Overview on Supernova Neutrinos

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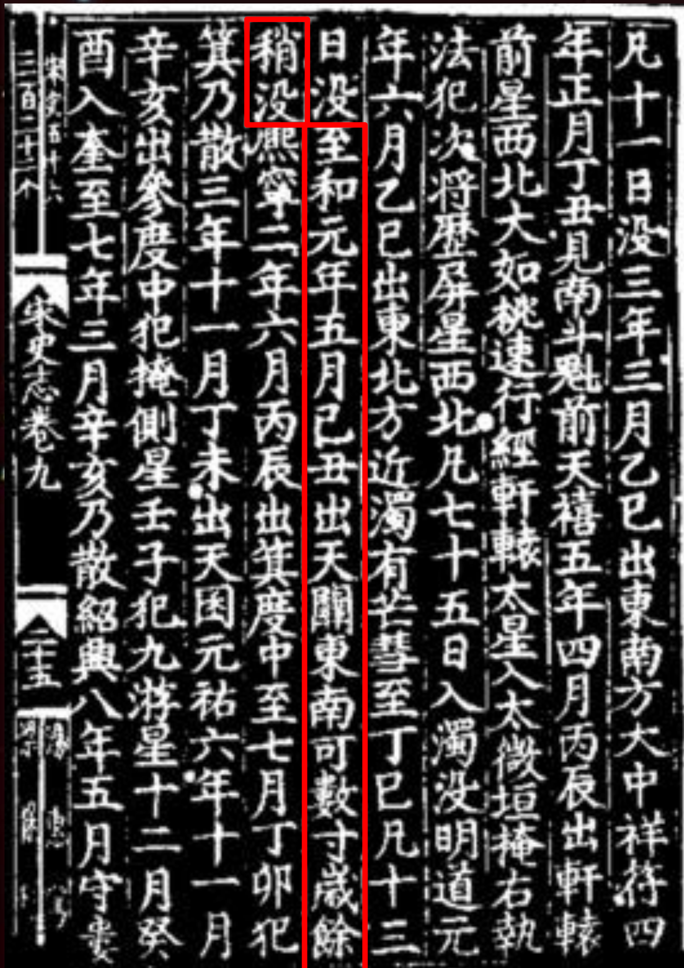
NNN16, Beijing，2016-11-03

Galactic SN 1054

Distance: 6500 light years (2 kpc)
Center: Neutron Star (R~30 km)
Progenitor : M ~ 10 solar masses



凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屛星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九斿星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

Red：Optical (Hubble)
Blue：X-Ray (Chandra)

Two things fill the mind with ever new and increasing admiration and awe, the more often and steadily we reflect upon them: the starry heavens above me and the moral law within me.

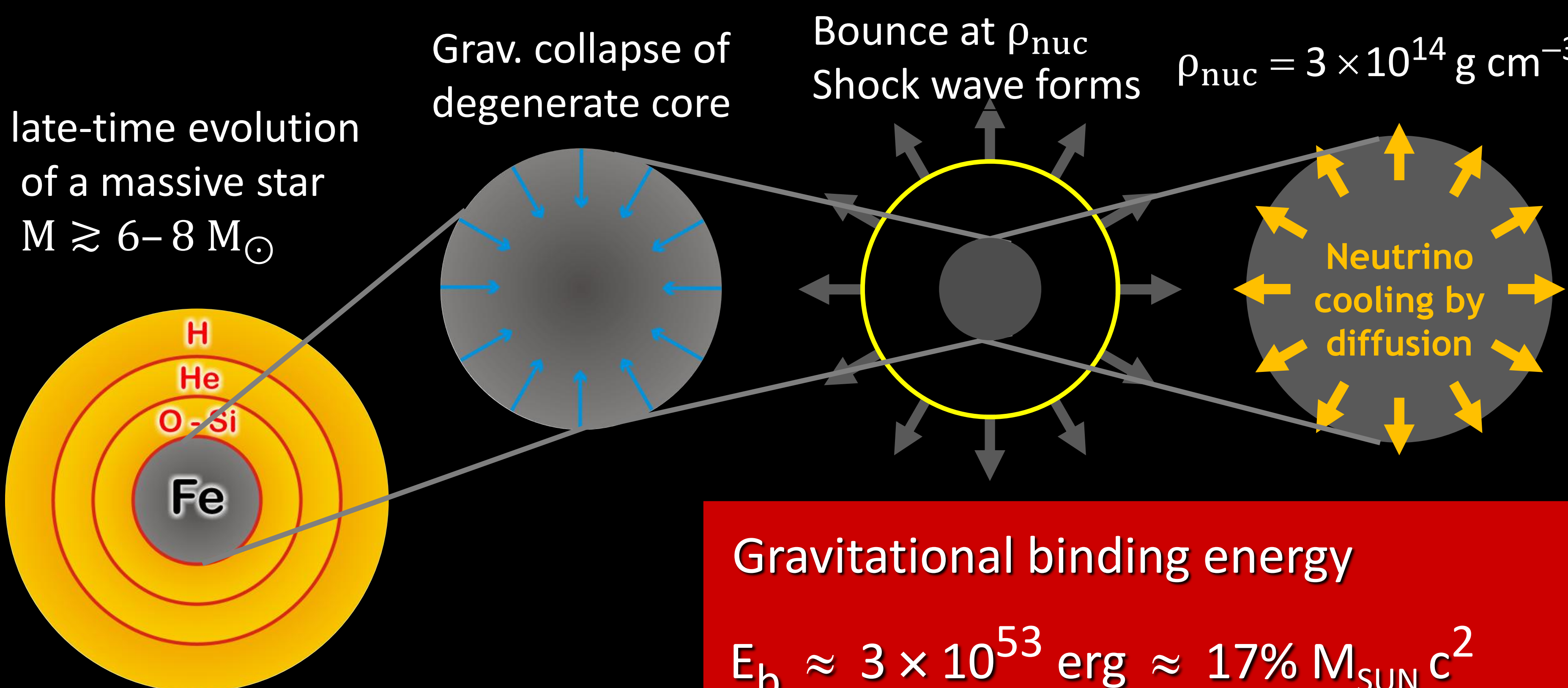
— Immanuel Kant, Critique of Practical Reason

Outline

- Introduction
- SN Neutrino Detection
- SN Flavor Conversions
- Physics Opportunities
- Summary and Outlook

I. Kant (1724 – 1804)

Stellar Collapse and SN Explosion



Degenerate iron core:

$\rho \approx 10^9\ {\rm g\ cm^{-3}}$
$T \approx 10^{10}\ {\rm K}$
$M_{\rm Fe} \approx 1.5\ M_{\rm sun}$
$R_{\rm Fe} \approx 8000\ {\rm km}$

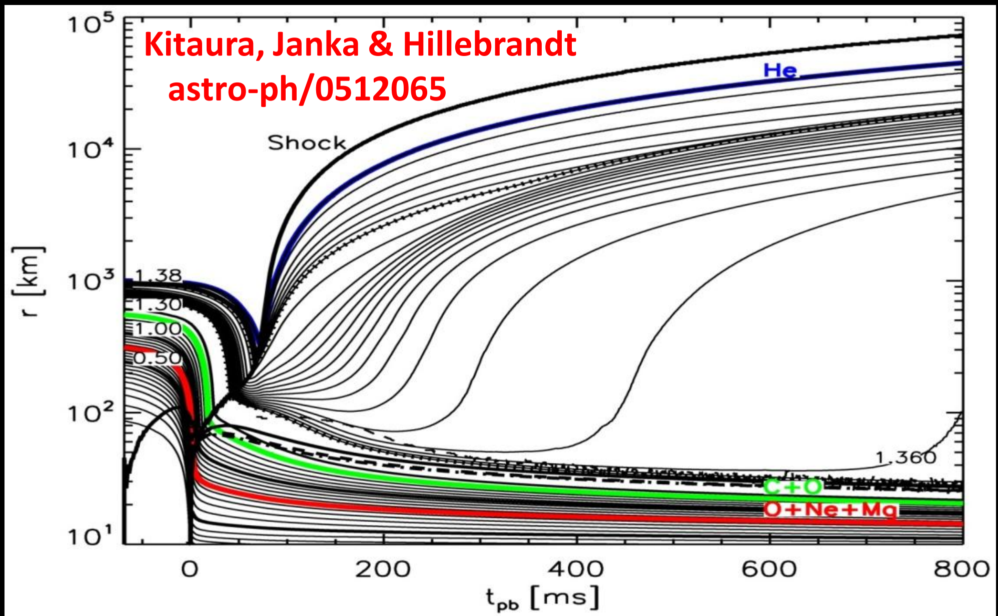
Gravitational binding energy

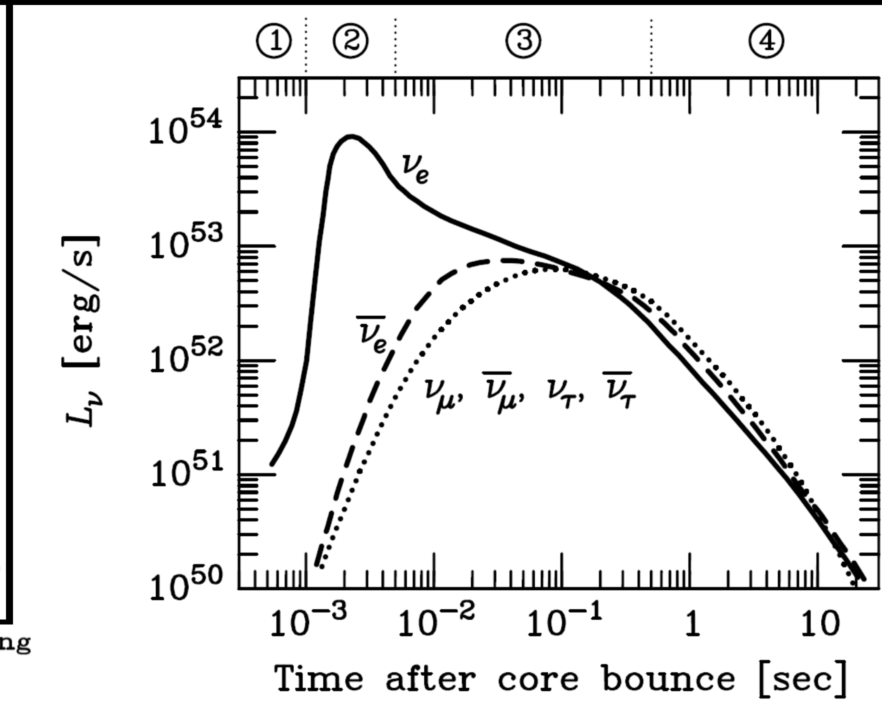
$E_b \approx 3 \times 10^{53}\ {\rm erg} \approx 17\%\ M_{\rm SUN}\, c^2$

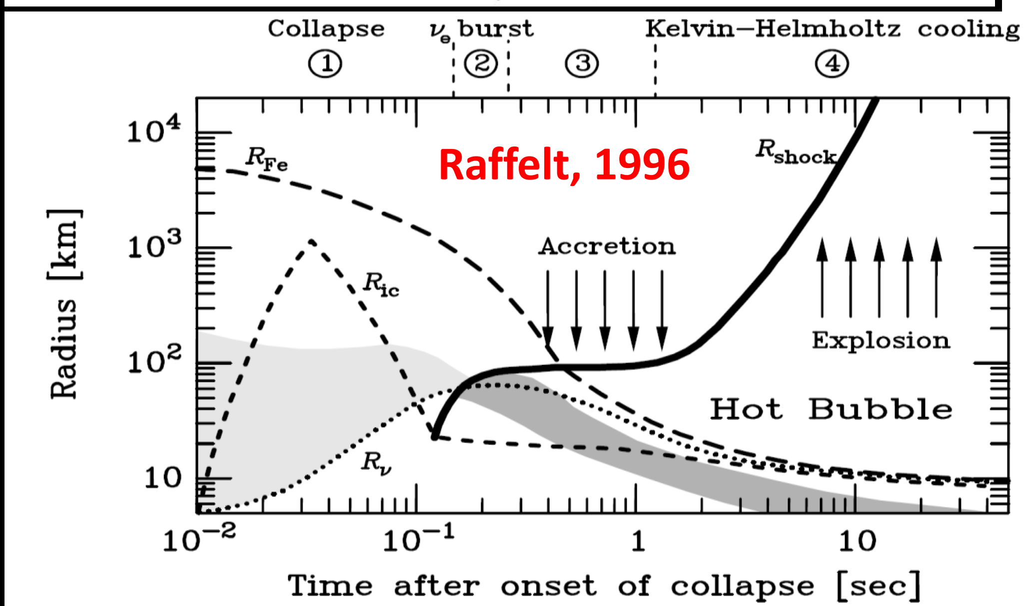
This shows up as

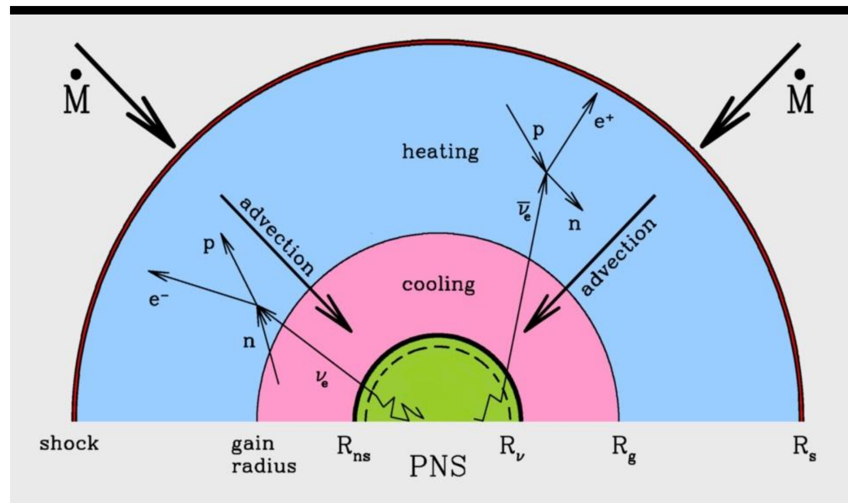
99% Neutrinos
1% Kinetic energy of explosion
(1% of this into cosmic rays)
0.01% Photons, outshine host galaxy

Supernova Neutrinos: theoretical predictions

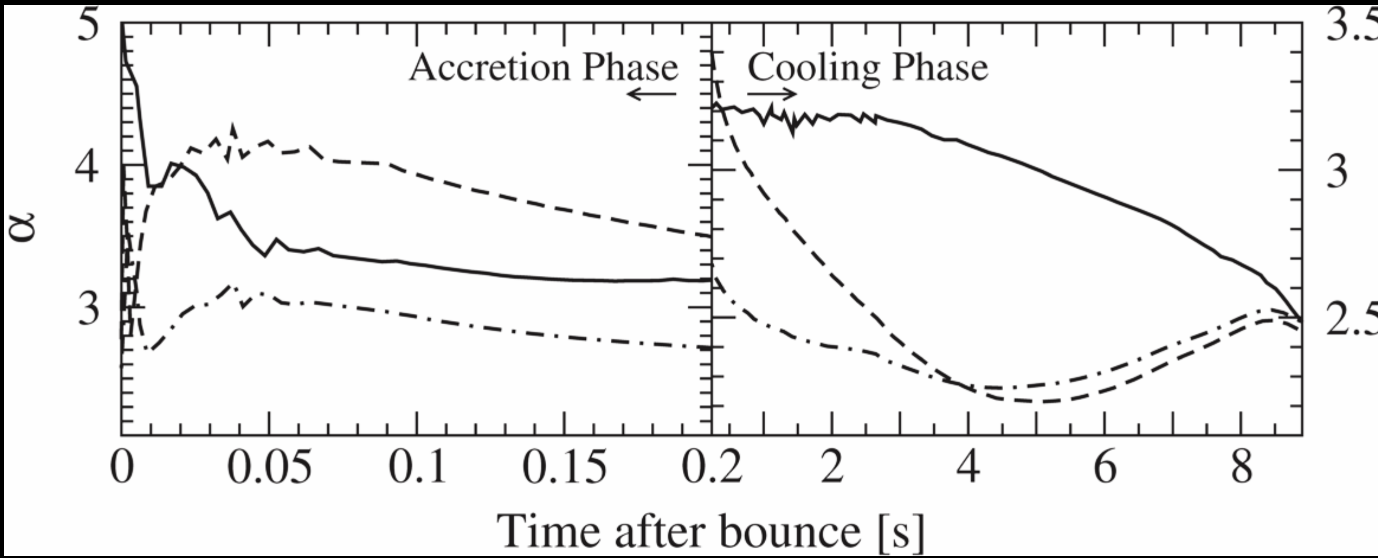








Supernova Neutrinos: theoretical predictions

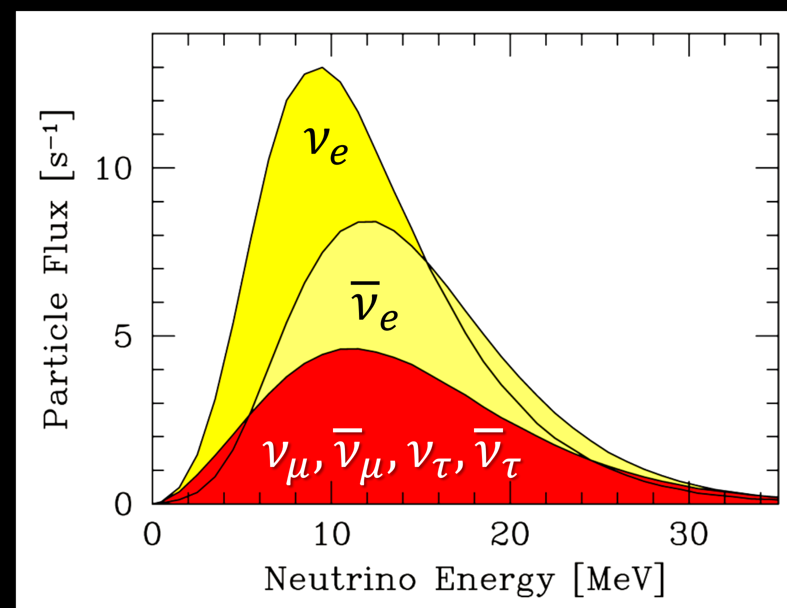


Hüdepohl et al. (Garching Group), arXiv:0912.0260

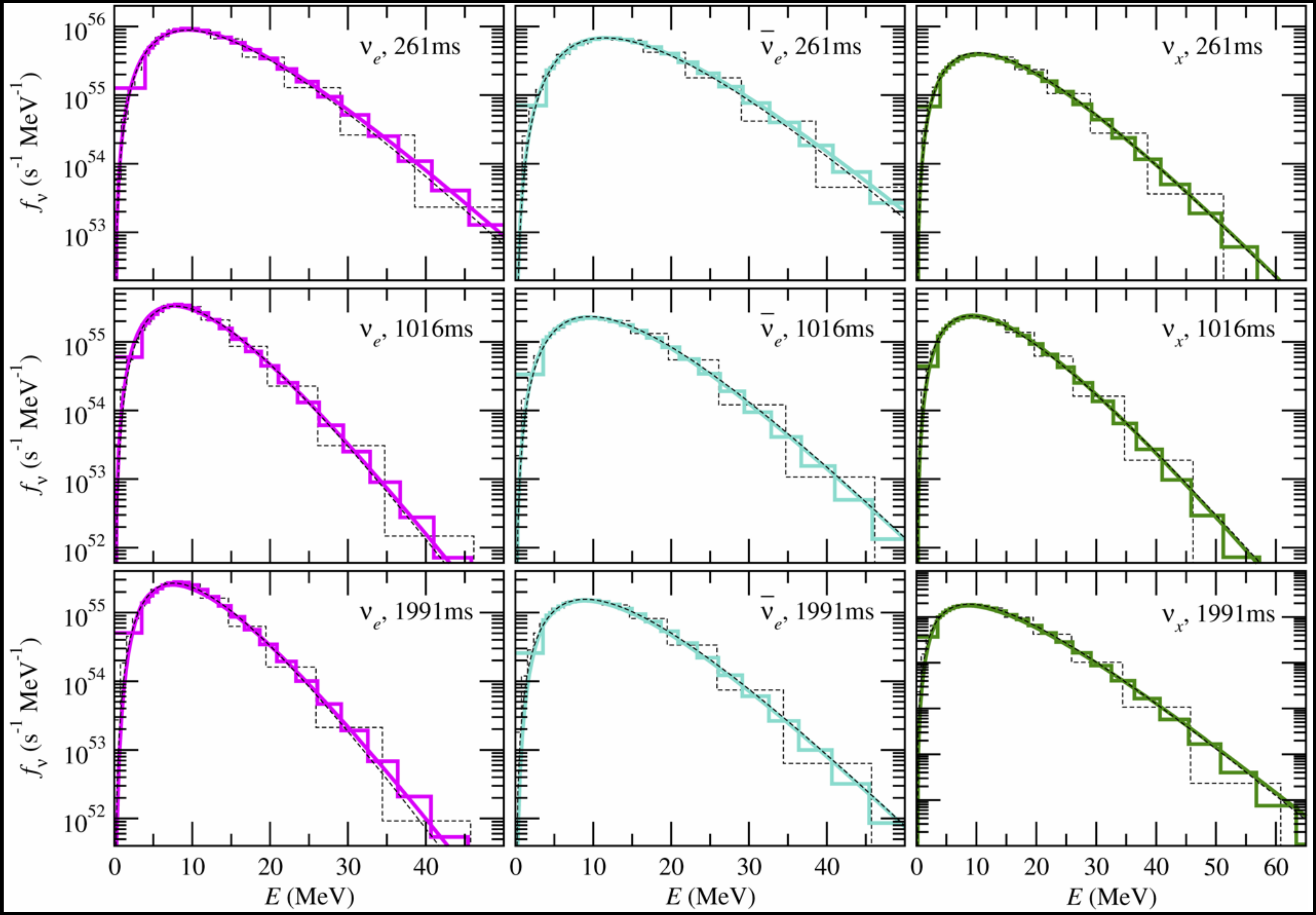
1. Nearly thermal neutrino spectra
2. Neutrino spectra represented by Gamma distribution (alpha-fit)

$$F(E) \propto E^{\alpha}\, e^{-(\alpha+1)E/\overline{E}}$$

3. Fermi-Dirac distribution with an effective degeneracy parameter



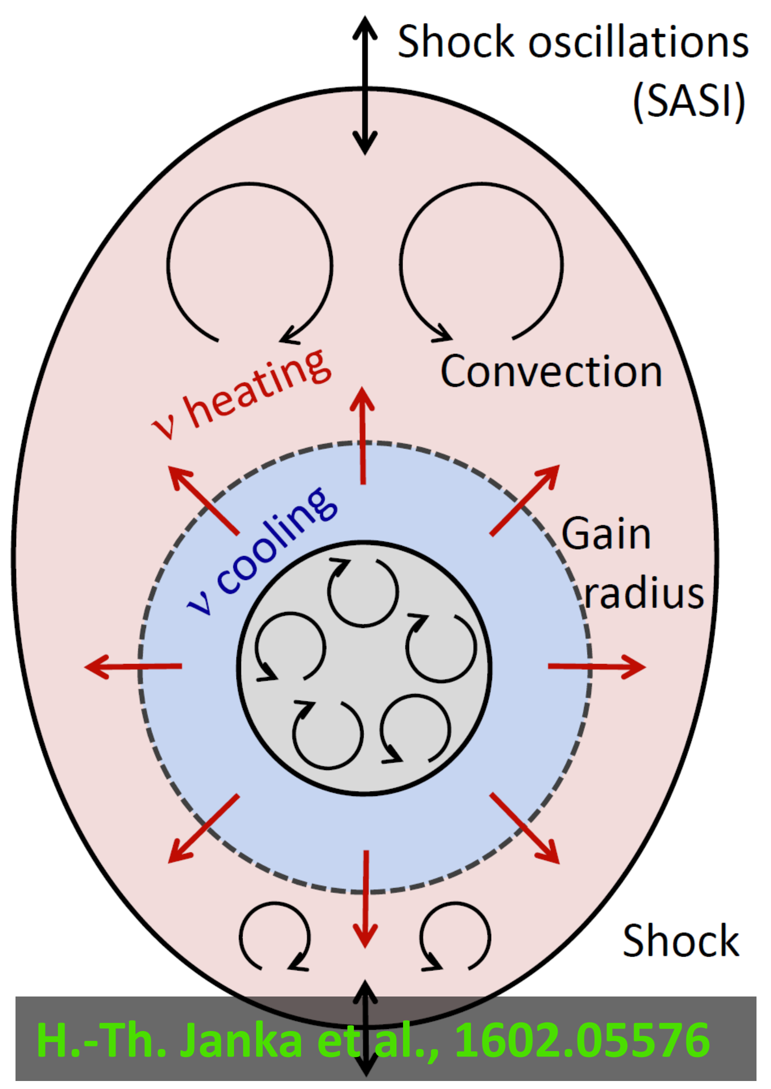
Supernova Neutrinos: theoretical predictions



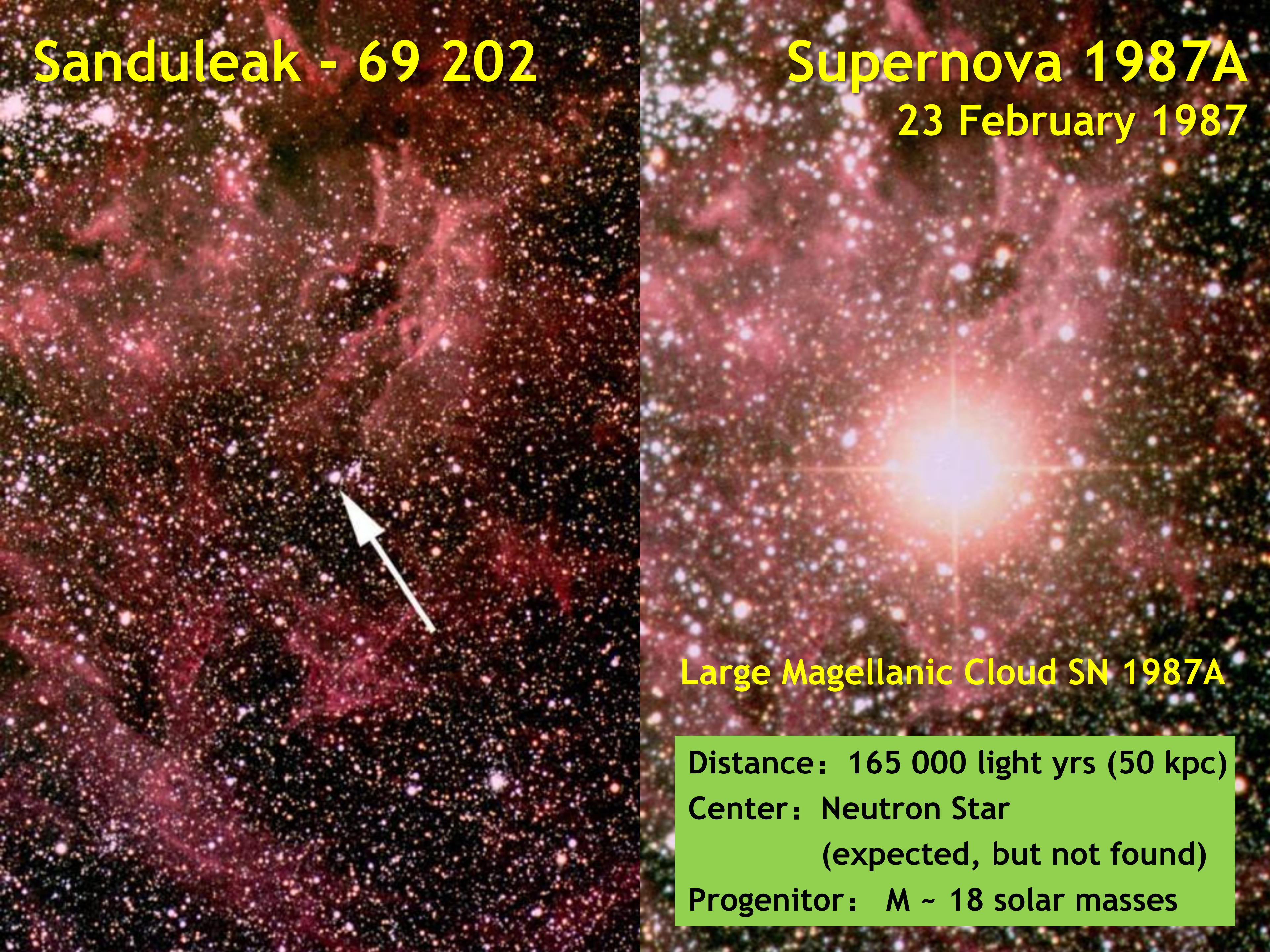
High-resolution alpha-fit to simulations, Tamborra et al., arXiv:1211.3920

■ Explosion Mechanism: Neutrino-driven Explosion

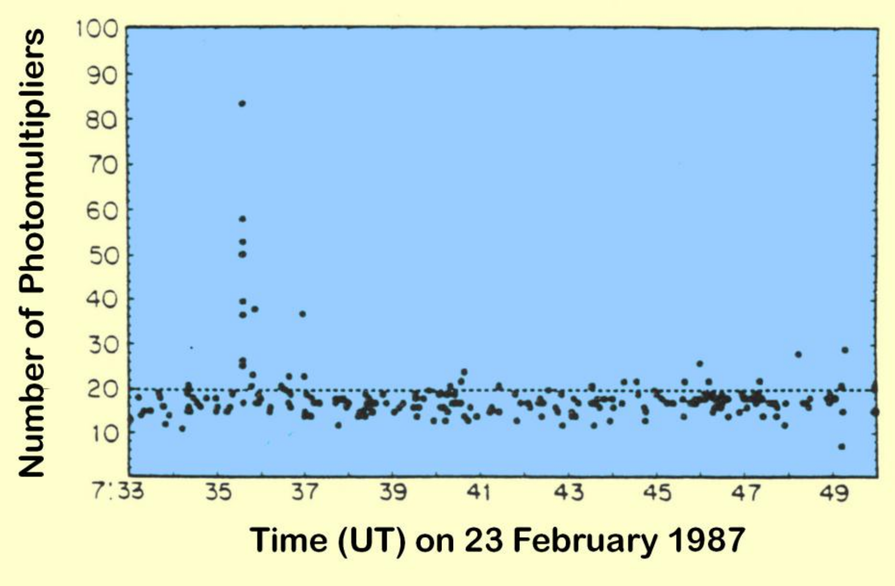
- The prompt shock halted at 150 km, by disintegrating heavy nuclei
- Neutrinos deposit their energies via interaction with matter; 1 % neutrino energy leads to successful explosion
- Simulations in 1D & 2D for different progenitor masses observe explosions
- 3D simulation has just begun; but no clear picture (resolution, progenitors)

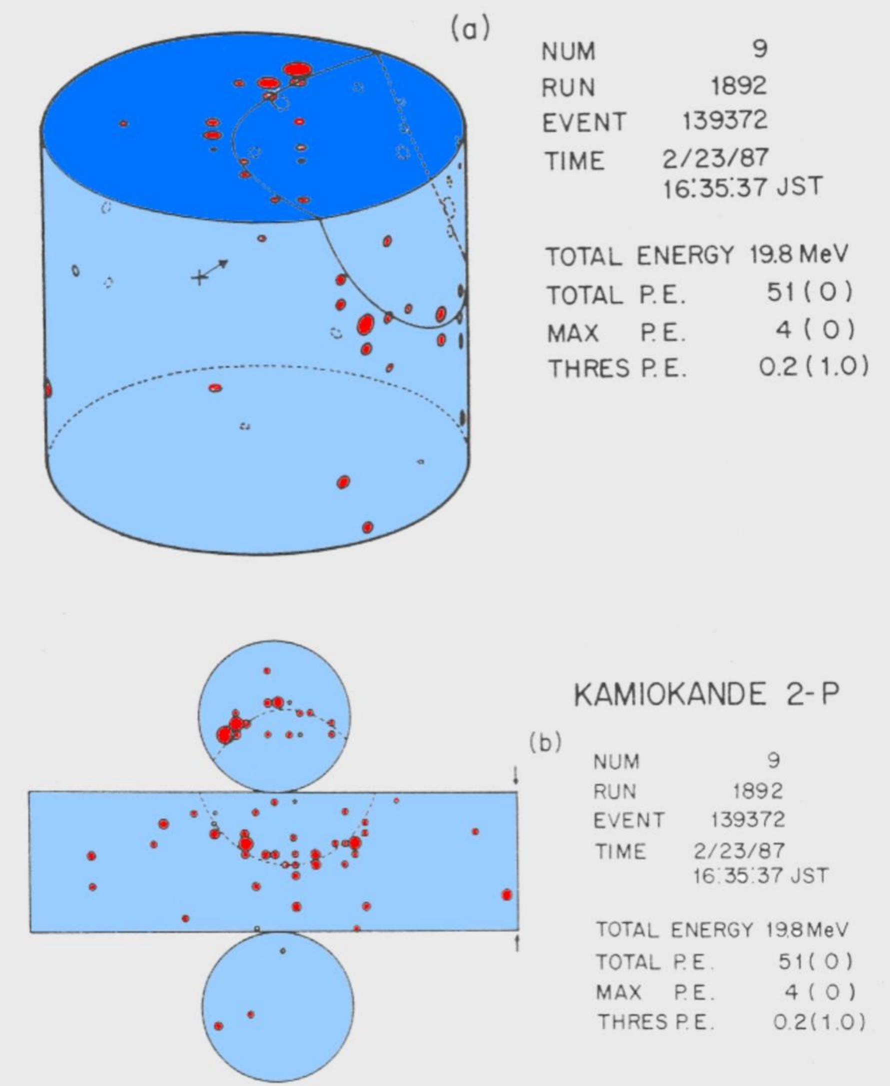


H.-Th. Janka et al., 1602.05576

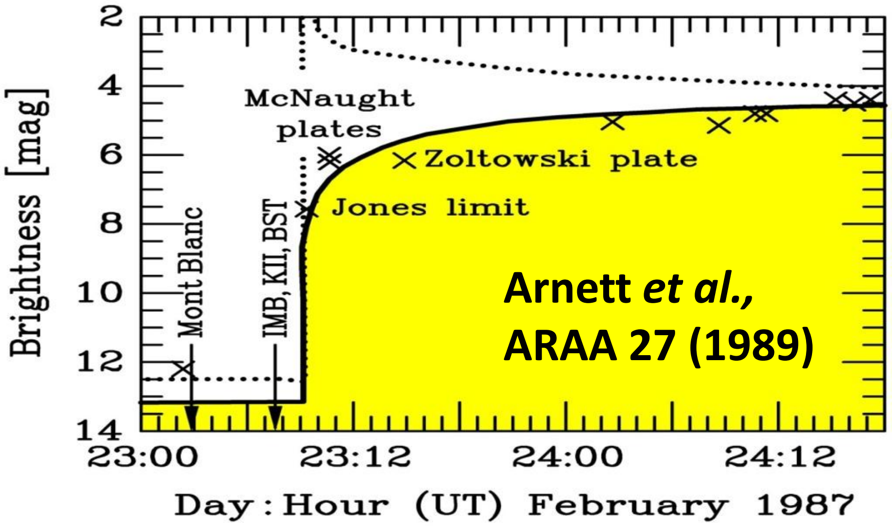

Sanduleak - 69 202
Supernova 1987A
23 February 1987
Large Magellanic Cloud SN 1987A
Distance：165 000 light yrs (50 kpc)
Center：Neutron Star
(expected, but not found)
Progenitor： M ~ 18 solar masses

Supernova Neutrinos: SN 1987A





Hirata et al., PRD 38 (1988) 448



Arnett *et al.*,
ARAA 27 (1989)

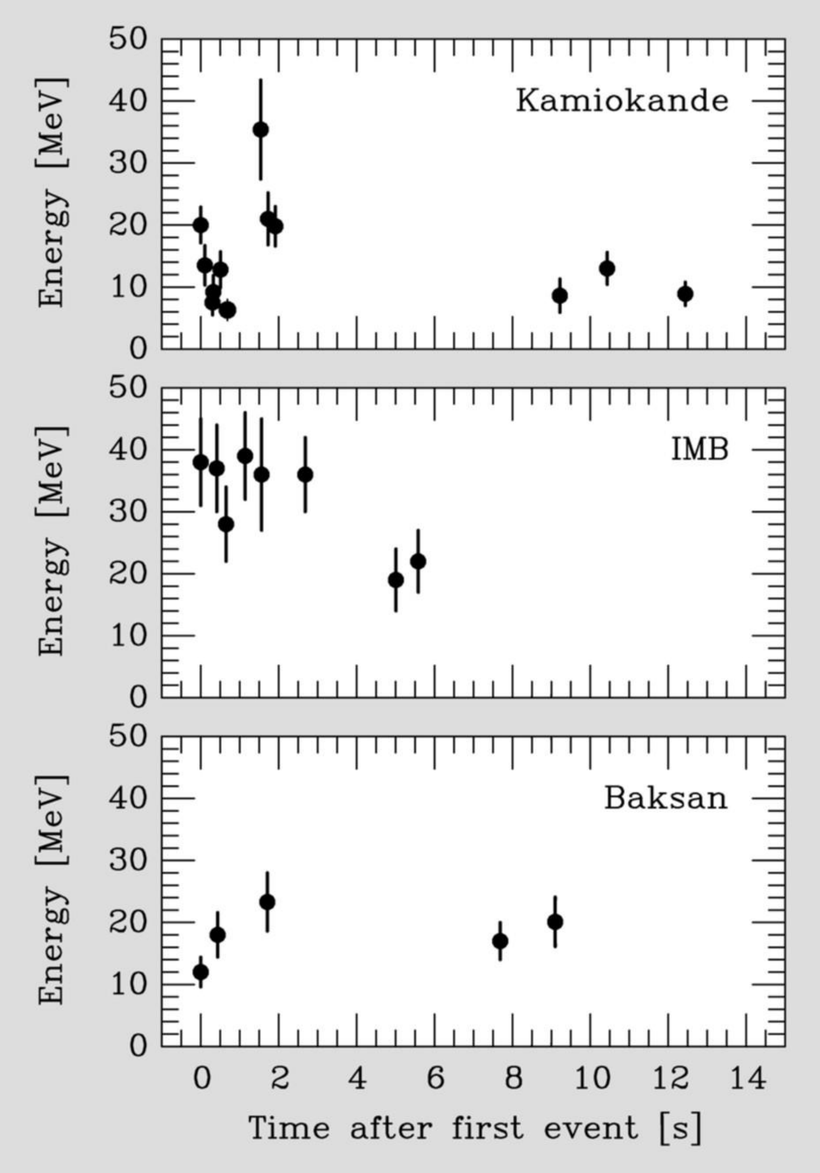
Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):
- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

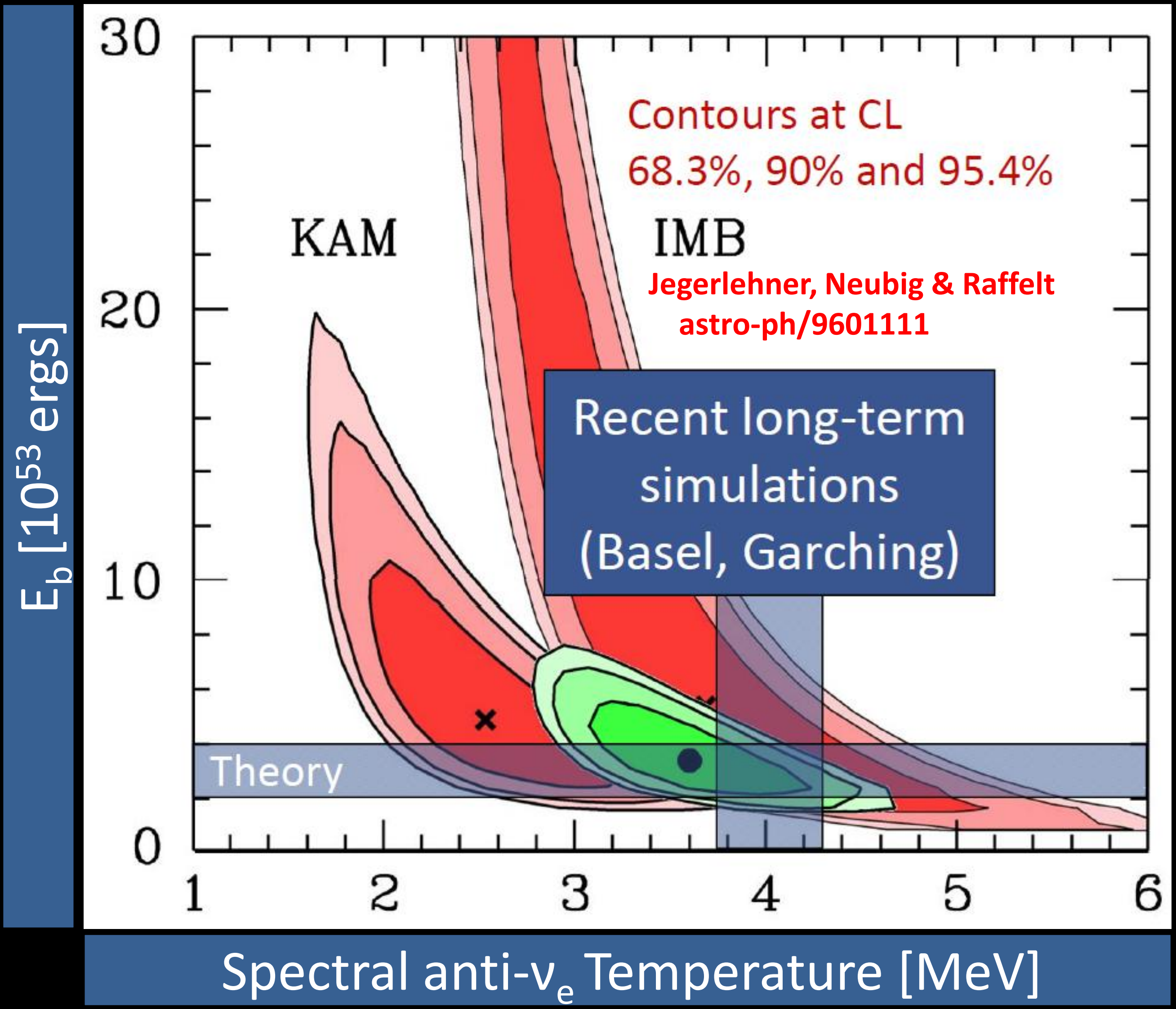
Irvine-Michigan-Brookhaven (US):
- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

Baksan LST (Soviet Union):
- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A



Assumptions:

- ☐ Thermal
- ☐ Equipart.

Conclusions:

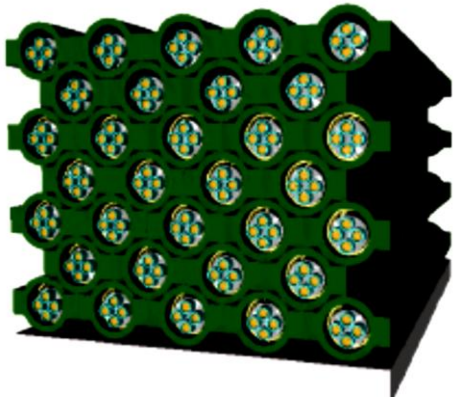
- ■ Collapse
- ■ Ave.Ener.
- ■ Duration

Problems:

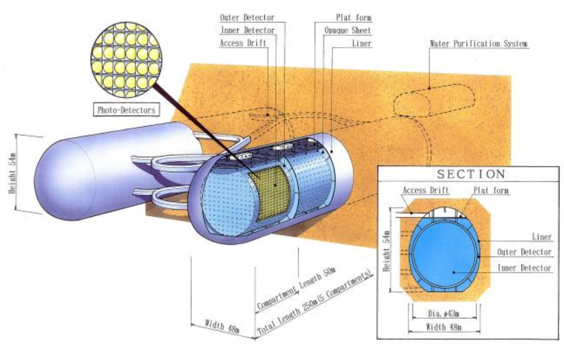
- ☐ 24 events
- ☐ by chance

SN ν Detection: present and future experiments

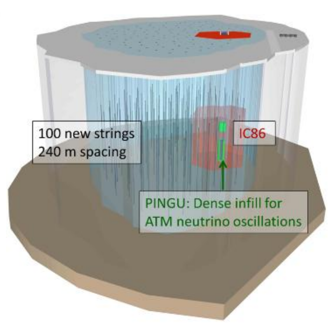
HALO@
SNOLAB



Hyper-K



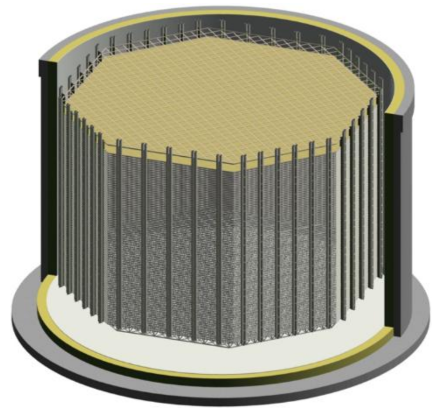
IceCube-Gen2

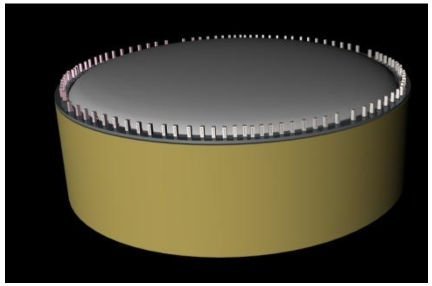


Mton-scale ice
or water Cherenkov

5–100 kton
liquid Argon

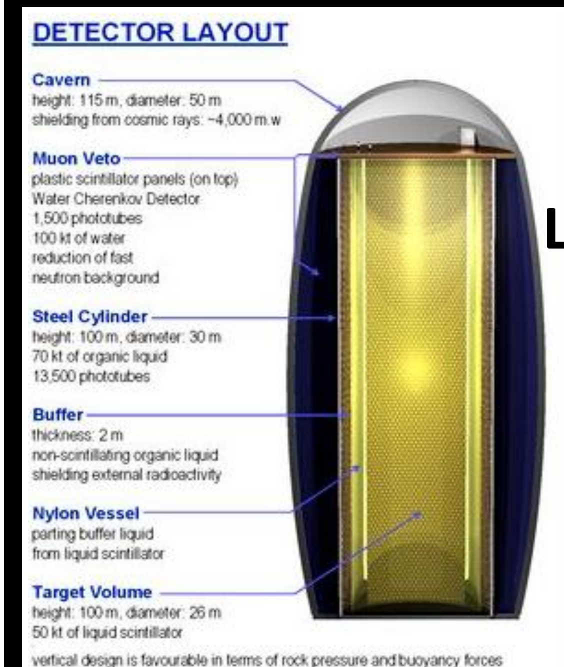
DUNE

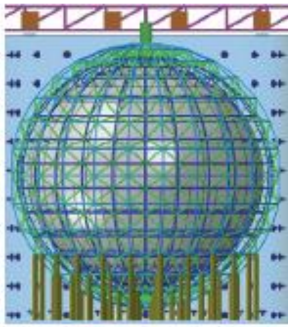




100 kton scale
scintillator

LENA





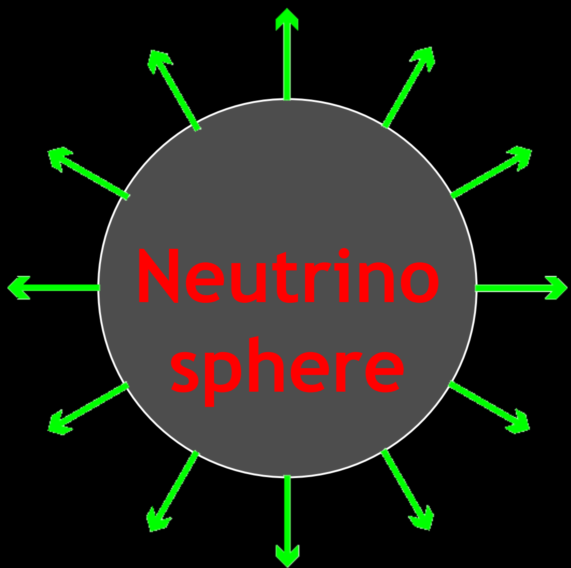
JUNO

SN ν Detection: present and future experiments

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

Supernova Neutrinos: Elementary Particle Physics

■ **Flavor Conversion & Matter Effects: Source — Prop. — Detector**



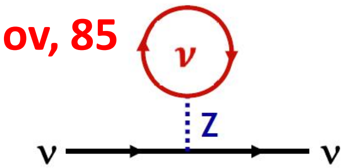
$$\rho > 10^{10}\ \mathrm{g\ cm^{-3}}$$

High Matter Density:

- ☐ High interaction rate
- ☐ Flavors conserved

$$\mathrm{i}\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Wolfenstein, 78
Mikheyev&Smirnov, 85
Pantaleone, 92

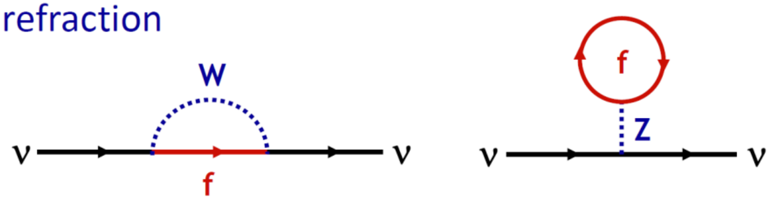


Effective mixing Hamiltonian

$$H = \frac{M^2}{2E} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

Vacuum	MSW	Collective

Neutrinos in a medium suffer flavor-dependent refraction



$$V_\mathrm{weak} = \sqrt{2}G_\mathrm{F} \times \begin{cases} N_\mathrm{e} - N_\mathrm{n}/2 & \text{for } \nu_\mathrm{e} \\ -N_\mathrm{n}/2 & \text{for } \nu_\mu \end{cases}$$

Typical density of Earth: 5 g/cm³

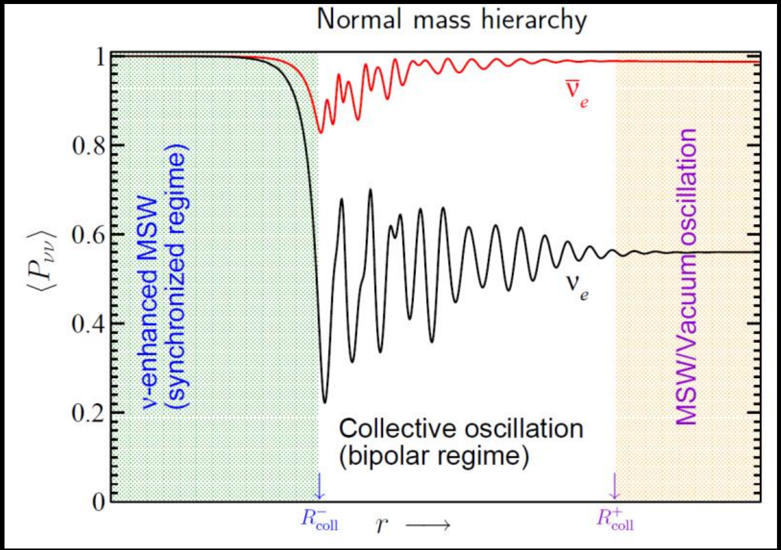
$$\Delta V_\mathrm{weak} \approx 2 \times 10^{-13}\ \mathrm{eV} = 0.2\ \mathrm{peV}$$

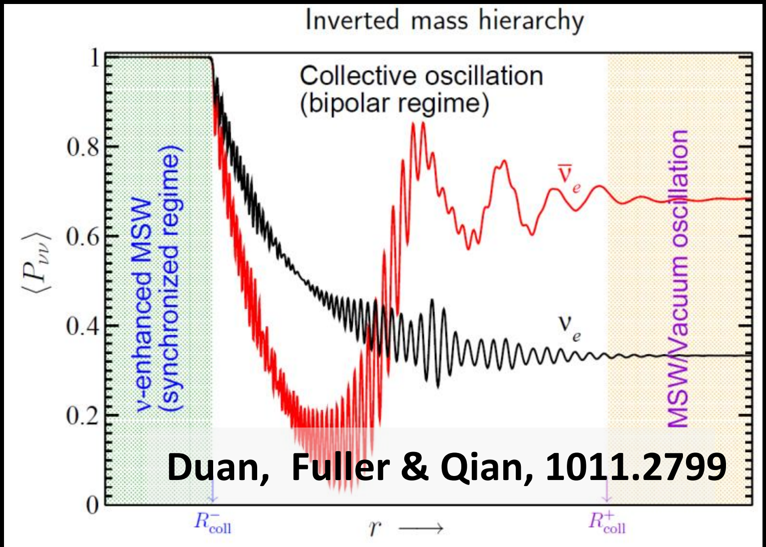
Matter Effects:

- ■ Envelope
- ■ Shock wave
- ■ Earth matter
- ■ Mass ordering

Supernova Neutrinos: Elementary Particle Physics

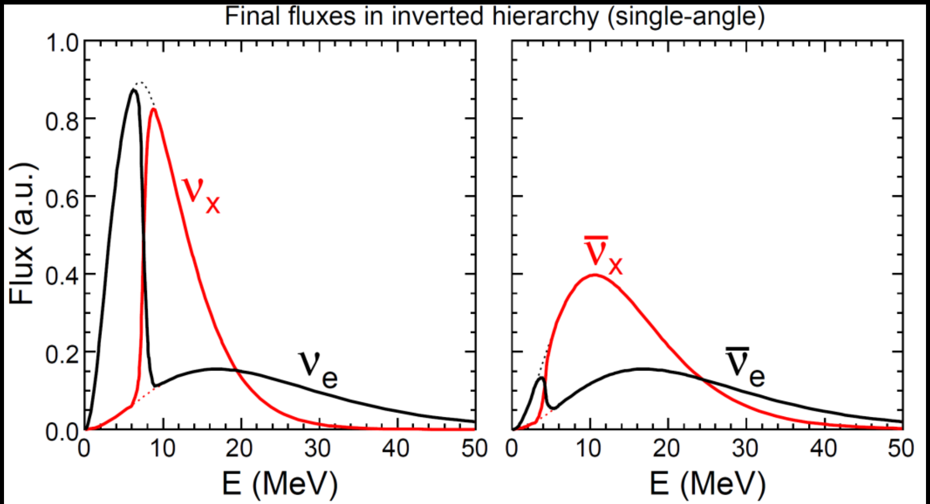
■ Flavor Conversion: collective effects (accretion phase)

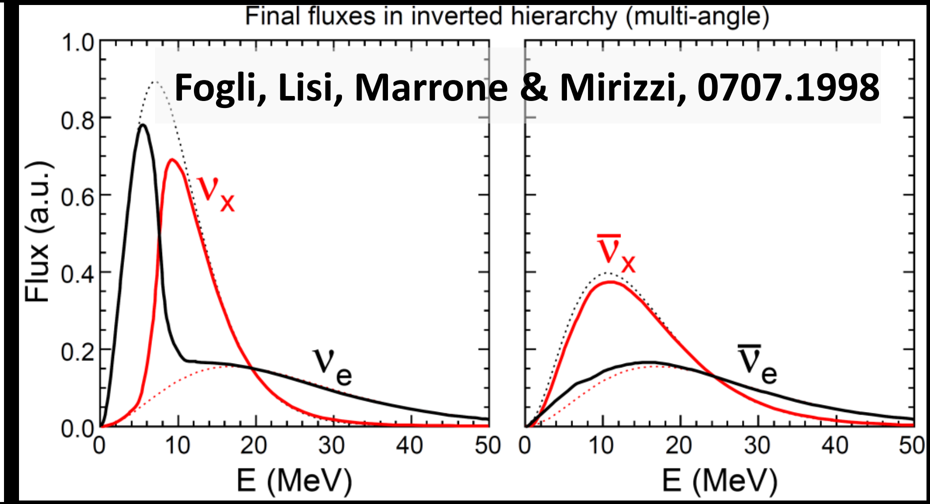




Left: Sketch of Collective effects

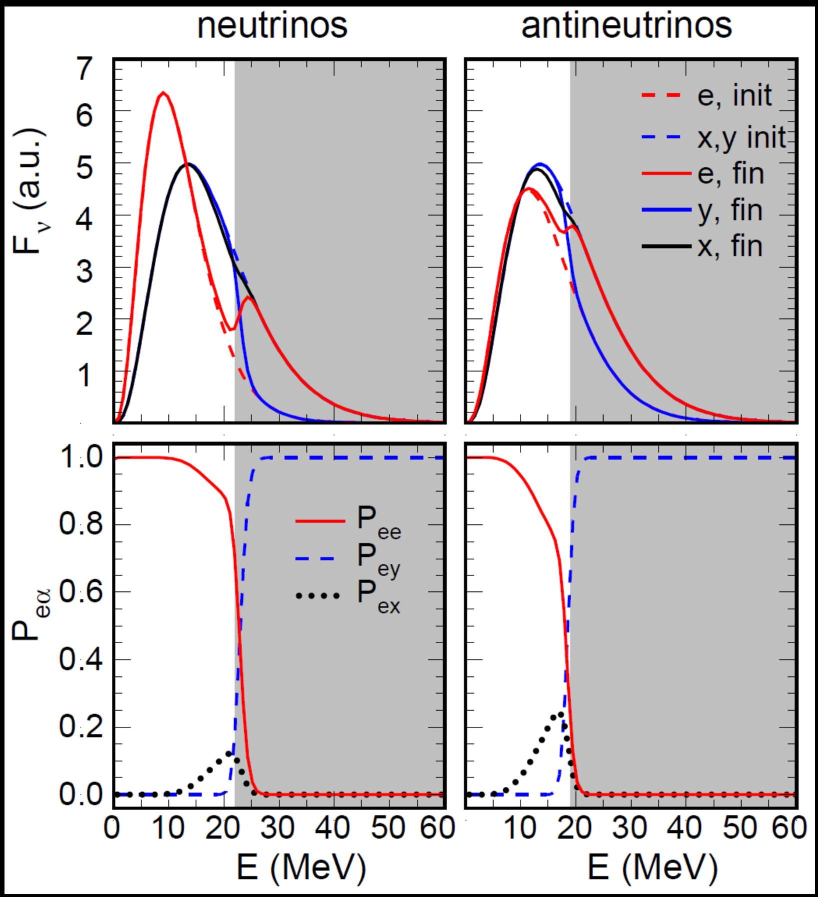
Bottom: Inverted + Accretion





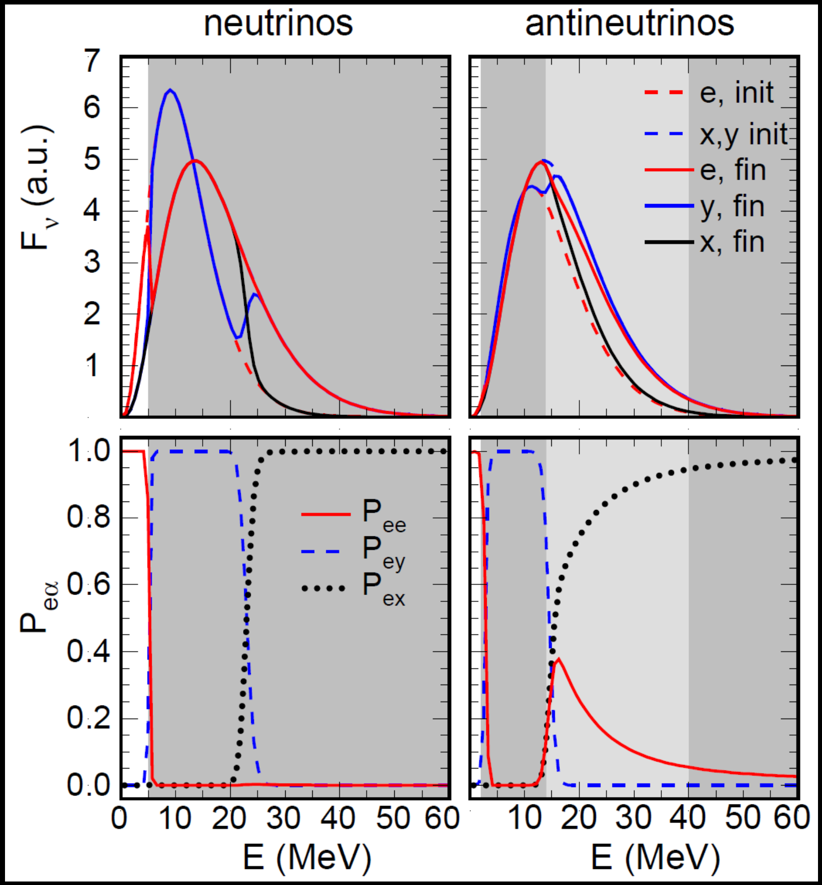
Supernova Neutrinos: Elementary Particle Physics

■ Flavor Conversion: collective effects (cooling phase)



NH

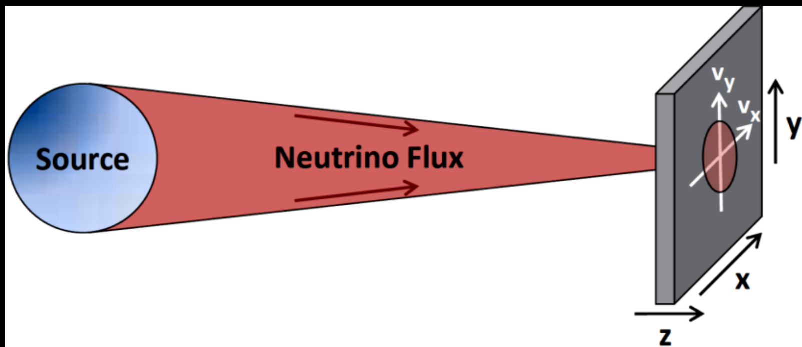
IH



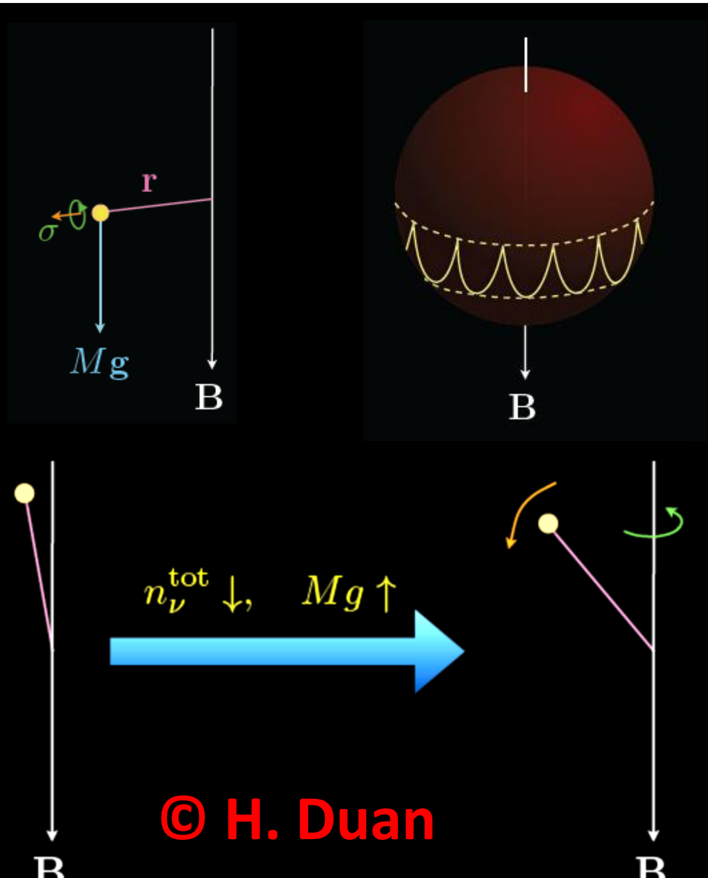
Dasgupta, Mirizzi, Tamborra&Tomàs, 1002.2943

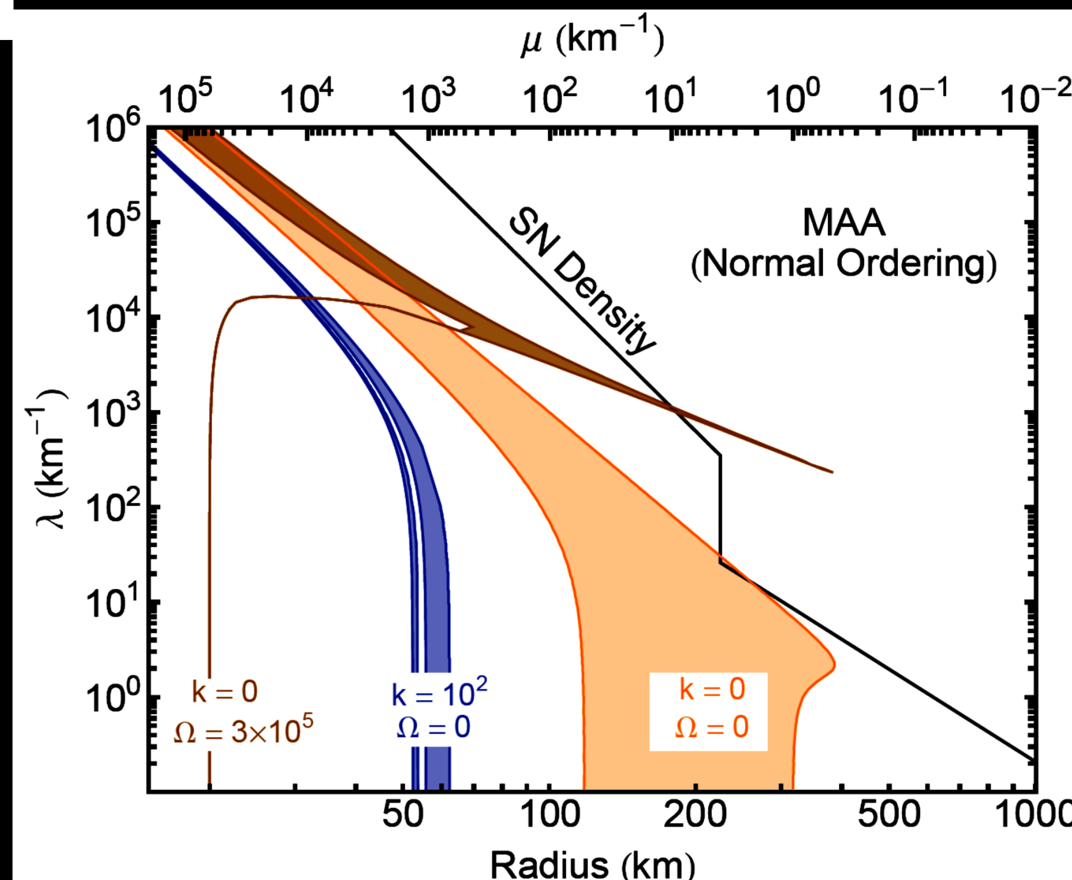
Note: compare between accretion and cooling results

■ Flavor Conversion: instability and symmetry breaking



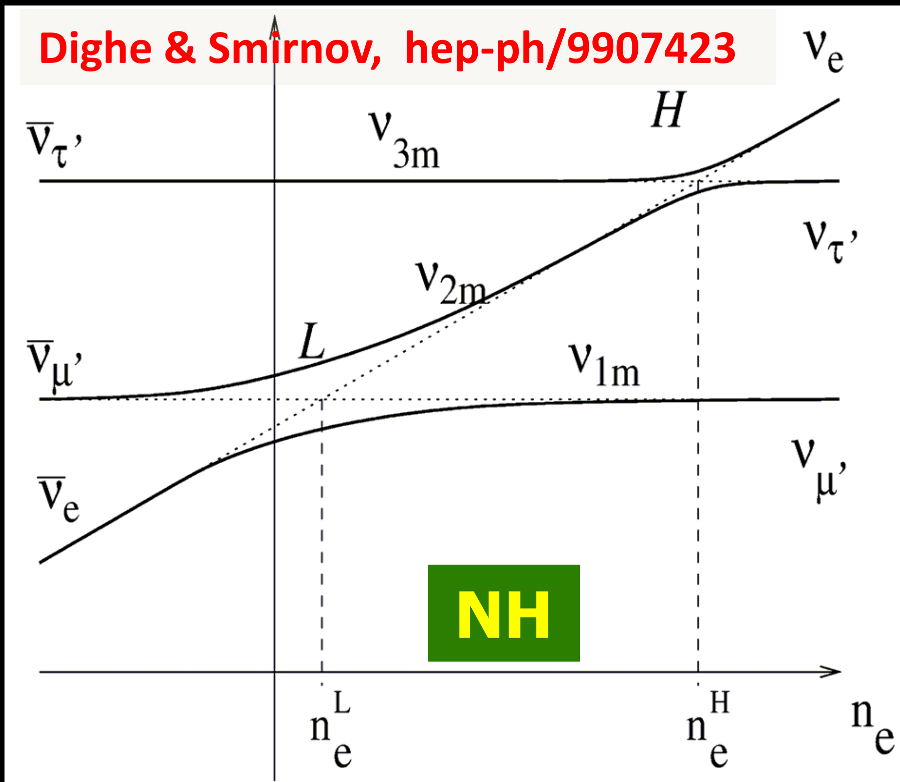
Solutions break the initial spatial symmetries: a recent review by Chakratborty et al., arxiv:1602.02766

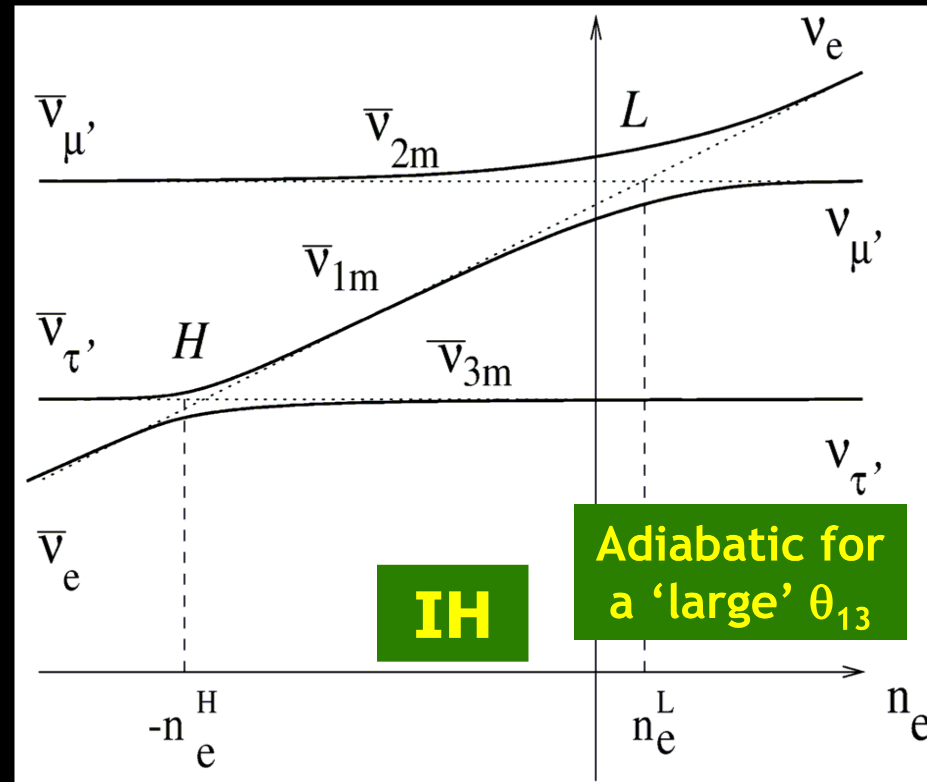




Supernova Neutrinos: Elementary Particle Physics

■ Flavor Conversion: MSW effects in the SN envelope





L – Resonance $\left(\Delta m^2_{21}, \theta_{12}\right)$
- ☐ Res. for neutrinos
- ☐ Always adiabatic

H – Resonance $\left(\Delta m^2_{31}, \theta_{13}\right)$
- ☐ Res. for neutrinos (NH)
- ☐ Res. for antineutrinos (IH)

Supernova Neutrinos: Elementary Particle Physics

■ Flavor Conversion: MSW effects in the SN envelope

F_e^0 for ν_e

$F_{\bar{e}}^0$ for $\bar{\nu}_e$

F_x^0 for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$

Primary fluxes (+ collective)

Dighe & Smirnov, hep-ph/9907423

$$F_e = p F_e^0 + (1-p) F_x^0$$

$$F_{\bar{e}} = \bar{p} F_{\bar{e}}^0 + (1-\bar{p}) F_x^0$$

$$\frac{1}{4} \sum F_x = \frac{2+p+\bar{p}}{4} F_x^0 + \frac{1-p}{4} F_e^0 + \frac{1-\bar{p}}{4} F_{\bar{e}}^0$$

Leaving the SN (+ Collective & MSW effects)

Dighe, Kachelriess, Raffelt & Tomàs, hep-ph/0311172

Case	Mass ordering	$\sin^2(2\theta_{13})$	Survival probabilities	
			p (for ν_e)	$\bar{p}$ (for $\bar{\nu}_e$)
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\theta_{12})$
B	Inverted	$\gtrsim 10^{-3}$	$\sin^2(\theta_{12})$	0

Supernova Neutrinos: Elementary Particle Physics

■ Flavor Conversion: including Earth Matter Effects

$$F_e^{\oplus} = (1 - P_{2e}) F_e^0 + P_{2e} F_x^0$$
$$F_{\bar{e}}^{\oplus} = (1 - \bar{P}_{2e}) F_{\bar{e}}^0 + \bar{P}_{2e} F_x^0$$

Dighe&Smirnov, hep-ph/9907423

$$P_{2e} = \sin^2\theta_{12} + \sin 2\theta_{12}^m \sin(2\theta_{12}^m - 2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 \sin 2\theta_{12}}{4E \sin 2\theta_{12}^m} L\right)$$
$$\bar{P}_{2e} = \sin^2\theta_{12} + \sin 2\bar{\theta}_{12}^m \sin(2\bar{\theta}_{12}^m - 2\theta_{12}) \sin^2\left(\frac{\Delta m_{21}^2 \sin 2\theta_{12}}{4E \sin 2\bar{\theta}_{12}^m} L\right)$$

Lunardini & Smirnov, hep-ph/0106149

for a 'large' θ_{13}

NH: Matter Effects -antineutrinos	IH: Matter Effects - neutrinos

If IH is determined from oscillation experiments, Earth matter effects indicate collective effects.

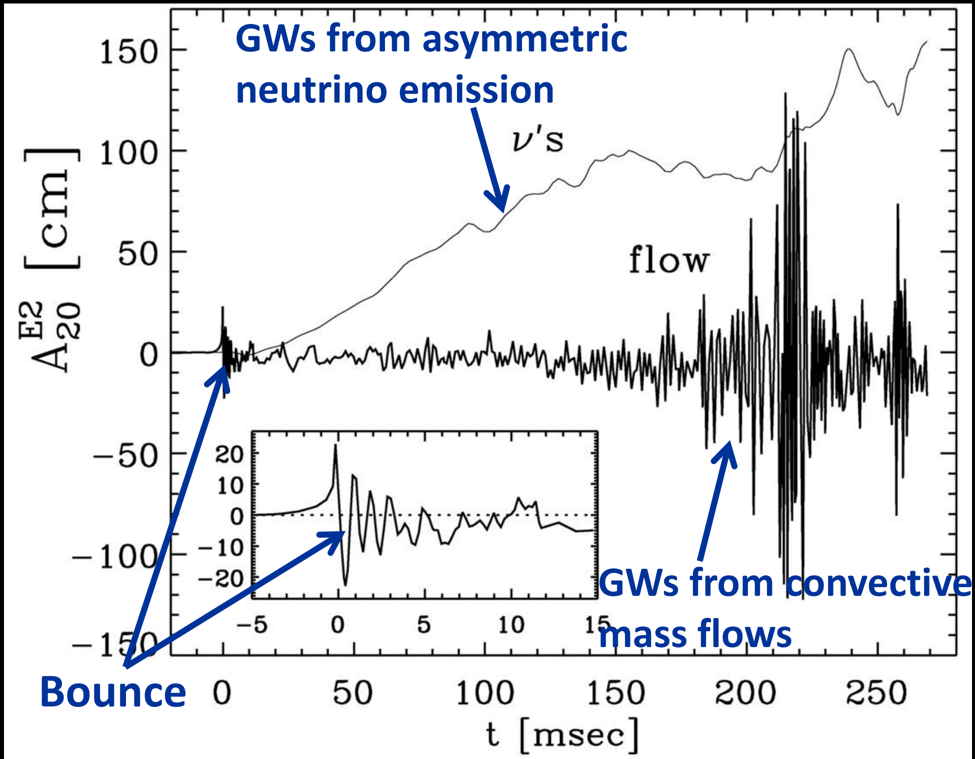
		Collective Neutrino Oscillations (accretion phase)			
		No		Yes	
Mass Ordering	$\sin^2\theta_{13}$	$\bar{\nu}_e$ survival	Earth matter	$\bar{\nu}_e$ survival	Earth matter
NH	$\gtrsim 10^{-3}$	$\cos^2\theta_{12}$	Yes	$\cos^2\theta_{12}$	Yes
IH	$\gtrsim 10^{-3}$	0	No	$\cos^2\theta_{12}$	Yes

Supernova Neutrinos: Astrophysics & Astronomy

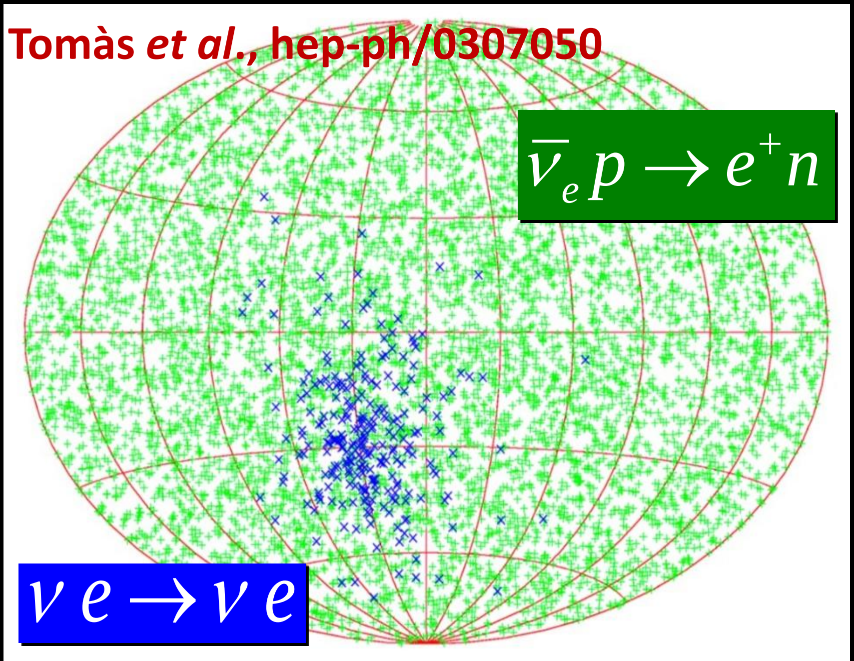
■ Gravitational waves from SN Explosions

Müller, Rampp, Buras, Janka,& Shoemaker, astro-ph/0309833

"Towards gravitational wave signals from realistic core collapse supernova models"



■ Locate the SN via neutrinos

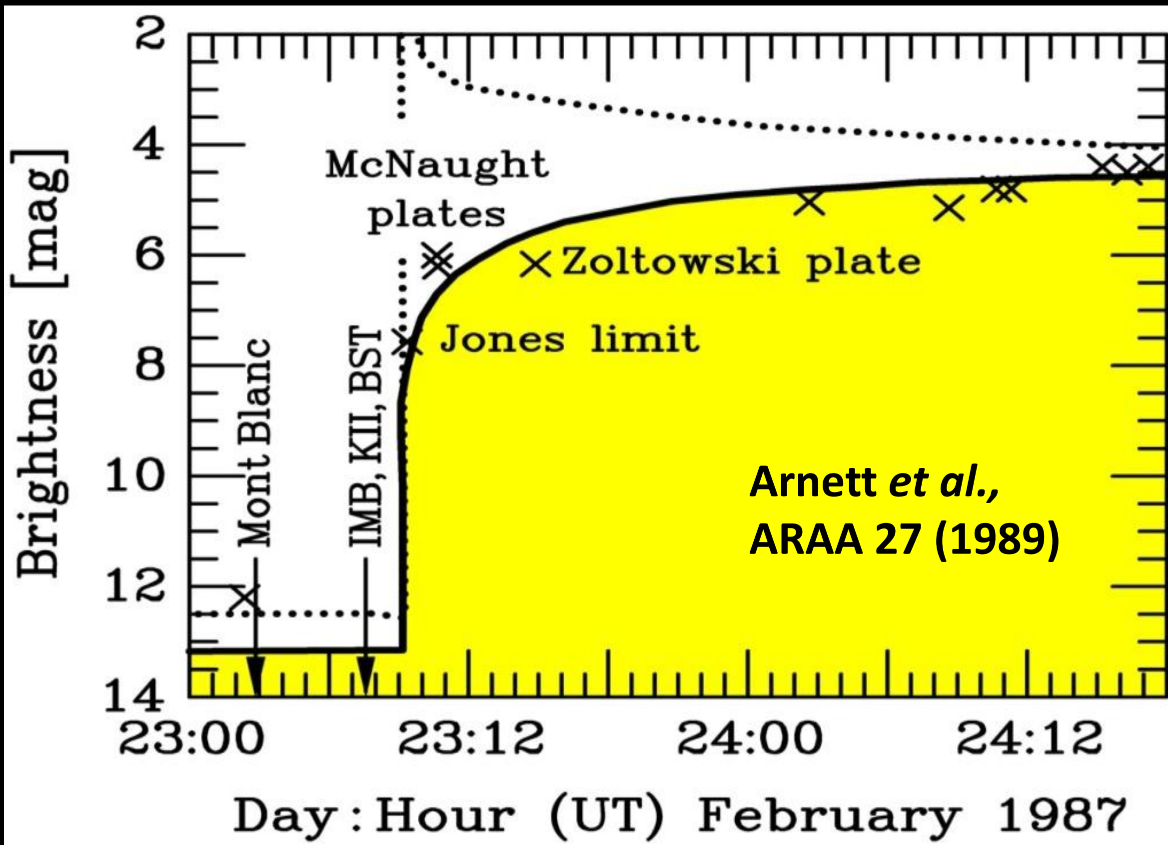


Beacom & Vogel, astro-ph/9811350

n-tagging efficiency		95% CL half-cone opening angle
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30

Supernova Neutrinos: Astrophysics & Astronomy

- For Optical Observations： SuperNova Early Warning System (SNEWS)



http://snews.bnl.gov/

Super-K

IceCube

LVD

Borexino

Daya Bay

Alert @BNL

Neutrinos arrive several hours before photons

To alert astronomers several hours in advance

Supernova Neutrinos: Elementary Particle Physics

■ Neutrino Mass Bound: Time delay of massive particles

$$\Delta t = 2.57\,\mathrm{s}\,\frac{D}{50\,\mathrm{kpc}}\left(\frac{10\,\mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m}{10\,\mathrm{eV}}\right)^2$$

G. Zatsepin, 1968

Kamiokande-II data

Event	Time [s]	Angle [degree]	Energy [MeV]
1	0.000	18 ± 18	20.0 ± 2.9
2	0.107	40 ± 27	13.5 ± 3.2
3	0.303	108 ± 32	7.5 ± 2.0
4	0.324	70 ± 30	9.2 ± 2.7
5	0.507	135 ± 23	12.8 ± 2.9
6[a]	0.686	68 ± 77	6.3 ± 1.7
7	1.541	32 ± 16	35.4 ± 8.0
8	1.728	30 ± 18	21.0 ± 4.2
9	1.915	38 ± 22	19.8 ± 3.2
10	9.219	122 ± 30	8.6 ± 2.7
11	10.433	49 ± 26	13.0 ± 2.6
12	12.439	91 ± 39	8.9 ± 1.9

Schramm, CNPP 17 (1987) 239

Estimate: $\Delta t(E_B, m) - \Delta t(E_A, m) < t_B - t_A$

- ■ Take the first event A: (t_A, E_A)
- ■ Take the last event B: (t_B, E_B)

$m < 22\,\mathrm{eV}$ Kam - II

$m < 37\,\mathrm{eV}$ IMB

Assumptions:

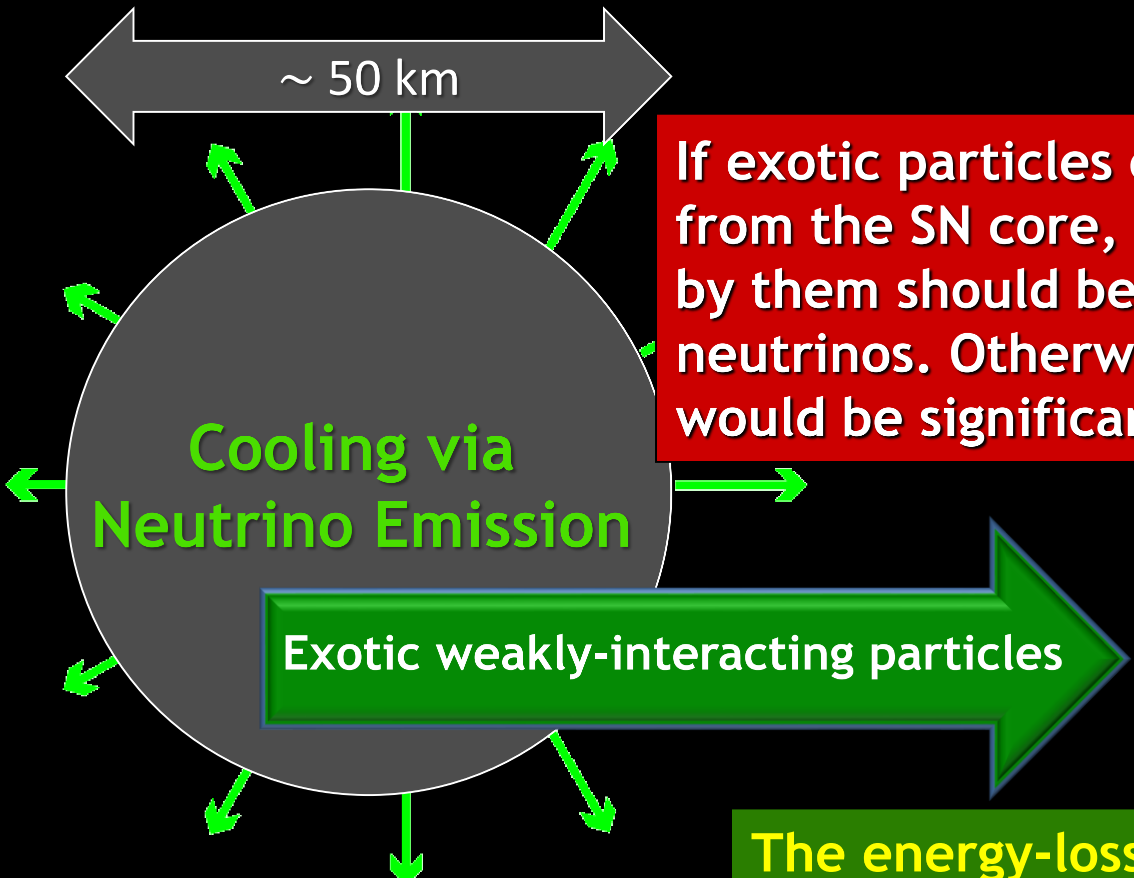
- ☐ Instant. emission
- ☐ Diff. only from *m*

IMB data

Event	Time [s]	Angle [degree]	Energy [MeV]
1	0.000	80 ± 10	38 ± 7
2	0.412	44 ± 15	37 ± 7
3	0.650	56 ± 20	28 ± 6
4	1.141	65 ± 20	39 ± 7
5	1.562	33 ± 15	36 ± 9
6	2.684	52 ± 10	36 ± 6
7	5.010	42 ± 20	19 ± 5
8	5.582	104 ± 20	22 ± 5

Supernova Neutrinos: Elementary Particle Physics

■ Extra energy-loss channels: Bound on particle physics models



If exotic particles can be produced and escape from the SN core, then the energy carried away by them should be at least smaller than that by neutrinos. Otherwise, the SN neutrino signal would be significantly reduced.

$$\varepsilon_{\rm new} < 3.0 \times 10^{33}\ {\rm erg\ cm^{-3} s^{-1}}$$

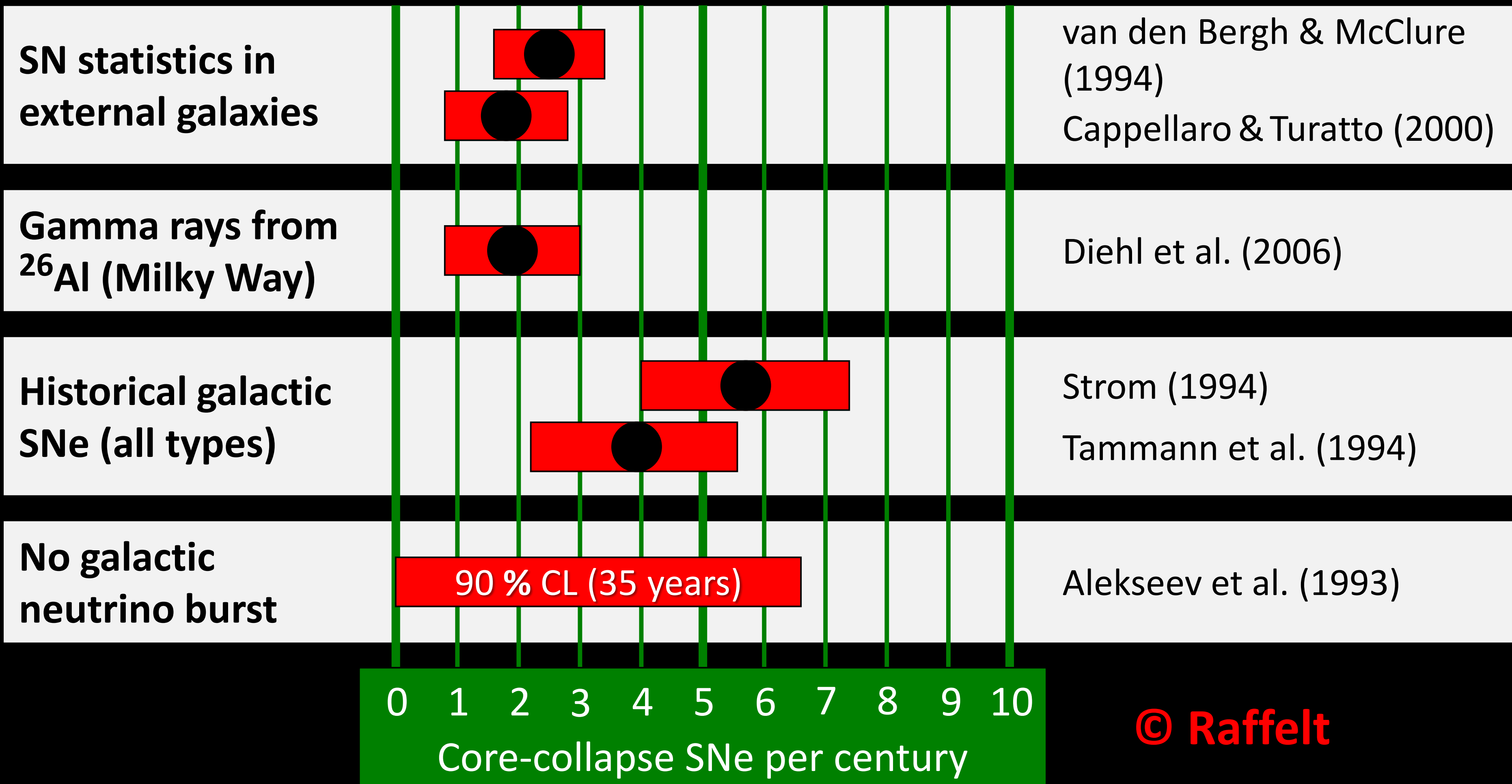
Proto-Neutron Star

$\rho \sim \rho_{\rm nuc} = 3 \times 10^{14}\ {\rm g\ cm^{-3}}$

$T \sim 30$ MeV

The energy-loss argument has been applied to the SN 1987A, and restrictive bounds on particle physics models have been obtained: Axion, Majoron, keV sterile neutrino, ……

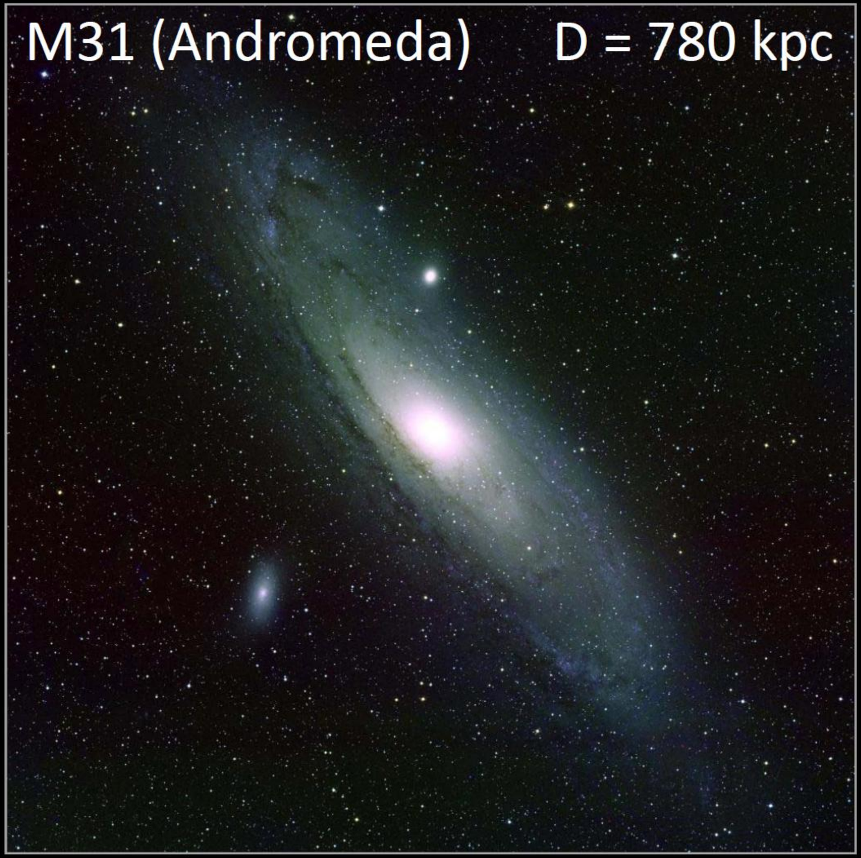
Key Problem: where and When?

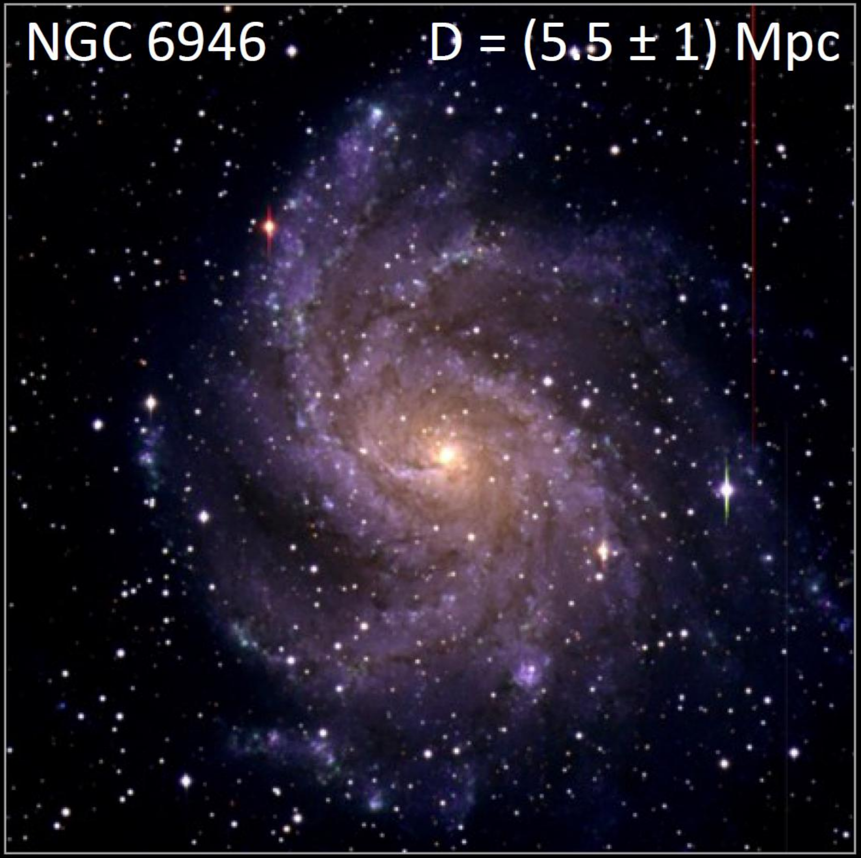


(1) Estimate from SN statistics in other galaxies; (2) Only massive stars produce ^{26}Al (with a half-life 7.2×10^5 years); (3) Historical SNe in the Milky Way; (4) No neutrino bursts observed by Baksan since June 1980

Key Problem: where and When?

High and Low Supernova Rates in Nearby Galaxies

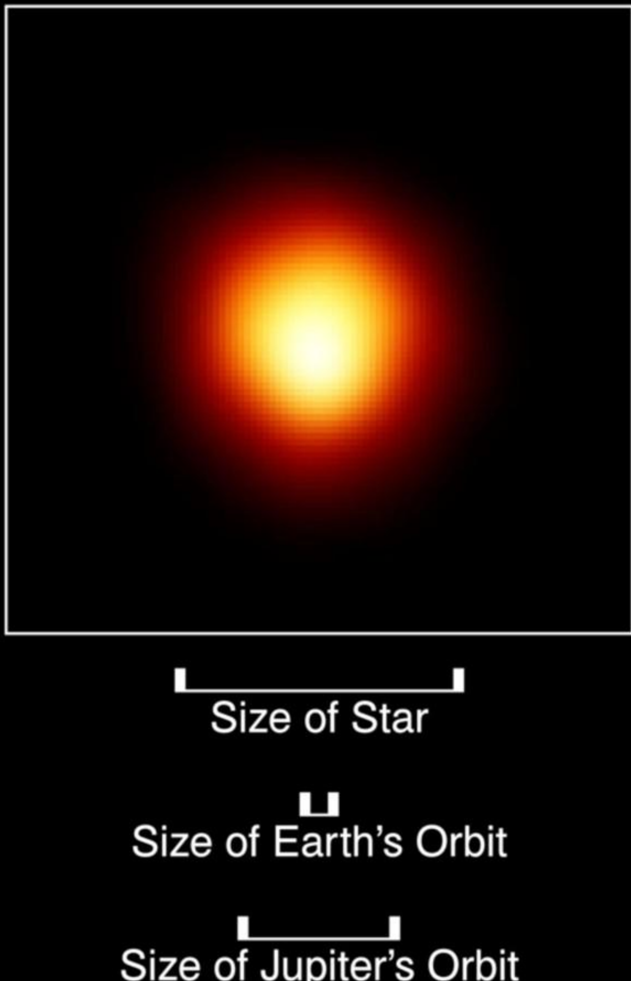


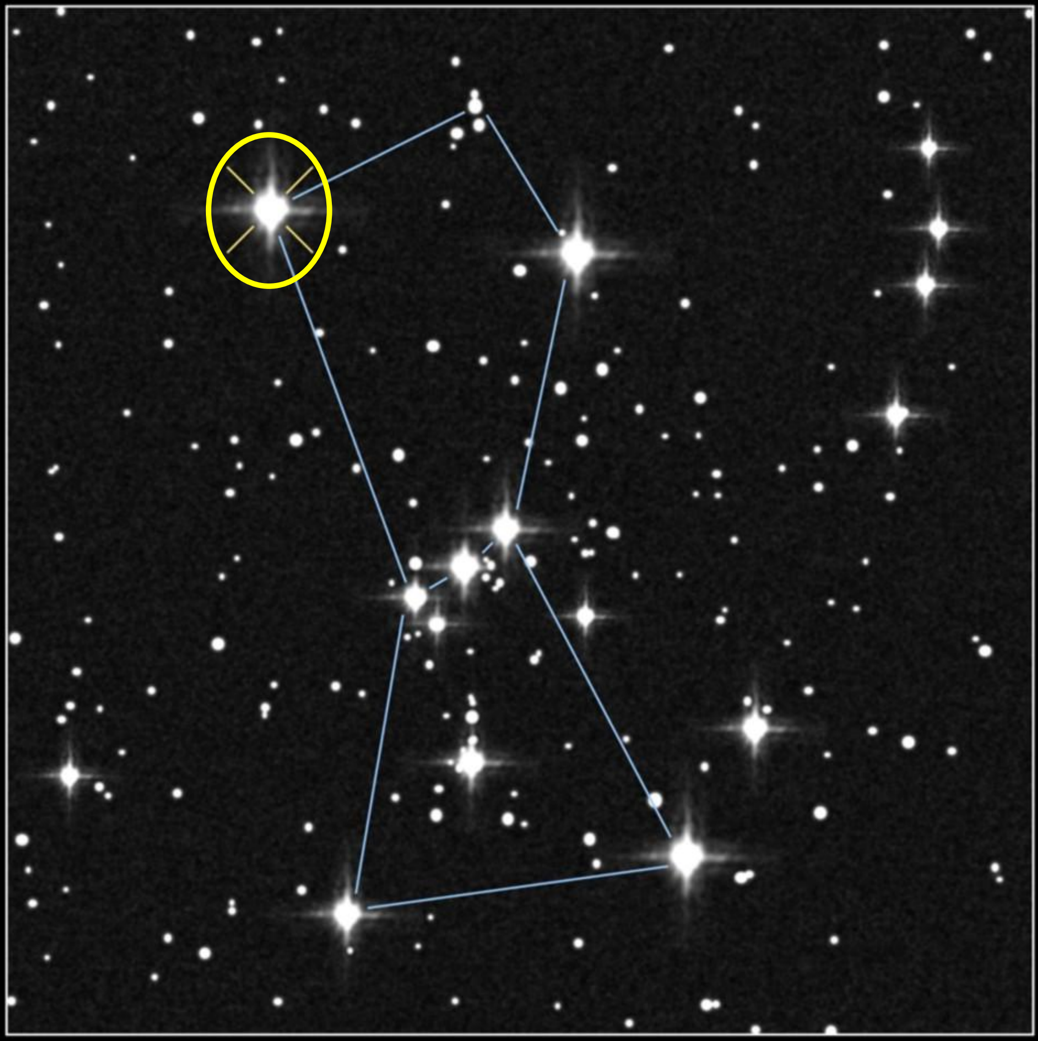


Last observed supernova: 1885A

Observed supernovae:
1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et, 2008S

SN Candidate: The Red Supergiant Betelgeuse (Alpha Orionis)



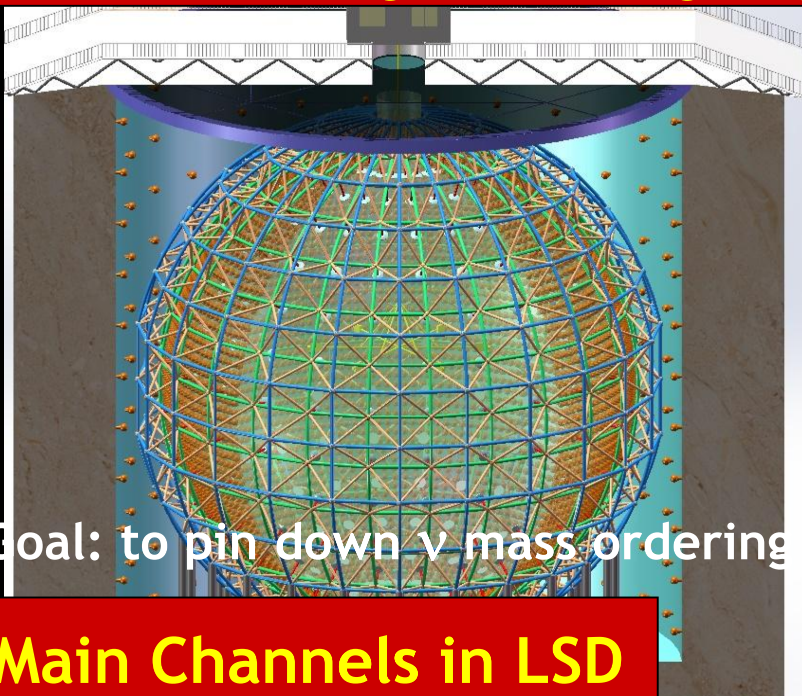


Distance: 425 ly (130 pc)
Type： Red Supergiant
Mass： ~ 18 solar masses

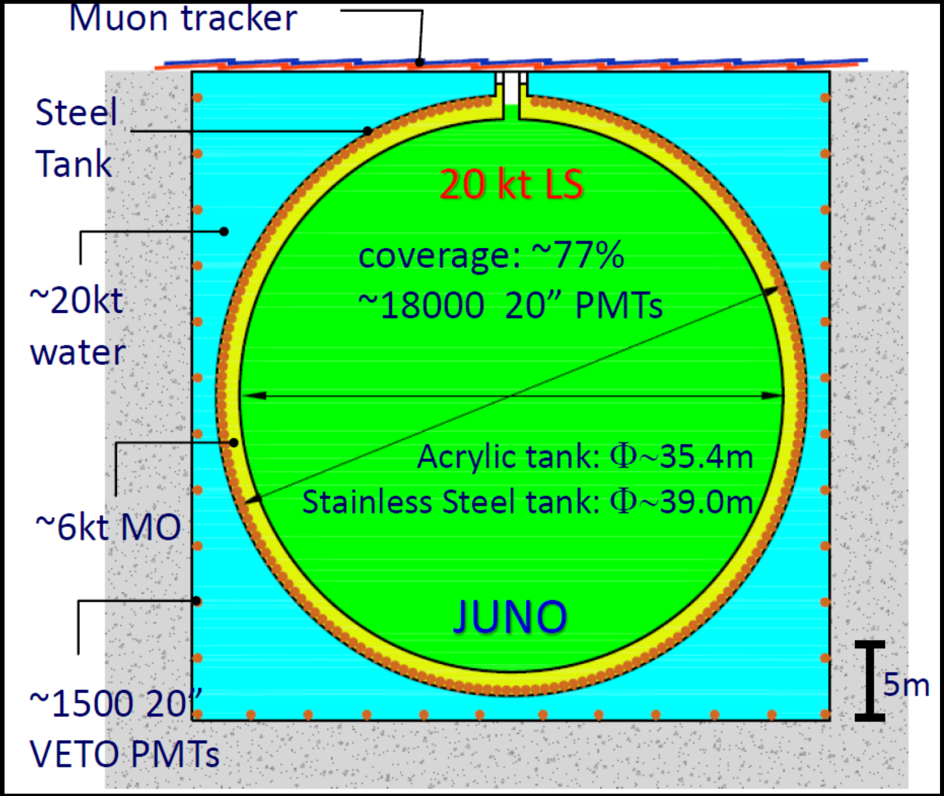
Expected to end its life as SN explosion
@ Super-K: 6×10^7 events

Detection of SN Neutrinos @JUNO

2015/1/10, Jiangmen, Guangdong



Goal: to pin down ν mass ordering

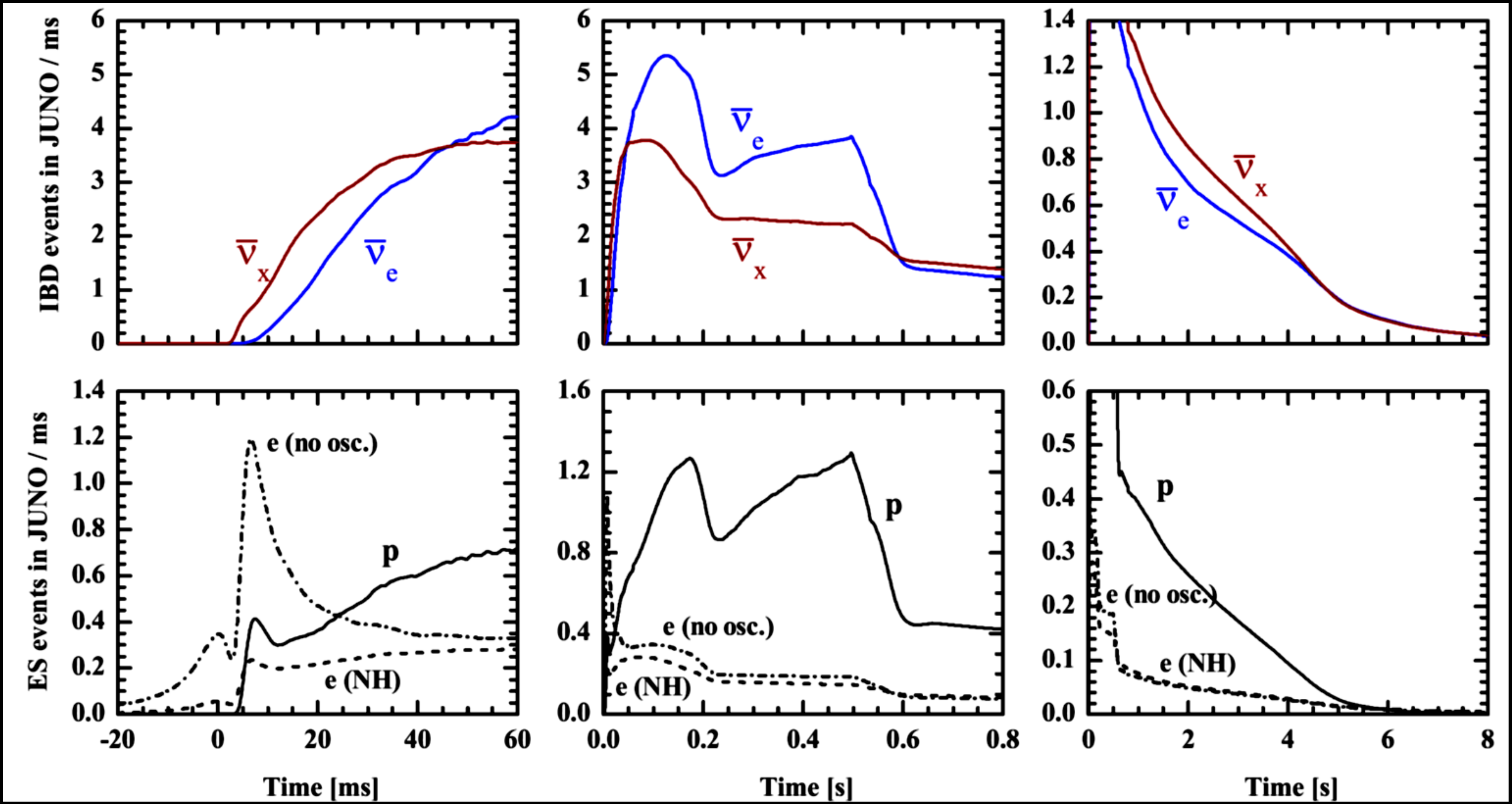


Main Channels in LSD

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

A typical SN @ 10 kpc

Detection of SN Neutrinos at JUNO



Fengpeng An et al., "Neutrino Physics with JUNO", arXiv:1507.05613