The Niels Bohr International Academy

DARK

The Ghostly Messengers of the Universe

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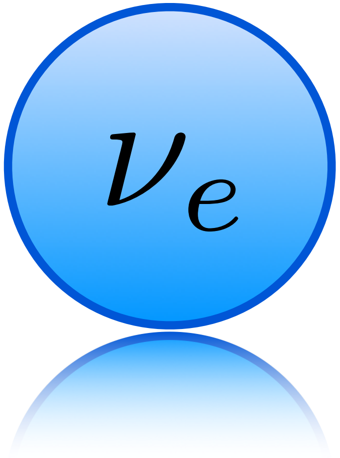
VILLUM FONDEN

Sapere Aude

CARLSBERG FOUNDATION

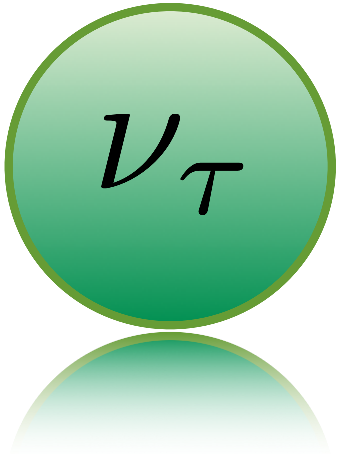
SFB 1258 Neutrinos Dark Matter Messengers

Neutrinos

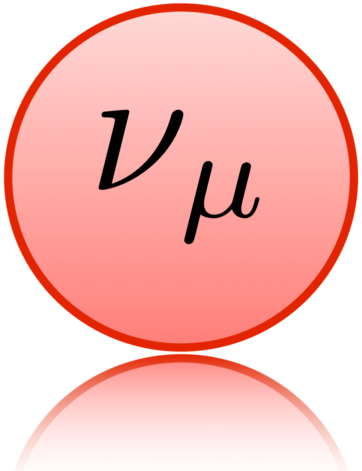


Ghostly

Abundant



Elusive



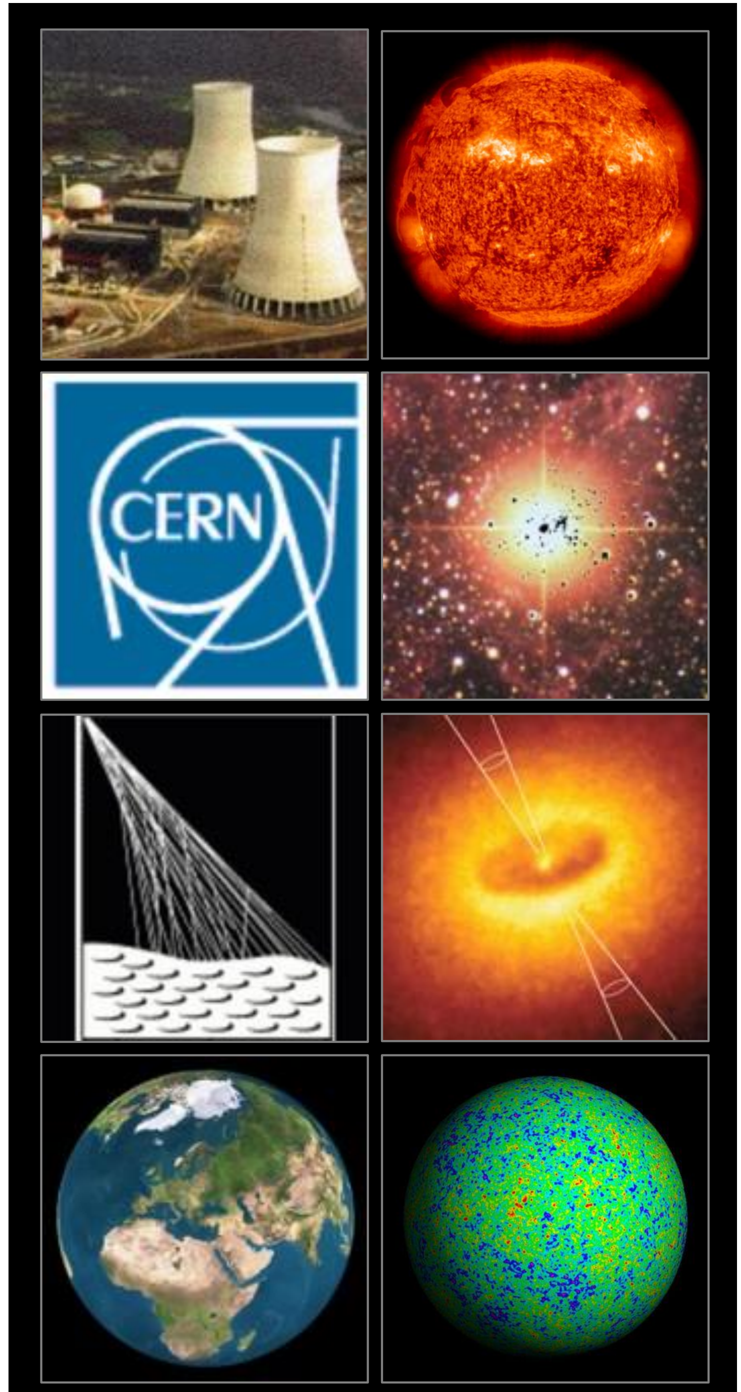
Where Are Neutrinos Produced?

Nuclear reactors

Particle accelerators

Atmosphere

Earth



Sun

Supernovae and binary mergers

Gamma-ray bursts and other cosmic accelerators

Big Bang

Grand Unified Neutrino Spectrum

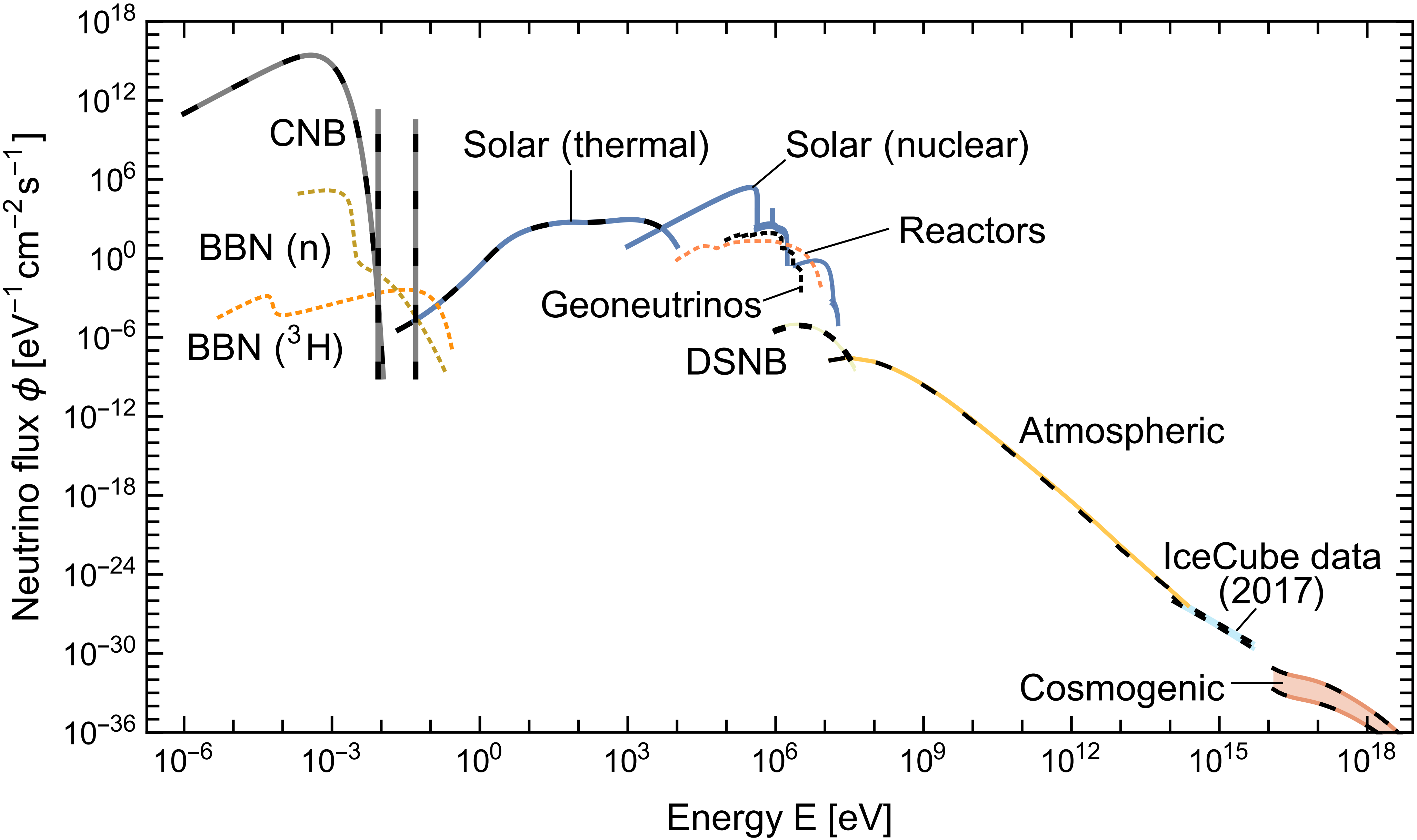
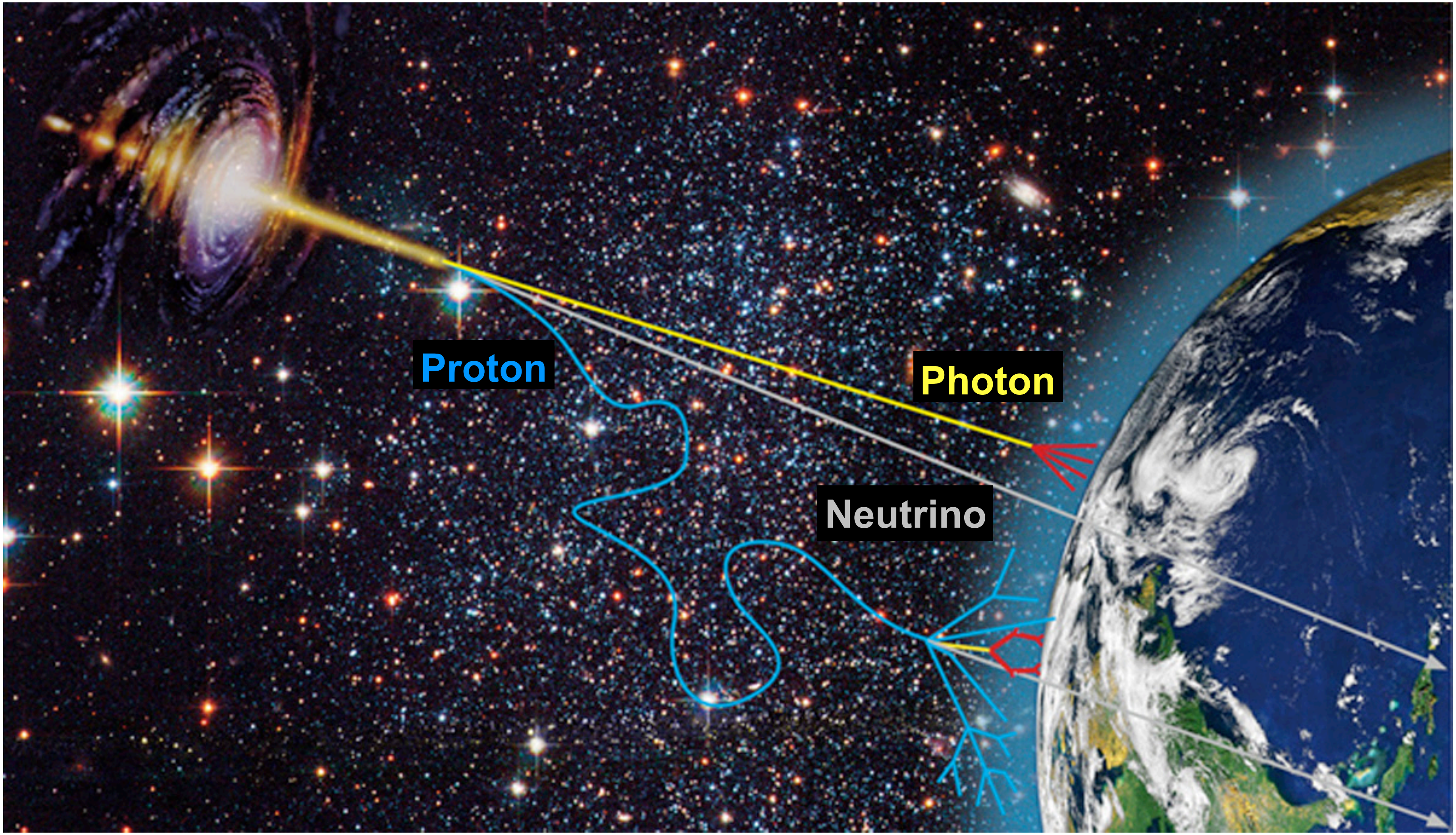


Figure from Vitagliano, Tamborra, Raffelt, arXiv: 1910.11878.

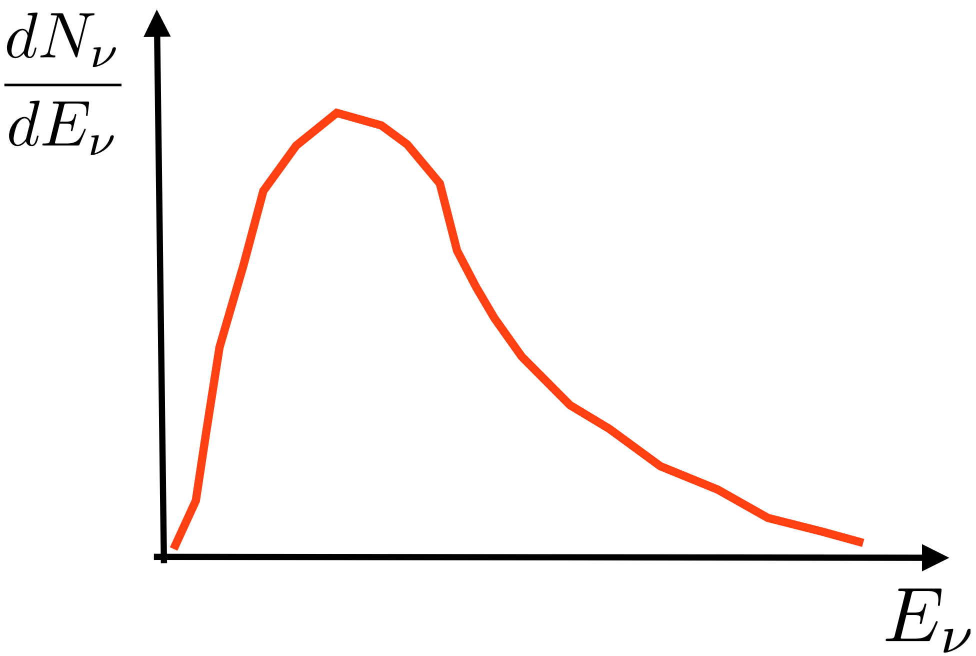
Ideal Messengers

Escaping unimpeded, neutrinos carry information about sources not otherwise accessible.



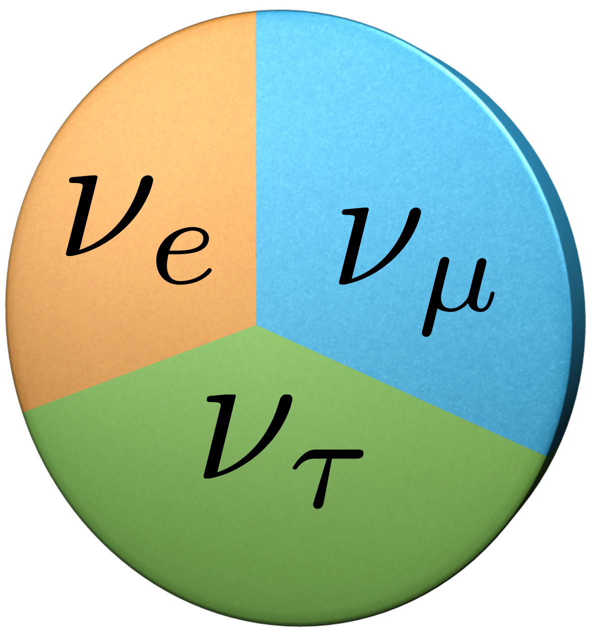
Powerful Probes in Astrophysics

Energy distribution



Similar to photons

Flavor ratio



Neutrinos only!

The Dream of Neutrino Astronomy

If [there are no new forces] -- one can conclude that there is no practically possible way of observing the neutrino.

Bethe and Peierls (1934)

Only neutrinos, with their extremely small cross sections, can enable us to see into the interior of a star ...

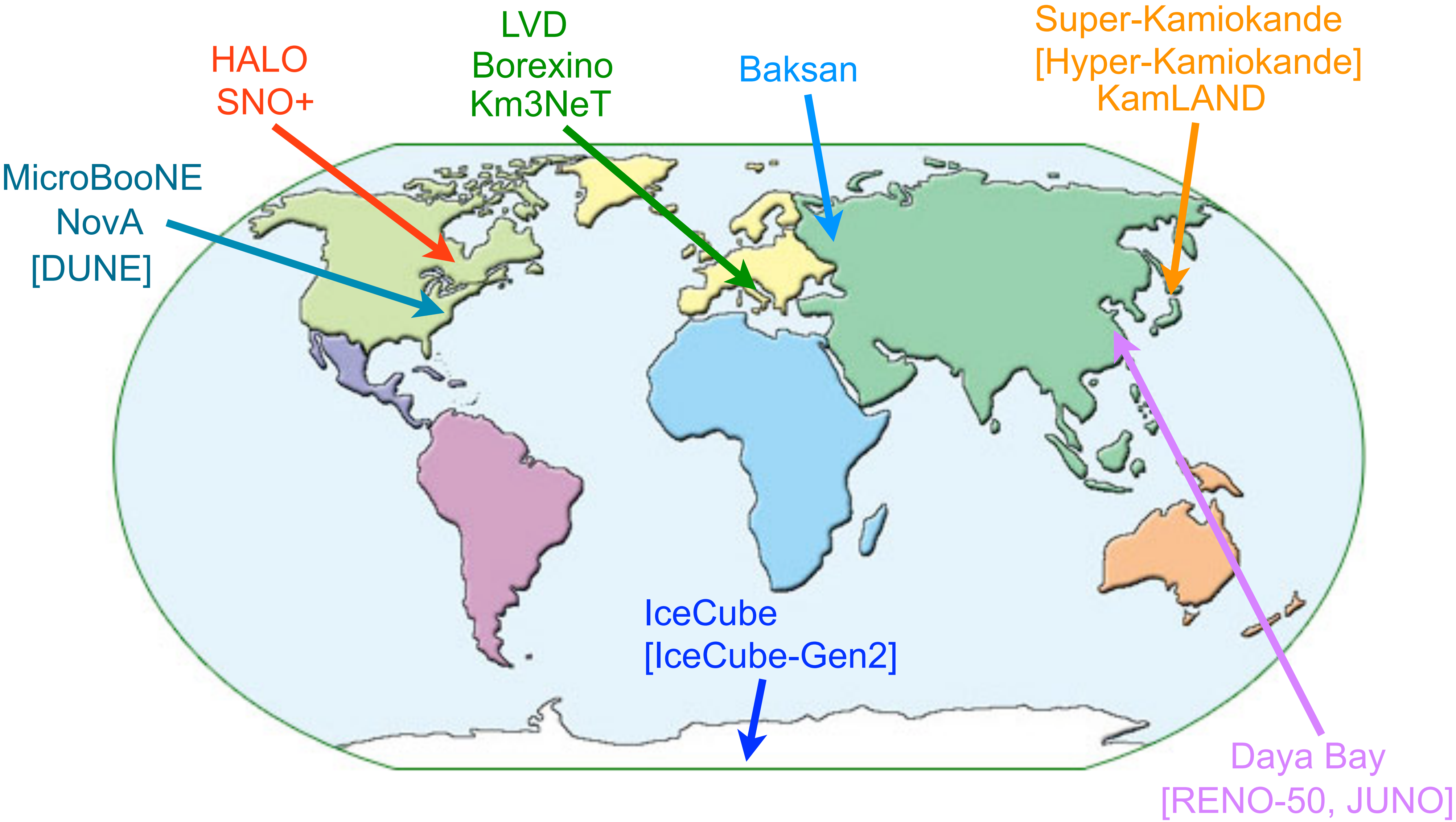
Bahcall (1964)

The title is more of an expression of hope than a description of the book's contents ...
the observational horizon of neutrino astrophysics may grow ... perhaps in a time as short as one or two decades.

Bahcall, Neutrino Astrophysics (1989)

John Bahcall

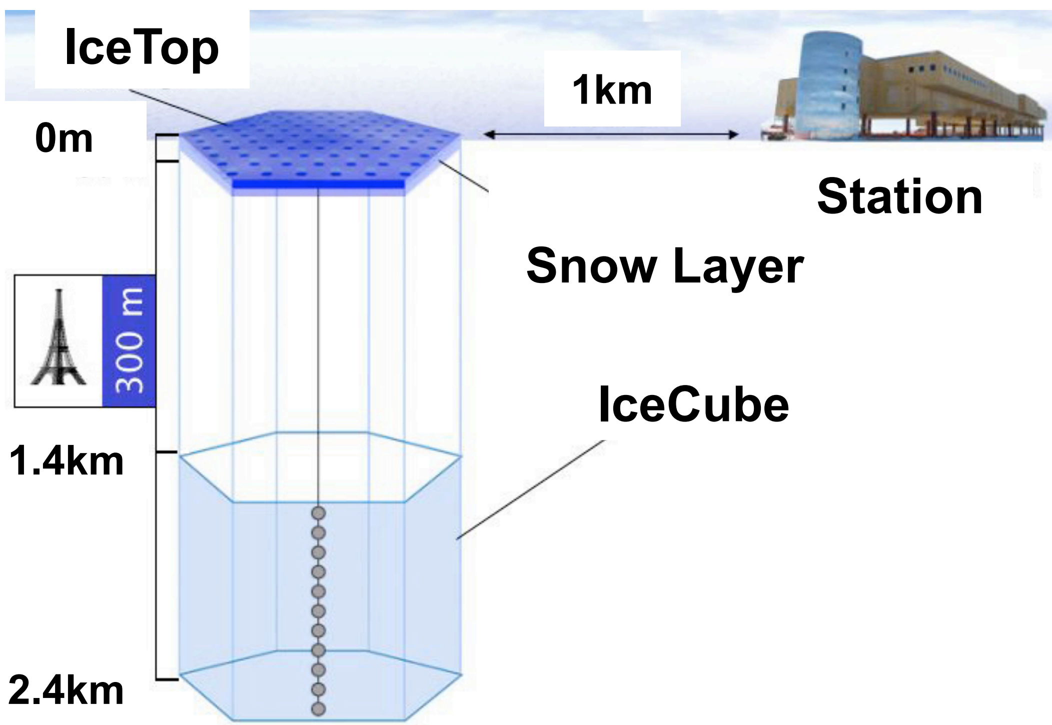
Astro-Neutrino Detectors



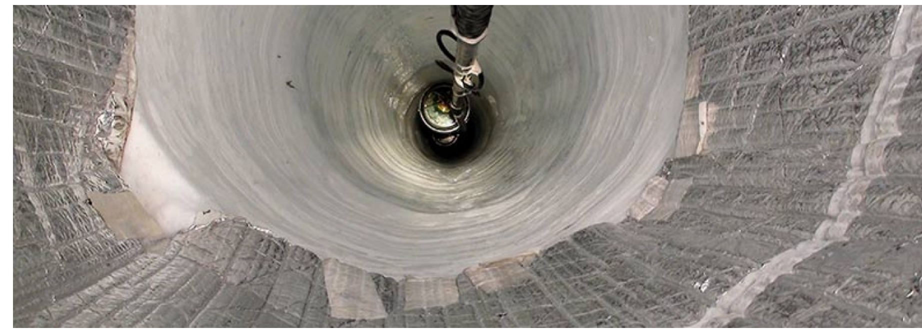
Fundamental to combine astrophysical signals from detectors employing different technologies.

The IceCube Neutrino Telescope

IceCube Telescope (South Pole)

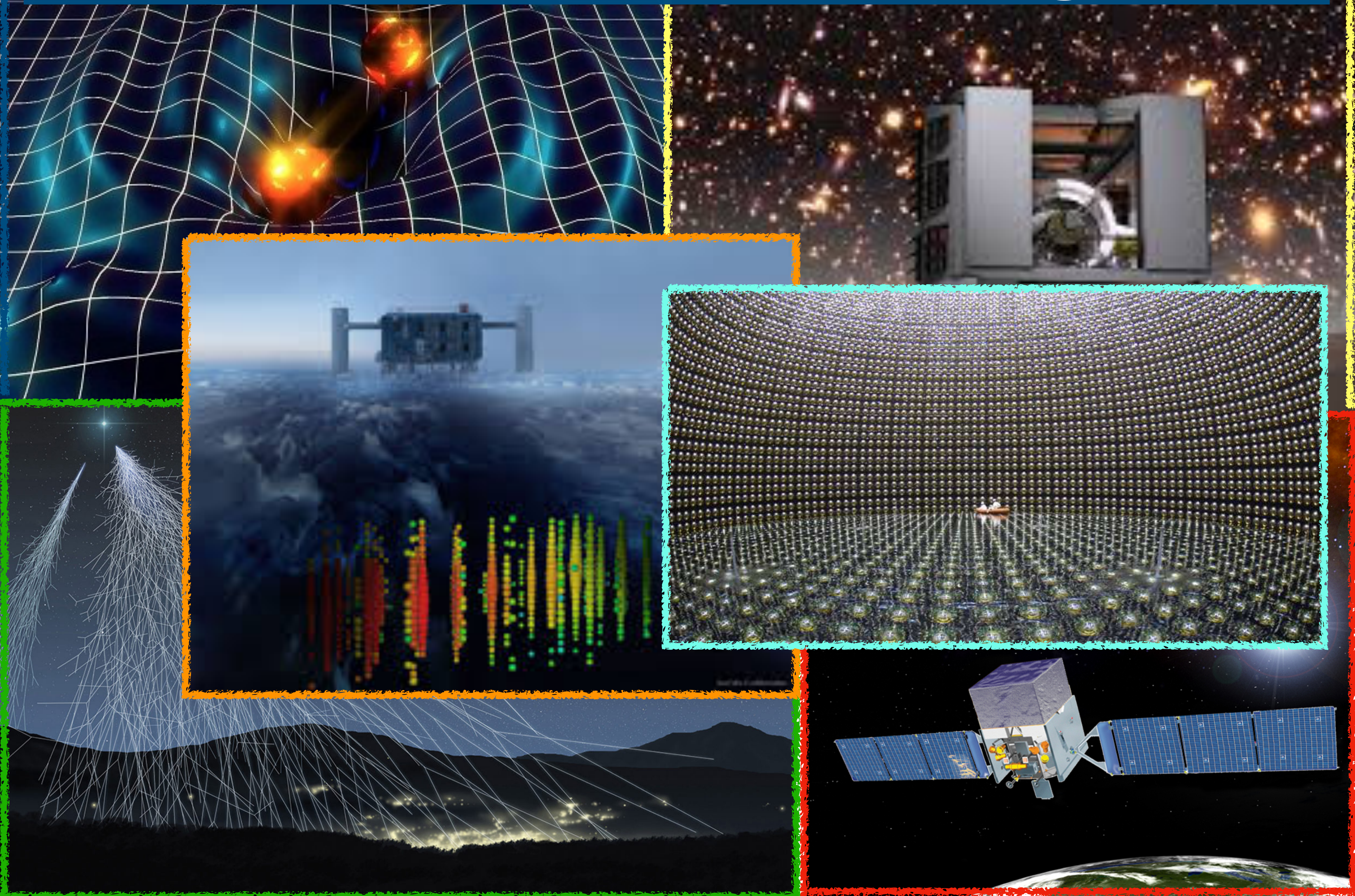


5,600 “electronic eyes”

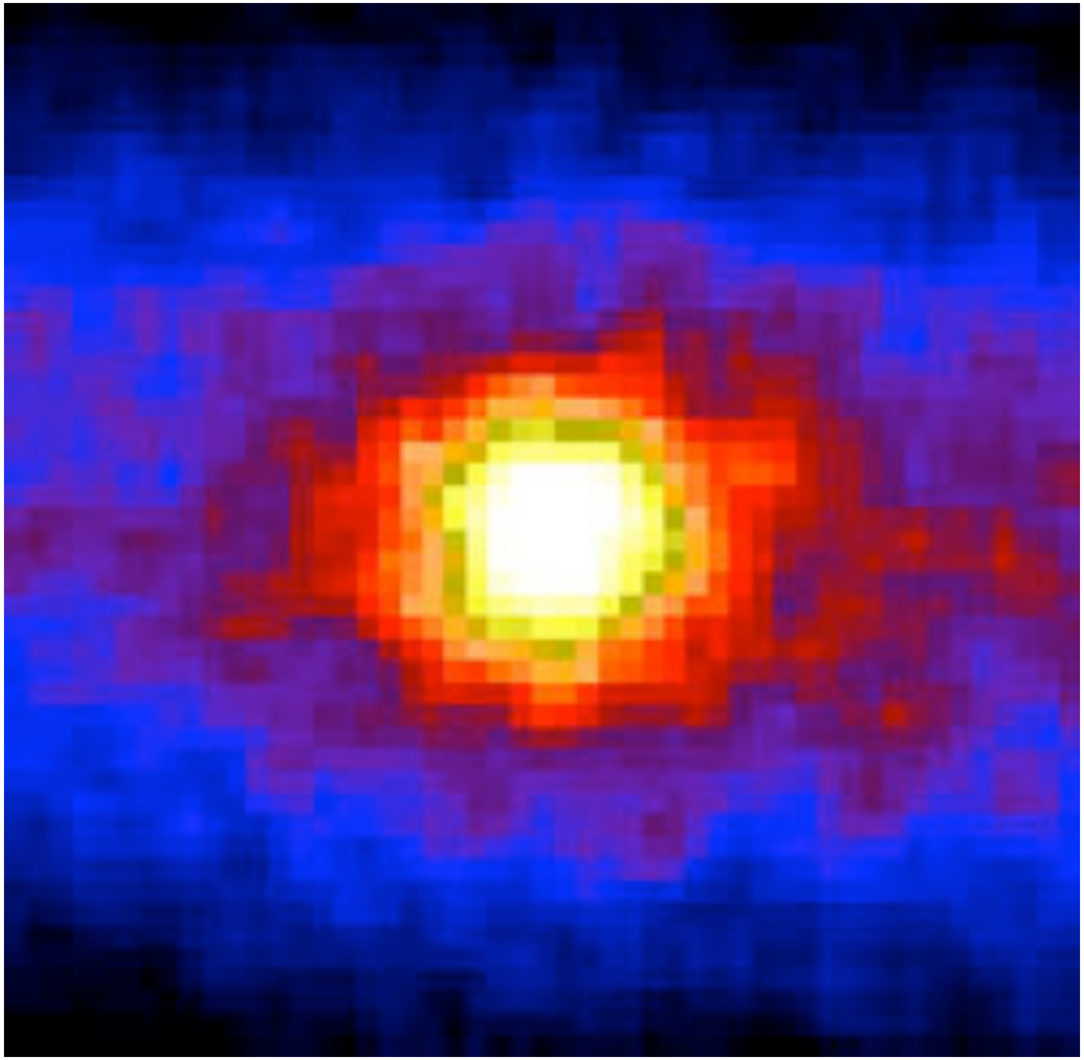


$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Dawn of the Multi-Messenger Era



The Sun in Neutrinos

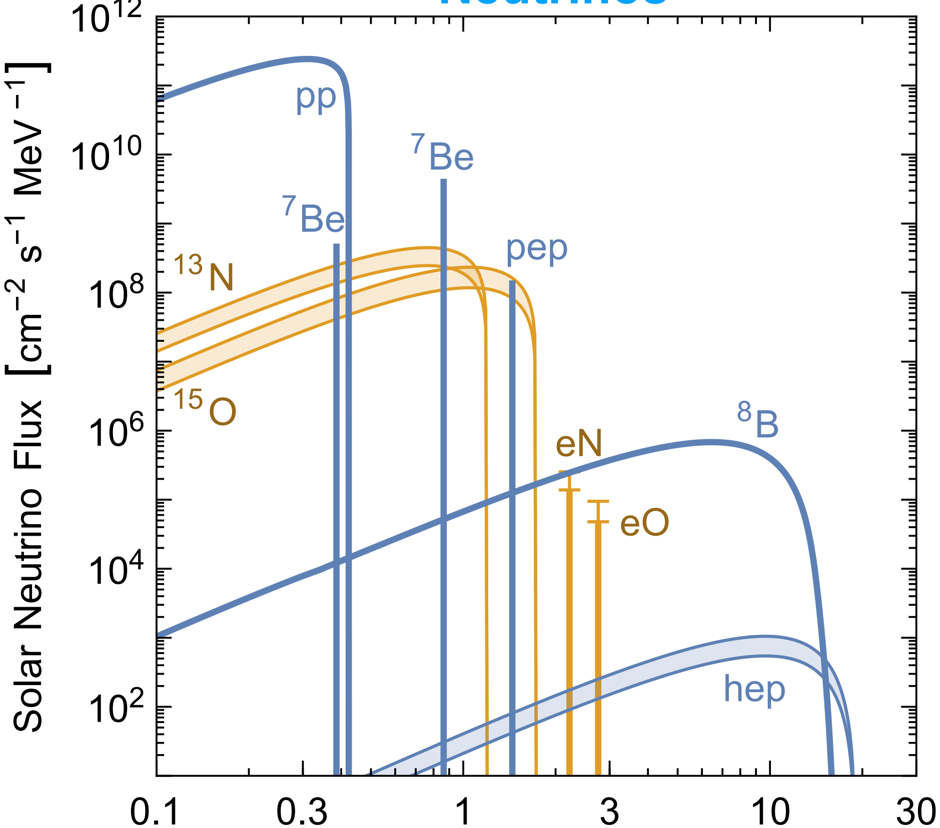


- Radiation from the Sun (98 % Light, 2% Neutrinos).
- Photons take 200,000 years to escape from the Sun, neutrinos 2 seconds.

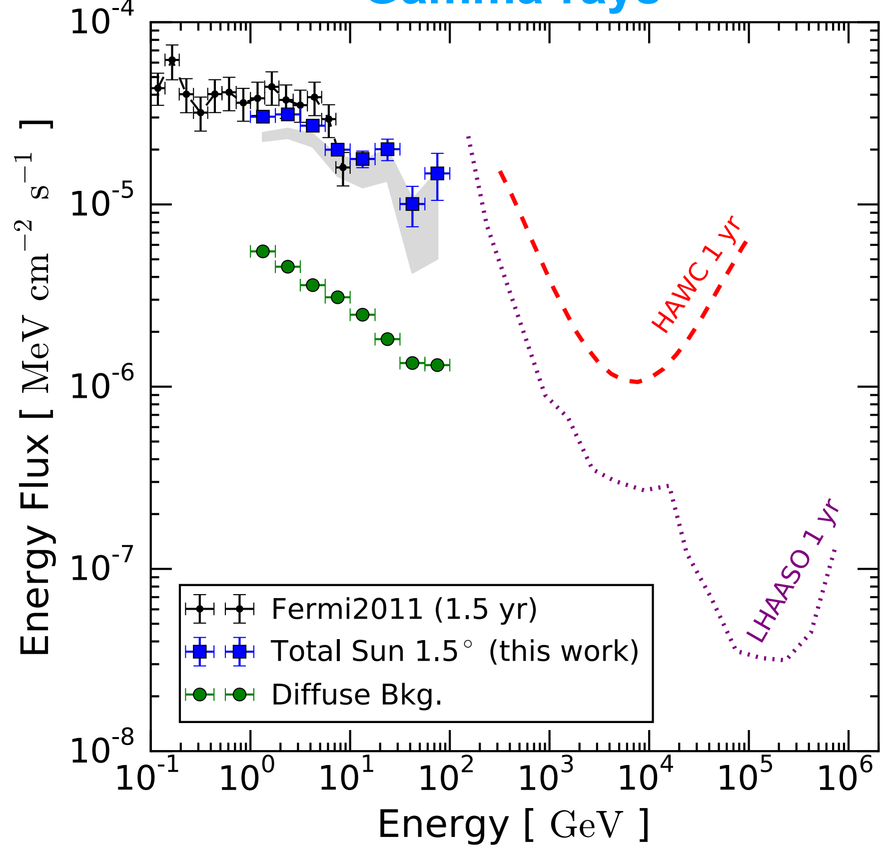
Image credits: Super-Kamiokande Collaboration.

The Sun

Neutrinos



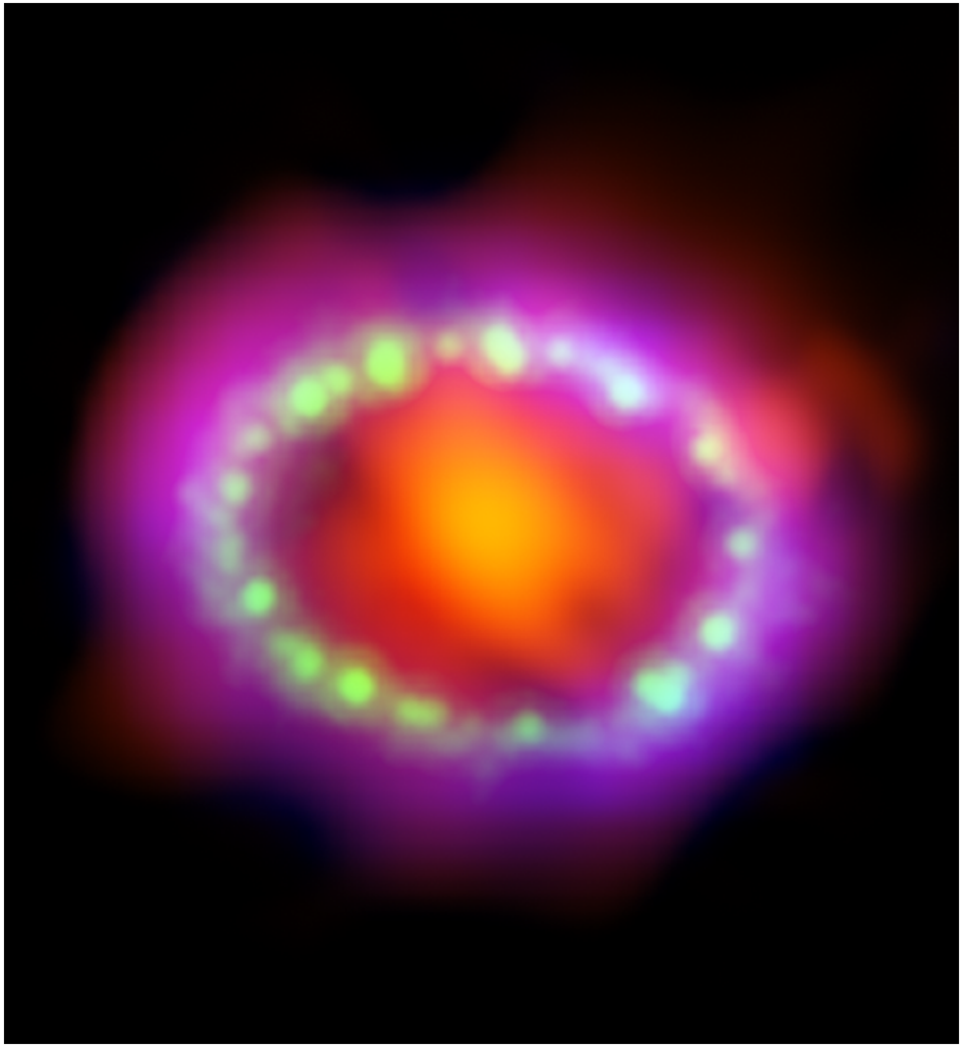
Gamma-rays

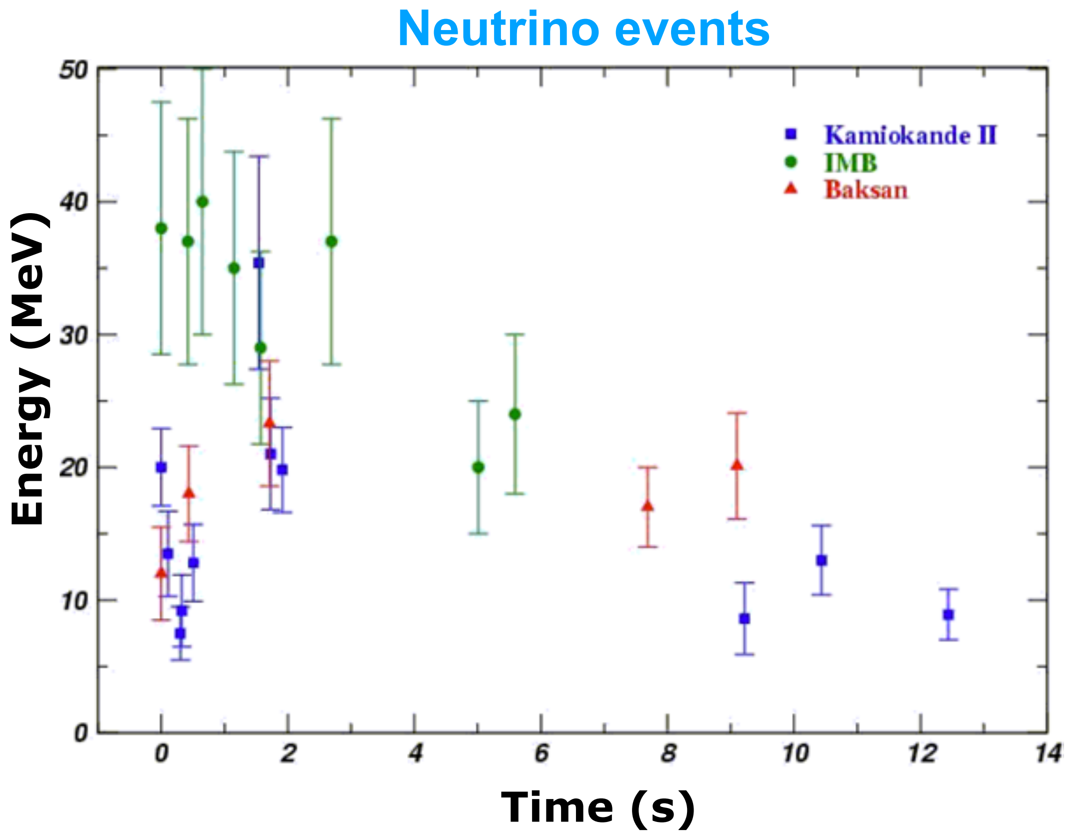


- Optical emission and neutrinos: the Sun is main-sequence star powered by nuclear fusion.
- Neutrinos: test of stellar structure and neutrino physics.
- Gamma-rays: probes of solar atmospheric magnetic fields and cosmic-ray physics.

Image credits: Vitagliano, Tamborra, Raffelt, arXiv: 1910.11878. Ng et al., PRD (2016). Fermi-LAT, ApJ (2011).

Supernova Neutrinos (SN 1987a)

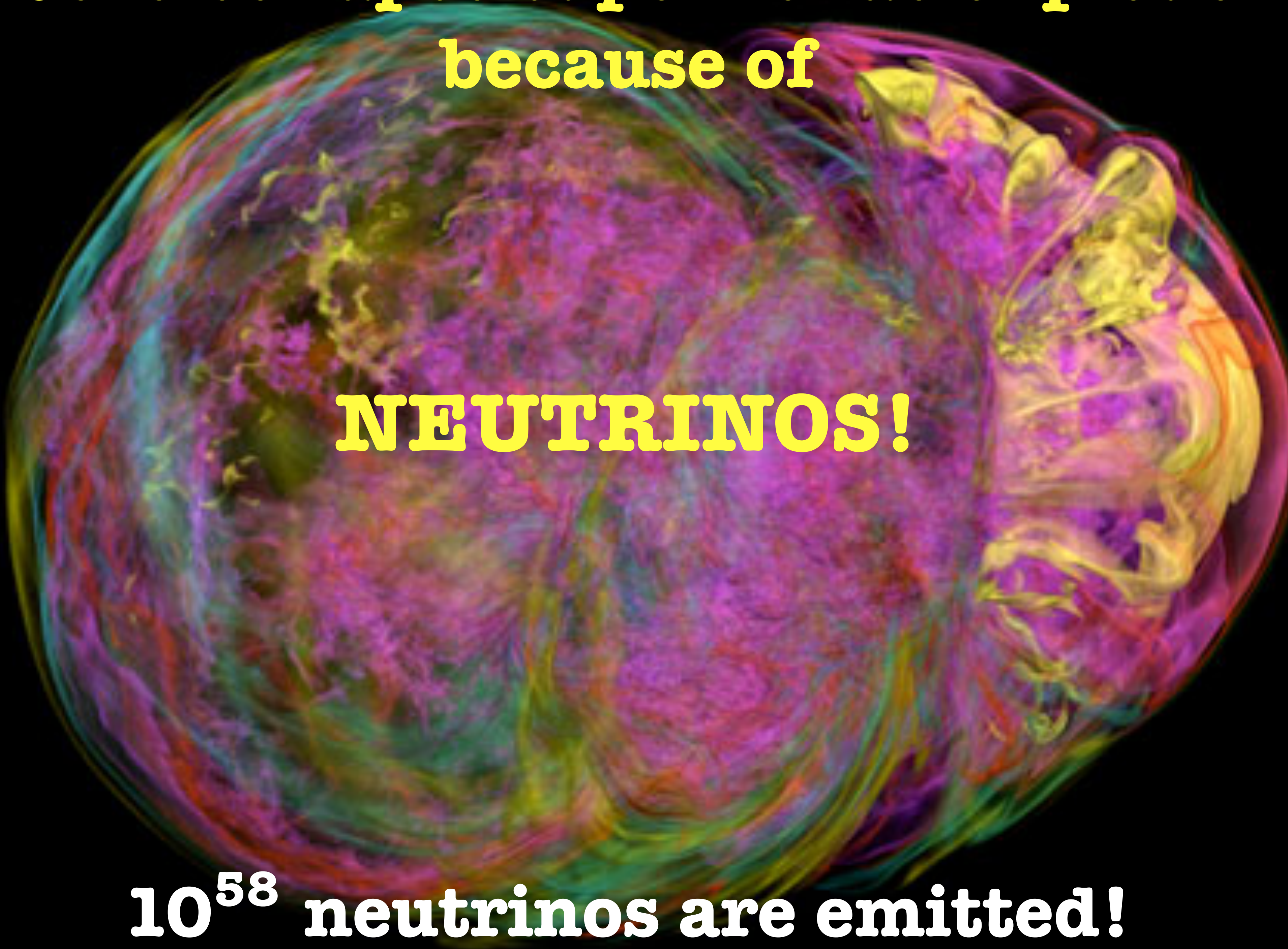




- Radiation from the Sun (0.01 % Light, 99% Neutrinos).
- Unique probe of stellar collapse and supernova mechanism.

Image credits: NASA, ESA.

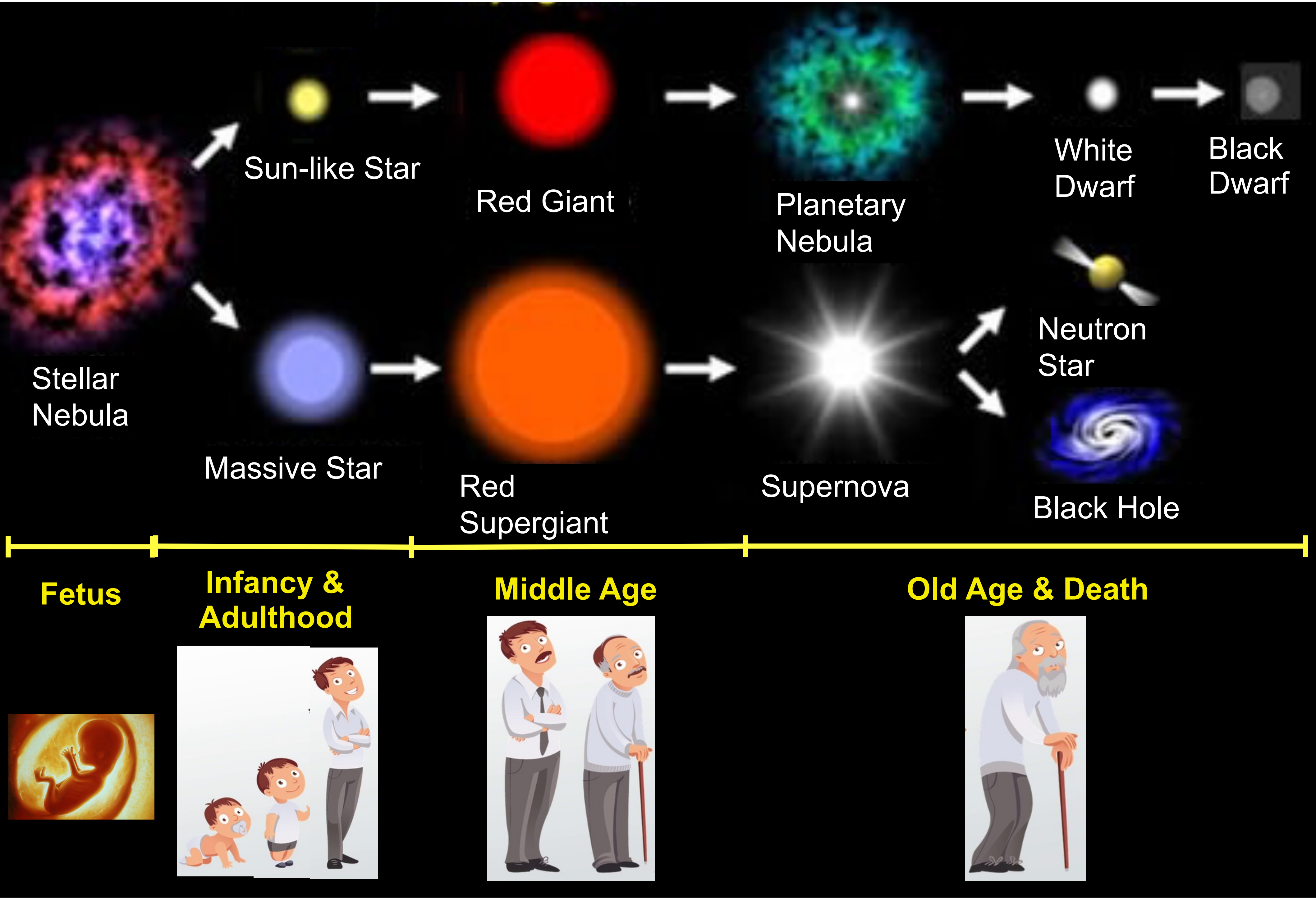
Core-collapse supernovae explode because of



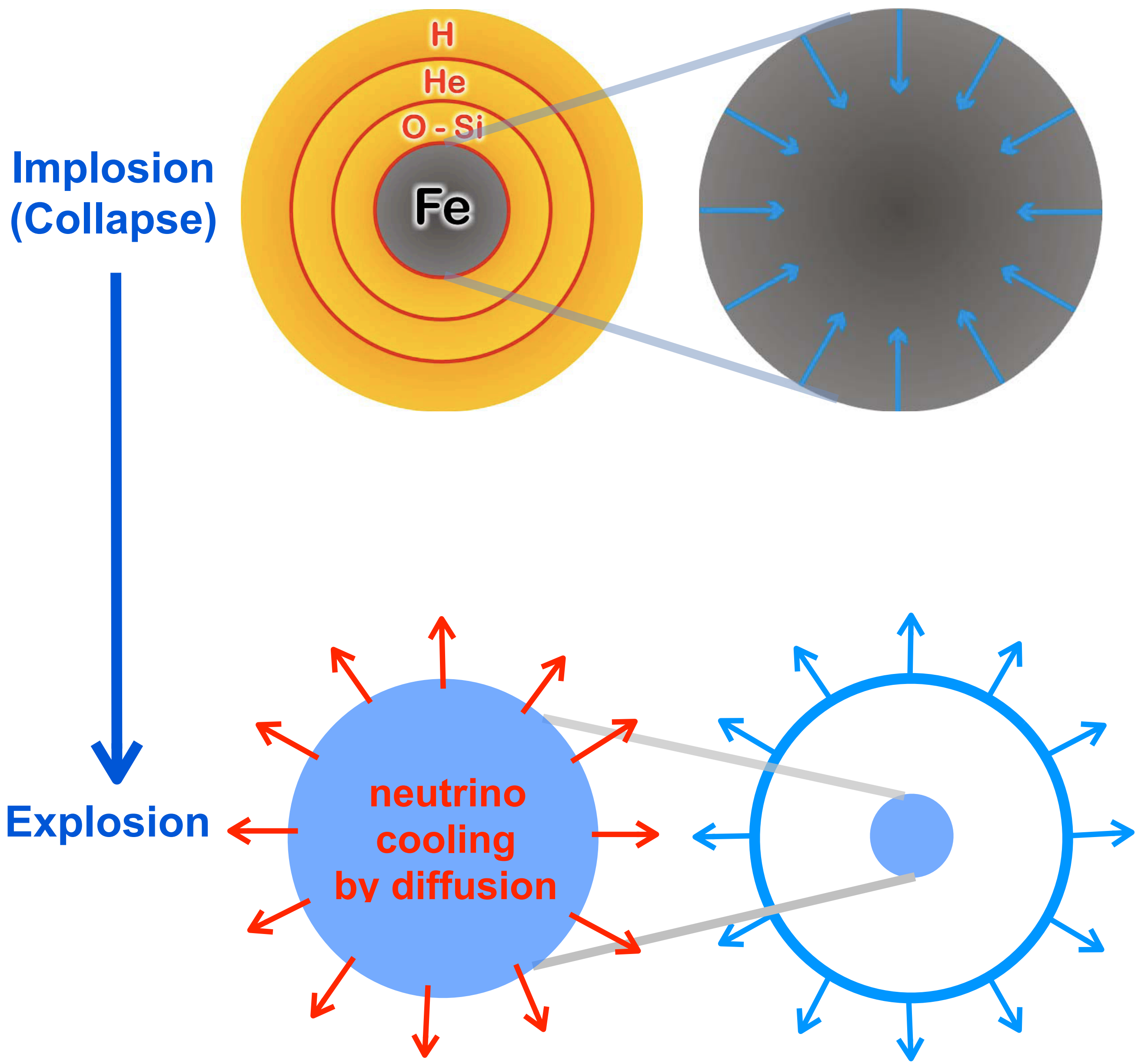
NEUTRINOS!

10^{58} neutrinos are emitted!

Lifecycle of a Star



Core-Collapse Supernova Explosion

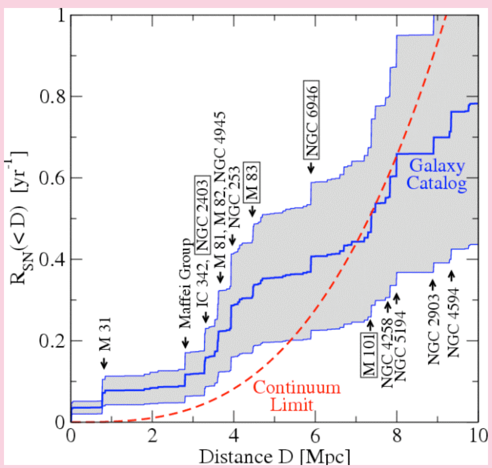


Neutrinos carry 99% of the released energy (~ 10^{53} erg).

Detection Frontiers

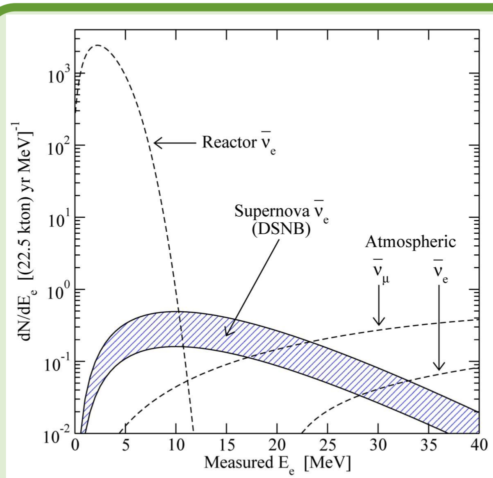
Supernova in our Galaxy (one burst per 40 years).

Excellent sensitivity to details.



Supernova in nearby Galaxies (one burst per year).

Sensitivity to general properties.



Diffuse Supernova Background
(one supernova per second).

Average supernova emission. Guaranteed signal.

The Next Nearby Supernova (SN 2XXXa)

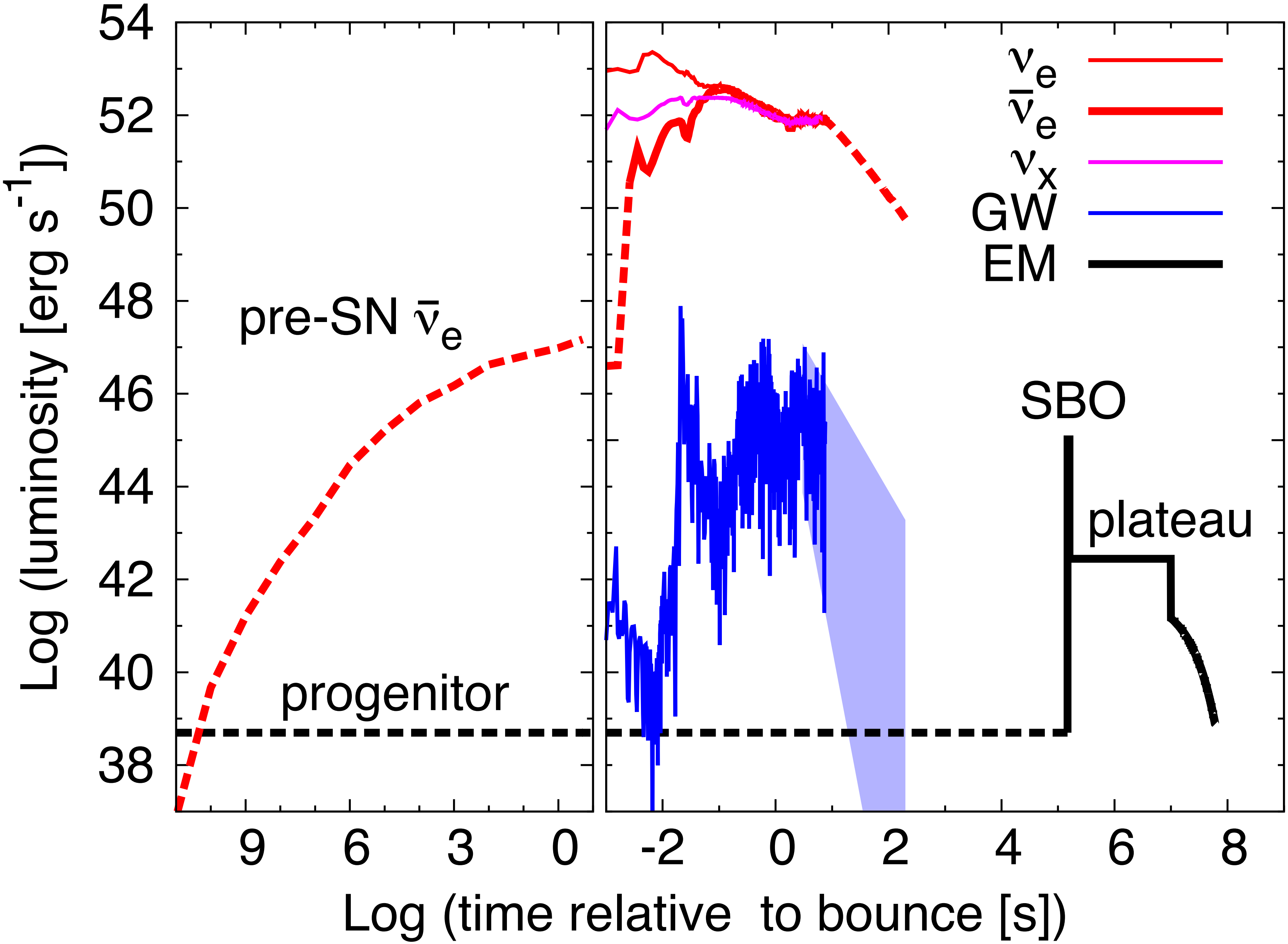
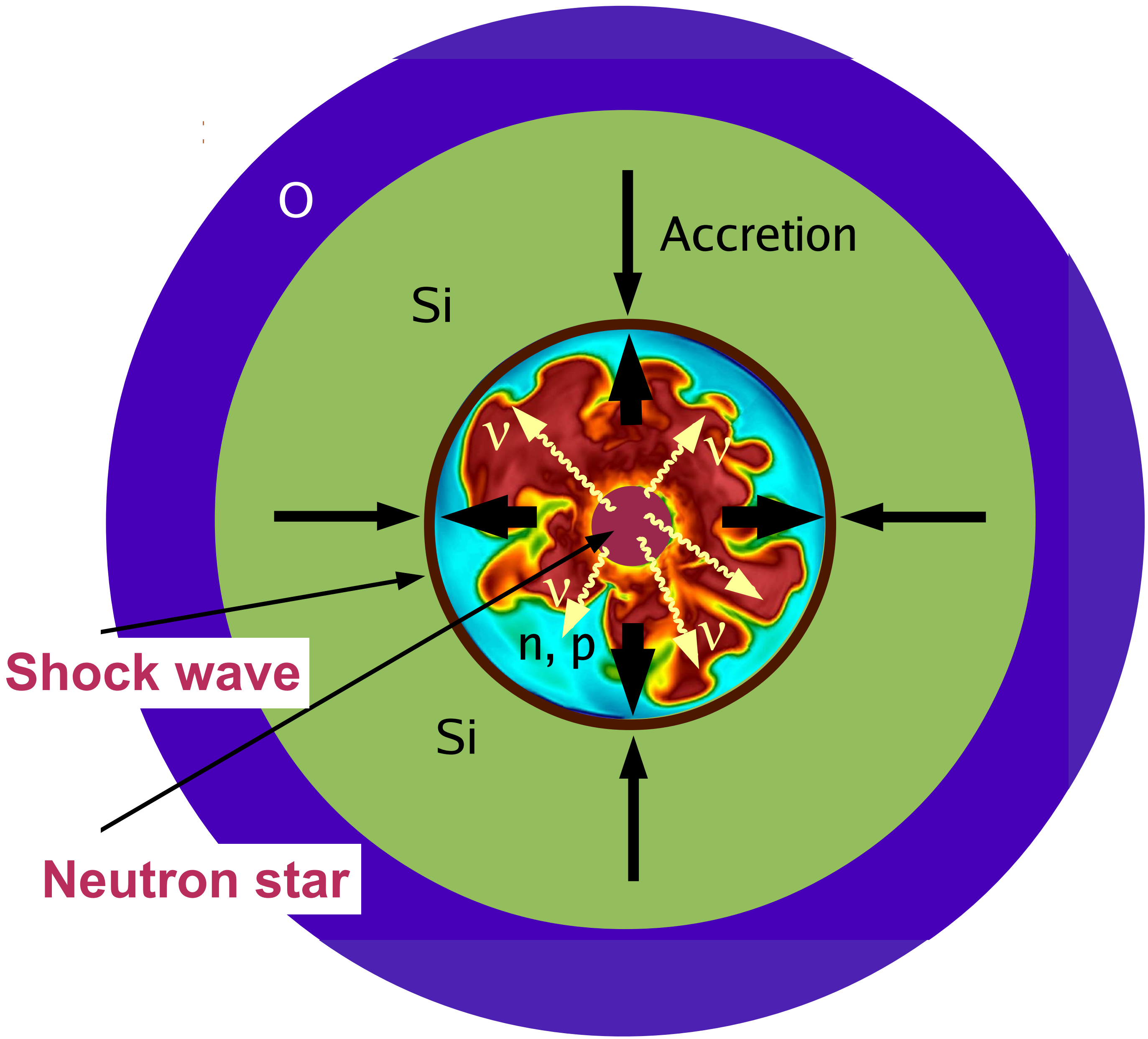


Figure from Nakamura et al., MNRAS (2016).

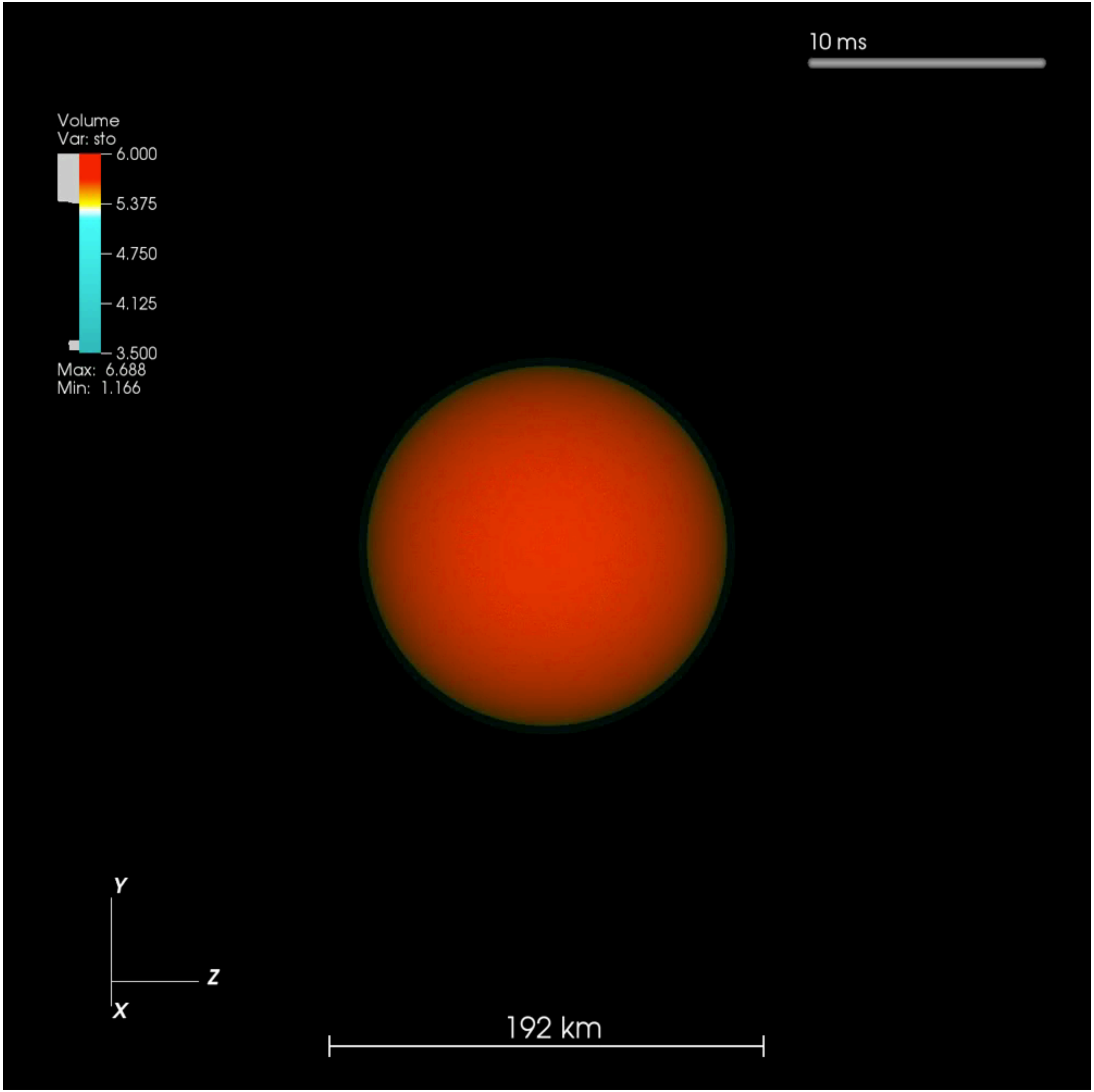
Supernova Explosion Mechanism

Shock wave forms within the iron core. It dissipates energy dissociating the iron layer.
Neutrinos provide energy to the stalled shock wave to start re-expansion.



Recent reviews: Janka (2017). Mirizzi, Tamborra et al. (2016).

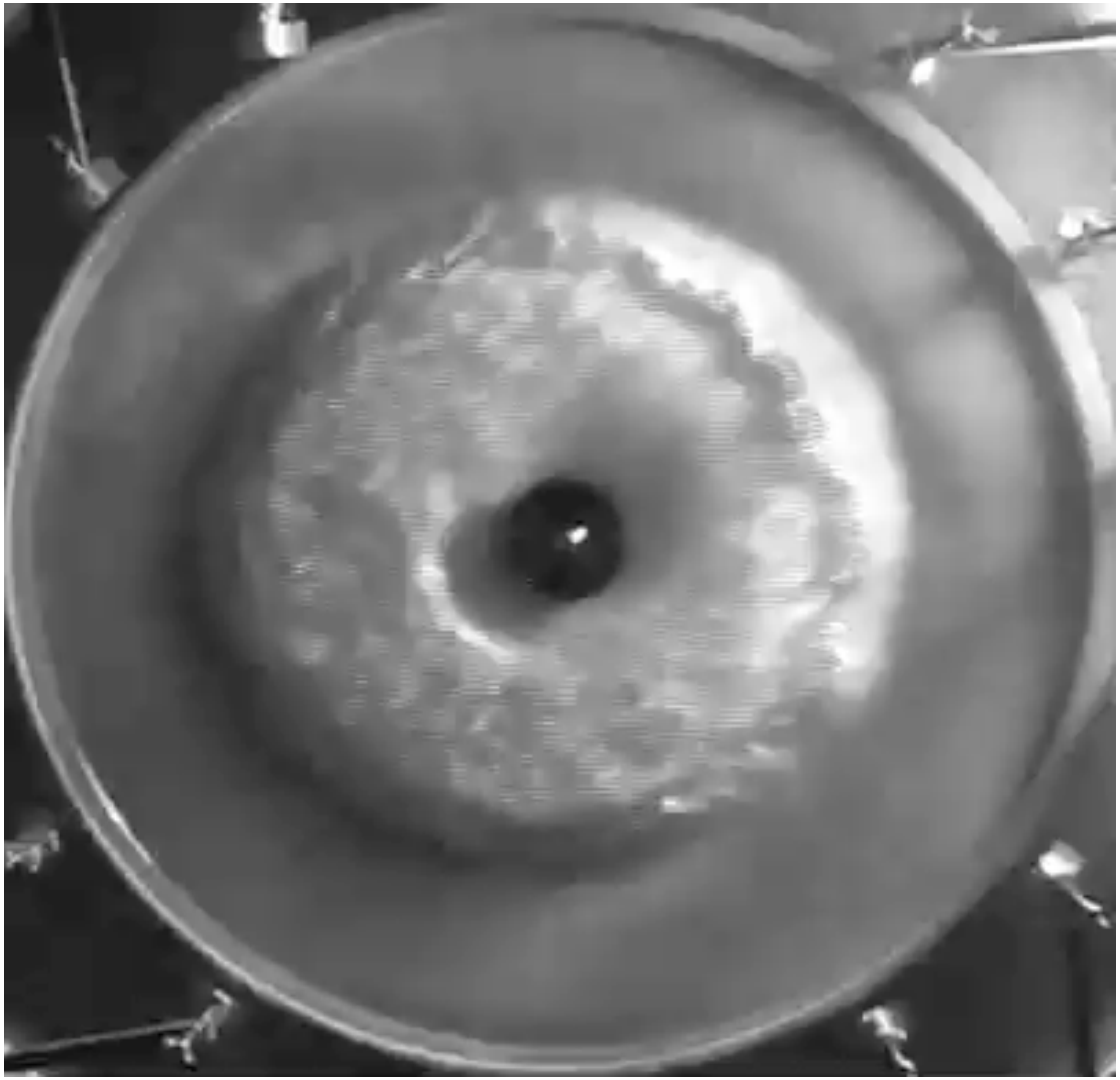
20 M_{sun} Supernova Model



Movie: 3D SN simulation (M=20 M_{sun}), Garching group.

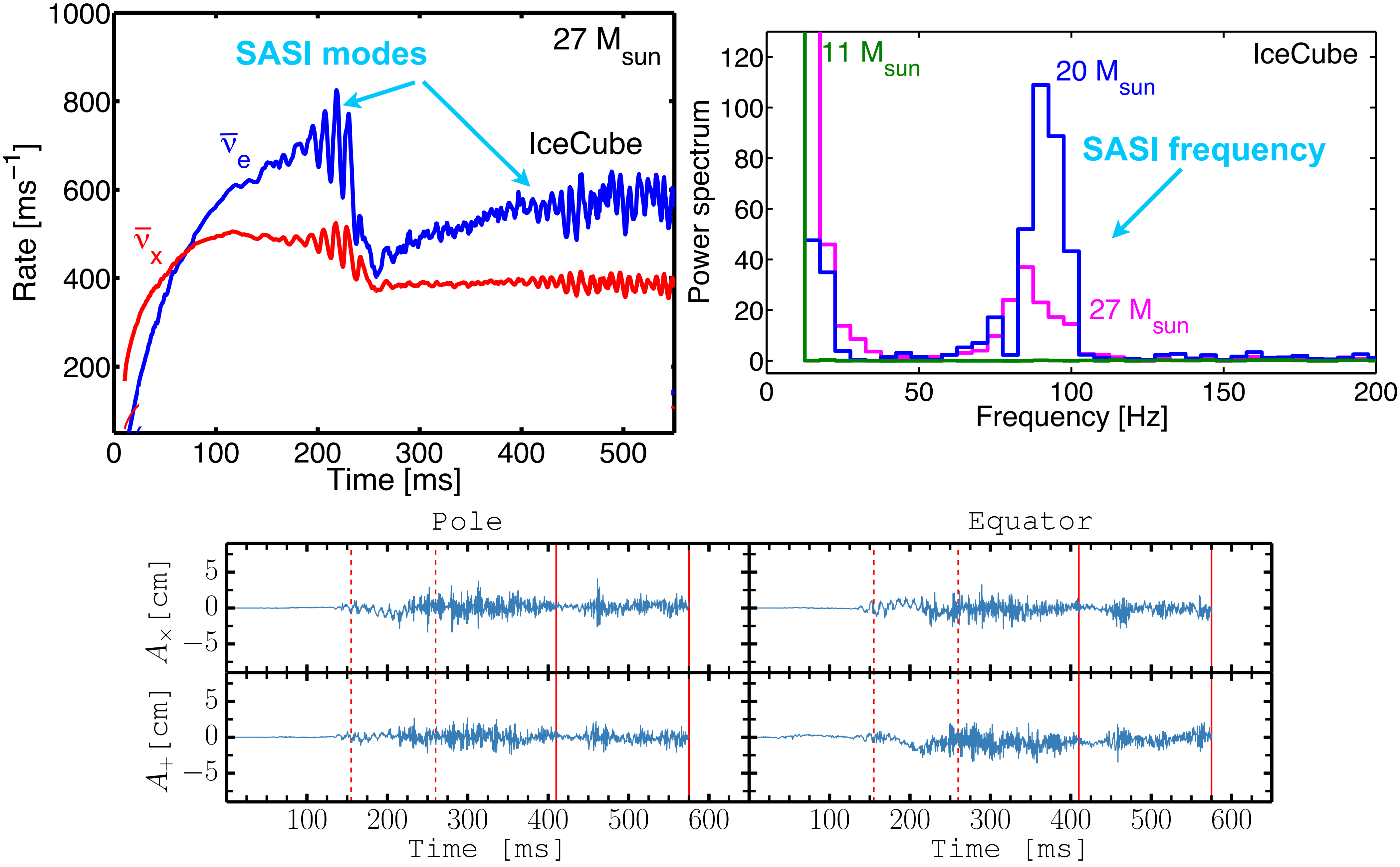
Standing Accretion Shock Instability

SWASI Experiment (Foglizzo et al., 2012)



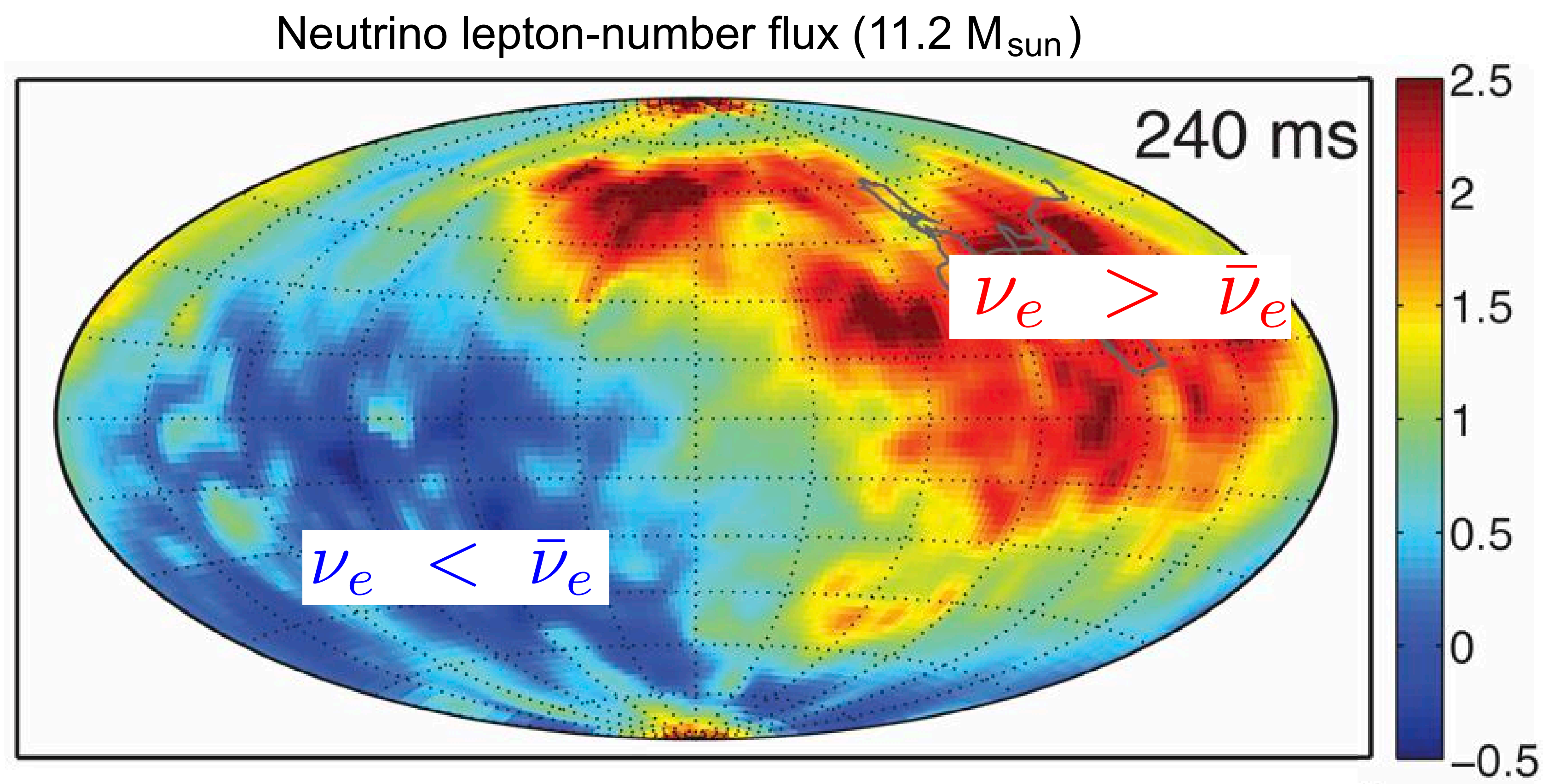
Analogue of the SASI instability, but one million times smaller and one hundred times slower than its astrophysical counterpart.

Fingerprints of the Explosion Mechanism



Tamborra et al., PRL (2013), PRD (2014). Andresen et al., MNRAS (2017). Kuroda et al., ApJ (2017).
Walk, Tamborra et al., PRD (2018), PRD (2019).

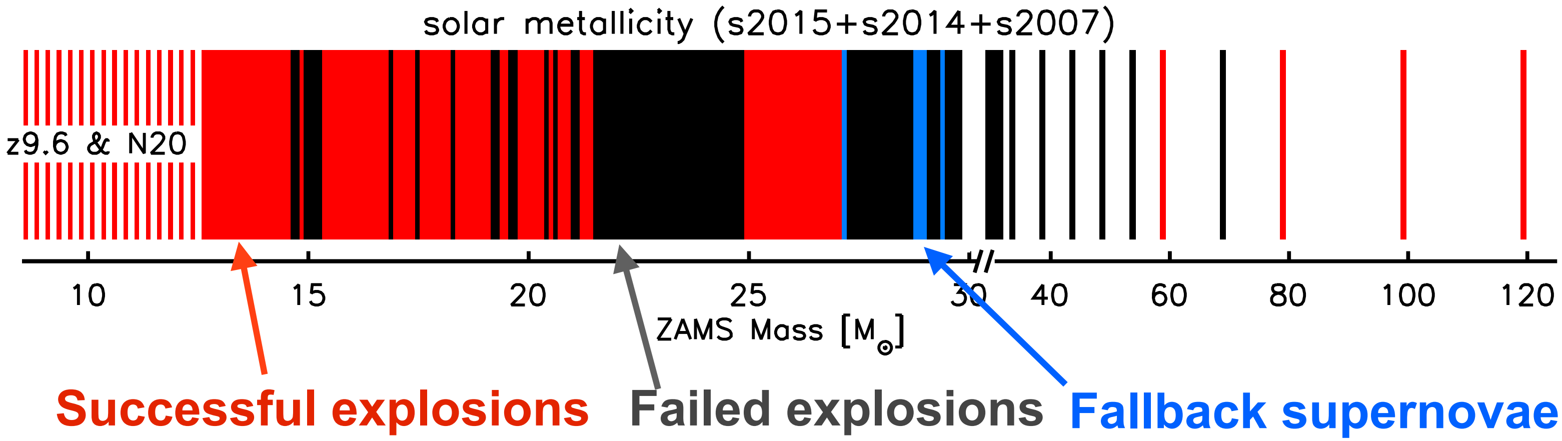
LESA: Neutrino-Driven Instability

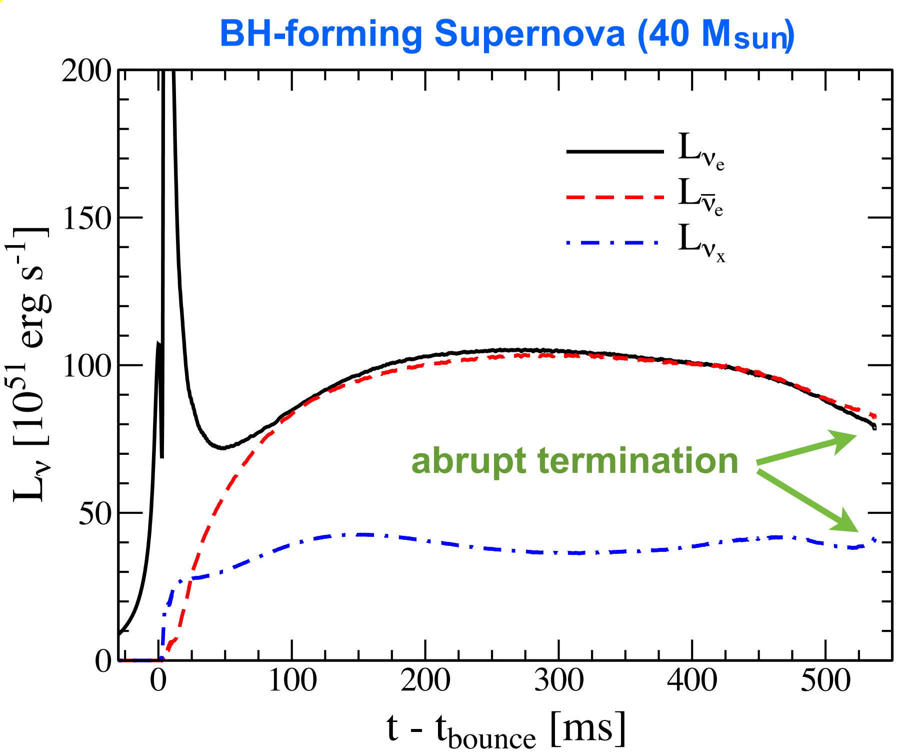


Lepton-number emission asymmetry (**LESA**): Large-scale feature with **dipole character**.

Tamborra, Hanke, Janka, Mueller, Raffelt, Marek, ApJ (2014).
Janka et al., ARNPS (2016). Glas et al., (2018), Vartanyan et al., MNRAS (2019), O'Connor & Couch, ApJ (2018).

Neutrinos Probe Black Hole Formation

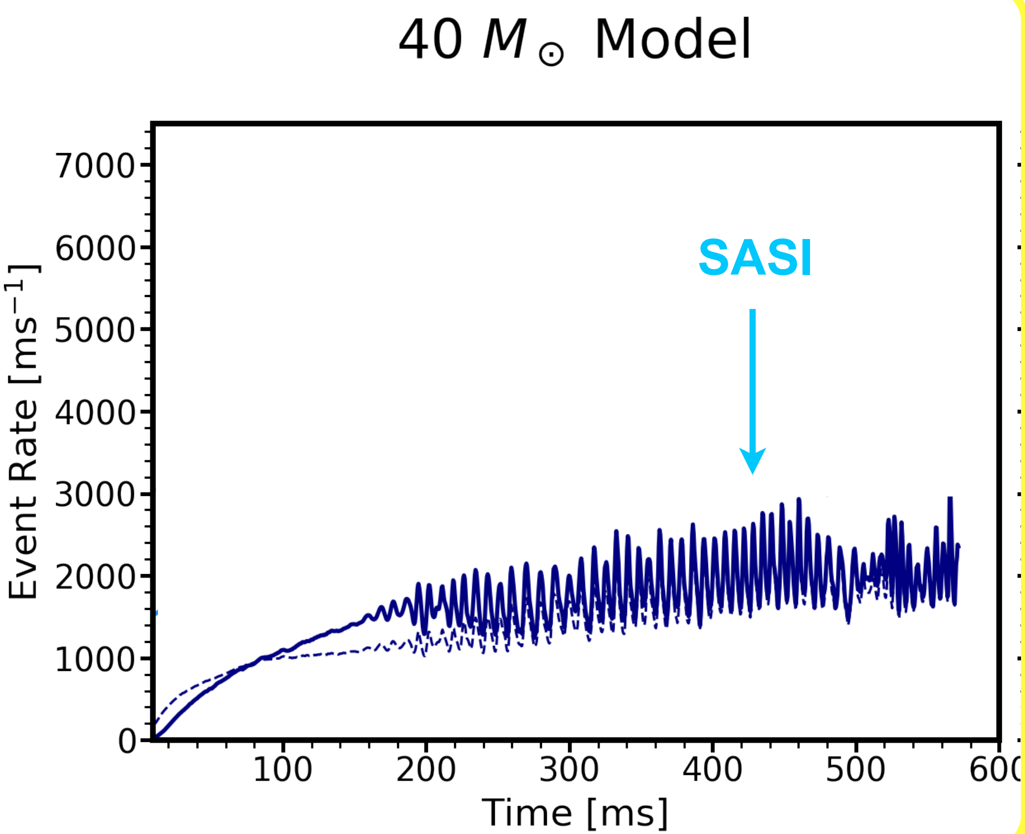




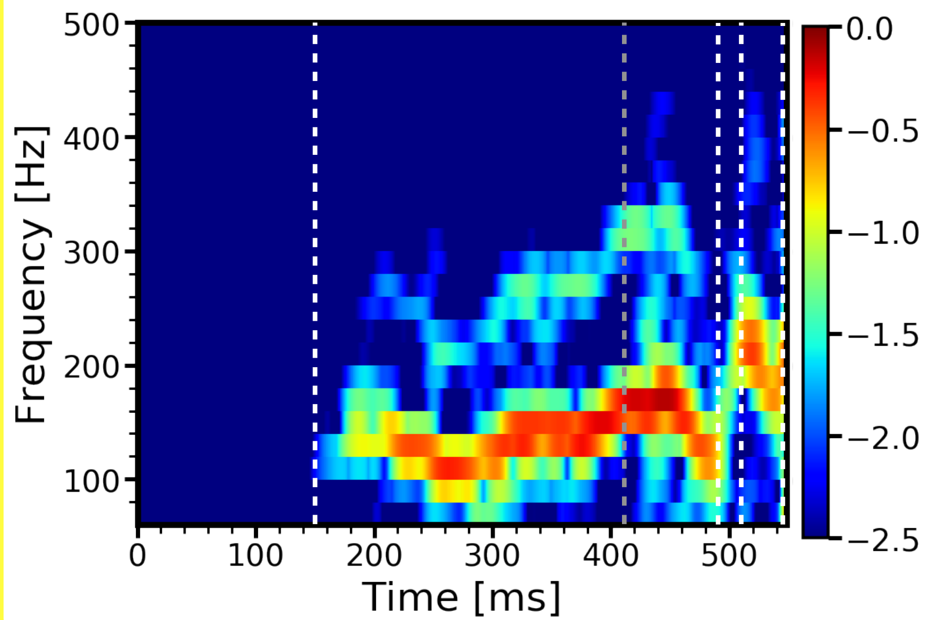
- Low-mass supernovae can form black holes.
- Neutrinos reveal black-hole formation.
- Failed supernovae up to 20-40% of total.

Sukhbold et al., ApJ (2016). Ertl et al., ApJ (2016). Horiuchi et al., MNRSL (2014). O'Connor & Ott, ApJ (2011). O'Connor, ApJ (2015). Kuroda et al., MNRAS (2018).

Neutrinos Probe Black Hole Formation



Neutrino (and gravitational waves) probe black-hole formation.



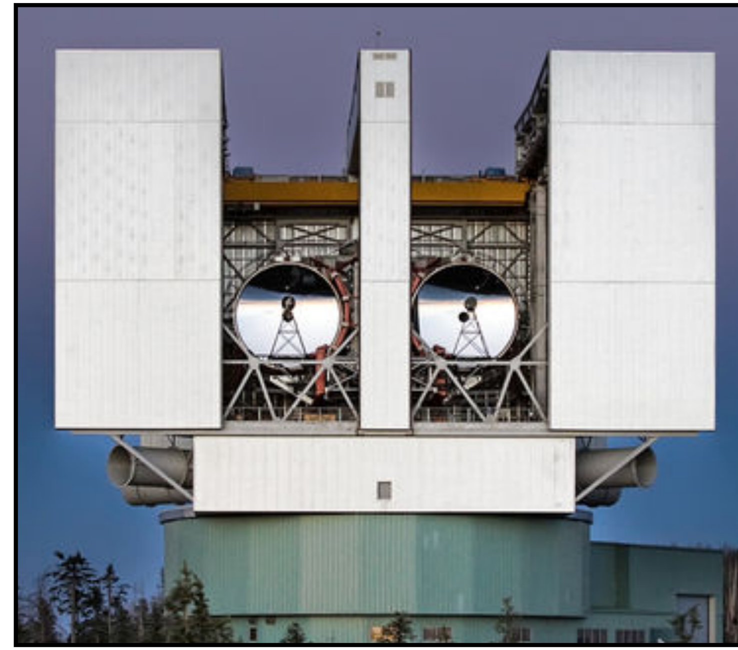
SASI frequency evolution = shock radius evolution

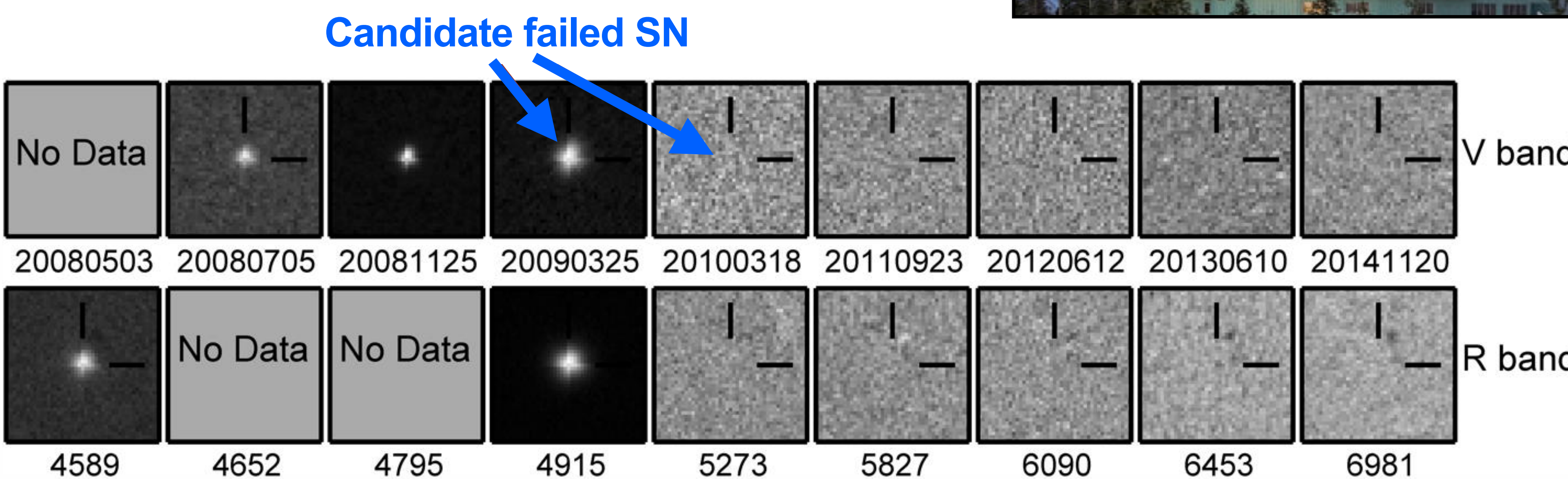
Walk, Tamborra, Janka, Summa, arXiv: 1910.12971.

A Survey About Nothing

- Search for disappearance of red supergiants
(27 galaxies within 10 Mpc with Large Binocular Telescope).

- First 7 years of survey:
6 successful core-collapse, **1 candidate failed supernova**.

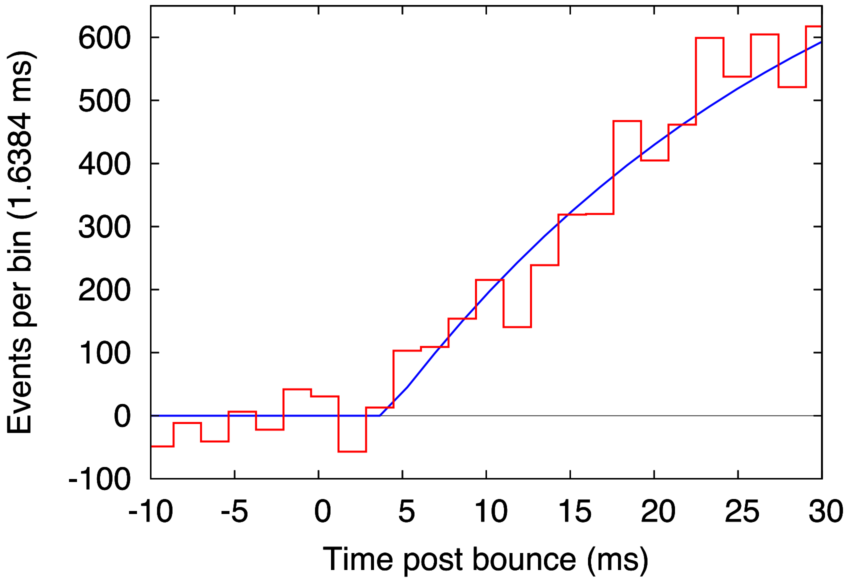




Failed core-collapse fraction: 4-43% (90% CL)

Adams et al., MNRAS (2017), MNRAS (2017). Gerke, Kochanek & Stanek, MNRAS (2015). Kochanek et al., ApJ (2008).

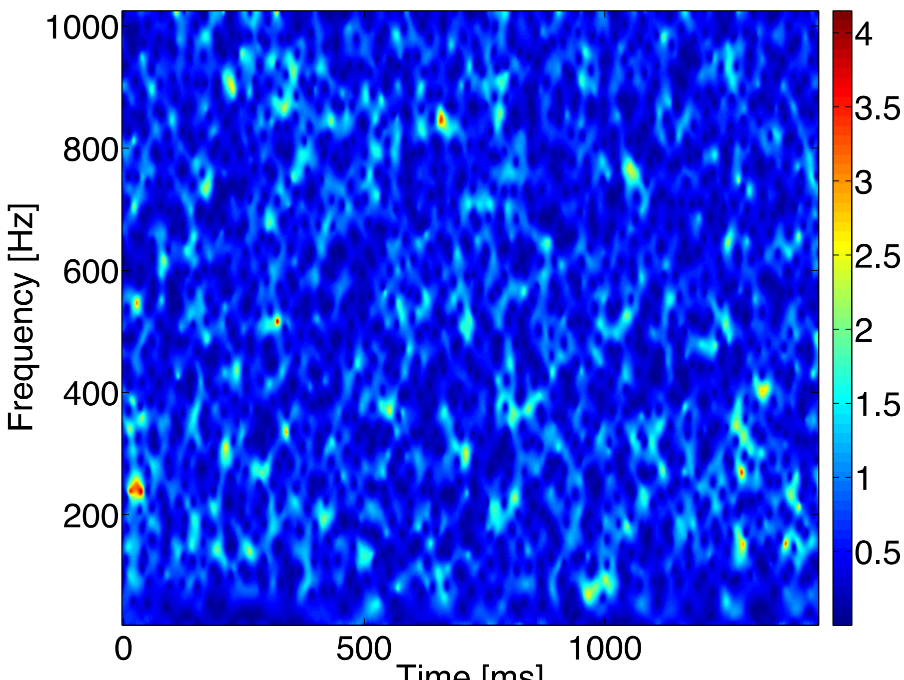
Neutrino Timing



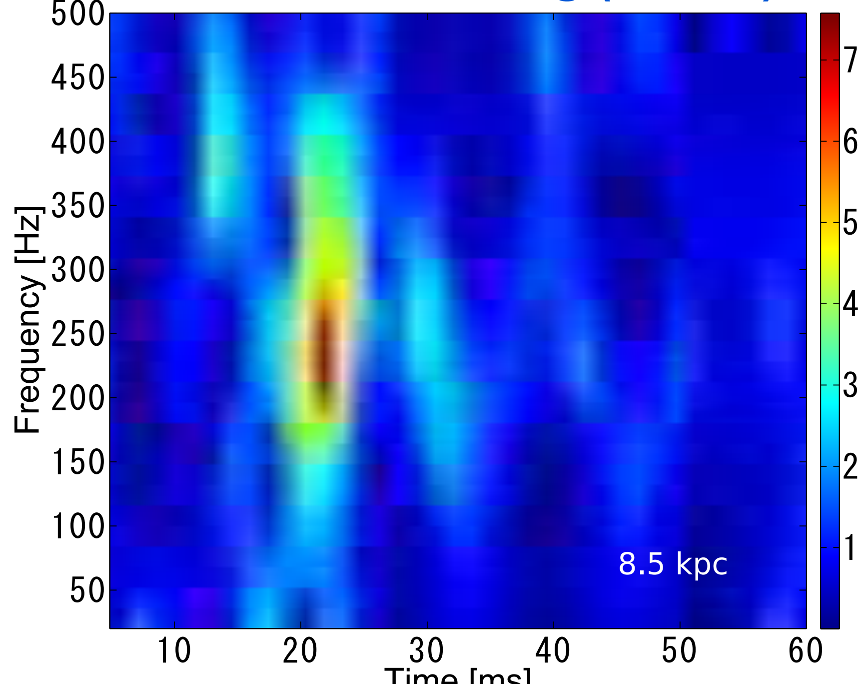
Probe core bounce time with neutrinos.

Timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)



With neutrino timing (S/N ~7)



Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016).

ν_e

ν_τ

Flavor Evolution

ν_μ

Neutrino Flavor Conversions

Neutrinos **convert** into each other by flavor mixing, because of their tiny non-vanishing mass.

Flavor eigenstates

ν_e

ν_μ

ν_τ

= **Linear combination**

Mass eigenstates

ν_1

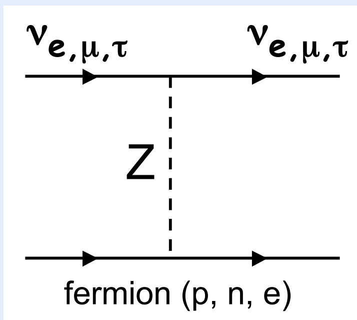
ν_2

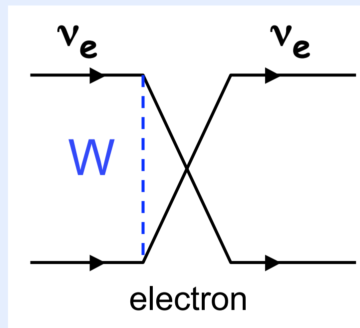
ν_3

Flavor Conversions

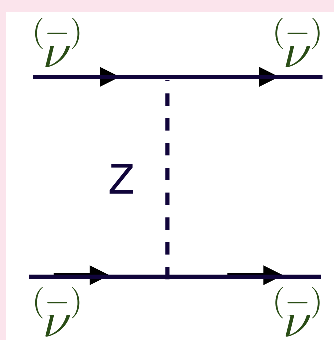
- Neutrino flavor ratio provides information about **neutrino properties**.
- Flavor conversions are affected by the matter distribution of the source.
- Flavor conversions strongly affect source dynamics.

Neutrino Interactions





Neutrinos interact with neutrons, protons and electrons (MSW enhanced conversions).

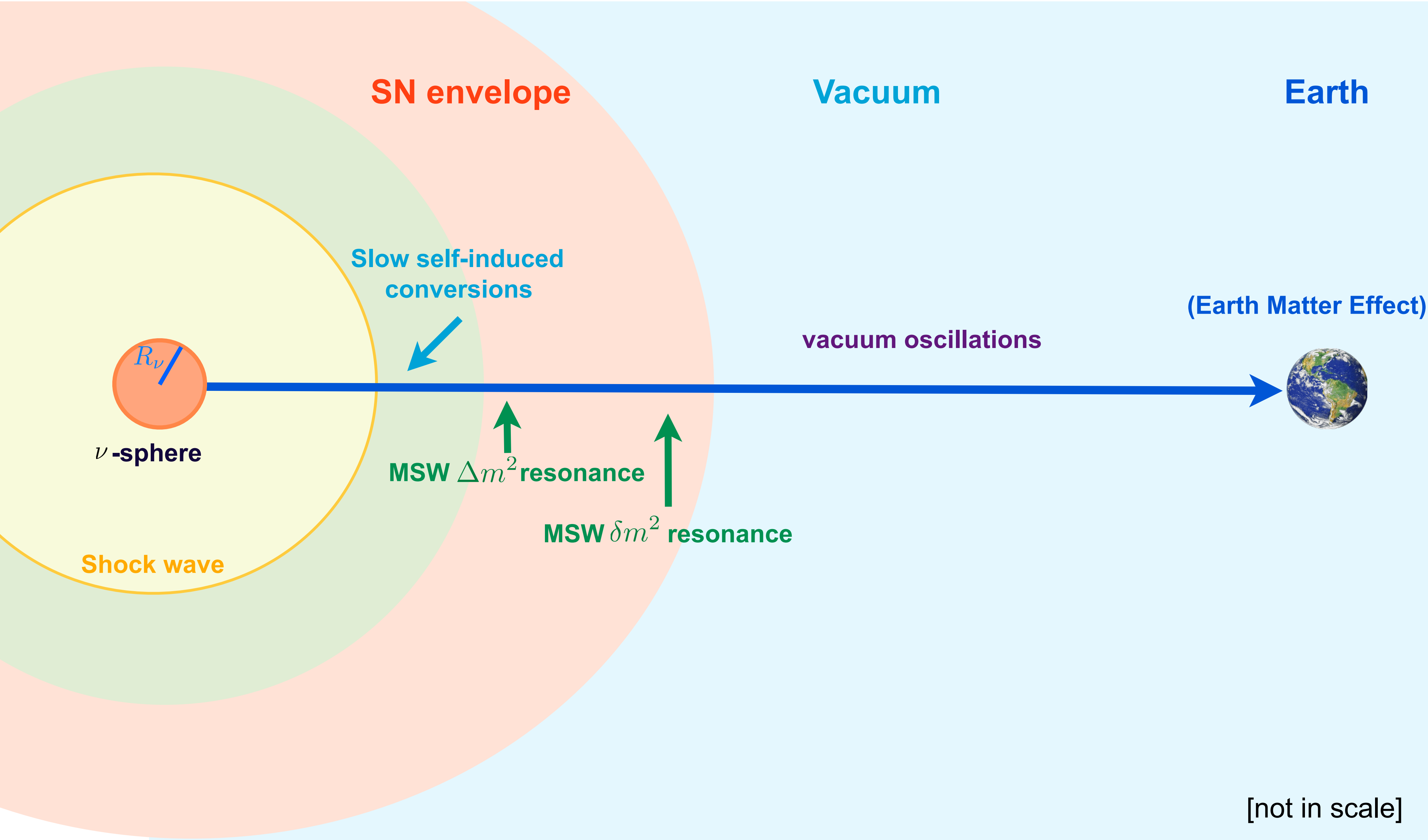


$\nu - \nu$ interactions

Non-linear phenomenon

Angular distributions crucial!

Simplified Picture of Flavor Conversions



Fast Pairwise Neutrino Conversions

Flavor conversion (vacuum or MSW): $\nu_e(p) \to \nu_\mu(p)$.
Lepton flavor violation by mass and mixing.

Pairwise flavor exchange by $\nu - \nu$ scattering: $\nu_e(p) + \bar{\nu}_e(k) \to \nu_\mu(p) + \bar{\nu}_\mu(k)$
$\nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k)$

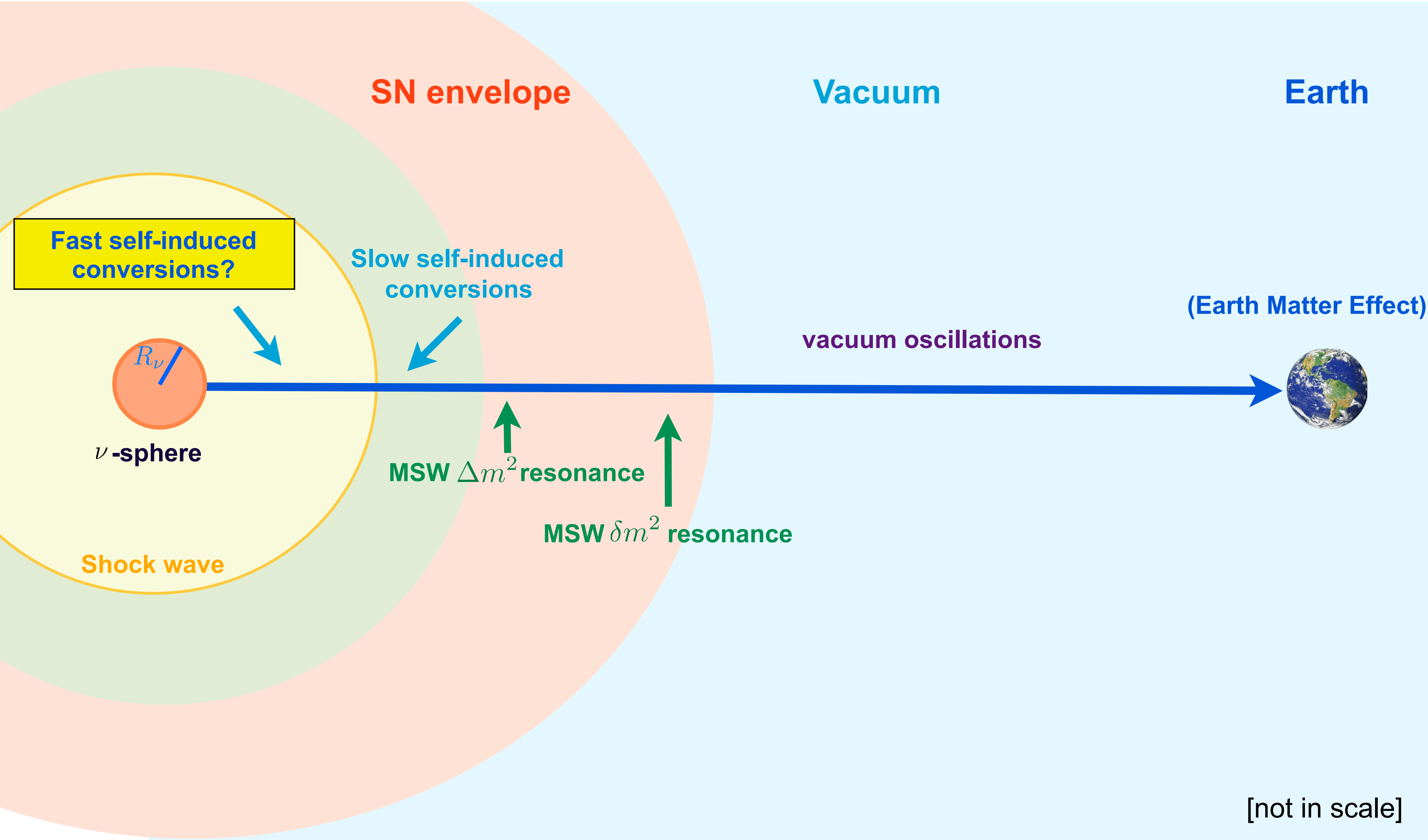
Can occur **without masses/mixing**. No net lepton flavor change.

Growth rate: $\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \simeq 6.42\ \mathrm{m}^{-1}$ vs. $\dfrac{\Delta m^2}{2E} \simeq 0.5\ \mathrm{km}^{-1}$ ⇒ **"Fast" conversions**

Flavor conversion may occur close to neutrino decoupling region. **Further work needed.**

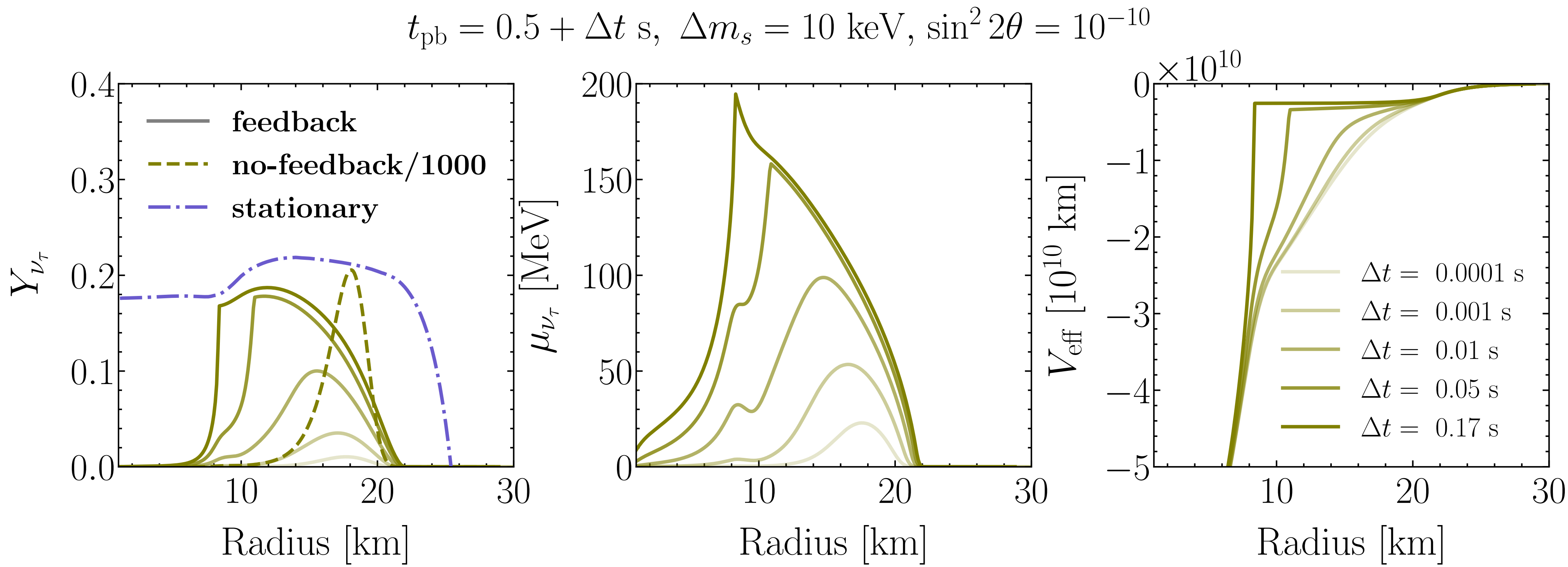
Izaguirre, Raffelt, Tamborra, PRL (2017). Tamborra et al., ApJ (2017). Shalgar & Tamborra, ApJ (2019). Capozzi et al., PRD (2017). Dasgupta et al., PRD 2018. Sawyer, PRD (2005), Sawyer, PRL (2016). Azari et al., PRD (2019).

Simplified Picture of Flavor Conversions



[not in scale]

Non Standard Physics in Supernovae

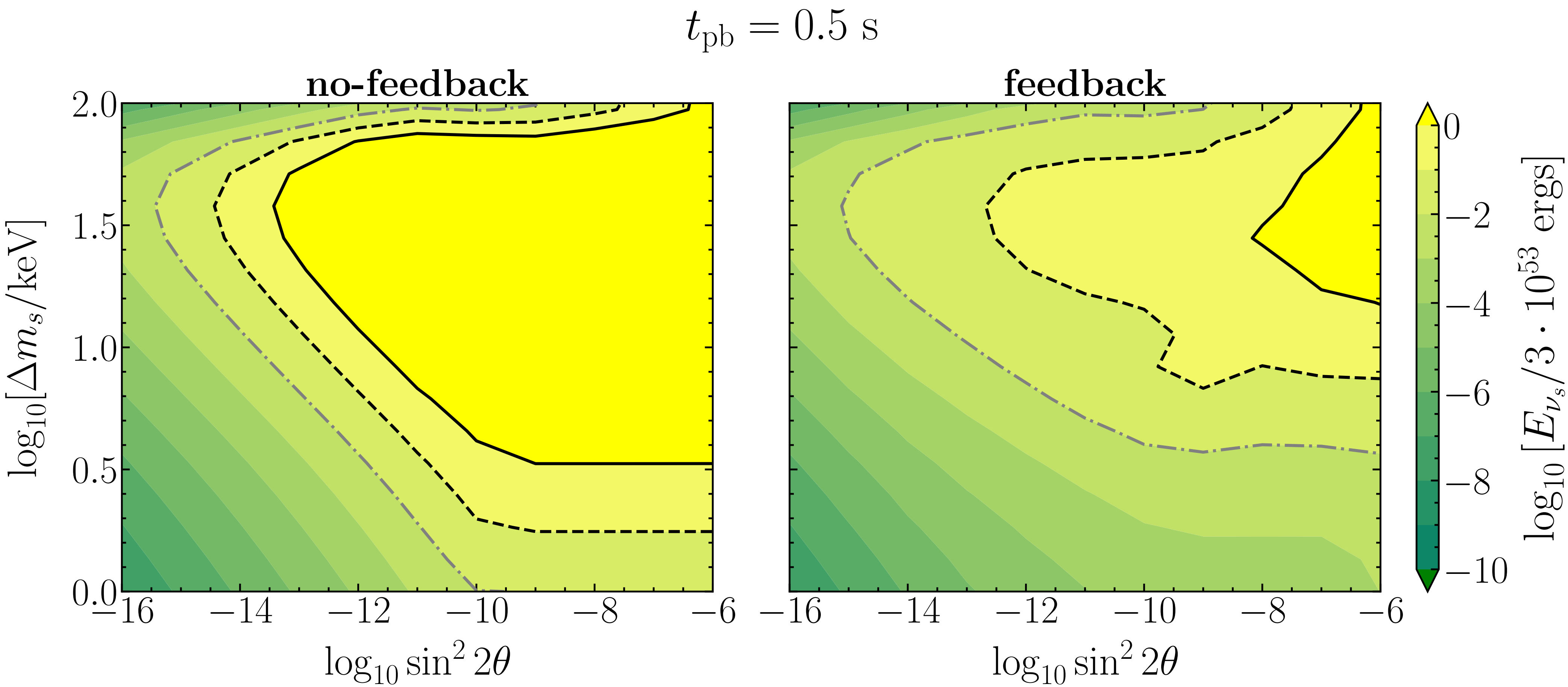


keV-mass sterile neutrinos significantly affect SN physics and observable signal.

Dynamical feedback on SN physics is crucial!

Suliga, Tamborra, Wu, JCAP (2019).

Non Standard Physics in Supernovae



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Compact Binary Mergers

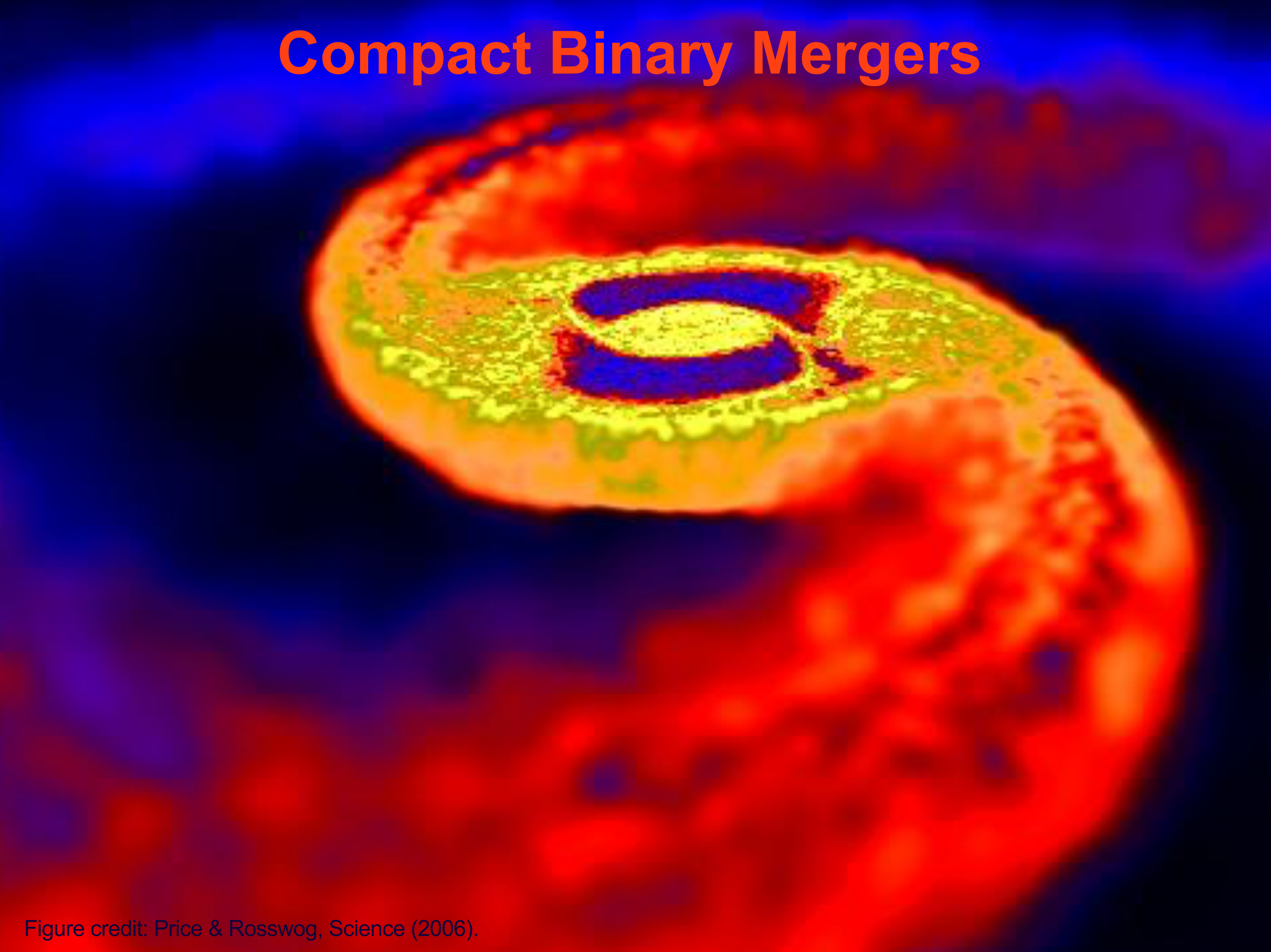
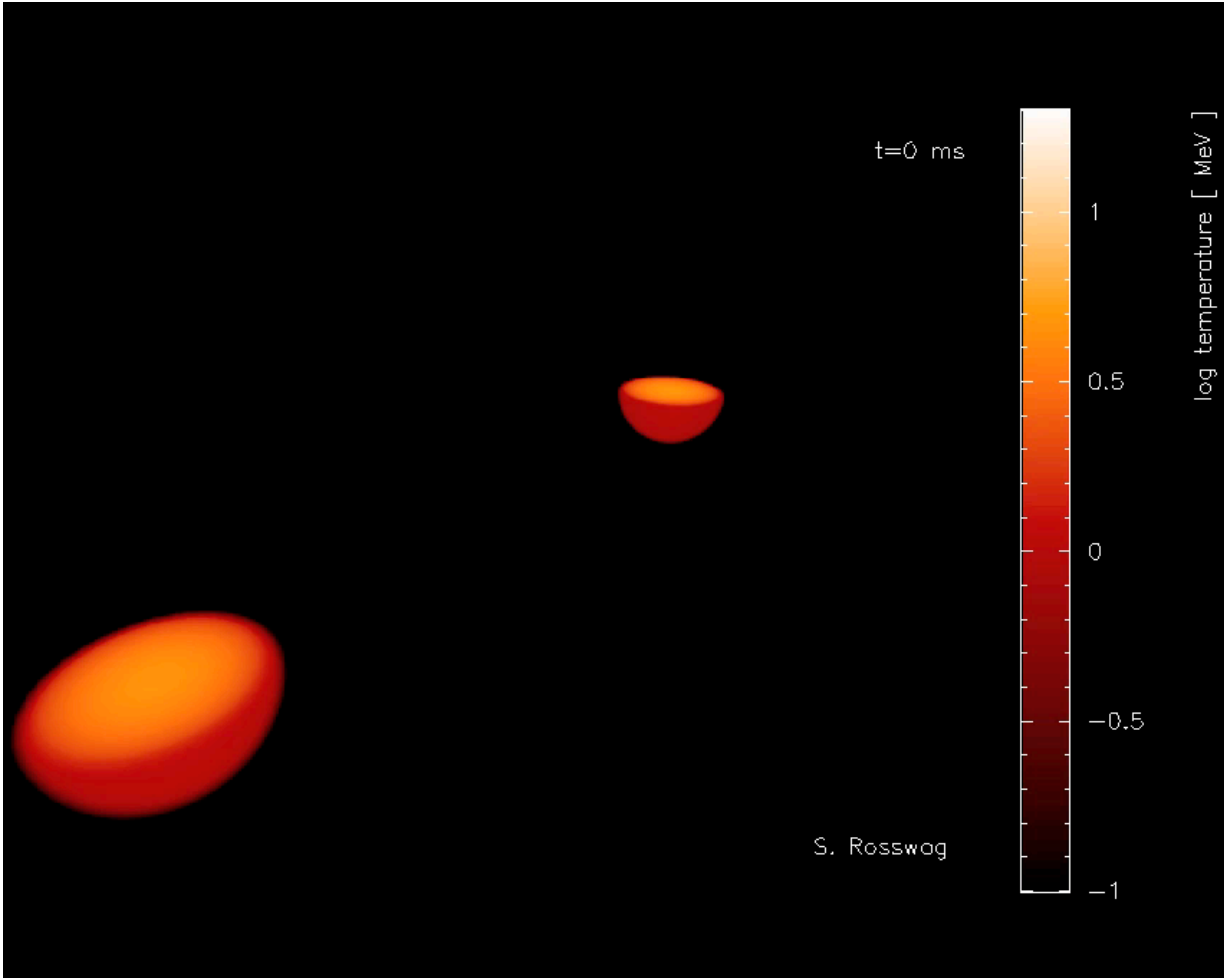


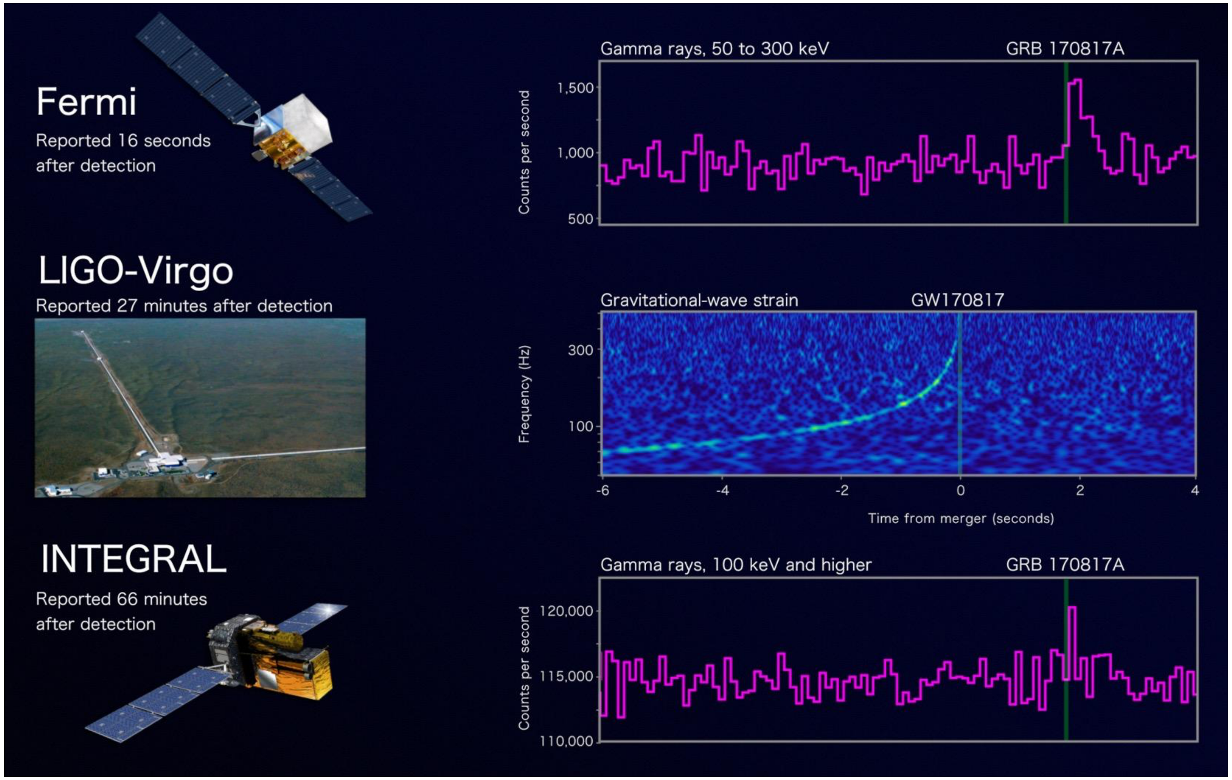
Figure credit: Price & Rosswog, Science (2006).

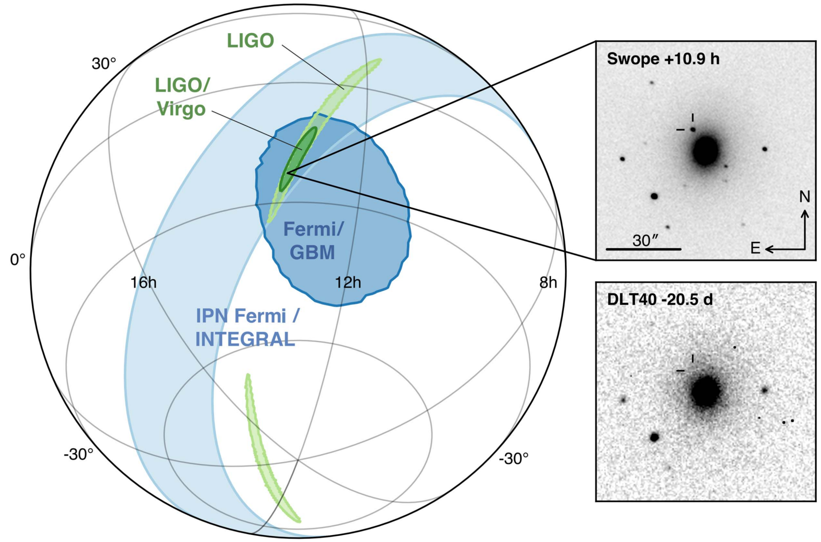
Neutron Star - Neutron Star Merger (1.3-1.4 M_{sun})



Coalescence of two neutron stars, Rosswog, Piran, Nakar, MNRAS (2013).

Multi-Messenger Fingerprints of Mergers

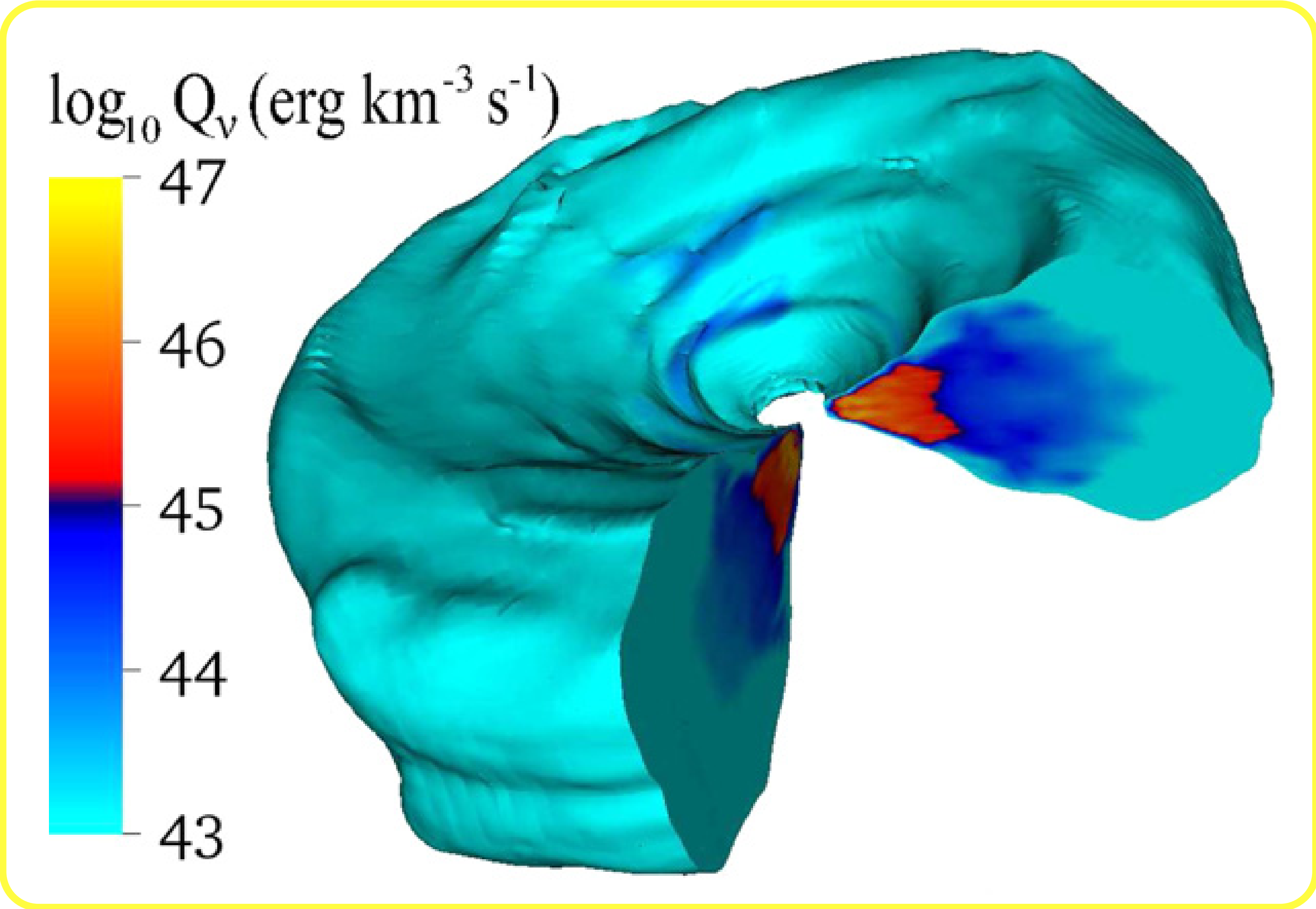




First joint detection of gravitational and electromagnetic radiation (GW170817 & GRB170817A).

Figure credits: Abbott et al., ApJ (2017), ESA.

Neutrinos and Compact Binary Mergers

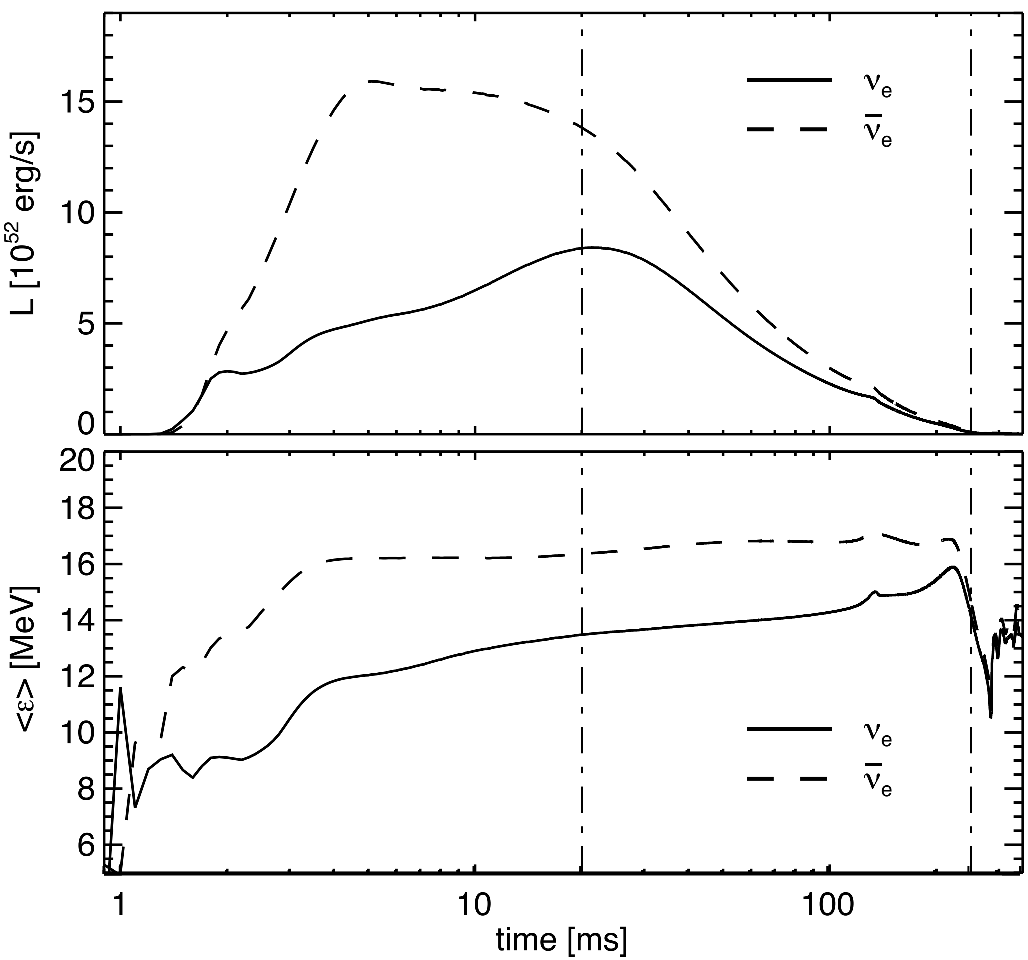


Compact binary mergers are neutrino rich environments (similarly to supernovae).

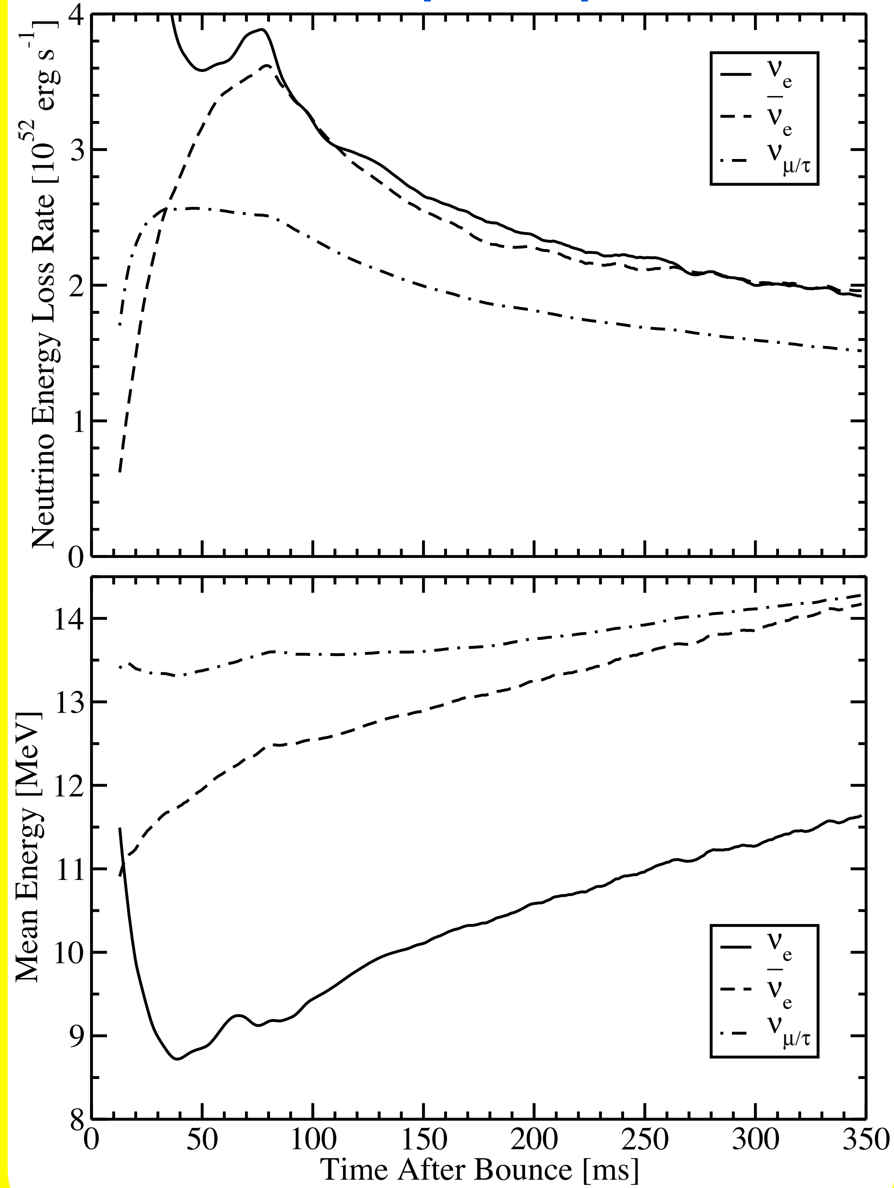
Figure from Deaton et al., ApJ (2013).

Neutrino Emission Properties

Neutron star merger remnant



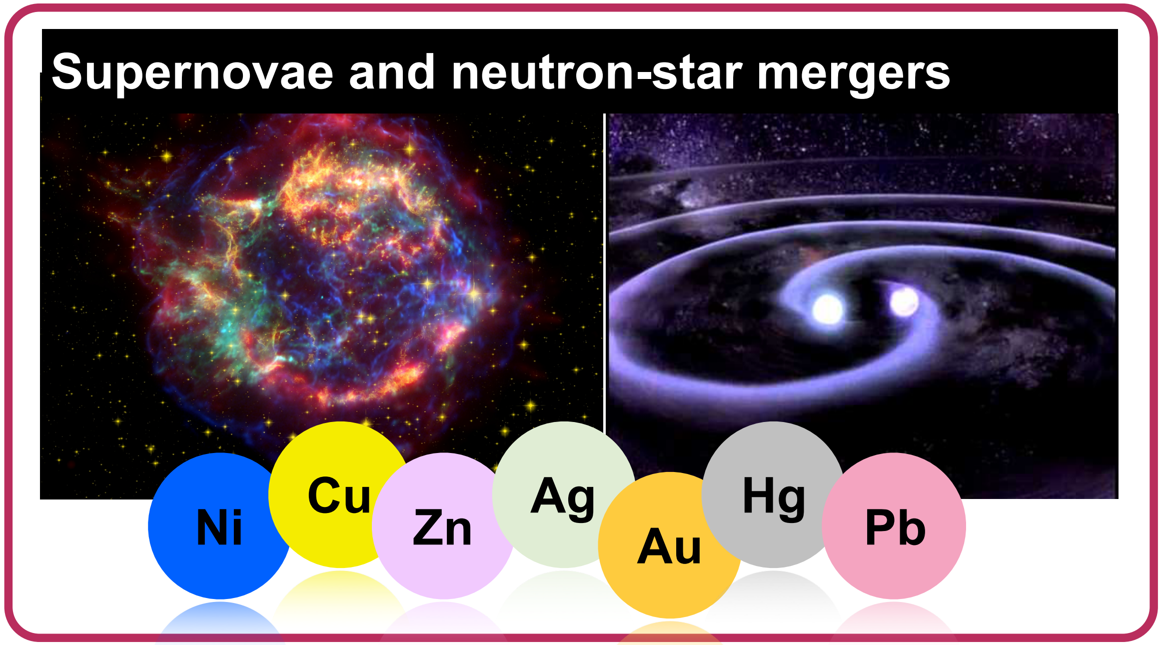
Core-collapse supernova



Mergers exhibit excess of anti-neutrinos over neutrinos (conversely to supernovae).

Figures from Wu, Tamborra et al., PRD (2017), Tamborra et al., PRD (2014).

Stellar Nucleosynthesis

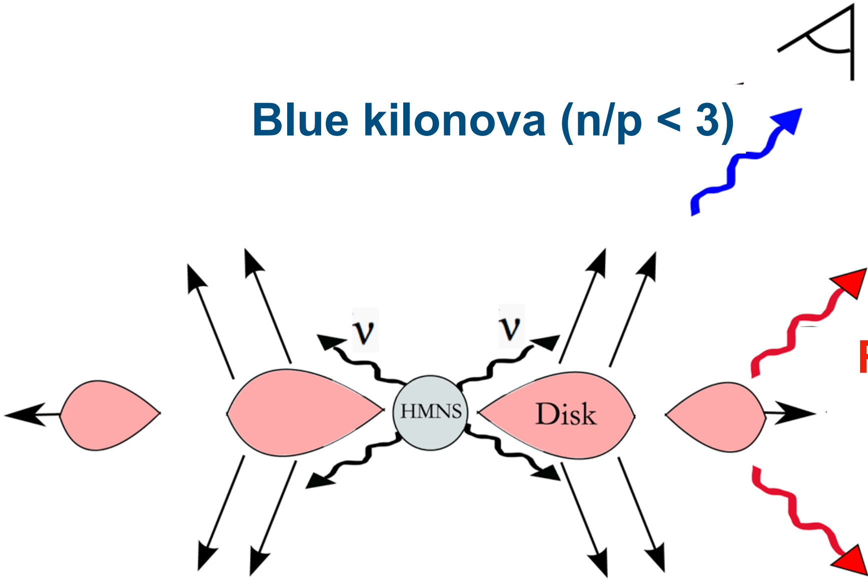


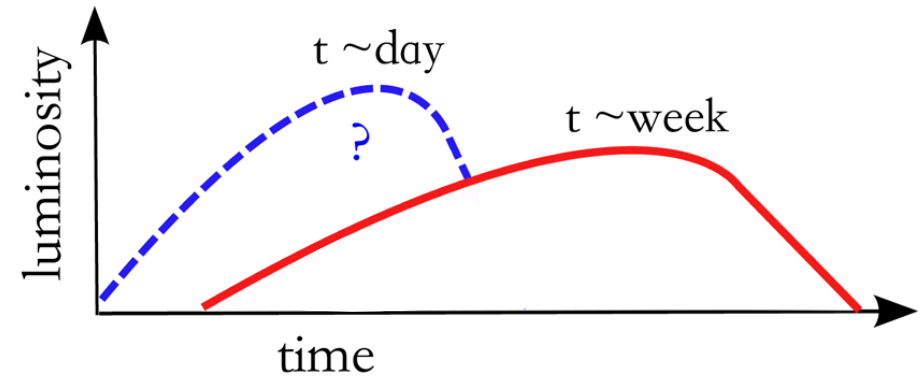
Synthesis of new elements could not happen without neutrinos.

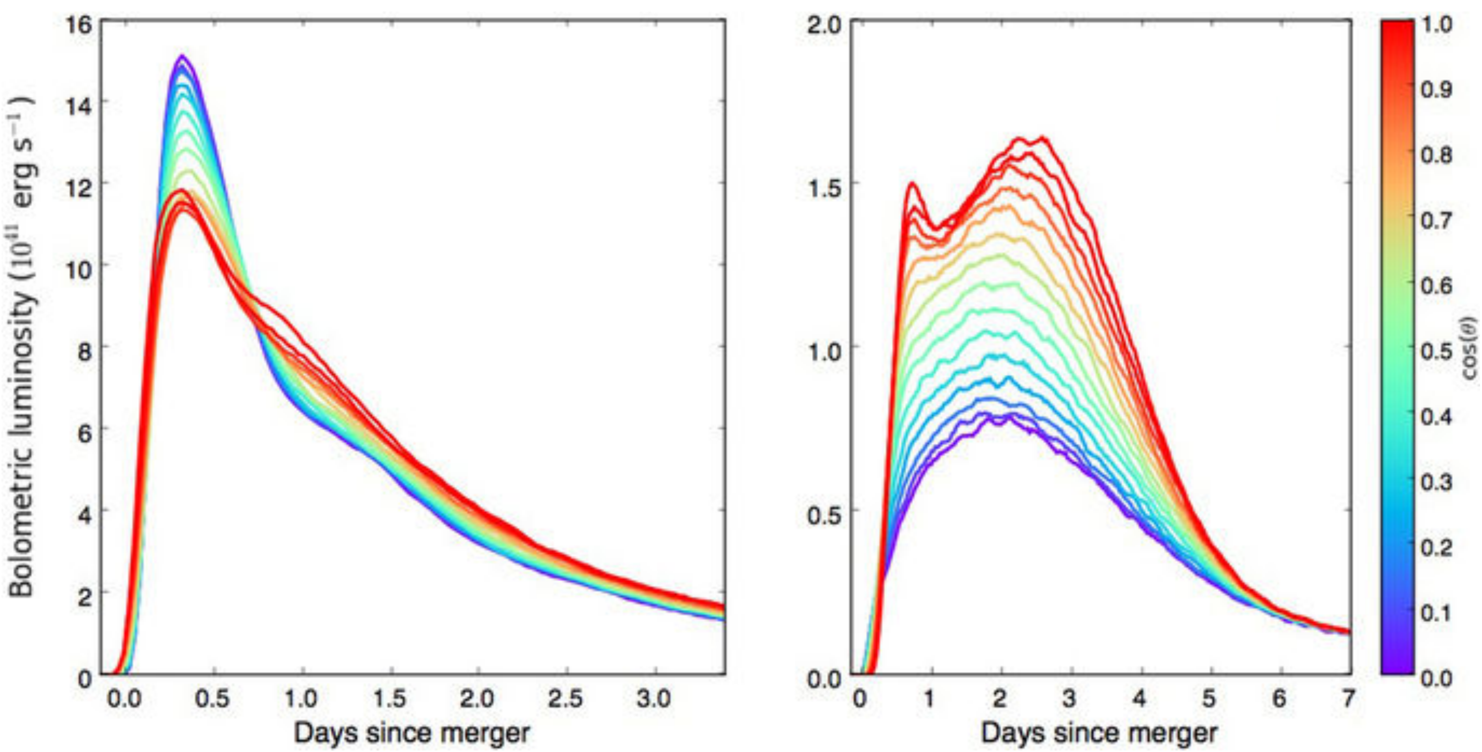
$$n + \nu_e \rightarrow e^- + p$$

$$p + \bar{\nu}_e \rightarrow e^+ + n$$

Red and Blue Kilonova Components

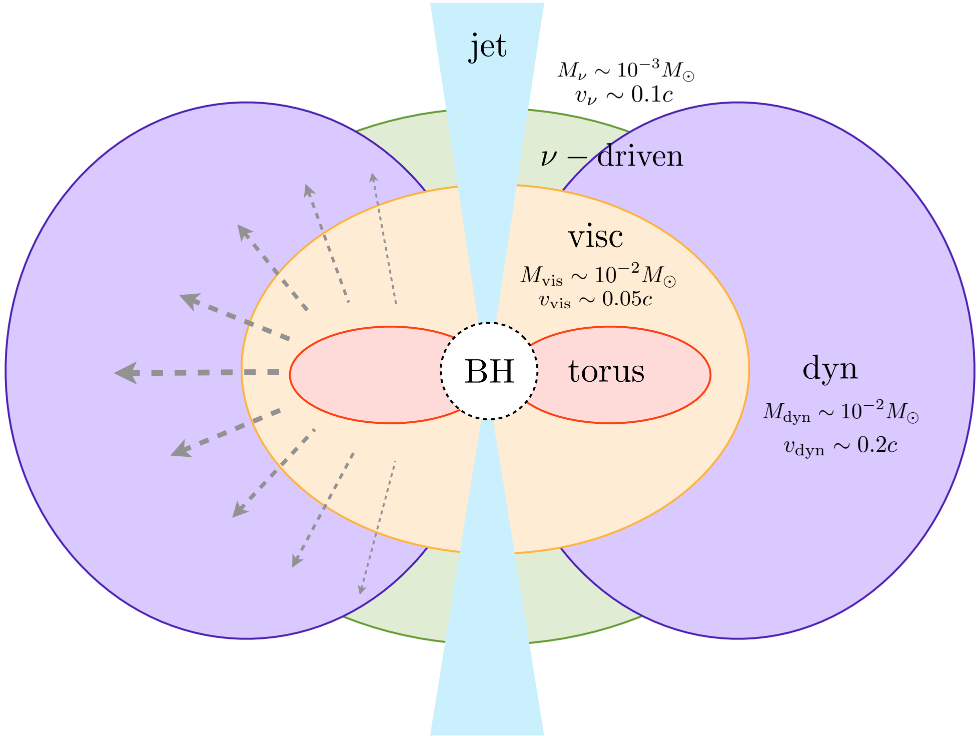


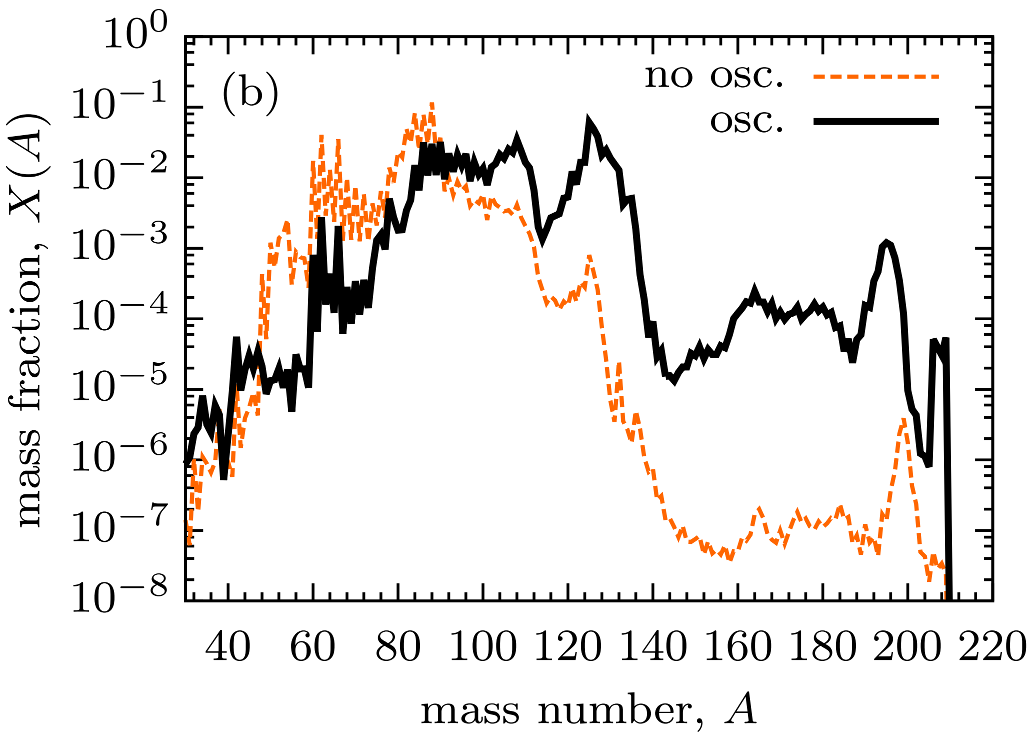




Figures taken from: Metzger & Fernandez, MNRAS (2014); Kasen et al., Nature 2017.

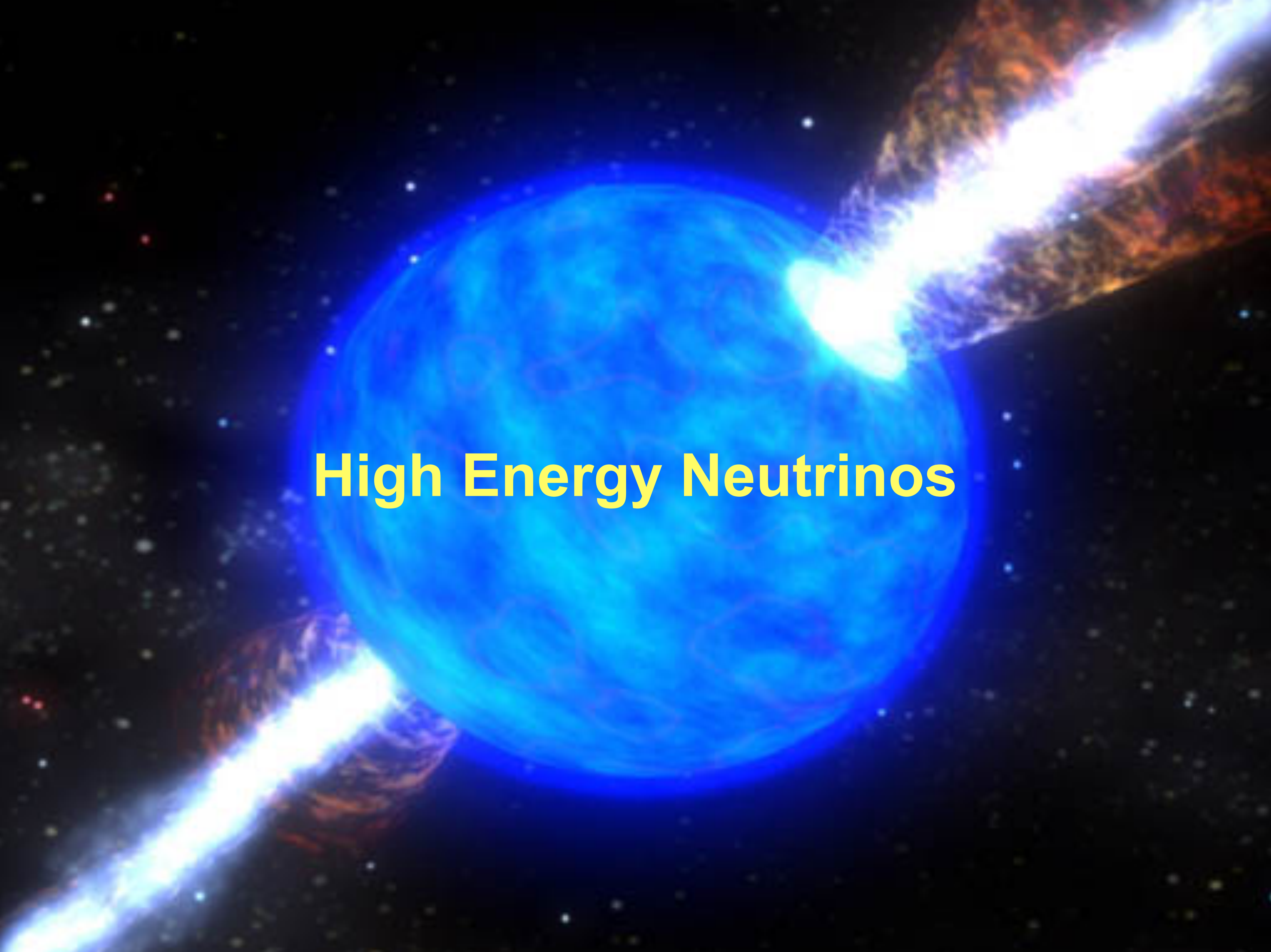
What About Neutrinos?





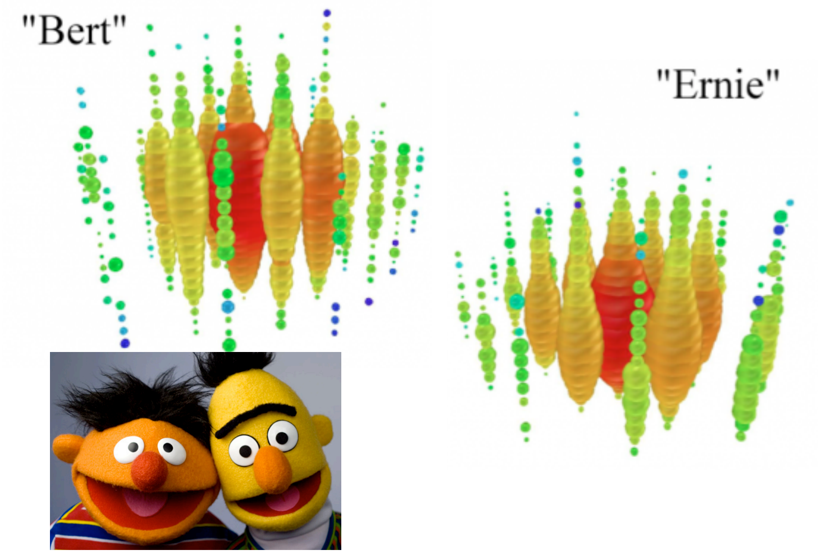
- Poor detection chances of MeV neutrinos from compact binary mergers.
- Neutrino may play an "indirect" major role in element production around the polar region.
- Possible implications for blue kilonova component.

Wu, Tamborra, et al., PRD (2017). Wu & Tamborra, PRD (2017). Kyutoku & Kashiyama, PRD (2018).

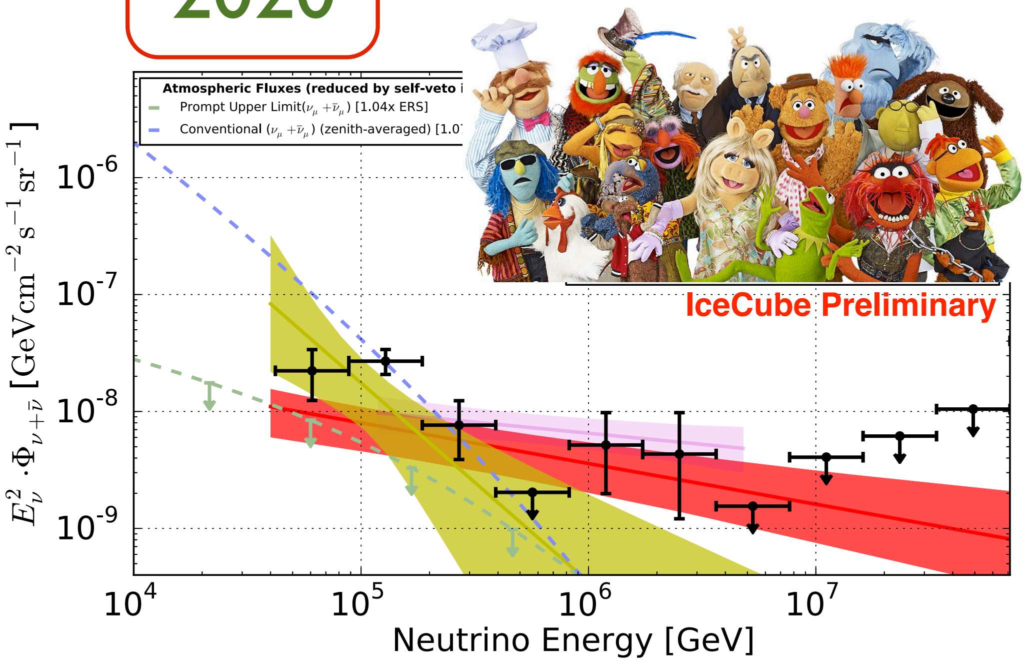

High Energy Neutrinos

Upper Limit on Neutrino Emission

2013



2020

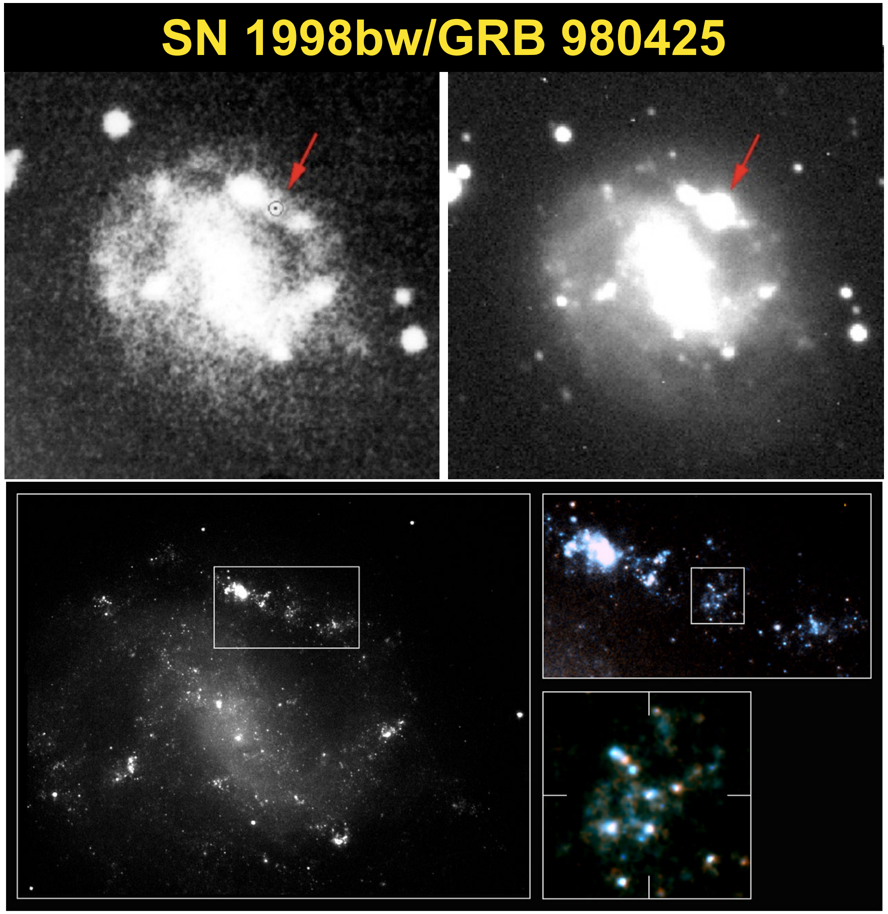


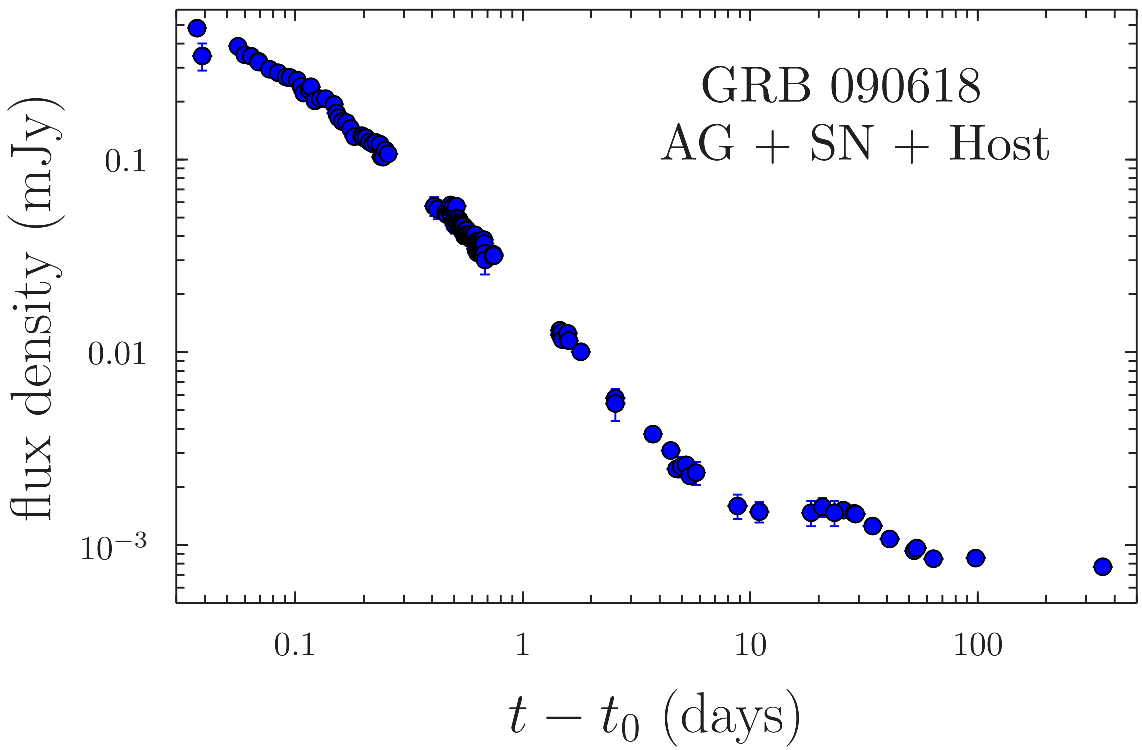
★ IceCube observed O(100) events in the TeV-PeV range.
★ Zenith Distribution compatible with isotropic flux.
★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

Evidence for astrophysical flux

IceCube Collaboration, Science (2013), PRL (2014), PRD (2015). IceCube Collaboration, ApJ (2015); PRL (2015). Ahlers & Halzen, Prog. Part. Phys. (2018).

Supernova-GRB Connection





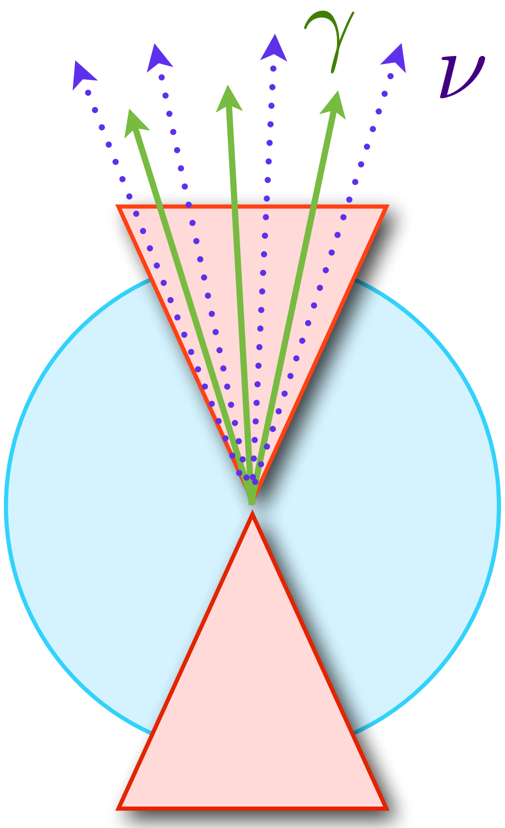
Limitations:

- Follow-up of SN-GRB biased towards low-z events.
- Several SN-GRB are low-luminosity GRBs that may not represent the GRB population.
- Systematic surveys begin to allow statistical studies (e.g. GTC GRB-SN program).

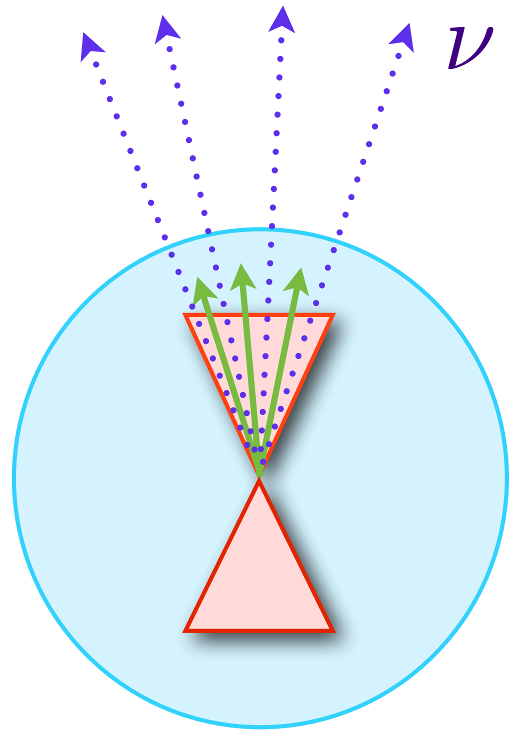
Figures taken from Bloom & Hjorth (2011) and Cano et al. (2017).

Supernova-GRB Connection

Successful GRB
(photons & neutrinos)



Choked GRB
(**neutrinos only**)

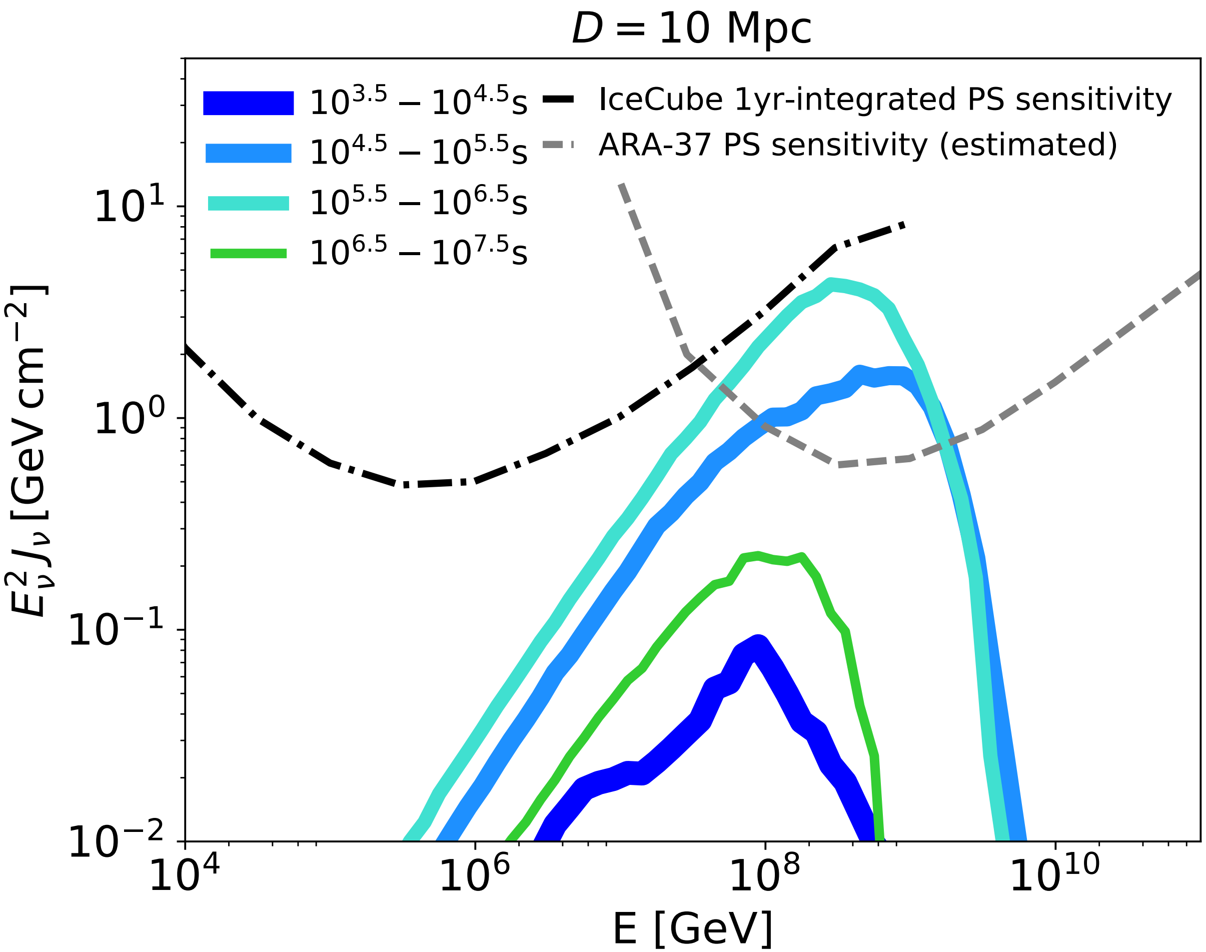


IceCube data can already constrain:

- Fraction of supernovae harboring jets
- Fraction of choked jets (compatible with electromagnetic observations).

Denton & Tamborra, ApJ (2018). Denton & Tamborra, JCAP (2018). Esmaili & Murase, JCAP (2018).
Tamborra & Ando, PRD (2016). Senno et al., PRD (2015). Meszaros & Waxman, PRL (2001). Levan et al., ApJ (2014).

Neutrinos from GRB 170817A



- Copious neutrino production from long-lived ms magnetar following the merger.
- Favorable detection opportunities with multi-messenger triggers.

Biehl et al., MNRAS (2018). Tamborra & Ando, JCAP (2015). Fang & Metzger, ApJ (2017). Kimura et al., ApJ (2017).

Conclusions

Neutrinos:

- **Fundamental in most energetic phenomena in our Universe.**
- **Ideal messengers.**
- **Carry imprints of the source inner working.**
- **Determine element formation in astrophysical sources.**

Grazie!