CCEPP Summer School 2021 on Neutrino Physics
Beijing 20–27 August 2021

# Supernova Neutrinos

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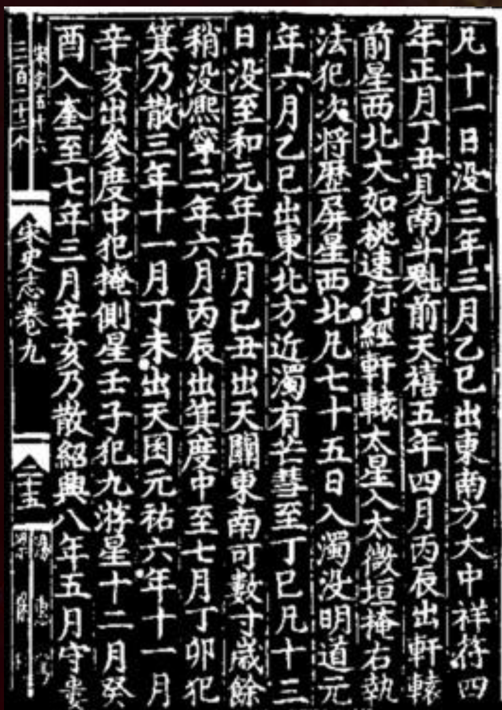
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

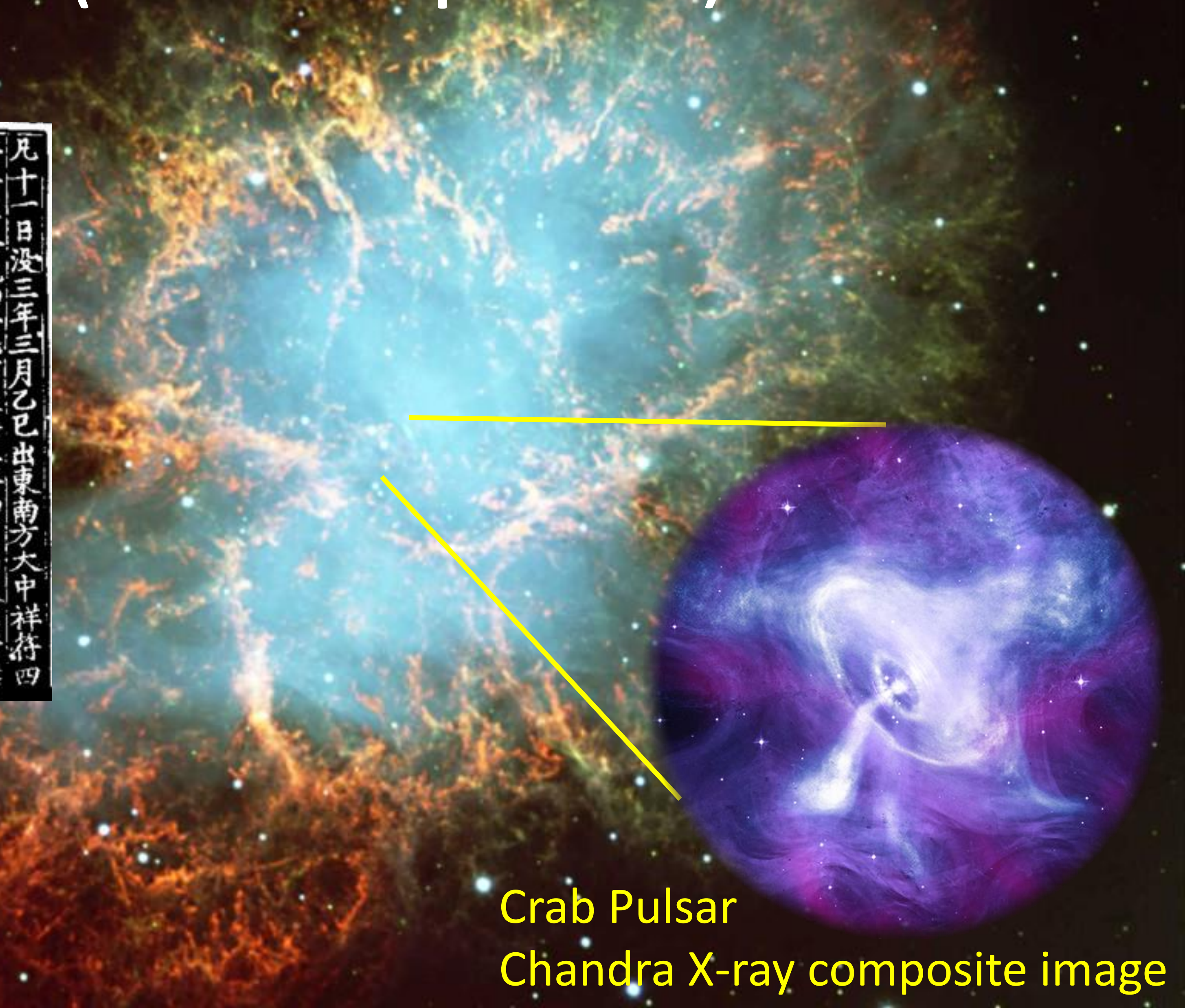
SFB 1258 Neutrinos Dark Matter Messengers

# Crab Nebula – Remnant of SN 1054 (“Chinese Supernova”)

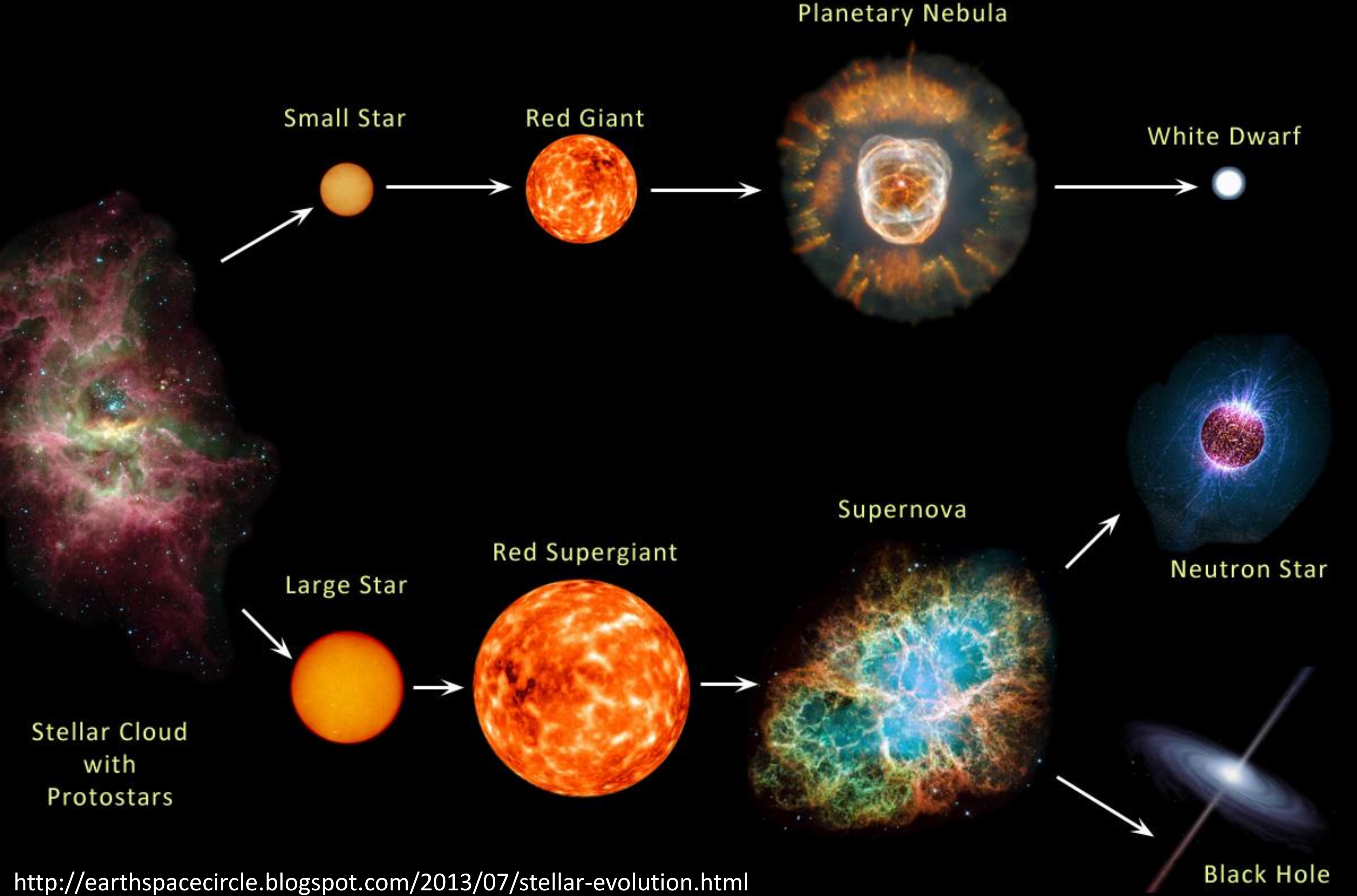


凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

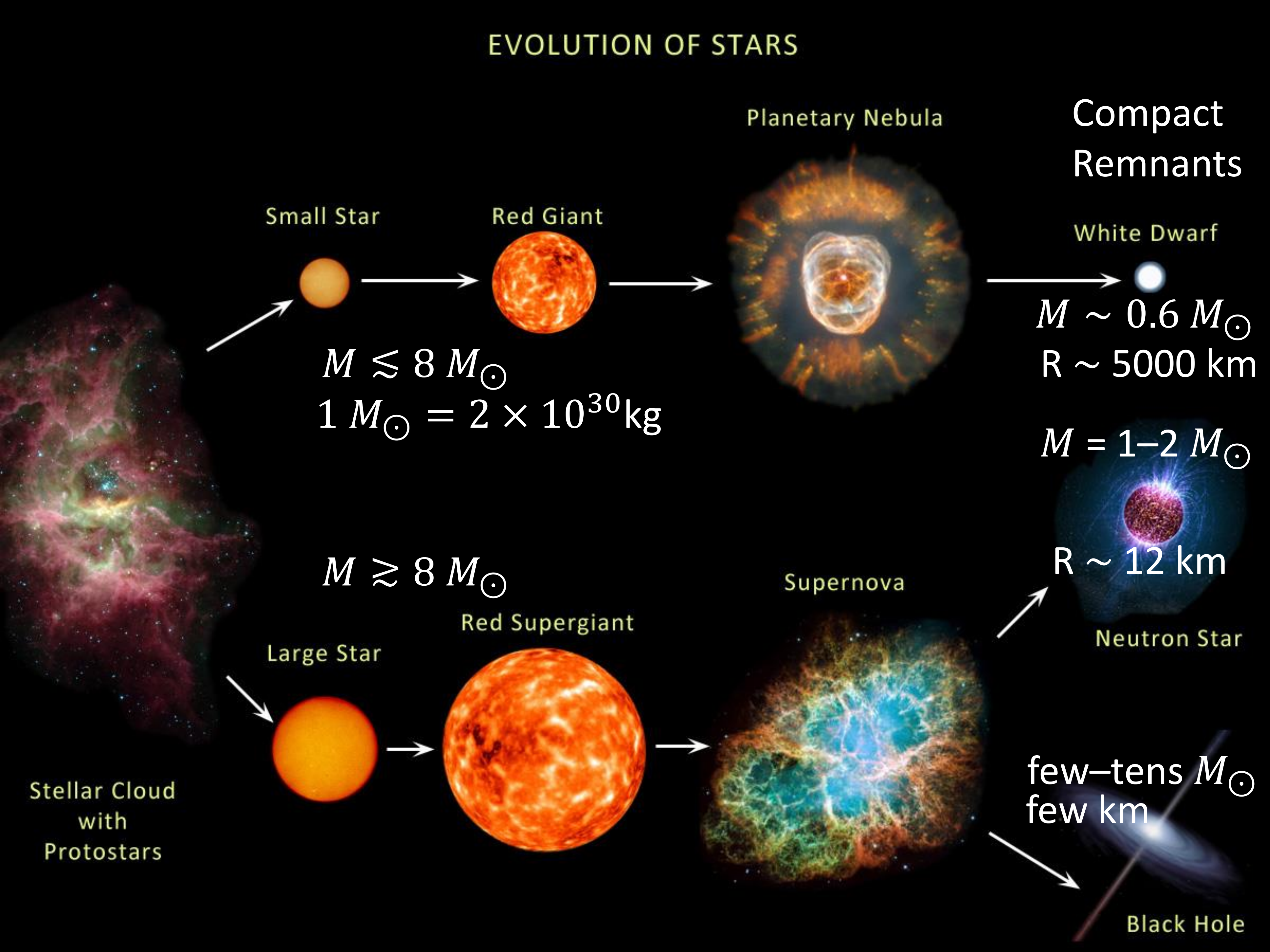
宋史志卷九



# EVOLUTION OF STARS

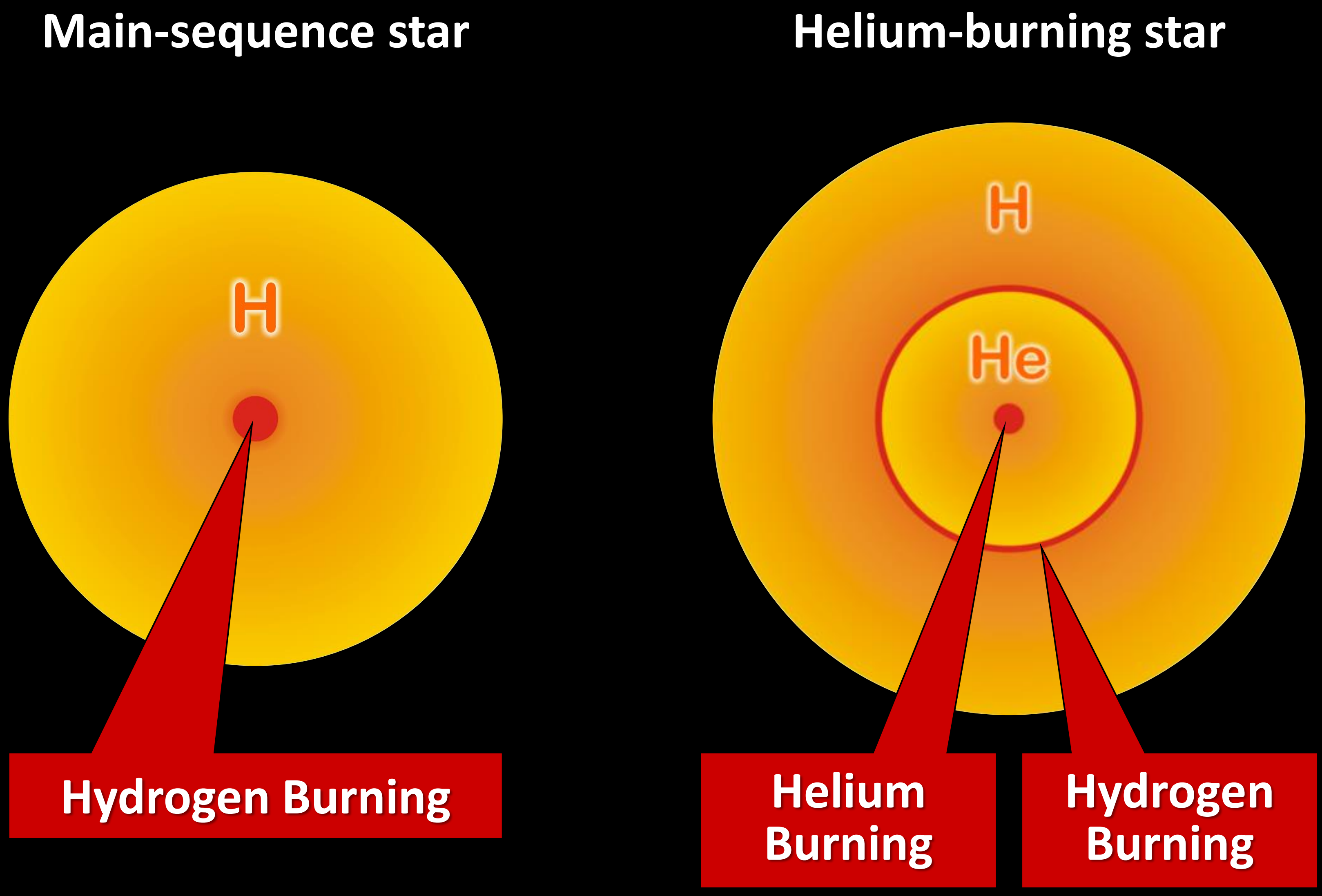



http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html



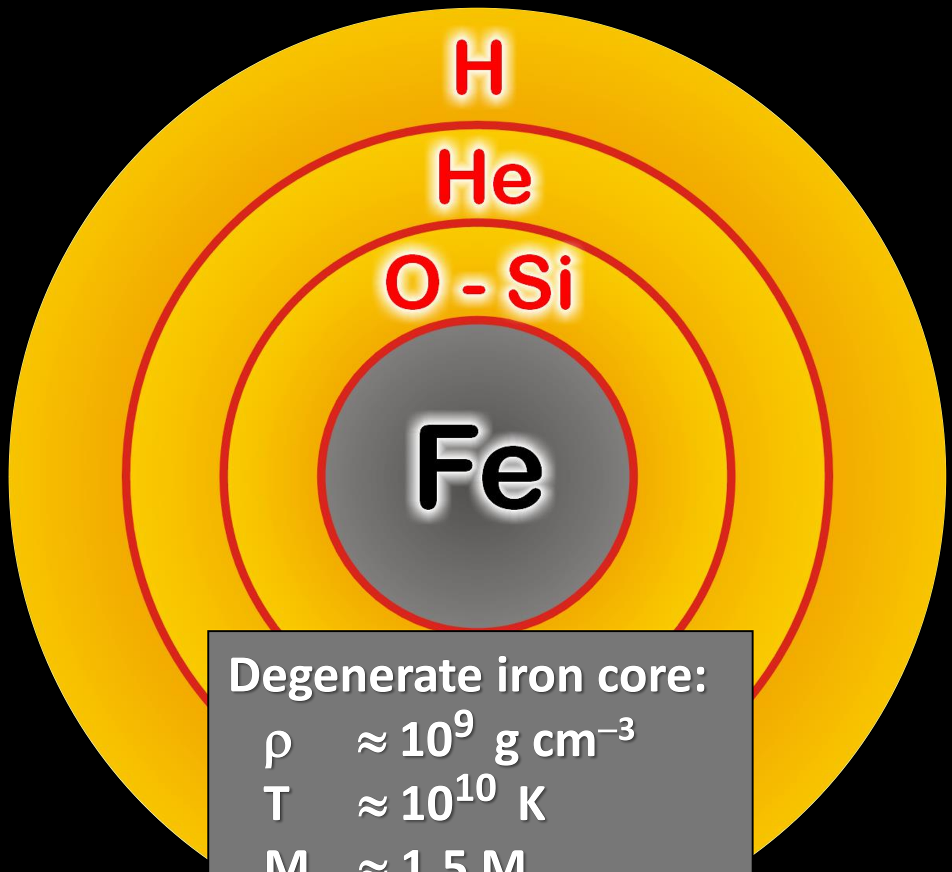
EVOLUTION OF STARS
Compact Remnants
Planetary Nebula
Small Star
Red Giant
White Dwarf
$M \sim 0.6\ M_\odot$
R ~ 5000 km
$M \lesssim 8\ M_\odot$
$1\ M_\odot = 2 \times 10^{30}$kg
$M$ = 1–2 $M_\odot$
R ~ 12 km
$M \gtrsim 8\ M_\odot$
Supernova
Red Supergiant
Large Star
Neutron Star
few–tens $M_\odot$
few km
Stellar Cloud with Protostars
Black Hole

# Stellar Collapse and Supernova Explosion



# Stellar Collapse and Supernova Explosion

## Onion structure




**Degenerate iron core:**

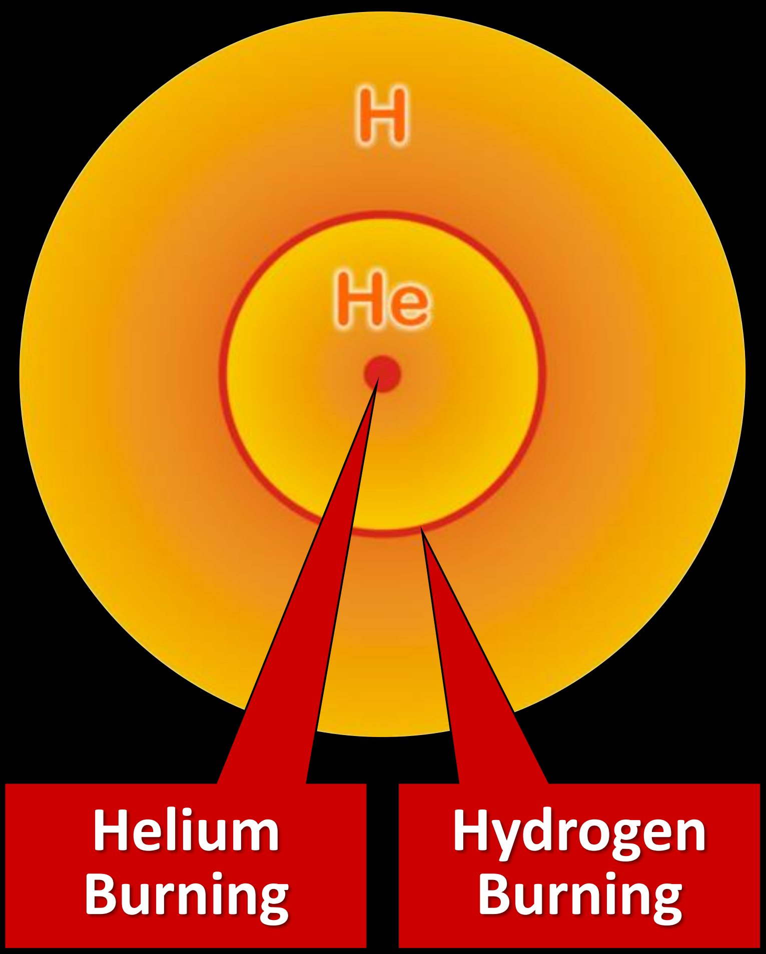
$\rho \approx 10^9$ g cm$^{-3}$

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

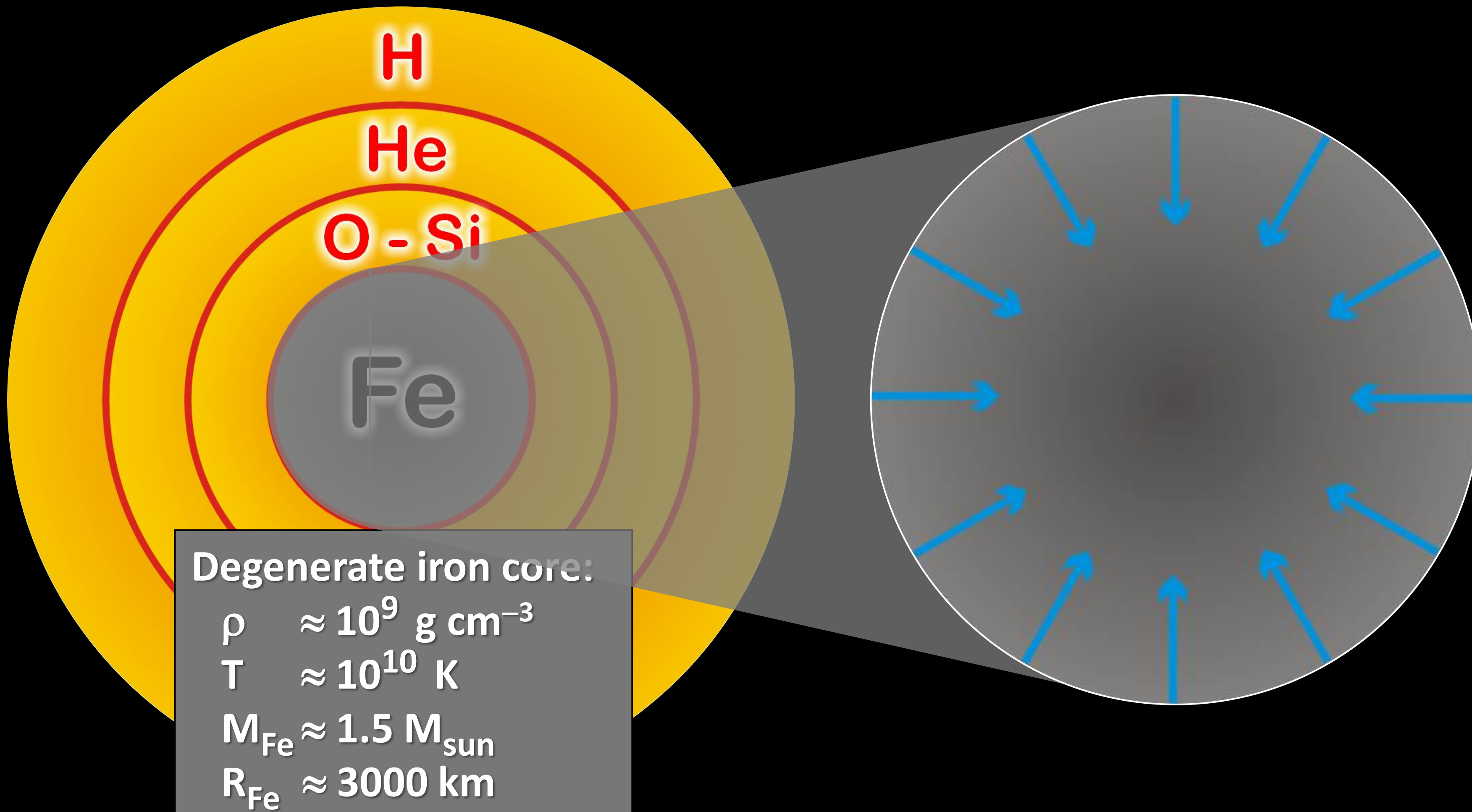
$R_{Fe} \approx 3000$ km

## Helium-burning star



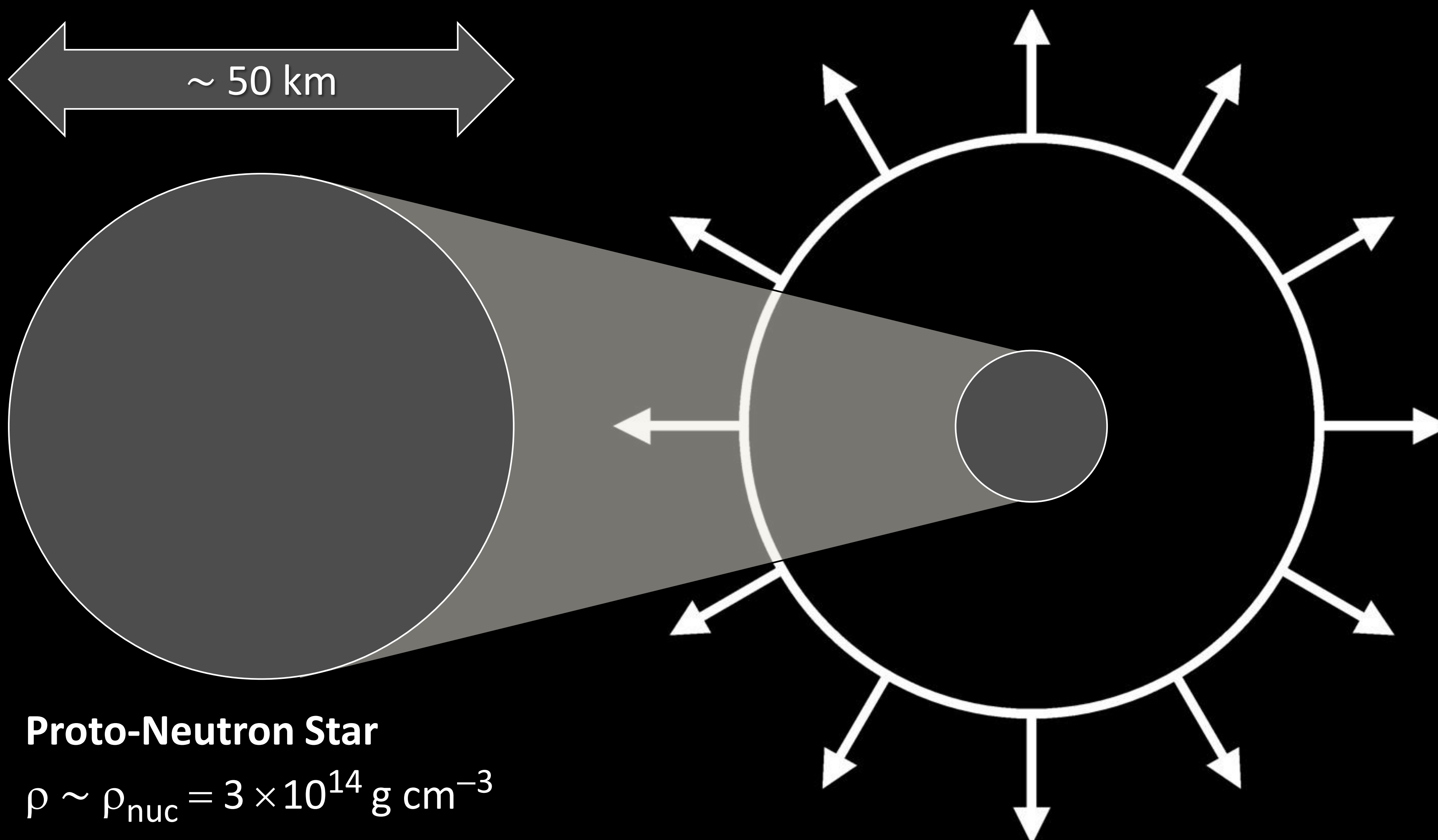
# Stellar Collapse and Supernova Explosion

**Onion structure** | **Collapse (implosion)**



# Stellar Collapse and Supernova Explosion

**Newborn Neutron Star** | **Explosion**



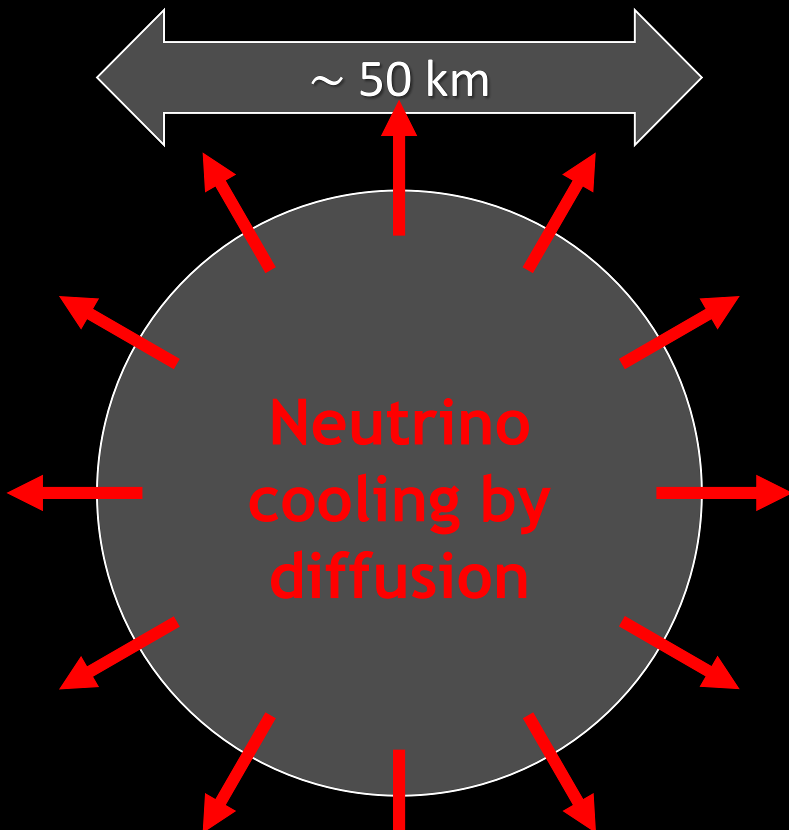

**Proto-Neutron Star**

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

$T \sim 10\ \mathrm{MeV}$

# Stellar Collapse and Supernova Explosion

**Newborn Neutron Star**




**Proto-Neutron Star**

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

$T \sim 10$ MeV

Gravitational binding energy

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

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

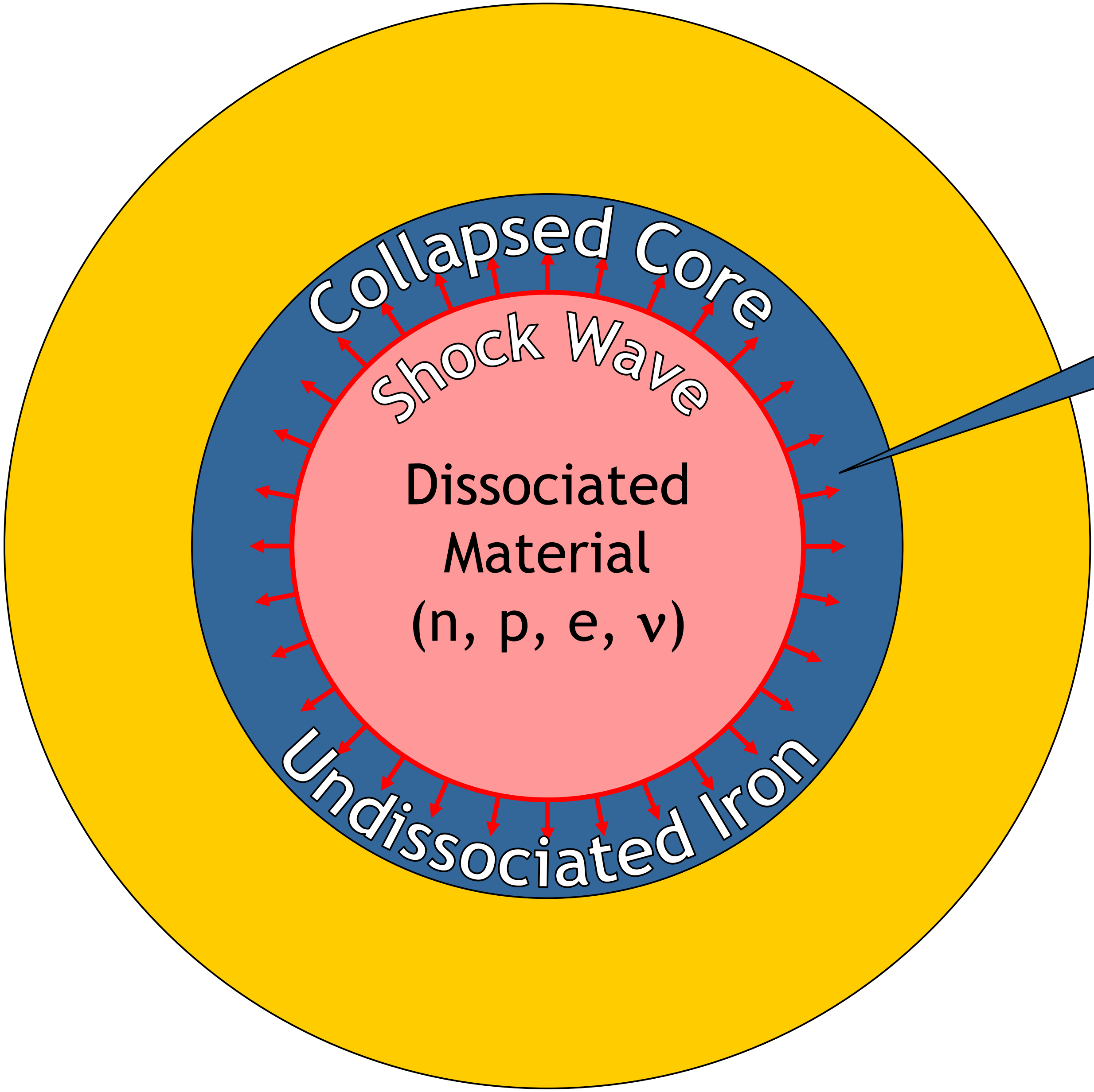
0.01% Photons, outshine host galaxy

Neutrino luminosity

$$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$$
$$\sim 3 \times 10^{19}\ L_{SUN}$$

While it lasts, outshines the entire visible universe

# Why No Prompt Explosion?



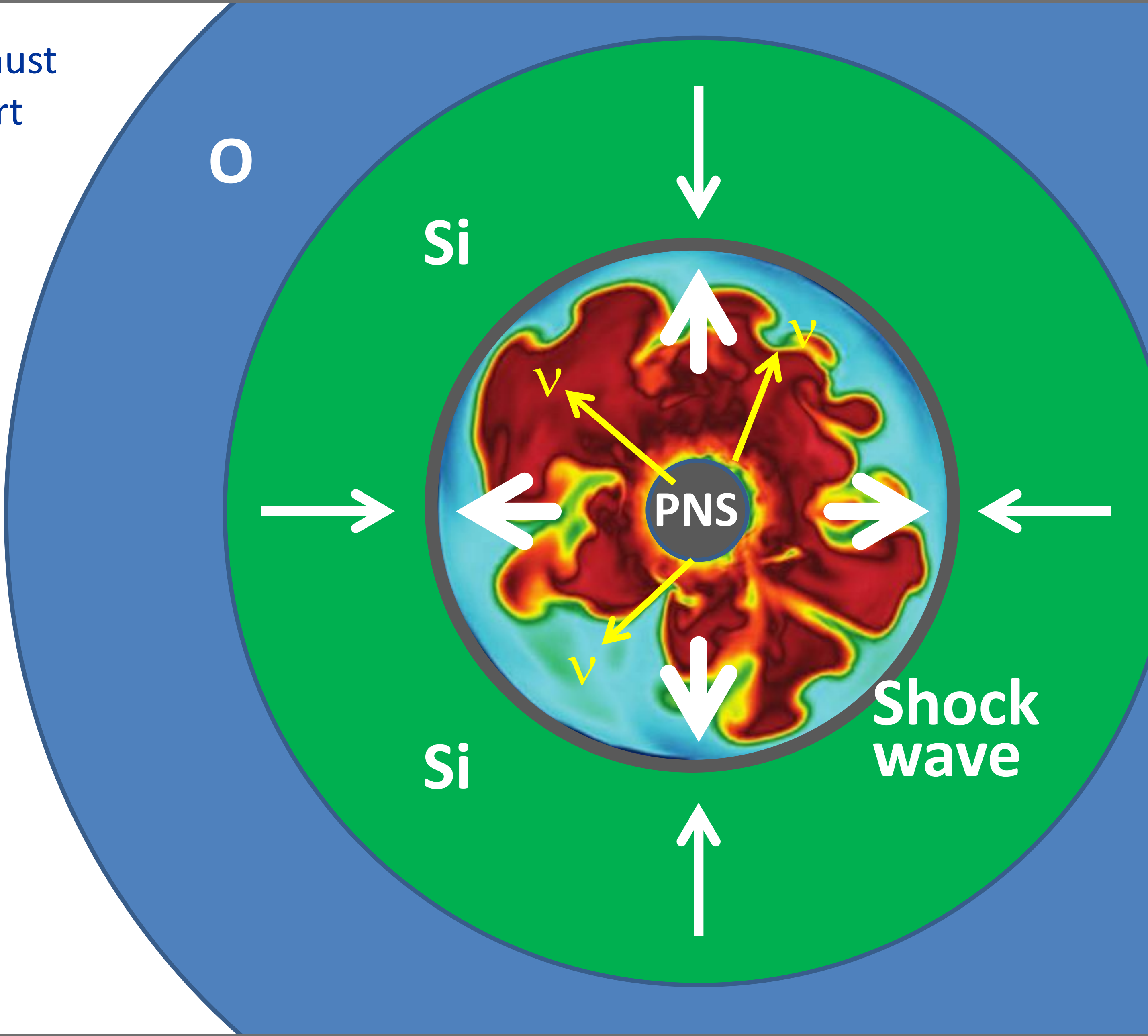

- 0.1 $M_{sun}$ of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

- **Shock wave forms within the iron core**
- **Dissipates its energy by dissociating the remaining layer of iron**

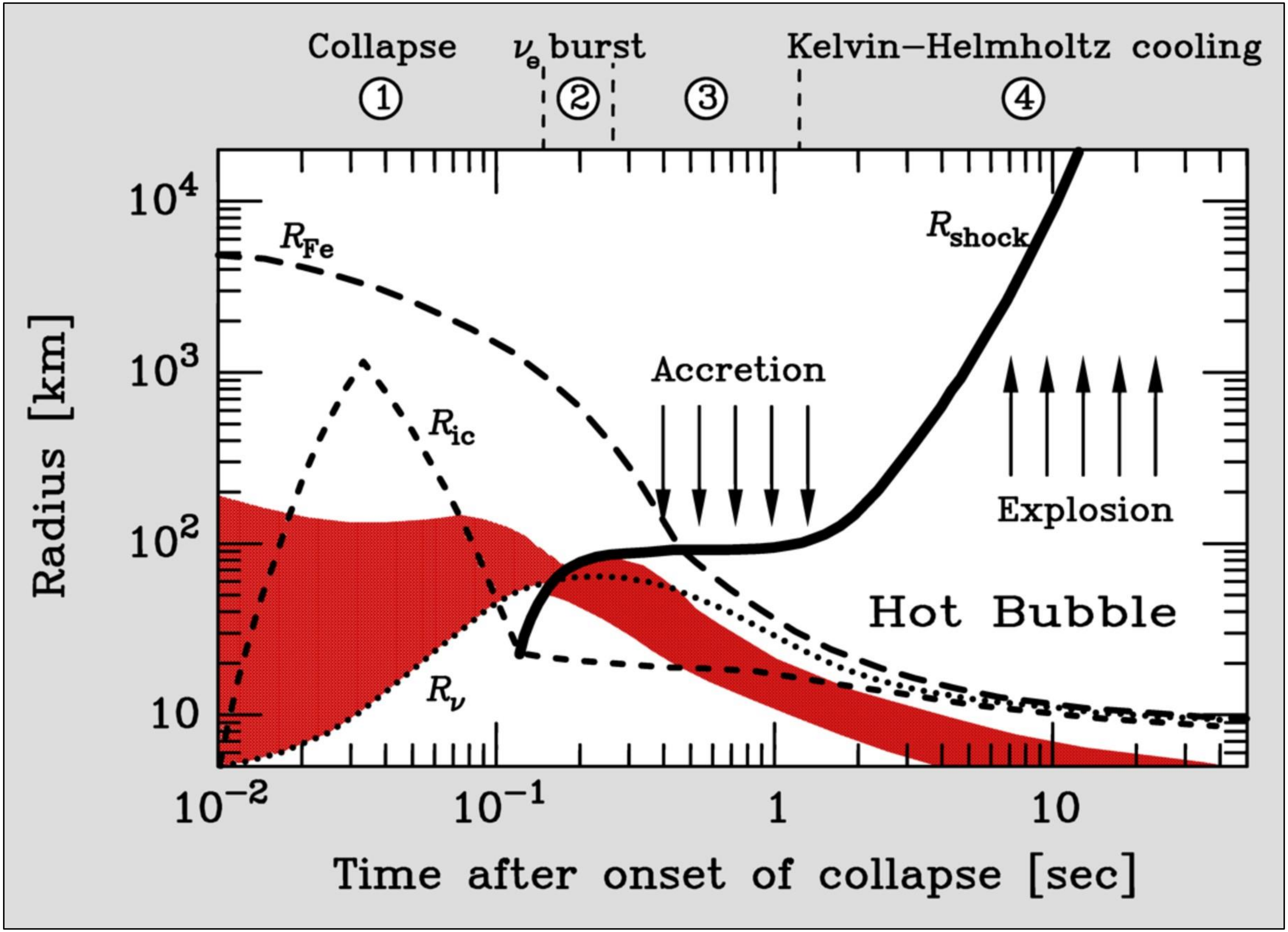
# Shock Revival by Neutrinos

Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

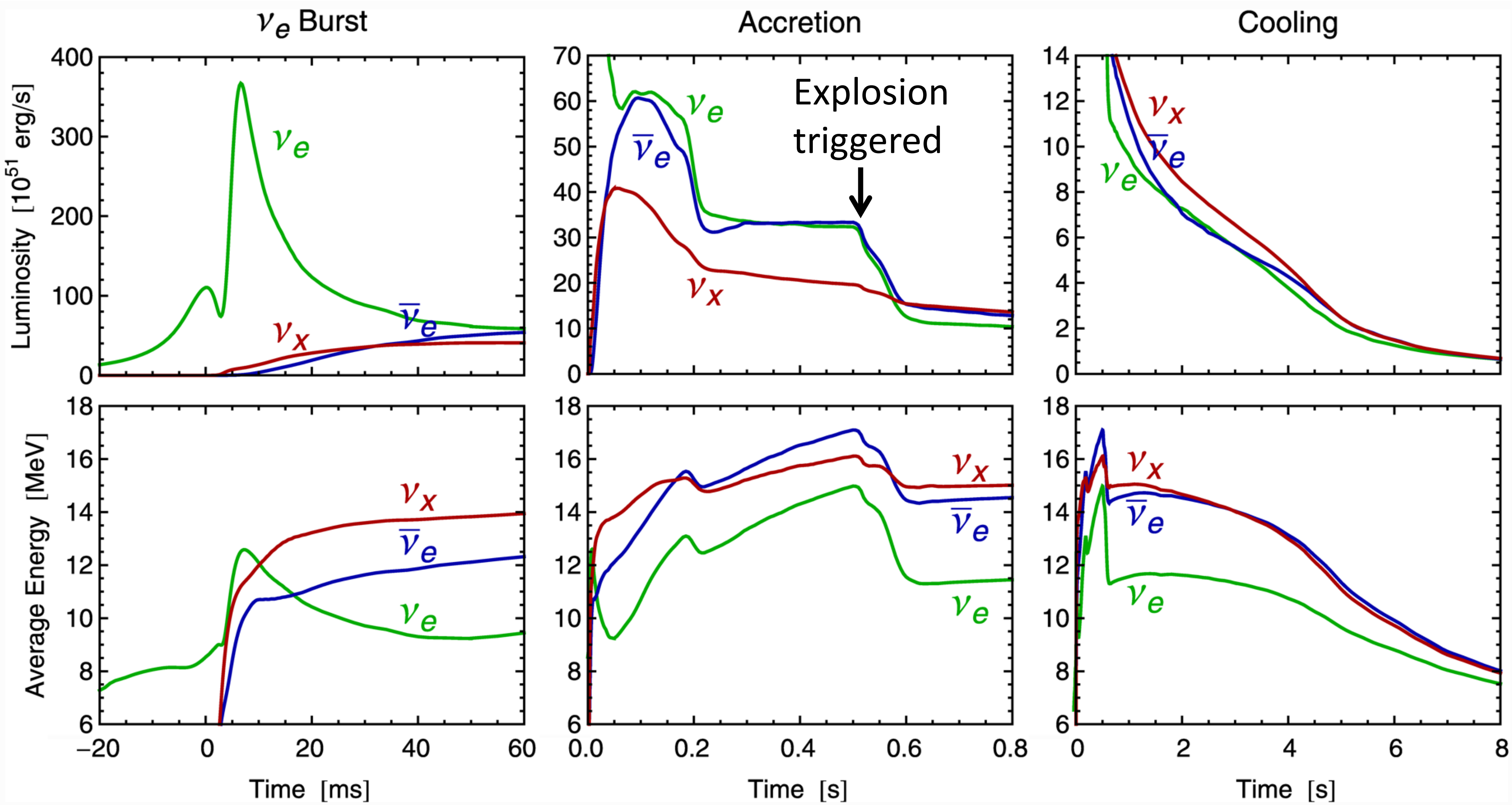
**Shock can receive fresh energy from neutrinos!**



# Supernova Delayed Explosion Scenario



# Three Phases of Neutrino Emission



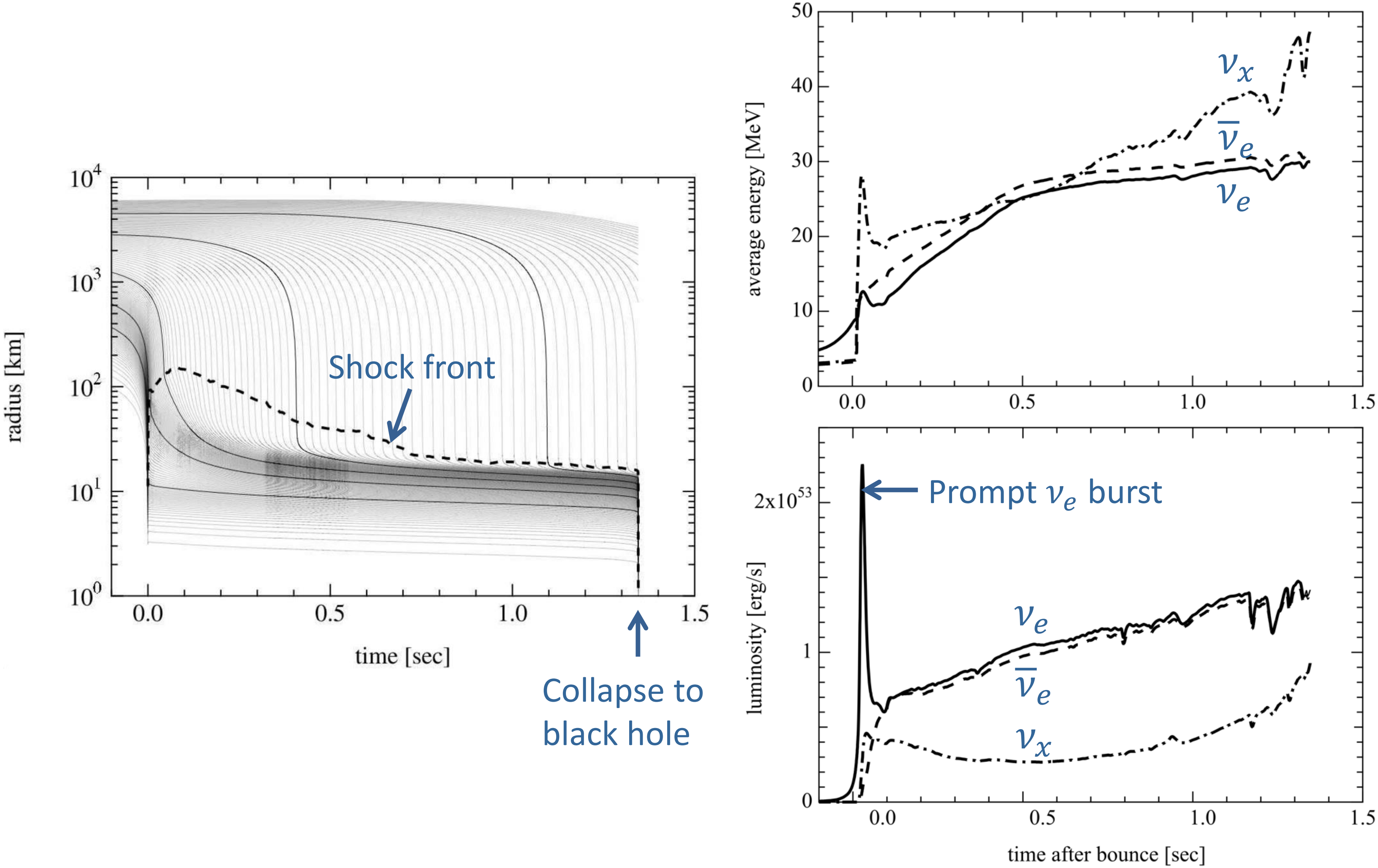

- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

**Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport**

# Neutrino Signal of a Failed Supernova (40 $M_{SUN}$)




Sumiyoshi, Yamada & Suzuki, arXiv:0706.3762

# What is an x-neutrino?

SN core: Large trapped e-lepton number (many electrons & electron neutrinos)
No trapped muon or tau lepton number

Typical interactions inside a SN core:

- Charged current $\nu_e + n \leftrightarrow p + e^-$ or $\overline{\nu}_e + p \leftrightarrow n + e^+$
- Neutral current $\nu_\tau + N \leftrightarrow N + \nu_\tau$ etc.,
  approx. same for $\nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau = \nu_x$
  (but weak magnetism distinguishes
  eg $\nu_\tau + N \leftrightarrow N + \nu_\tau$ and $\overline{\nu}_\tau + N \leftrightarrow N + \overline{\nu}_\tau$)

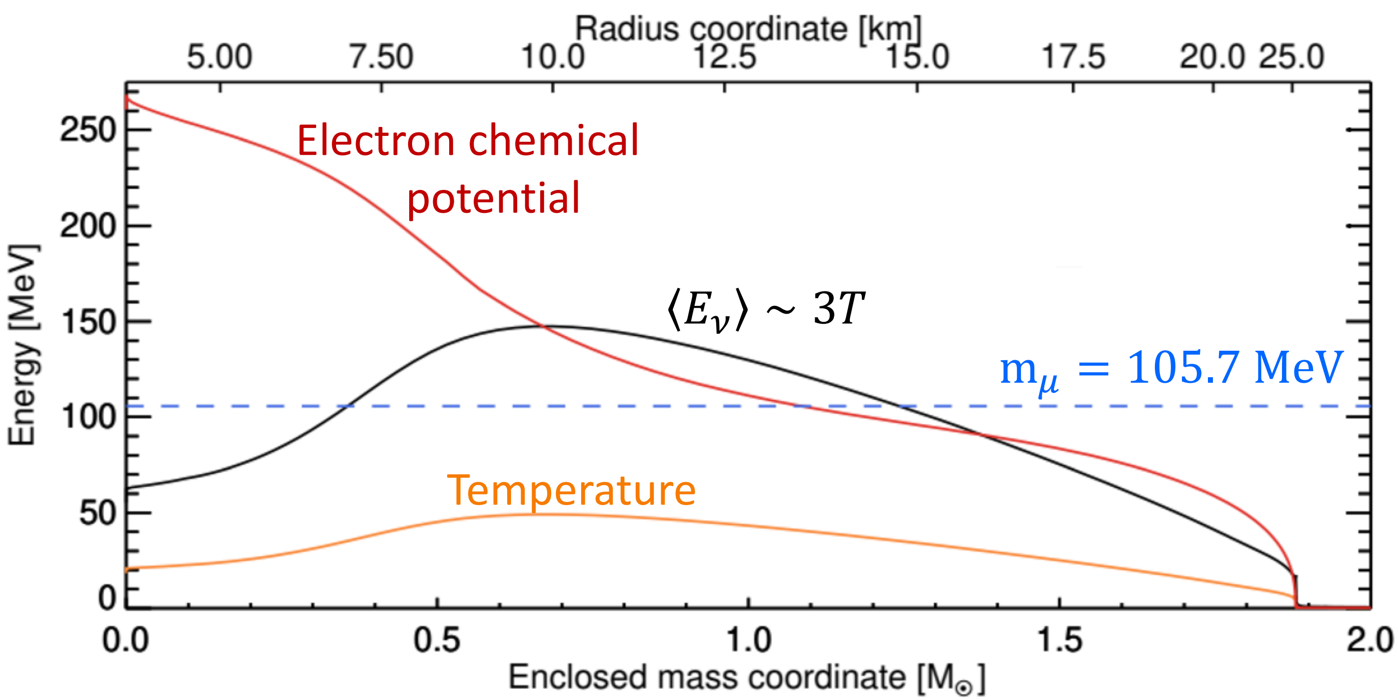
- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$
- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{or } \bar{\nu}_\tau)$
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

**Traditional SN simulations:**
Three-species neutrino transport of $\nu_e, \overline{\nu}_e, \nu_x$ (representing any of $\nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau$)
Neutrino transport the numerically expensive part of SN simulations!

**Flavor oscillations:**
Typically studied in 2-flavor limit
(But anyway not included in numerical SN simulations)

# Muonisation of a Supernova Core

- Muon production energetically favored $(m_\mu = 105.7\ \mathrm{MeV})$
- Local e-μ conversion prevented by large matter effect for ν oscillations (but BSM processes?)
- Emission of excess $\bar{\nu}_\mu$ flux builds up transient muon number density
- Emission of excess $\nu_e$ flux runs down electron lepton number (ELN)
- Requires six-species neutrino transport and muonic reactions (Robert Bollig's PhD)



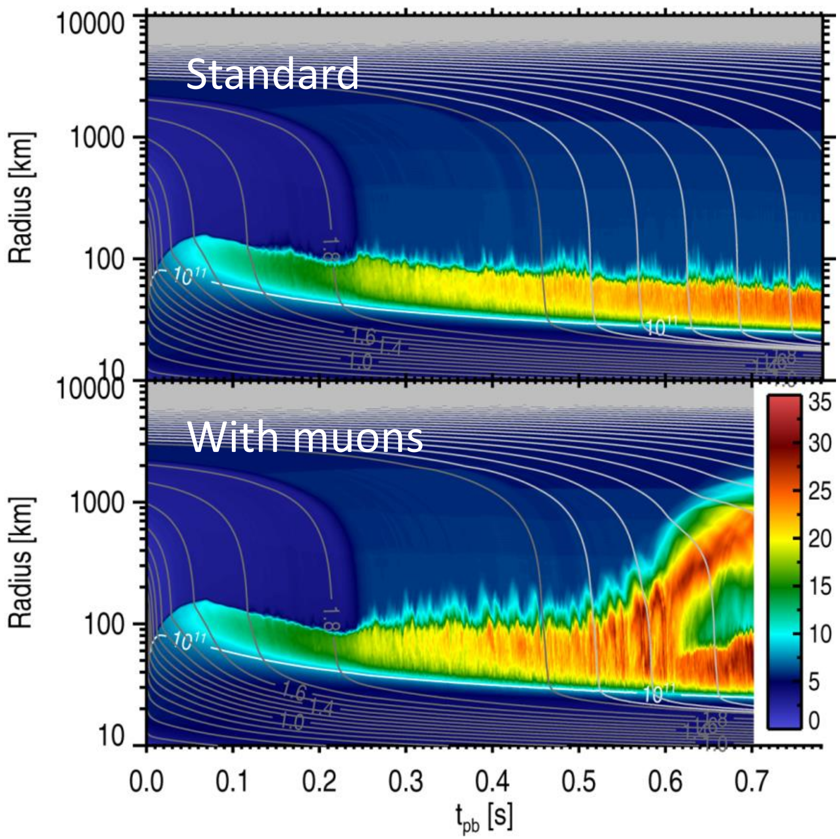

Proto neutron star (PNS) profile
350 ms postbounce

PRL 119, 242702 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

# Muon Creation in Supernova Matter Facilitates Neutrino-Driven Explosions

R. Bollig,[1,2] H.-T. Janka,[1] A. Lohs,[3] G. Martínez-Pinedo,[3,4] C. J. Horowitz,[5] and T. Melson[1]

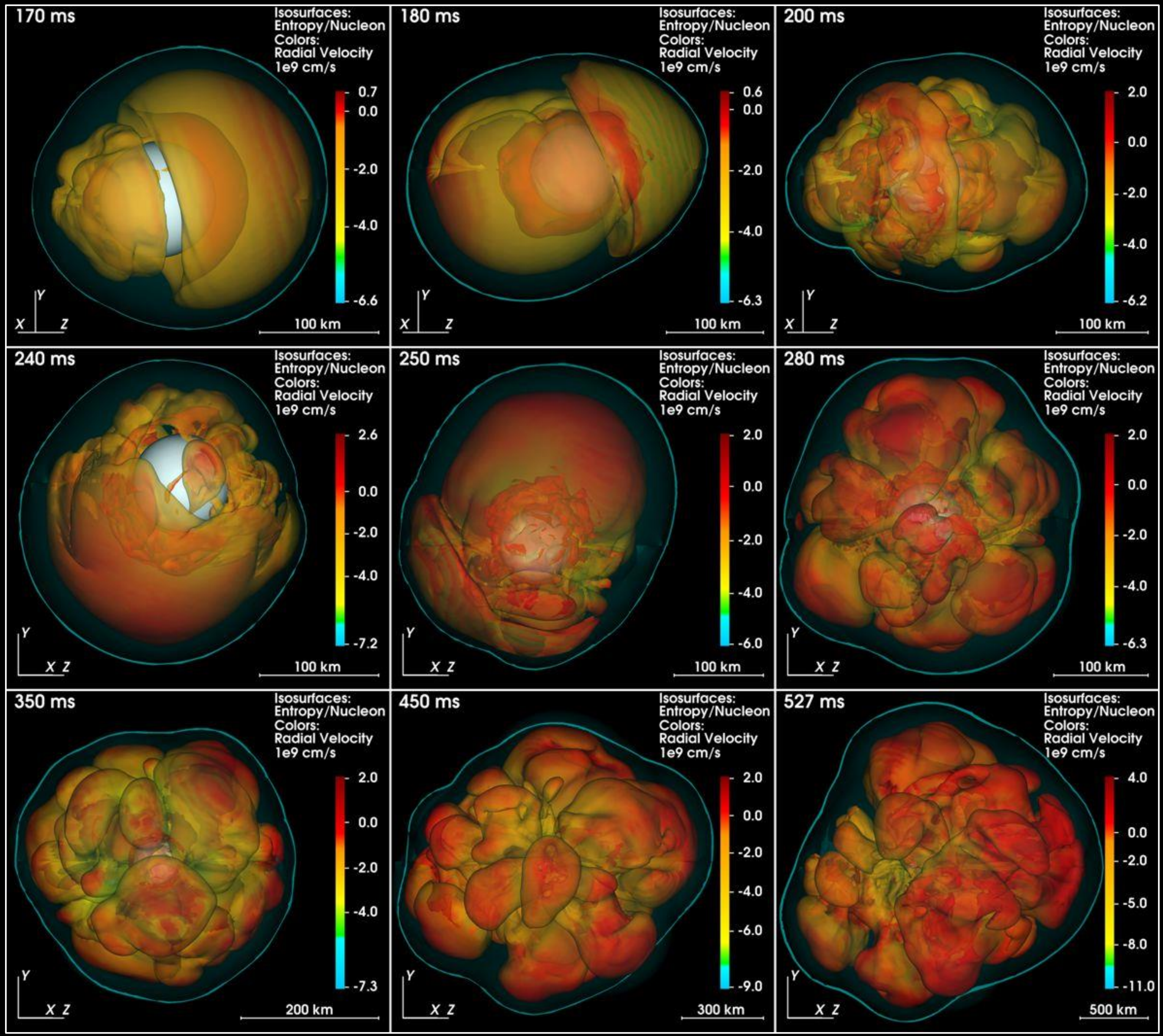
Average entropy/nucleon (2D model)




## Muons

- Facilitate neutrino-driven explosion
- Affect compactness of hot NSs
- Change neutrino emission
- May affect ν oscillations / nucleosynthesis
- Affect grav. instability of hot NS → BH
- Should be included in SN and NS-NS/BH merger simulations
- Require six-species neutrino transport with coupling of different flavors

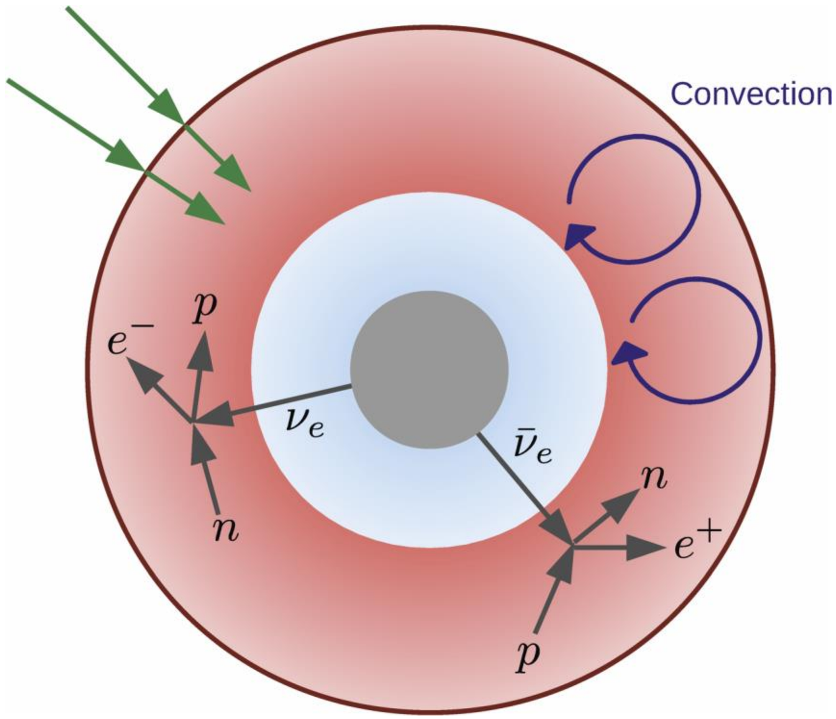
# Breaking Spherical Symmetry (3D Effects)




Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

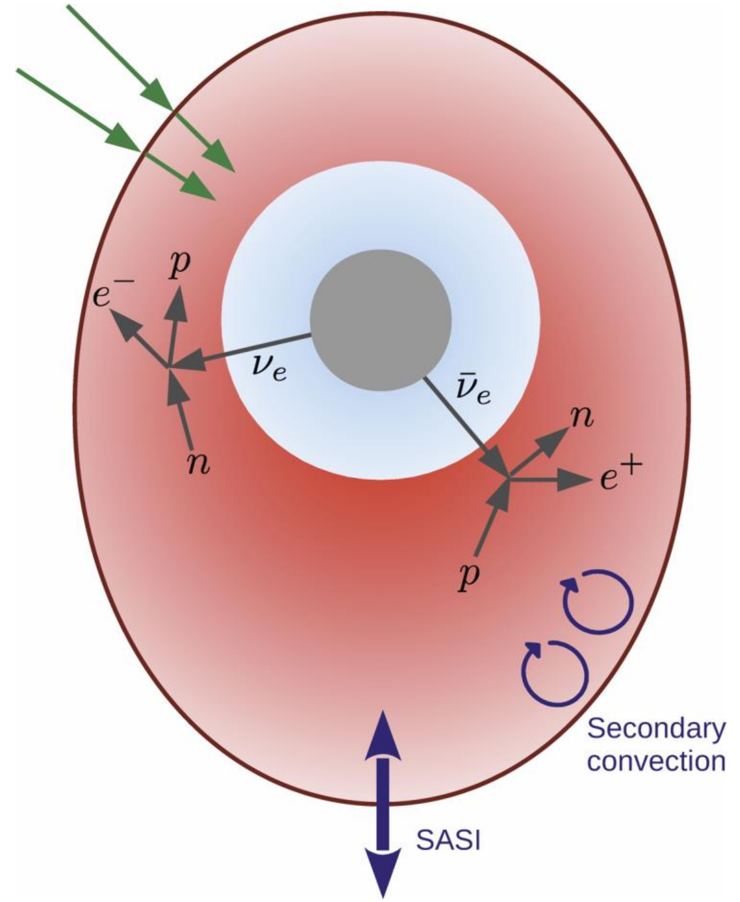
# Hydrodynamic Instabilities (3D Simulations)

## Convection




## SASI

### Standing accretion shock instability



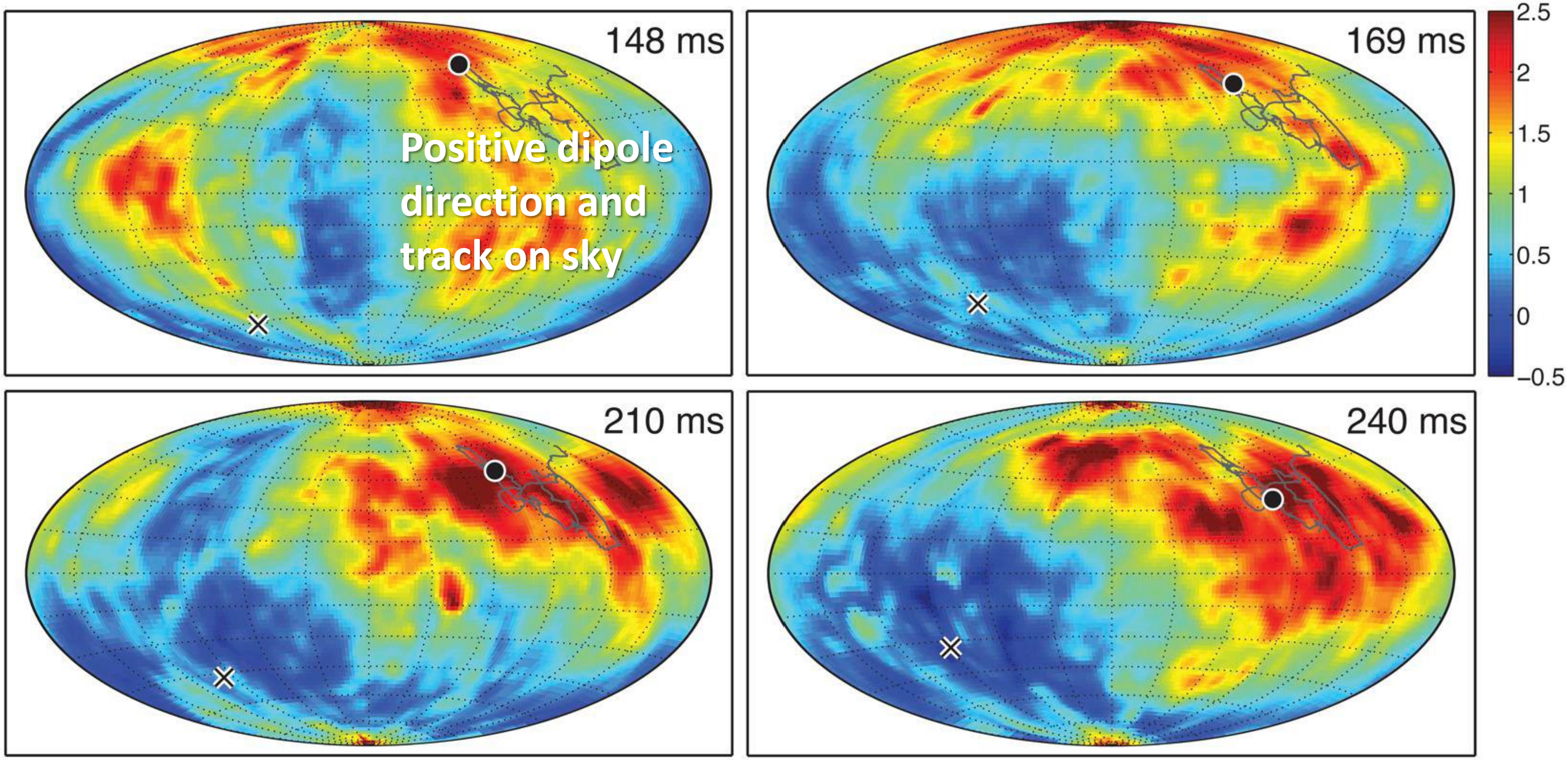

Images: Tobias Melson

**→ 3D Model of Princeton Group (YouTube)**

# LESA – A New Instability

## Lepton Emission Self-Sustained Asymmetry

**Sky map of lepton-number flux ($\nu_e - \overline{\nu}_e$) relative to 4π average (11.2 $M_{SUN}$ model)**
**Deleptonization flux into one hemisphere, roughly dipole distribution**

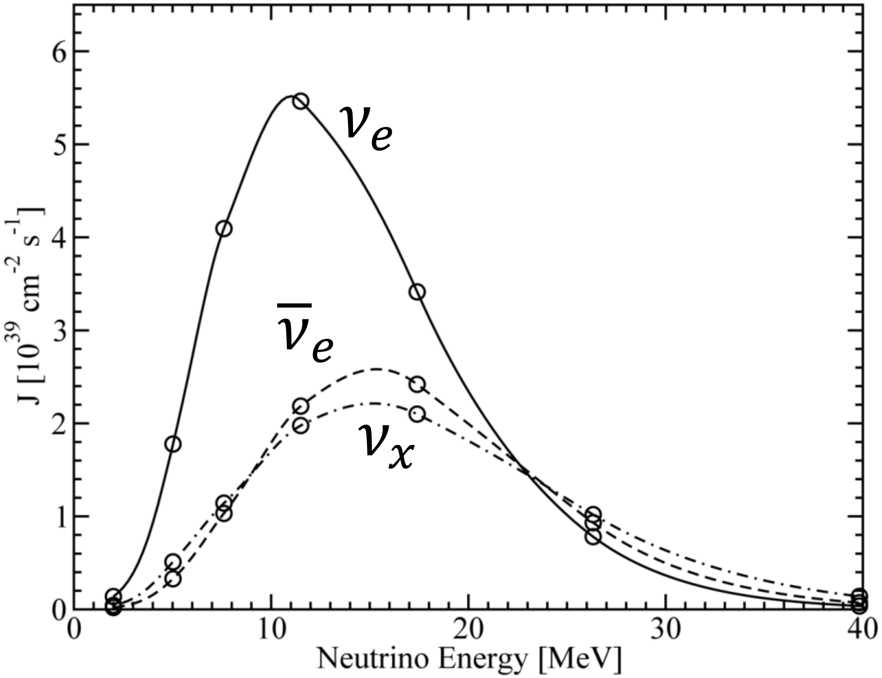



Tamborra, Hanke, Janka, Müller, Raffelt & Marek, arXiv:1402.5418

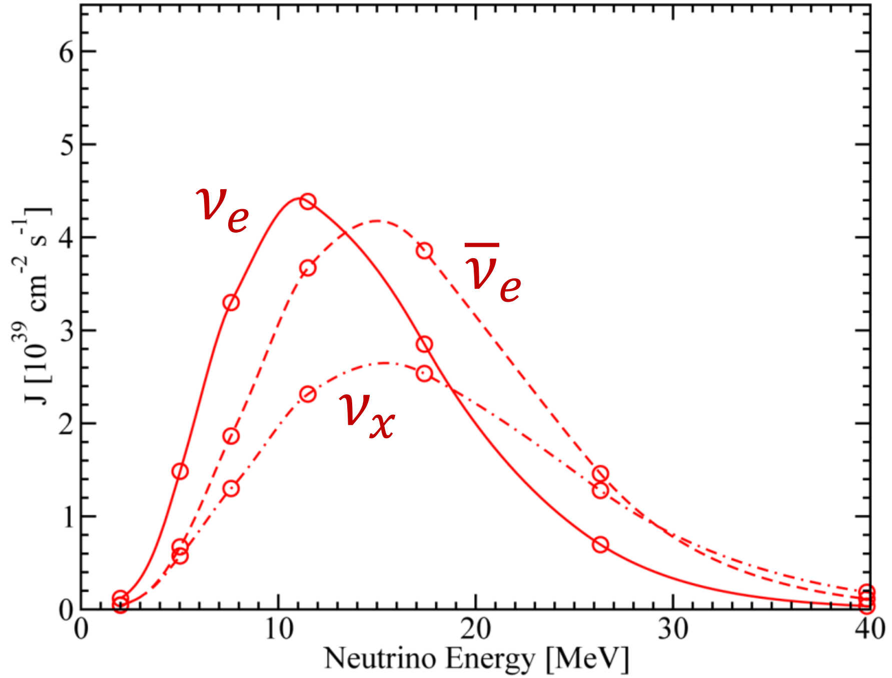
# Spectra in the two Hemispheres

**Neutrino flux spectra (11.2 $M_{SUN}$ model at 210 ms) in opposite LESA directions**

Direction of
**maximum** lepton-number flux



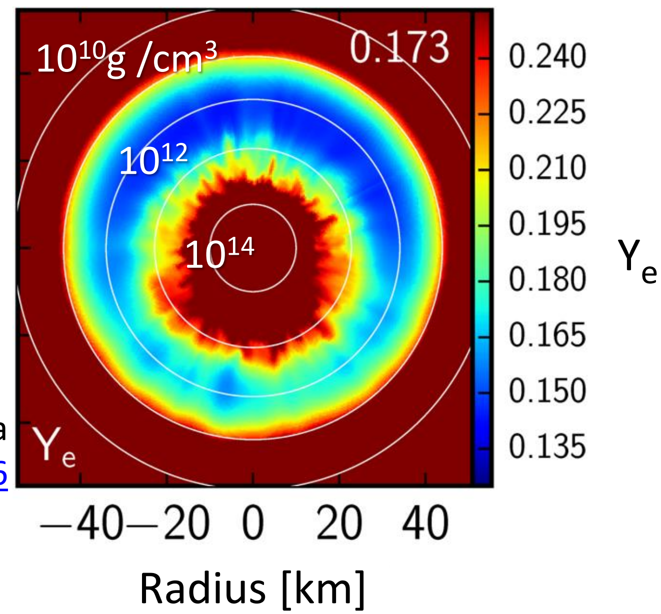

Direction of
**minimum** lepton-number flux




**During accretion phase, flavor-dependent fluxes can vary strongly with observer direction!**

# Status of LESA

- **After skeptical comments, confirmed by other groups**
- **Not an artifact of neutrino transport approximation**
  Glas, Janka, Melson, Stockinger & Just, *Effects of LESA in three-dimensional supernova simulations with multi-D and ray-by-ray-plus neutrino transport,* arXiv:1809.10146
- **Suppressed by fast rotation of progenitor**
  Walk, Tamborra, Janka & Summa, *Effects of SASI and LESA in the neutrino emission of rotating supernovae,* arXiv:1901.06235
- **LESA is a consequence of asymmetric proto-neutron star (PNS) convection**
- **But not yet a simple explanation ("in 25 words or less")**




Janka, Melson, Summa
arXiv:1602.05576

SELF-CONSISTENT 3D SUPERNOVA MODELS FROM −7 MINUTES TO +7 SECONDS: A 1-BETHE EXPLOSION OF A ~19 $M_\odot$ PROGENITOR

ROBERT BOLLIG,[1] NAVEEN YADAV,[1,2] DANIEL KRESSE,[1,3] HANS-THOMAS JANKA,[1] BERNHARD MÜLLER,[4,5,6] AND ALEXANDER HEGER[4,5,7,8]

arXiv:2010.10506

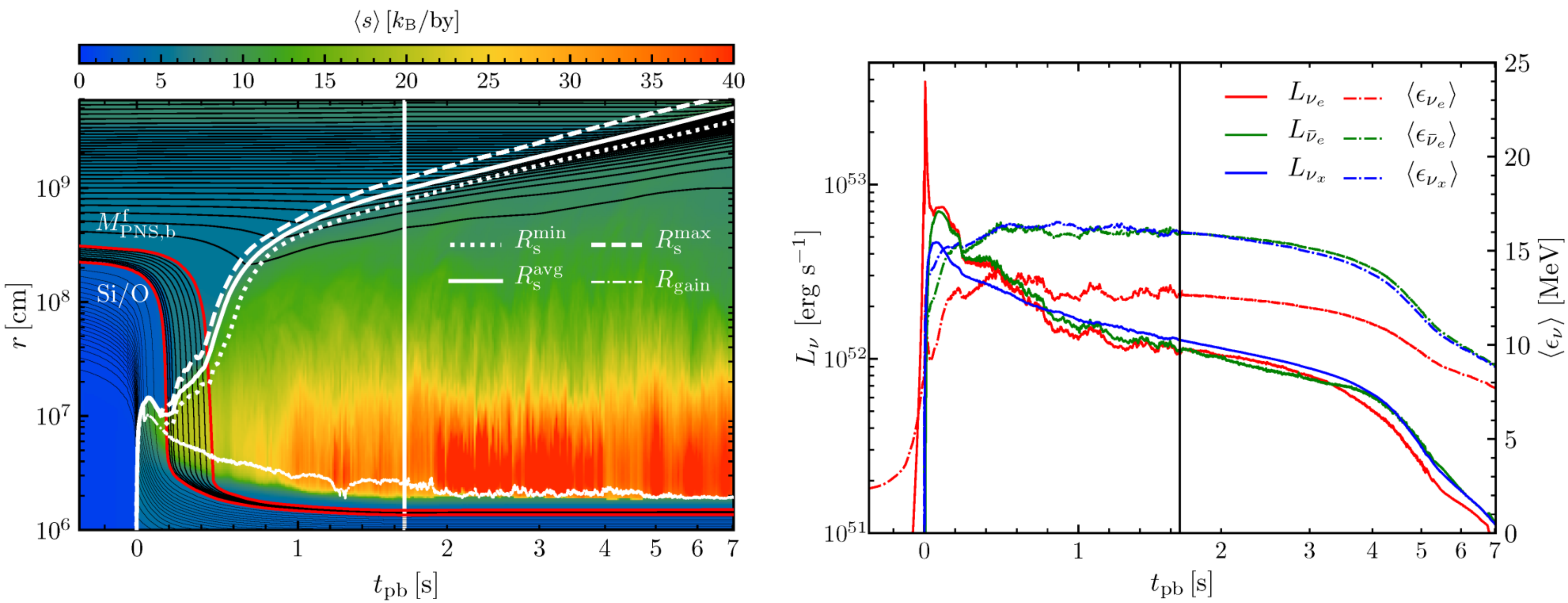



**Figure 1.** Explosion dynamics and neutrino emission of model `M_P3D_LS220_m−` and its extension `M_P3D_LS220_m−HC`. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of Si/O shell interface and final NS mass are marked. The vertical white line separates VERTEX transport (left, time linear) and HC neutrino approximation (right, time logarithmic). *Right:* Emitted luminosities and mean energies of $\nu_e$, $\bar{\nu}_e$, and a single species of heavy-lepton neutrinos. The time axis is split as in the left panel. Right of the vertical solid line we show neutrino data from the artificially exploded 1D simulation.

# Landscape of SN and BH forming core collapses

Kresse+, arXiv:2010.04728

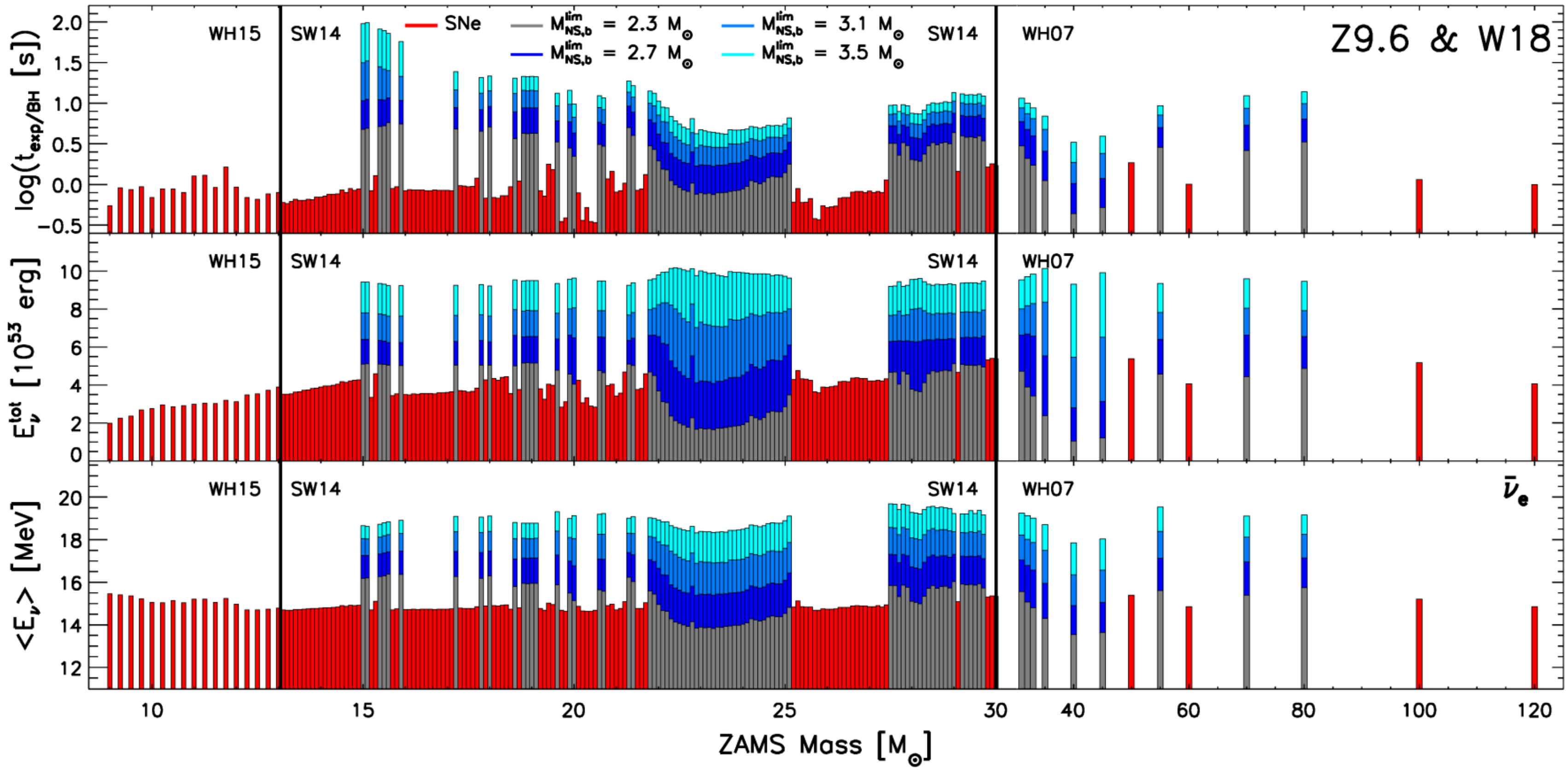



**Figure 2.** Landscape of SN and BH formation cases for the combined progenitor sets of WH15, SW14, and WH07, simulated with the neutrino engine model of Z9.6 and W18. From top to bottom: time of explosion or BH formation, total energy radiated in all species of neutrinos, and mean energy of electron antineutrinos vs. ZAMS mass of the progenitors. Note the logarithmic scale in the top panel. Red bars indicate successful SN explosions and fallback SNe, while the outcomes of BH-forming, failed SNe are shown for our different cases of baryonic NS mass limits in gray (2.3 $M_\odot$), dark blue (2.7 $M_\odot$), light blue (3.1 $M_\odot$), and cyan (3.5 $M_\odot$). The outcome of the ECSN by Hüdepohl et al. (2010) is not shown in the figure but discussed in the main text.

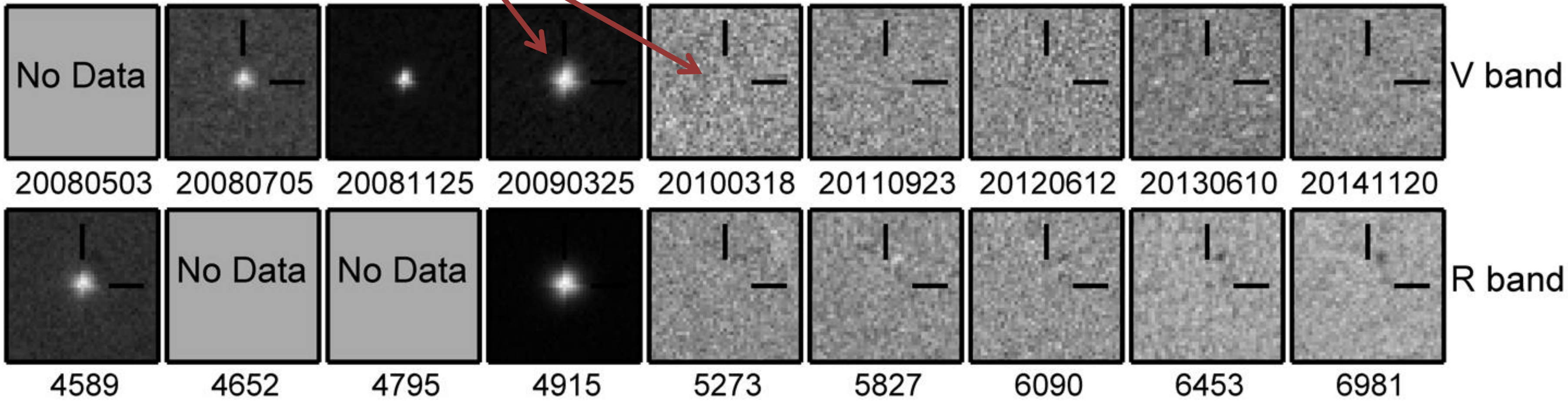
Fraction of “failed SNe” (BH forming core collapses) around 25% ?

# Death Watch of a Million Supergiants

- Monitoring 27 galaxies within 10 Mpc for many years
- Visit typically twice per year
- $10^6$ supergiants (lifetime $10^6$ years)
- Combined SN rate: about 1 per year

**First 7 years of survey:**

- 6 successful core-collapse SNe
- 1 candidate failed SN

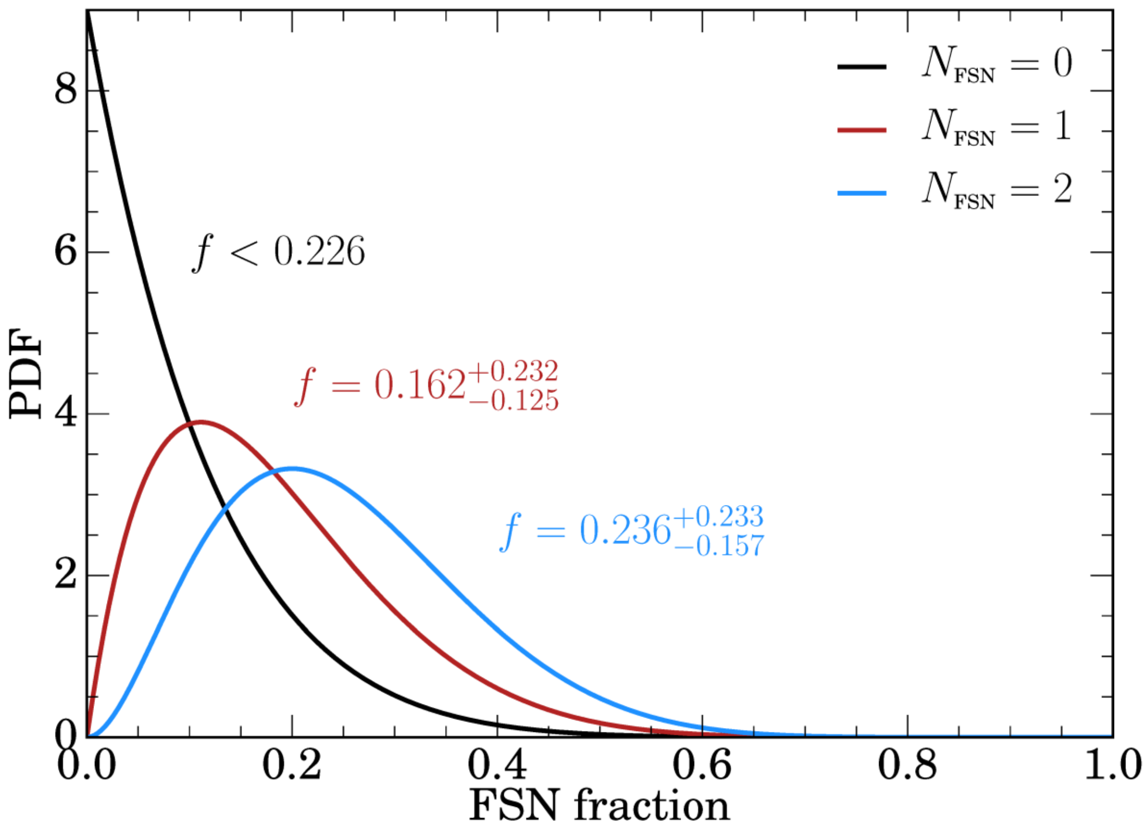

Gerke, Kochanek & Stanek, arXiv:1411.1761

Adams, Kochanek, Gerke, Stanek (& Dai), arXiv:1610.02402 (1609.01283)

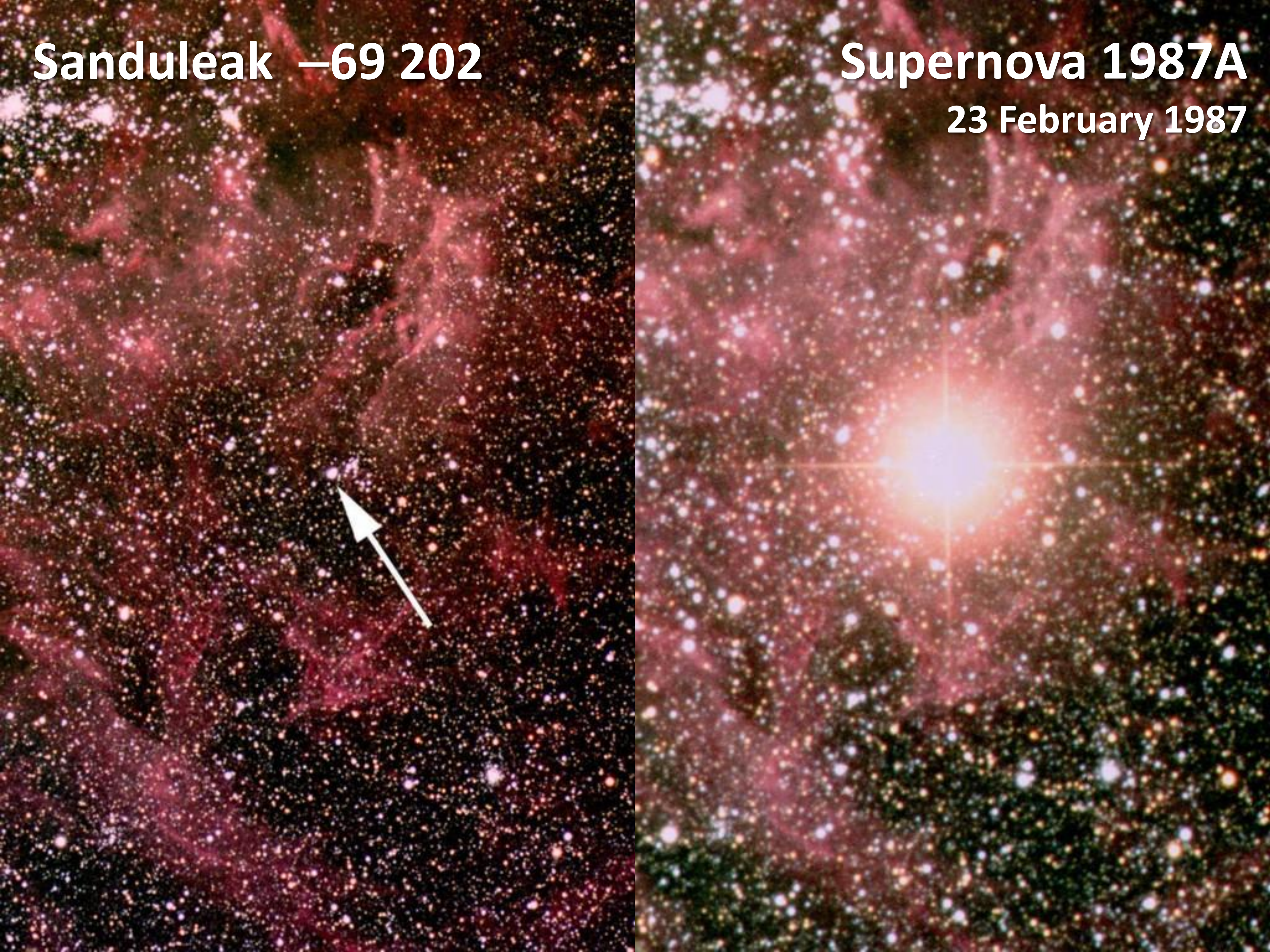
# Empirical Fraction of Black-Hole Formation

2020 update: 11 yr baseline, 8 SNe, 1 old & 1 new candidate for failed SN

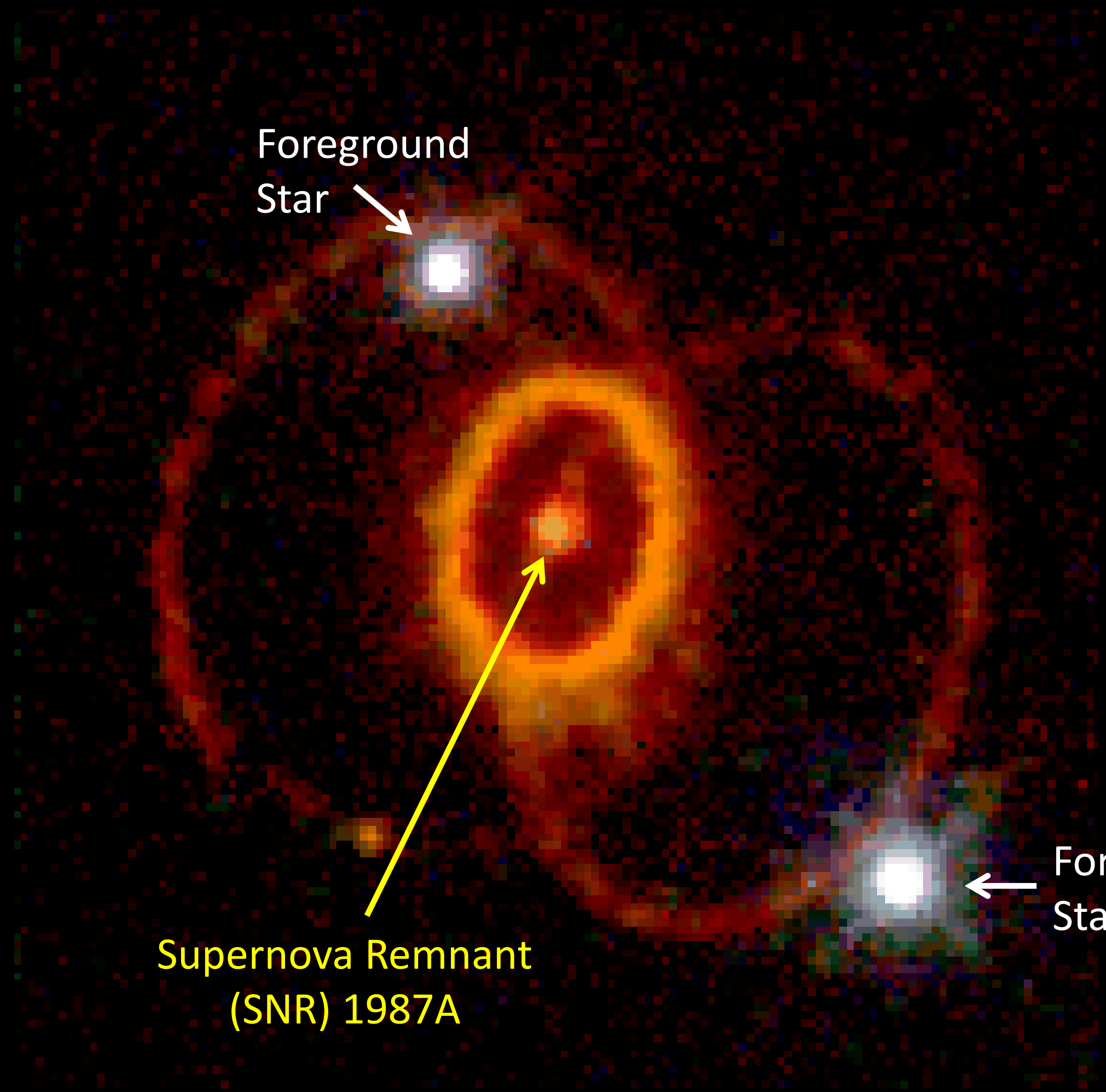
Neustadt, Kochanek, Stanek, et al., arXiv:2104.03318




Roughly a quarter of all core-collapses could lead to BH formation, in agreement with theory estimates!


Sanduleak –69 202
Supernova 1987A
23 February 1987

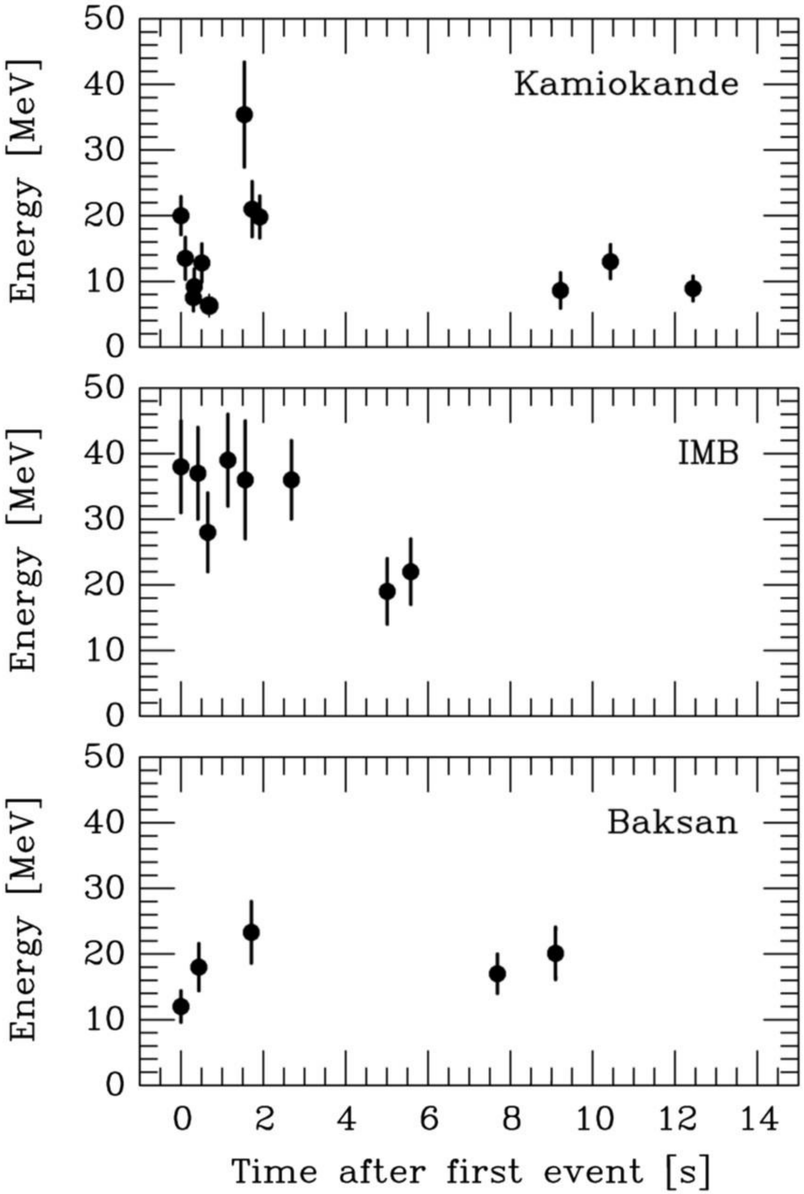
# SN 1987A Rings (Hubble Space Telescope 4/1994)





Artist's impression
http://www.eso.org/public/images/eso1032a

# Neutrino Signal of Supernova 1987A



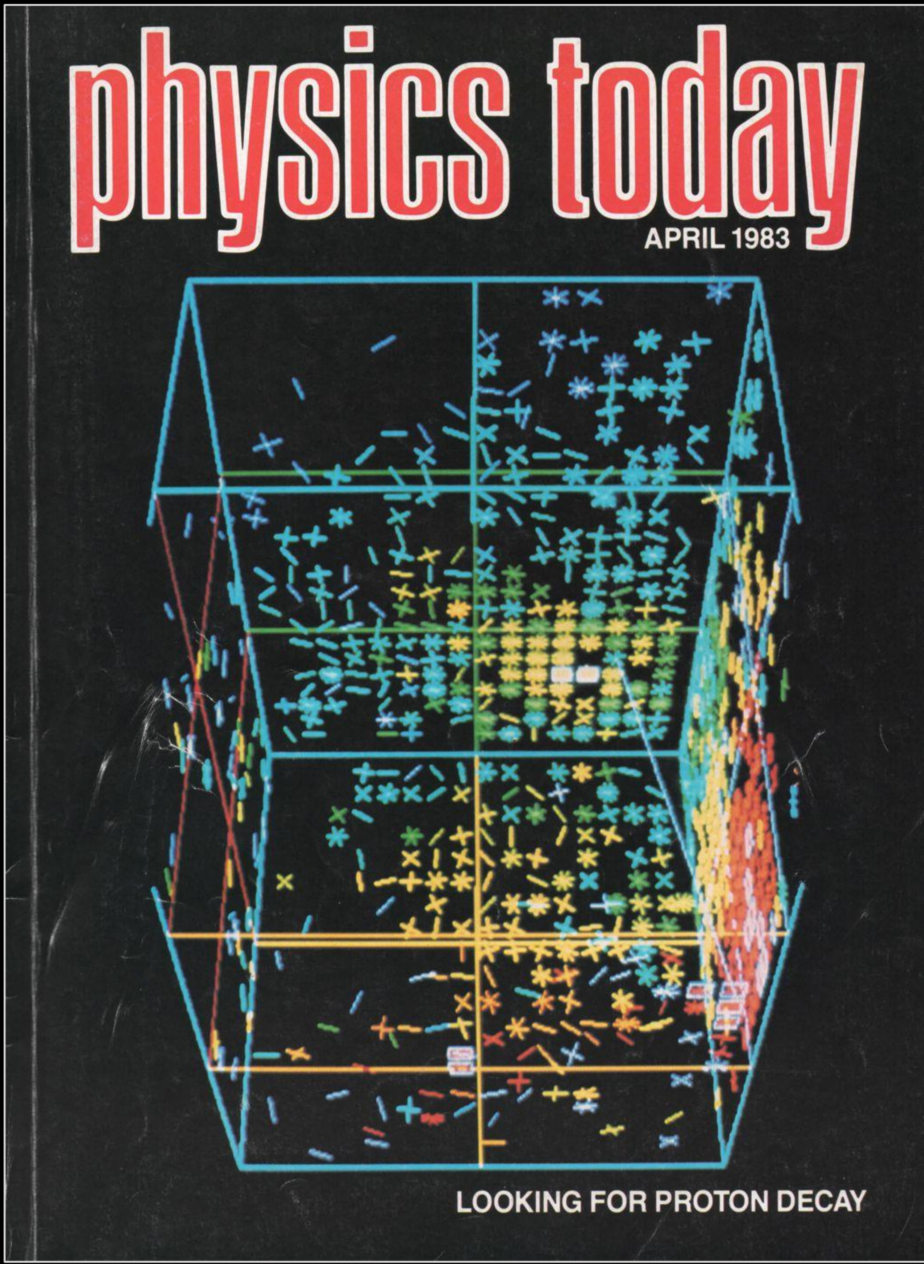

Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty $\pm$50 ms

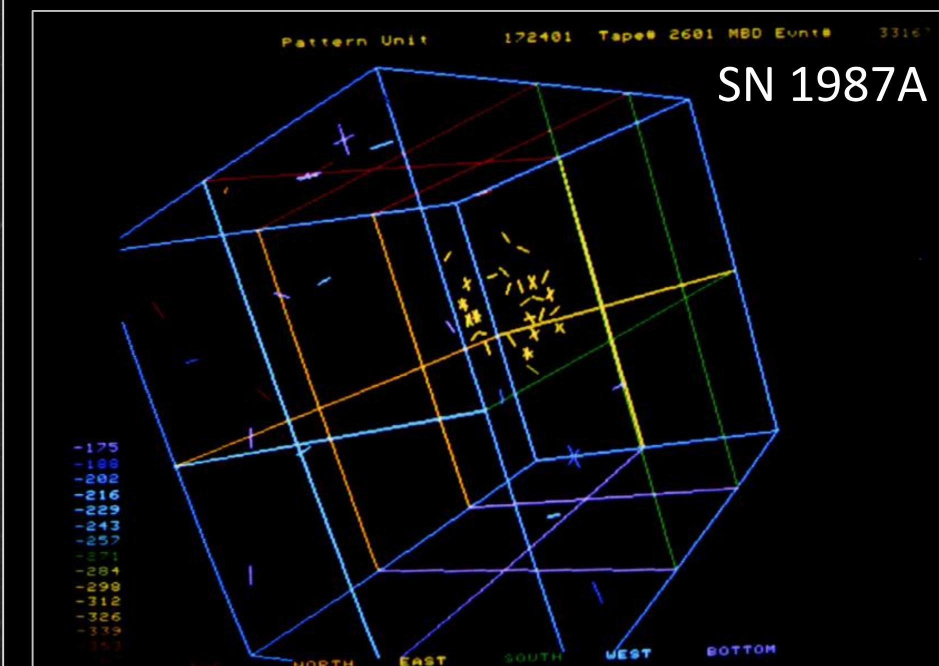
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster $\sim$ 0.7/day
Clock uncertainty +2/–54 s

**Within clock uncertainties, all signals are contemporaneous**

# Irvine-Michigan-Brookhaven (IMB) Detector

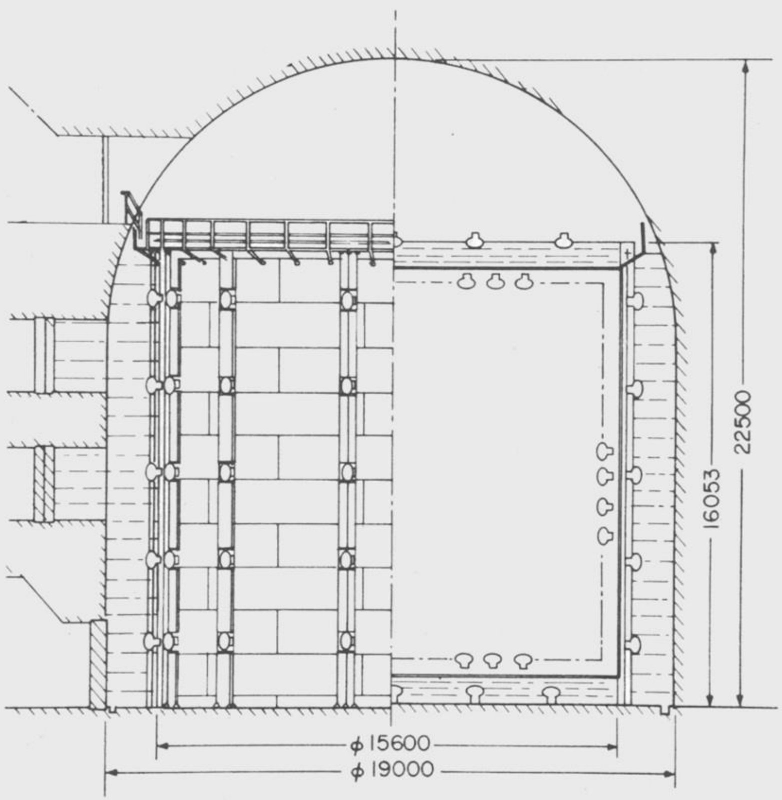




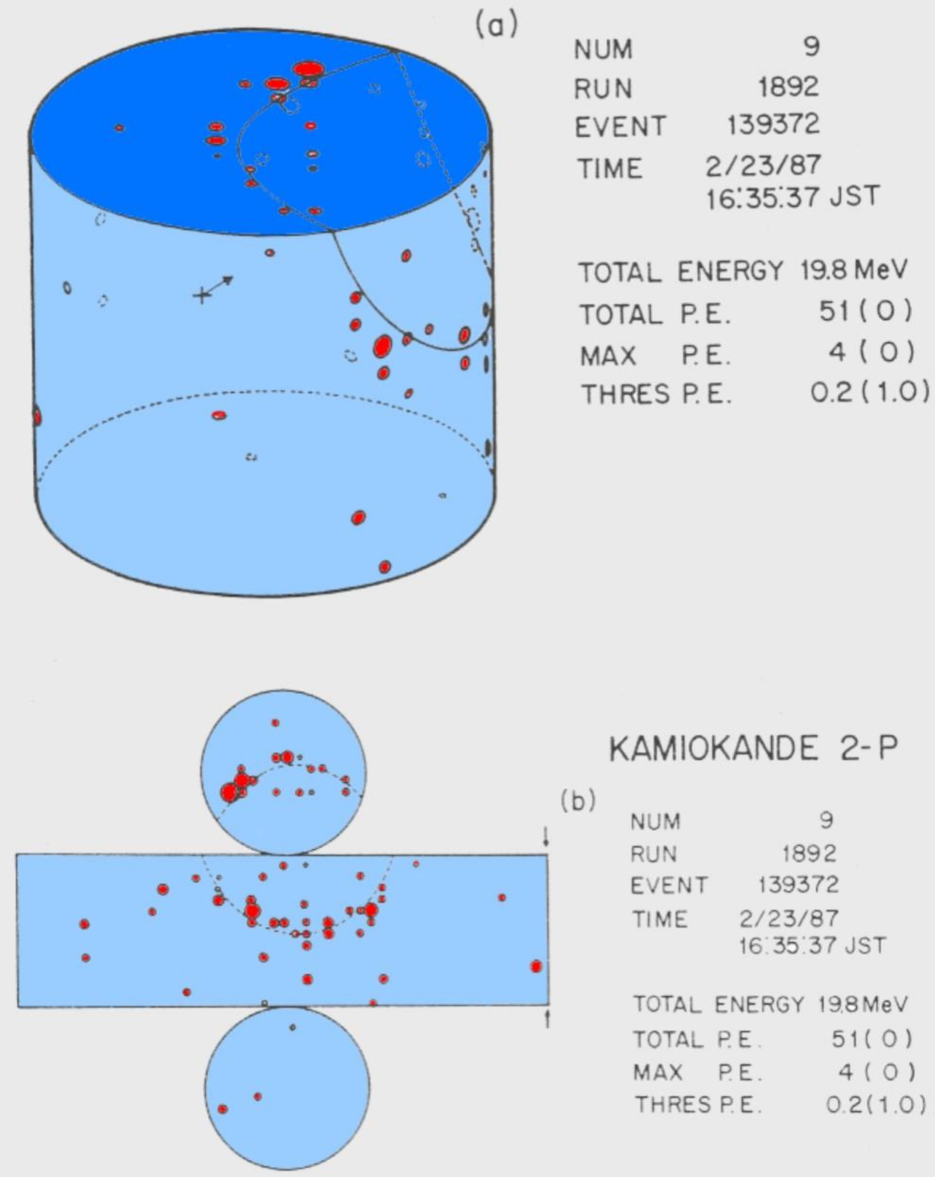


# SN 1987A Event No.9 in Kamiokande

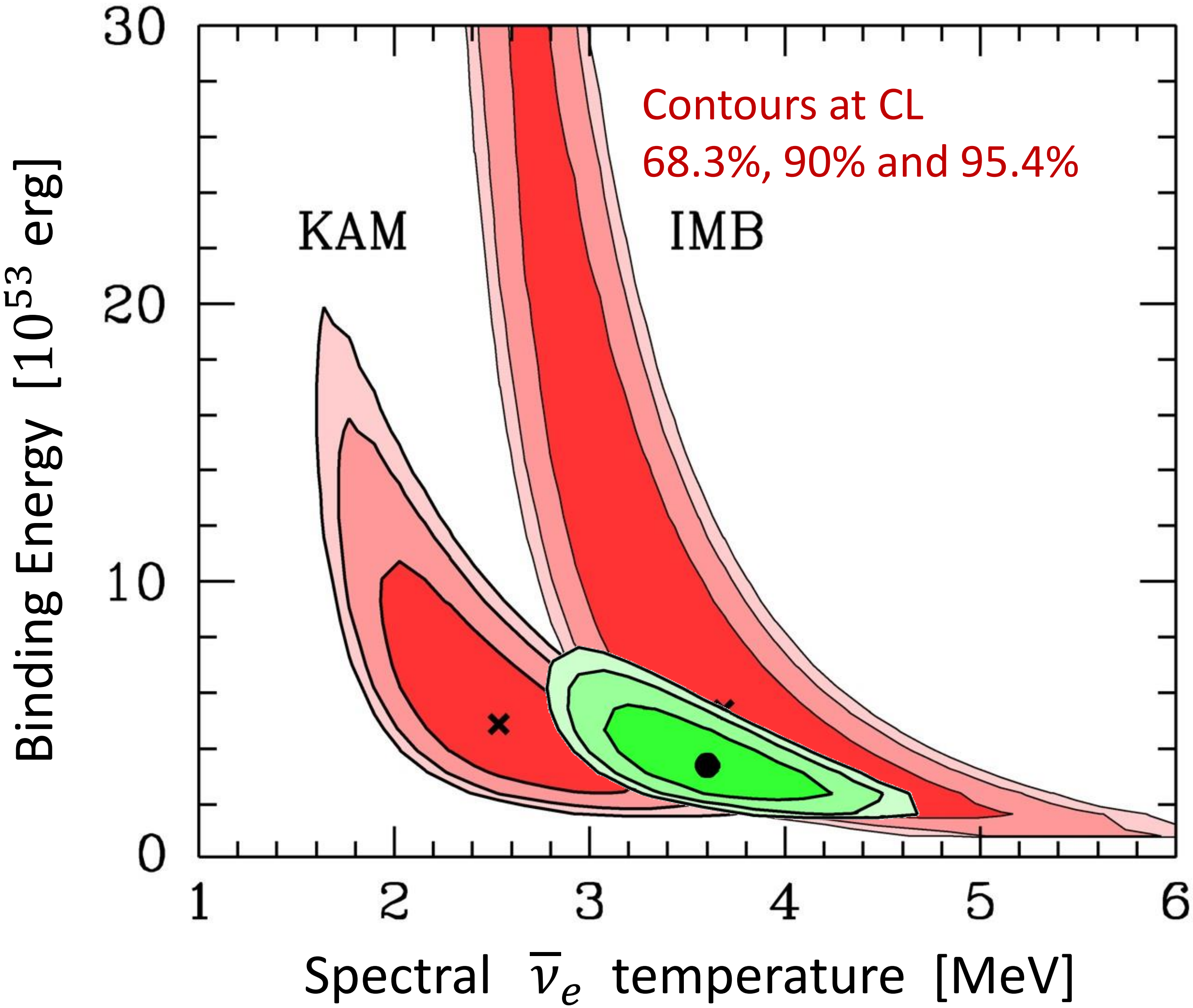
**Kamiokande-II Detector**
**(2140 tons of water)**




Hirata et al., PRD 38 (1988) 448



# Interpreting SN 1987A Neutrinos

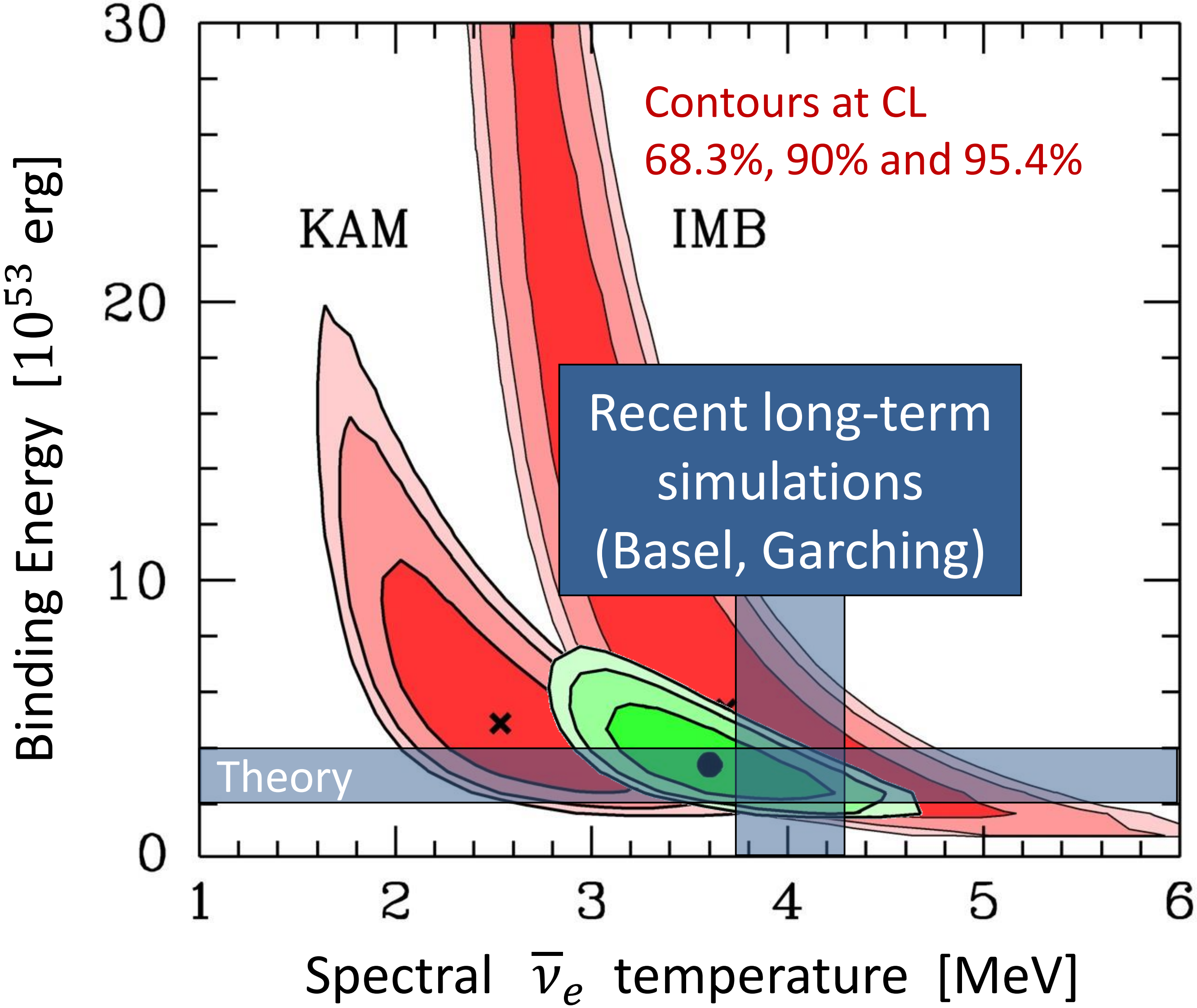



Assume

- Thermal spectra
- Equipartition of energy between $\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau$ and $\overline{\nu}_\tau$

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

# Interpreting SN 1987A Neutrinos




Assume
- Thermal spectra
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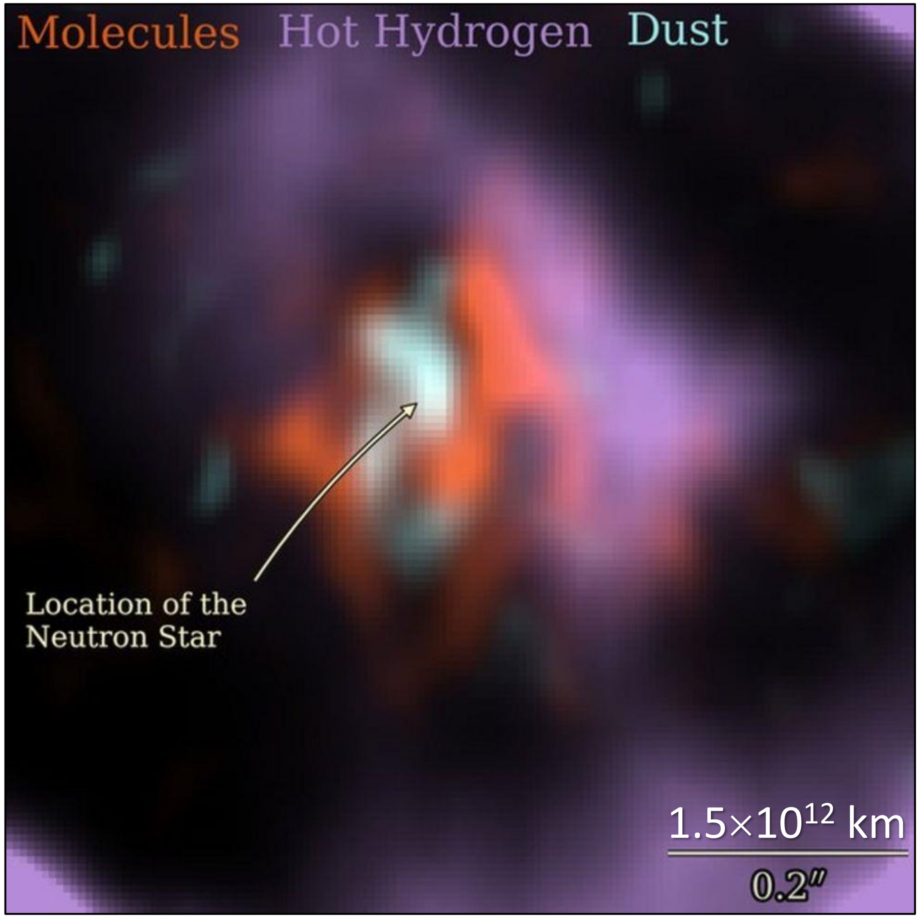
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

# Where is the Neutron Star of SN 1987A?

**No pulsar or neutron star has been seen until now (35 years later)**

- Infra-red excess observed by ALMA: In “the blob” strong indication for NS
  Expected position, remnant hidden by dust [Cigan+ arXiv:1910.02960]
- Most plausible model: Thermally cooling non-pulsar NS [Page+ arXiv:2004.06078]

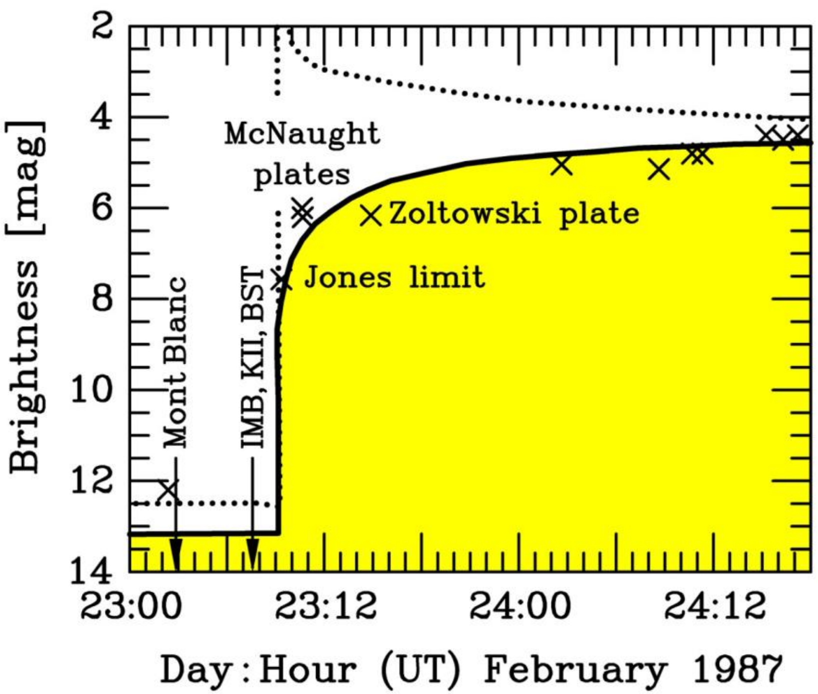
https://www.bbc.com/news/science-environment-50473482




**Atacama Large Millimeter/Submillimeter Array (ALMA) at ESO in Chile**

# Do Neutrinos Gravitate?

Early light curve of SN 1987A




- Neutrinos arrived several hours before photons as expected
- Transit time for $\nu$ and $\gamma$ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt\, \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5 \text{ months}$$

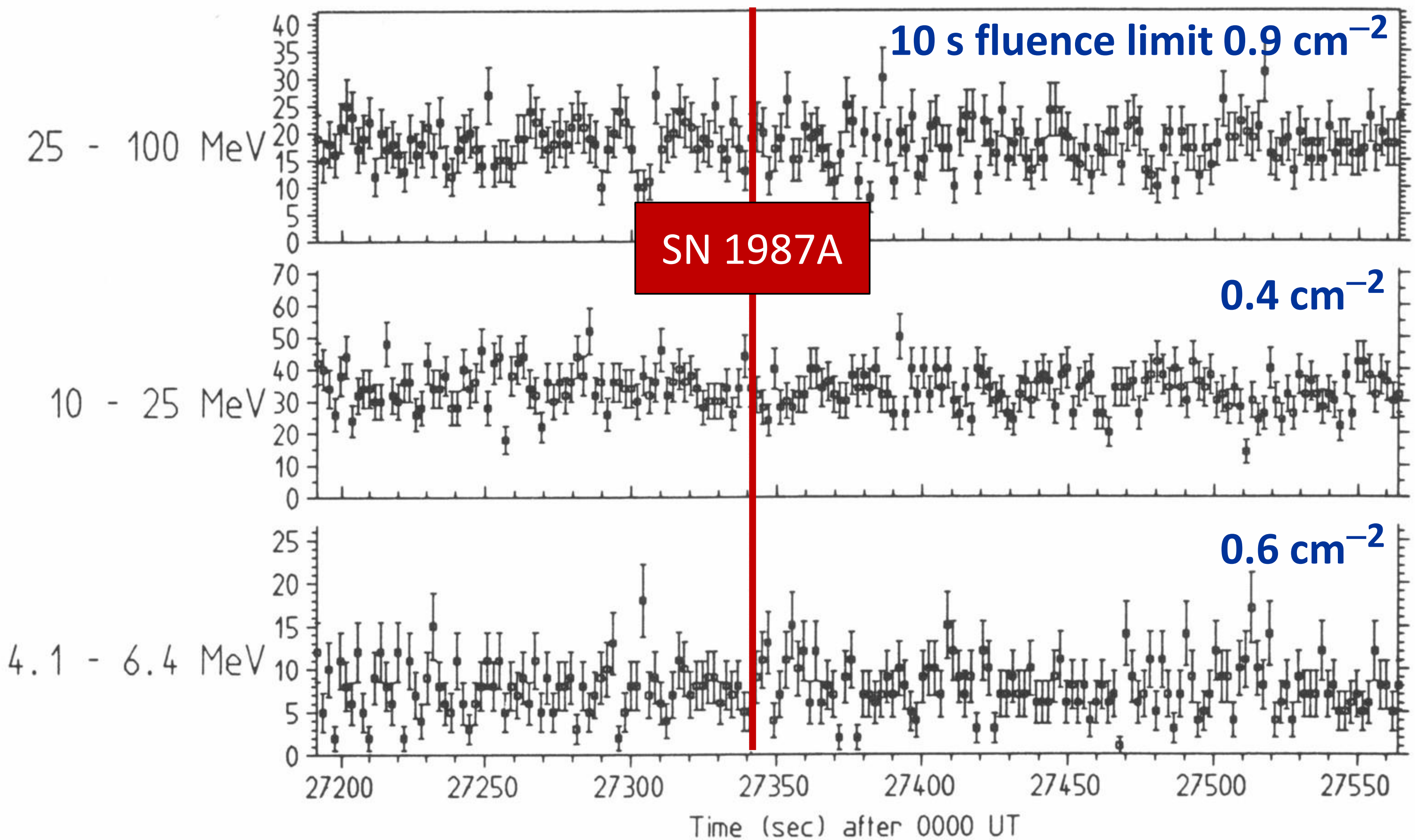
Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

# Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite

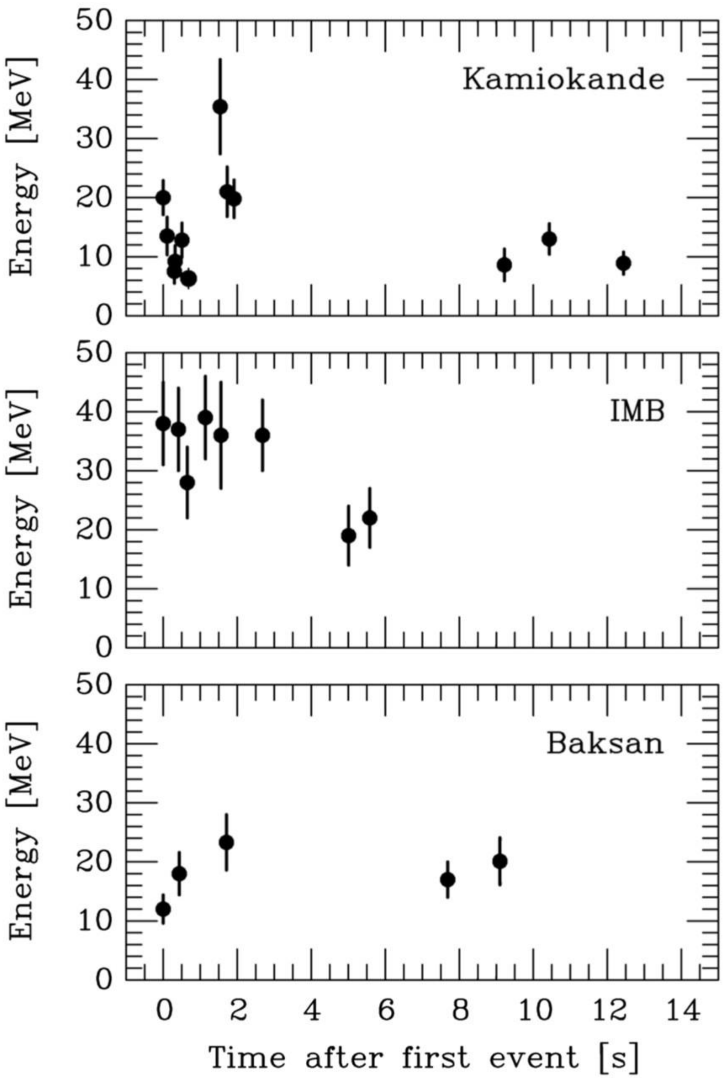


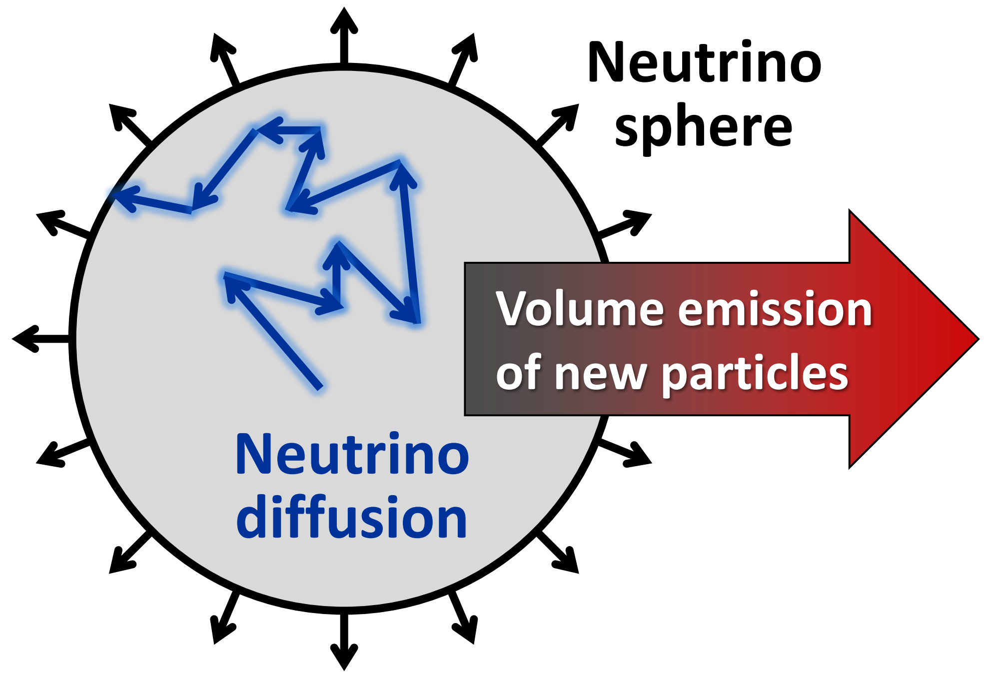

SN 1987A neutrino fluence $\sim 10^{10}\,\mathrm{cm}^{-2}$

$< 10^{-10}$ of neutrinos have decayed to photons on their way to Earth

# Supernova 1987A Energy-Loss Argument

**SN 1987A neutrino signal**

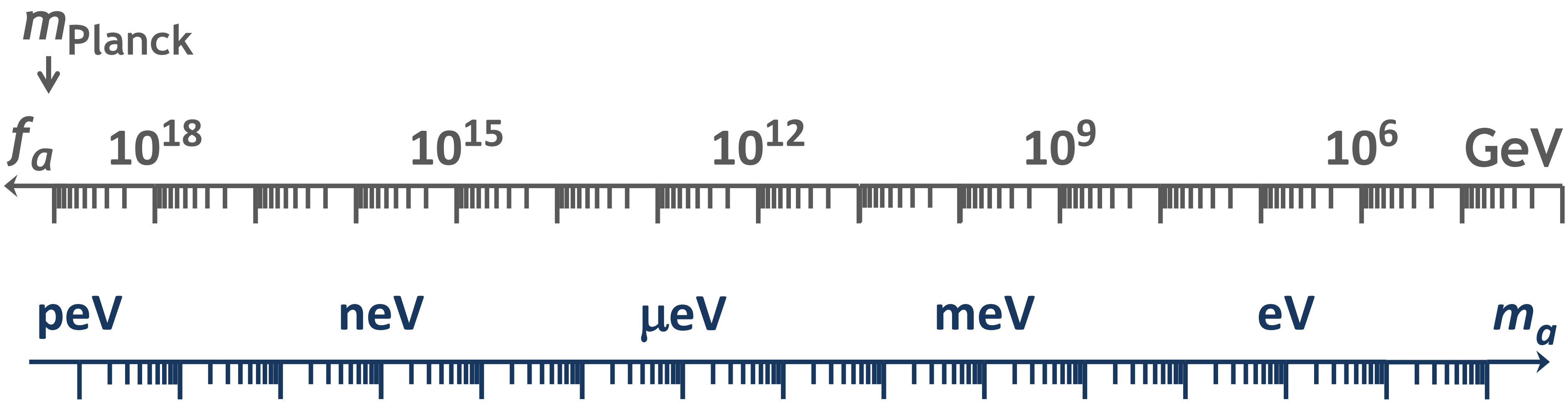



Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

**Late-time signal most sensitive observable**

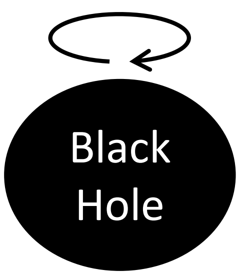
# Axions and Stars

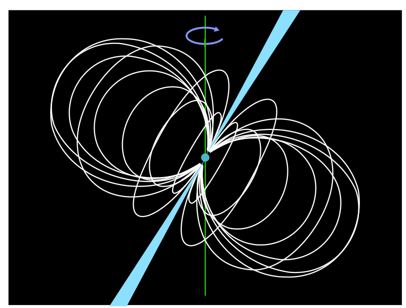


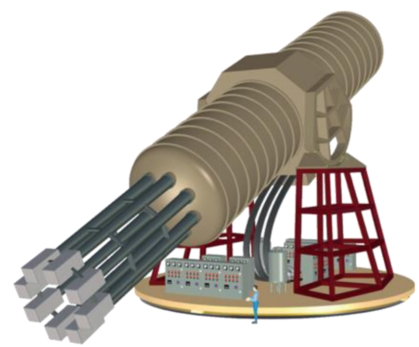

**Super Radiance**

**Opportunities for detection**

**Astrophysical Bounds (Energy loss of stars)**



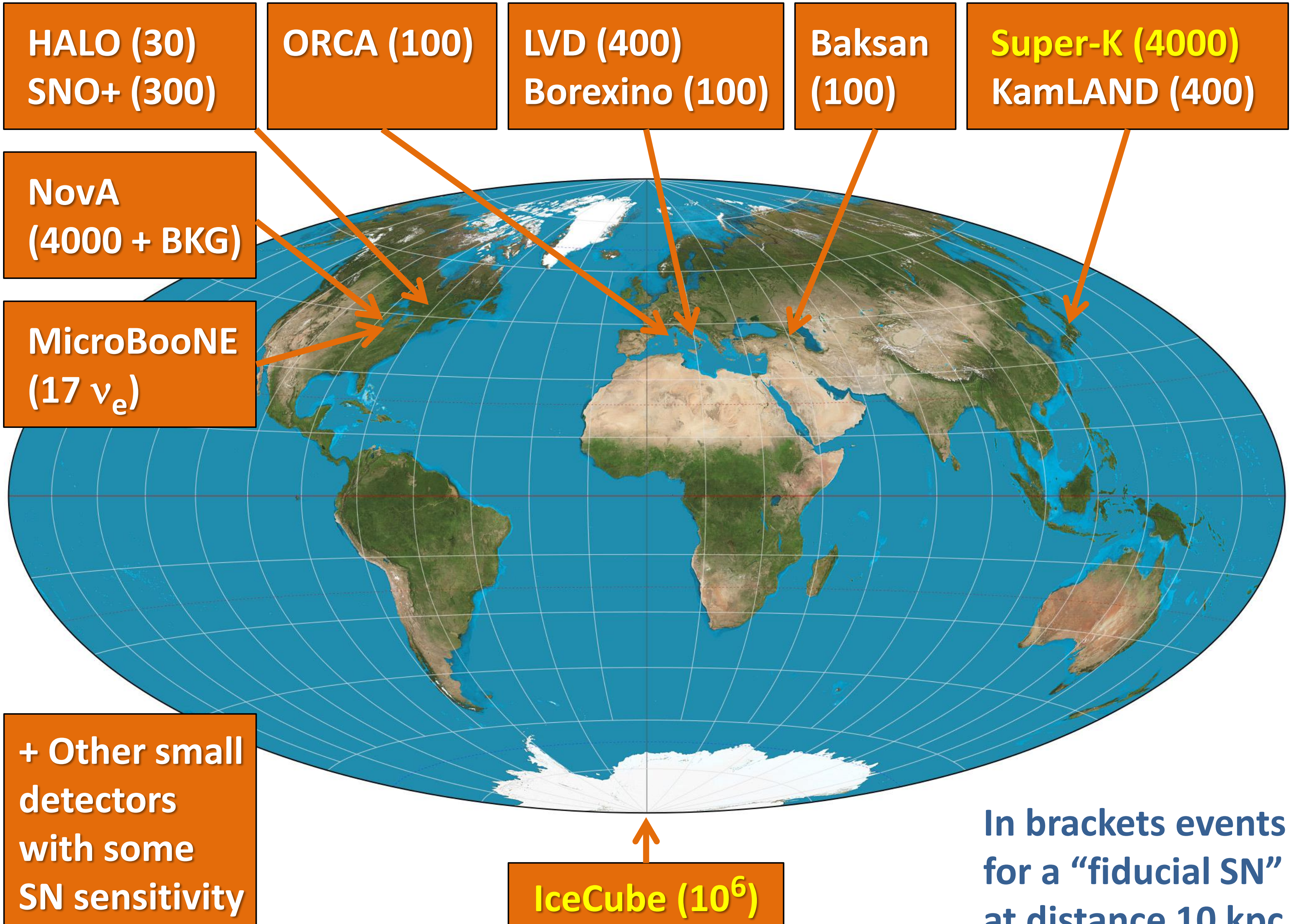





IAXO Solar Axion Telescope

Axion conversion in neutron star magnetospheres

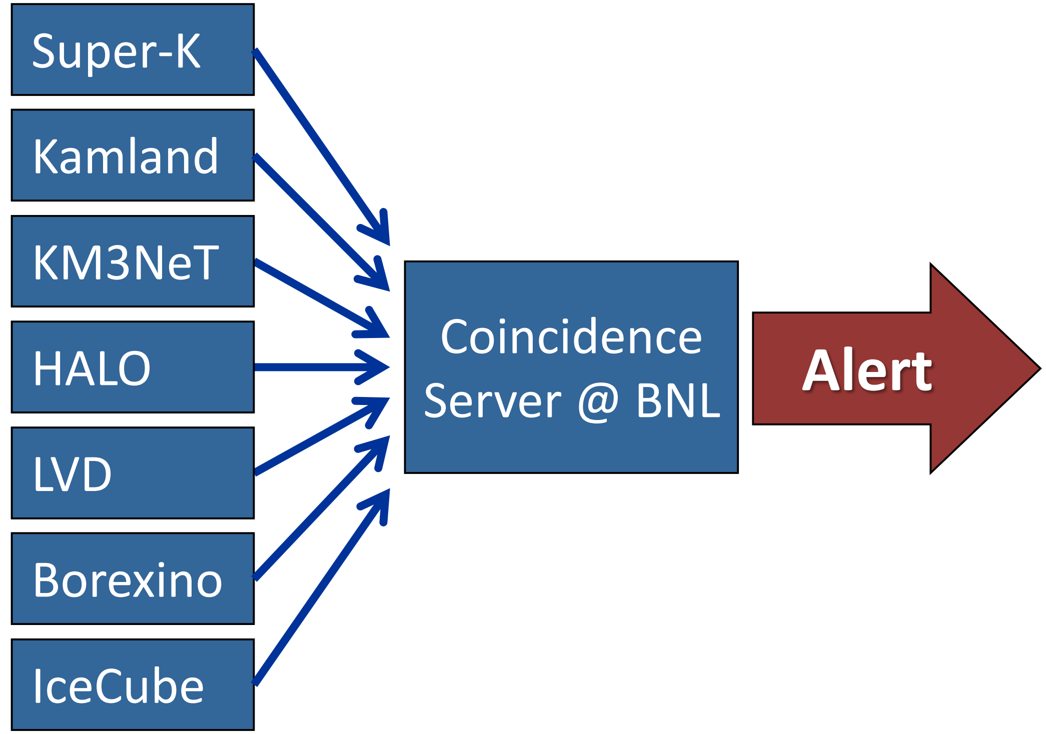
# Operational Detectors for Supernova Neutrinos




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

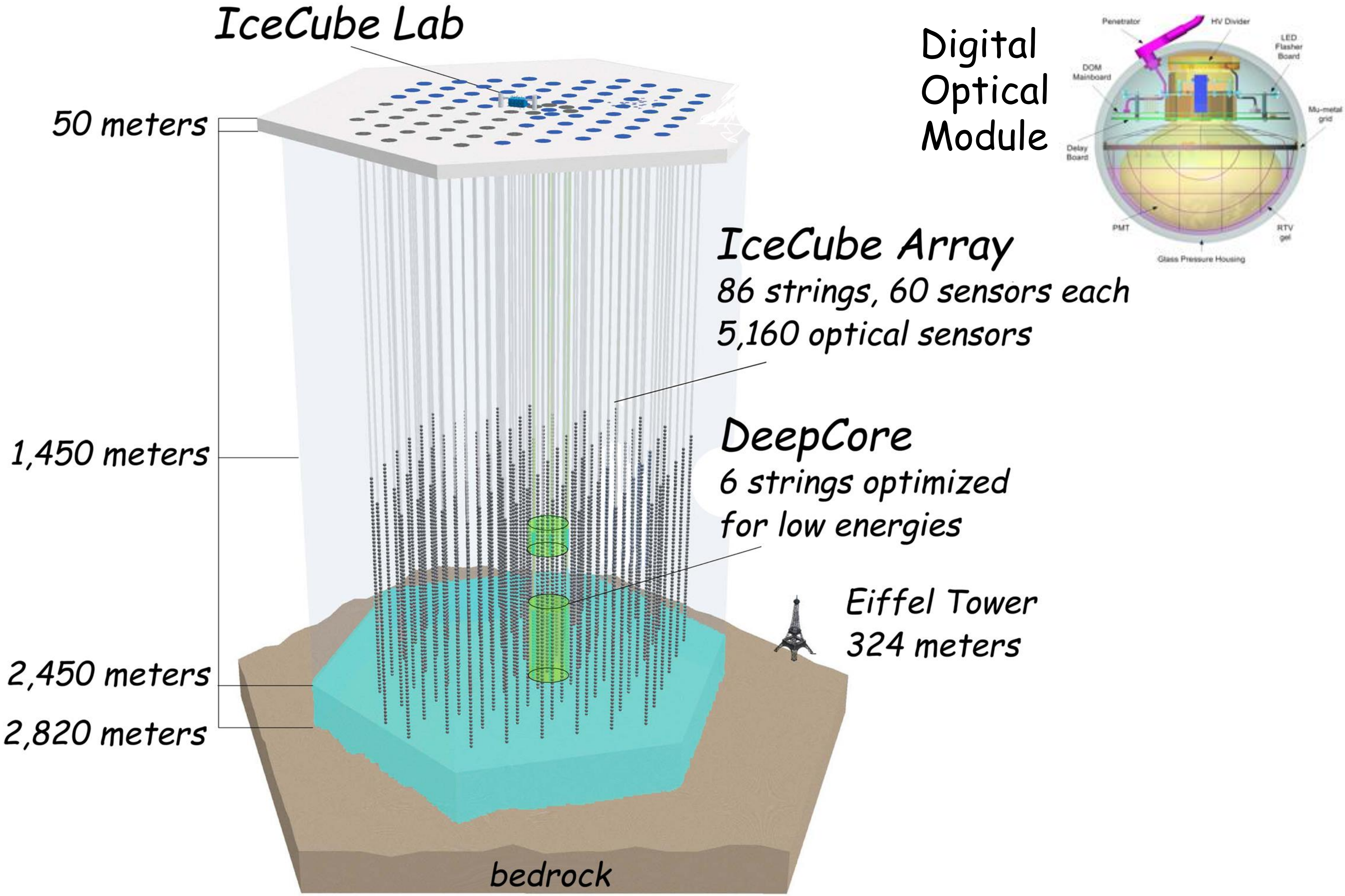
# SuperNova Early Warning System (SNEWS)

https://snews.bnl.gov

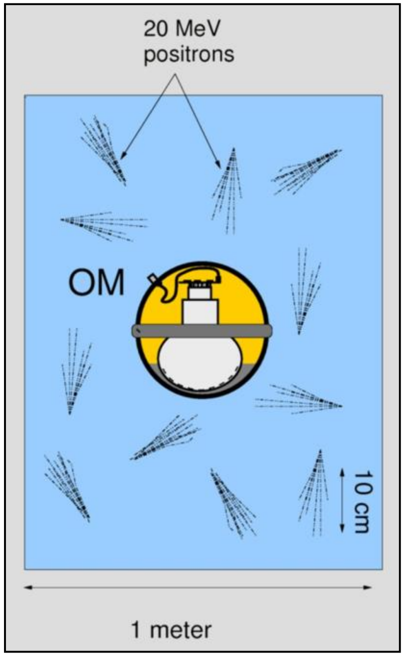


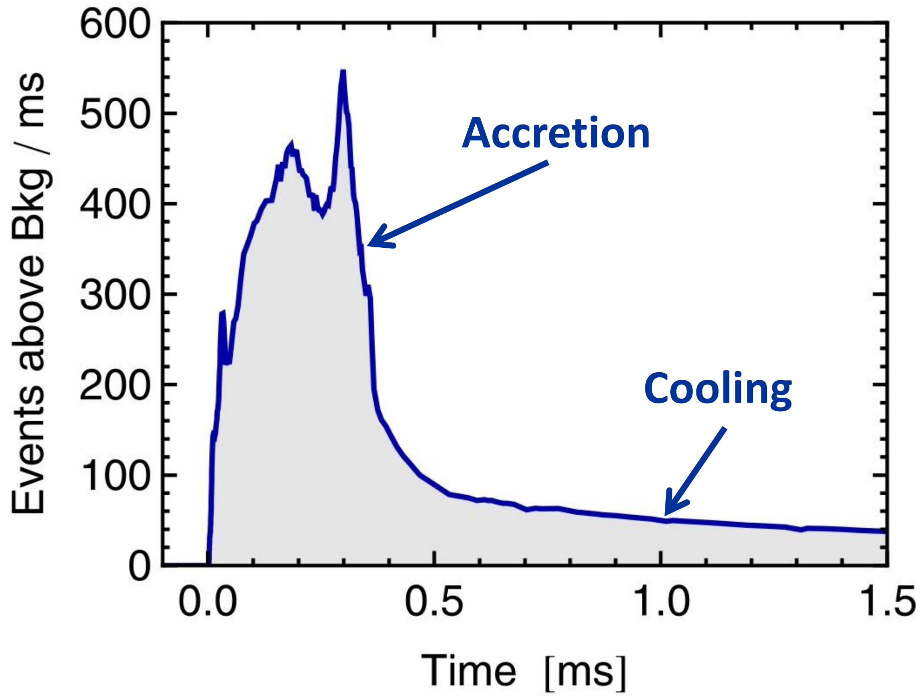

- Neutrinos arrive several hours before optical outburst
- Issue an alert to astronomical community
- Trigger to LIGO, NOvA, GCN

# IceCube Neutrino Telescope at the South Pole



# IceCube as a Supernova Neutrino Detector



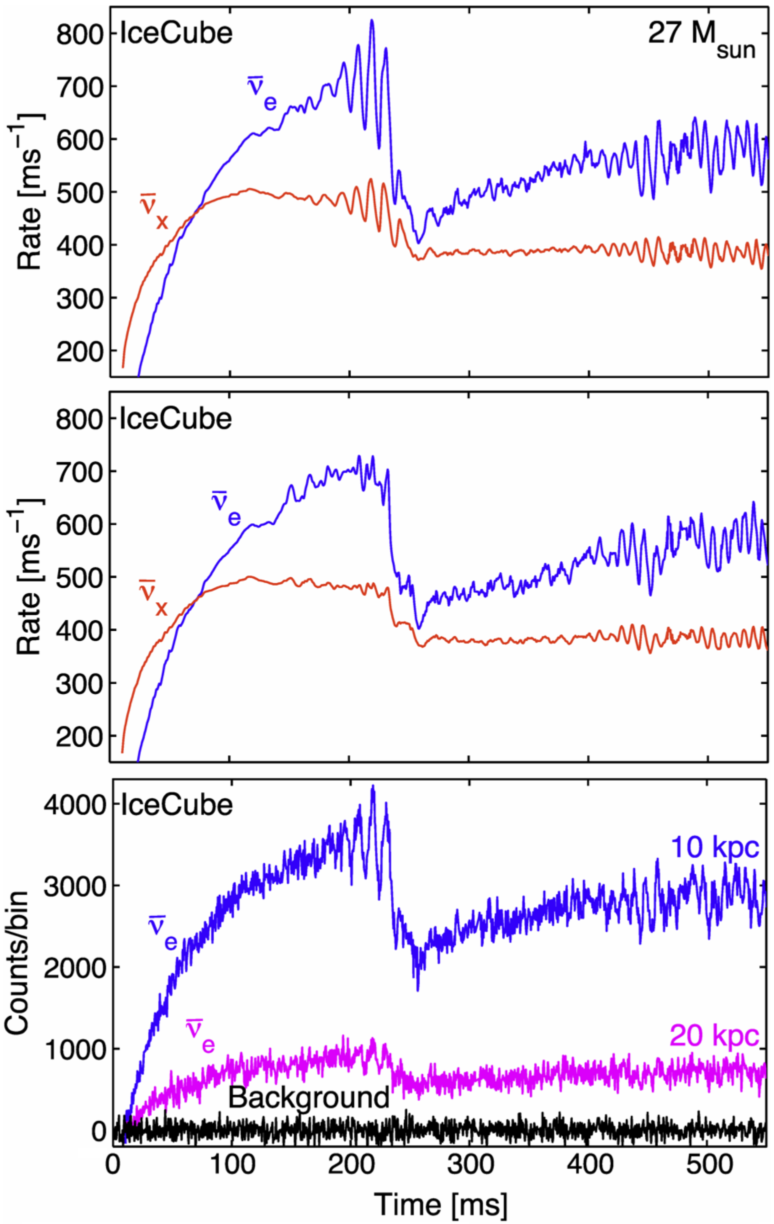




SN signal at 10 kpc
10.8 $M_{sun}$ simulation of Basel group [arXiv:0908.1871]

- Each optical module (OM) picks up Cherenkov light from its neighborhood
- ~ 300 Cherenkov photons per OM from SN at 10 kpc, bkgd rate in one OM < 300 Hz
- SN appears as “correlated noise” in ~ 5000 OMs
- Significant energy information from time-correlated hits

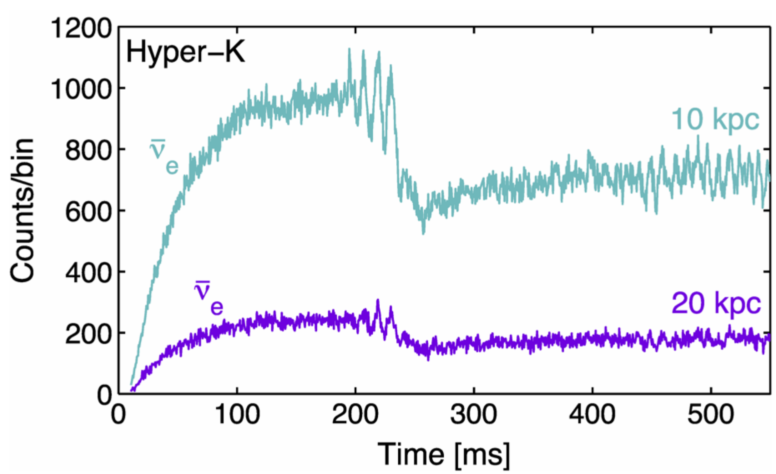
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

# SASI Detection Perspectives (27 $M_{SUN}$ Model)




Optimistic Observer Direction (along SASI dipole)

Pessimistic Observer Direction




With shot noise

Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936. See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

# Neutrino Mass and Resolving Time Variations

**Time-of-flight signal dispersion for next nearby supernova**

$$\Delta t = 51\ \mu\mathrm{s}\left(\frac{D}{10\ \mathrm{kpc}}\right)\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{100\ \mathrm{meV}}\right)^2$$

- Laboratory: $m_\nu < 1.0$ eV
- Cosmological limit $\sum m_\nu < 0.23$ eV, so that $m_\nu < 0.1$ eV
- KATRIN sensitivity roughly 0.2 eV

**To measure fast SN signal variations, cosmological limit and future KATRIN measurement/limit very important!**

# SN Neutrino Detection Channels

| Channel | Observable(s)[a] | Interactions[b] |
|---|---|---|
| $\nu_x + e^- \rightarrow \nu_x + e^-$ | C | 17/10 |
| $\bar{\nu}_e + p \rightarrow e^+ + n$ | C, N, A | 278/165 |
| $\nu_x + p \rightarrow \nu_x + p$ | C | 682/351 |
| $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}^{(*)}$ | C, N, G | 3/9 |
| $\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}^{(*)}$ | C, N, G, A | 6/8 |
| $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + {}^{12}\mathrm{C}^*$ | G, N | 68/25 |
| $\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^{(*)}$ | C, N, G | 1/4 |
| $\bar{\nu}_e + {}^{16}\mathrm{O} \rightarrow e^+ + {}^{16}\mathrm{N}^{(*)}$ | C, N, G | 7/5 |
| $\nu_x + {}^{16}\mathrm{O} \rightarrow \nu_x + {}^{16}\mathrm{O}^*$ | G, N | 50/12 |
| $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ | C, G | 67/83 |
| $\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$ | C, A, G | 5/4 |
| $\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$ | N | 144/228 |
| $\nu_x + {}^{208}\mathrm{Pb} \rightarrow \nu_x + {}^{208}\mathrm{Pb}^*$ | N | 150/55 |
| $\nu_x + A \rightarrow \nu_x + A$ | C | 9,408/4,974 |

[a]The observables column lists primary observable products relevant for interactions in current detectors. Abbreviations: C, energy loss of a charged particle; N, produced neutrons; G, deexcitation $\gamma$s; A, positron annihilation $\gamma$s. Note there may, in principle, be other signatures for future detector technologies or detector upgrades.

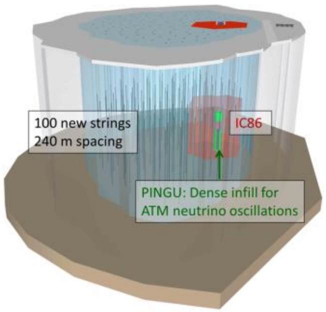
[b]The interactions column gives interactions per kilotonne at 10 kpc for two different neutrino flux models for neutrino energies greater than 5 MeV, computed according to **http://www.phy.duke.edu/~schol/snowglobes**. No detector response is taken into account here, and actual detected events may be significantly fewer. For elastic scattering and inverse $\beta$ decay, the numbers per kilotonne refer to water; for other detector materials, the numbers need to be scaled by the relative fraction of electrons or protons, respectively. For neutrino-proton elastic scattering, the numbers per kilotonne refer to scintillators.

Scholberg, arXiv:1205.6003, see also http://www.phy.duke.edu/~schol/snowglobes

# Current and Near-Future SN Neutrino Detectors

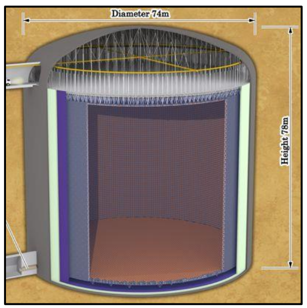
| Detector | Type | Mass (kt) | Location | Events | Flavors | Status |
|---|---|---|---|---|---|---|
| Super-Kamiokande | $H_2O$ | 32 | Japan | 7,000 | $\bar{\nu}_e$ | Running |
| LVD | $C_nH_{2n}$ | 1 | Italy | 300 | $\bar{\nu}_e$ | Running |
| KamLAND | $C_nH_{2n}$ | 1 | Japan | 300 | $\bar{\nu}_e$ | 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 | $\nu_e, \nu_x$ | Running |
| Daya Bay | $C_nH_{2n}$ | 0.33 | China | 100 | $\bar{\nu}_e$ | Running |
| NO$\nu$A* | $C_nH_{2n}$ | 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 | $\nu_e$ | Near future |
| DUNE | Ar | 34 | USA | 3,000 | $\nu_e$ | 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 |

# Next Generation Very-Large-Scale Detectors (2020+)




**IceCube Gen-2**
- Dense infill (PINGU)
- Larger volume (statistics for high-E events)

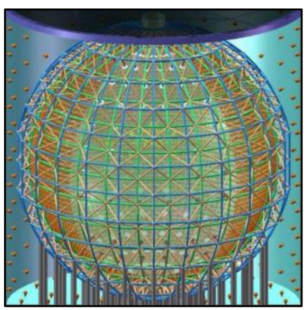
Doubling the number of optical modules



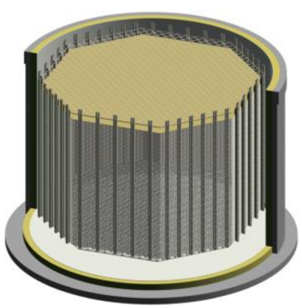

**Megaton-class water Cherenkov detector**

Notably Hyper-Kamiokande

SN neutrino statistics comparable to IceCube, but with event-by-event energy information



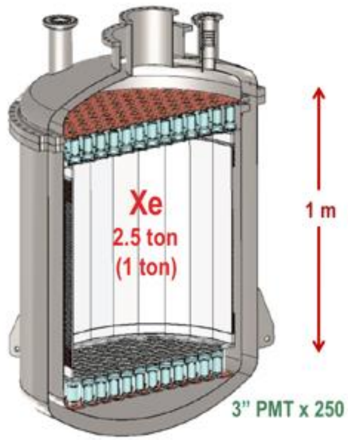
**Scintillator detectors (20 kilotons)**
- JUNO in China for reactor nus (construction)
- RENO-50 in Korea for reactor nus (plans)
- Baksan Large Volume Scintillator Detector (discussions in Russia)

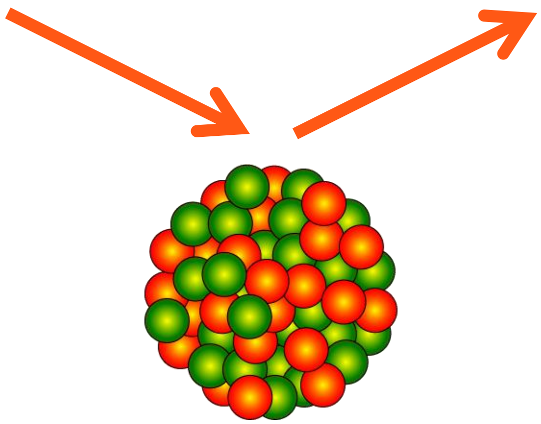


**Liquid argon time projection chamber**

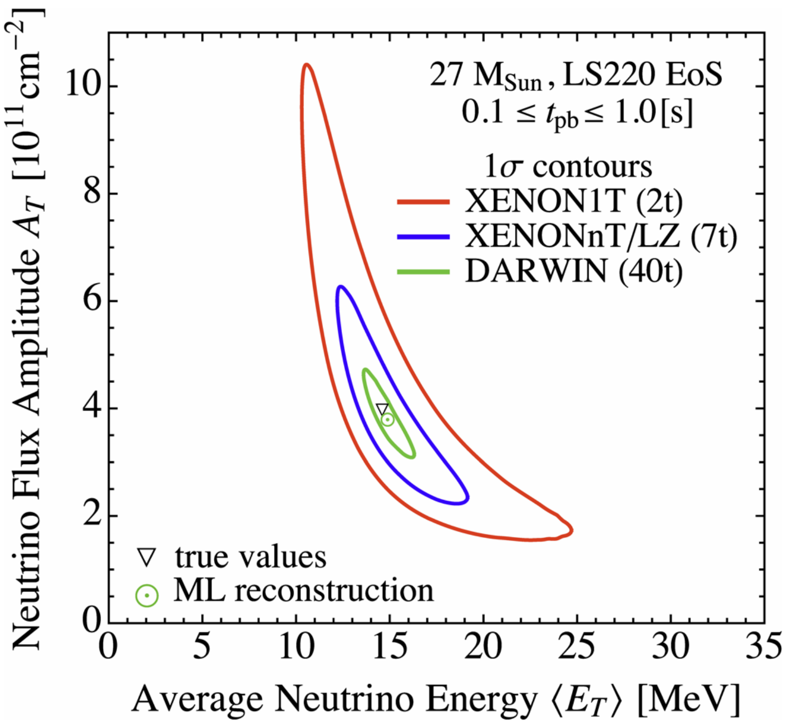
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC $\nu_e$ signal)
- But cross sections poorly known

# Xenon Dark Matter Detectors



- Coherent scattering of low-E nus on Xe (77 neutrons)
- All 6 nu species contribute

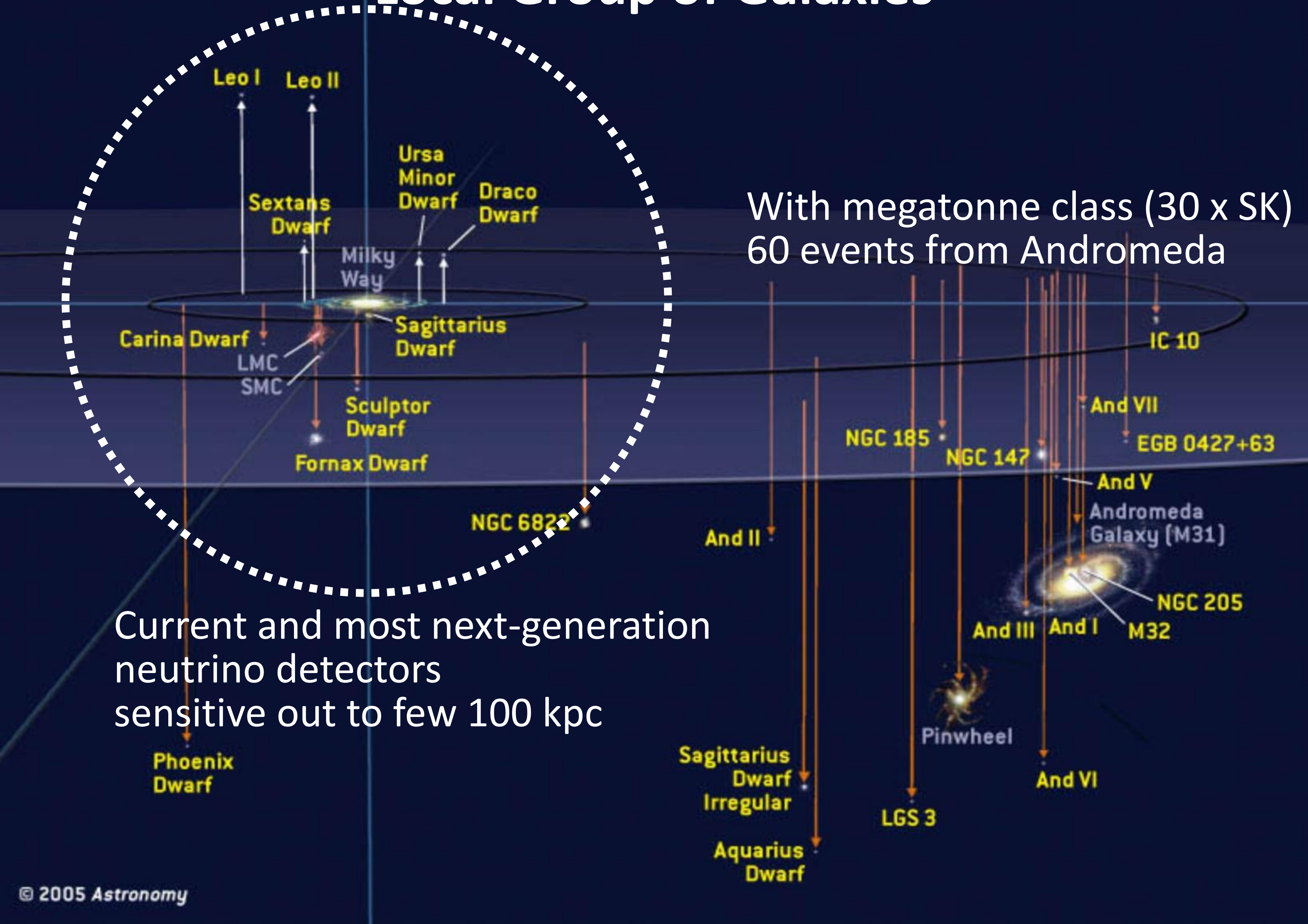



Pinning down SN neutrino flux and average energy

See for example
Horowitz et al. (astro-ph/0302071)
Chakraborty et al. (arXiv:1309.4492)
XMASS Collaboration (arXiv:1604.01218)
Lang et al. (arXiv:1606.09243)

# Local Group of Galaxies

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




Current and most next-generation
neutrino detectors
sensitive out to few 100 kpc

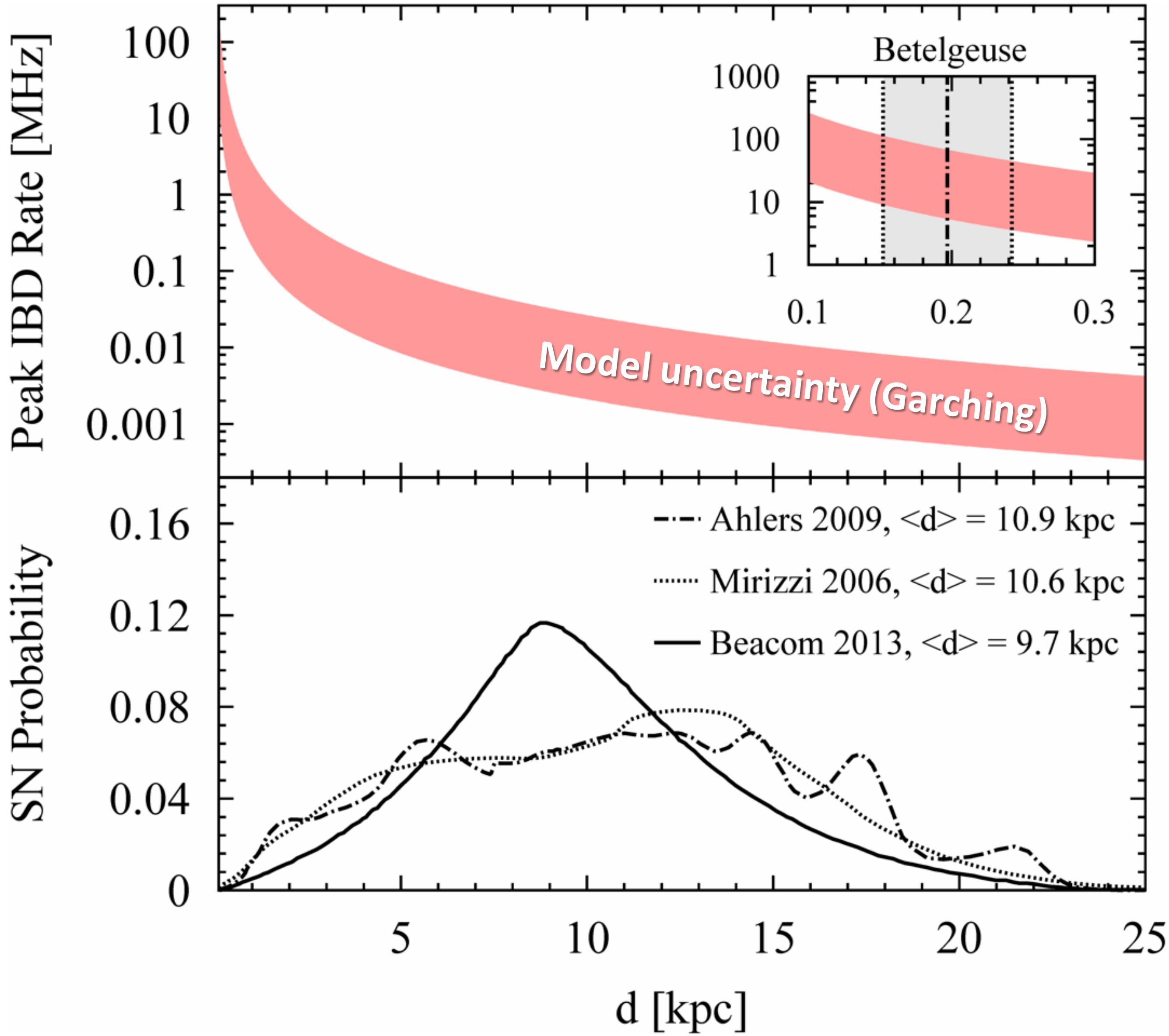
# SN Distance Distribution and Peak Count Rate

**Peak count rate in JUNO (20 kt) depending on SN distance**

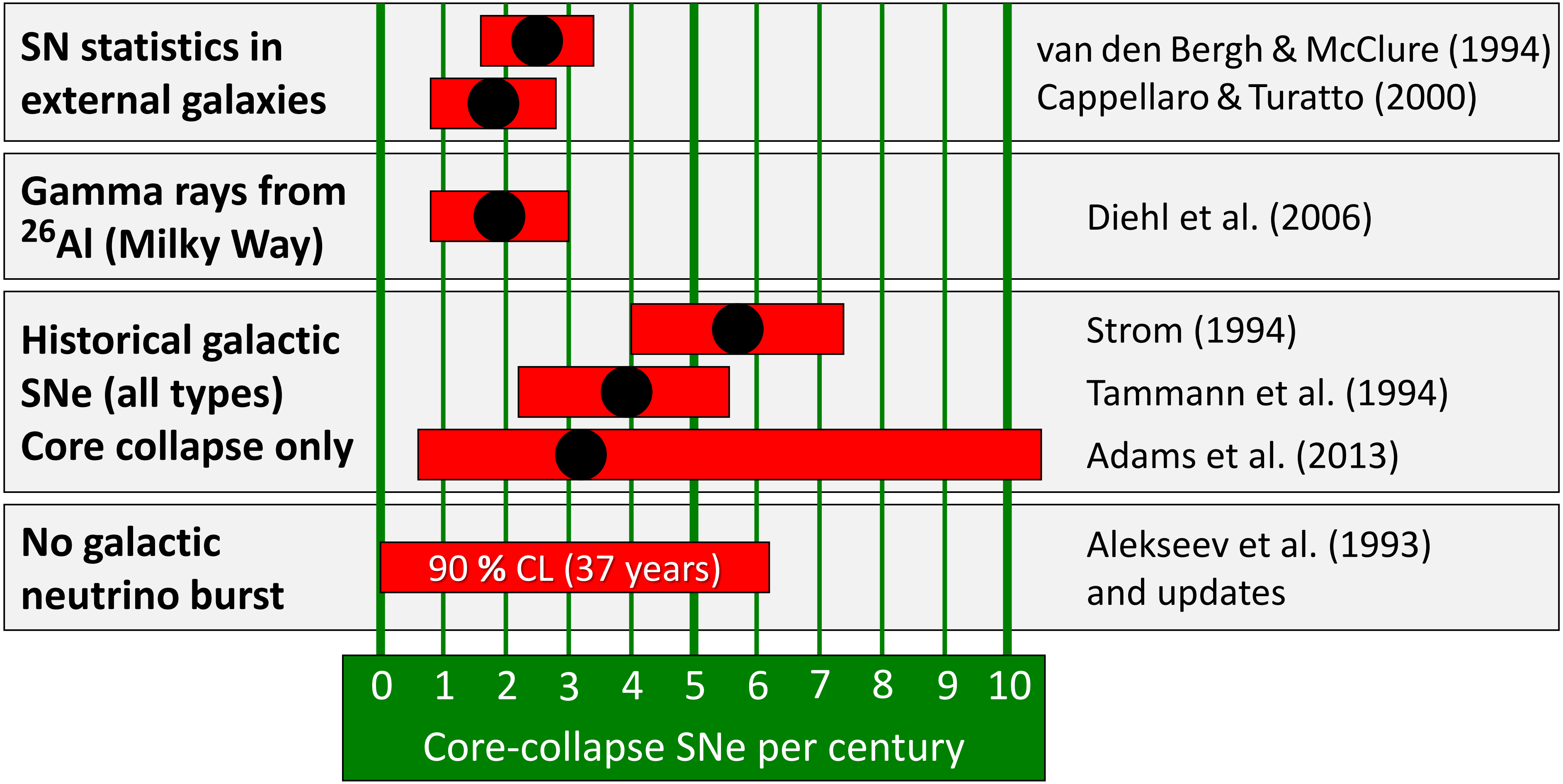
**× 10 in 1 tank Hyper-K**

**SN distance probability in Milky Way**

JUNO Yellow Book, arXiv:1507.05613

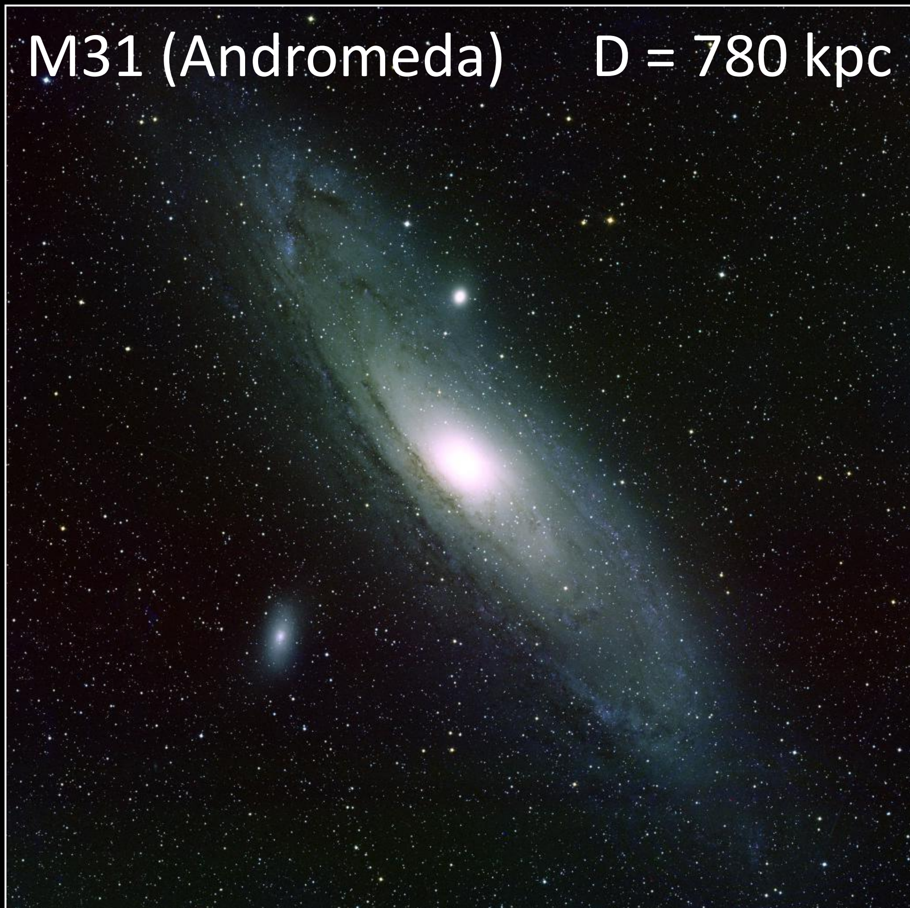


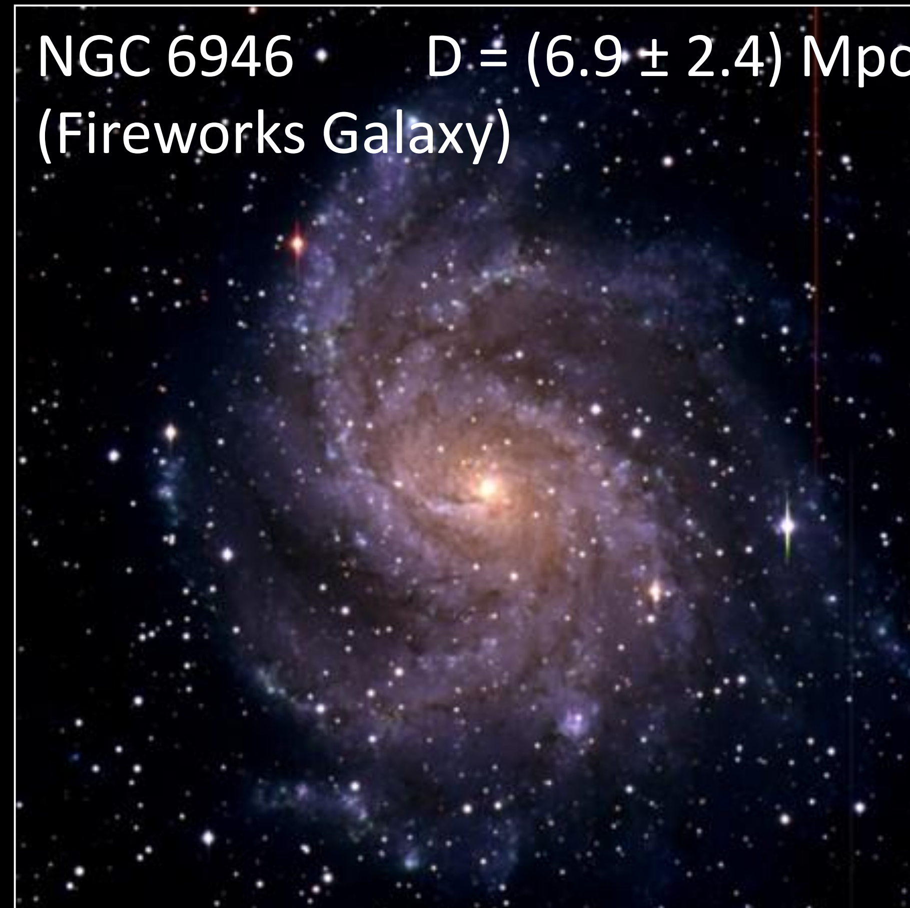
# Core-Collapse SN Rate in the Milky Way




van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455.
Diehl et al., Nature 439 (2006) 45. Strom, A&A 288 (1994) L1.
Tammann et al., ApJ 92 (1994) 487. Adams et al., ApJ 778 (2013) 164.
Alekseev et al., JETP 77 (1993) 339.

# High and Low Supernova Rates in Nearby Galaxies

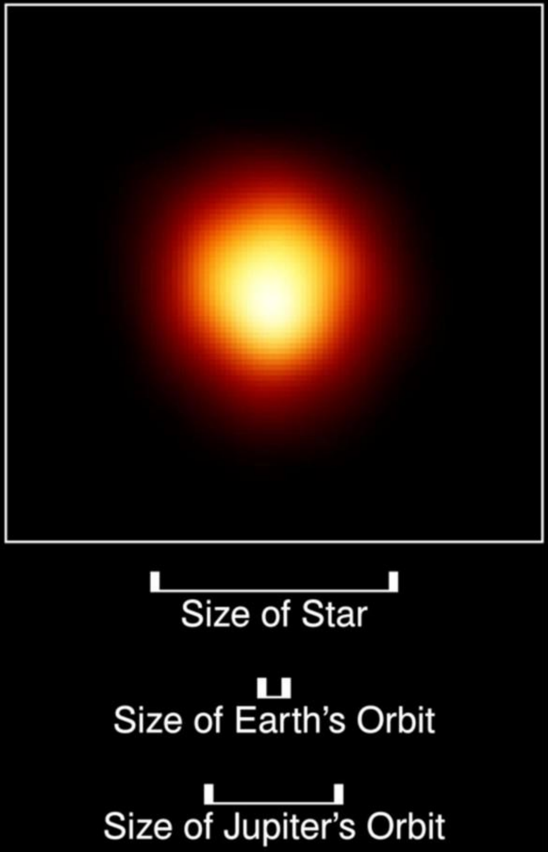


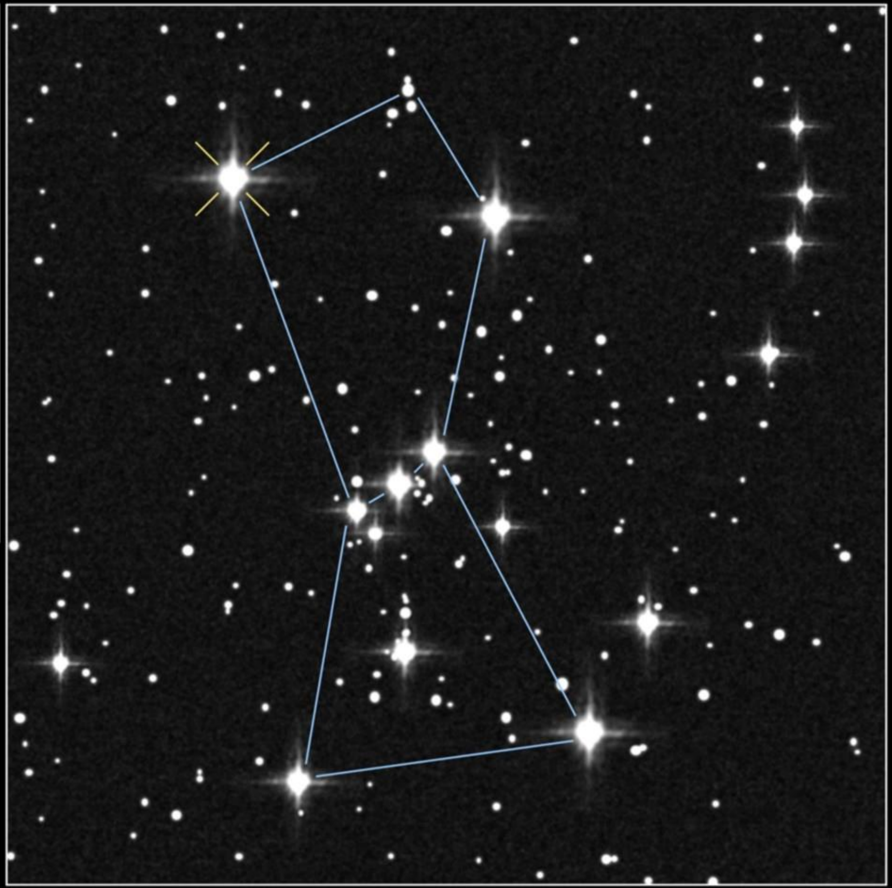




Last Observed Supernova: 1885A

Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S, 2017eaw
N6946-BH1 (failed SN 2009/10)

# The Red Supergiant Betelgeuse (Alpha Orionis)



First resolved image of a star other than Sun

Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova:

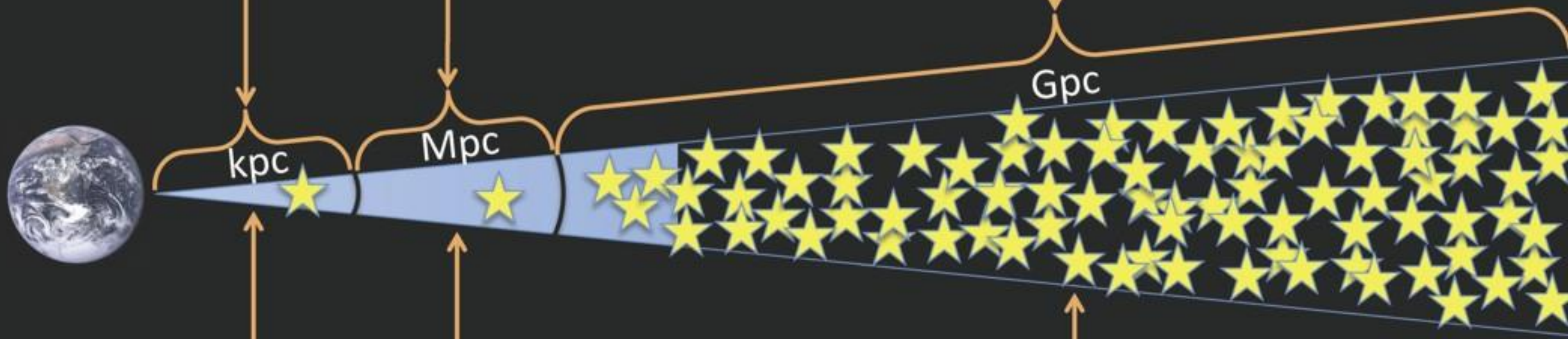
- $6 \times 10^7$ neutrino events in Super-Kamiokande
- $2.4 \times 10^3$ neutrons /day from Si burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

# Distance Scales and Detection Strategies

N >> 1 : Burst

N ~ 1 : Mini-Burst

N << 1 : DSNB




Rate ~ 0.01/yr

Rate ~ 1/yr

Rate ~ $10^8$/yr

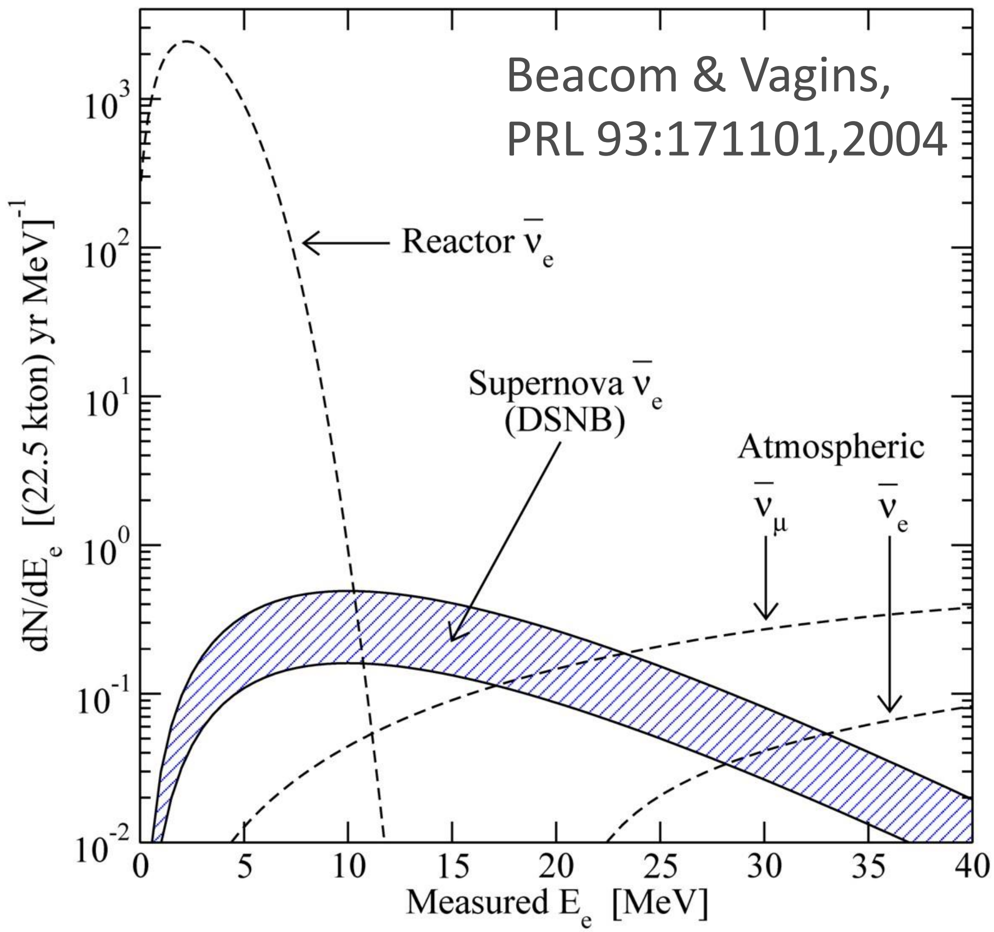
high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

# Diffuse Supernova Neutrino Background (DSNB)

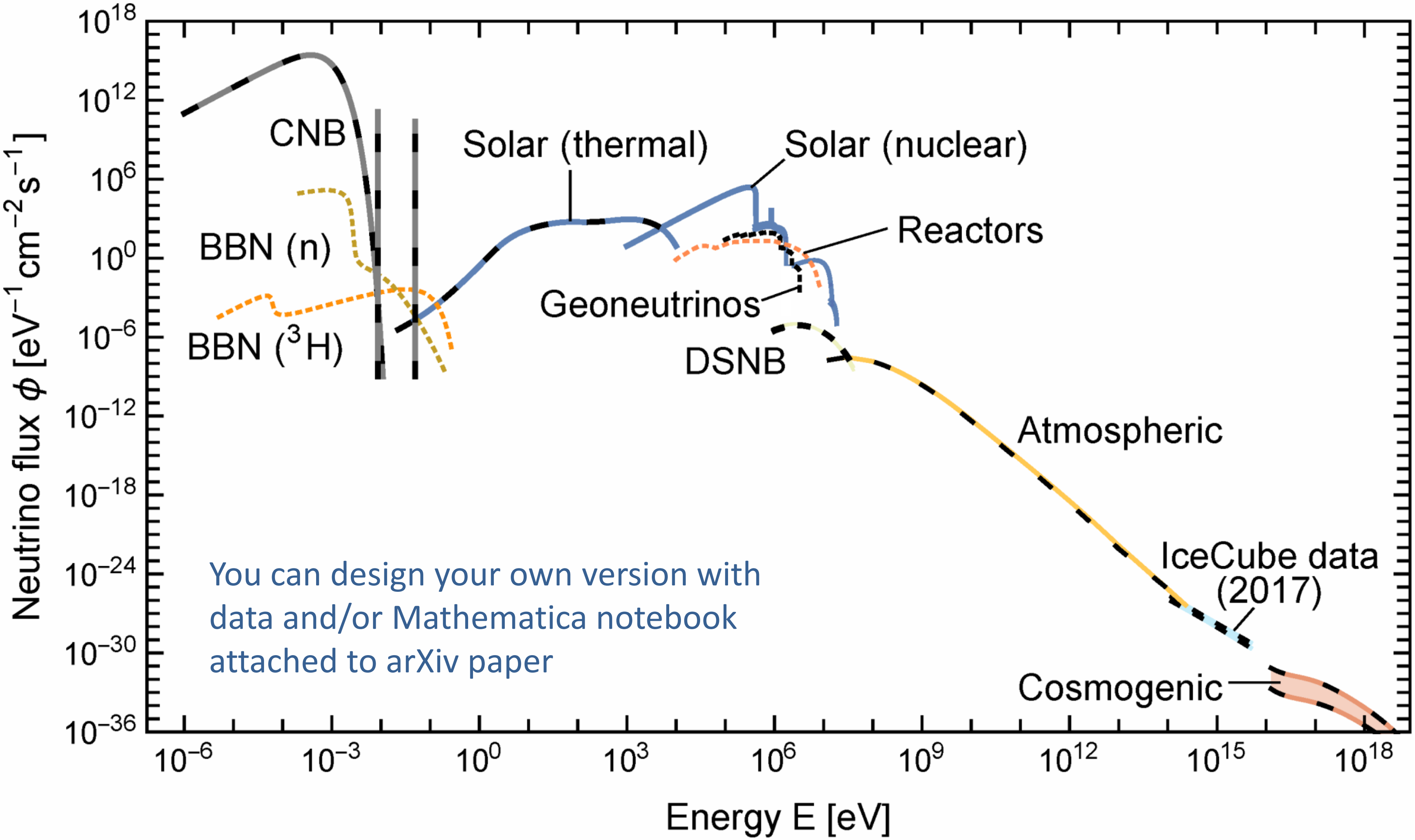
- A few core collapses/sec in the visible universe
- Emitted $\nu$ energy density
  ~ extra galactic background light
  ~ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  $\sim 10~\mathrm{cm}^{-2}~\mathrm{s}^{-1}$
  mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!




Window of opportunity between reactor $\overline{\nu}_e$ and atmospheric $\nu$ bkg

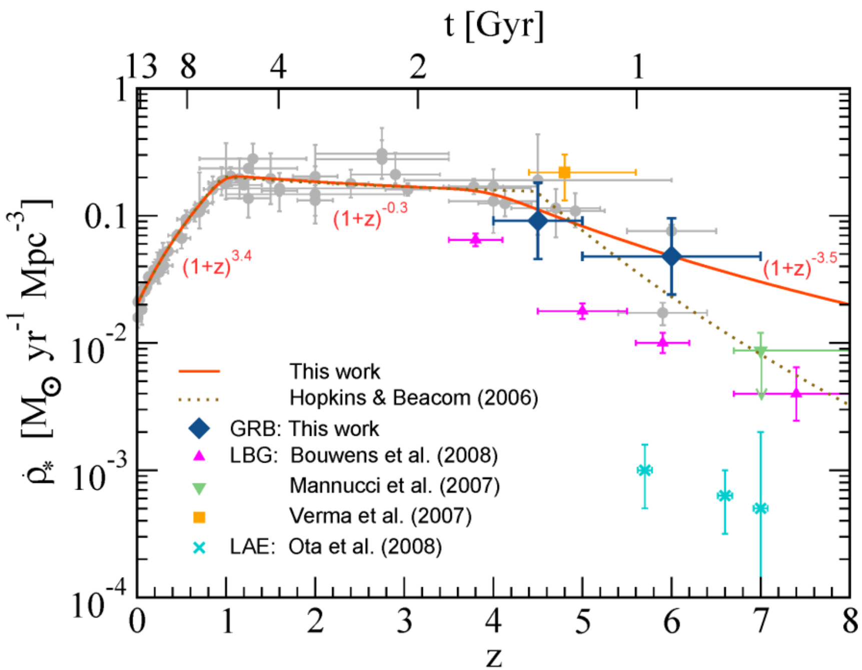
# Grand Unified Neutrino Spectrum (GUNS) at Earth

**Vitagliano, Tamborra & Raffelt, arXiv:1910.11878**



# Cosmic Star Formation and Core Collapse Rates

## Star-formation rate (1)



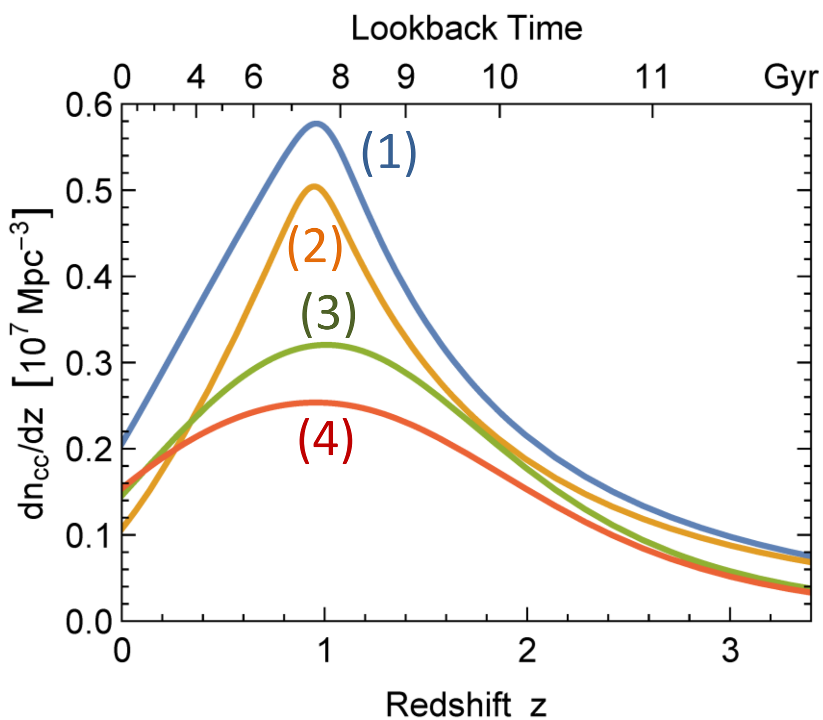

(1) Yüksel+ arXiv:0804.4008

(2) Mathews+ arXiv:1405.0458

(3) Robertson+ arXiv:1502.02024

(4) Madau+ arXiv:1403.0007

## Core-collapse distribution

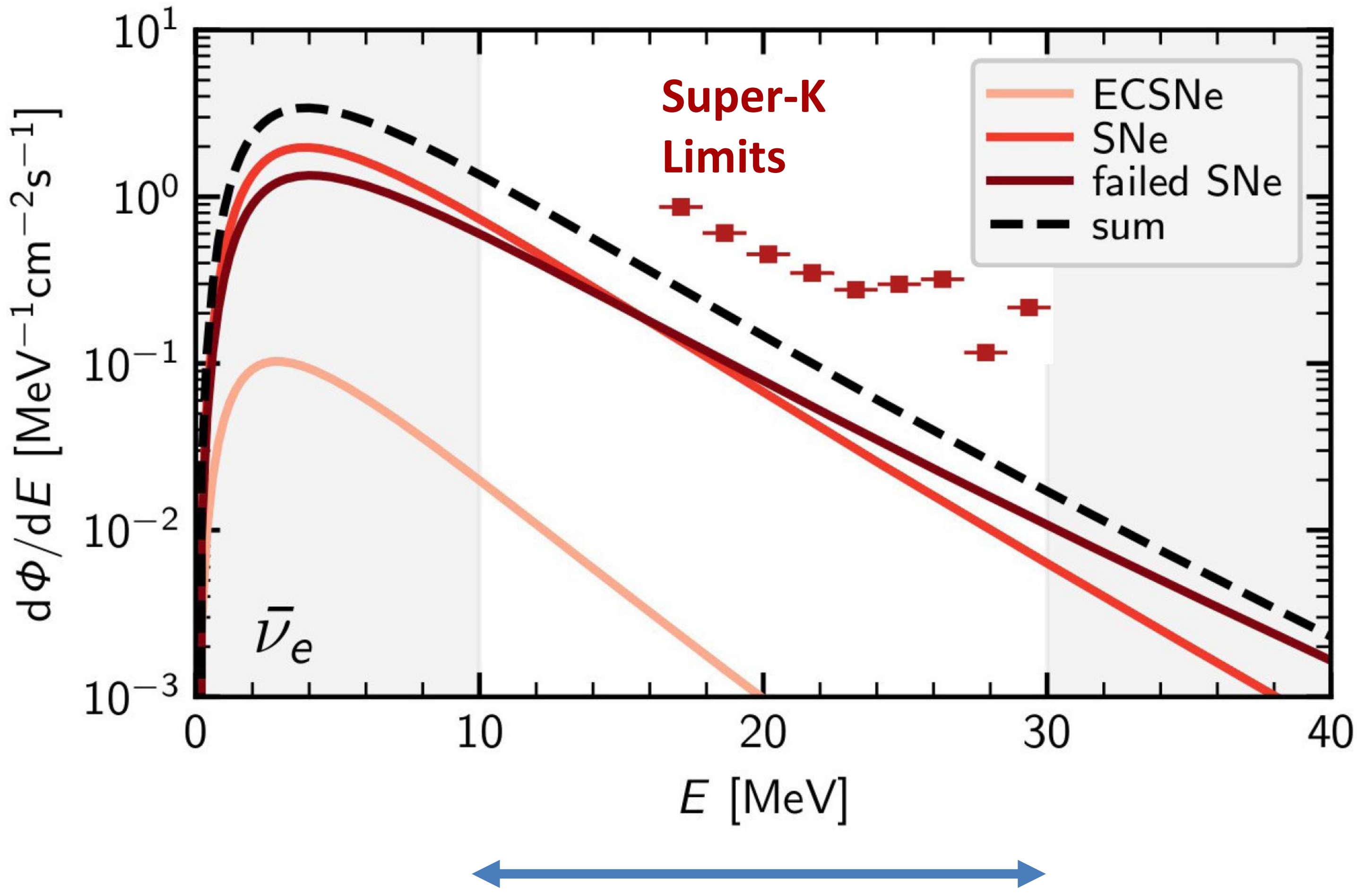



Total cc density

$0.6 - 1 \times 10^7$ Mpc$^{-3}$

# DSNB Prediction

Kresse+, arXiv:2010.04728



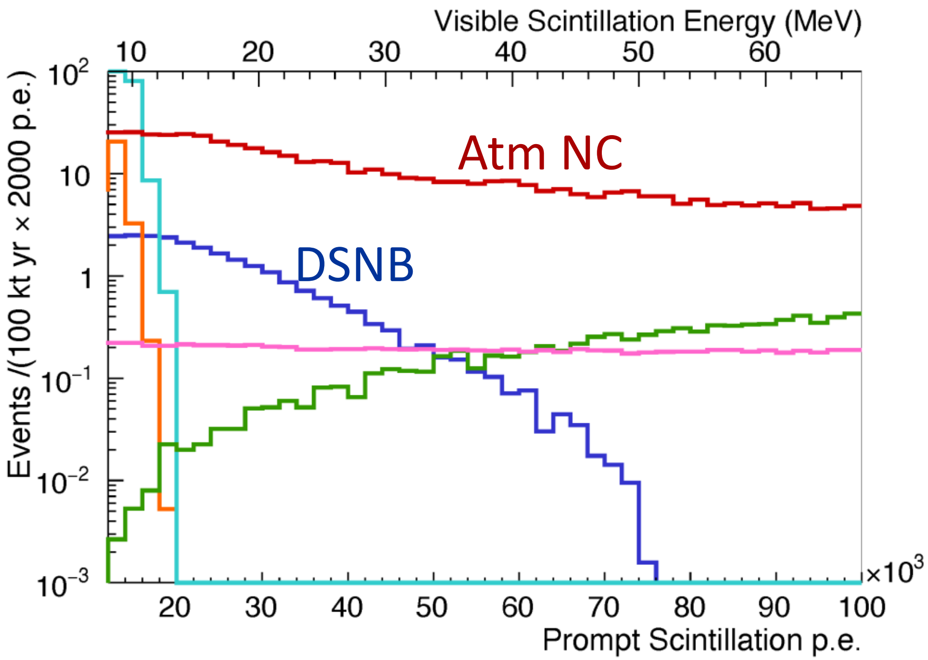

In the detection window, essentially $\frac{d\Phi}{dE} \propto e^{-E/E_0}$

# DSNB Signal in JUNO

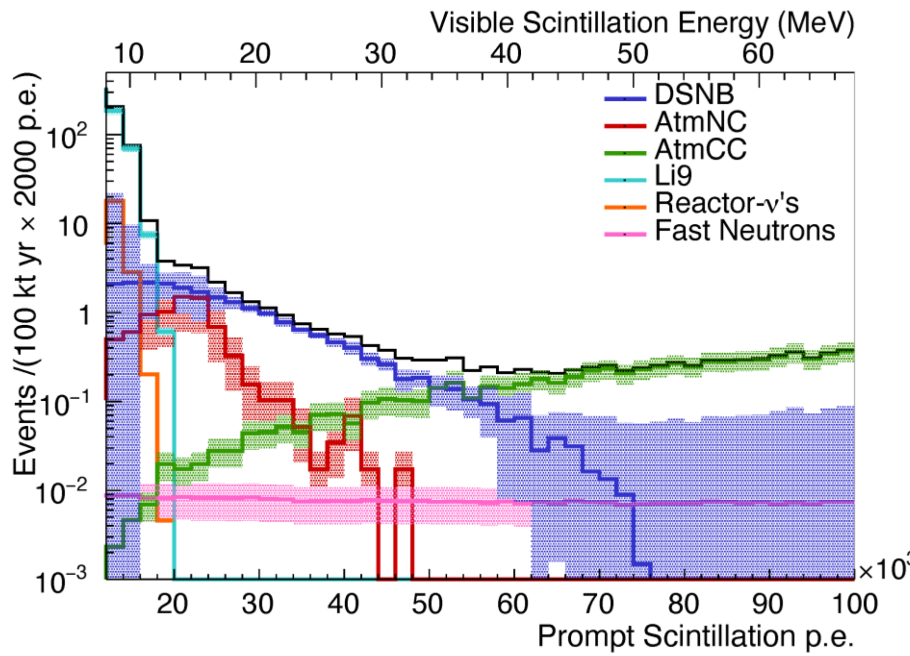
Detection in scintillator by inverse beta decay (IBD)

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

**Expected signal without cuts**



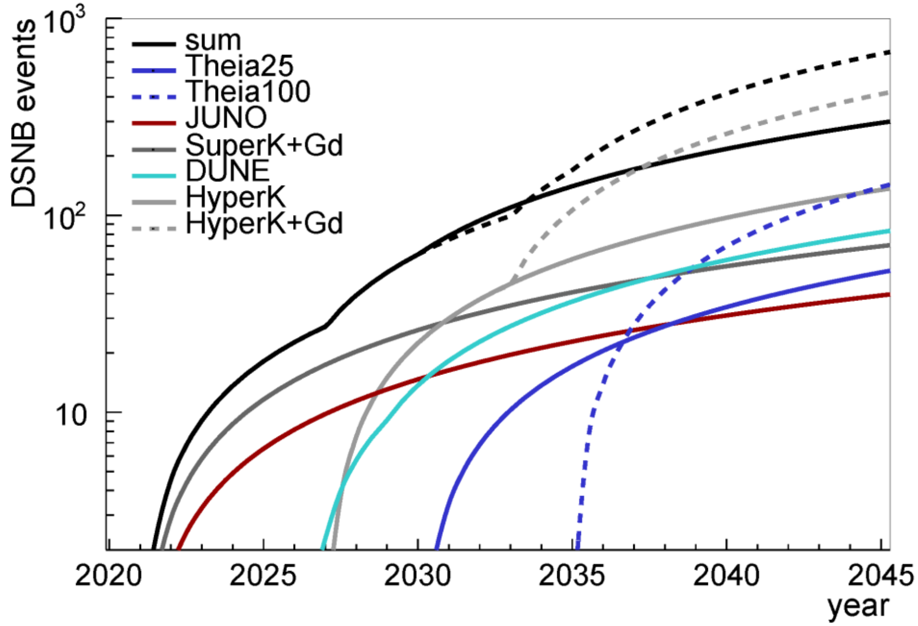

**Forecast after analysis cuts**




Background rejection crucial for detecting DSNB!

J.Sawatzki, PhD Thesis (2020) TUM

# DSNB Detection Prospect

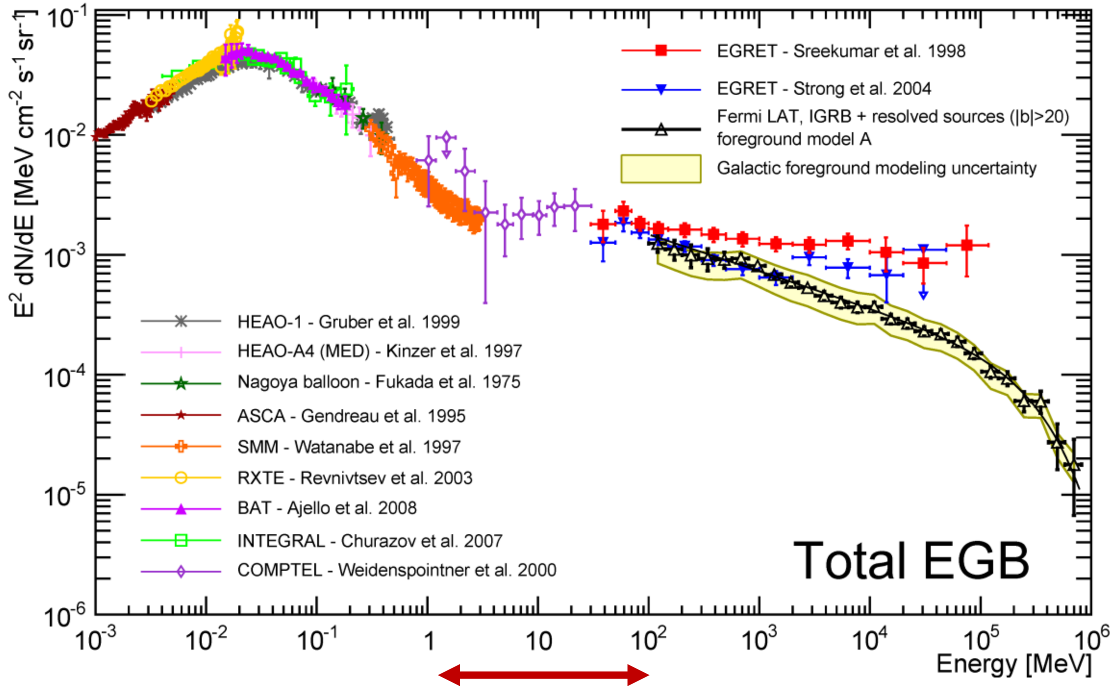



| Technology | Experiment | FM [kt] | Start | Energy Window [MeV] | Signal Efficiency | Signal [/(100 kt yr)] | BG | $\frac{S}{\sqrt{S+B}}$ | t[yr] for 3(5)$\sigma$ |
|---|---|---|---|---|---|---|---|---|---|
| WbLS | Theia25 | 20 | 2030 | 8–30 | 0.8 | 17.2 | 9.5 | 3.3 | 4.1 (11.4) |
| | Theia100 | 80 | 2035 | | | 17.5 | 9.1 | 3.4 | 1.0 (2.7) |
| LS | JUNO | 17.0 | 2021 | 10.2–29.2 | 0.5 | 9.6 | 4.2 | 2.6 | 7.9 (22.0) |
| WCD | SK-Gd | 22.5 | 2021 | 10–30 | 0.7 | 12.9 | 14.0 | 2.5 | 6.5 (18.0) |
| | HK | 187 | 2027 | 20–30 | 0.9 | 4.0 | 39.3 | 0.6 | 13.0 (36.2) |
| | HK-Gd | 187 | 2033 | 10–30 | 0.67 | 12.4 | 14.0 | 2.4 | 0.8 (2.3) |
| LAr | DUNE | 20+20 | 2026 | 16–40 | | 11.4 | 6.0 | 2.7 | 3.0 (8.4) |

Sawatzki+, arXiv:2007.14705

# Bounds on Radiatively Decaying Particles

Extra-galactic background light [arXiv:1410.3696]

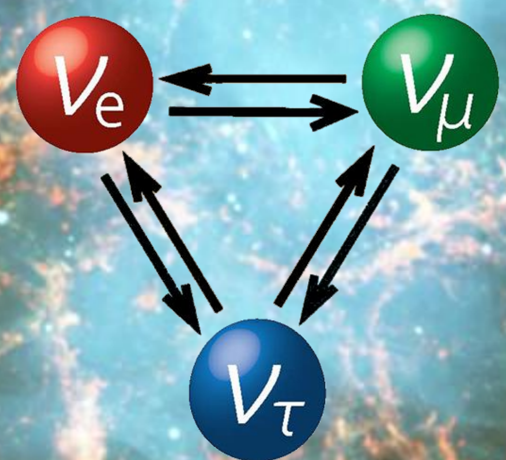



SN emitted particle energies

New particles emitted from SN core, radiatively unstable, eg axion-like particles (ALPs)

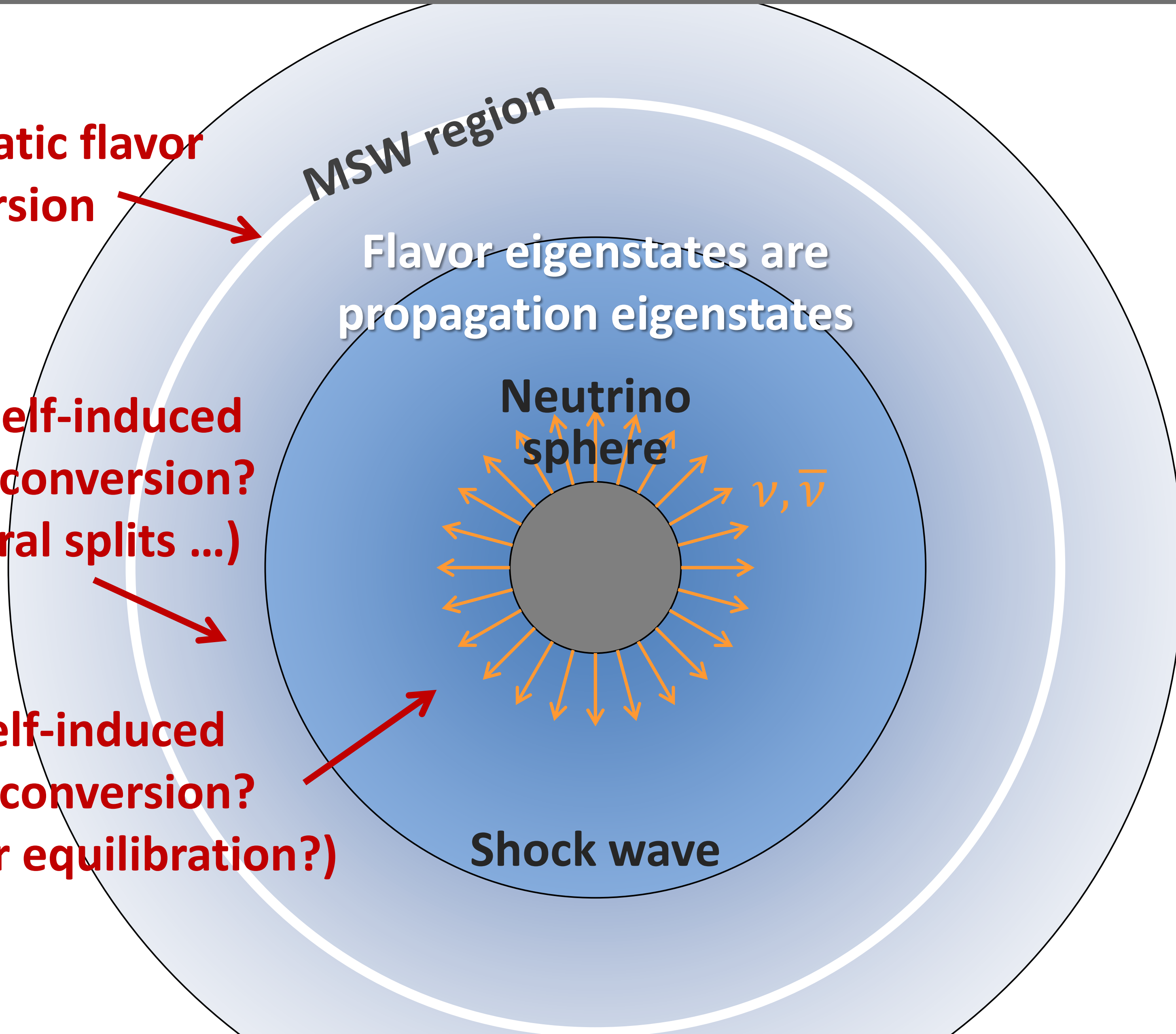
- Radiative decay outside SN: $a \to 2\gamma$, 100 MeV energies
- Contributes to diffuse cosmic $\gamma$-ray background
- Less than $10^{-4}$ of typical SN energy may appear in this form (Caputo+, in progress)
- For specific ALP constraints see arXiv:2008.11741
- Measuring the DSNB would make this more precise: correct core-collapse rate

# Supernova Neutrino Flavor Conversion



# Flavor Conversion in Core-Collapse Supernovae

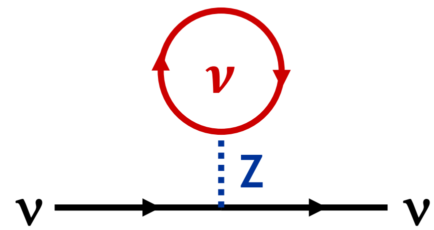
- **Adiabatic flavor conversion**
- **Slow self-induced flavor conversion? (Spectral splits …)**
- **Fast self-induced flavor conversion? (Flavor equilibration?)**



# Flavor-Off-Diagonal Refractive Index

2-flavor neutrino evolution as an effective 2-level problem

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




Effective mixing Hamiltonian

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

Mass term in flavor basis: causes vacuum oscillations

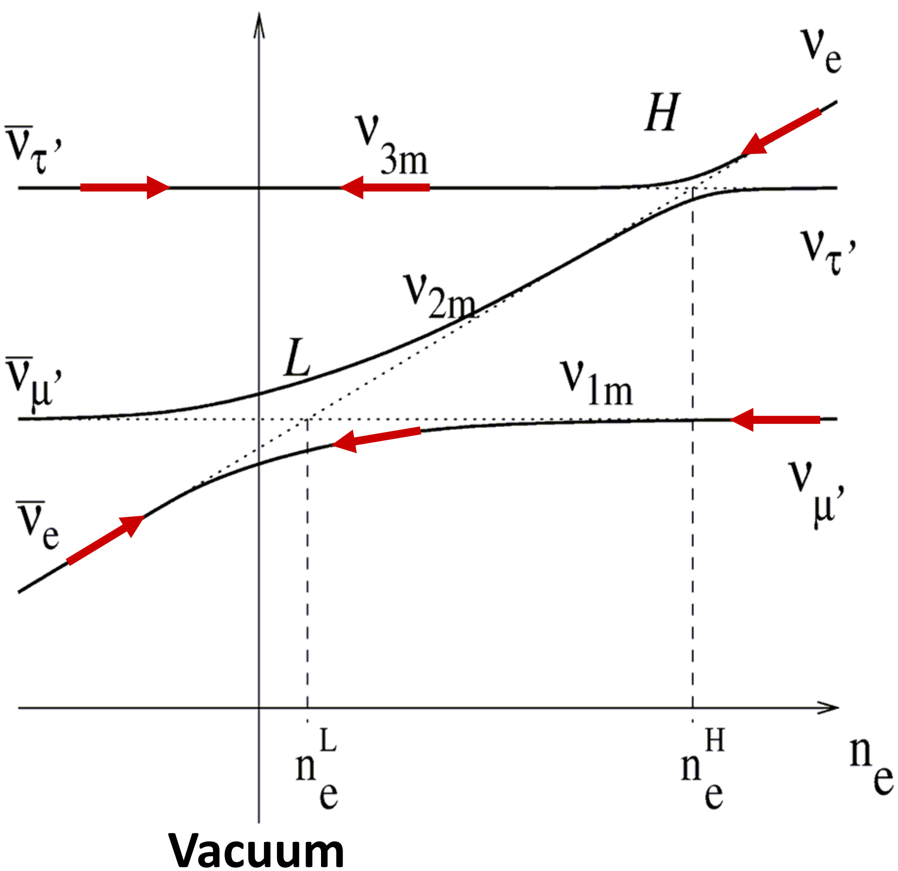
Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum term

Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

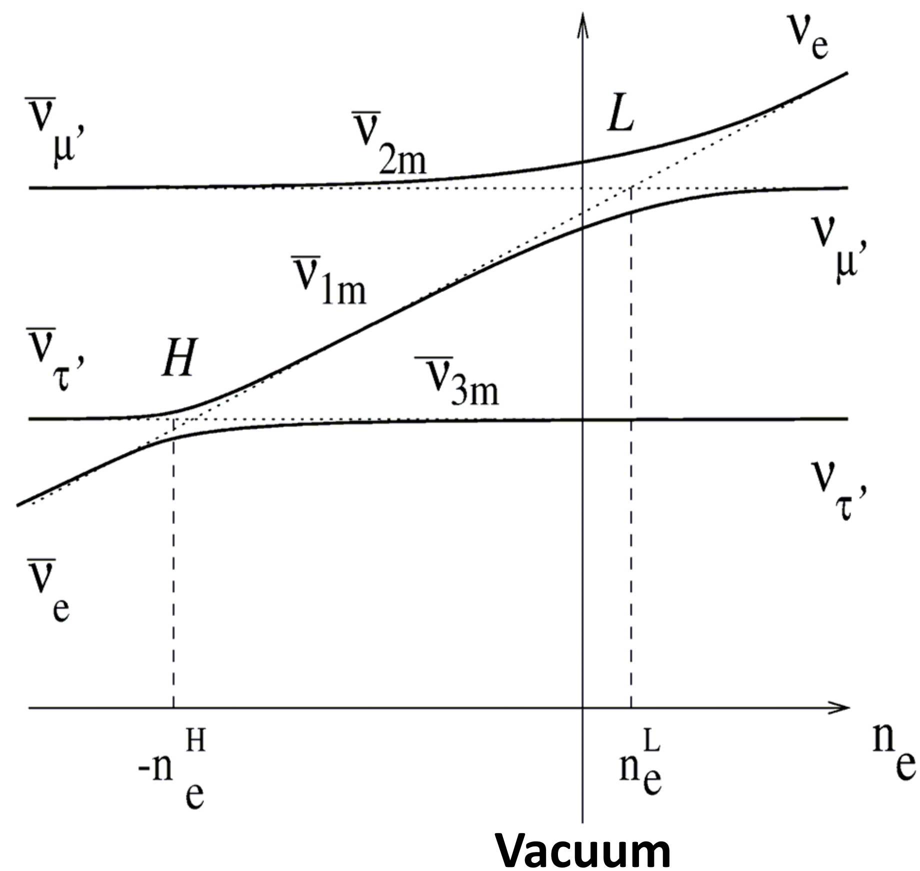
**Flavor oscillations feed back on the Hamiltonian: Nonlinear effects!**

# Level-Crossing Diagram in a Supernova Envelope

**Normal mass hierarchy**




**Inverted mass hierarchy**




Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

# SN Flavor Oscillations and Mass Ordering

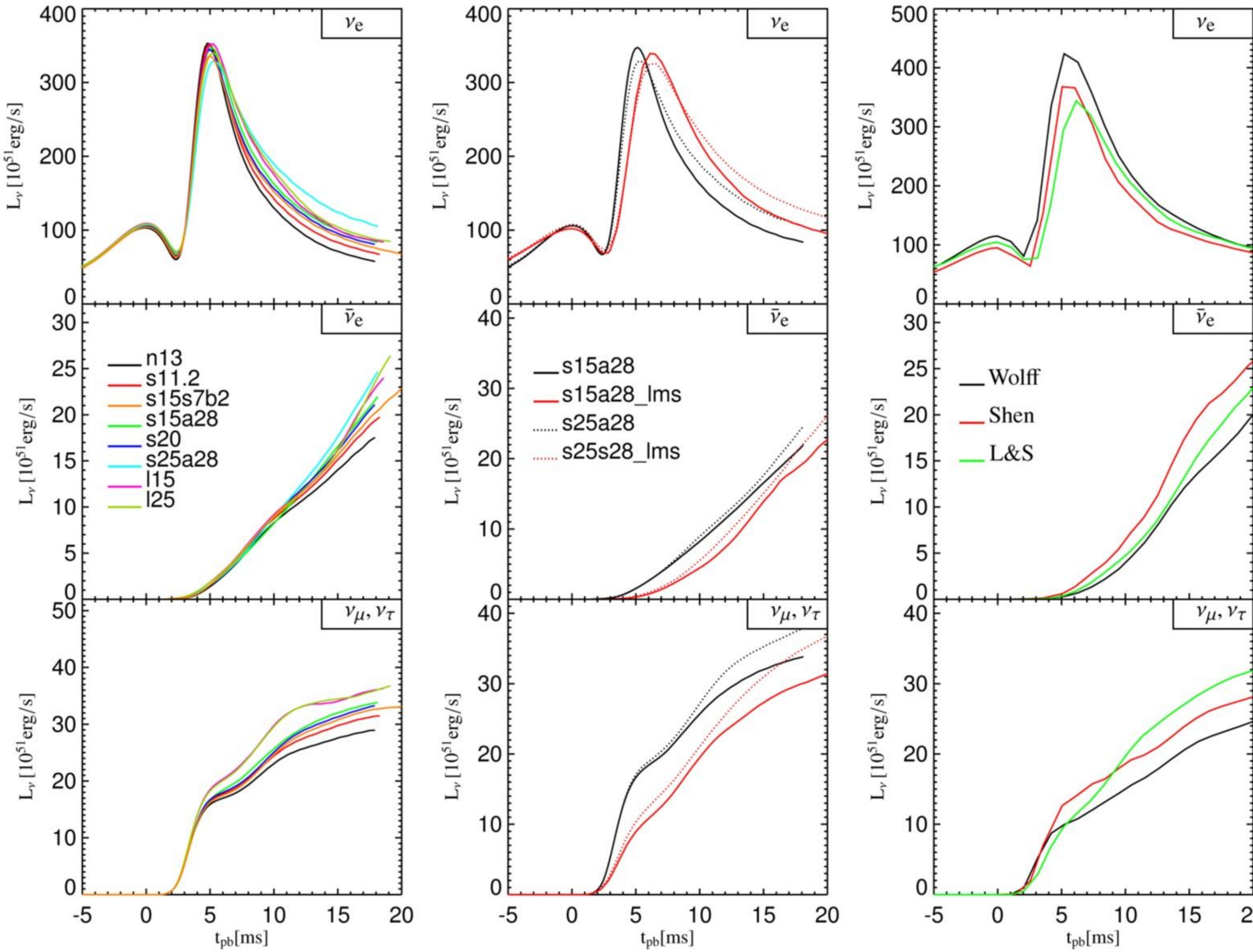
- Mixing angle $\Theta_{13}$ has been measured to be "large"
- MSW conversion in SN envelope adiabatic
- Assume that collective flavor oscillations are not important

| | Mass ordering | |
|---|---|---|
| | Normal (NO) | Inverted (IO) |
| $\nu_e$ survival prob. | 0 | $\sin^2\theta_{12} \approx 0.3$ |
| $\overline{\nu}_e$ survival prob. | $\cos^2\theta_{12} \approx 0.7$ | 0 |
| $\overline{\nu}_e$ Earth effects | Yes | No |

- When are collective oscillations important?
- How to detect signatures of ordering?

# Neutronization Burst as a Standard Candle

Different Mass | Neutrino Transport | Nuclear EoS




If mixing scenario is known, can determine SN distance (better than 5-10%)

Kachelriess, Tomàs, Buras, Janka, Marek & Rampp, astro-ph/0412082

# Deleptonization $\nu_e$ Burst in DUNE

## Neutrino mass ordering in argon detector

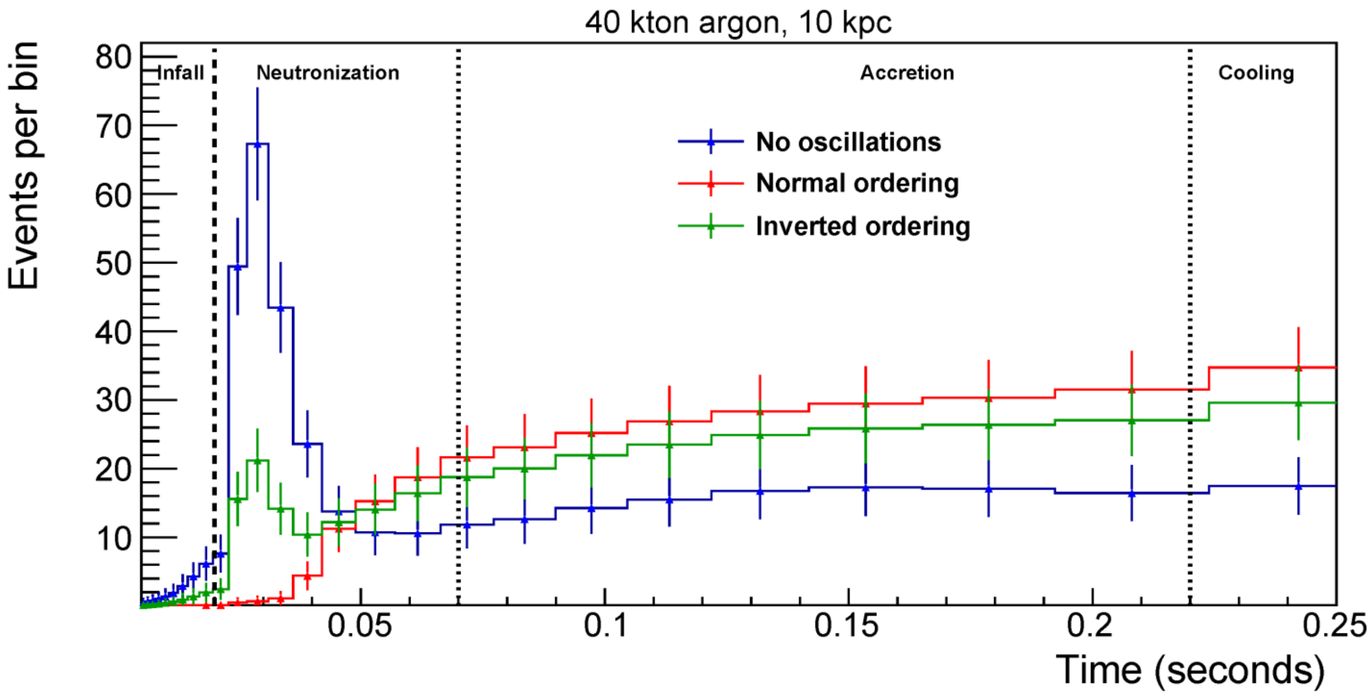
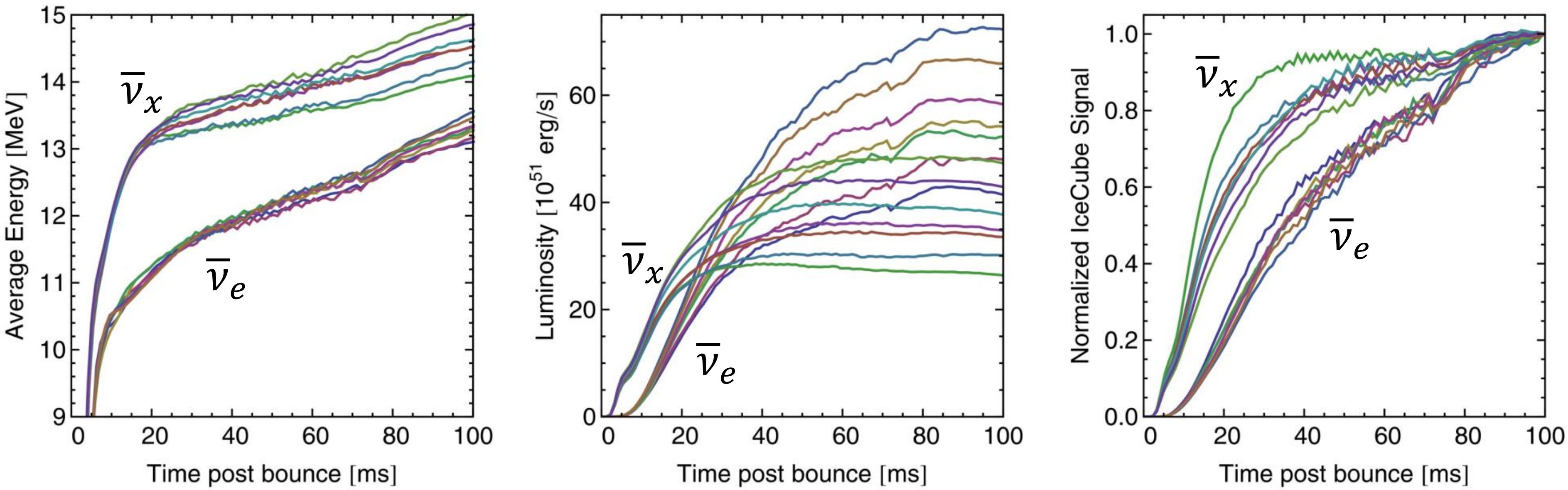



**Fig. 11** Expected event rates as a function of time for the electron-capture model in [8] for 40 kton of argon during early stages of the event – the neutronization burst and early accretion phases, for which self-induced effects are unlikely to be important. Shown are: the event rate for the unrealistic case of no flavor transitions (blue) and the event rates including the effect of matter transitions for the normal (red) and inverted (green) orderings. Error bars are statistical, in unequal time bins.

→ DUNE Collaboratation, arXiv:2008.06647

## Garching Models with M = 12–40 $M_\odot$

**Average Energy** **Luminosity** **IceCube Signature**




- In principle very sensitive to ordering, notably IceCube or HK
- "Standard candle" to be confirmed by other than Garching models

Abbasi et al. (IceCube Collaboration) A&A 535 (2011) A109
Serpico, Chakraborty, Fischer, Hüdepohl, Janka & Mirizzi, arXiv:1111.4483

# Self-Induced Flavor Conversion

**Flavor conversion (vacuum or MSW) for a neutrino of given momentum $p$**

- Requires lepton flavor violation by masses and mixing

$$\nu_e(p) \rightarrow \nu_\mu(p)$$

$$\frac{\Delta m^2_{\rm atm}}{2E} = 10^{-10}\,{\rm eV} = 0.5\ {\rm km}^{-1}$$

**Pair-wise flavor exchange by $\nu$–$\nu$ refraction (forward scattering)**

- No net flavor change of pair
- Requires dense neutrino medium (collective effect of interacting neutrinos)
- **Can occur without masses/mixing (and then does not depend on $\Delta m^2/2E$)**
- Familiar as neutrino pair process $\mathcal{O}(G_{\rm F}^2)$ Here as coherent refractive effect $\mathcal{O}(G_{\rm F})$

$$\nu_e(p) + \overline{\nu}_e(k) \rightarrow \nu_\mu(p) + \overline{\nu}_\mu(k)$$

$$\nu_e(p) + \nu_\mu(k) \rightarrow \nu_\mu(p) + \nu_e(k)$$

$$\sqrt{2}G_{\rm F}n_\nu = 10^{-5}\,{\rm eV} = 0.5\ {\rm cm}^{-1}$$

$$E = 12.5\ {\rm MeV}$$
$$R = 80\ {\rm km}$$
$$L_\nu = 40 \times 10^{51}\,{\rm erg/s}$$

**Fast Flavor Conversion (FFC)**

**Conditions and impact on SN is subject of a lot of current research!**

# Many Open Questions

**Flavor evolution in dense neutrino flows still on the level of simplified toy models and parametric studies**

- **Realistic normal-mode analysis without symmetry assumptions?**
- **Realistic triggering of stable or unstable flavor waves?**
- **Do tachyonic modes really lead to flavor equilibration?**
  **(Going beyond linearised stability analysis)**
- **Realistic impact on SN explosion and nucleosynthesis?**


**It is only the beginning.**
**A lot more work ahead of us …**

# Shifting Targets

## Important questions circa 1987

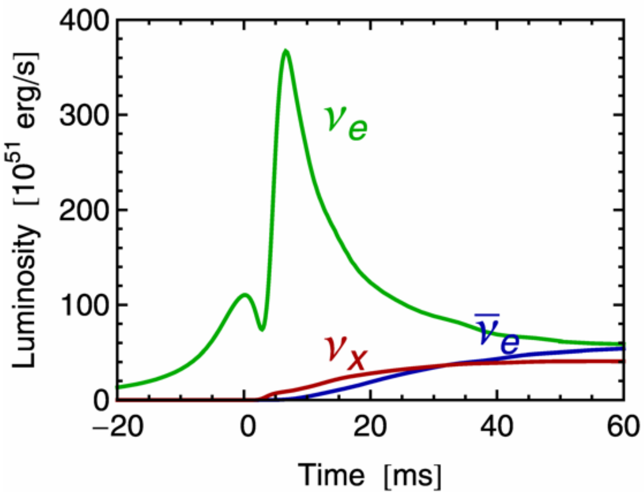
- How many neutrino flavors? (Z decay width early 1990s)
- What are neutrino masses?
- Do neutrinos oscillate? (MSW effect 1985)
- How do core-collapse SNe explode? (Bethe-Wilson 1982–1985)

## Status circa 2021

- Mass: restrictive cosmo limits, measurement “in the sky” foreseen
- KATRIN: sub-eV limit, new experiments foreseen
- Large mixing between three flavors ($\theta_{13}$ not small, 2012)
- Mass ordering and CP violation foreseen in the lab (JUNO, ...)
- Collective flavor conversion needs to be fully understood
- Modern SN models now in 3D, explosions probably ok
- Significant fraction of black-hole formation
- Huge amount of relevant astro observations

# Three Phases – Three Opportunities

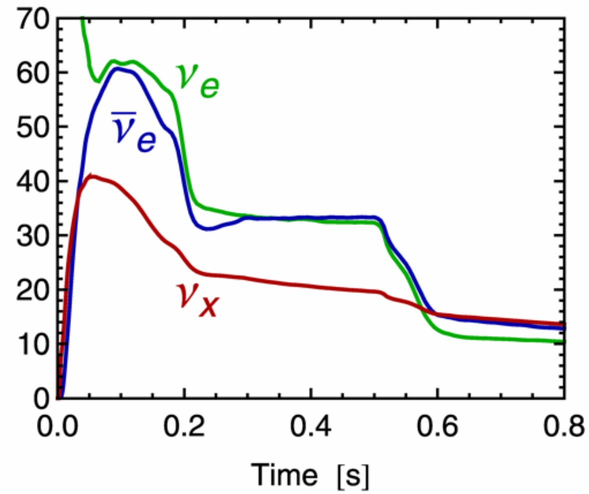
## Prompt $\nu_e$ burst




“Standard Candle”

- SN theory
- Distance
- Flavor conversions
- Multi-messenger time of flight

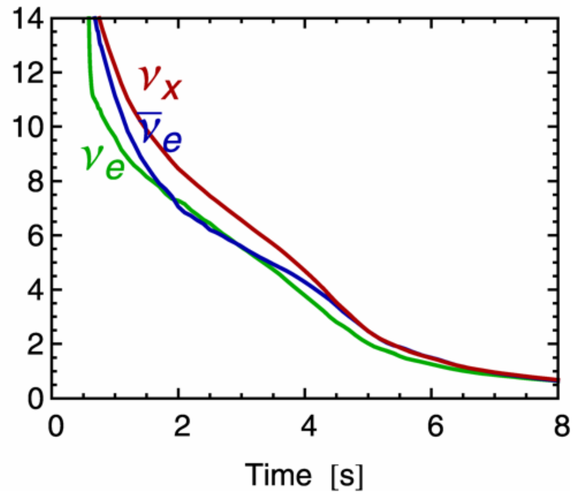
## Accretion




Strong variations (progenitor, 3D effects, black hole formation, …)

- Testing astrophysics of core collapse
- Flavor conversion has strong impact on signal

## Cooling

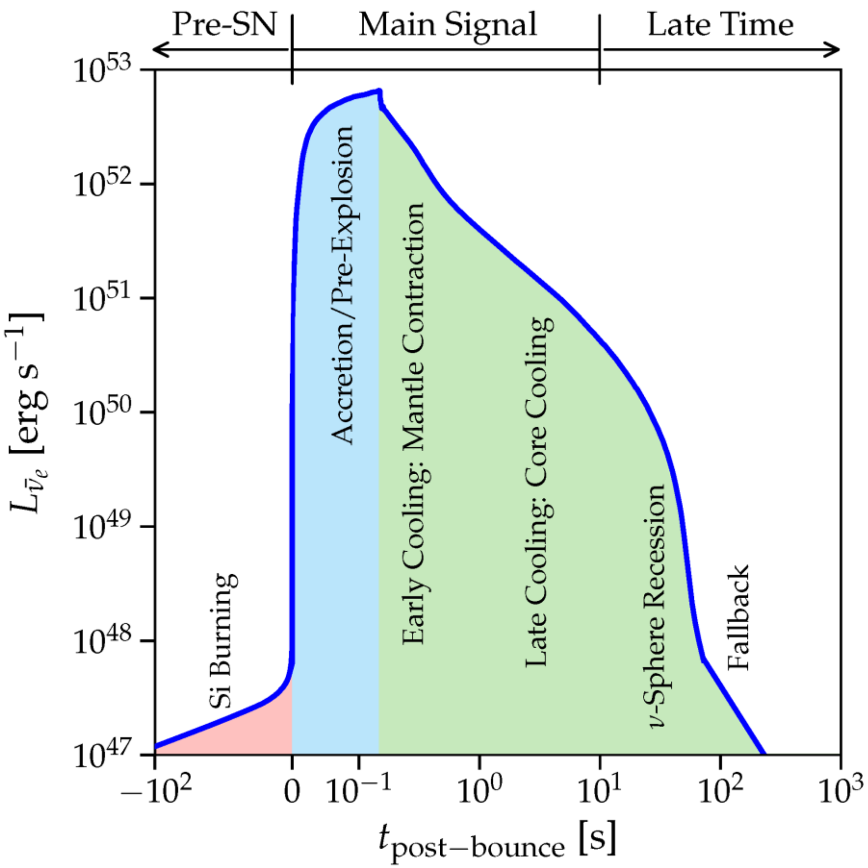



EoS & mass dependence

- Testing Nuclear Physics
- Nucleosynthesis in neutrino-driven wind
- Particle bounds from cooling speed (axions …)

# Five Phases – Yet More Opportunities

Li, Roberts & Beacom [arXiv:2008.04340]

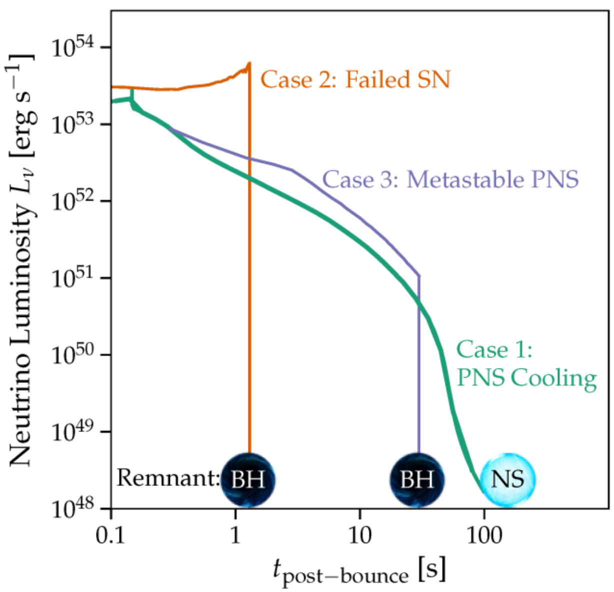


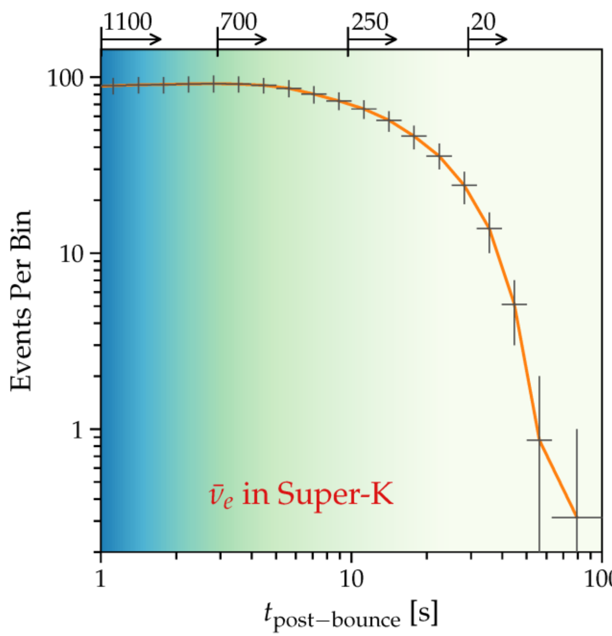

| Phase | Physics Opportunities |
|---|---|
| Pre-SN | early warning, progenitor physics |
| Neutronization | flavor mixing, SN distance, new physics |
| Accretion | flavor mixing, SN direction, multi-D effects |
| Early cooling | equation of state, energy loss rates, PNS radius, diffusion time, new physics |
| Late cooling | NS vs. BH formation, transparency time, integrated losses, new physics |

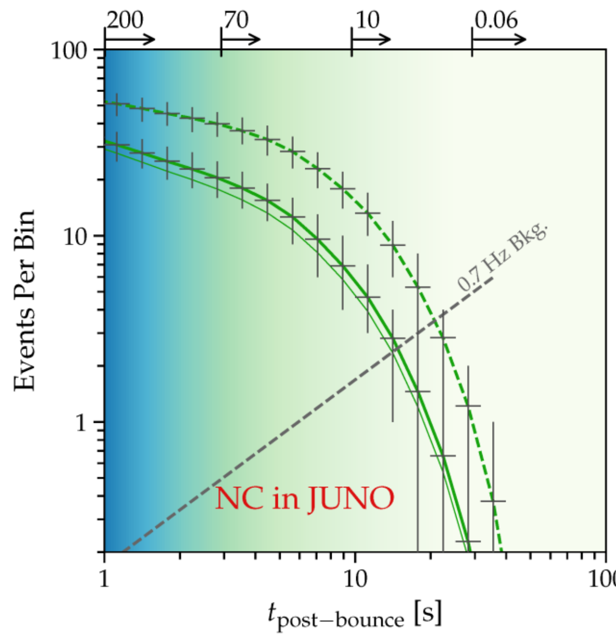
TABLE I. Key physics opportunities from detecting supernova neutrinos in different phases.

# Late-Time Signal

Li, Roberts & Beacom [arXiv:2008.04340]




**Late-time signal under-appreciated aspect in big detectors!**

**Many large detectors online for next decades**

**Every year a 3% chance**

**I am optimistic to see more supernova neutrinos!**

# Some Reviews

- Mirizzi, Tamborra, Janka, Saviano & Scholberg:
  **Supernova Neutrinos: Production, Oscillations and Detection**
  → arXiv:1508.00785

- Burrows & Vartanyan: **Core-Collapse Supernova Explosion Theory**
  → arXiv:2009.14157

- Janka: **Neutrino Emission from Supernovae**
  → arXiv:1702.08713

- Beacom: **The Diffuse Supernova Neutrino Background**
  → arXiv:1004.3311

- Himmel & Scholberg: **Supernova Neutrino Detection**
  → arXiv:1205.6003