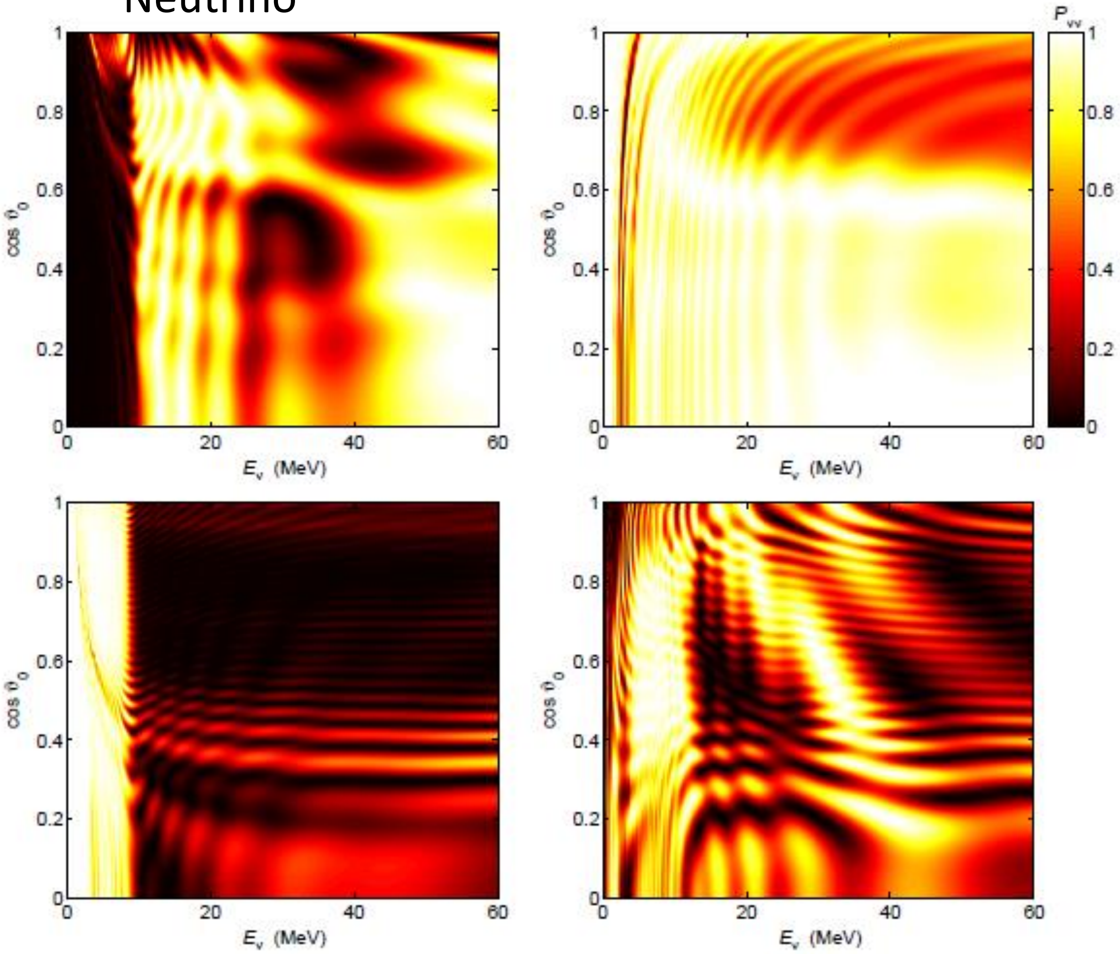
MULTI-ANGLE LARGE SCALE SIMULATIONS

First multi-angle simulations in 2006 by Duan, Fuller, Qian (2006). Major breakthrough!

Survival probability of ν_e vs E and emission angle cos θ

Neutrino

Anti-neutrino



Normal hierarchy

Inverted hierarchy

Significant angular dependence on the Pee

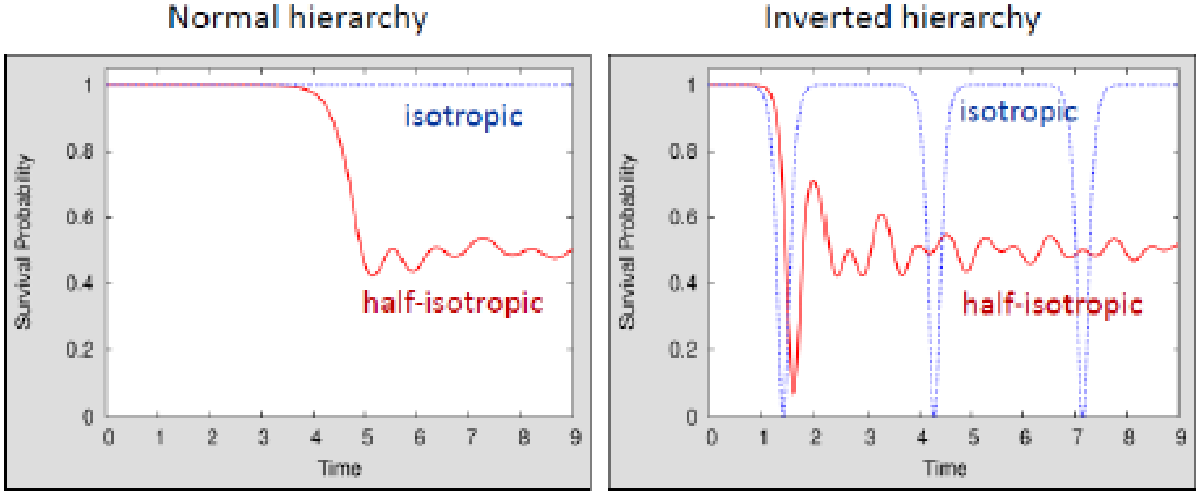
Convergence required > 10^3 angular bins ⟶ Large scale numerical simulations

MULTI-ZENITH-ANGLE DECOHERENCE

$$H_{\nu\nu} = \sqrt{2} G_F \int d\vec{q} \, \left(1 - \cos\theta_{pq}\right) \left(\rho_{q,x} - \bar{\rho}_{q,x}\right)$$

Flux term

Symmetric $\nu_e \bar{\nu}_e$ systems decoheres in both hierarchies [*Raffelt & Sigl, hep-ph/0701182*]



Flux term does not vanish in a non-isotropic medium, like ν streaming off a SN

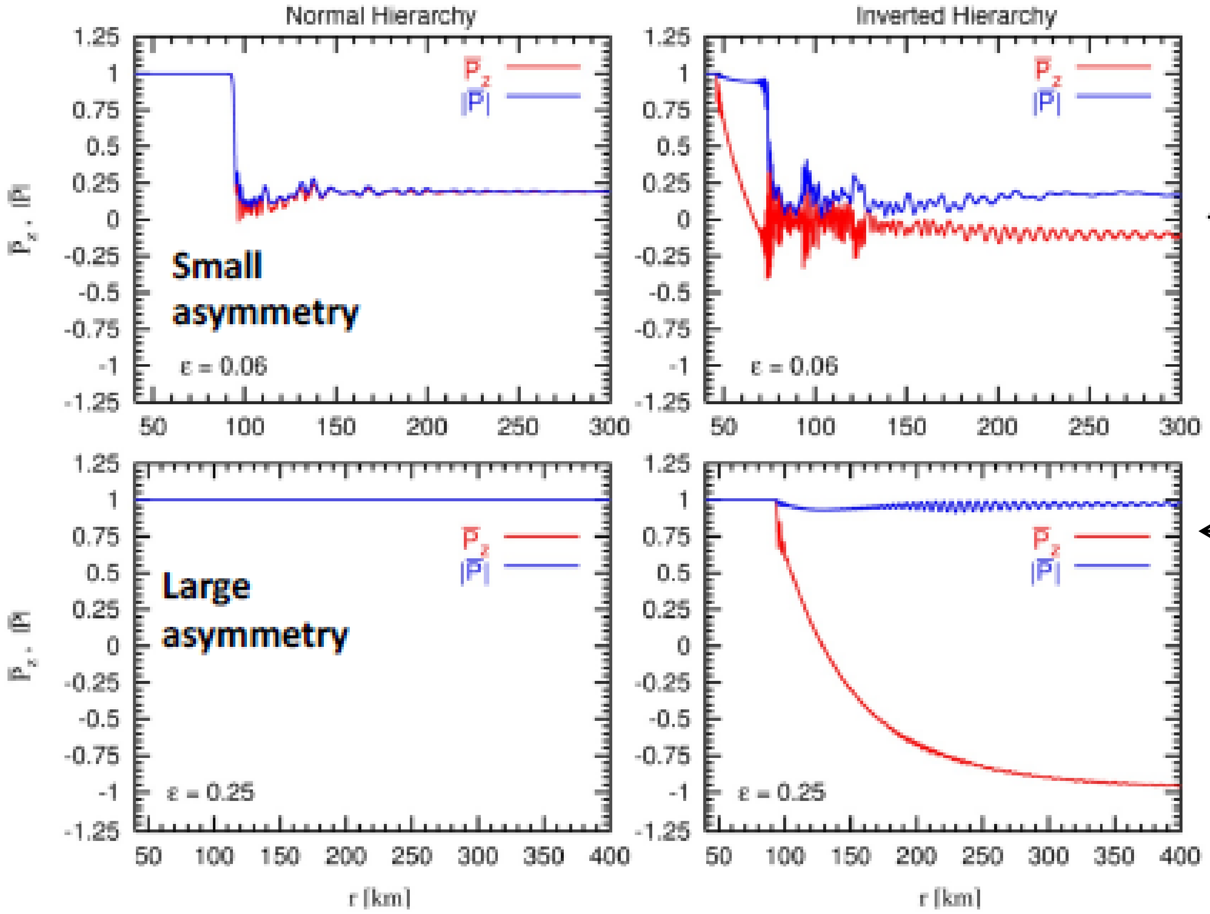
Is the MZA decoherence relevant for SN neutrinos?

MZA EFFECTS FOR SN NEUTRINOS

$$\varepsilon = \frac{F(\nu_e)-F(\bar{\nu}_e)}{F(\bar{\nu}_e)-F(\bar{\nu}_x)}$$

Flavor asymmetry

[Esteban-Pretel et al.,0706.2498]



Small asymmetry

Large asymmetry

decoherence

- Flavor equilibration in both NH & IH

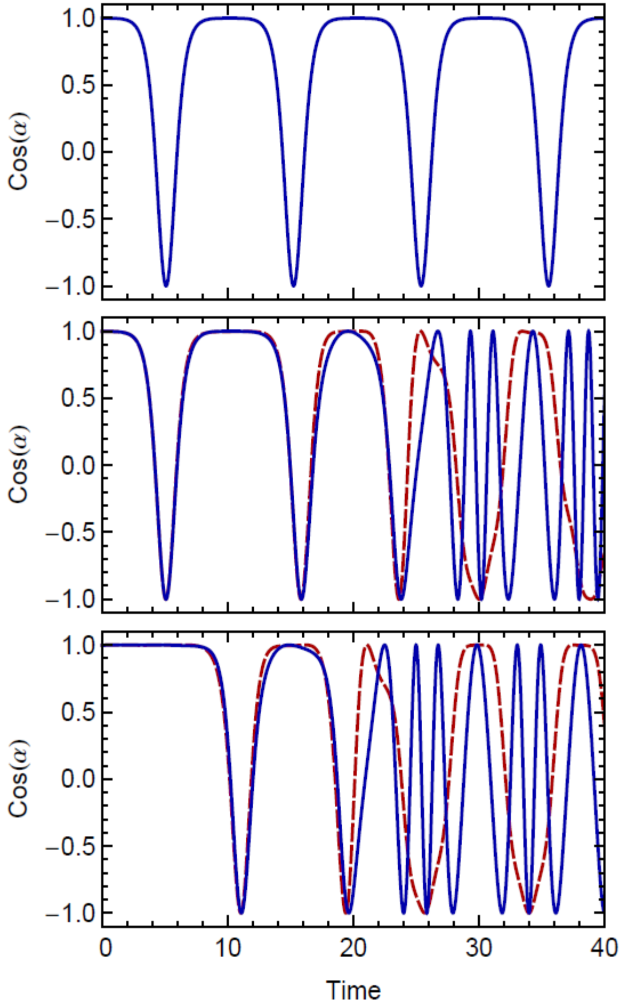
Quasi single-angle behaviour

- Nothing occurs in NH (stable configuration)
- Complete conversions in IH (bimodal instability)

Large $\nu_e\bar{\nu}_e$ asymmetry required to suppress multi-angle decoherence

NEUTRINO FLAVOR PENDULUM IN BOTH HIERARCHIES

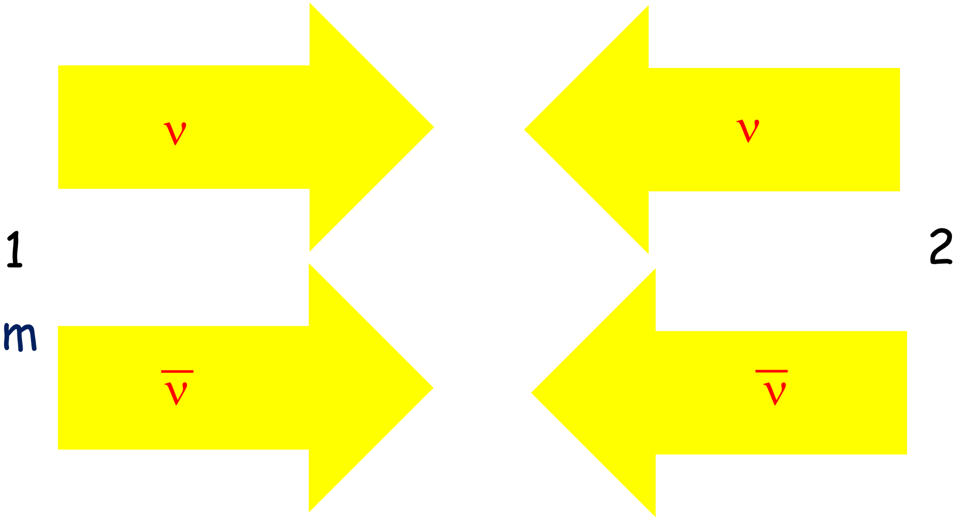
[Raffelt & Seixas, 1307.7625]



IH
1-2 symm

IH
no 1-2 symm

NH
no 1-2 symm



Two beams

- If one breaks 1 -2 symmetry, flavor conversions also in NH
- Just a seed is enough, self-interacting nu's would induce spontaneous symmetry breaking (SSB)

MULTI-AZIMUTHAL-ANGLE (MAA) INSTABILITY

- Self-induced flavor conversions are associated to an instability in the flavor space *[Sawyer,0803.4319; Banerjee, Dighe & Raffelt, 1107.2308]*

- Instability required to get started (exponential growth of the off-diagonal density matrix part)

- The onset of the conversions can be found through a stability analysis of the linearized EOMs.

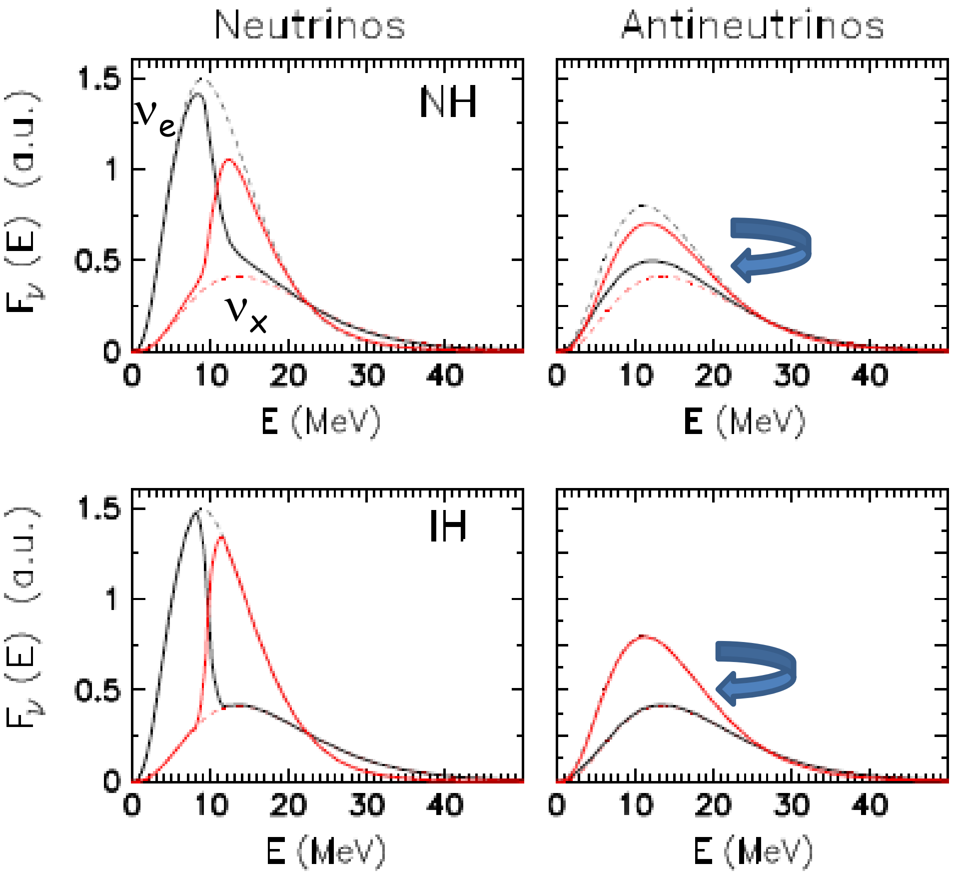
In *[Raffelt, Sarikas, Seixas, 1305.7140]* a stability analysis of the EOMs has been performed including the azimuthal angle ϕ of the ν propagation and without enforcing axial symmetry also starting with an intial axial symmetric ν emission.

A new multi-azimuthal-angle (MAA) instability has been found!!

- In the unstable case, numerical simulations are mandatory.

SPECTRAL SPLITS FOR SN NEUTRINO FLUXES

[Chakraborty, A.M., 1308.5255]



- Nu fluxes present a spectral split at E= 12 MeV (fixed by lepton number conservation)
- Antinu fluxes are swapped

SPONTANEOUS SYMMETRY BREAKING IN SELF-INDUCED OSCILLATIONS

- Symmetries have been used to reduce the complexity of the SN ν flavor evolution (e.g. the bulb model).

- However, ν can lead to a spontaneous symmetry breaking (SSB) of the symmetry inherent to the initial conditions *[Raffelt, Sarikas, Seixas, 1305.7140]* .

- Small deviations from the space/time symmetries of the bulb model have to be expected. Can these act as seed for new instabilities?

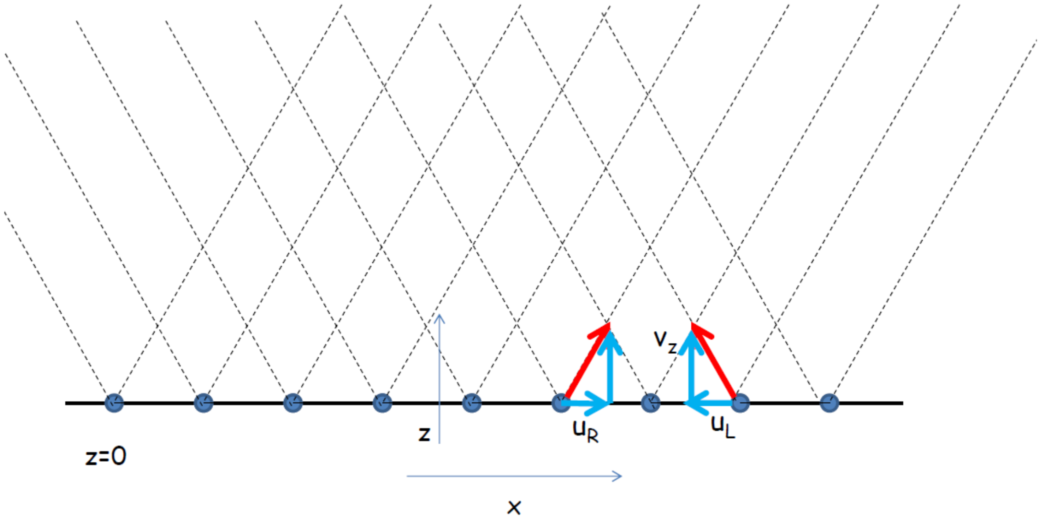
FIRST INVESTIGATIONS WITH TOY MODELS

- With a simple toy model in *[Mangano, A.M. & Saviano, 1403.1892]* it has been shown that self-interacting ν can break translational symmetries in space and time.

- By a stability analysis in *[Duan & Shalgar, 1412.7097]* is has been found that self-interacting ν can break the spatial symmetries of a 2D model.

2D MODEL FOR SELF-INTERACTING ν

[Duan & Shalgar, 1412.7097]

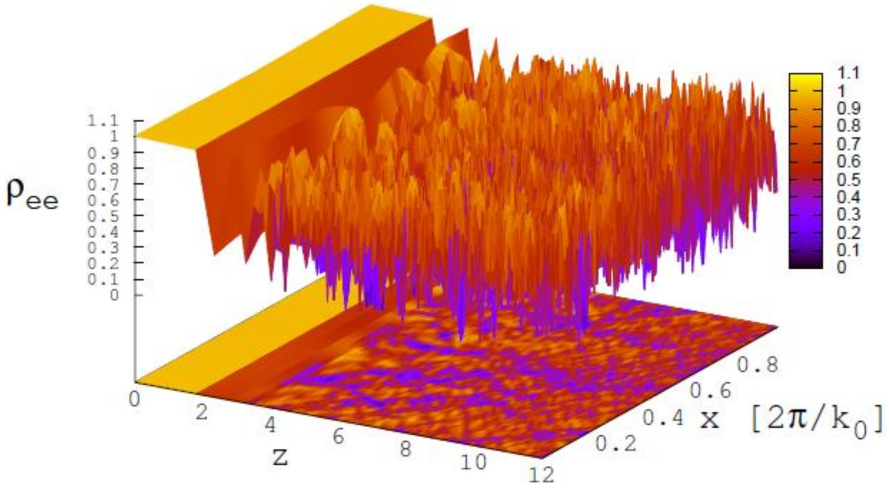


A. M., Mangano and Saviano, [arXiv:1503.03485 [hep-ph]].

Nu evolving in the plane (x,z) emitted from an infinite boundary at z=0, in only two directions (L and R). Excess of ν_e over $\bar{\nu}_e$.

~~L-R~~

~~TRANSLATIONAL~~



Large variations in the x direction at smaller and smaller scales.

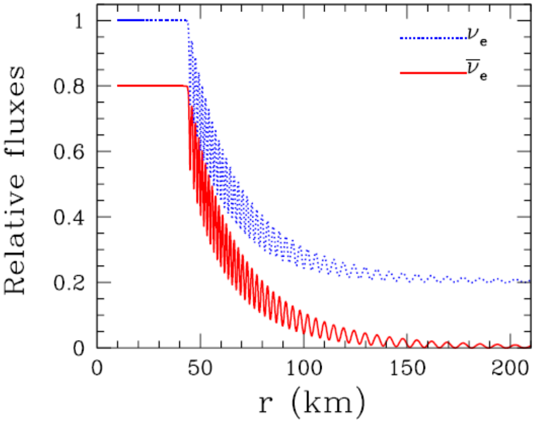
Planes of common phase broken.

Coherent behavior of oscillation lost.

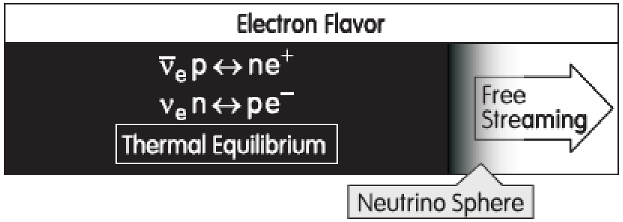
RECENT PAPERS ON SSB

- G. Mangano, A. M. and N. Saviano, *"Damping the neutrino flavor pendulum by breaking homogeneity,"* Phys. Rev. D **89**, no. 7, 073017 (2014) [arXiv:1403.1892 [hep-ph]].
- H. Duan and S. Shalgar, *"Flavor instabilities in the neutrino line model,"* Phys. Lett. B **747**, 139 (2015) [arXiv:1412.7097 [hep-ph]].
- A. M., G. Mangano and N. Saviano, *"Self-induced flavor instabilities of a dense neutrino stream in a two-dimensional model,"* Phys. Rev. D **92**, no. 2, 021702 (2015) [arXiv:1503.03485 [hep-ph]].
- S. Chakraborty, R. S. Hansen, I. Izaguirre and G. Raffelt, *"Self-induced flavor conversion of supernova neutrinos on small scales,"* JCAP **1601**, no. 01, 028 (2016) [arXiv:1507.07569 [hep-ph]].
- S. Abbar and H. Duan, *"Neutrino flavor instabilities in a time-dependent supernova model,"* Phys. Lett. B **751**, 43 (2015) [arXiv:1509.01538 [astro-ph.HE]].
- B. Dasgupta and A. M., *" Temporal Instability Enables Neutrino Flavor Conversions Deep Inside Supernovae,"* Phys. Rev. D 92, no. 12, 125030 (2015) [arXiv:1509.03171 [hep-ph]].
- F. Capozzi, B. Dasgupta and A. M., *"Self-induced temporal instability from a neutrino antenna,"* JCAP **1604**, no. 04, 043 (2016) [arXiv:1603.03288 [hep-ph]].

FLAVOR CONVERSIONS NEAR SN CORE?



- Most of the studies assume no flavor conversion at r < 50 km (only synchronized oscillations). After self-induced conversions develop with a rate $\sim \sqrt{\omega\mu}$ *[see, e.g., Hannestad et al, astro-ph/0608695]*



Electron Flavor

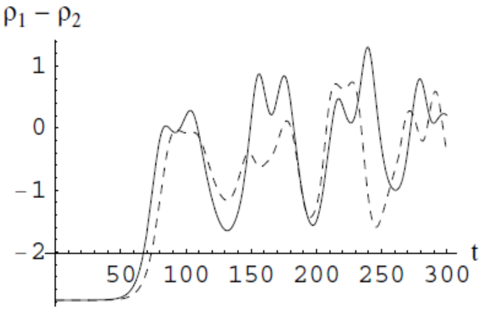
$\bar{\nu}_e p \leftrightarrow n e^+$

$\nu_e n \leftrightarrow p e^-$

Thermal Equilibrium

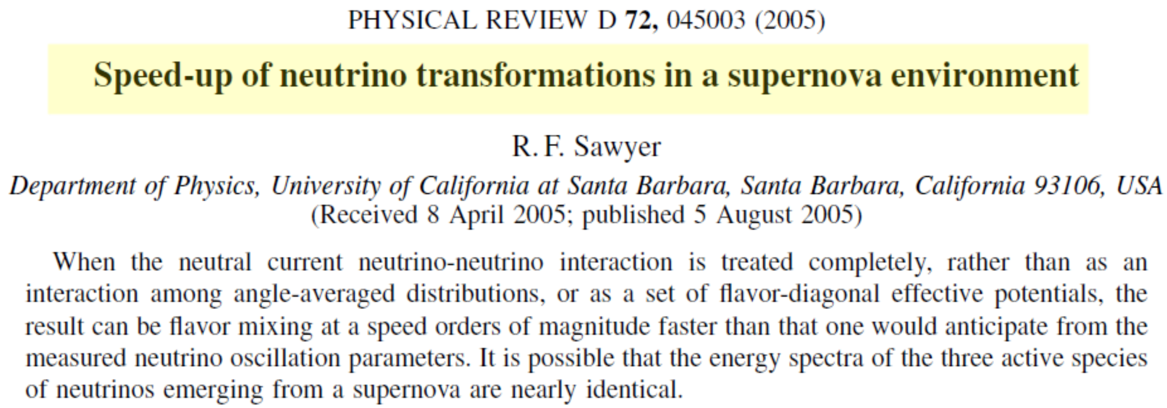
Free Streaming

Neutrino Sphere



- However, since more than a decade Ray Sawyer is pointing out that close to nu-sphere nu angular distributions of different species are rather different. This would lead to a new flavor instability (absent assuming equal angular distributions). The outcome would be a possible complete flavor mixing of the outgoing stream just above the nu-sphere. Fast rate $\sim\mu$

FAST FLAVOR CONVERSIONS NEAR SN CORE



PHYSICAL REVIEW D **72,** 045003 (2005)

Speed-up of neutrino transformations in a supernova environment

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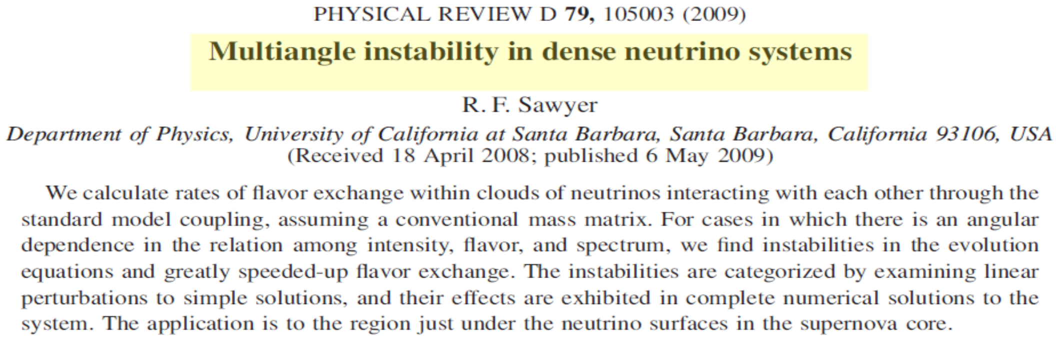
(Received 8 April 2005; published 5 August 2005)

When the neutral current neutrino-neutrino interaction is treated completely, rather than as an interaction among angle-averaged distributions, or as a set of flavor-diagonal effective potentials, the result can be flavor mixing at a speed orders of magnitude faster than that one would anticipate from the measured neutrino oscillation parameters. It is possible that the energy spectra of the three active species of neutrinos emerging from a supernova are nearly identical.



PHYSICAL REVIEW D **79,** 105003 (2009)

Multiangle instability in dense neutrino systems

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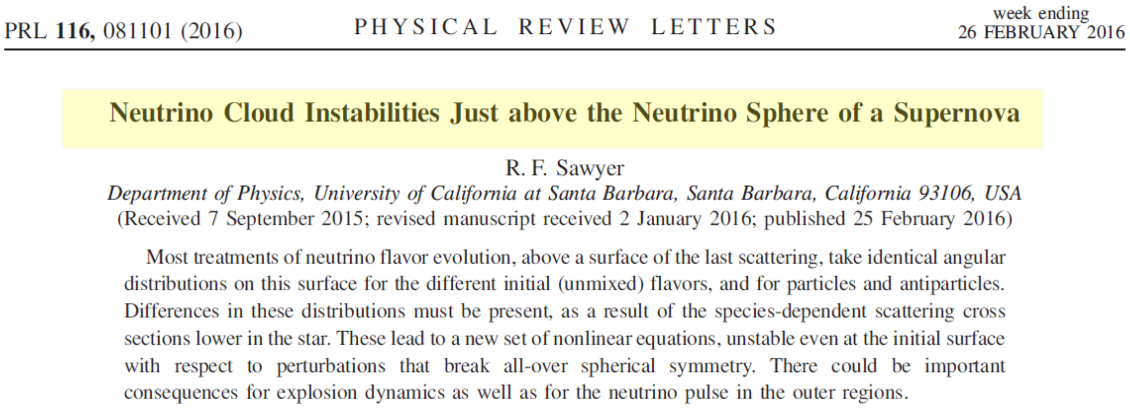
(Received 18 April 2008; published 6 May 2009)

We calculate rates of flavor exchange within clouds of neutrinos interacting with each other through the standard model coupling, assuming a conventional mass matrix. For cases in which there is an angular dependence in the relation among intensity, flavor, and spectrum, we find instabilities in the evolution equations and greatly speeded-up flavor exchange. The instabilities are categorized by examining linear perturbations to simple solutions, and their effects are exhibited in complete numerical solutions to the system. The application is to the region just under the neutrino surfaces in the supernova core.



PRL **116,** 081101 (2016) PHYSICAL REVIEW LETTERS week ending 26 FEBRUARY 2016

Neutrino Cloud Instabilities Just above the Neutrino Sphere of a Supernova

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(Received 7 September 2015; revised manuscript received 2 January 2016; published 25 February 2016)

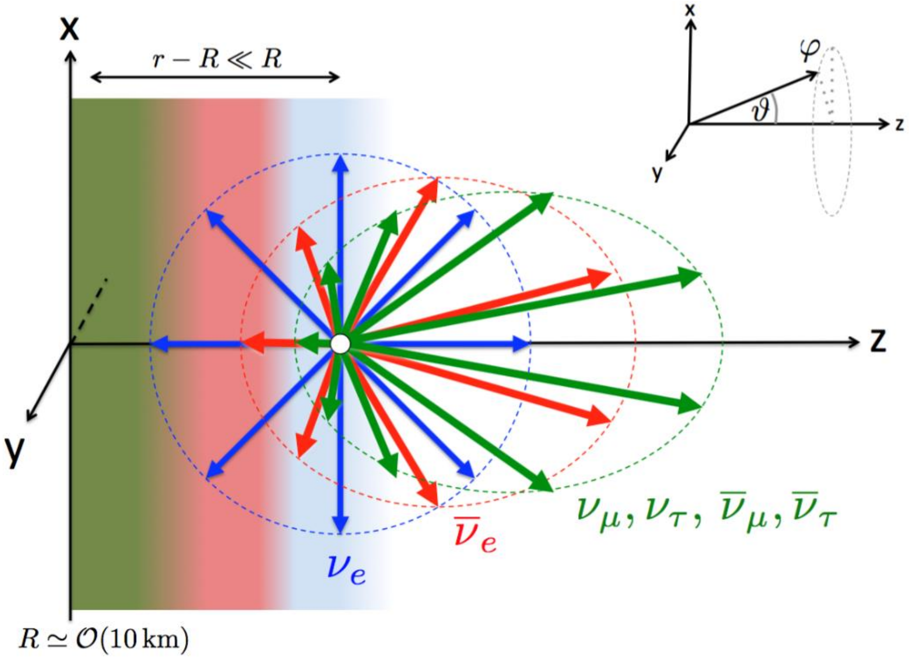
Most treatments of neutrino flavor evolution, above a surface of the last scattering, take identical angular distributions on this surface for the different initial (unmixed) flavors, and for particles and antiparticles. Differences in these distributions must be present, as a result of the species-dependent scattering cross sections lower in the star. These lead to a new set of nonlinear equations, unstable even at the initial surface with respect to perturbations that break all-over spherical symmetry. There could be important consequences for explosion dynamics as well as for the neutrino pulse in the outer regions.

Literature on Fast Flavor Conversion

1. Speed-up of neutrino transformations in a supernova environment
   Sawyer, hep-ph/0503013
2. The multi-angle instability in dense neutrino systems
   Sawyer, arXiv:0803.4319
3. Neutrino cloud instabilities just above the neutrino sphere of a supernova
   Sawyer, arXiv:1509.03323
4. Self-induced neutrino flavor conversion without flavor mixing
   Chakraborty, Hansen, Izaguirre & Raffelt, arXiv:1602.00698
5. Fast pairwise conversion of supernova neutrinos: A dispersion-relation approach
   Izaguirre, Raffelt & Tamborra, arXiv:1610.01612
6. Fast neutrino flavor conversions near the supernova core with realistic flavor-dependent angular distributions
   Mirizzi & Dasgupta, arXiv:1609.00528
7. Fast neutrino conversions: Ubiquitous in compact binary merger remnants
   Wu & Tamborra, arXiv:1701.06580

NEUTRINO ANGULAR DISTRIBUTIONS AT DECOUPLING

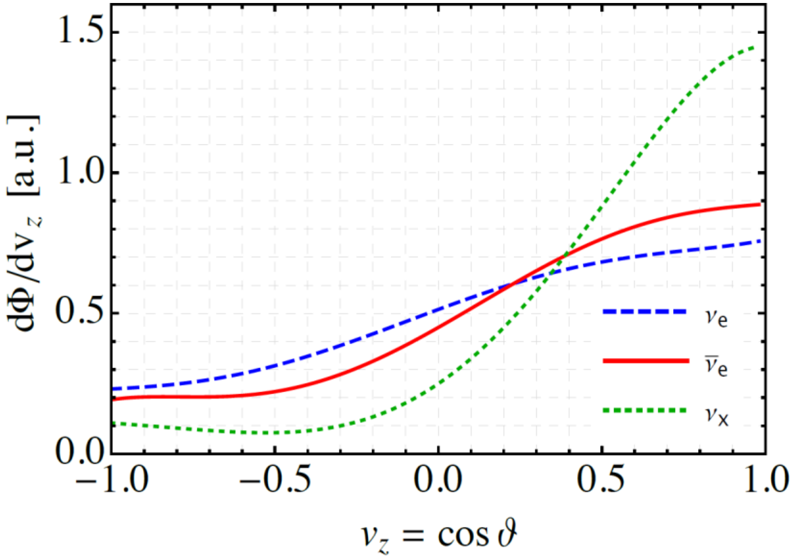
[Dasgupta, A.M., Sen, arXiV:1609.00528]



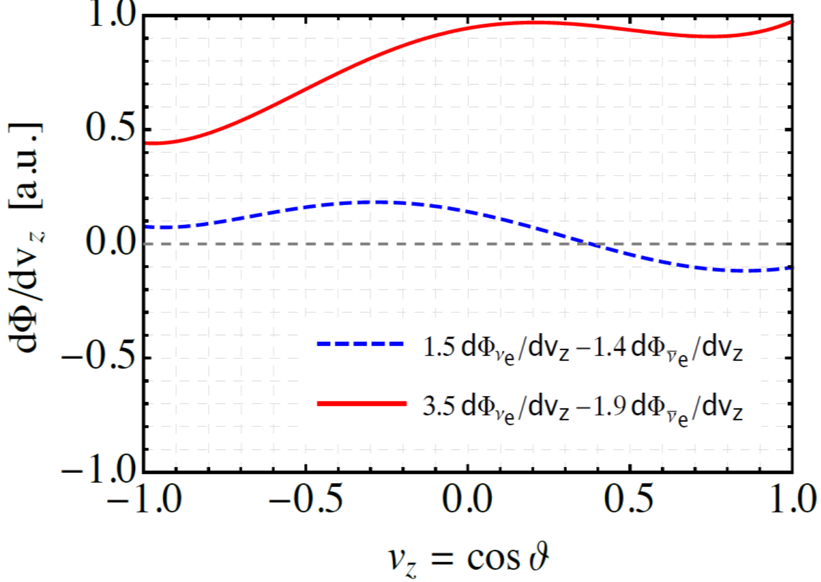
- Electron flavors remain in equilibrium with matter for a longer period than the non-electron flavors, due to the largest cross-sections of CC interactions
- Non-electron flavors decouple deeper in the star (more fwd-peaked distributions)
- Neutron-richness enhances CC interactions for ν_e keeping them more coupled to matter (more isotropic distribution) than $\bar{\nu}_e$.

FAST FLAVOR CONVERSIONS

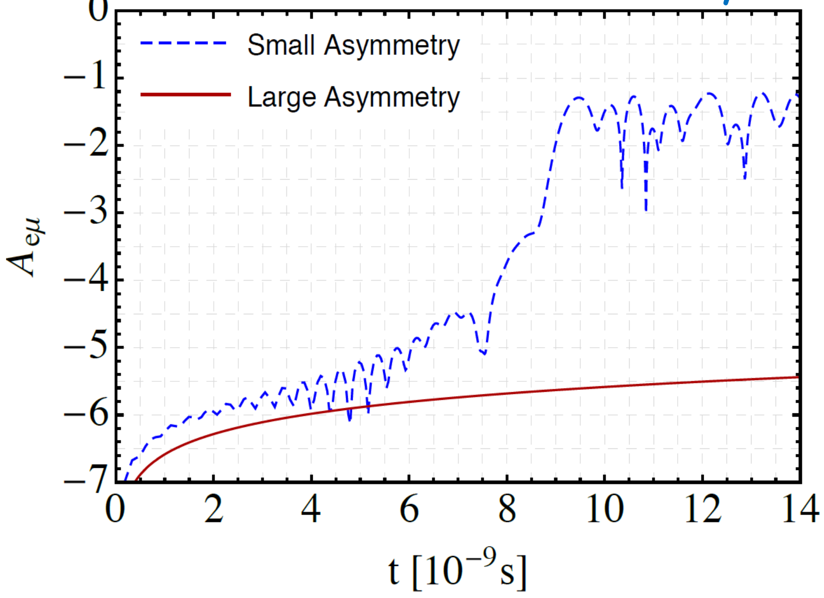
Nu angular distributions



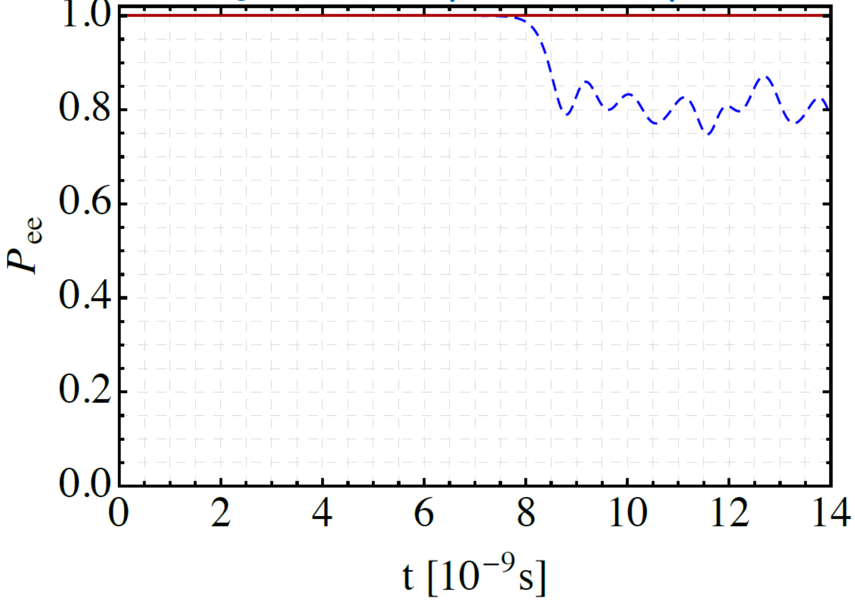
$\nu_e - \overline{\nu}_e$ difference



Growth rate of instability



$\overline{\nu}_e$ survival probability



CONCLUSIONS

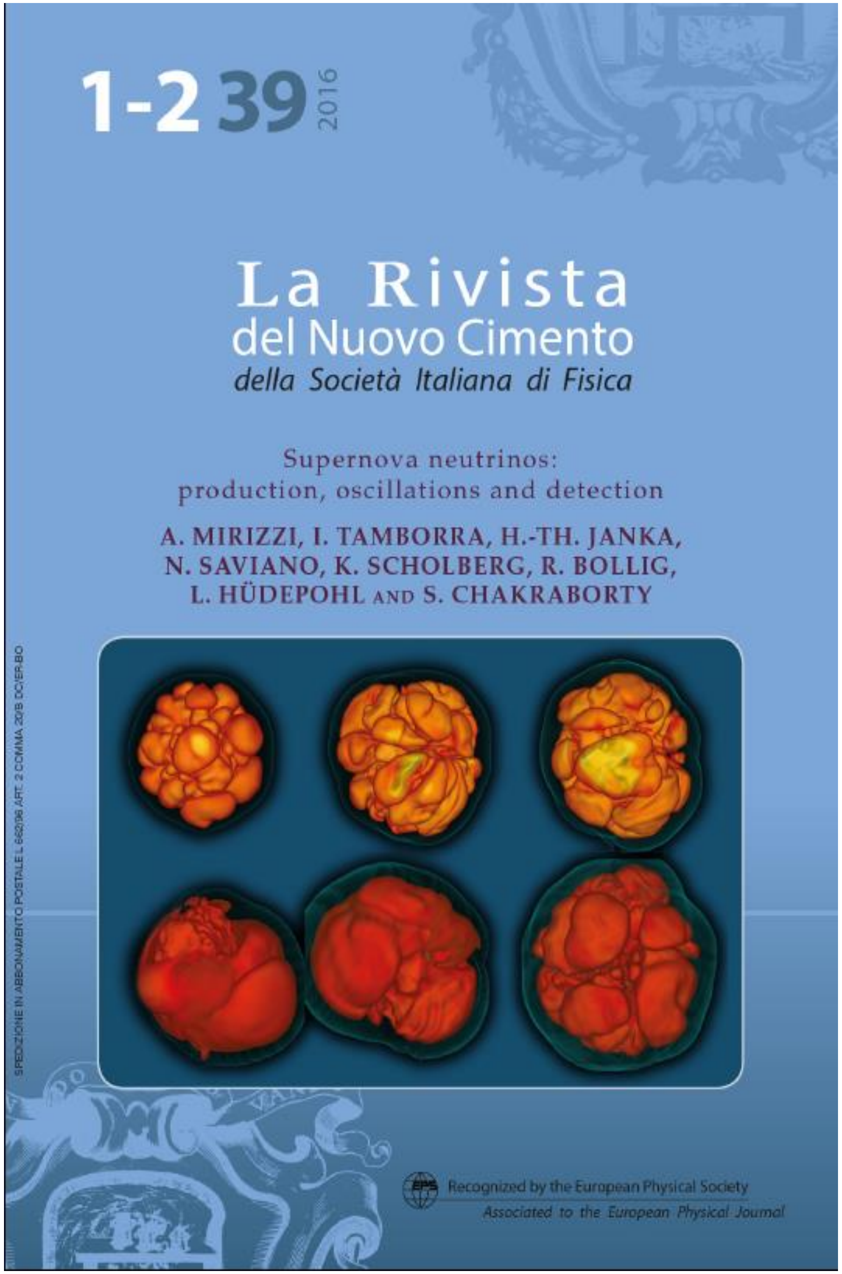
Observing SN neutrinos is the next frontiers of low-energy neutrino astronomy

The physics potential of current and next-generation detectors in this context is enormous, both for particle physics and astrophysics.

SN provide very extreme conditions, where the shock-wave, matter turbulence, neutrino-neutrino interactions prove to be surprisingly important in the ν oscillations.

Further investigations needed to better understand neutrino flavor conversions during a stellar collapse….

LOOKING FORWARD TO THE NEXT GALACTIC SN !



1-2 39 2016

La Rivista
del Nuovo Cimento
della Società Italiana di Fisica

Supernova neutrinos:
production, oscillations and detection

A. MIRIZZI, I. TAMBORRA, H.-TH. JANKA,
N. SAVIANO, K. SCHOLBERG, R. BOLLIG,
L. HÜDEPOHL AND S. CHAKRABORTY

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