Neutrino Astronomy : The Supernova Story (Lecture 1)

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Indian Institute of Technology Guwahati

2-3, May 2024
Understanding The Universe Through Neutrinos
ICTS-TIFR, Bengaluru.

Neutrino Astronomy

- Spin ½
- **Chargeless**

No bending in magnetic fields ➔ Points back to the source

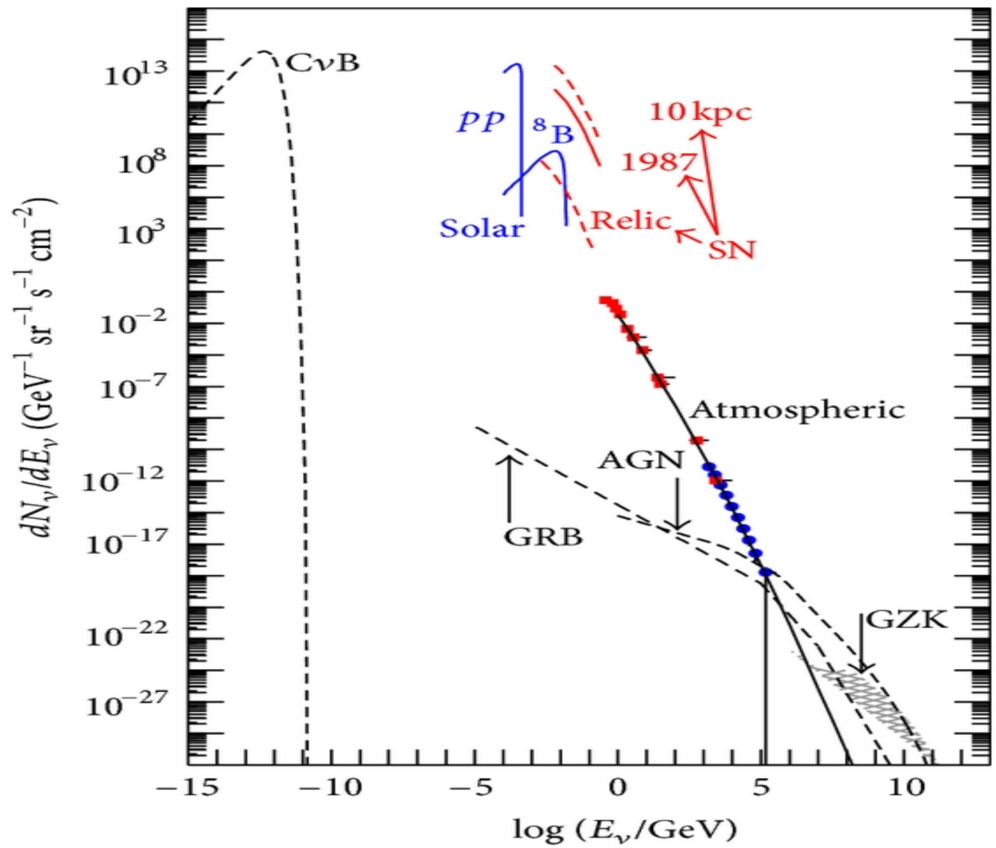
- **Weakly interacting**

Minimal scattering ➔ Arrive from regions opaque to light

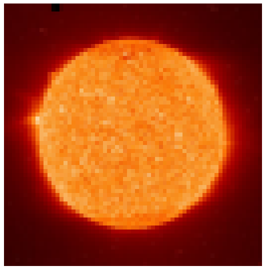
Excellent Astronomical Messenger!!

- Almost massless

Neutrino Oscillations



Neutrino Sources



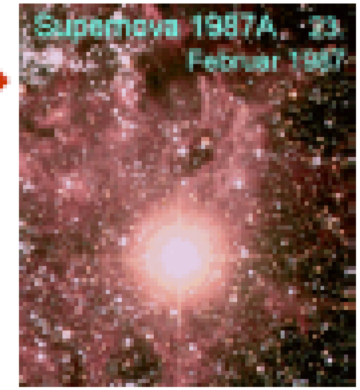
← Sun

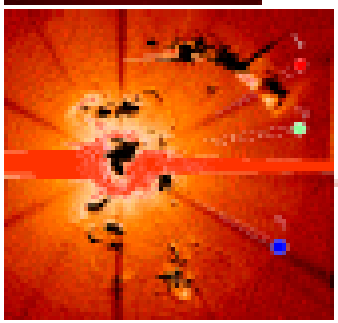
Astronomy: →

Supernovae

GRBs

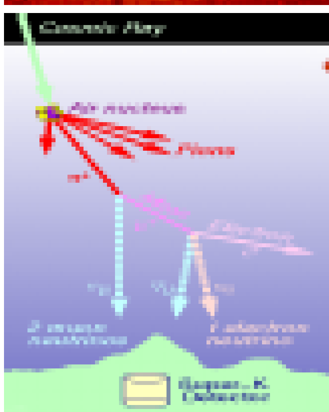
UHE ν's





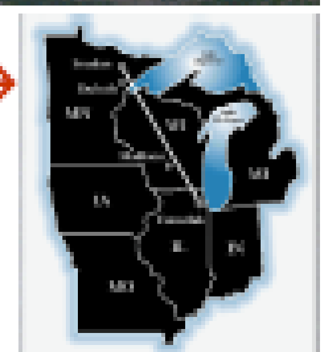
← Cosmology

Reactors →



← Atmosphere

Accelerators →



β-Sources →

← Earth

Supernova Neutrinos: WHAT?

Supernova one of the most energetic events in nature:

Terminal phase of a massive star ($M > 8\sim10\ M_{\odot}$), collapses & ejects the outer mantle in a shock wave driven explosion.

Energy & Time Scale:

99% energy (10^{53} ergs) is emitted by neutrinos (Energy ~ 10 MeV) in ~10 s

Supernova Neutrinos: WHY?

SN Explosion: the most powerful neutrino source (10^{57}/10 sec) in the Universe

Neutrino detection : (L1 & L3)

High-statistics of events (10^5-10^6 event/10 sec) for galactic SN

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Neutrino theory/phenomenology : (L2)

Neutrino Oscillations in extreme astrophysical environment.

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Neutrino astrophysics : (L1)

Crucial role of neutrino in the explosion mechanism.

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Neutrino astrophysics : (L1)

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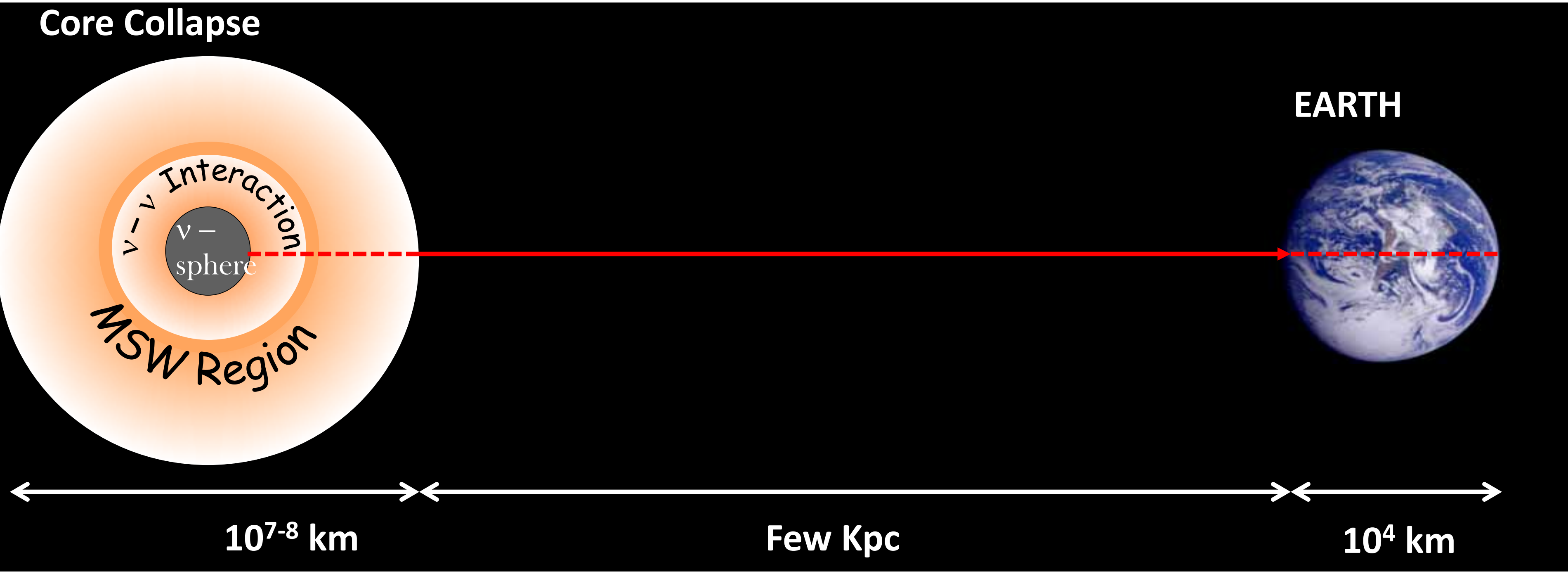
Neutrino nuclear astrophysics :

Nucleosynthesis in supernovae is a neutrino-driven process

Supernova Neutrinos: HOW?

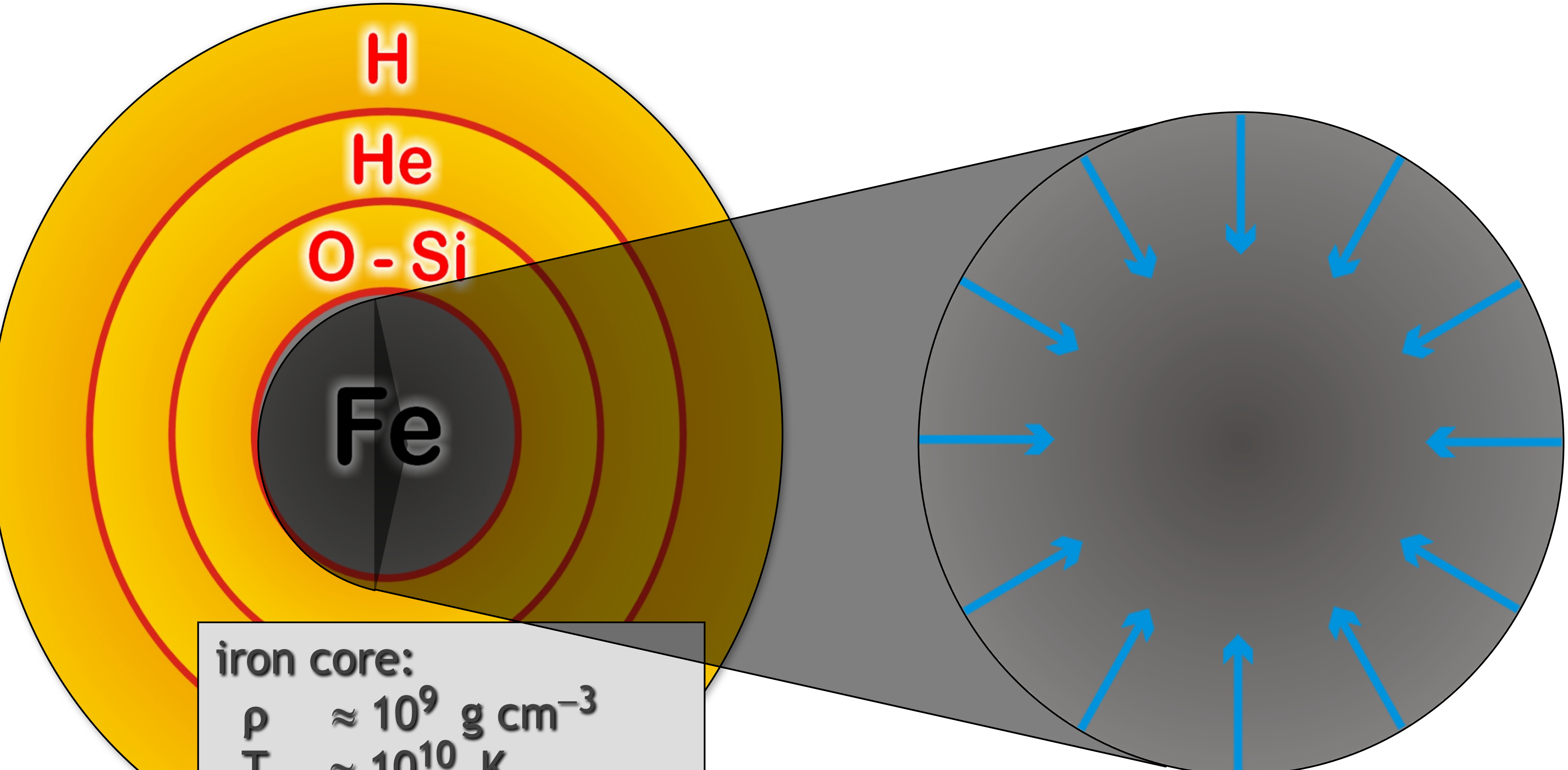


Production	Propagation	Detection
• Simulation of SN Explosion	• Dense Neutrino Background	• Different detectors
• Intial energy spectra	• Dense matter effect	• Different interection channels
• Initial time spectra	• Shock wave, Earth effect	• Final energy spectra
• Initial Angular spectra	• New interactions	• Final time spectra

Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



iron core:

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

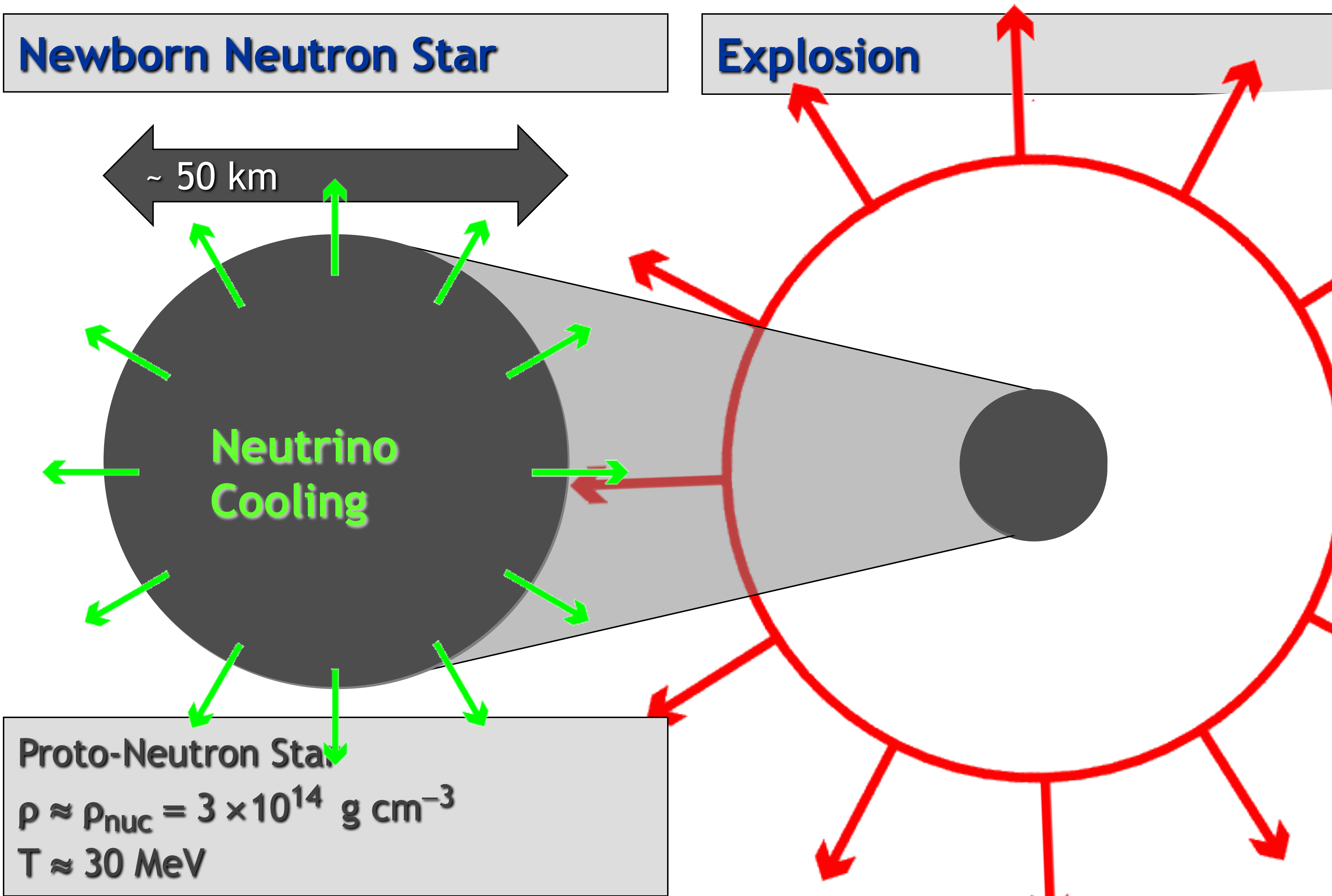
$T \approx 10^{10}$ K

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

$R_{Fe} \approx 8000$ km

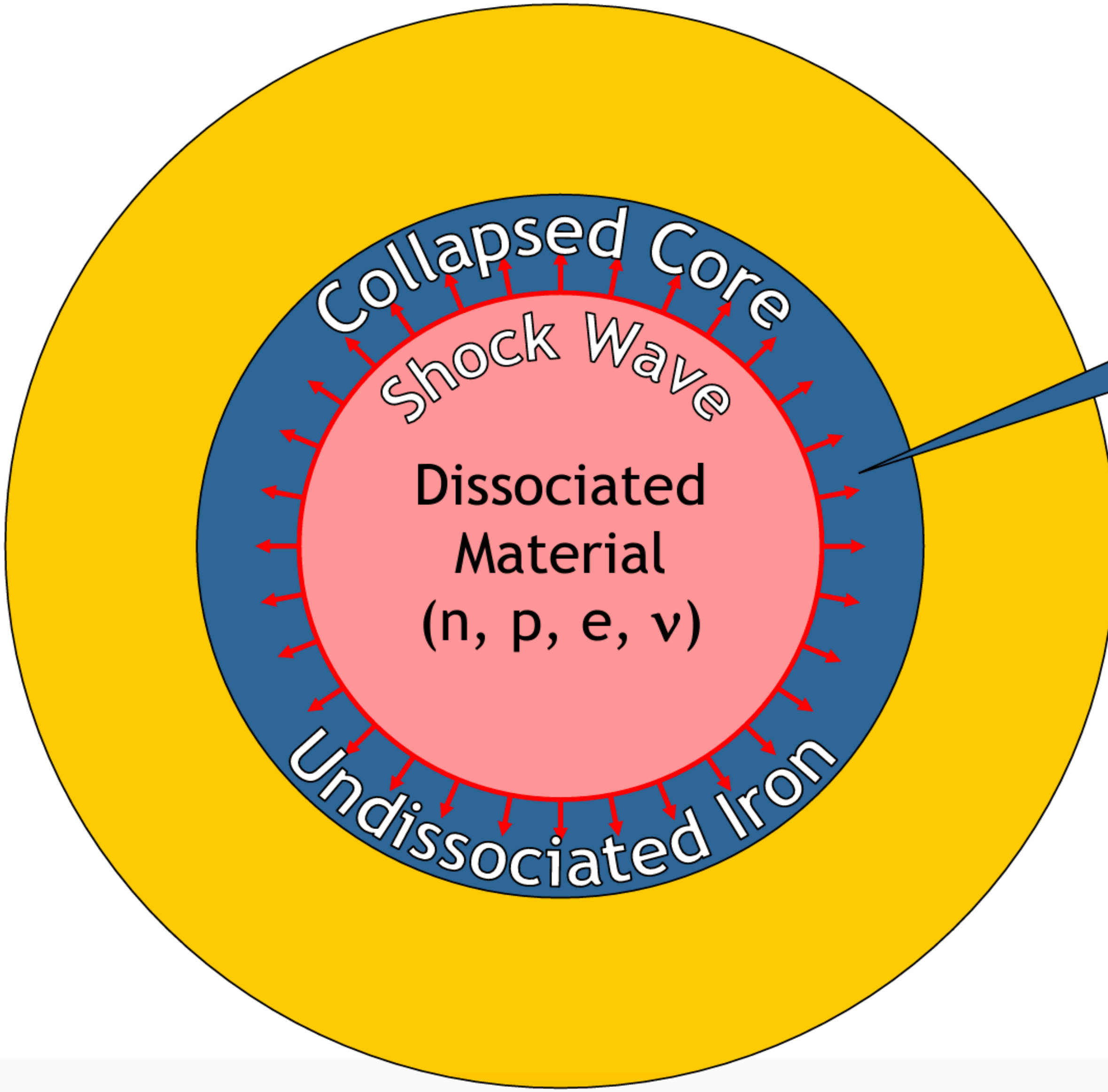
[slides from G. Raffelt]

Stellar Collapse and Supernova Explosion



Problems in SN explosion simulations

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**

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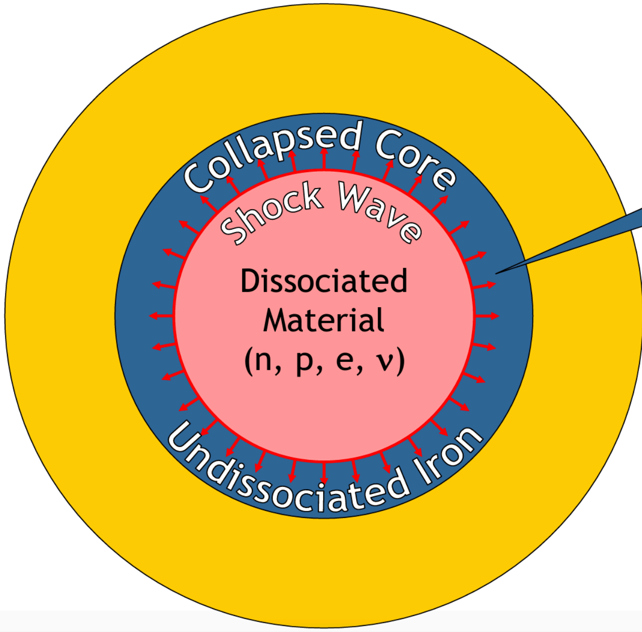

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Slide from G.Raffelt

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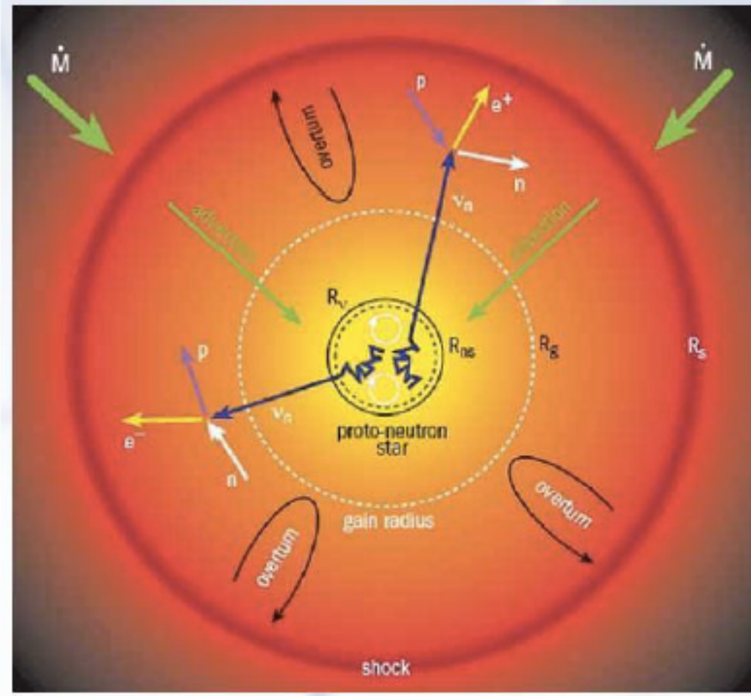

"Neutrino-heating mechanism": Neutrinos revive stalled shock by energy deposition

[Colgate & White, 1966, Wilson, 1982, Bethe & Wilson, 1985]

Convective processes & hydrodynamic instabilities enhance the heating mechanism

[Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08]

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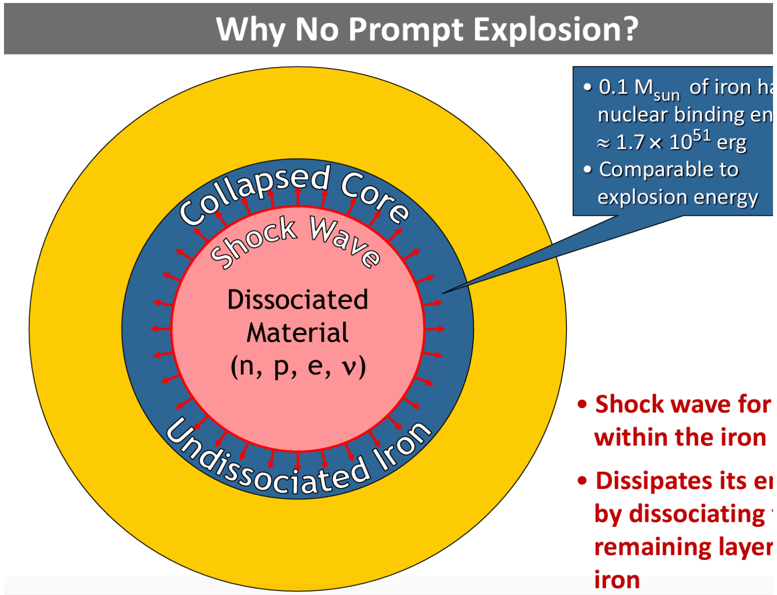

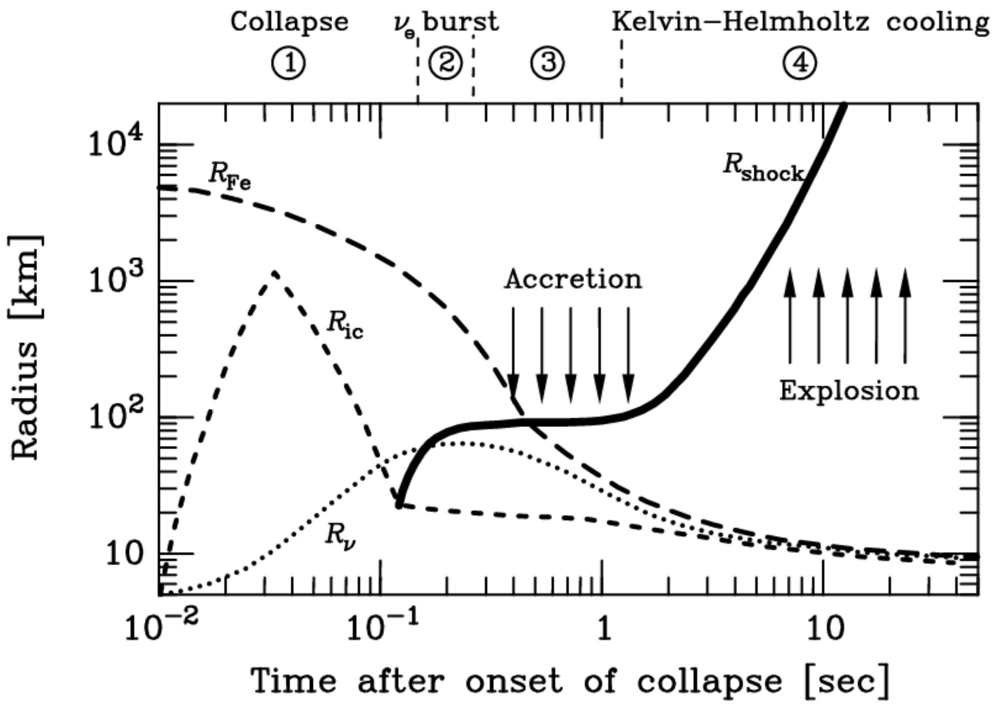

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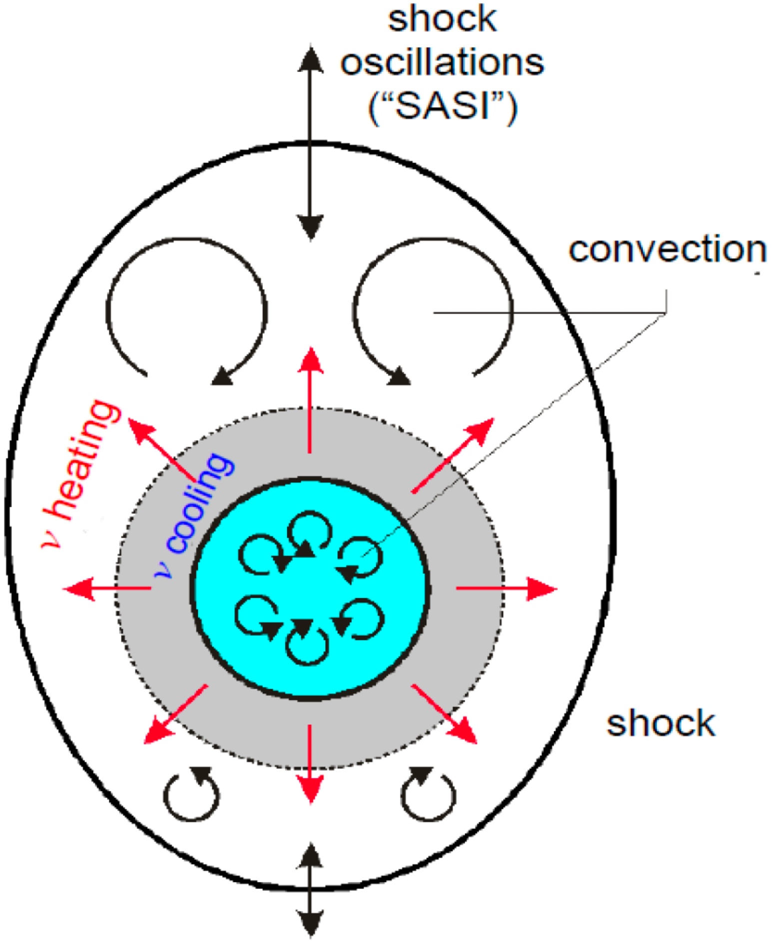
Neutrino-Driven Supernovae

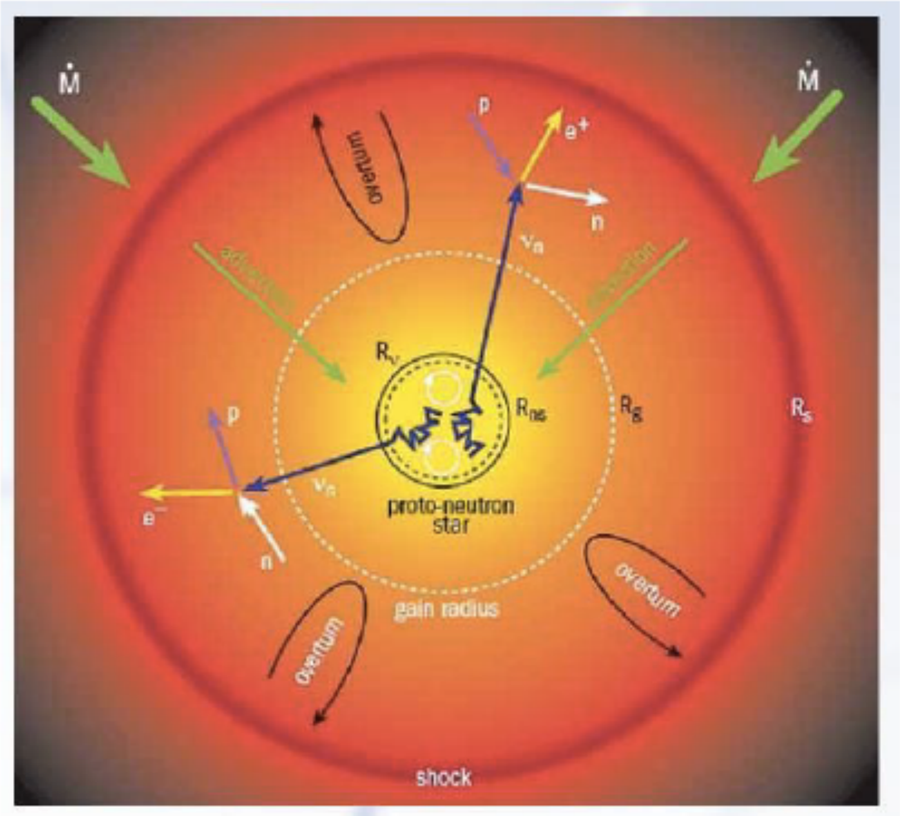
- Stalled accretion shock still pushed outward to ~150km as matter piles up on the PNS, then recedes again
- *Heating* or *gain* region develops some tens of ms after bounce
- Convective overturn & shock oscillations “SASI” enhance the efficiency of ν-heating, which finally revives the shock
- **Big challenge: Show that this works!**

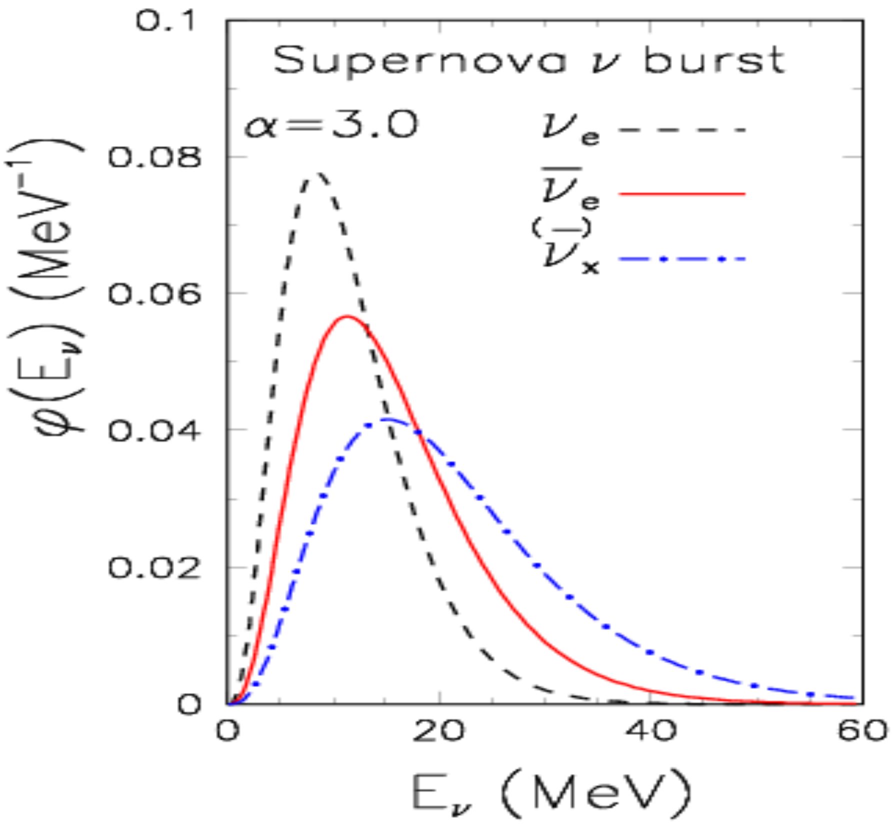


Slide by B. Müller

Problems in SN explosion simulations

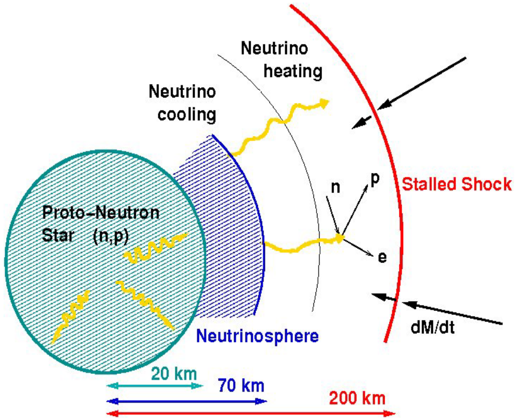
Neutrino oscillation can influence the energy deposition due to different heating efficiency of the different **Flavors**





PROBLEMS IN SN EXPLOSION SIMULATIONS

- Small mass stars: successful explosion
  even with spherical symmetry
- Shock looses energy :
  Failed SN for >$10M_{SUN}$



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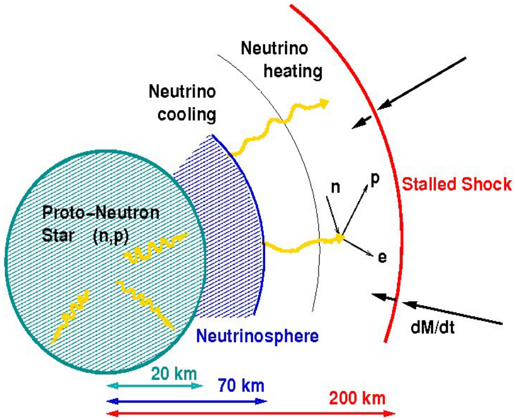
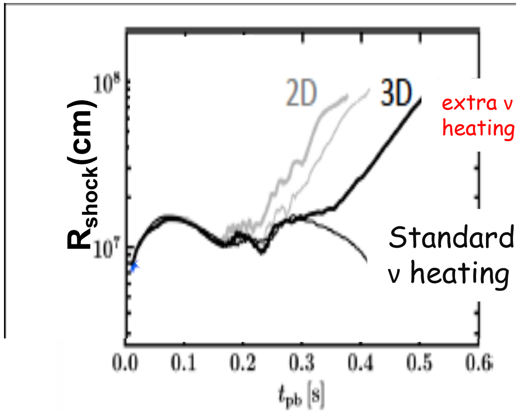


- Numerical explosions ok for broad mass range in 2D **(axial symmetry)**
- In 3D, mostly failed simulation



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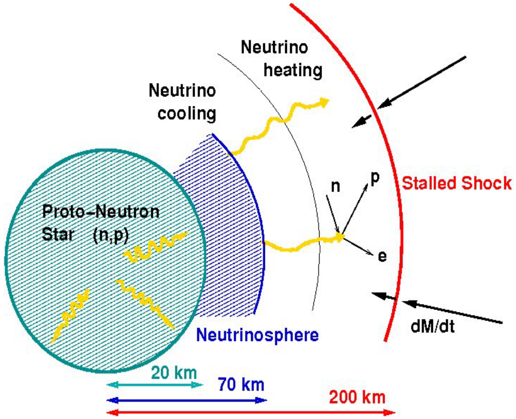

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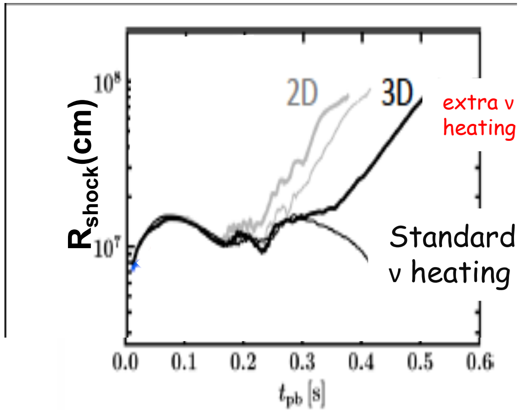
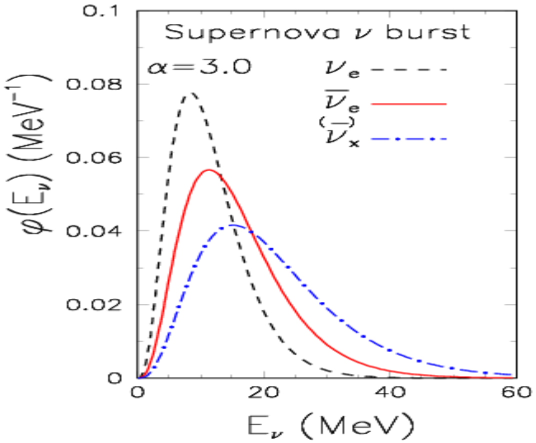


EXTRA Heating???

- Oscillation give harder ν_e and $\bar{\nu}_e$ spectra
- $\bar{\nu}_e$ and ν_e dump energy more efficiently



PROBLEMS IN SN EXPLOSION SIMULATIONS

- Small mass stars: successful explosion even with spherical symmetry
- Shock looses energy : Failed SN
- Failed within few 100 ms

- N road mass ra
- In n

Flavor conversion (few 100 km) behind the stalled shock in few 100 ms

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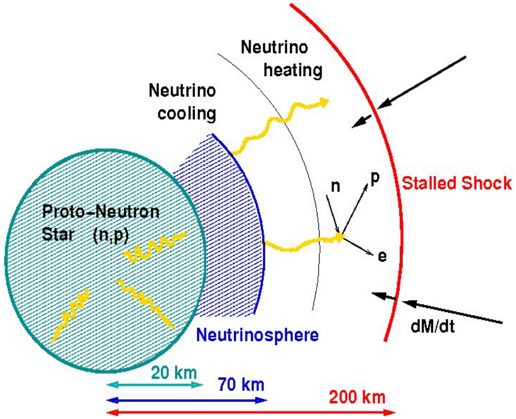
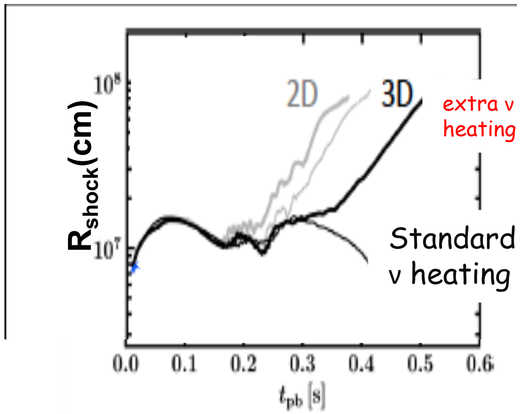
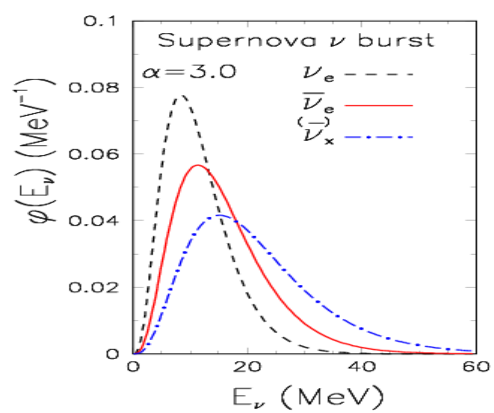
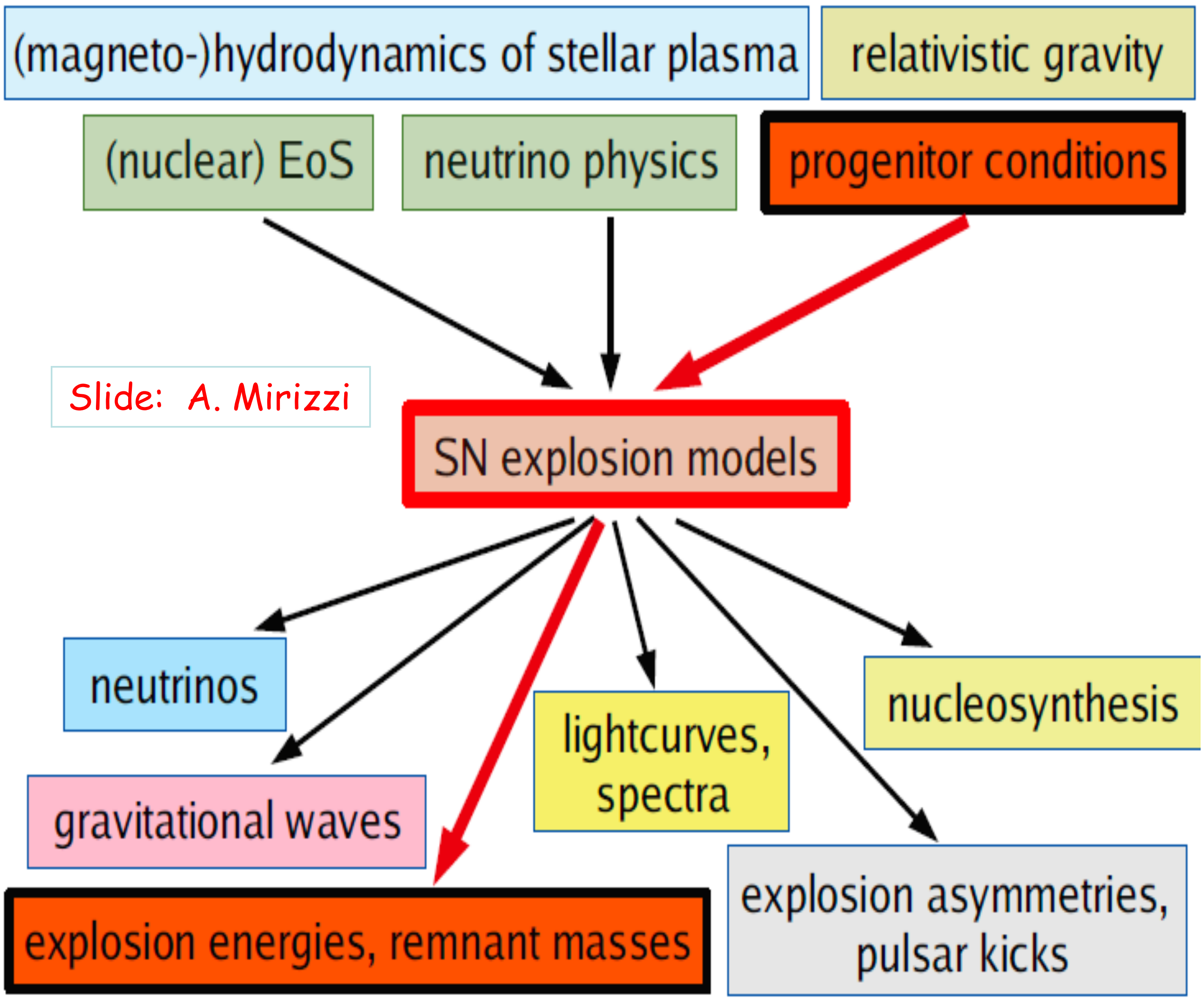






Multi messenger signals from SNe



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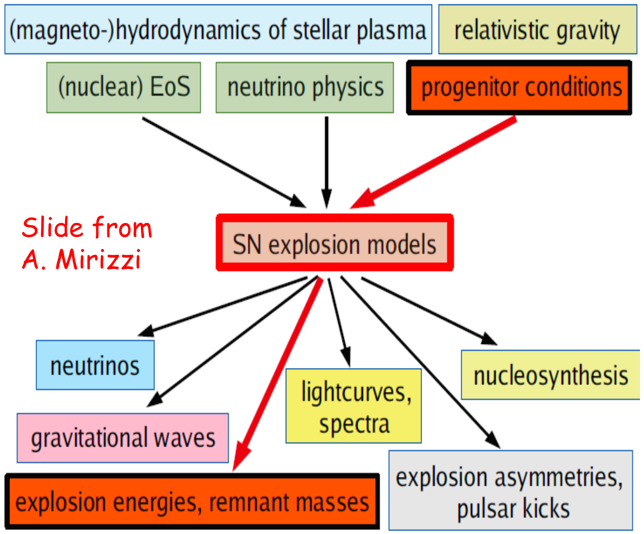
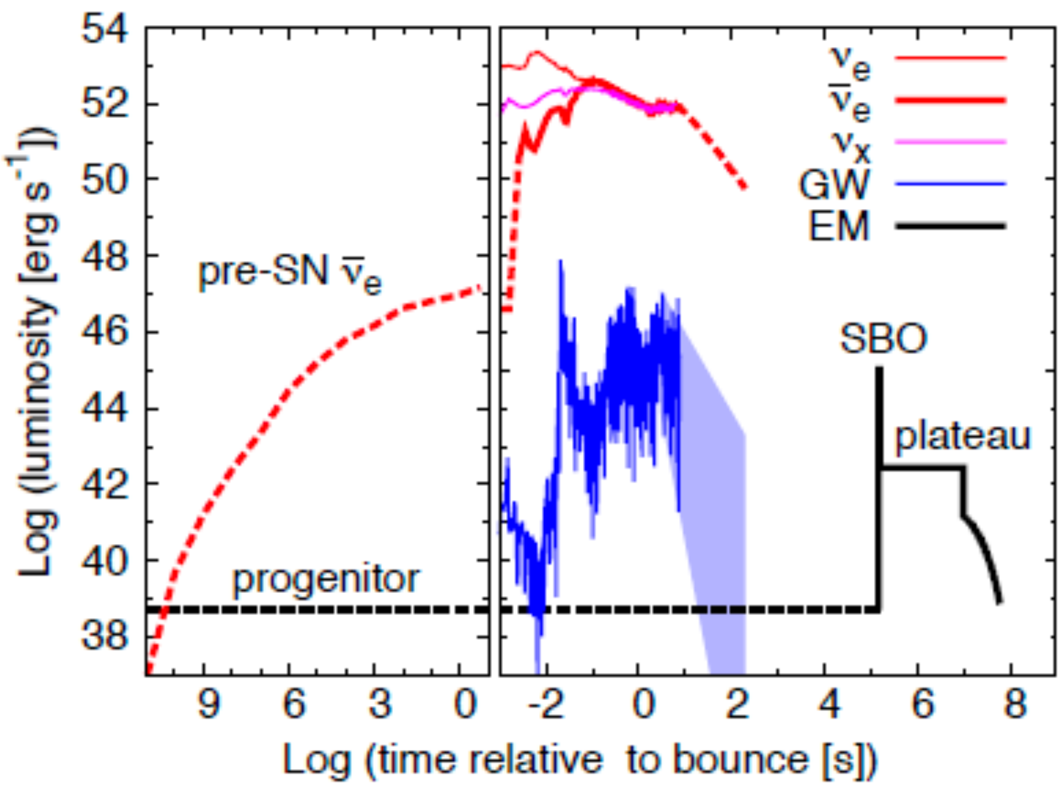
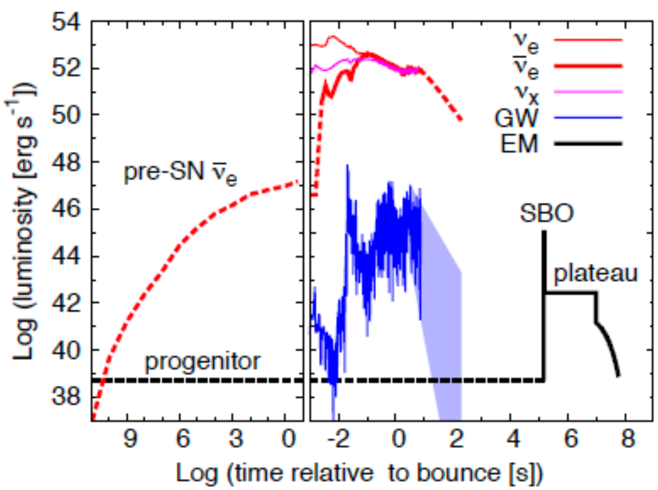
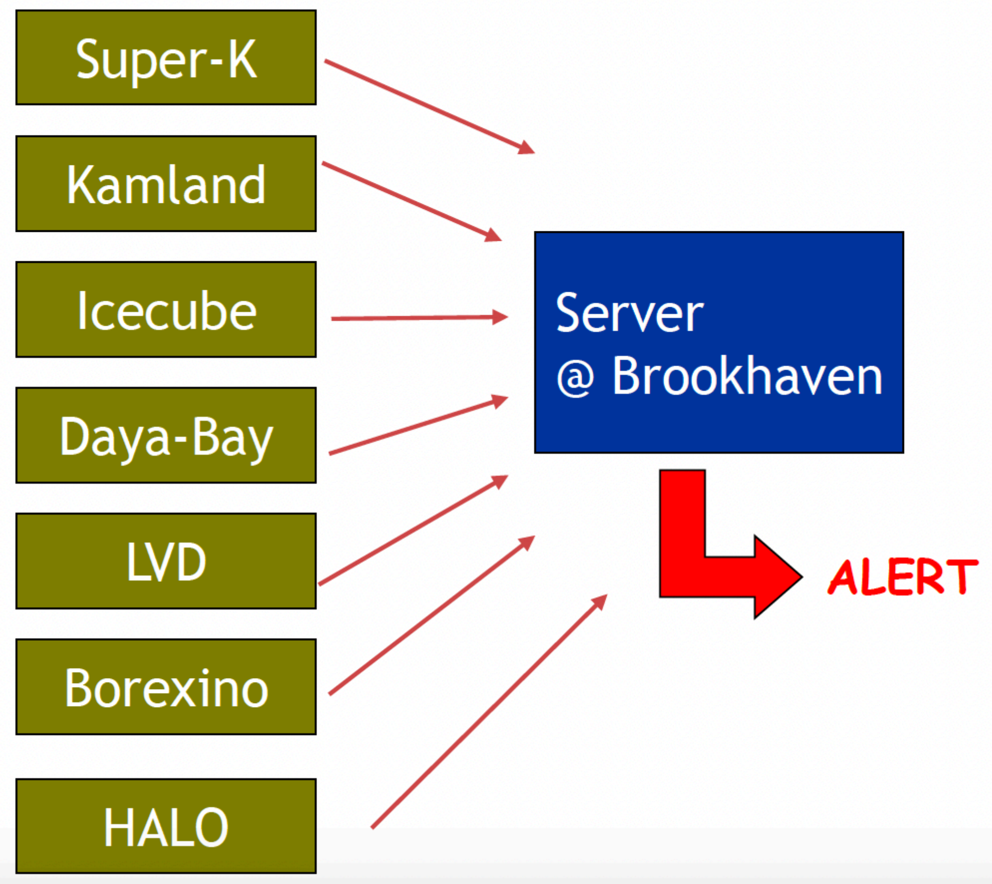


Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki & Kotake, arXiV:1602.03028



Large Detectors for Supernova Neutrinos





- Neutrinos arrive several hours before light: Alert for Astronomers
- GW-neutrino timing correlation: Probing neutrino flight time, Triangulation

Neutrino Emission Phases

Neutronization burst ~ 50 ms

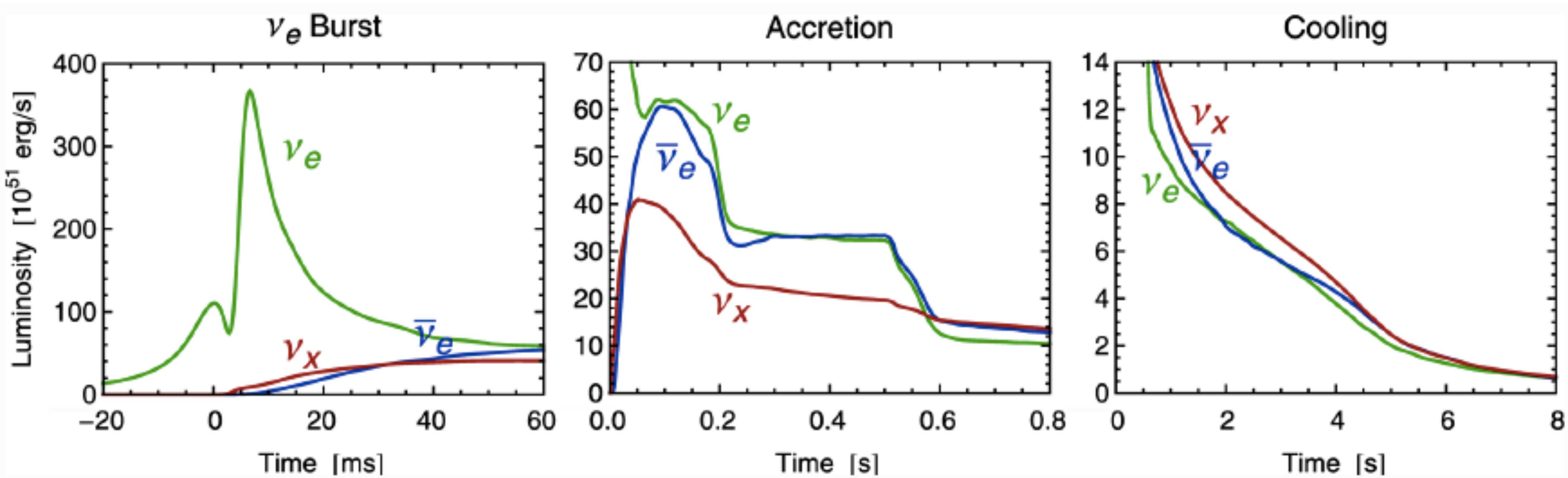
- Shockbreakout
- De-leptonization of outer core layers
- **Electron Capture**

Accretion: ~ 0.5 s

- powered by infalling matter
- Stalled shock
- **Thermal Burst: pair production**

Cooling ~ 10 s

- Cooling by ν diffusion

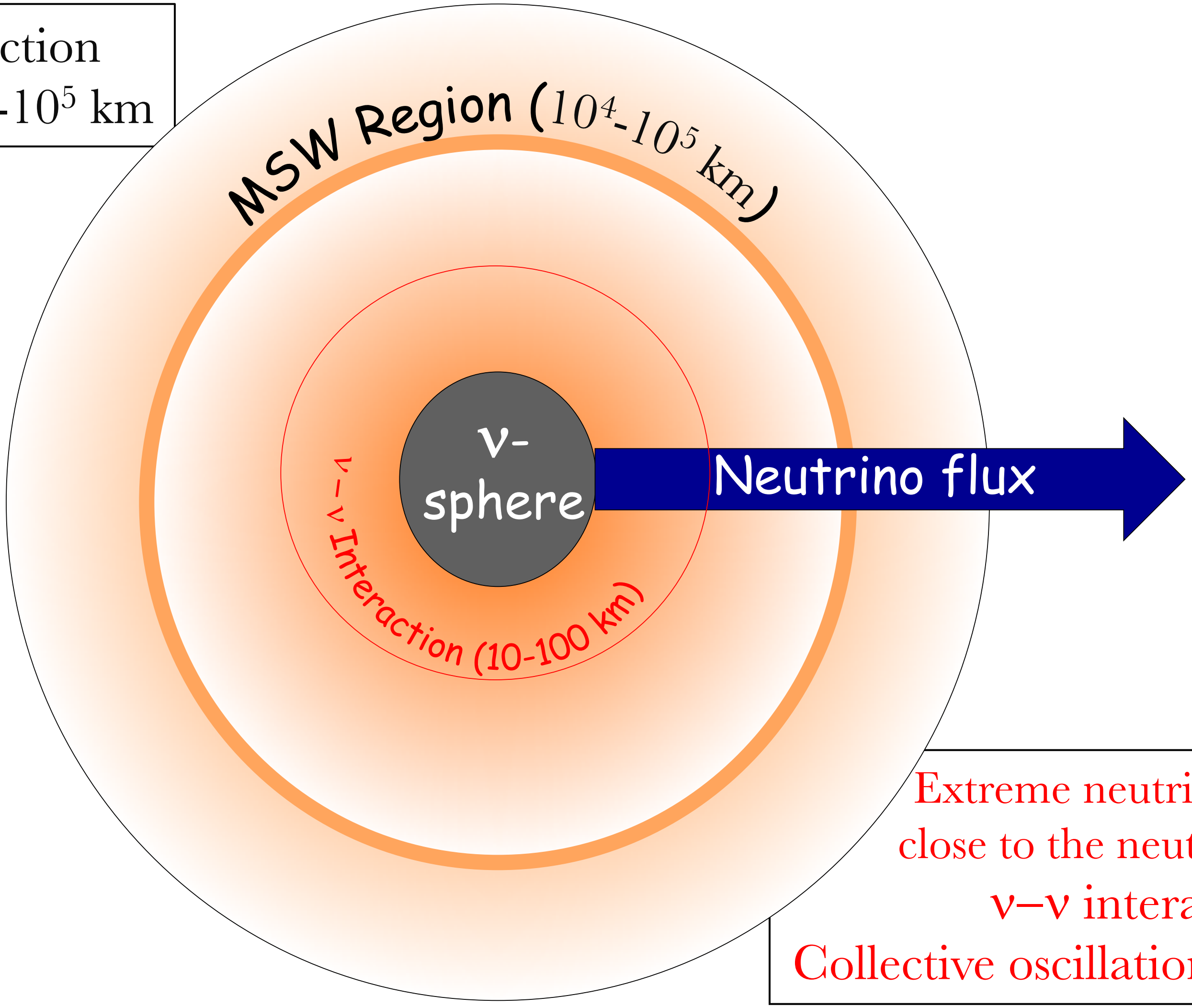


- ν_e Burst and Accretion: Best phase to study oscillation.
- Cooling: Oscillation effects are negligible.
- Accretion: How to rejuvenate the stalled shock?

[Fischer et al. (Basel Simulations), A&A, 2010, 10. 8 M_{sun} progenitor mass]

SN ν Flavor Transitions: Collective Oscillation

ν–e⁻ interaction
MSW ~ 10^4-10^5 km



Extreme neutrino density
close to the neutrino-sphere
ν–ν interaction
Collective oscillation~ 10^1 - 10^2 km

- Flavor Oscillation: In far separated regions, can be treated independently

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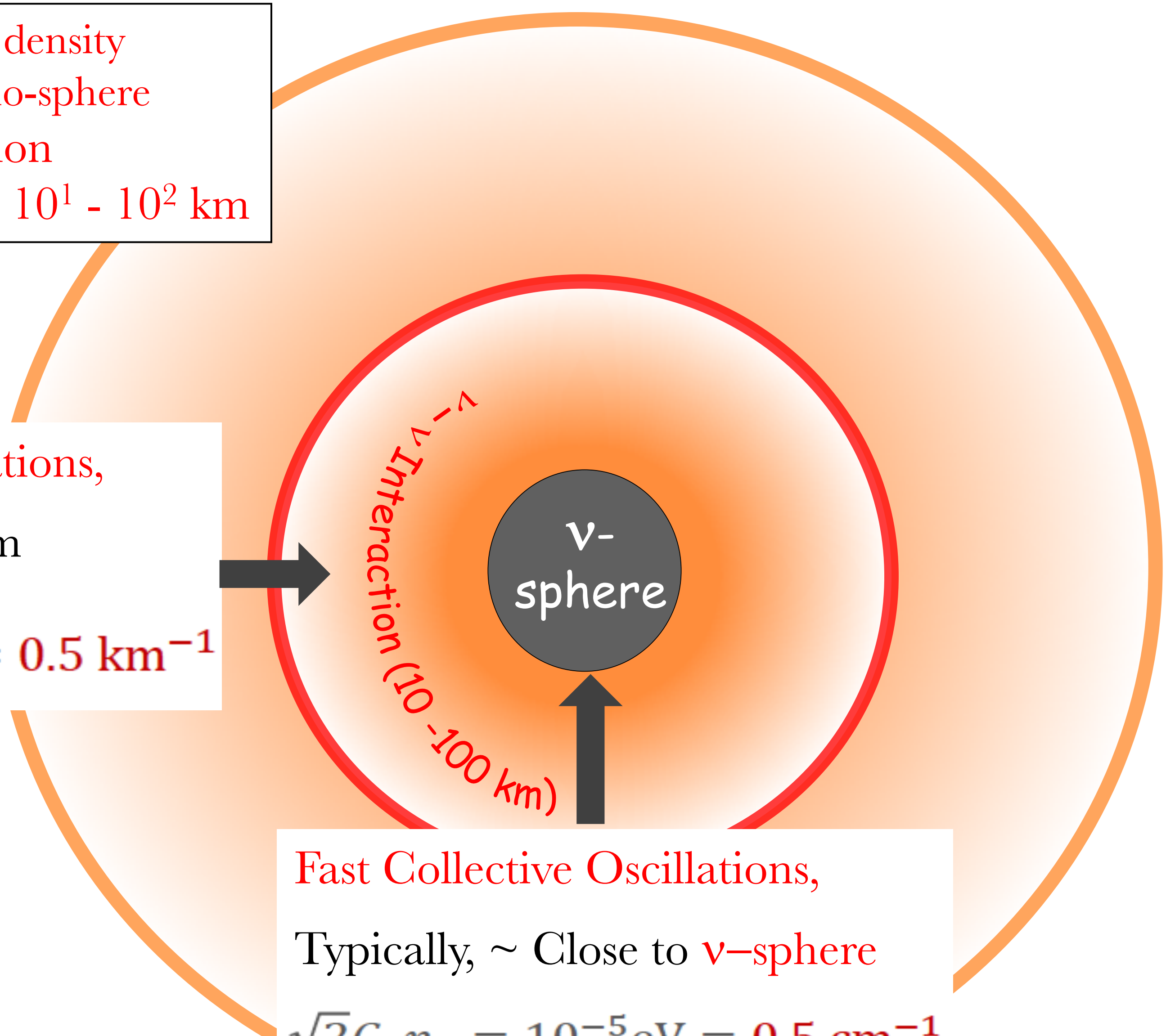


Slow Collective Oscillations,

Typically, ~ few 100 km

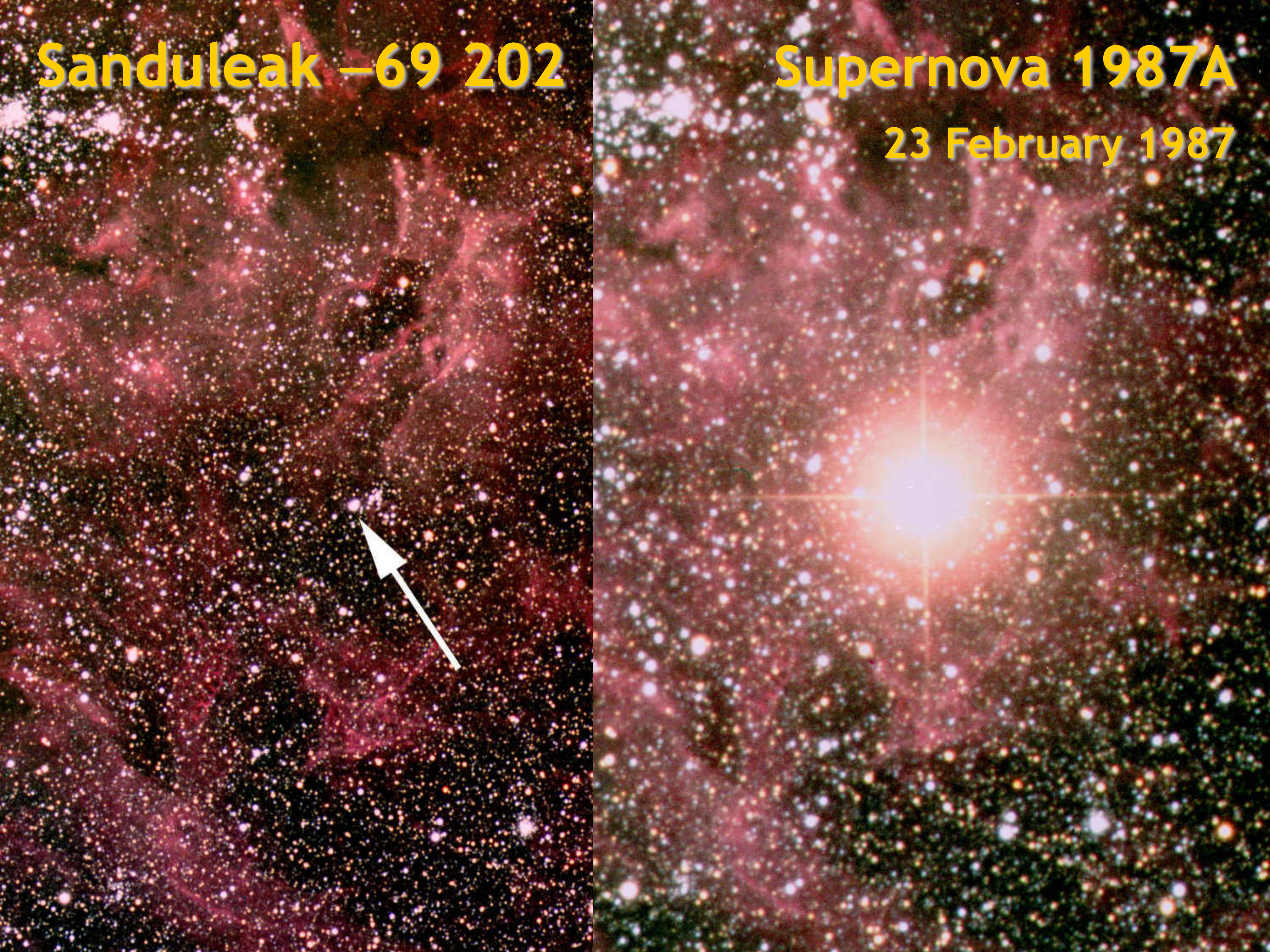
$$\frac{\Delta m^2_{\rm atm}}{2E} = 10^{-10}\,{\rm eV} = 0.5\ {\rm km}^{-1}$$

Fast Collective Oscillations,

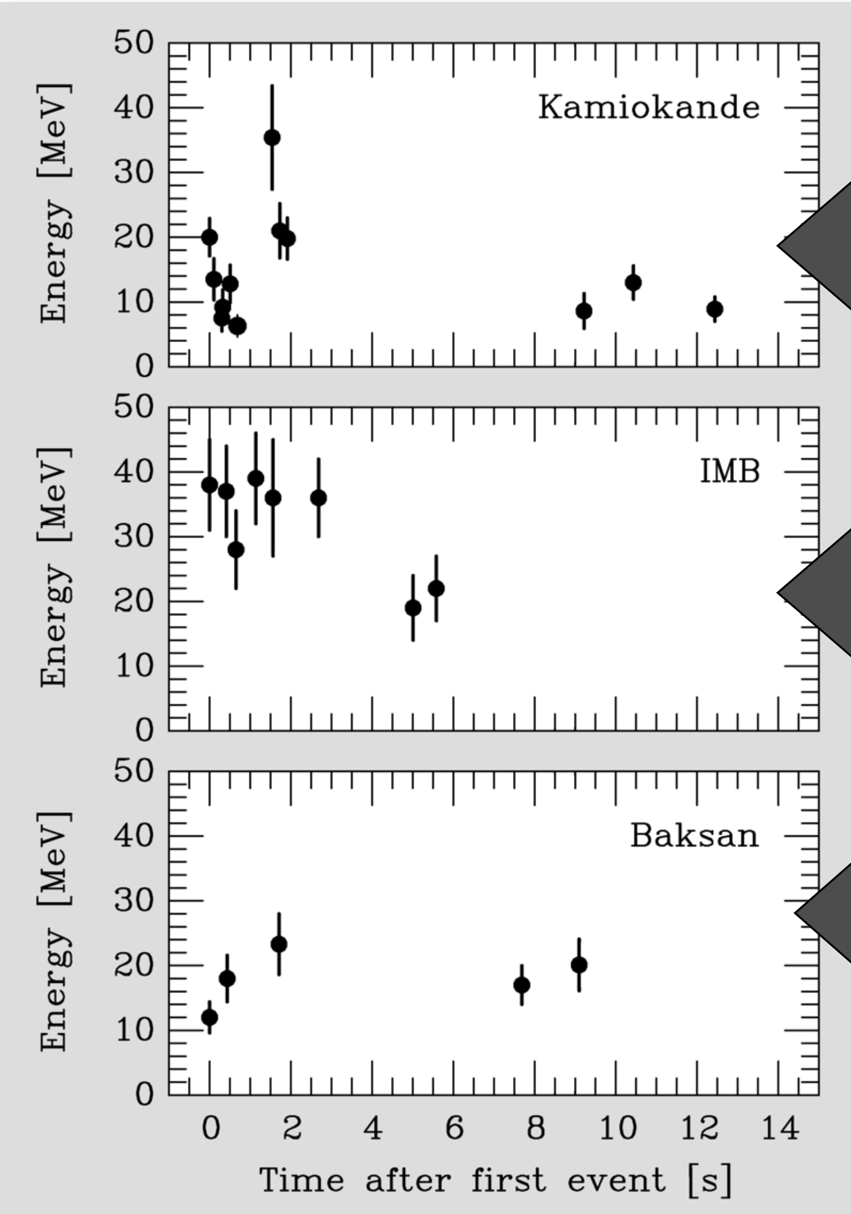
Typically, ~ Close to ν–sphere

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

S.C, Hansen, Izaguirre & Raffelt,
JCAP 2016


Sanduleak −69 202
Supernova 1987A
23 February 1987

…but about two hours before:



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

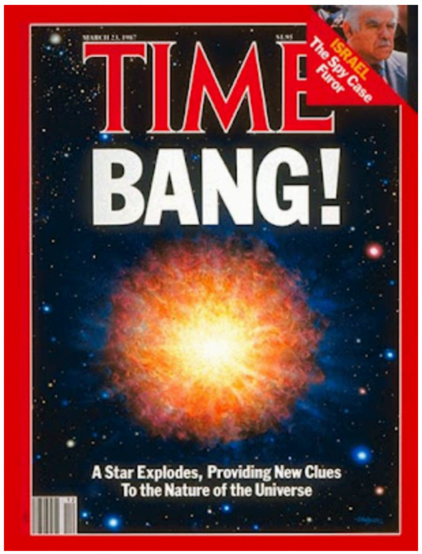
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

The core collapse and ν cooling mechanism confirmed!

Neutrino Burst Observation : First verification of stellar evolution mechanism

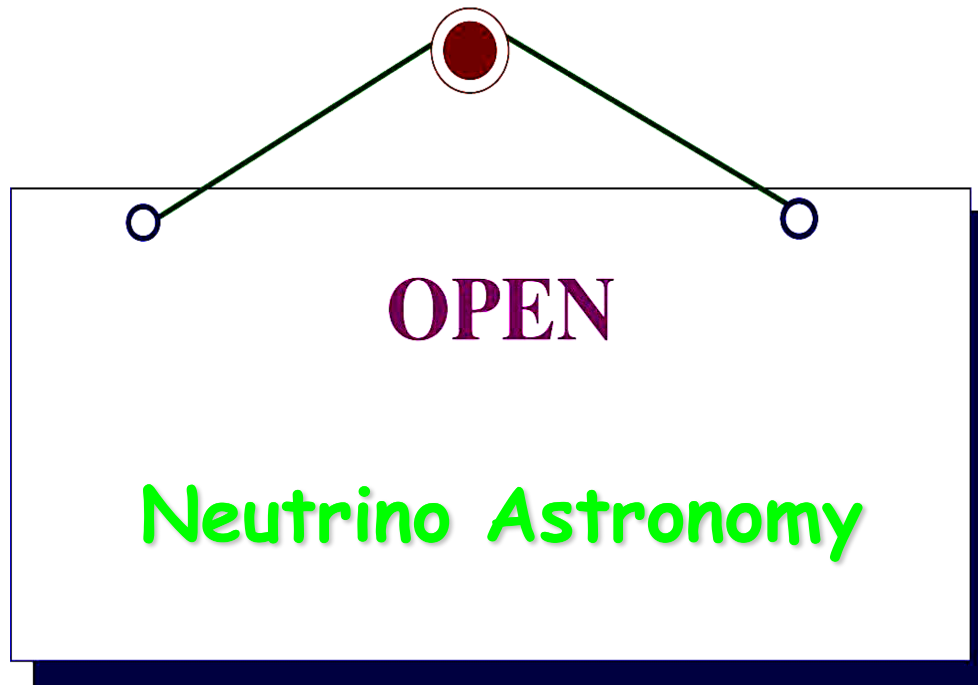
Friday, February 23, 2007

Supernova 1987A

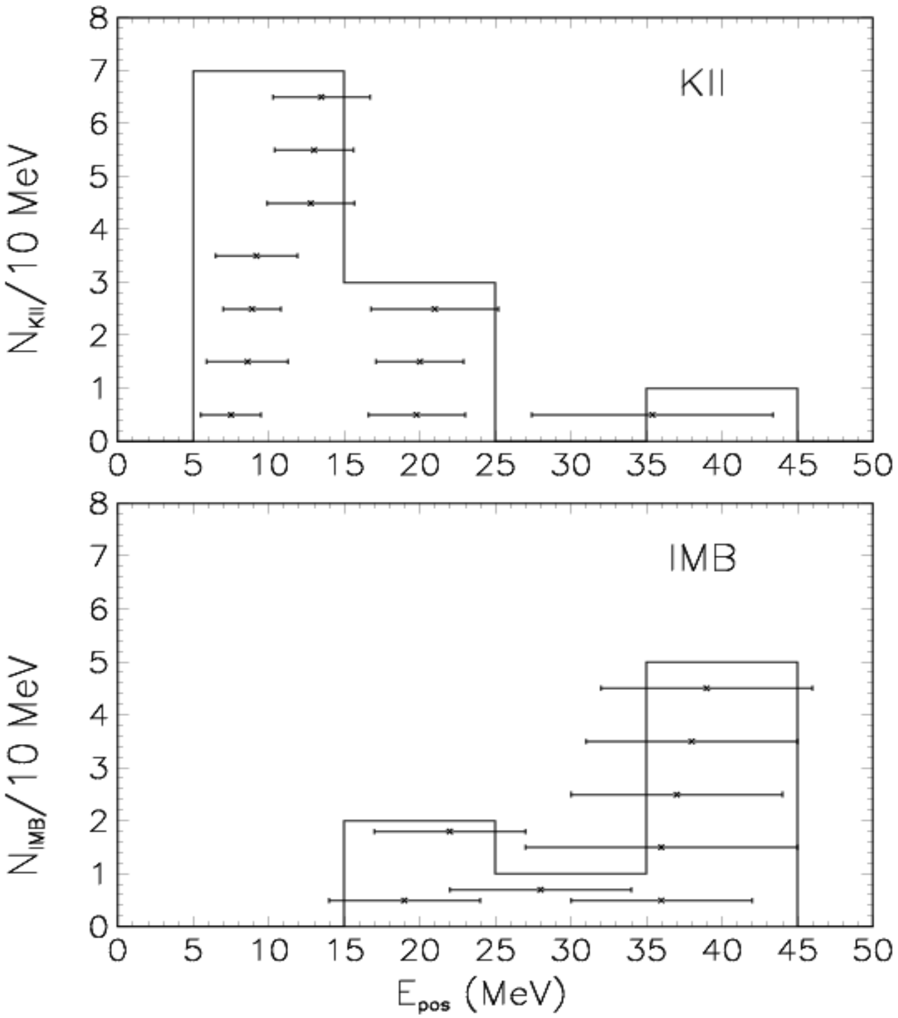


23 February 1987, 7:35 UT	Anomalously high neutrino counting rates observed in the Kamiokande, IMB, and Baksan neutrino detectors
23 February 1987, 10:30 UT	Robert McNaught photographs the Large Magellanic Cloud. When he develops the plate, a bright new star shows up.
24 February 1987, 5:30 UT	Astronomer Ian Shelton at the Las Campanas Observatory, Chile, sees with his naked eyes a new star in the Large Magellanic Cloud.

html



Energy Distribution of SN 1987A Neutrinos



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons

Irvine-Michigan-Brookhaven (US)
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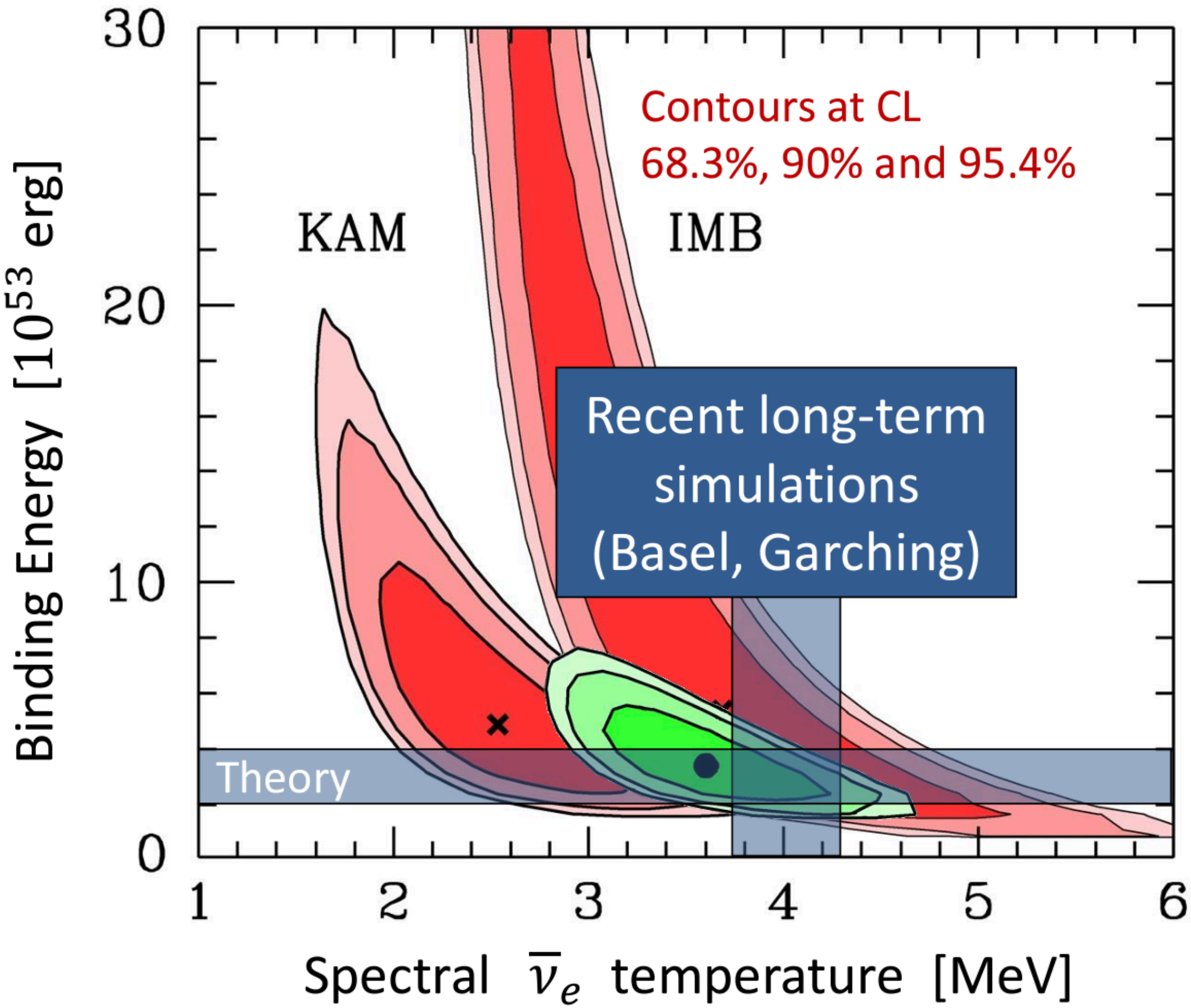
Interpreting SN1987A neutrinos



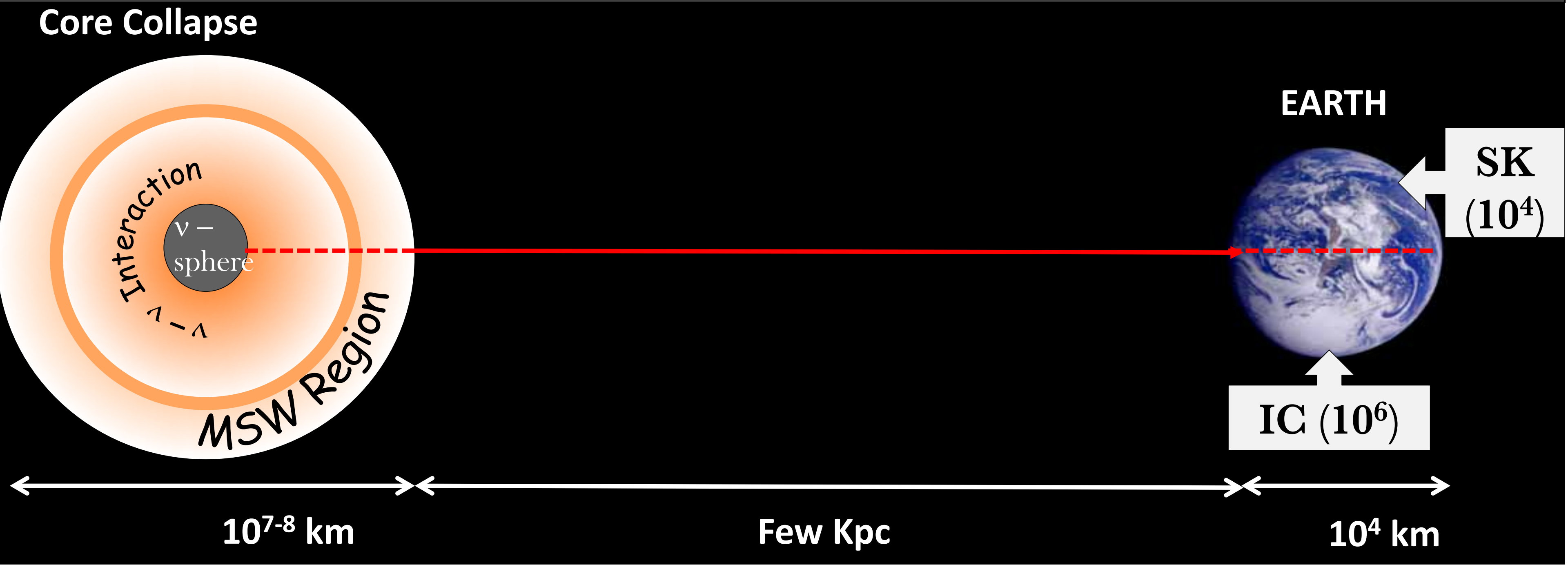
Assume
- Thermal spectra
- Equipartition of energy between $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$

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

Mirizzi and G. Raffelt, PRD **72**, 063001 (2005)

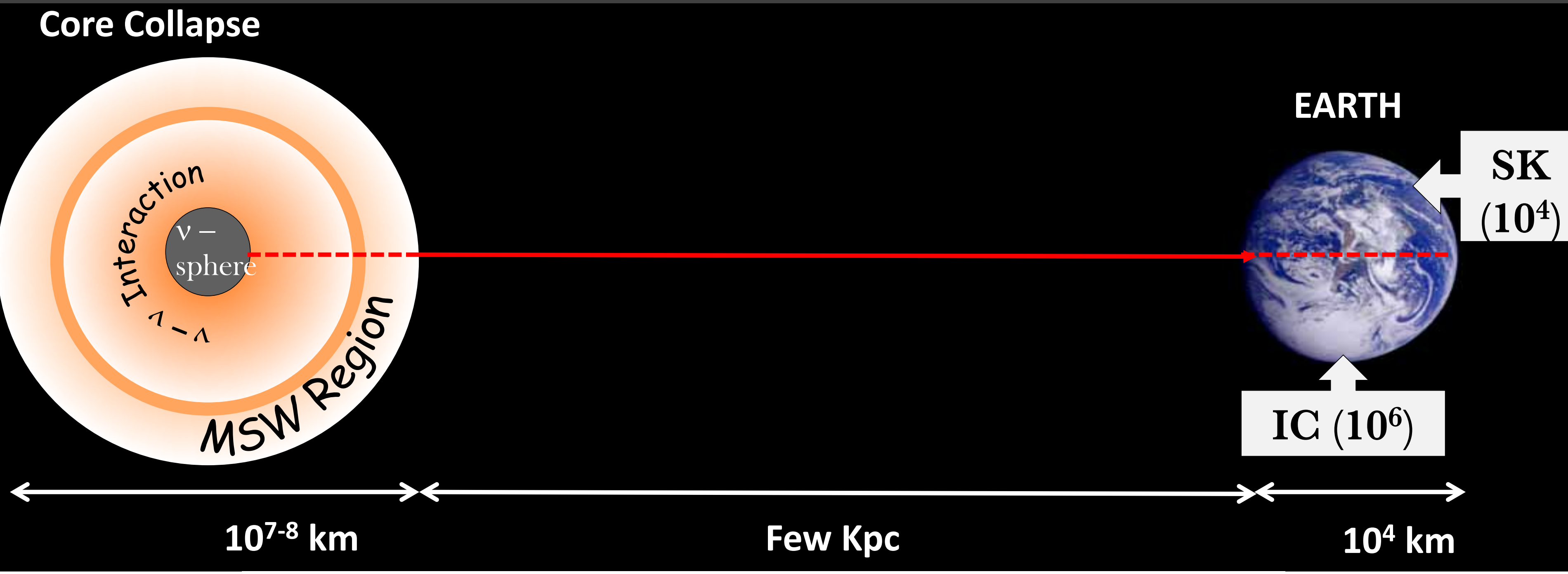

What could we see “tomorrow”?
SN 20XXA !

Typical problems in supernova neutrinos



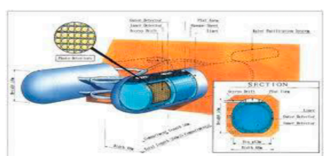
In brackets events for a “fiducial SN” at distance 10 kpc

Typical problems in supernova neutrinos

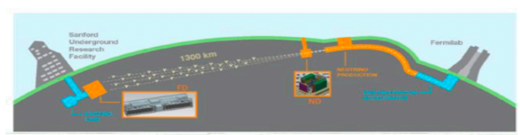


Mton scale water Cherenkov detectors
(10^5 events) ($\bar{\nu}_e$)

HYPER-KAMIOKANDE



40 kton Liquid Argon TPC
(3000 events) (ν_e)

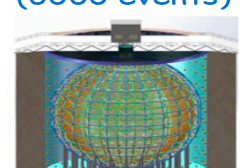


DUNE

Dark matter detectors

DARWIN
40 tons
(700 events)
($\nu_{e,x}, \bar{\nu}_{e,x}$)

20 kton scintillator
(6000 events) ($\bar{\nu}_e$)



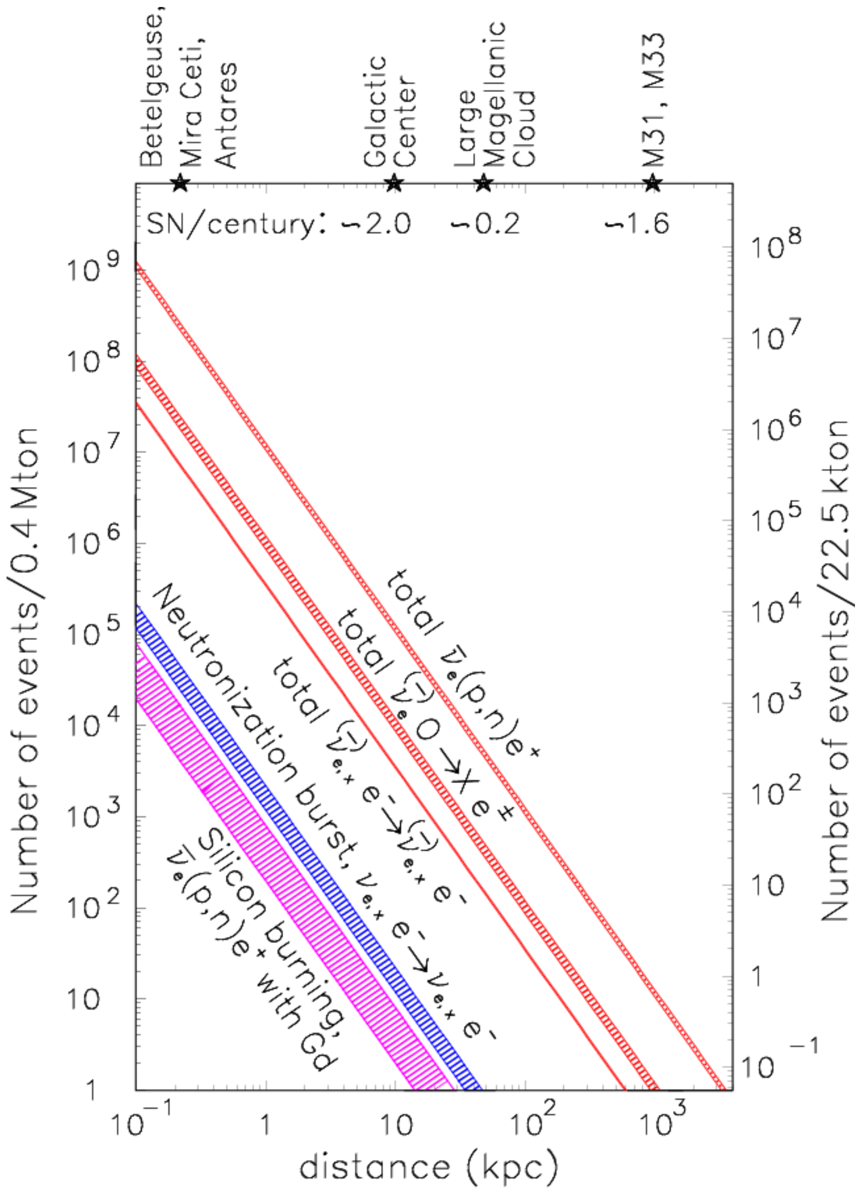
JUNO

Large Detectors for Supernova Neutrinos

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
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

Mirizzi, Tamborra, Janka, Saviano, Scholberg, SC et al., arXiv:1508.00785

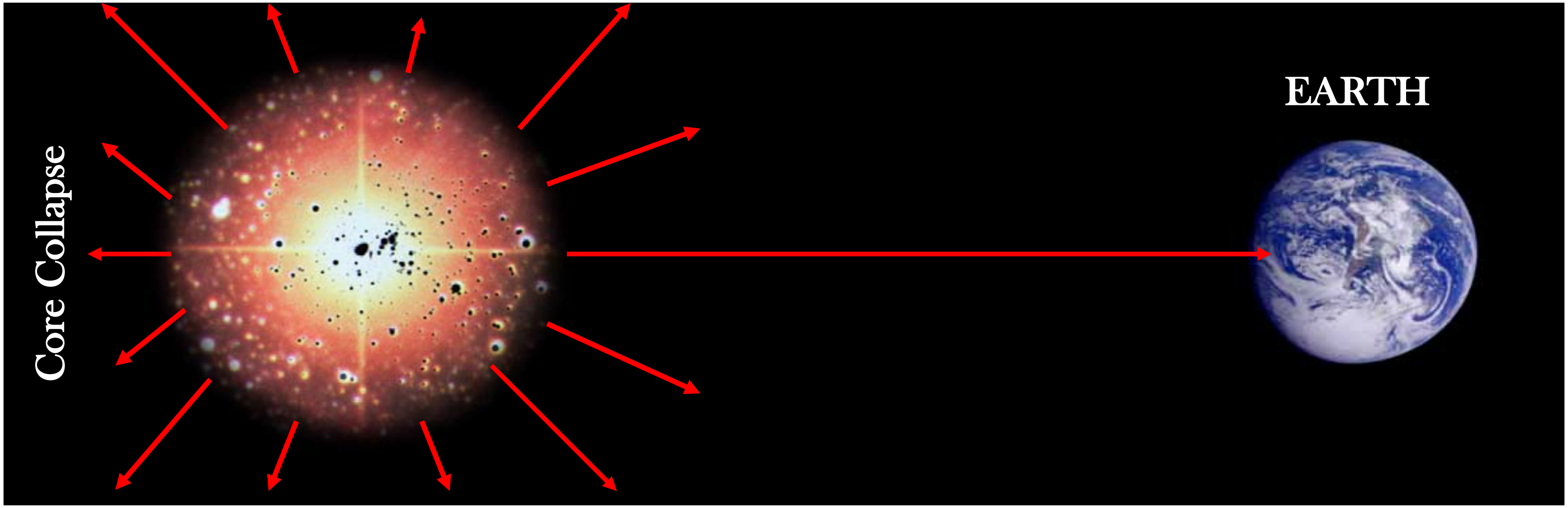
Large Detectors for Supernova Neutrinos



Example of 0.4 Mton WC detector

Mirizzi, Tamborra, Janka, Saviano, Scholberg, SC et al., arXiv:1508.00785

Supernova neutrino signal at detectors



SN neutrinos arrive several hours before photons: Alert Astronomers

http://snews.bnl.gov

- Energy Sepctra:
  - Spectral split, Earth matter effect
- Time Spectra:
  - Neutronization Burst, SASI Modes, Bound on Neutrino velocity, Shock wave effect, earth effect, Rise Time Analysis etc..

Energy and Flavor Identification

- WC (SK/HK): $\bar{\nu}_e$ average energy can be reconstructed to ~ 6-10 % accuracy, can measure flux, spectrum and angular distributions vs time.

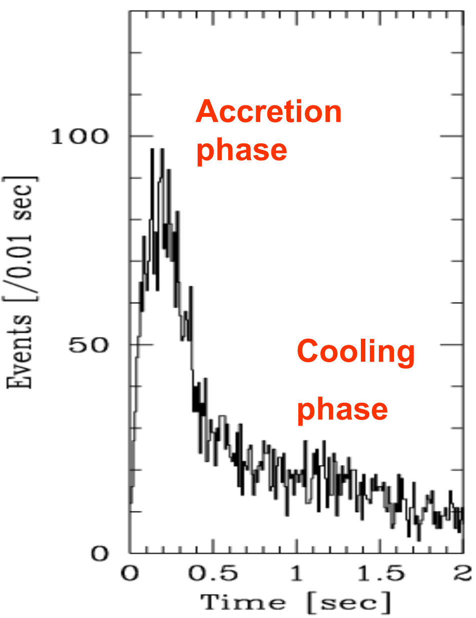
- Liquid Ar: ν_e crucial flavor for Neutronization Burst.
  GDSK, GDHK?? [Nikrat, Laha, Horiuchi, 1711.0008]

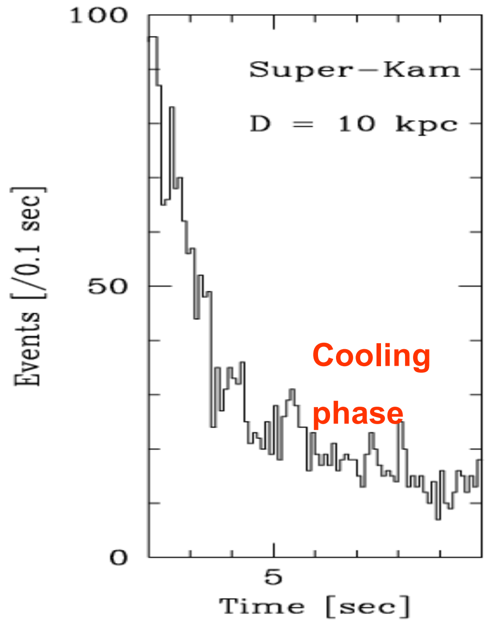
- ν_x ?? Large scintillator spectral technique? [Beacom, Farr, Vogel, hep-ph/0205220, Dasgupta and Beacom, 1103.2768]

  Direct Dark Matter detector?

Bandopadhaya, Bhattacharya, SC, Kar PRD 2014,
Lang, McCabe, Reichard, Selvi & Tamborra, arXiv:1606.09243

Simulated Supernova Signal: Super-Kamiokande

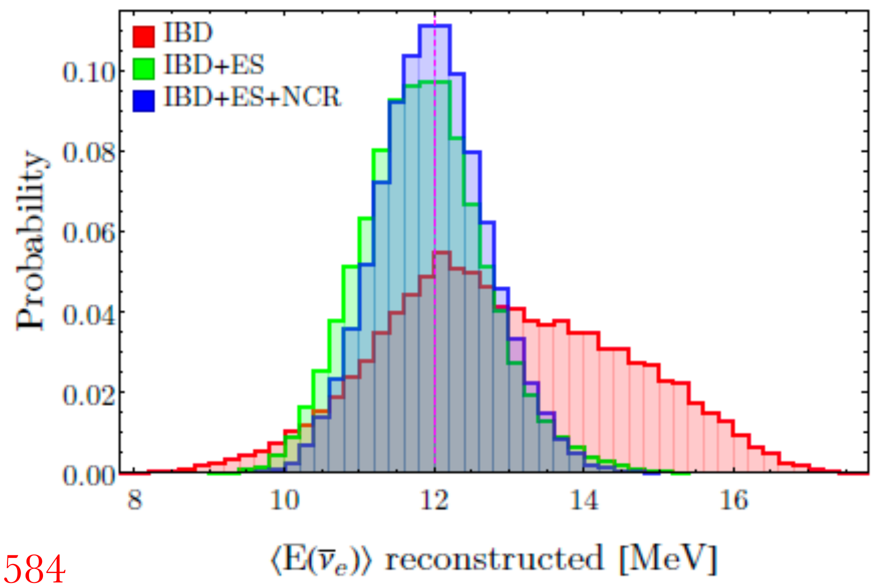




Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model

Totani, Sato, Dalhed & Wilson, ApJ 1998.

Electron antineutrino average energy can be reconstructed with ~ 6 % accuracy

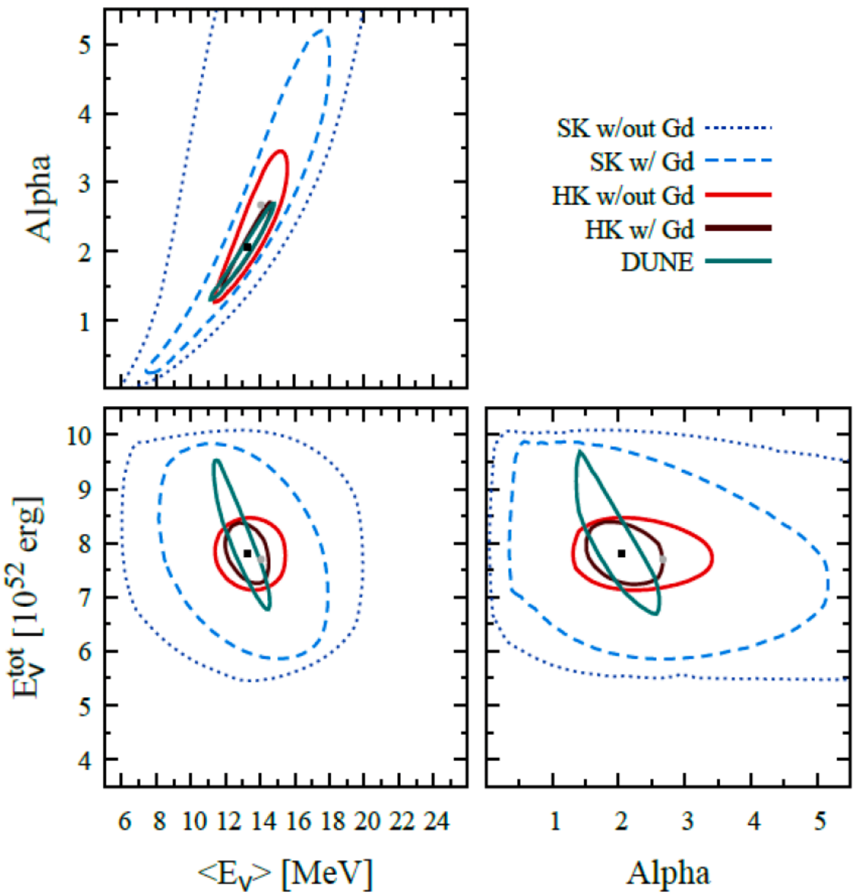


(a) $\langle E_{\bar{\nu}_e} \rangle$ in Super-Kamiokande

Gallo Rosso, Vissani and Volpe, 1708.00760; 1712.05584

Identifying Electron Neutrinos

[Nikrat, Laha, Horiuchi, 1711.0008]



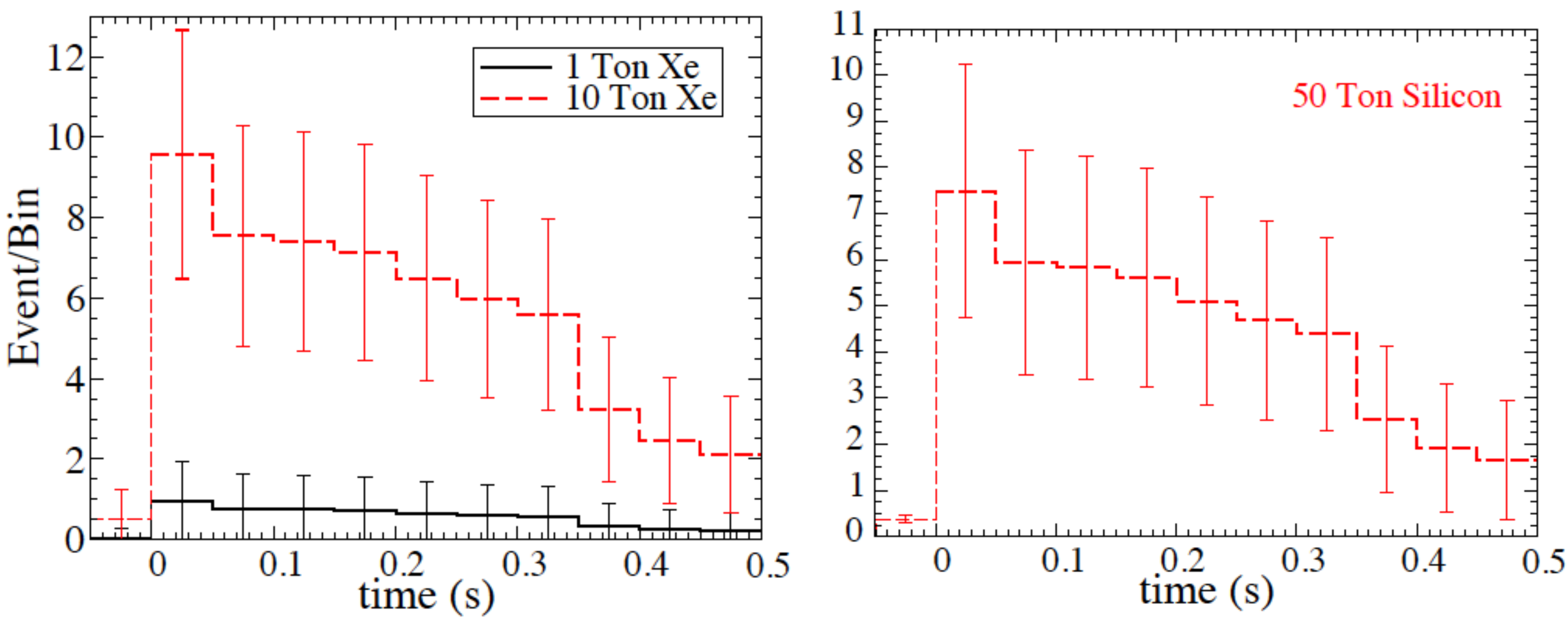
Parameter	SK	SK+Gd	HK	HK+Gd	DUNE
$\langle E_{\nu_e} \rangle$	±50%	±40%	±15%	±10%	±10%
$E_{\nu_e}^{tot}$	±30%	±20%	±10%	±7%	±20%
α_{ν_e}	N/A	±110%	±50%	±30%	±30%

Channel	Super-K	Hyper-K	DUNE
ν_e scattering	300	3,500	260
$\bar{\nu}_e$ scattering	84	970	73
ν_x scattering	41	480	36
$\bar{\nu}_x$ scattering	31	370	28
^{16}O	110	1,300	$\cdots$
IBD	9,800	110,000	$\cdots$
^{40}Ar	$\cdots$	$\cdots$	2,200

Accretion phase in a Direct Dark Matter detector

Coherent Elastic Neutrino-Nucleus Scattering (CENNS)

Neutral current: Measure of mu and tau flavor neutrinos



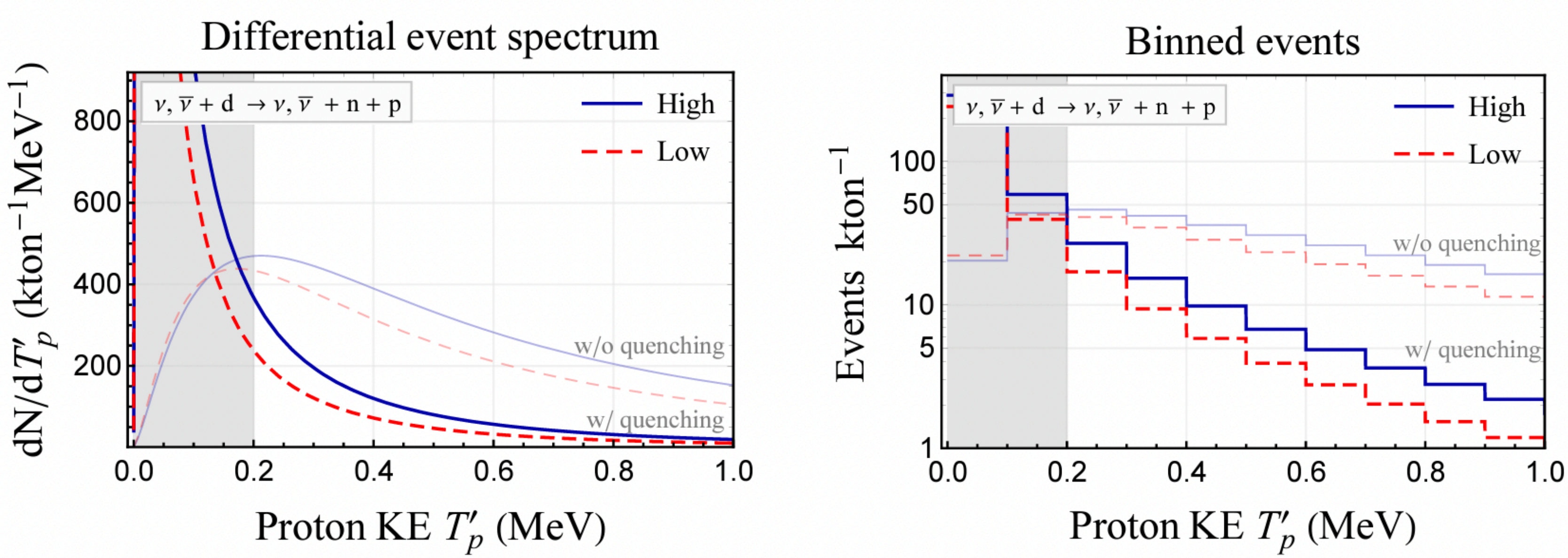
S.C, P. Bhattacharjee & Kamales Kar PRD, 2014

Lang,McCabe, Reichard, Selvi & Tamborra, arXiv:1606.09243

Deuterated liquid scintillator detector (DLS)

Neutral current: Measure of mu and tau flavor neutrinos

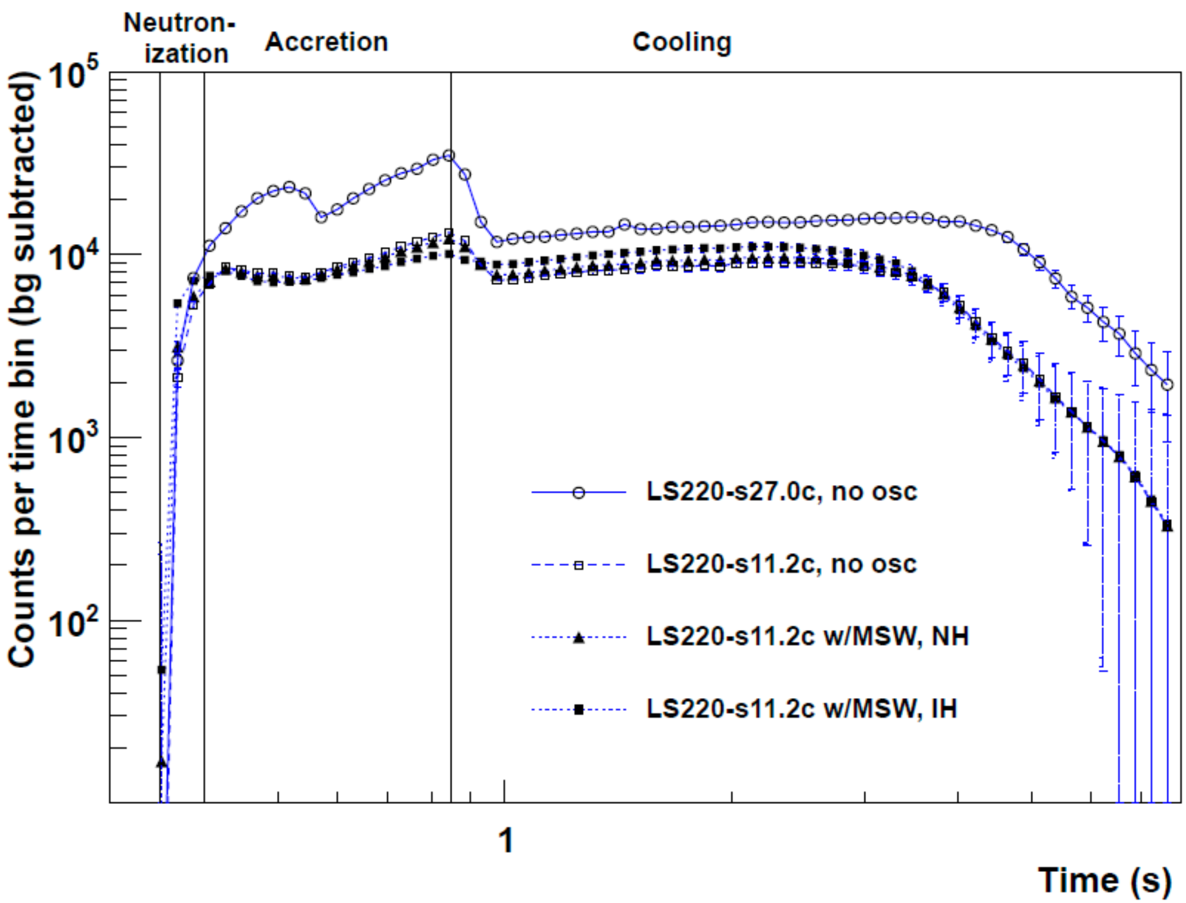
$$\nu + d \rightarrow \nu + n + p$$
$$\bar{\nu} + d \rightarrow \bar{\nu} + n + p$$



Few 100 events for Galactic SNe

Chauhan, Dasgupta & Datar, JCAP 2021

Simulated Supernova Signal: IceCube

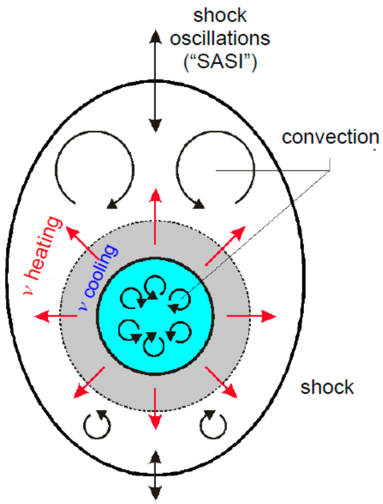


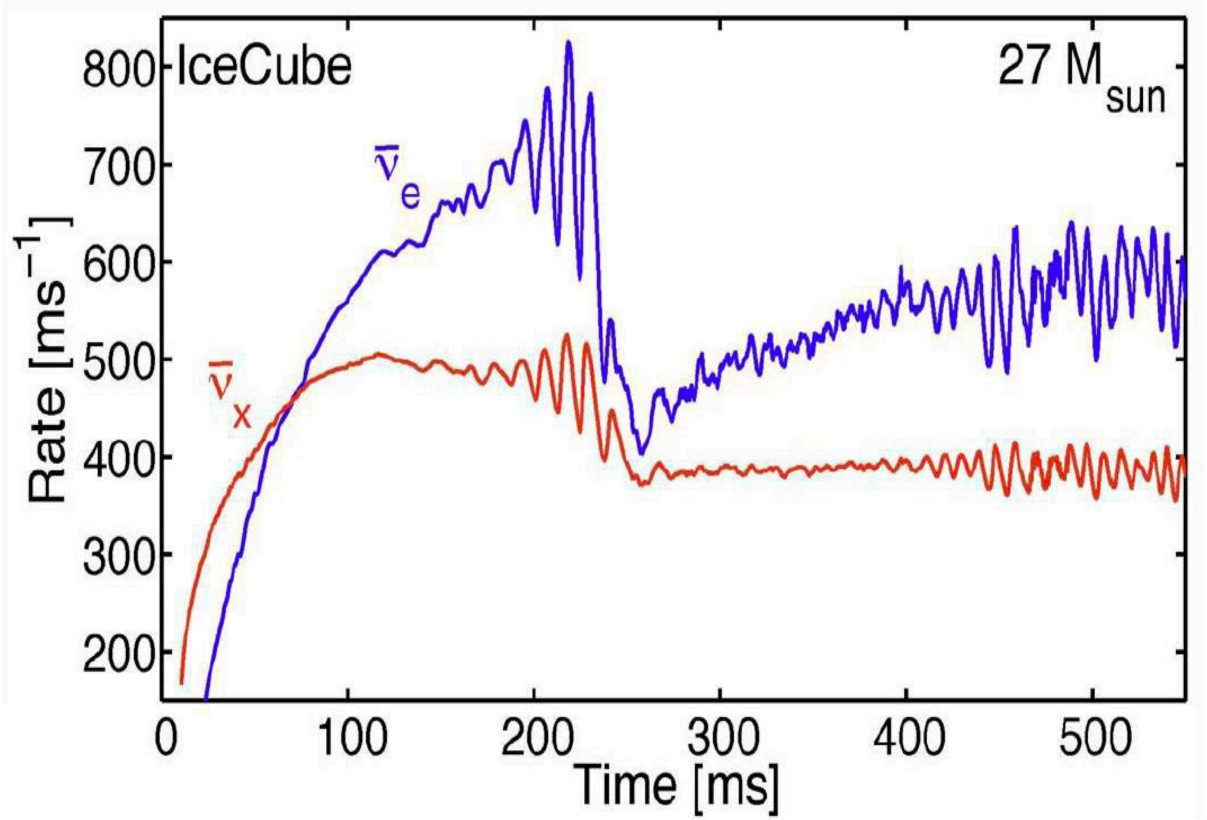
- Reconstruction of the electron anti-neutrino light curve.
- Possible to distinguish the different post-bounce phases.

Mirizzi, Tamborra, Janka, Saviano, Scholberg, S.C et al., arXiv:1508.00785

Short Time Variations In SN neutrino Signal

Convective overturn & shock oscillations “SASI” enhance the efficiency of ν-heating, which finally revives the shock





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

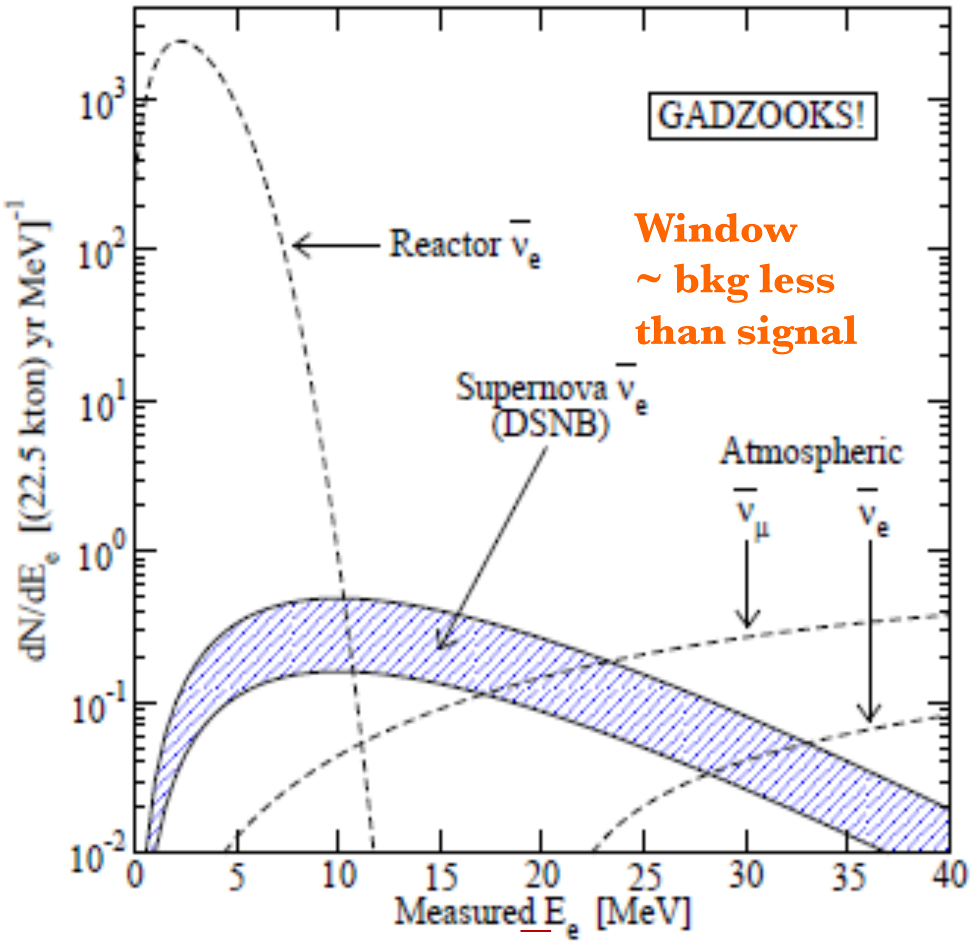
Necessary high statistics and high time resolution: IceCube

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

Diffuse SN Neutrino Background (DSNB)

- Approx. 10 core-collapse/sec in the visible universe
- mostly from redshift z~1
- Confirm star formation rate

[Beacom & Vagins, hep-ph/0309300]



SK-doped with Gd would detect few clear DSNB neutrino events/year.

Neutrino astronomy at cosmic distances !

Neutrino Astronomy

- Spin ½
- **Chargeless**

No bending in magnetic fields ➔ Points back to the source

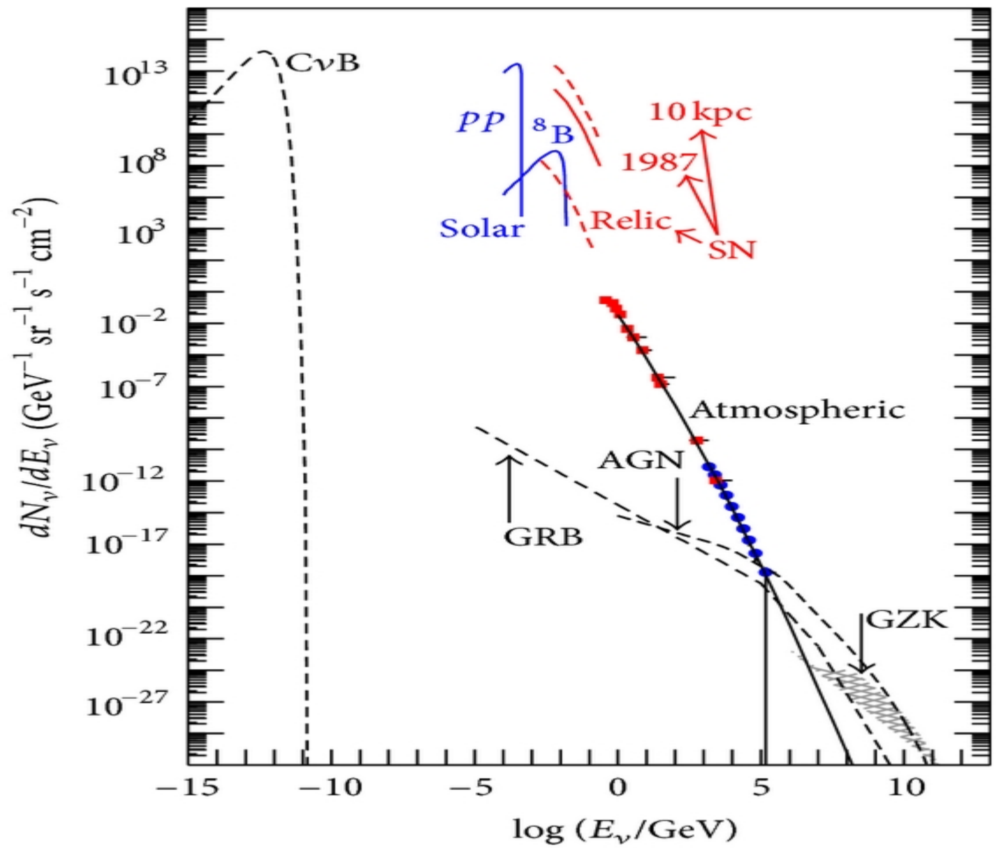
- **Weakly interacting**

Minimal scattering ➔ Arrive from regions opaque to light

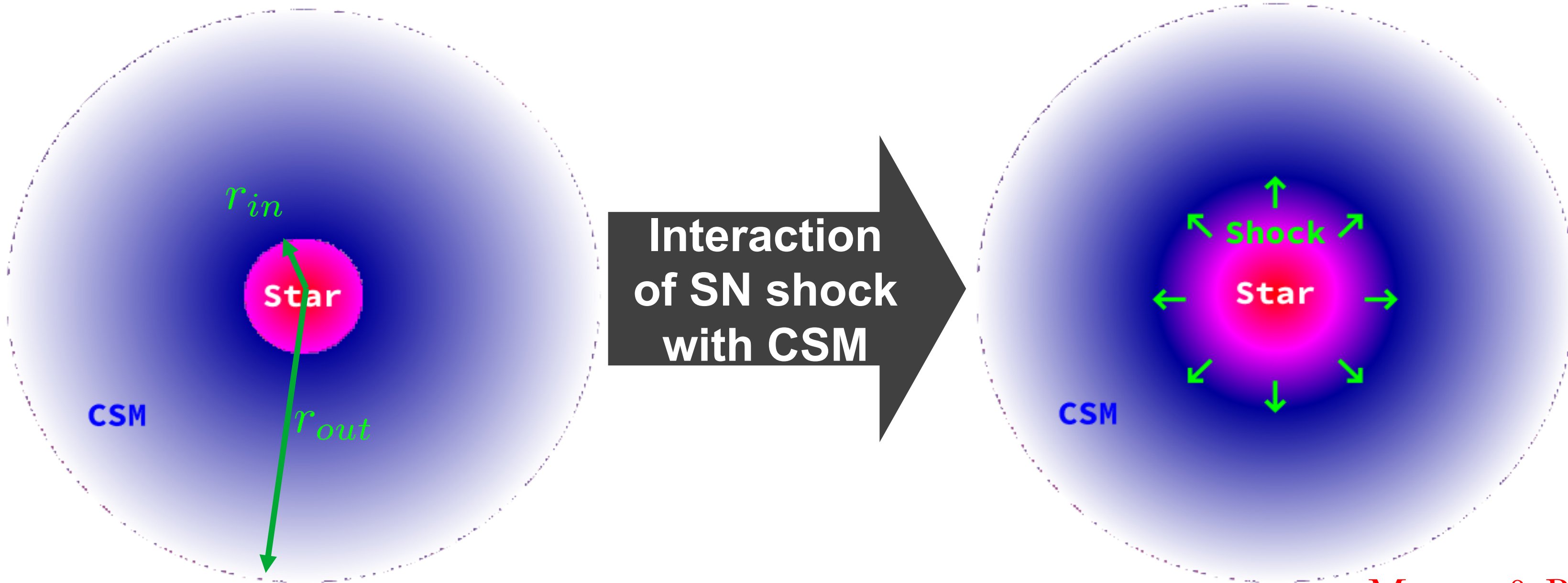
Excellent Astronomical Messenger!!

- Almost massless

Neutrino Oscillations



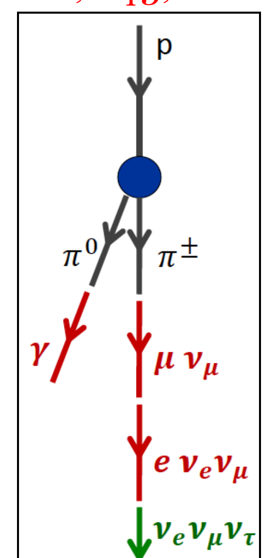
Young SNe and Dense Circumstellar Material



Murase & Beacom, 2011
Ofek et al, ApJ, 2014

- Heavy mass loss (up to 10 M$_\odot$/yr) prior to explosion creates a Dense Circumstellar Medium (CSM), mostly protons.

- Shock-CSM interaction: Accelerates protons to up to 10-100 PeV, initiating hadronic channels for neutrinos and gamma ray's

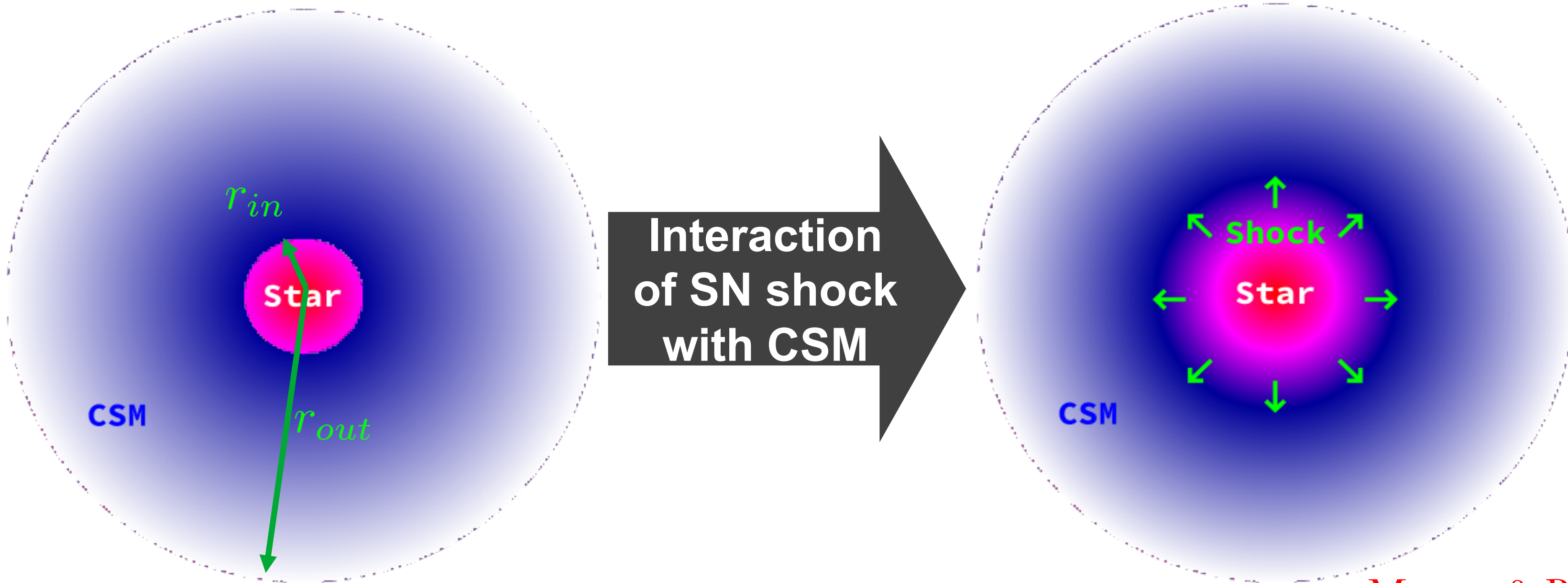


Fluxes at source:

$$\phi^S_{\nu/\gamma}(E_{\nu/\gamma}, r) \propto n_{CSM}(r) N_p(E_p, r) F_{\nu/\gamma}(E_p, E_{\nu/\gamma})$$

(P. Sarmah, S.C, I Tamborra, K. Auchettl, JCAP 2022, PRD 2023

Young SNe and Dense Circumstellar Material

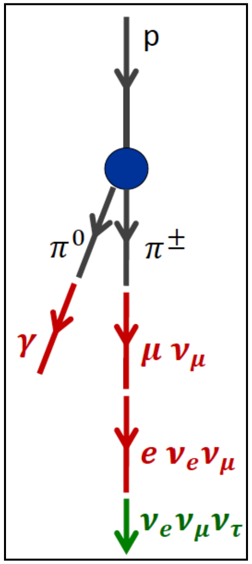


Murase & Beacom, 2011
Ofek et al, ApJ, 2014

Fluxes at source:

$$\phi^S_{\nu/\gamma}(E_{\nu/\gamma}, r) \propto n_{CSM}(r) N_p(E_p, r) F_{\nu/\gamma}(E_p, E_{\nu/\gamma})$$

- Gamma rays are lost in source and cascade to low energies
- Gamma rays are attenuated due to EBL, important for 100 Mpc



Fluxes at detector:

$$\phi^S_{\nu/\gamma}(E_{\nu/\gamma}, r) \propto n_{CSM}(r) N_p(E_p, r) F_{\nu/\gamma}(E_p, E_{\nu/\gamma}) f_a(E_\gamma)$$

(P. Sarmah, S.C, I Tamborra, K. Auchettl, JCAP 2022, PRD 2023)

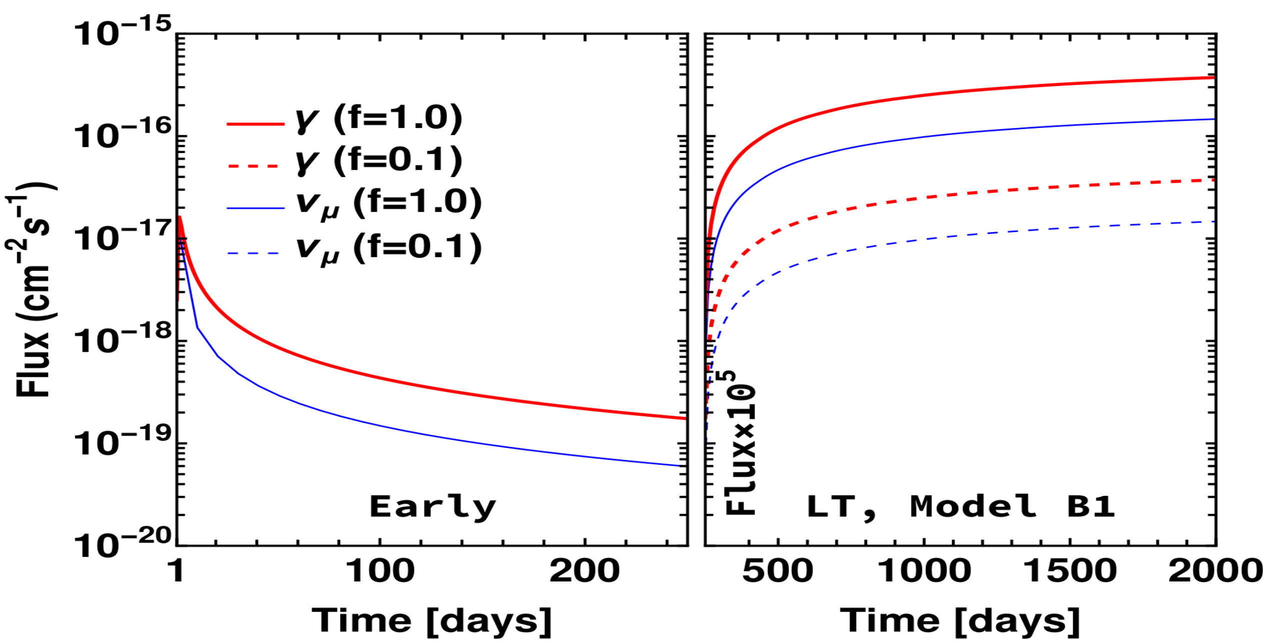
Young SNe and Dense Circumstellar Material

D. Brethauer et. al. 2020, 2022

Example: SN 2014C:

- Re-brightens after about a few hundred days.
- Due to interaction with a CSM far away from the progenitor (6 x 10^{16} cm).
- The CSM profile is not well understood.

Parameters	Early phase	Typical value (LT)	Uncertainty (LT)
v_{sh} (km s^{-1})	2×10^4	10^4	$(4\text{–}4.5) \times 10^4$
r_i (cm)	3×10^{11}	6×10^{16}	$(5.5\text{–}6) \times 10^{16}$
r_o (cm)	6×10^{16}	2.5×10^{17}	$(1\text{–}2.5) \times 10^{17}$
n_{CSM} (cm^{-3})	2×10^{12}	2×10^6	—
ϵ_p	10^{-1}	5×10^{-2}	10^{-2}–10^{-1}
ϵ_B	10^{-2}	1.5×10^{-2}	10^{-3}–10^{-2}
D_L (Mpc)	14.7	14.7	14.1 – 15.3
Onset time	180 s	250 days	(100–400) days
Declination	34°		—



(P. Sarmah, S.C, I Tamborra, K. Auchettl, JCAP 2022, PRD 2023)

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r_o (cm)	6×10^{16}	2.5×10^{17}	$(1–2.5)\times10^{17}$
n_{CSM} (cm^{-3})	2×10^{12}	2×10^6	—
ϵ_p	10^{-1}	5×10^{-2}	$10^{-2}–10^{-1}$
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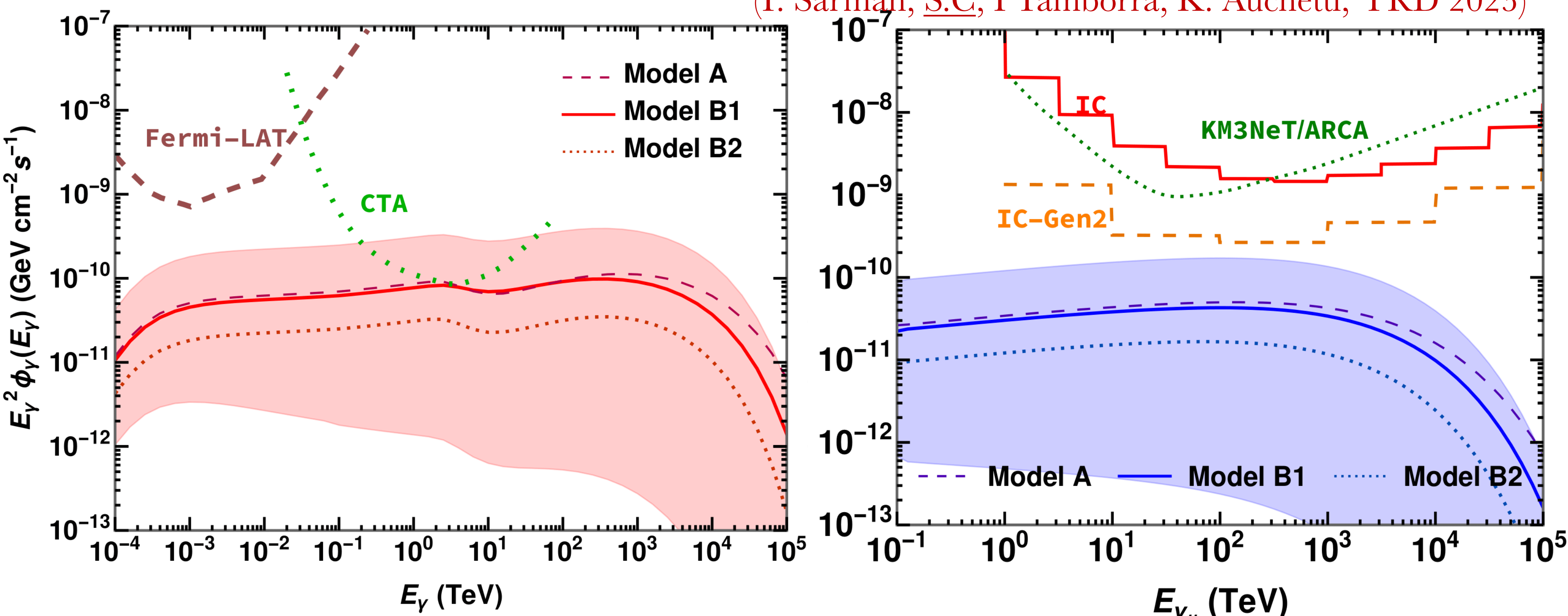

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n_{CSM} (cm^{-3})	2×10^{12}	2×10^6	—
ϵ_p	10^{-1}	5×10^{-2}	$10^{-2}\text{–}10^{-1}$
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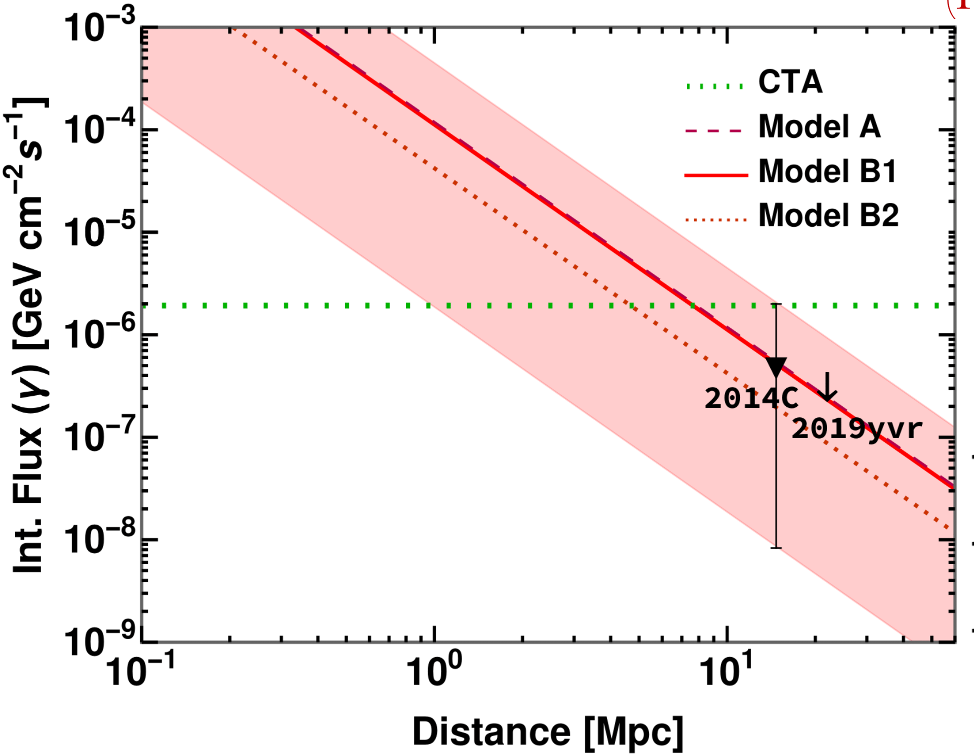
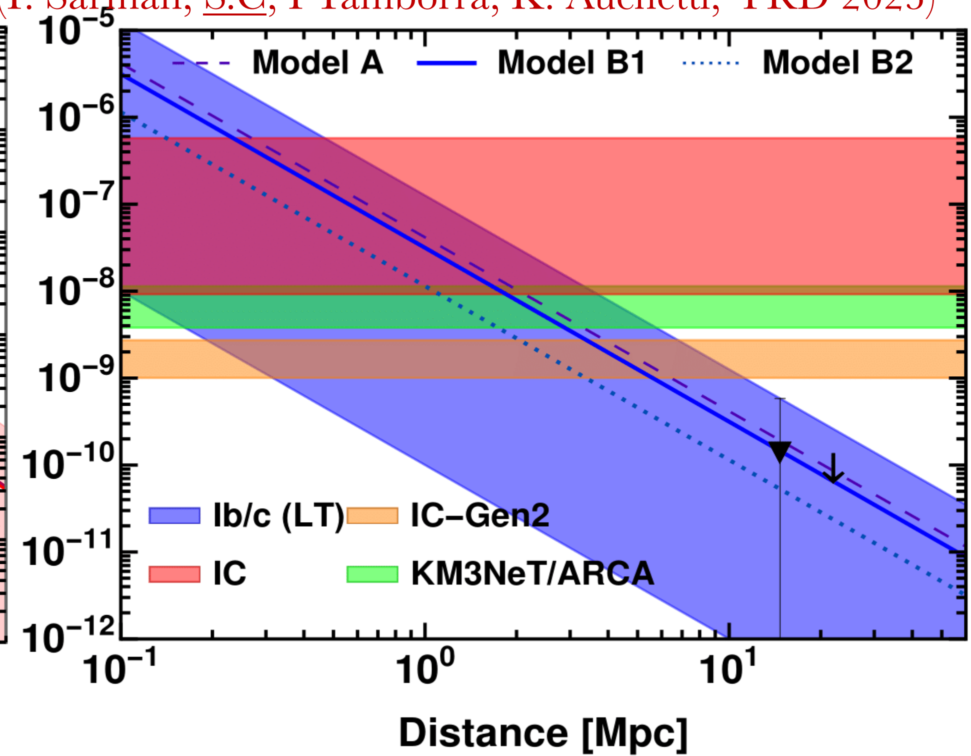
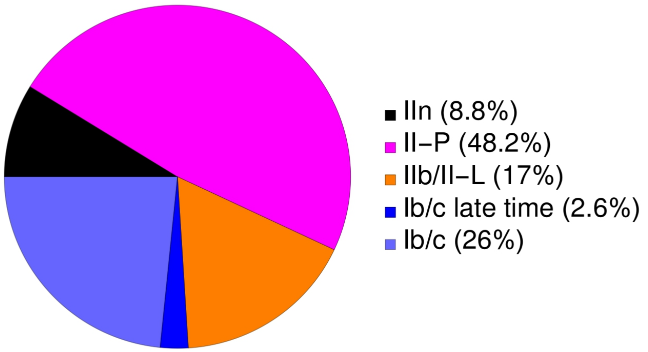
(P. Sarmah, S.C, I Tamborra, K. Auchettl, PRD 2023)





Young SNe and Dense Circumstellar Material

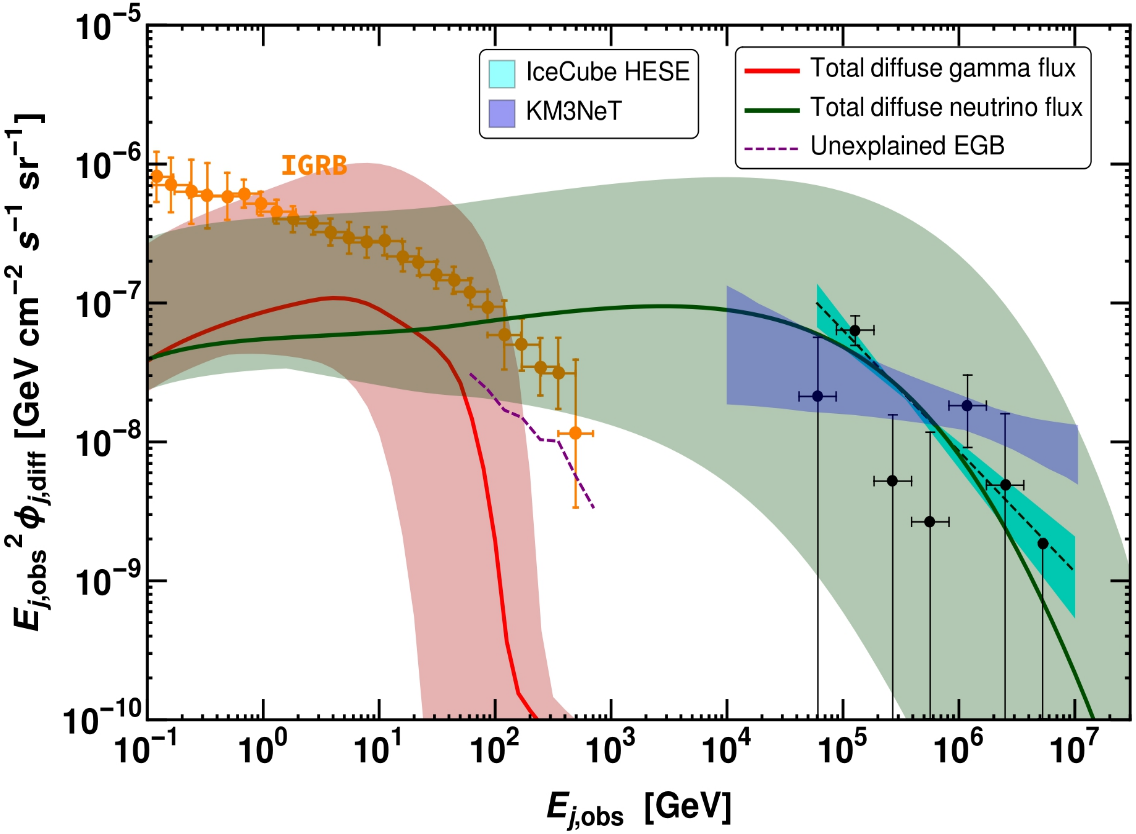
Classification of CCSNe



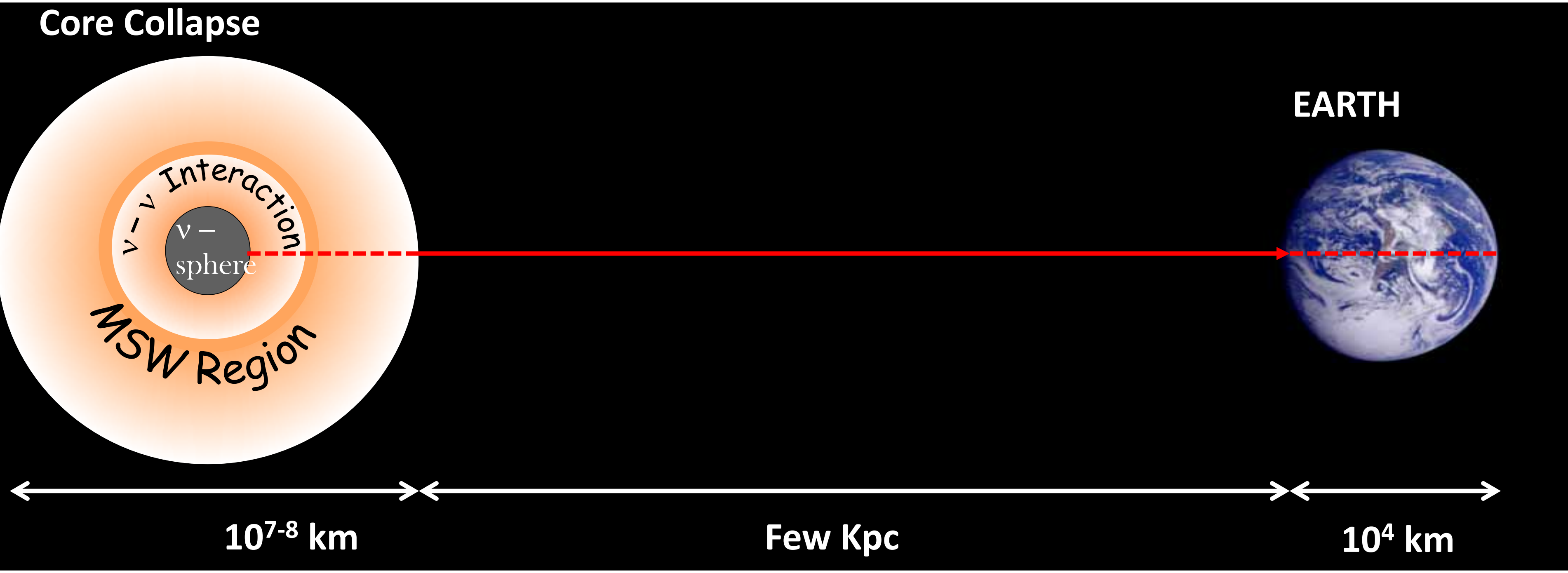
Ref: arXiv:1006.3899, 1601.06806

(P. Sarmah, S.C, I Tamborra, K. Auchettl, JCAP 2022)

Diffuse Flux



Supernova Neutrinos: HOW?



Production

- Simulation of SN Explosion
- Intial energy spectra
- Initial time spectra
- Initial Angular spectra

Propagation

- Dense Neutrino Background
- Dense matter effect
- Shock wave, Earth effect
- New interactions

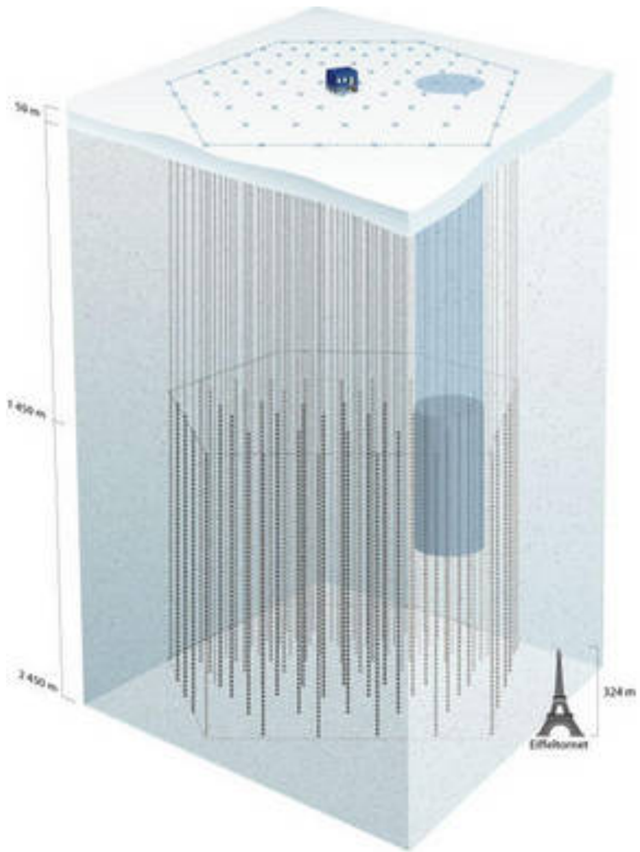
Detection

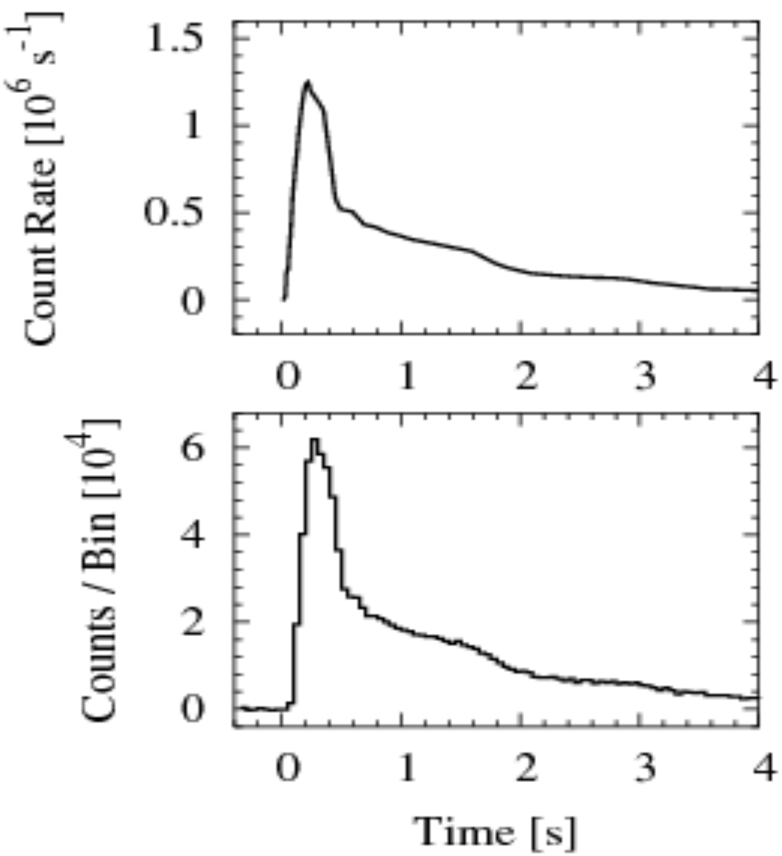
- Different detectors
- Different interection channels
- Final energy spectra
- Final time spectra

Thank you!

Simulated Supernova Signal at IceCube

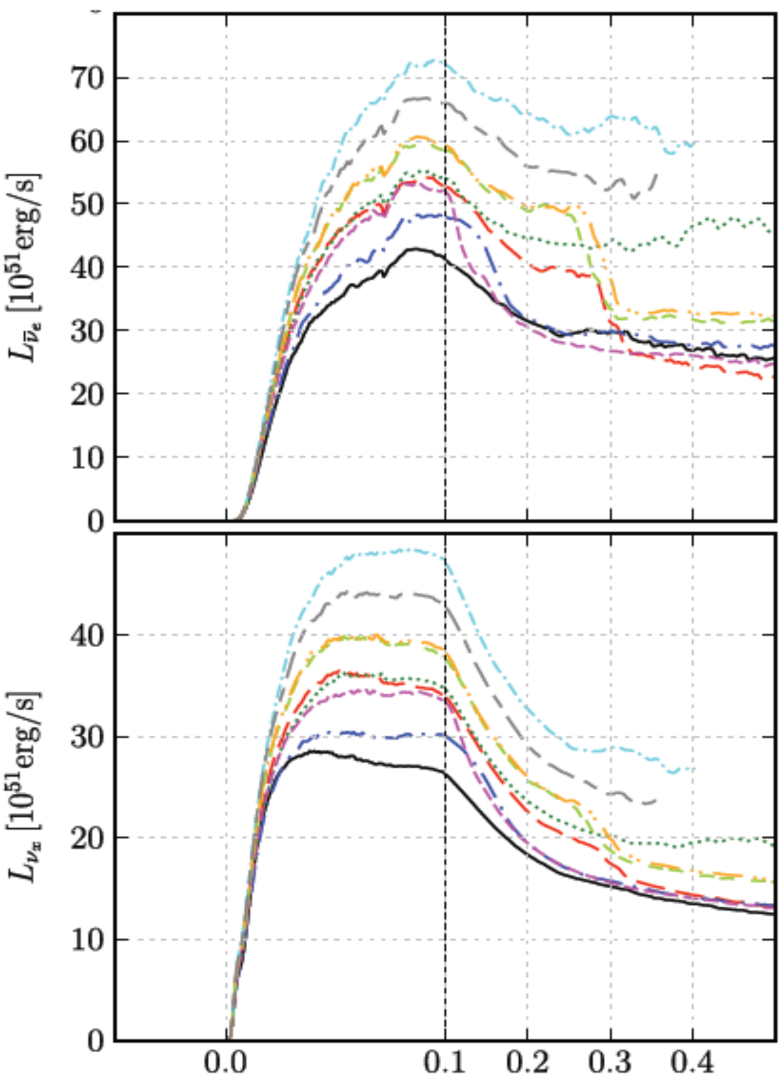
[Dighe, Keil and Raffelt, hep-ph/0303210]





Possible to reconstruct the SN lightcurve with current detectors.

Rise time Analysis: Hierarchy Determination



Garching group, 2011

- High degeneracy of ν_e and e, suppresses $\bar{\nu}_e$ production.
- $\bar{\nu}_e$ more in equilibrium with environment than ν_x

Consistent feature in wide variety of simulations

Flux of ν_x rises faster than $\bar{\nu}_e$

NH: $F_{\bar{\nu}_e} = \cos^2\vartheta_{12}(F^0_{\bar{\nu}_e} - F^0_{\nu_x}) + F^0_{\nu_x}$

IH: $F_{\bar{\nu}_e} = F^0_{\nu_x}$

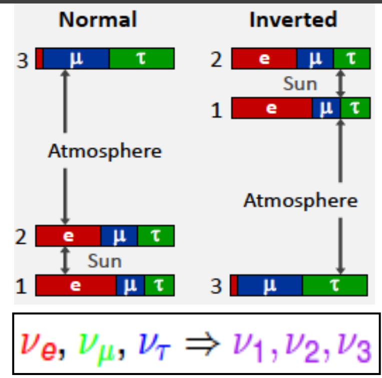
Flux in IH (ν_x) rises faster than NH (ν_x, $\bar{\nu}_e$)

[Serpico, S.C, Fischer, Hüdepohl, Janka & Mirizzi
PRD 85:085031,2012]

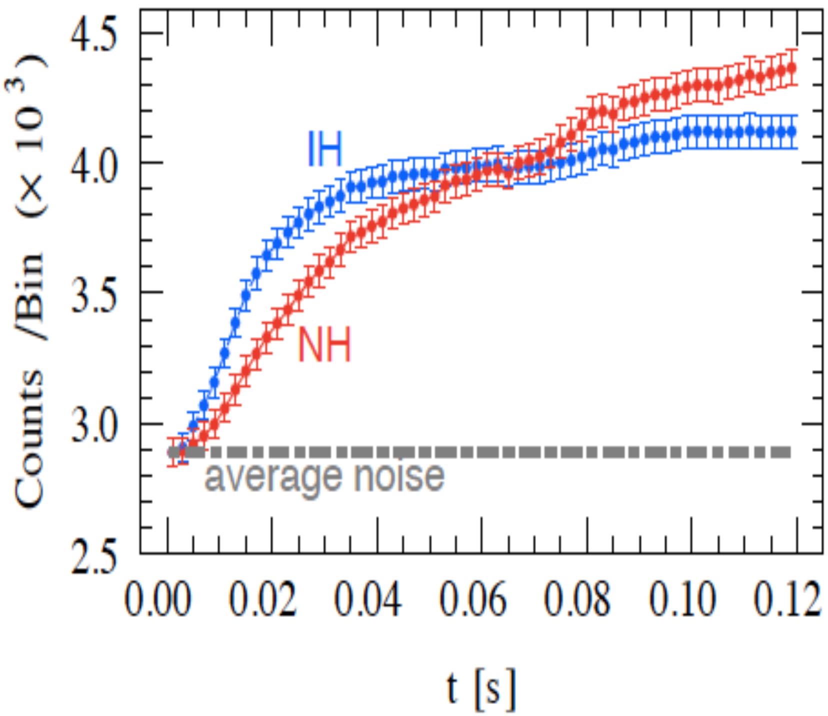
Rise time analysis: Hierarchy determination

Normalized Count rate : Electron anti-neutrino

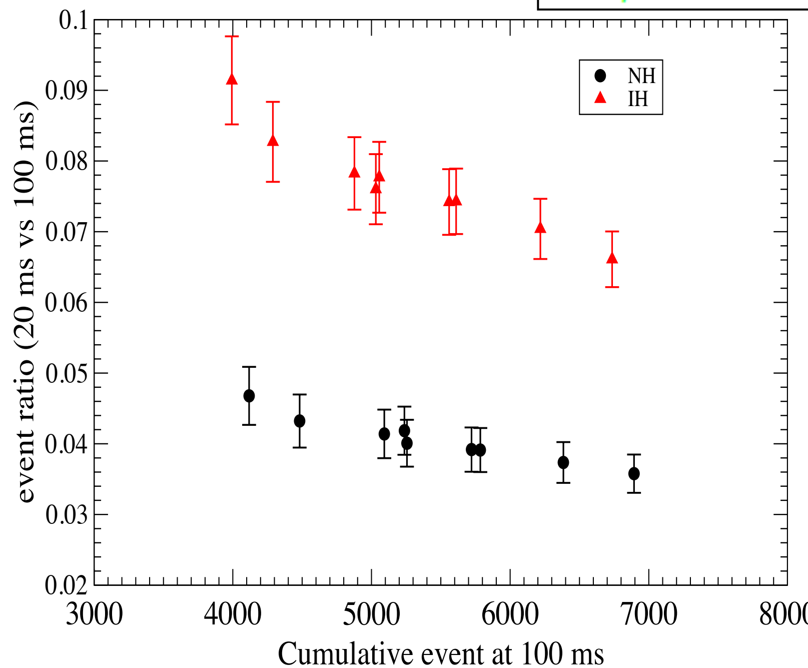
10 different models (12 $M_\odot$-40 $M_\odot$)



IC



Mton



Flux in IH rises faster than NH

P. Serpico, S.C, T. Fischer, L. Hüdepohl, T. Janka & A. Mirizzi PRD, 2012

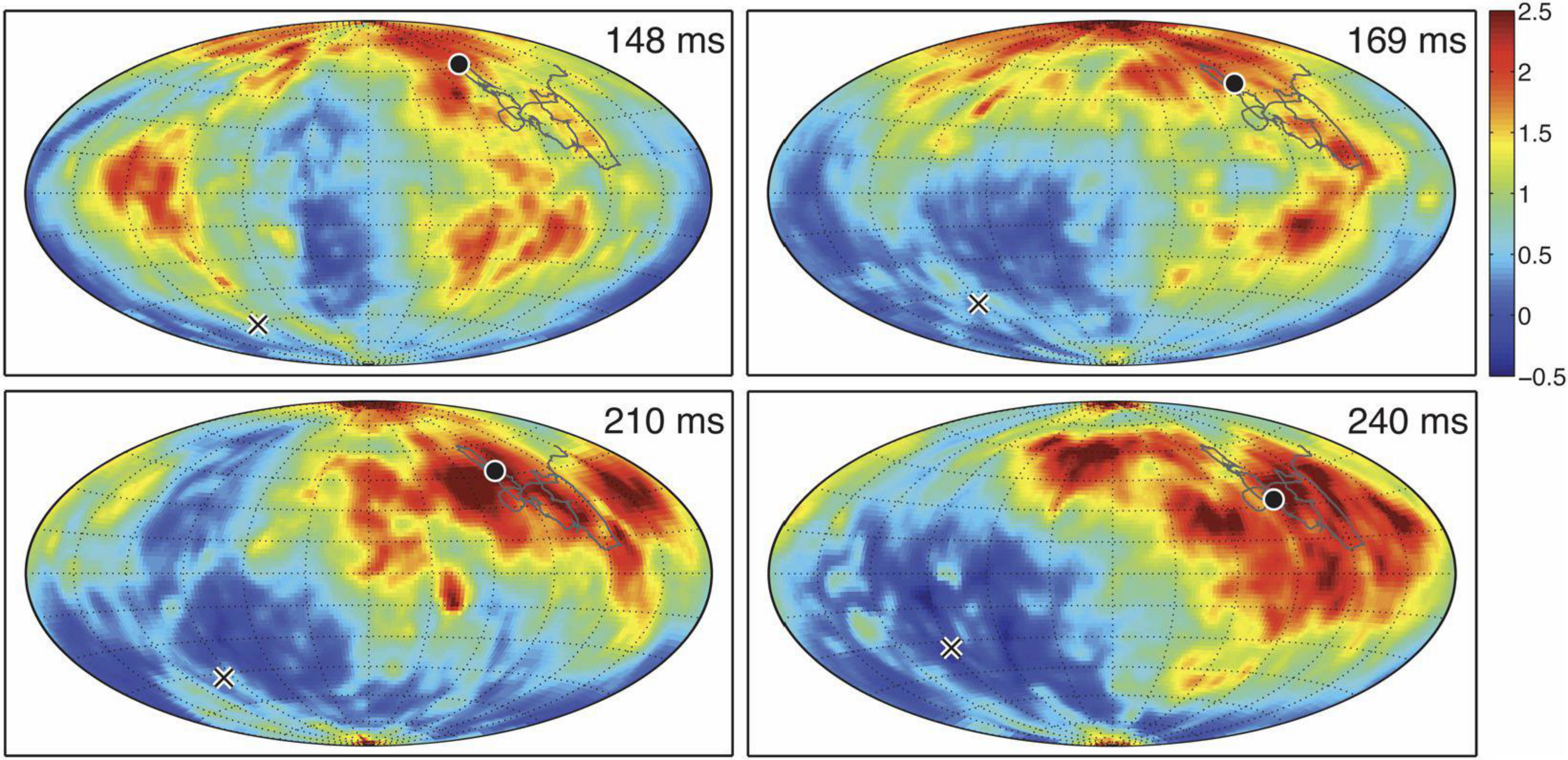
P. Sarmah, A. Medhi, D. Bose, S.C & M. Devi, in preparation

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 et al., arXiv:1402.5418