Neutrino Astrophysics: Challenges and Possibilities

Sovan Chakraborty

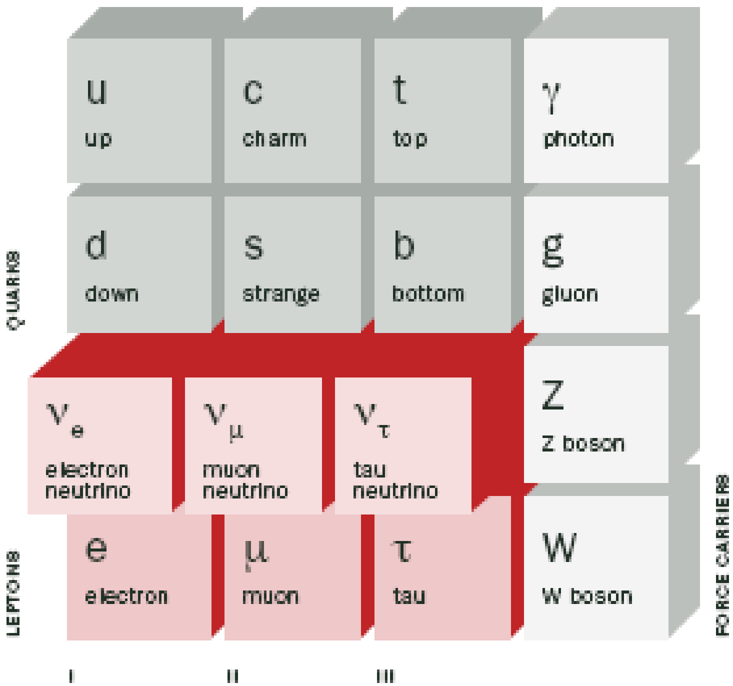
MPI for Physics, Munich

Institute of Physics,
Bhubaneswar

MARIE CURIE ACTIONS

MAX-PLANCK-GESELLSCHAFT

NEUTRINOS



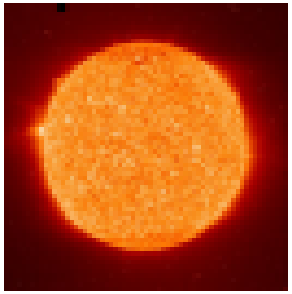
- Chargeless
- Spin ½
- Weakly interacting
- Almost massless

Neutrino oscillations → Neutrinos have a tiny but finite mass

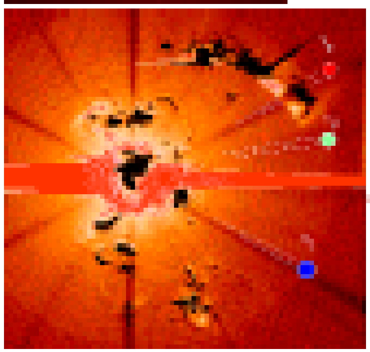
No bending in magnetic fields ➔ Point back to the source

Minimal obstruction / scattering ➔ Arrive directly from regions opaque to light.

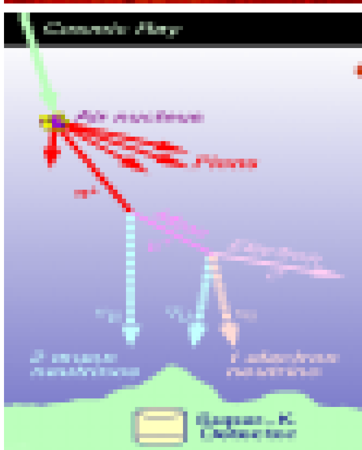
NEUTRINO SOURCES



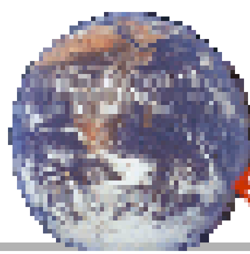
← Sun



← Cosmology

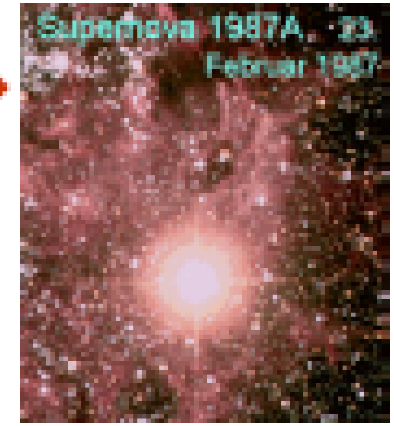


← Atmosphere



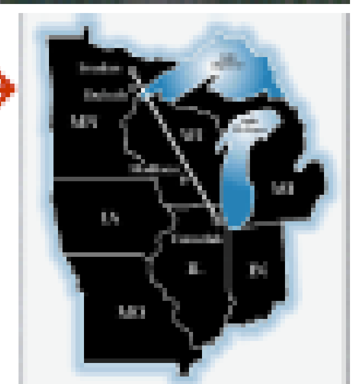
← Earth

Astronomy: →
Supernovae
GRBs
UHE ν's

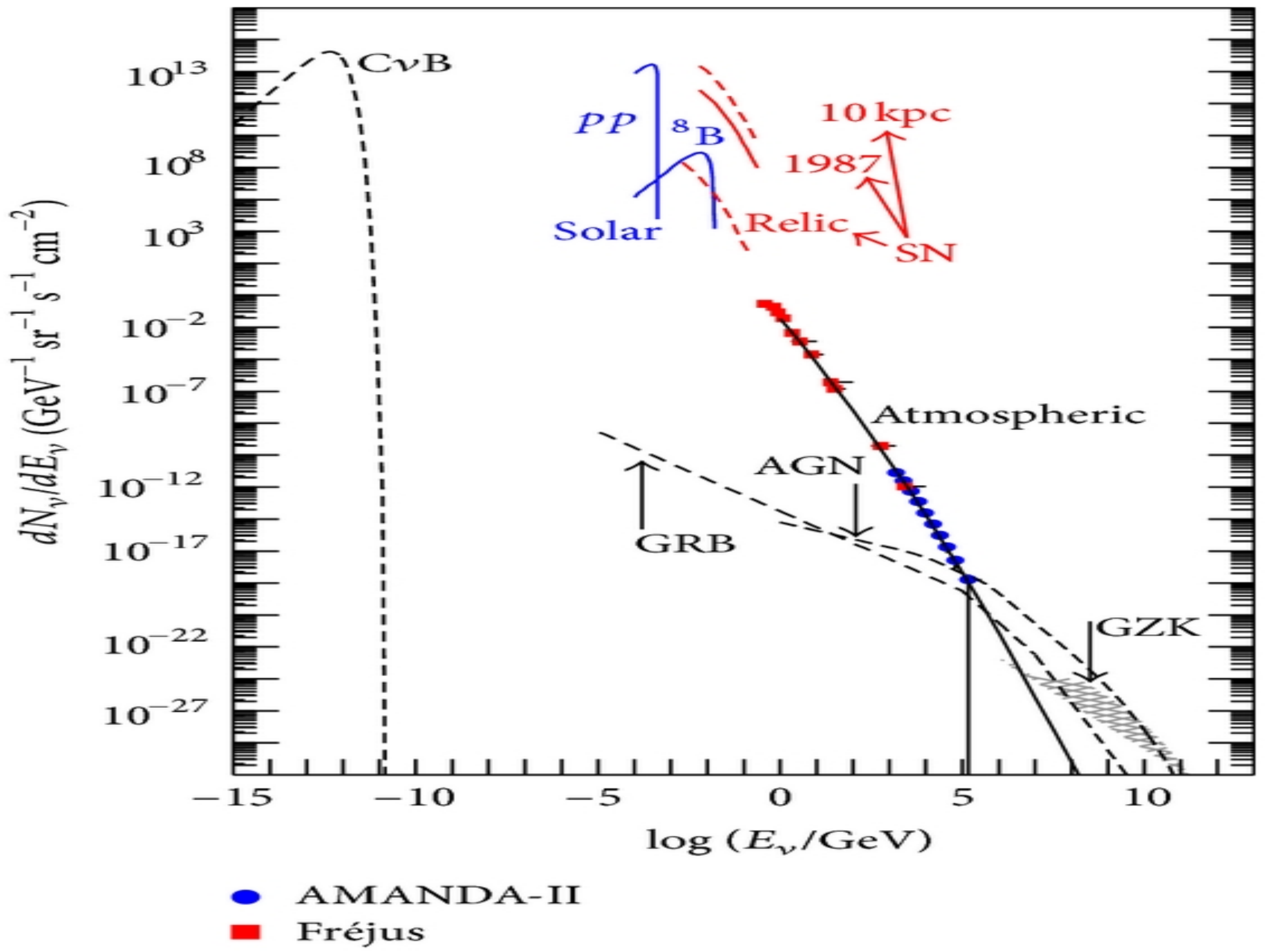


Reactors →

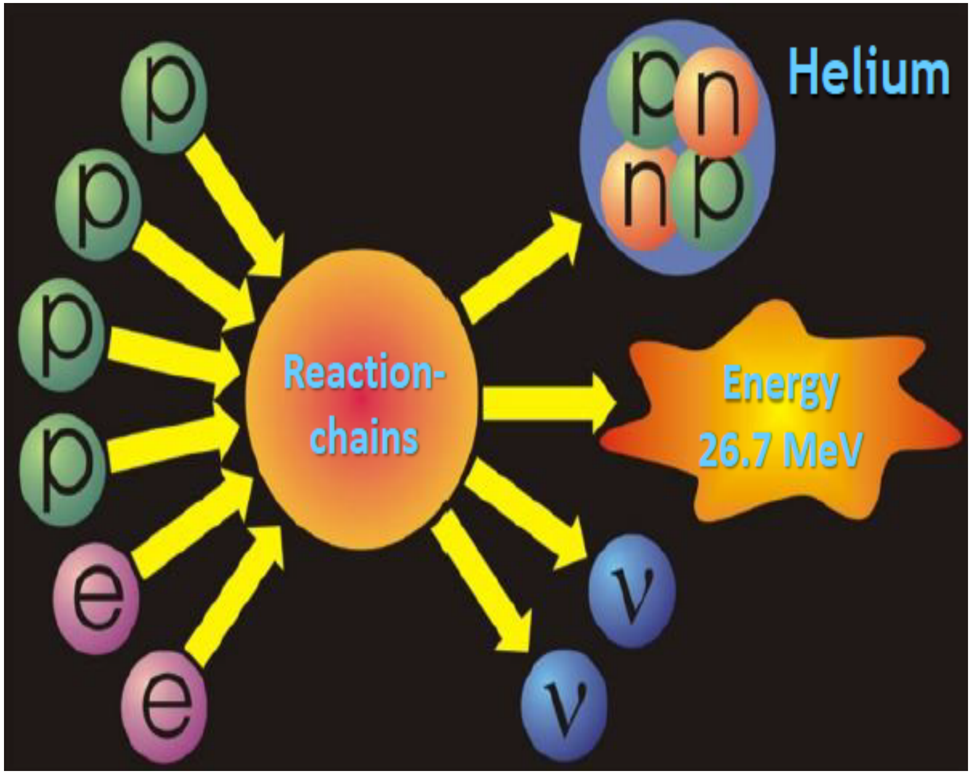
Accelerators →



NEUTRINO SOURCE SPECTRA

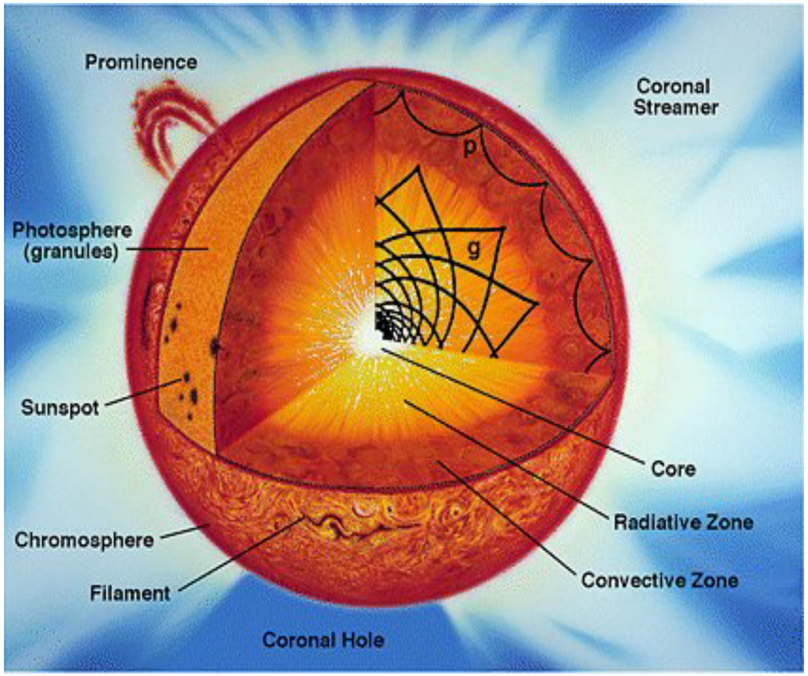


NEUTRINOS FROM SUN



Thermonuclear Reaction Chain 1938

Hans Bethe (1906–2005, Nobel prize 1967)



Solar Radiation:
98% light, 2% neutrinos
66 billion neutrinos/cm^2 sec
1-10 MeV

Bethe & Peierls 1934:
… this evidently means that one will never be able to observe a neutrino.

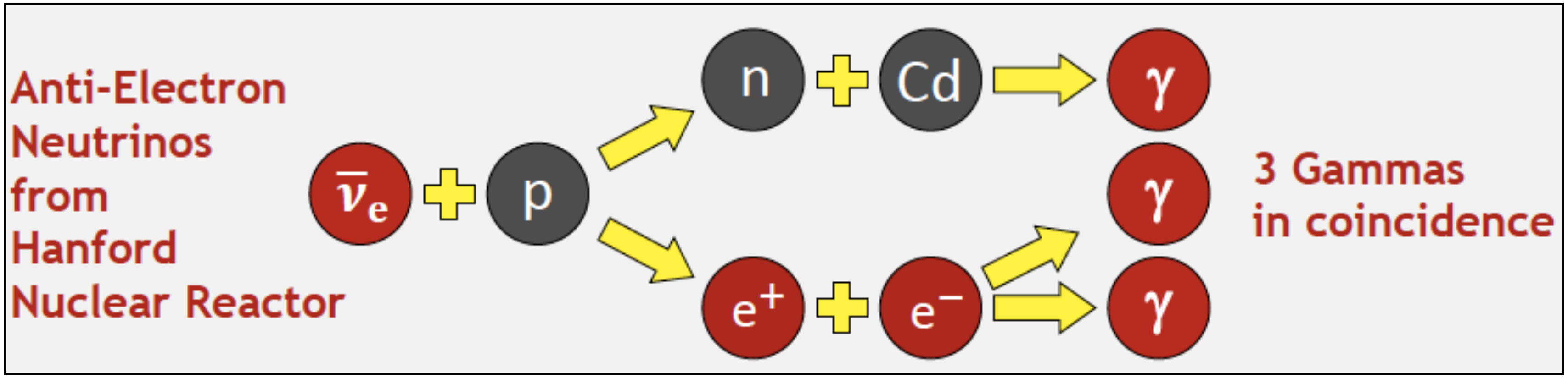
NEUTRINOS DETECTION

Neutrino Detection (1954-1956)

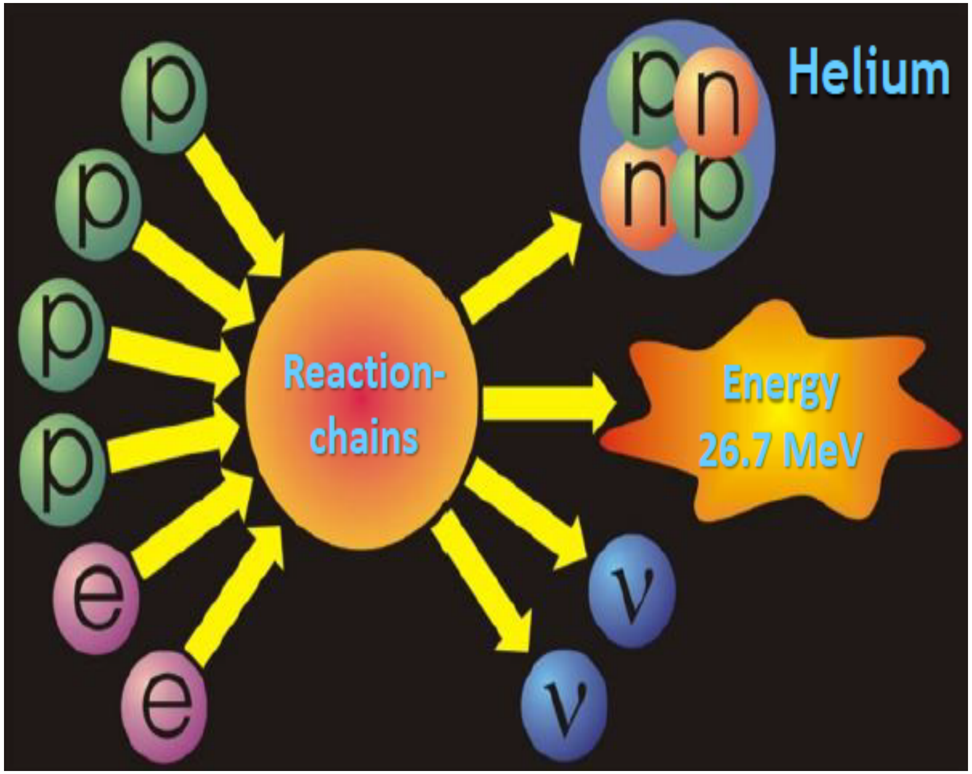
Reactor Anti-Electron Neutrinos were detected

Clyde Cowan and Fred Reines

Fred Reines (1918-1998), Nobel Prize 1995



NEUTRINOS FROM SUN

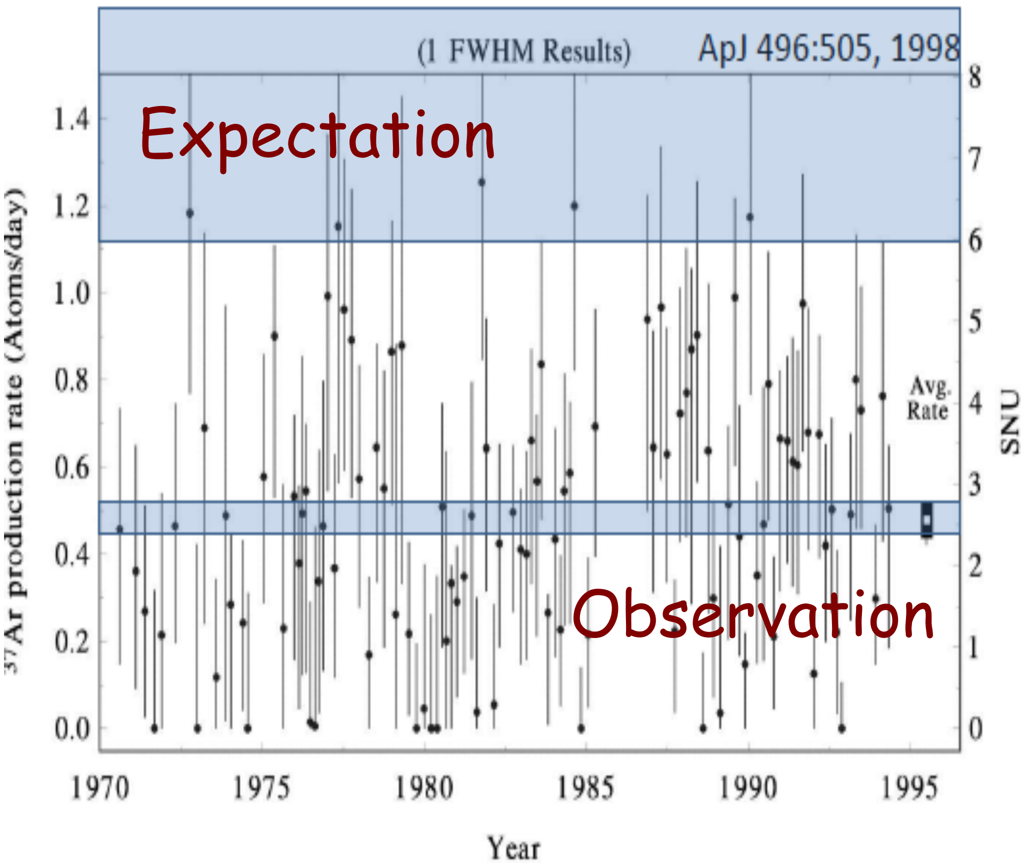


Solar Neutrino Detection
Homestake Solar neutrino Observatory
(1967-2002)
Inverse Beta Decay on Chlorine

Ray Davis Jr. (1914–2006)
Masatoshi Koshiba (*1926)

Nobel Prize 2002 for Neutrino Astronomy

SOLAR NEUTRINO PUZZLE



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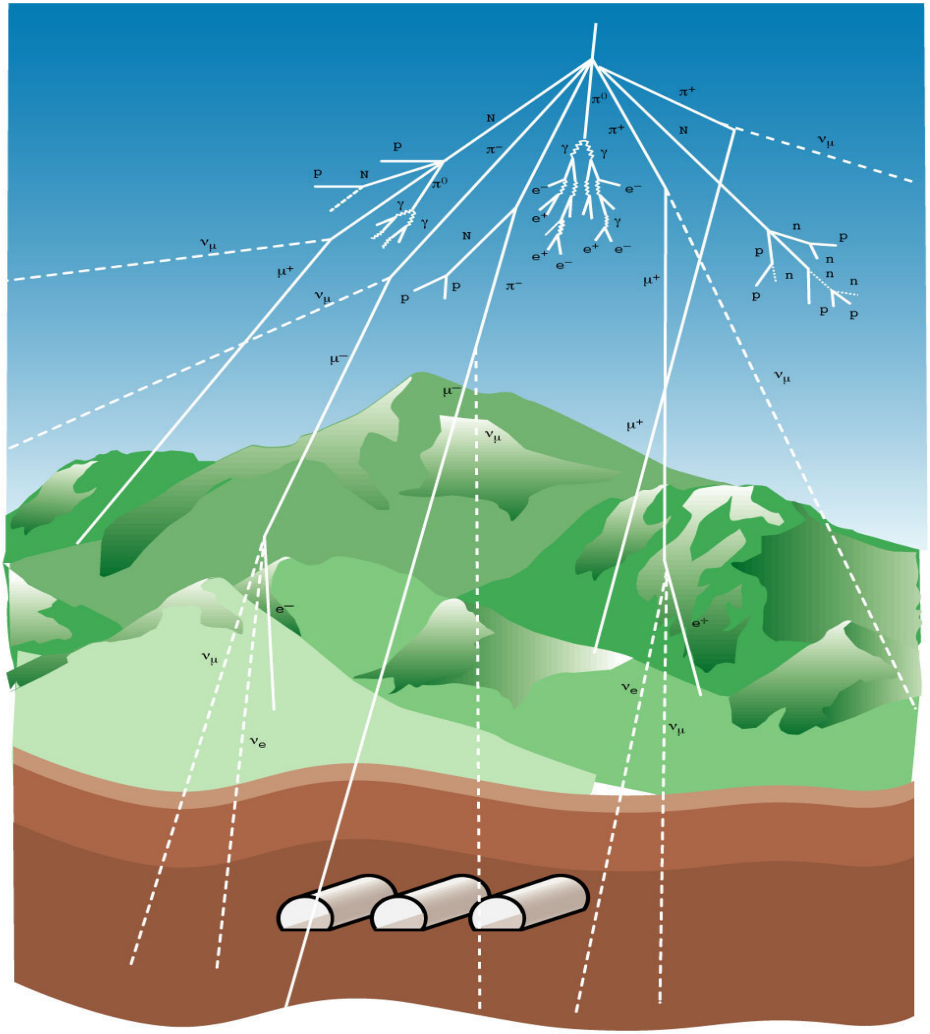
ATMOSPHERIC NEUTRINO PUZZLE



Cosmic rays ⊕ atmosphere ⇒ pions and muons ⇒ decay to neutrinos (ν_μ and ν_e)

Expect almost isotropic flux of neutrinos

Almost half the ν_μ are lost while passing through the Earth, no ν_e are lost.

Solution :
Neutrino flavor oscillations

NEUTRINO FLAVOR OSCILLATIONS

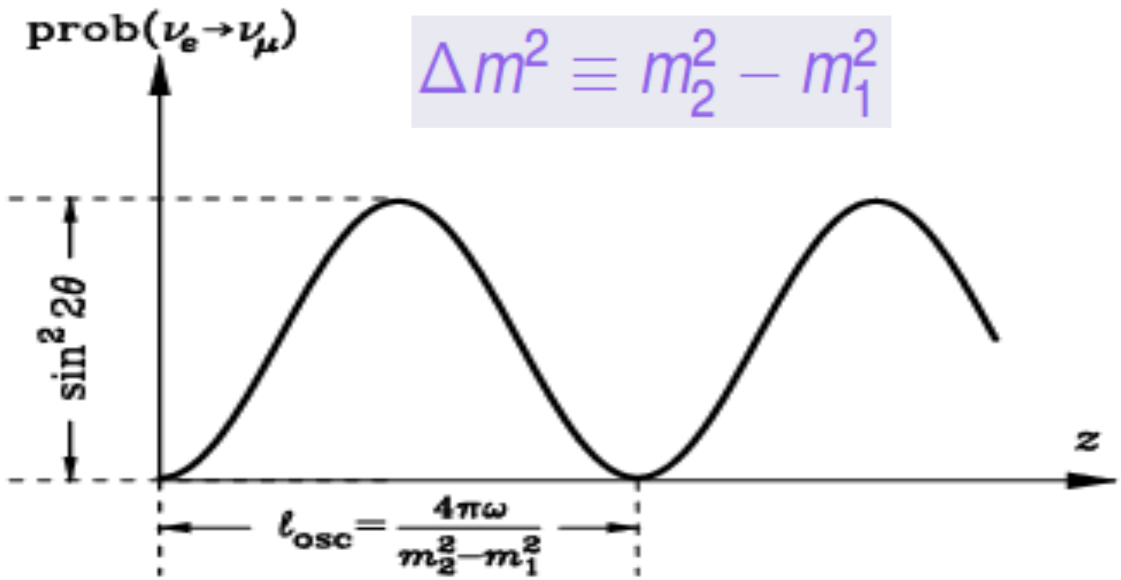
- **Two flavor mixing** $$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Each mass eigenstates propagates as $\mathbf{e^{ipz}}$ with $p_i = \sqrt{E^2 - m^2} \approx E - \frac{m_i^2}{2E}$

$$\left|\nu_\mu(z)\right\rangle = -\sin\theta\, e^{-ip_1 z}\left|\nu_1\right\rangle + \cos\theta\, e^{-ip_2 z}\left|\nu_2\right\rangle$$

- **2 ν oscillation probability** $P(\nu_e \to \nu_\mu) = \left|\left\langle \nu_\mu(z) \middle| \nu_e(0)\right\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$



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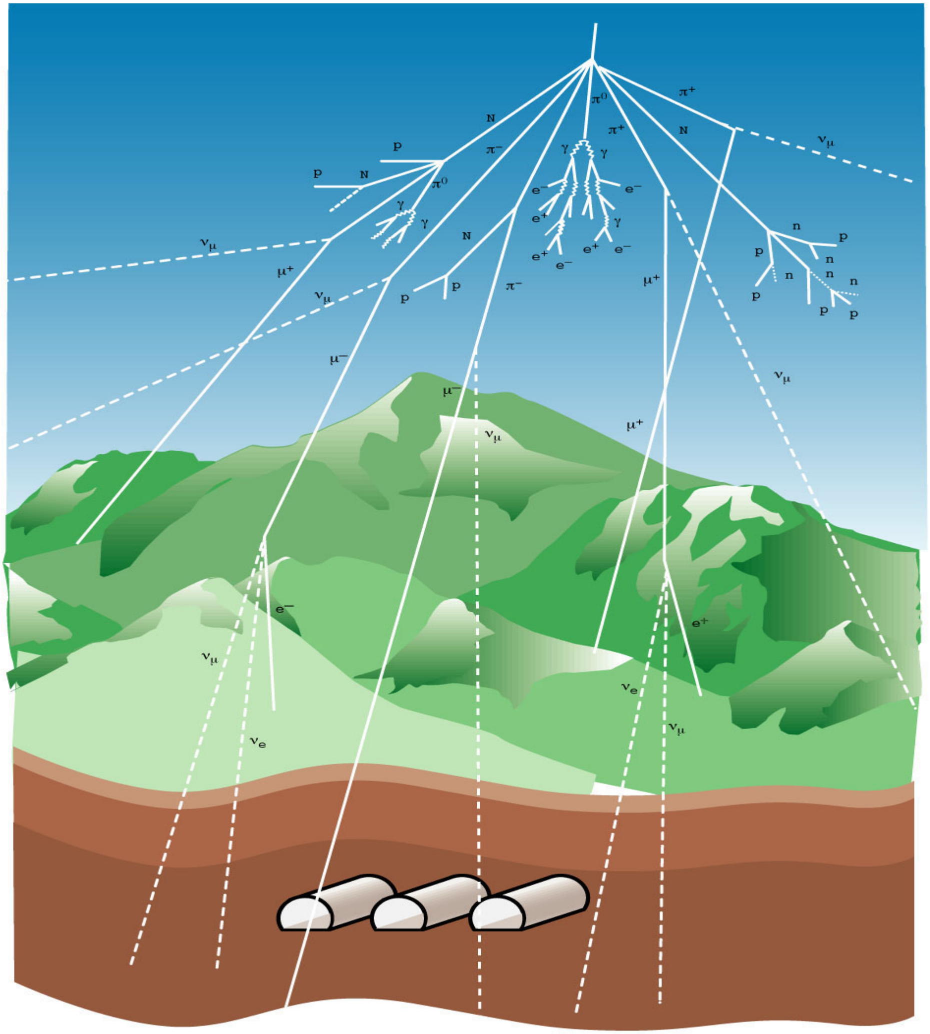

Cosmic rays $\oplus$ atmosphere $\Rightarrow$ pions and muons $\Rightarrow$ decay to neutrinos (ν_μ and ν_e)

Expect almost isotropic flux of neutrinos

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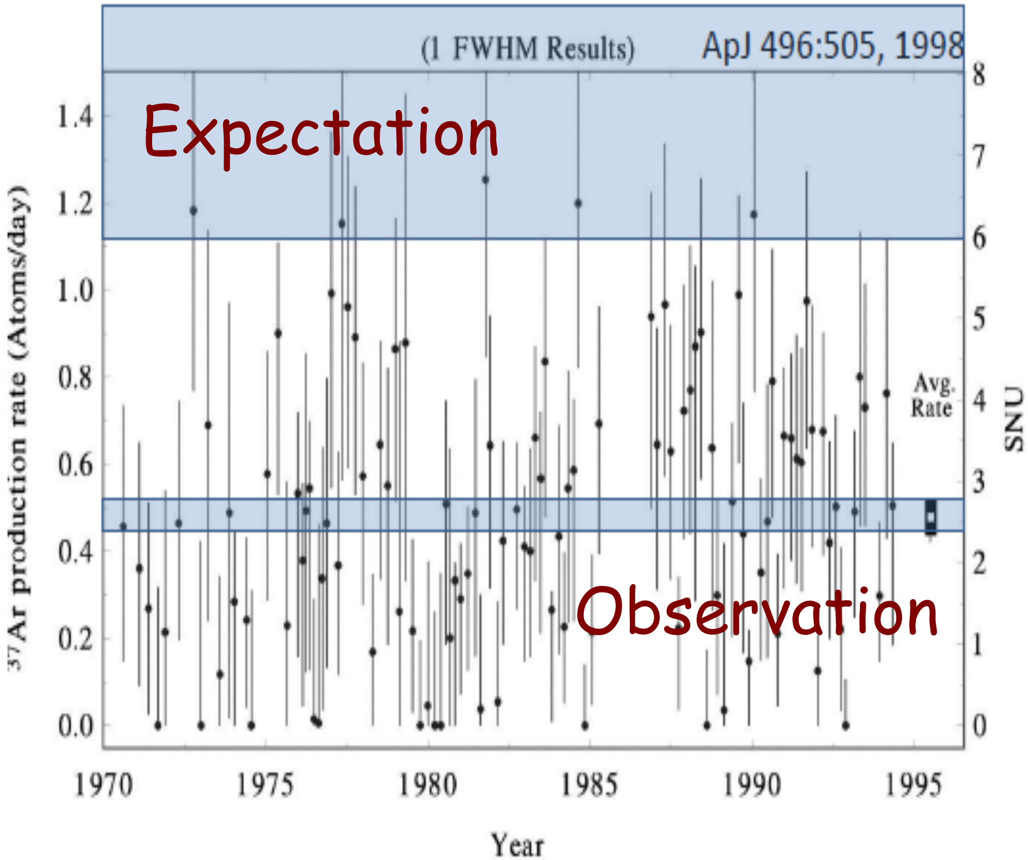
Solution :

Neutrino flavor oscillations

ν_μ and ν_τ mix

Measure $\Delta m^2_{\rm atm}$ and $\theta_{\rm atm}$

SOLAR NEUTRINO PUZZLE



Solution : Neutrino flavor oscillations in matter

ν_e mixes with other flavors.

Resonance mixing inside the Sun

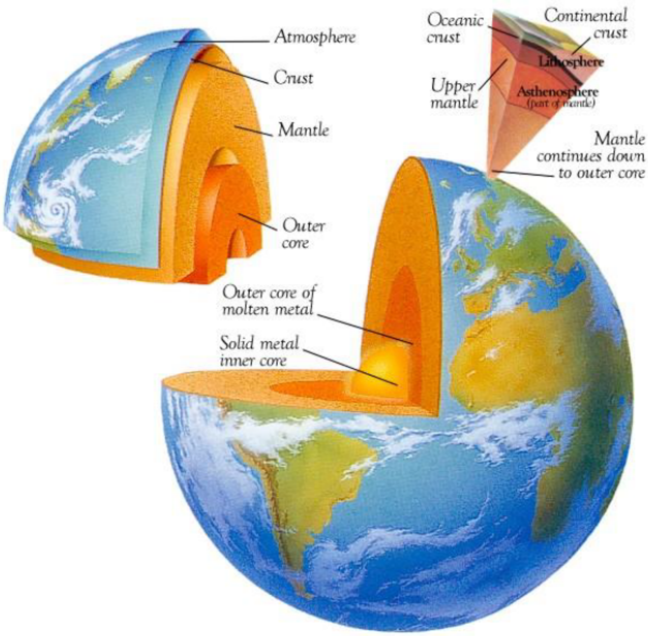
Measure $\Delta m^2_{\odot}$ and $\theta_{\odot}$

RREACTOR AND GEO NEUTRINO

Reactor Neutrinos:

Confirmed oscillations through solar neutrino parameters even in vacuum

Measure $\theta_{reactor}$



Geo Neutrinos:

Produced by natural radioactivity in Earth's crust

KamLAND, Borexino

Useful for understanding Earth's radioactivity

Neutrino Geophysics!!

3ν FRAMEWORK and OPEN QUESTIONS

- **Mixing parameters:** $U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{-i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{12} = \cos\theta_{12}$, etc.,

δ CP phase

- **Mass-gap parameters:** $M^2 = \left[-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm \Delta m^2 \right]$

"solar" "atmospheric"

$$\Delta m^2_{\rm atm} \approx 2.4 \times 10^{-3}\ {\rm eV}^2$$

$$\Delta m^2_{\odot} \approx 8 \times 10^{-5}\ {\rm eV}^2$$

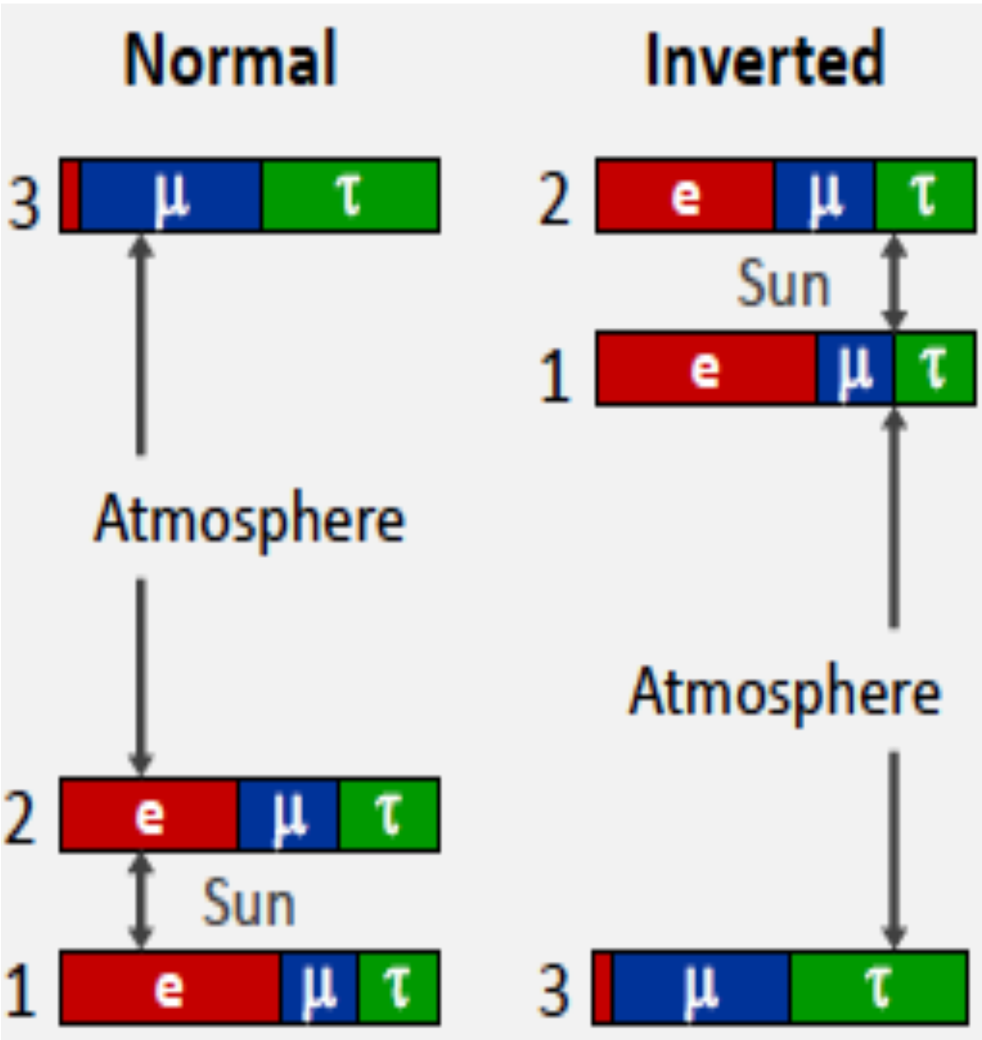
$$\theta_{\rm atm} \approx 45^\circ$$

$$\theta_{\odot} \approx 32^\circ$$

$$\theta_{\rm reactor} \approx 9^\circ$$

3ν FRAMEWORK and OPEN QUESTIONS

$$\nu_e, \nu_\mu, \nu_\tau \Rightarrow \nu_1, \nu_2, \nu_3$$

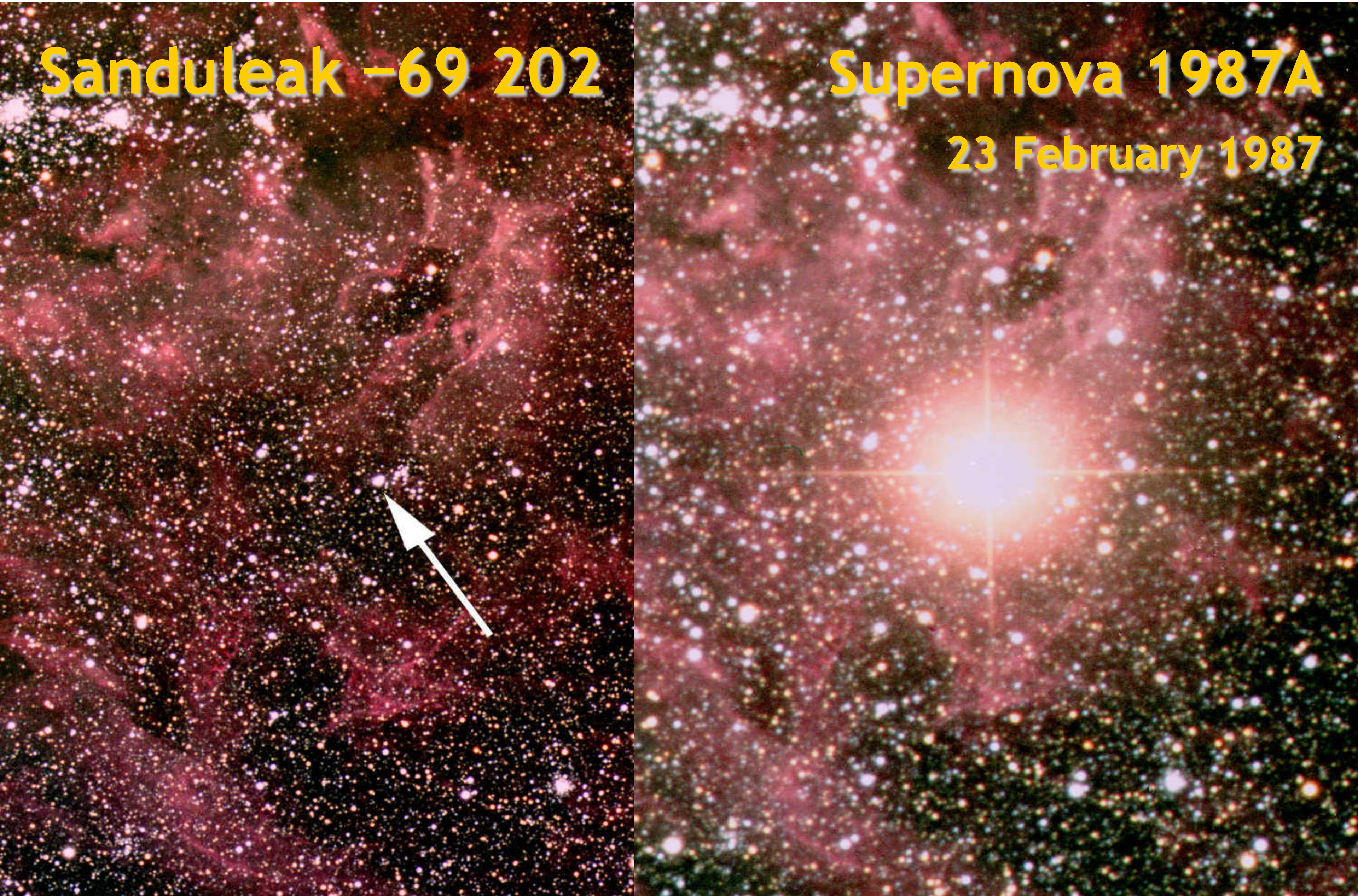


$$: \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2 \right)$$

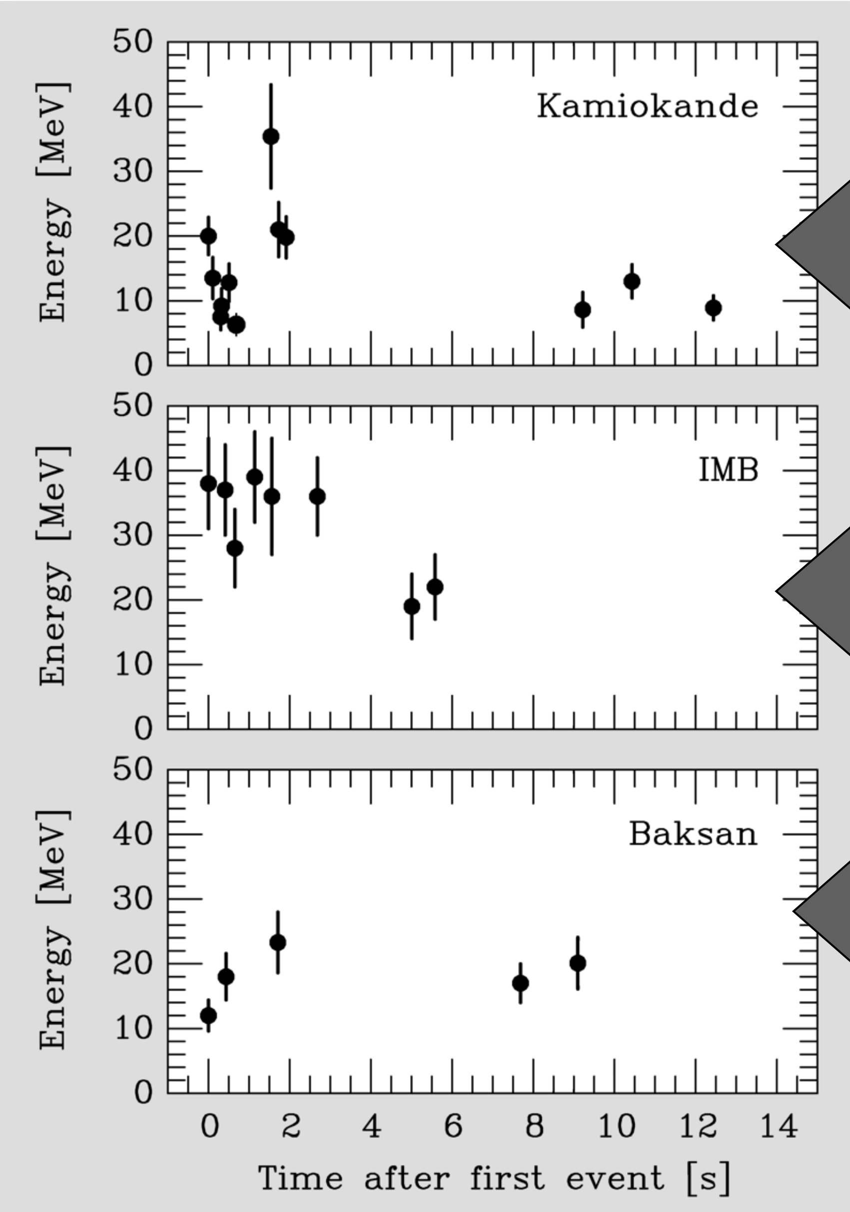
"solar" "atmospheric"

Mass Ordering: Normal vs Inverted

Neutrinos from Supernovae



…but about two hours before:



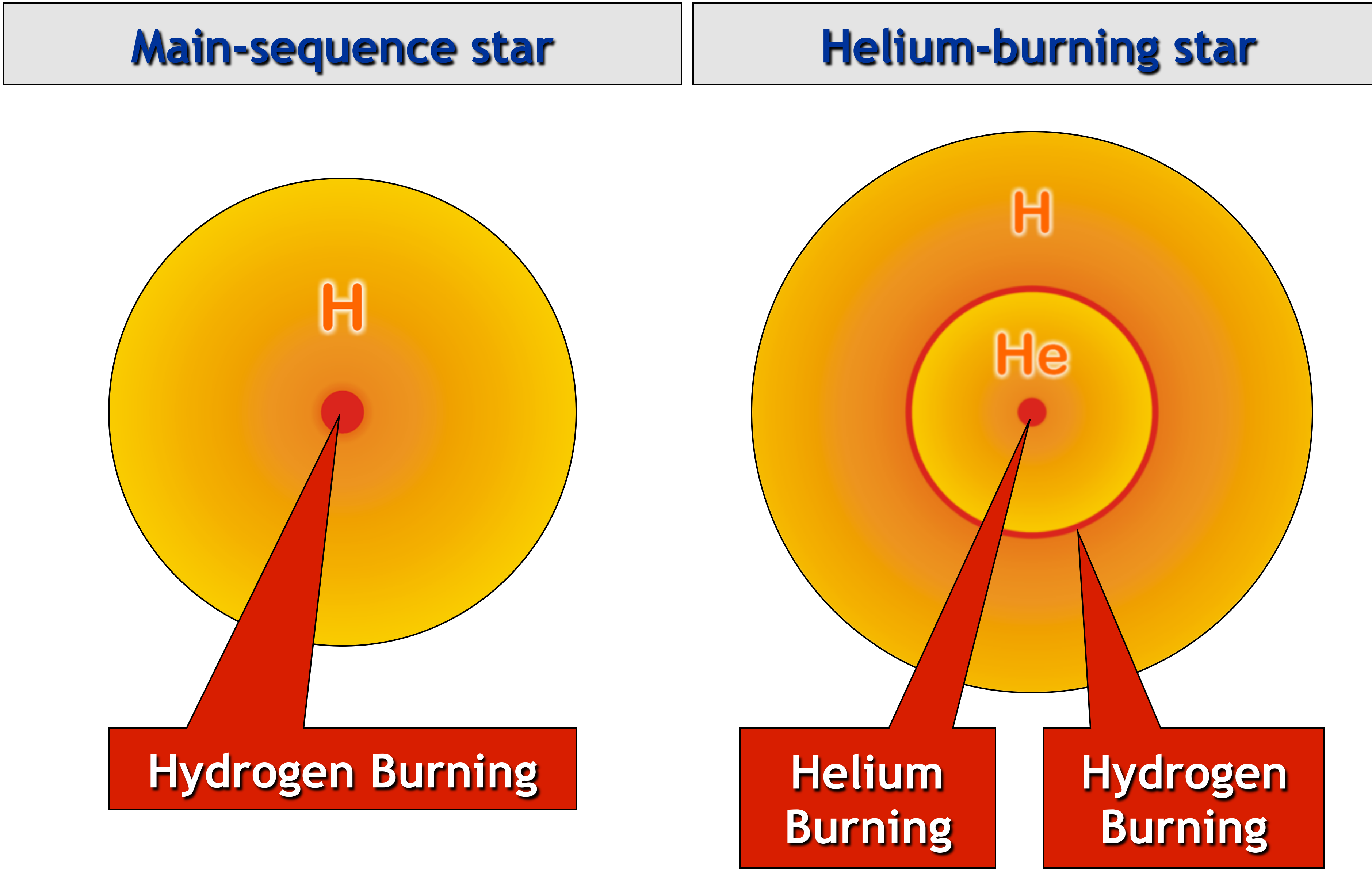
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

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!

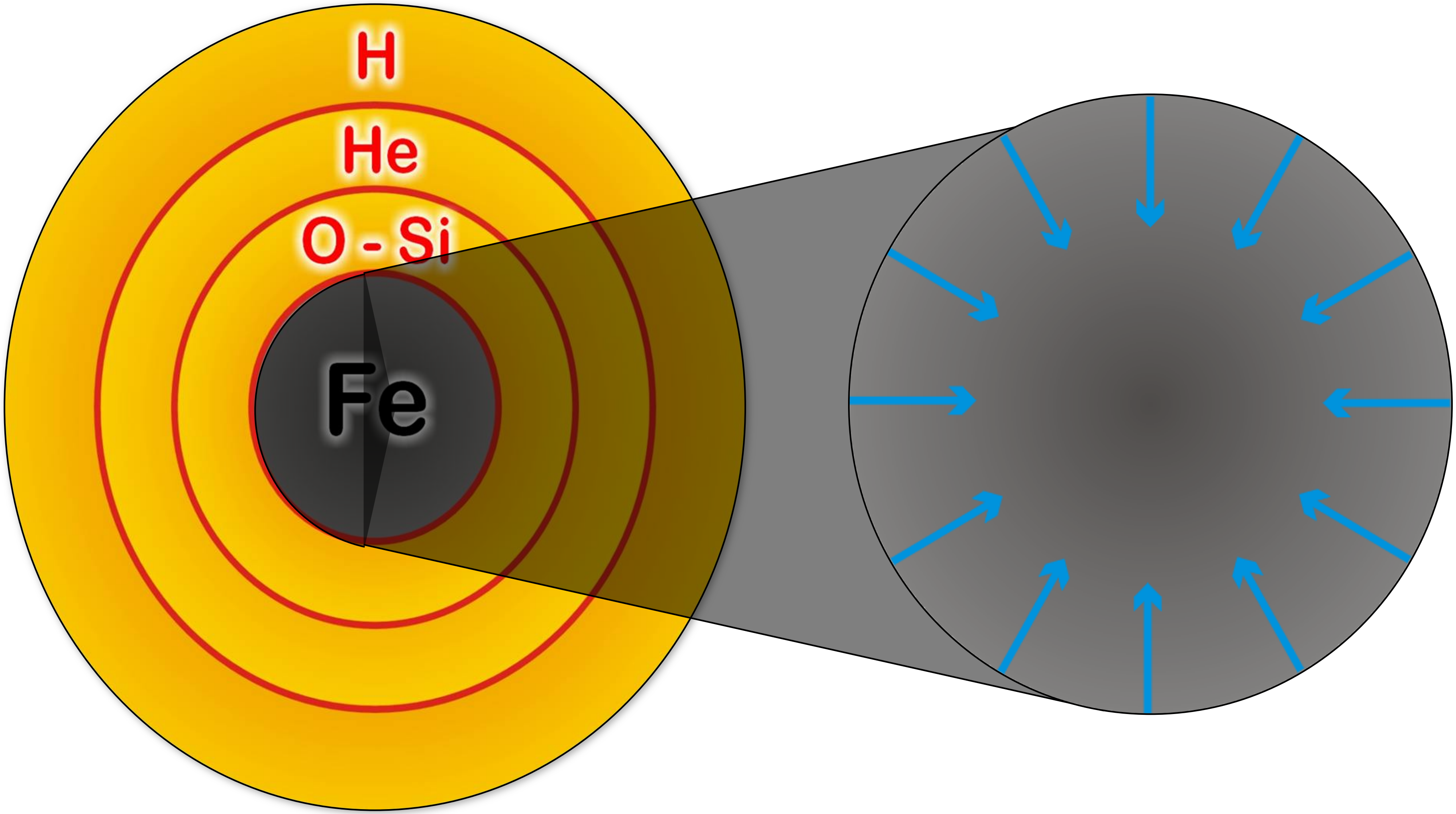
Stellar Collapse and Core-Collapse Supernova



[slides from G. Raffelt]

Stellar Collapse and Core-Collapse Supernova

Onion structure	Collapse (implosion)



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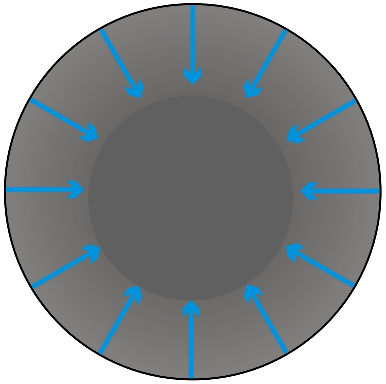
Stellar Collapse and Core-Collapse Supernova

Collapse (implosion)



Stellar Collapse and Core-Collapse Supernova

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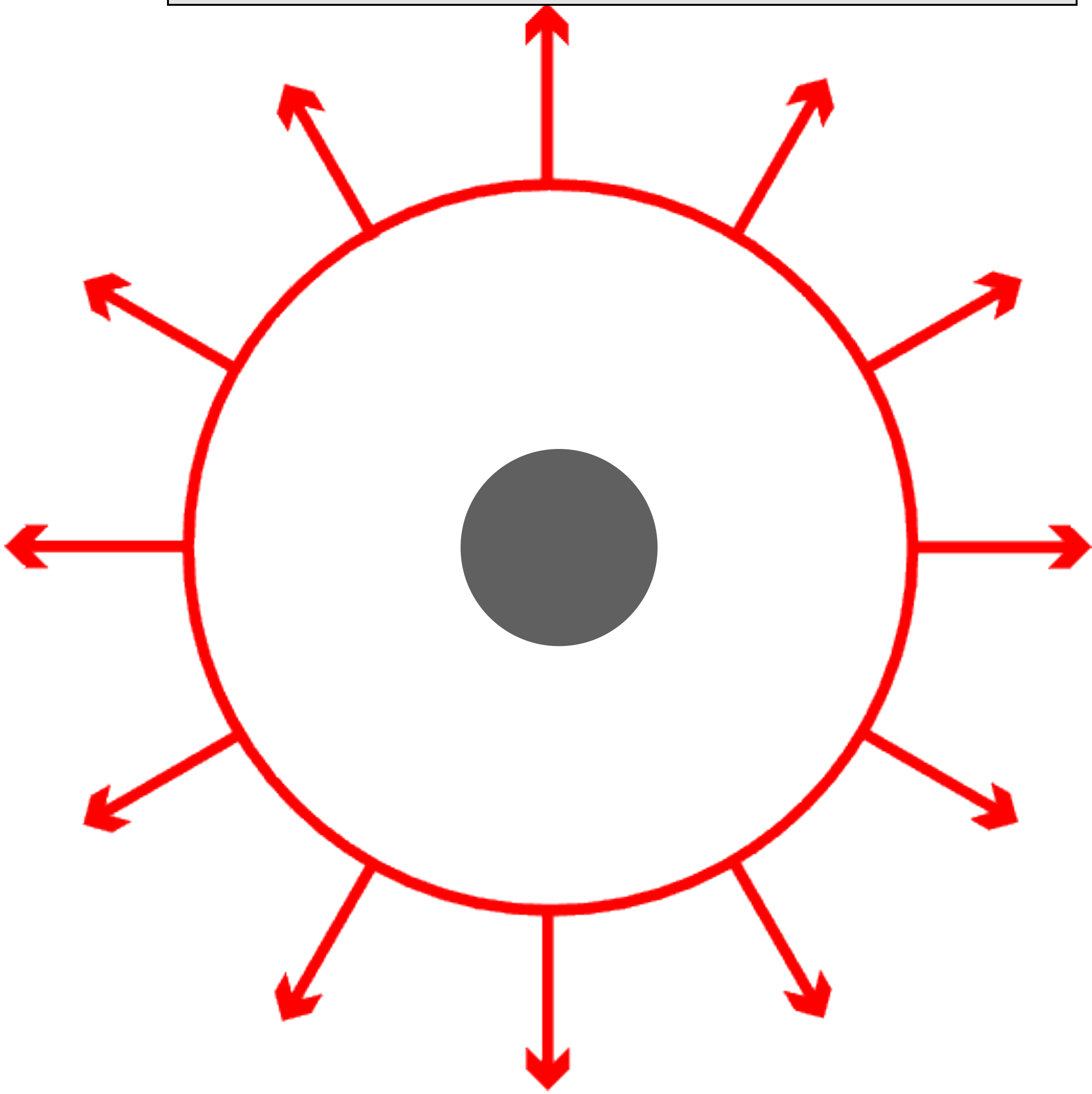

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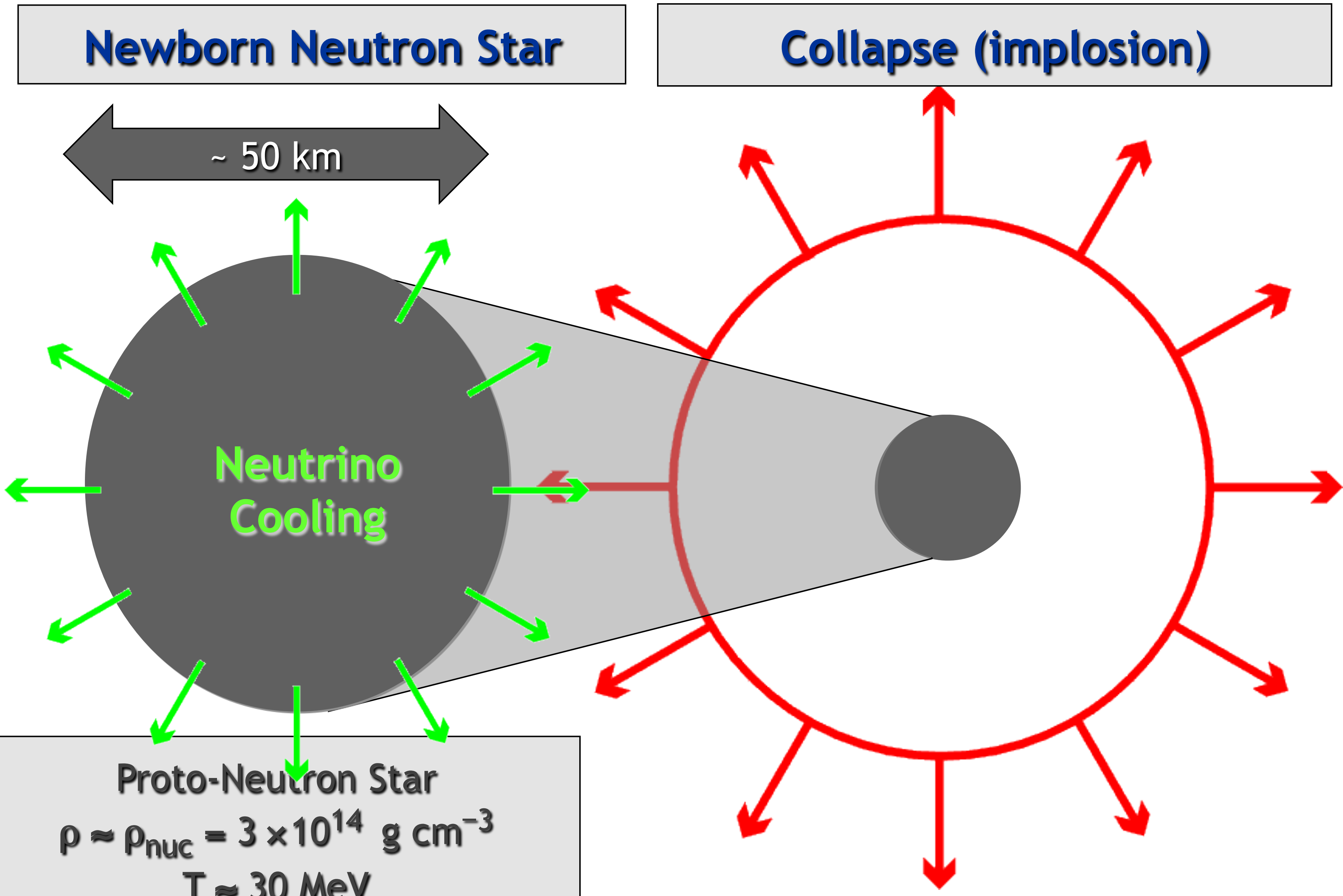
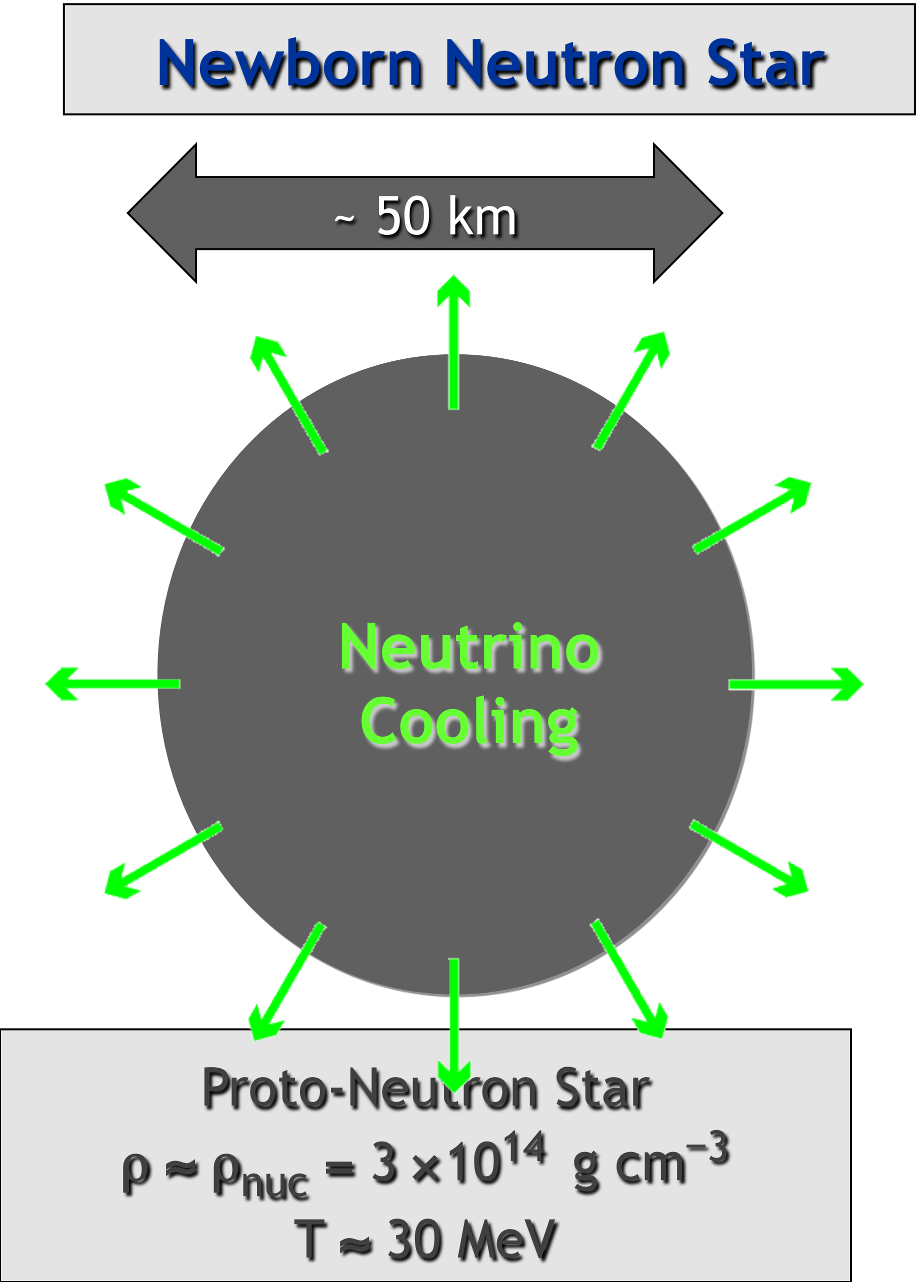


Proto-Neutron Star

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

$T \approx 30\ \mathrm{MeV}$

Stellar Collapse and Core-Collapse Supernova



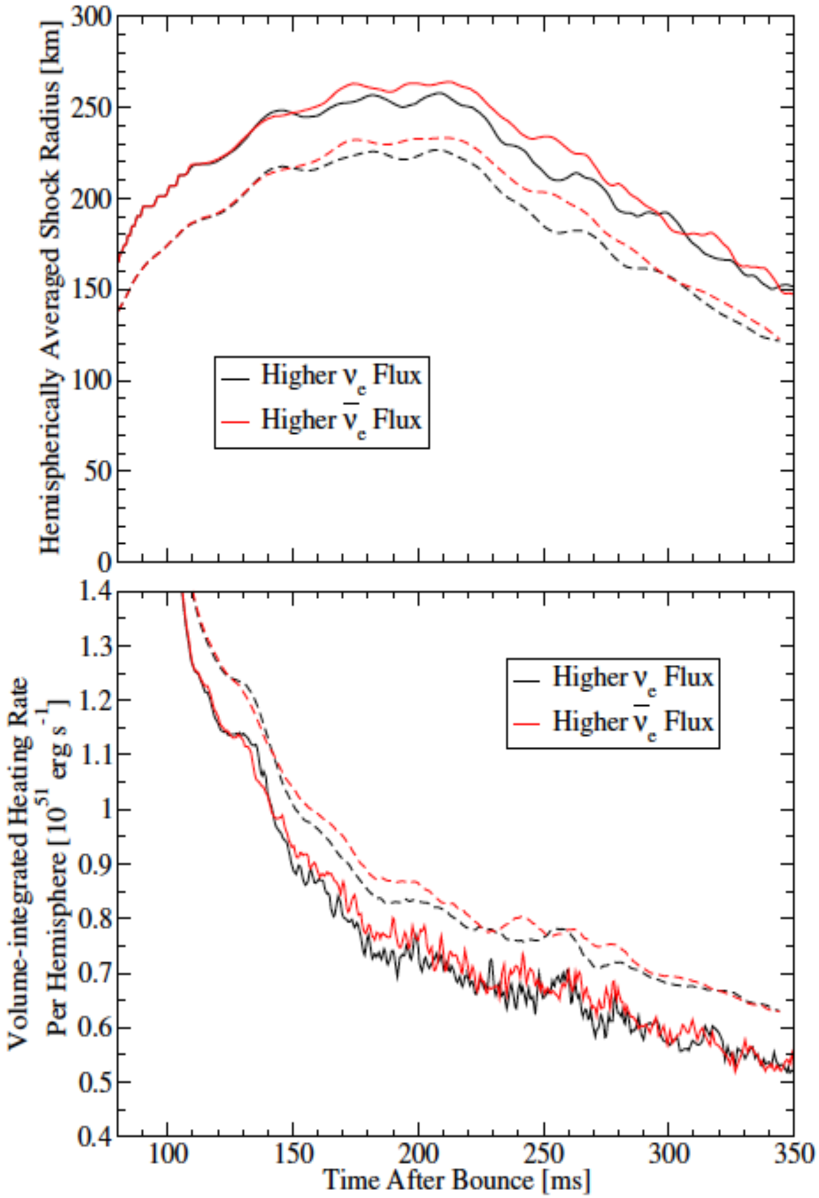
ENERGY SCALE:

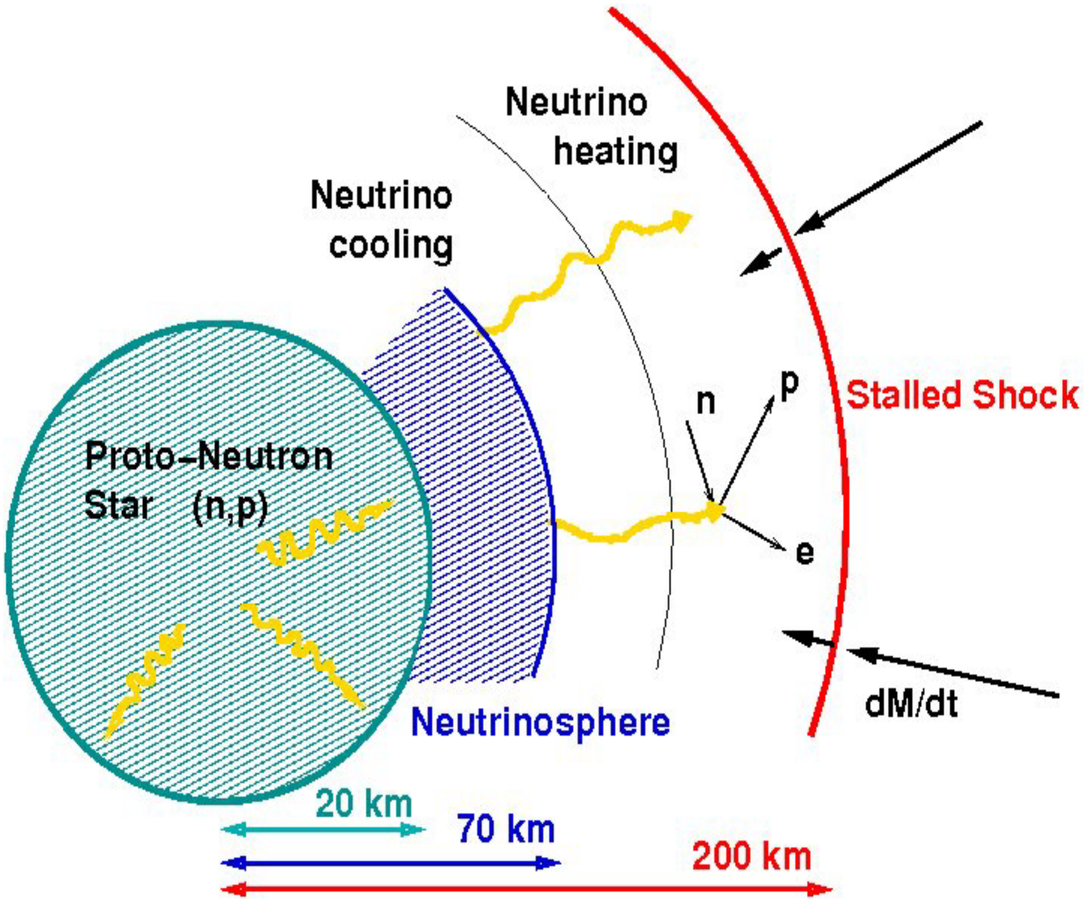
99% energy (10^{53} ergs) is emitted by neutrinos (Energy ~ 10 MeV).

TIME SCALE:

The duration of the burst lasts ~10s.

Shock Revival by Neutrinos





Shock receive fresh energy from neutrinos!!

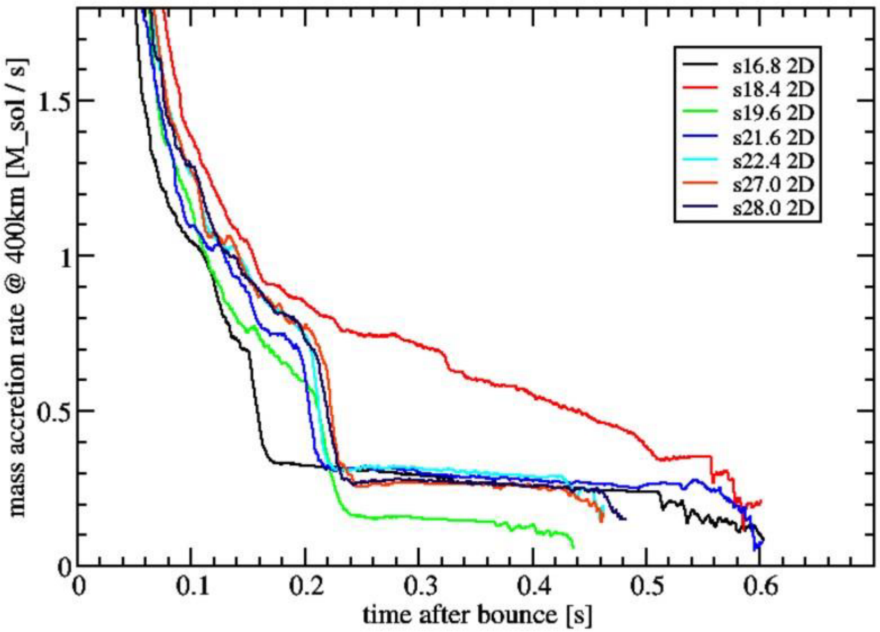
Delayed Mechanism

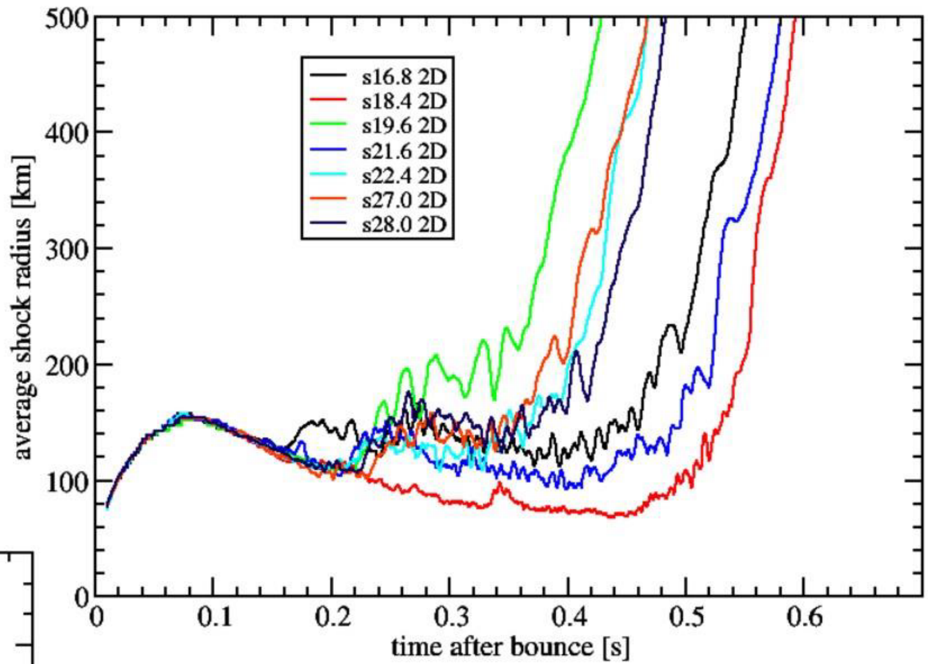
Growing Set of 2D Exploding Models

Realistic neutrino transport, convection and turbulence, hydrodynamical instabilities (SASI).

Hanke et al, 1303.6269

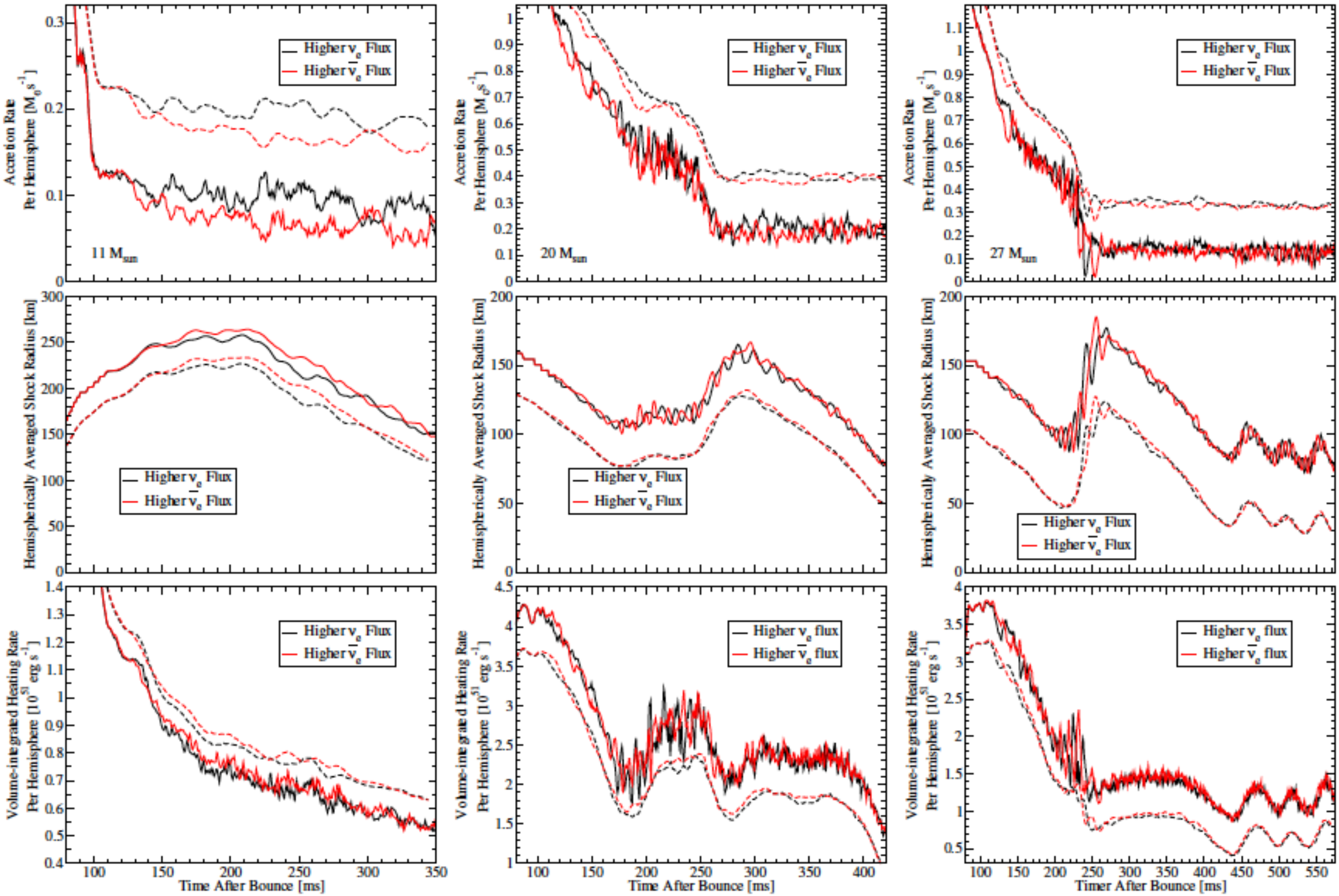
Mass accretion rate





Average shock radius

Failed Explosion



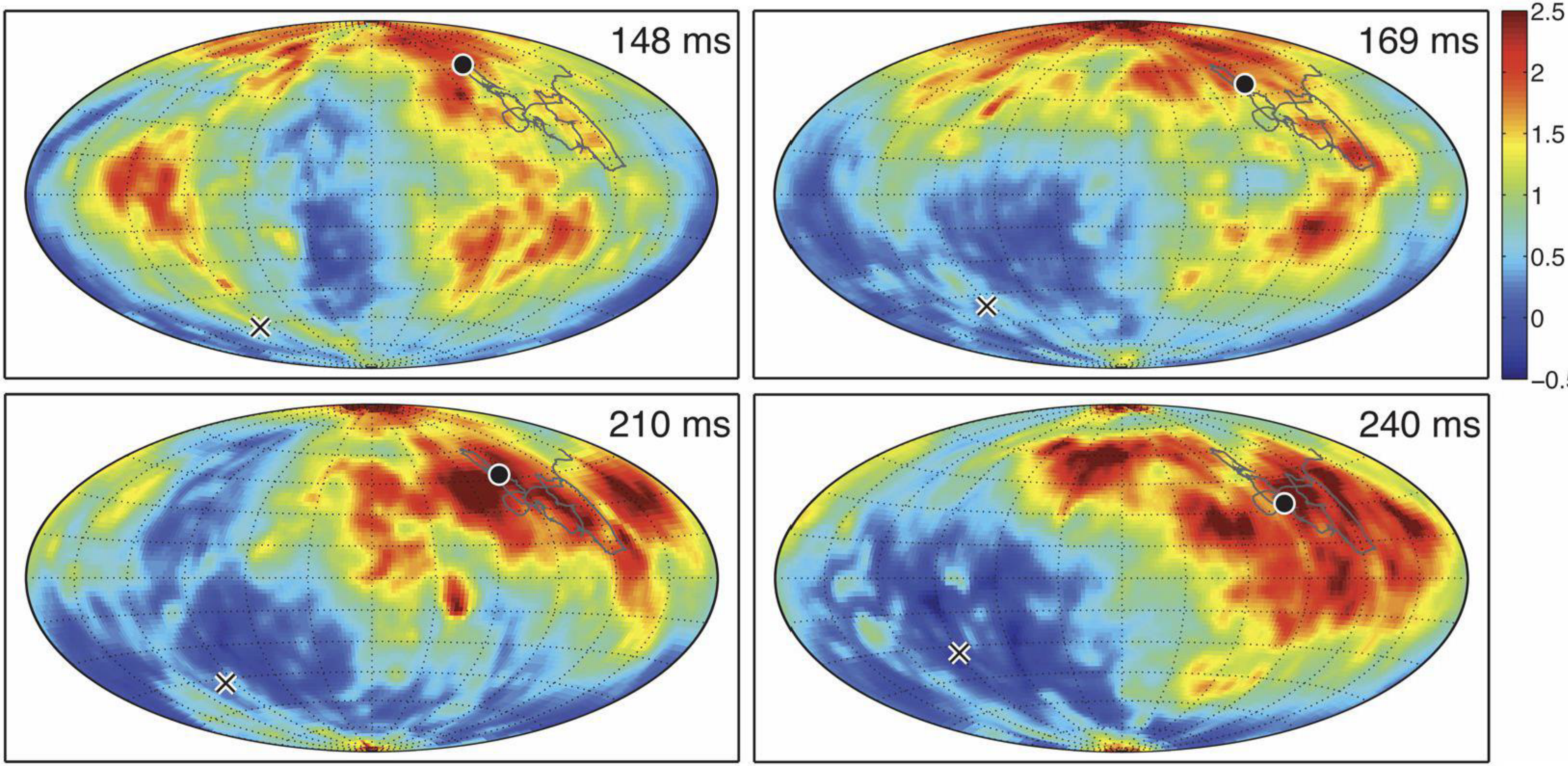
Tamborra et al., arXiv:1402.5418

Status of SN Explosion

- Standard paradigm for many years: Neutrino-driven explosion
  (delayed explosion, Wilson mechanism)
- Numerical explosions ok for small-mass progenitors in 1D
  (spherical symmetry)
- Numerical explosions ok for broad mass range in 2D
  (axial symmetry)
- 3D studies only beginning – no clear picture yet
  Better spatial resolution needed?

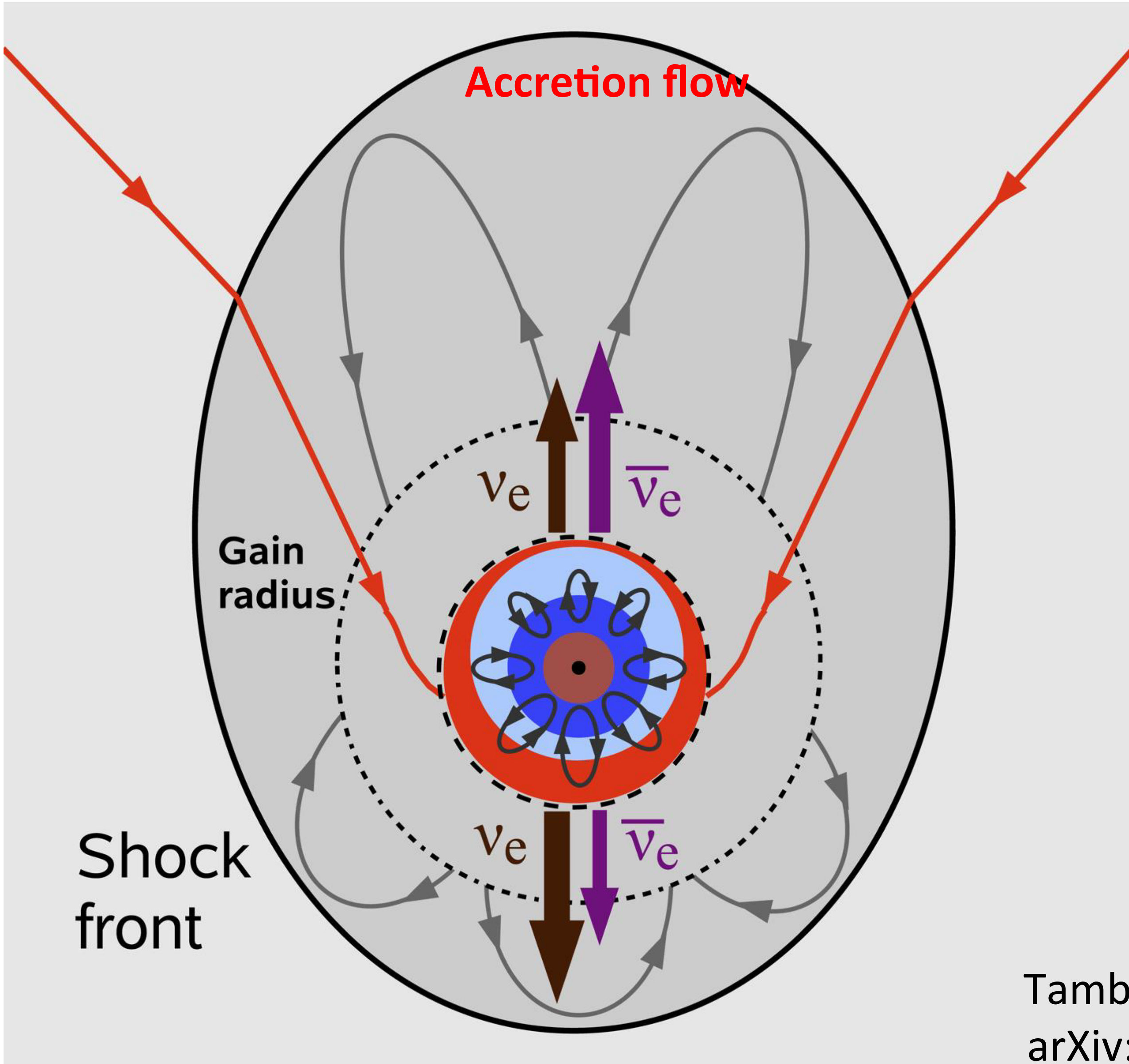
Sky Map of Lepton-Number Flux (11.2 M_{SUN} Model)

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

LESA Schematic Description



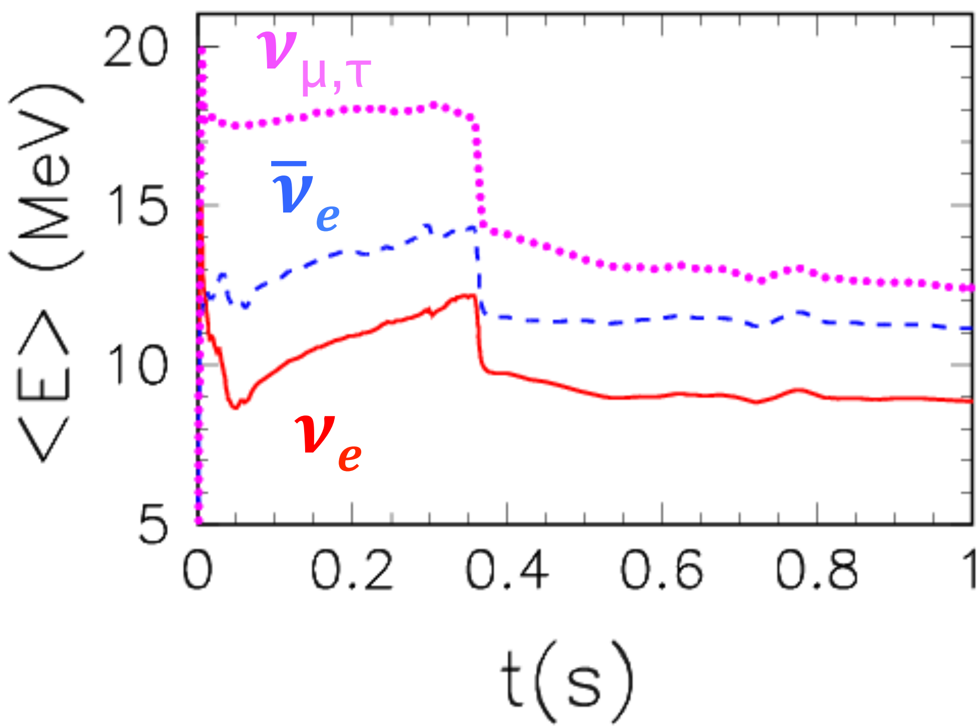
Tamborra et al., arXiv:1402.5418

Neutrino Average Energy

Accretion

- powered by infalling matter
- Stalled shock

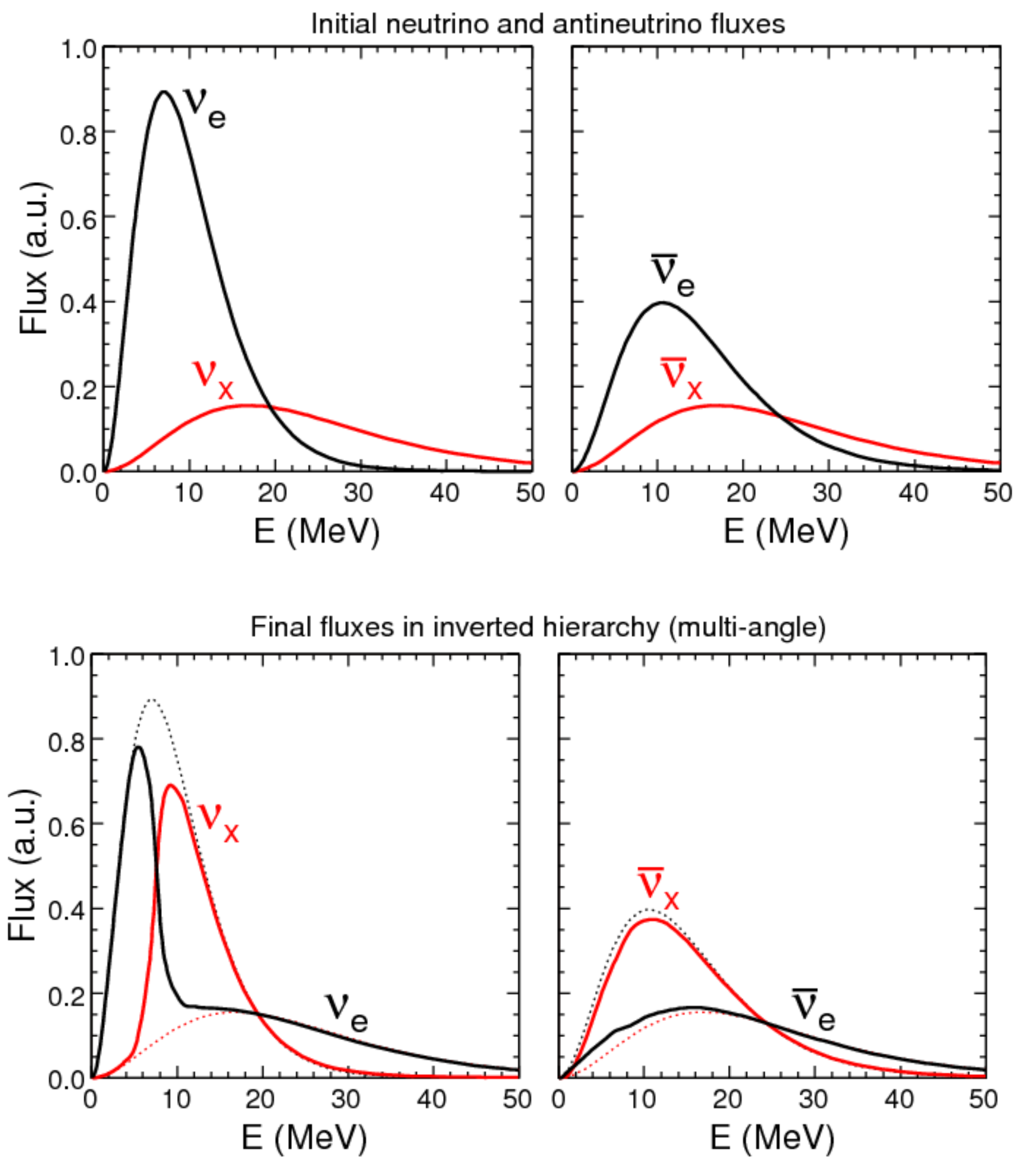
Accretion: ~ 0.5 s



Flavor Oscillation can give harder ν_e and $\bar{\nu}_e$ spectra

[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Neutrino Emission Phases



Flavor Oscillation can give harder ν_e and $\bar{\nu}_e$ spectra

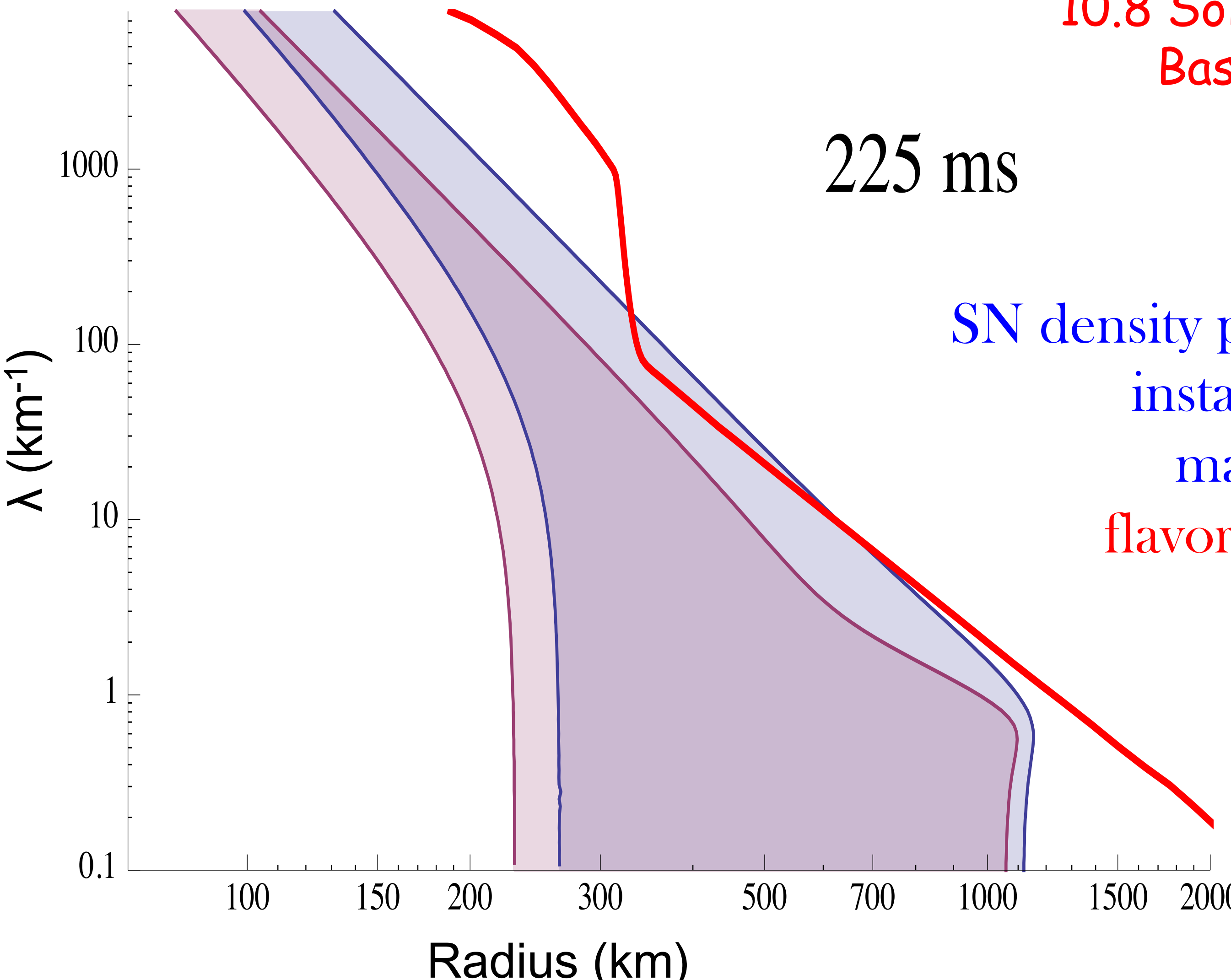
Instabilities in neutrino evolution due to Neutrino-Neutrino interaction

EXTRA Heating???

[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Stability Analysis

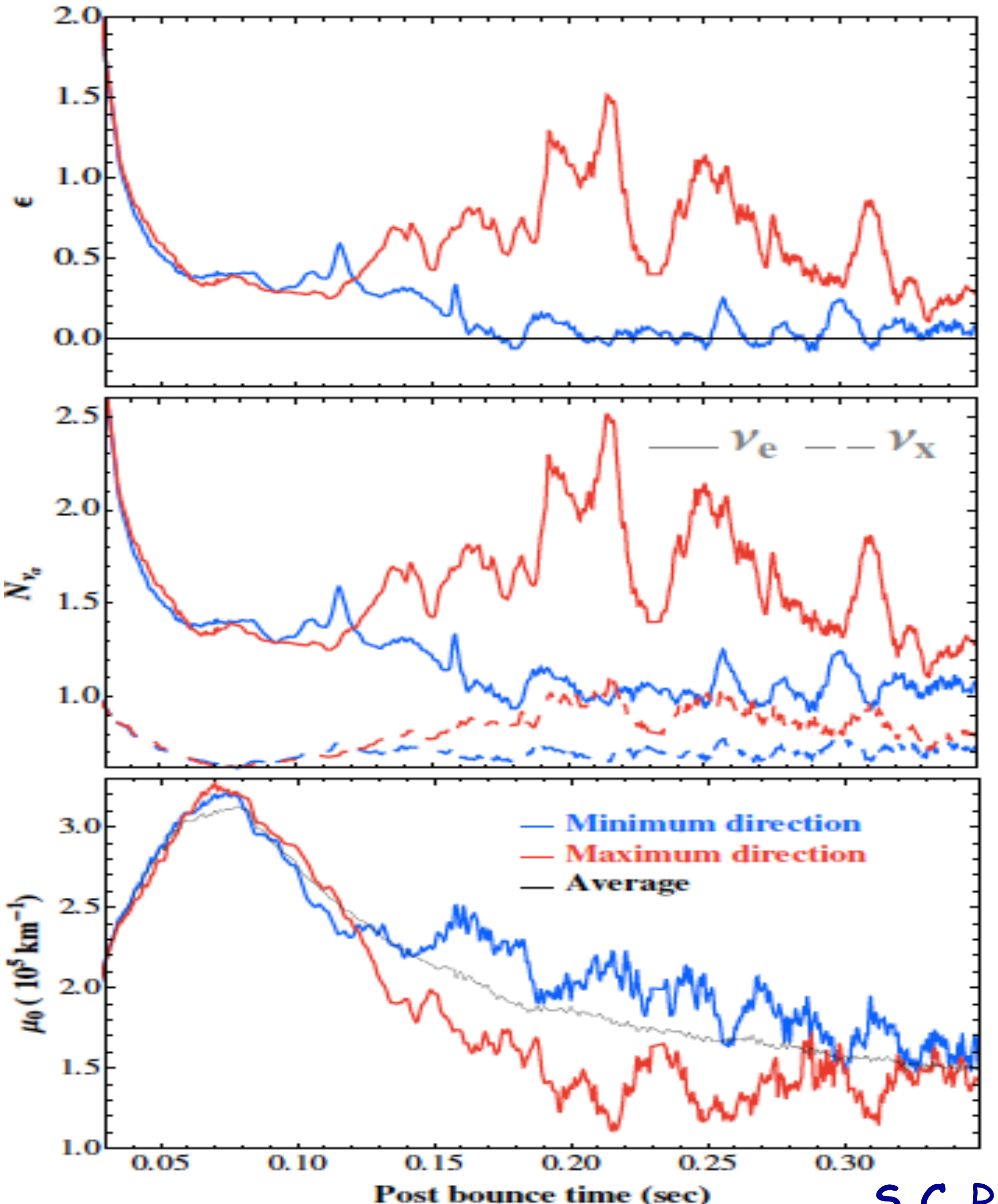
10.8 Solar Mass, 225 ms
Basel simulation



SN density profile crossing the instability zone may trigger flavor conversion

S.C, Mirizzi, Saviano & Seixas PRD, 2014

LESA Schematic Description

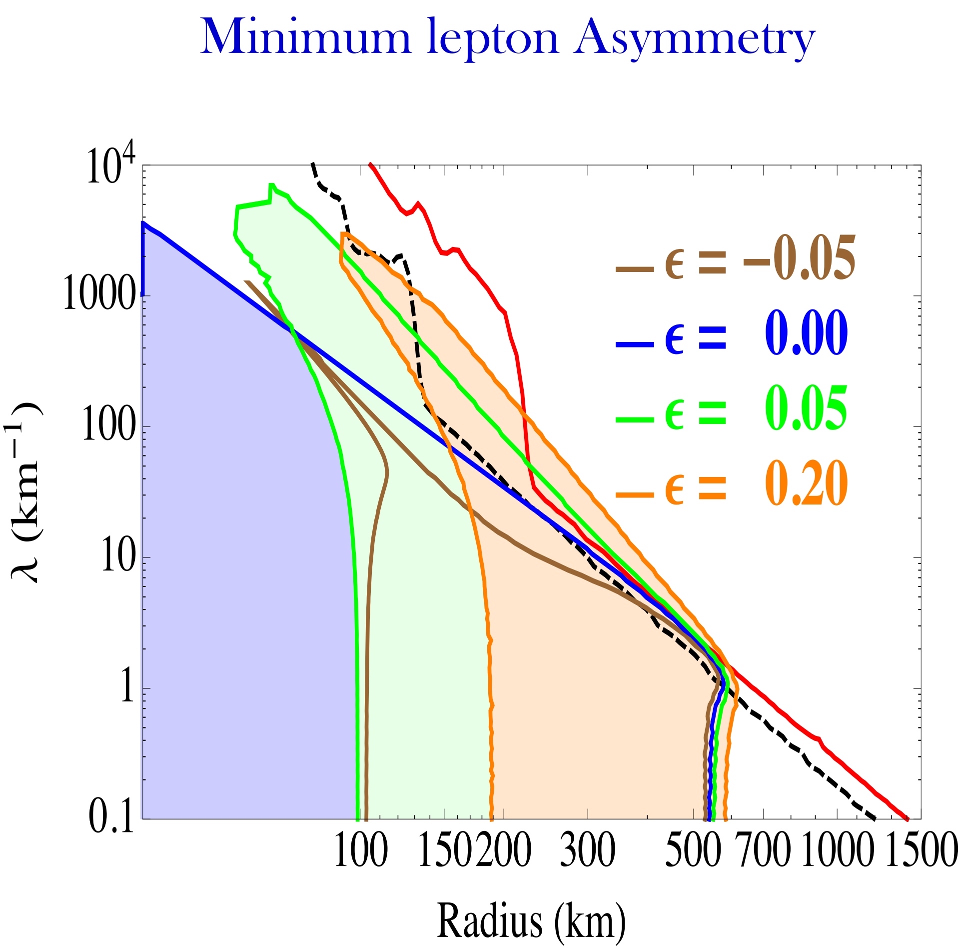


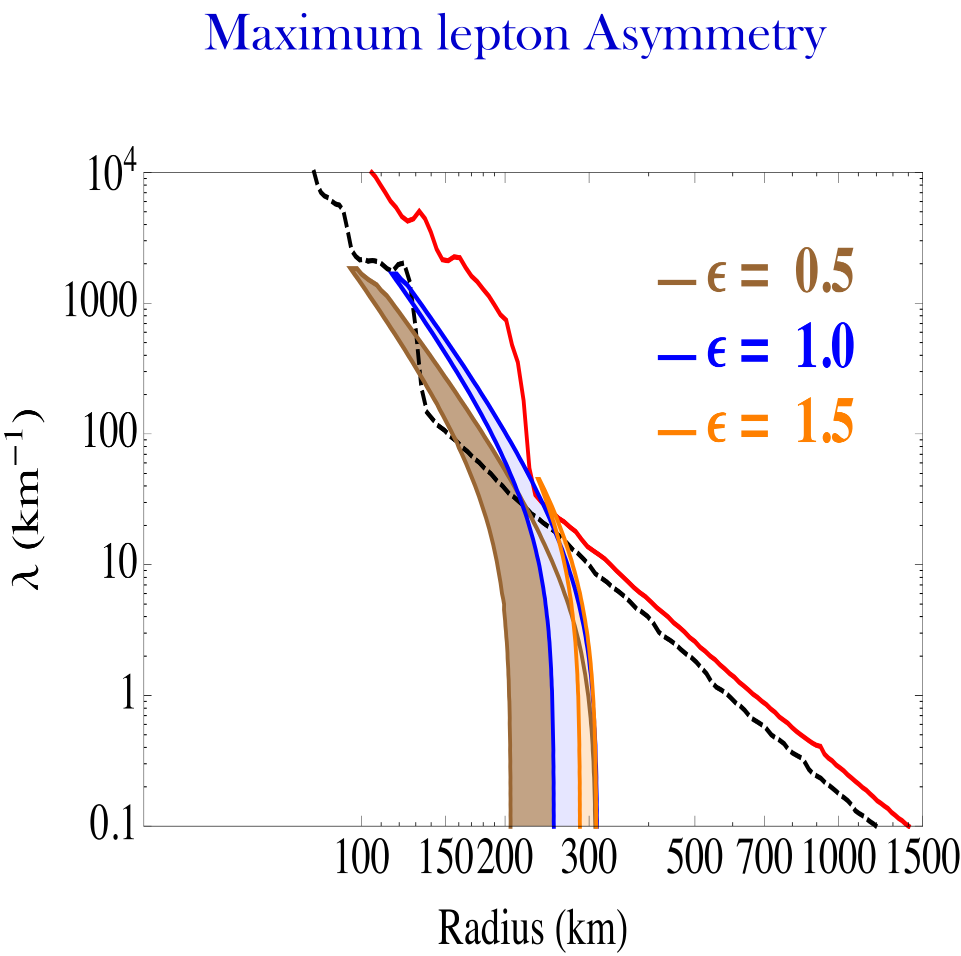
LESA lepton asymmetry

Large lepton asymmetry prohibits instability in neutrino evolution

S.C, Raffelt, Janka & Mueller, arXiv:1412.0670

Stability Analysis: LESA

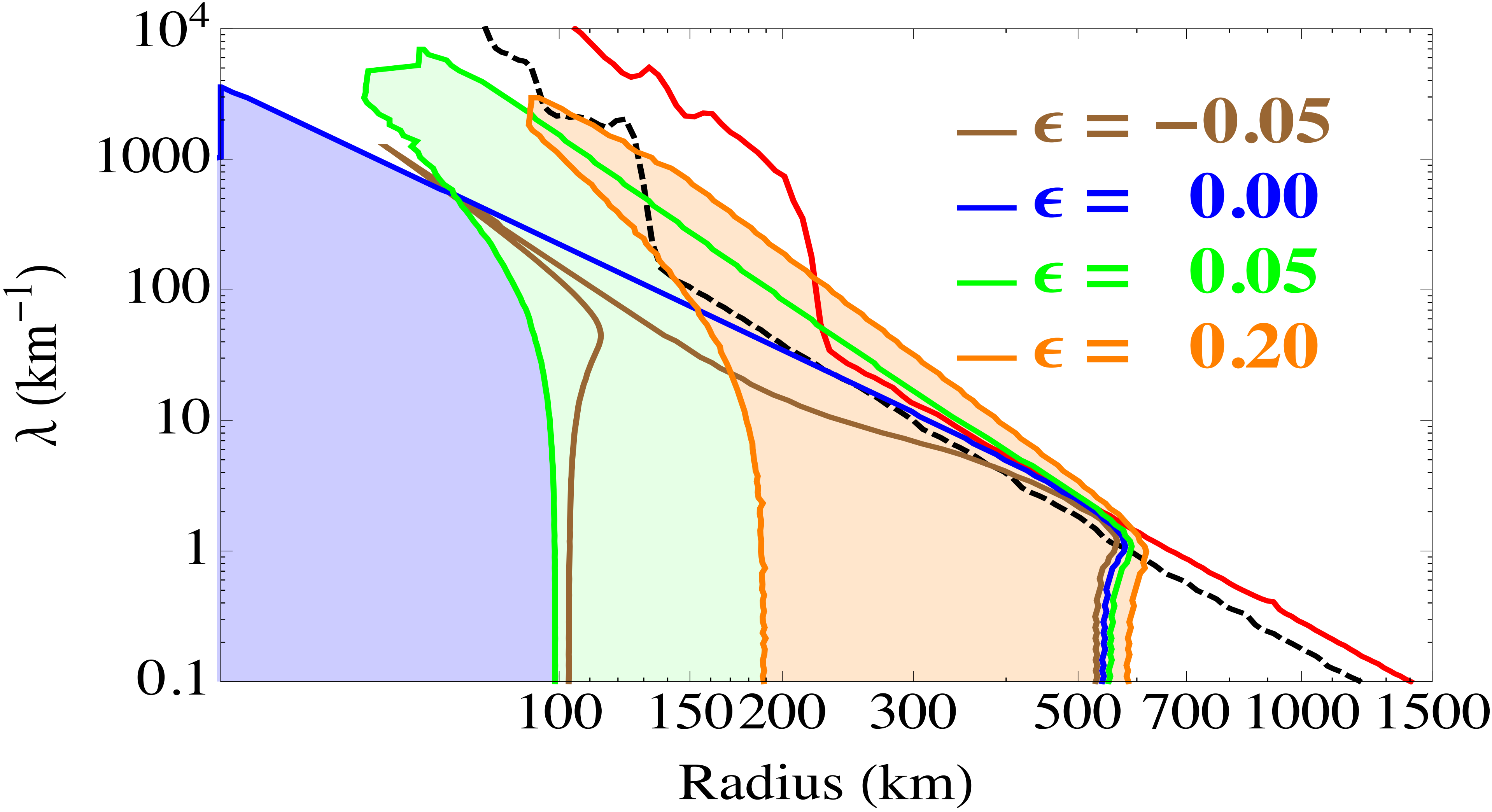




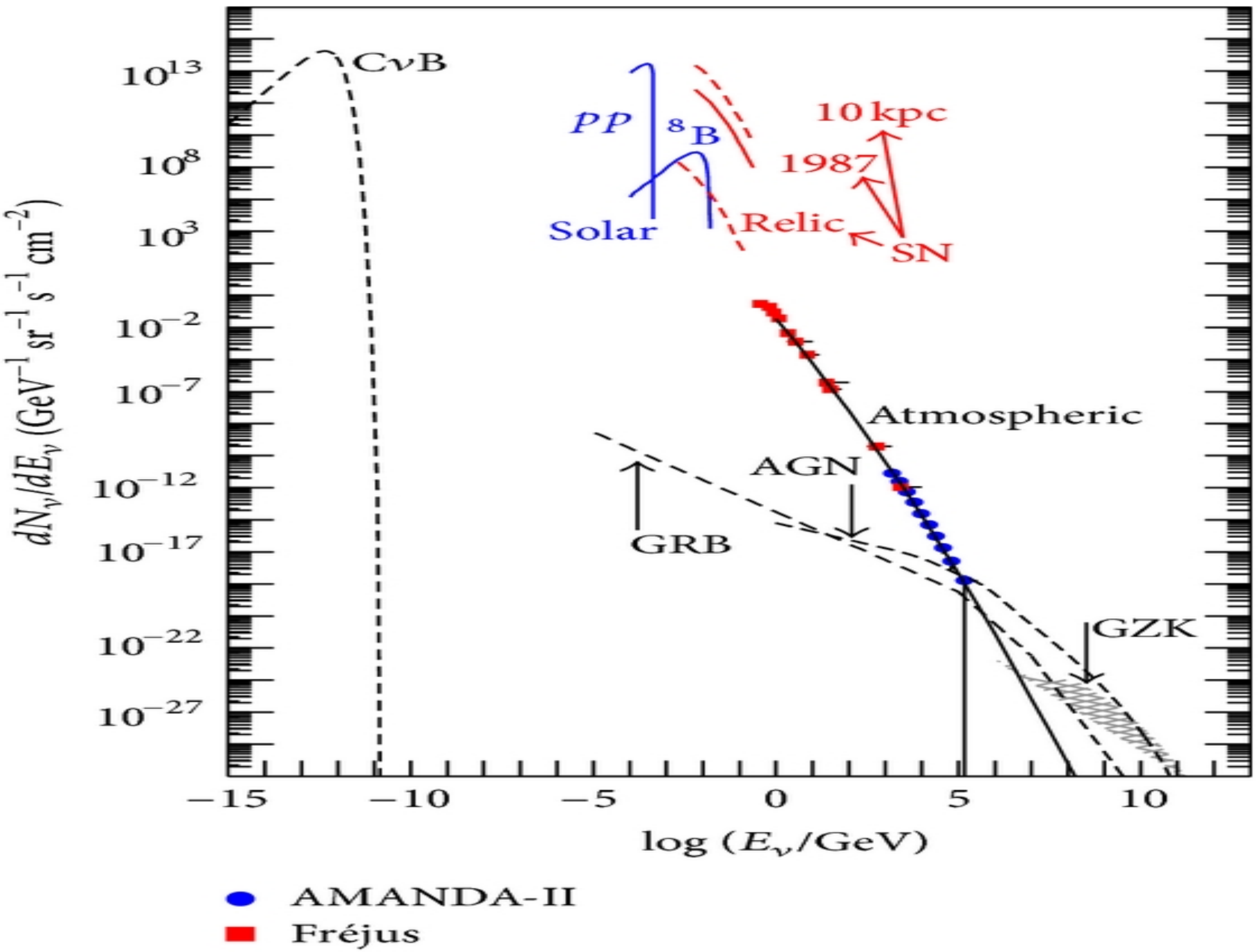
<u>S.C</u>, Raffelt, Janka & Mueller, arXiv:1412.0670

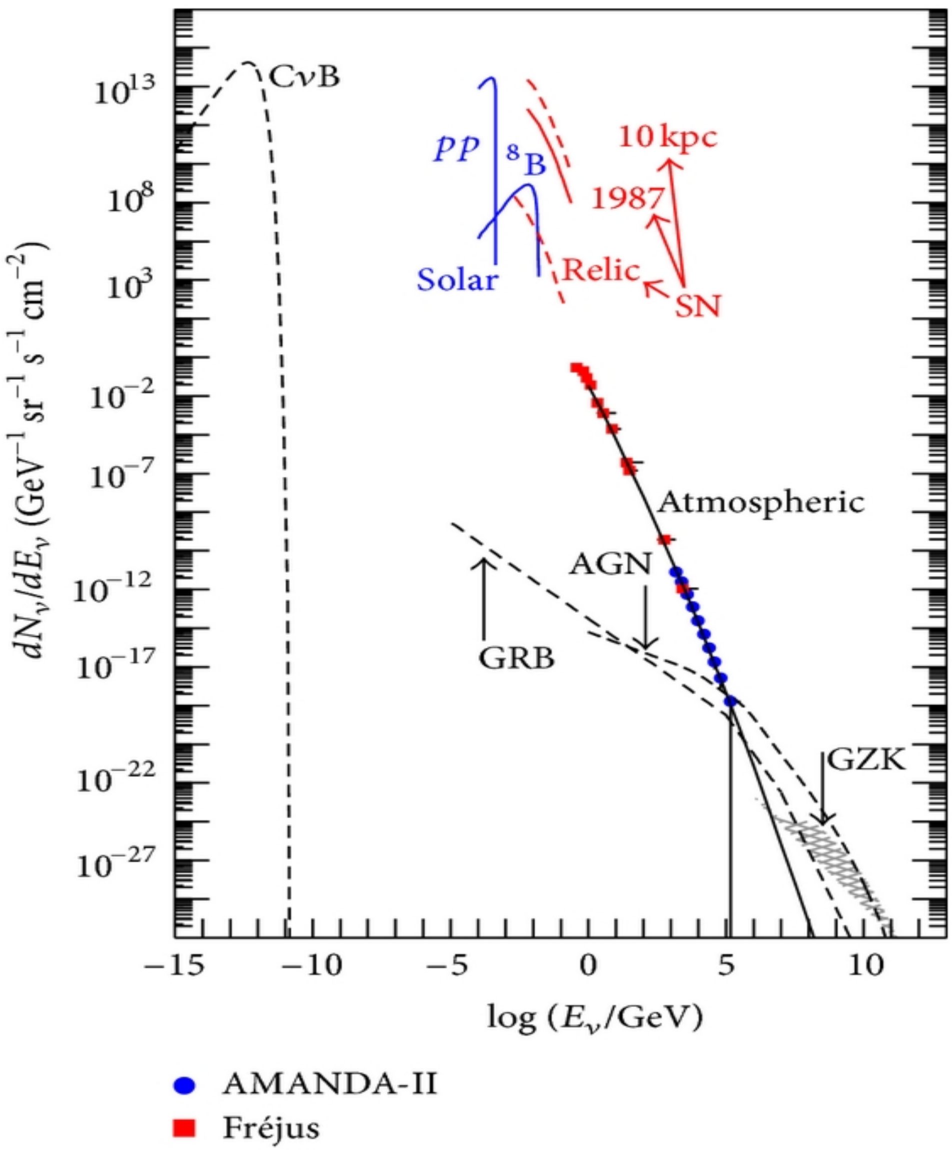
Stability Analysis: LESA

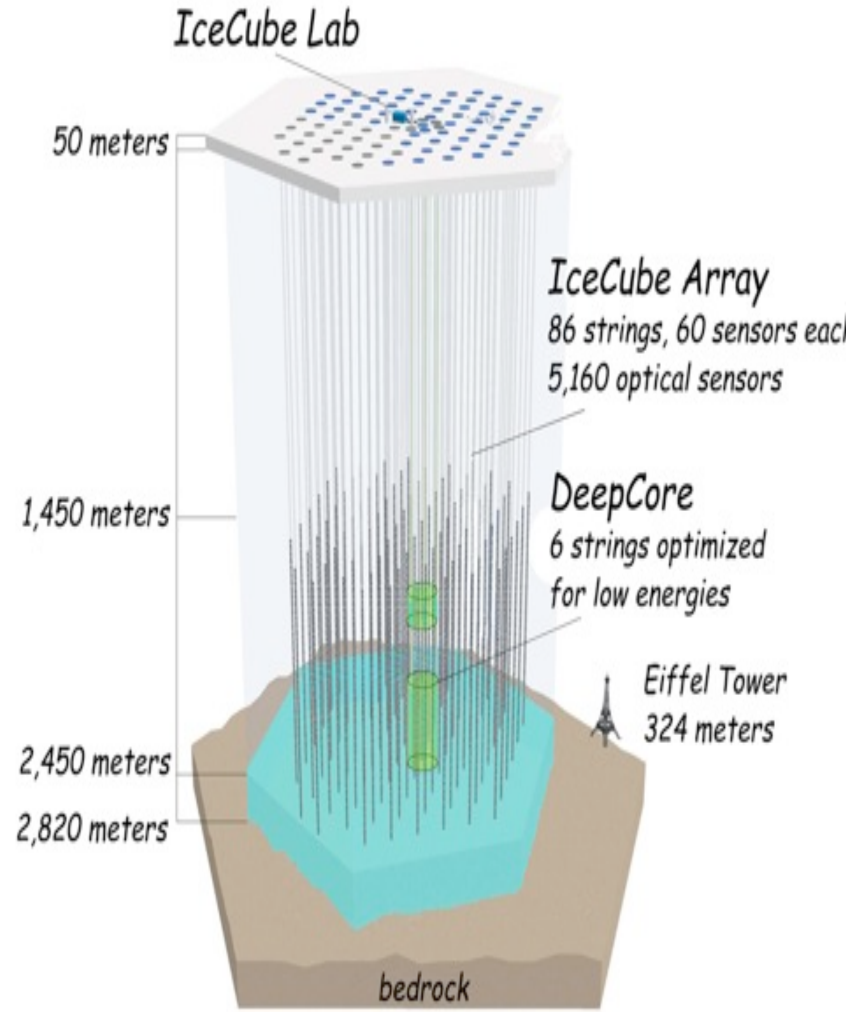
Minimum lepton Asymmetry



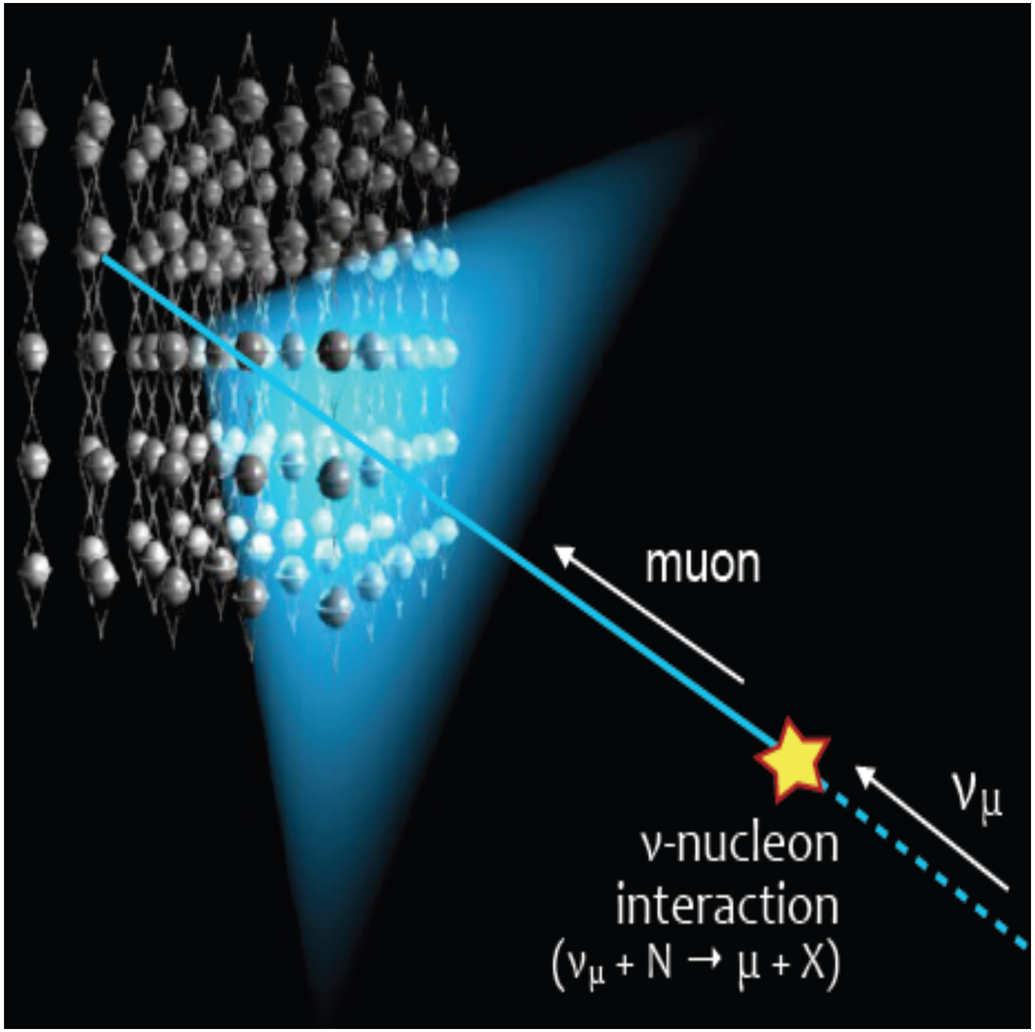
High Energy Neutrinos

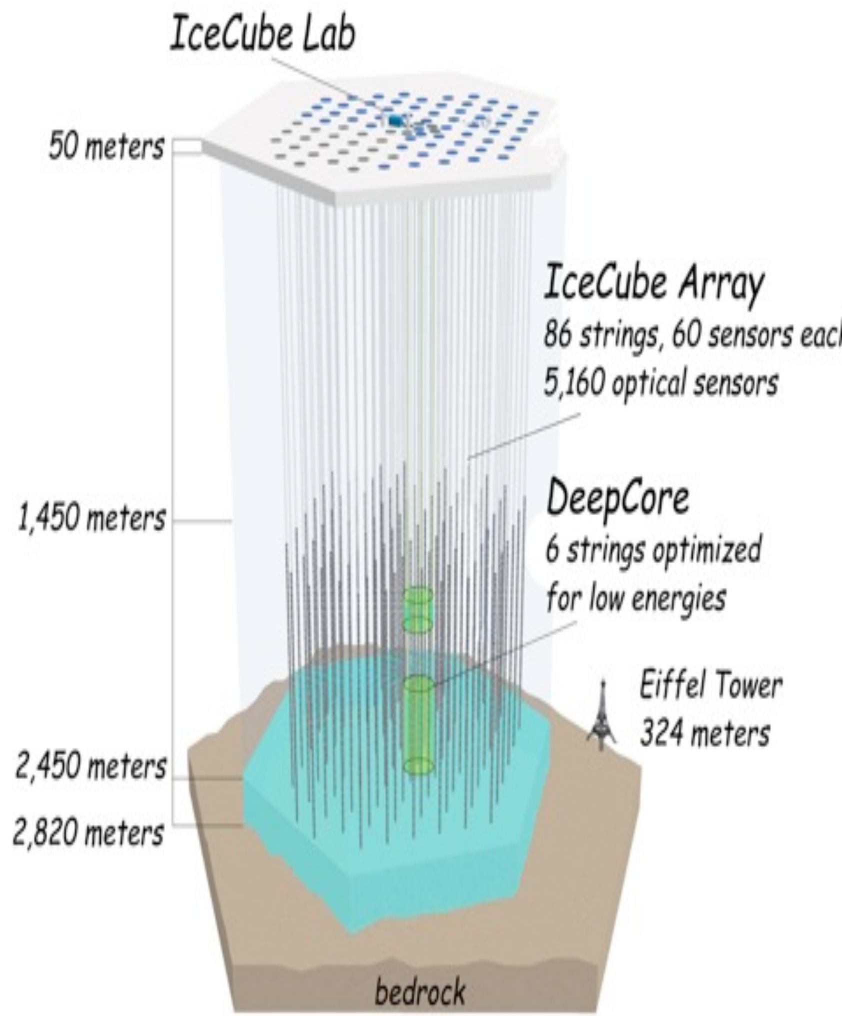



CνB
pp
8B
Solar
10 kpc
1987
Relic
SN
Atmospheric
AGN
GRB
GZK
dN_ν/dE_ν (GeV^{-1} sr^{-1} s^{-1} cm^{-2})
10^{13}
10^{8}
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
10^{-22}
10^{-27}
−15
−10
−5
0
5
10
log (E_ν/GeV)
AMANDA-II
Fréjus


IceCube Lab
50 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
1,450 meters
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
2,450 meters
2,820 meters
bedrock

What do we know?





Background and Signals

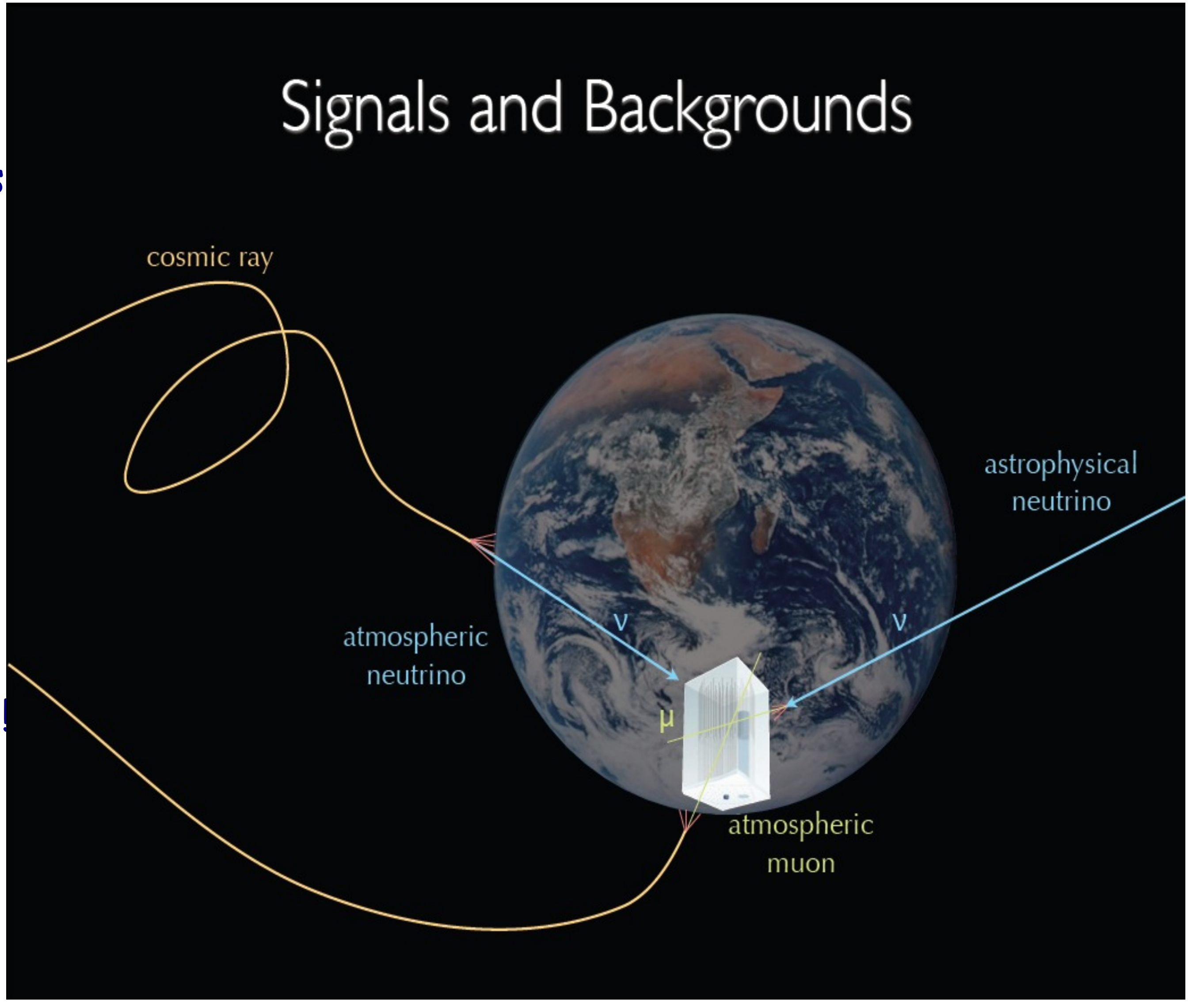
Atmospheric neutrino
& muon production
in cosmic ray air showers

Muons are absorbed
inside the Earth.
Only events from above.

Atmospheric neutrino
background From
North and South.

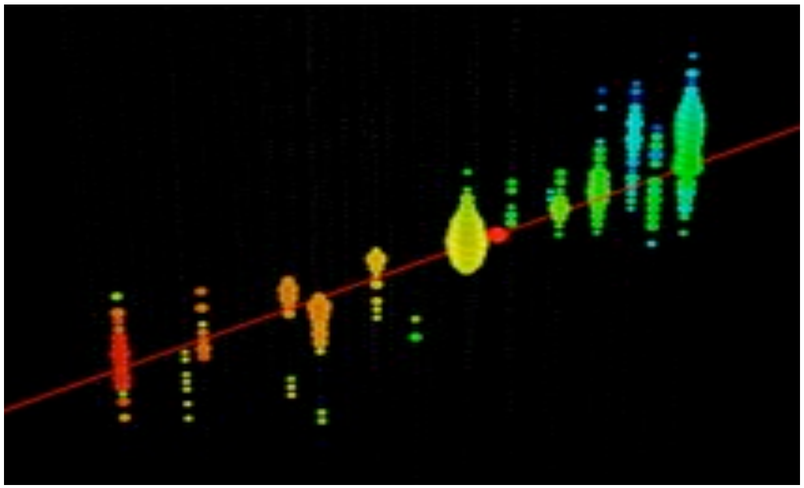
Earth becomes opaque
to high-energy neutrinos!

PeV events are coming
from above.



Event classes in IceCube

TRACKS



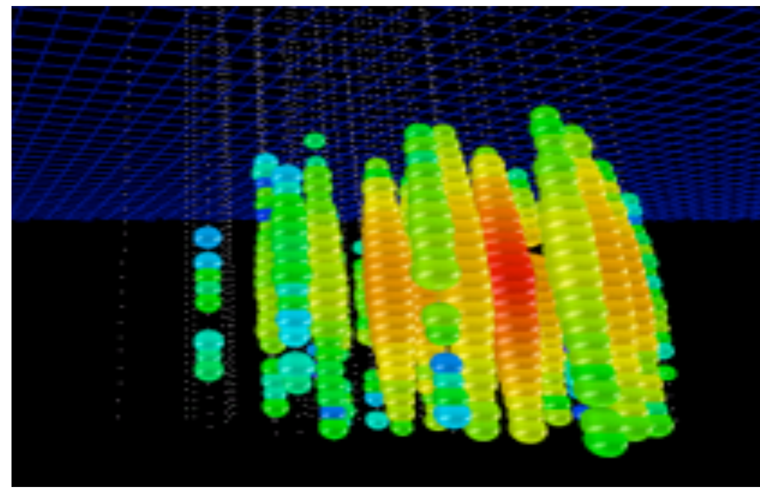
Source:

ν_{μ} CC interaction

Good angular resolution (<1°)

Moderate energy resolution

CASCADES



Source:

ν_e, ν_{μ}, ν_{τ} NC + ν_e CC interaction

Limited angular resolution (≳10°)

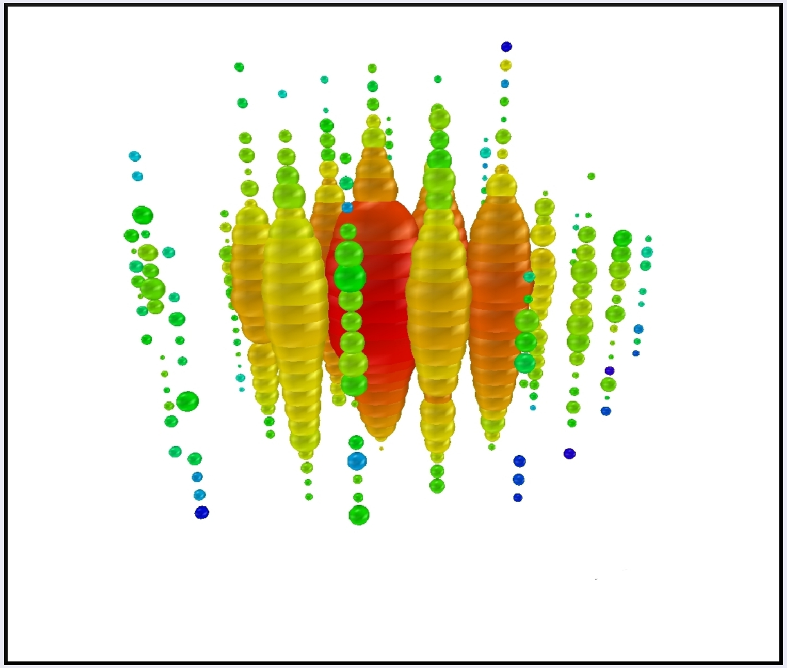
Good energy resolution

PeV Events in IceCube

- Shown at Neutrino'12
- Both downgoing cascades
- Expected background: 0.082

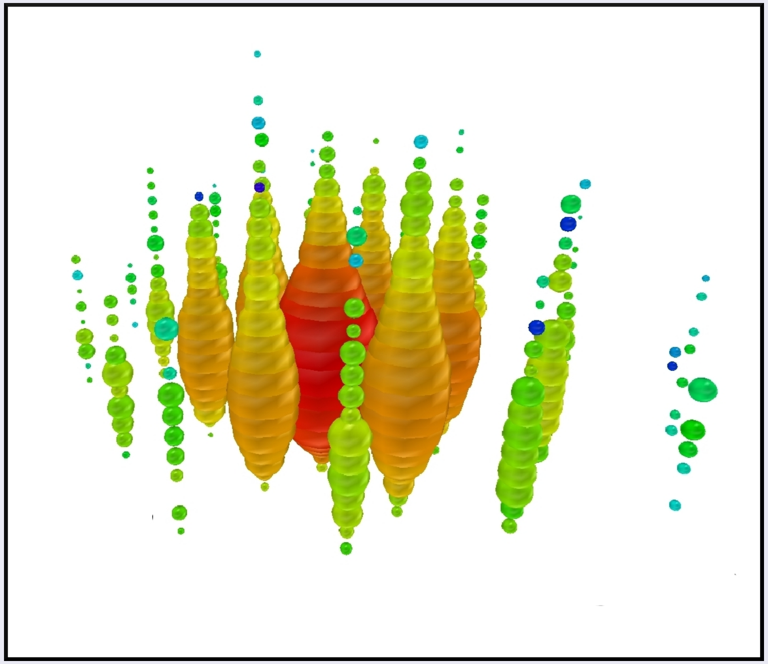
August 9th, 2011

1.04 ± 0.16 PeV



January 3rd, 2012

1.14 ± 0.17 PeV



IceCube Collaboration, PRL 111, 021103(2013)

PeV Events in IceCube

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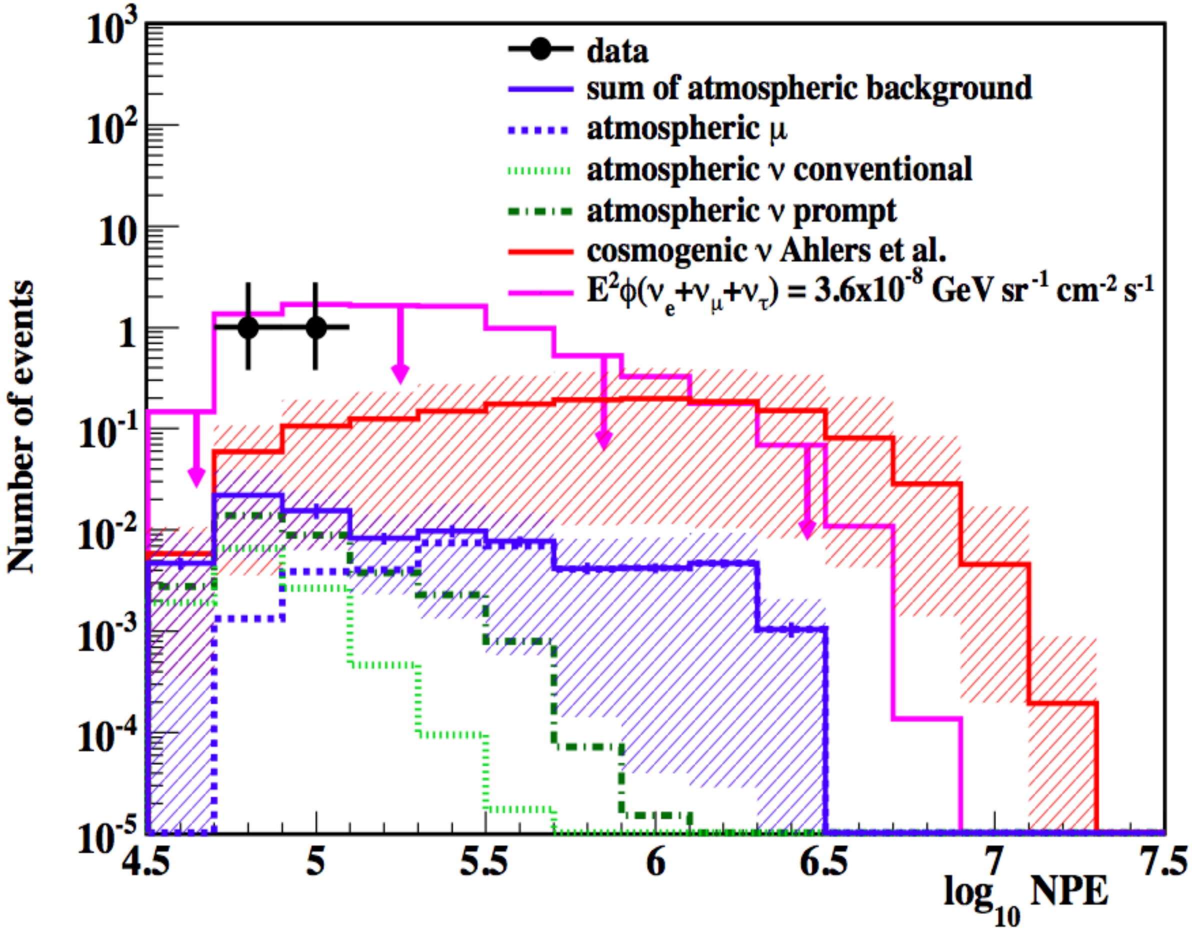


Needed more statistics

Extends sensitivity to lower energies

Optimized on events starting inside detector

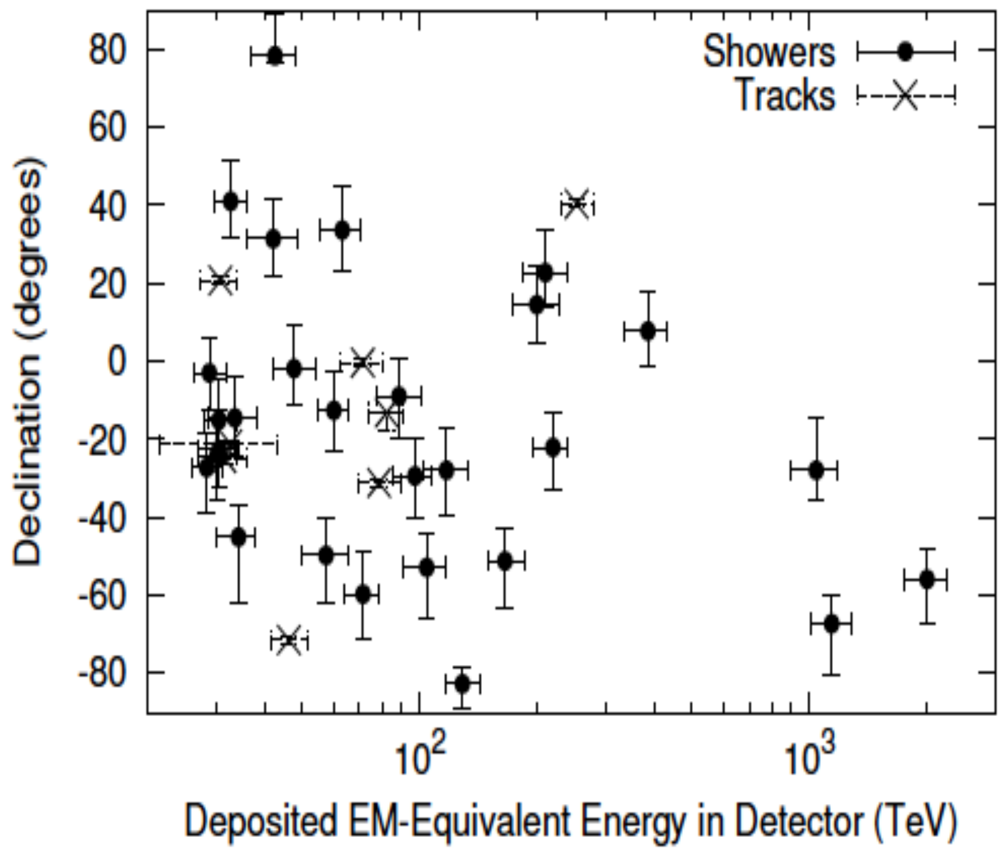
IceCube Collaboration, PRL 111, 021103(2013)

Results of the follow-up search

36 events observed including
3 PeV events

8 Tracks events

Expected background
15
7 atmospheric neutrinos
8 atmospheric muons



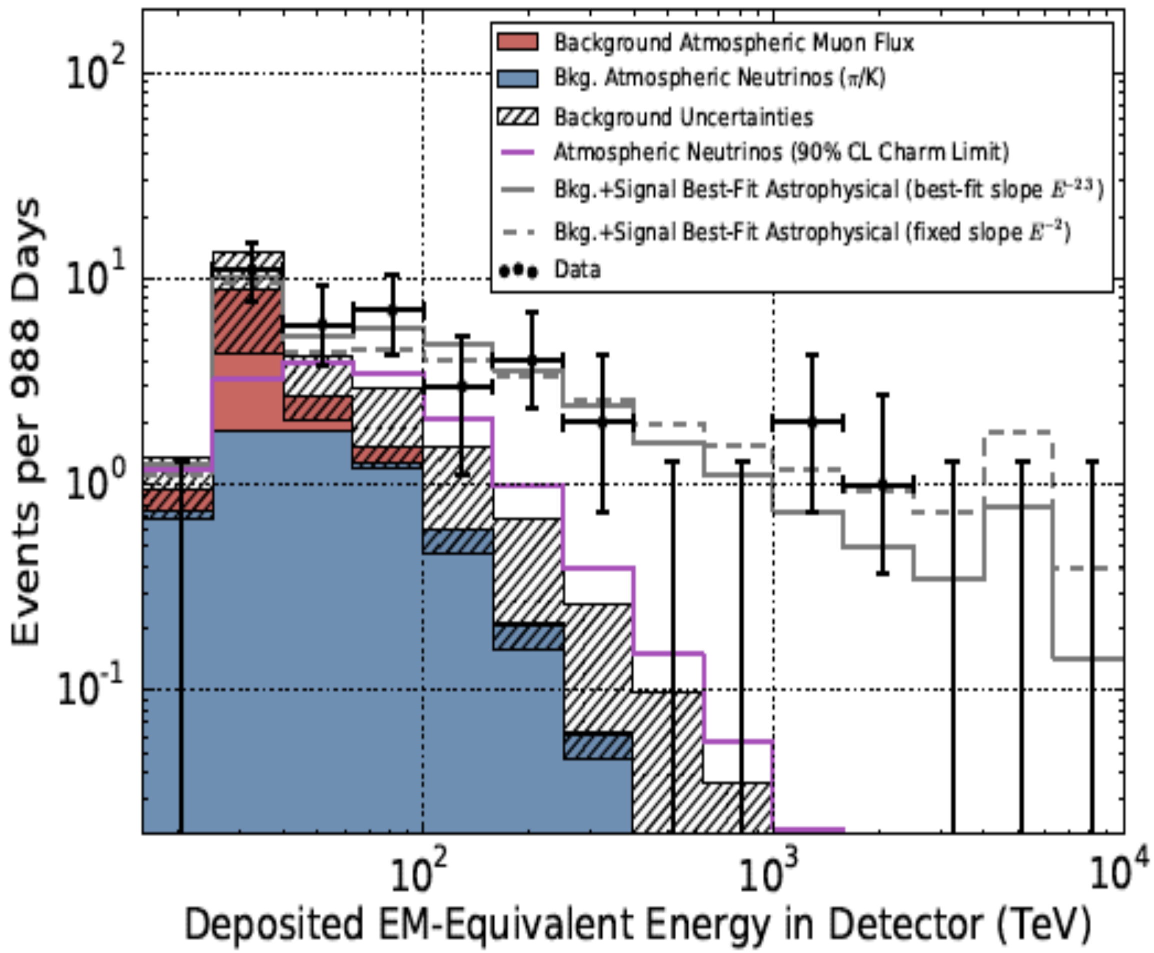
[IceCube PRL 113 (2014)]

Energy and Zenith Distribution

Harder than atmospheric background

Excess compatible with isotropic flux (1 : 1 : 1)

Potential cutoff at 2.0 PeV



[IceCube PRL 113 (2014)]

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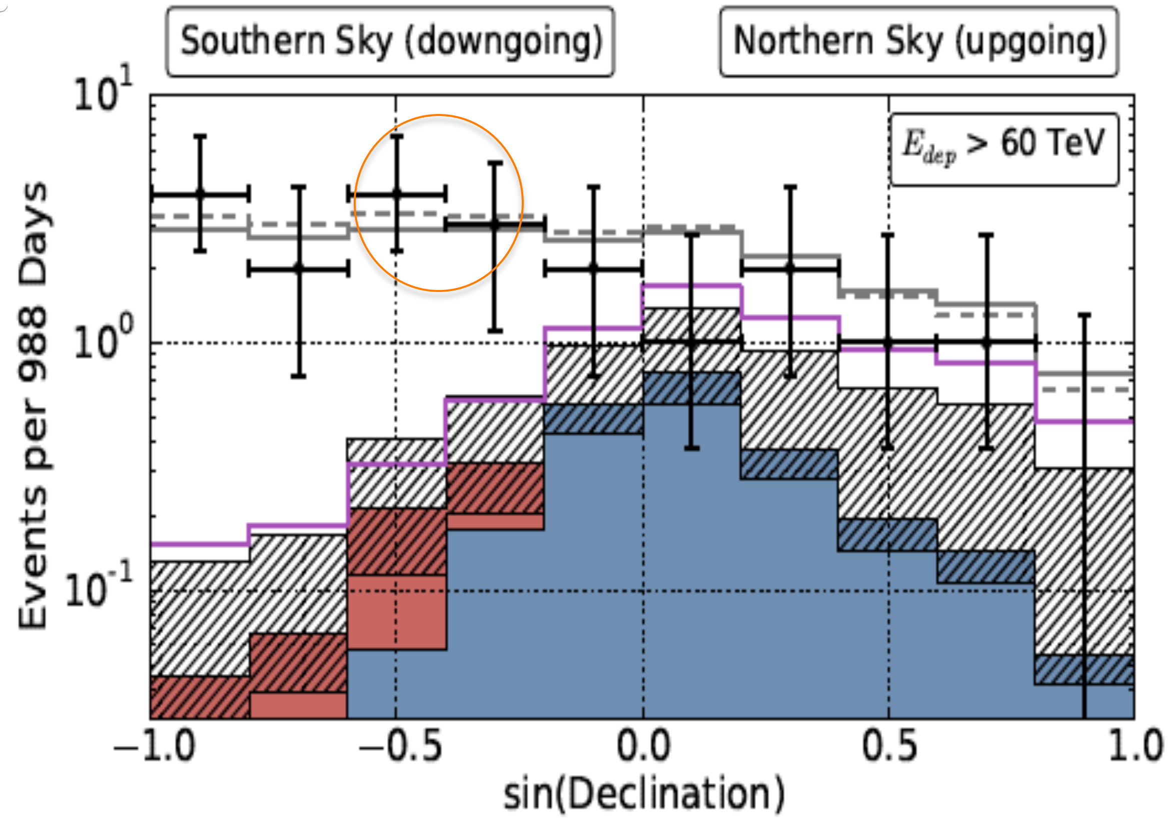
No clustering of events

No significant correlation with Galactic plane (Slight Excess)



[IceCube PRL 113 (2014)]

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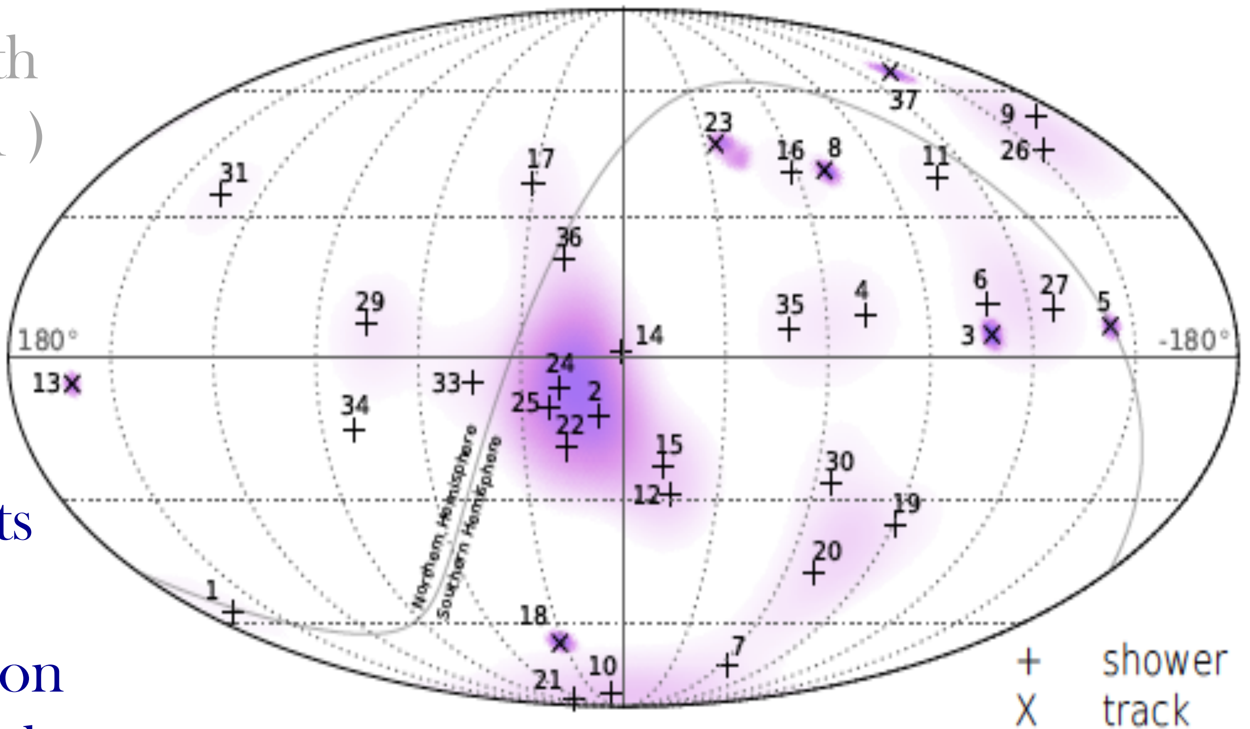
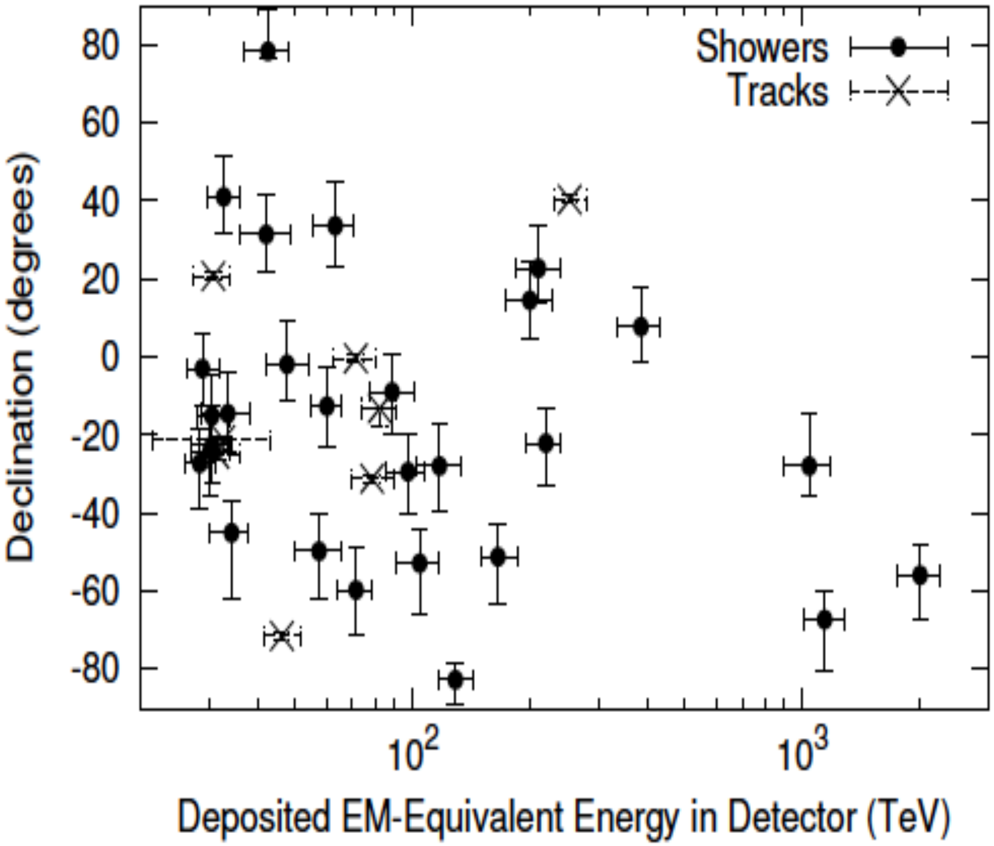
Neutrino Sky Map !!



[IceCube PRL 113 (2014)]

Questions Regarding the Origin

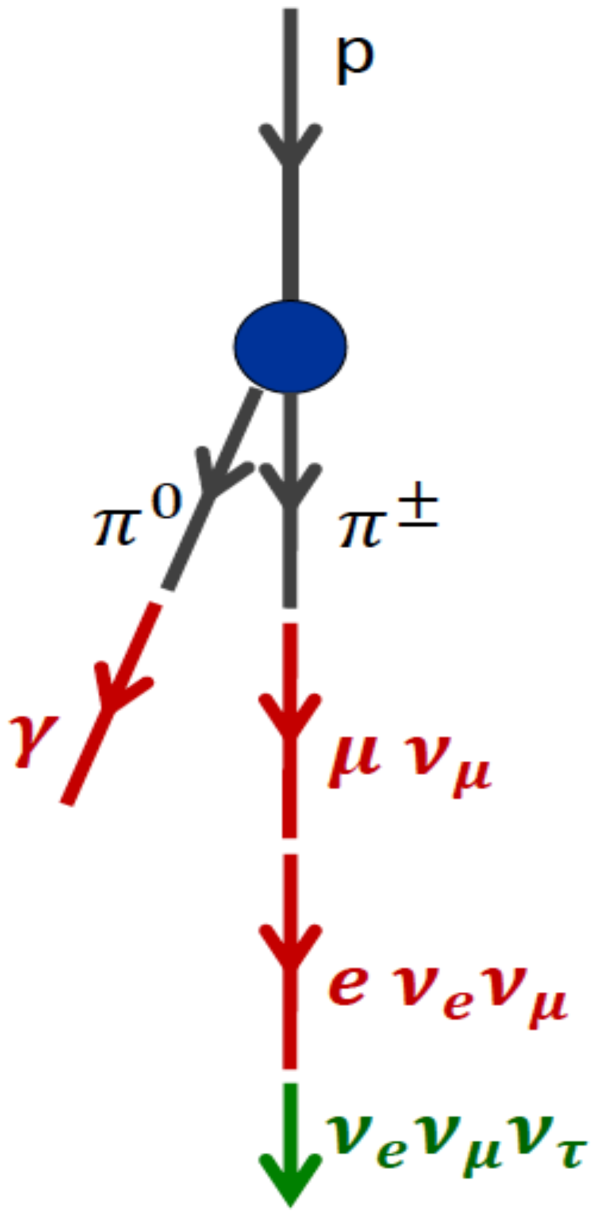


Several Possibilities:

- Active galactic Nuclei (AGN)
- Low power GRB's
- Star burst Galaxies
- Fermi bubble
- PeV dark matter decay
- ......

especially with some post-data tweaks!

Neutrino Beams:



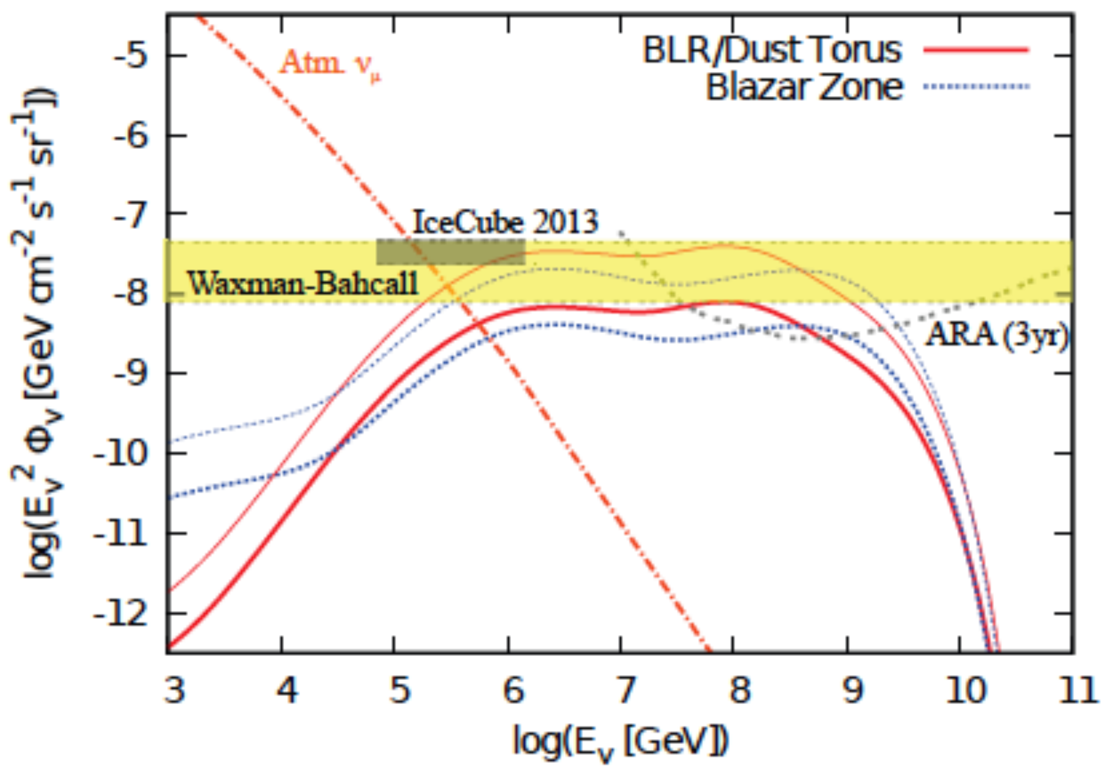
Target:
Protons or Photons

Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

Active Galactic Nuclei

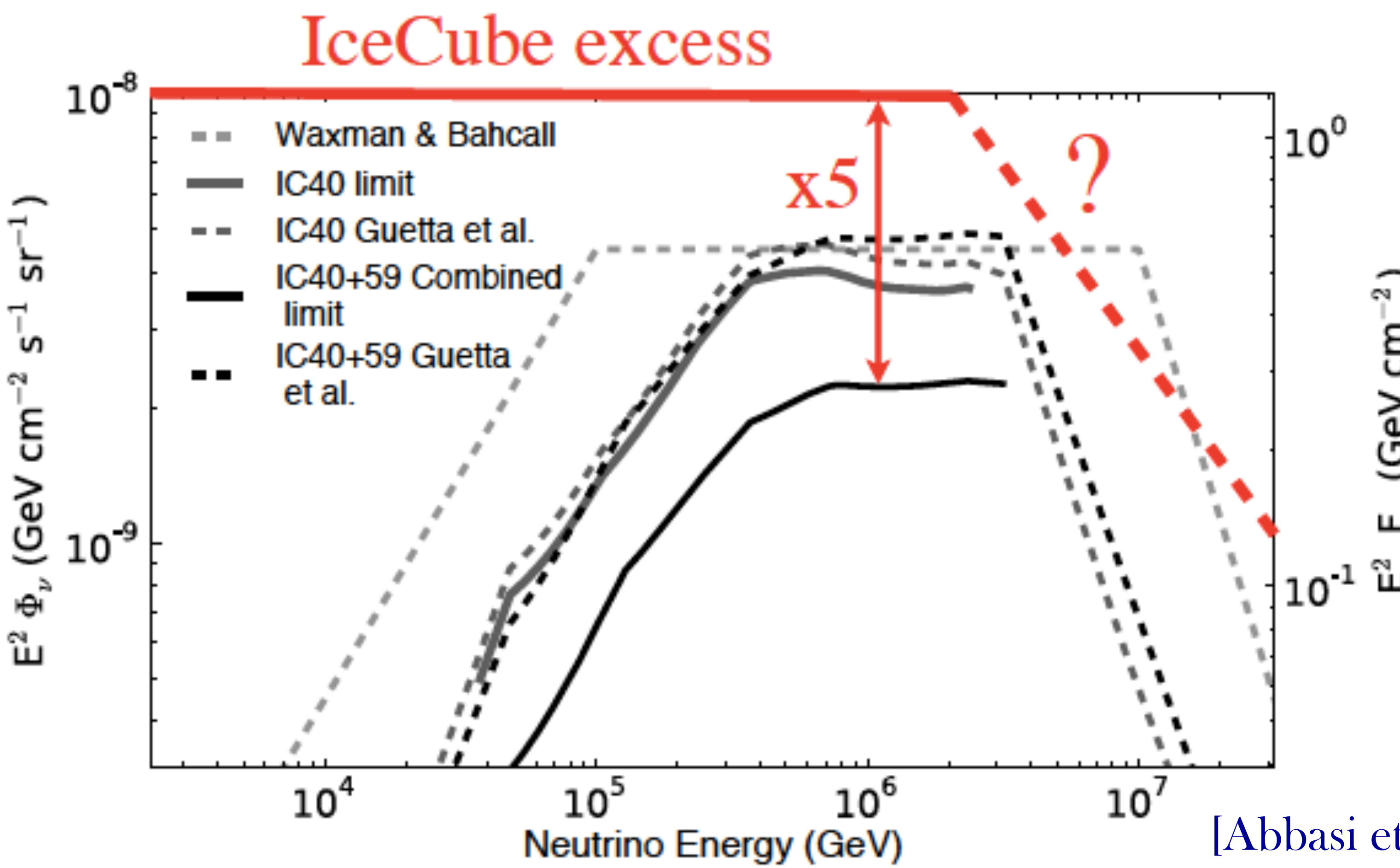
- Neutrino interactions from pγ interactions in AGN cores [Stecker et al.'91]
  - Complex spectra from various photon backgrounds
    - Deficit of sub-PeV and excess of EeV neutrinos



[Murase, Inoue & Dermer 1403.4089]

Gamma Ray Bursts

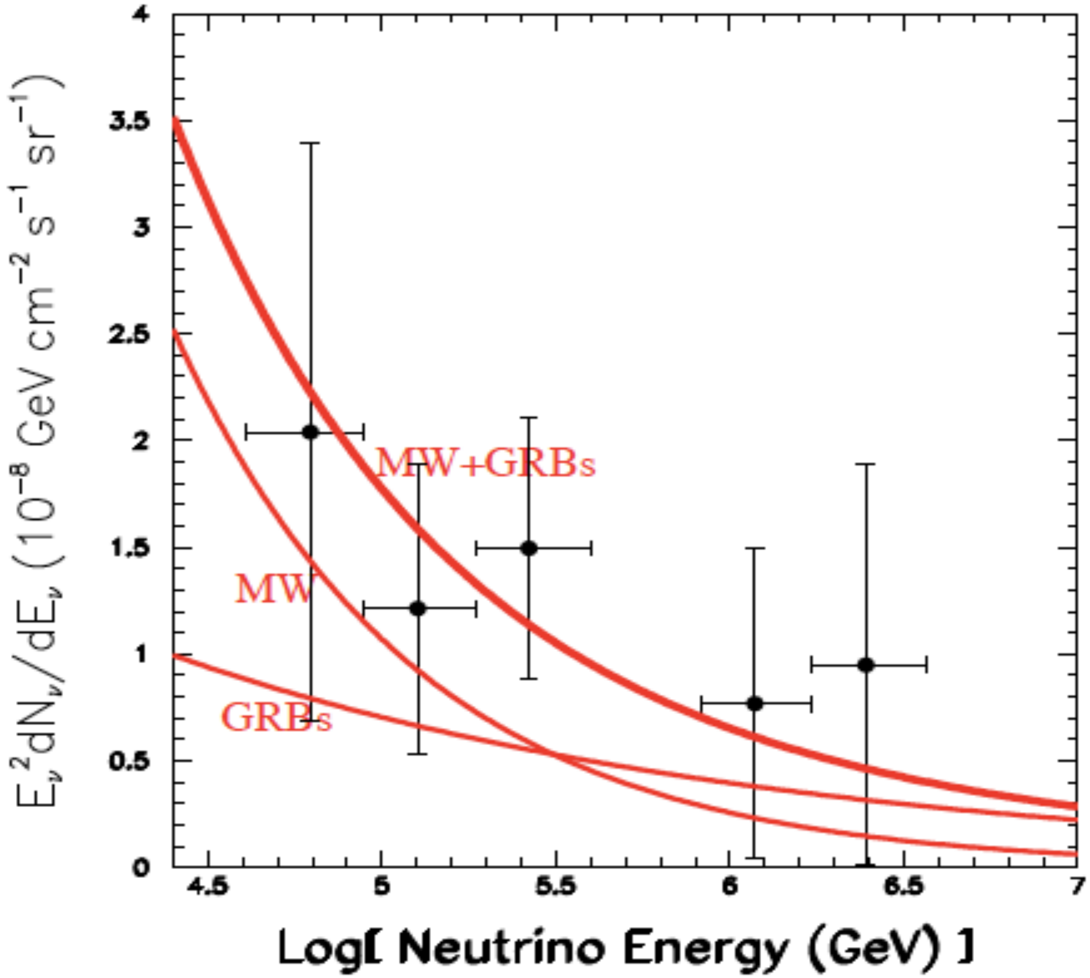
- Strong limits of neutrino emission with the fireball model [Abbasi et al. '12]
  - IC excess exceeds limit by factor of around 5
- What about undetected low-power GRB [Murase et al. arxiv 1306.2274]



[Abbasi et al. '12]

Gamma Ray Bursts

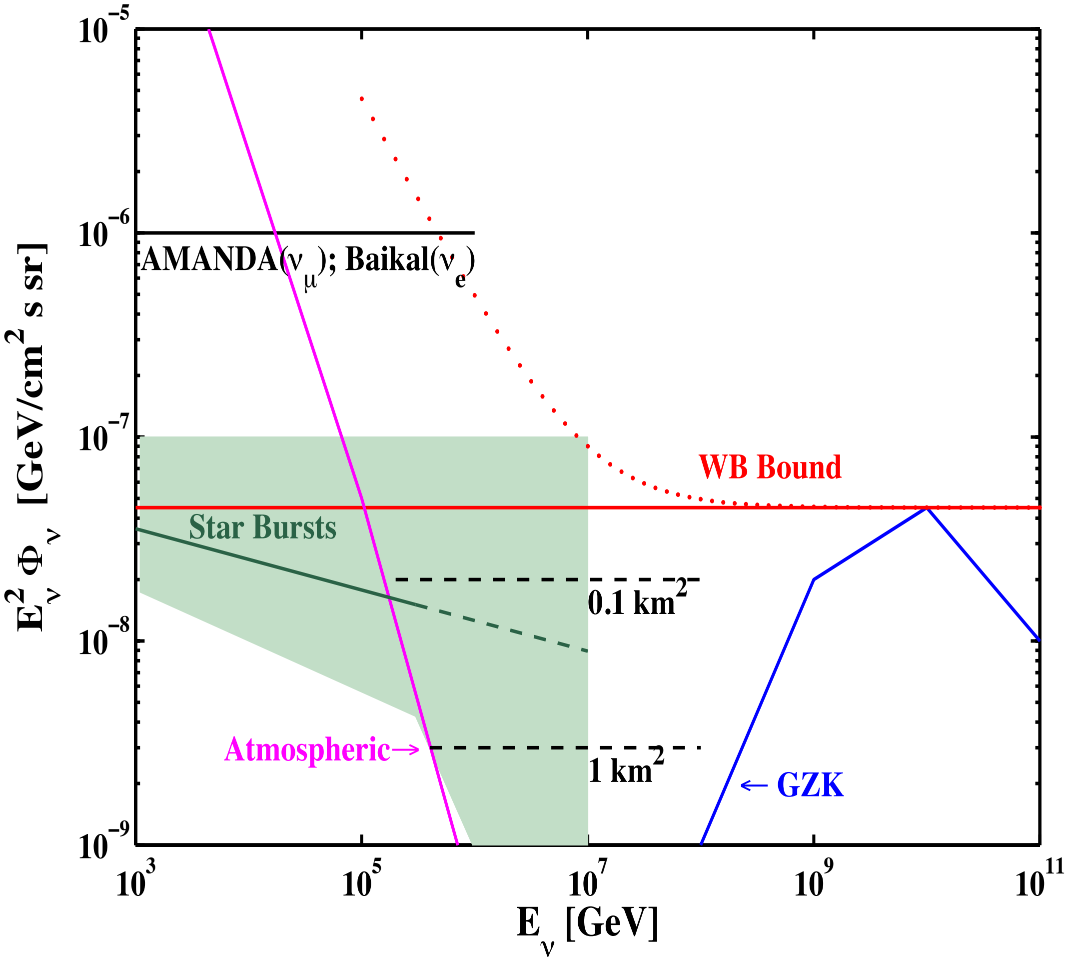
CRs accelerated in GRB colliding in the galactic molecular cloud



[Dado and Dar. PRL'14]

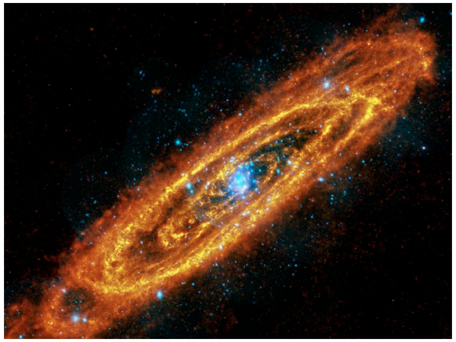
Starburst galaxies

- Intense CR interactions (and acceleration) in dense starburst galaxies
- Cutoff/break feature **(0:1-1)** PeV at the CR knee (of these galaxies)



Loeb and Waxman '06

Normal galaxies
(i.e., Milky Way, Andromeda)

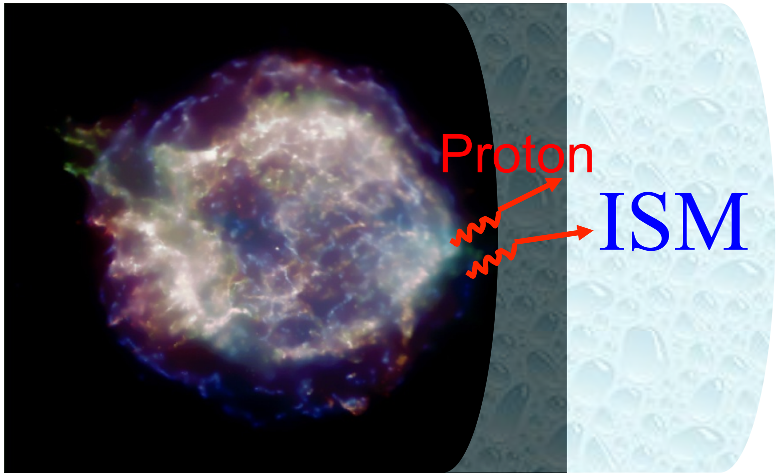


Starburst galaxies
(i.e., M82, NGC 253)

Neutrino spectrum from HN remnants

- pp efficiency

$$f_\pi = \min\left(1, t_{\rm esc}/\tau_{pp}\right)$$
$$\tau_{pp}(\varepsilon_p) = \left[\kappa\sigma_{pp}(\varepsilon_p) n c\right]^{-1}$$



- Two escape ways: 1) diffusion 2) advection

$$t_{\rm diff} = h^2/4D \qquad t_{\rm adv} = h/V_w$$

- Hypernovae occur in star-forming galaxies
  & starburst galaxies

$$f_\pi^{\rm N} = t_{\rm diff}^{\rm N}/\tau_{pp}^{\rm N} \simeq 0.01 \text{ and } f_\pi^{\rm B} = t_{\rm diff}^{\rm B}/\tau_{pp}^{\rm B} \simeq 0.4$$

Murase et al. arXiv:1306.3417, Liu et al. arXiv:1310.1263,
Tomborra et al. arXiv:1404.1189

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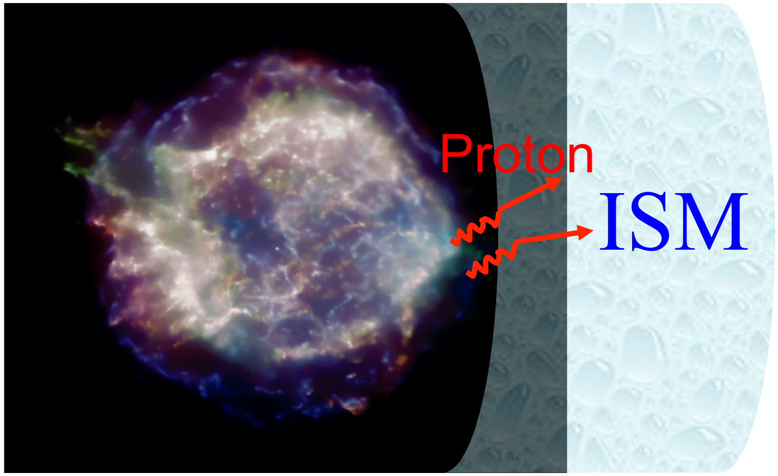

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$$\varepsilon_{p,\rm b}^{\rm B} = 1.6\,{\rm PeV}\left(\frac{h}{1\,{\rm kpc}}\right)^{3.3}\left(\frac{V_w}{1500\,{\rm km\,s^{-1}}}\right)^{3.3}\left(\frac{D_0}{10^{27}\,{\rm cm^2\,s^{-1}}}\right)^{-3.3}$$

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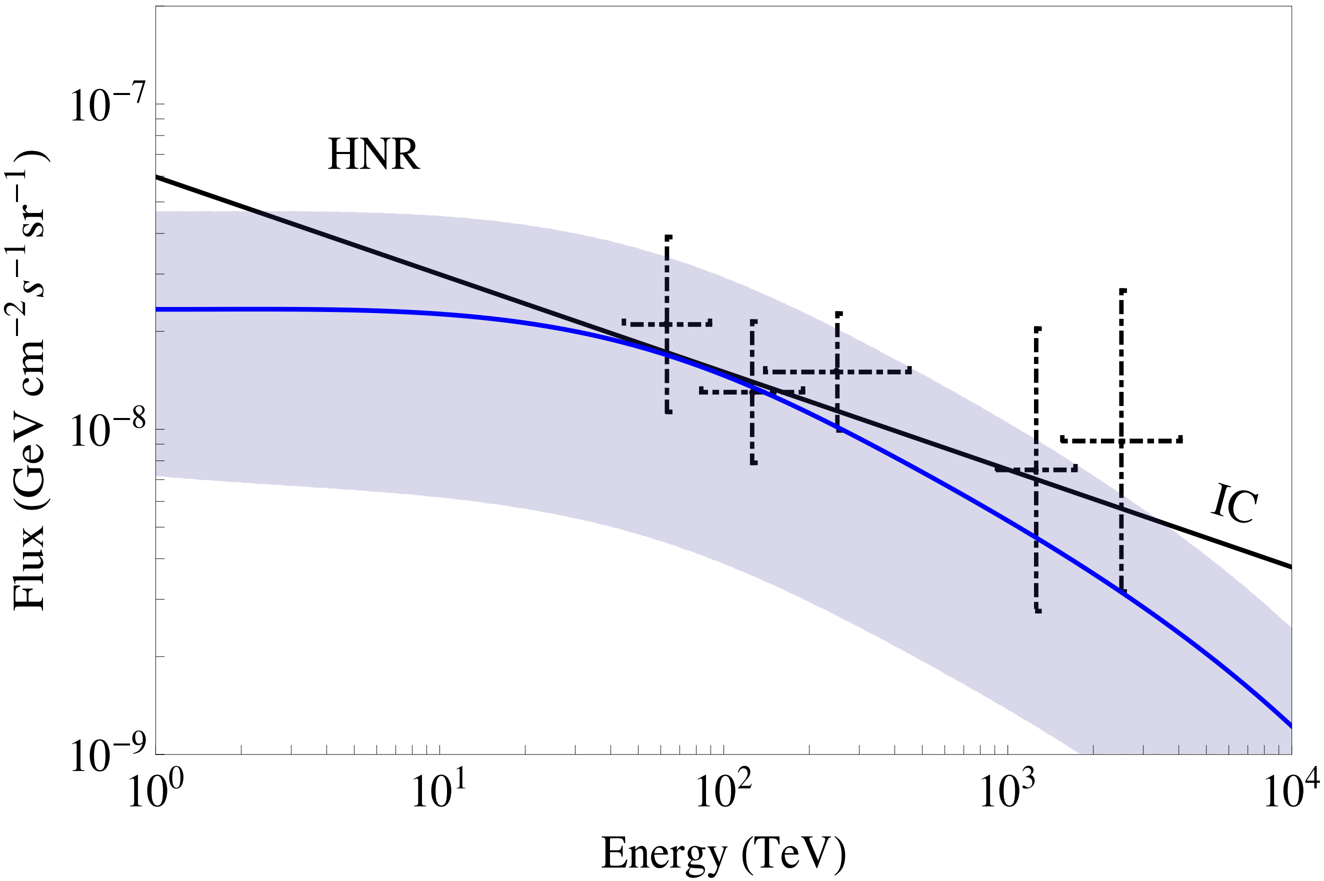

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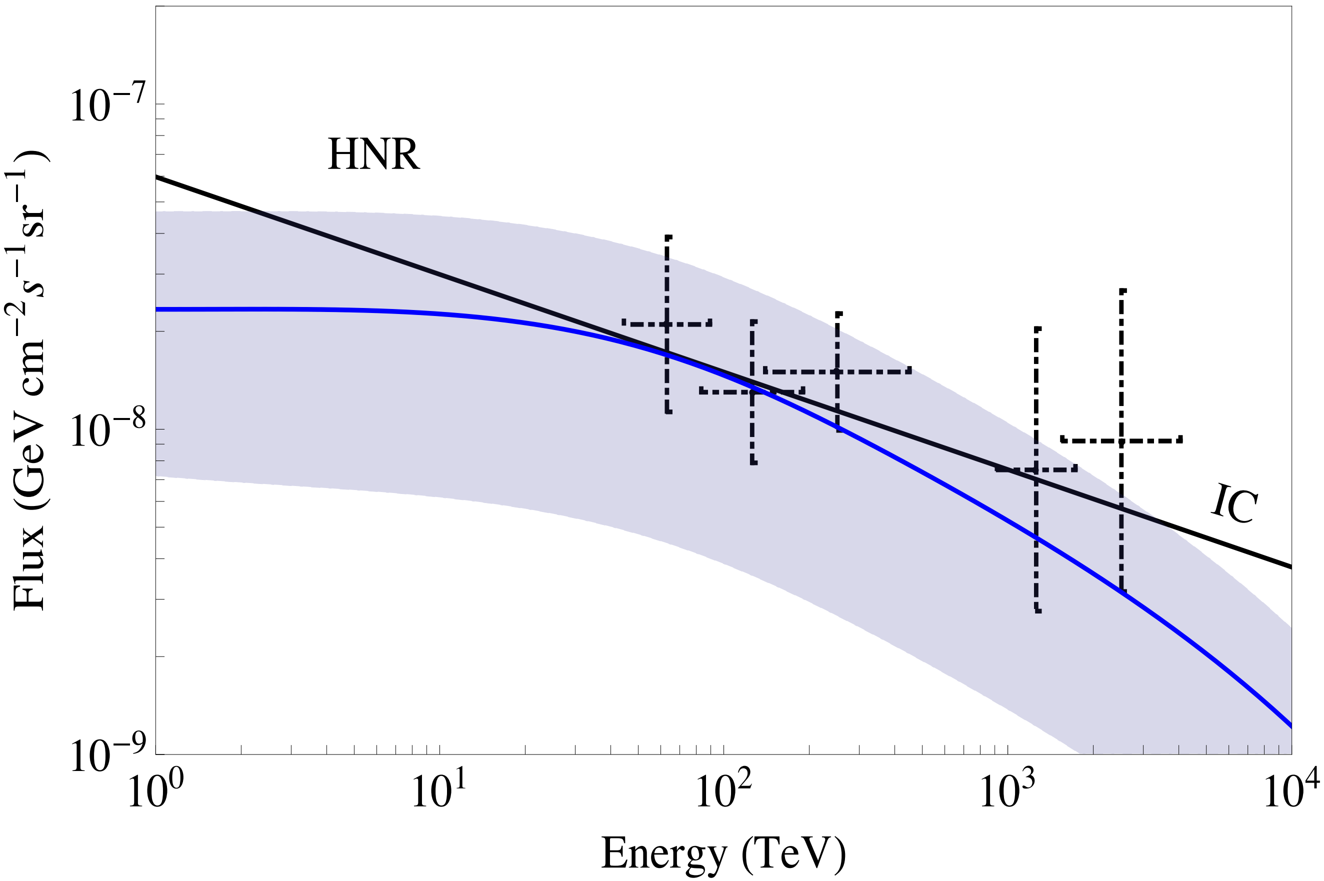
Liu et al. 13

Neutrino spectrum from HN remnants



What about ordinary SNR?

- Local SNR rate ~100 × HNR rate
- However SNR Ejecta Energy ~0.1 × HNR Ejecta Energy

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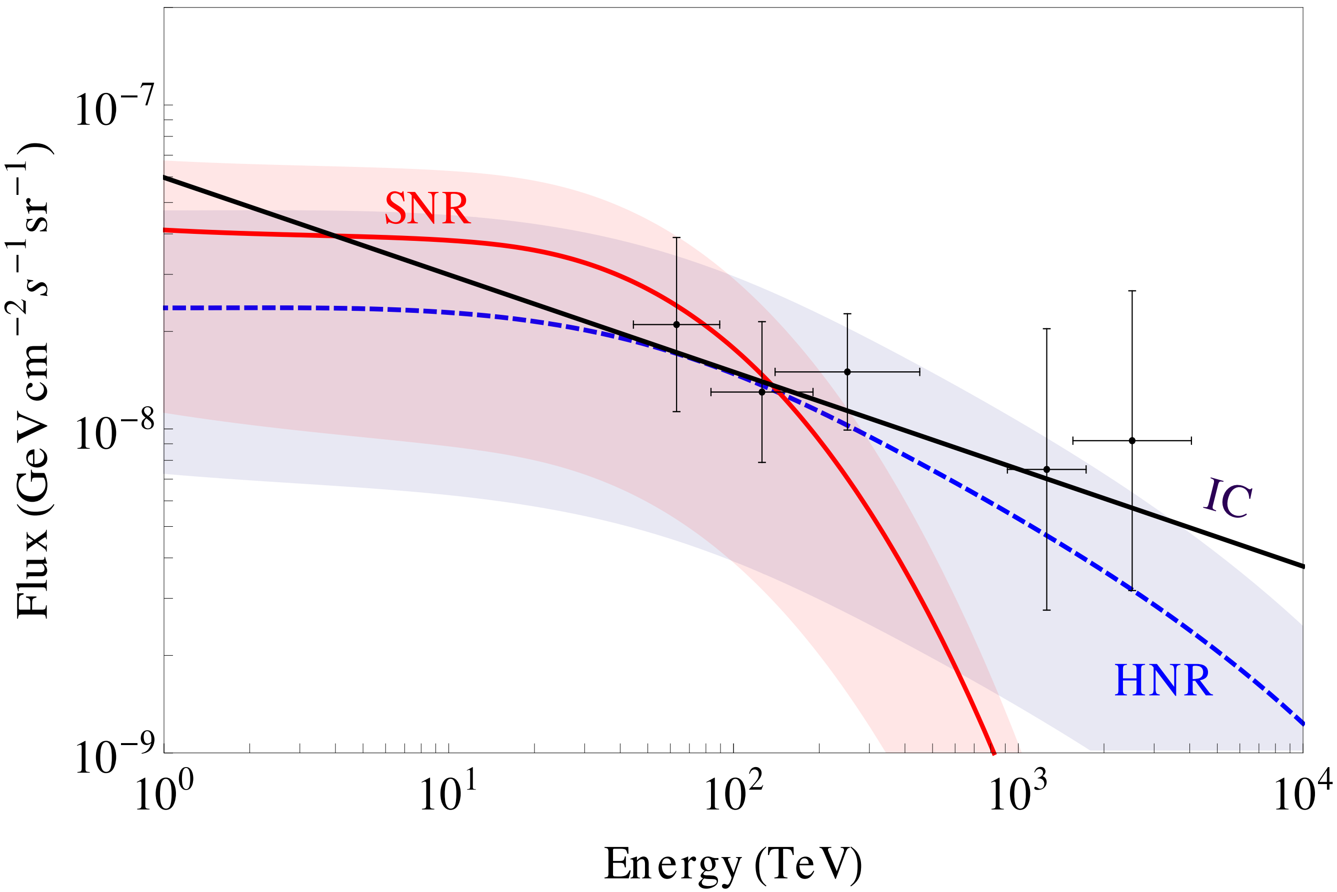
Liu et al. 13

Neutrino spectrum from HN+SN remnants



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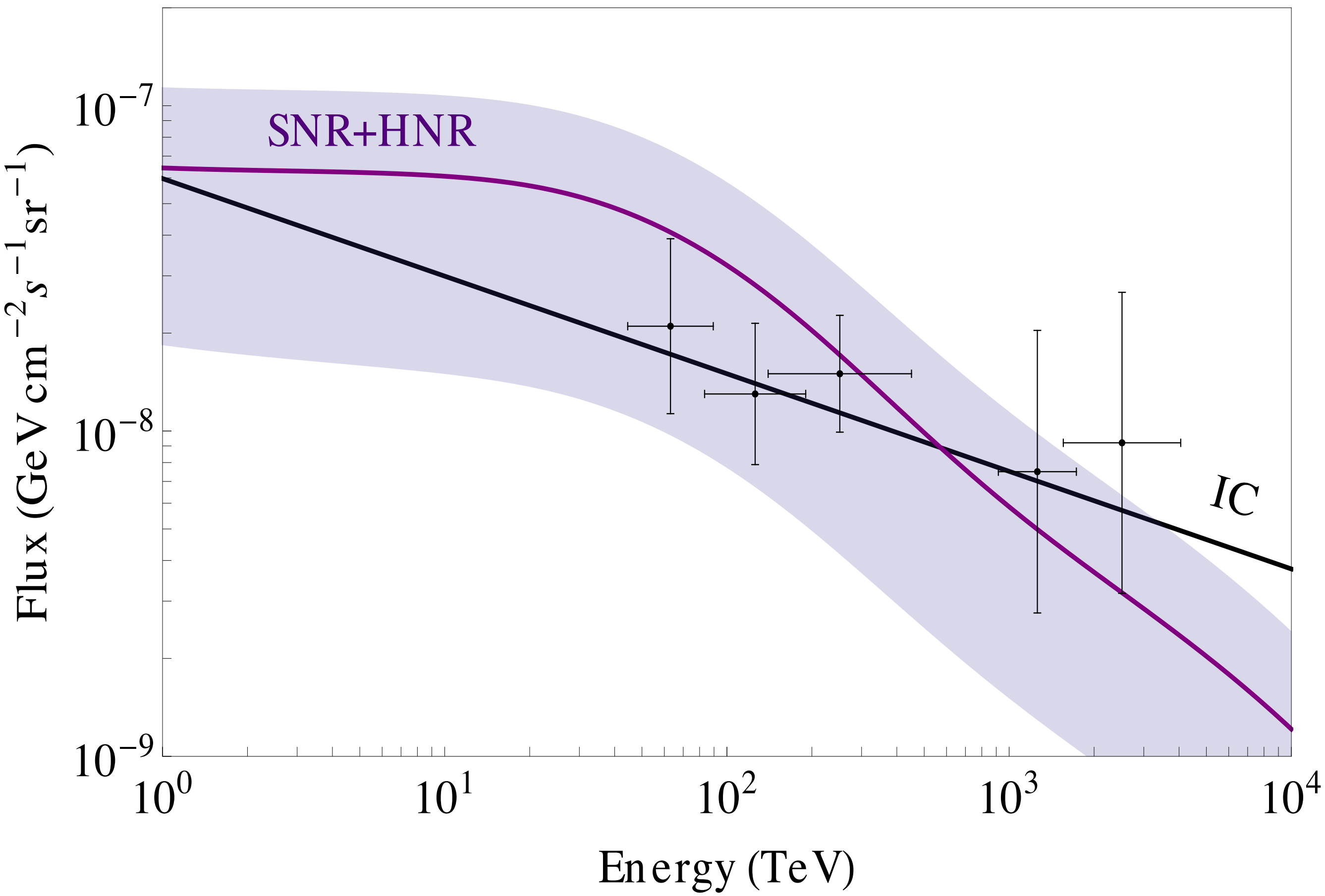
S.C and I. Izzaguire, arXiv:1501.02615

Neutrino spectrum from HN+SN remnants



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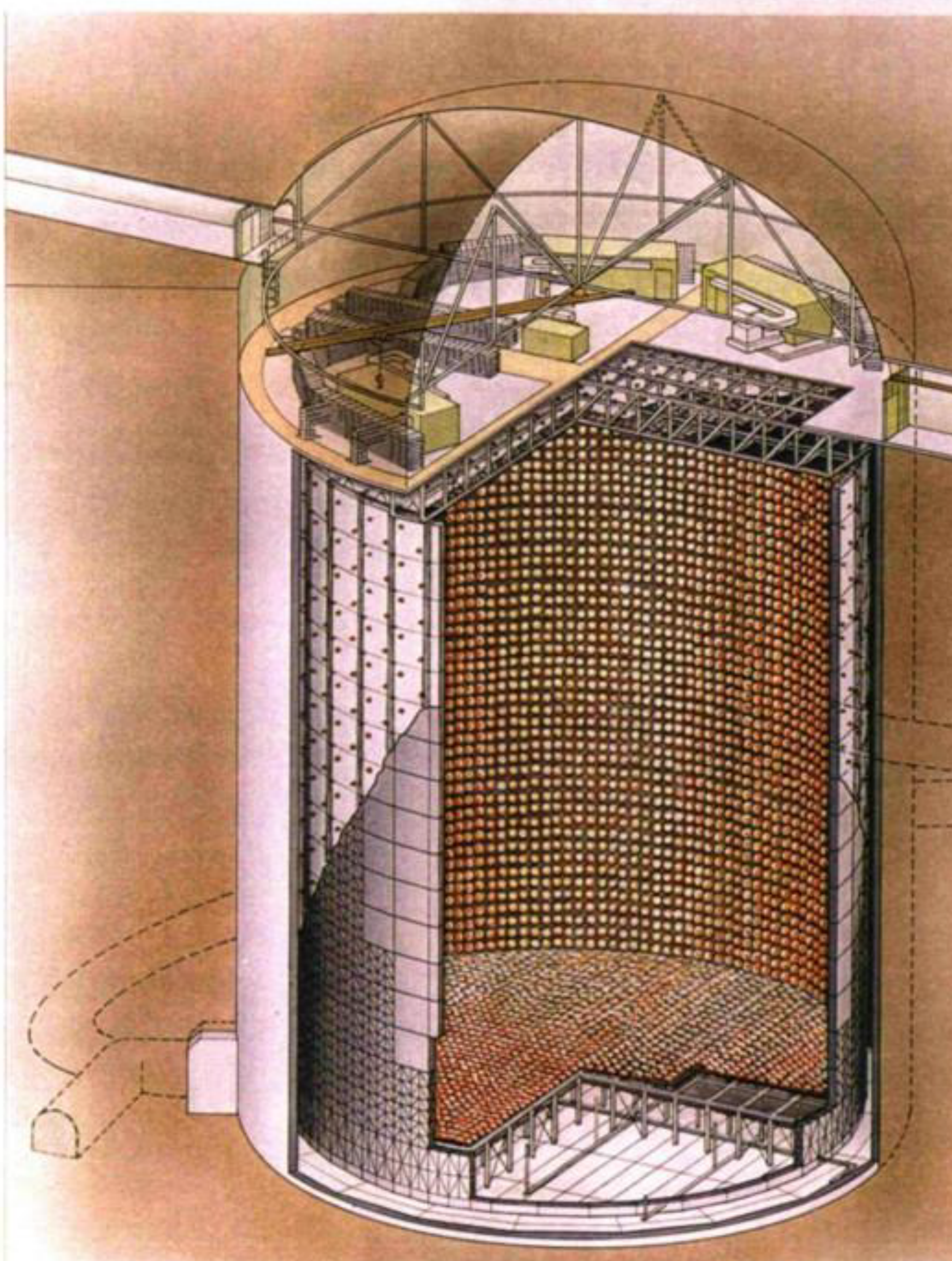
The HNR flux normalization should come from 100 TeV flux dominated by SNR

Summary and Outlook

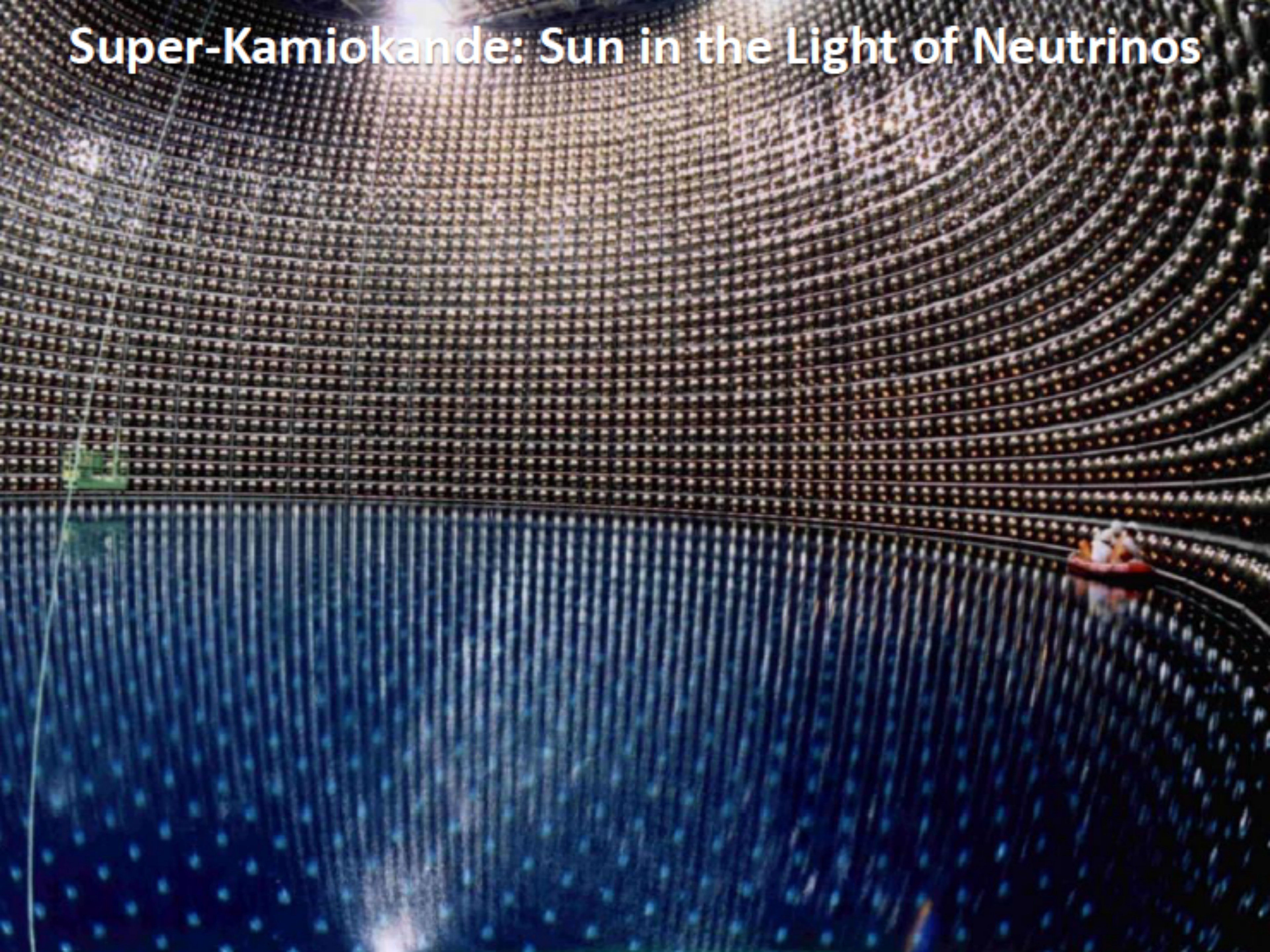
- Important progress in neutrino astrophysics in the last years.
- Neutrinos as extremely important to understand the stellar dynamics.
- Novel flavor conversion phenomena uncovered in supernovae but key questions remain open.
- IceCube TeV-PeV background has opened yet another area of neutrino astrophysics.

Extra Slides

NEUTRINOS FROM SUN



Super-Kamiokande: Sun in the Light of Neutrinos



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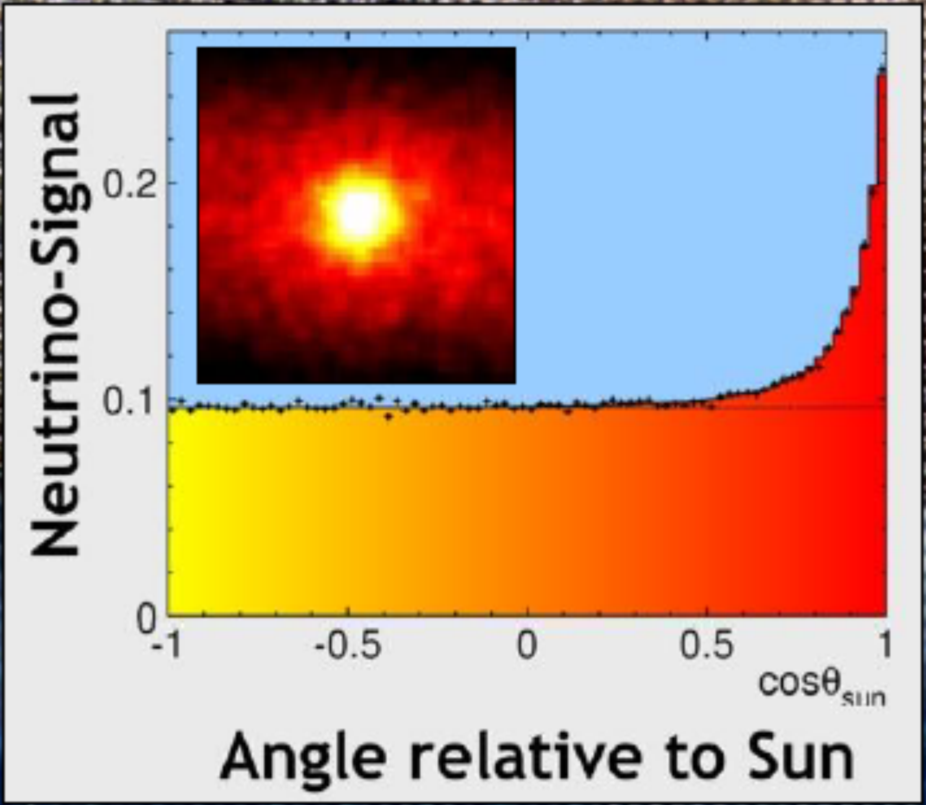
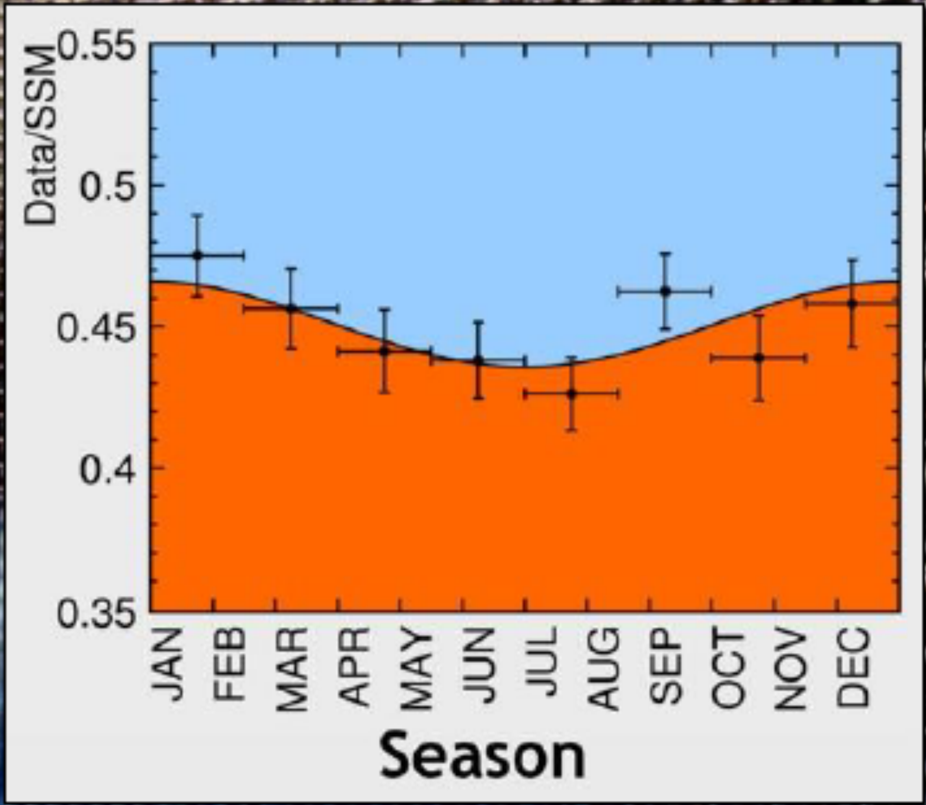




ca. 60,000 solar neutrinos measured in Super-K (1996–2012)

Neutrino Emission Phases

Neutronization burst

- Shock breakout
- De-leptonization of outer core layers
- **Duration ~ 25 ms**

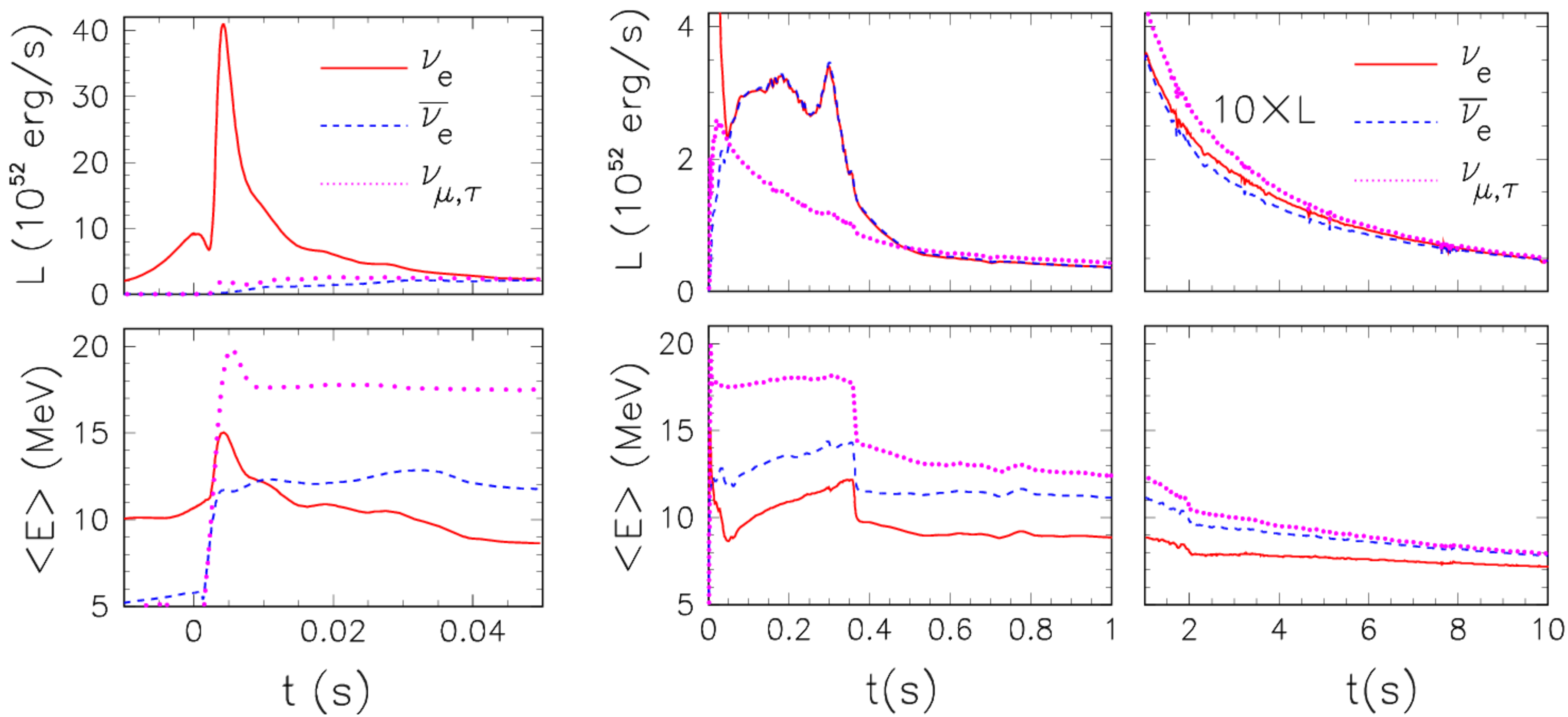
Accretion

- powered by infalling matter
- Stalled shock

Cooling

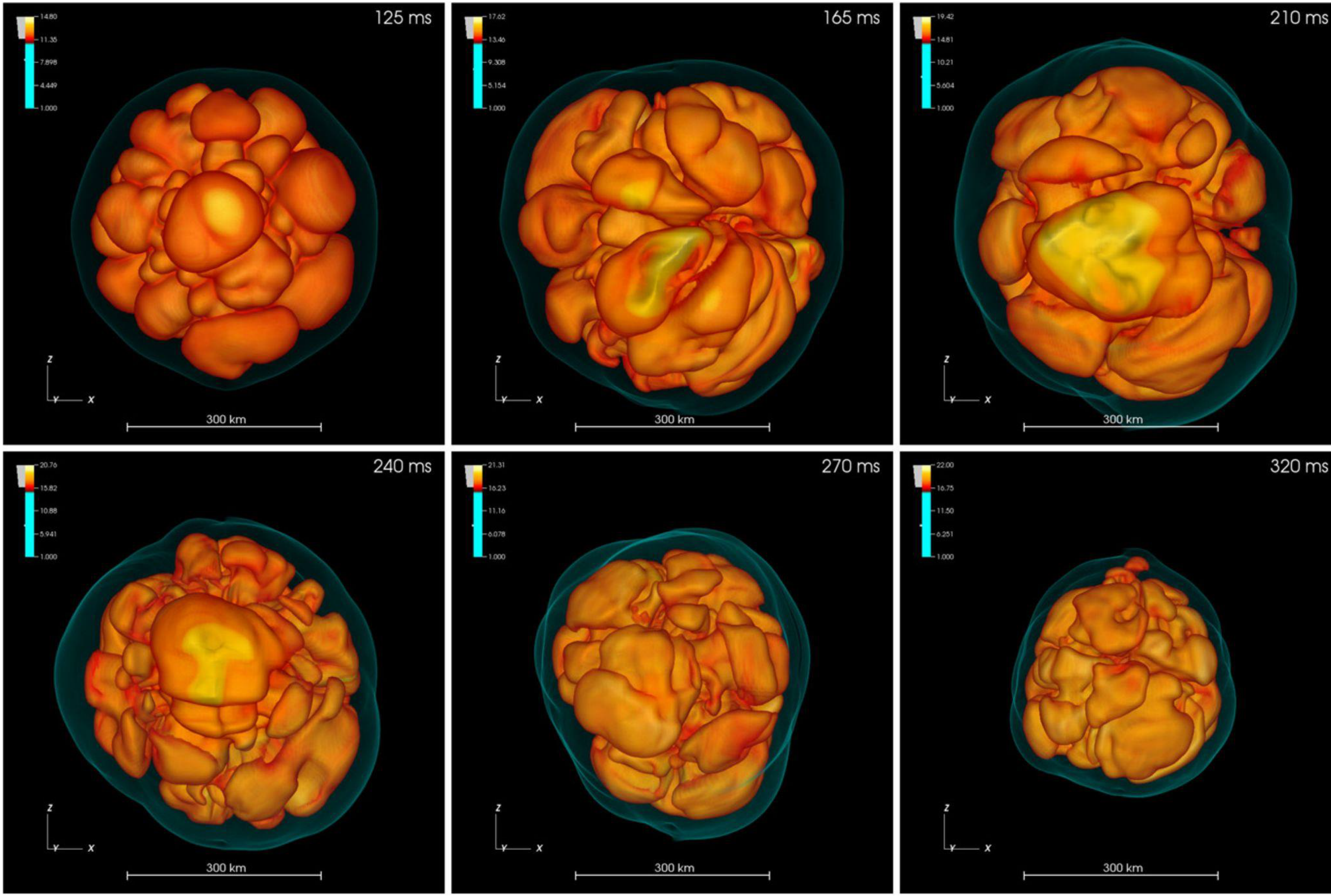
- Cooling by ν diffusion

Accretion: ~ 0.5 s ; Cooling: ~ 10 s



[Fischer et al. (Basel Simulations), A&A 517:A80,2010, 10. 8 M_{sun} progenitor mass]

Large-Scale Convection in 3D (11.2 M_{SUN})



Tamborra et al., arXiv:1402.5418

r-Process Nucleosynthesis

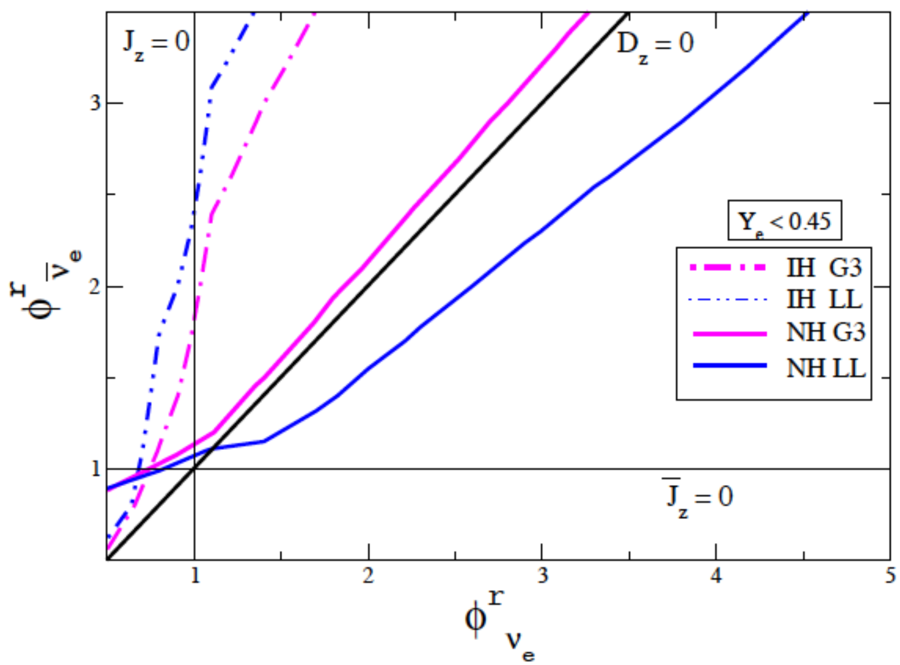
- Heating by neutrino driven wind coming from neutrino-sphere

  $$\nu_e + n \rightleftharpoons e^- + p; \quad \bar{\nu}_e + p \rightleftharpoons e^+ + n$$

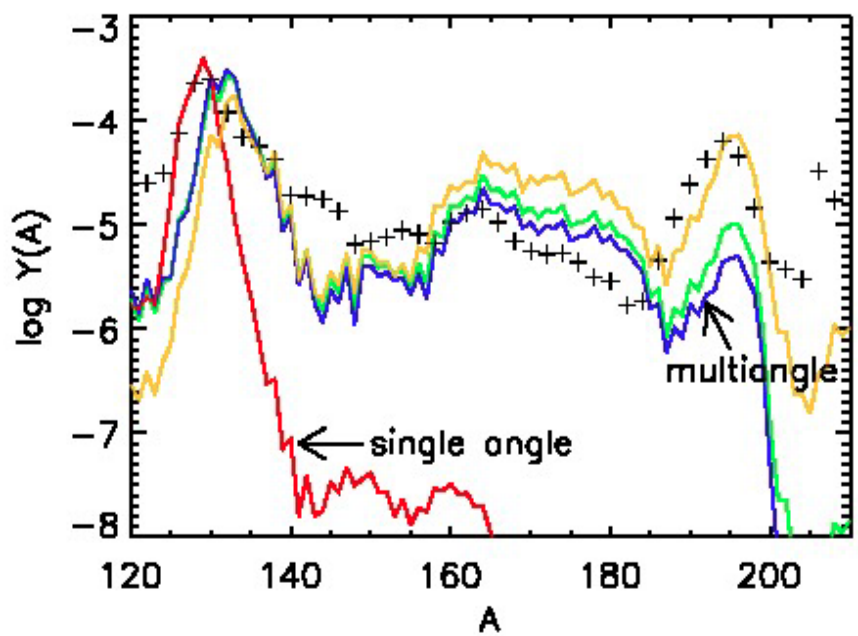
- Important quantity whose evolution should be studied is

  Electron fraction (Ye) = No of electrons/No of Baryons

- For Neutron rich conditions Ye < 0.5 (Preferably < 0.45).



S C, Choubey, Goswami and Kar, JCAP 2010



Duan, et al, JPG (2010)

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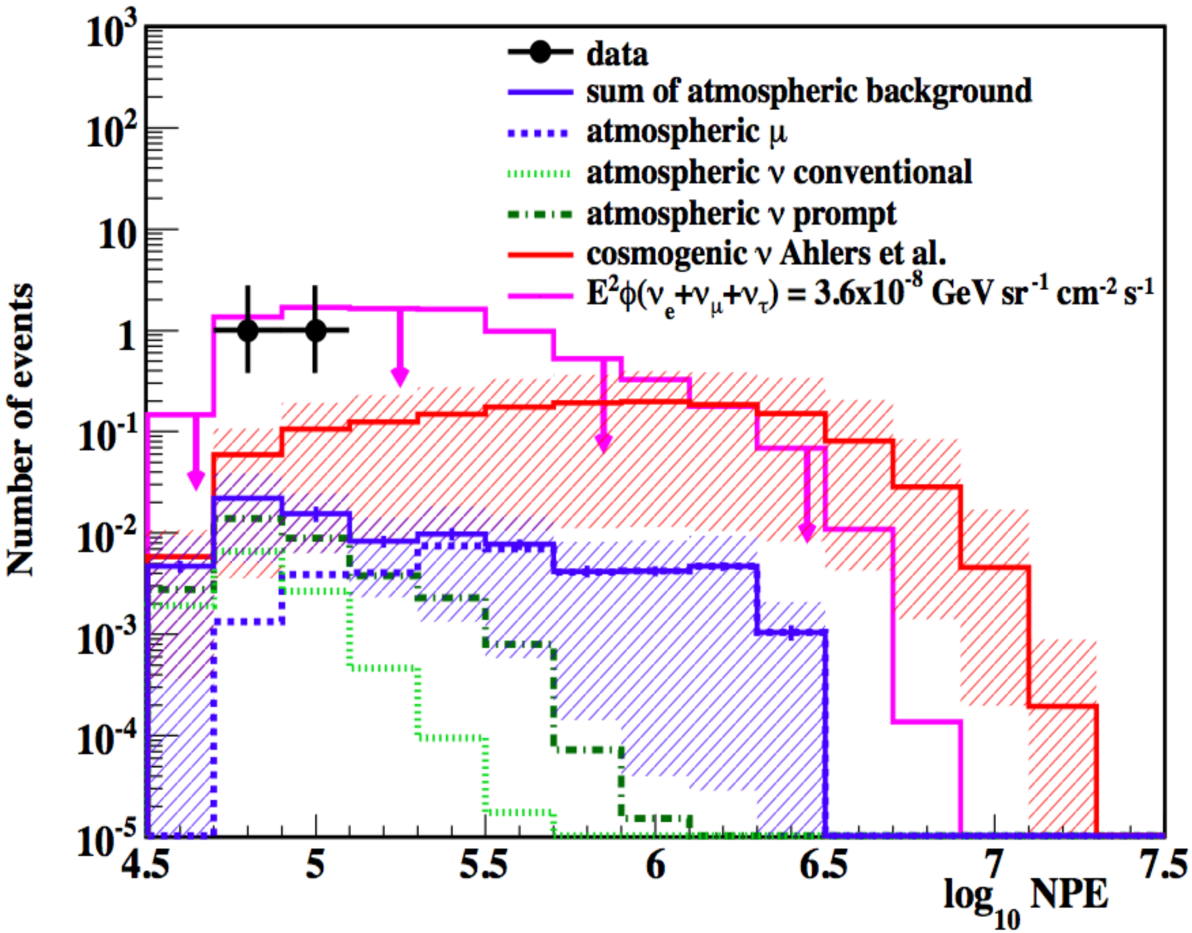


IceCube Collaboration, PRL 111, 021103(2013)

GZK ?

cosmic rays interact with the microwave background

$$p+\gamma \rightarrow n+\pi^{+} \;\; and \;\; p+\pi^{0}$$

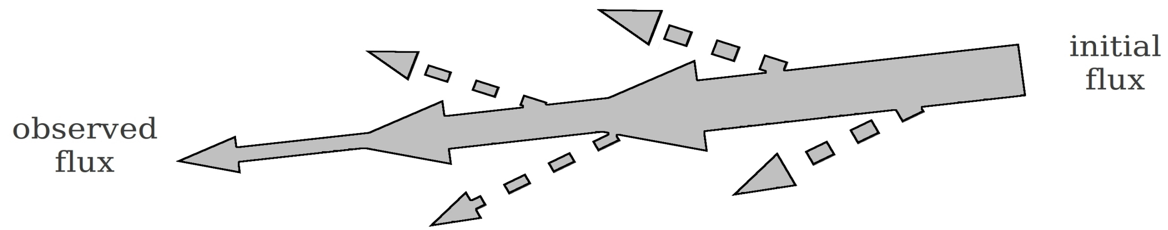
Too low energy, more events should be seen in higher energies

Glashow-Cohen Radiation

Superluminal propagation allows kinematically forbidden processes :

LIV Processes (neutrino) ***Cohen & Glashow 2011***

$$\nu \rightarrow \nu \; e^{+} \, e^{-}$$



Depletion of the high-energy neutrino fluxes during their propagation

$$\text{observed flux} \;= e^{-\Gamma L} \;\text{initial flux}$$

- The two PeV cascade neutrino events detected by IceCube –if attributed to extragalactic diffuse events– can place the strongest bound on LIV in the neutrino sector.

$$\delta = (v^2 - 1) < 10^{-18}$$

Extra-Galactic Diffuse γ -ray Emission

$$\nu \rightarrow \nu \; e^{+} e^{-}$$

- $e^{\pm}$ propagate only few kpc before scattering off the CMB populating a γ -ray flux between 1 ~ 100 GeV.

Extra-Galactic Diffuse γ -ray Emission
flux is constrained by Fermi data :

γ Energy Density

$$\omega_\gamma = \frac{4\pi}{c} \int_{E_1}^{E_2} E \, \frac{d\varphi_\gamma}{dE} \, \mathrm{d}E \lesssim 5.7 \times 10^{-7} \, \mathrm{eV/cm}^3 \, .$$

Abdo et al. 2010

Extra-Galactic Diffuse γ -ray Emission

$$\nu \rightarrow \nu \; e^{+} e^{-}$$

Observed
ν Energy Density

$$\omega_{\nu}^{\rm obs} = \frac{4\pi}{c} \int_{1\,\rm PeV}^{1.1\,\rm PeV} E \, \frac{d\varphi_E}{dE} \, {\rm d}E \sim 10^{-9}\,{\rm eV/cm^3}$$

Extra-Galactic Diffuse γ -ray Emission
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γ Energy Density

$$\omega_{\gamma} = \frac{4\pi}{c} \int_{E_1}^{E_2} E \, \frac{d\varphi_\gamma}{dE} \, {\rm d}E \lesssim 5.7 \times 10^{-7}\,{\rm eV/cm^3}\,.$$

Abdo et al. 2010

Bound on δ

$$e^{-\Gamma\, d} \gtrsim \frac{\omega_\nu^{\rm obs}}{\omega_\gamma} \sim 10^{-2}$$

Initial flux ≤ 10^2 Observed flux

$$\Gamma_{e\pm} = \frac{1}{14}\frac{G_F^2 E^5 \delta^3}{192\,\pi^3} = 2.55 \times 10^{53} \delta^3 E^5_{\rm PeV}\ {\rm Mpc}^{-1}$$

$\delta^3\, E^5_{PeV}\, L_{Mpc} \leq 1.8 \times 10^{-53}$

For a source L ~ Mpc: $\delta \leq 2.6 \times 10^{-18}$

Borriello, SC, Mirizzi & Serpico, PRD (201