Neutrino Summer Lectures 2021 @ Fermilab (virtual)

Supernova Neutrinos

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

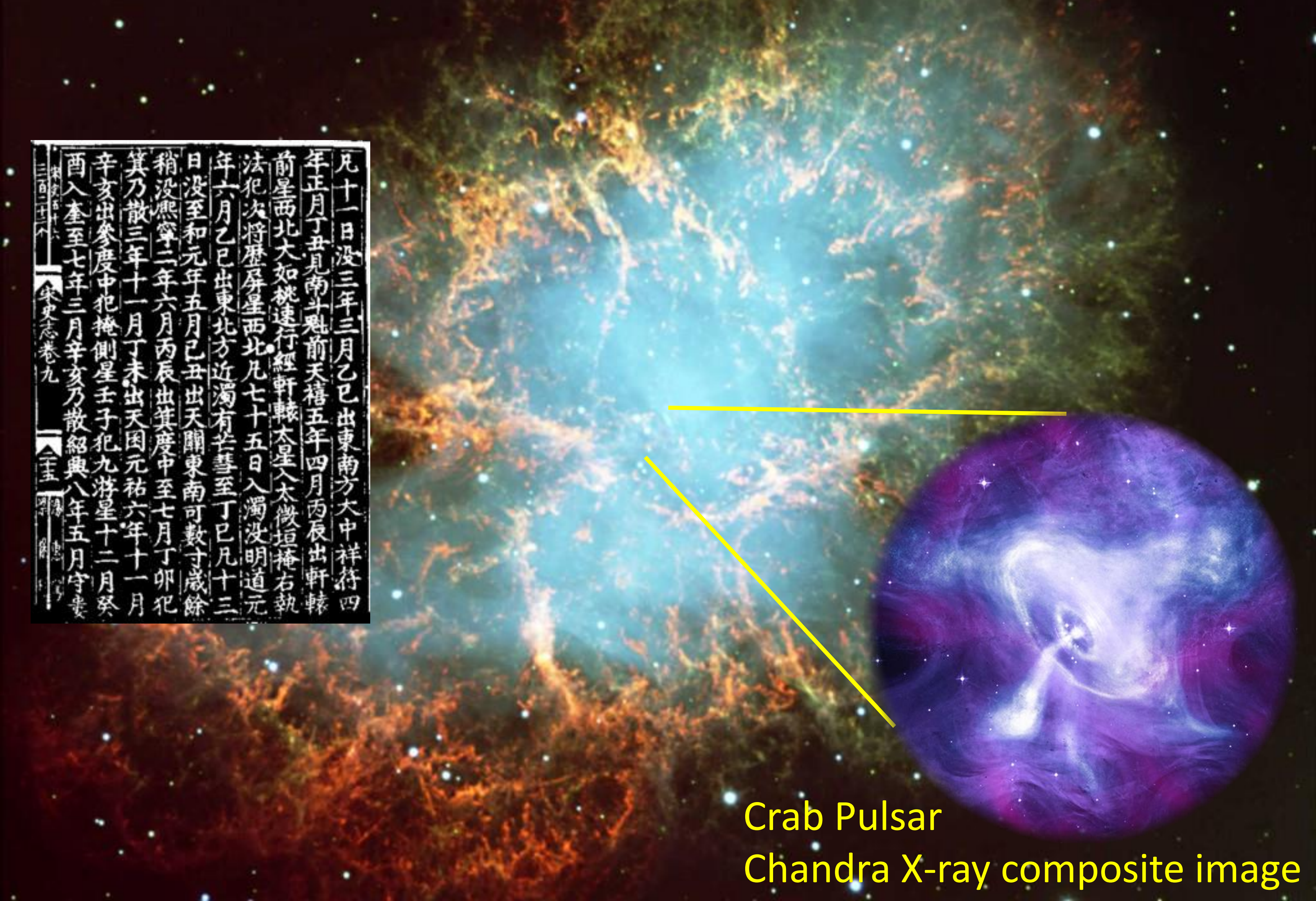
SFB 1258 Neutrinos Dark Matter Messengers

Crab Nebula – Remnant of SN 1054

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

Crab Nebula – Remnant of SN 1054



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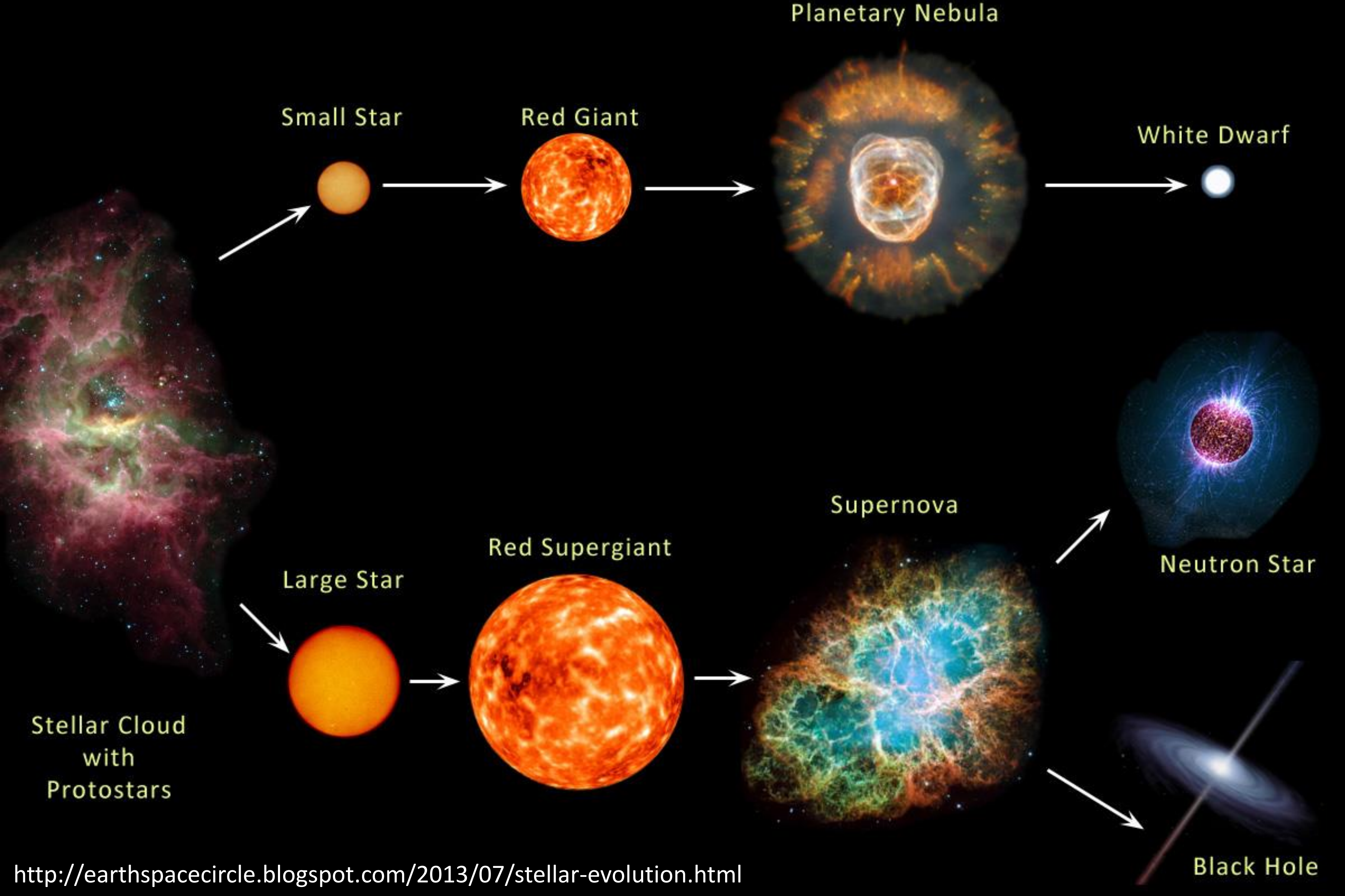
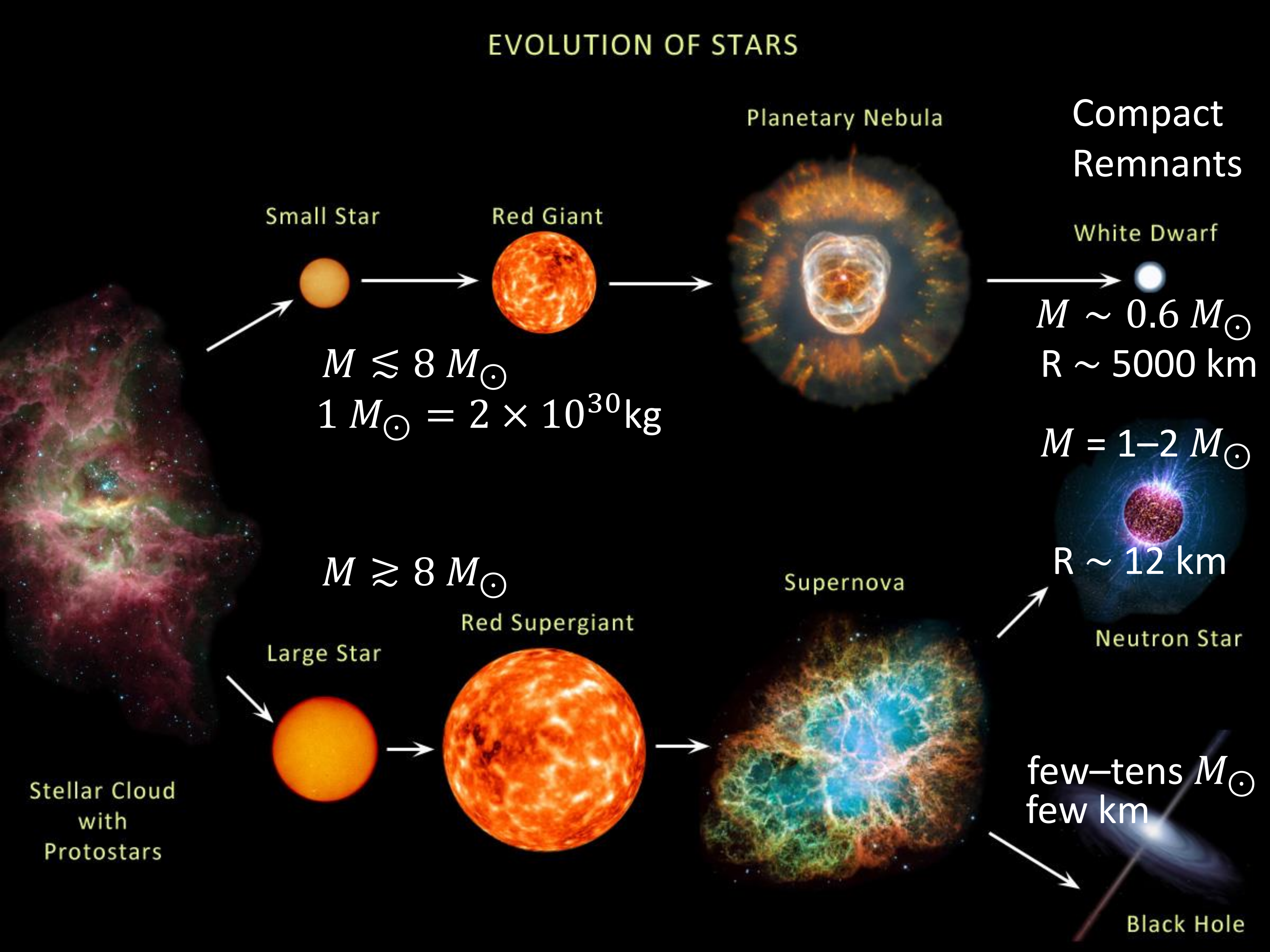
Crab Pulsar
Chandra X-ray composite image

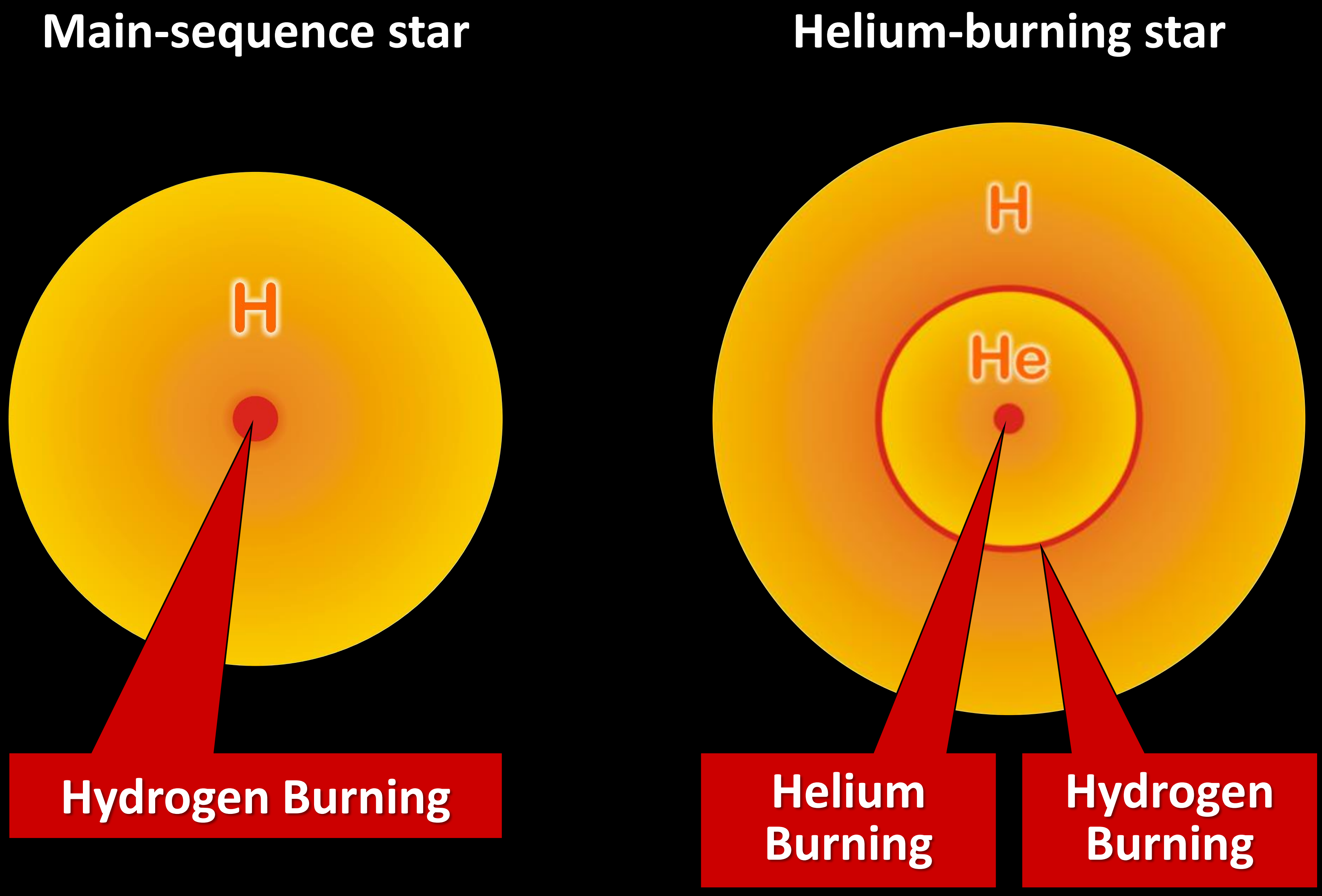
EVOLUTION OF STARS



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

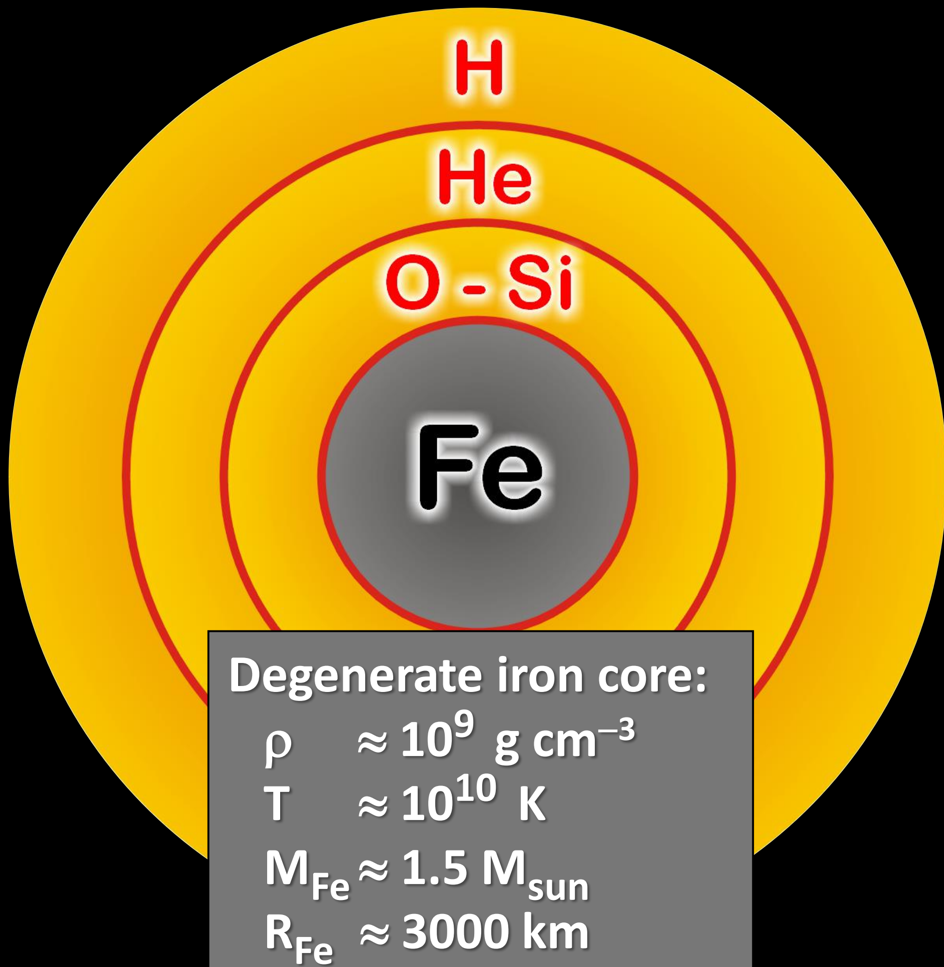

EVOLUTION OF STARS
Planetary Nebula
Compact Remnants
Small Star
Red Giant
White Dwarf
$M \sim 0.6\ M_\odot$
R ~ 5000 km
$M \lesssim 8\ M_\odot$
$1\ M_\odot = 2 \times 10^{30}$kg
M = 1–2 $M_\odot$
R ~ 12 km
$M \gtrsim 8\ M_\odot$
Supernova
Red Supergiant
Neutron Star
Large Star
few–tens $M_\odot$
few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

Stellar Collapse and Supernova Explosion

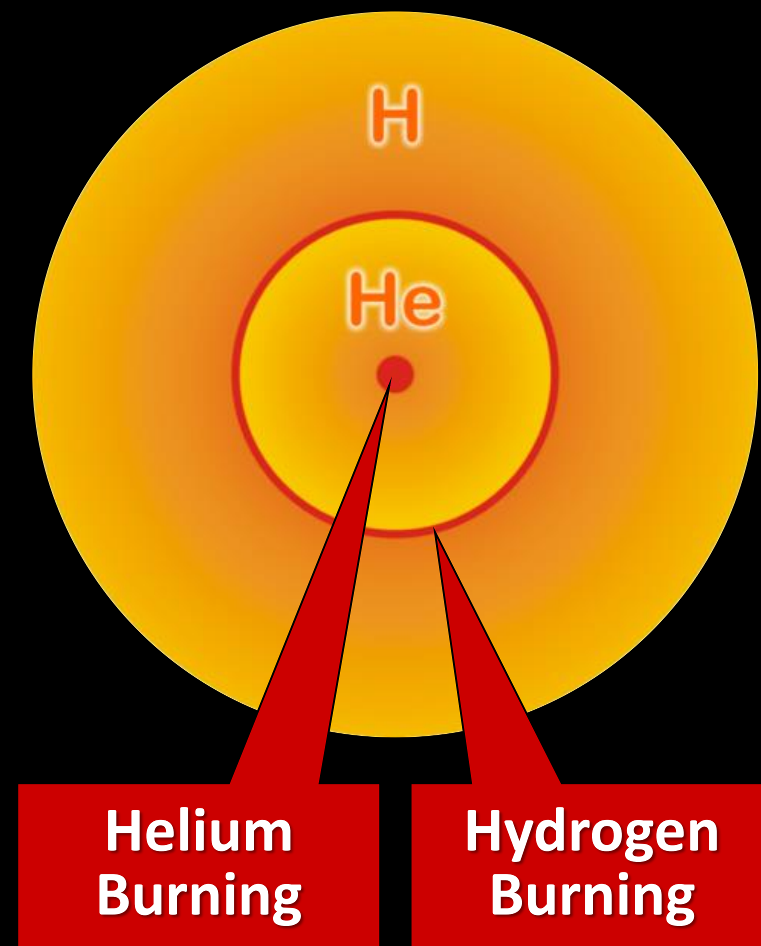


Stellar Collapse and Supernova Explosion

Onion structure

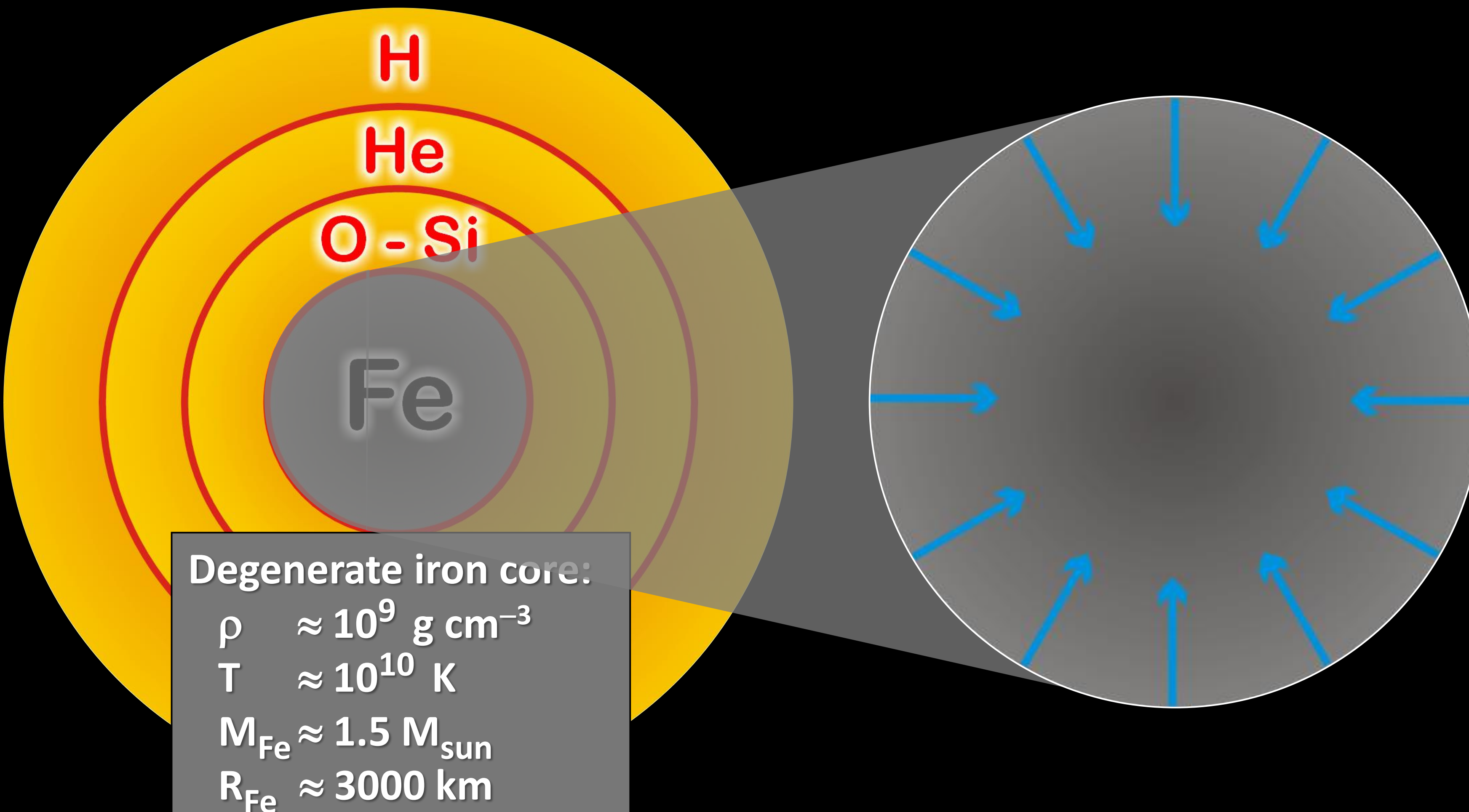


Helium-burning star



Stellar Collapse and Supernova Explosion

Onion structure | **Collapse (implosion)**



Degenerate iron core:

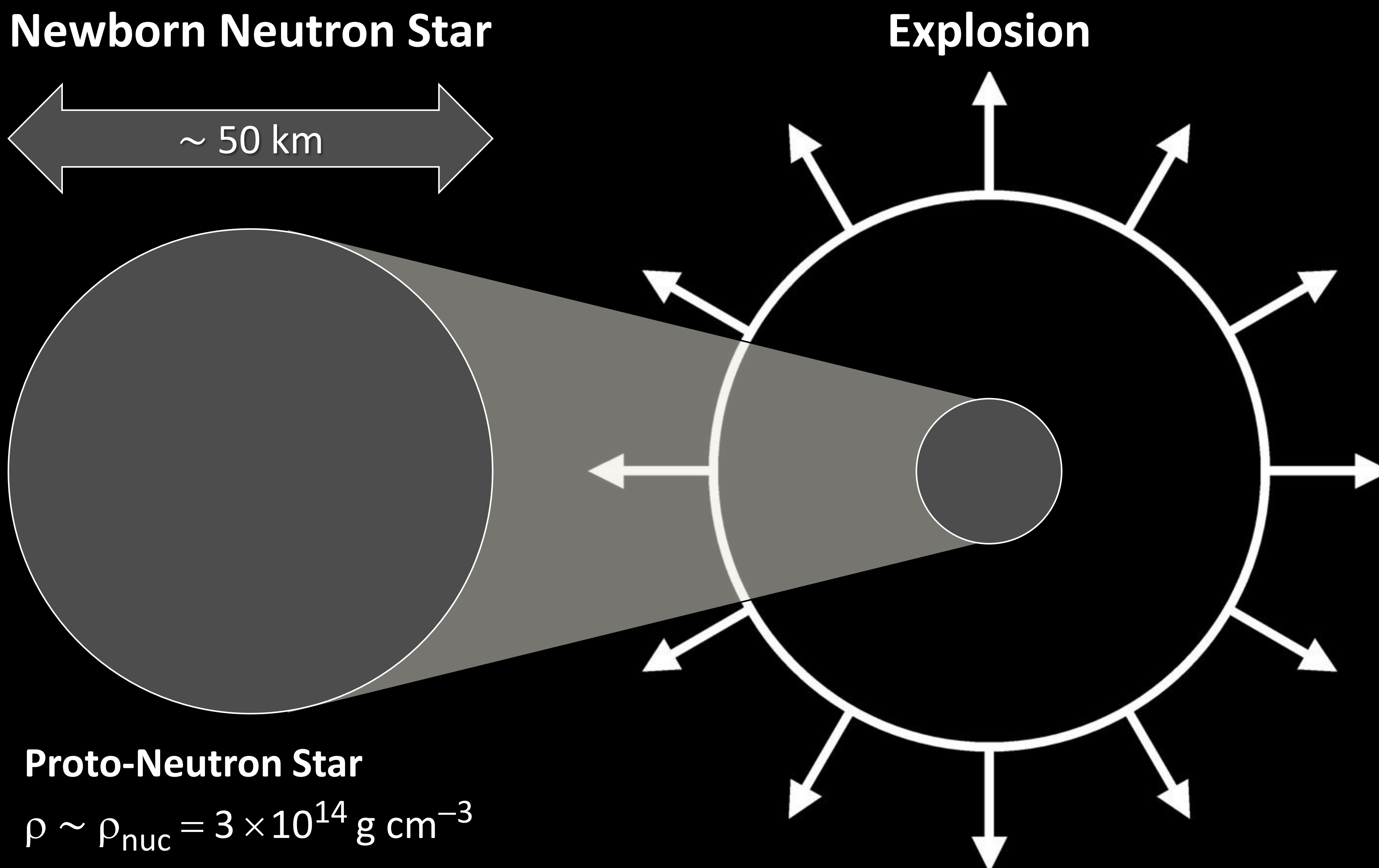
$\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$

$T \approx 10^{10}\ \mathrm{K}$

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

$R_{Fe} \approx 3000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion



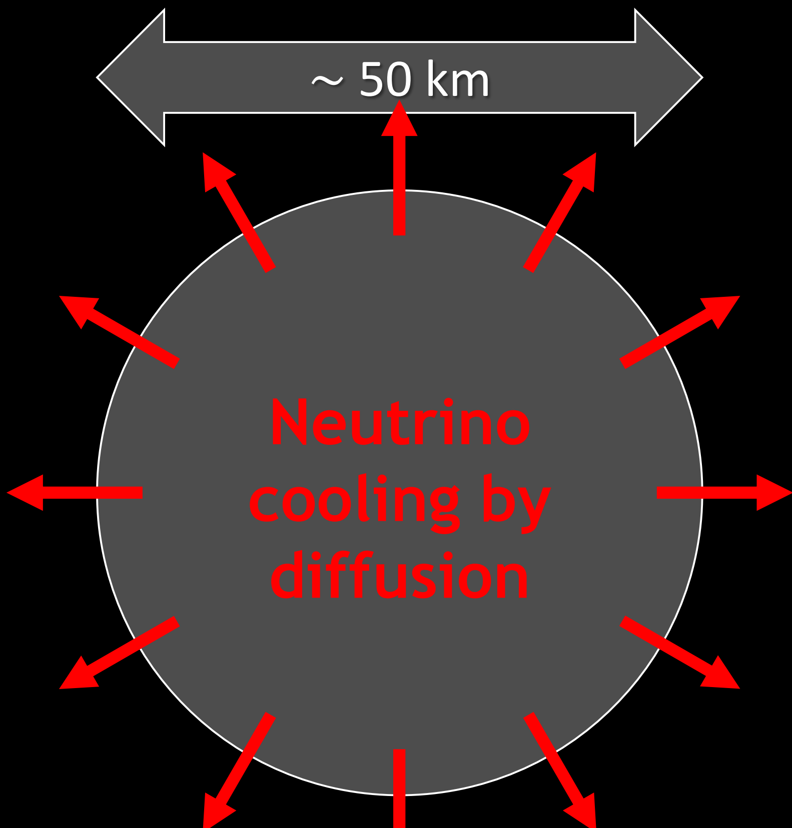
Proto-Neutron Star

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

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

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

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

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

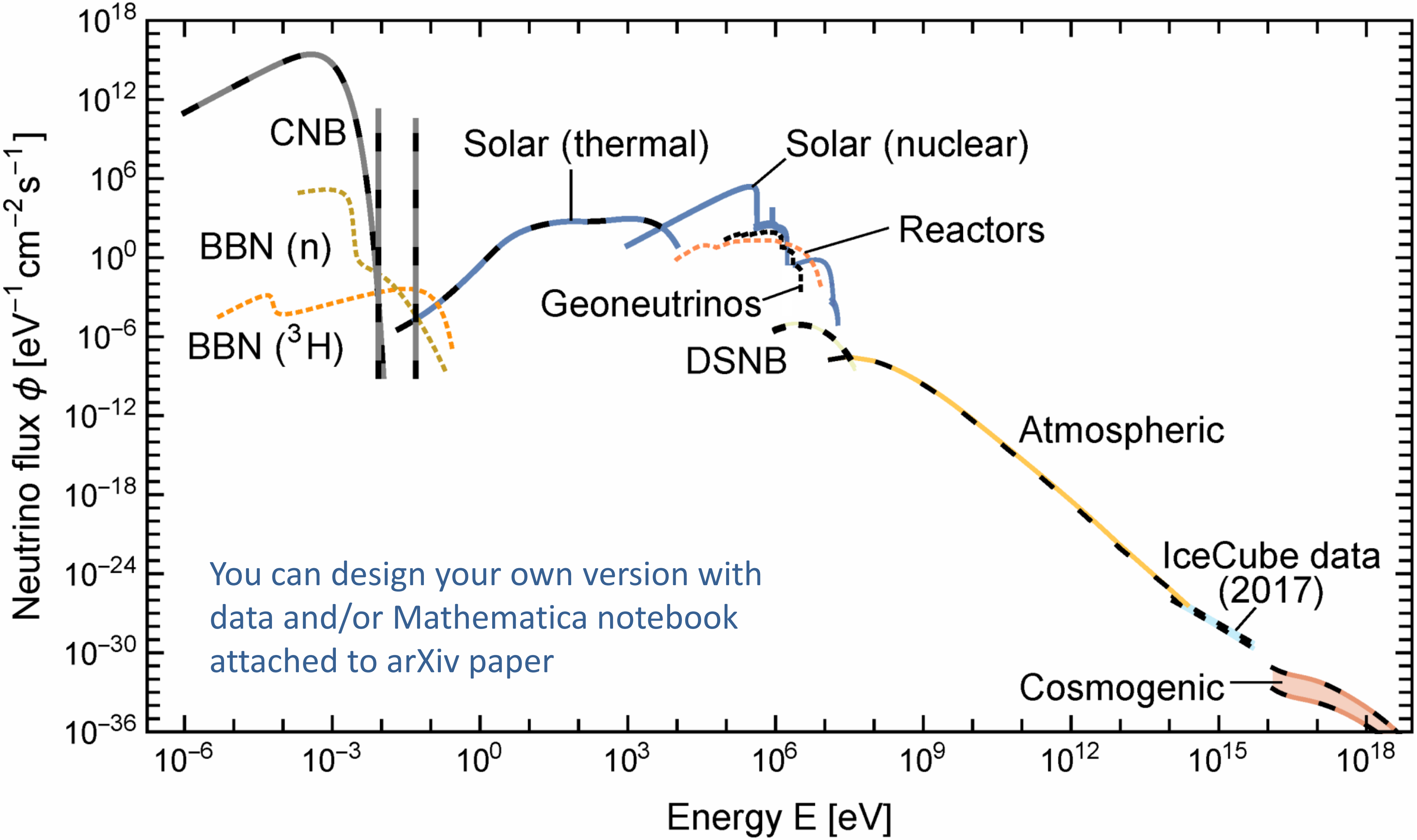
$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$\sim 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

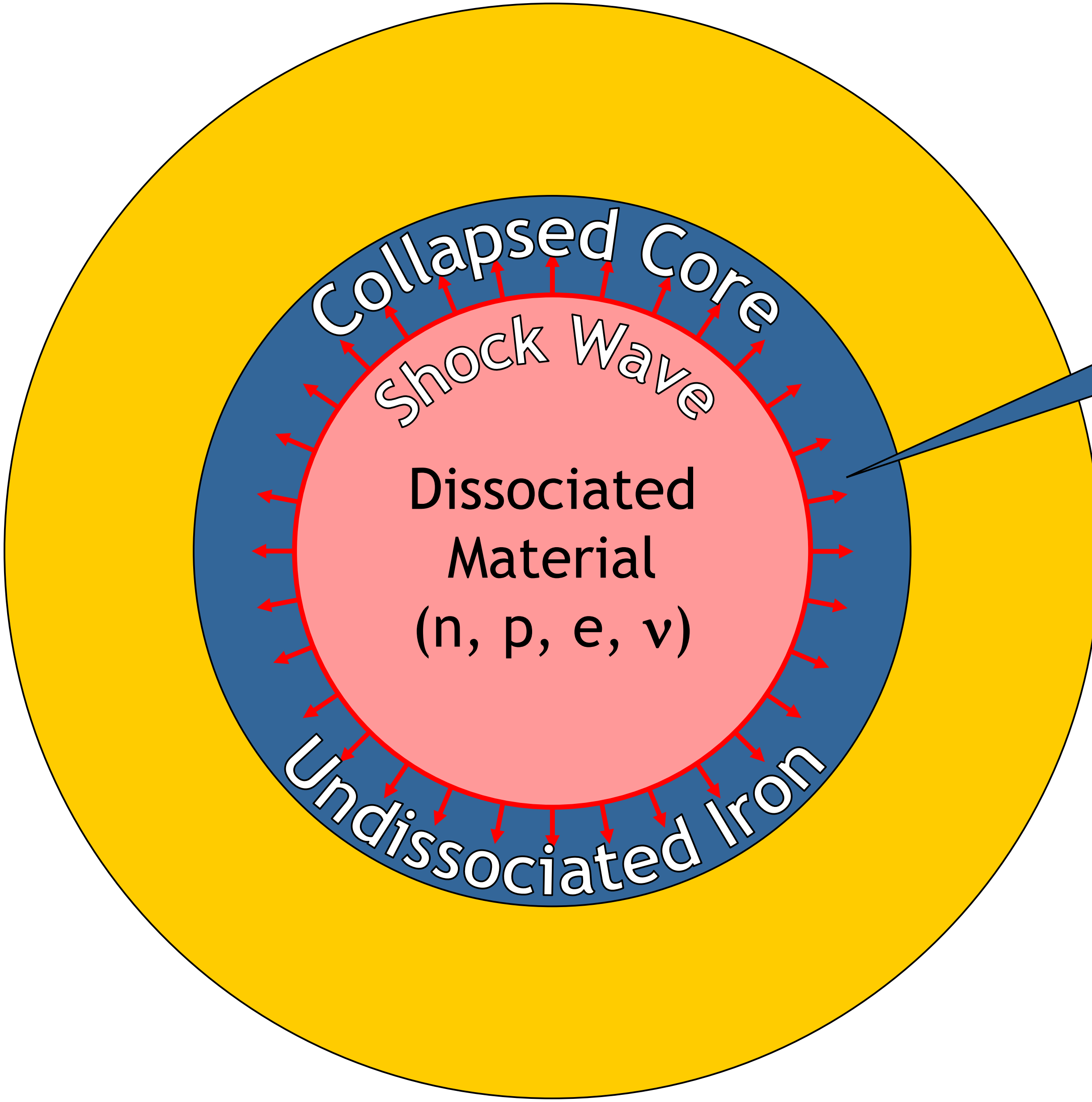
Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



You can design your own version with data and/or Mathematica notebook attached to arXiv paper

Why No Prompt Explosion?



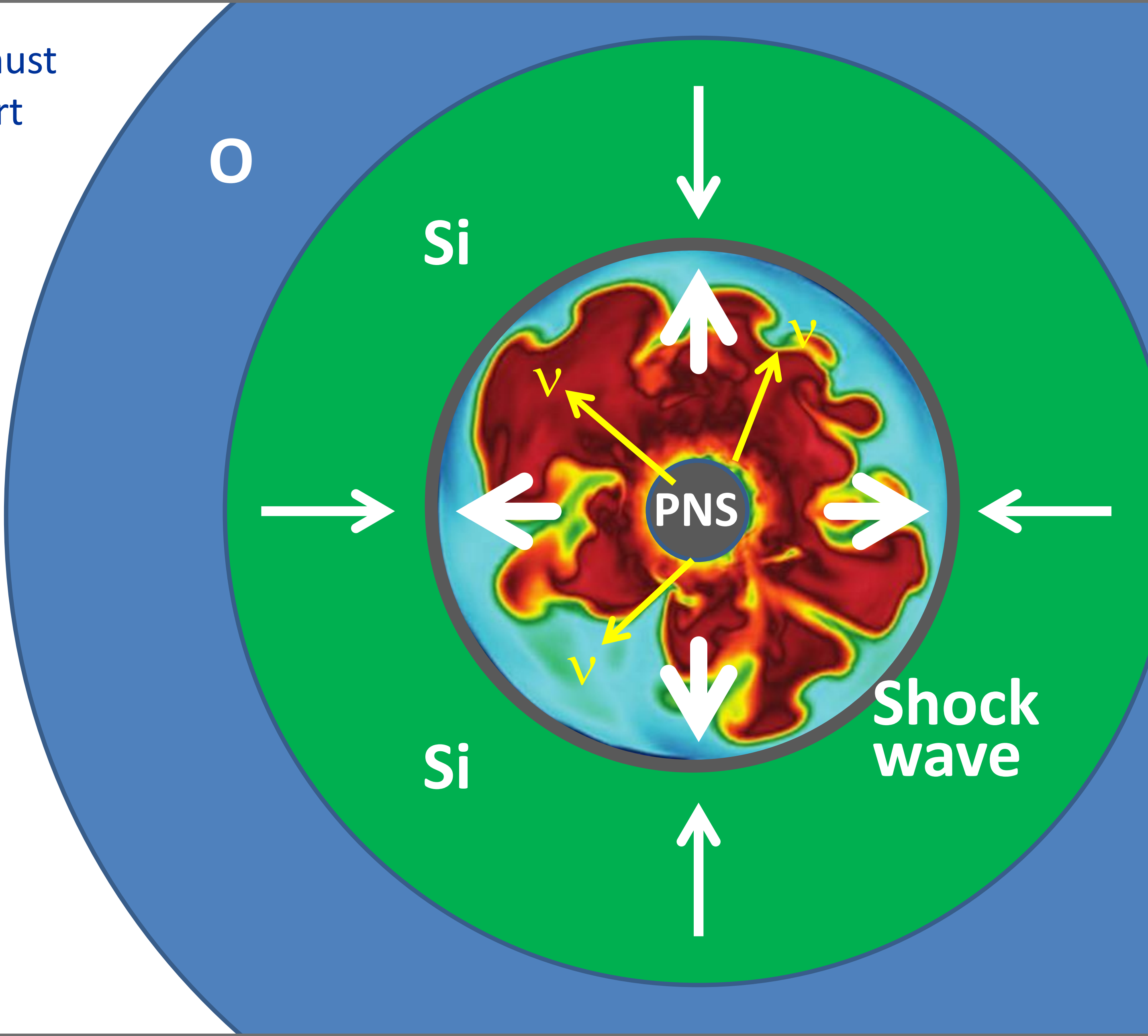
- 0.1 M_{sun} of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

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

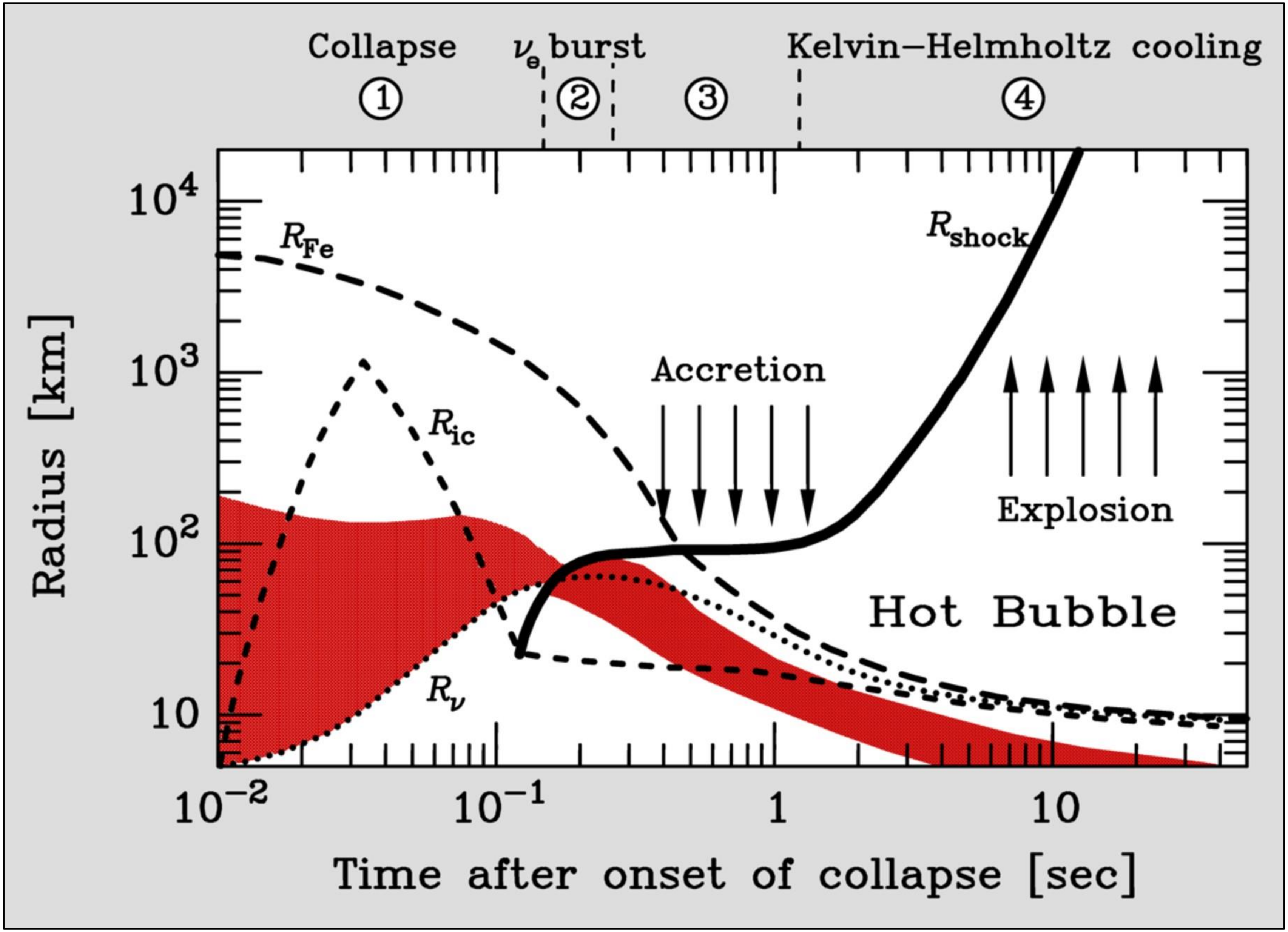
Shock Revival by Neutrinos

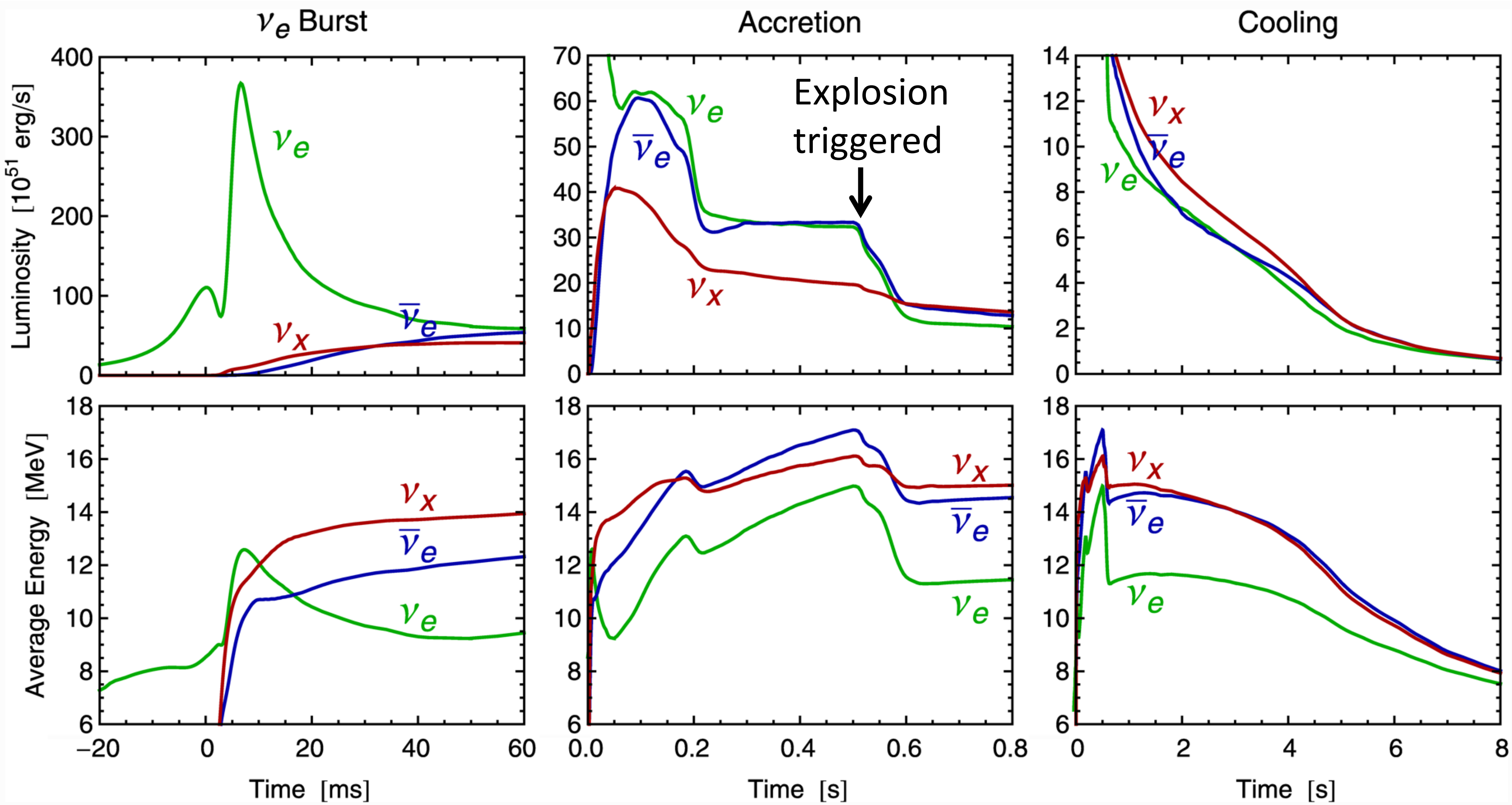
Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

Shock can receive fresh energy from neutrinos!



Supernova Delayed Explosion Scenario





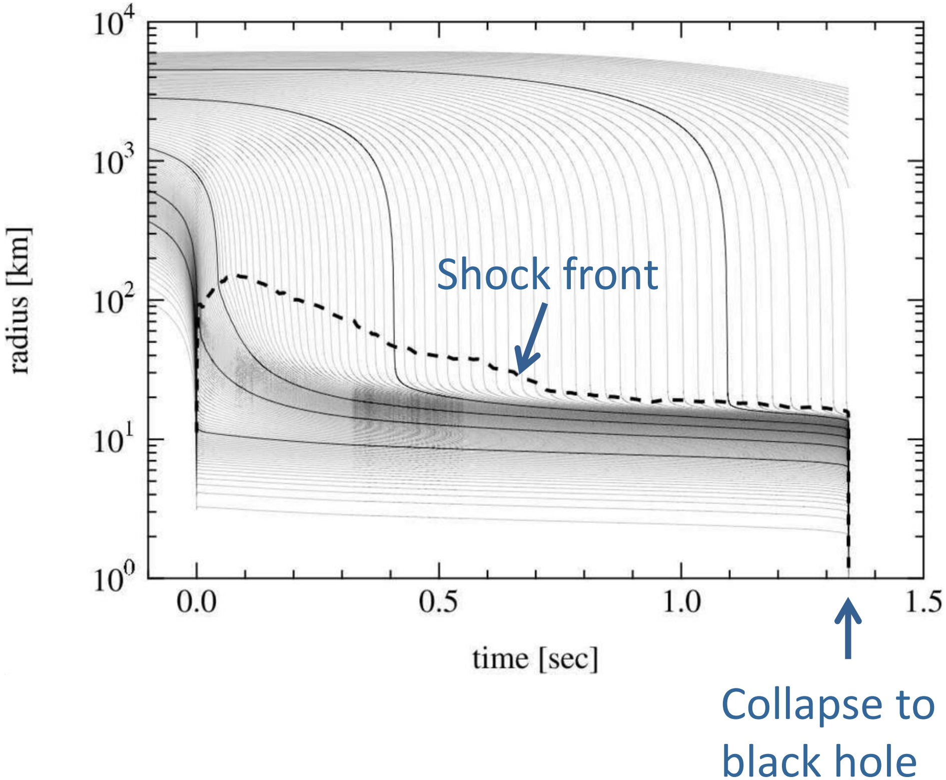
- Shock breakout
- De-leptonization of outer core layers

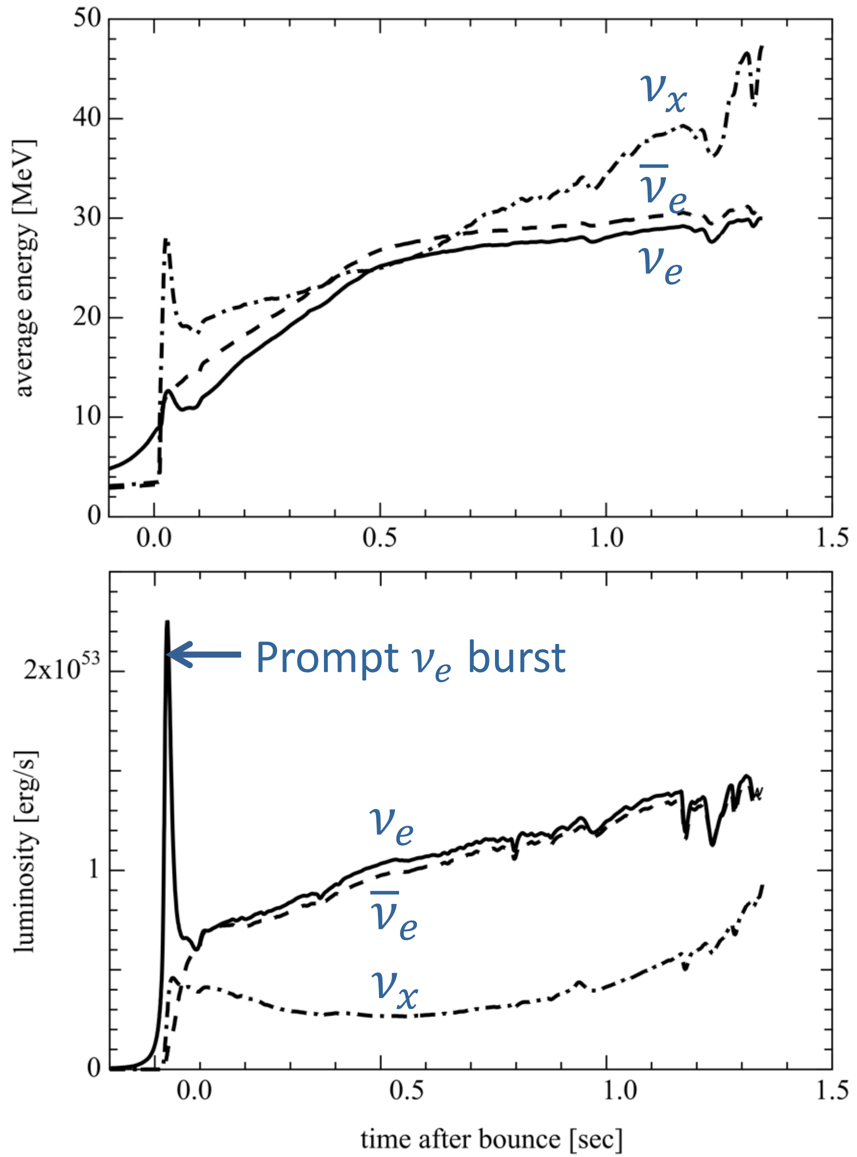
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

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

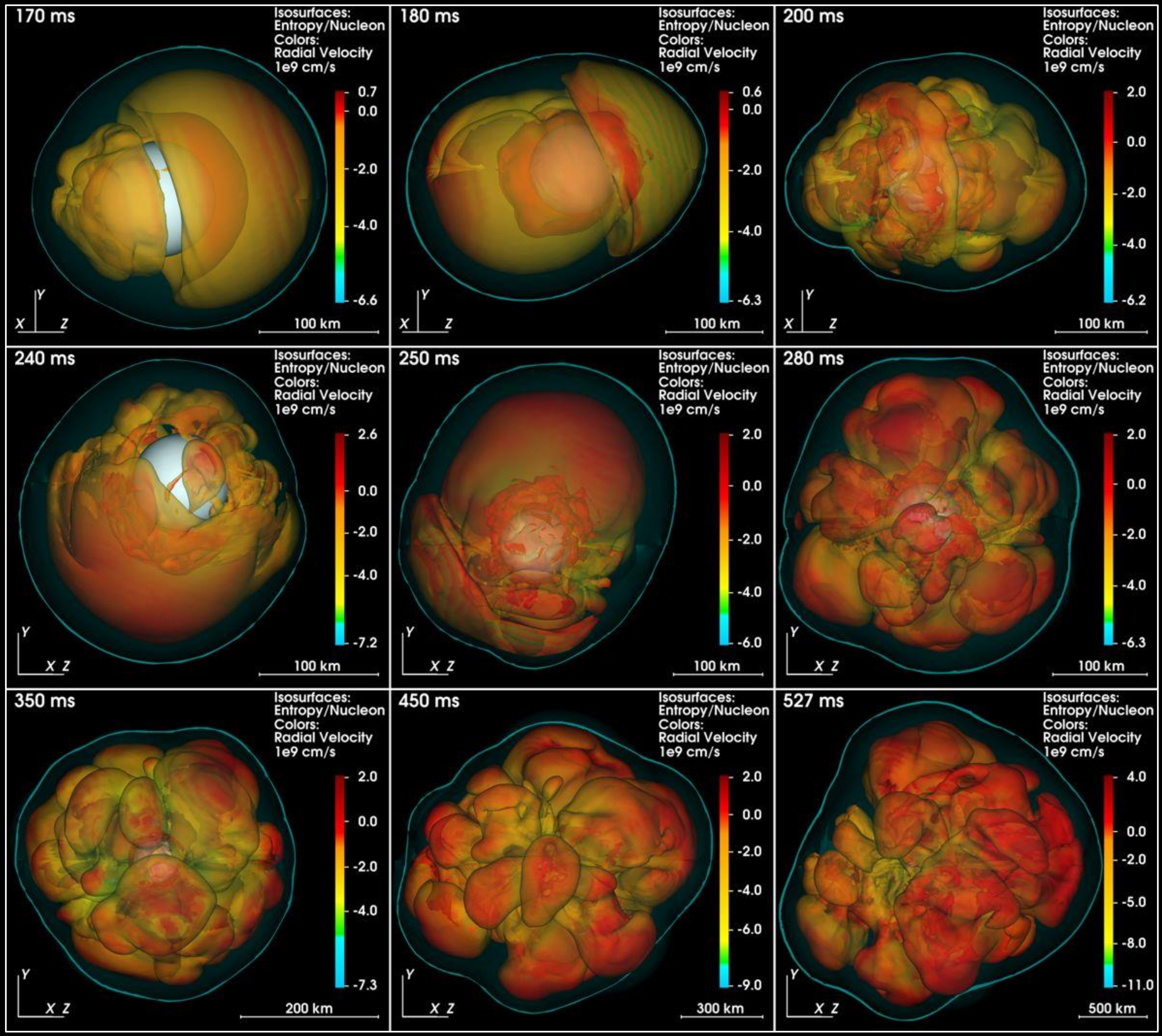
Neutrino Signal of a Failed Supernova (40 M_{SUN})





Sumiyoshi, Yamada & Suzuki, arXiv:0706.3762

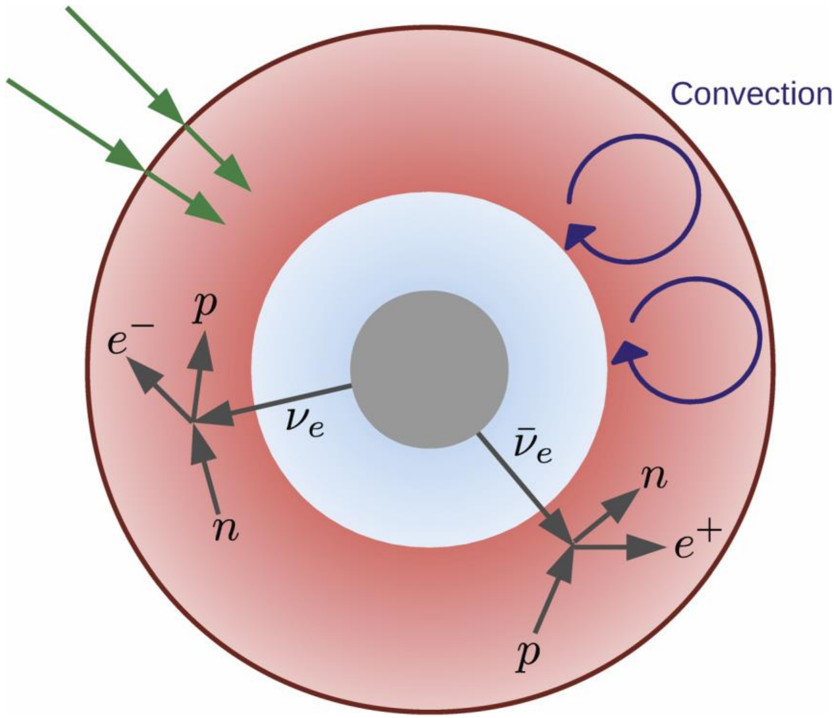
Breaking Spherical Symmetry (3D Effects)



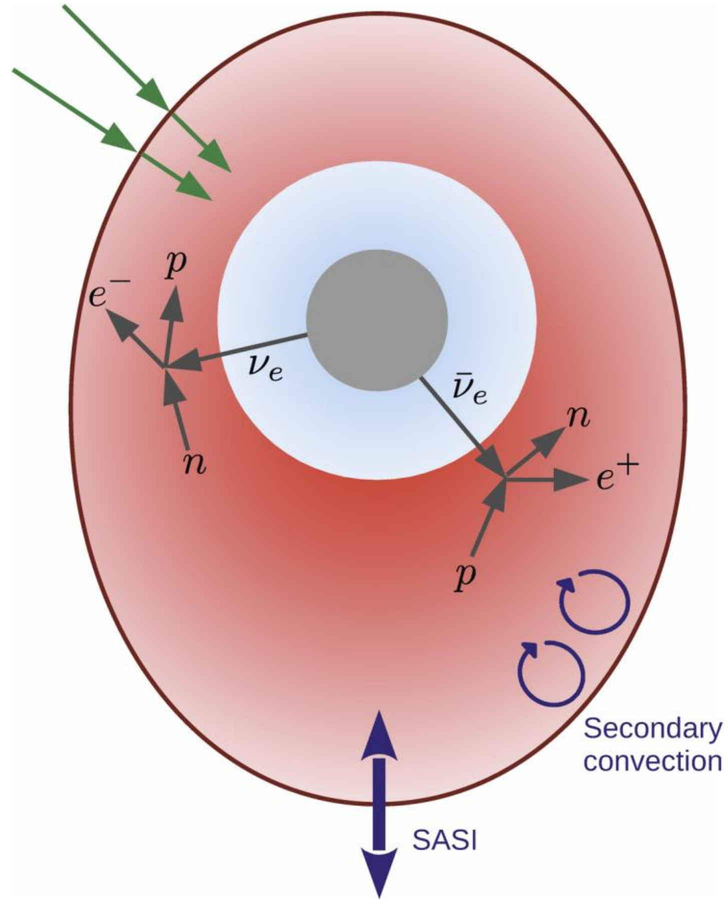
Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

Hydrodynamic Instabilities (3D Simulations)

Convection



SASI
Standing accretion shock instability



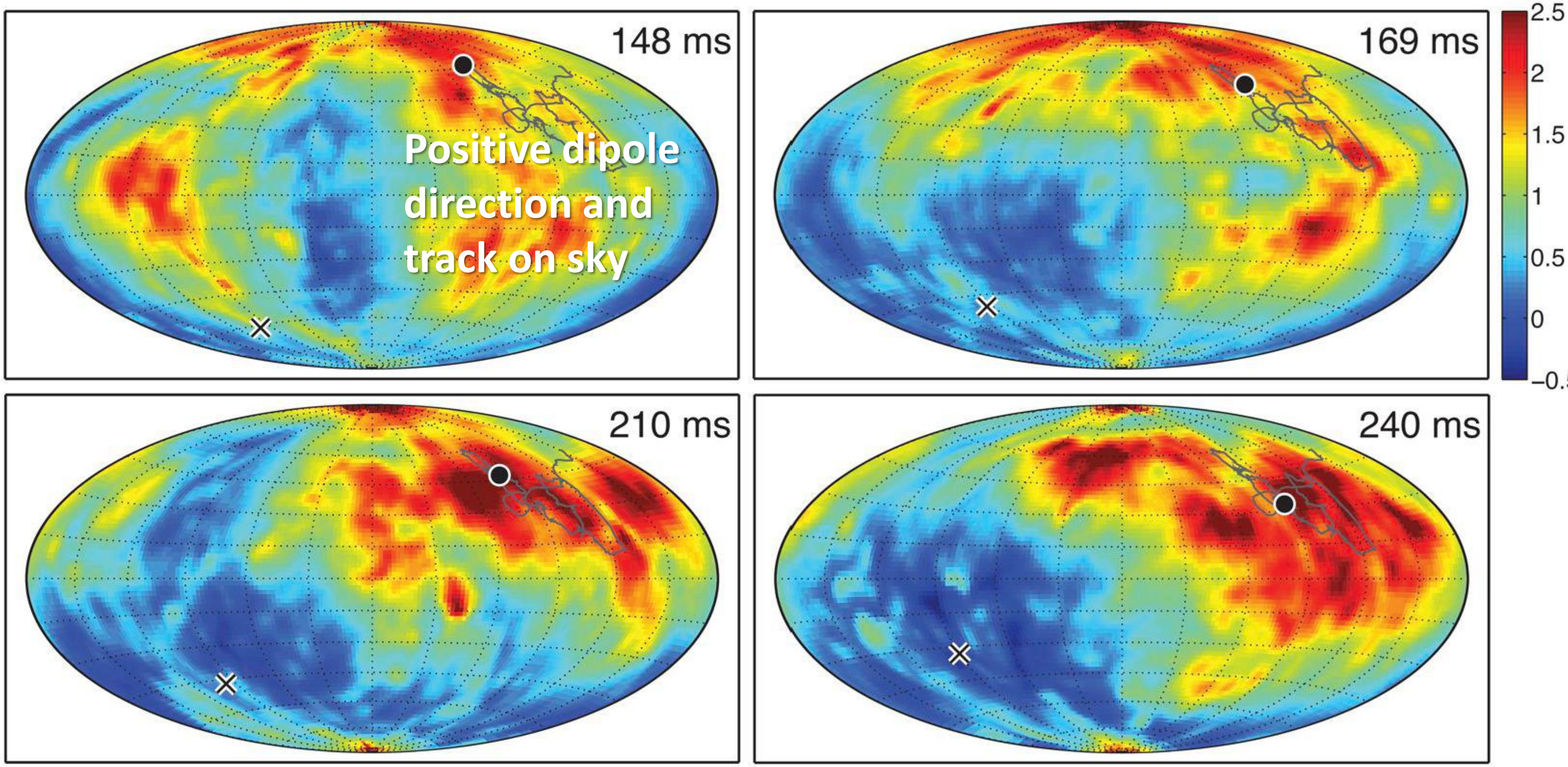
Images: Tobias Melson

→ 3D Model of Princeton Group (YouTube)

LESA – A New Instability

Lepton Emission Self-Sustained Asymmetry

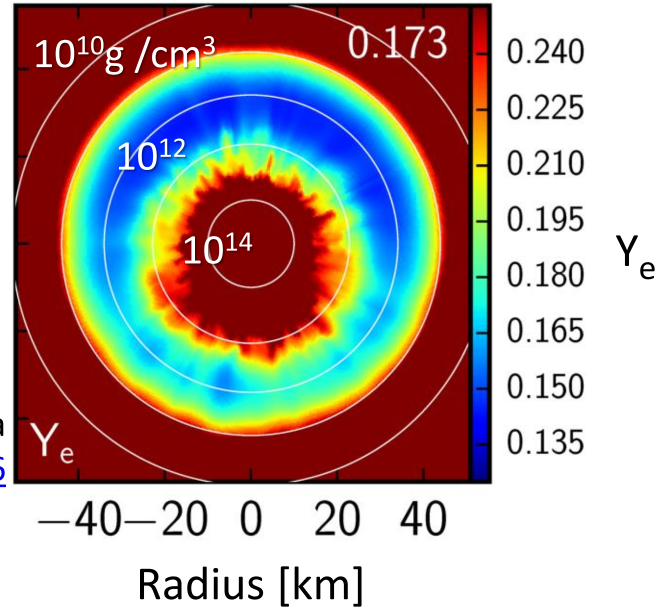
Sky map of lepton-number flux ($\nu_e - \overline{\nu}_e$) relative to 4π average (11.2 M_{SUN} model)
Deleptonization flux into one hemisphere, roughly dipole distribution



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

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

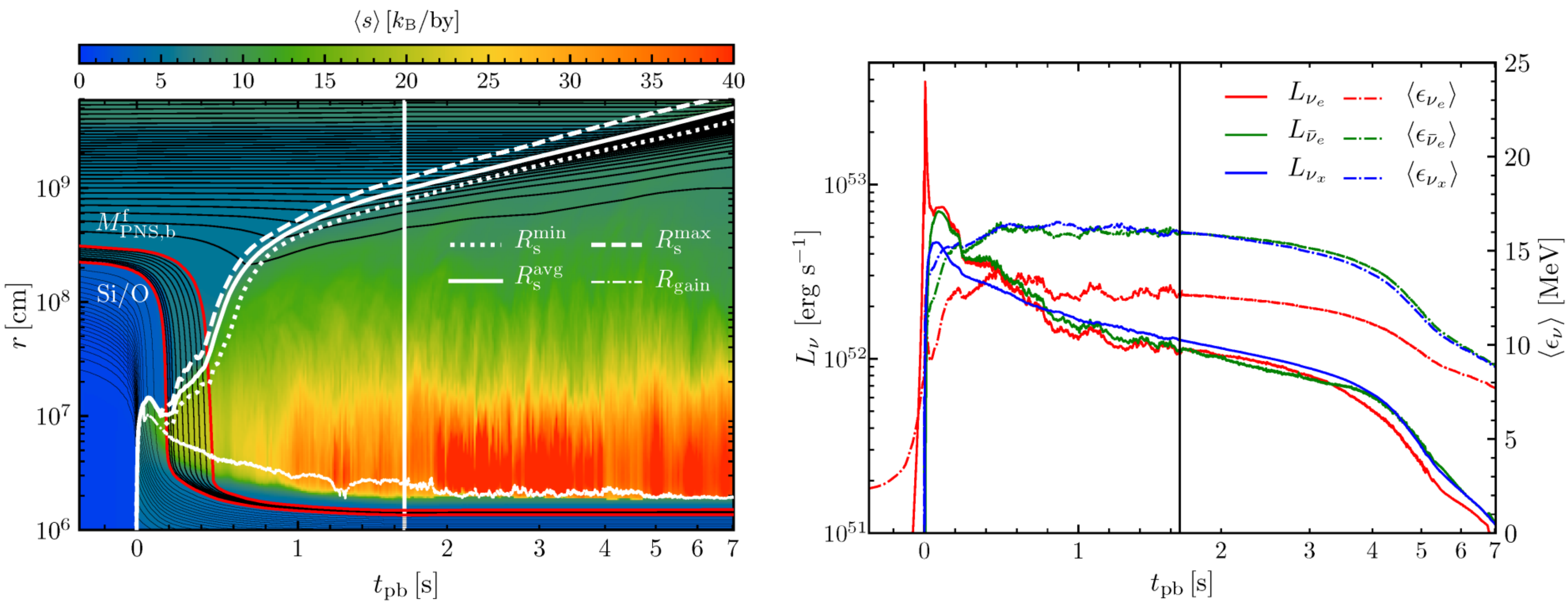


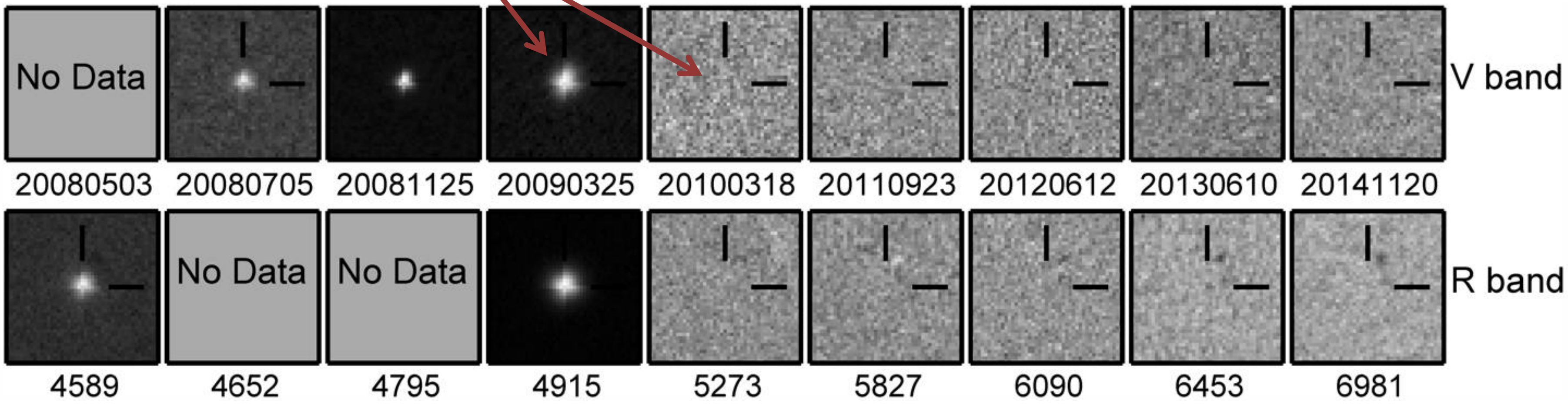
Figure 1. Explosion dynamics and neutrino emission of model `M_P3D_LS220_m−` and its extension `M_P3D_LS220_m−HC`. The time axes are chosen for optimal visibility. *Left:* Mass shells with entropy per nucleon color-coded. Maximum, minimum, and average shock radii, gain radius, and the mass shells of 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 ν_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.

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



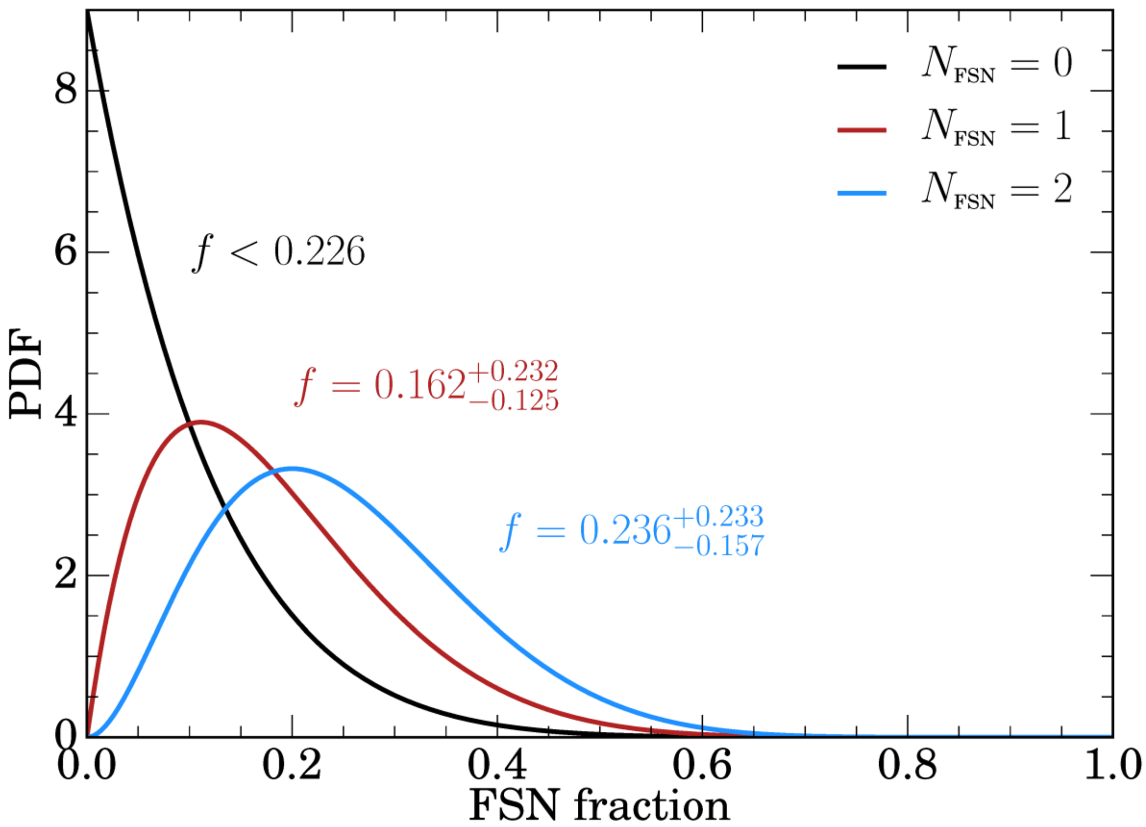
Gerke, Kochanek & Stanek, arXiv:1411.1761

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

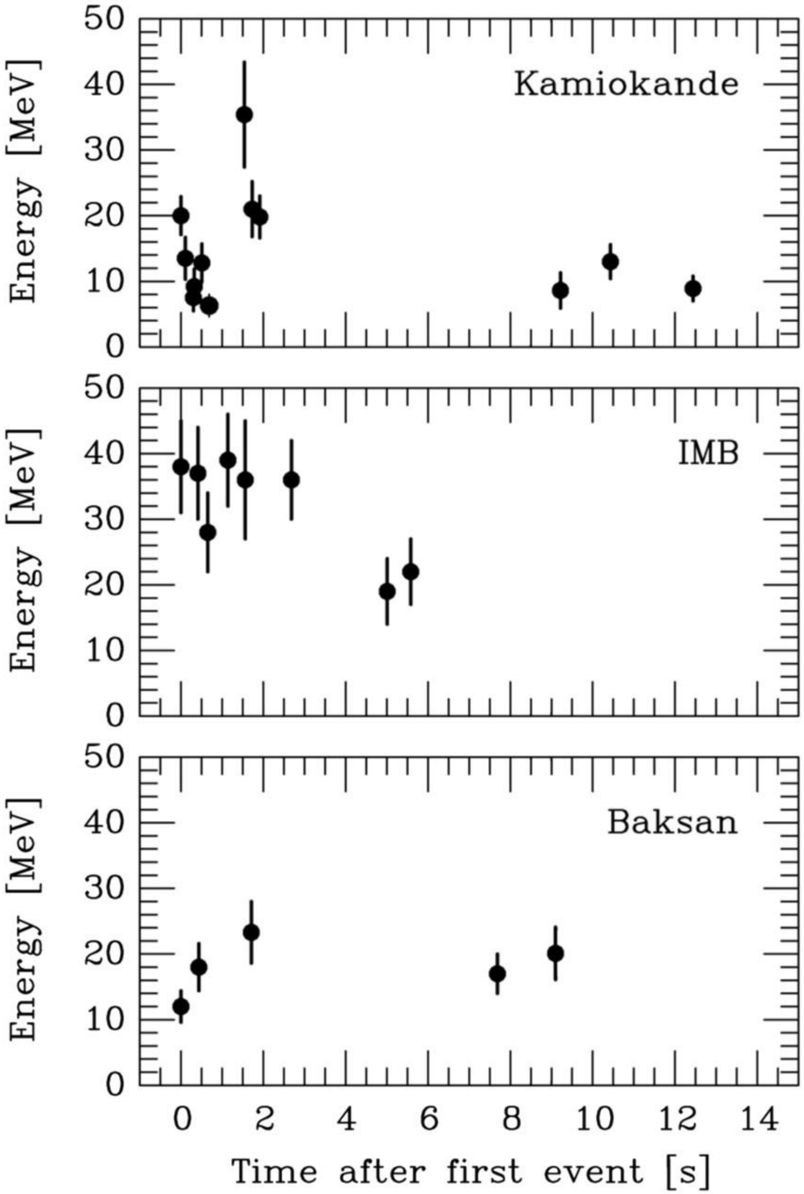


Roughly a quarter of all core-collapses could lead to BH formation, in agreement with theory estimates!


Sanduleak –69 202


Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



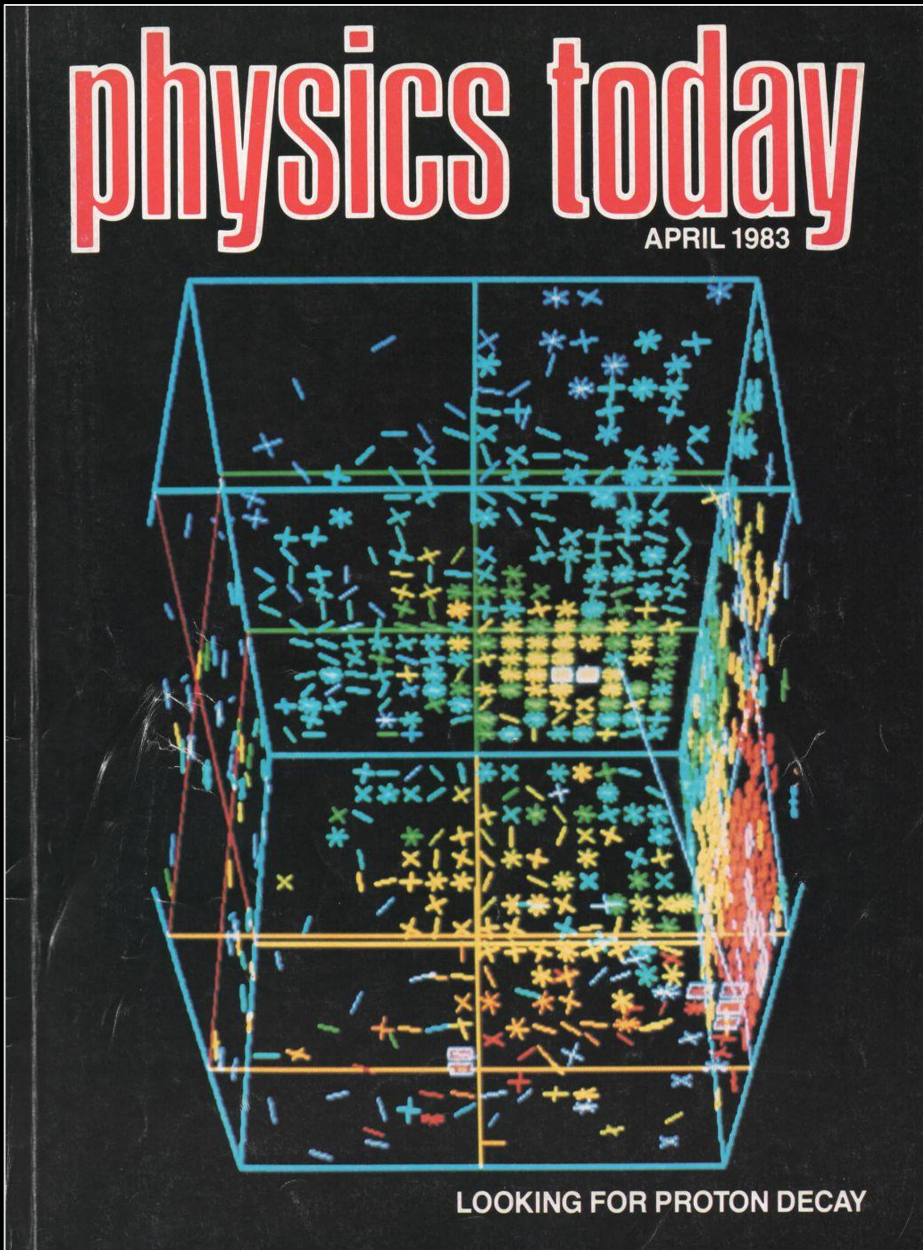
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ± 1 min

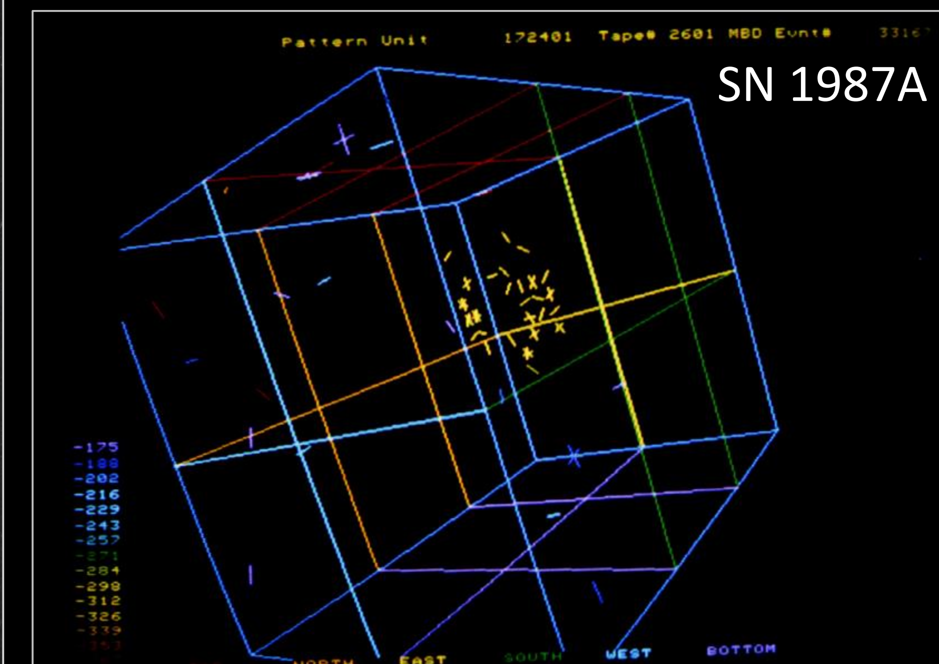
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ± 50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty $+2/{-54}$ s

Within clock uncertainties,
all signals are contemporaneous

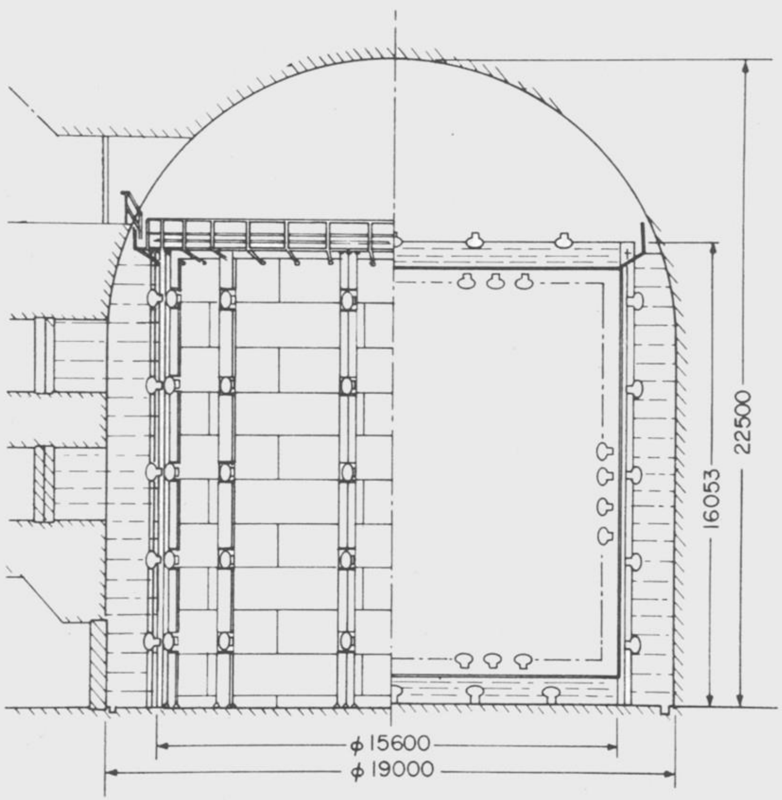
Irvine-Michigan-Brookhaven (IMB) Detector

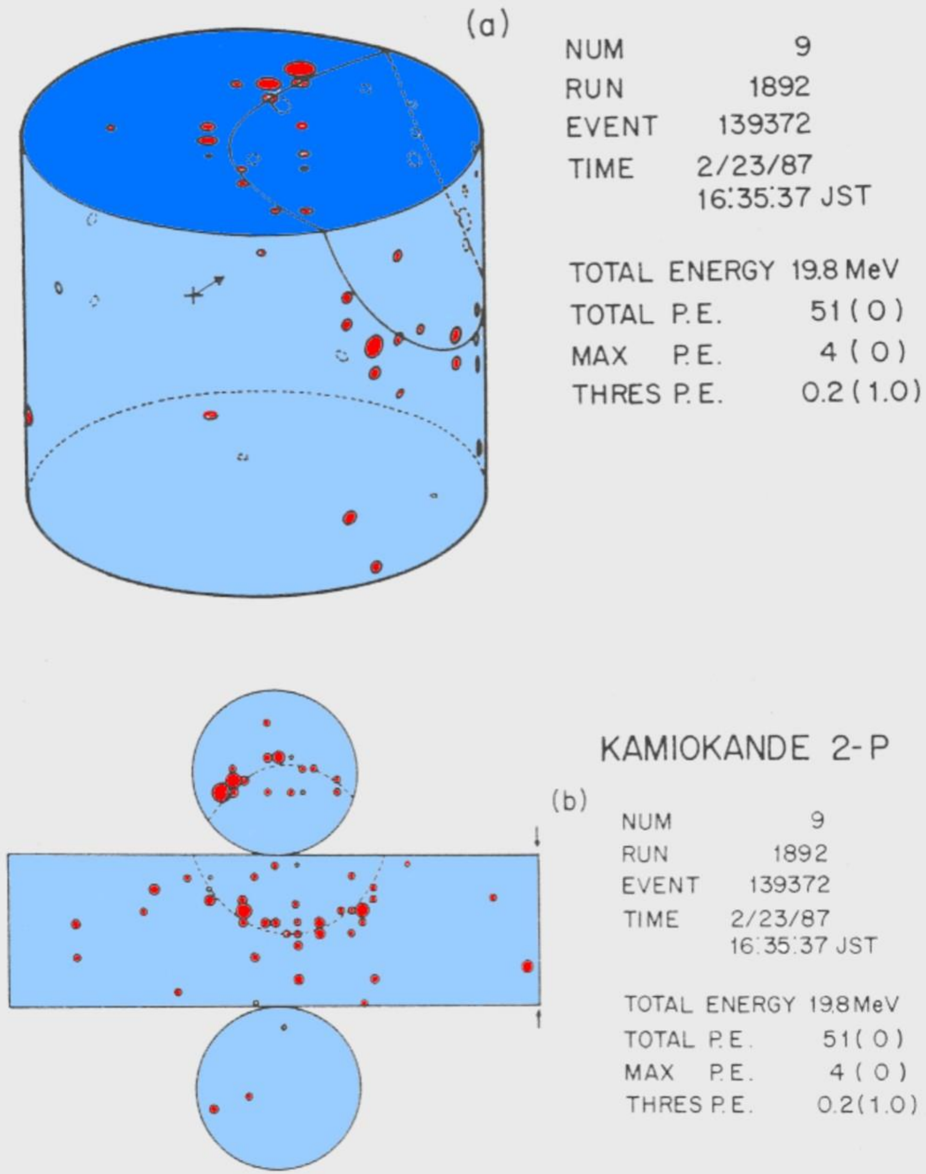




SN 1987A Event No.9 in Kamiokande

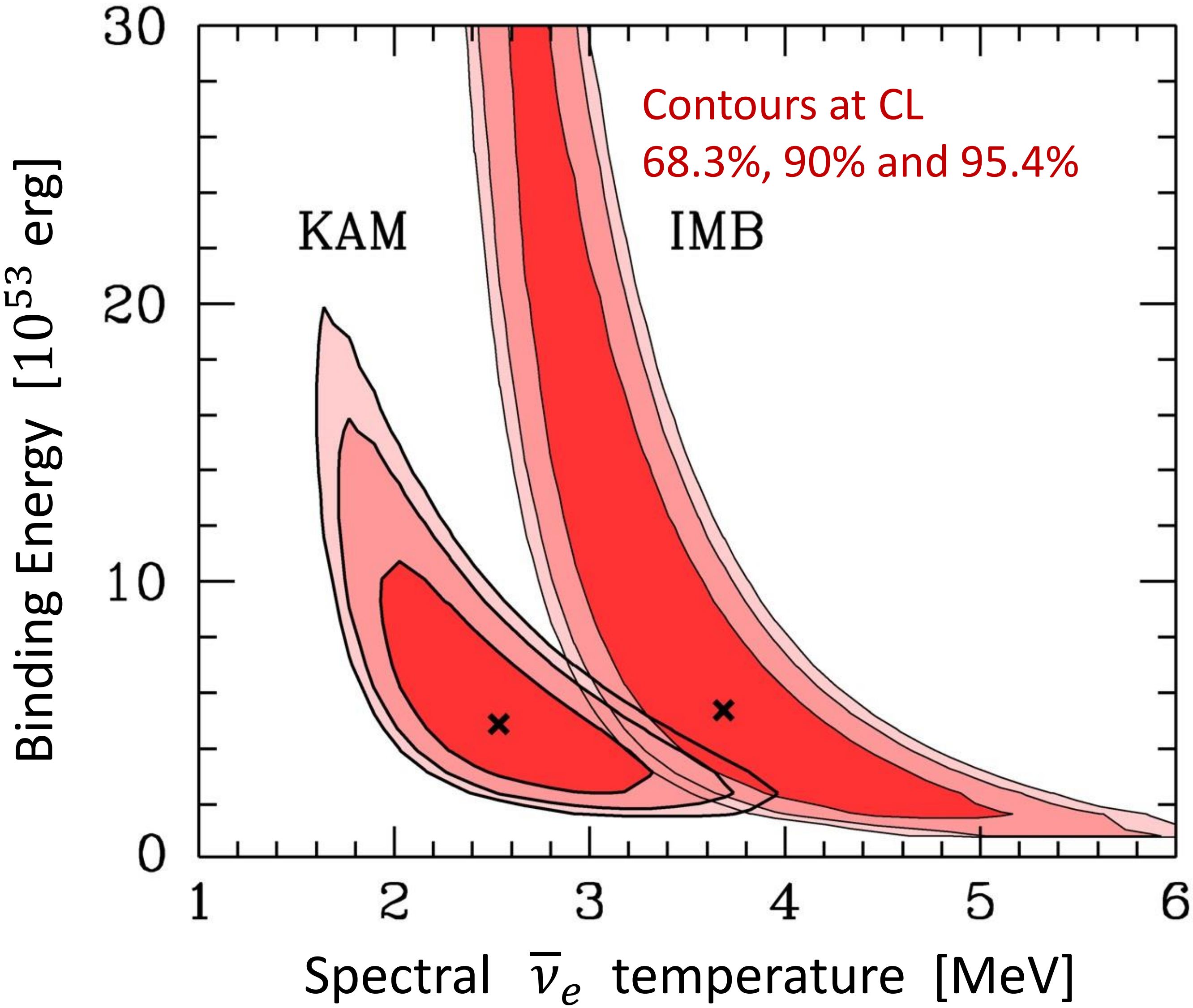
Kamiokande-II Detector
(2140 tons of water)





Hirata et al., PRD 38 (1988) 448

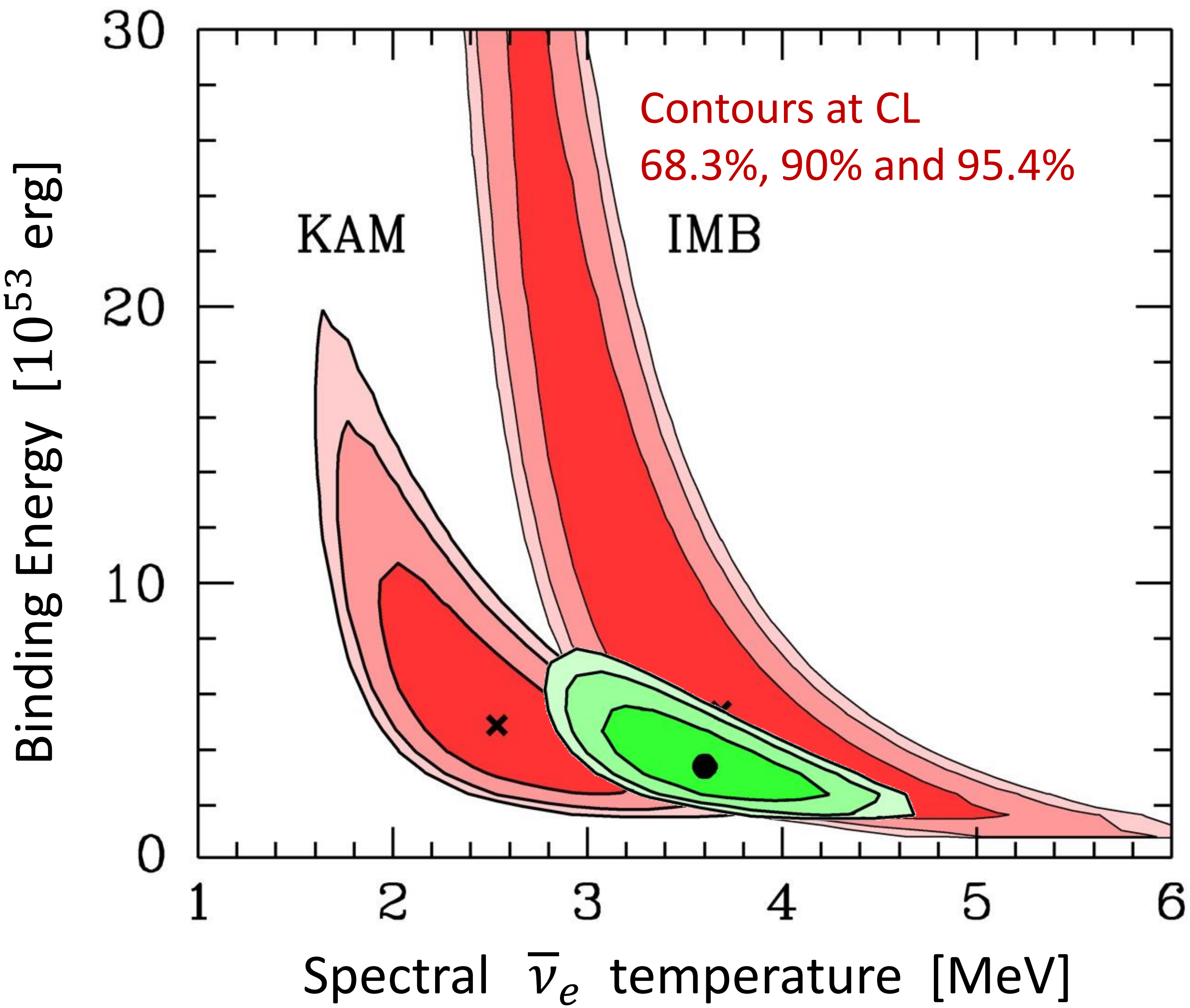
Interpreting SN 1987A Neutrinos



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

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

Interpreting SN 1987A Neutrinos



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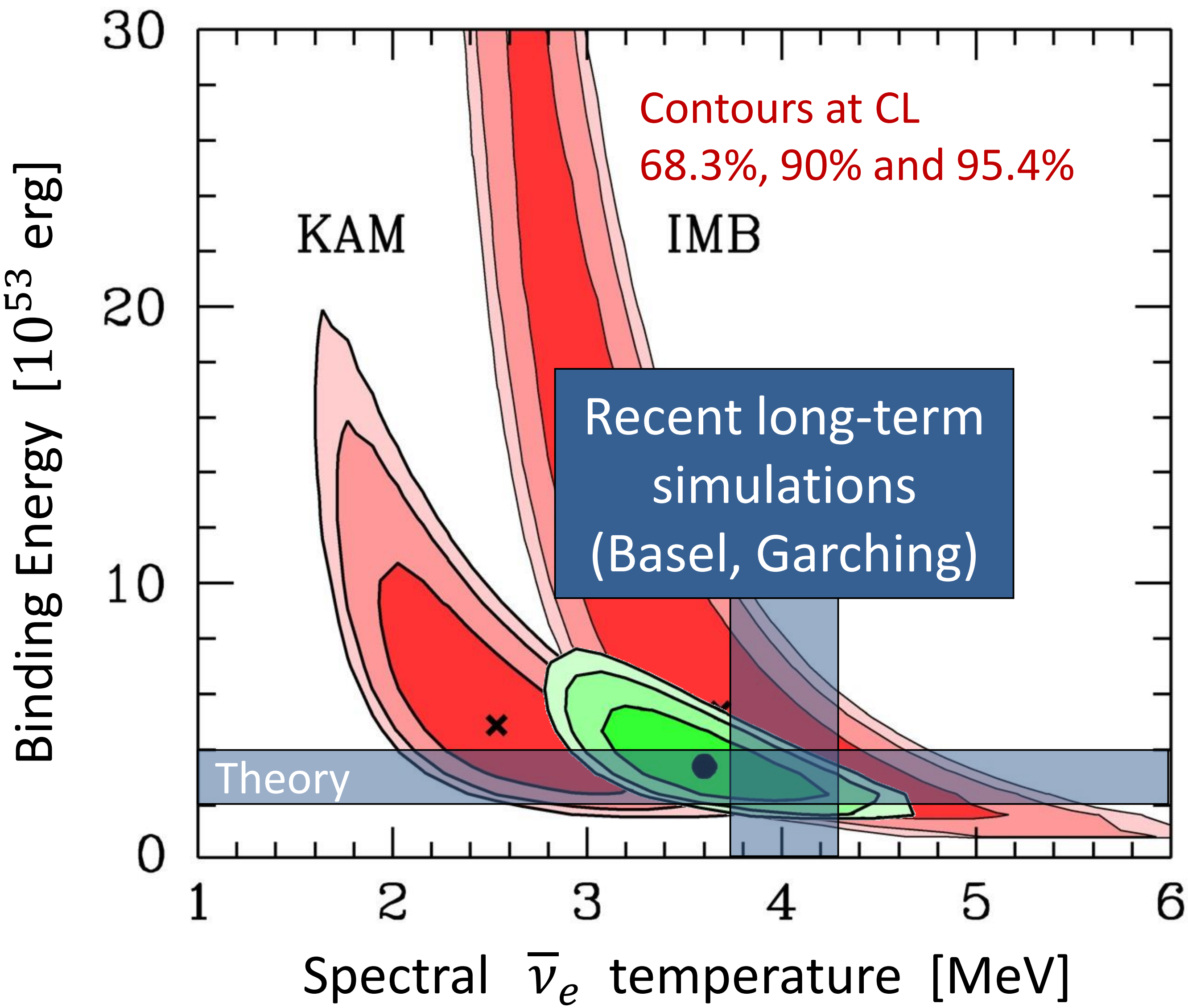
Interpreting SN 1987A Neutrinos



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

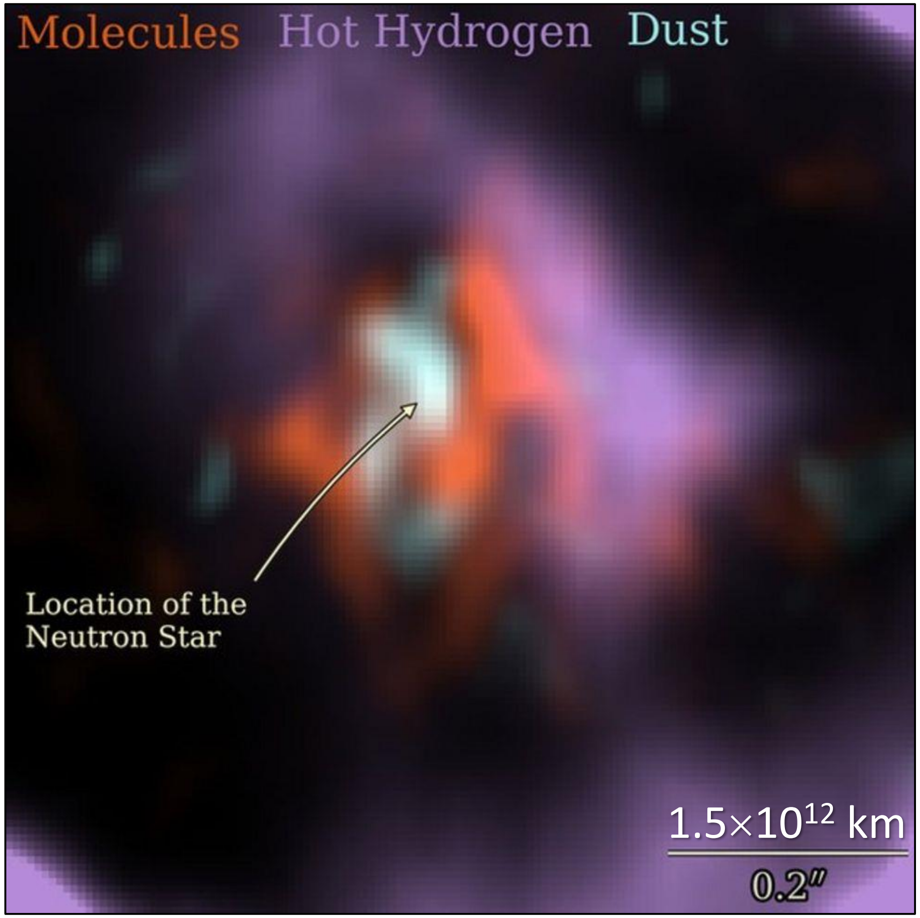
Where is the Neutron Star of SN 1987A?

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]

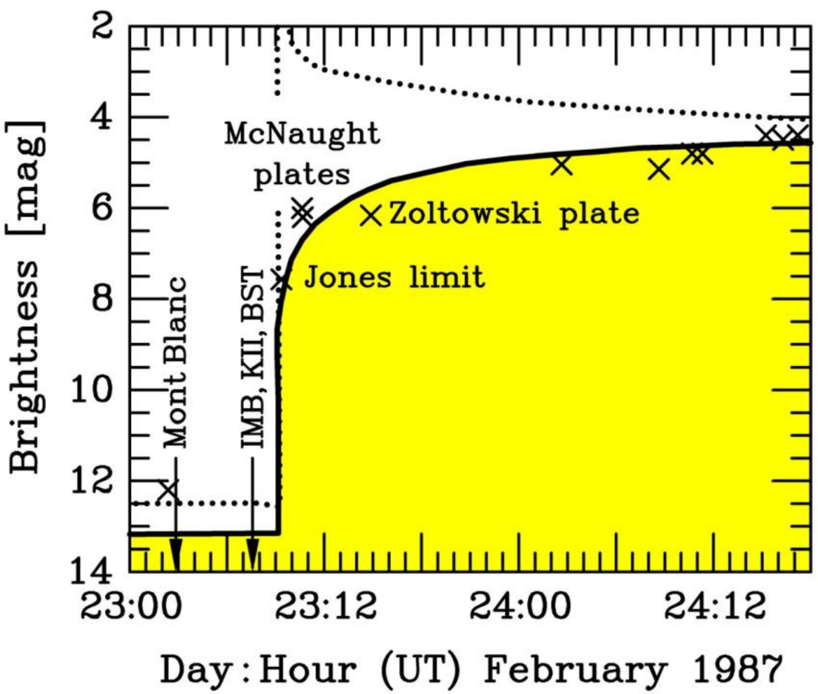
https://www.bbc.com/news/science-environment-50473482

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 ν and γ 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,

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

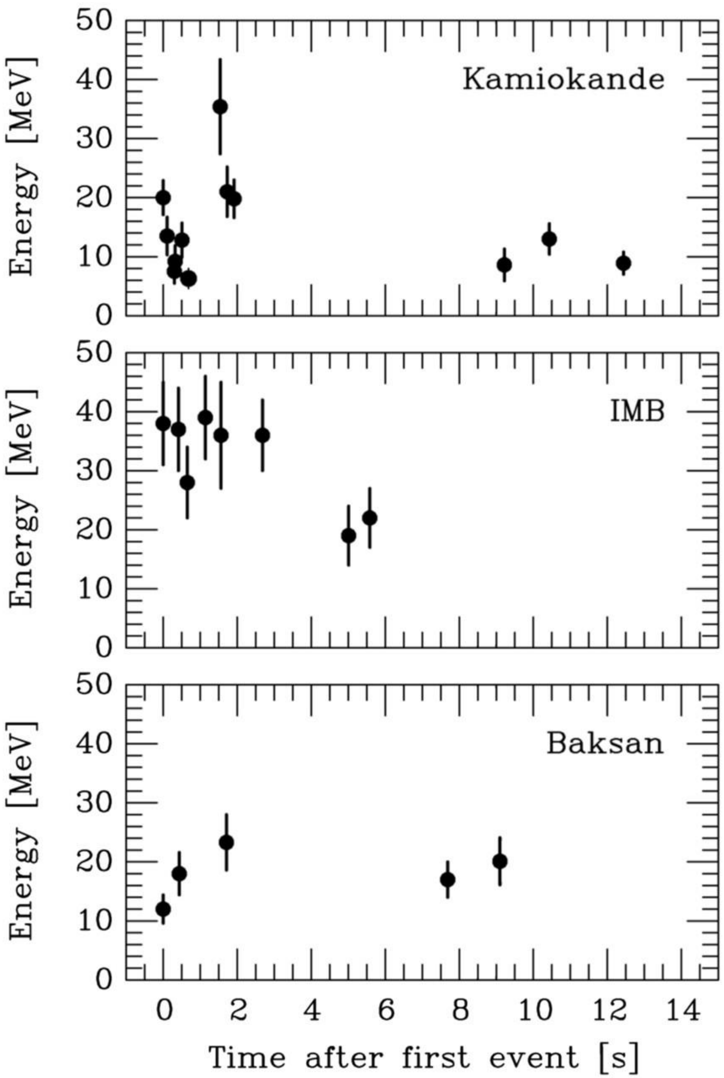
Neutrinos and photons respond to gravity the same to within

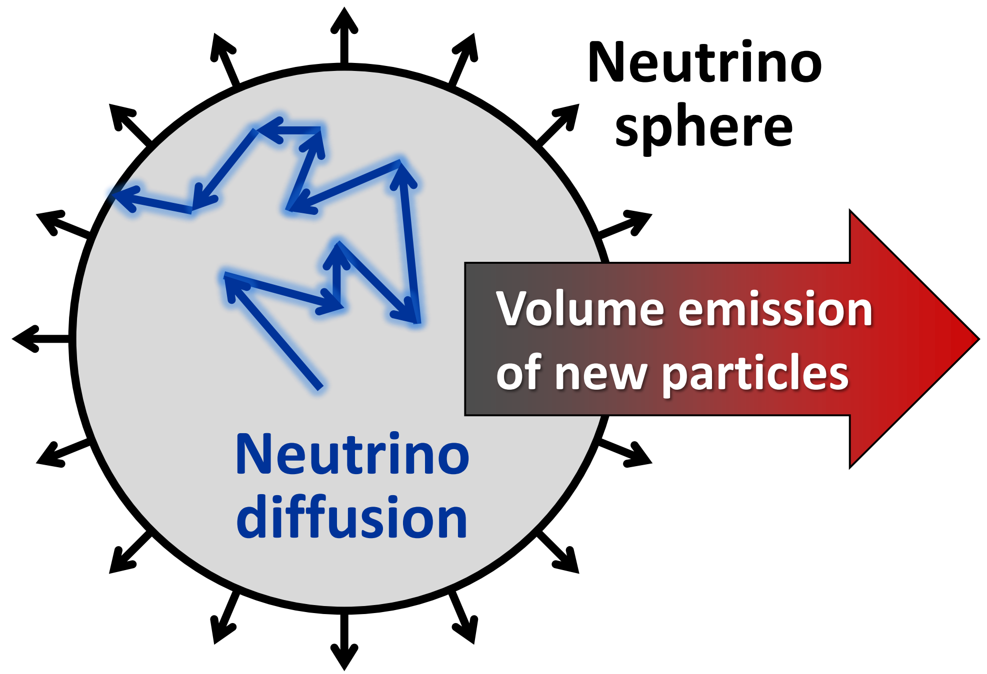
$$1\text{–}4 \times 10^{-3}$$

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

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

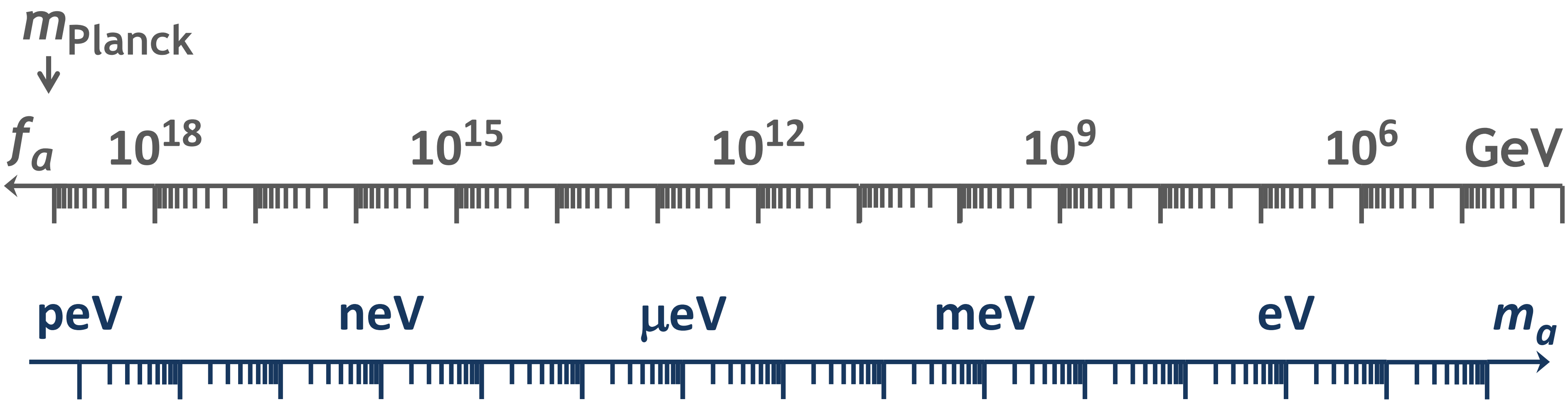




Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

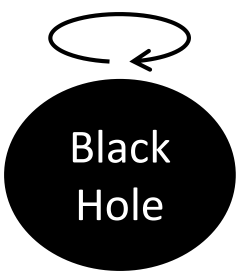
Axions and Stars

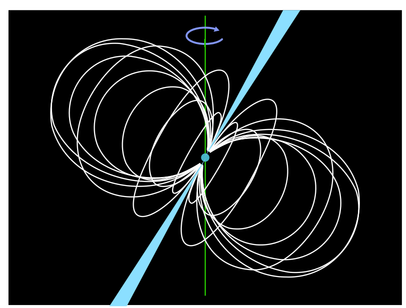


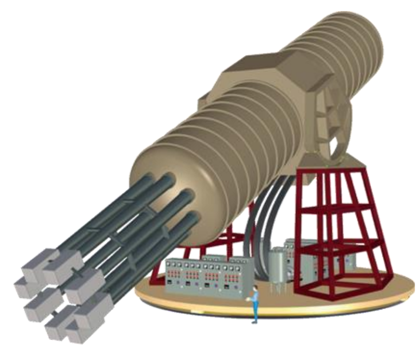
Super Radiance

Opportunities for detection

Astrophysical Bounds (Energy loss of stars)







IAXO Solar Axion Telescope

Axion conversion in neutron star magnetospheres

Operational Detectors for Supernova Neutrinos

HALO (30)
SNO+ (300)

ORCA (100)

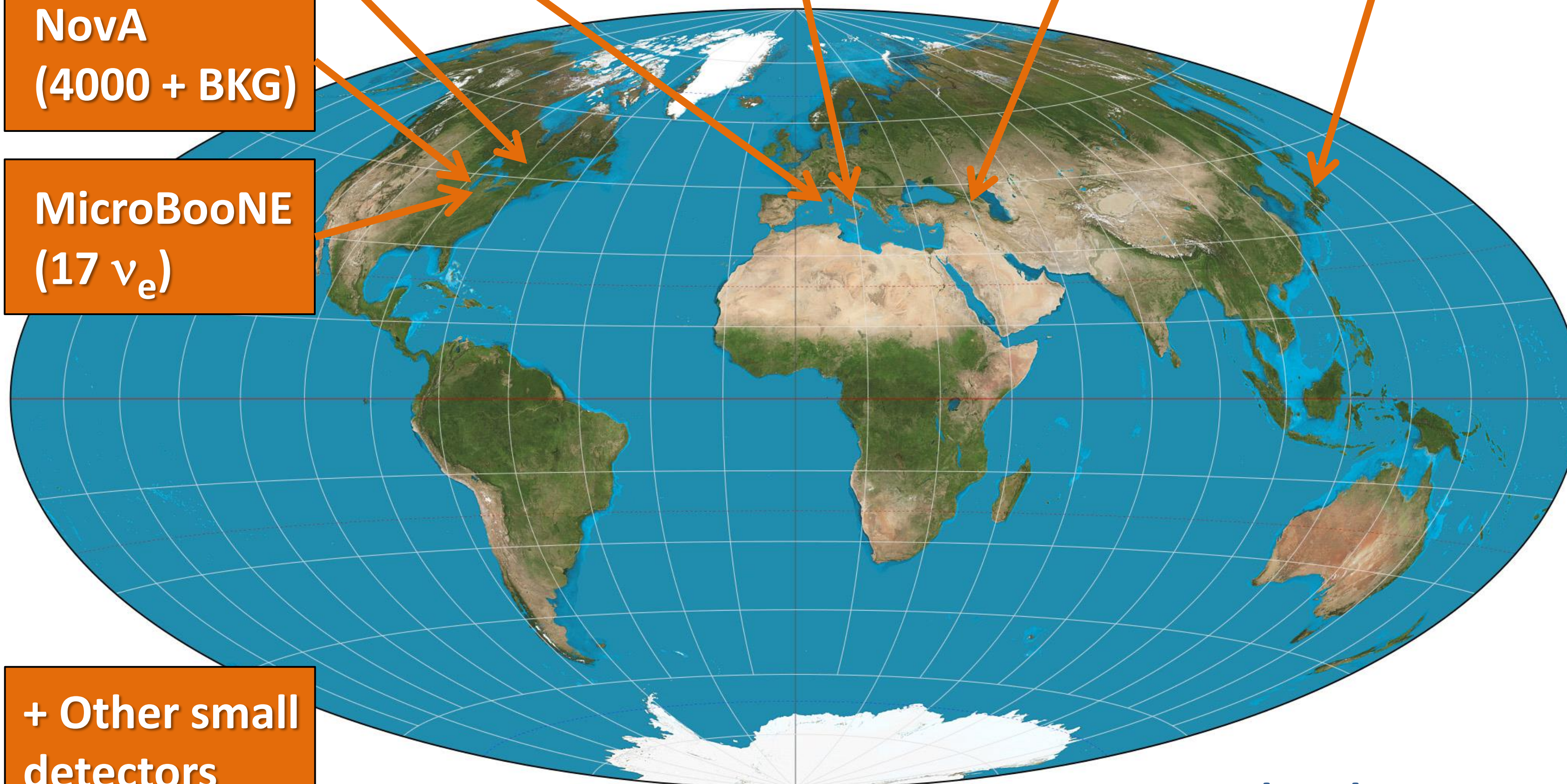
LVD (400)
Borexino (100)

Baksan
(100)

Super-K (4000)
KamLAND (400)

NovA
(4000 + BKG)

MicroBooNE
(17 ν_e)



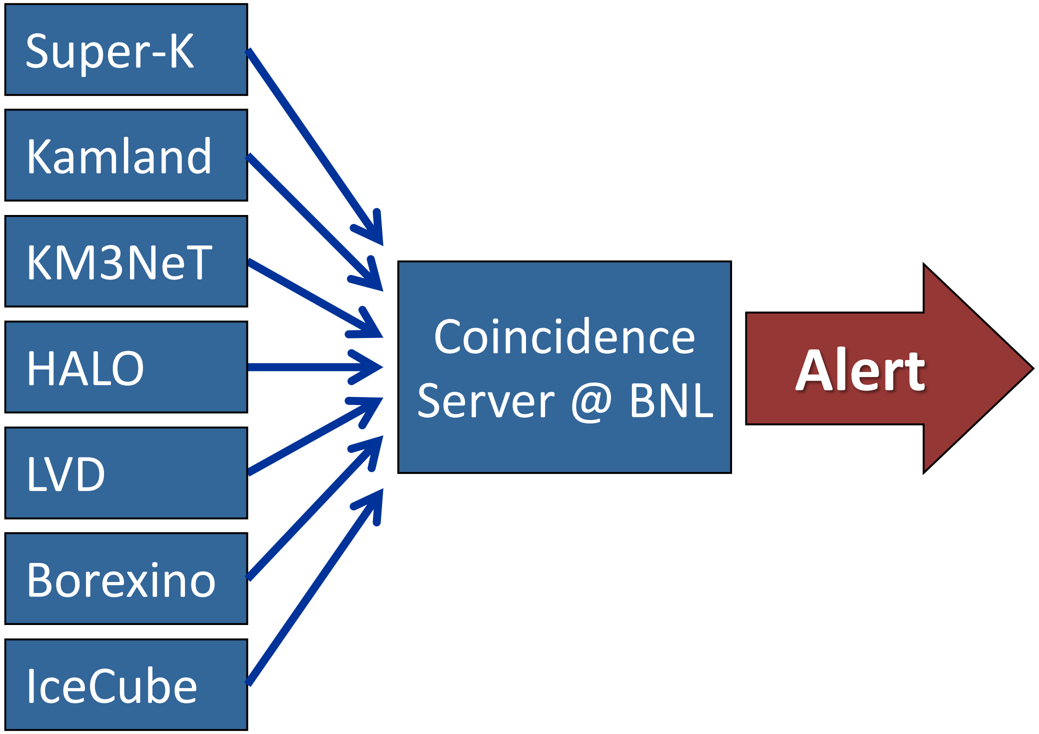
+ Other small detectors with some SN sensitivity

IceCube (10^6)

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

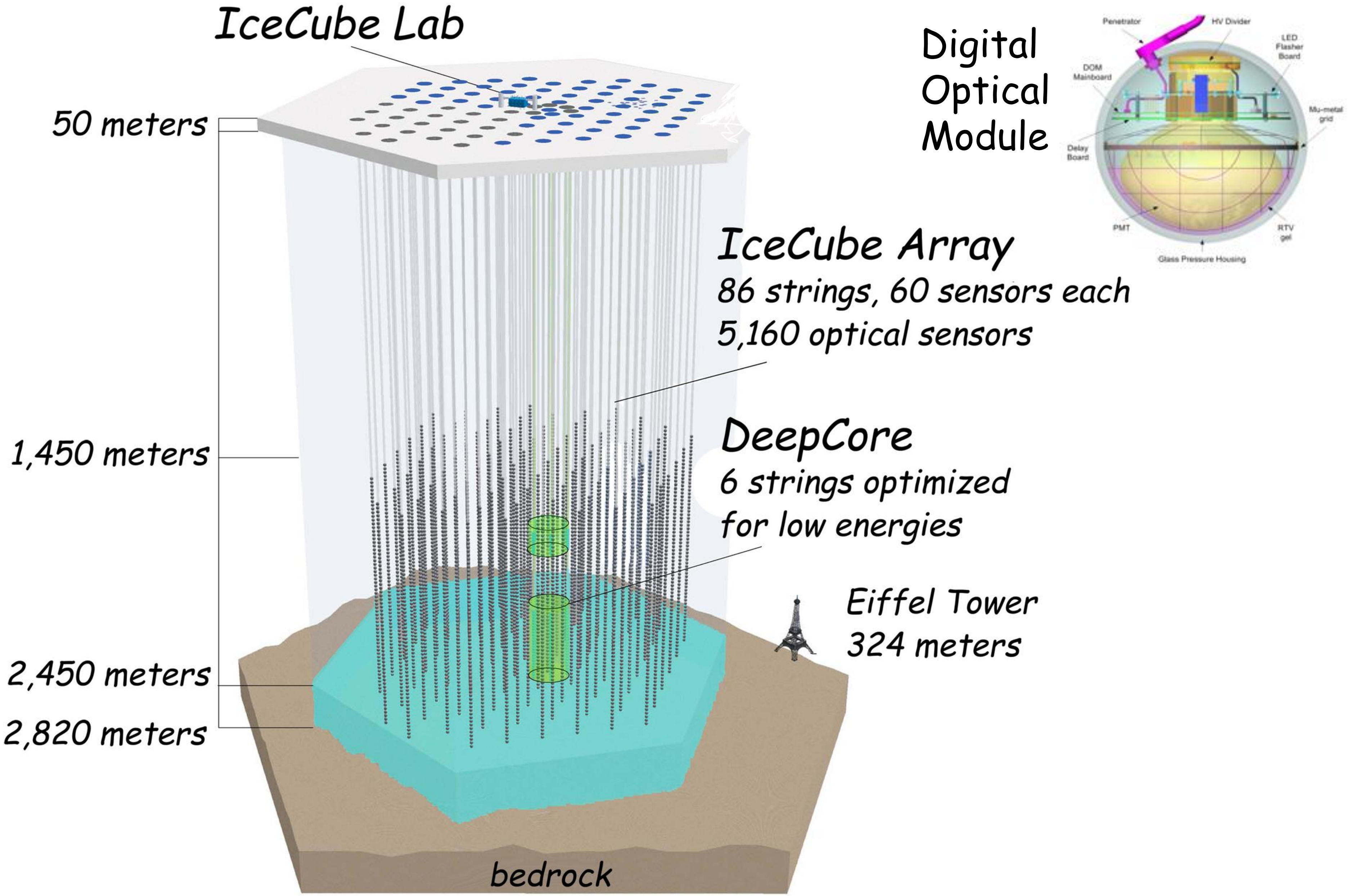
SuperNova Early Warning System (SNEWS)

https://snews.bnl.gov

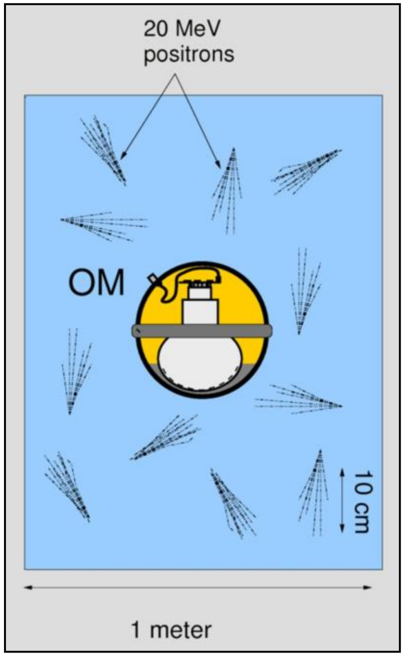


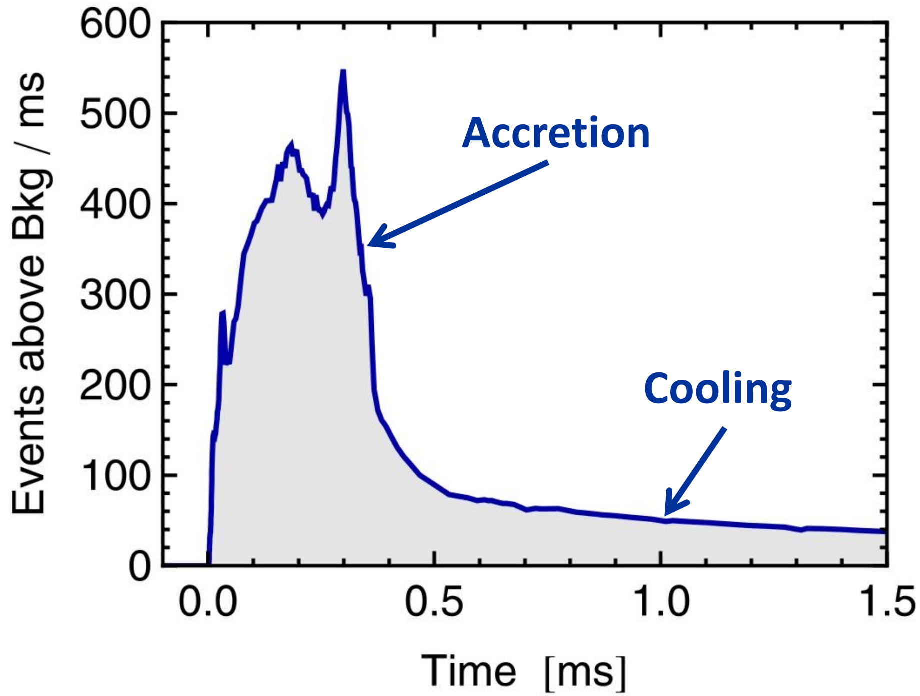
- Neutrinos arrive several hours before optical outburst
- Issue an alert to astronomical community
- Trigger to LIGO, NOvA, GCN

IceCube Neutrino Telescope at the South Pole



IceCube as a Supernova Neutrino Detector



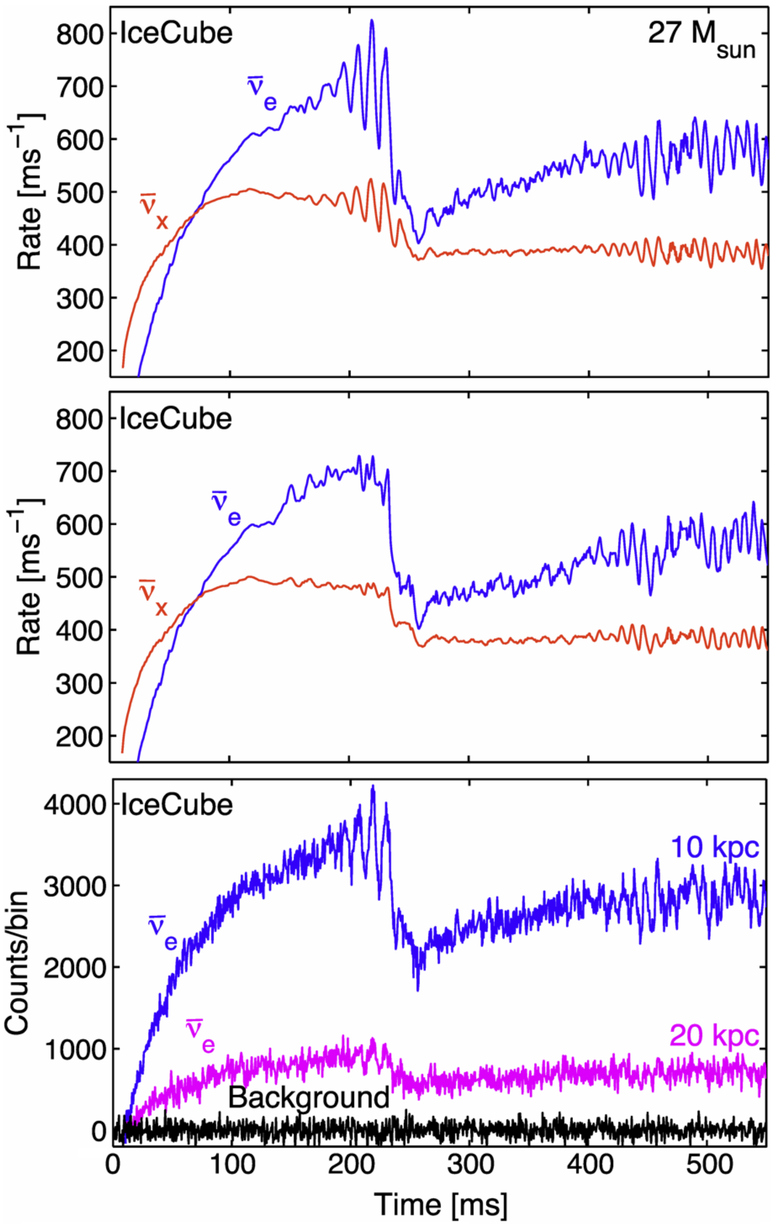


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group [arXiv:0908.1871]

- 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

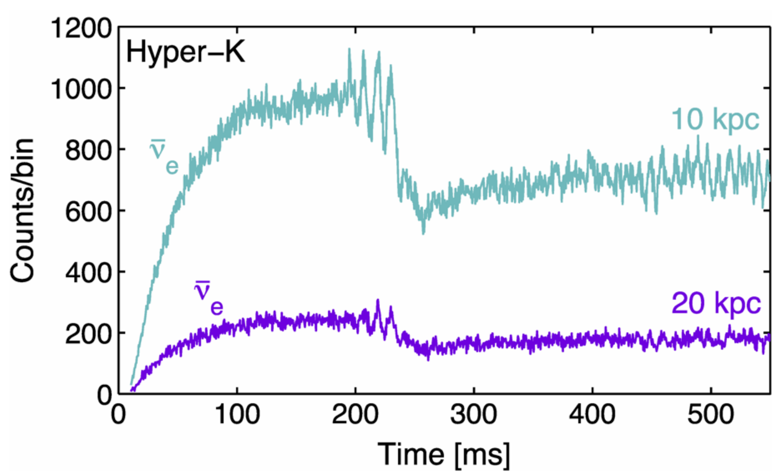
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

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 γs; A, positron annihilation γs. Note there may, in principle, be other signatures for future detector technologies or detector upgrades.

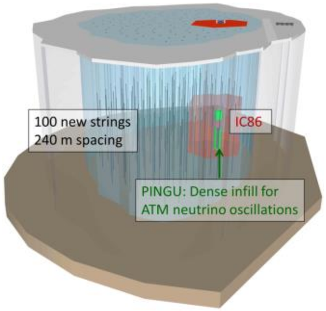
[b]The interactions column gives interactions per kilotonne at 10 kpc for two different neutrino flux models for neutrino energies greater than 5 MeV, computed according to **http://www.phy.duke.edu/~schol/snowglobes**. No detector response is taken into account here, and actual detected events may be significantly fewer. For elastic scattering and inverse β 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.

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	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

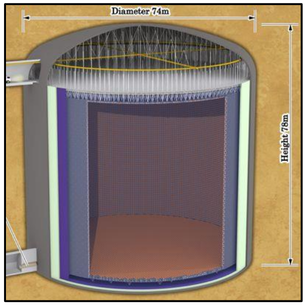
K. Scholberg in arXiv:1508.00785

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



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

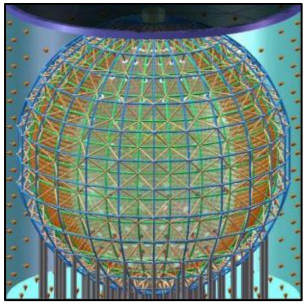
Doubling the number of optical modules



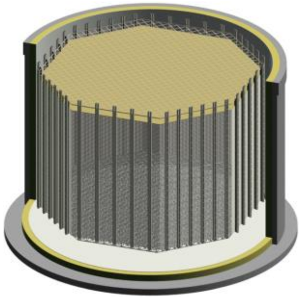
Megaton-class water Cherenkov detector

Notably Hyper-Kamiokande

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



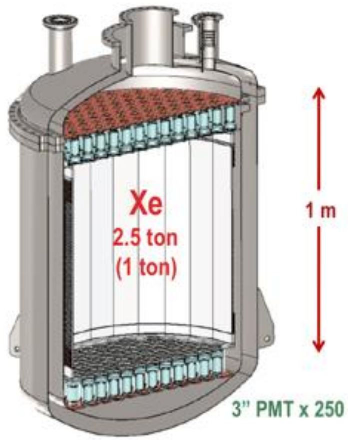
Scintillator detectors (20 kilotons)
- JUNO in China for reactor nus (construction)
- RENO-50 in Korea for reactor nus (plans)
- Baksan Large Volume Scintillator Detector (discussions in Russia)

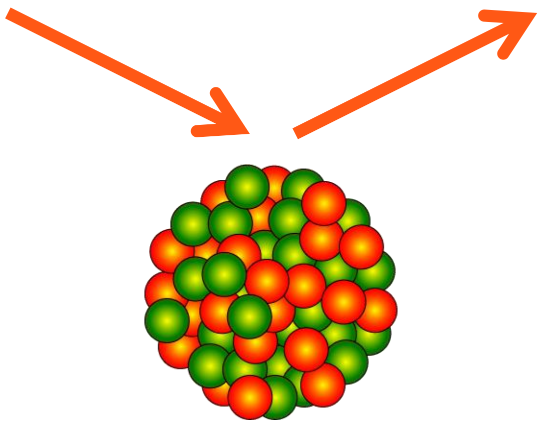


Liquid argon time projection chamber

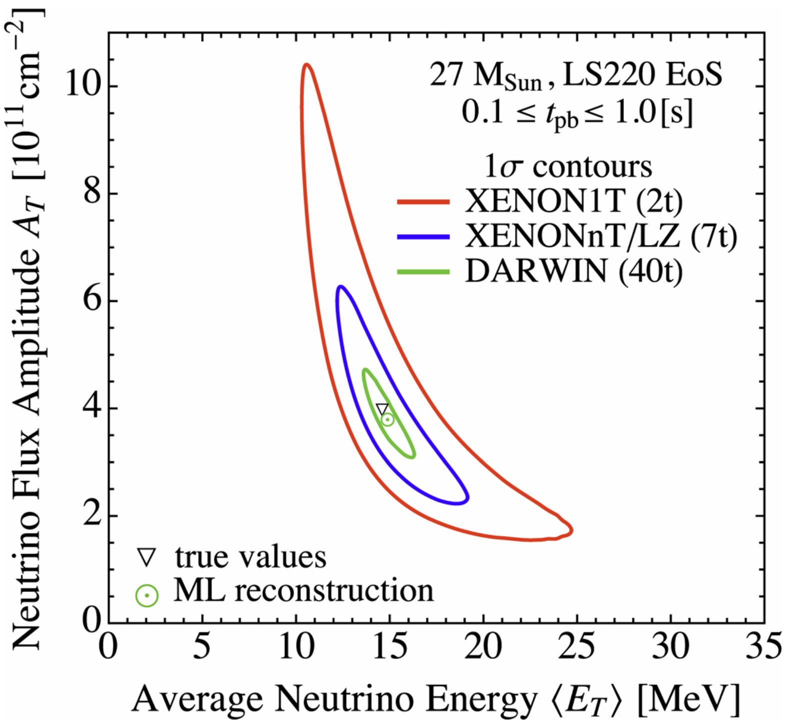
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC ν_e signal)
- But cross sections poorly known

Xenon Dark Matter Detectors





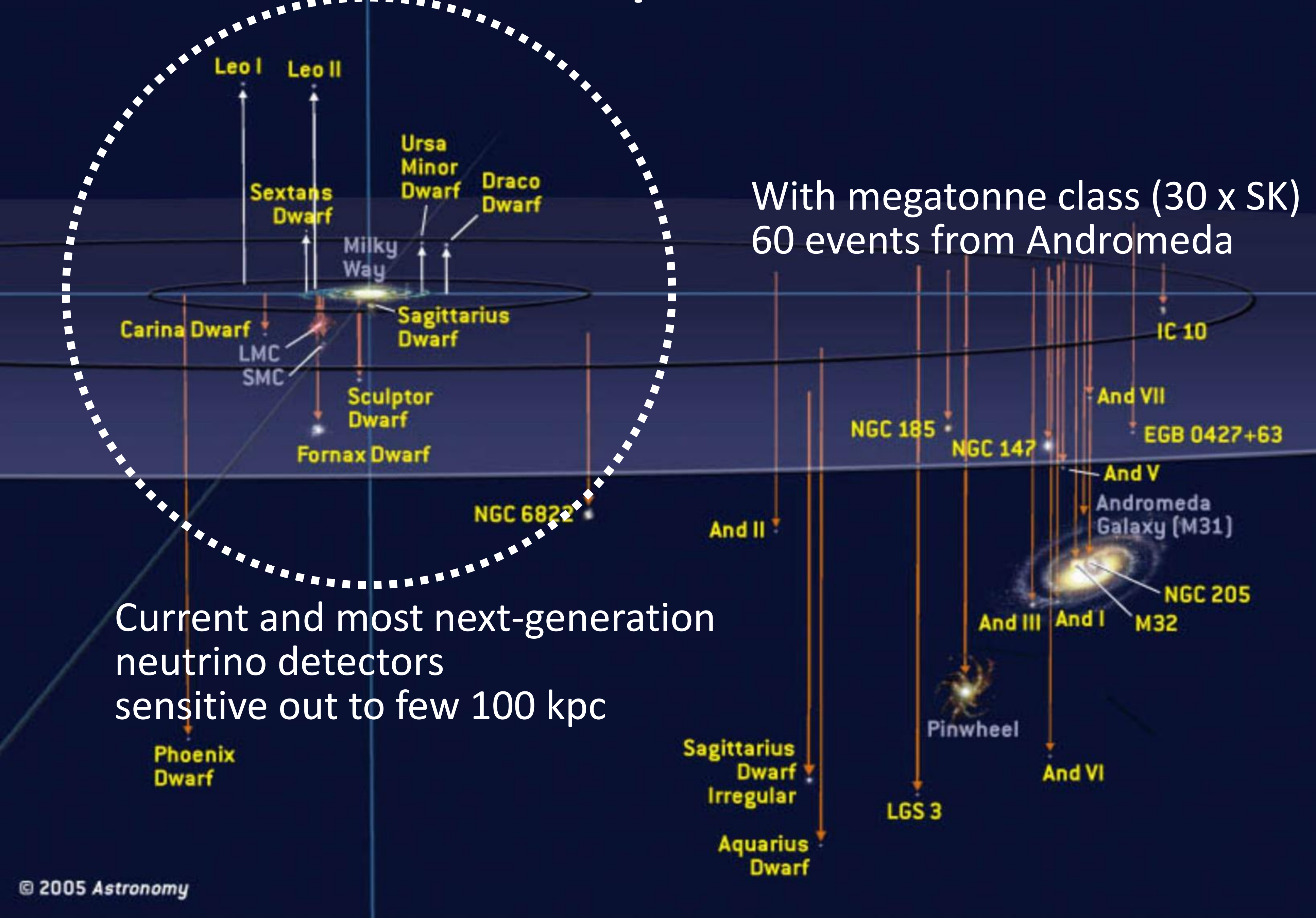
- Coherent scattering of low-E nus on Xe (77 neutrons)
- All 6 nu species contribute



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

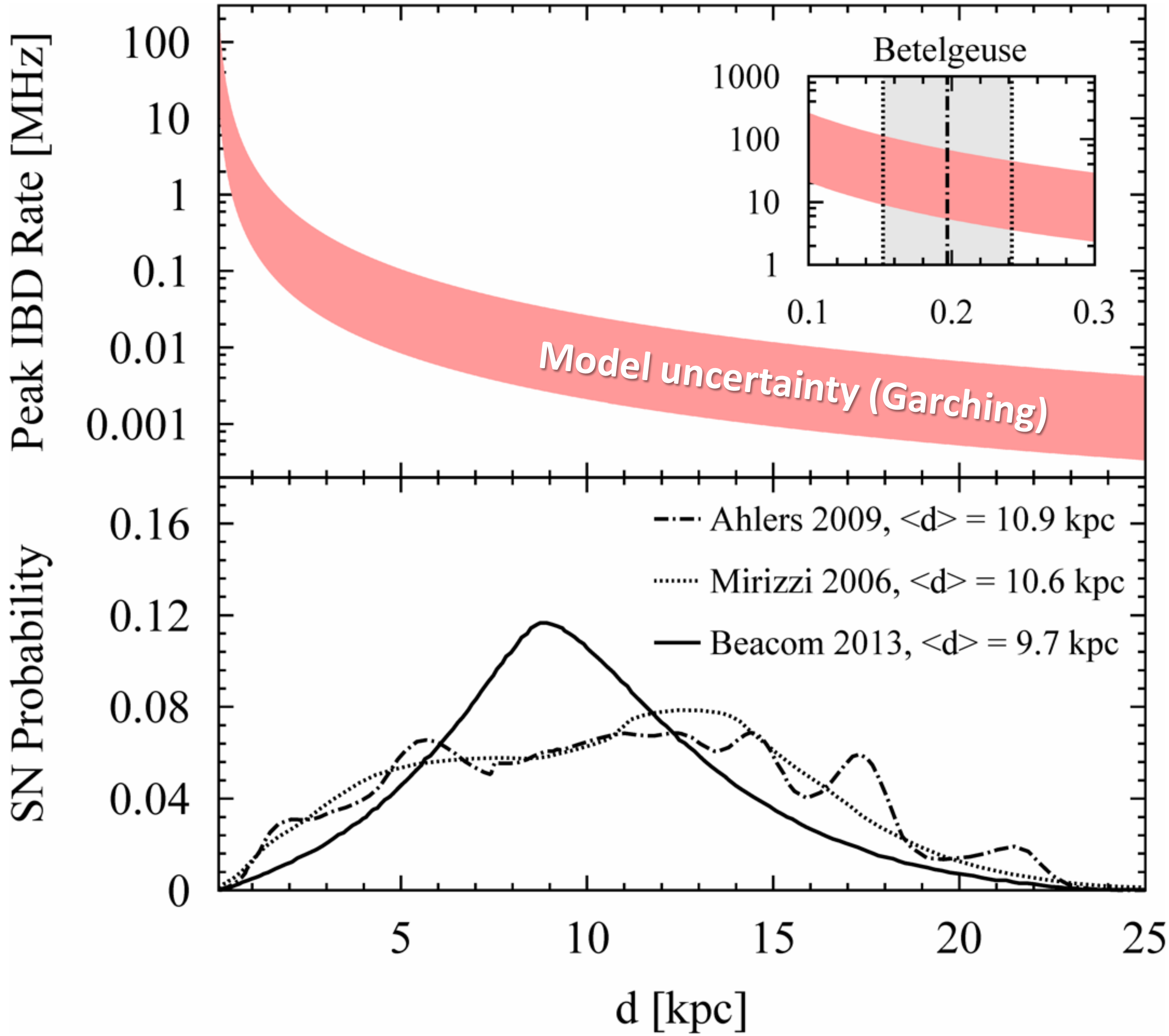
SN Distance Distribution and Peak Count Rate

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

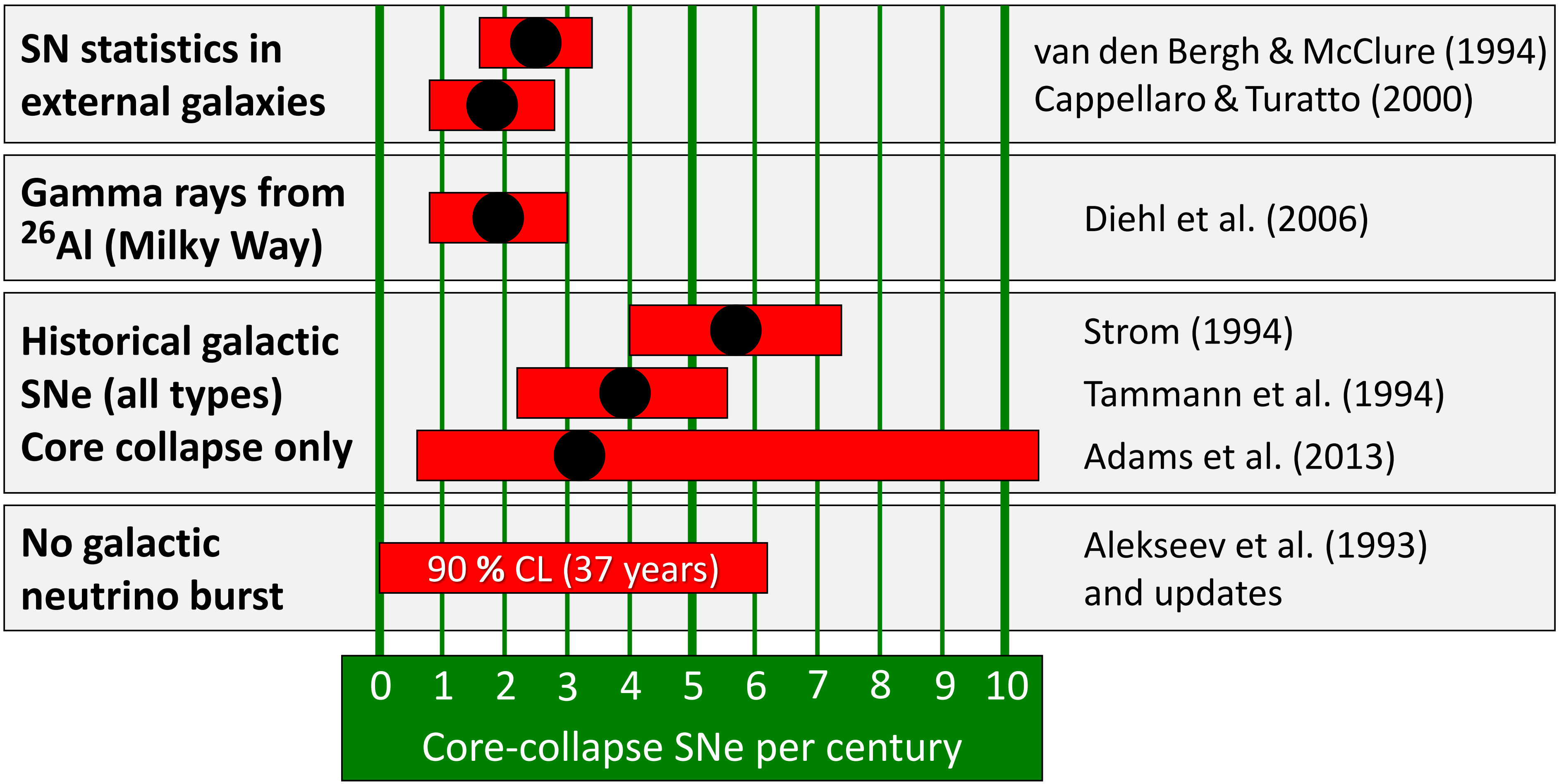
× 10 in 1 tank Hyper-K

SN distance probability in Milky Way

JUNO Yellow Book, arXiv:1507.05613

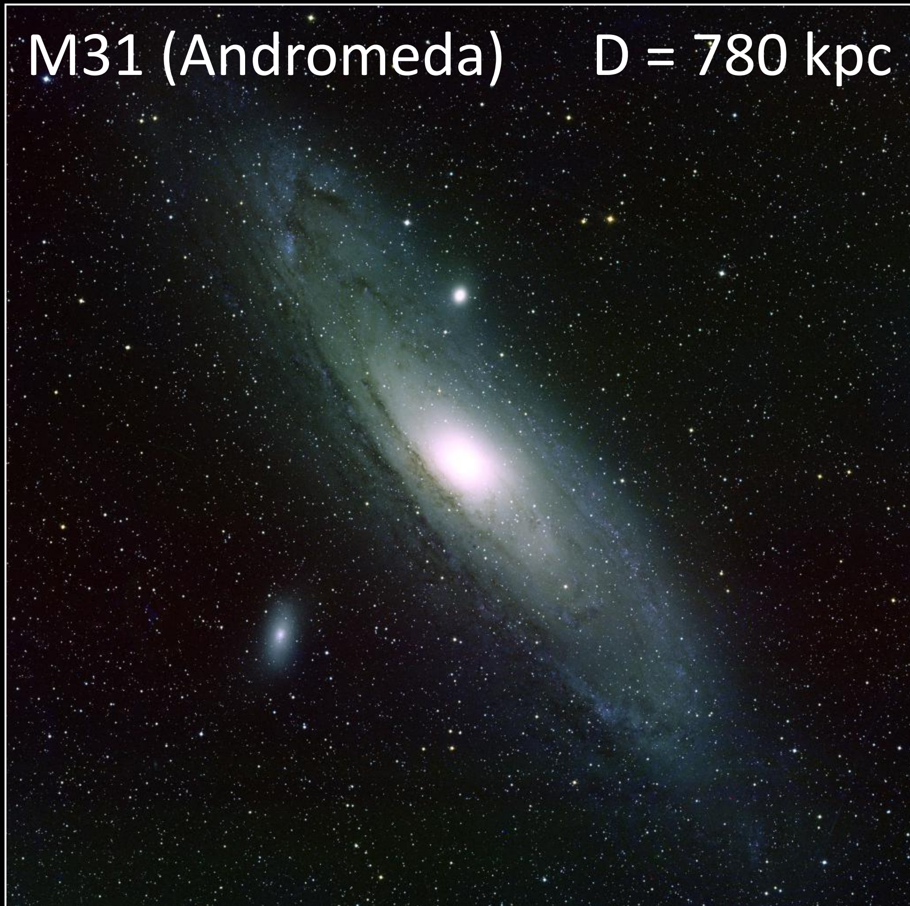


Core-Collapse SN Rate in the Milky Way



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.

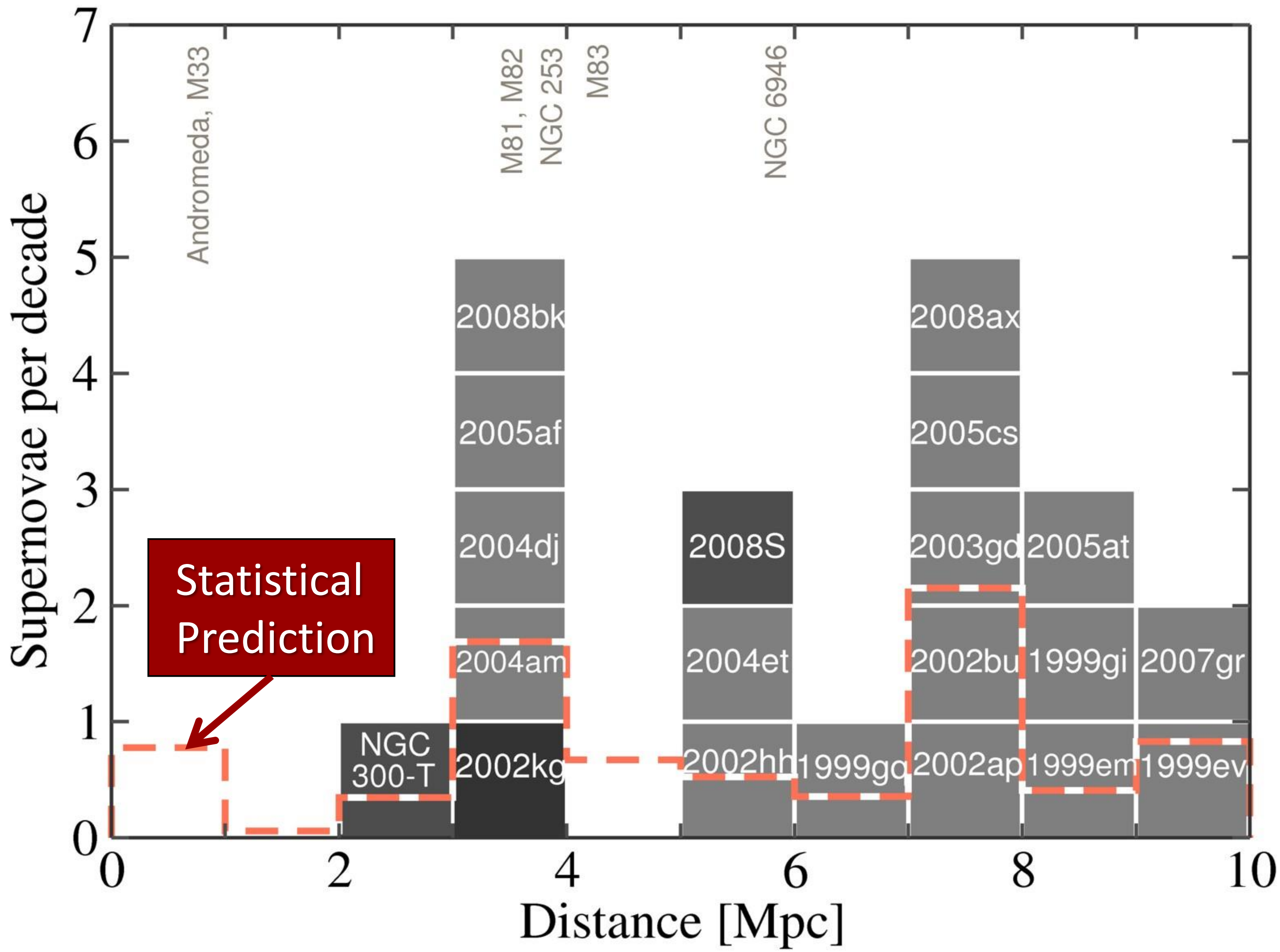
High and Low Supernova Rates in Nearby Galaxies



Last Observed Supernova: 1885A

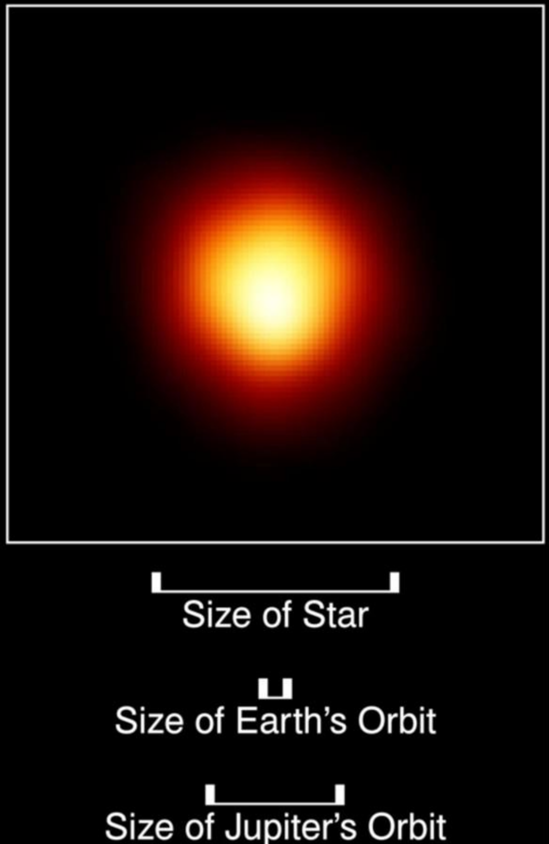
Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et, 2008S, 2017eaw
N6946-BH1 (failed SN 2009/10)

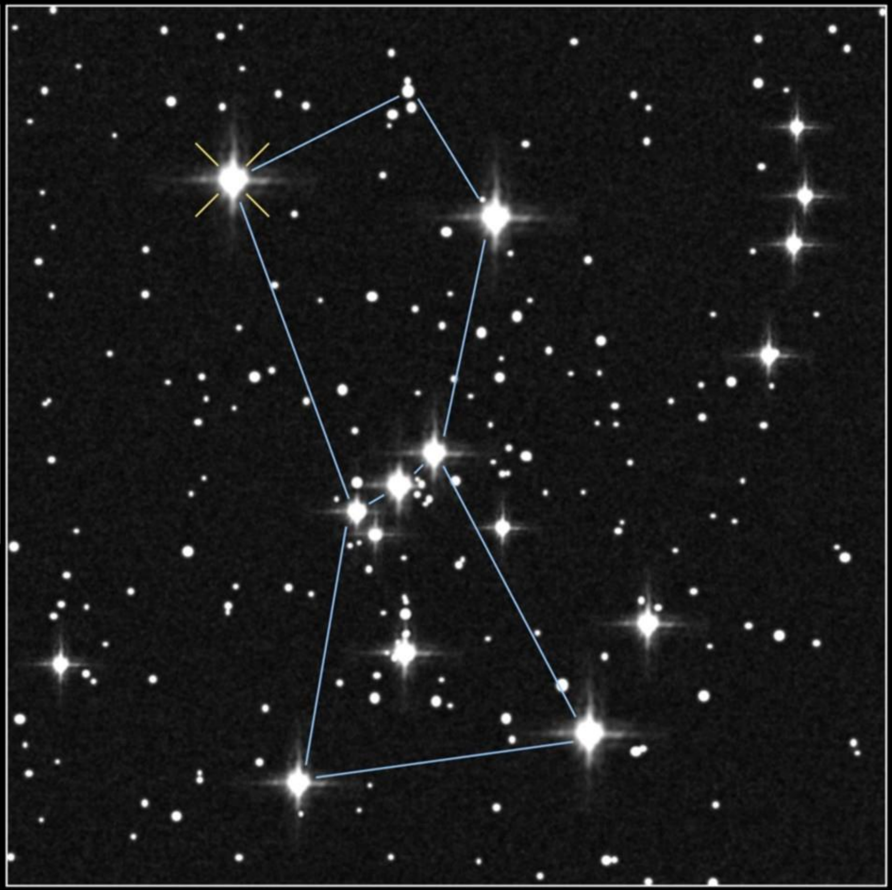
Supernova Rate in the Local Universe (Past Decade)



Kistler, Yüksel, Ando, Beacom & Suzuki, arXiv:0810.1959

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:

- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 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

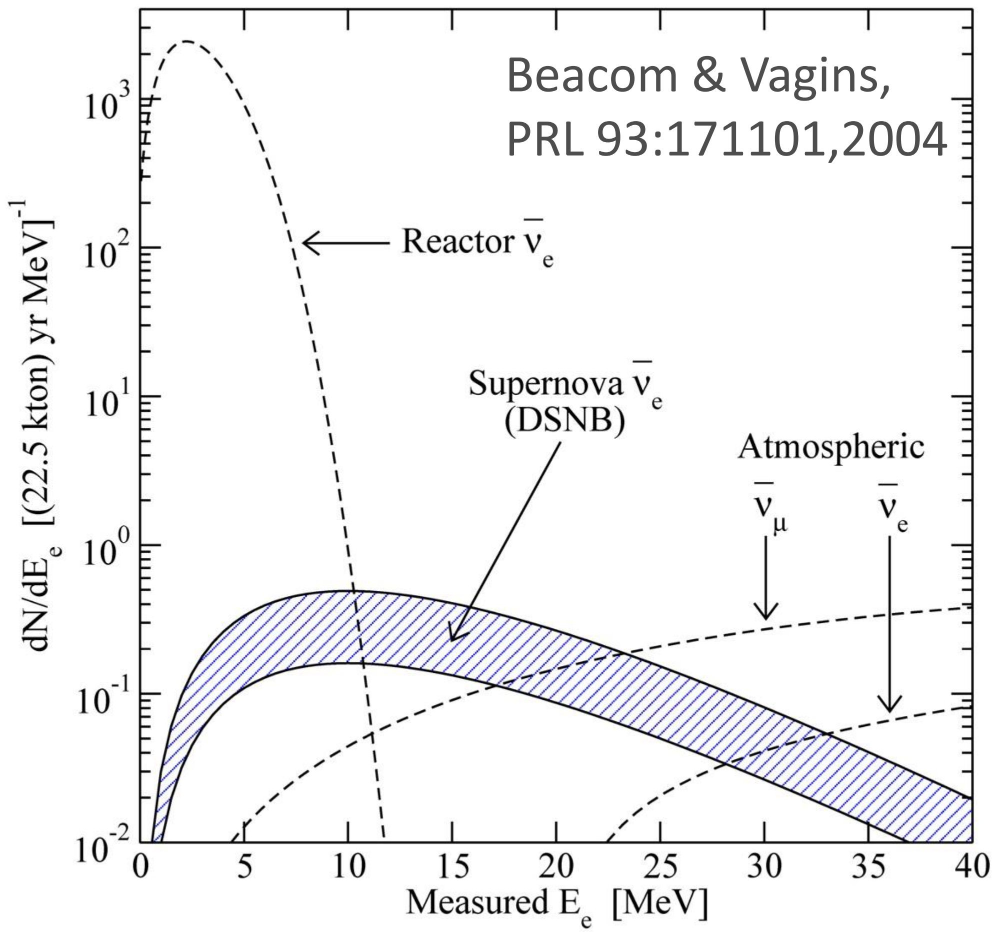
high statistics,
all flavors

object identity,
burst variety

cosmic rate,
average emission

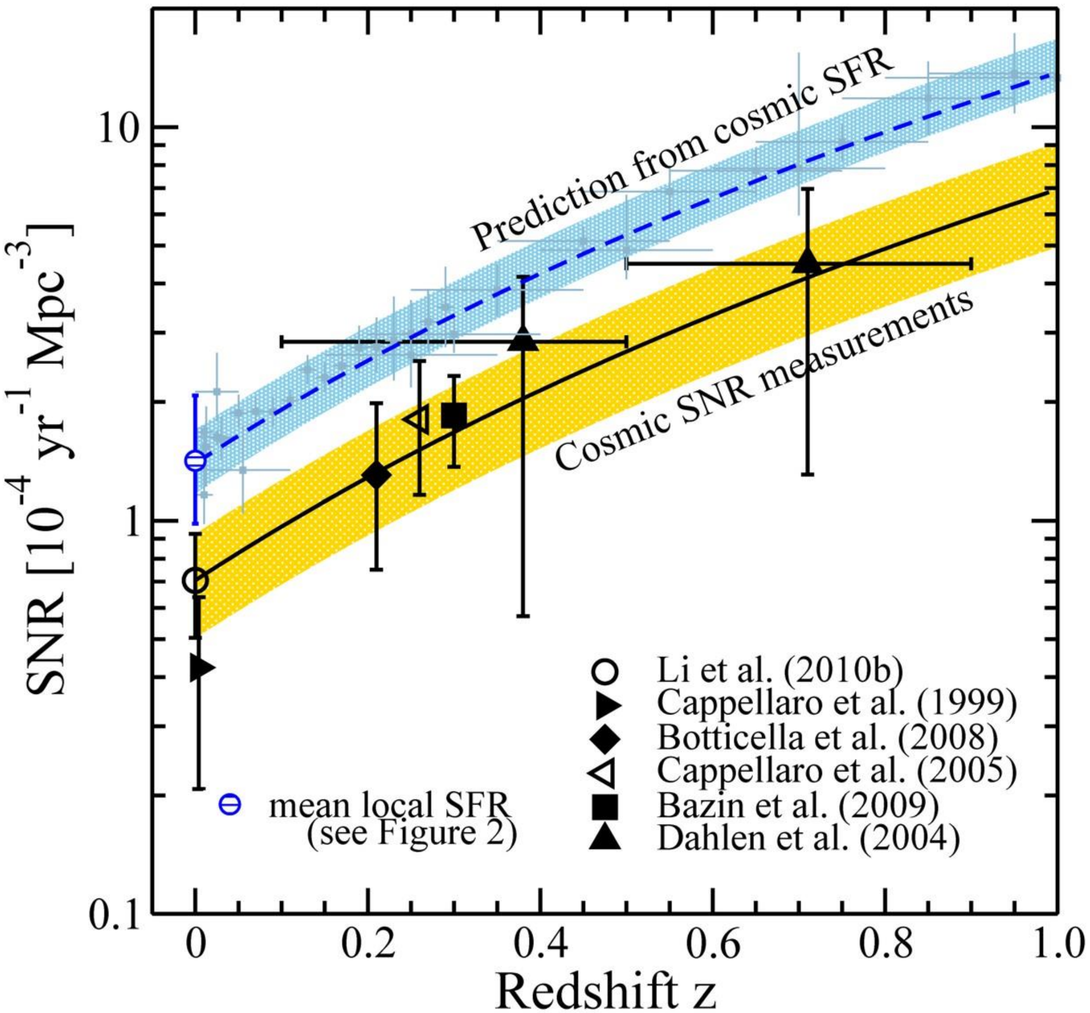
Diffuse Supernova Neutrino Background (DSNB)

- A few core collapses/sec in the visible universe
- Emitted ν 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 ν bkg

Supernova vs. Star Formation Rate in the Universe

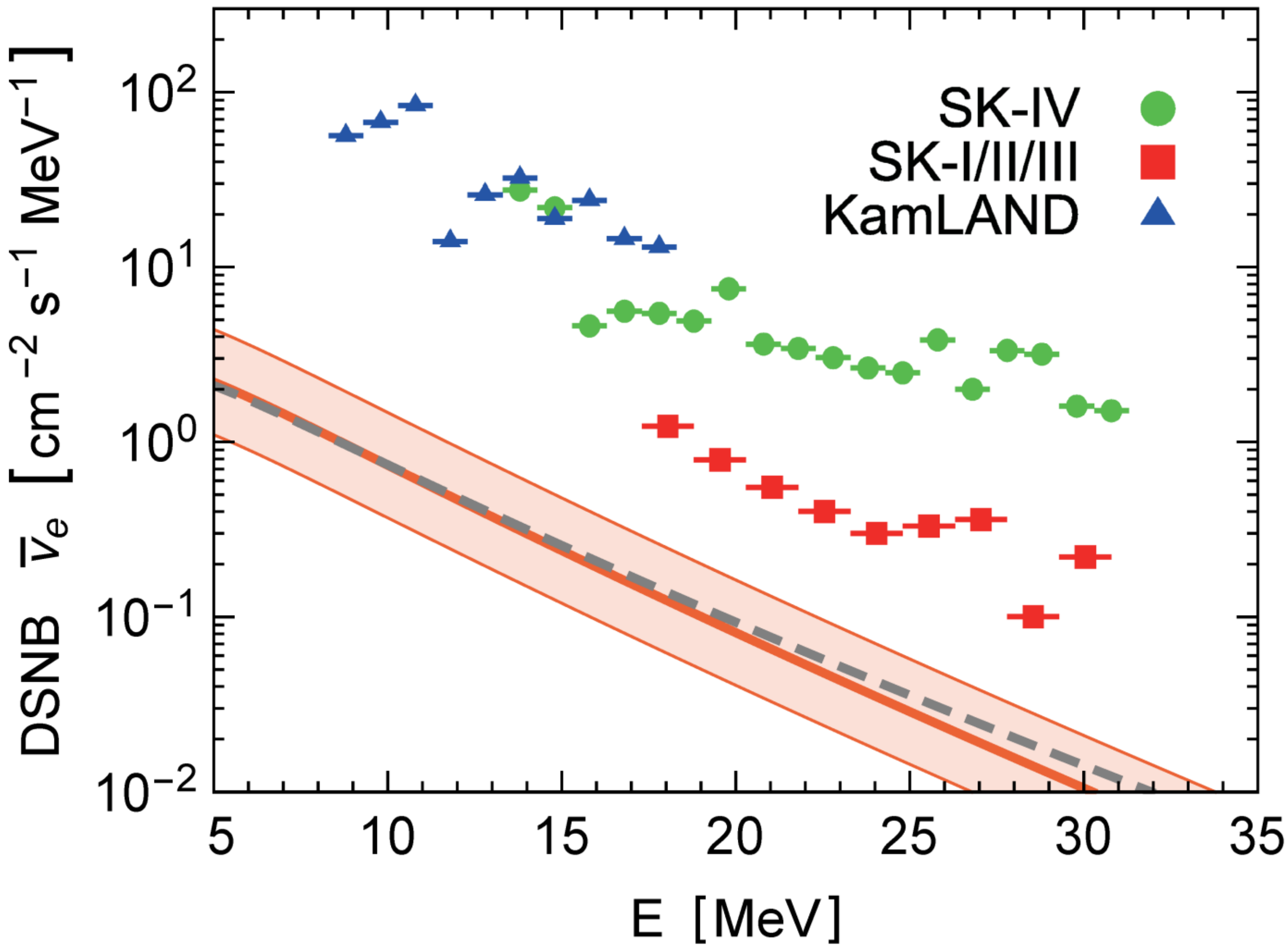


Measured SN rate about half the prediction from star formation rate

Many “dark SNe” ?

Horiuchi, Beacom, Kochanek, Prieto, Stanek & Thompson
arXiv:1102.1977

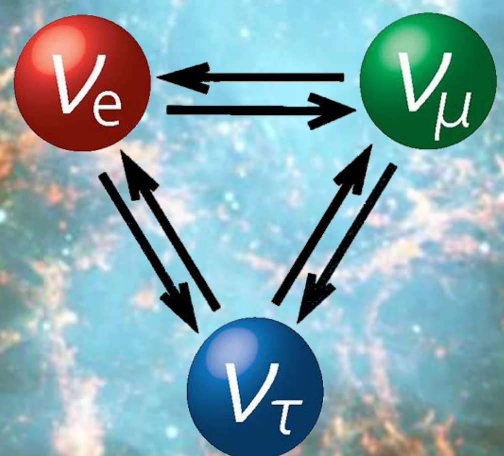
Experimental DSNB Searches



DSNB detection should succeed over the next decade (2023+)

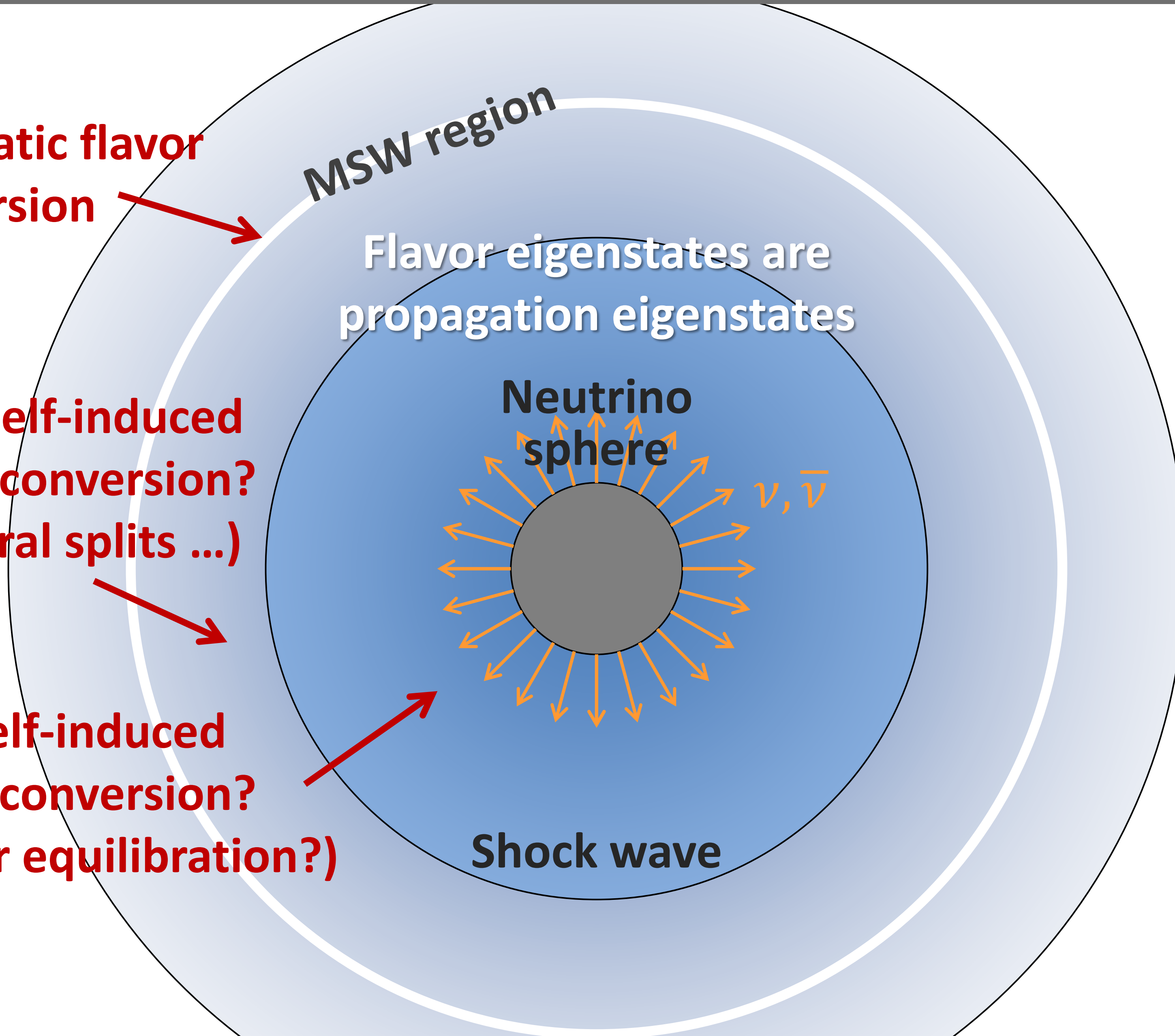
- Super-K with gadolinium enhancement
- JUNO scintillator detector

Supernova Neutrino Flavor Conversion

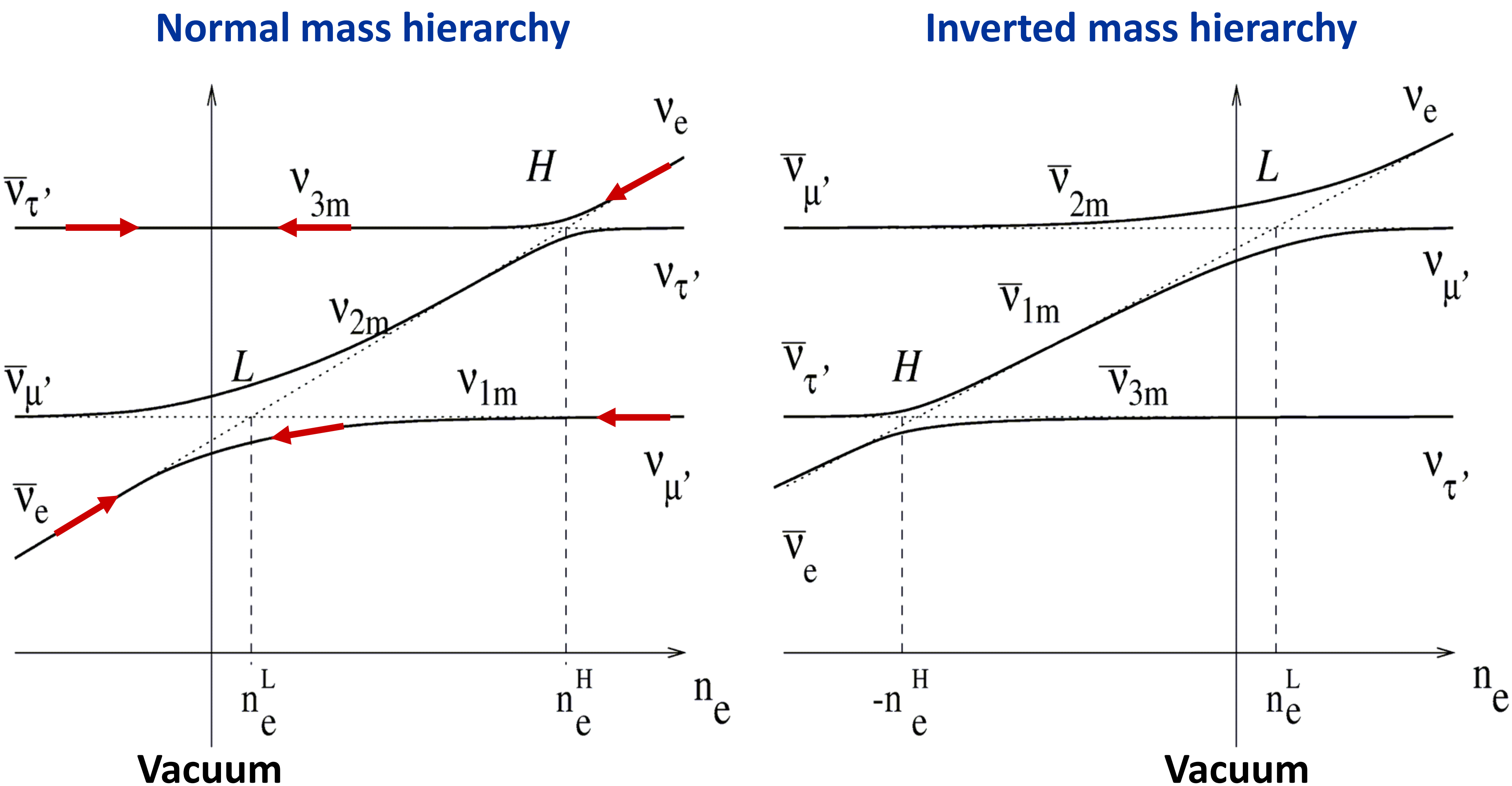


Flavor Conversion in Core-Collapse Supernovae

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



Level-Crossing Diagram in a Supernova Envelope



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

SN Flavor Oscillations and Mass Hierarchy

- Mixing angle Θ_{13} has been measured to be “large”
- MSW conversion in SN envelope adiabatic
- Assume that collective flavor oscillations are not important

	Mass ordering	
	Normal (NH)	Inverted (IH)
ν_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 hierarchy?

Deleptonization ν_e Burst in DUNE

Neutrino mass ordering in argon detector

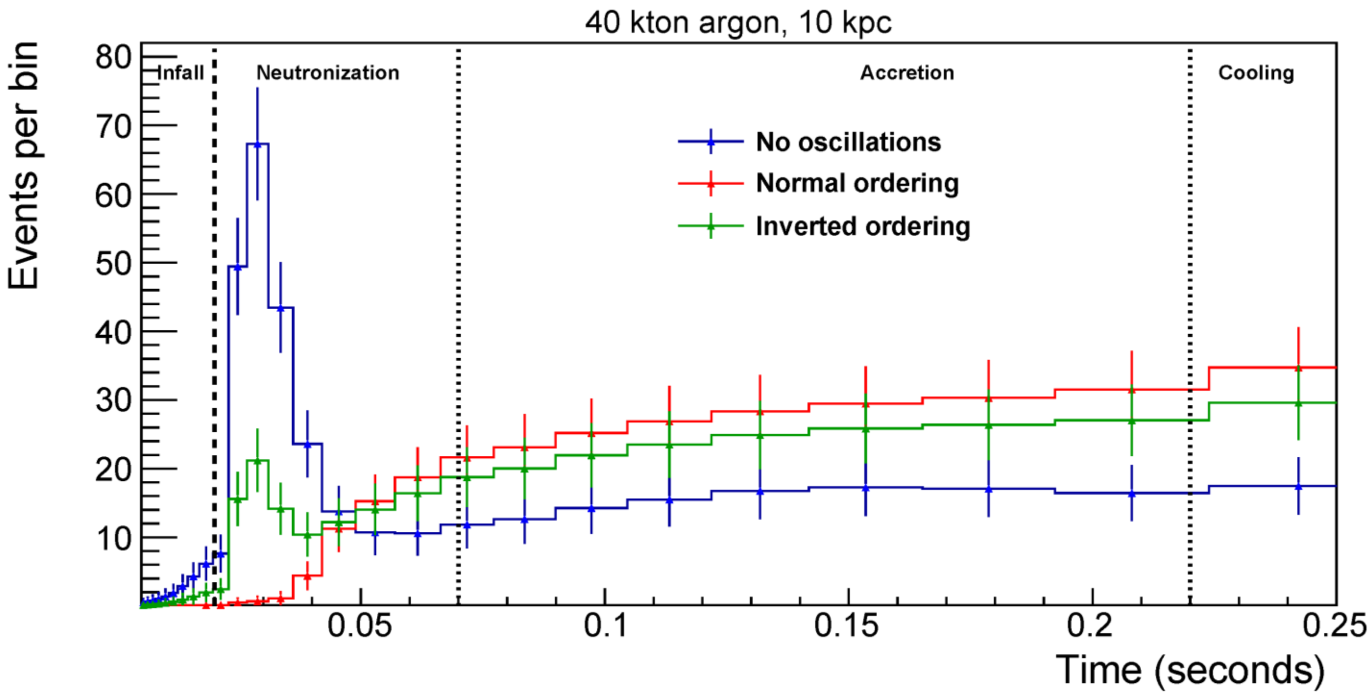
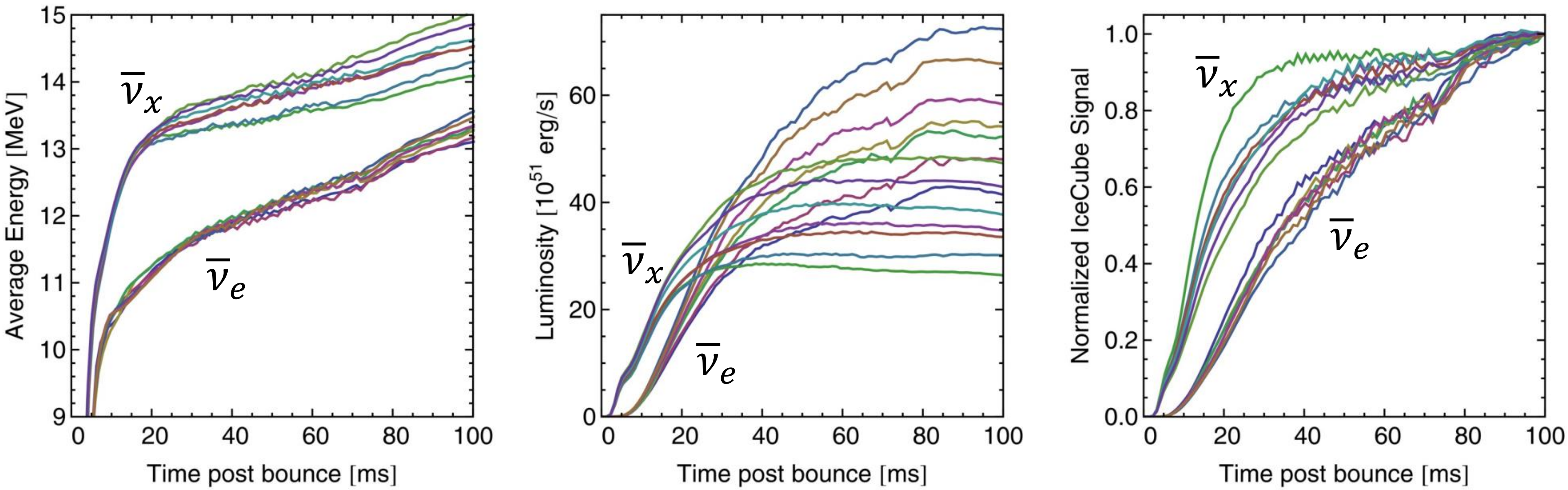


Fig. 11 Expected event rates as a function of time for the electron-capture model in [8] for 40 kton of argon during early stages of the event – the neutronization burst and early accretion phases, for which self-induced effects are unlikely to be important. Shown are: the event rate for the unrealistic 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**



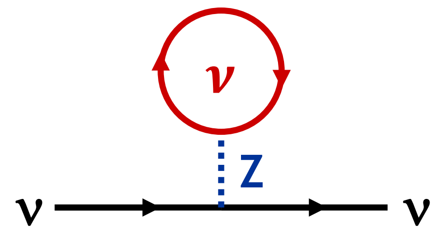
- In principle very sensitive to hierarchy, notably IceCube or HK
- "Standard candle" to be confirmed by other than Garching models

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

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!

Self-Induced Flavor Conversion

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

- Requires lepton flavor violation by masses and mixing

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

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

Pair-wise flavor exchange by ν–ν 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 $\mathcal{O}(G_\mathrm{F}^2)$
  Here as coherent refractive effect $\mathcal{O}(G_\mathrm{F}\ )$

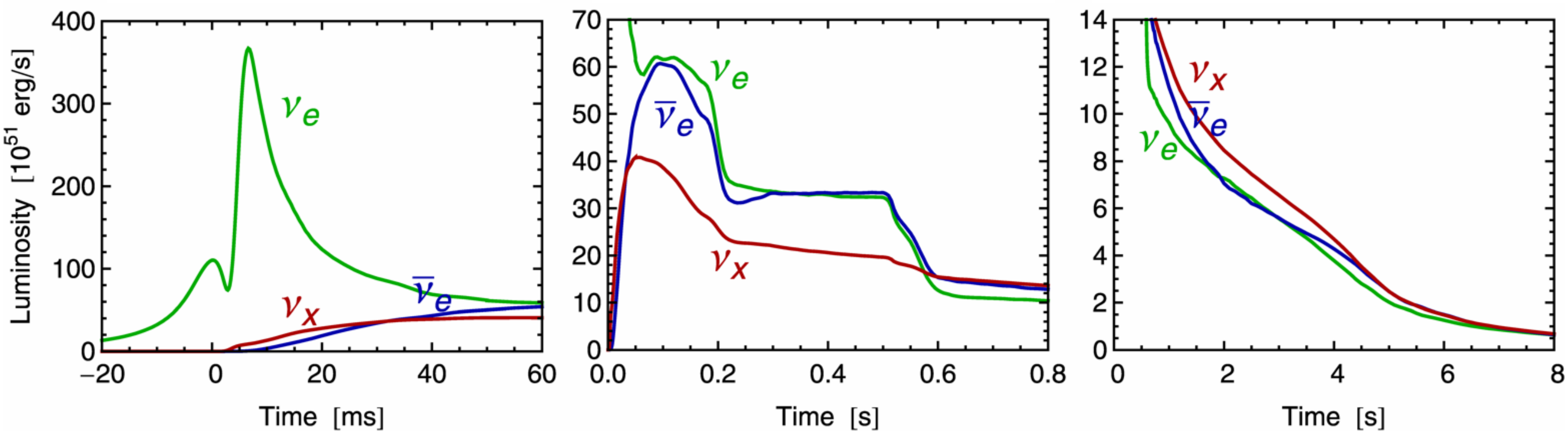
$$\nu_e(p) + \overline{\nu}_e(k) \to \nu_\mu(p) + \overline{\nu}_\mu(k)$$

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

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

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

Prompt ν_e burst | Accretion | Cooling



"Standard Candle"

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

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

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

EoS & mass dependence

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

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