KING'S College LONDON

Neutrino Astronomy with Hyper-Kamiokande and SNEWS 2.0

Jost Migenda
they/them

Agenda

One sees clearly only with [neutrinos].
The important things are invisible to the eye.

—Antoine de Saint Exupéry
in "The Little Prince"

- Neutrino Astronomy (for EM Astronomers)
- Hyper-Kamiokande
- Supernova Neutrino Observations with HK
- Supernova Early Warning System (SNEWS)

Standard Model of Particle Physics

Strong Force

Electro-magnetic

Weak Force

mass	≃2.2 MeV/c²	≃1.28 GeV/c²	≃173.1 GeV/c²
charge	⅔	⅔	⅔
spin	½	½	½
QUARKS	u up	c charm	t top
	≃4.7 MeV/c²	≃96 MeV/c²	≃4.18 GeV/c²
	−⅓	−⅓	−⅓
	½	½	½
	d down	s strange	b bottom
LEPTONS	≃0.511 MeV/c²	≃105.66 MeV/c²	≃1.7768 GeV/c²
	−1	−1	−1
	½	½	½
	e electron	μ muon	τ tau
	<1.0 eV/c²	<0.17 MeV/c²	<18.2 MeV/c²
	0	0	0
	½	½	½
	νe electron neutrino	νμ muon neutrino	ντ tau neutrino

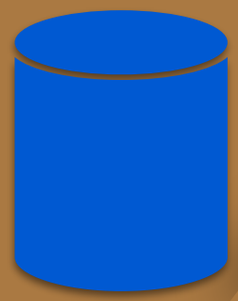
Neutrinos Are Like Ghosts 👻

- Flux of solar neutrinos on Earth: 6×10^{10} cm^{-2} s^{-1}
- … even in the middle of the night!
  (You'd need about 1 light year of lead to block them.)
- Great for astronomy!
  - Can view places that are otherwise inaccessible
- Terrible for astronomy!
  - Incredibly hard to detect, poor angular resolution

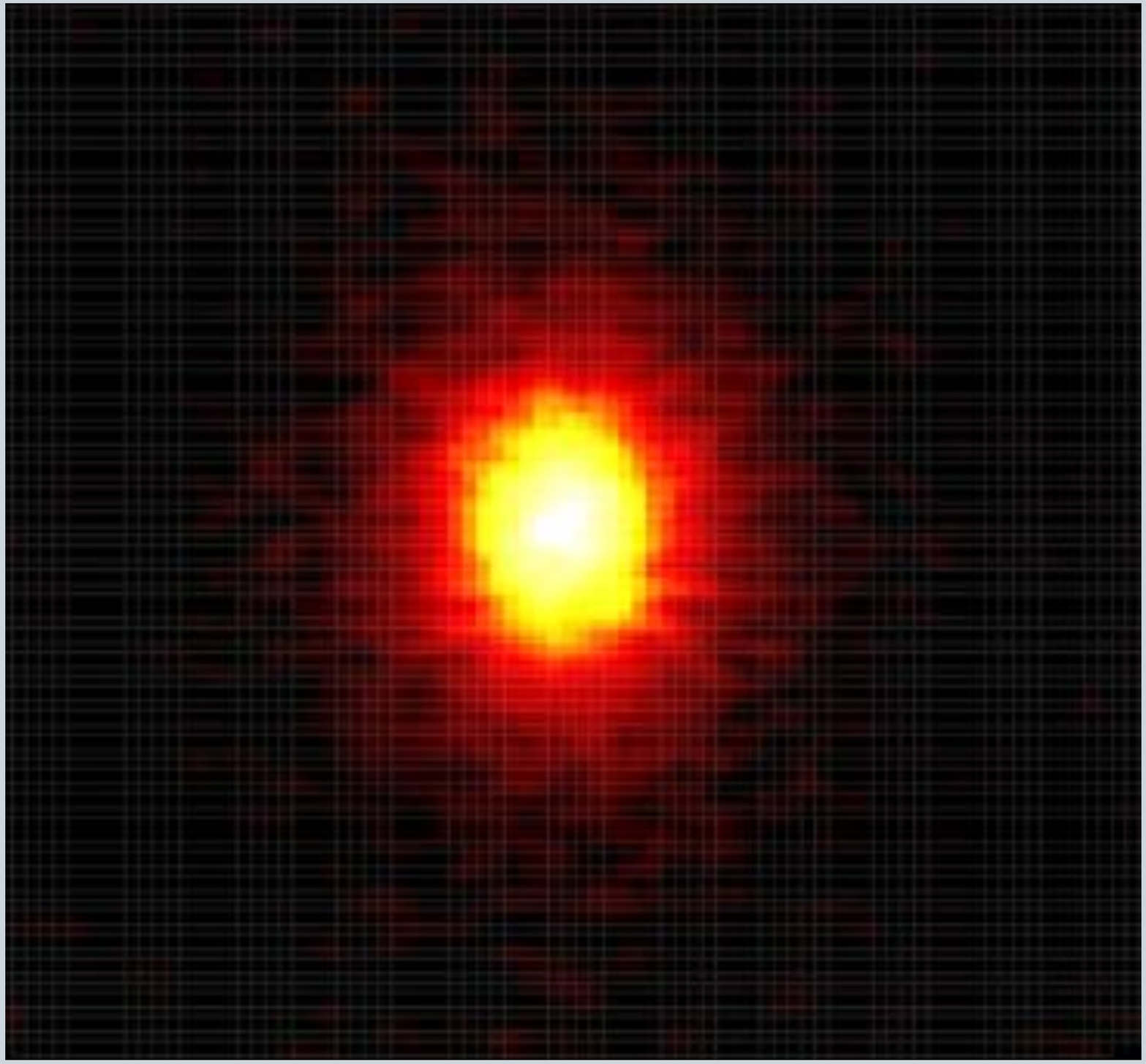
Neutrino Astronomy

Telescope

Neutrino
Telescope

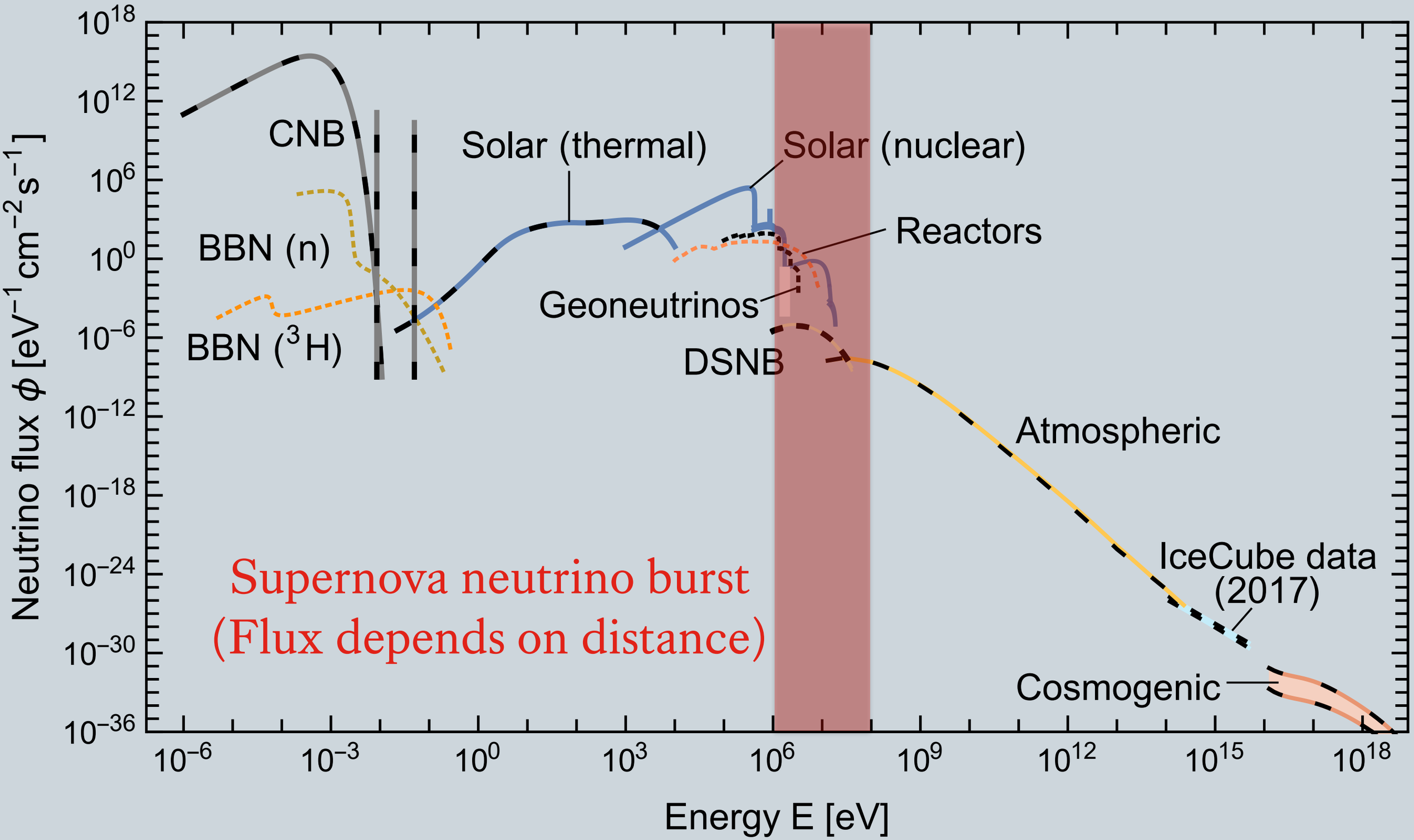


The Sun (Viewed in Neutrinos)



Y. Nakano (Super-Kamiokande collaboration)
https://indico.cern.ch/event/606690/contributions/2591501/

Neutrino Astronomy



Vitagliano et al., https://arxiv.org/abs/1910.11878

Agenda

Things are easy when you're big in Japan

—Alphaville

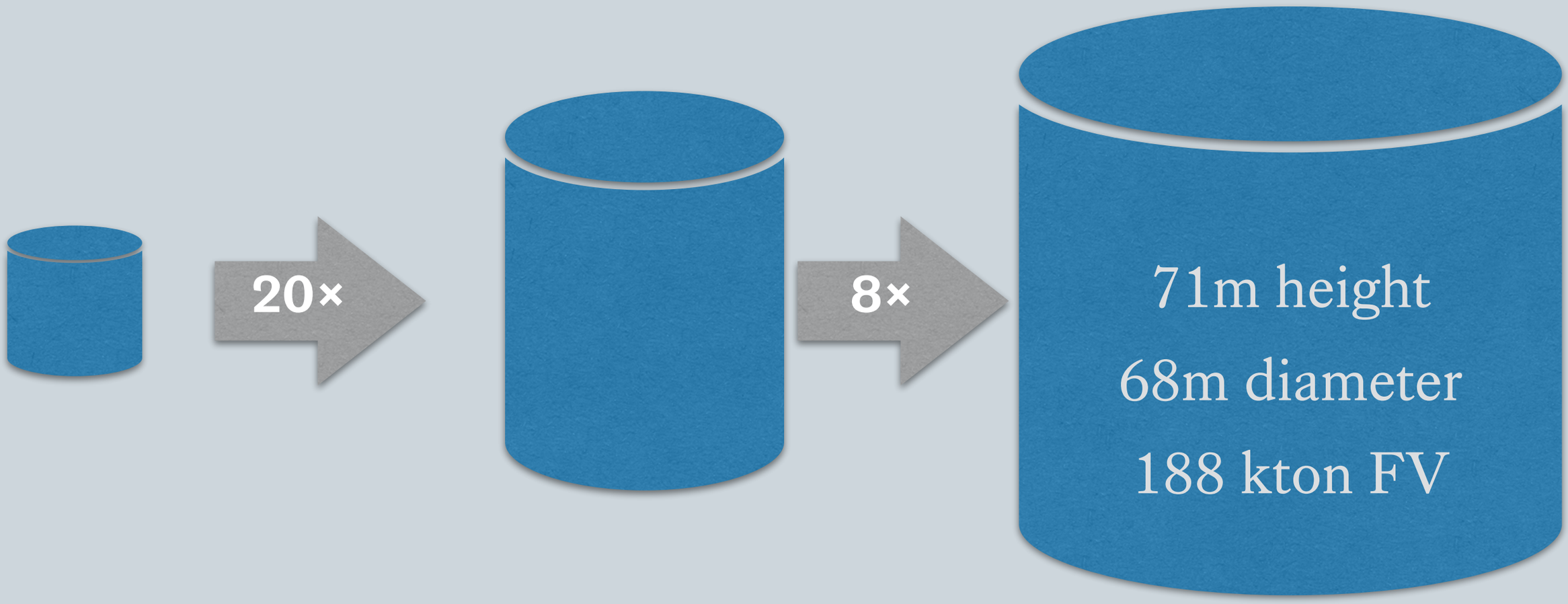
- Neutrino Astronomy
- Hyper-Kamiokande
- Supernova Neutrino Observations with HK
- Supernova Early Warning System (SNEWS)

Hyper-Kamiokande

Kamiokande
1983–1996

Super-Kamiokande
1996–today (and beyond)

Hyper-Kamiokande
~2027–???



Koshiba, 2002

Kajita, 2015

???, 20??

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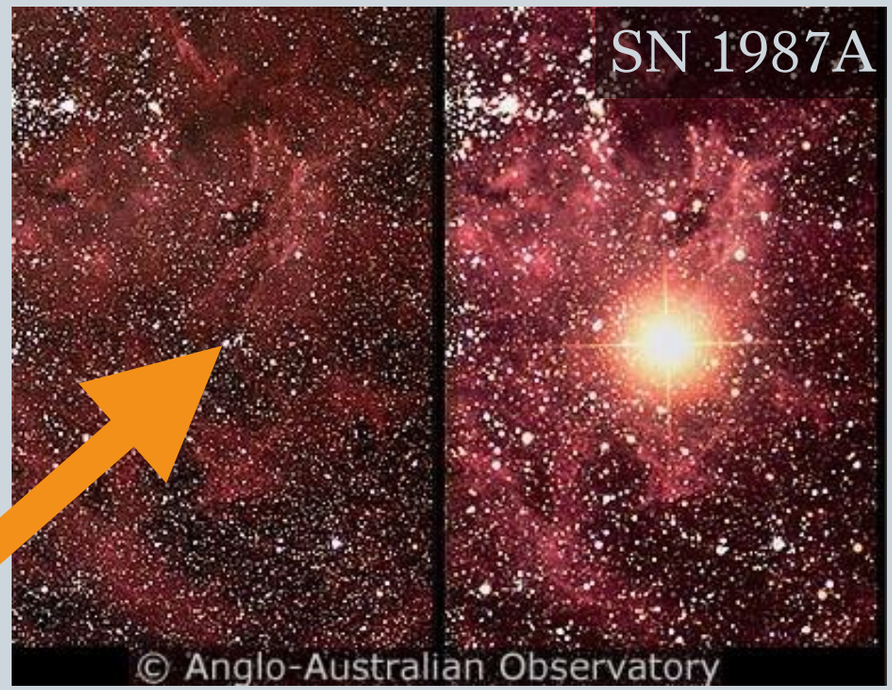

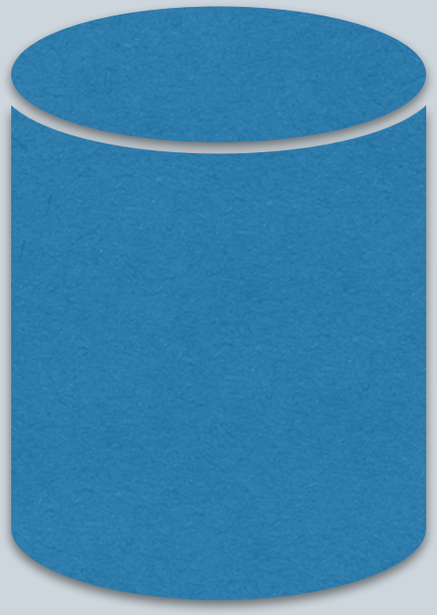

8×


Koshiba, 2002


Kajita, 2015

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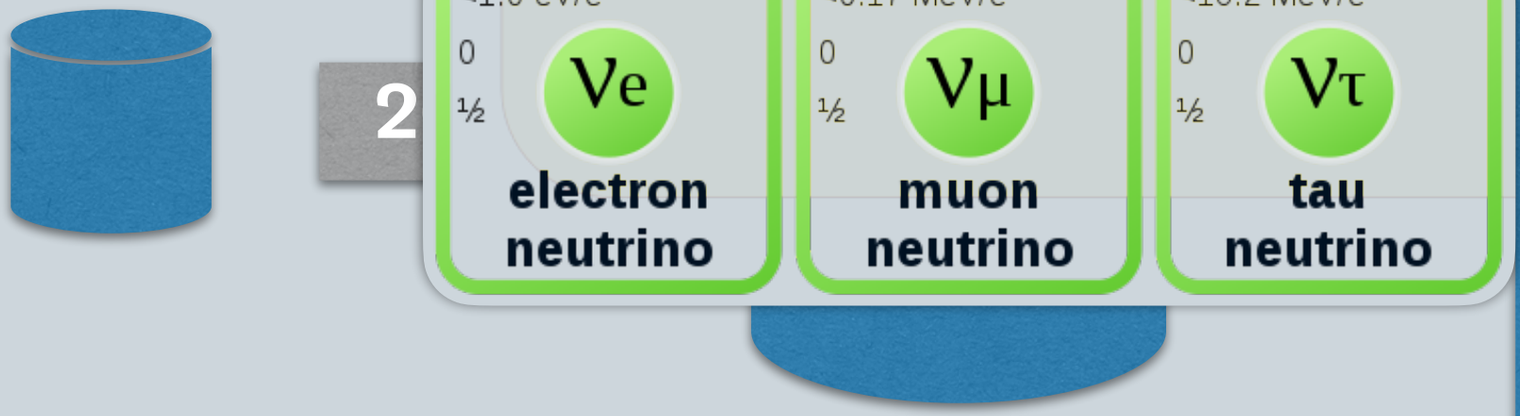


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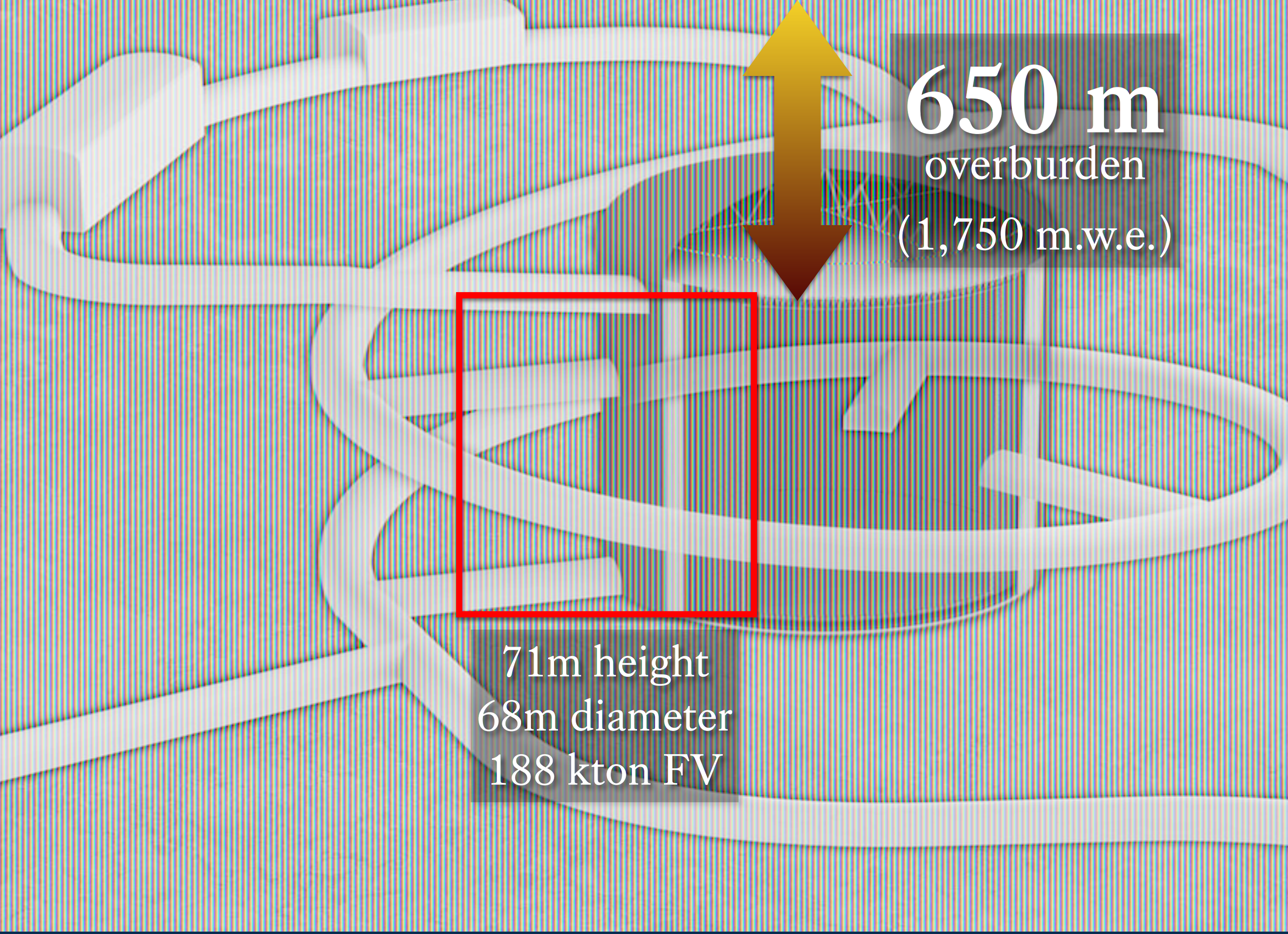
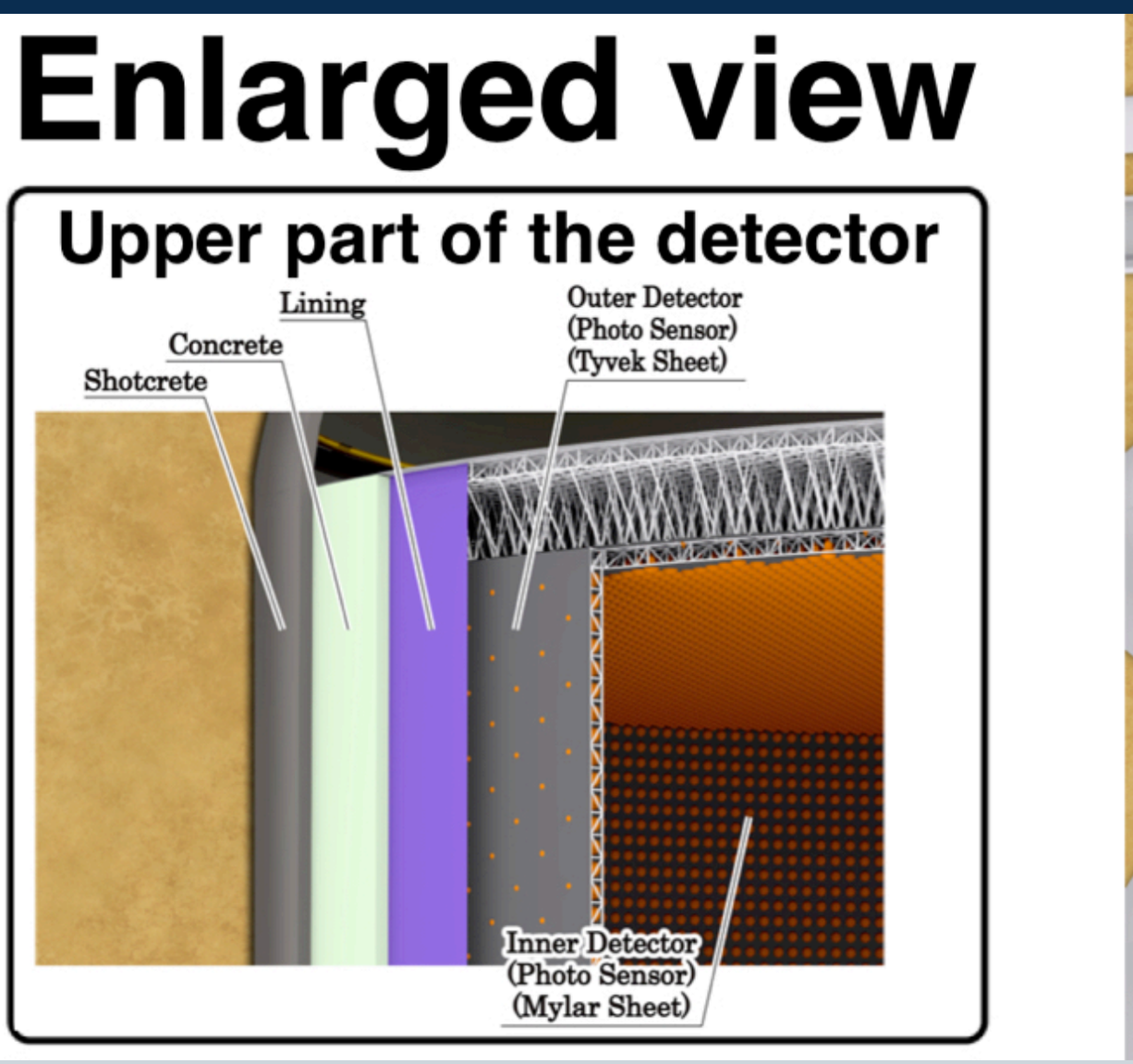
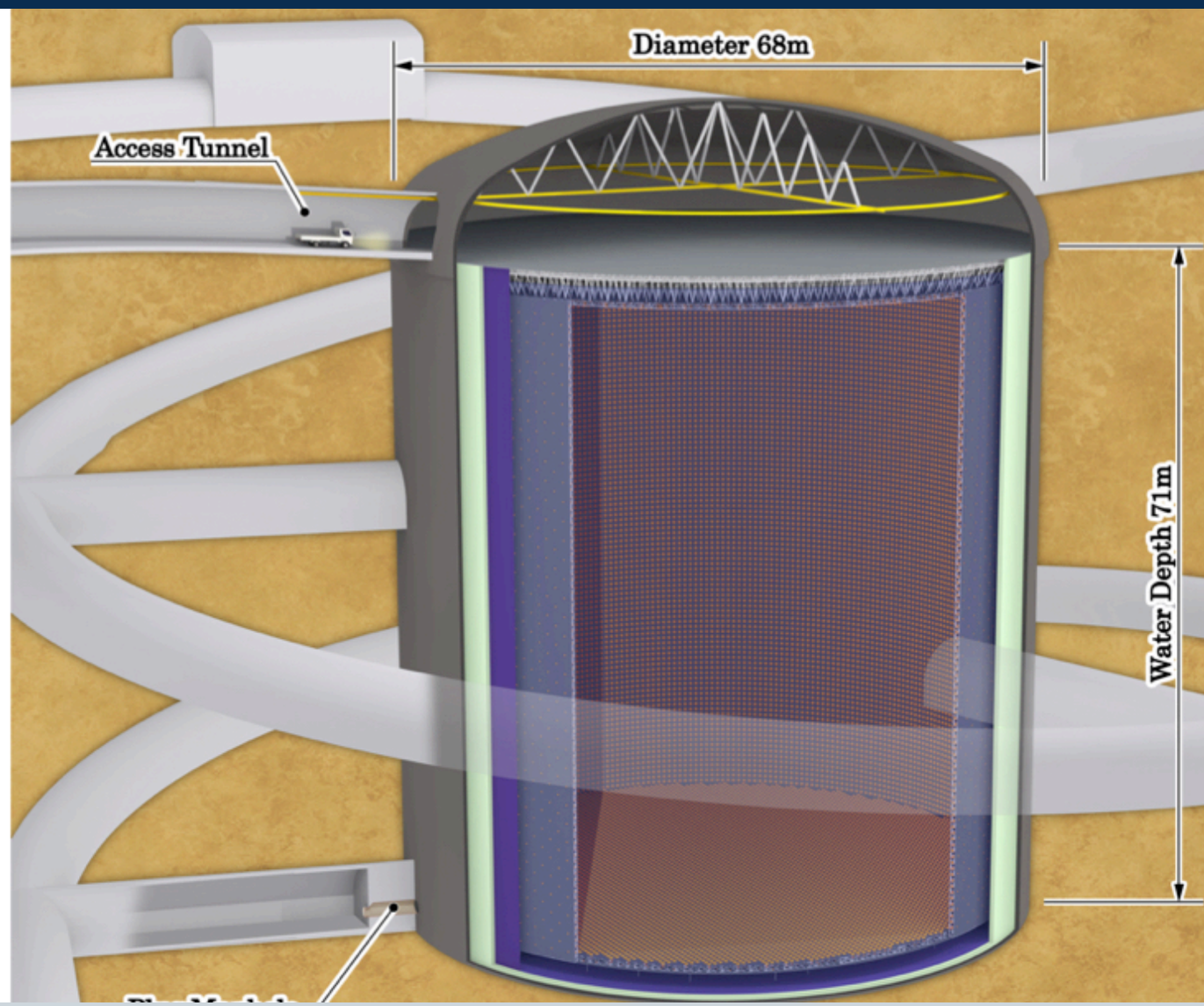

650 m
overburden
(1,750 m.w.e.)
71m height
68m diameter
188 kton FV

Hyper-K

University of Warwick Physics building
(Photo by Ares Osborn)

Outer Detector





- 1–2 m wide
- Both active veto & passive shielding
- Investigating design with 8cm PMTs and wavelength-shifting plates
  (DOI:10.1088/1742-6596/1468/1/012240)

Photosensors detect Cherenkov light

Use “fuzzyness” & number of rings for PID:

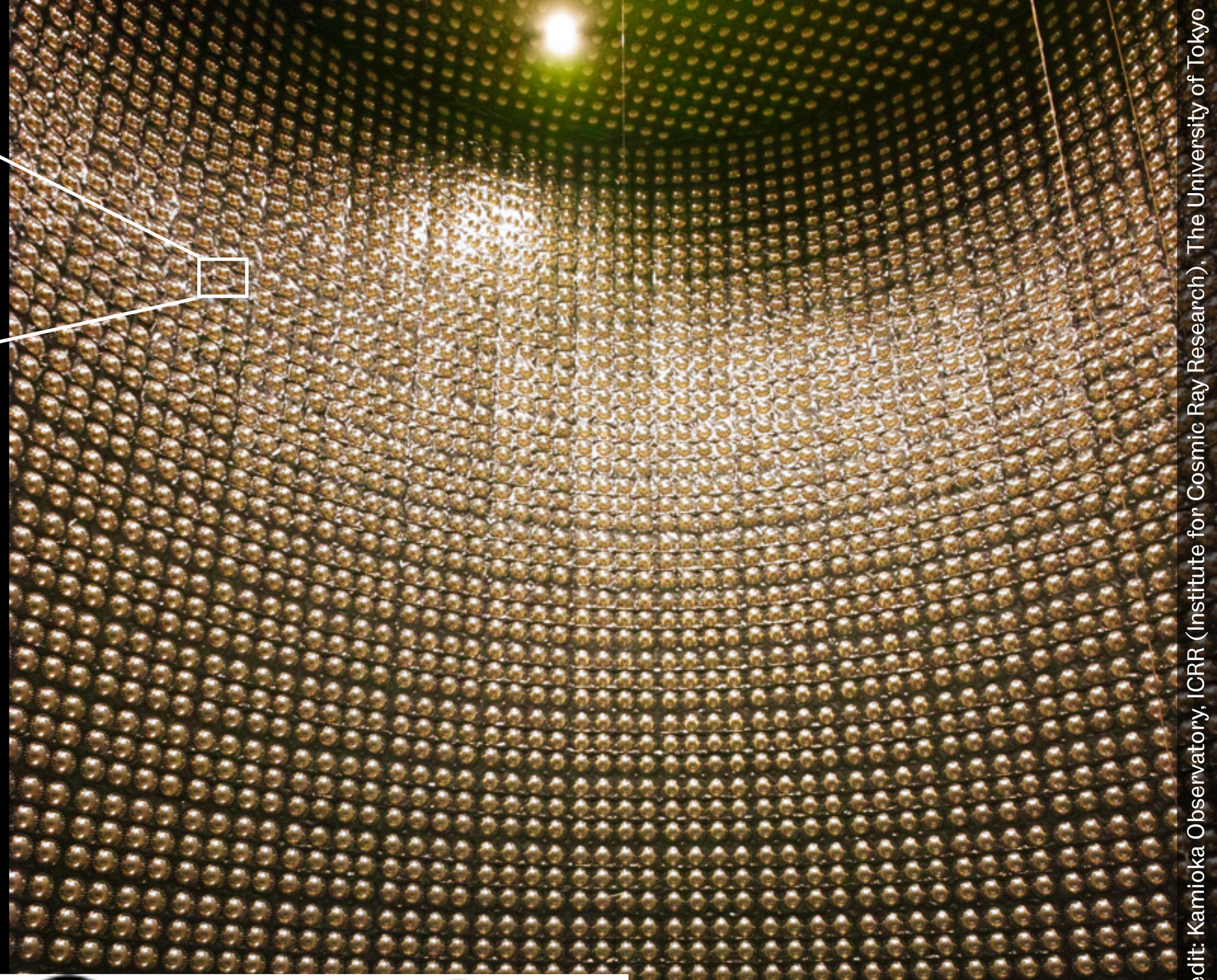
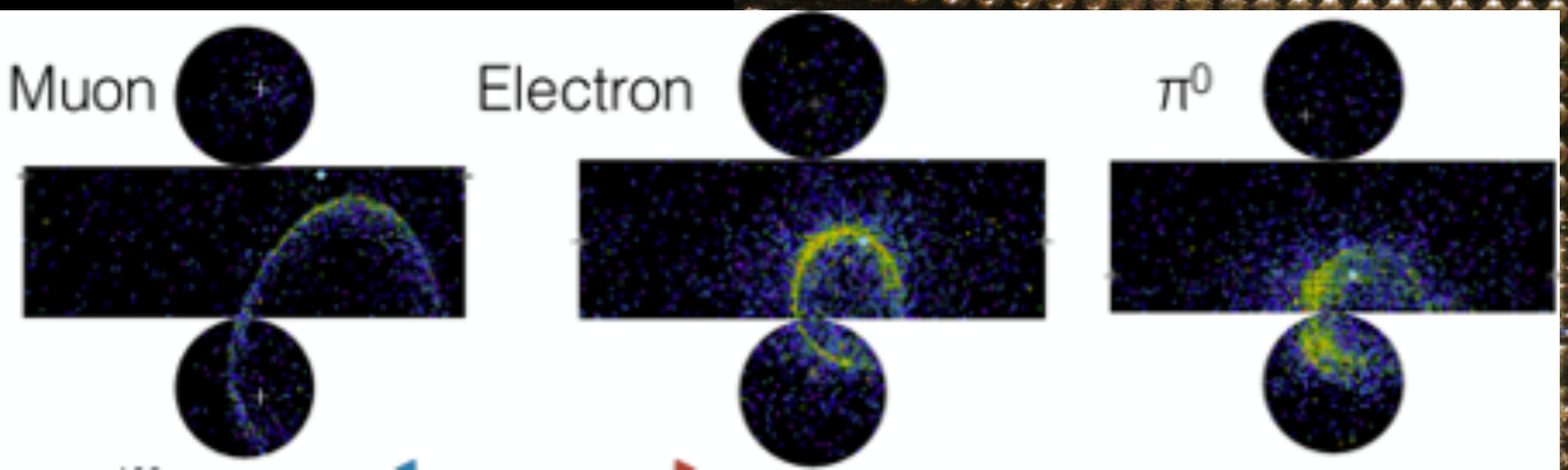
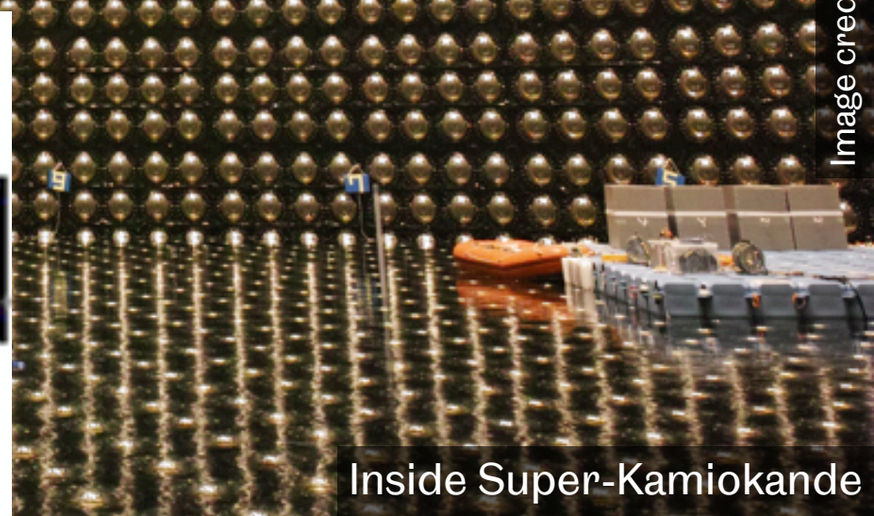


Image credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

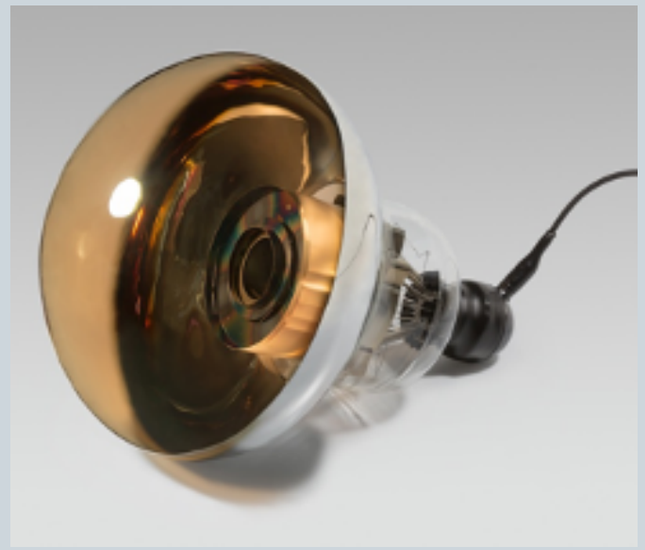




Inside Super-Kamiokande

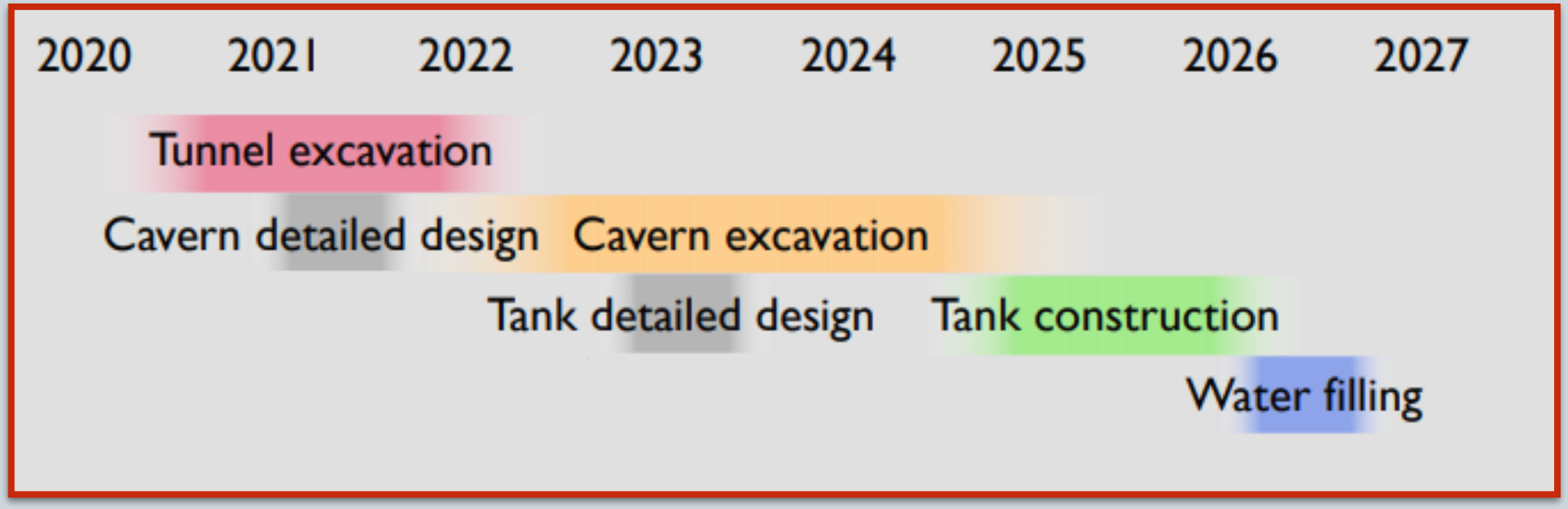
Photosensors

- 50 cm PMTs with box-and-line dynode
  - 2× timing resolution & 2× photon detection efficiency compared to Super-K PMTs
  - More pressure-resistant
  - Up to 40,000 in ID (40% photocoverage)
  - Mass production started in December 2020

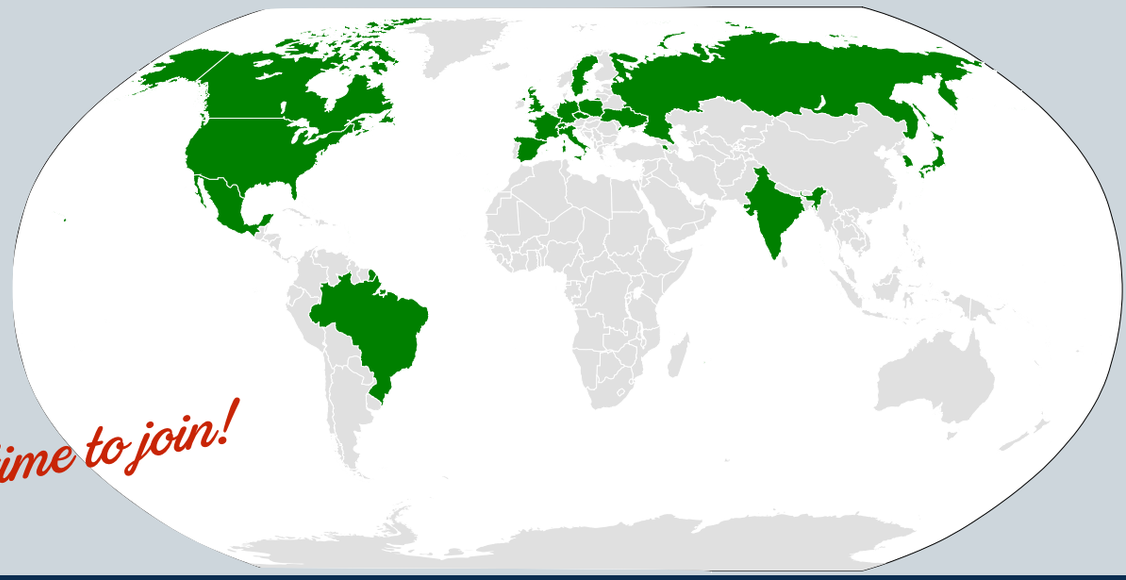


- Multi-PMT (mPMT) modules
  - 19× 8 cm PMTs in hemispherical pressure vessel
  - Directional information, improved timing & spatial resultion
  - Consider adding up to 10,000 mPMTs to ID

Current Status



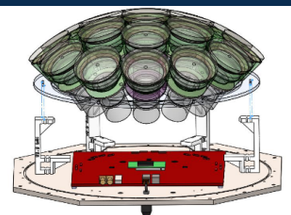
- Funding approved by Japanese government in 2020
- Excavation has started, geological survey ongoing
- Detector R&D still ongoing
- 400+ members from 19 countries:

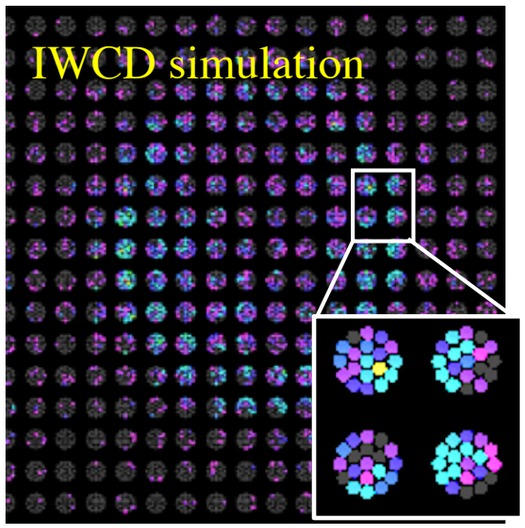


Now is a great time to join!

Detector R&D for HK

Multi-PMT module:
(ref. KM3NeT)
High resolution Cherenkov ring imaging essential for IWCD
Consider to use for part of HK

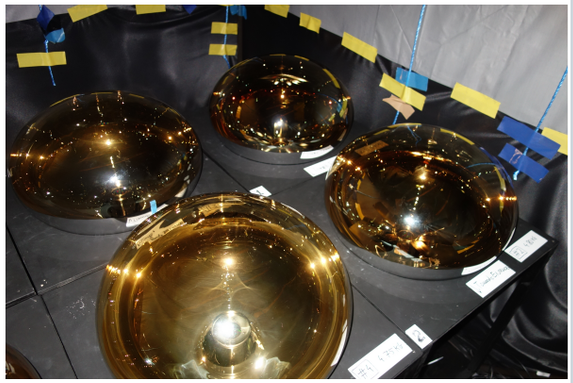


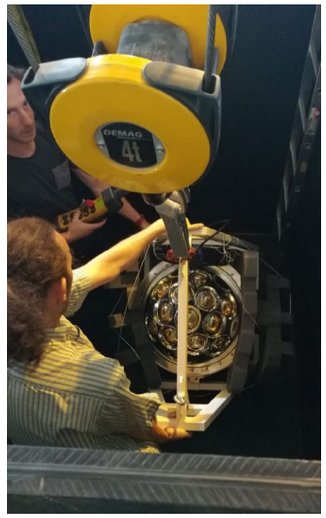


Prototype at TRIUMF

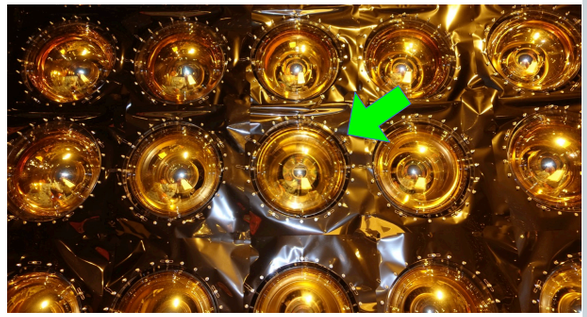
Electronics at INFN

20-inch MCP PMT:
Test in dark room





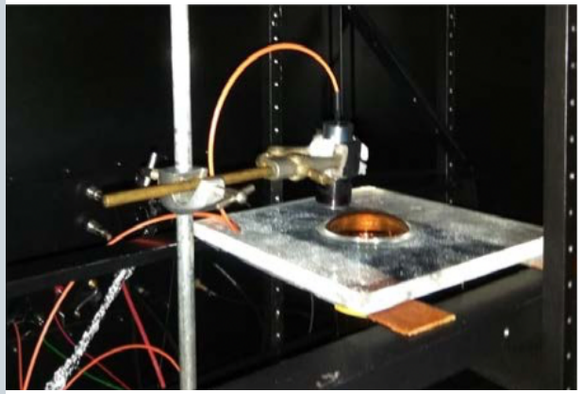
mPMT in Memphyno water tank in France

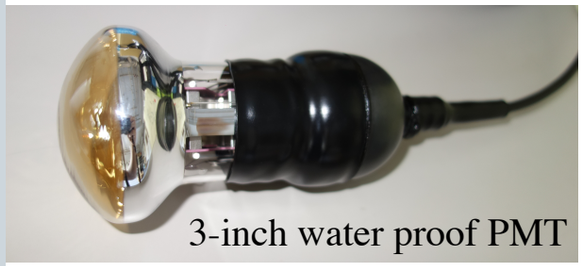


Box&Line PMT in Super-K

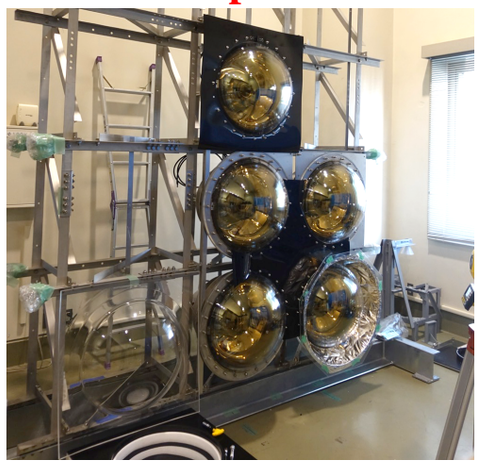
DAQ System

Outer detector:
PMT + WLS plate (UK)



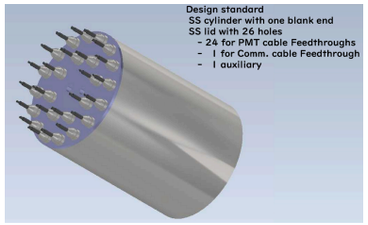


ID mockup at ICRR

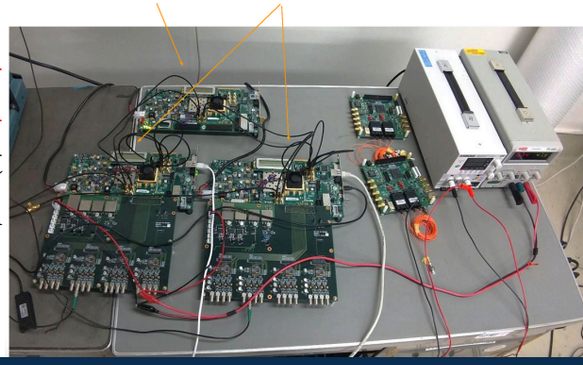


PMT cover
in Spain

Underwater electronics:
Case design and feedthrough



Sync and clock system
test bench at TokyoTech



From slides by M. Ishitsuka (Neutrino 2020)

Physics Goals

- Precision measurements of neutrino oscillation parameters (including δ_{CP})
- Proton decay searches (reaching ~10^{35} years)
- Neutrino Astronomy
  - Supernova Neutrinos
  - Solar neutrinos (~100 events per day)
    - Try to detect Hep neutrinos: $^3He + p \rightarrow {}^4He + e^+ + \nu_e$
    - Sensitivity to shorter time variations
    - High-energy neutrinos associated with solar flares
  - Search for neutrinos coincident with binary mergers (detected by LIGO/Virgo/KAGRA) or other transient events
  - Indirect searches for Dark Matter annihilating/decaying into neutrinos
- ... and more!

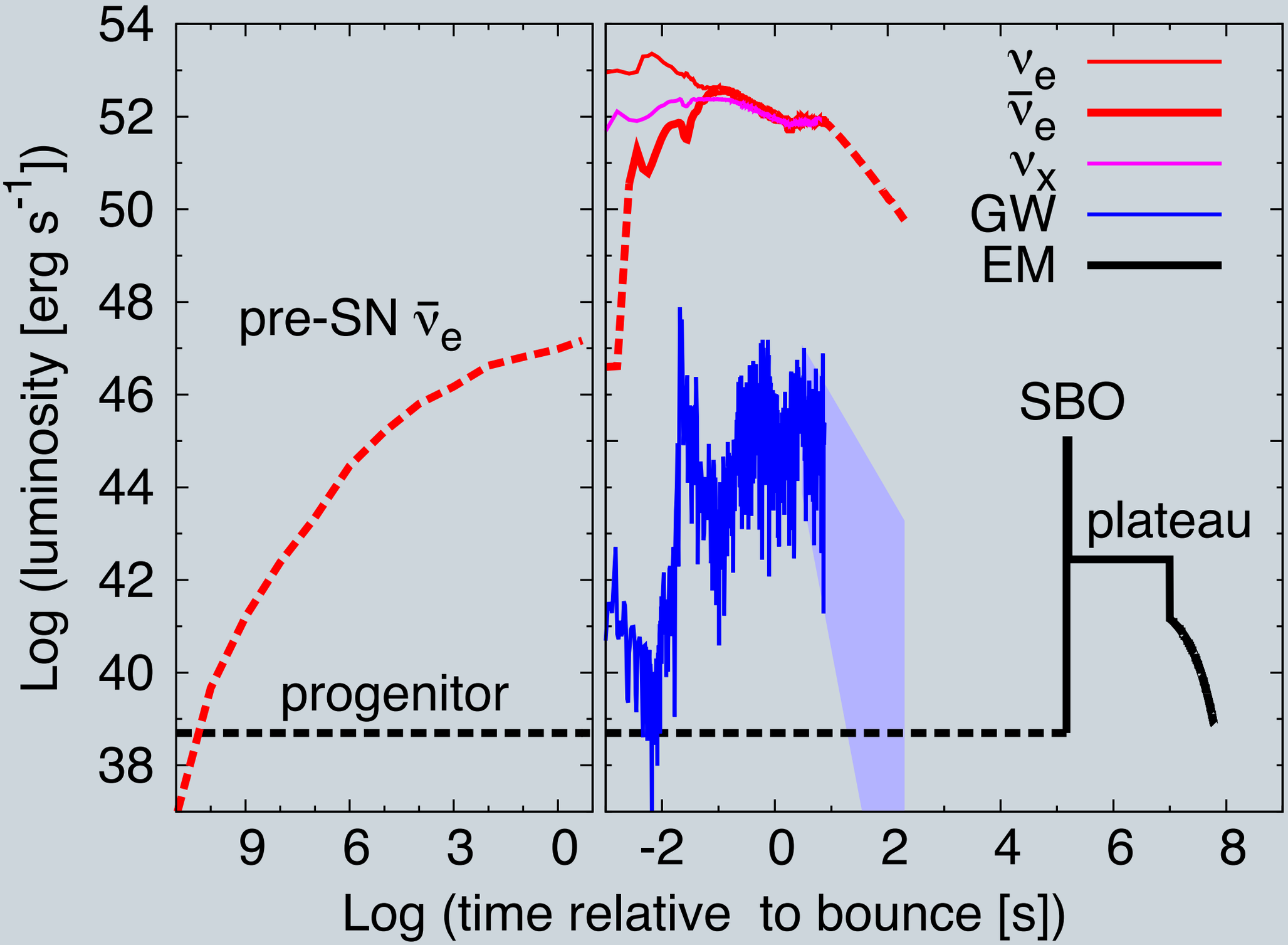
Agenda

A real Galactic supernova cannot, unfortunately, be guaranteed on the timescale of a PhD studentship…

—Susan Cartwright

- Neutrino Astronomy
- Hyper-Kamiokande
- Supernova Neutrino Observations with HK
- Supernova Early Warning System (SNEWS)

Supernova Neutrino Signal

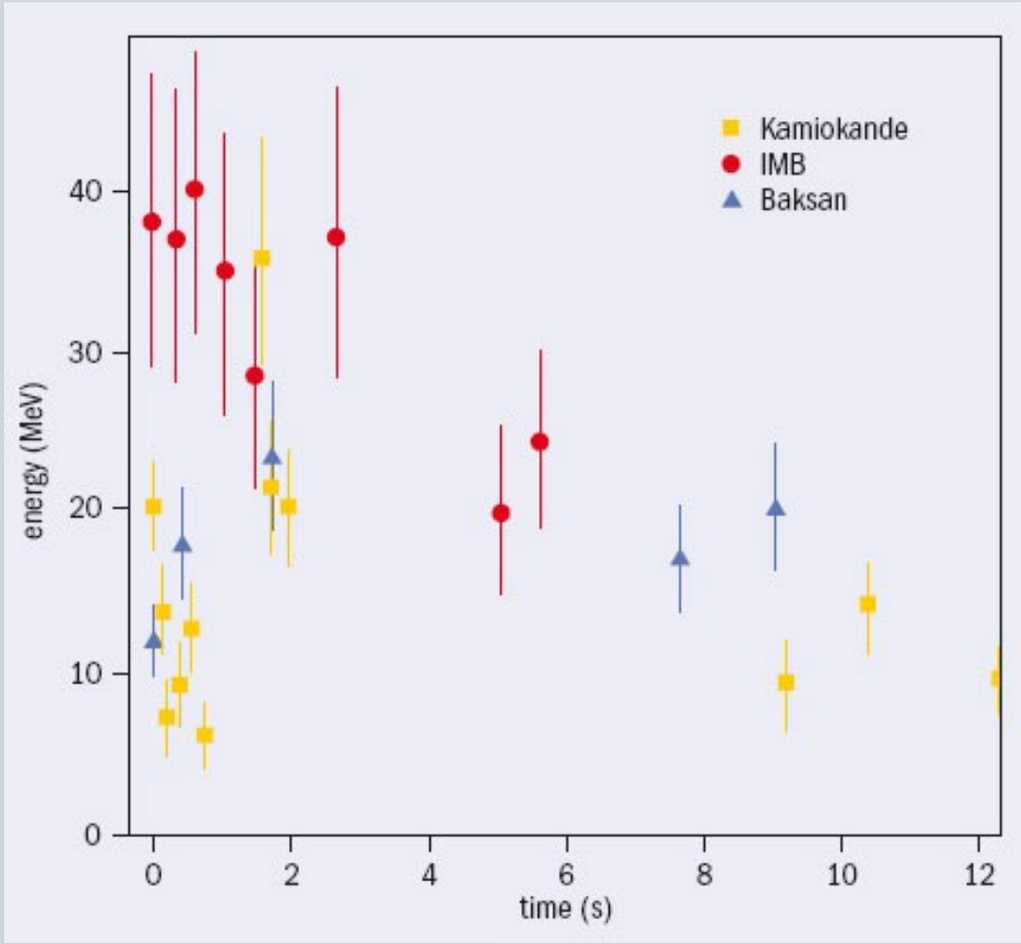


arXiv:1602.03028

What We (Think We) Know …

- SN1987A: two dozen events, ~half of them in Kamiokande

- Confirmed basic picture:
  - ν burst ≈99% of energy
  - ~10^{53} erg, ~10^{58} ν
  - ν arrive ~hours before light



- Energy loss argument can constrain exotic particles

G. Raffelt, arXiv:hep-ph/9903472

- Simulations still limited by available computing power
  → take any numbers with a grain of salt

What We (Think We) Know …

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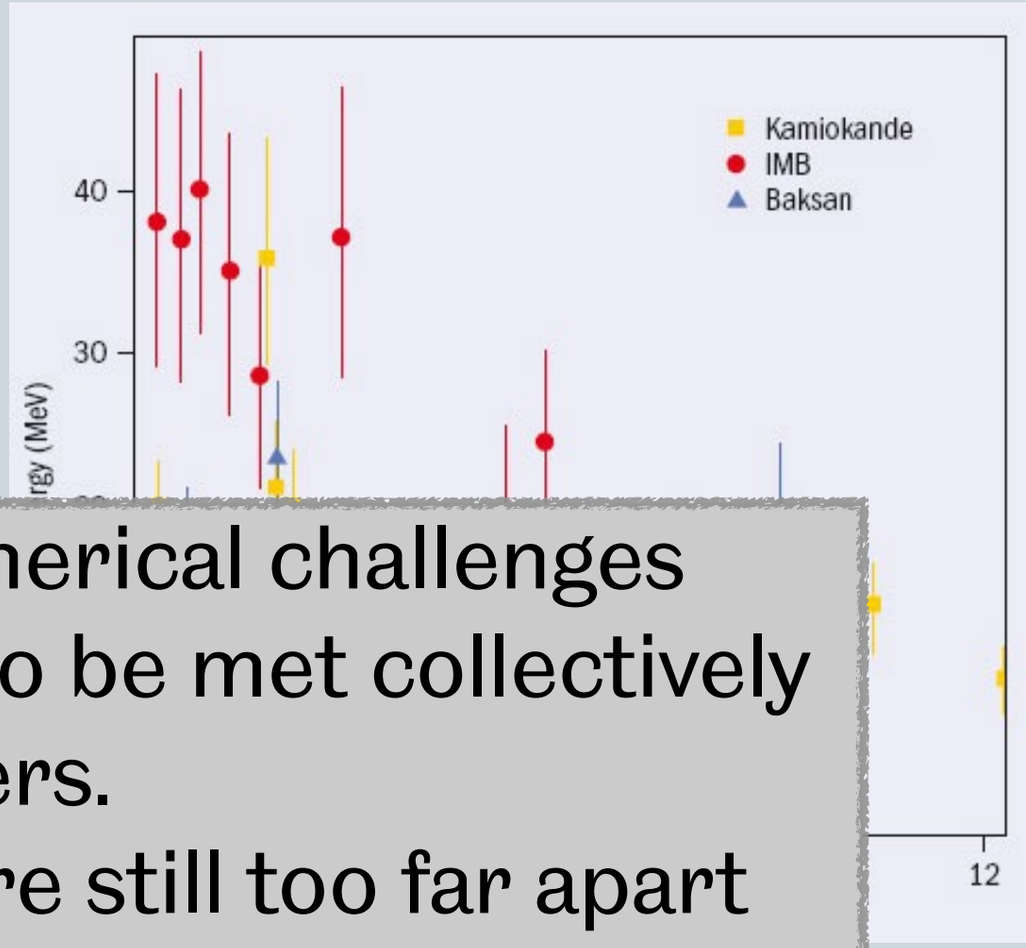

- Confirmed basic picture:

> "There is a rather long list of numerical challenges and code verification issues yet to be met collectively by the world's supernova modelers.
> The results of different groups are still too far apart to lend ultimate credibility to any one of them."
>
> — Skinner, Burrows, Dolence (arXiv:1512.00113)

9903472

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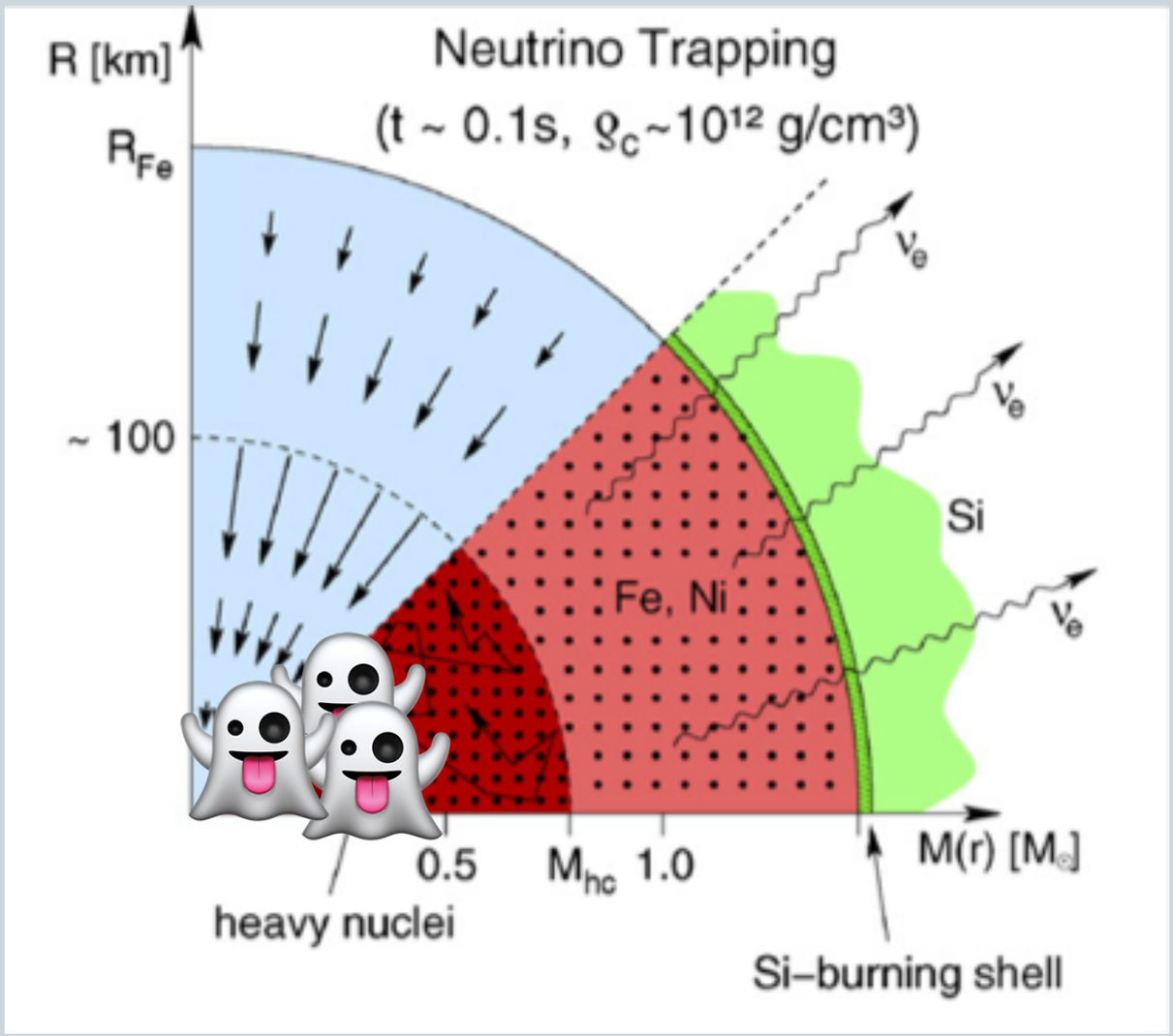
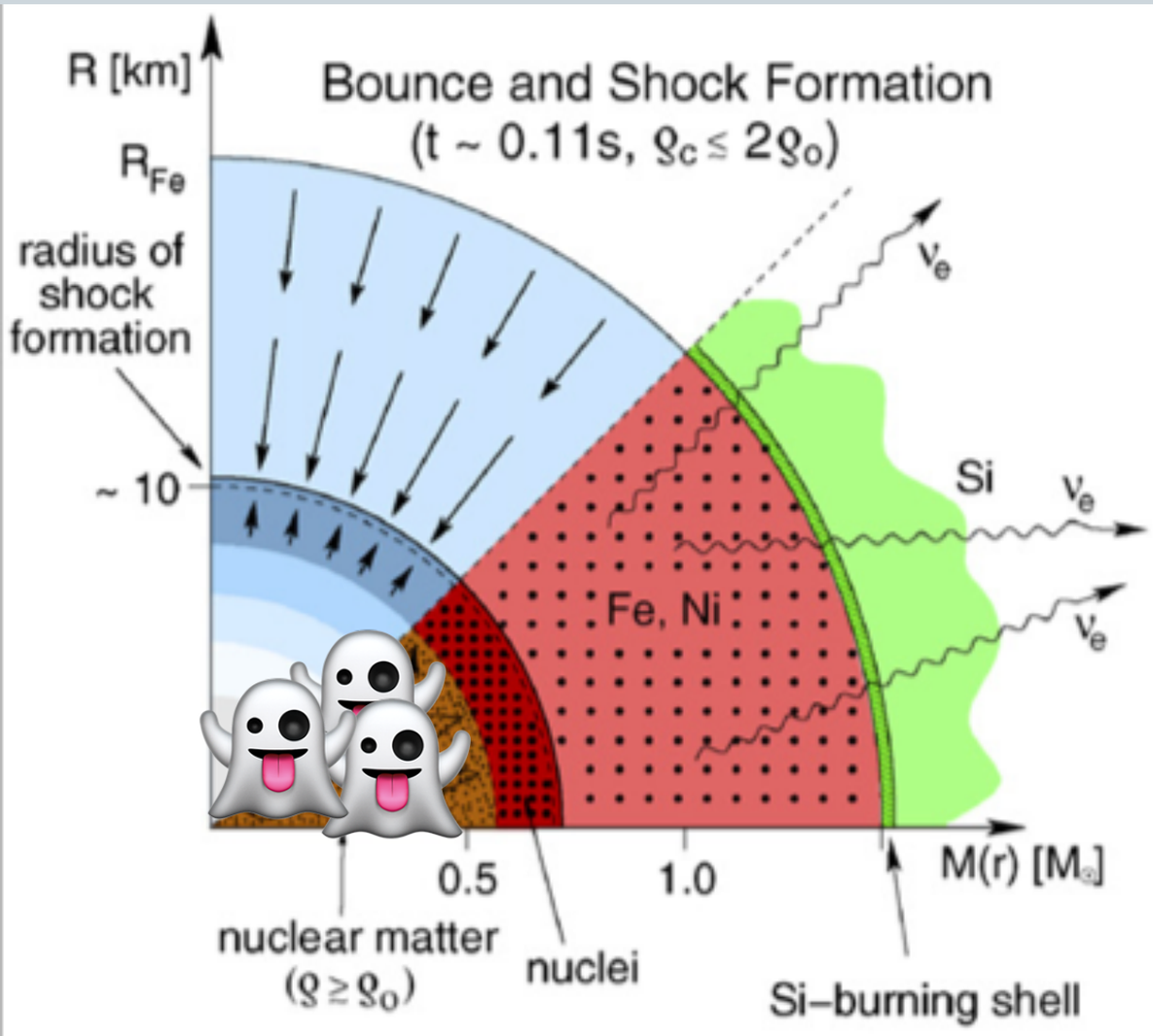
1) The Star Collapses

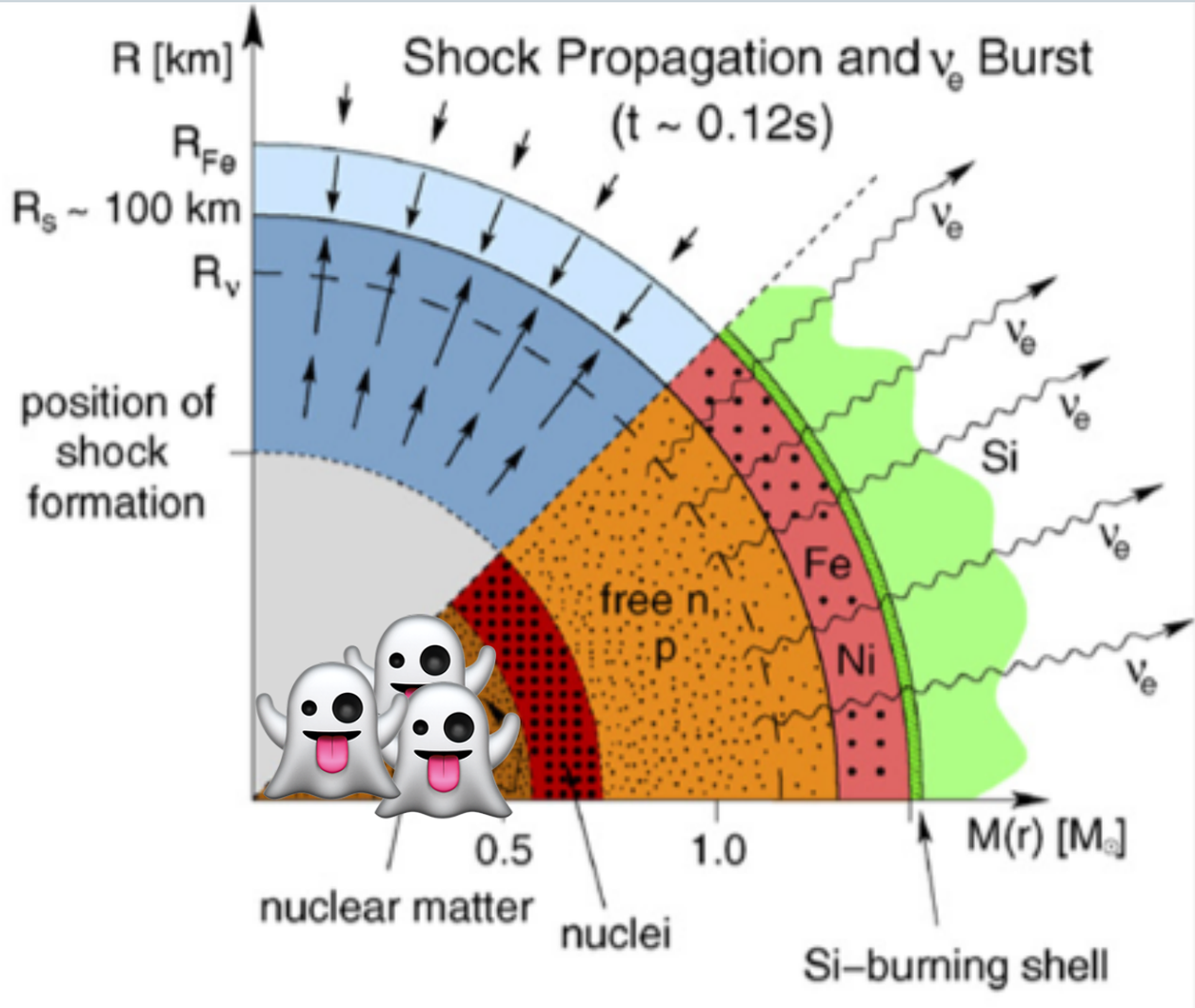


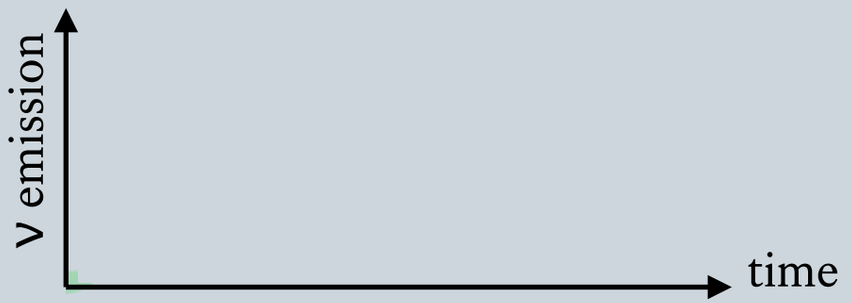
[Janka *et al.*, Phys.Rep. 442, pp. 38–74]

2) A Shock Wave Forms

[Janka *et al.*, Phys.Rep. 442, pp. 38–74]







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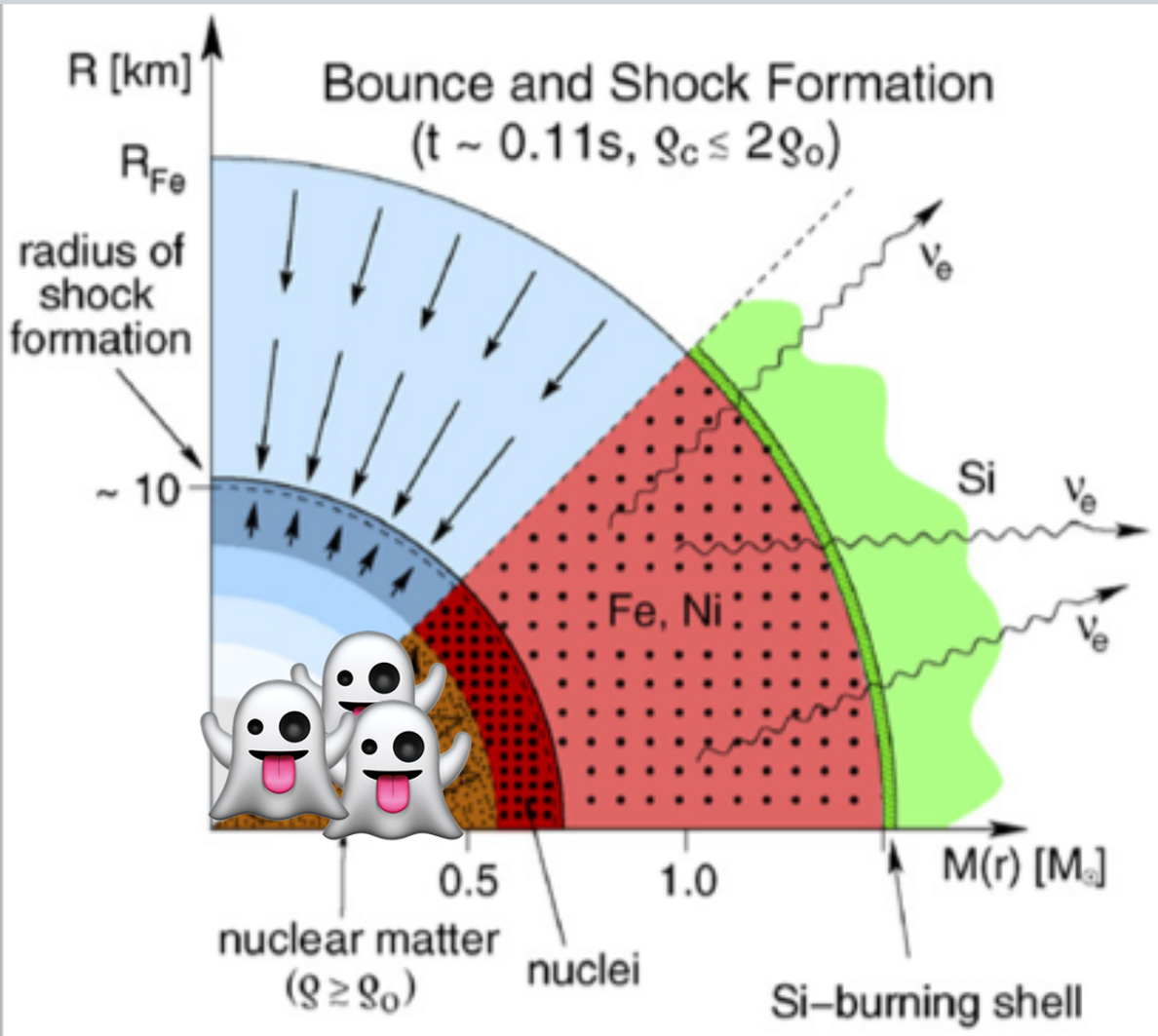

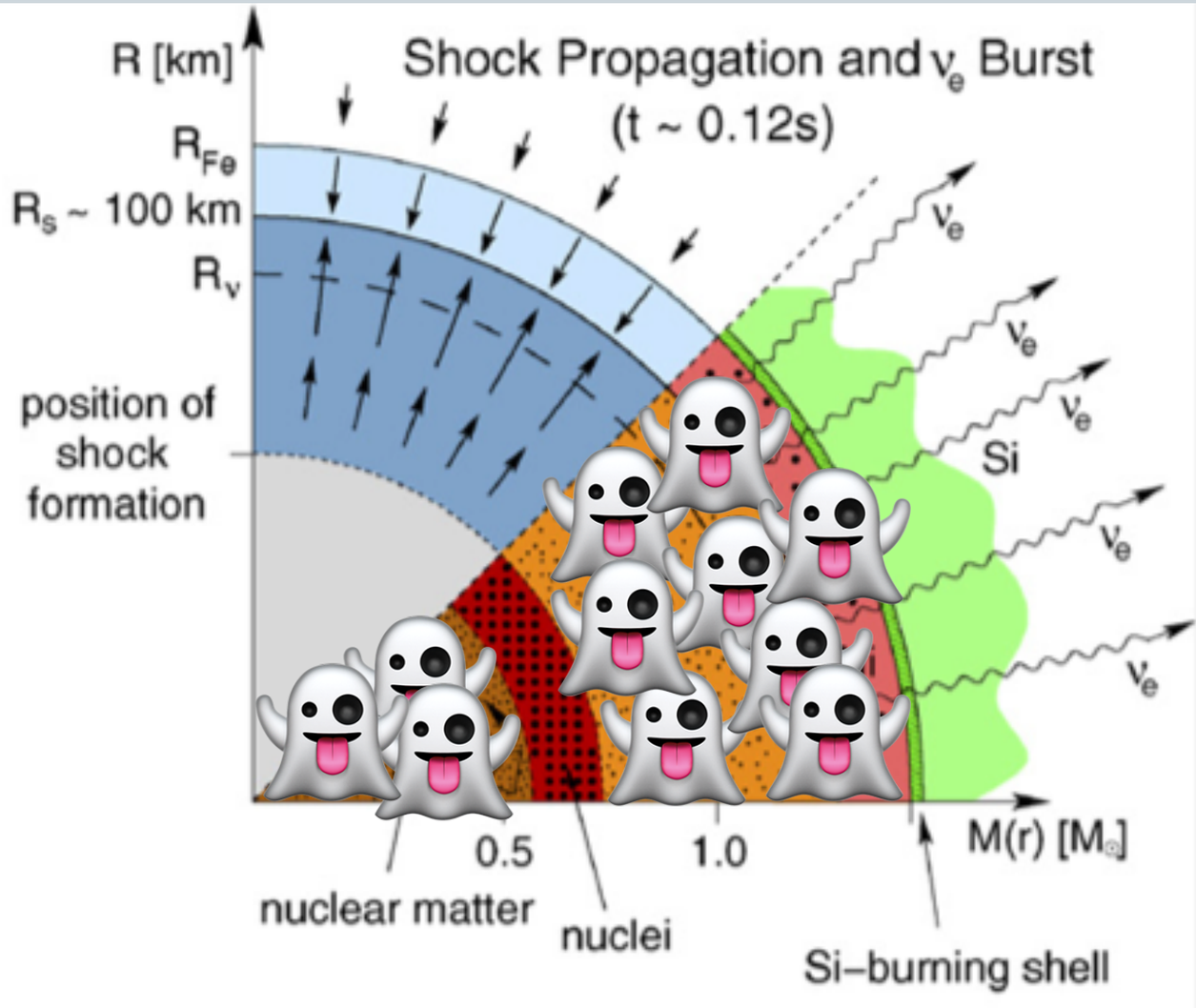

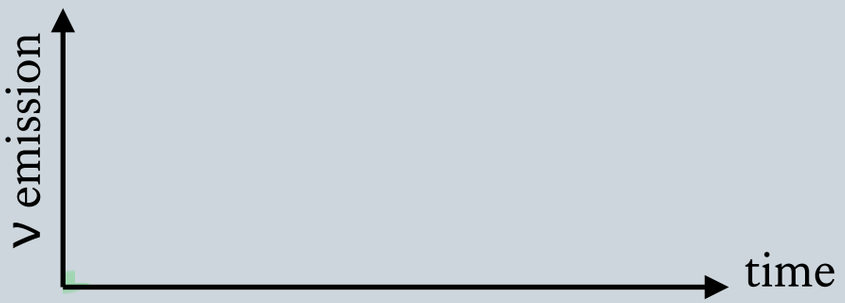

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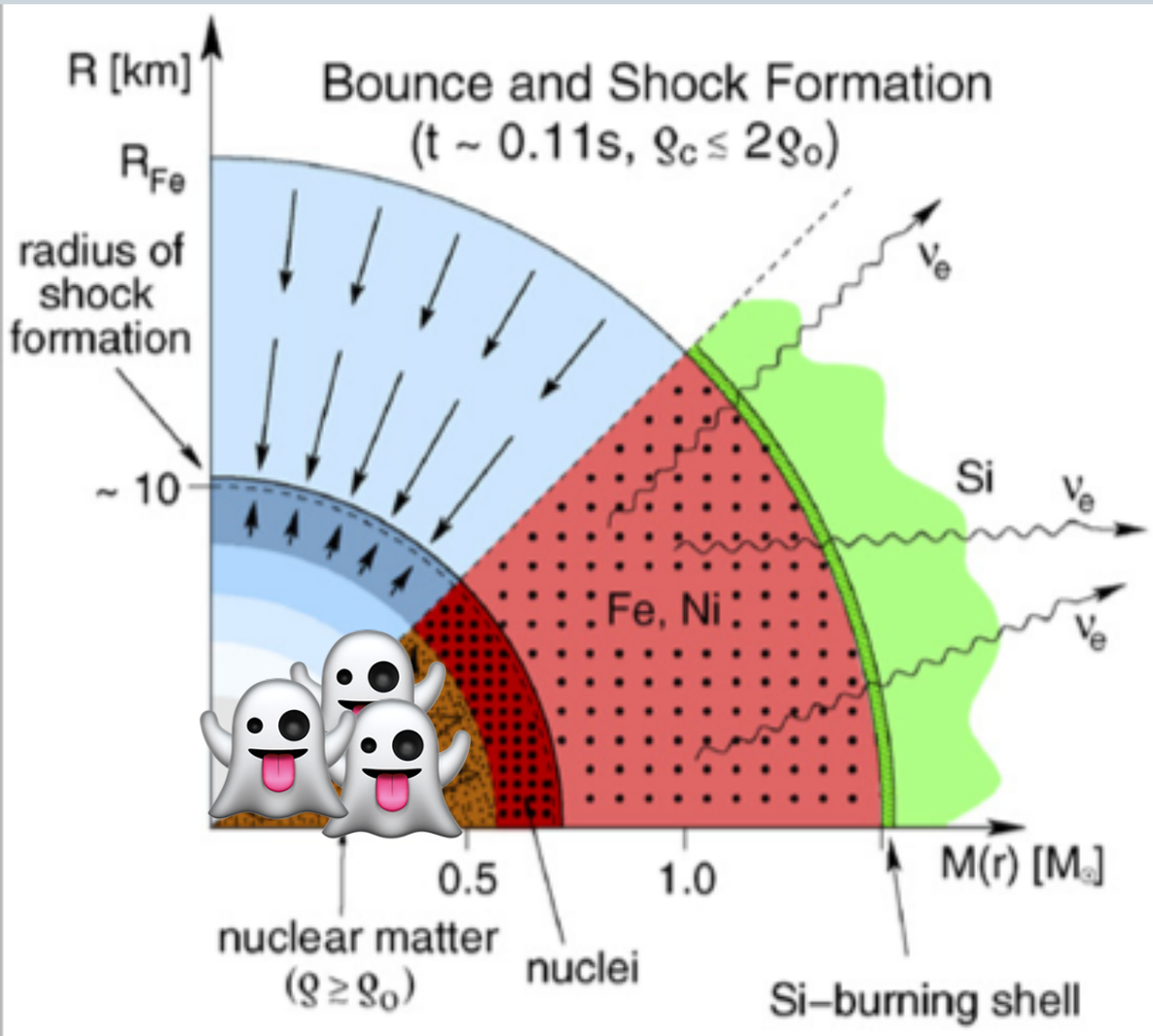
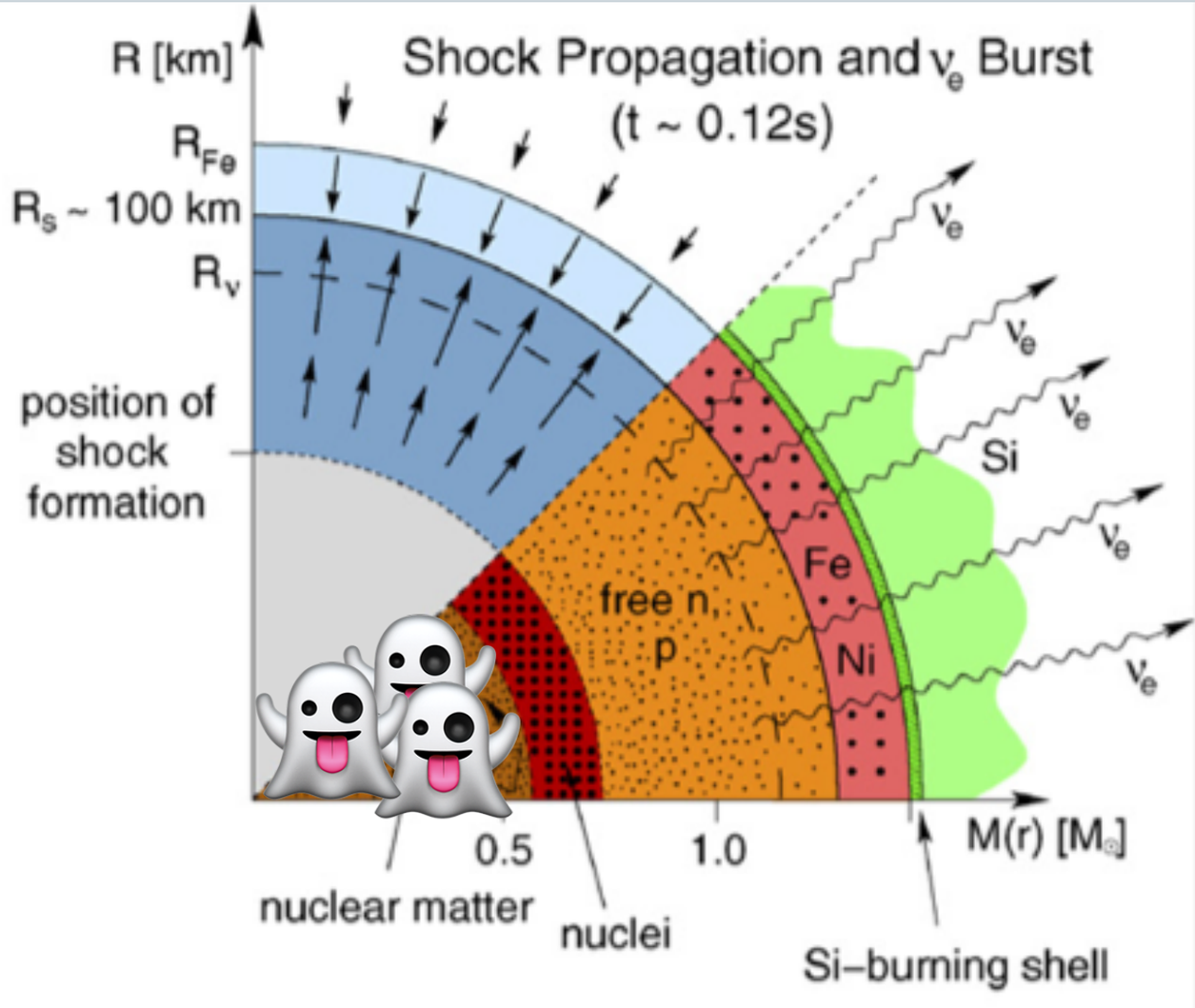
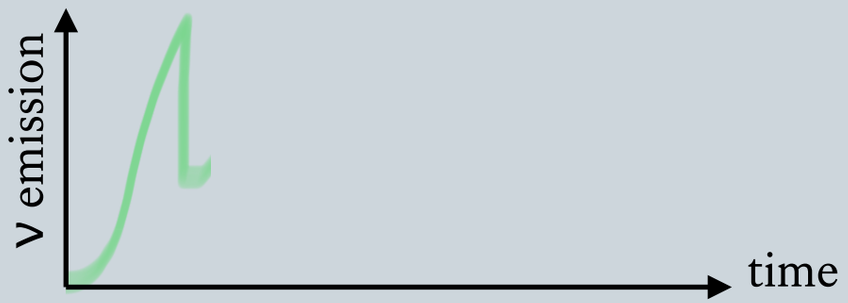
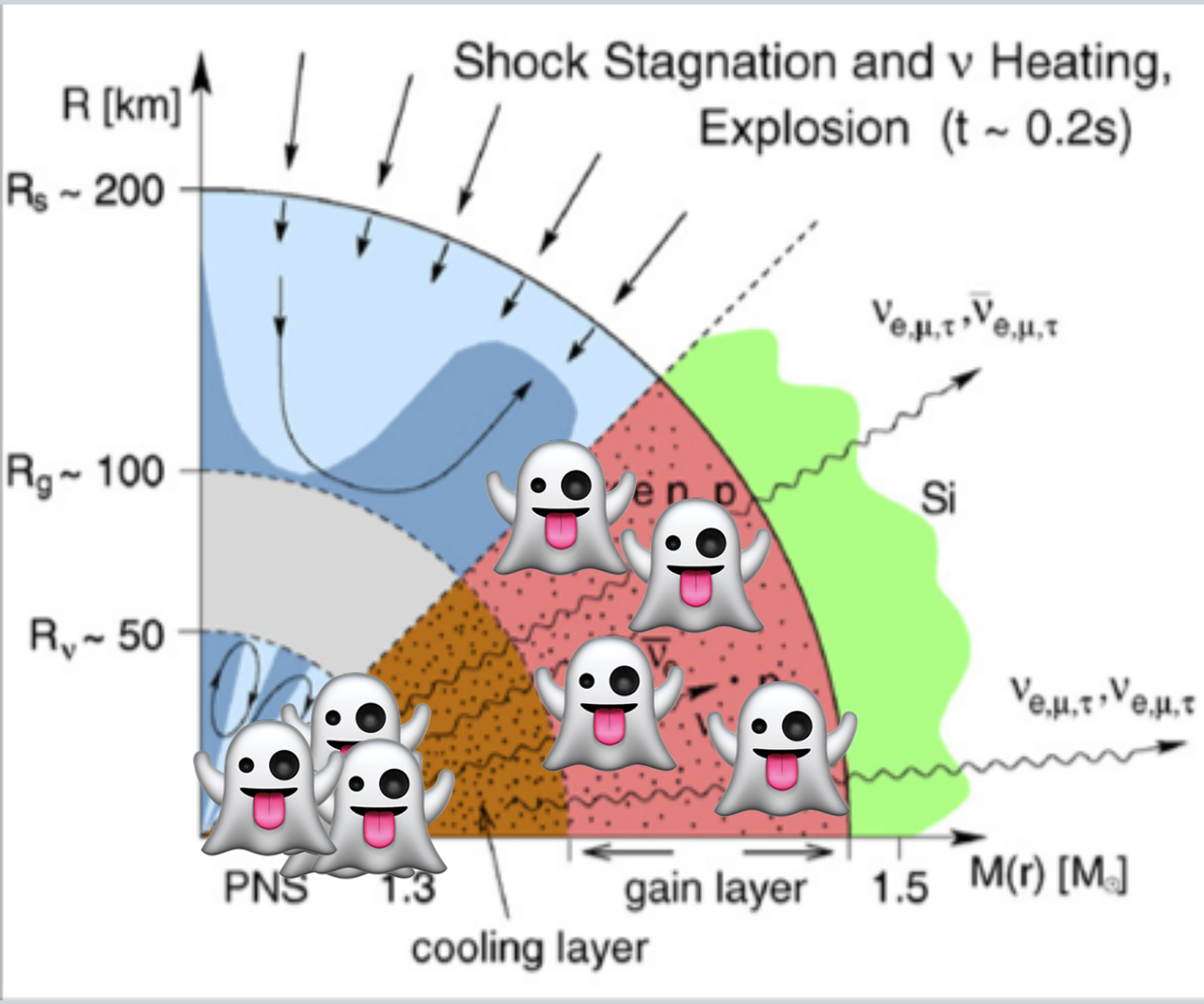


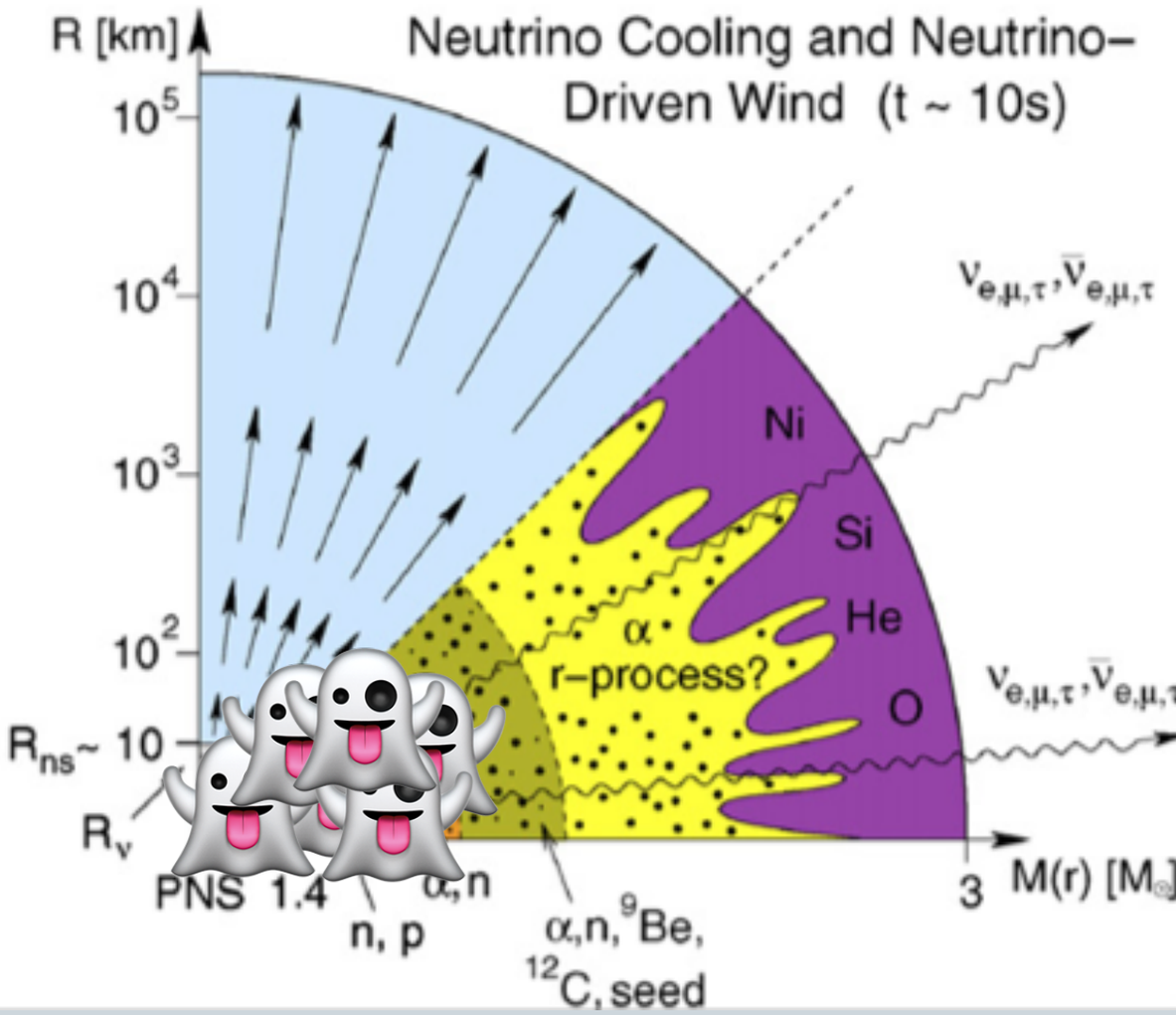


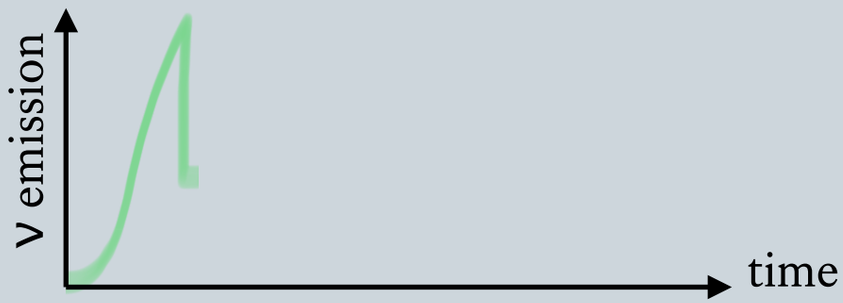


3) Shock Wave Is Restarted & Explodes

[Janka *et al.*, Phys.Rep. 442, pp. 38–74]







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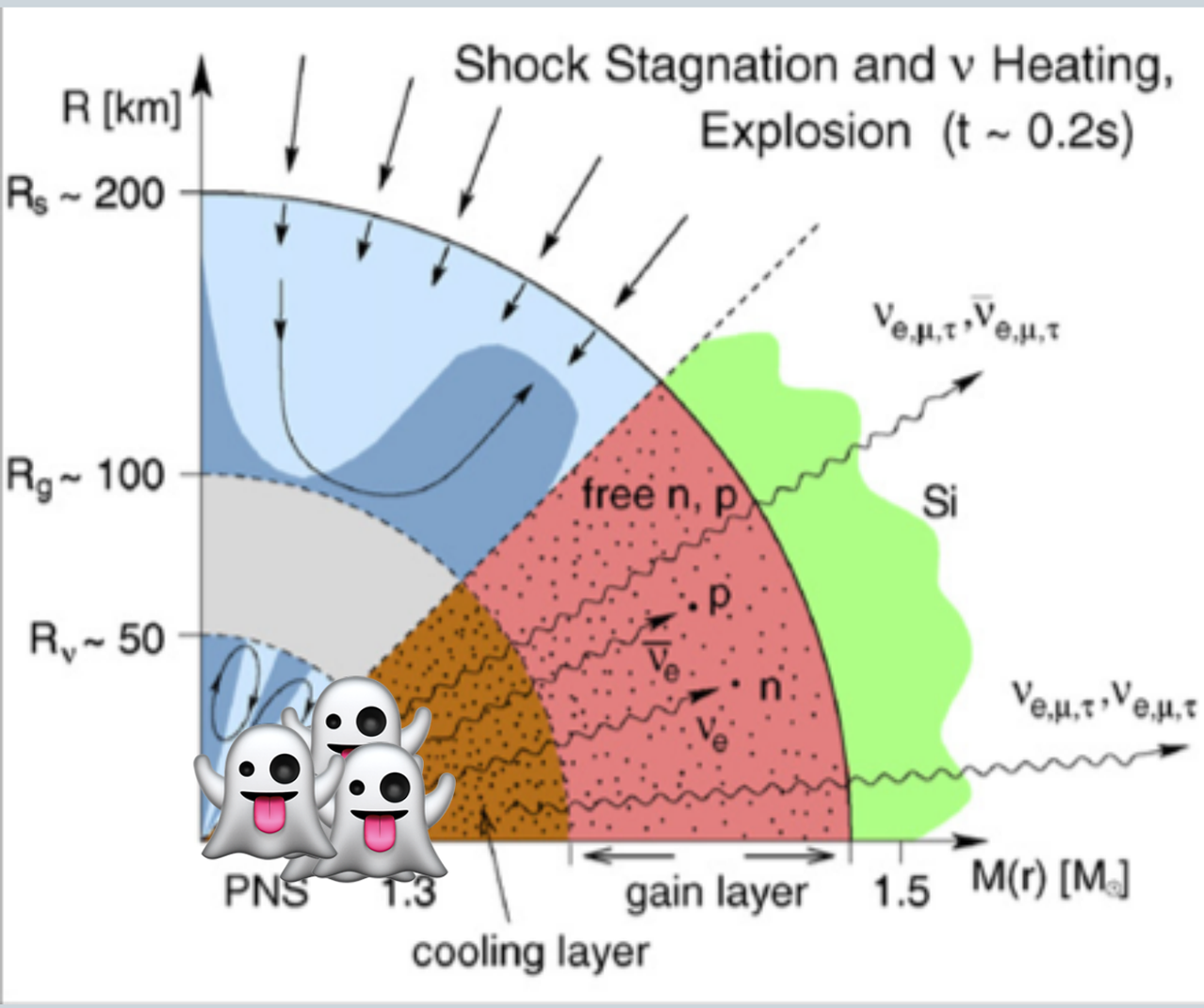

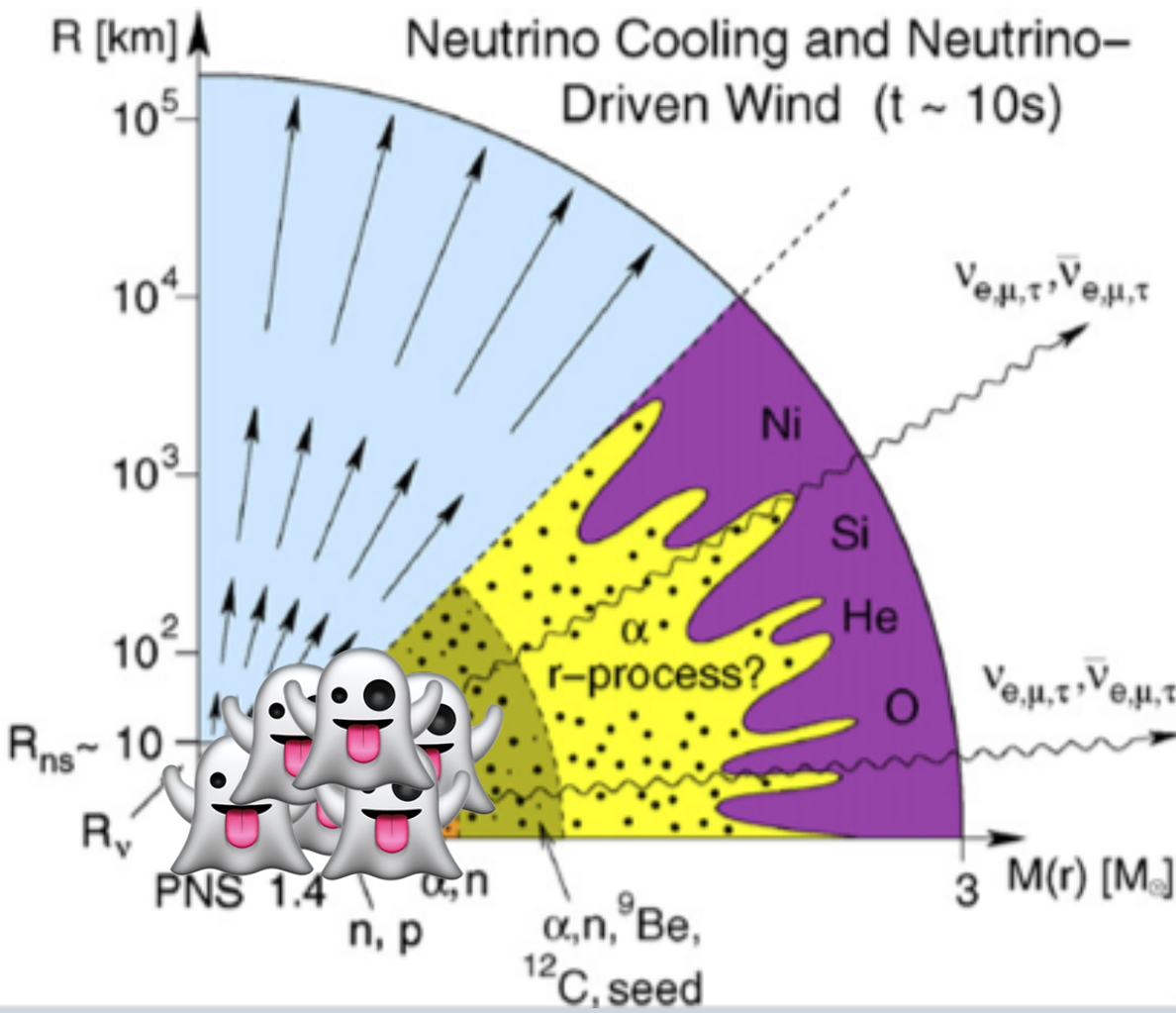

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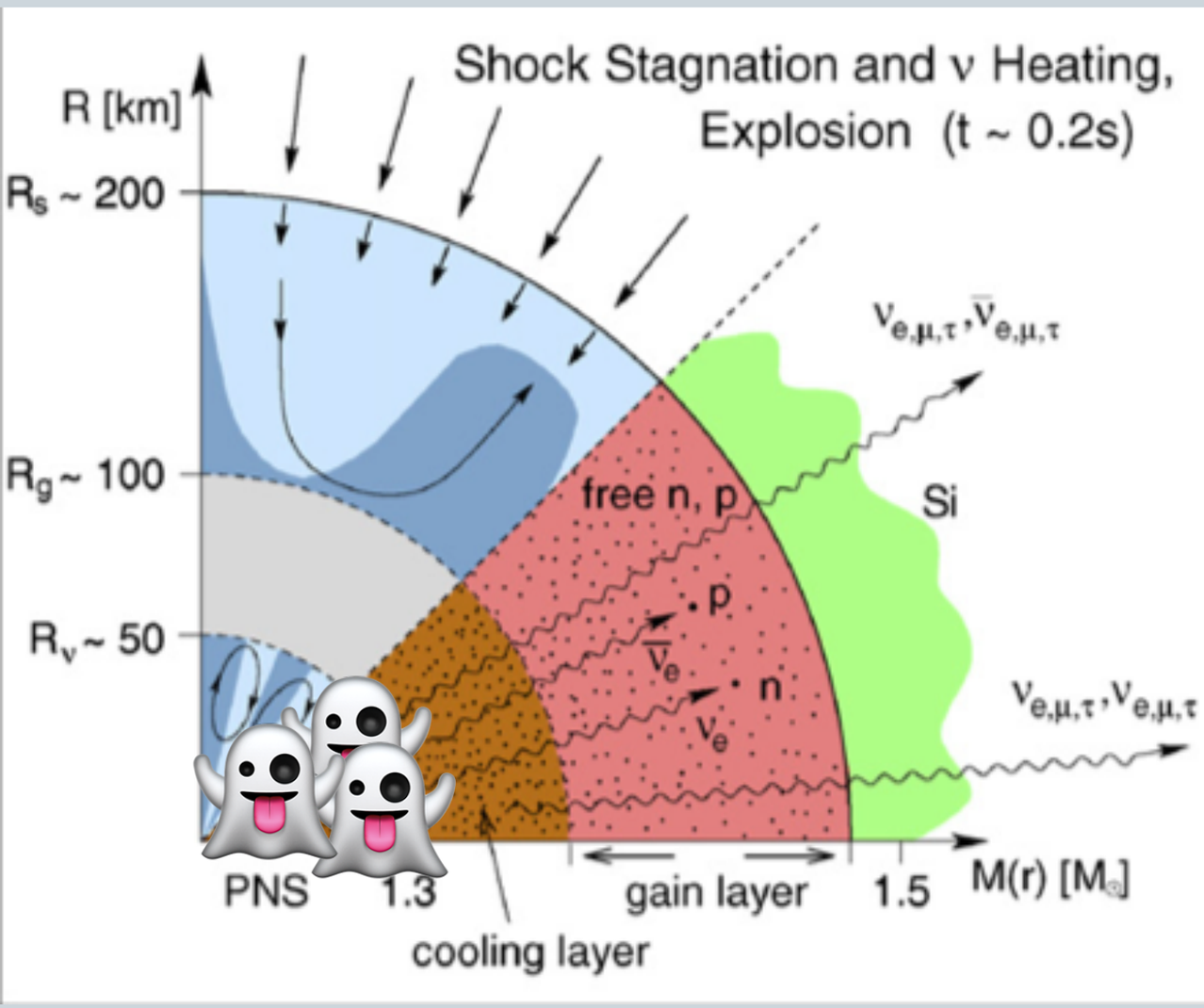
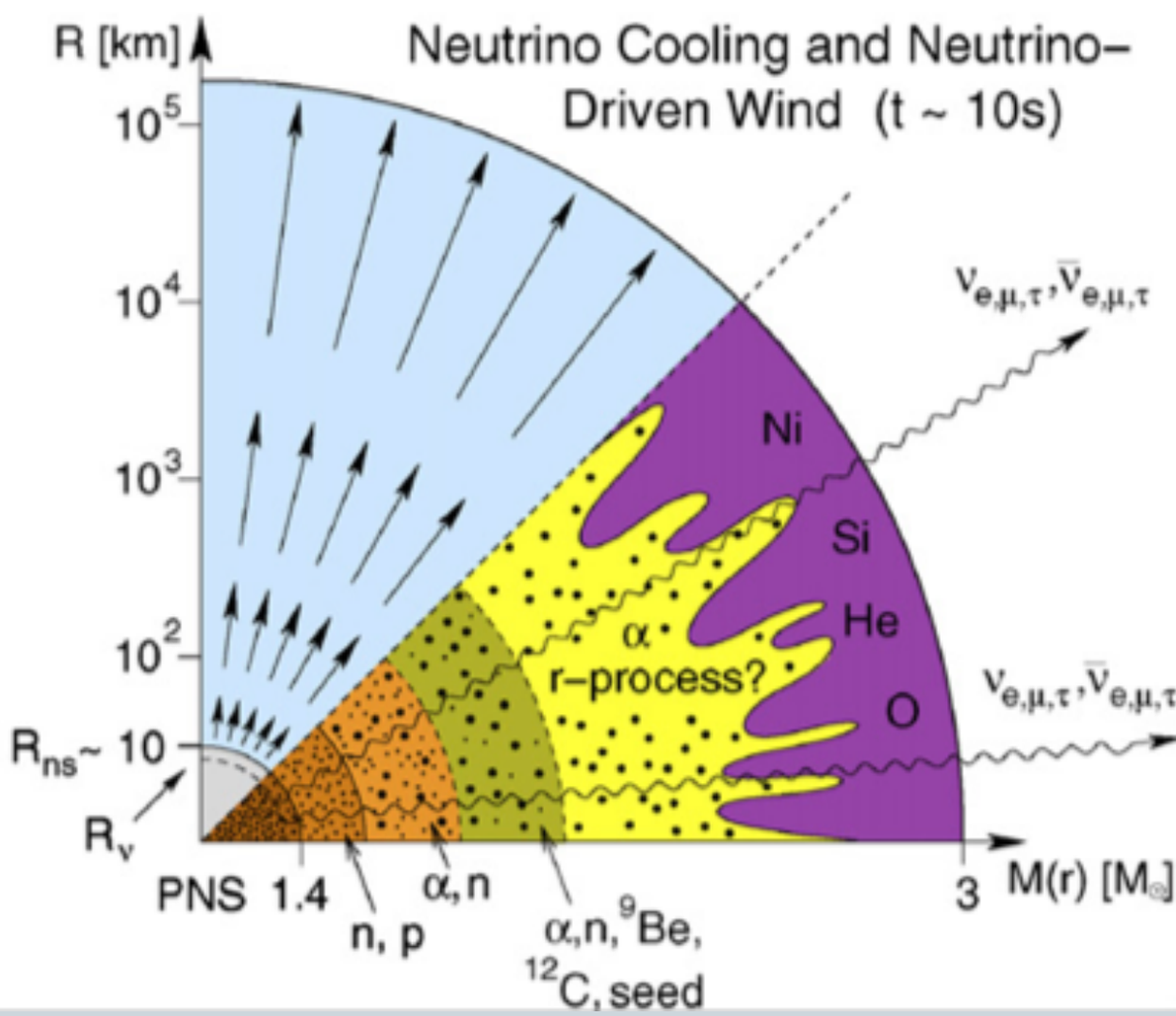
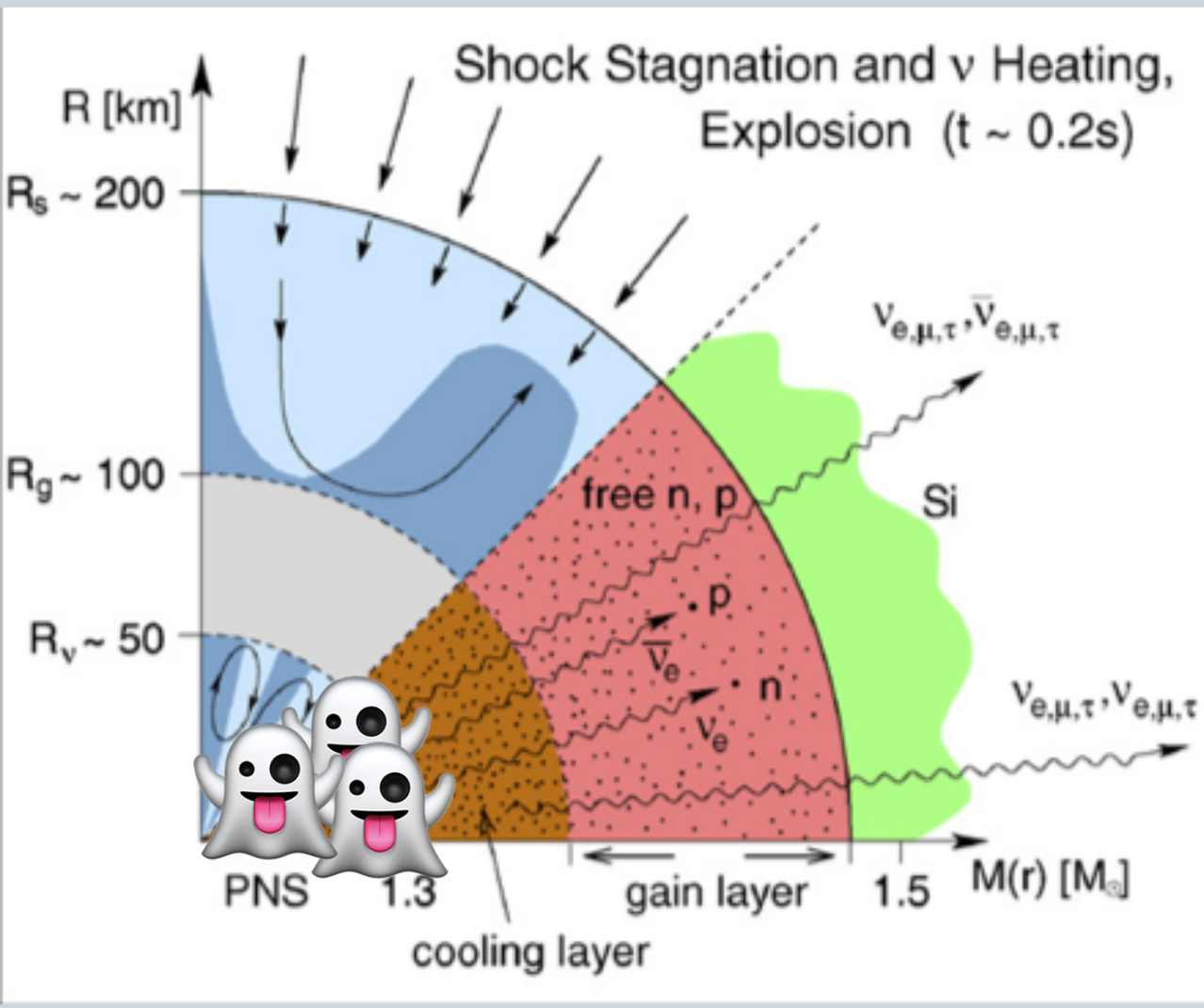
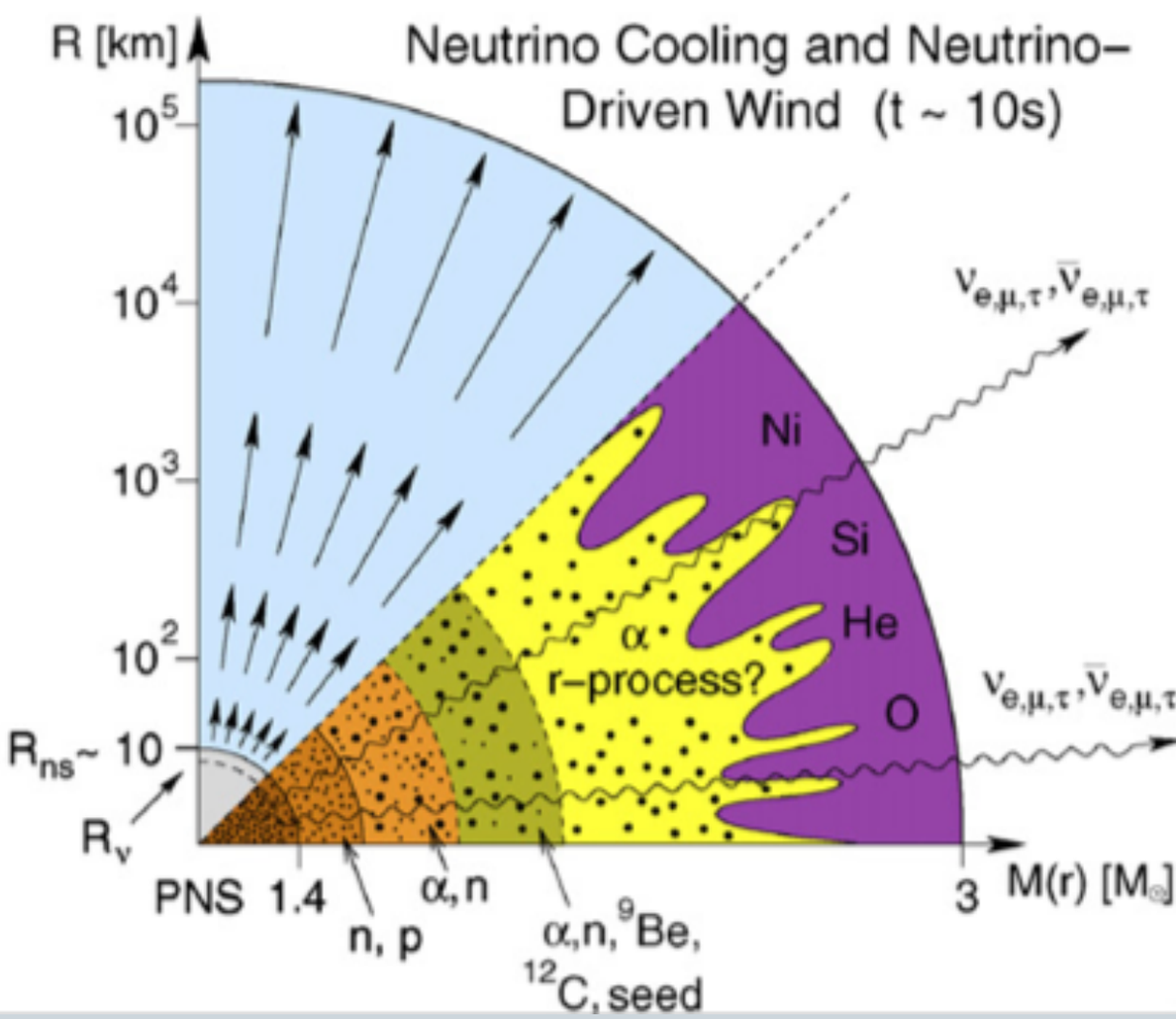


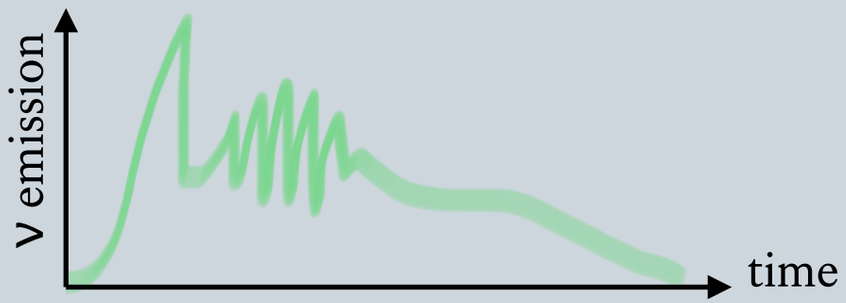


3) Shock Wave Is Restarted & Explodes

[Janka *et al.*, Phys.Rep. 442, pp. 38–74]



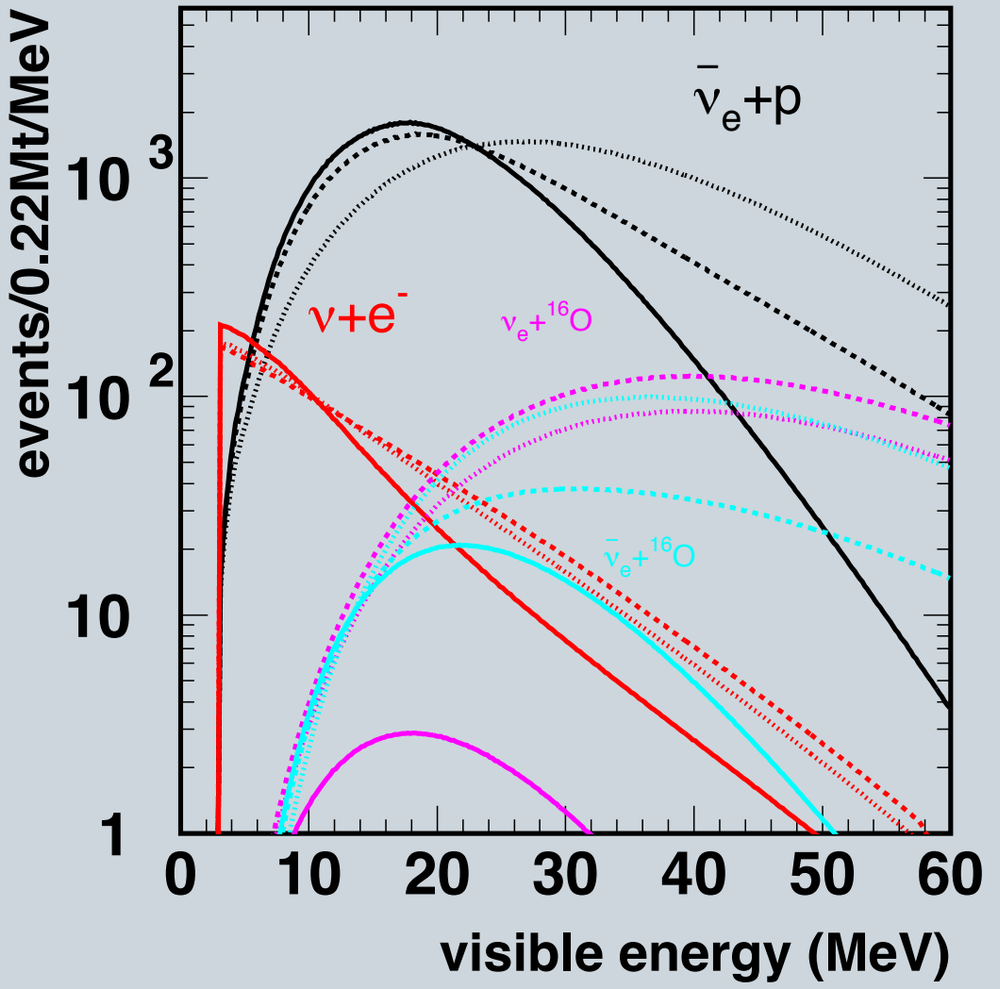


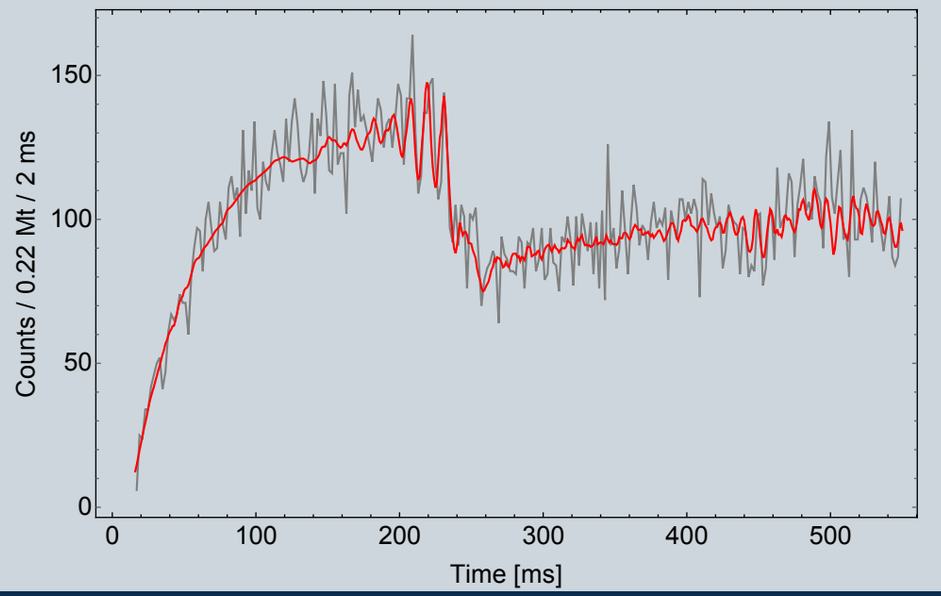


Supernova ν Burst

- At 10 kpc: 10^5–10^6 events in ~10 s
- Precise event-by-event time & energy information
- Directionality: ~1° (via νe-scattering)
- Most sensitive to $\overline{\nu}_e$ (~90% inverse beta decay on H)

➔ Detailed information on SN explosion mechanism (e.g. Standing Accretion Shock Instability – SASI)





Supernova Model Discrimination

- To understand explosion mechanism, need to compare observation with simulations
  - Look for specific features (e.g. SASI: Lund et al. arXiv:1006.1889)
  - Compare full t & E dependence (JM, arXiv:2002.01649 & 2101.05269)

- Use 5 supernova models
- 1000 MC data sets per model using new event generator https://github.com/JostMigenda/sntools
- Full detector simulation & reconstruction toolchain
- Which model best matches the reconstructed t & E distribution?

(Details in backup slides.)

True model \ Identified as (100 events*)	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	795	57	122	12	14
Nakazato	33	**961**	3	1	2
Tamborra	84	0	853	33	30
Totani	4	0	16	**979**	1
Vartanyan	0	1	17	3	**979**

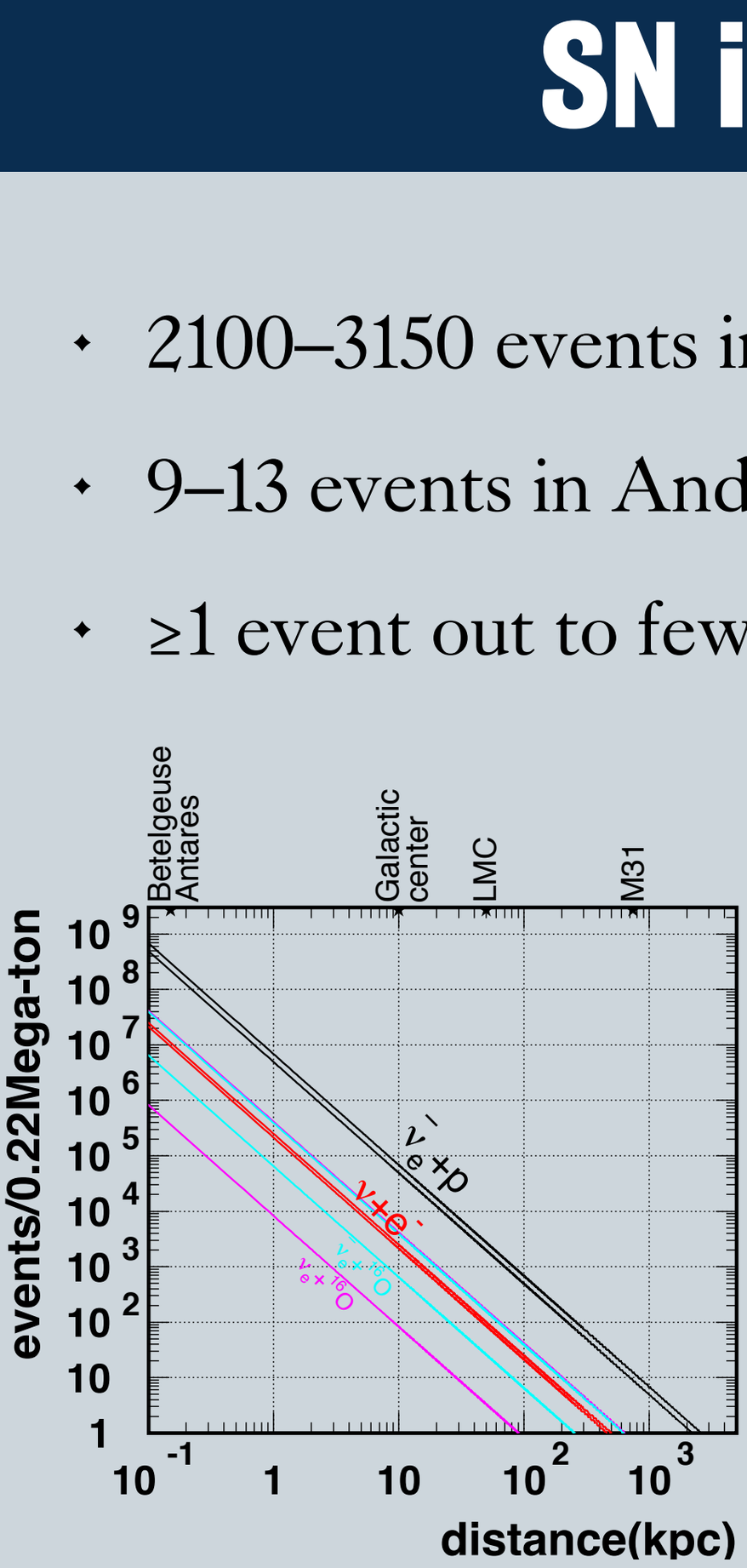
True model \ Identified as (300 events*)	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**982**	2	16	0	0
Nakazato	1	**999**	0	0	0
Tamborra	16	0	**980**	2	2
Totani	0	0	0	**1000**	0
Vartanyan	0	0	0	0	**1000**

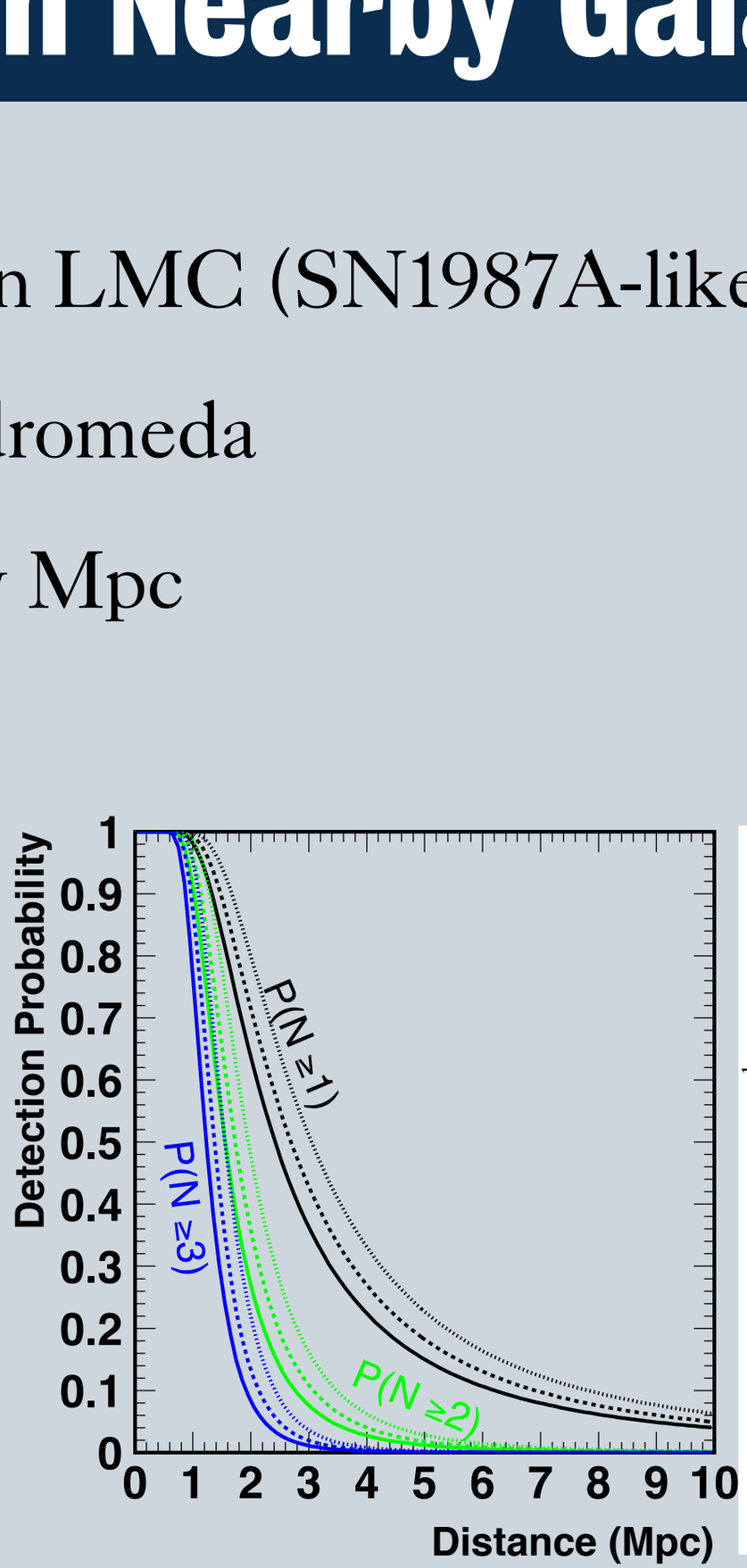
* during 20–520ms after core bounce, assuming Normal Ordering

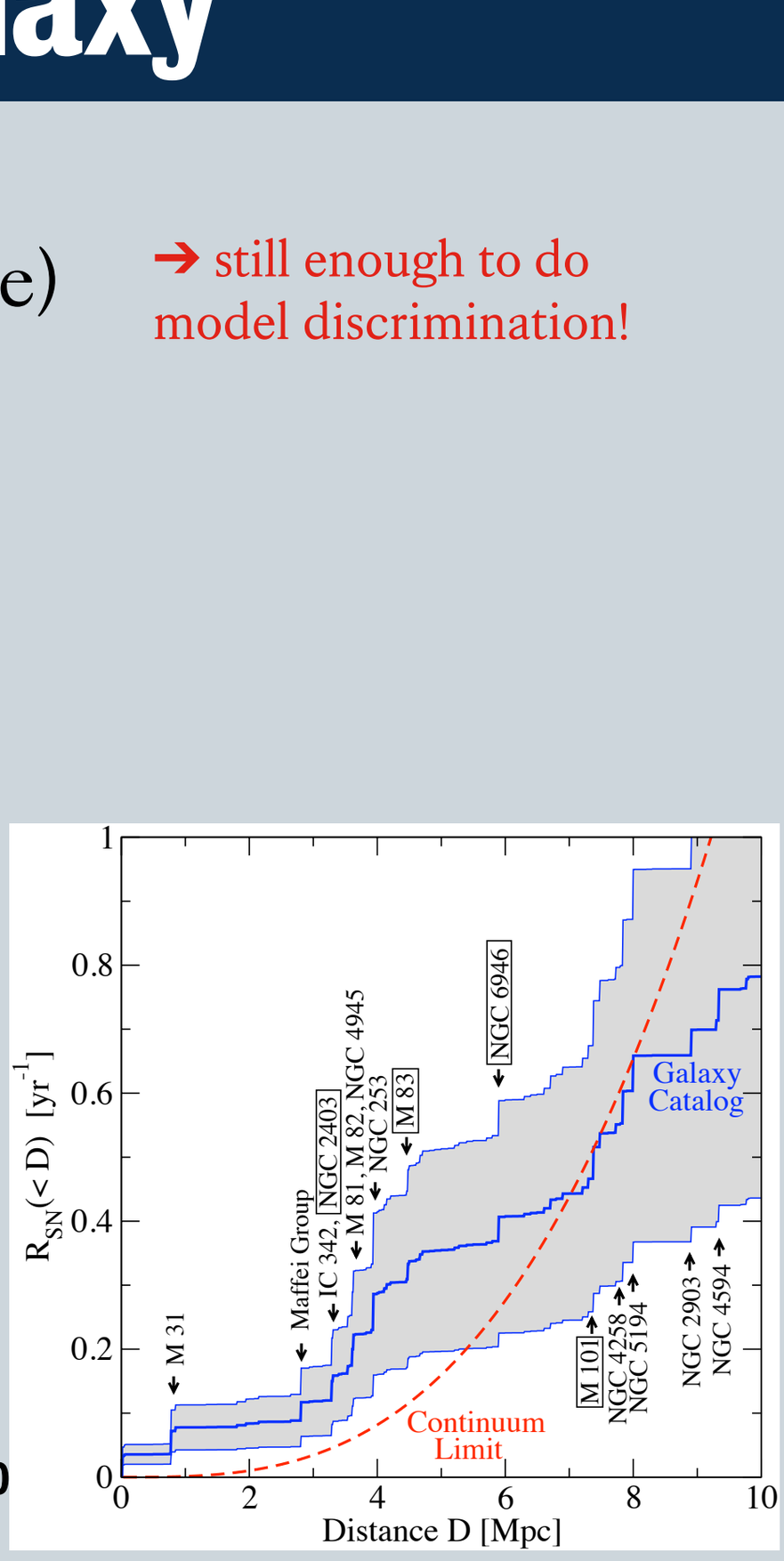
SN in Nearby Galaxy

- 2100–3150 events in LMC (SN1987A-like)
- 9–13 events in Andromeda
- ≥1 event out to few Mpc

➔ still enough to do model discrimination!

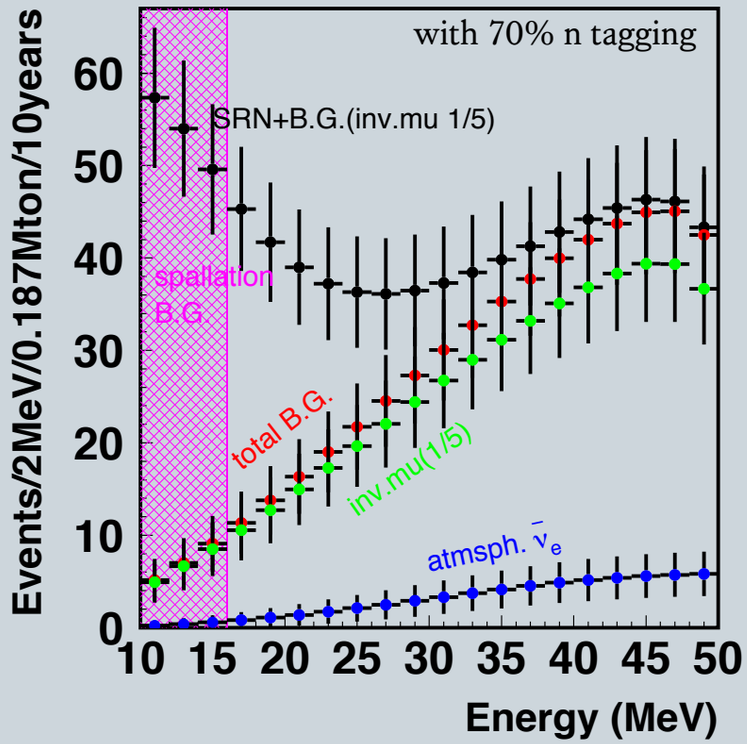


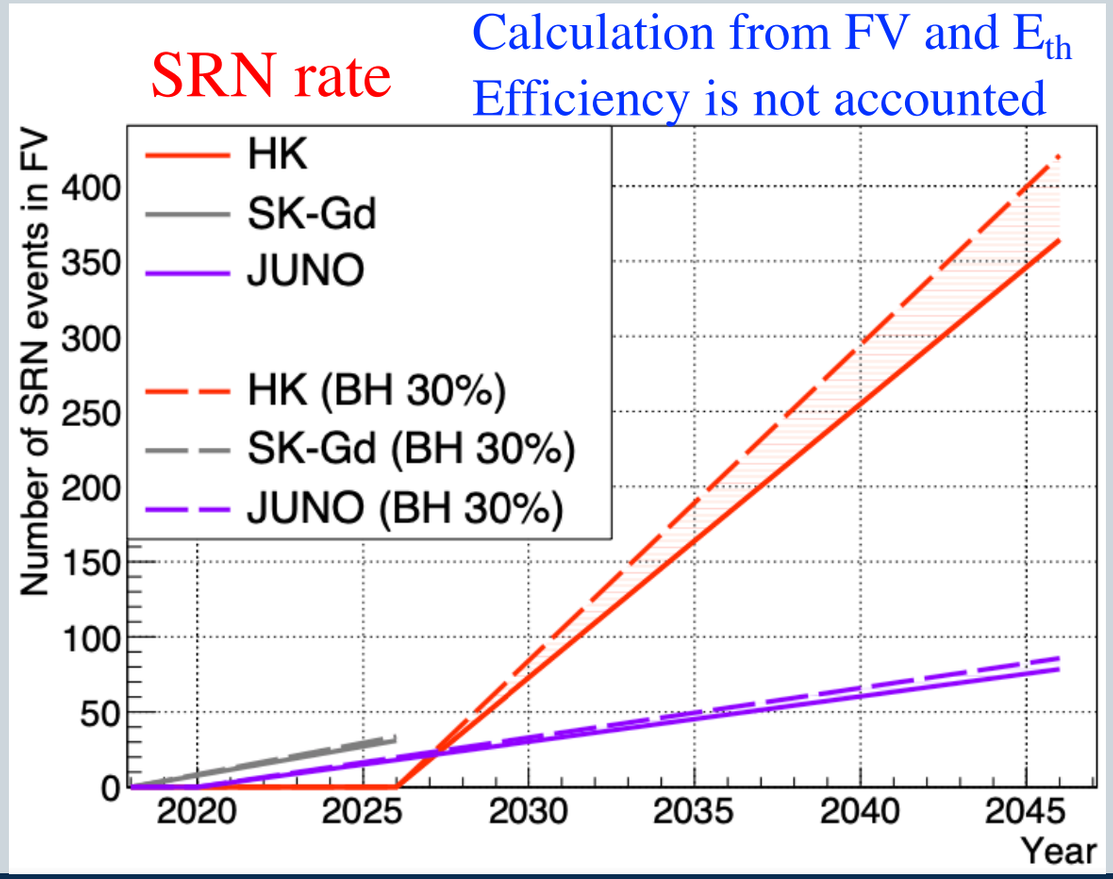


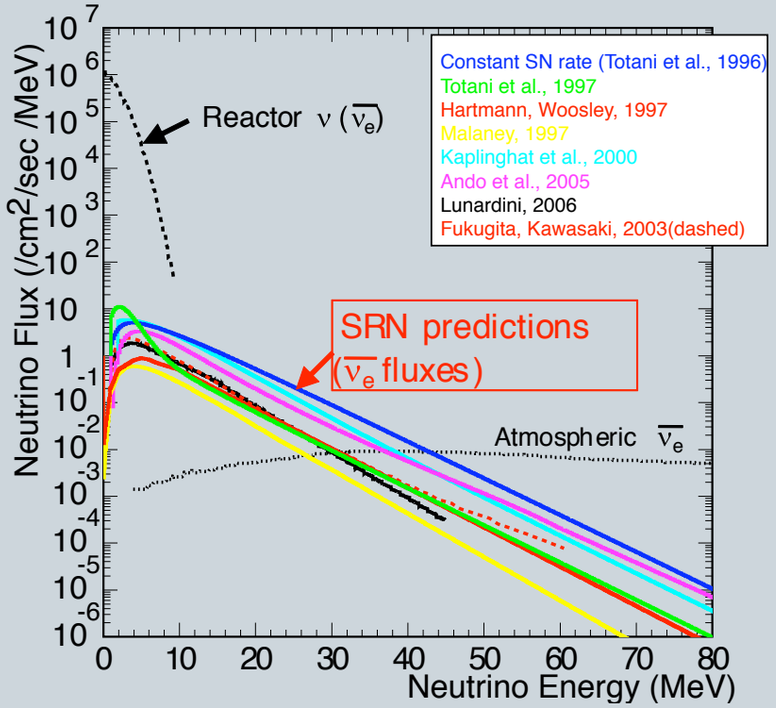


Supernova Relic Neutrinos

- a.k.a. Diffuse Supernova Neutrino Background (DSNB)
- ν from all SN integrated over the history of the universe
  - Encode history of star formation
  - Information on dim SNe & black hole formation
- SK-Gd: First detection — HK: first spectrum







Agenda

Point Over There At That Old Exploding Star

—Ed Kearns
https://snews.bnl.gov/amuse.html

- Neutrino Astronomy
- Hyper-Kamiokande
- Supernova Neutrino Observations with HK
- Supernova Early Warning System (SNEWS)

Operational Detectors for Supernova Neutrinos

HALO (30)
SNO+ (300)

LVD (400)
Borexino (100)

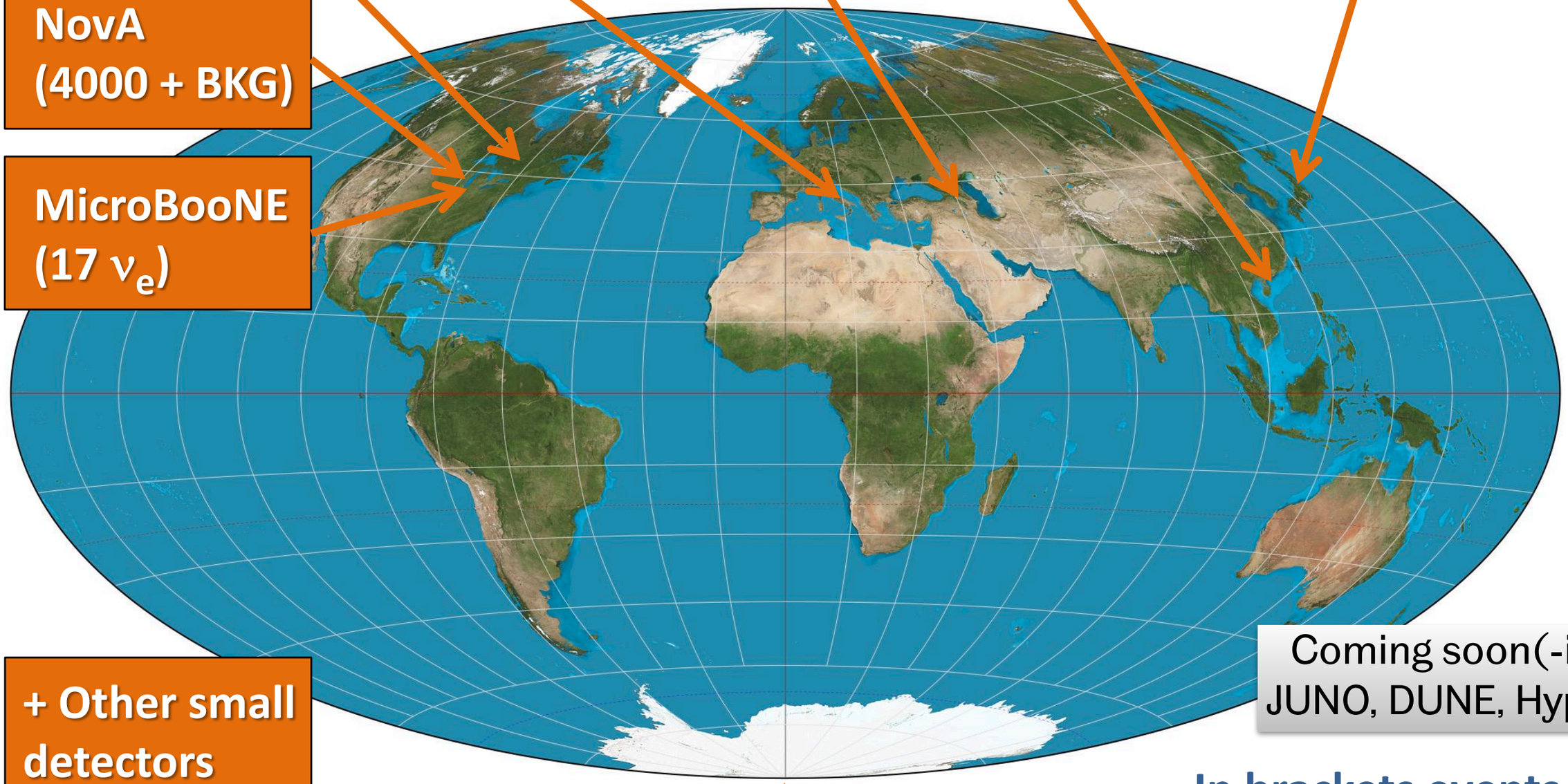
Baksan (100)

Daya Bay (100)

Super-K (4000)
KamLAND (400)

NovA
(4000 + BKG)

MicroBooNE
(17 ν_e)



+ Other small detectors with some SN sensitivity

IceCube (10^6)

Coming soon(-ish):
JUNO, DUNE, Hyper-K

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

Motivation

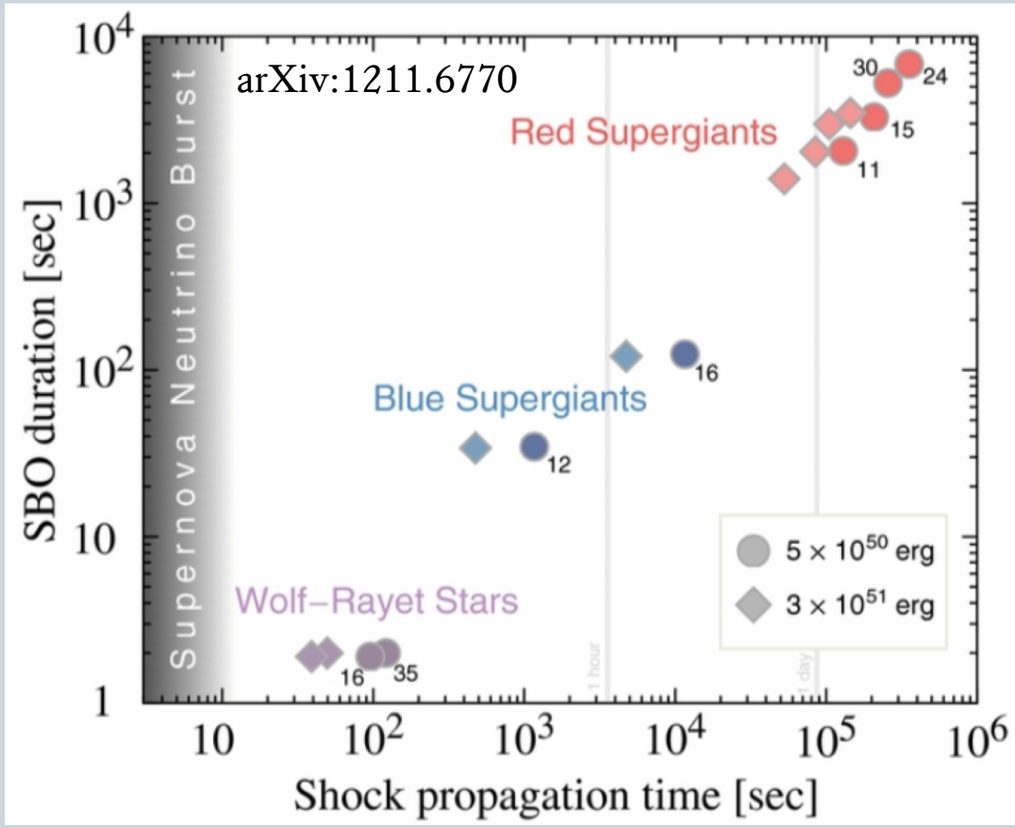
- Use coincidence of multiple neutrino detectors to alert astronomers* of galactic SN & reduce false alarm rate

  * and GW detectors, other neutrino experiments that can't trigger, …

- Neutrinos are produced immediately

- Light produced when shock wave reaches the surface of the star

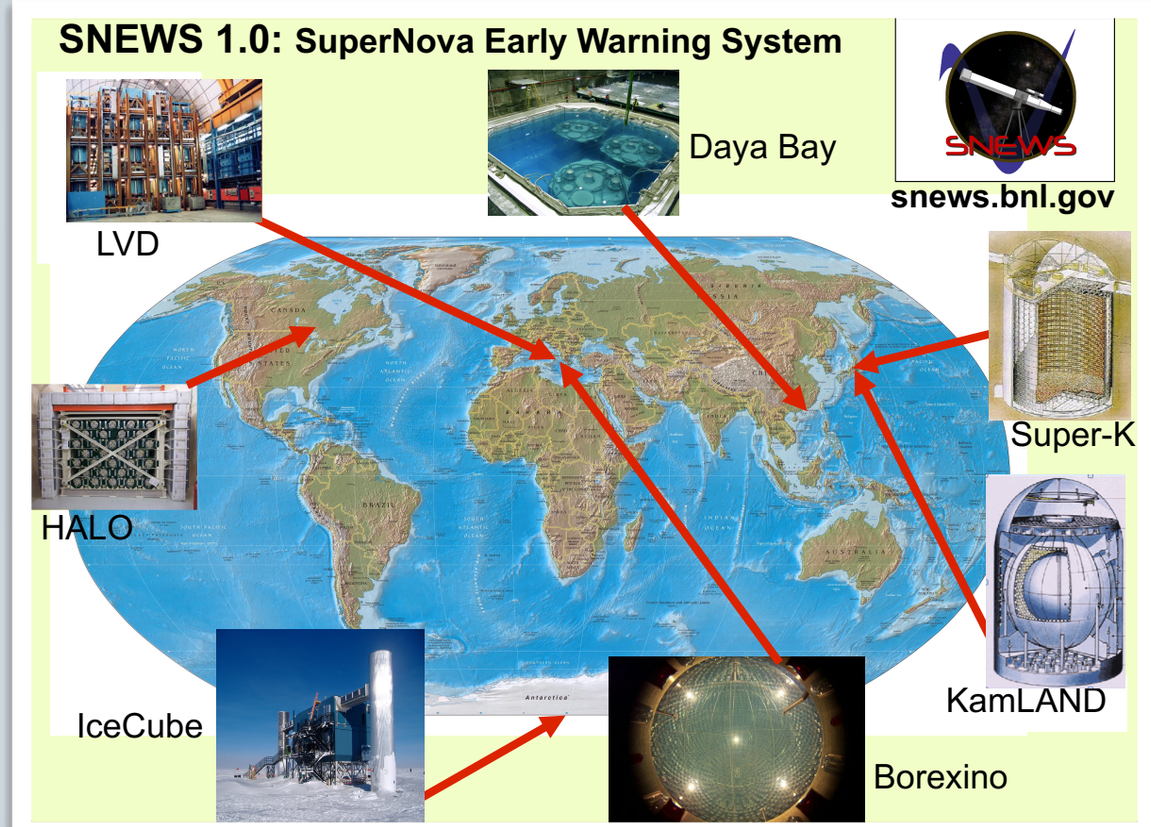
➔ Neutrino signal arrives minutes to hours before light



- A galactic SN is a once-in-a-lifetime event (expected rate: 1.63±0.46 per century [arXiv:2009.03438])

SNEWS (1.0)

- Started ~20 years ago, running in automated mode since 2005
- Today: 7 participating detectors →



Slide by Kate Scholberg

- "3 P's" of a good alert (from K. Scholberg, 2000)
  - Prompt: send alert within ~min
  - Pointing: (up to individual experiments)
  - Positive: false-alarm rate < 1 per 100 years

Developments Since SNEWS 1.0

- New generation of large detectors coming up soon (Hyper-K, JUNO, DUNE, …)

- Multimessenger Astronomy is commonplace (GW + EM, neutrinos + EM)

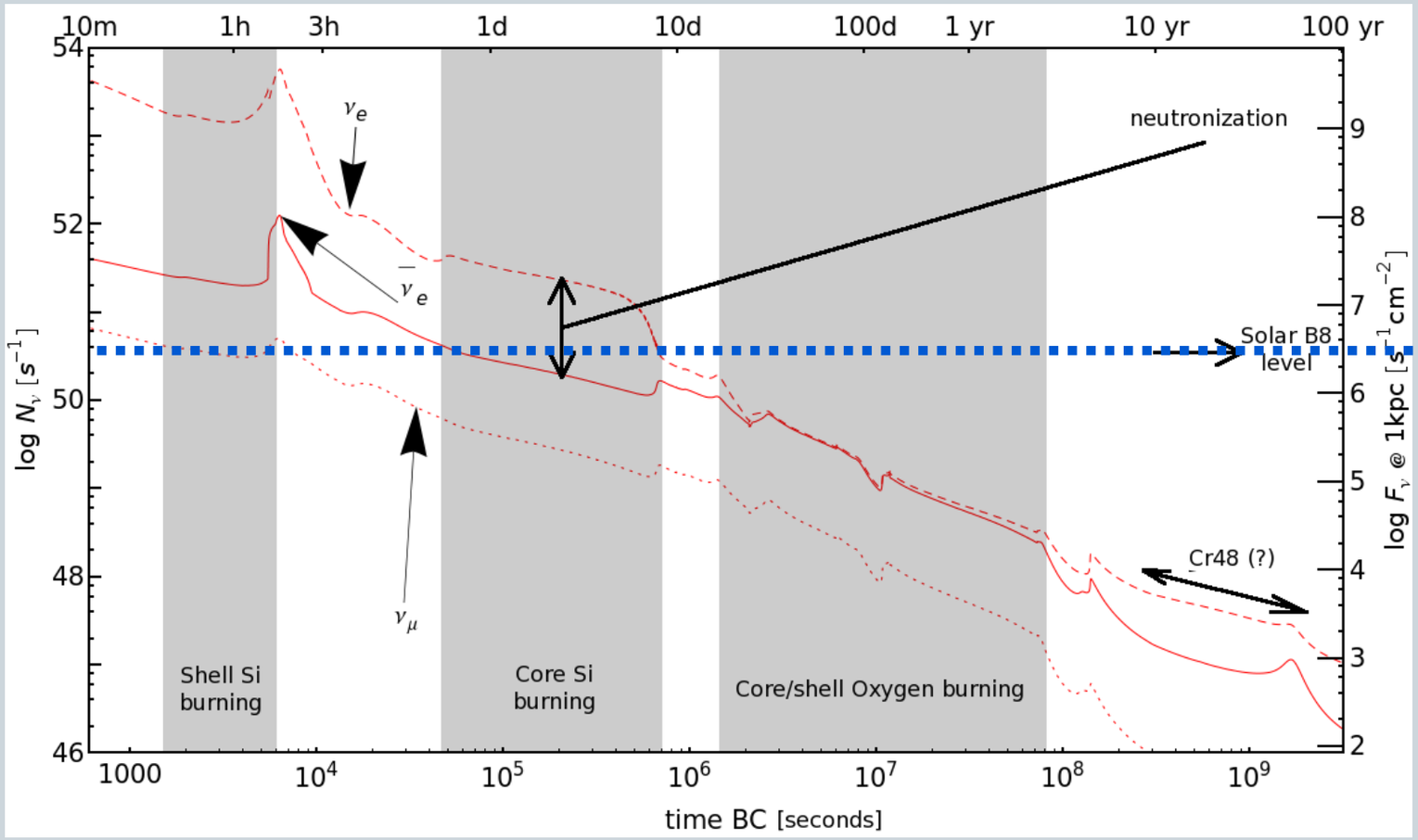
- Improved capabilities for follow-up (new telescopes, including some automated ones)

➔ SNEWS 2.0 workshop in June 2019 (https://snews2.0.snolab.ca)

- White paper published (arXiv:2011.00035)
- Improvements to all 3 P's planned

SNEWS 2.0: Prompt

- Use pre-SN neutrinos emitted during O/Si burning phase
- Low flux, only visible at <1 kpc by current experiments
- Combine significances from multiple experiments to increase range



Flux similar to solar neutrinos (but at lower energy)

Odrzywolek & Heger, Acta Phys.Polon.B 41 (2010) 1611-1628

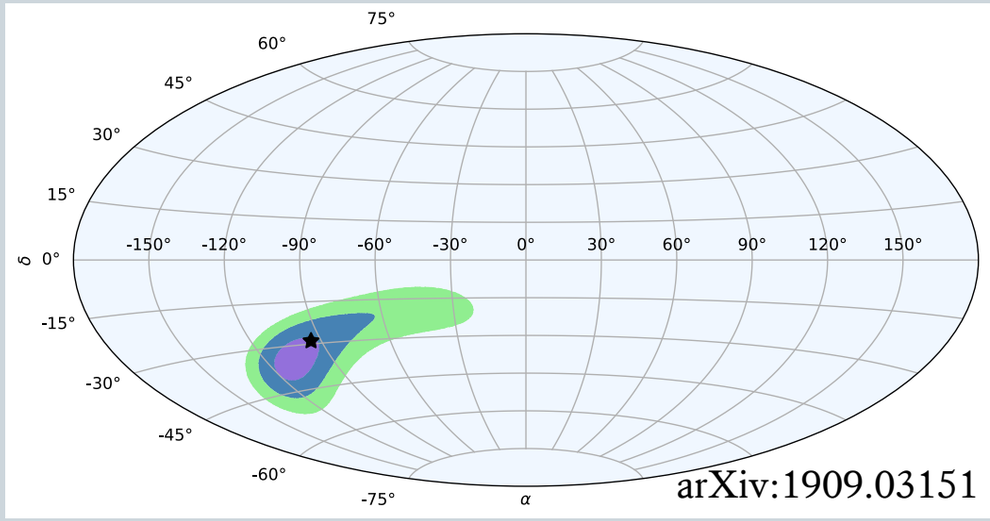
SNEWS 2.0: Pointing

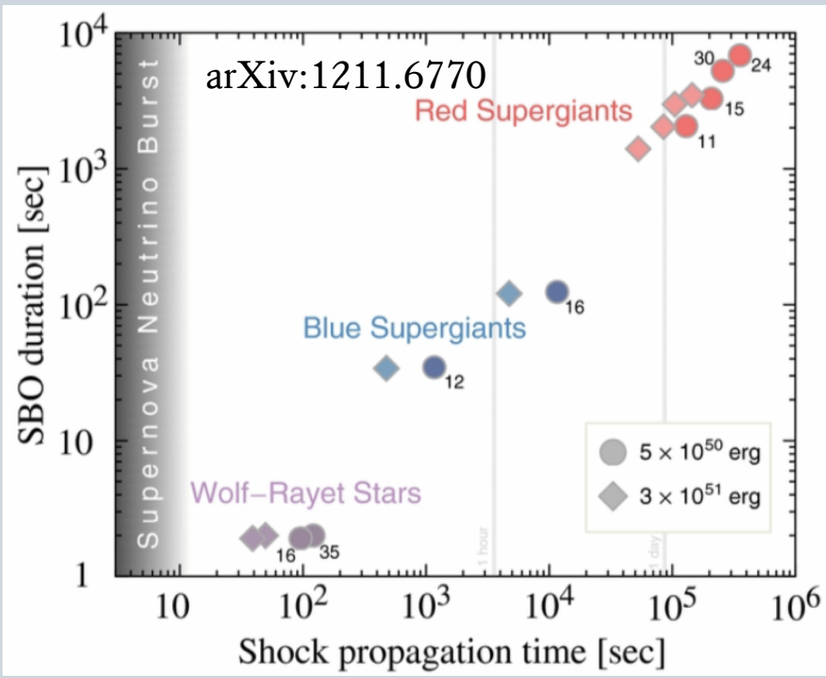
- Triangulation using arrival time at multiple detectors

- O(10°) uncertainty*, but very fast (important e.g. for WR stars)

* arXiv:2003.04864, arXiv:1909.03151, arXiv:1904.11461, arXiv:1802.02577, arXiv:1304.5006

- Experiments can send out more accurate pointing information later, as it becomes available





SNEWS 2.0: Positive

- From GW, astronomers now have experience dealing with frequent alerts & false alarms

- Can set lower thresholds (i.e. accept higher FAR) to improve detection range

- Multiple alert channels with different thresholds?

Conclusions

- Neutrino astronomy opens a new window onto the universe that's complementary to the EM spectrum
- Hyper-Kamiokande is a next-gen neutrino detector
  - Will observe 10^5–10^6 neutrinos from the next galactic SN
  - Model discrimination possible out to ~100 kpc
- Supernova Early Warning System (SNEWS)
  - SNEWS 2.0: alert astronomers more promptly, with fast pointing, maybe not-quite-as-positive