
ISAPP 2017, Arenzano, Italy, 13–24 June 2017
Supernova Neutrinos
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Max-Planck-Institut für Physik
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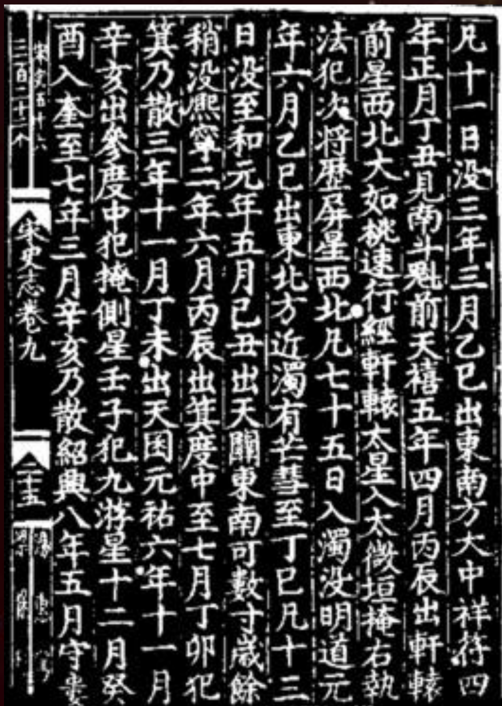
elusives
neutrinos, dark matter & dark energy physics
SFB 1258
Neutrinos
Dark Matter
Messengers

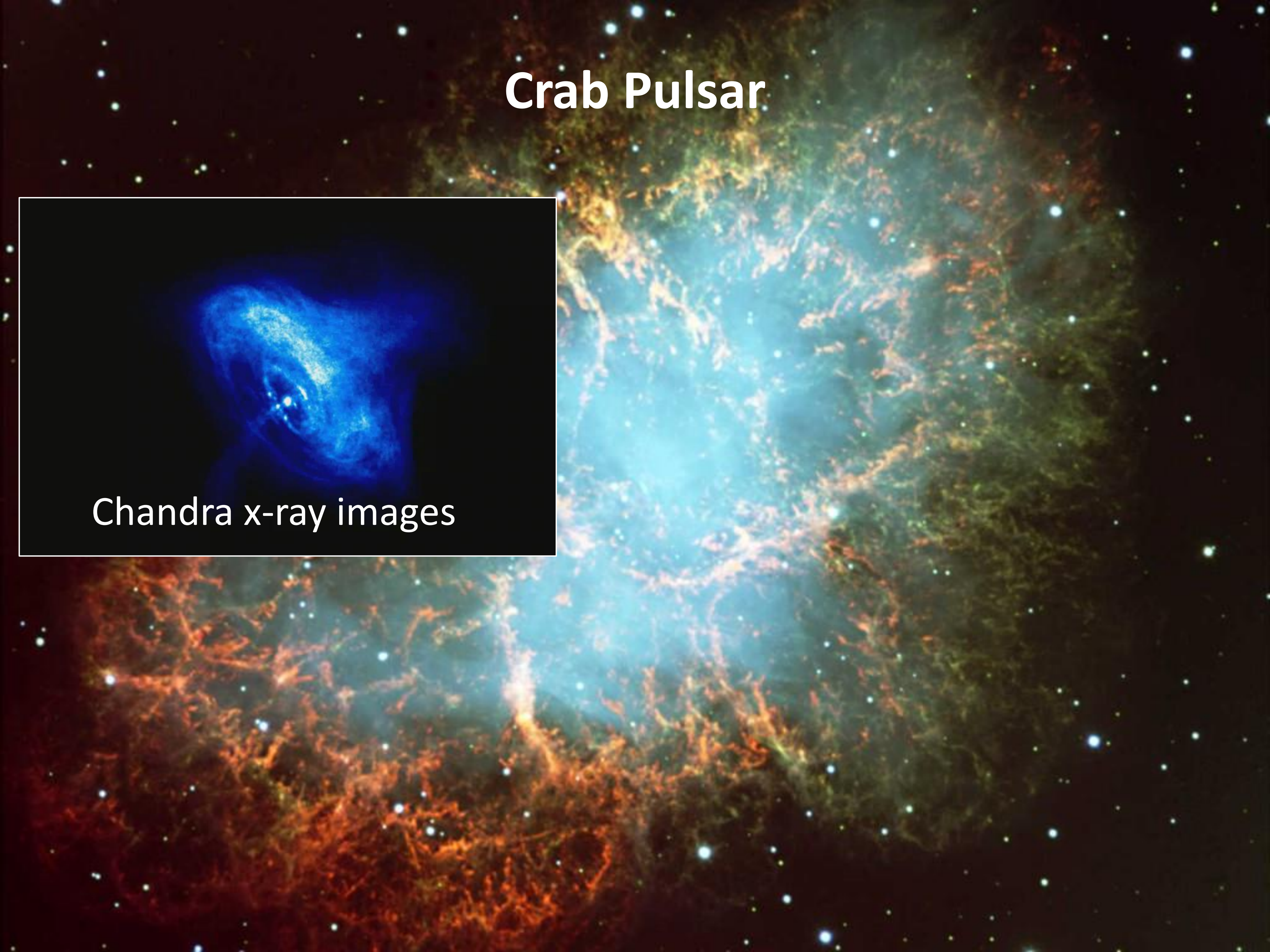
Crab Nebula – Remnant of SN 1054



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大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

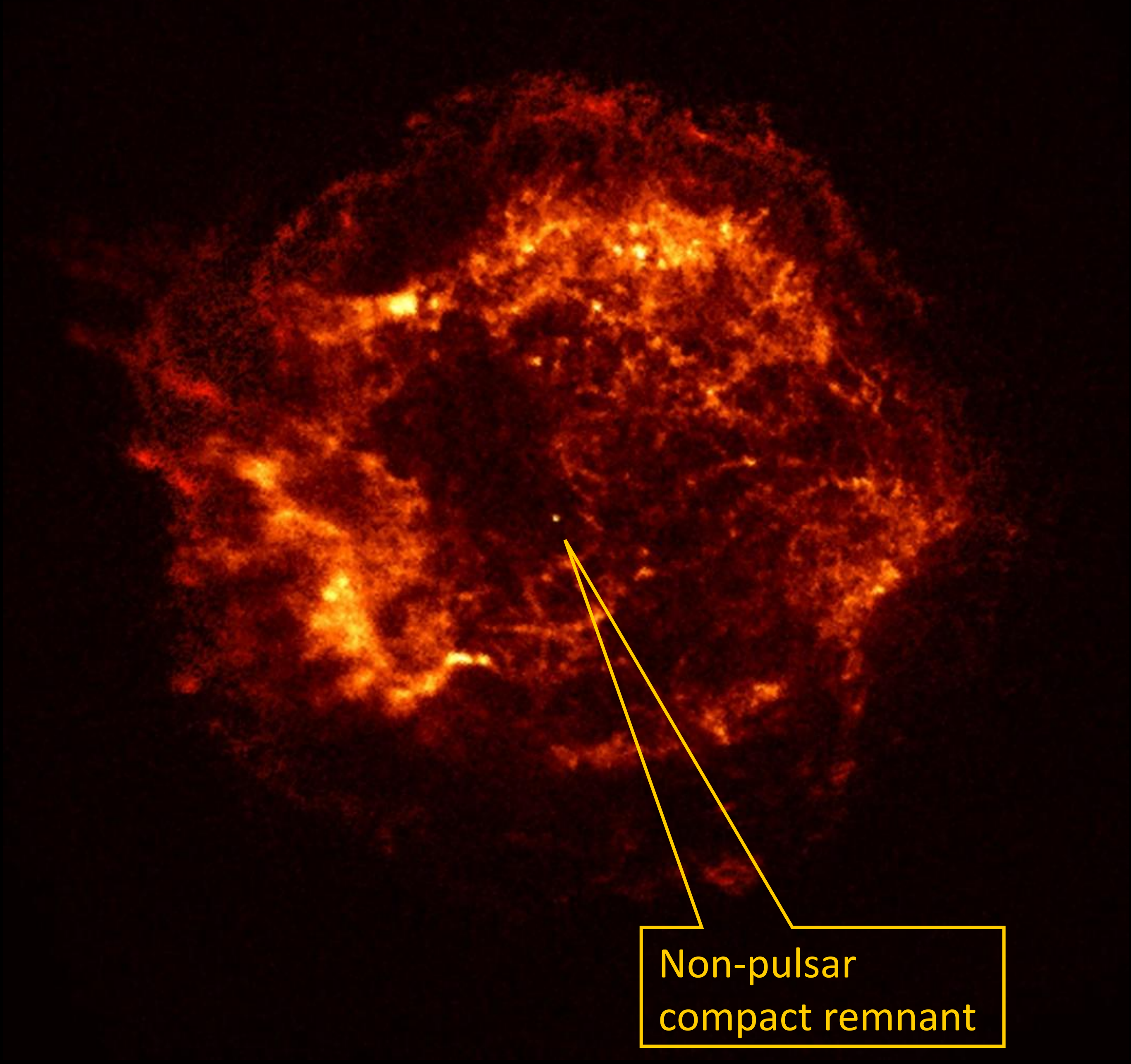
Crab Pulsar



Chandra x-ray images

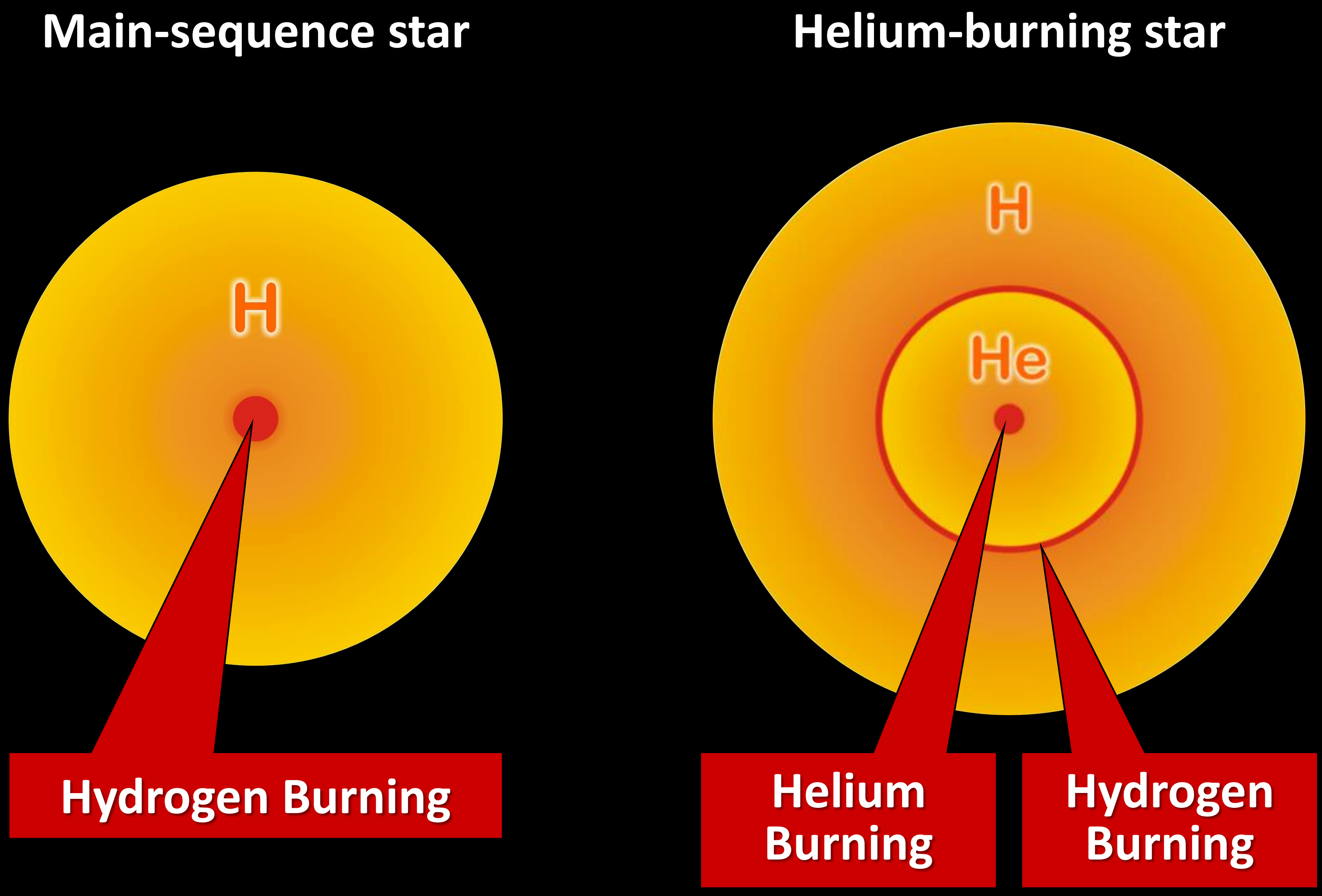
Supernova Remnant in Cas A (SN 1680?)

Chandra
x-ray image



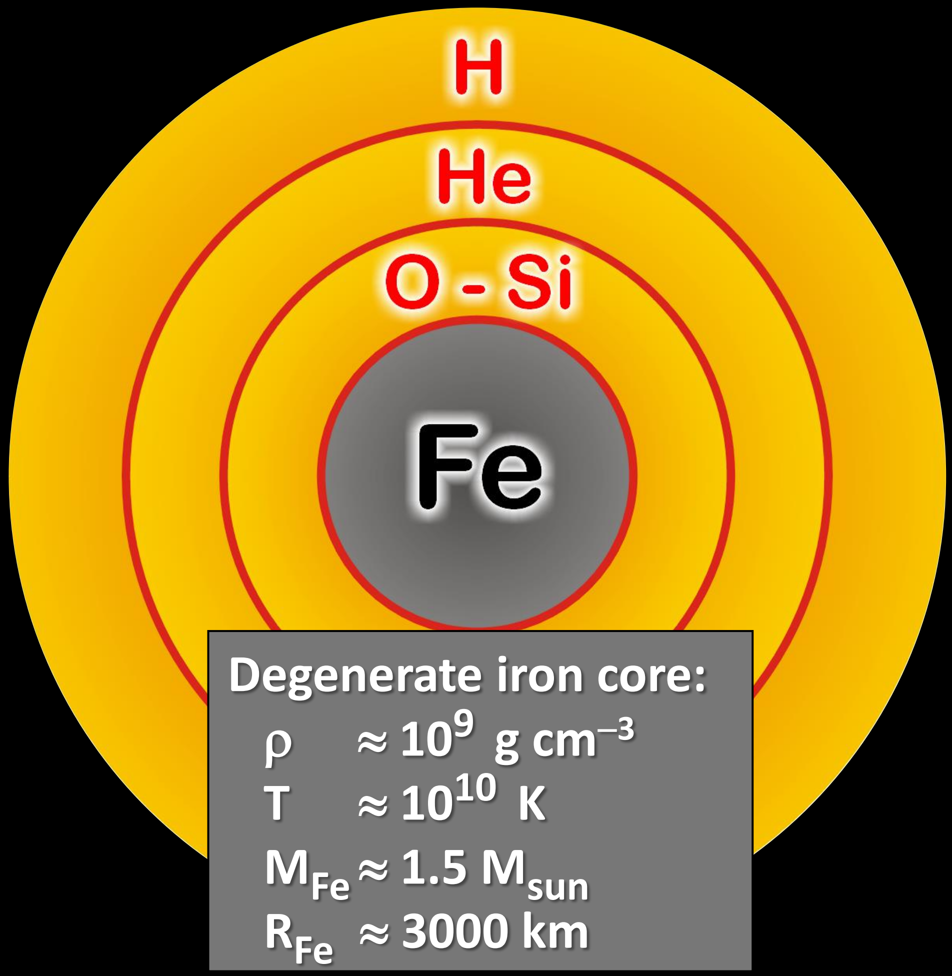
Supernova Explosions

Stellar Collapse and Supernova Explosion

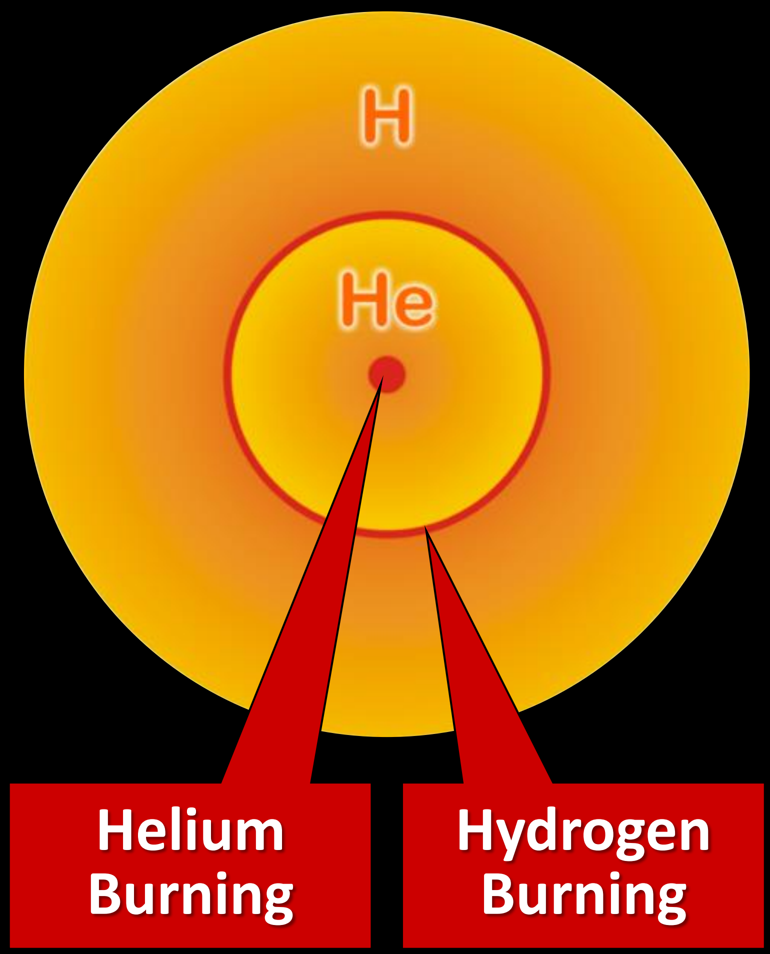


Stellar Collapse and Supernova Explosion

Onion structure



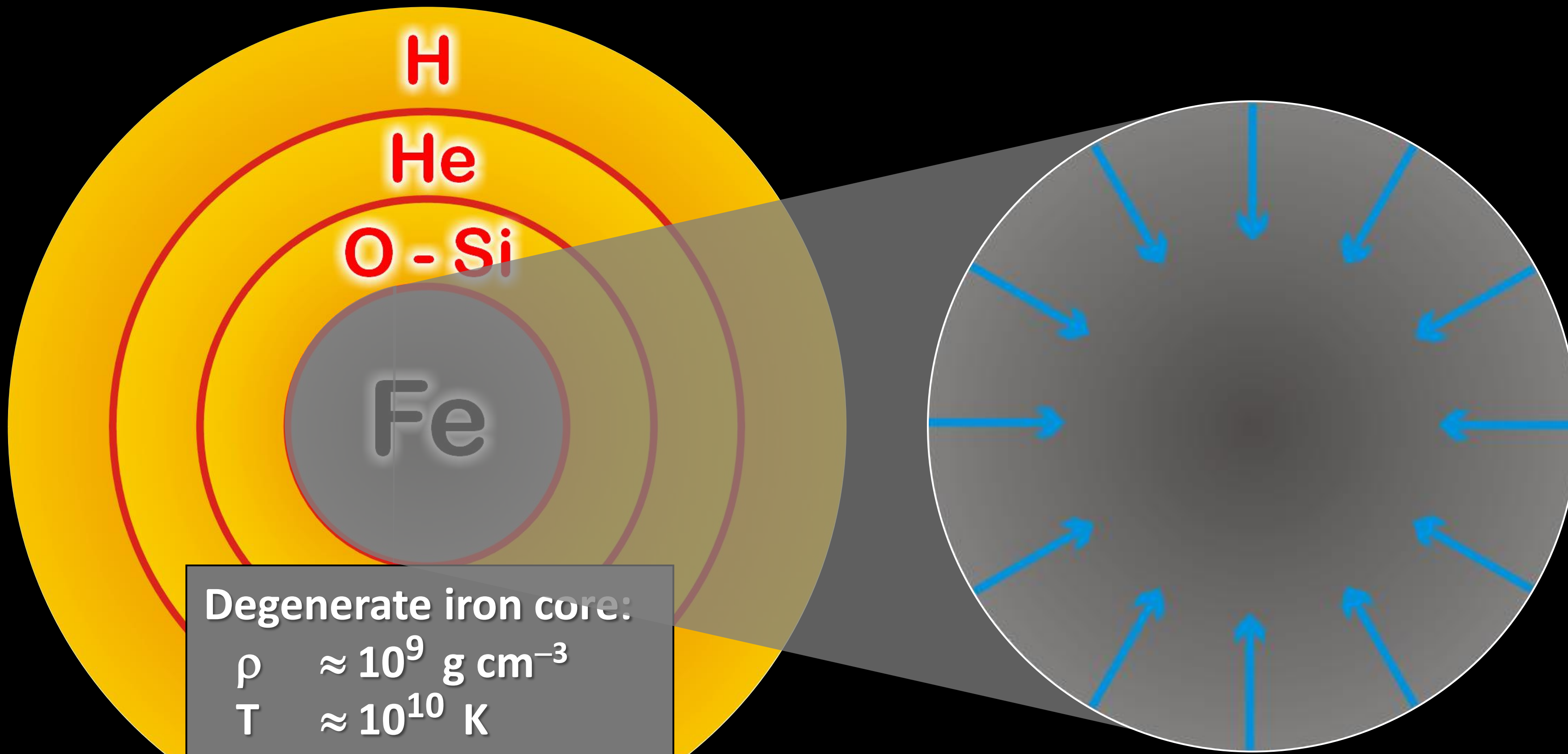
Helium-burning star



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

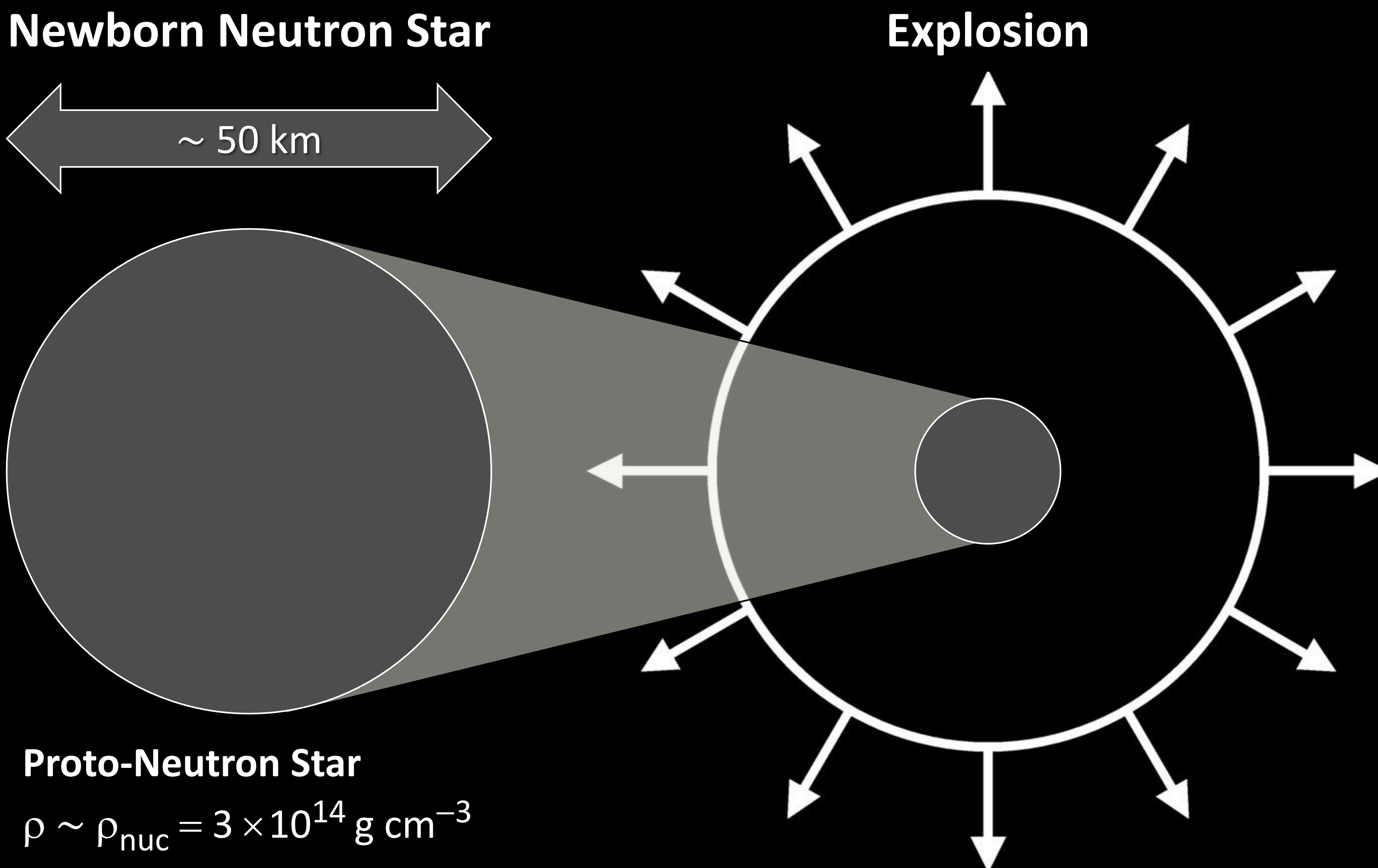
$\rho \approx 10^{9}\ \mathrm{g\ cm^{-3}}$

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

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

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

Stellar Collapse and Supernova Explosion



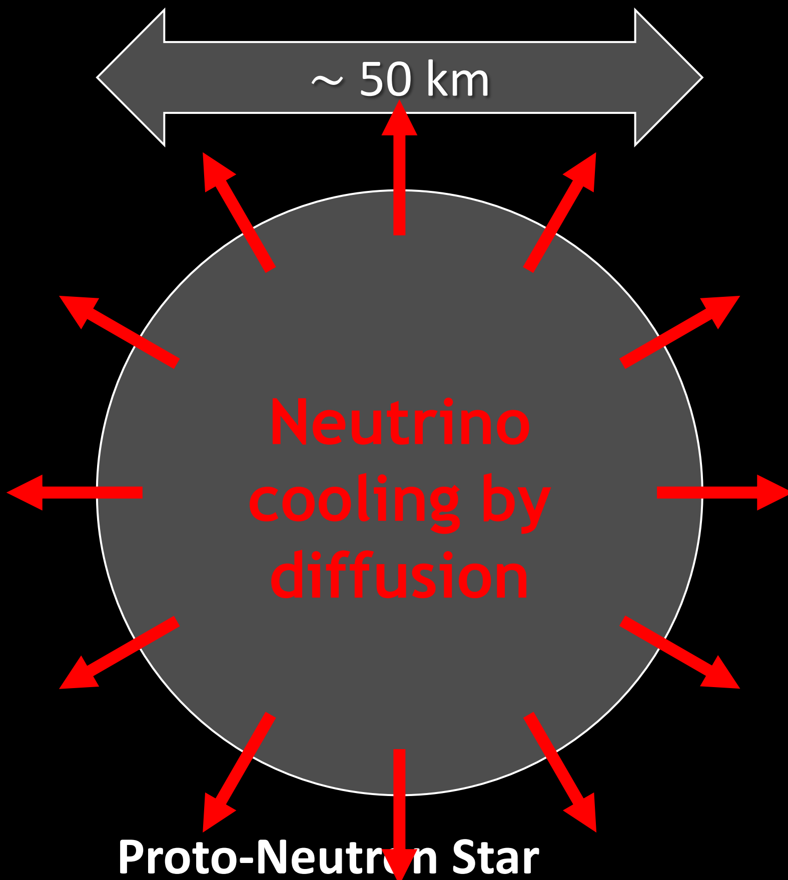
Proto-Neutron Star

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

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

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

$E_b \approx 3 \times 10^{53}$ 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

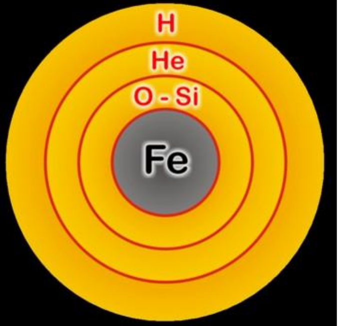
$L_\nu \sim 3 \times 10^{53}$ erg / 3 sec

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

While it lasts, outshines the entire visible universe

Thermonuclear vs. Core-Collapse Supernovae

Thermonuclear (Spectral type Ia)	Core collapse (Spectral type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface



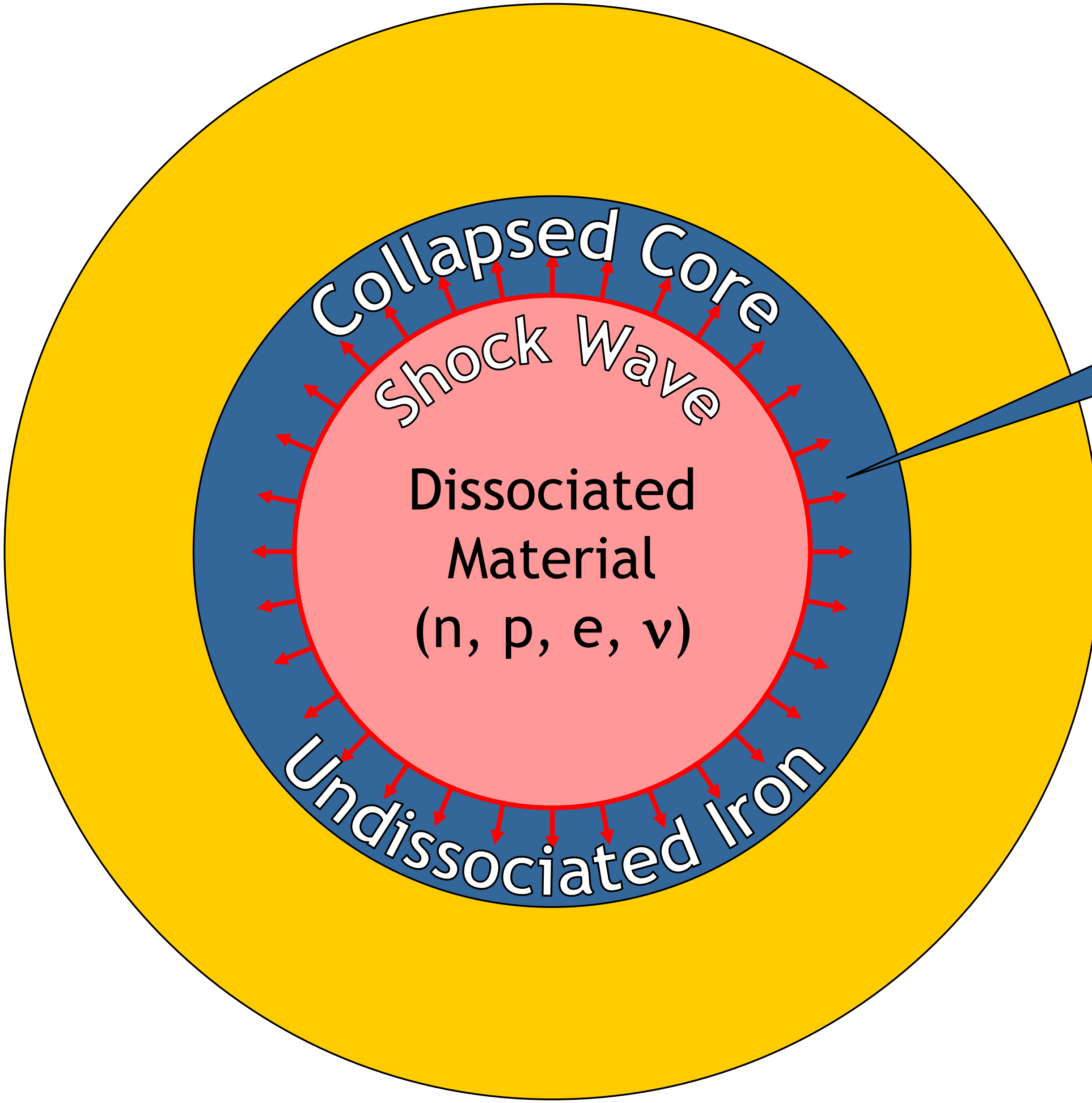
Chandrasekhar limit is reached — $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

Thermonuclear	Core collapse
Nuclear burning of C and O ignites → Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Comparable "visible" energy release of $\sim 3 \times 10^{51}$ erg

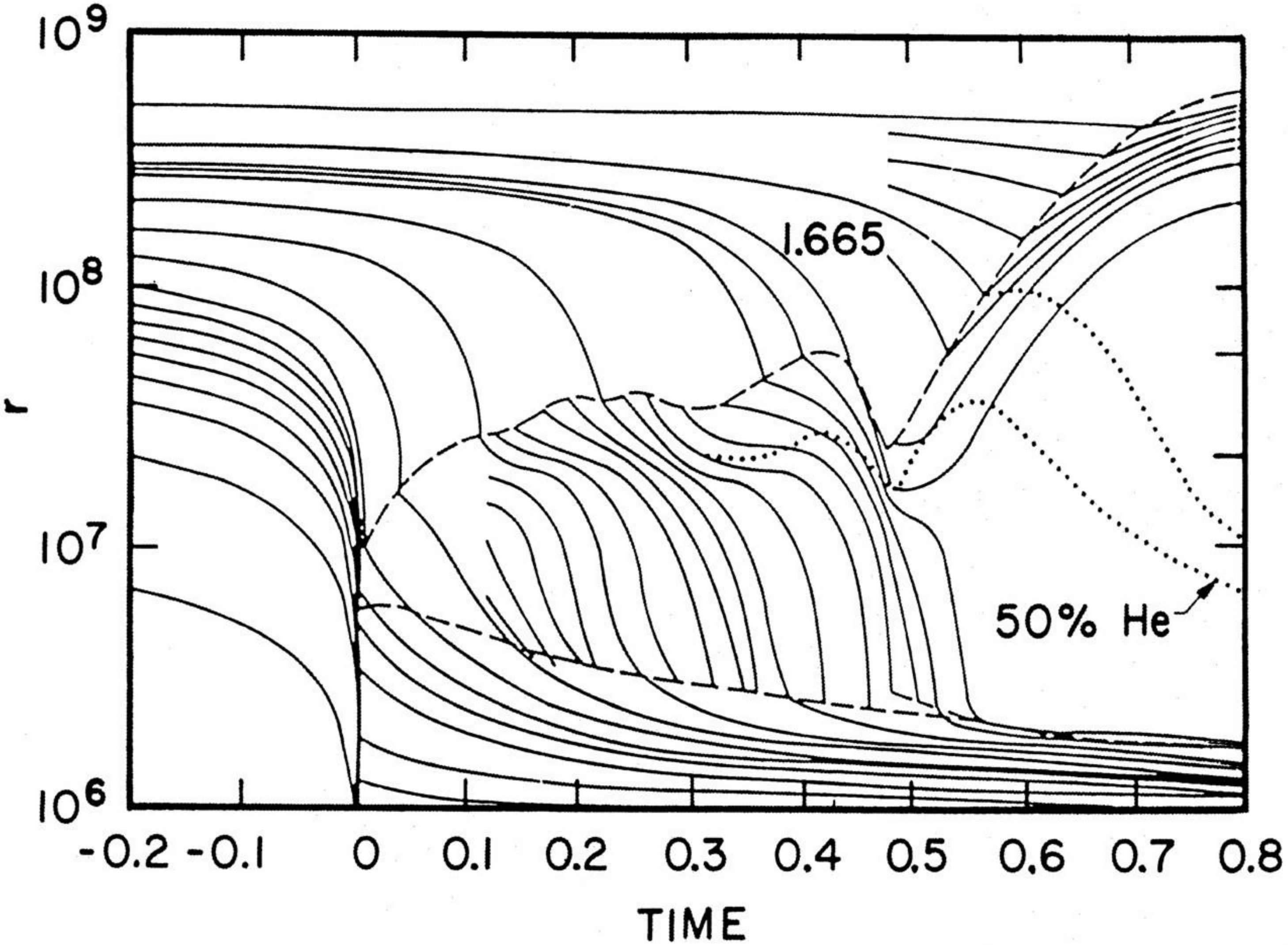
Why No Prompt Explosion?



- 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**

Delayed (Neutrino-Driven) Explosion

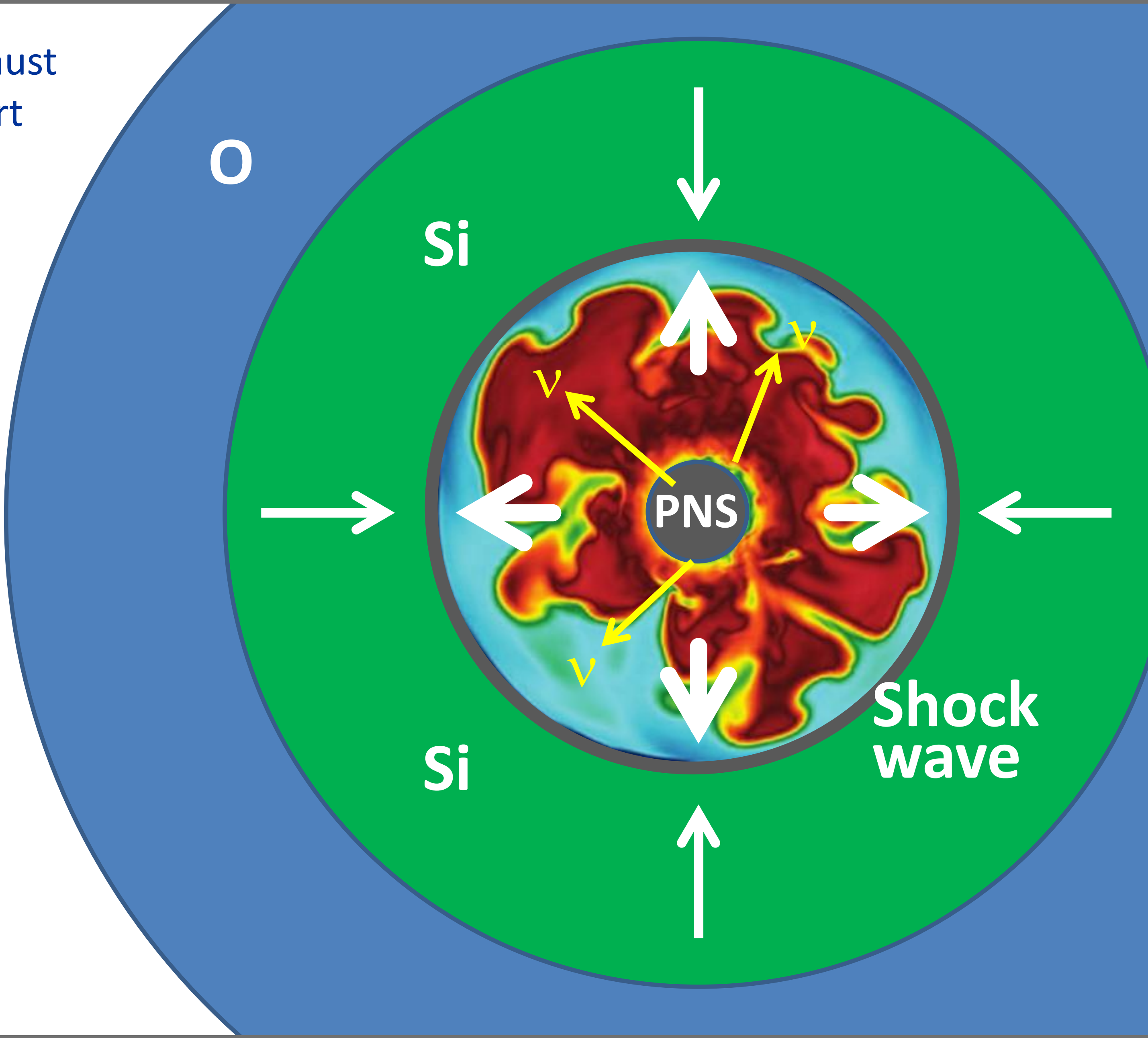


Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys. (1982)
Bethe & Wilson, ApJ 295 (1985) 14

Shock Revival by Neutrinos

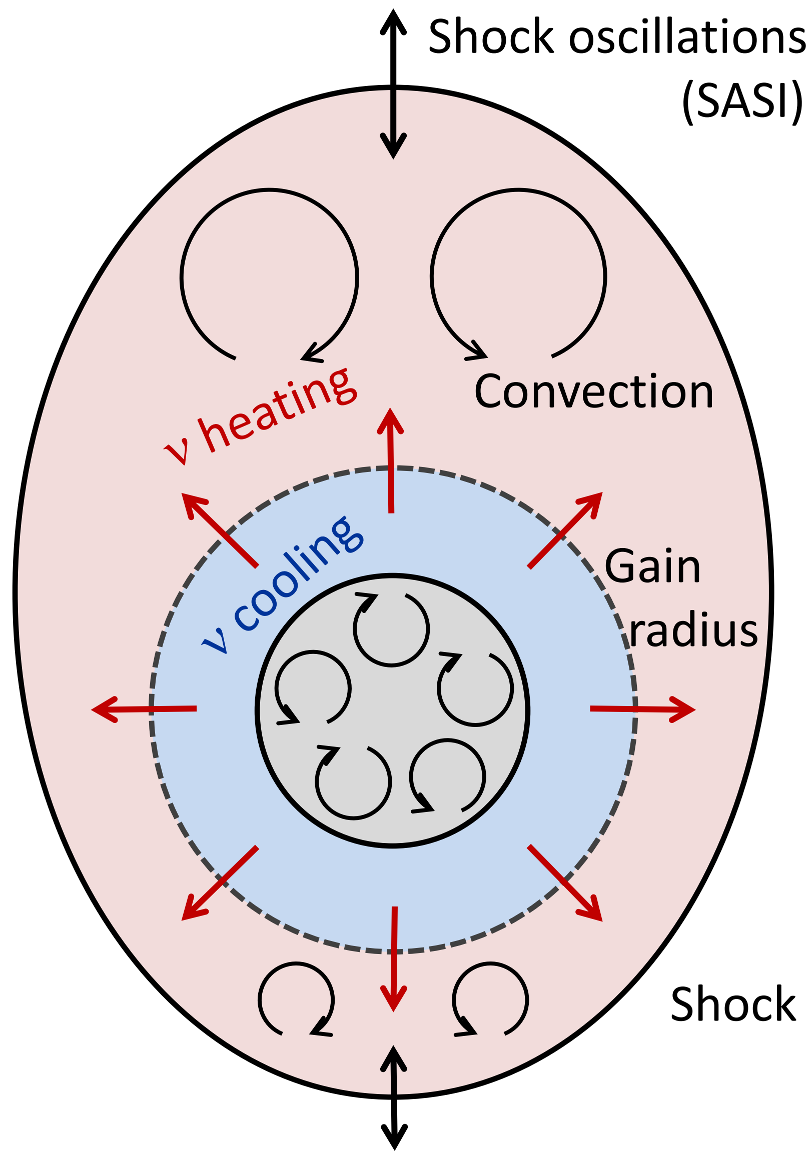
Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

Shock can receive fresh energy from neutrinos!



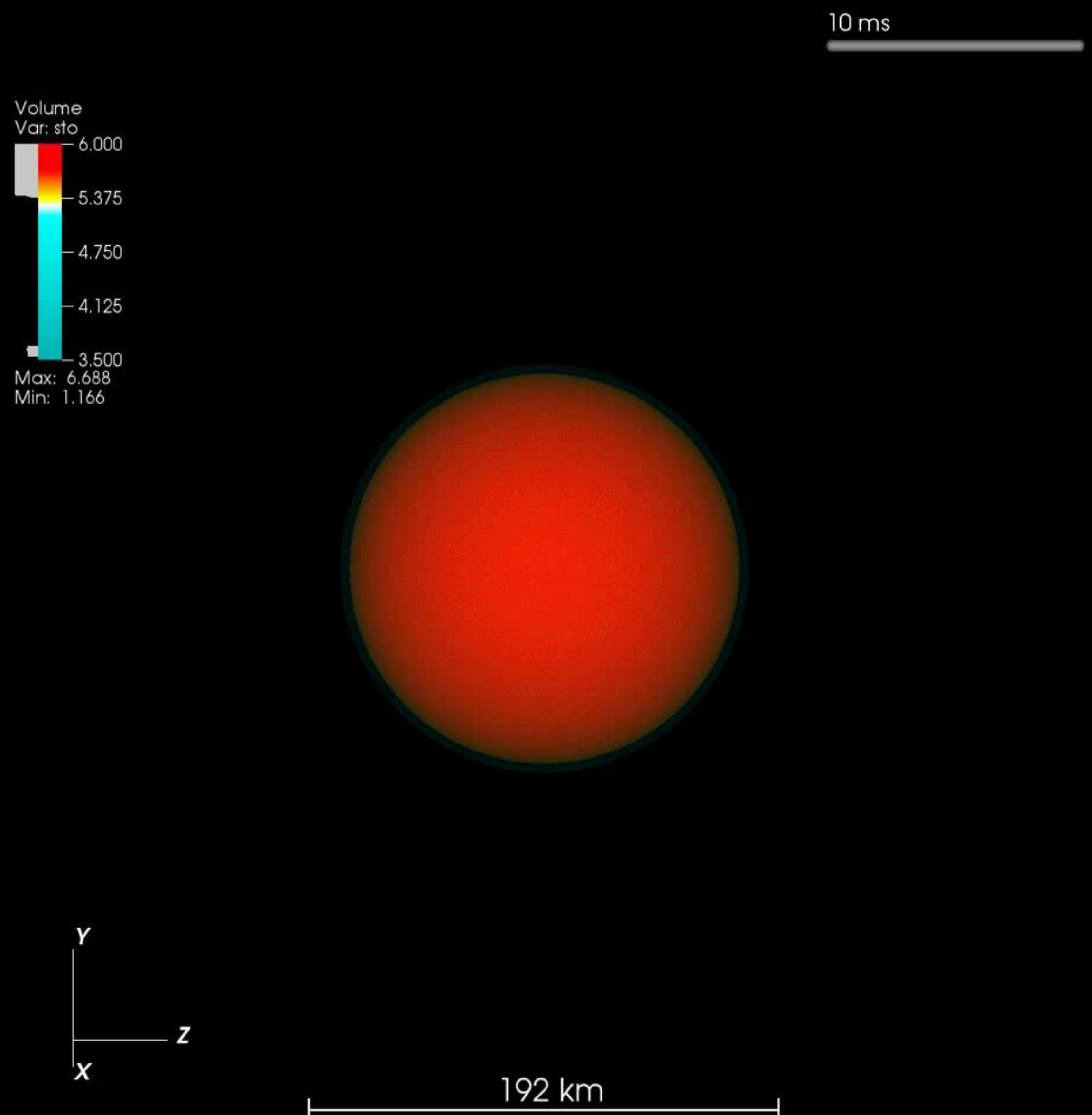
Neutrino-Driven Mechanism – Modern Version

- Stalled accretion shock pushed out to ~150 km as matter piles up on the PNS
- Heating (gain) region develops within some tens of ms after bounce
- Convective overturn & shock oscillations (SASI) enhance efficiency of ν-heating, finally revives shock
- Successful explosions in 1D and 2D for different progenitor masses (e.g. Garching group)
- Details important (treatment of GR, ν interaction rates, etc.)
- First self-consistent 3D studies being performed, sometimes successful explosions

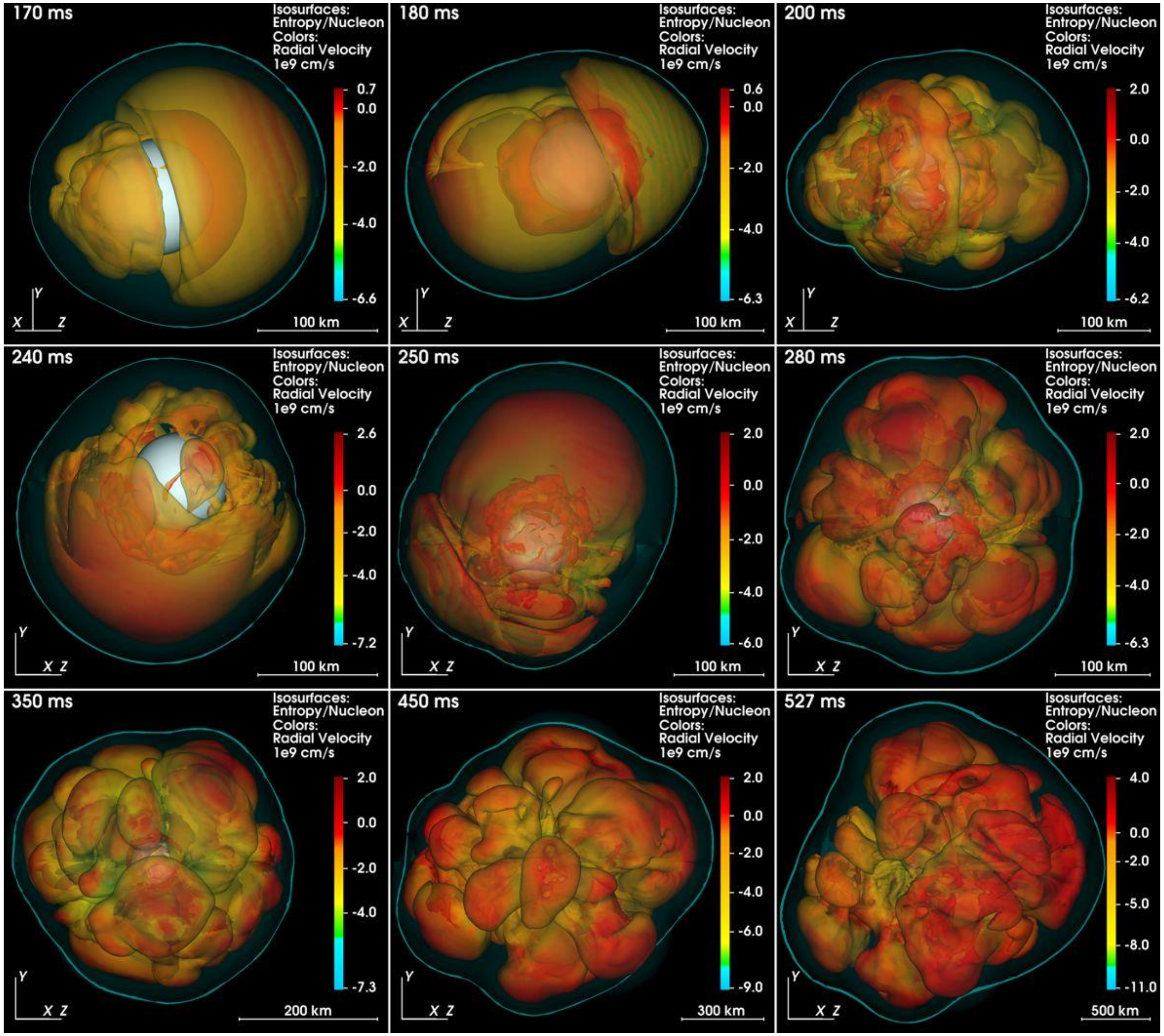


Adapted from B. Müller

Exploding 3D Simulation (20 $M_\odot$ Garching Group)



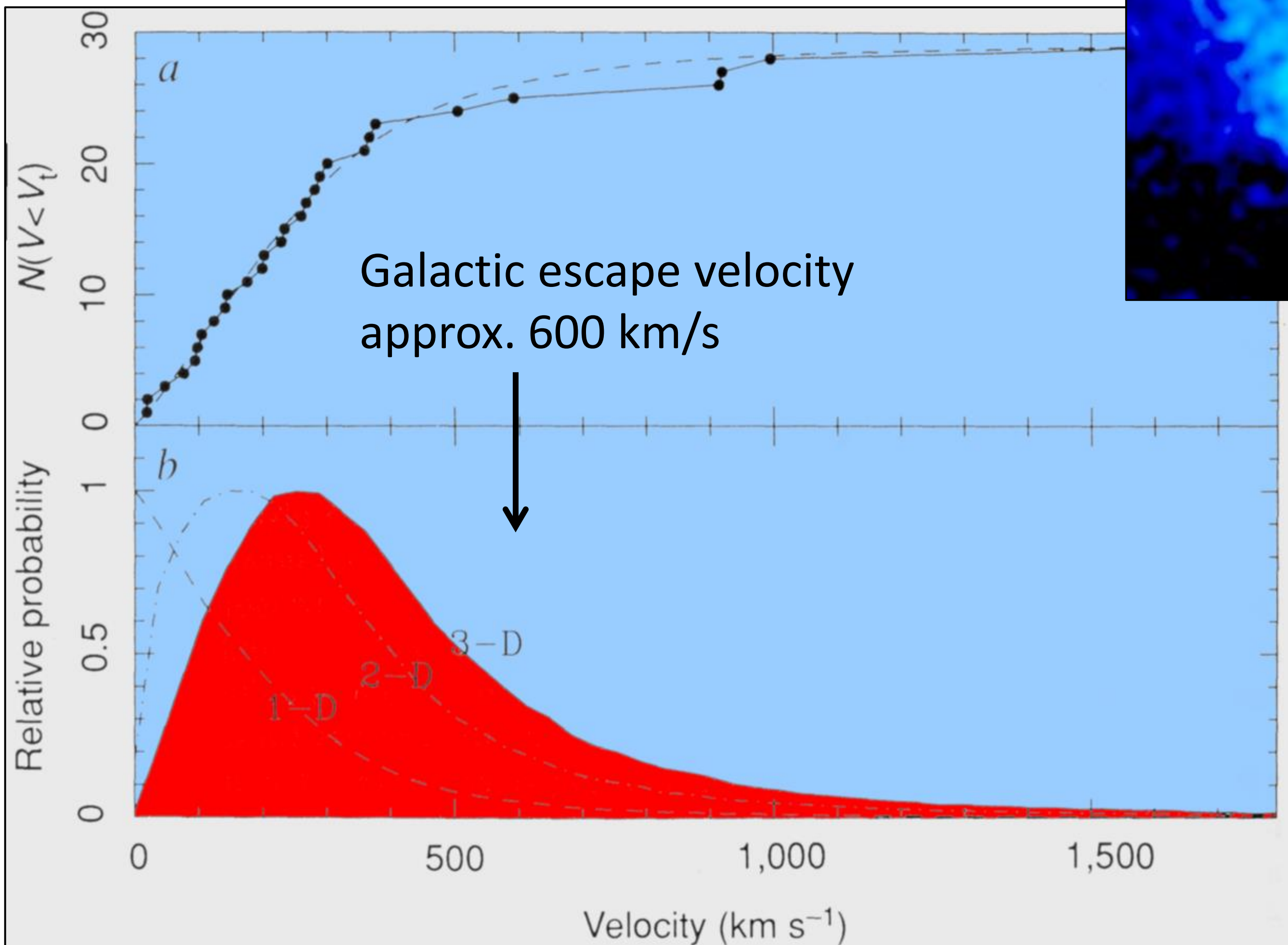
Exploding 3D Garching Model (20 M_{SUN})

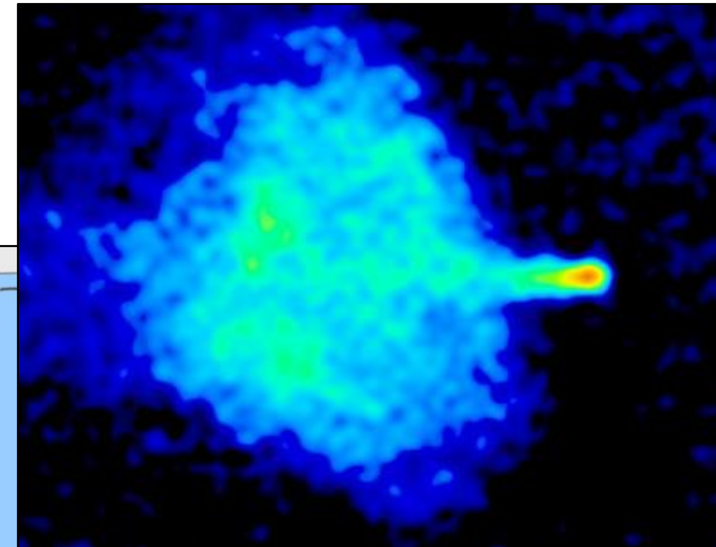


Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

High-Velocity Pulsars

False-color radio image of the SNR G5.4-1.2
and the young radio pulsar PSR 1757-24
(v = 1300–1700 km/s away from the galactic plane)

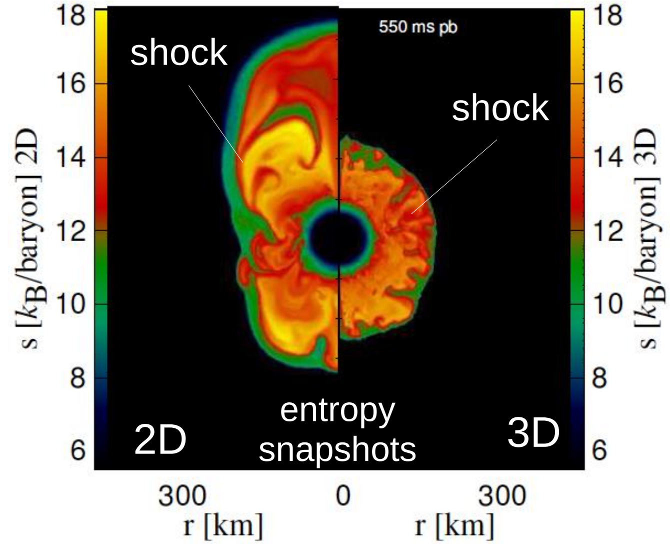




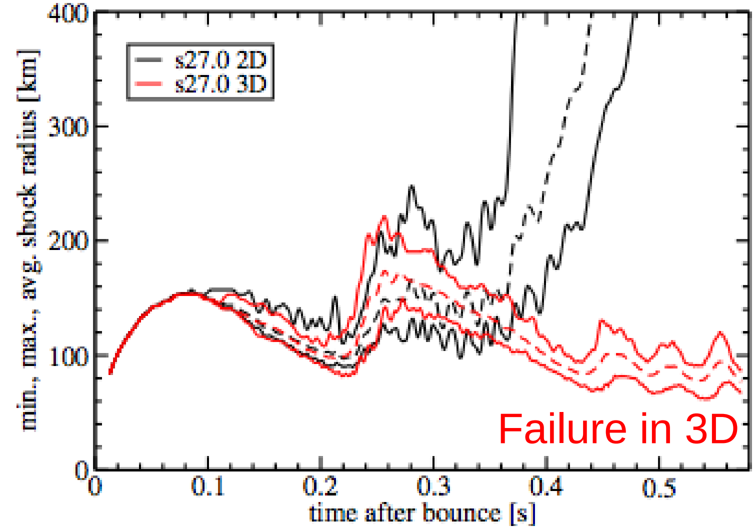
Pulsar velocity distribution

Lyne & Lorimer,
Nature 369 (1994) 127

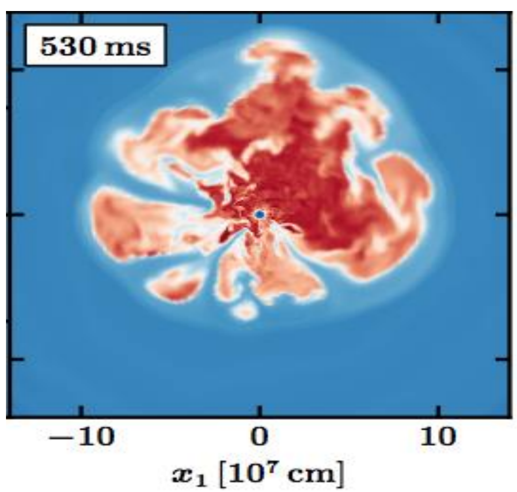
Problems with Shock Revival in 3D Simulations

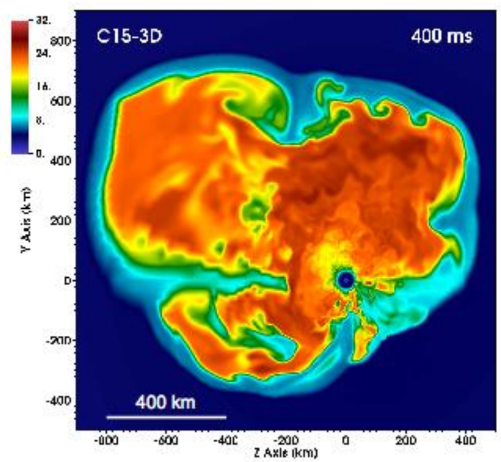


Simplified “light-bulb” model (Hanke et al. 2012)
Turbulent convection in 2D and 3D



27 $M_\odot$ Hanke et al. (2013)





15 $M_\odot$ Lentz et al. (2015)

First-principle 3D models:

- Mixed record: failures or **explosions delayed vs. 2D**
- Close to threshold: ok, we expect failures in nature!
- No proof that ν-mechanism is *robust*

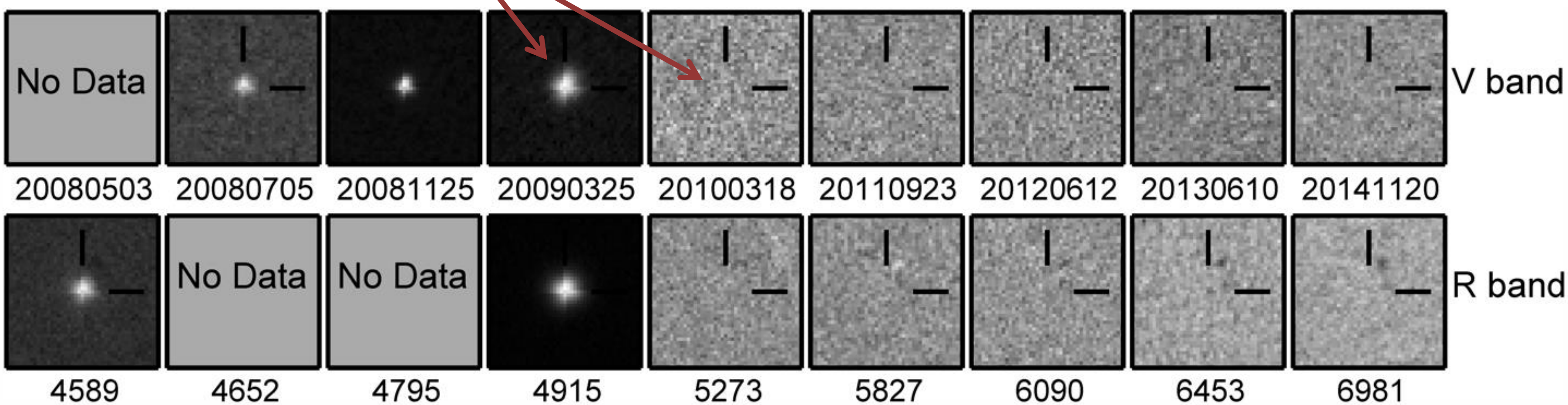
Or with simpler schemes: e.g. IDSA+leakage Takiwaki et al. (2014)

Death Watch for 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:

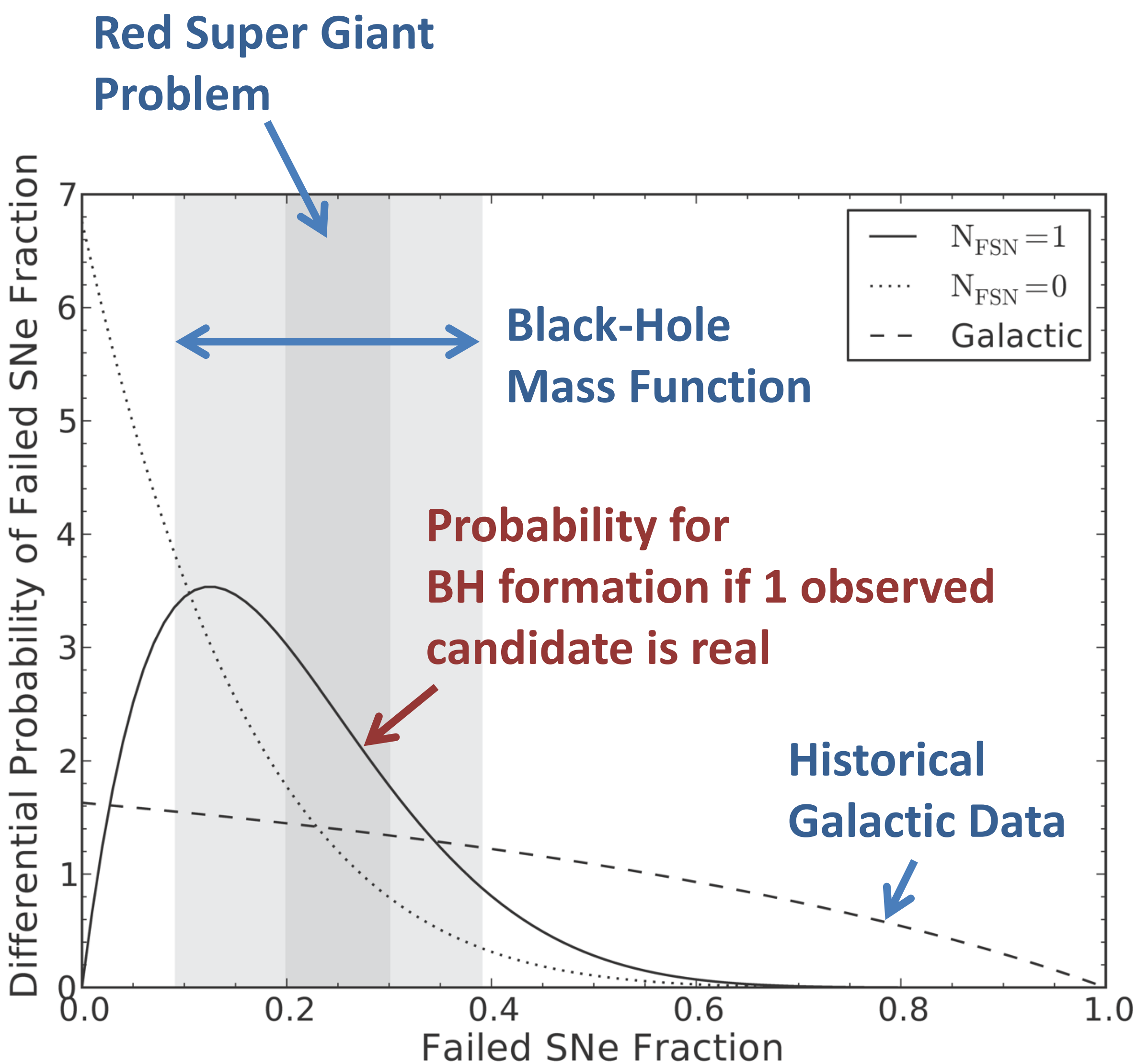
- 6 successful core-collapse SNe
- 1 candidate failed SN



Gerke, Kochanek & Stanek, arXiv:1411.1761

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

Empirical Fraction of Black-Hole Formation



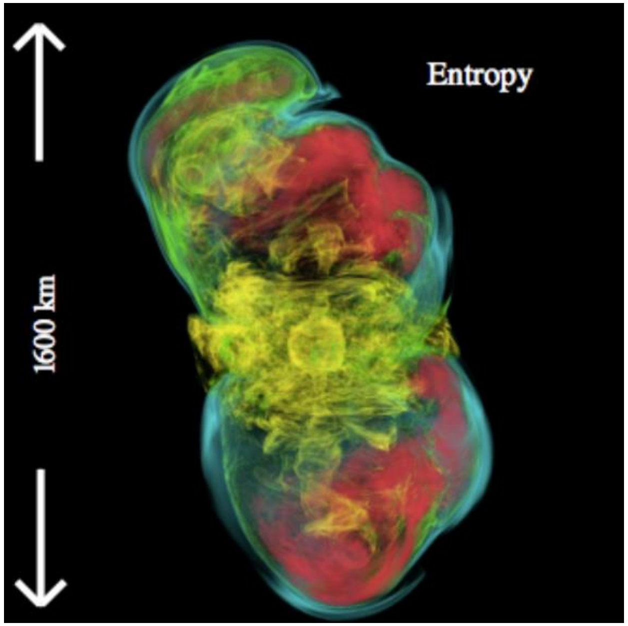
Adams, Kochanek, Gerke & Stanek, arXiv:1610.02402

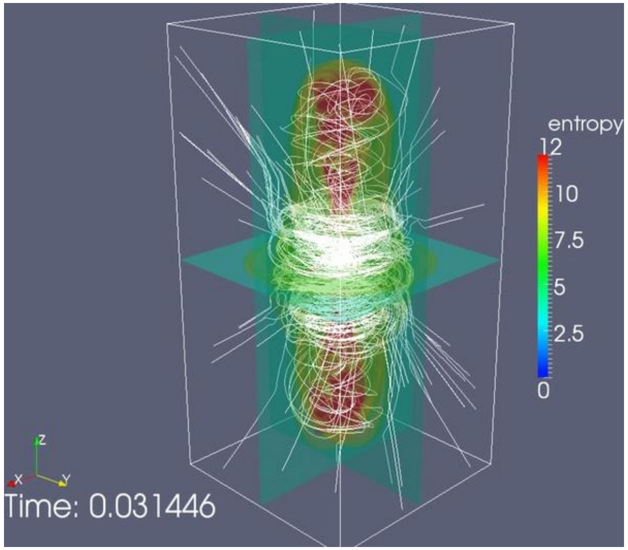
Modelling Neutrino-Driven Mechanism: Summary

- 3D simulations on the verge between explosion and failure (which is ok ...)
- Several promising ideas to make neutrino-driven explosions robust, solution likely a combination plus improved modeling (nu transport, resolution, …)
  - Improved microphysics (e.g. Melson et al. 2015, Burrows et al. 2016)
  - Convective seed perturbations for "perturbation-aided" mechanism (Couch et al. 2015, Müller 2016)
  - Rotation (Janka et al. 2016, Takiwaki et al. 2016)
  - Lower explosion threshold in SASI-dominated regime (Fernandez 2015)?
- Perspectives for confronting simulations with observations:
  - First-principle simulations somewhat premature, encouraging trends from recent 3D models – energies of 10^{51} erg in reach?
  - Soon to become a predictive tool for exploring explosion energies, nickel masses, kicks, spins, nucleosynthesis (Meanwhile parametric simulations to bridge the gap to observations)
  - **High-statistics neutrino observations from next nearby supernova**

MHD Driven Supernovae

- Inherent limit of $\sim 2\times10^{51}$ erg for explosion energy in ν-driven mechanism
  $\rightarrow$ cannot explain hypernovae
- Tapping rotational energy of "millisecond magnetar" or BH/torus-system (collapsar scenario) is viable
- Many Challenges for simulations
  – Operation & saturation of MRI (recent work by Guilet, Obergaulinger, Rembiasz, Moesta ...) with non-ideal MHD effects
  – Seed fields & high initial rotation rate (special stellar evolution channels needed)
  – Timescales: Engine operates for seconds, but simulations of Moesta et al. (2014) < 200 ms, Winteler et al. (2012) < 50 ms
- For slower rotation/smaller B-fields: Energetics dominated by ν-heating, MHD subdominant role (Obergaulinger, Janka & Aloy 2014)

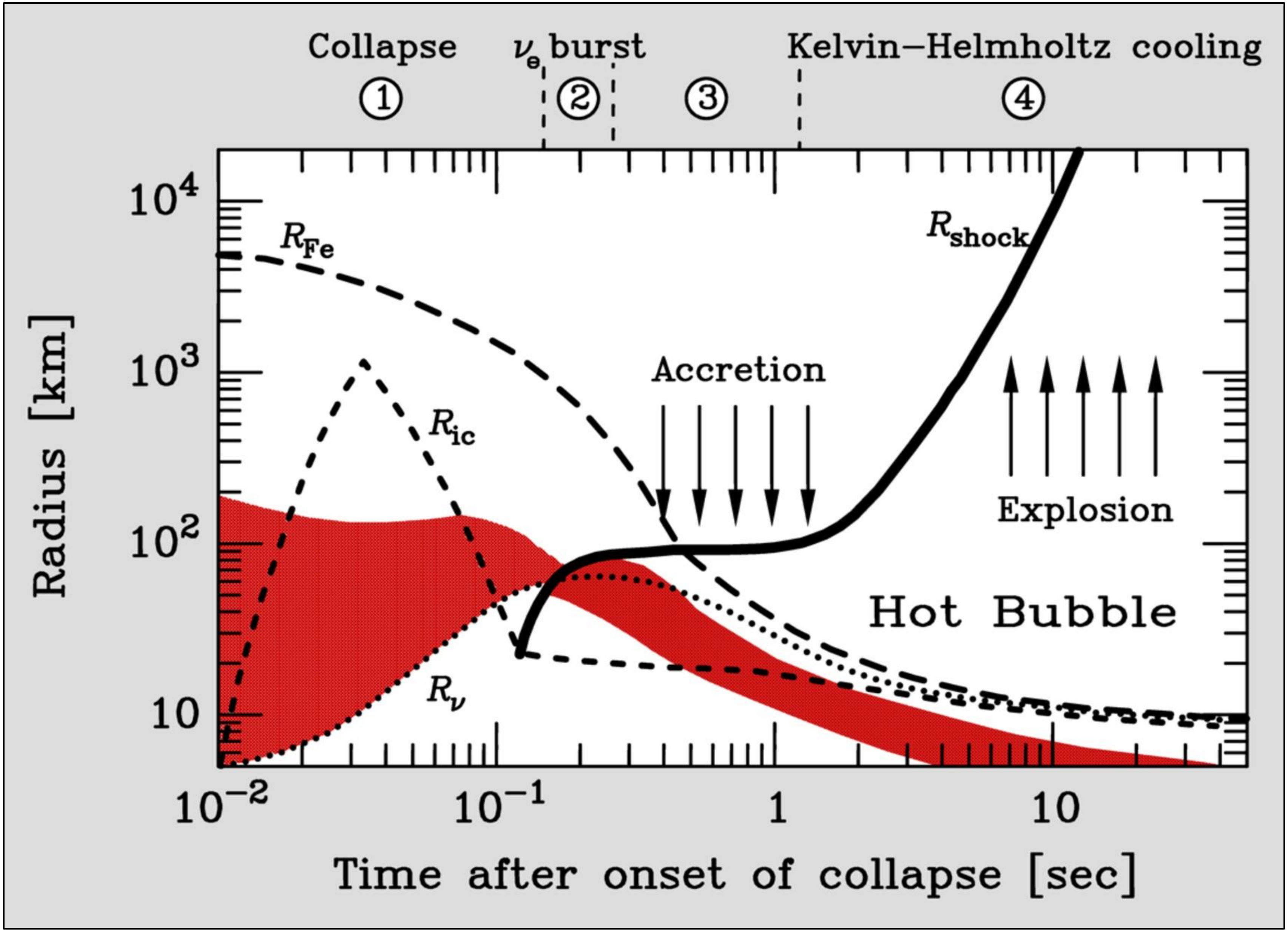




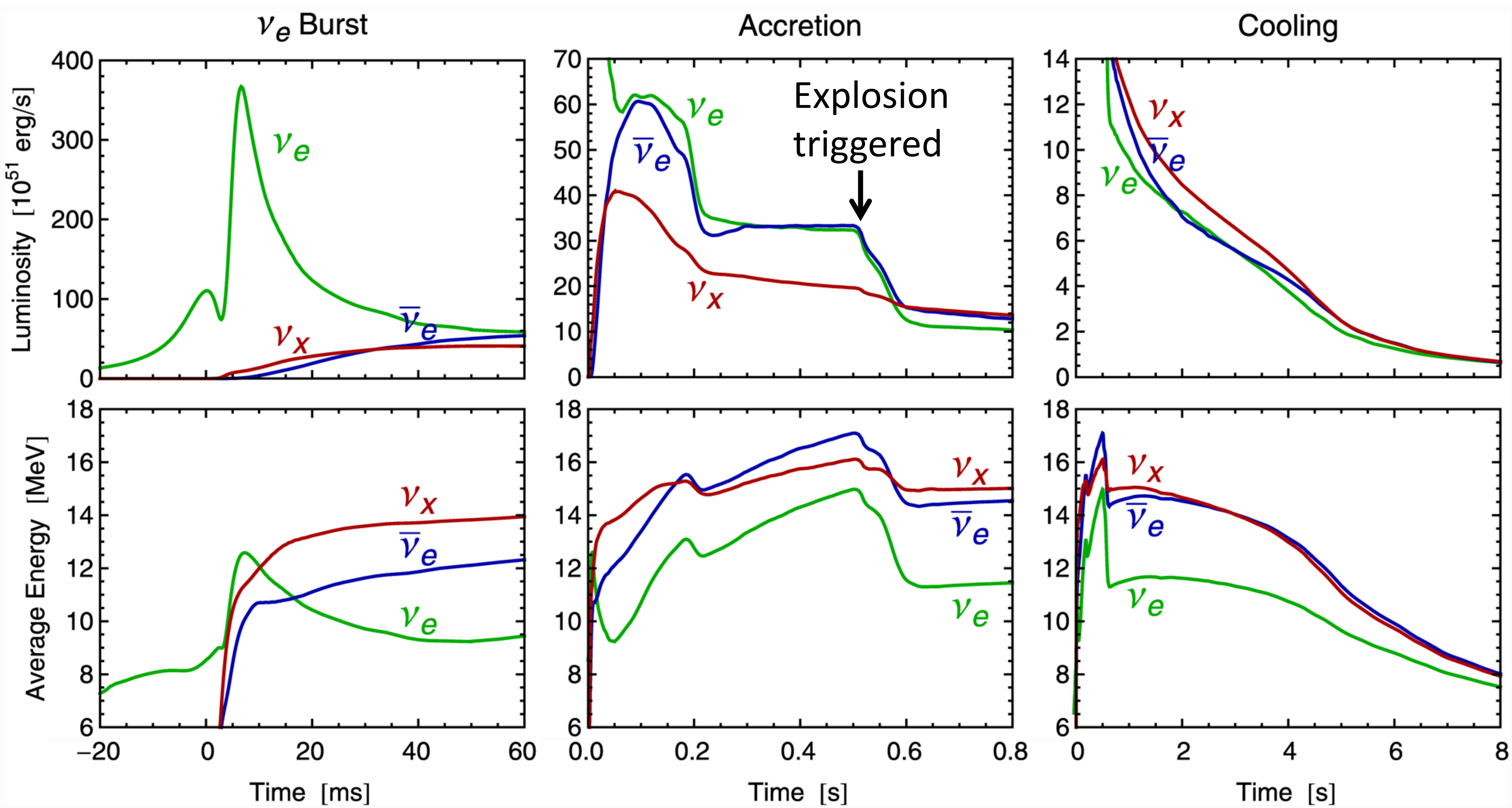

Diversity

Characteristics of Neutrino Signal

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

What determines the time scale?

Main neutrino reactions

$$\nu_e + n \to p + e^-,\ \ \overline{\nu}_e + p \to n + e^+,\ \ \nu + N \to N + \nu$$

Neutral-current scattering cross section

$$\sigma(\nu N \to N\nu) = \frac{C_\mathrm{V}^2 + 3C_\mathrm{A}^2}{\pi}\, G_\mathrm{F}^2 E_\nu^2 \approx 2 \times 10^{-40}\mathrm{cm}^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$$

Nucleon density

$$n_B = \frac{\rho_\mathrm{nuc}}{m_N} \approx 1.8 \times 10^{38}\ \mathrm{cm}^{-3}$$

Scattering rate

$$\Gamma = \sigma n_B \approx 1.1 \times 10^9\ \mathrm{s}^{-1} \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$$

Mean free path

$$\lambda = (\sigma n_B)^{-1} \approx 28\ \mathrm{cm} \left(\frac{100\ \mathrm{MeV}}{E_\nu}\right)^2$$

Diffusion time

$$t_\mathrm{diff} \approx \frac{R^2}{\lambda} \approx 1.2\ \mathrm{s} \left(\frac{R}{10\ \mathrm{km}}\right)^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$$

What Determines the Neutrino Energies?

Hydrostatic equilibrium (virial equilibrium)

$$-\frac{1}{2}\langle\Phi_{\mathrm{grav}}\rangle = \langle E_{\mathrm{kin}}\rangle = \frac{3}{2}k_{\mathrm{B}}T$$

Assume SN core is homogeneous sphere with

$$M = 1.5\,M_{\odot},\quad \rho = \rho_{\mathrm{nuc}} = 3\times 10^{14}\,\mathrm{g/cm^3},\quad R = 13.4\,\mathrm{km}$$

Gravitational potential of nucleon at center

$$\Phi_{\mathrm{grav}} = -\frac{3}{2}\,\frac{\mathrm{G_N M_{core} m_p}}{\mathrm{R}} \sim -234\,\mathrm{MeV}$$

For non-interacting and non-degenerate nucleons implies

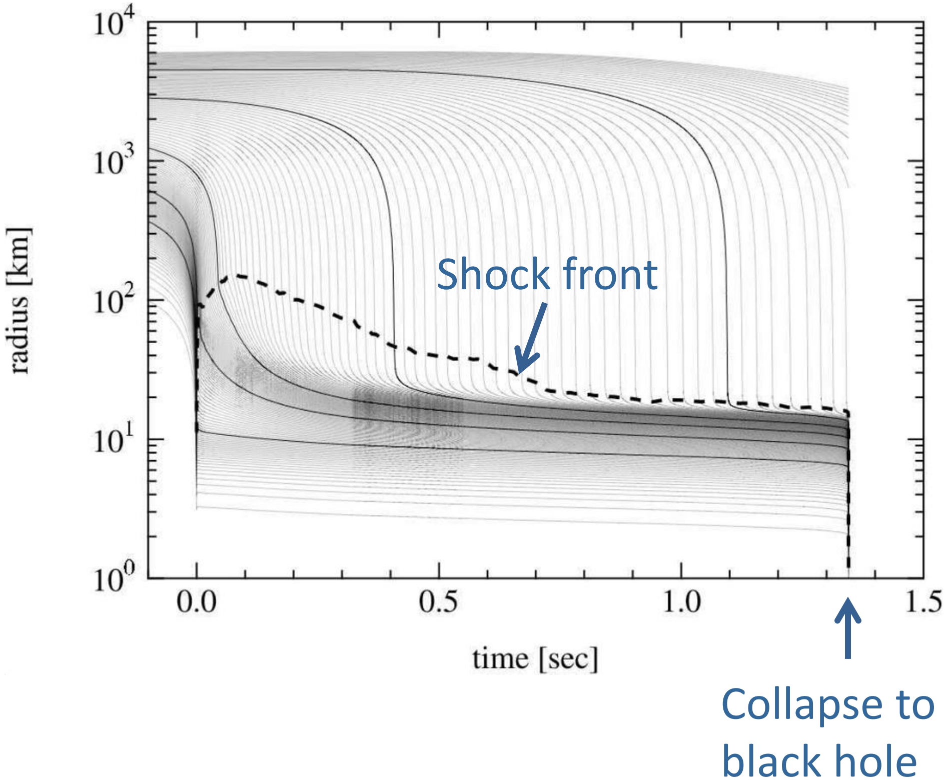
$$T \sim 80\ \mathrm{MeV}$$

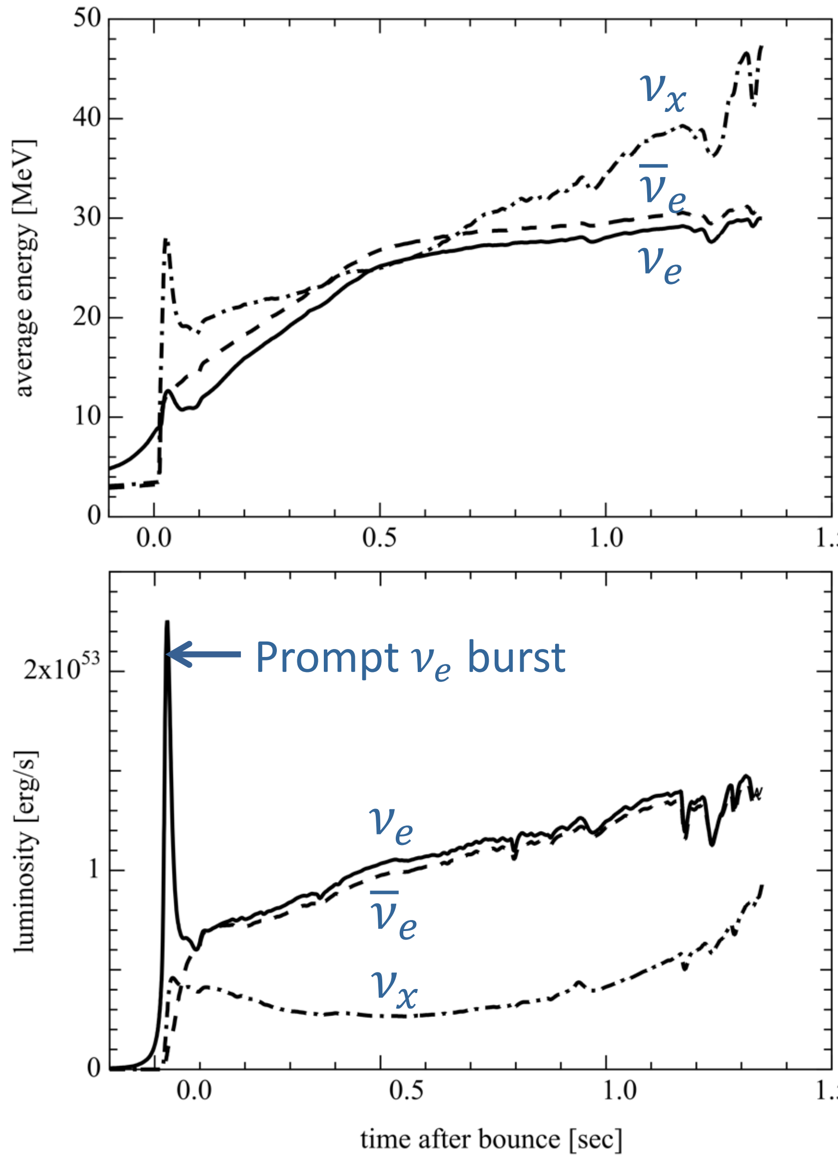
More realistic, nuclear equation-of-state dependent values

$$T \sim 20\text{–}40\ \mathrm{MeV}$$

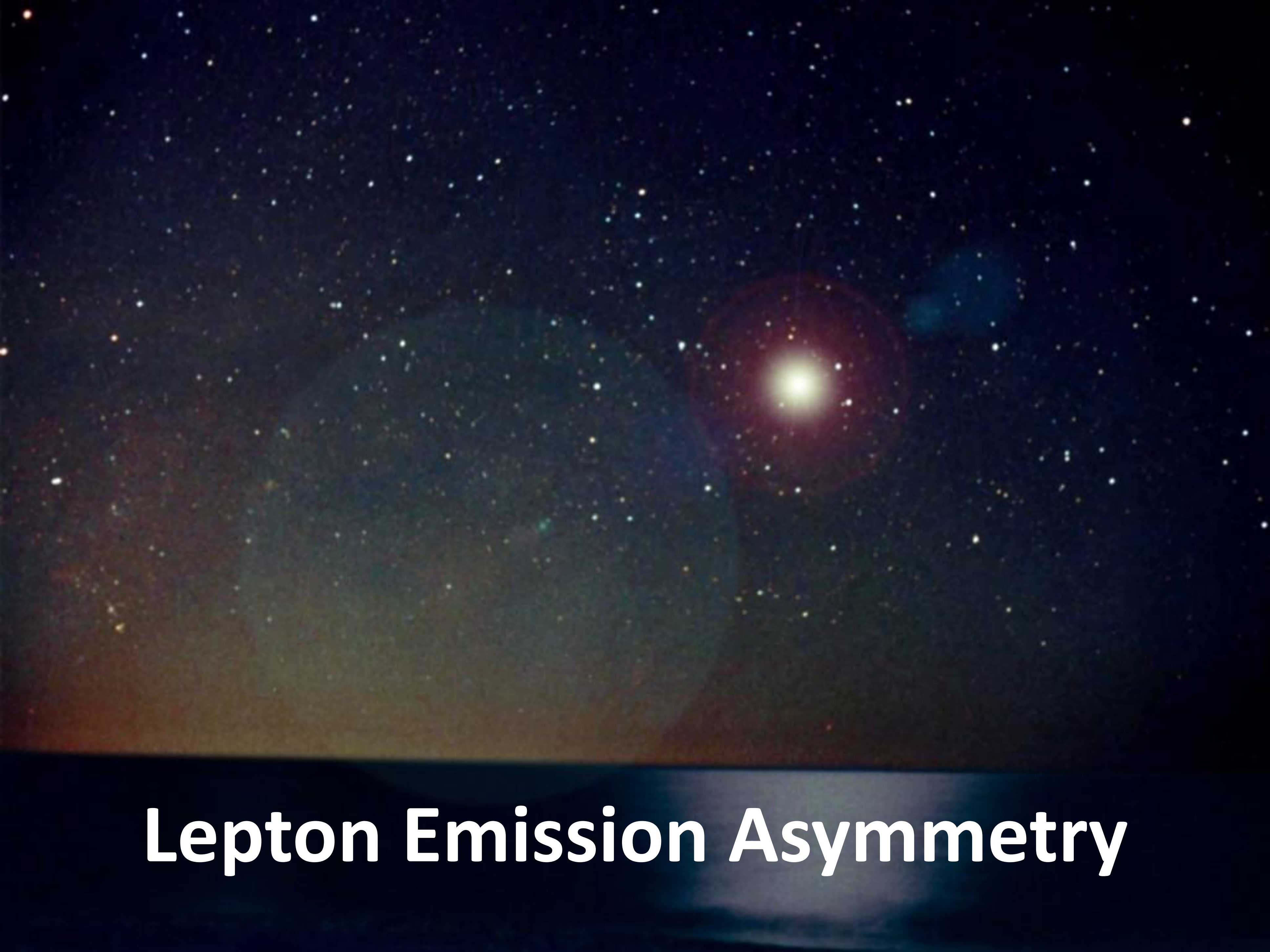
Energy scale in the multi-10 MeV range set by gravitational potential

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





Sumiyoshi, Yamada & Suzuki, arXiv:0706.3762



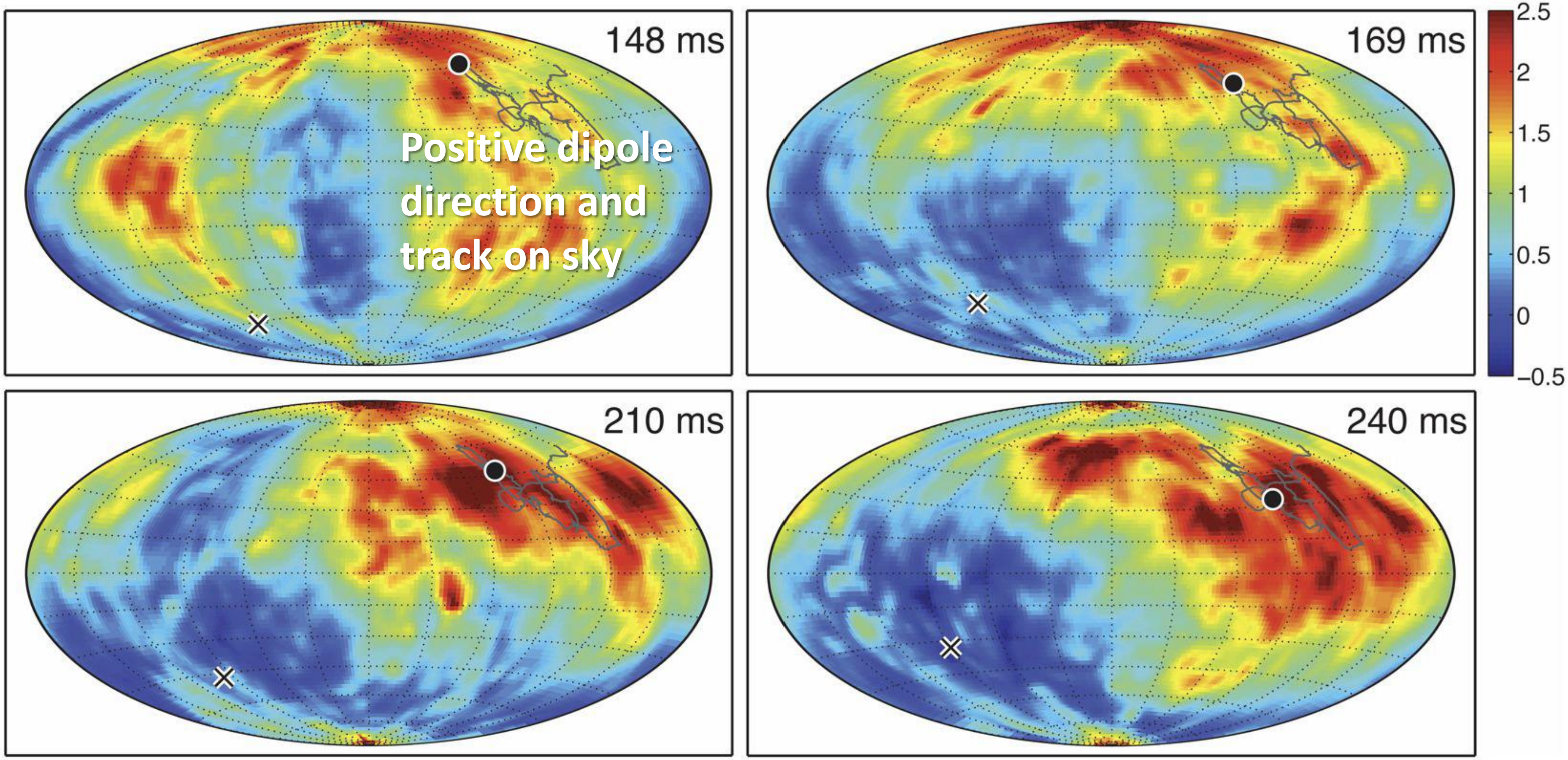
Lepton Emission Asymmetry

Sky Map of Lepton-Number Flux (11.2 M_{SUN} Model)

Lepton-number flux ($\nu_e - \overline{\nu}_e$) relative to 4π average

Deleptonization flux into one hemisphere, roughly dipole distribution

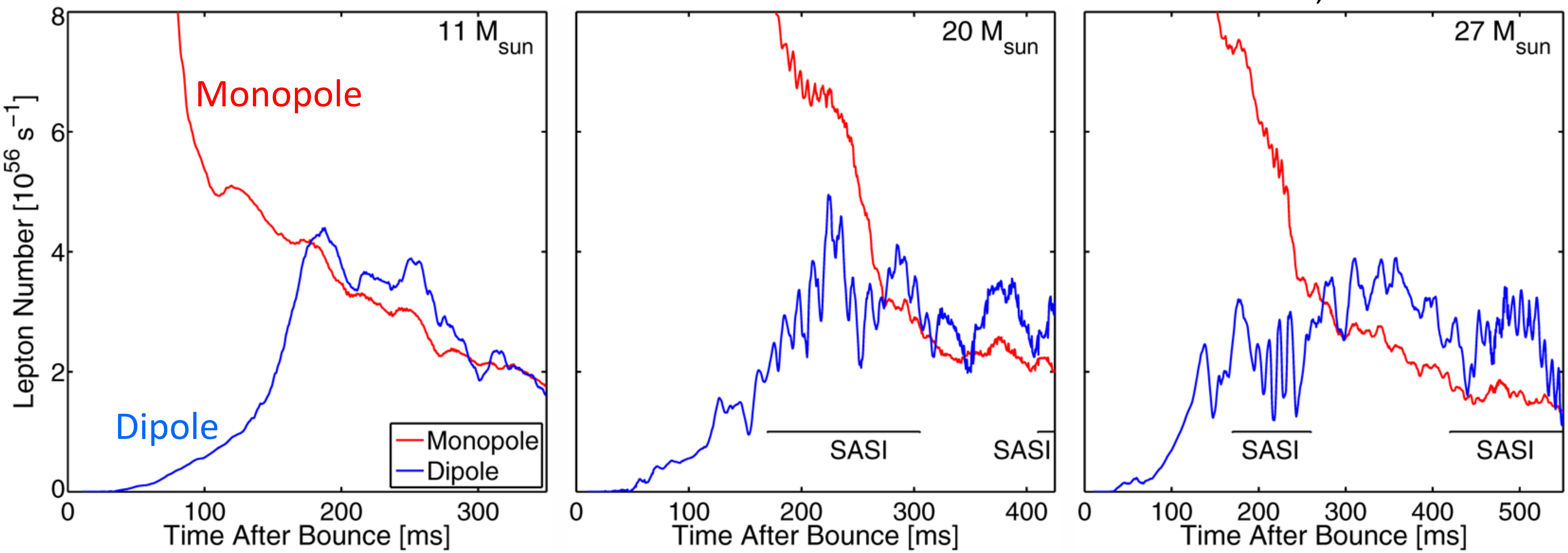
(LESA — Lepton Emission Self-Sustained Asymmetry)



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

Growth of Lepton-Number Flux Dipole

Tamborra et al., arXiv:1402.5418



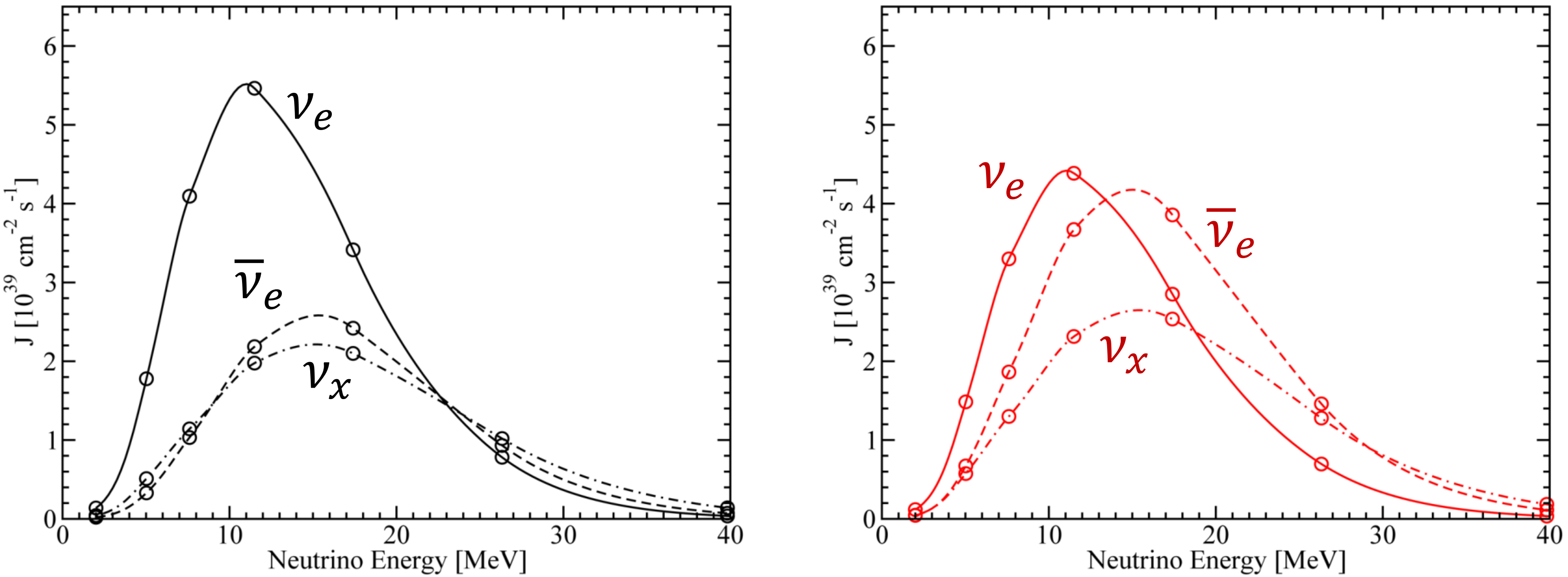
- Overall lepton-number flux (monopole) depends on accretion rate, varies between models
- Maximum dipole similar for different models
- Dipole persists (and even grows) during SASI activity
- SASI and LESA dipoles uncorrelated

Spectra in the two Hemispheres

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

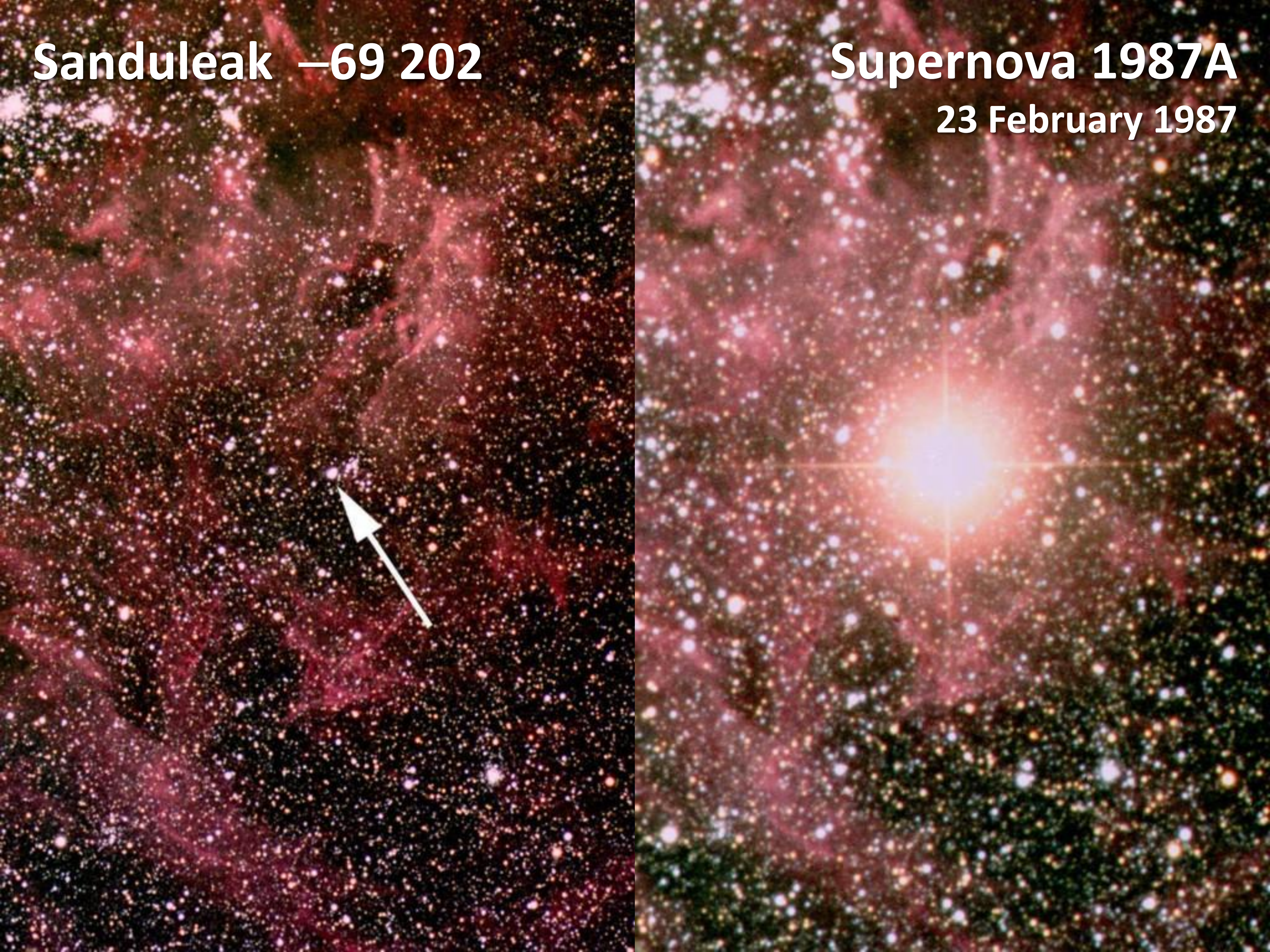
Direction of **maximum** lepton-number flux

Direction of **minimum** lepton-number flux

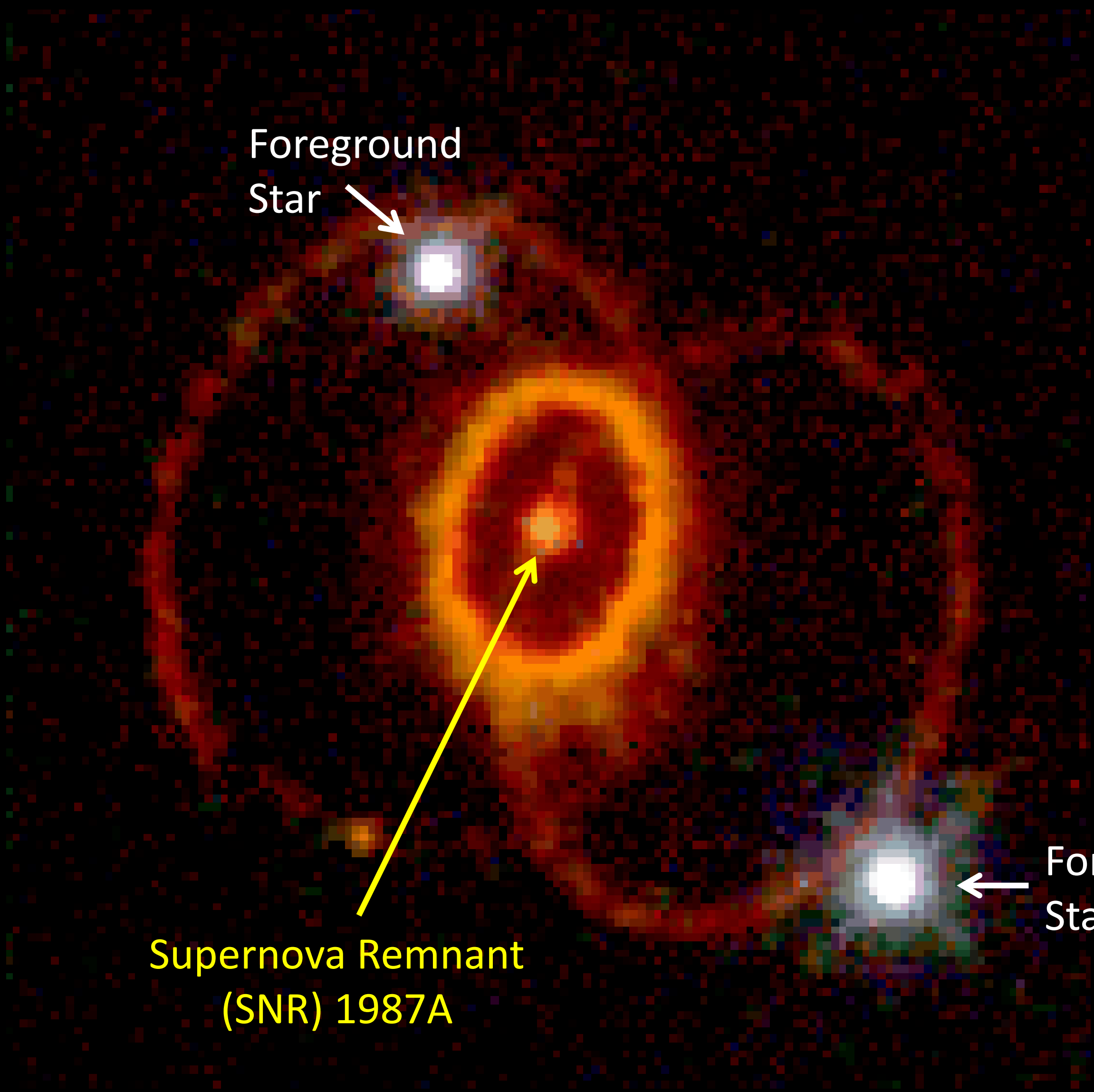


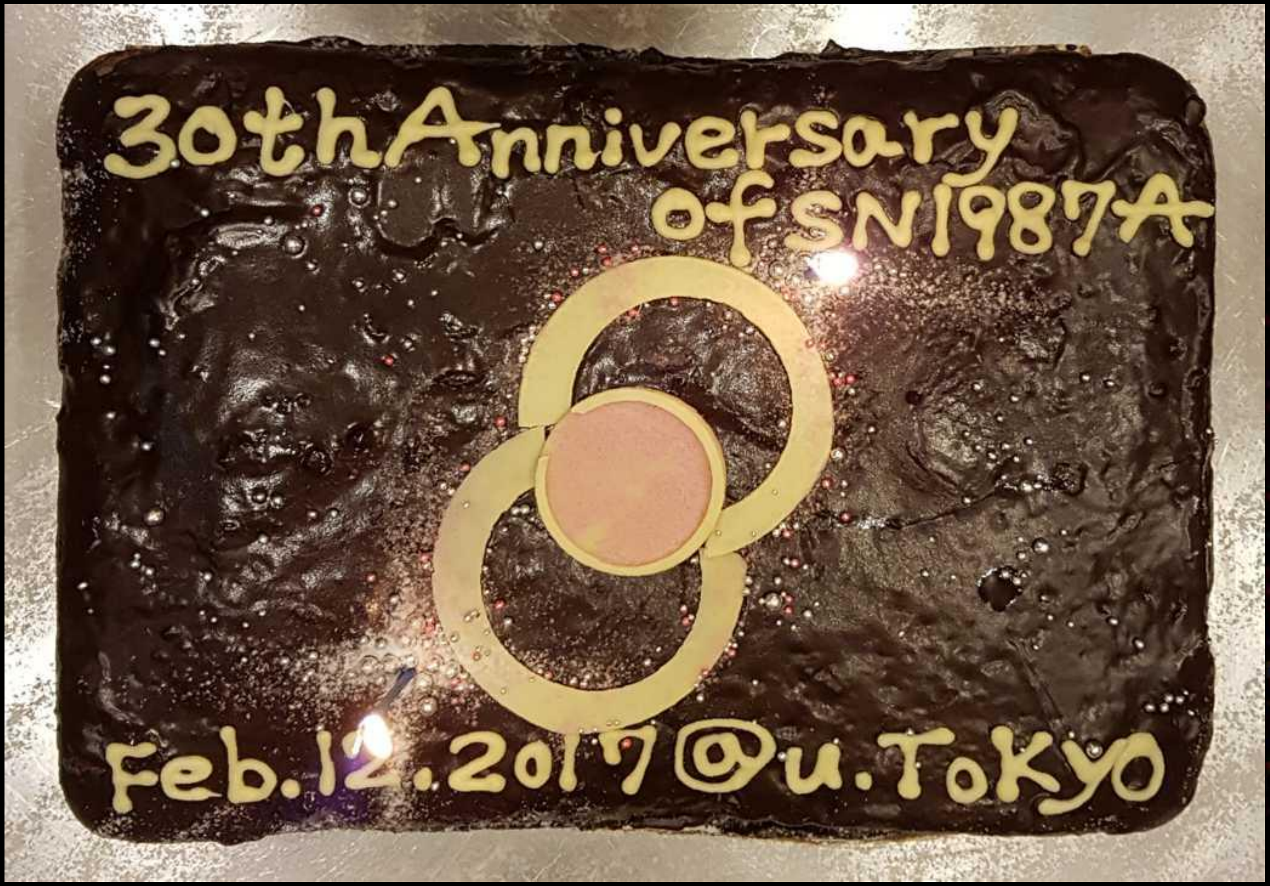
During accretion phase, flavor-dependent fluxes vary strongly with observer direction!

Neutrinos from Supernova 1987A

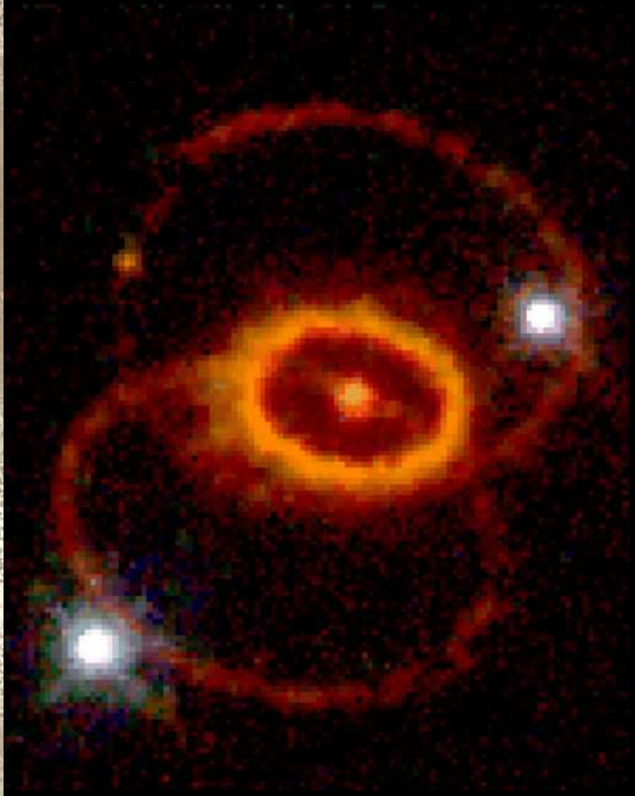

Sanduleak –69 202
Supernova 1987A
23 February 1987

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

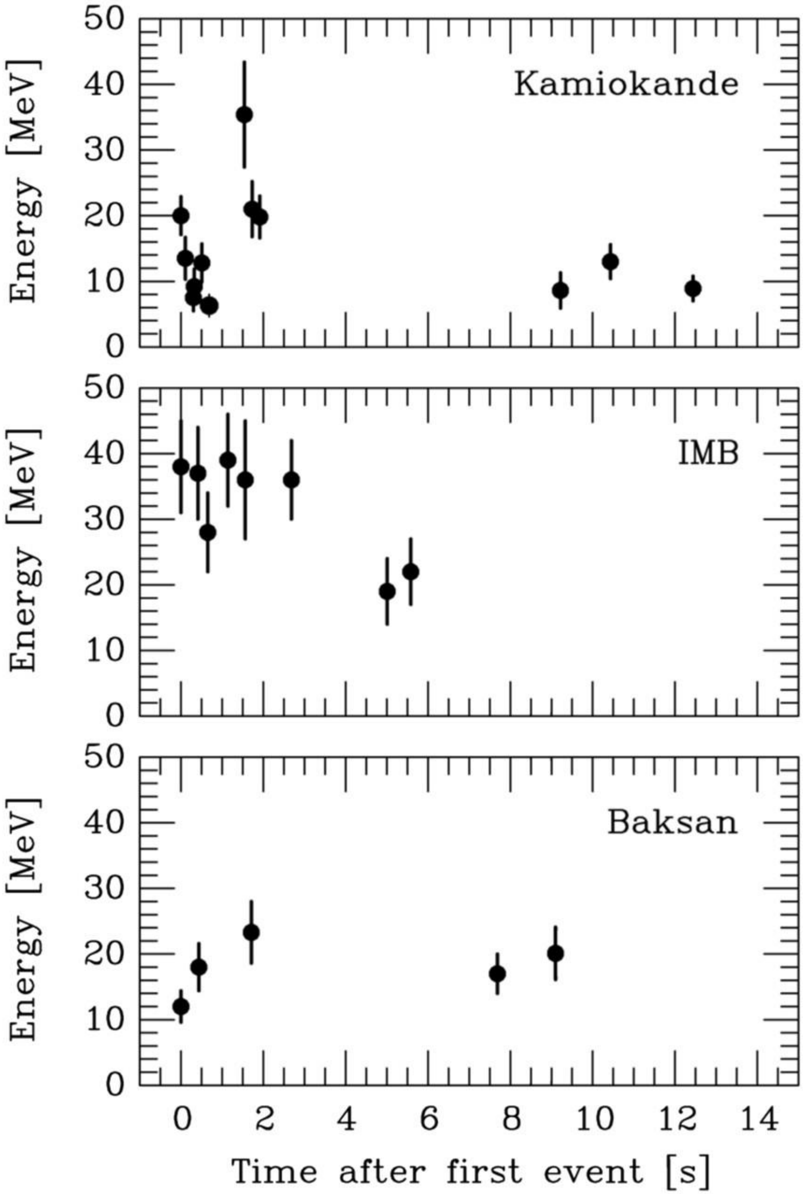




30th Anniversary
of SN1987A
Feb.12.2017@U.Tokyo



Neutrino Signal of Supernova 1987A



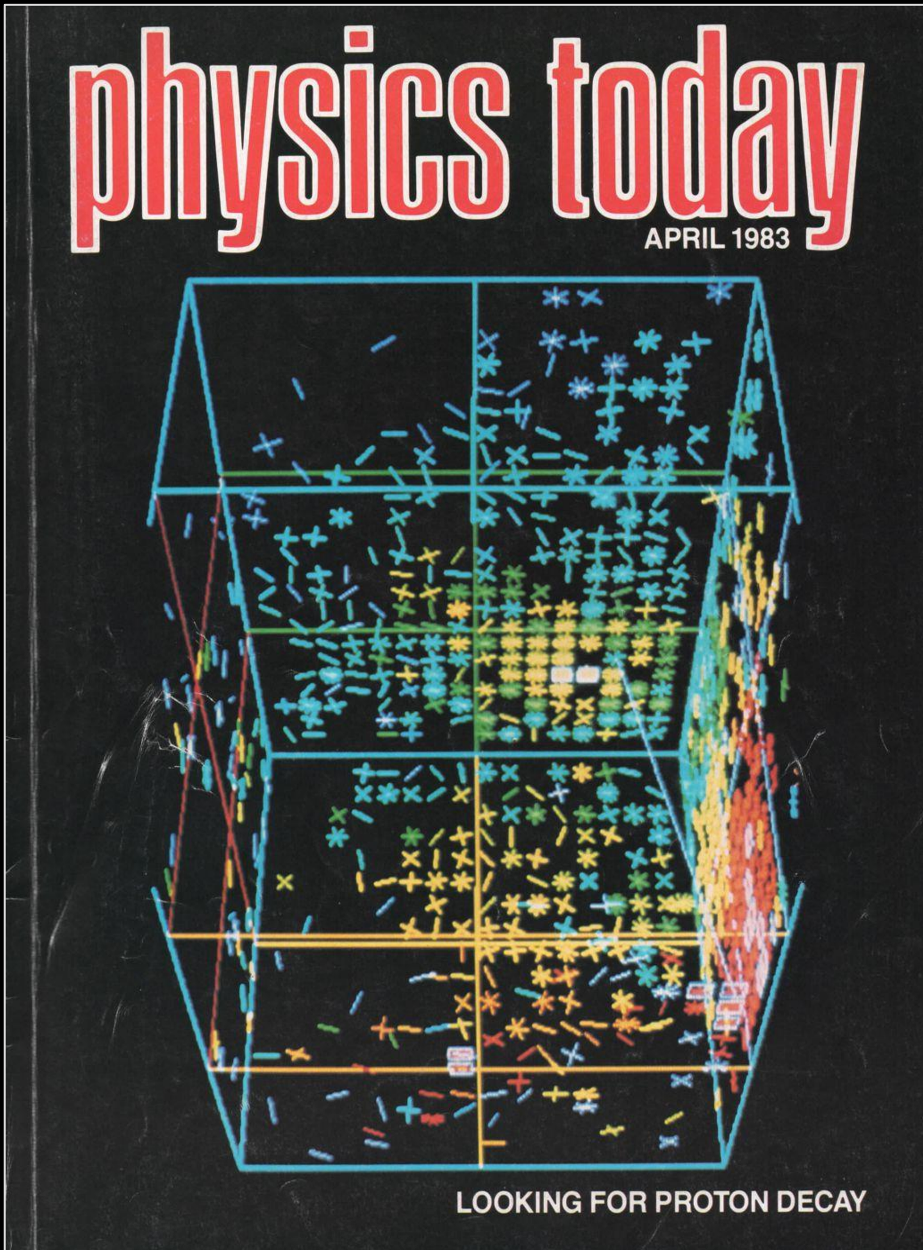
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

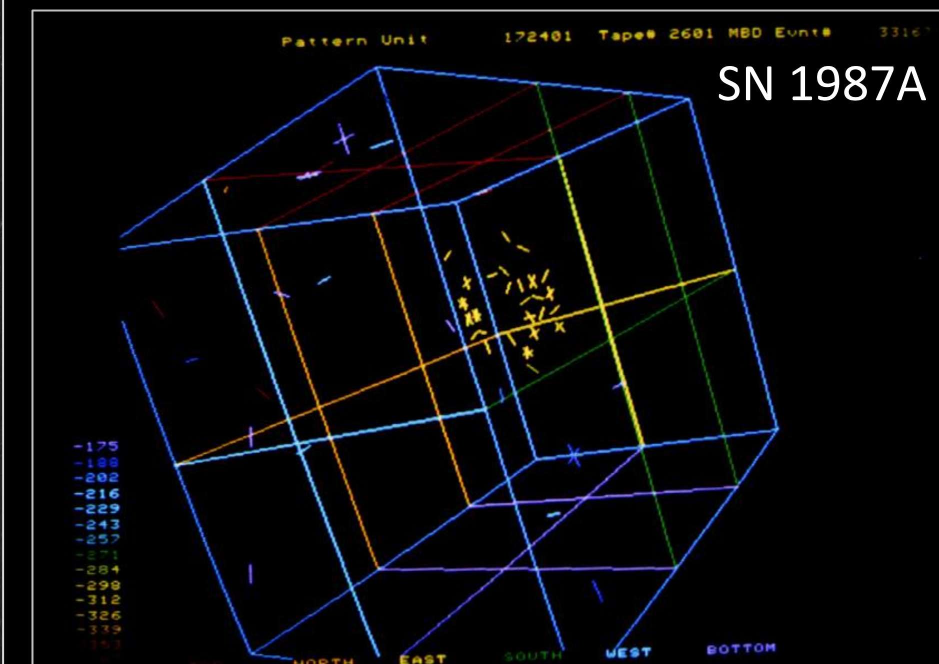
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

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

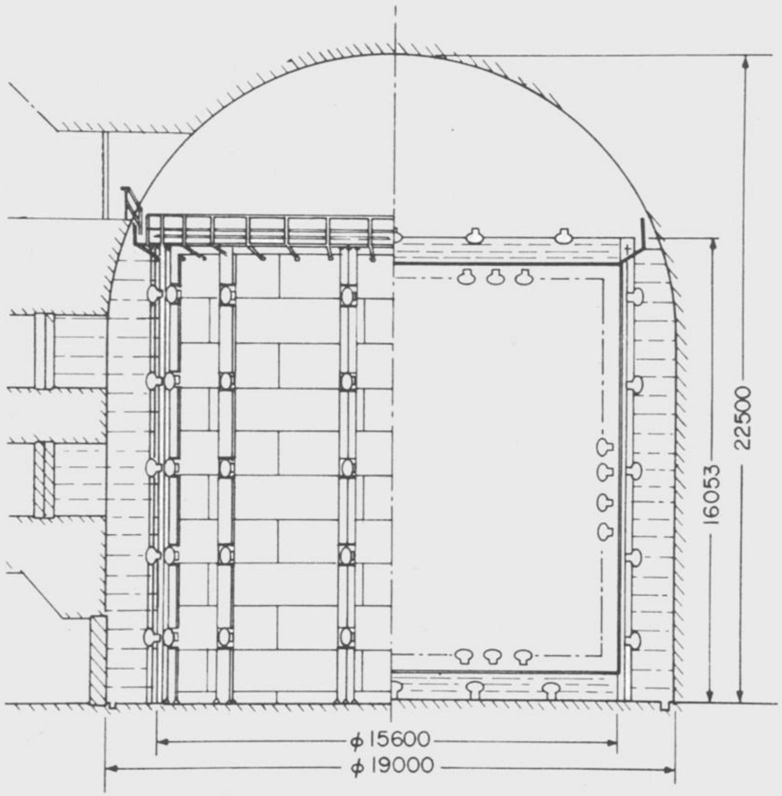
Irvine-Michigan-Brookhaven (IMB) Detector



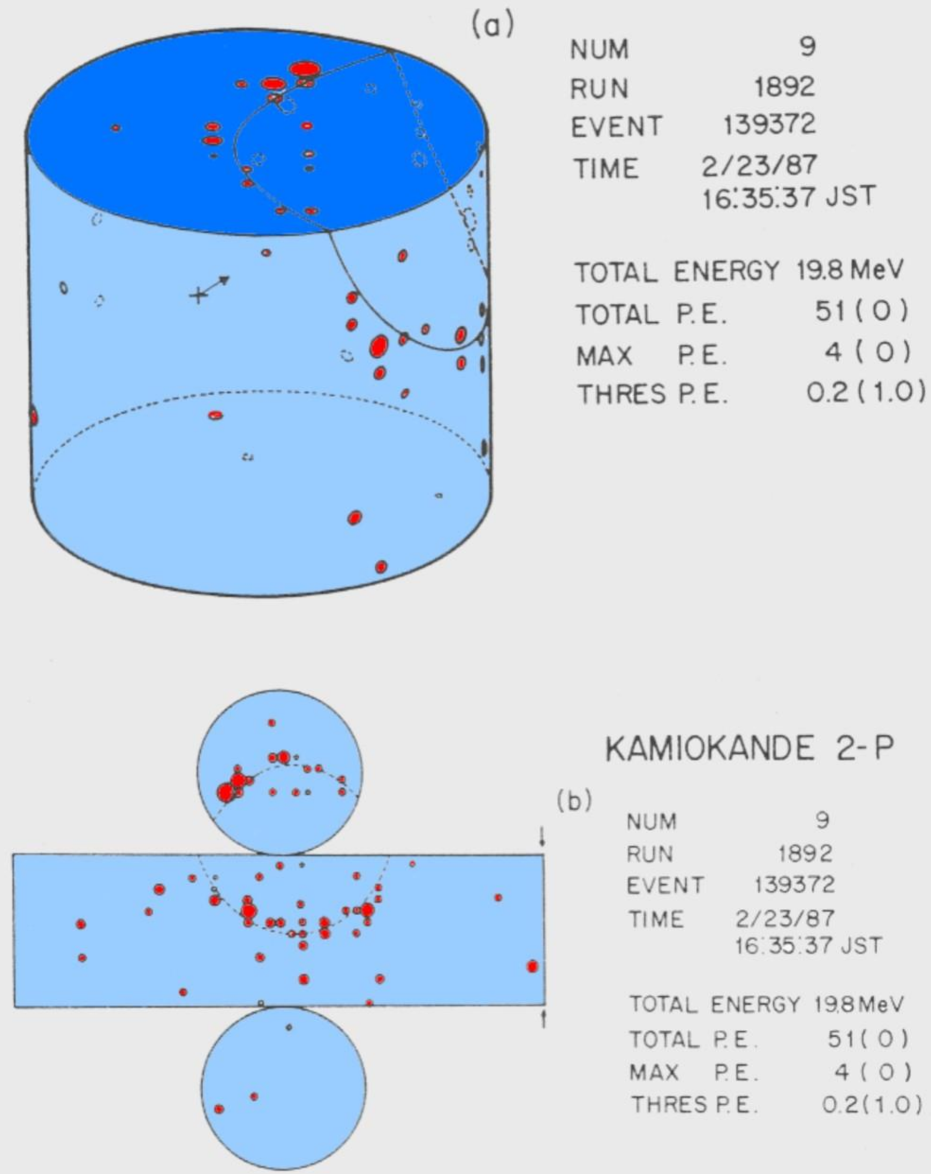


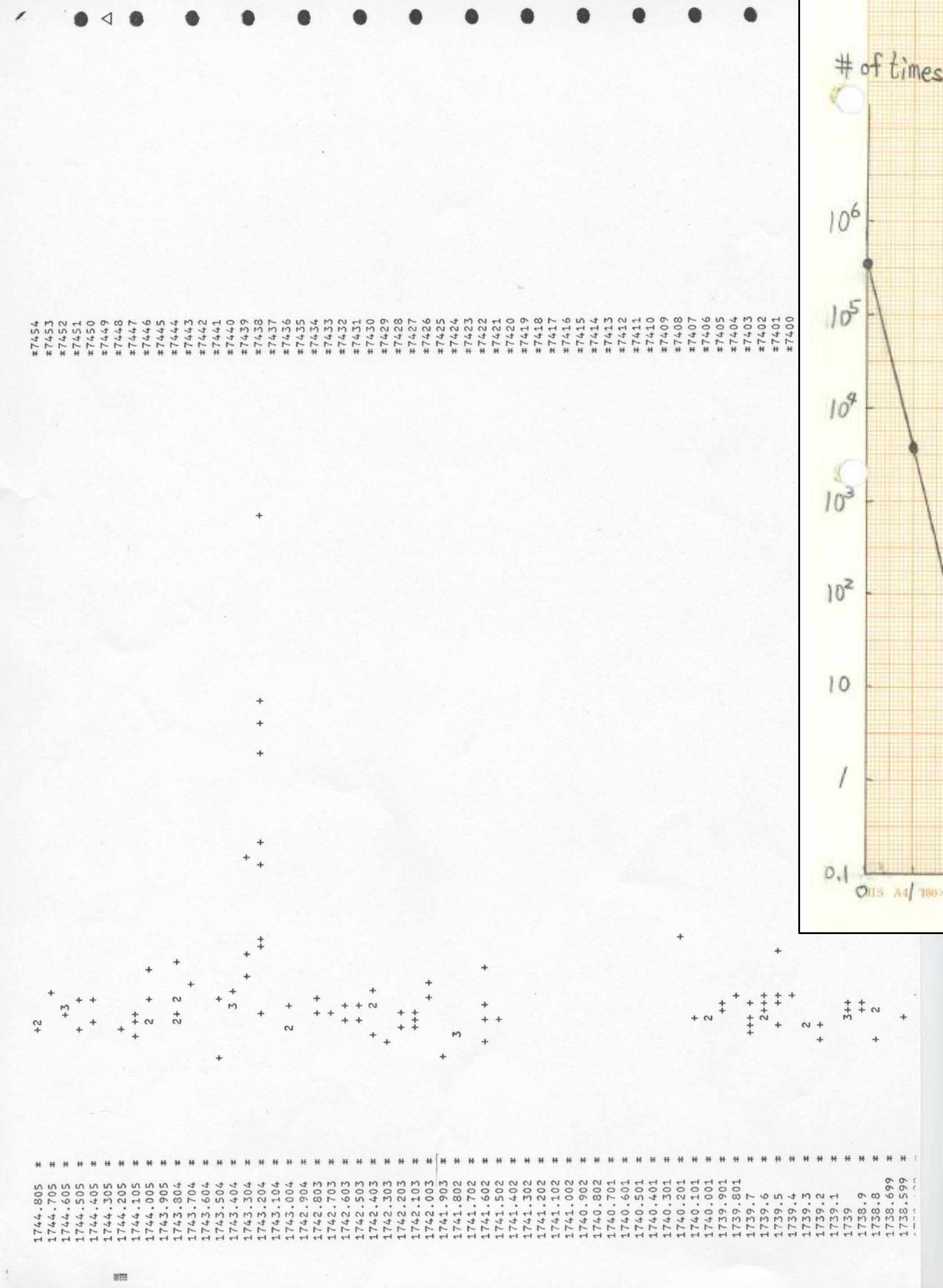
SN 1987A Event No.9 in Kamiokande

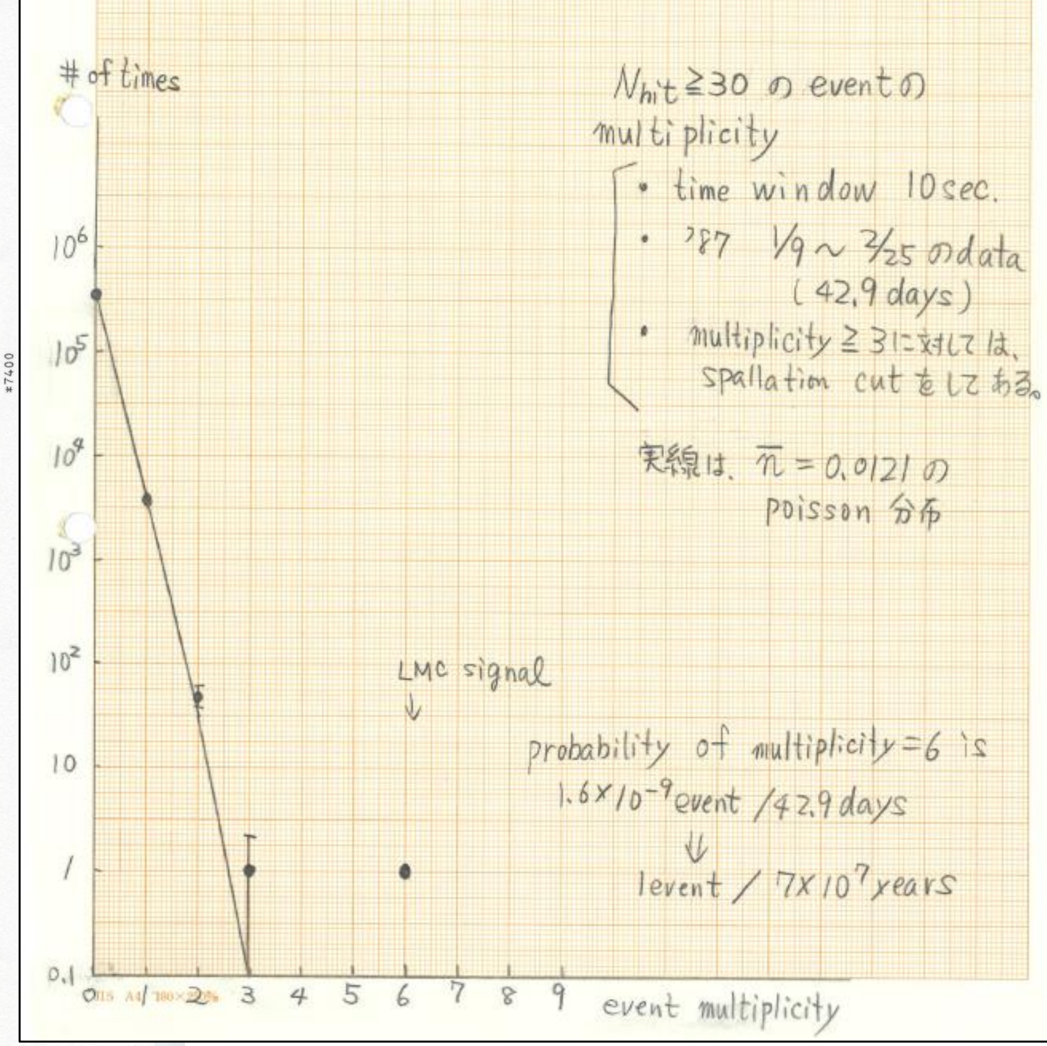
Kamiokande-II Detector
(2140 tons of water)



Hirata et al., PRD 38 (1988) 448

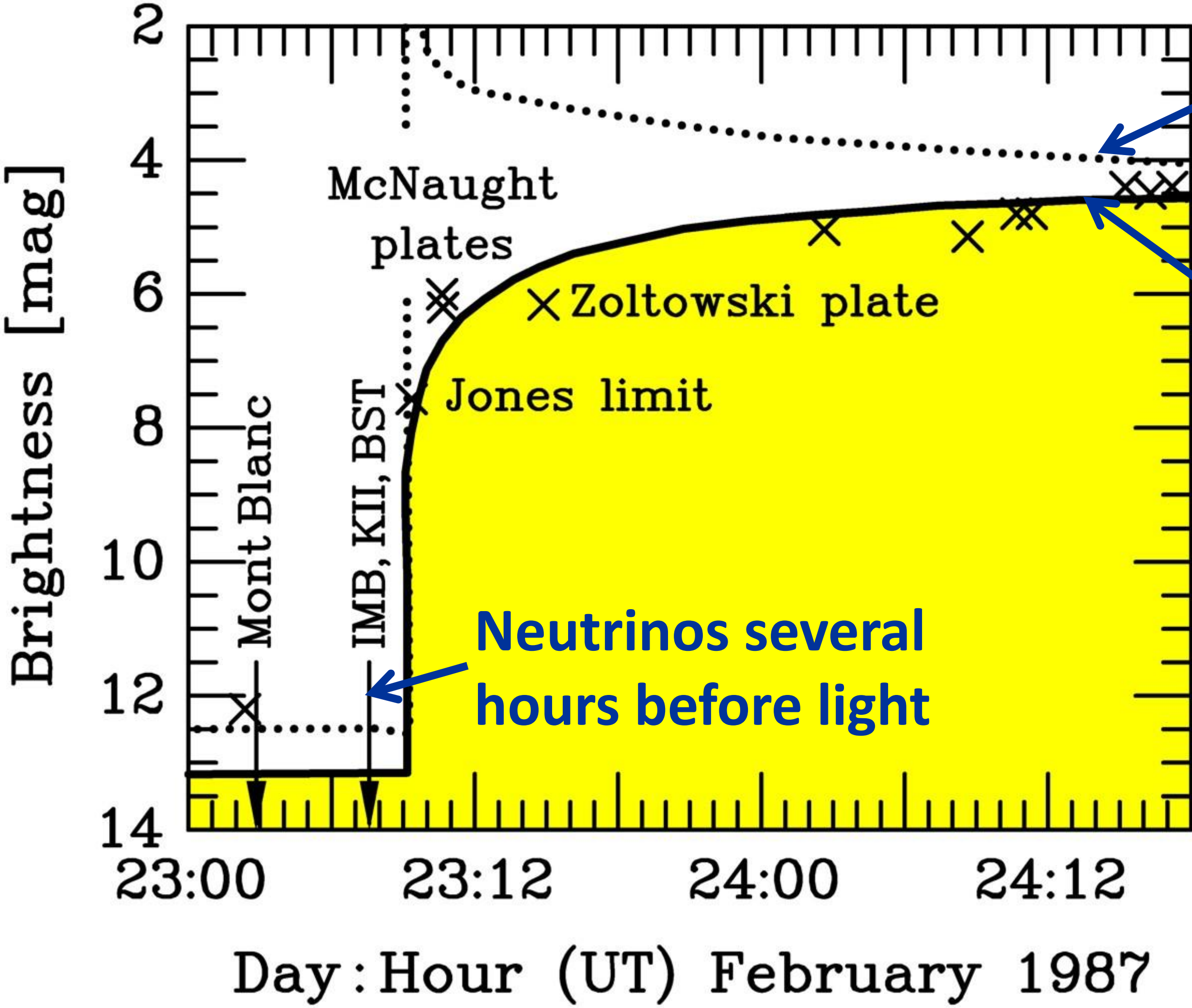






M.Nakahata's notes after the analysis (now director of Kamioka Observatory)

Early Lightcurve of SN 1987A



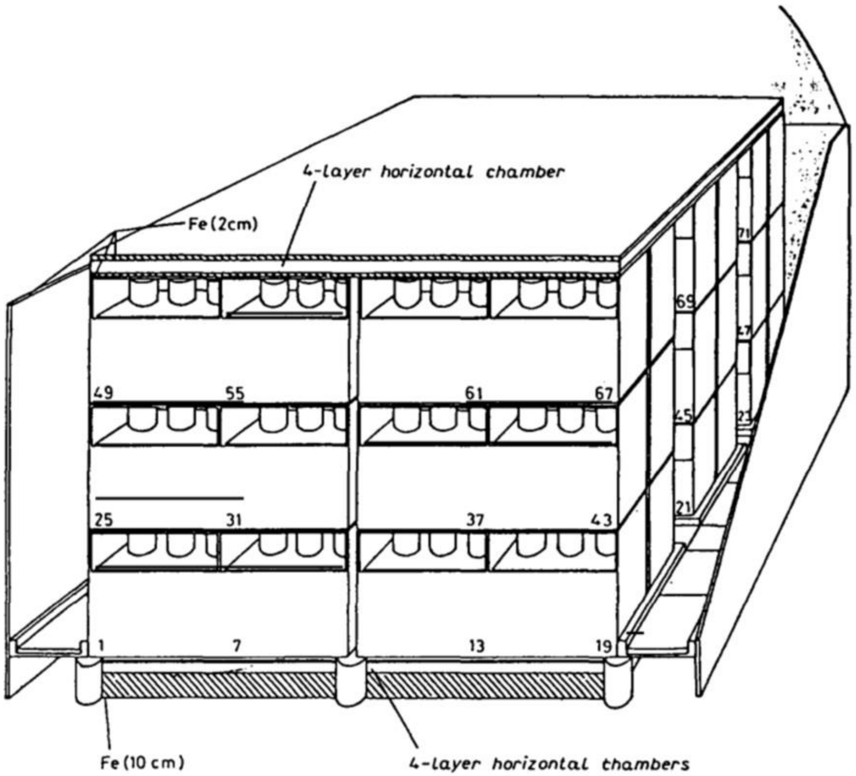
Expected bolometric brightness evolution

Expected visual brightness evolution

Neutrinos several hours before light

Adapted from Arnett et al., ARAA 27 (1989)

SN 1987A Signal in LSD (Mont Blanc)?

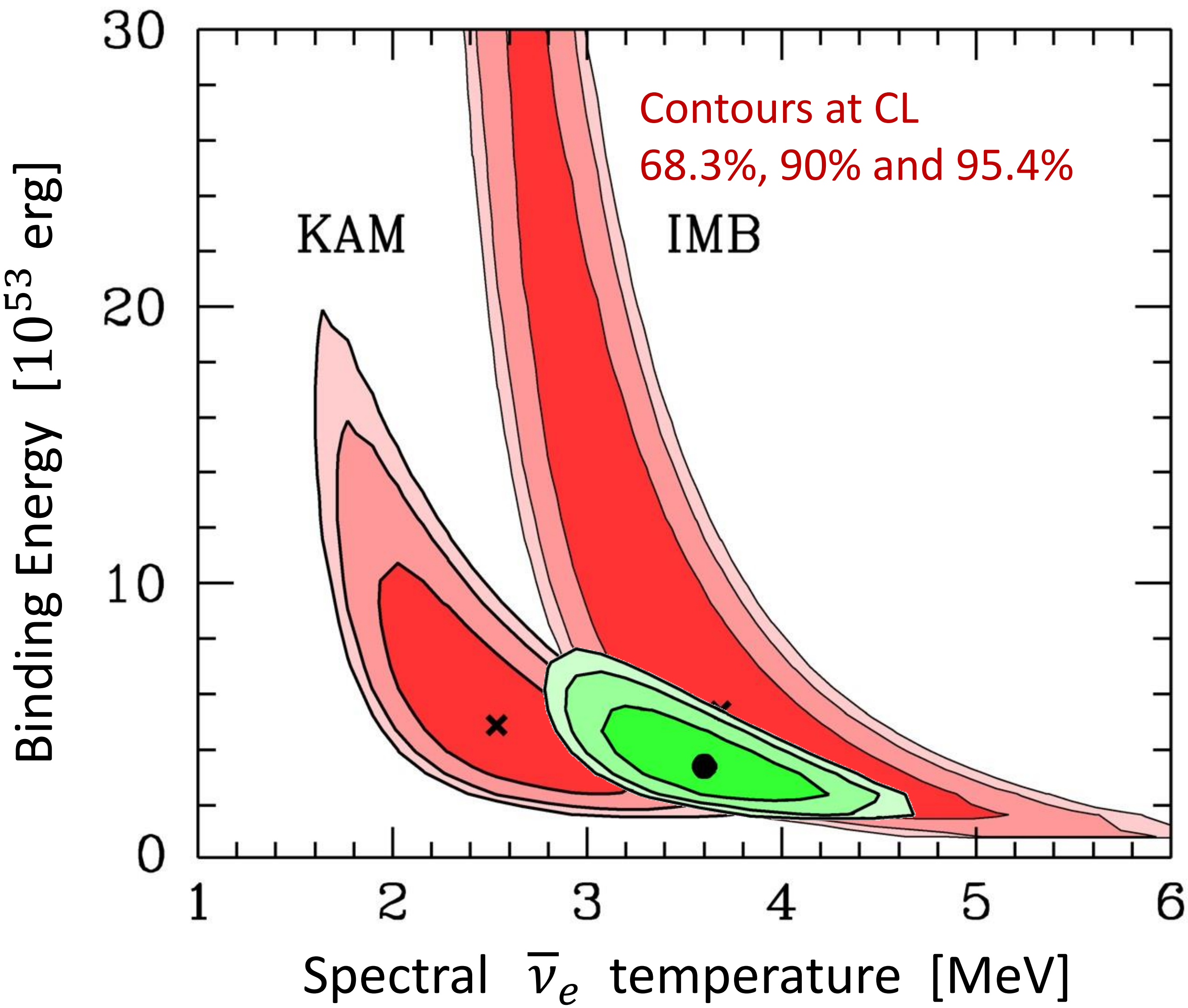


LSD (Liquid Scintillator Detector)
in the Mont Blanc Tunnel
(Oct. 1984 – March 1999)
Supernova monitor for our galaxy
90 tons scintillator
200 tons iron (support structure)

- Observed a 5-event cluster 4.72 hours before IMB/Kam-II
- Triggered autmatic SN alert
- Statistical fluctuation very unlikely
- No significant signal in IMB/Kam-II at LSD time
- No significant LSD signal at IMB time

- One interpretation as "double bang": Huge ν_e flux (~ 40 MeV) at LSD time
- LSD signal caused by interactions in iron of support structure
- Second bang ordinary multi-flavor signal

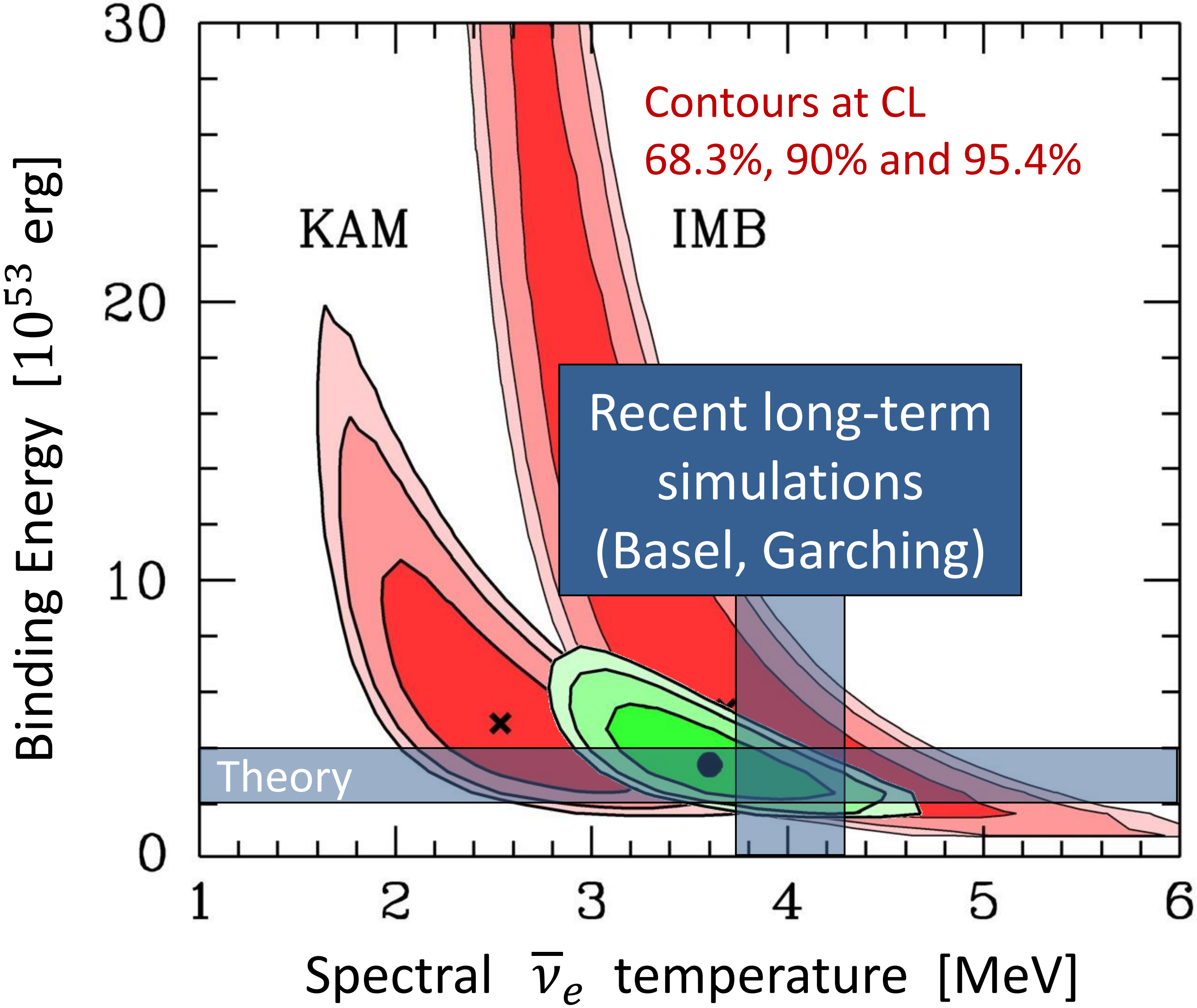
(Imshennik & Ryazhskaya, "A rotating collapsar and possible interpretation of the LSD neutrino signal from SN 1987A", astro-ph/0401613)



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

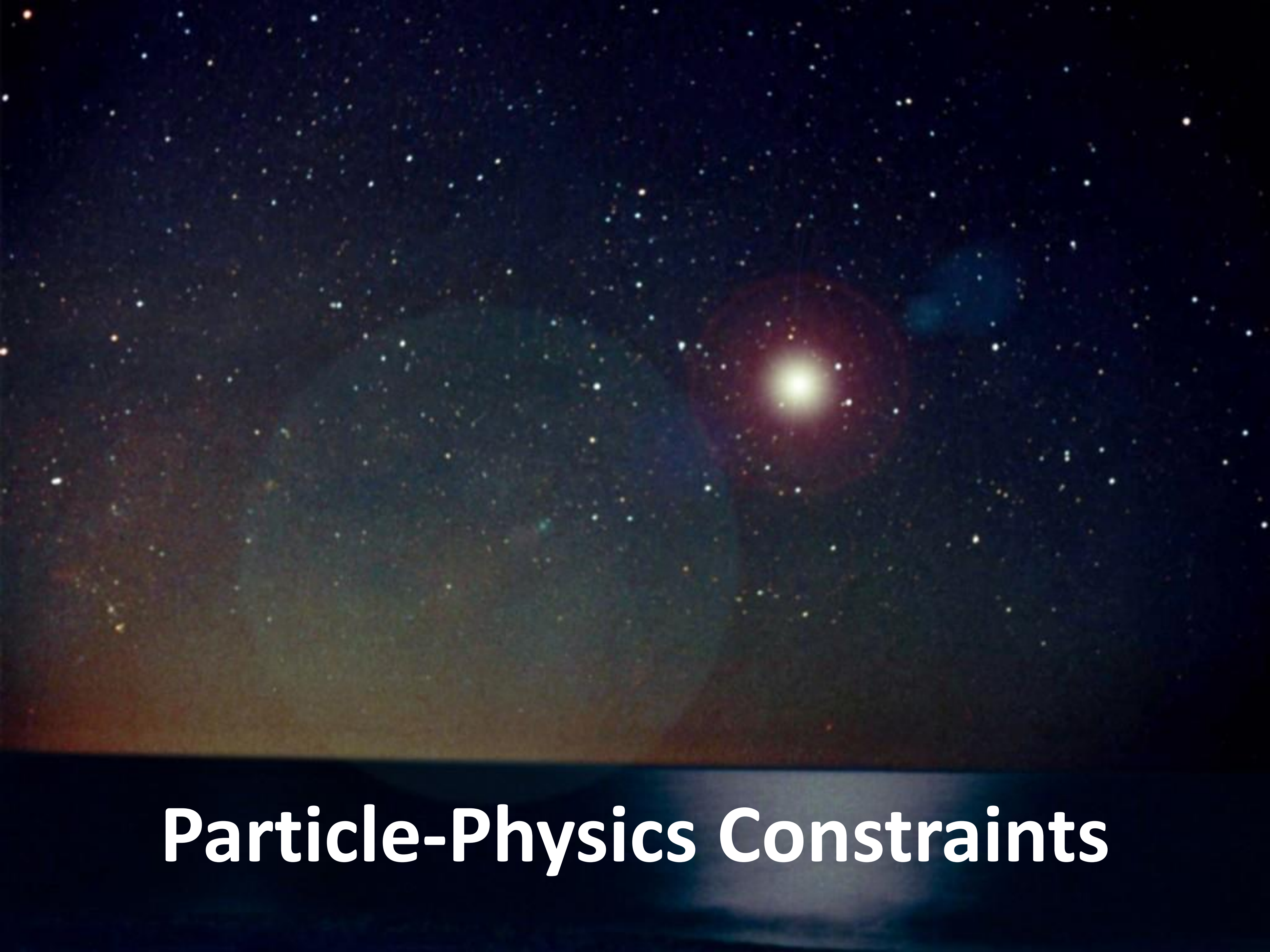
Interpreting SN 1987A Neutrinos



Assume

- Thermal spectra
- 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



Particle-Physics Constraints

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

G. Zatsepin, JETP Lett. 8:205, 1968

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

SN 1987A signal duration implies

$$m_{\nu_e} \lesssim 20\ \mathrm{eV}$$

Loredo & Lamb
Ann N.Y. Acad. Sci. 571 (1989) 601
find 23 eV (95% CL limit) from detailed maximum-likelihood analysis

- At the time of SN 1987A competitive with tritium end-point
- Today $\mathrm{m}_\nu < 2.2\ \mathrm{eV}$ from tritium
- Cosmological limit today $m_\nu \lesssim 0.1\ \mathrm{eV}$

"Milli charged" neutrinos

Path bent by galactic magnetic field, inducing a time delay

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3\times10^{-12}$$

SN 1987A signal duration implies

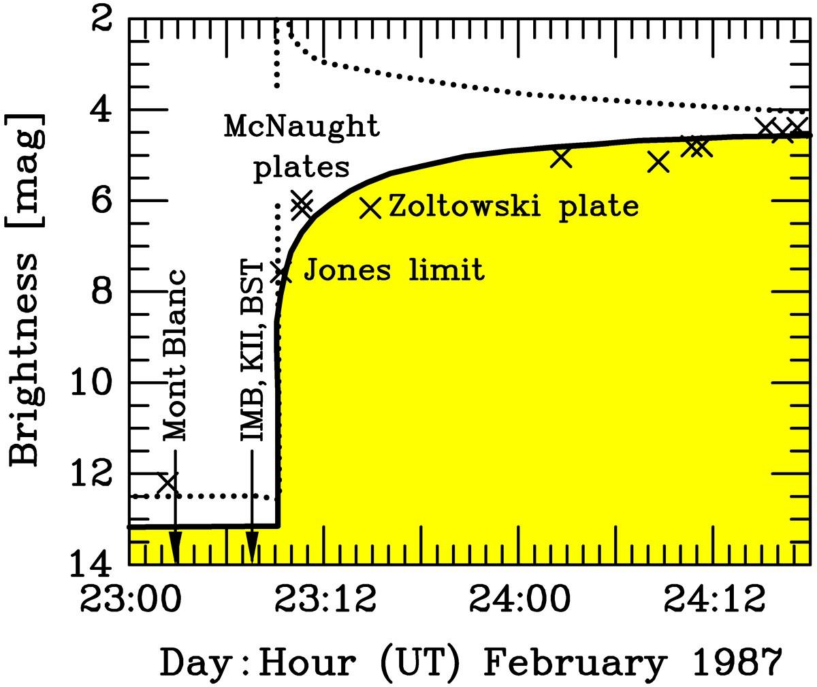
$$\frac{e_\nu}{e} < 3\times10^{-17}\ \frac{1\mu G}{B_\perp}\ \frac{1\ \mathrm{kpc}}{d_B}$$

- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

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,

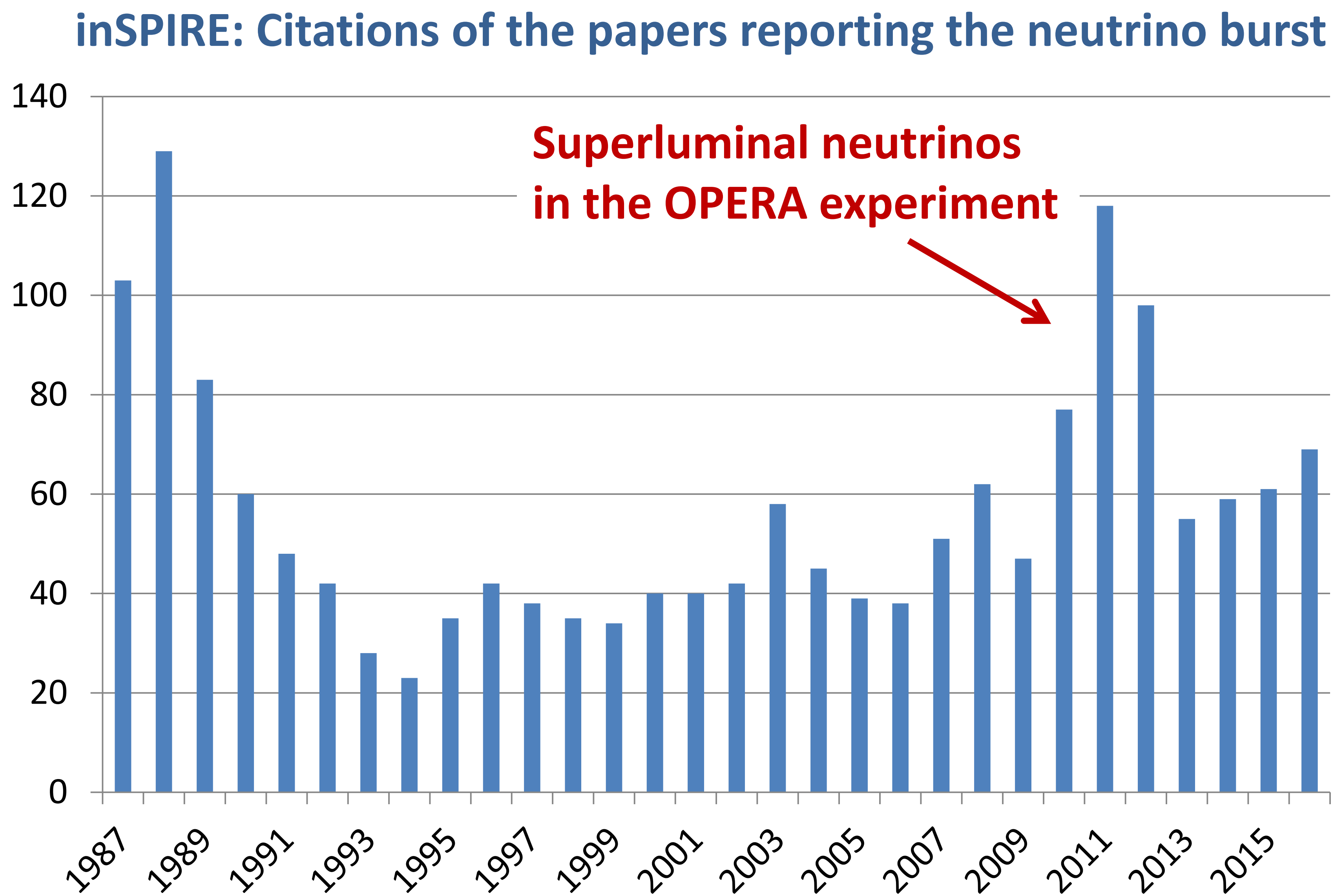
$$\Delta t \approx 1\text{–}5 \text{ months}$$

Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

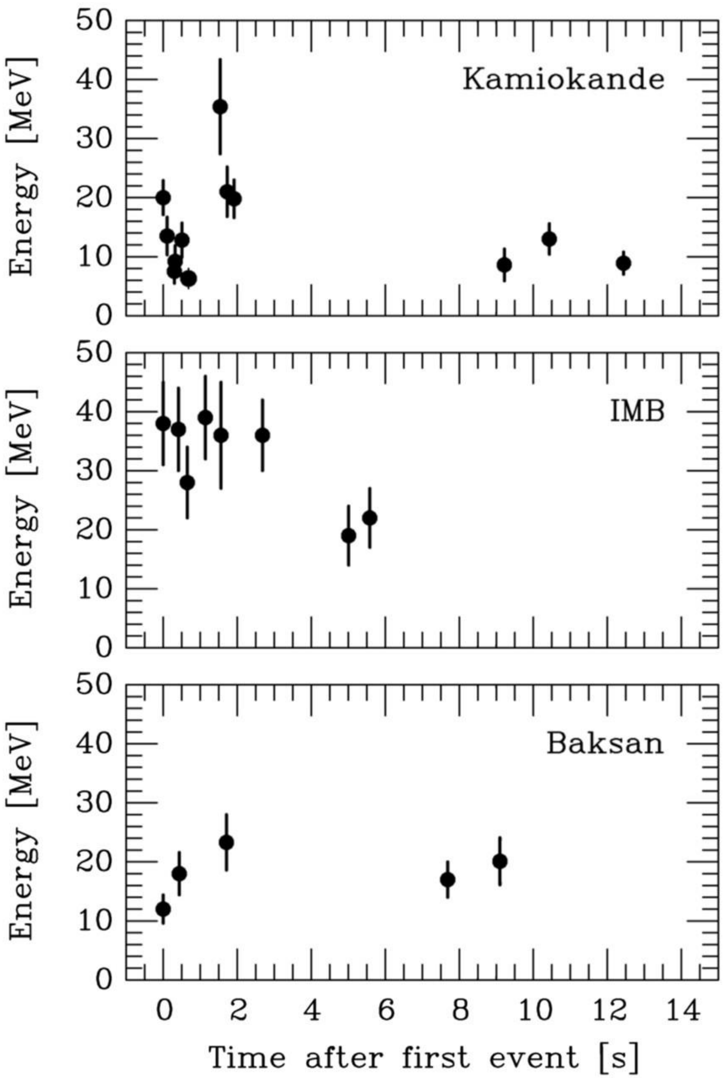
Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

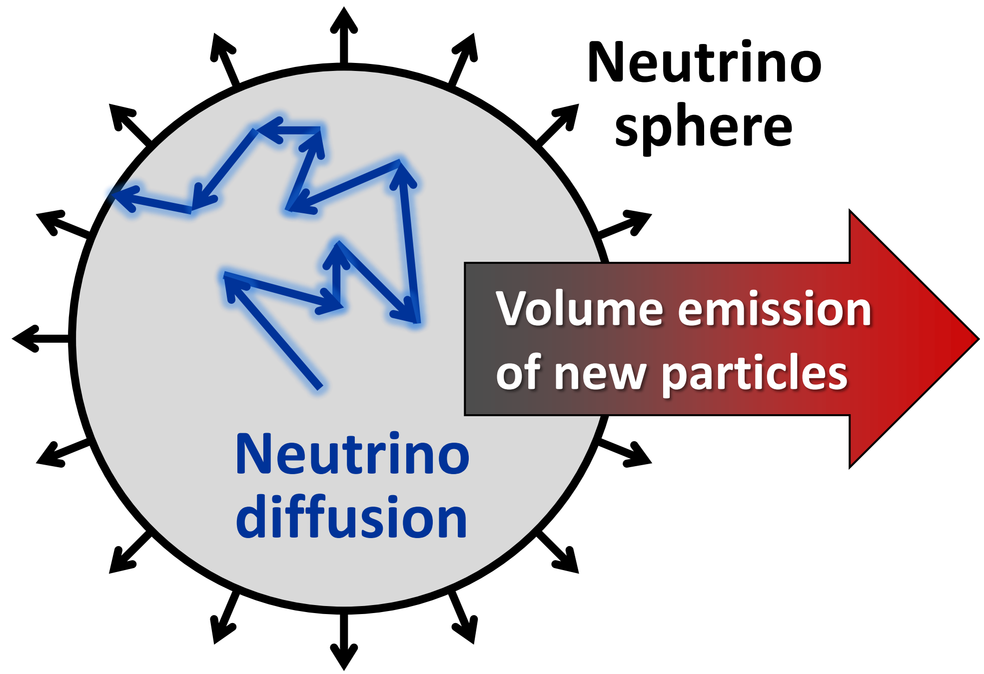
SN 1987A Burst of Neutrino Papers



Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

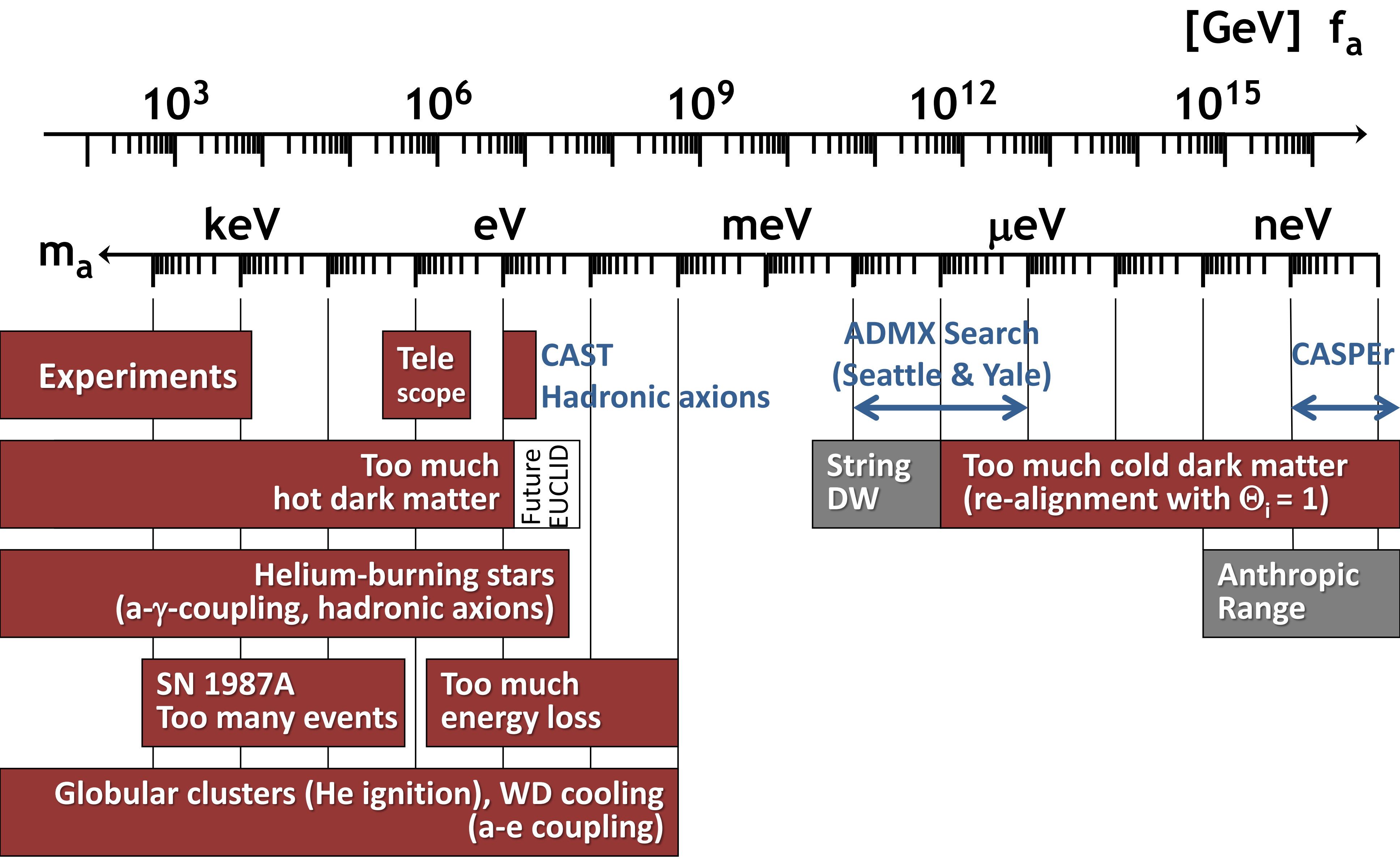




Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Bounds and Searches



Supernova 1987A Limit on Large Extra Dimensions

Cullen & Perelstein, hep-ph/9904422, Hanhart et al., nucl-th/0007016

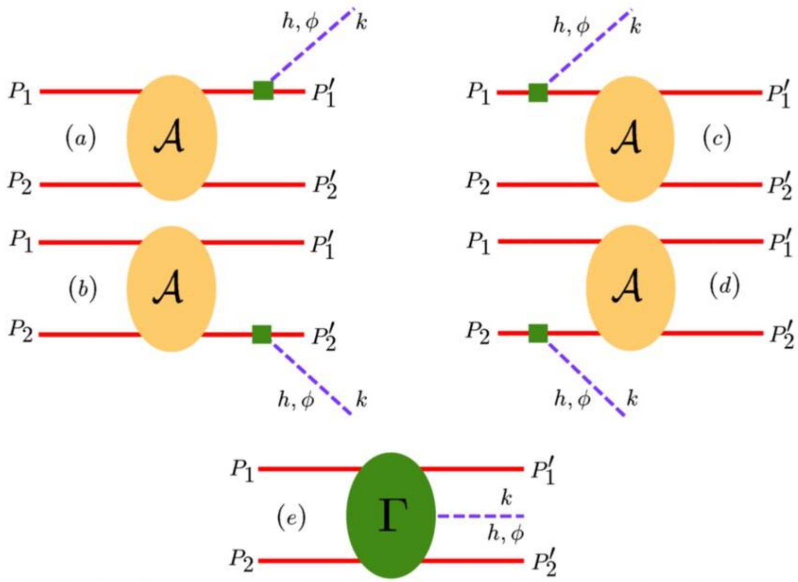


FIG. 1. *The leading diagrams contributing to processes $NN \to NNh$ and $NN \to NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing $\mathcal{A}$ denote an insertion of the full NN scattering amplitude. The solid oval containing Γ denotes the non-pole vertex required for the sum of diagrams to satisfy $\partial_\mu M^{\mu\nu} = 0$.*

SN core emits large flux of KK gravity modes by nucleon-nucleon bremsstrahlung

$$\text{Rate} \propto M_{\text{Pl}}^{-2}$$

Large multiplicity of modes

$$RT \sim 10^{11}$$

for R ~ 1 mm, T ~ 30 MeV

$$\text{Rate} \propto \frac{(RT)^n}{M_{\text{Pl}}^2} \propto \frac{T^n}{M_{\text{Pl}}^{2+n}}$$

SN 1987A energy-loss argument:

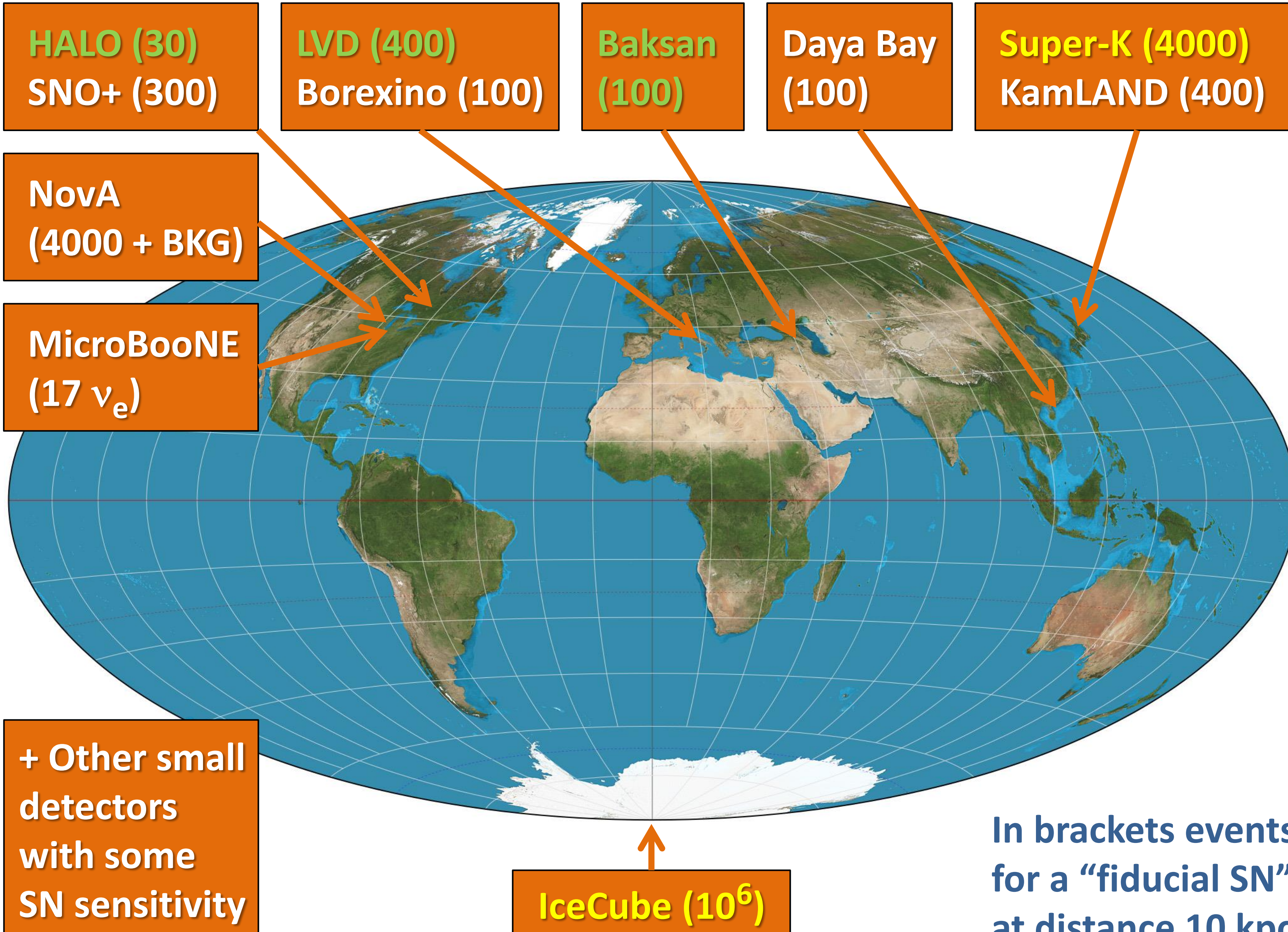
R < 1 mm, M > 9 TeV (n = 2)

R < 1 nm, M > 0.7 TeV (n = 3)

Originally the most restrictive limit on such theories, except for cosmological arguments. Other restrictive limits from neutron stars.

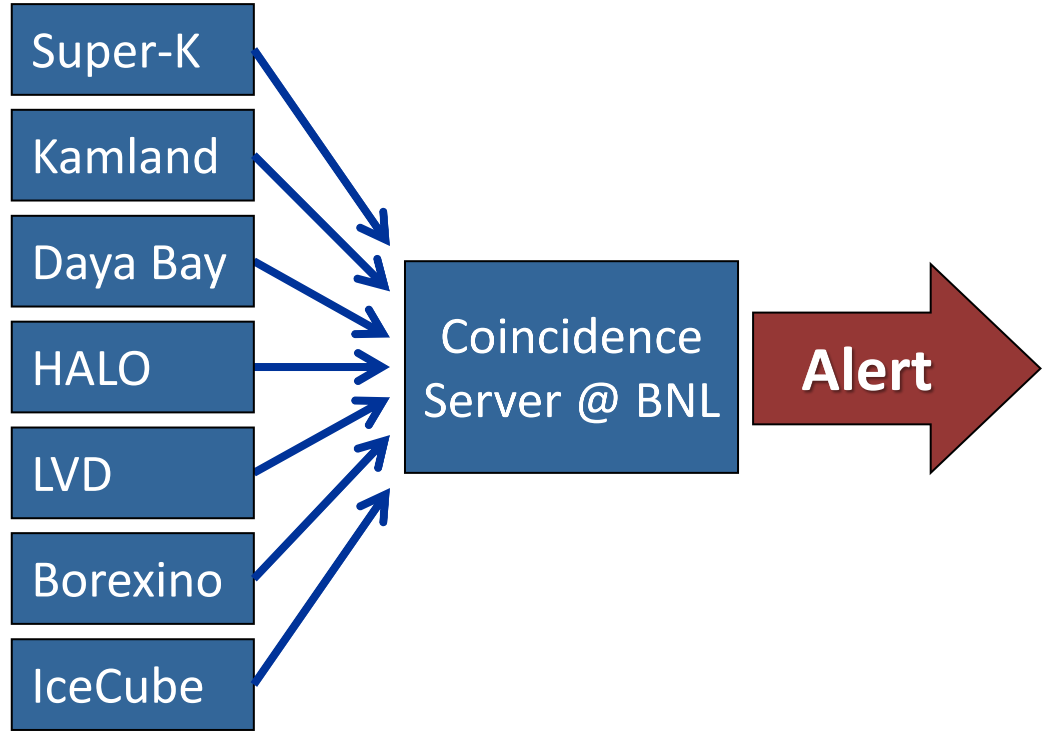
Neutrinos from Next Nearby SN

Operational Detectors for Supernova Neutrinos



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

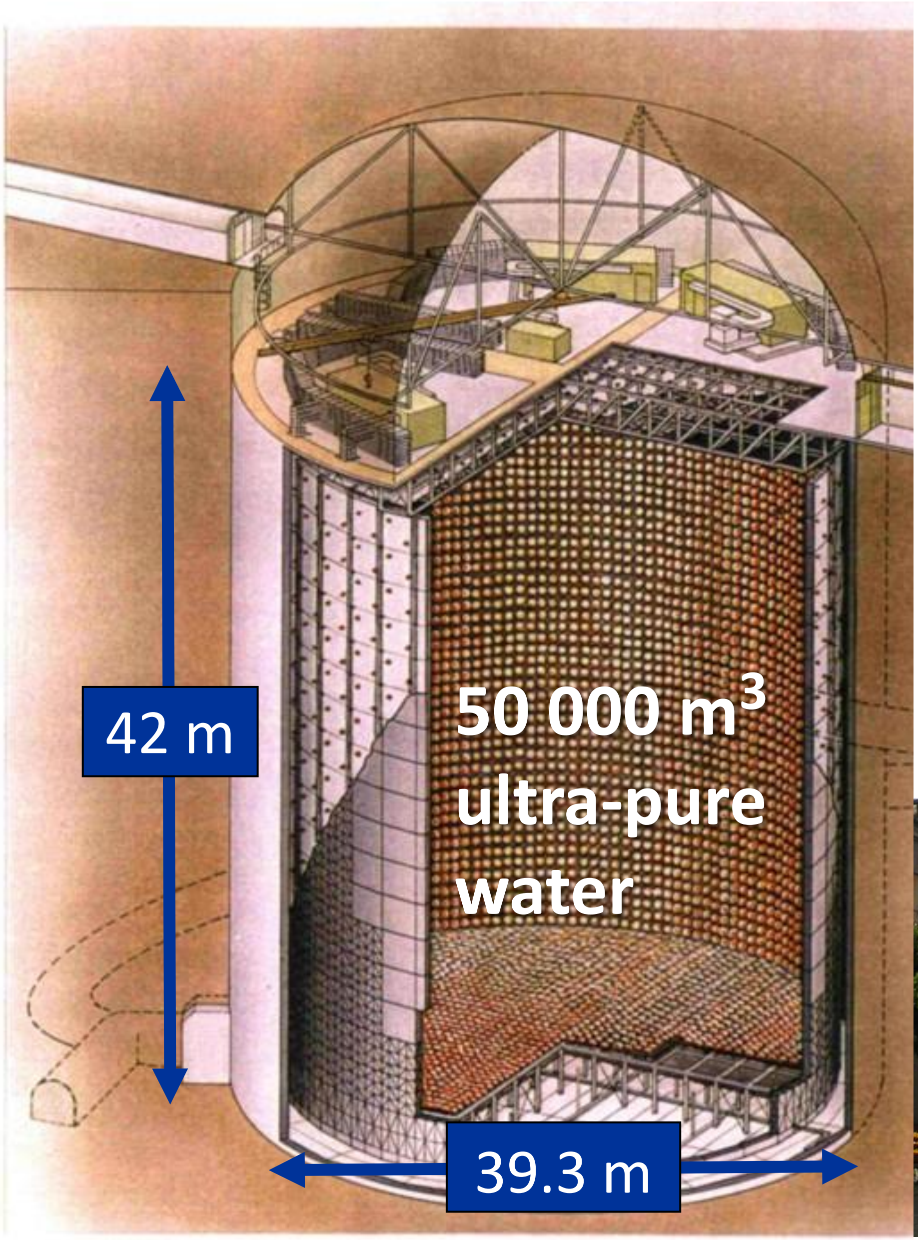
SuperNova Early Warning System (SNEWS)



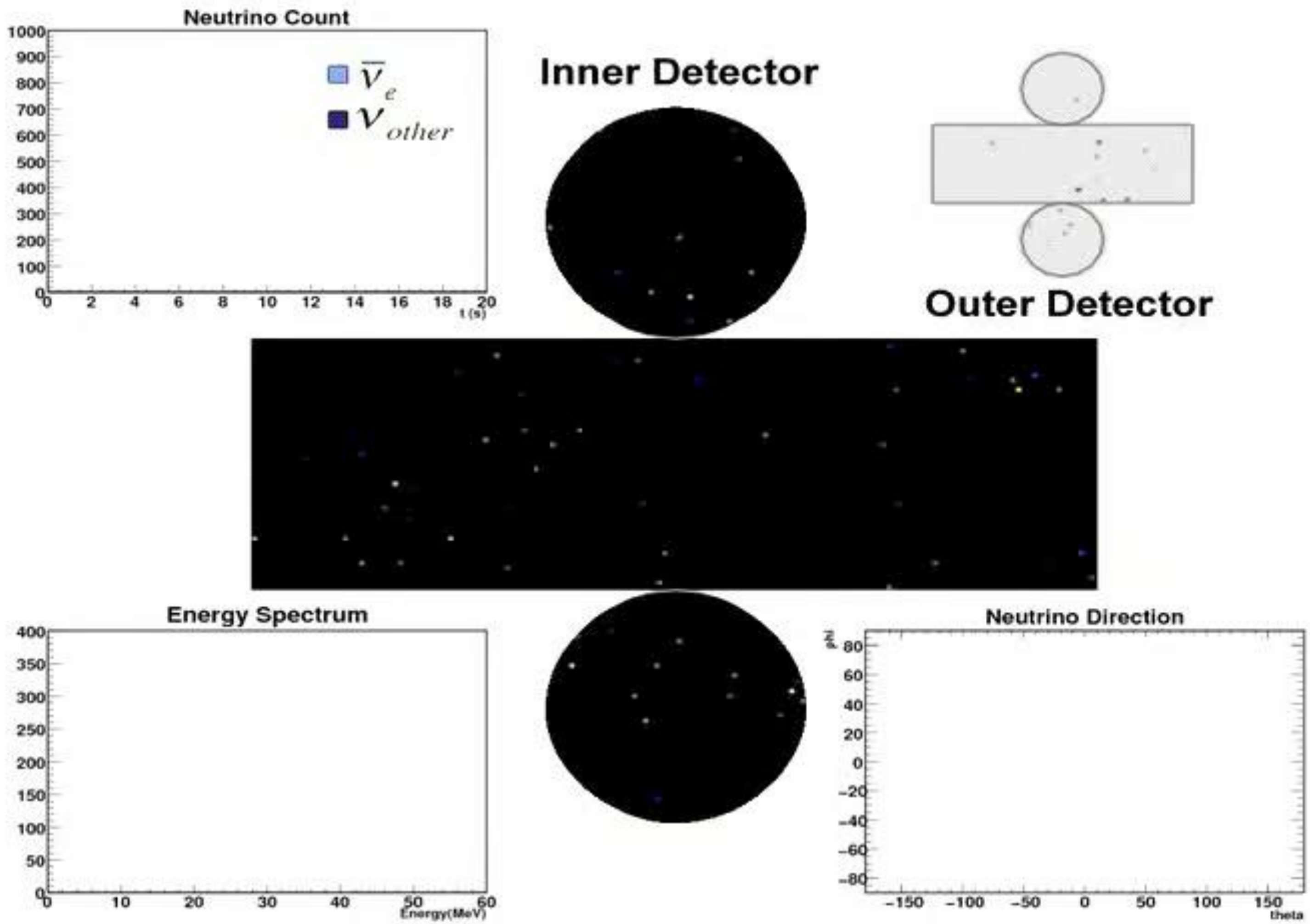
http://snews.bnl.gov

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

Super-Kamiokande Detector (Since 1996)

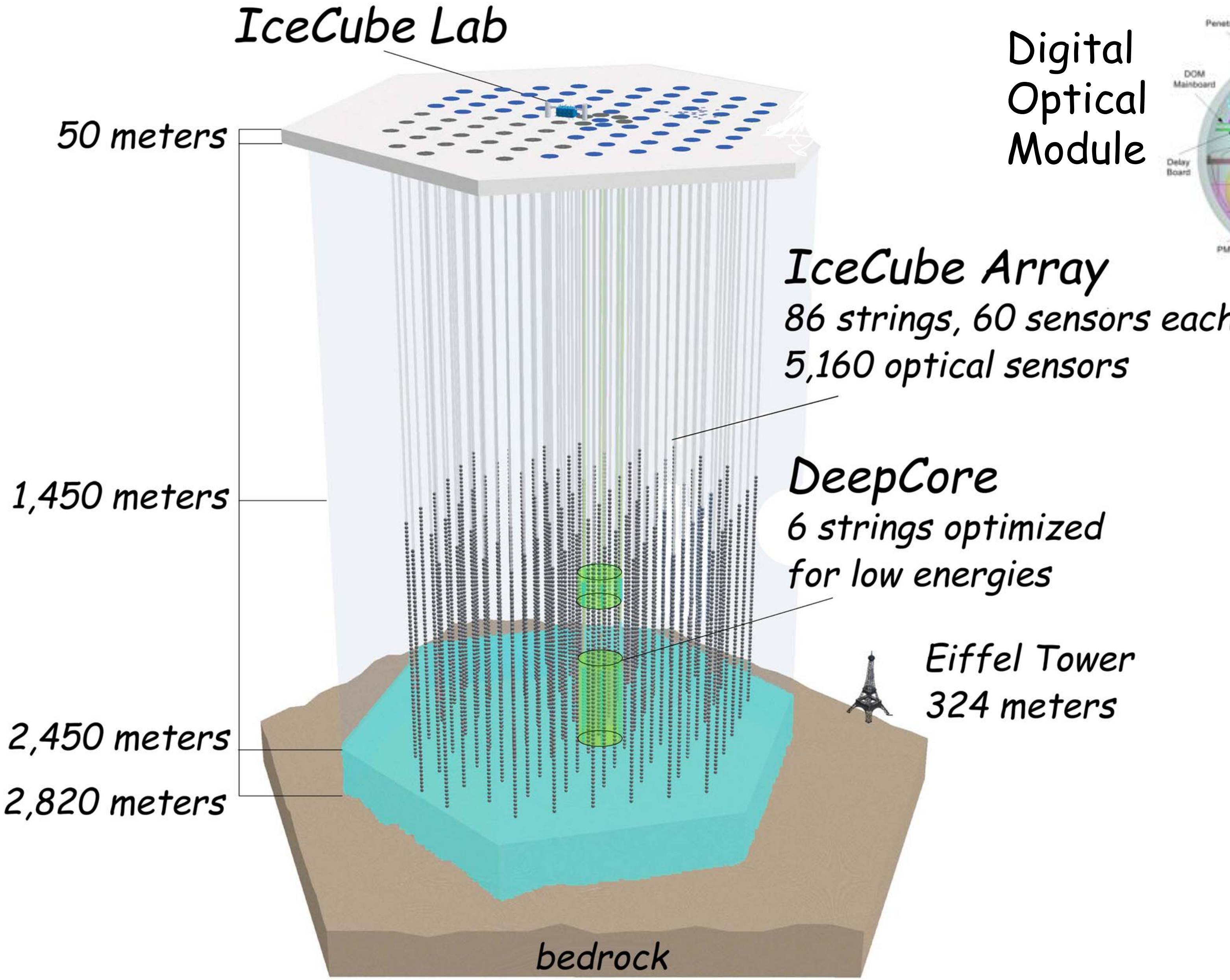


Simulated Supernova Burst in Super-Kamiokande

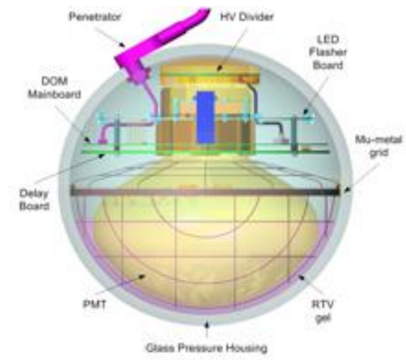


Movie by C. Little, including work by S. Farrell & B. Reed,
(Kate Scholberg's group at Duke University)
http://snews.bnl.gov/snmovie.html

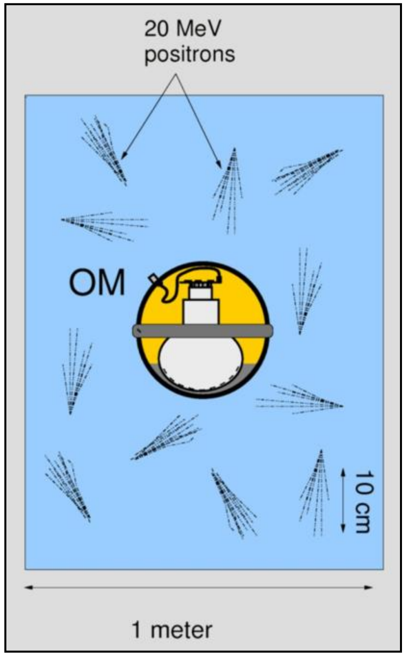
IceCube Neutrino Telescope at the South Pole

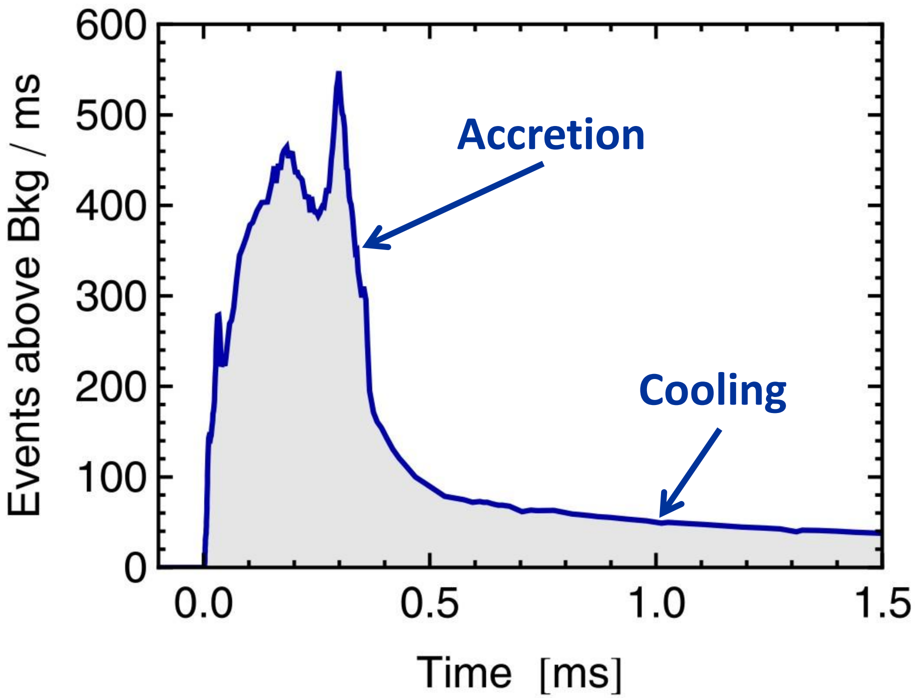


Digital Optical Module



IceCube as a Supernova Neutrino Detector



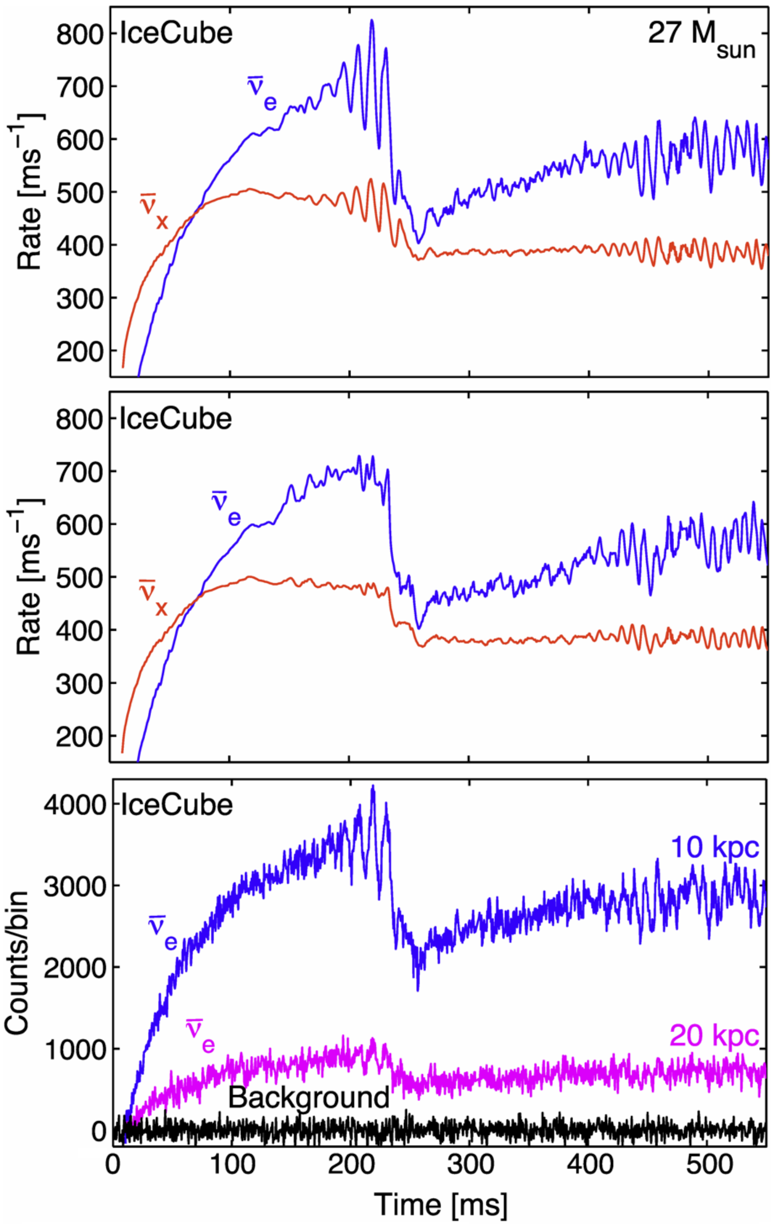


SN signal at 10 kpc
10.8 M_{sun} simulation
of Basel group
[arXiv:0908.1871]

- 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

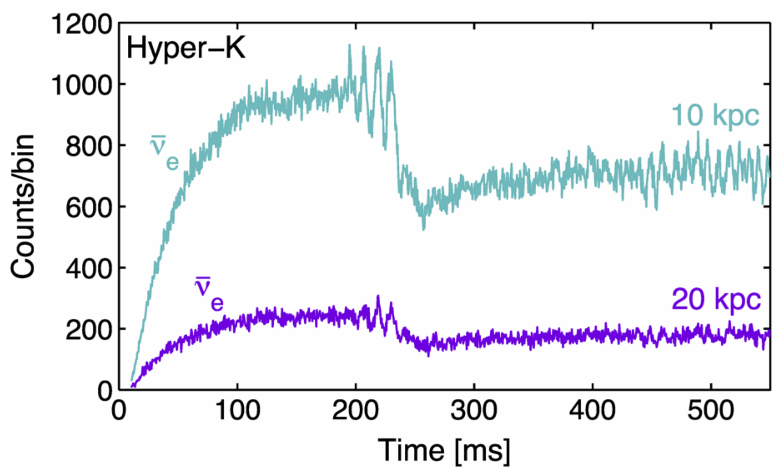
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080.
Demirörs, Ribordy & Salathe, arXiv:1106.1937.

SASI Detection Perspectives (27 M_{SUN} Model)



Optimistic Observer Direction (along SASI dipole)

Pessimistic Observer Direction



With shot noise

Neutrino Mass and Resolving Time Variations

Time-of-flight signal dispersion for next nearby supernova

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

- Laboratory: $m_\nu < 2.2$ 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!

Time-of-flight measurement of nu mass hopeless with SN nus.

HALO Lead Neutrino Detector in SNO Lab

Neutrino detection in lead using liberated neutrons

(CC) $\nu_e + {}^{208}\text{Pb} \rightarrow {}^{207}\text{Bi} + n + e$

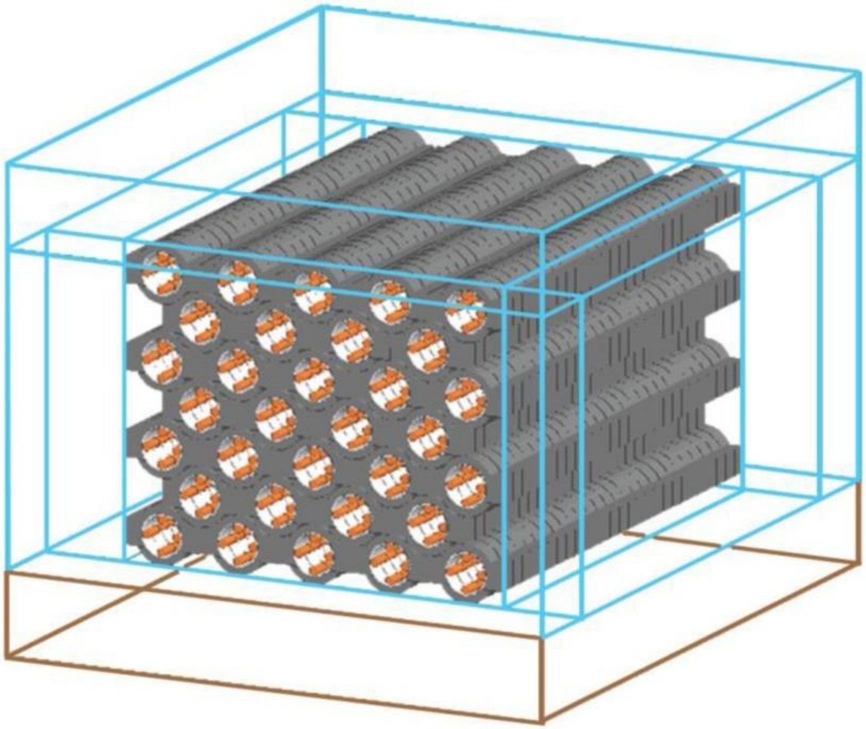
$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{206}\text{Bi} + 2n + e$

(NC) $\nu + {}^{208}\text{Pb} \rightarrow {}^{207}\text{Pb} + n$

$\nu + {}^{208}\text{Pb} \rightarrow {}^{206}\text{Pb} + 2n$

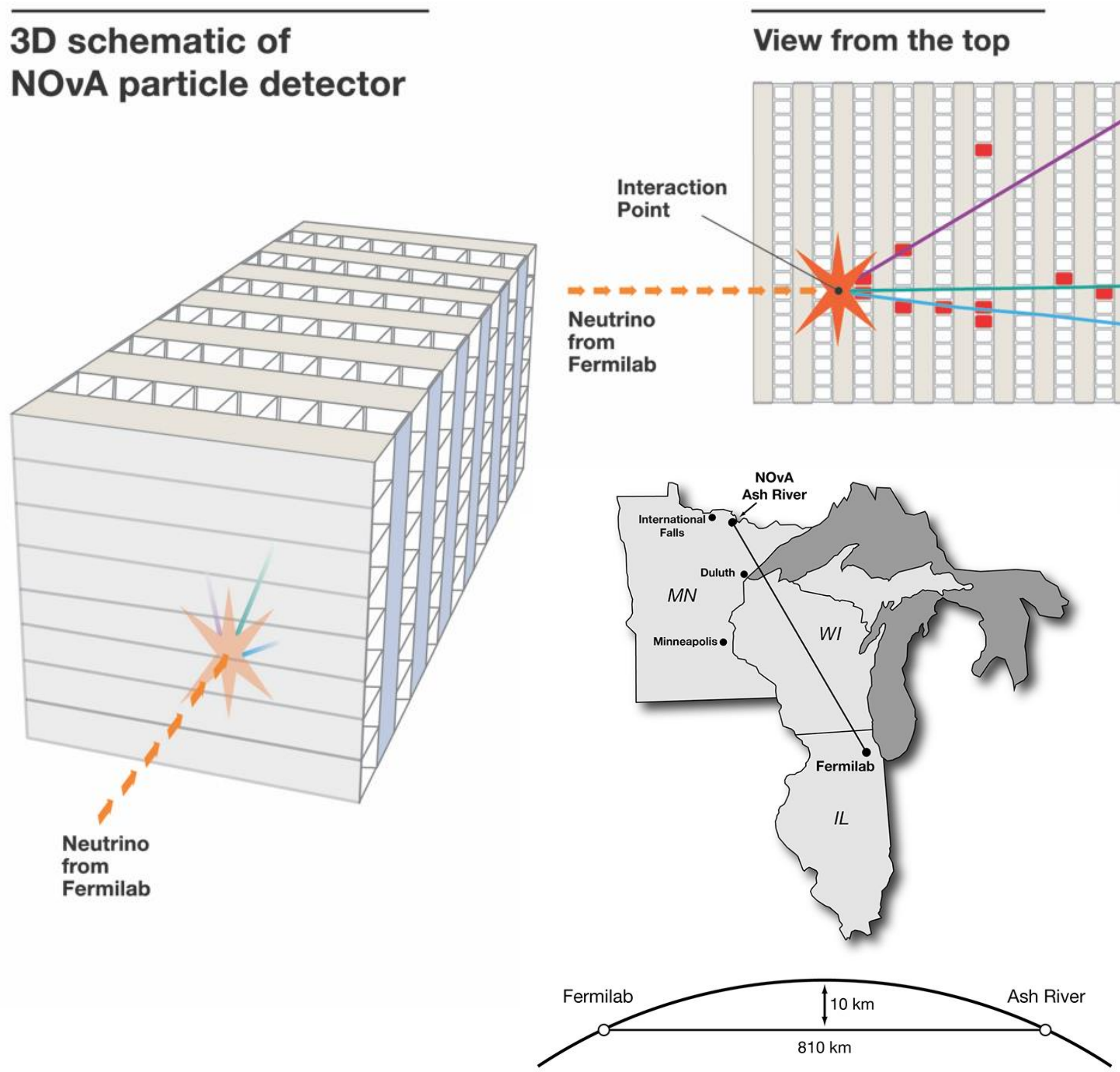
High threshold

→ Sensitive to high-E tail of distribution



- Lead array (79 tonnes) of 32 annular columns (3 m long)
- Neutron detectors He-3 from SNO experiment
- tens of events for 10 kpc SN

Nova 15 kt Liquid Scintillator Detector



Canonical SN at 10 kpc

- 4000 IBD events
- Shallow location:
  Large backgrounds
- Triggered by SNEWS

SN Neutrino Detection Channels

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

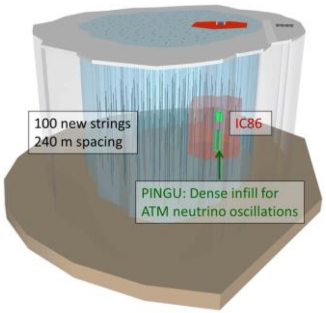
Scholberg, arXiv:1205.6003, see also http://www.phy.duke.edu/~schol/snowglobes

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	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

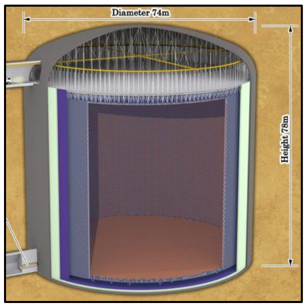
K. Scholberg in arXiv:1508.00785

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



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

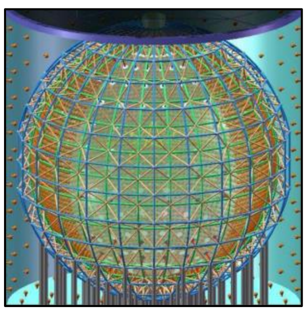
Doubling the number of optical modules



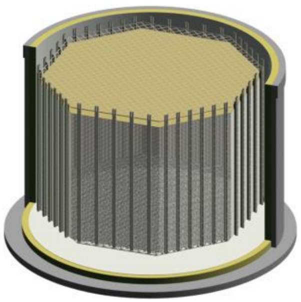
Megaton-class water Cherenkov detector

Notably Hyper-Kamiokande

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



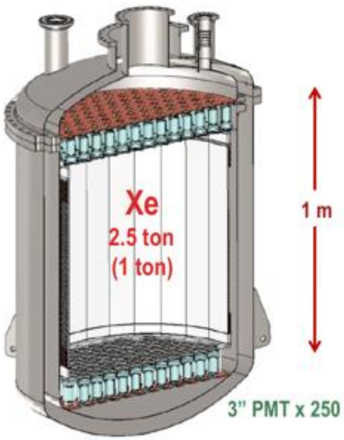
Scintillator detectors (20 kilotons)
- JUNO in China for reactor nus (construction)
- RENO-50 in Korea for reactor nus (plans)
- Baksan Large Volume Scintillator Detector (discussions in Russia)

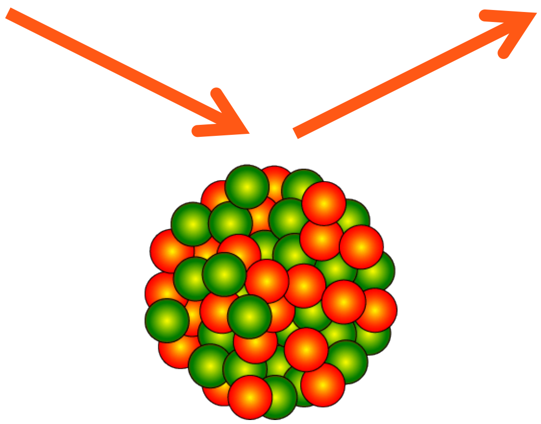


Liquid argon time projection chamber

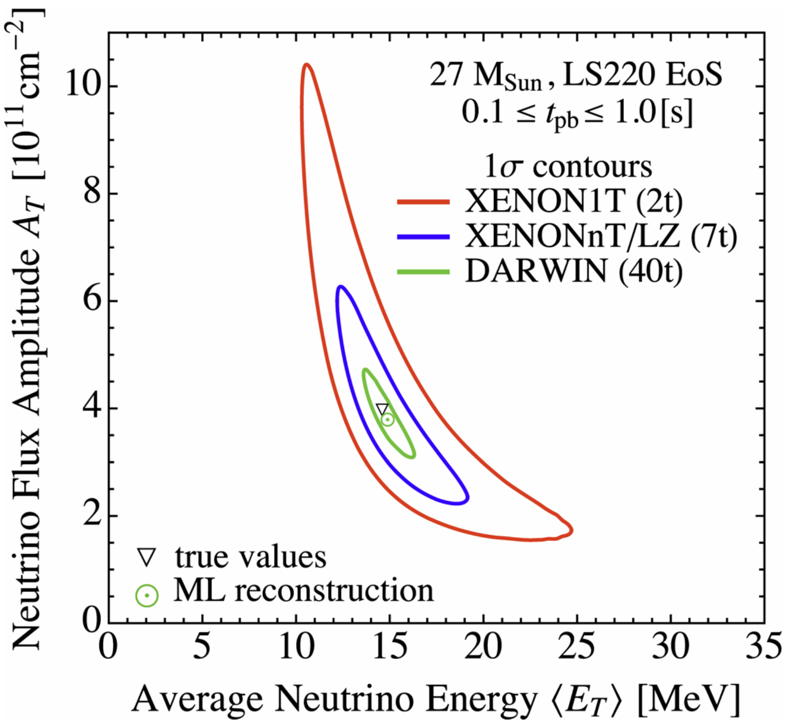
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC ν_e signal)
- But cross sections poorly known

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

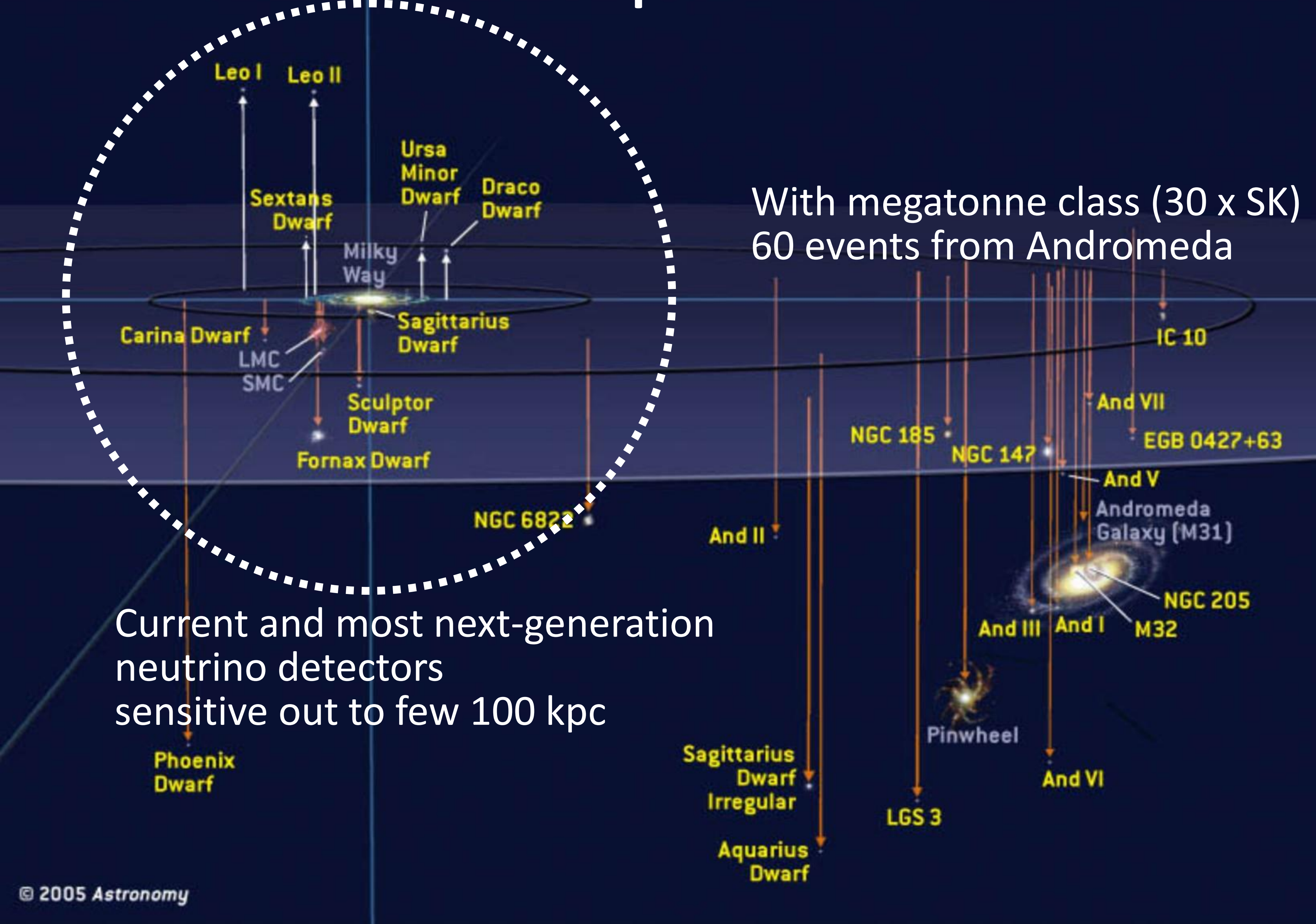
See for example
Horowitz et al. (astro-ph/0302071)
Chakraborty et al. (arXiv:1309.4492)
XMASS Collaboration (arXiv:1604.01218)
Lang et al. (arXiv:1606.09243)

Supernova Rate

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



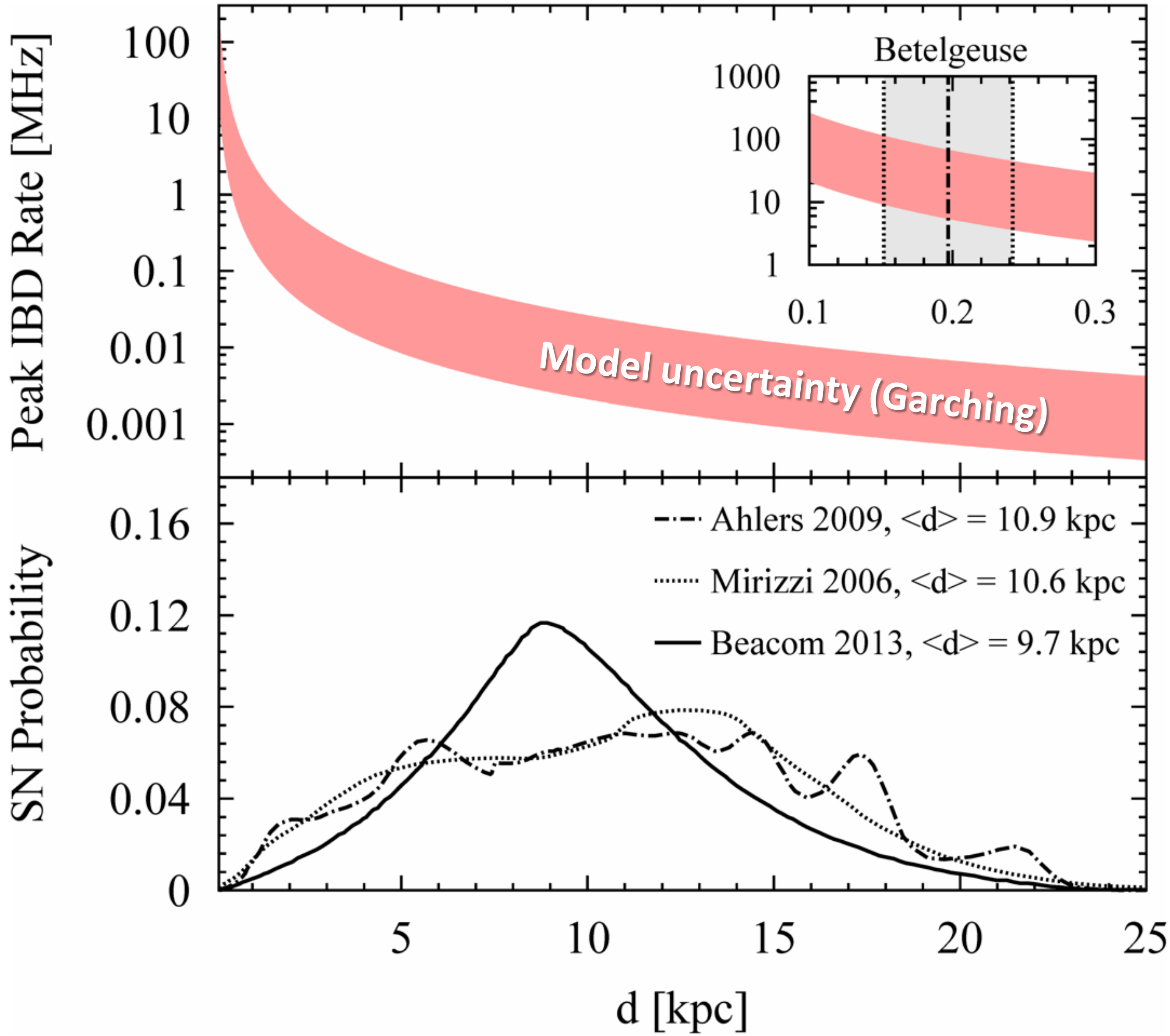
SN Distance Distribution and Peak Count Rate

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

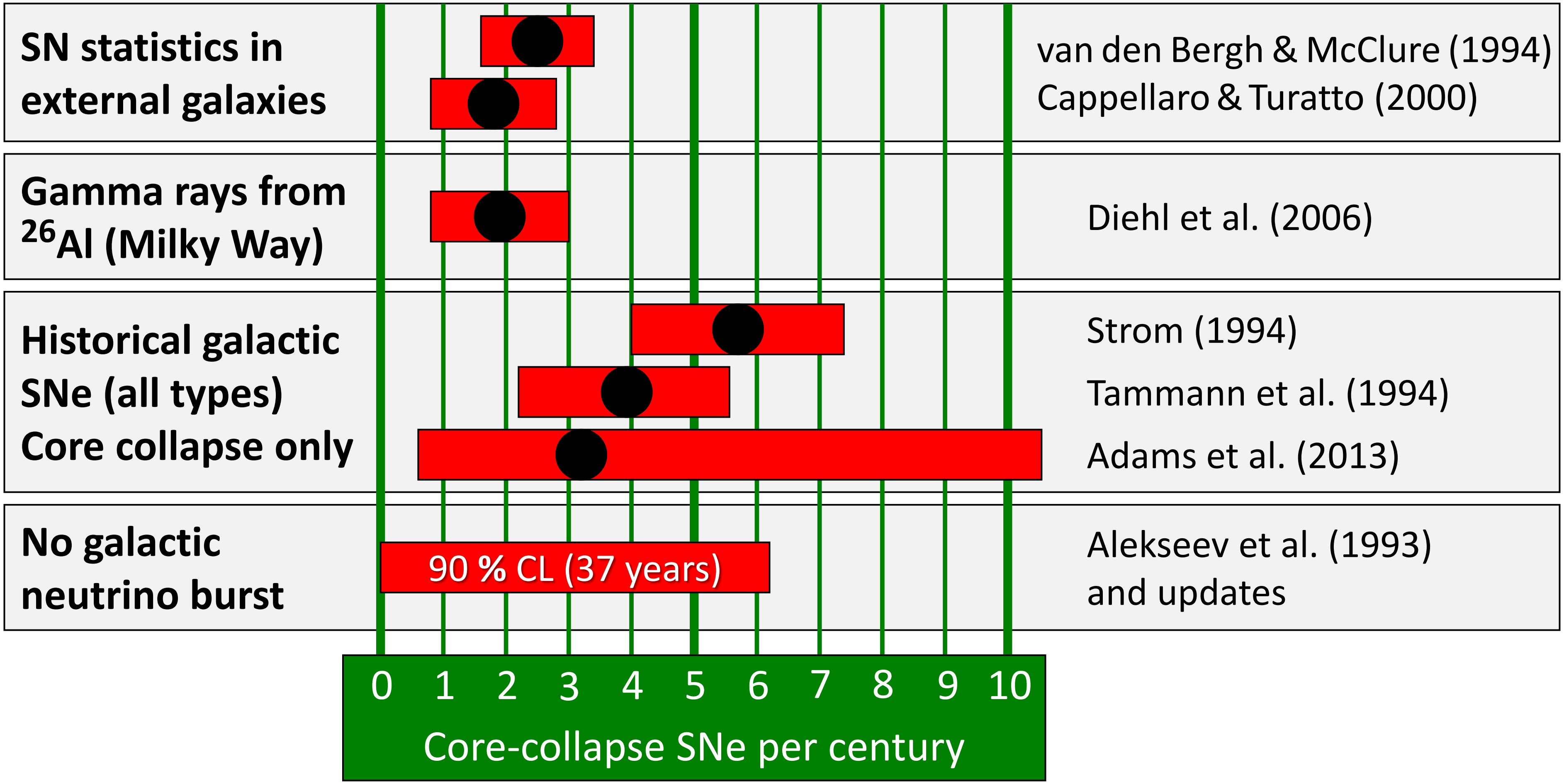
× 10 in 1 tank Hyper-K

SN distance probability in Milky Way

JUNO Yellow Book, arXiv:1507.05613

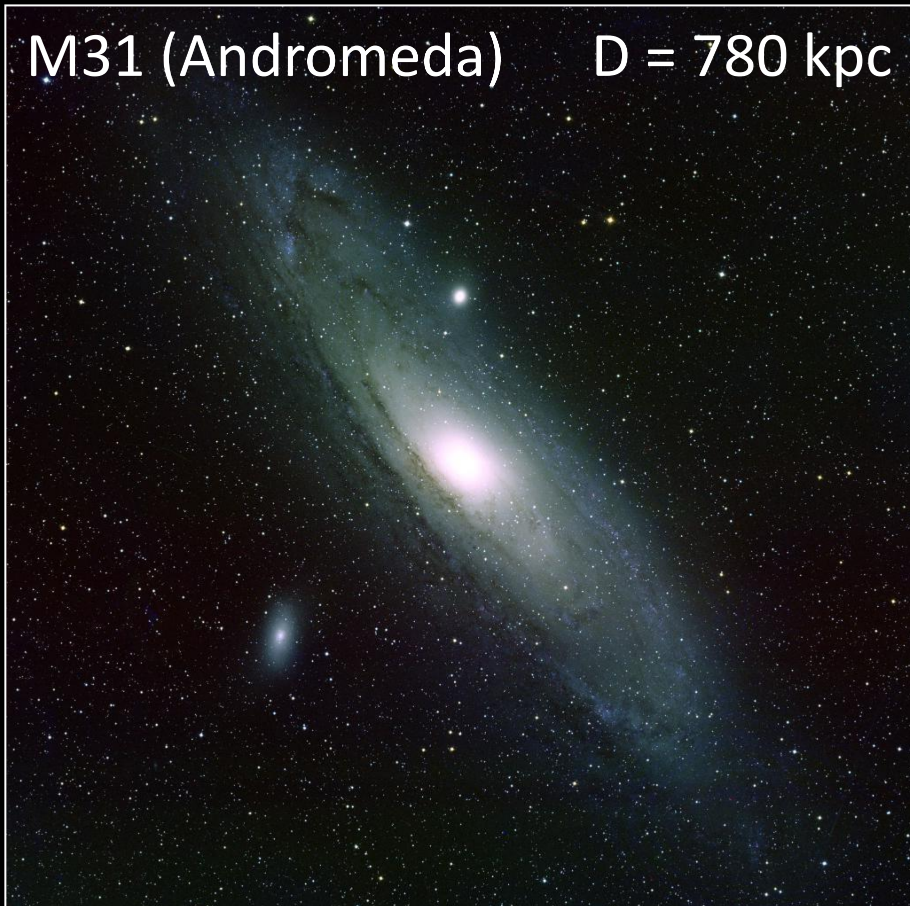


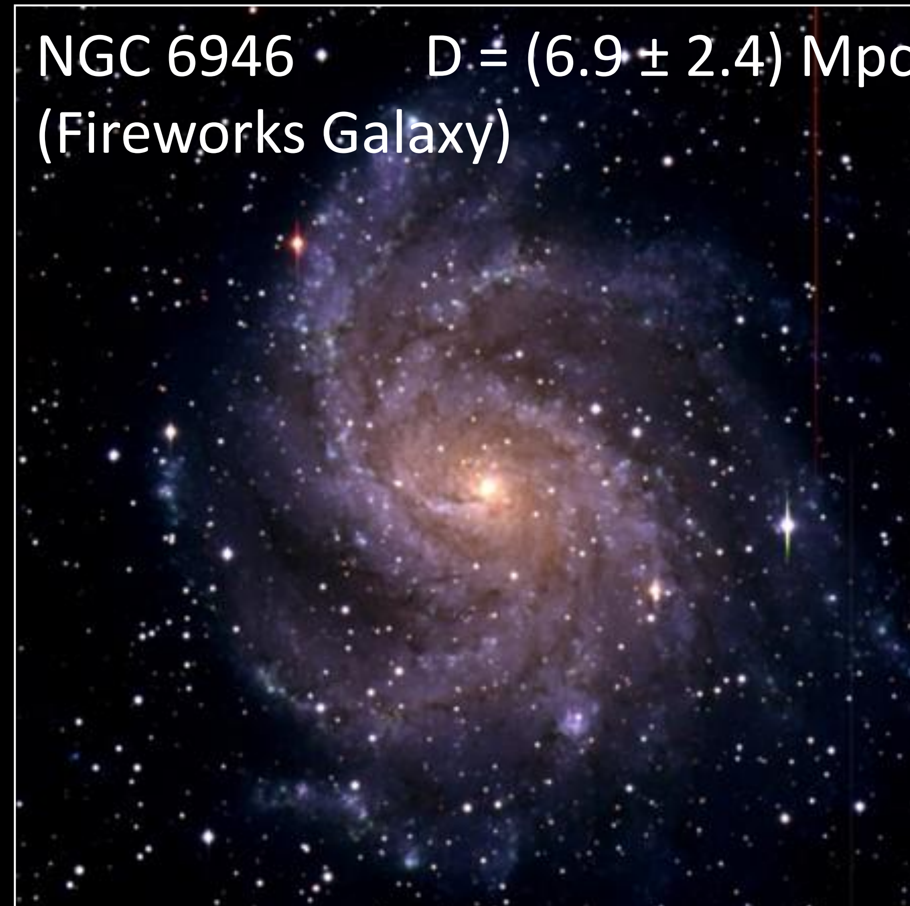
Core-Collapse SN Rate in the Milky Way



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

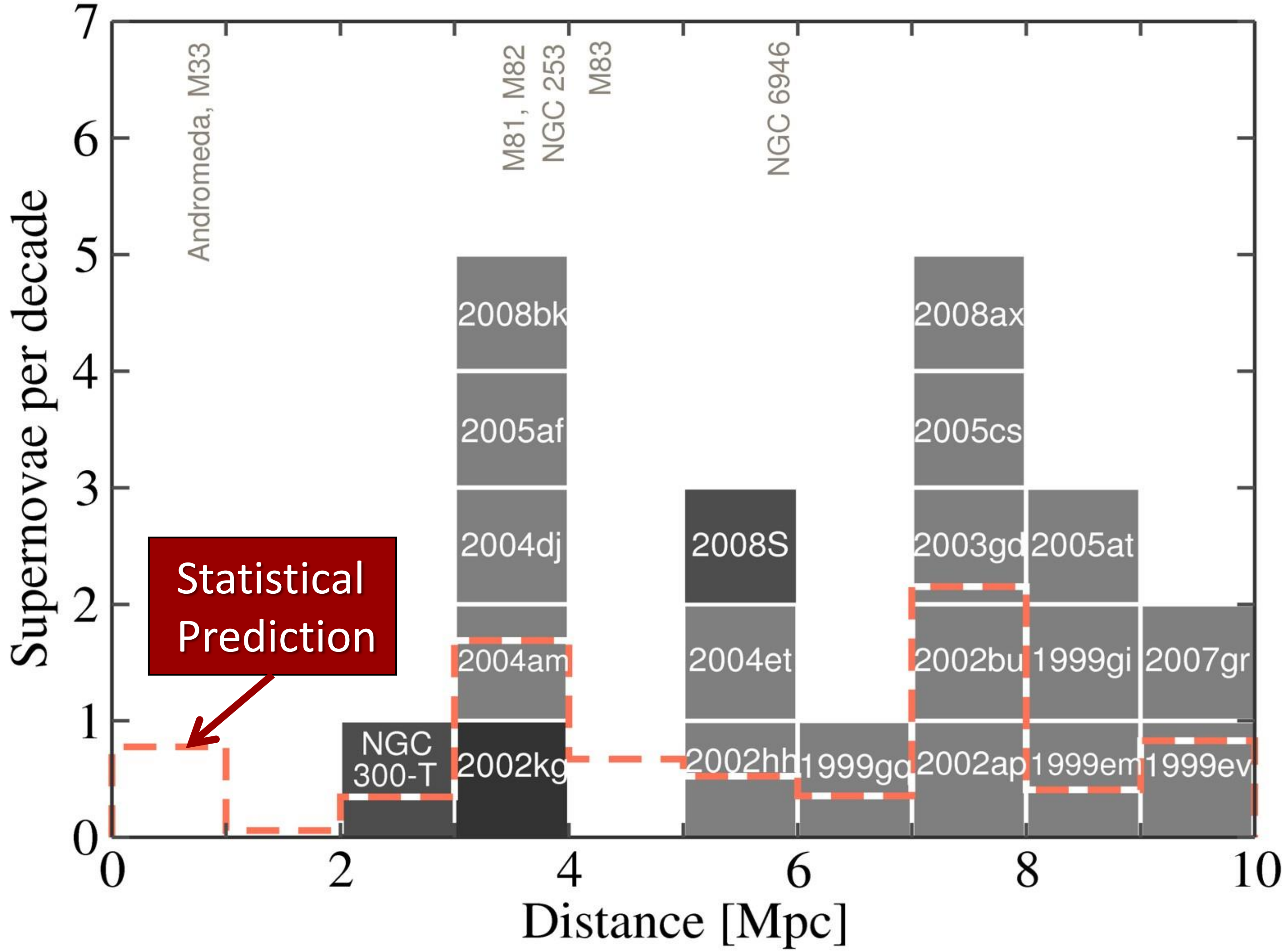




Last Observed Supernova: 1885A

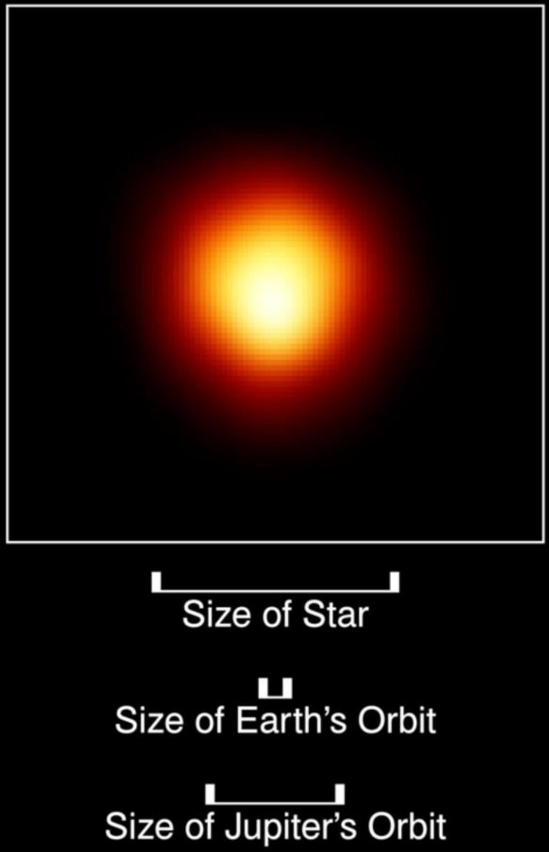
Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S,
N6946-BH1 (failed SN 2009/10)

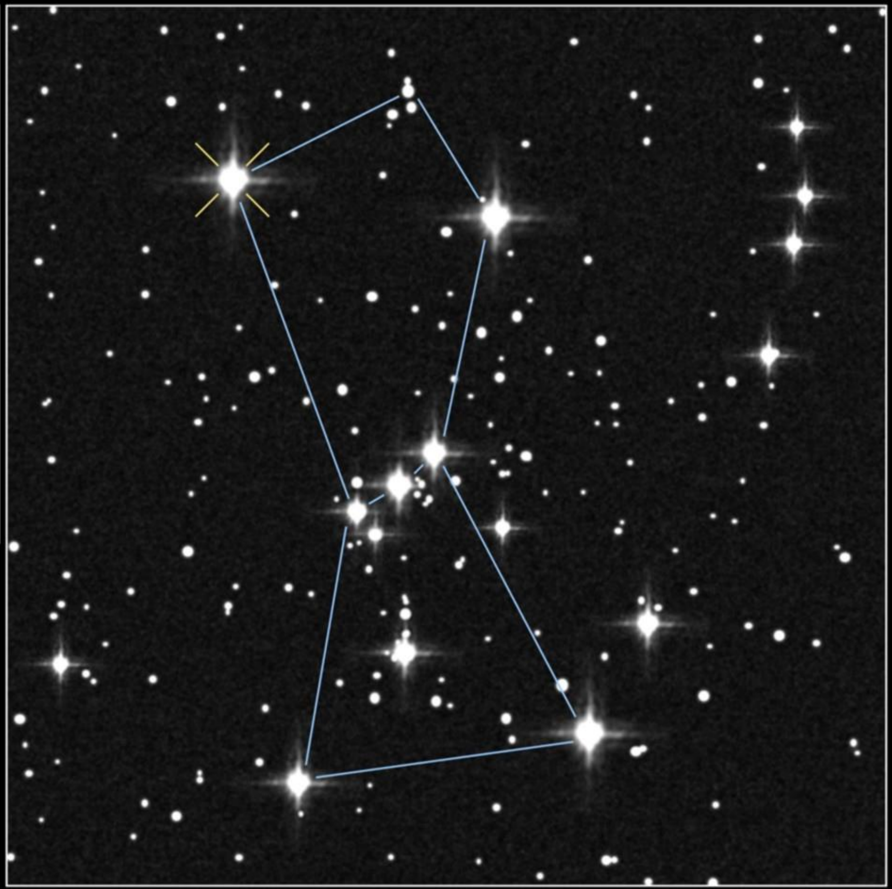
Supernova Rate in the Local Universe (Past Decade)



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)

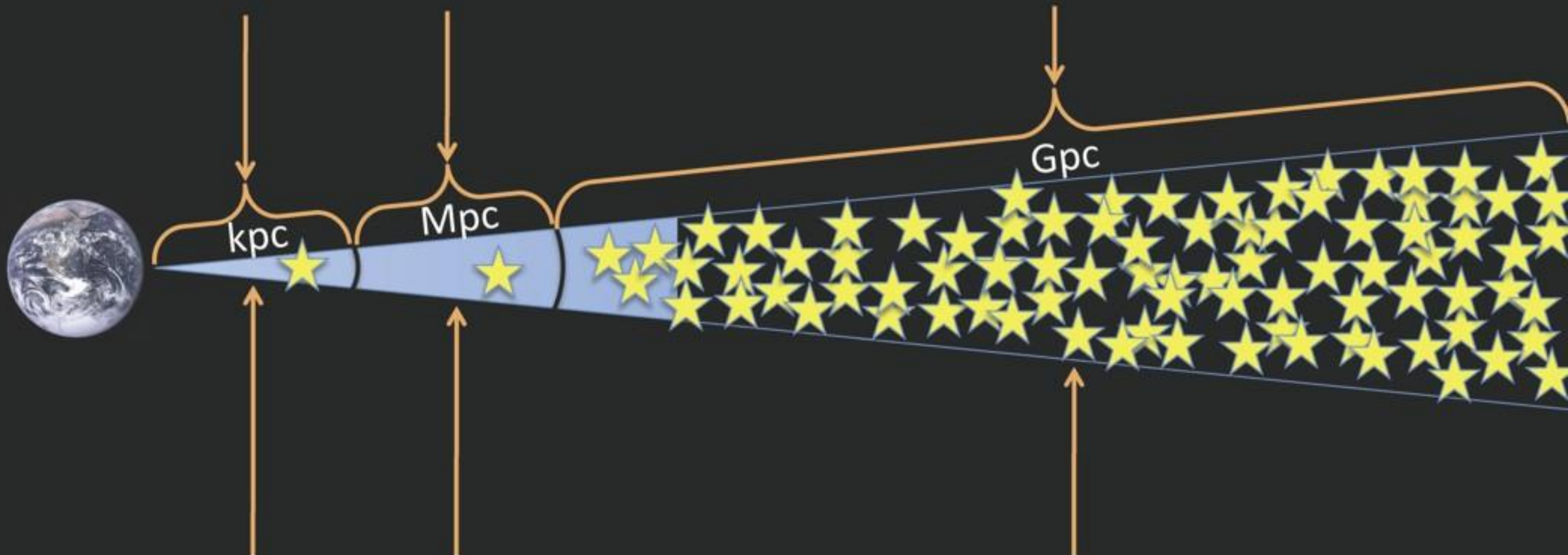
If Betelgeuse goes Supernova:

- 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]

Diffuse SN Neutrino Background

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

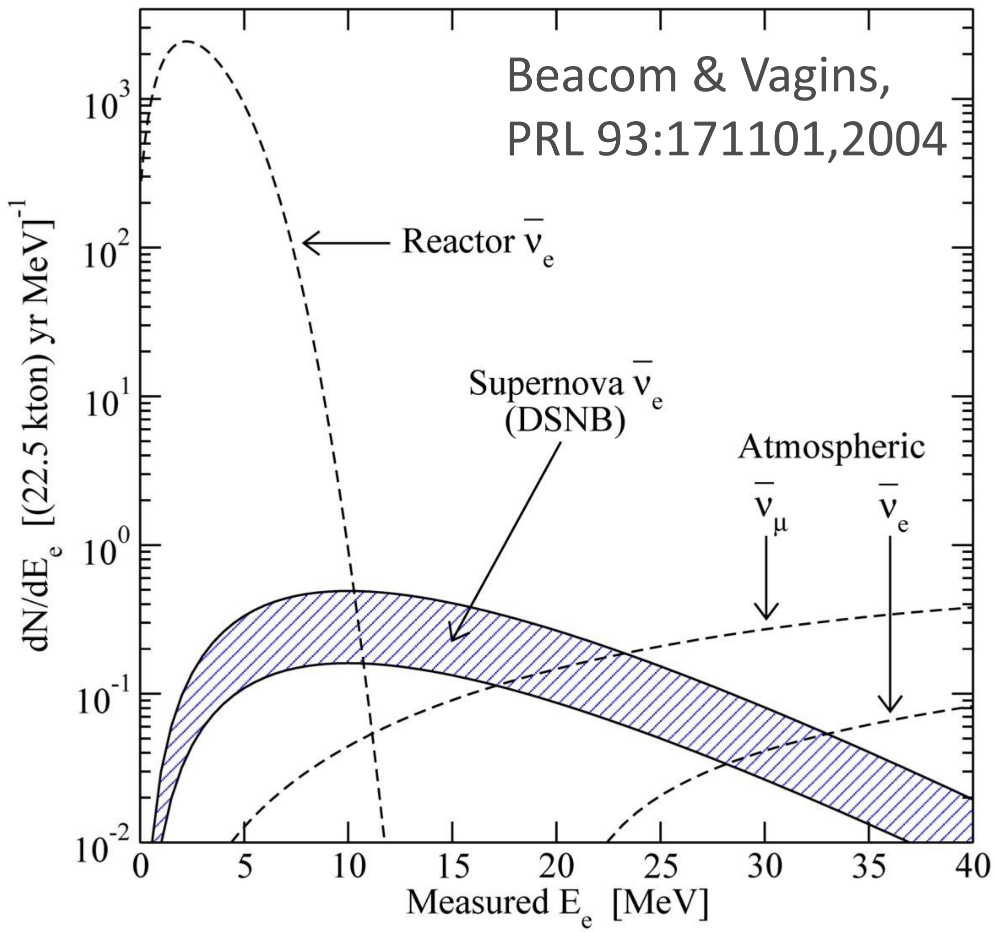
high statistics, all flavors

object identity, burst variety

cosmic rate, average emission

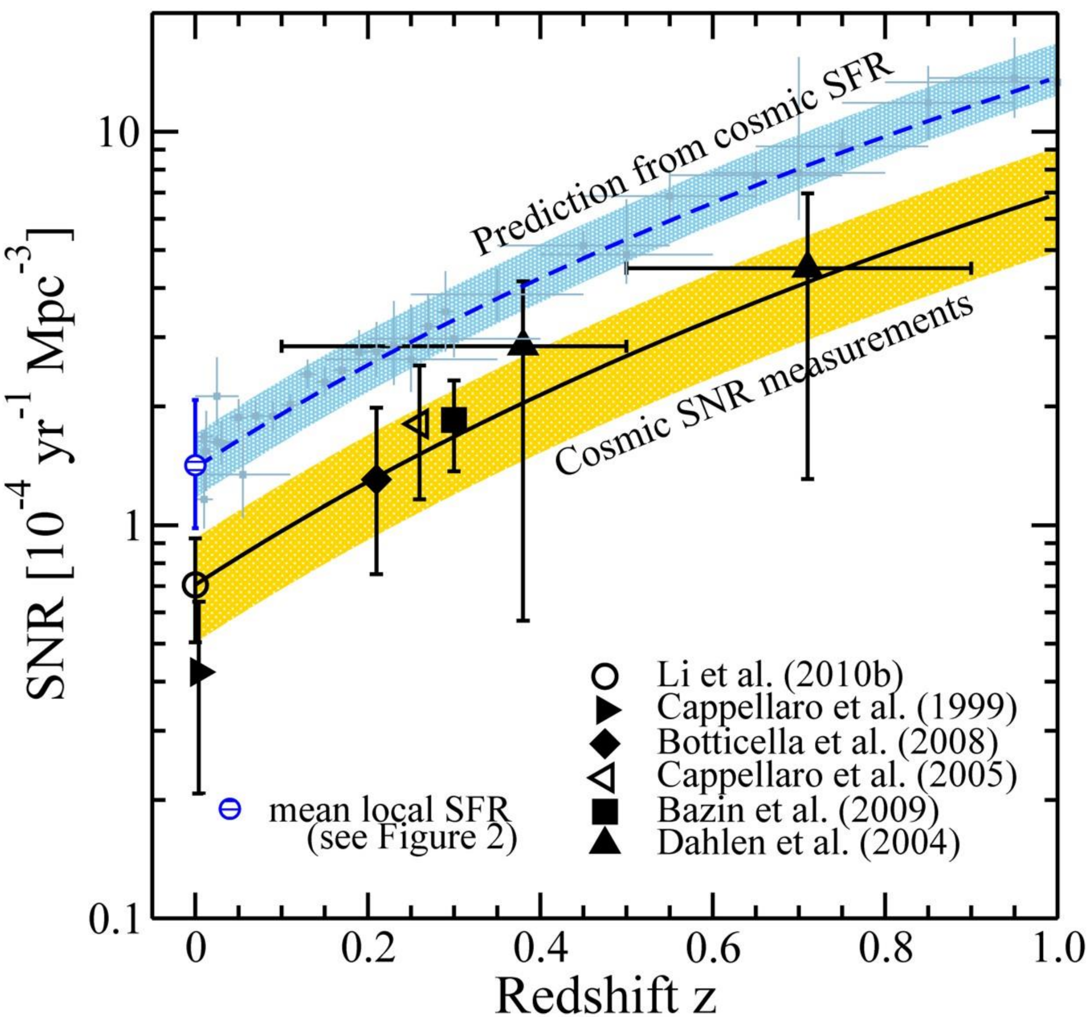
Diffuse Supernova Neutrino Background (DSNB)

- 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

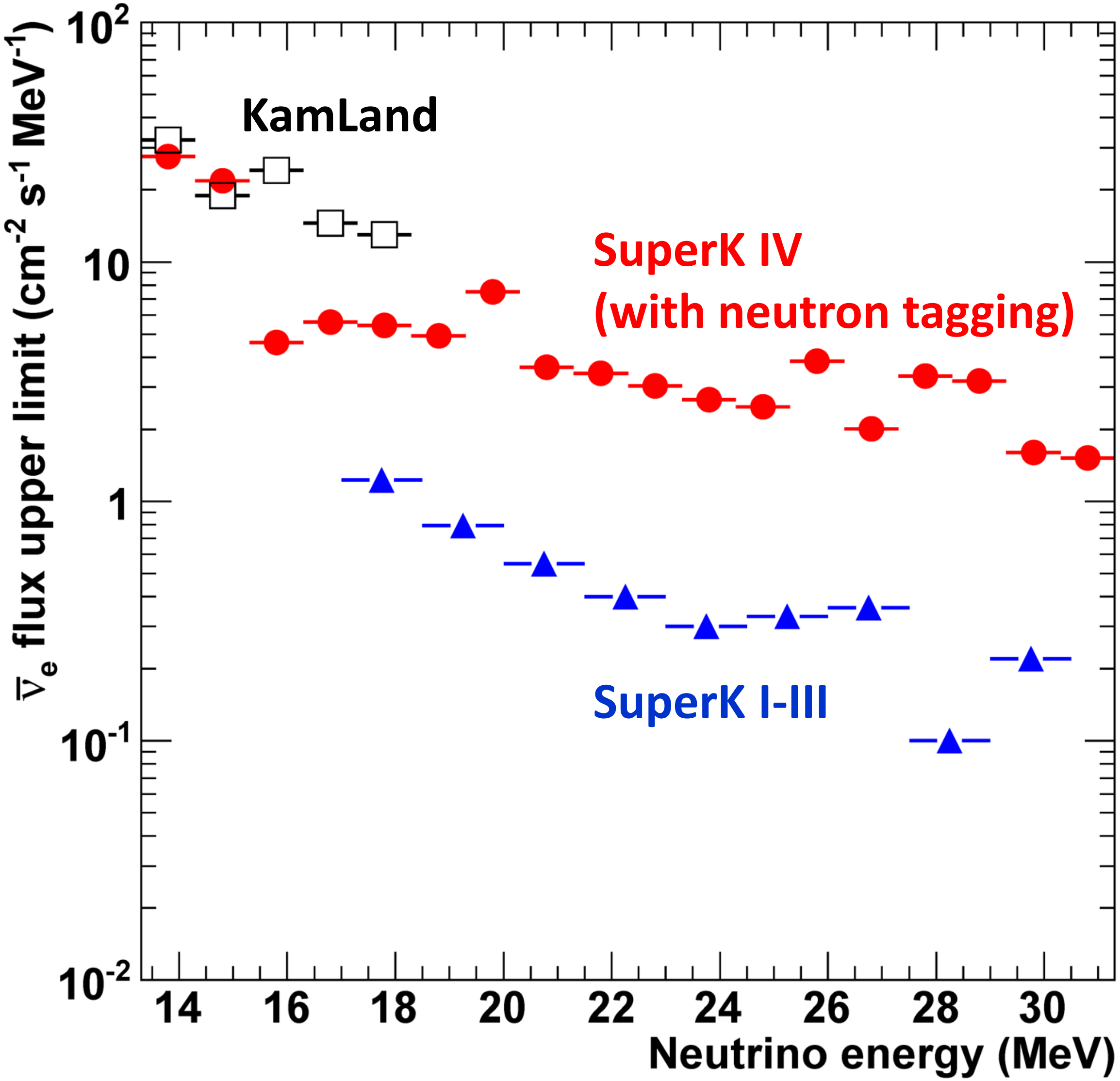


Measured SN rate about half the prediction from star formation rate

Many "dark SNe" ?

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

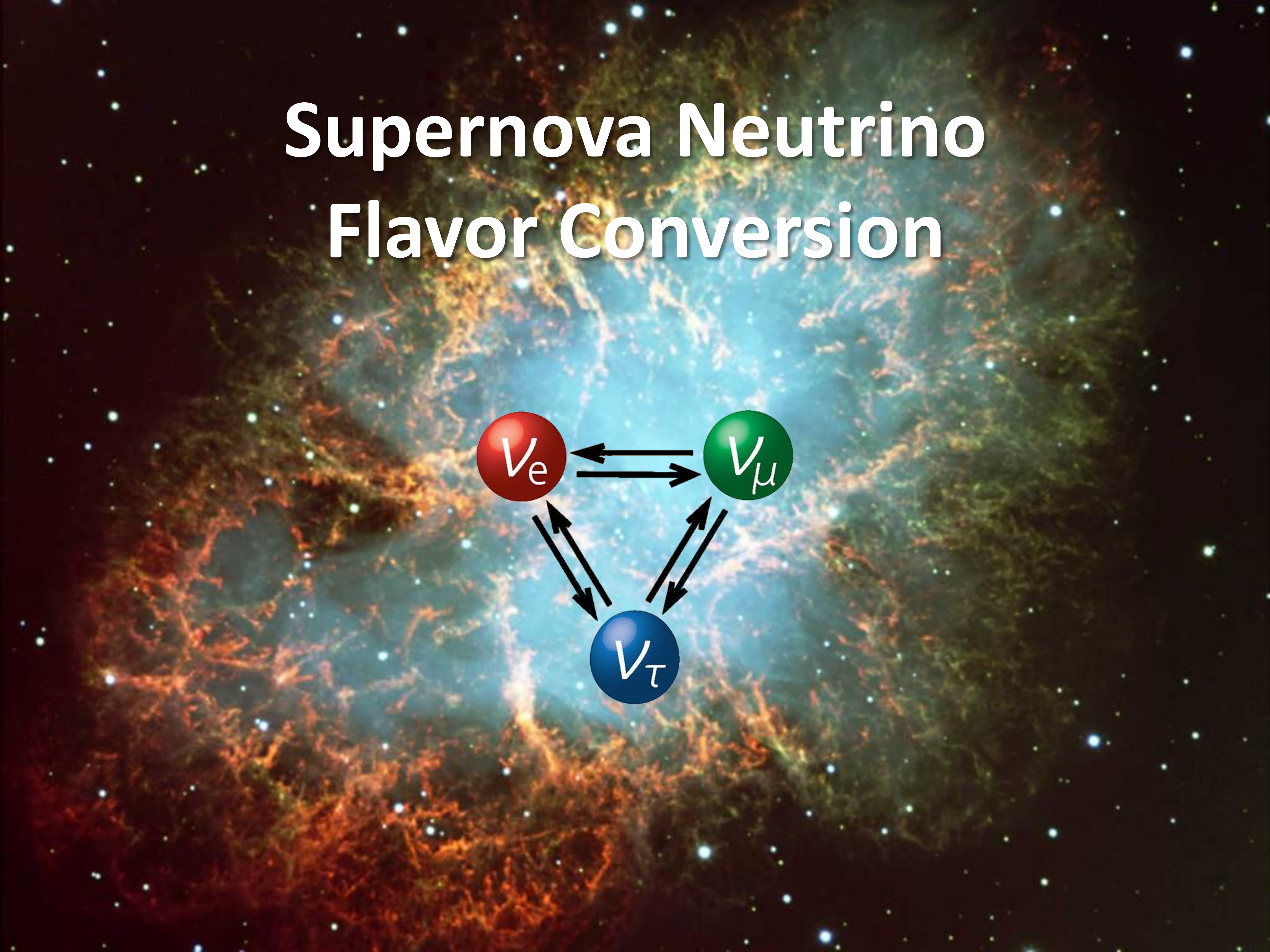
Experimental DSNB Limits



Super-K with Gadolinium enhancement (neutron tagging) will strongly improve sensitivity

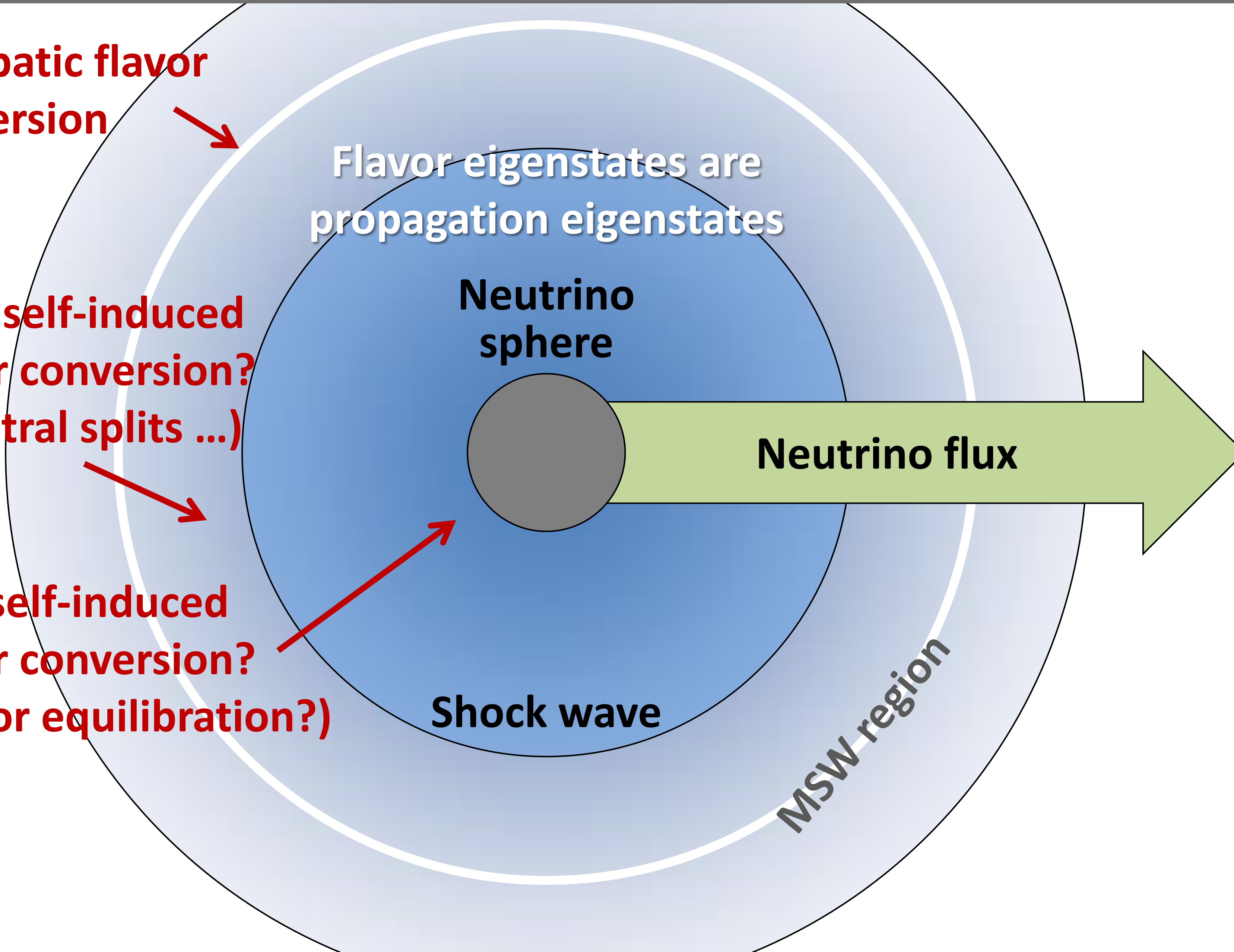
Super-Kamiokande Collaboration, arXiv:1311.3738

Supernova Neutrino Flavor Conversion



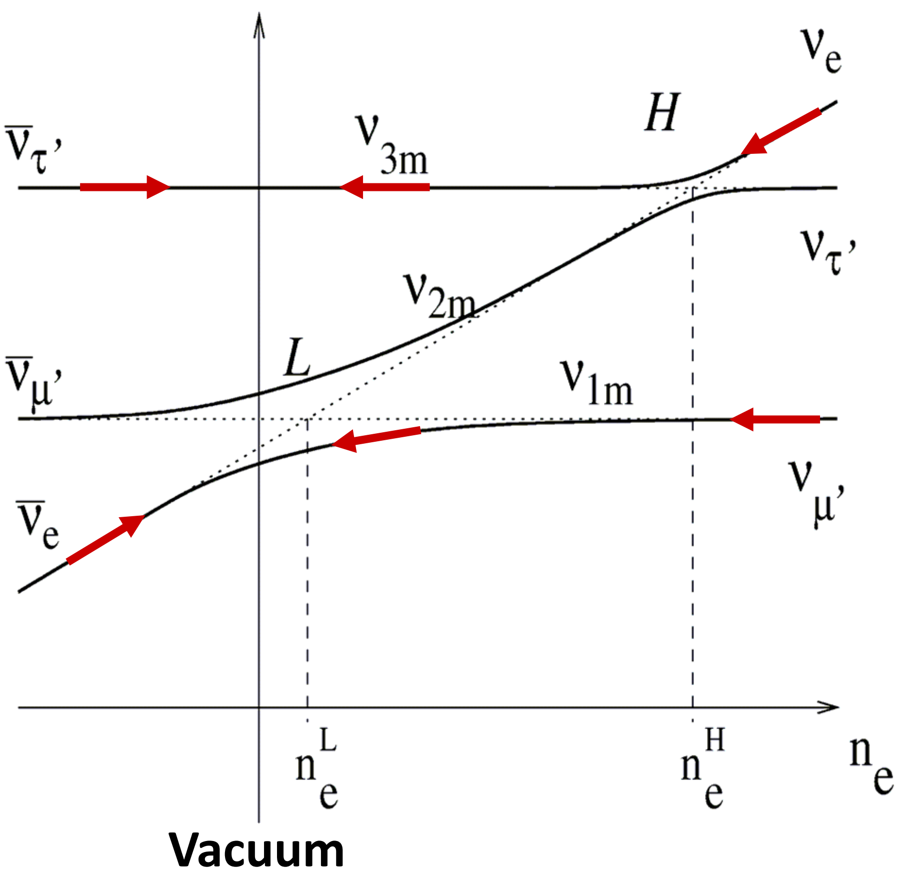
Flavor Oscillations in Core-Collapse Supernovae

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

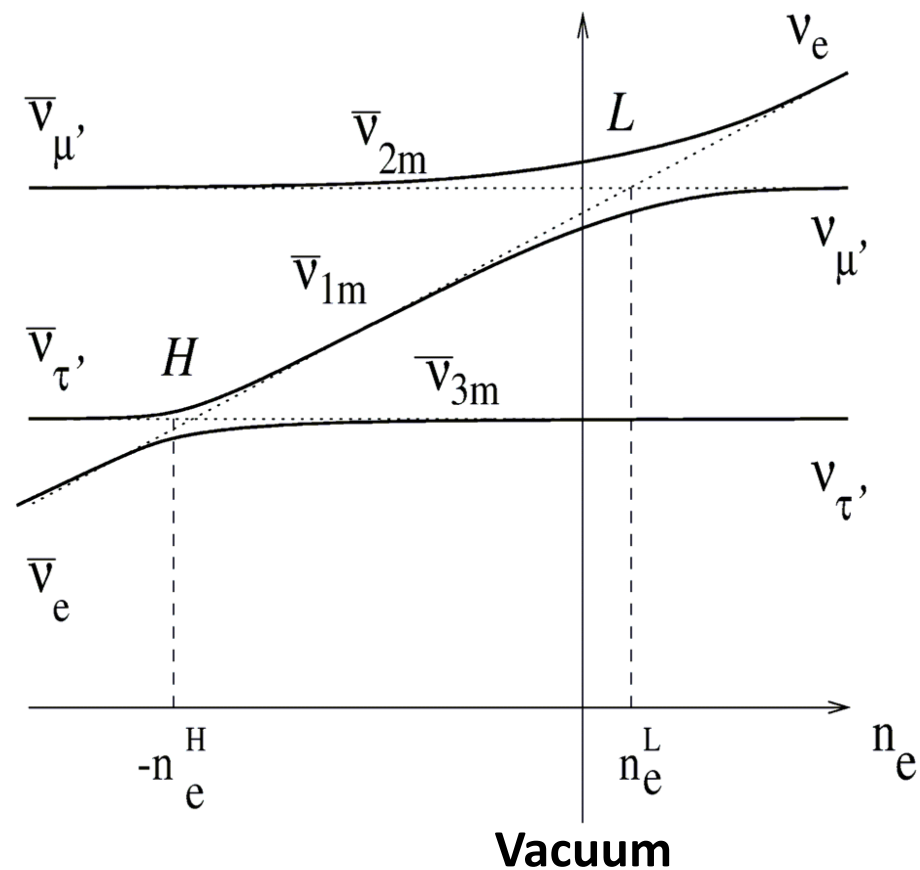


Level-Crossing Diagram in a Supernova Envelope

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 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

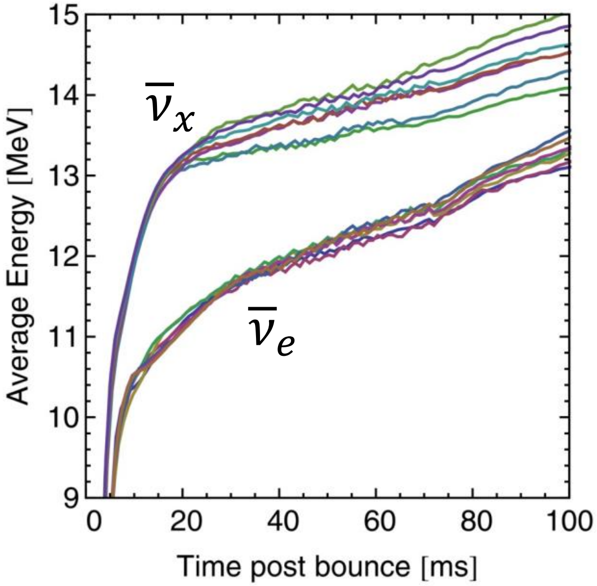
	Mass ordering	
	Normal (NH)	Inverted (IH)
ν_e survival prob.	0	$\sin^2\theta_{12} \approx 0.3$
$\overline{\nu}_e$ survival prob.	$\cos^2\theta_{12} \approx 0.7$	0
$\overline{\nu}_e$ Earth effects	Yes	No

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

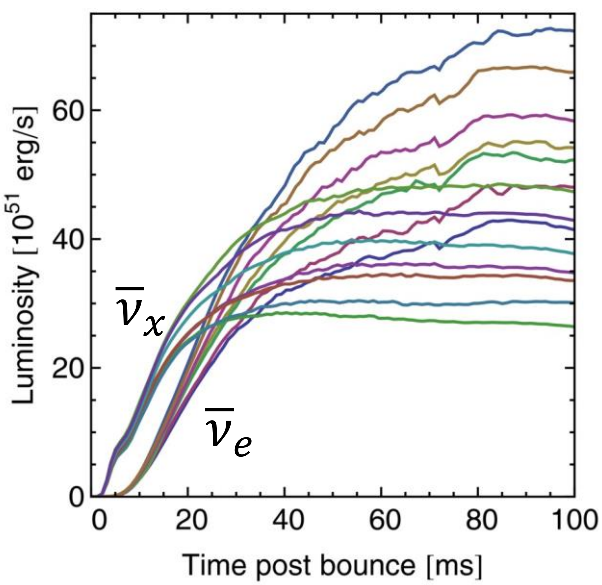
Early-Phase Signal in Anti-Neutrino Sector

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

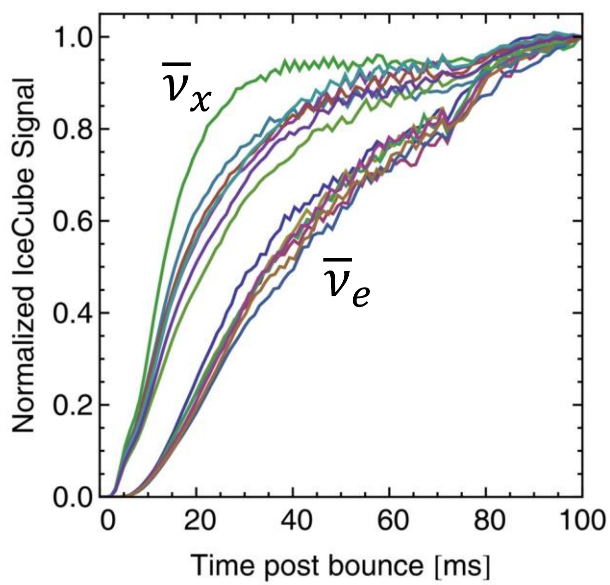
Average Energy



Luminosity



IceCube Signature



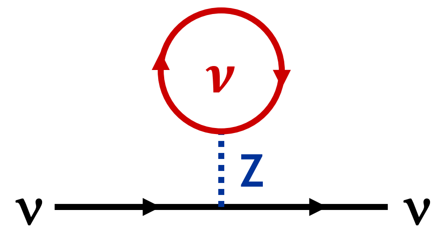
- In principle very sensitive to hierarchy, notably IceCube or HK
- "Standard candle" to be confirmed by other than Garching models

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

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

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

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 $\mathcal{O}(G_{\rm F}^2)$
  Here as coherent refractive effect $\mathcal{O}(G_{\rm F})$

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

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

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

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

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Fast Pairwise Conversion of Supernova Neutrinos: A Dispersion Relation Approach

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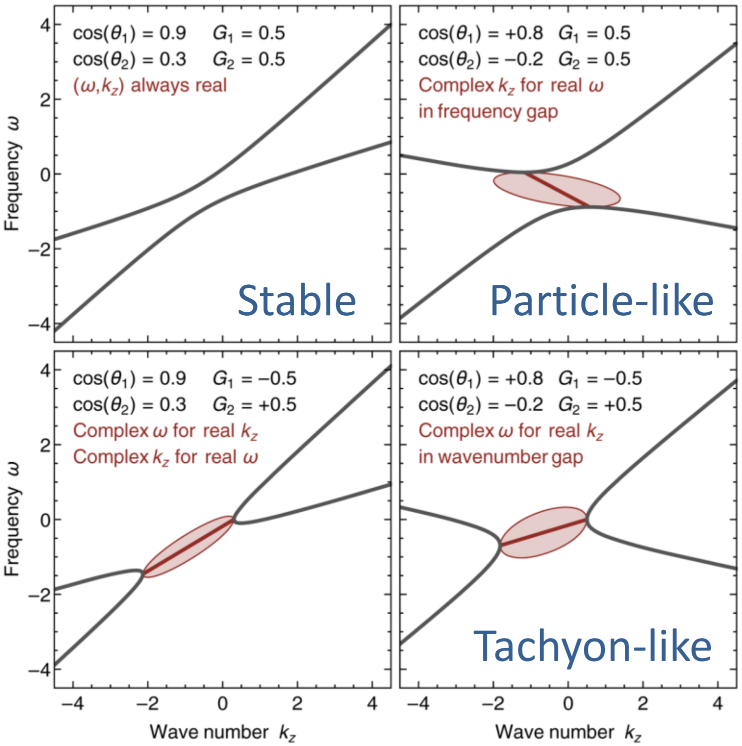
Classification of instabilities of "flavor waves"



Classification of instabilities of plasma waves

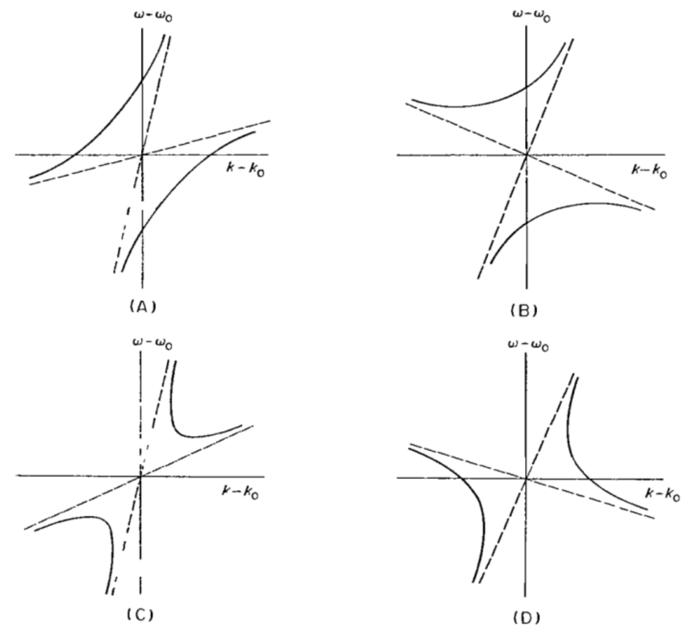
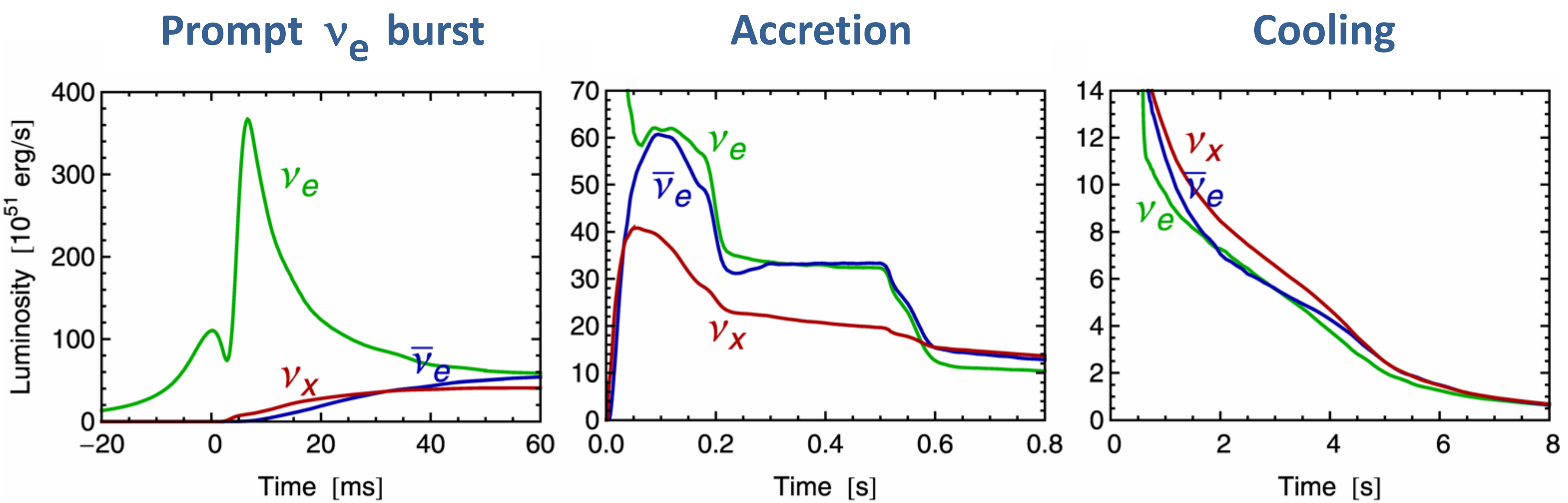


Fig. 23.

Landau & Lifshitz, Vol.10, Physical Kinetics
Chapter VI, Instability Theory

Three Phases – Three Opportunities



"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!