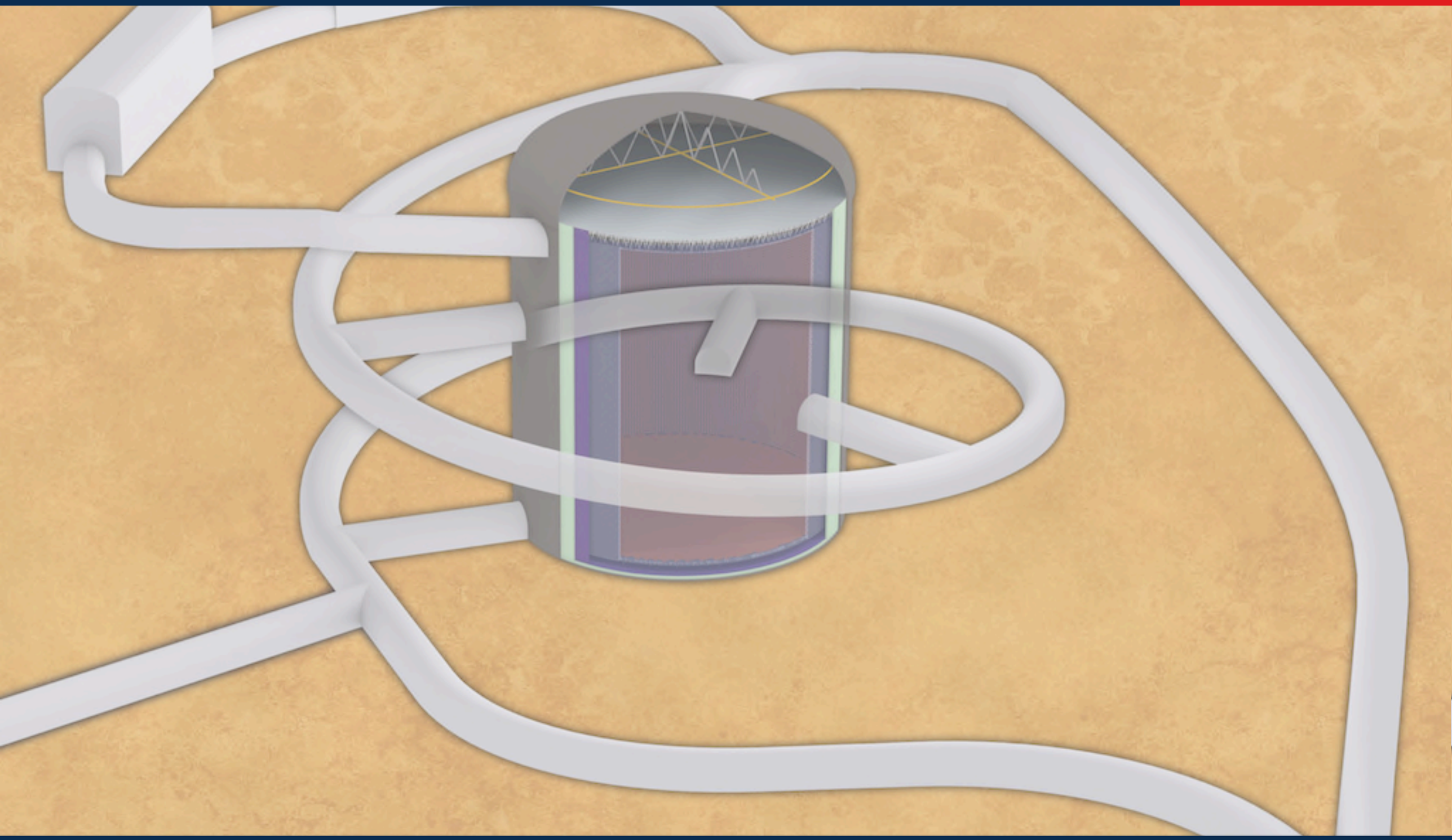
Hyper-Kamiokande

Dr. Jost Migenda (they/them)

KING'S College LONDON



Agenda

Things are easy when you're big in Japan.

—Alphaville

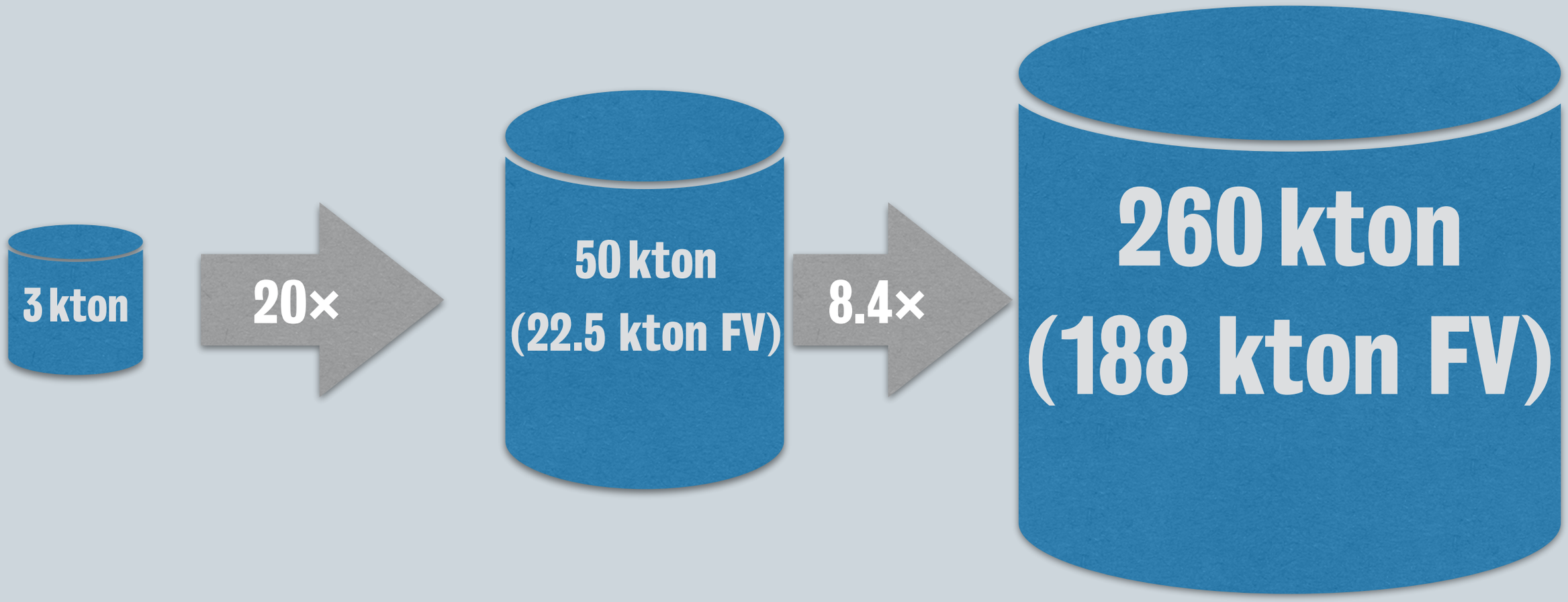
- Overview & Status
- Proton Decay
- Neutrino Oscillations
- Neutrino Astronomy

History Doesn't Repeat Itself ... but it rhymes

Kamiokande
1983–1996

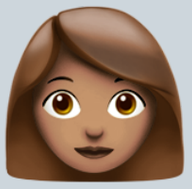
Super-Kamiokande
1996–today *(and beyond)*

Hyper-Kamiokande
~2027–???

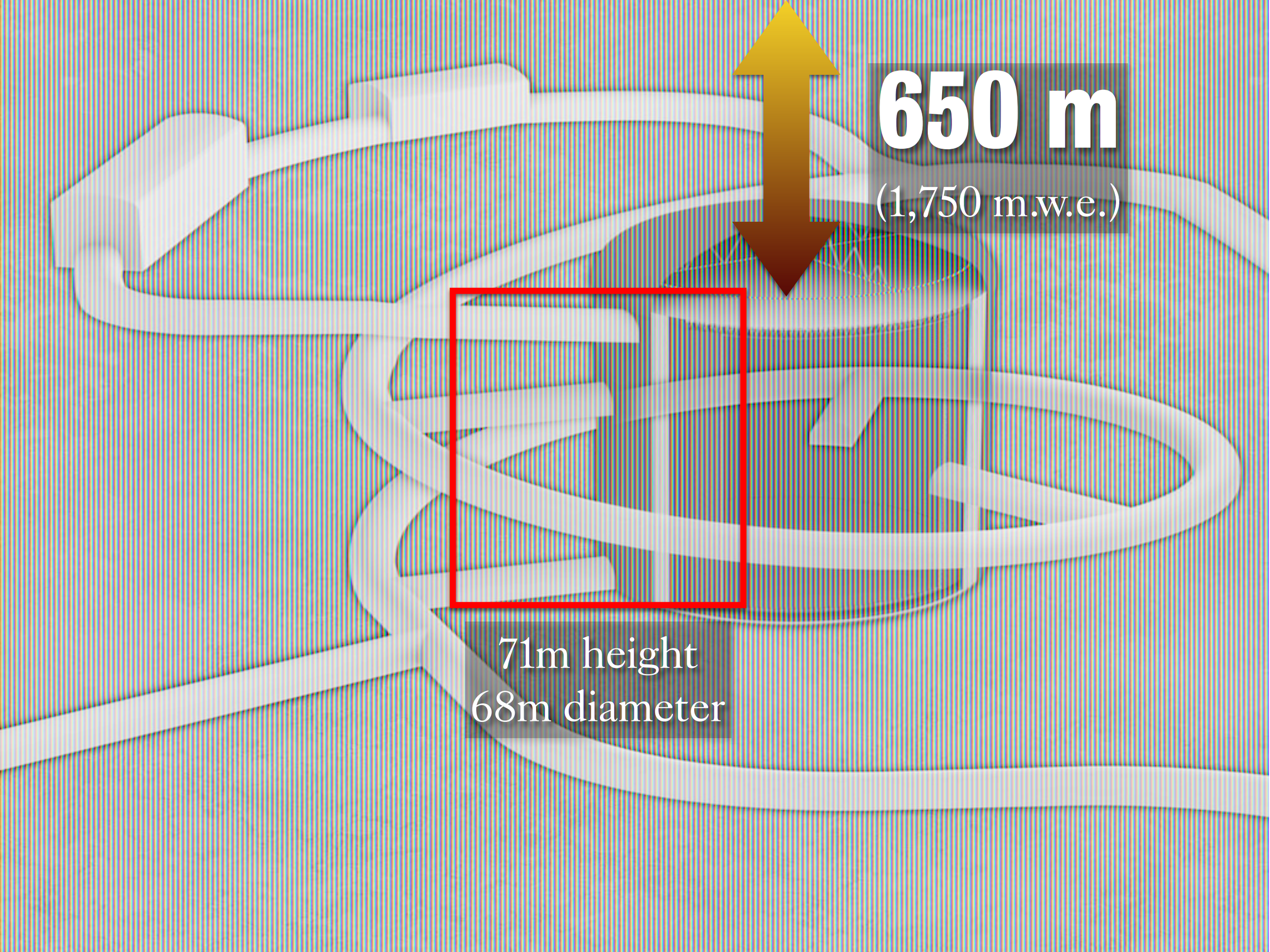


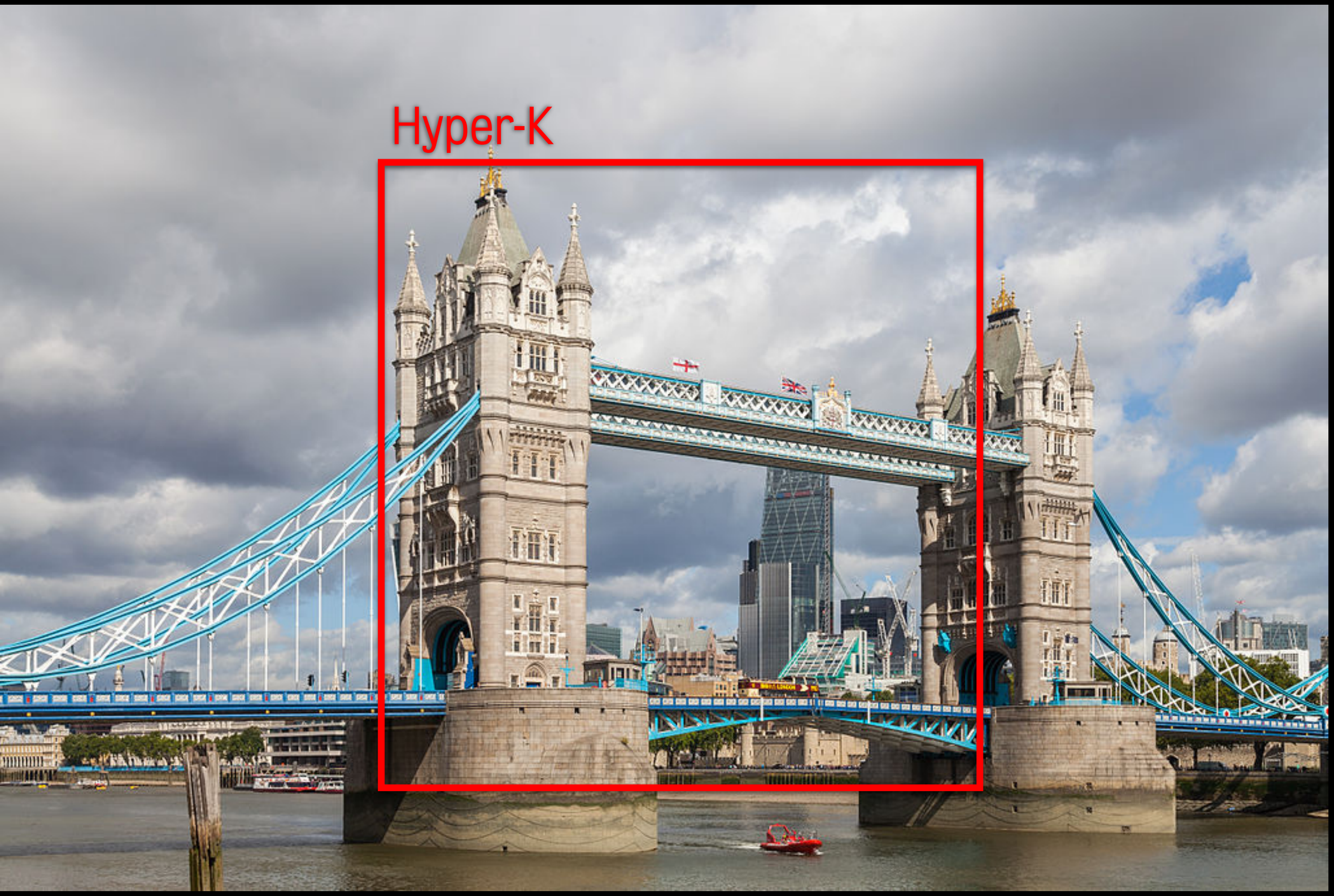

Koshiba, 2002


Kajita, 2015

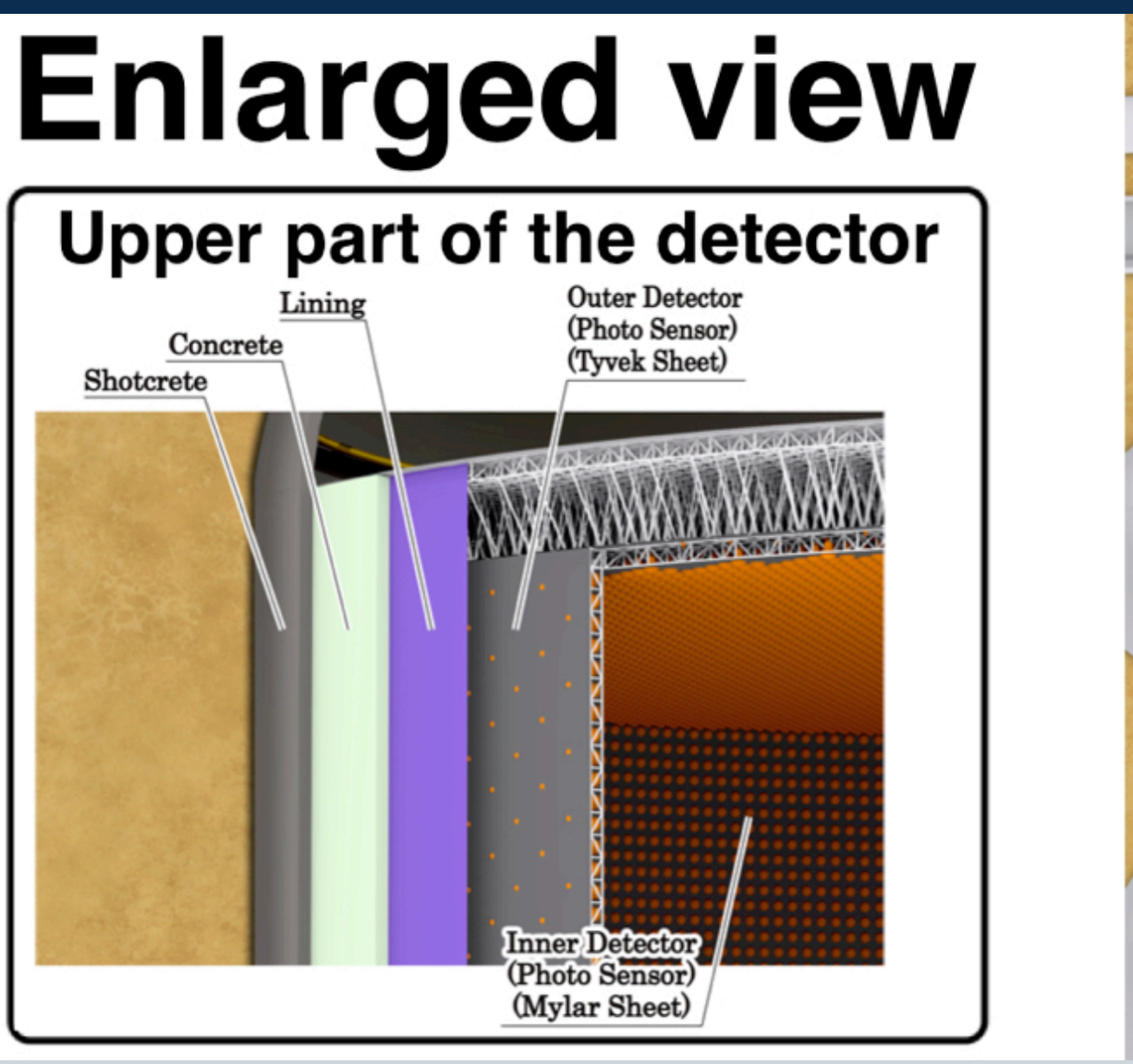



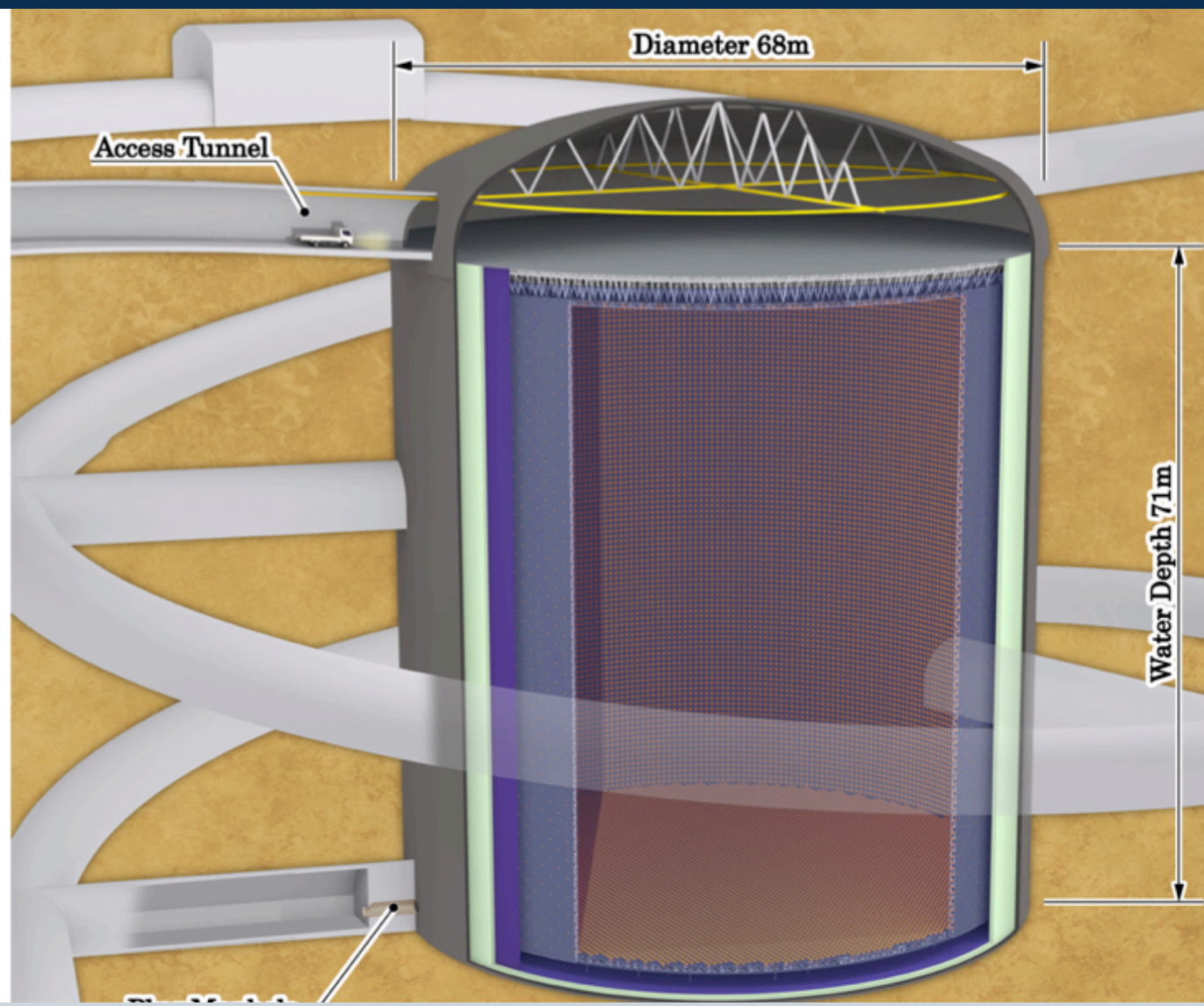
To be determined ...


650 m
(1,750 m.w.e.)
71m height
68m diameter



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:

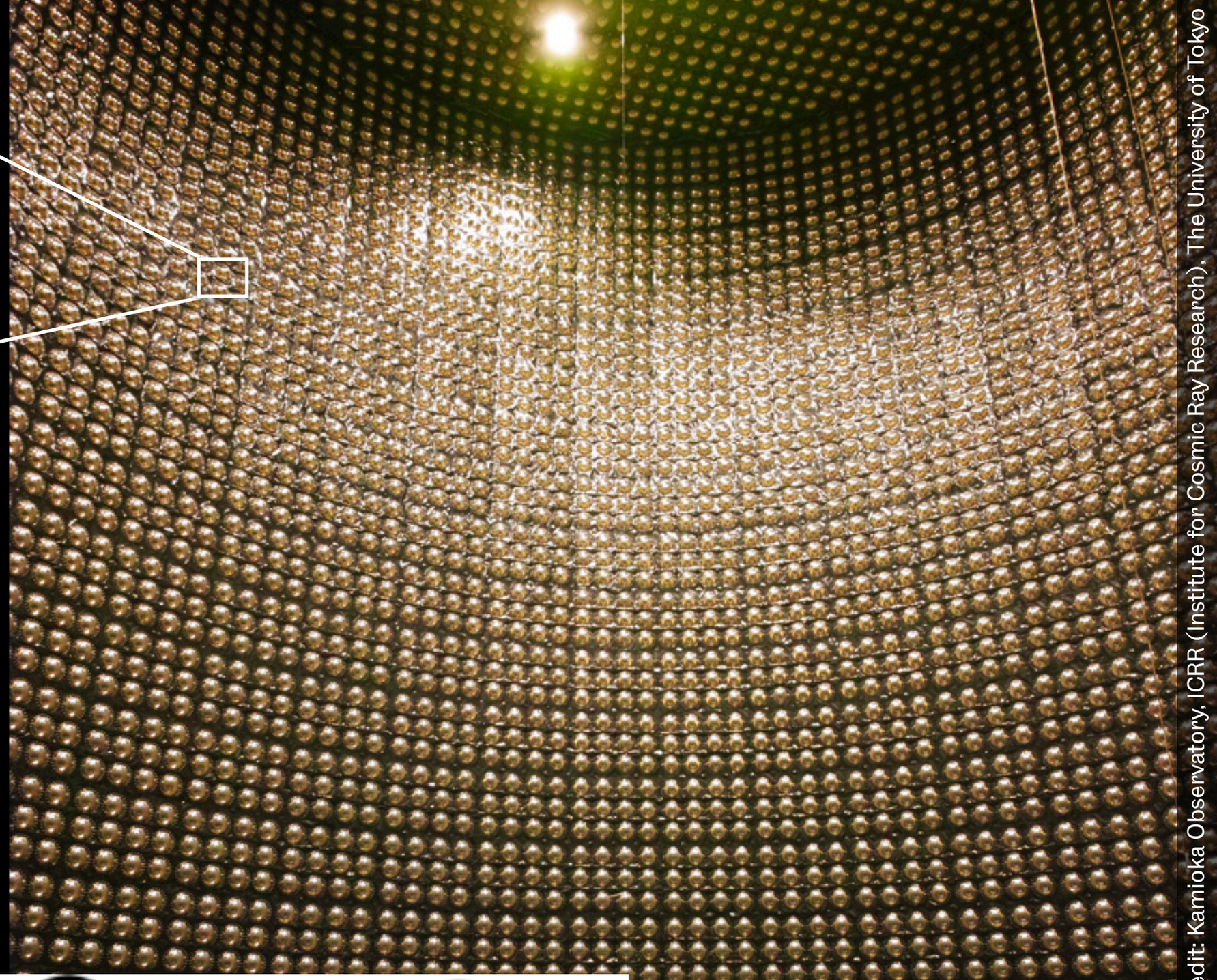
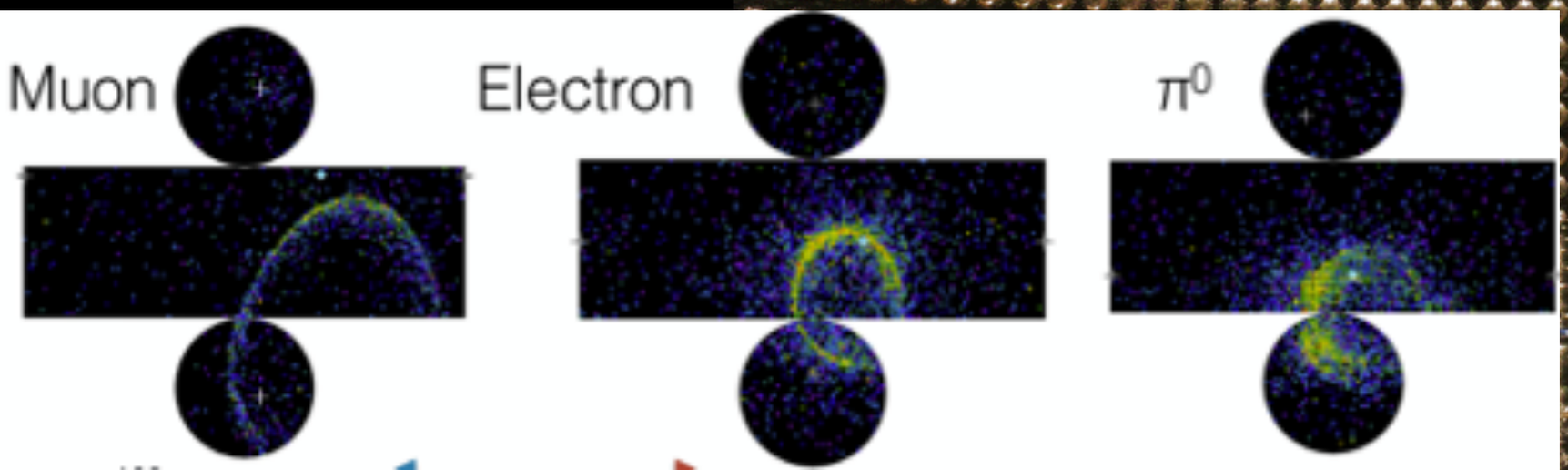
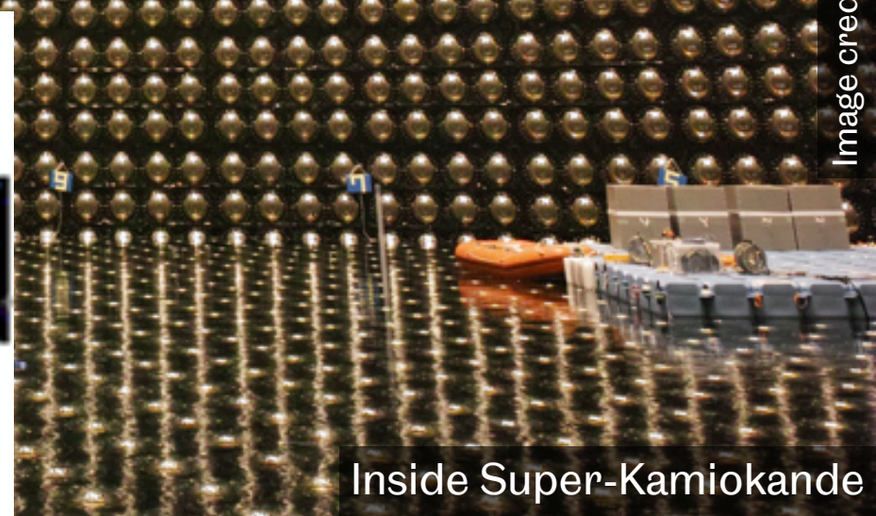


Image credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

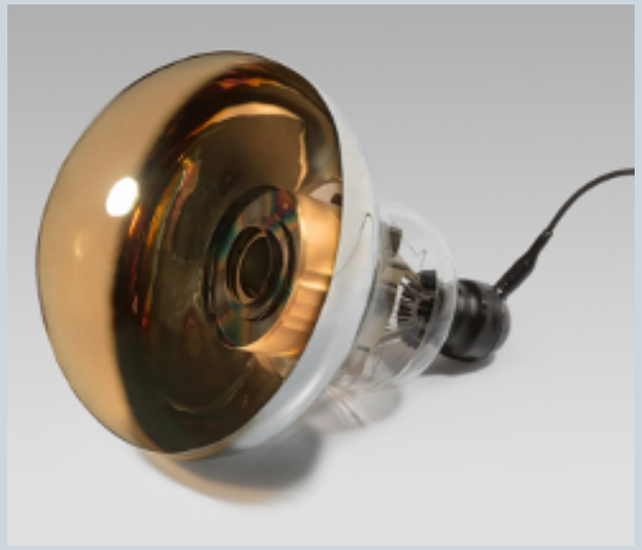




Inside Super-Kamiokande

Photosensors

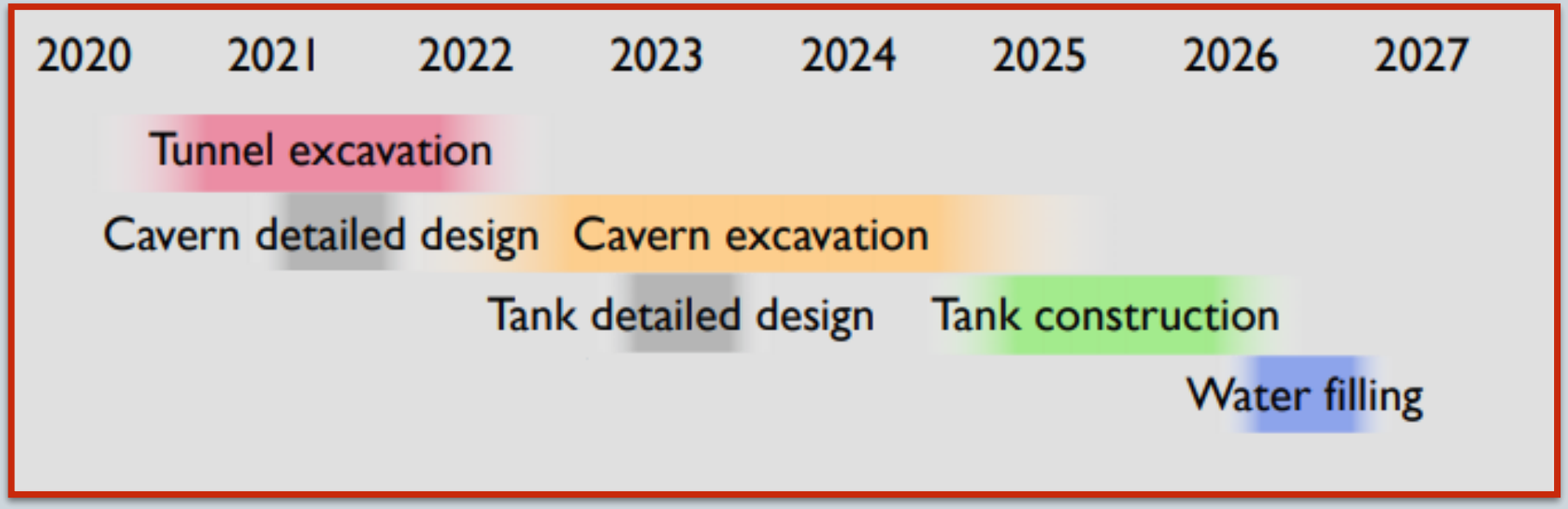
- 50 cm PMTs with box-and-line dynode
  - Compared to SK PMTs: 2× timing resolution & 2× photon detection efficiency at same dark rate
  - More pressure-resistant
  - At least 20% photocoverage for ID (0.5× SK)
  - Mass production started in December 2020



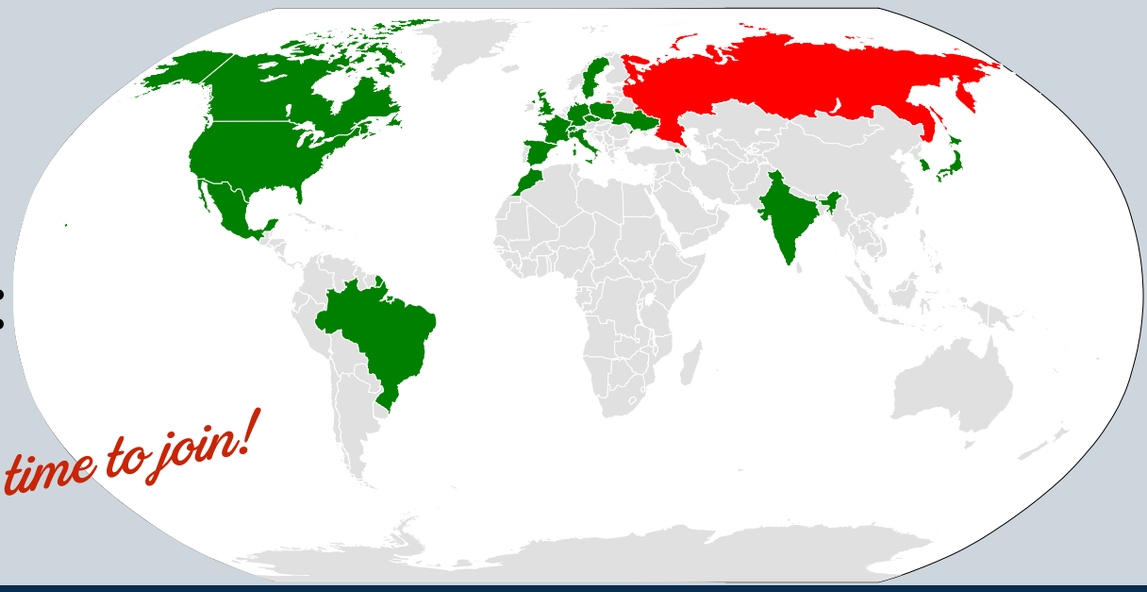
→ *similar energy threshold as in SK*

- Multi-PMT (mPMT) modules
  - 19× 8 cm PMTs in hemispherical pressure vessel
  - Directional information, improved timing & spatial resolution
  - Plan to add ~1000 mPMTs to ID

Current Status

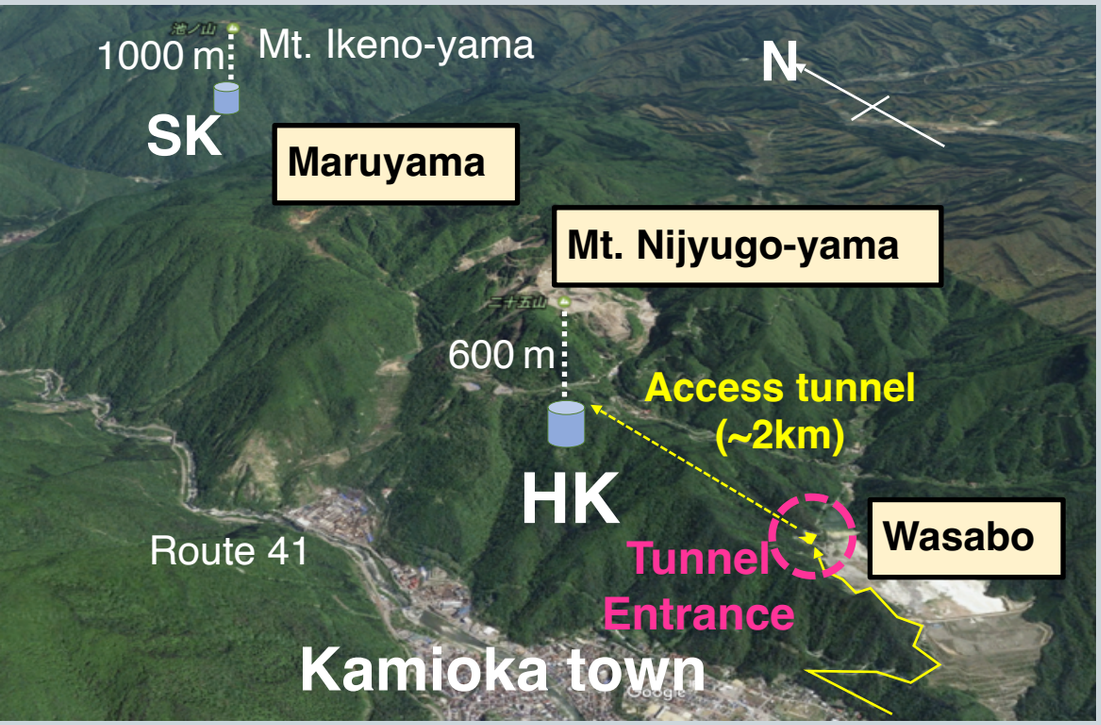


- Funding approved by Japanese government in 2020
- Excavation ongoing, reached centre of dome on June 23rd
- Detector R&D still ongoing
- 500+ members from 20 countries:

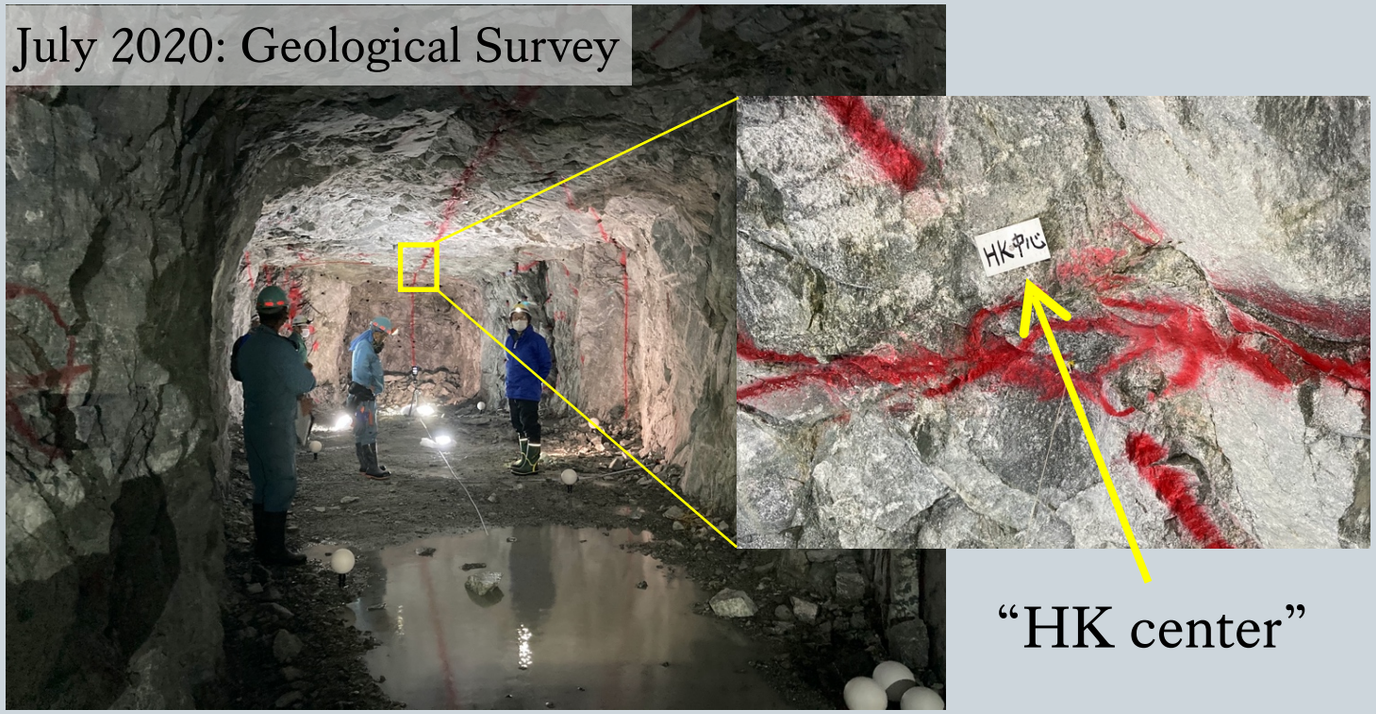


Now is a great time to join!

Construction Progress

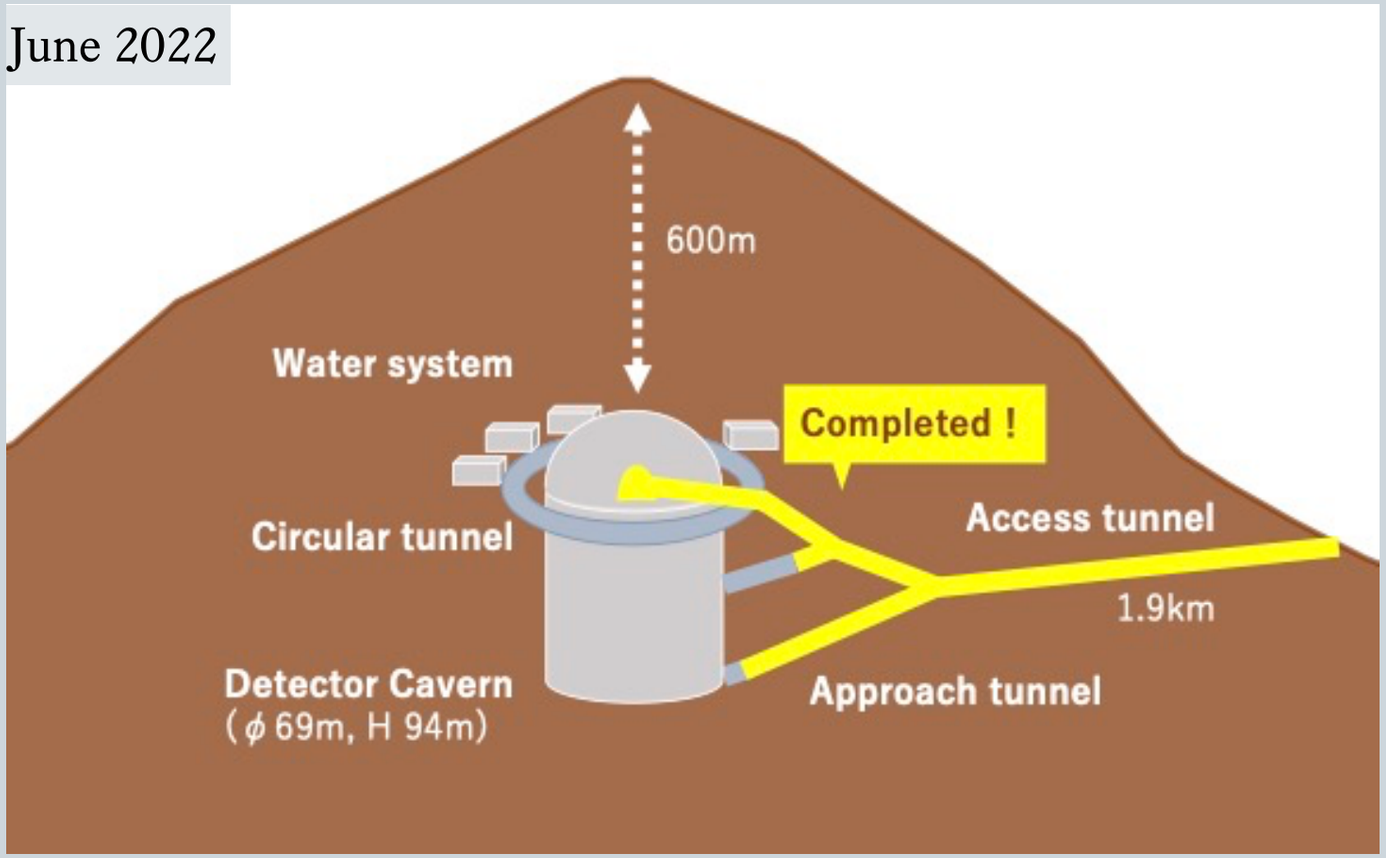


July 2020: Geological Survey



May 2021: Excavation of access tunnels started

June 2022



New Research Building at Kamioka

- New research building now completed
- It has 4 floors and 3,050 m² total floor area

Dormitory rooms

Dining rooms

Many visiting researchers' rooms on 2nd and 3rd floor

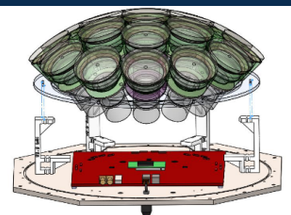
Lab rooms to construct detector components

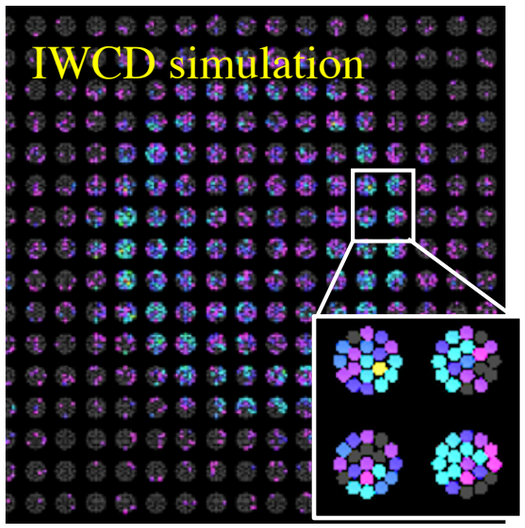
Big hall to accommodate about 150 people on the 1st floor.

Image of new research building

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

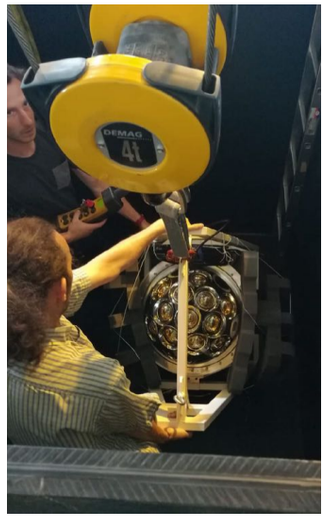




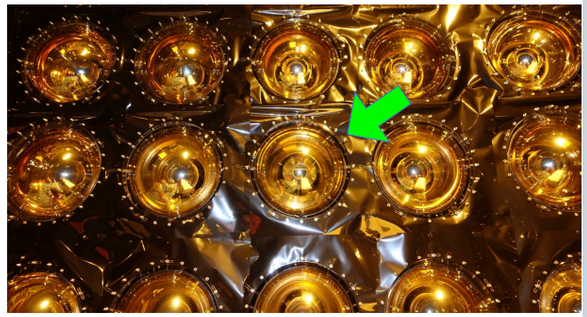
Prototype at TRIUMF

Electronics at INFN

20-inch MCP PMT:
Test in dark room

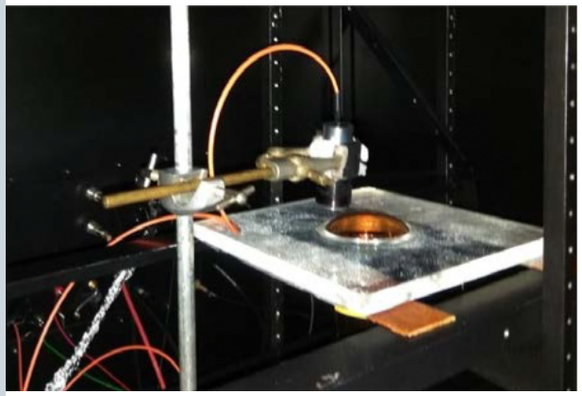


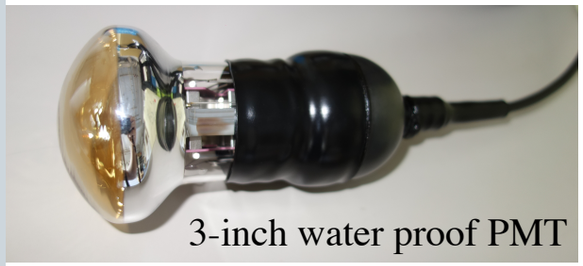
mPMT in Memphyno water tank in France



Box&Line PMT in Super-K

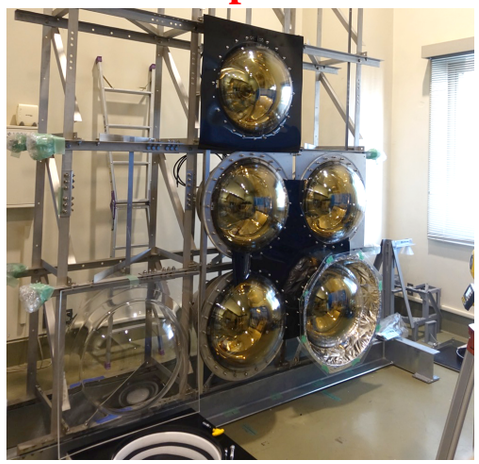
Outer detector:
PMT + WLS plate (UK)



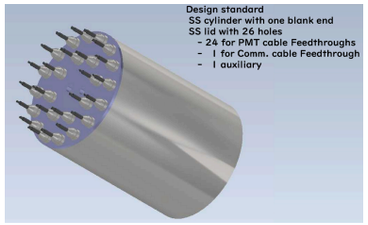


3-inch water proof PMT

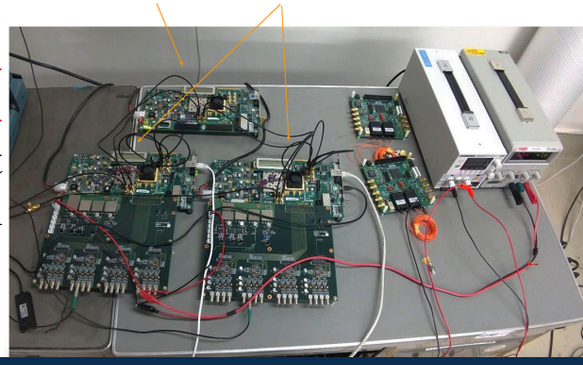
ID mockup at ICRR



Underwater electronics:
Case design and feedthrough



Sync and clock system
test bench at TokyoTech



PMT cover
in Spain

From slides by M. Ishitsuka (Neutrino 2020)

Agenda

I shall decay when the proton returns.

—Sheldon Lee Glashow

- Overview & Status
- Proton Decay
- Neutrino Oscillations
- Neutrino Astronomy

Proton Decay

- Proton is stable in SM
- PDK has been a generic prediction of Grand Unified Theories since these were proposed in the 70s ➔ access to GUT scale!
  - Kamioka Nucleon Decay Experiment

Theoretically preferred

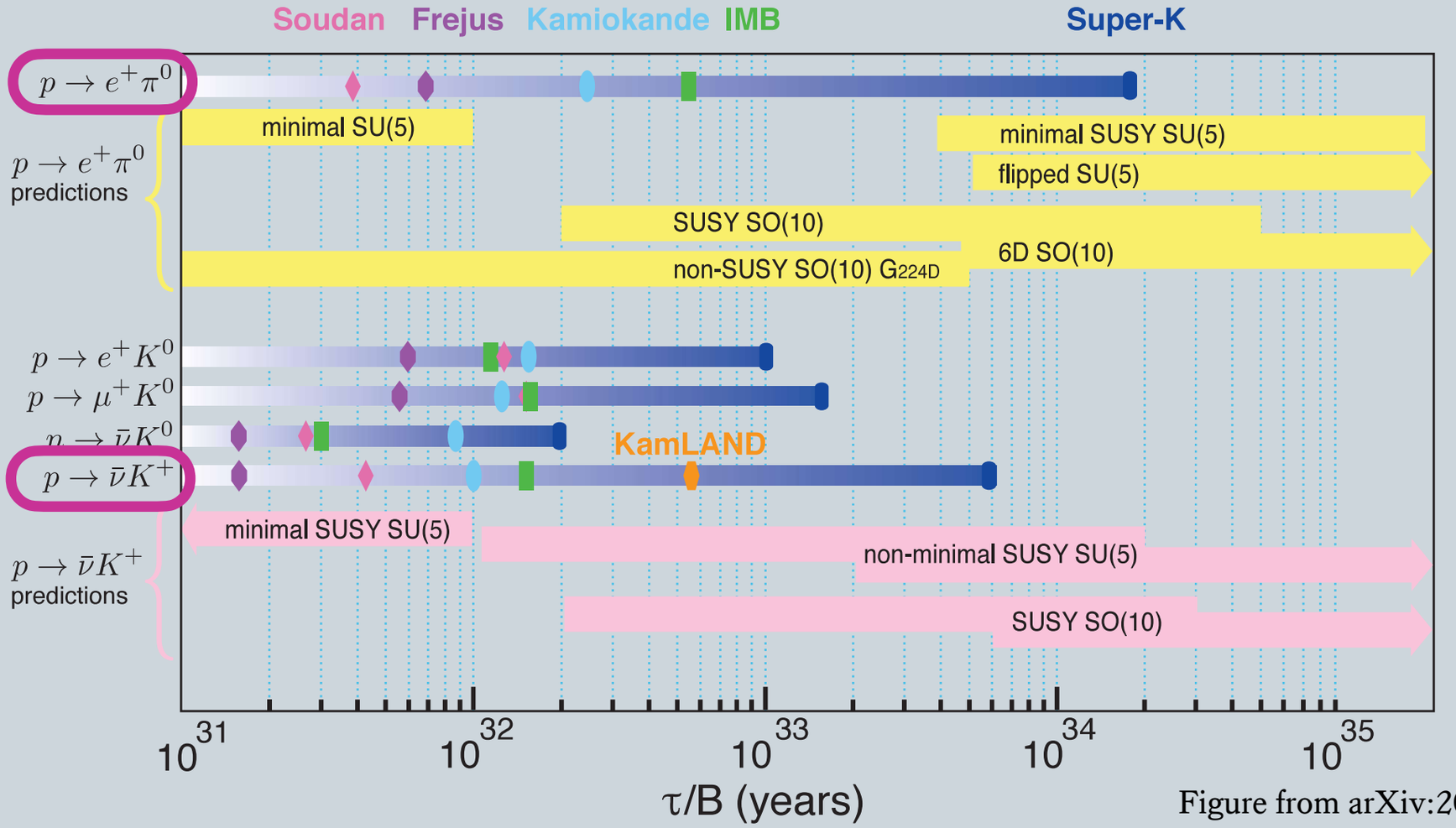
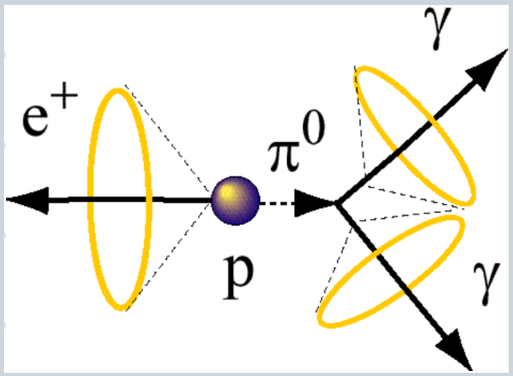
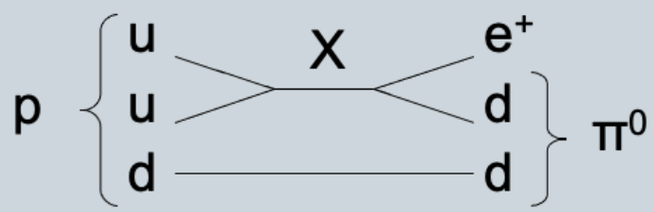


Figure from arXiv:2002.03005

Proton Decay Sensitivity



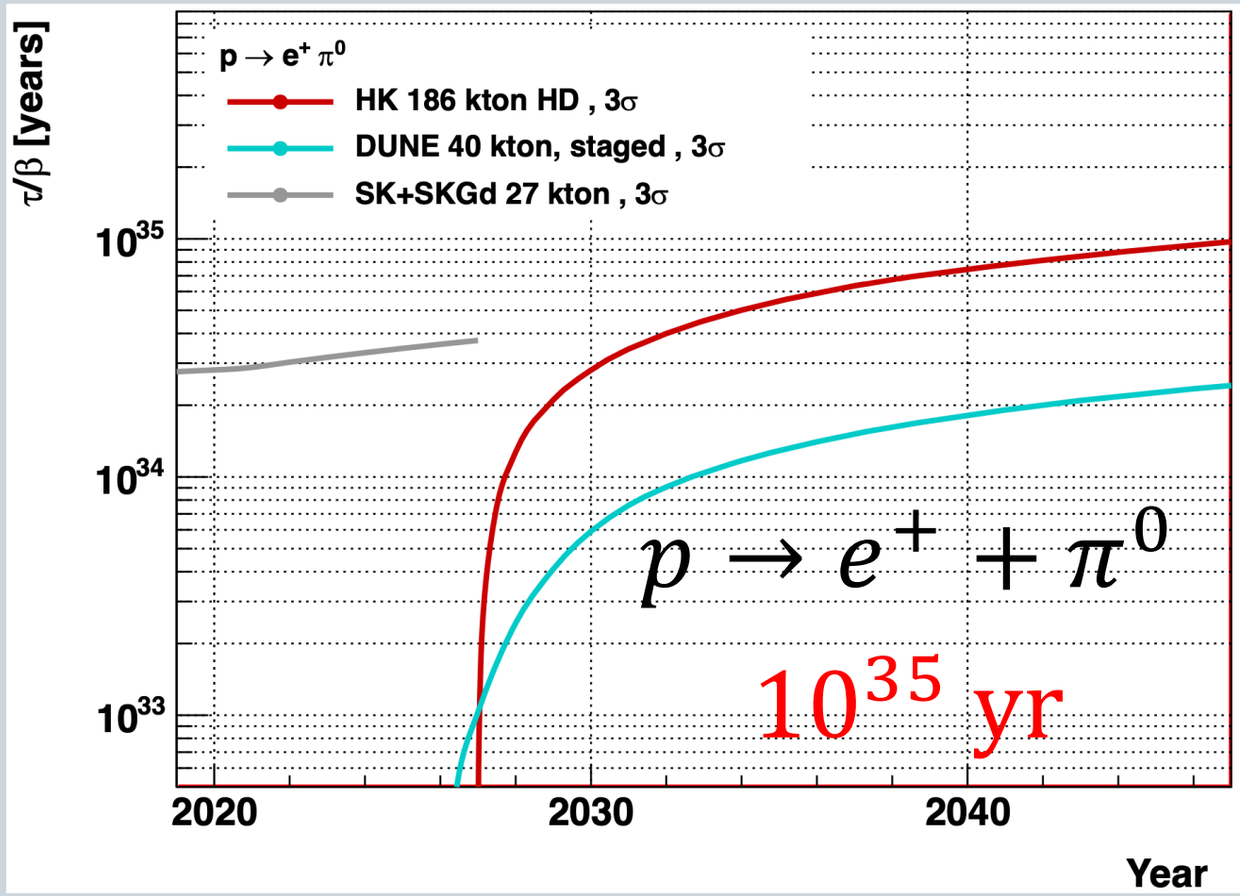


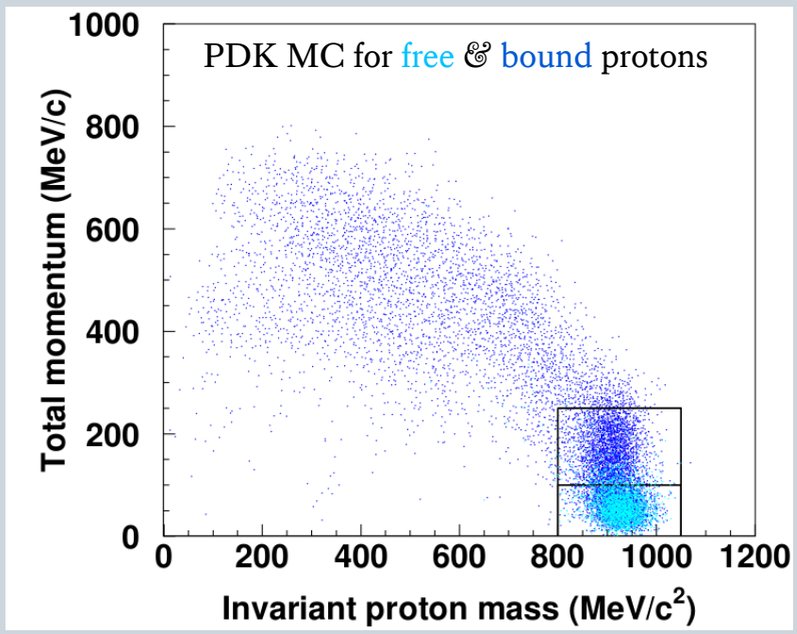
- Most sensitive channel for SK, HK:
  p ➔ $e^+ + \pi^0$

- Experimentally very clean:
  - Three rings for the Elven kings under the sky ...
  - $E_{total} = m_p$
  - Low p_{total}

- Reach >10^{35} years after 20 years of data taking

3σ discovery potential





Proton Decay Sensitivity

- Alternative channel:
  $p \rightarrow \bar{\nu} + K^+$

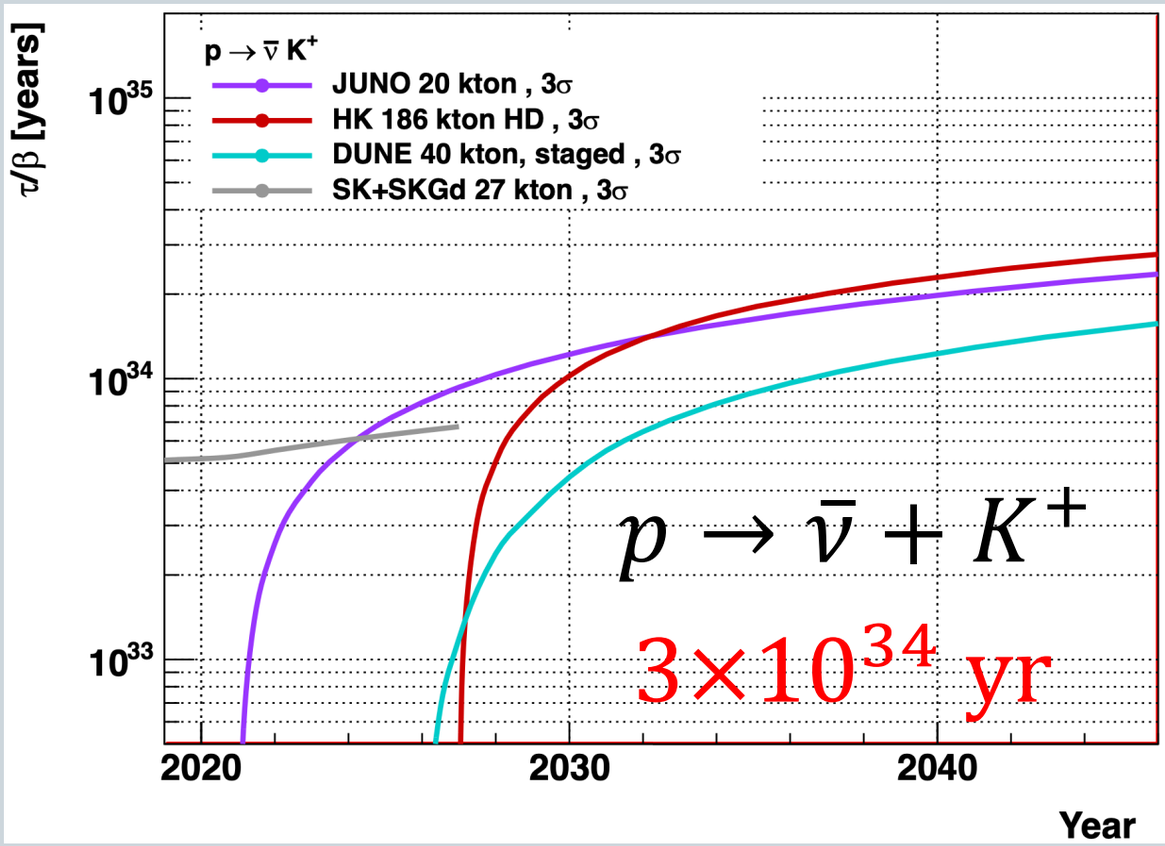
- But: Kaon is below the Cherenkov threshold ➔ HK can only observe decay products

  - $K^+ \rightarrow \mu^+ + \nu_\mu$ (64%)
    significant backgrounds

  - $K^+ \rightarrow \pi^+ + \pi^0$ (21%)
    π^+ barely above Cherenkov threshold

- Reach 3×10^{34} years after 20 years of data taking

3σ discovery potential



Agenda

Turn and face the strange
Ch-ch-changes!

—David Bowie

- Overview & Status
- Proton Decay
- Neutrino Oscillations
- Neutrino Astronomy

What are Neutrino Oscillations?

Flavour eigenstates interact

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates propagate

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric & accelerator

Reactor & accelerator

Reactor & solar

Mixing angles ⇔ Amplitude

$\theta_{23} \approx 45^\circ$

$\theta_{13} \approx 8^\circ$

$\delta_{\mathrm{CP}} = ???$

$\theta_{12} \approx 34^\circ$

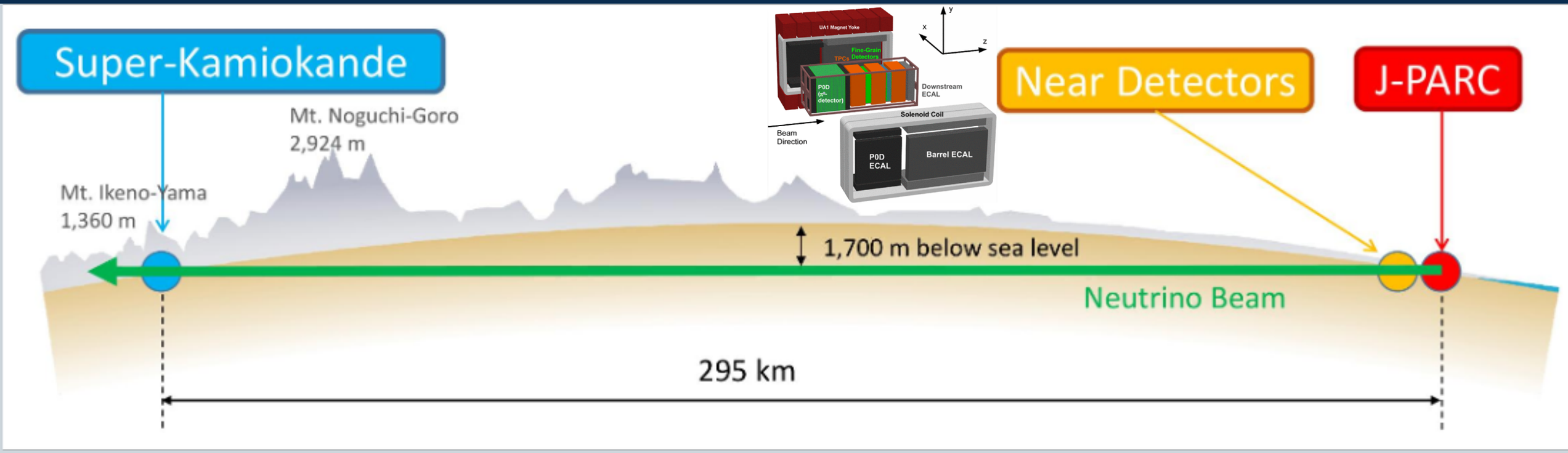
Mass differences ⇔ Length scale

$\left|\Delta m^2_{32}\right| \approx 2.5 \times 10^{-3}\mathrm{eV}^2$

$\left|\Delta m^2_{31}\right| \approx 2.5 \times 10^{-3}\mathrm{eV}^2$

$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\mathrm{eV}^2$

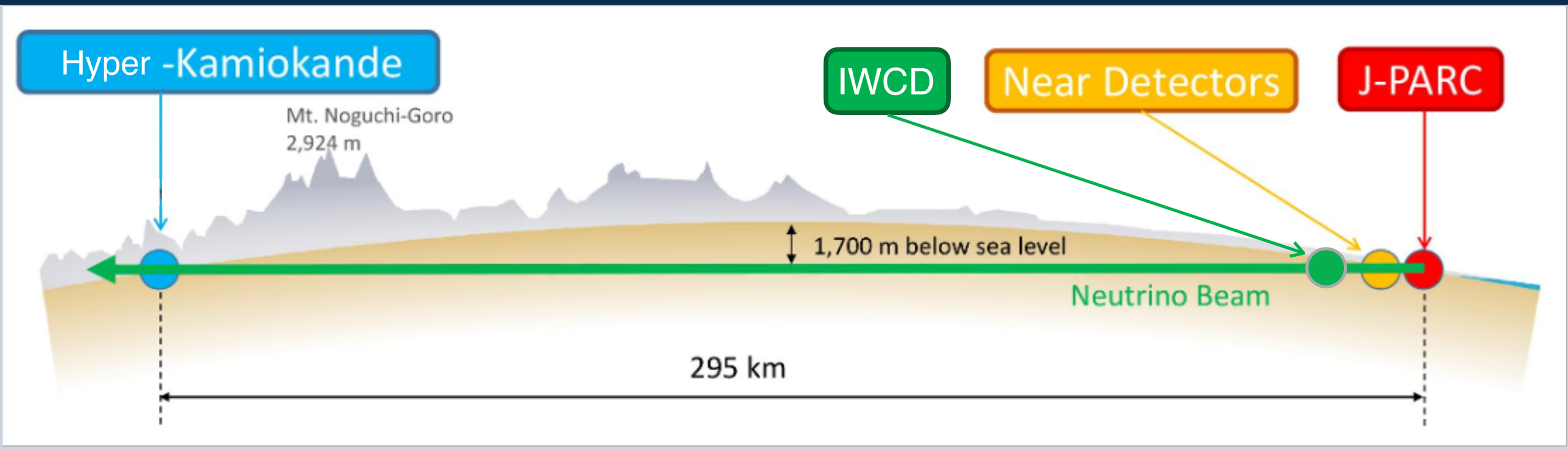
The T2K Experiment



- Send ν_μ ($\bar{\nu}_\mu$) beam from J-PARC (Tokai) to Kamioka
- In SK, look for ν_μ disappearance & ν_e appearance

➔ Could fill *another* seminar talk with details!

Long-Baseline Physics with HK



- Increased beam power (500 kW ➔ 700 kW ➔ 1.3 MW)

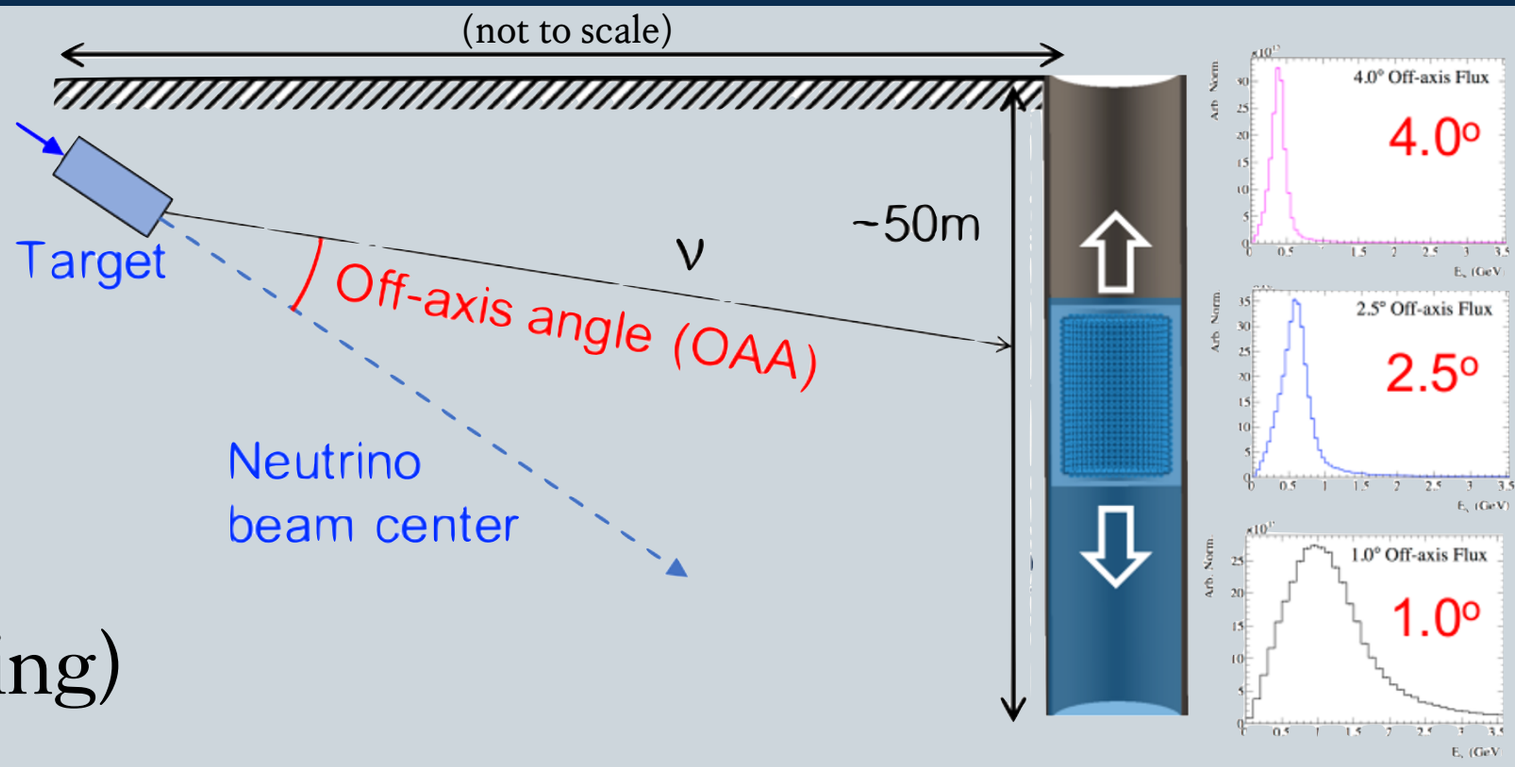
arXiv:2004.06877

- ND upgrades ongoing for next T2K runs
- Add a new Intermediate Water Cherenkov Detector
- Larger far detector

Intermediate Water Cherenkov Detector

- Distance: ~1 km
  from the beam target

- Water target, like HK
  (plus Gd for neutron tagging)

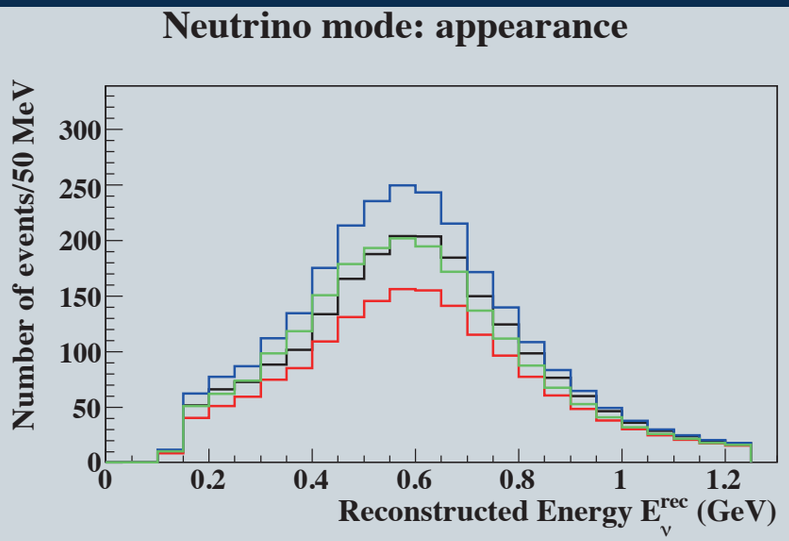


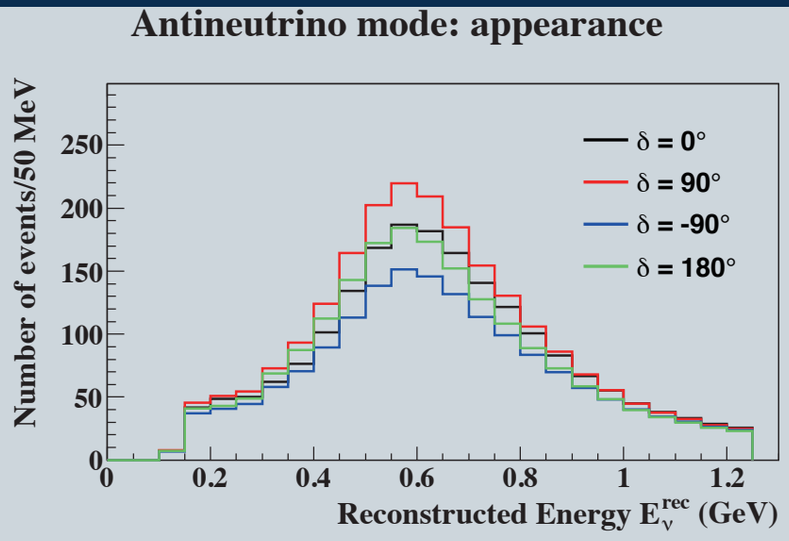
- Detector can move up/down to measure flux at different off-axis-angles ➔ different energy spectra!

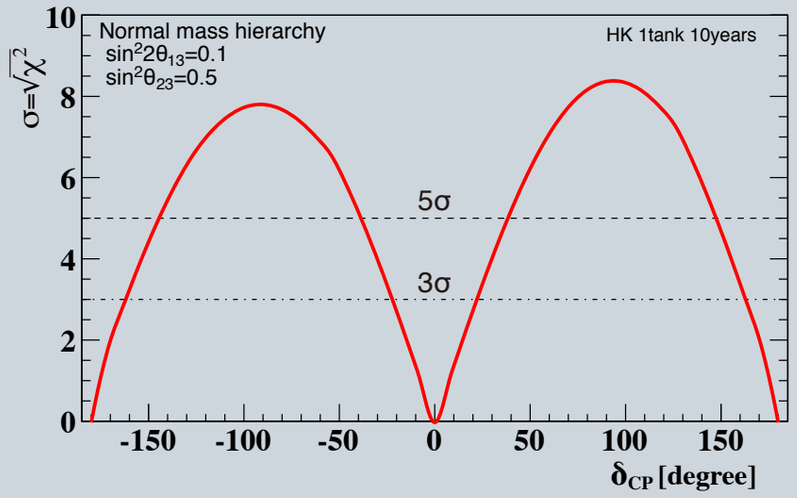
- Use multi-PMT modules for better timing/spatial resolution

- Goal: Constrain flux & neutrino cross-sections to reduce systematic uncertainty!

Oscillation Results



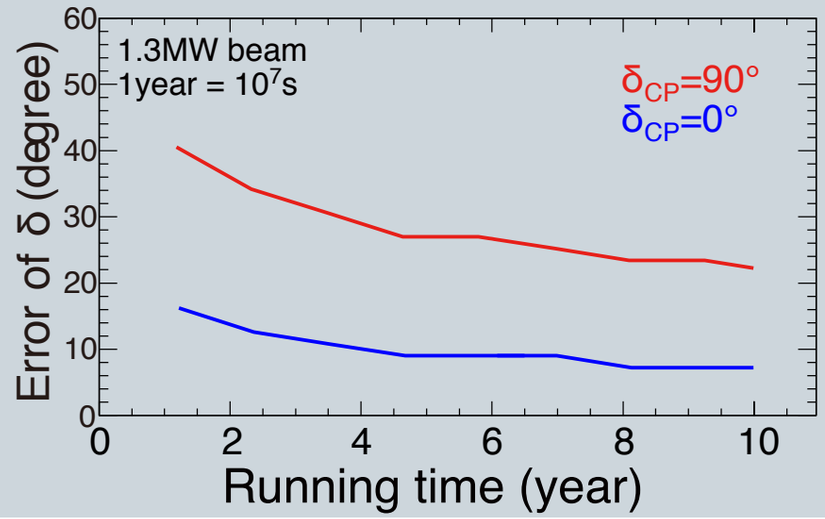


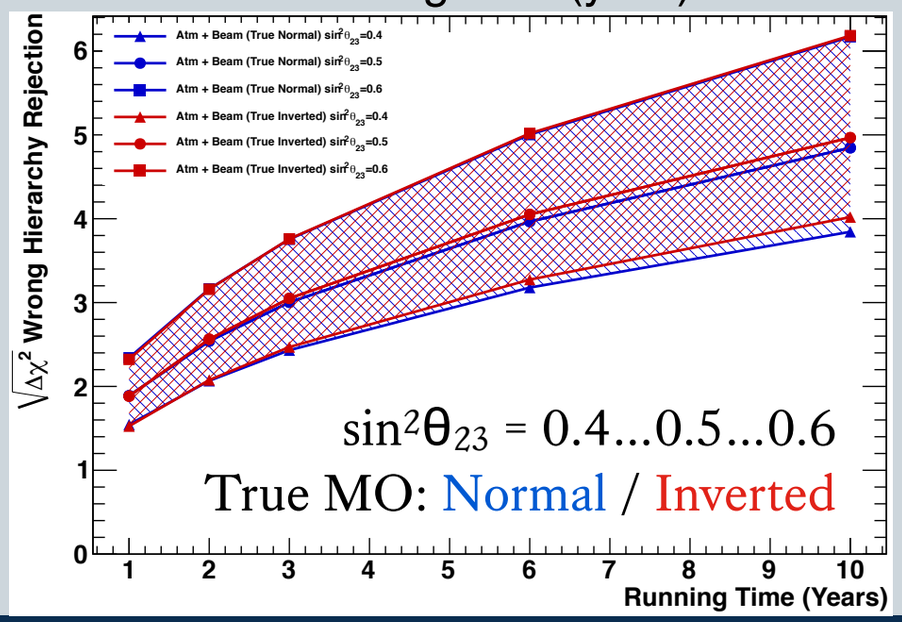


- Fit to measured spectra of all data sets (appearance/disappearance, ν_μ / $\bar{\nu}_\mu$) to determine oscillation parameters

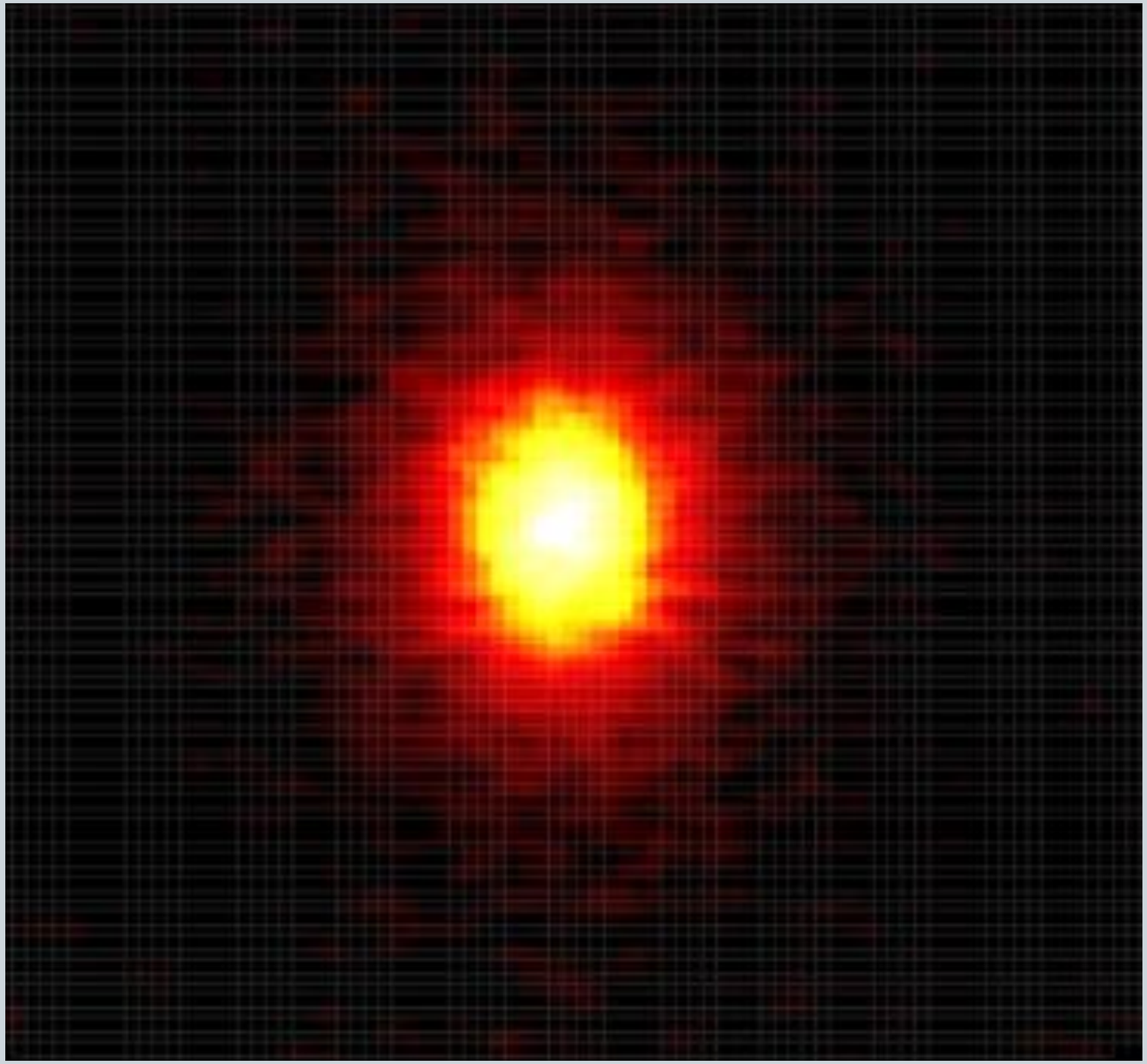
- Atmospheric neutrinos help determine mass ordering, clear up degeneracies

- Essential to reduce systematic error!





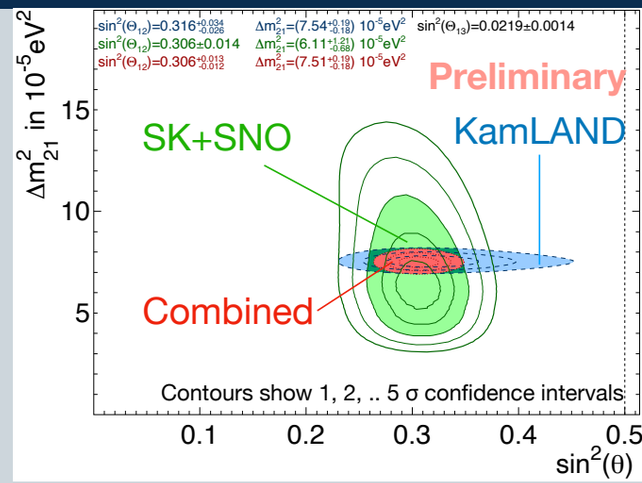
Oscillation of Solar Neutrinos



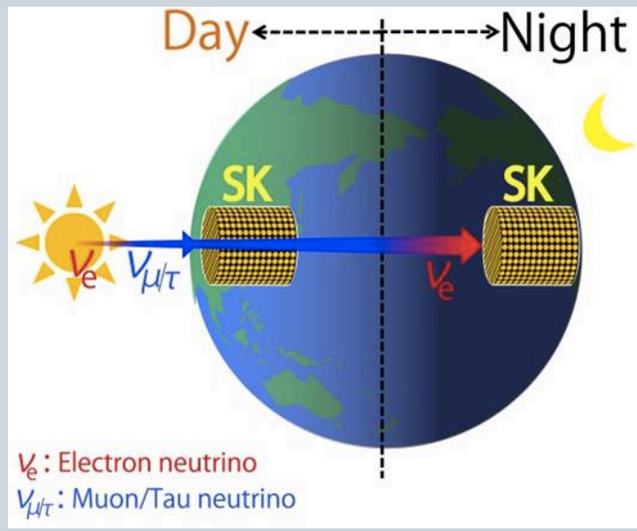
Y. Nakano (Super-Kamiokande collaboration)
https://indico.cern.ch/event/606690/contributions/2591501/

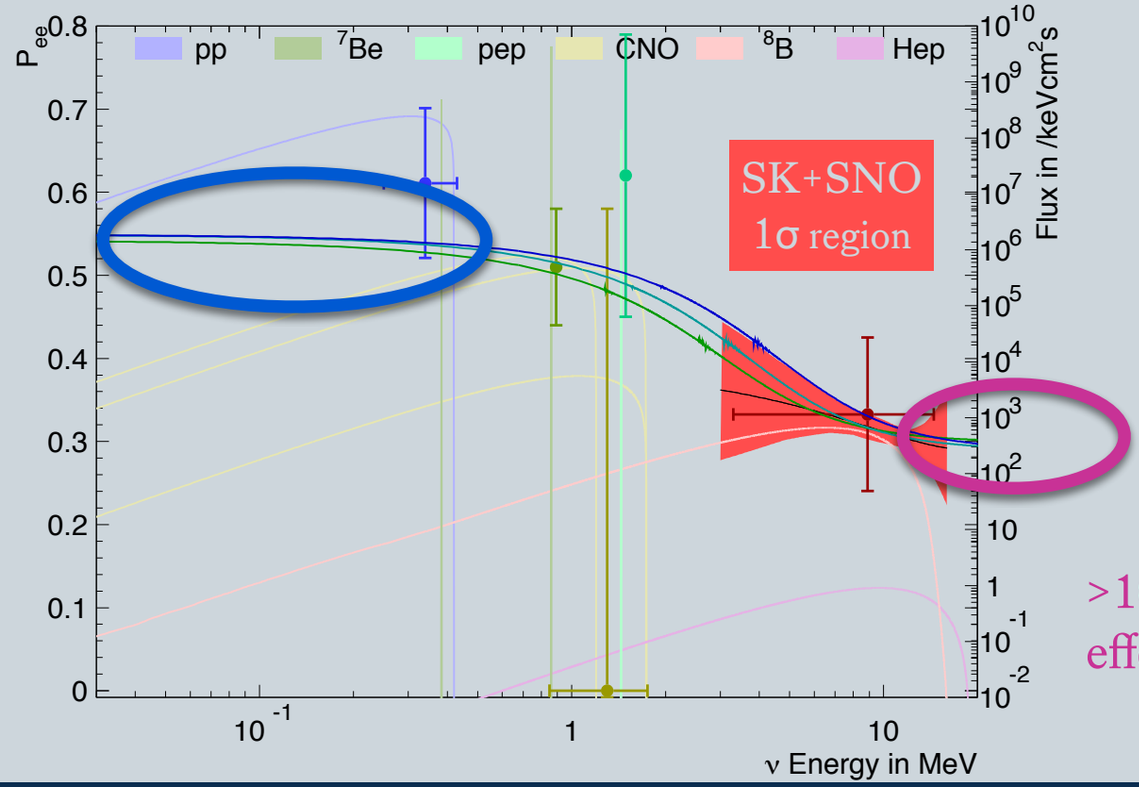
Oscillation of Solar Neutrinos

- Mainly sensitive to θ_{12} and Δm^2_{21}
- Slight difference between solar (neutrino) and reactor (antineutrino) measurements of Δm^2_{21} ➔ HK's high statistics will reduce uncertainty
- Measure day/night asymmetry of solar neutrinos
- Look for spectral upturn between matter effect & vacuum oscillation



SK preliminary, Neutrino 2020





<1 MeV:
vacuum oscillation

>10 MeV: MSW matter effect while exiting Sun

Current SK measurement:

$$\frac{\Phi_{\text{day}} - \Phi_{\text{night}}}{0.5\left(\Phi_{\text{day}} + \Phi_{\text{night}}\right)} = (-2.1 \pm 1.1)\,\%$$

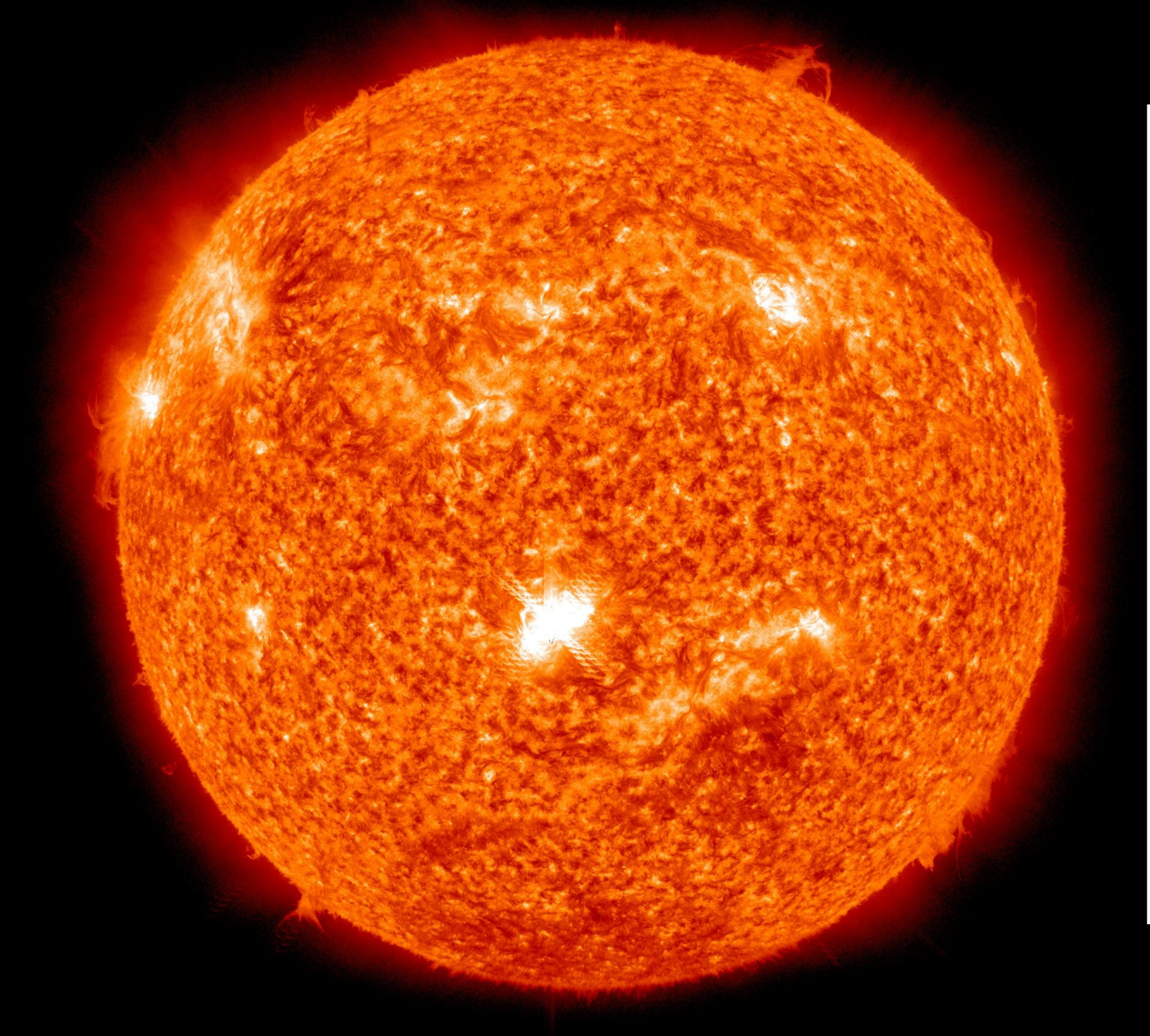
Agenda

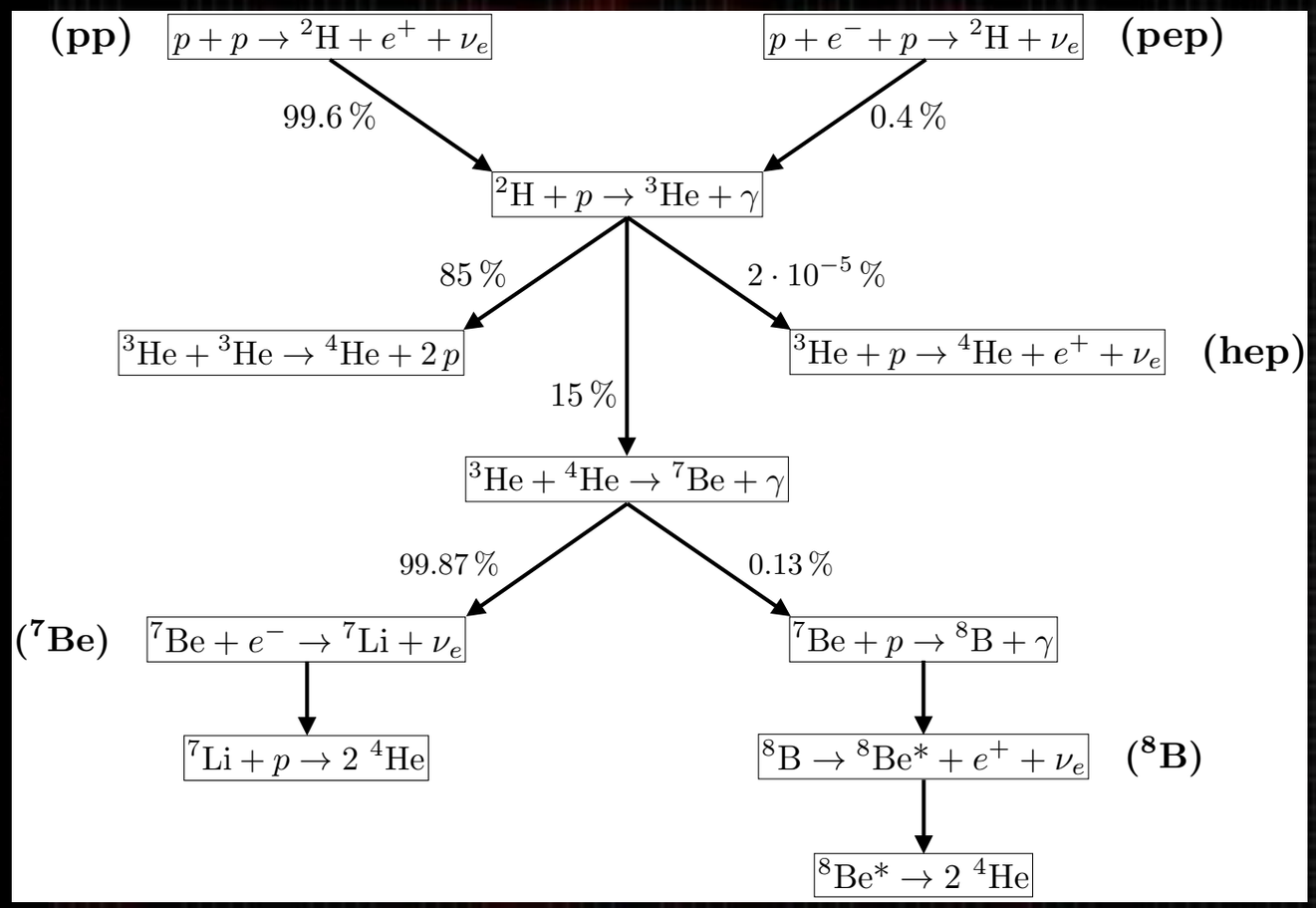
One sees clearly only with [neutrinos].
The important things are invisible to the eye.

—Antoine de Saint Exupéry ("The Little Prince")

- Overview & Status
- Proton Decay
- Neutrino Oscillations
- Neutrino Astronomy

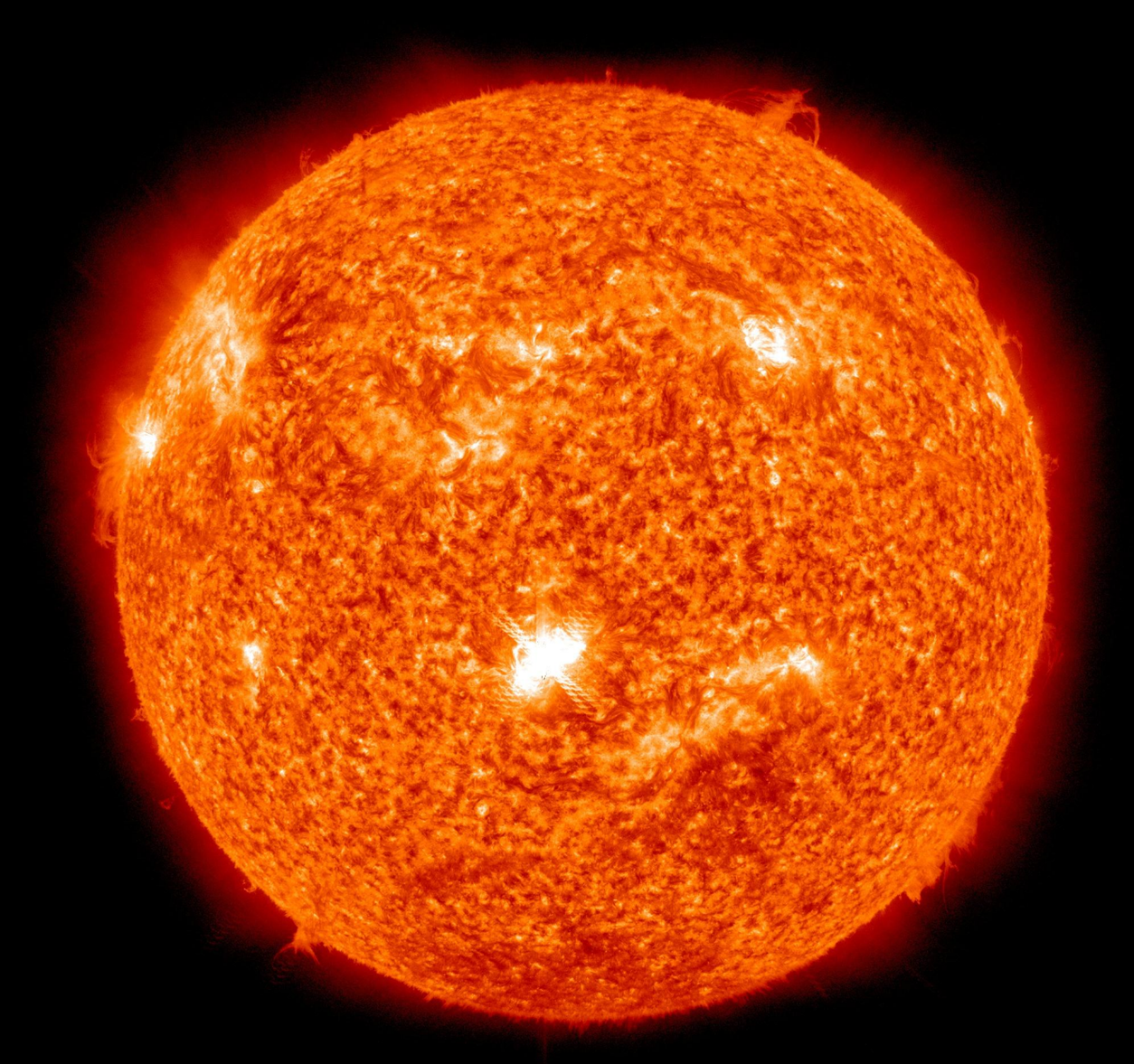
Neutrino Astronomy is Awesome

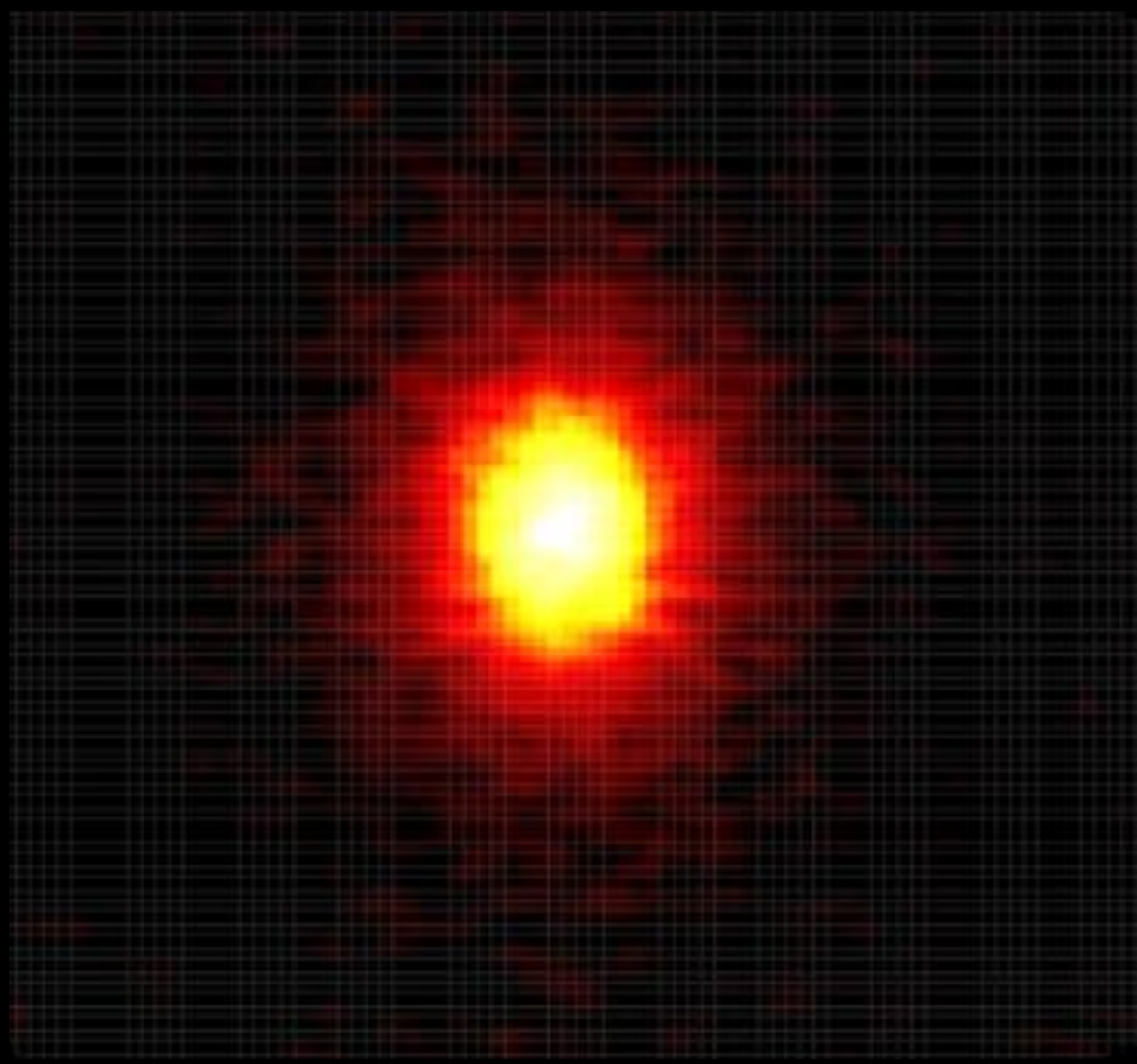




NASA/SDO: https://www.nasa.gov/mission_pages/sunearth/news/News021311-flare.html

Neutrino Astronomy is Awful

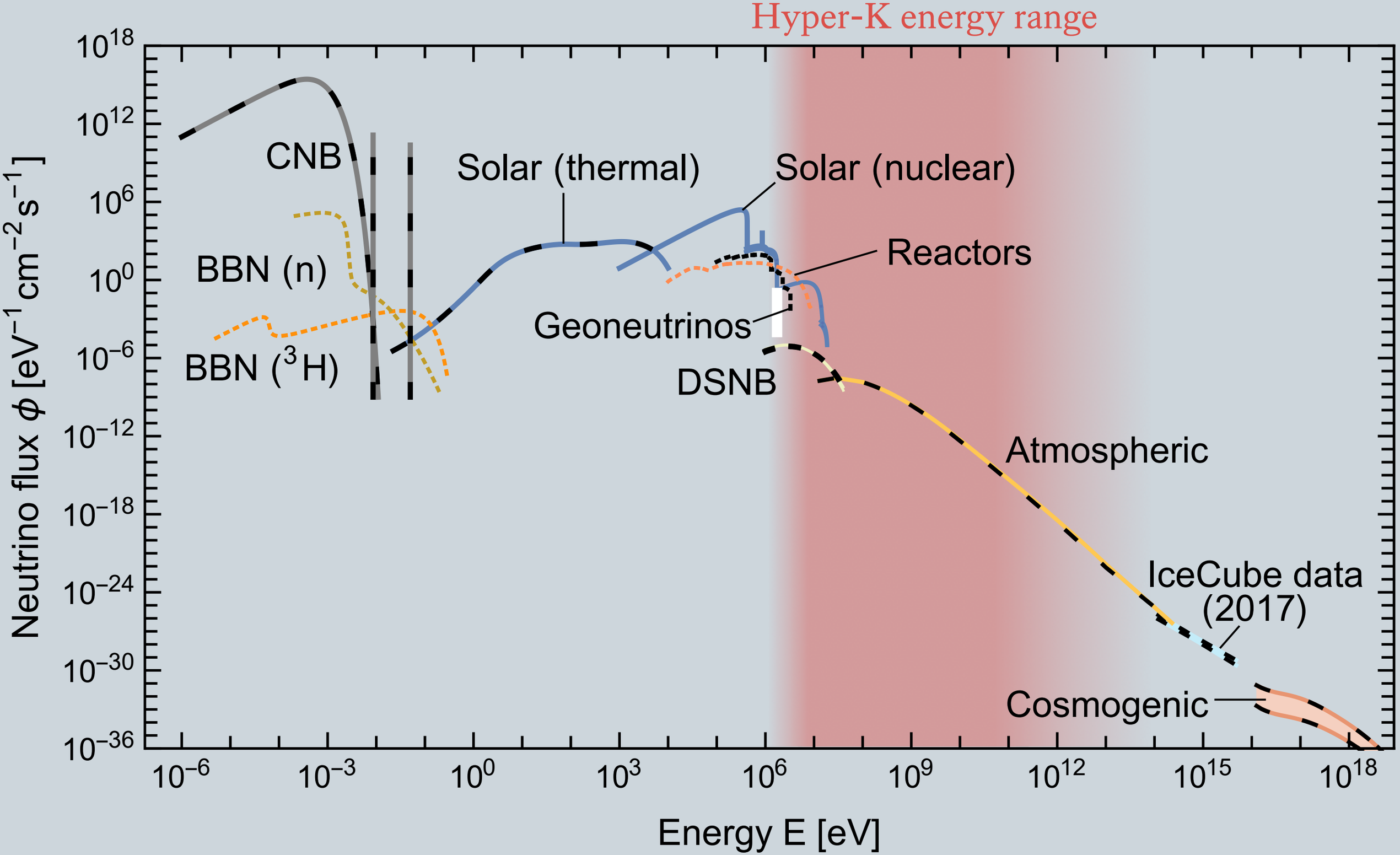




The sun, photographed in neutrinos

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

Neutrino Astronomy



Vitagliano et al., arXiv:1910.11878

→ *Note: only includes known, continuous fluxes*

Astrophysical Targets

- Solar neutrinos
  - Unprecedented statistics: ~100 events per day
  - Try to detect Hep neutrinos: $^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + \mathrm{e}^+ + \nu_e$
  - Resolve production regions of ν inside the sun

    J. Davis: PRL 117, 211101 (2016)
  - Sensitivity to shorter time variations

- Indirect searches for Dark Matter (e.g. in the Sun or Galactic Centre) annihilating/decaying into neutrinos

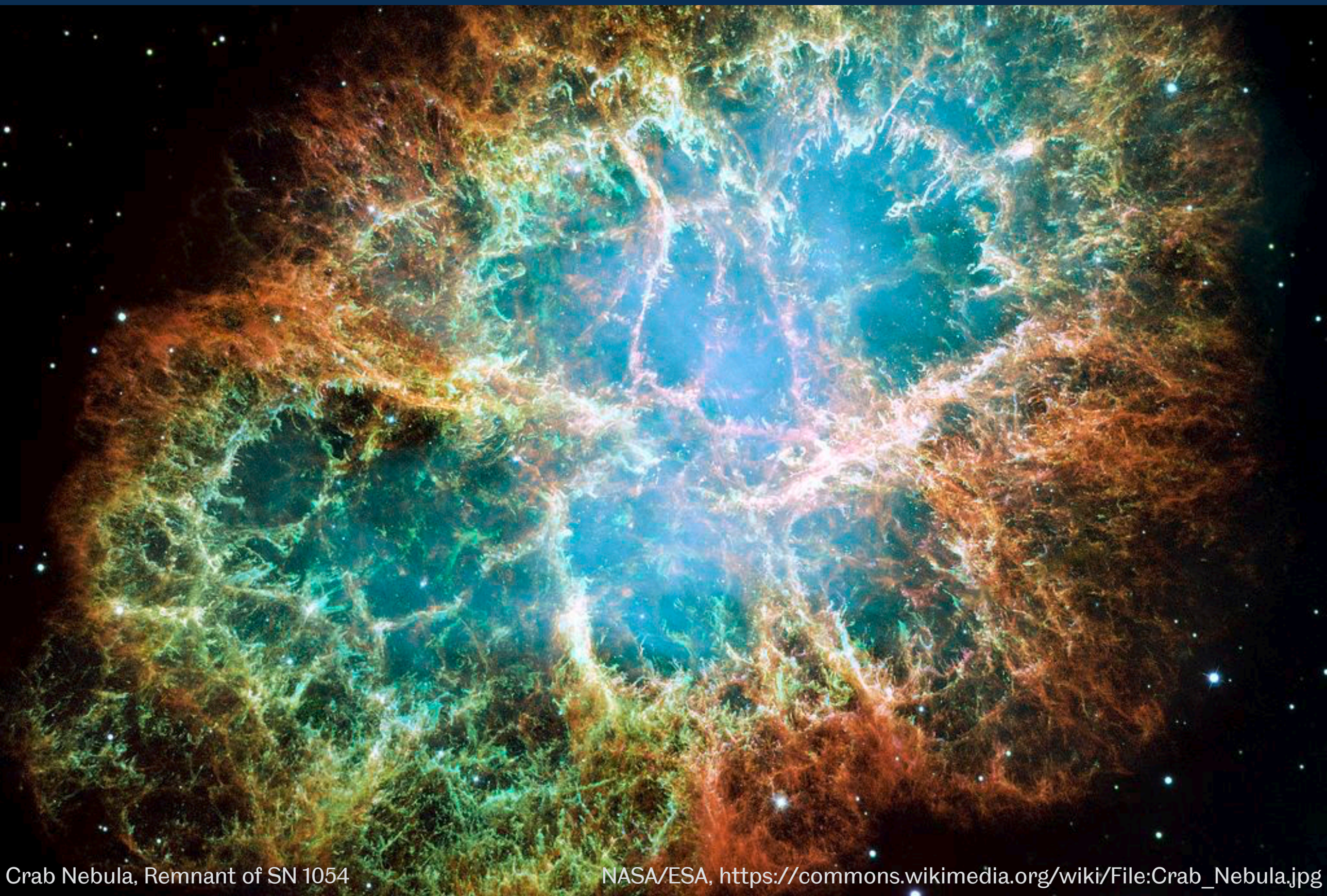
- Multi-messenger Astronomy → *next slide*

- Supernova Neutrinos → *rest of the talk*

Multi-Messenger Astronomy

- Expect an order-of-magnitude improvement over Super-K
- Main sensitivity at MeV–GeV scale
- Wide range of transient sources:
  - Gamma-Ray Bursts
    - Tens of MeV scale (SK result: arXiv:2101.03480)
    - GeV–PeV scale (if efficient UHECR acceleration in GRBs)
  - Binary mergers (SK results: arXiv:1608.08745, arXiv:1802.04379, arXiv:2104.09196)
  - Blazars like TXS 0506+056 (SK result: arXiv:1910.07680)
  - SN shock wave interacting with circumstellar material
    - e.g. Eta Carinae: large CSM mass, expect ~300 high-energy neutrinos in HK over ~months
  - High-energy neutrinos from solar flares (prediction: arXiv:0812.4592)

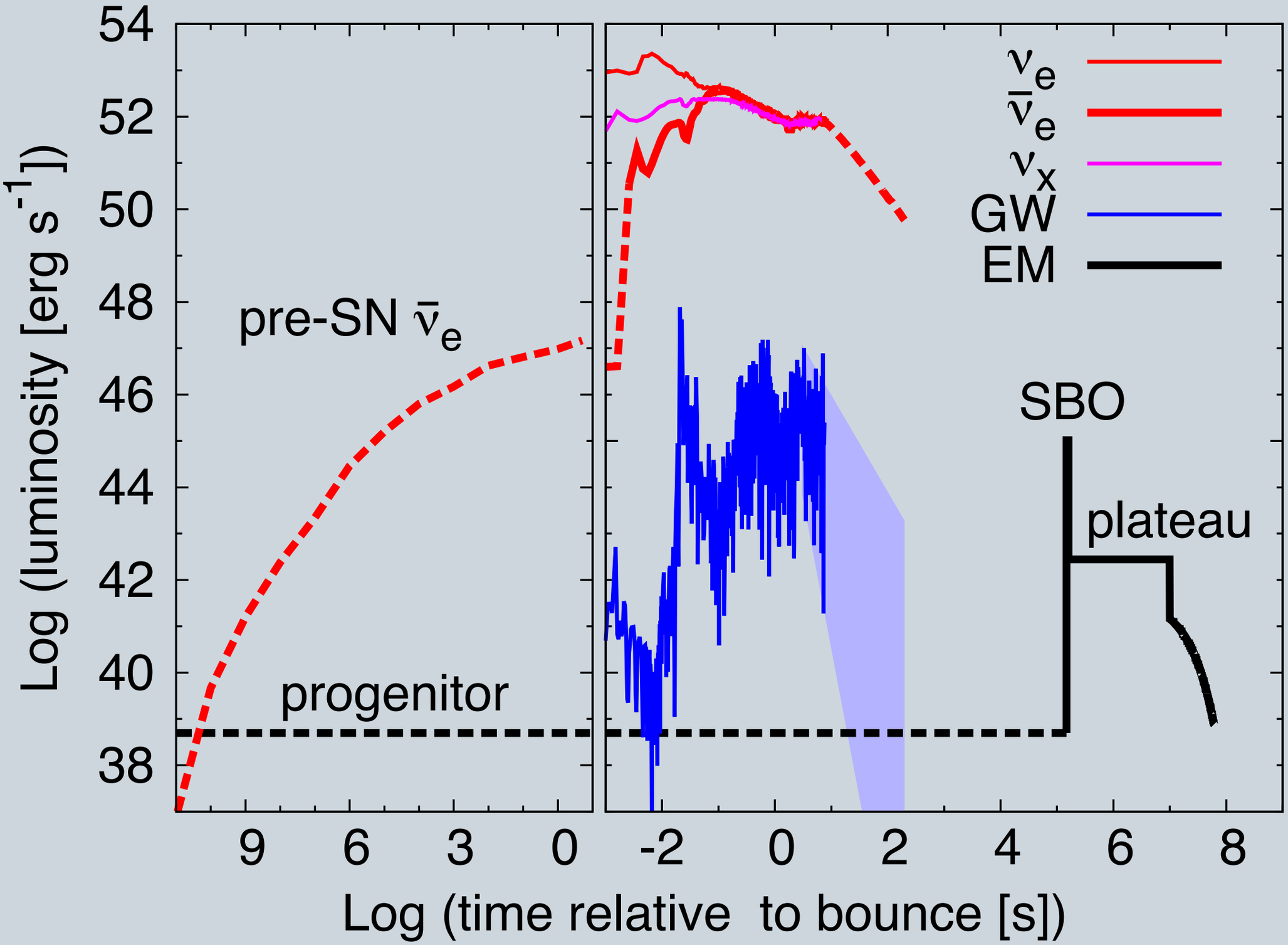
(Core-Collapse) Supernova Neutrinos



Crab Nebula, Remnant of SN 1054

NASA/ESA, https://commons.wikimedia.org/wiki/File:Crab_Nebula.jpg

Supernova Neutrino Signal

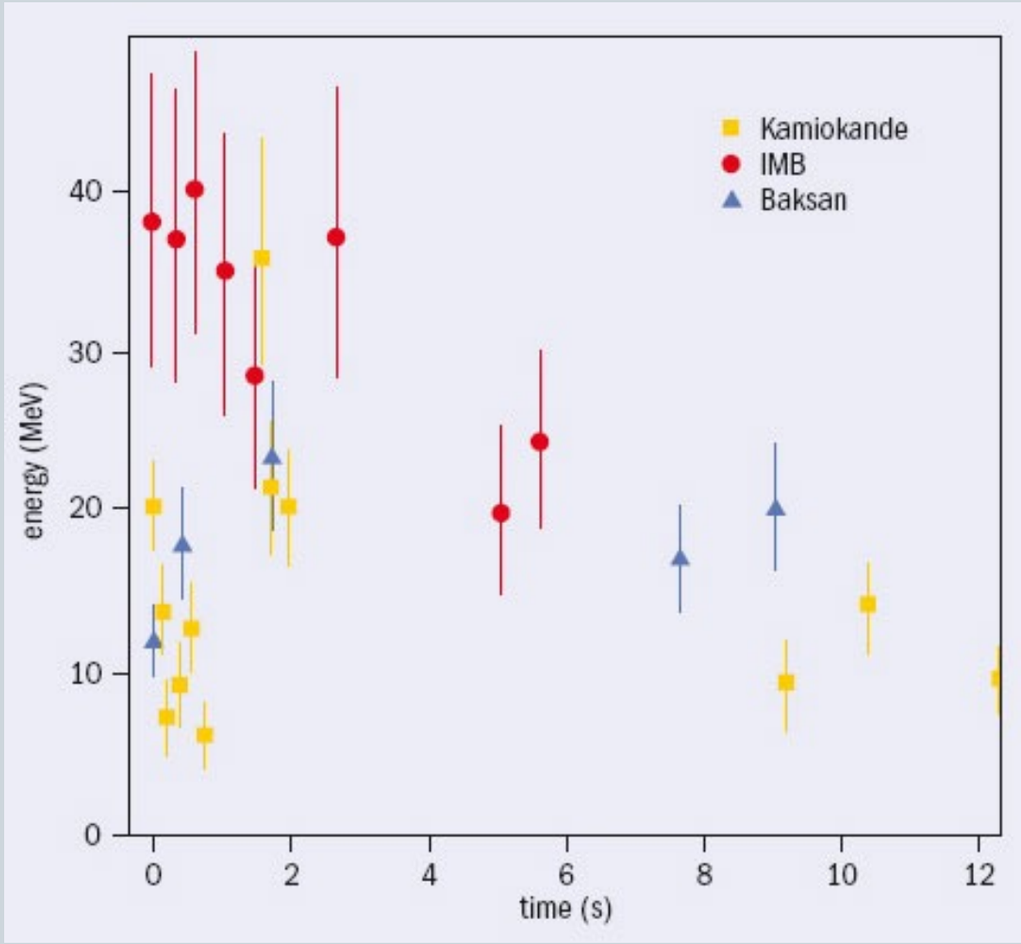


arXiv:1602.03028

What We (Think We) Know …

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

- Confirmed basic picture:
  - ν burst ≈99% of energy
  - $\sim 10^{53}$ erg, $\sim 10^{58}$ 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

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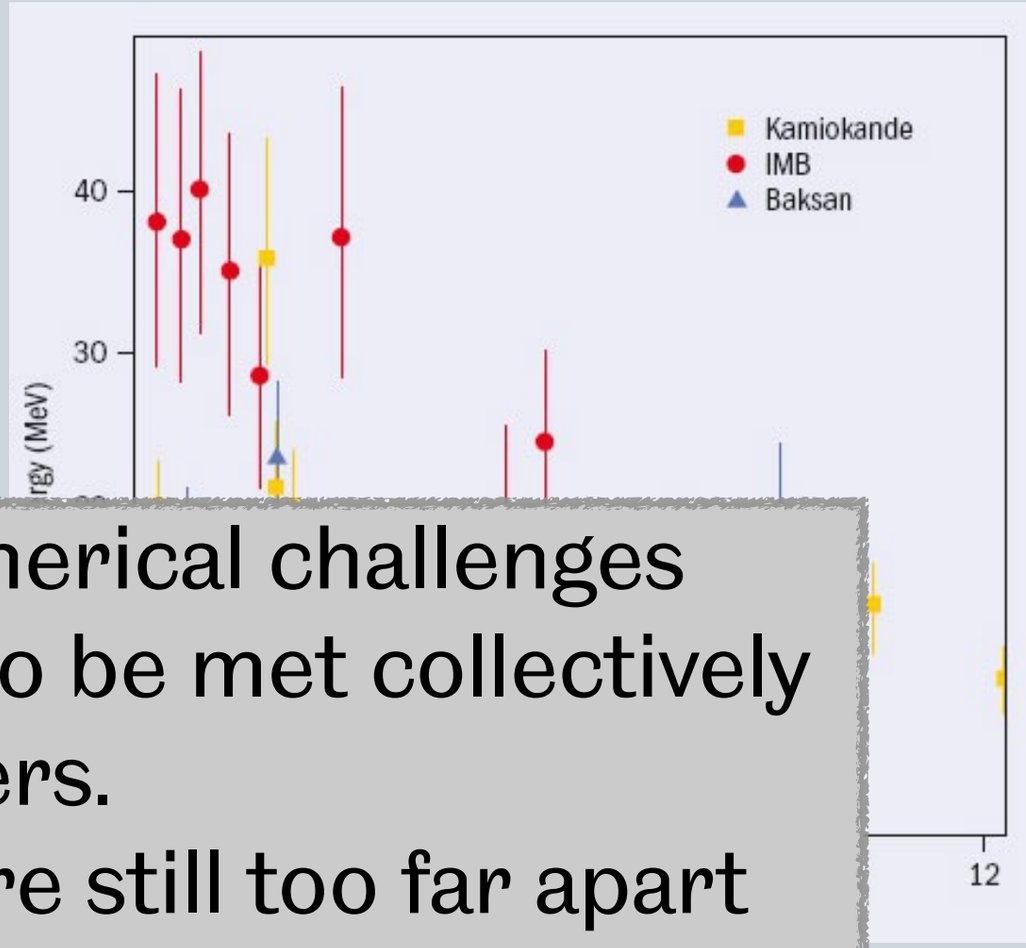

- Confirmed basic picture:

> "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

- Simulations still limited by available computing power
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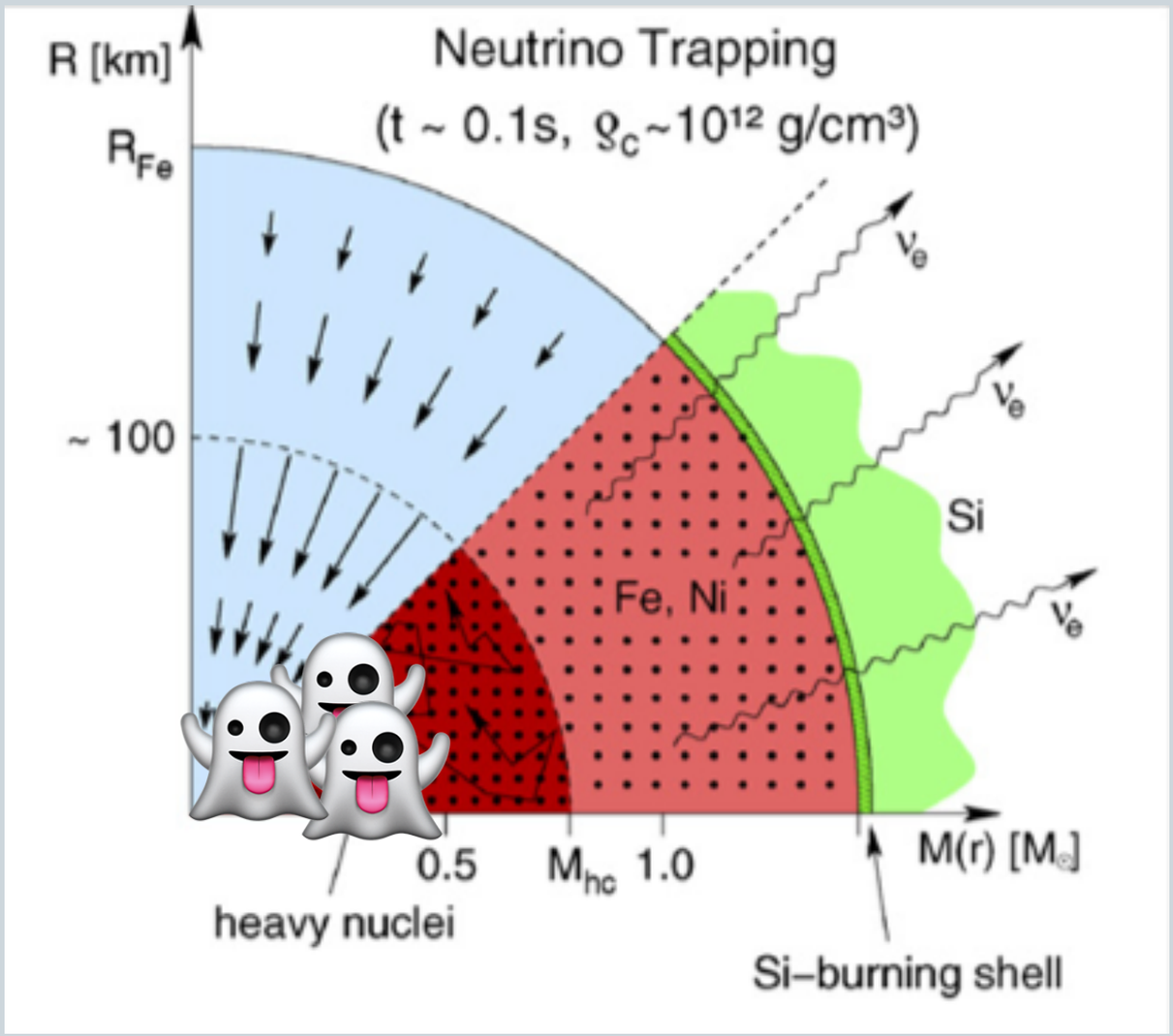
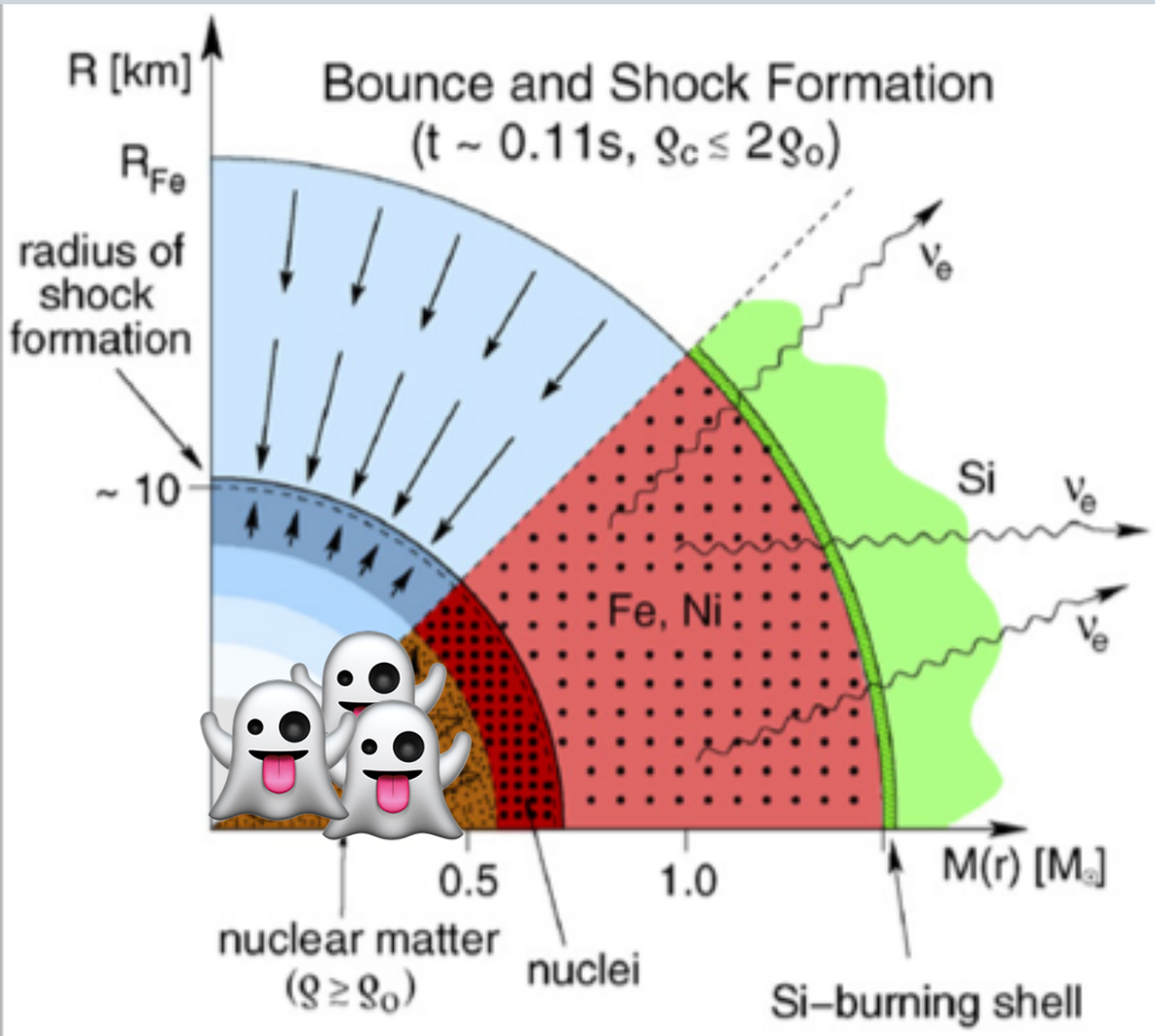
1) The Star Collapses

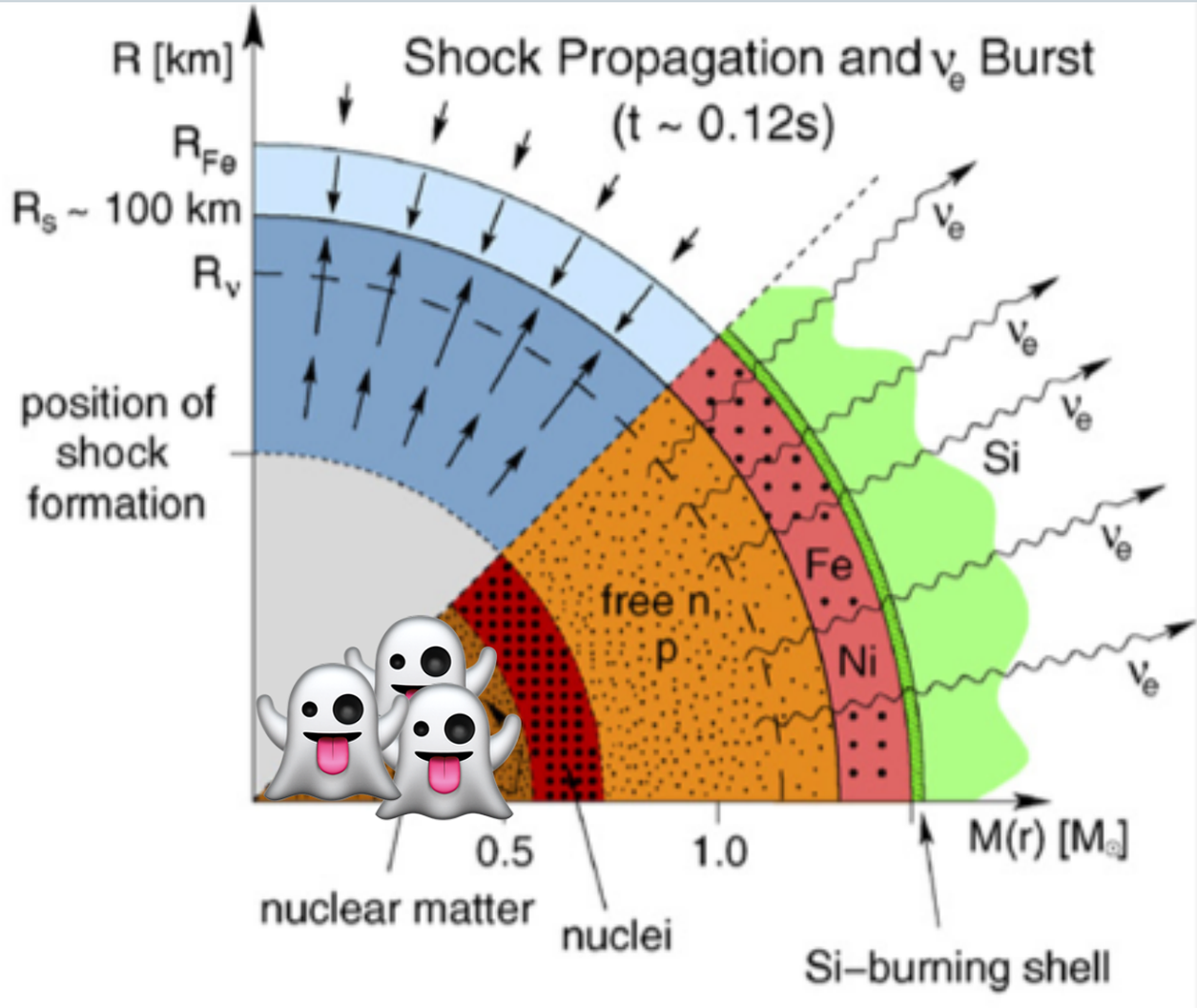


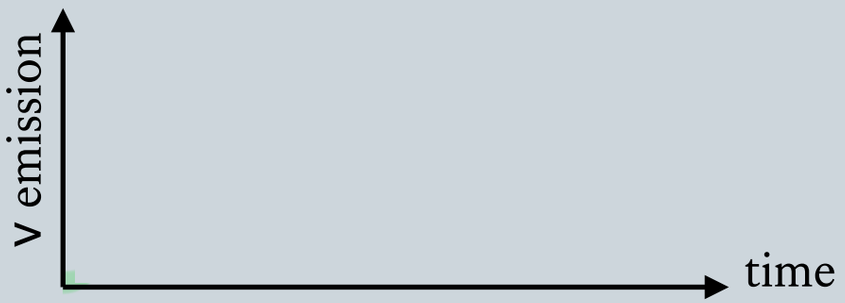
[Janka *et al.*, Phys.Rep. 442, pp. 38–74]

2) A Shock Wave Forms

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







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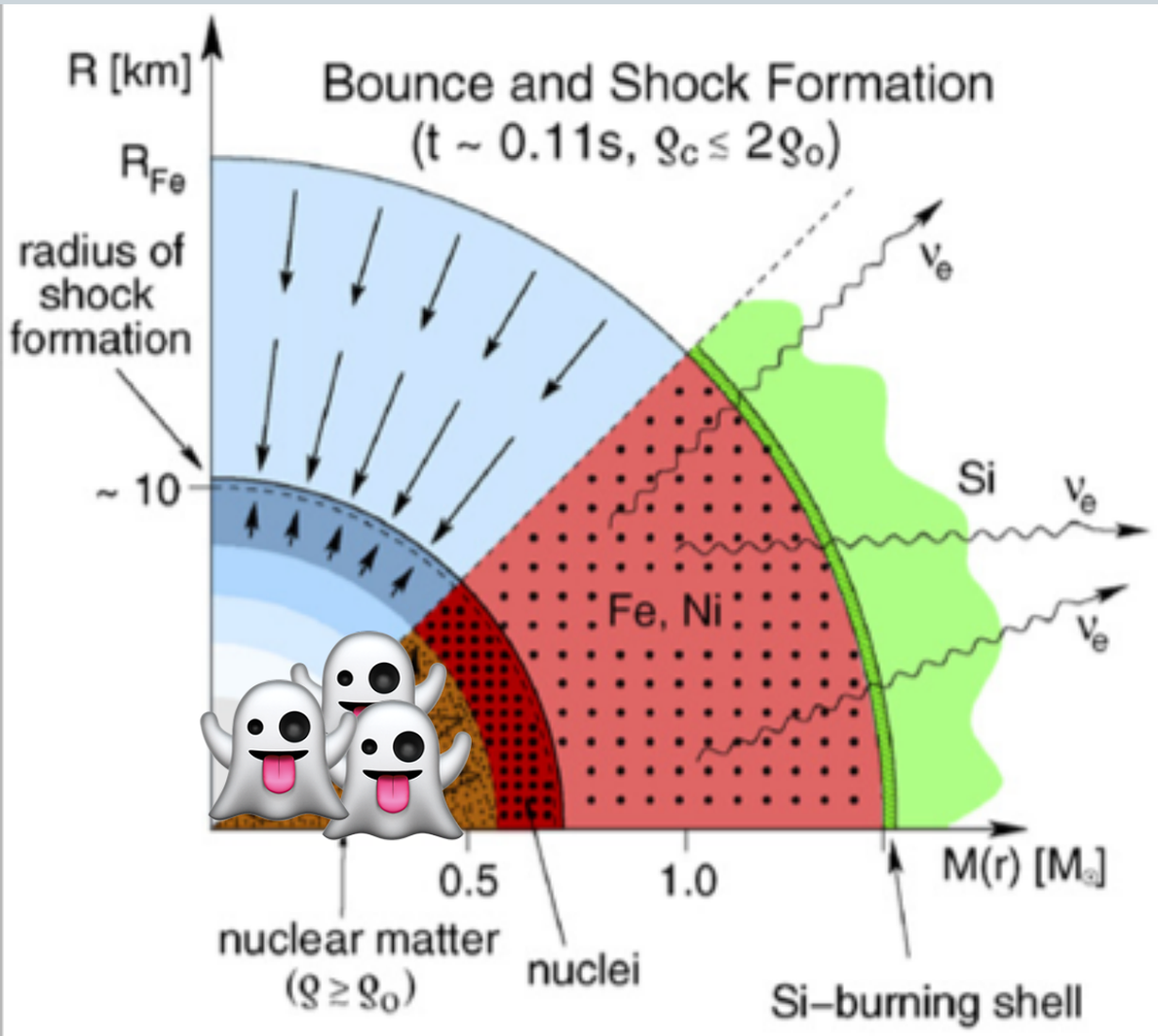

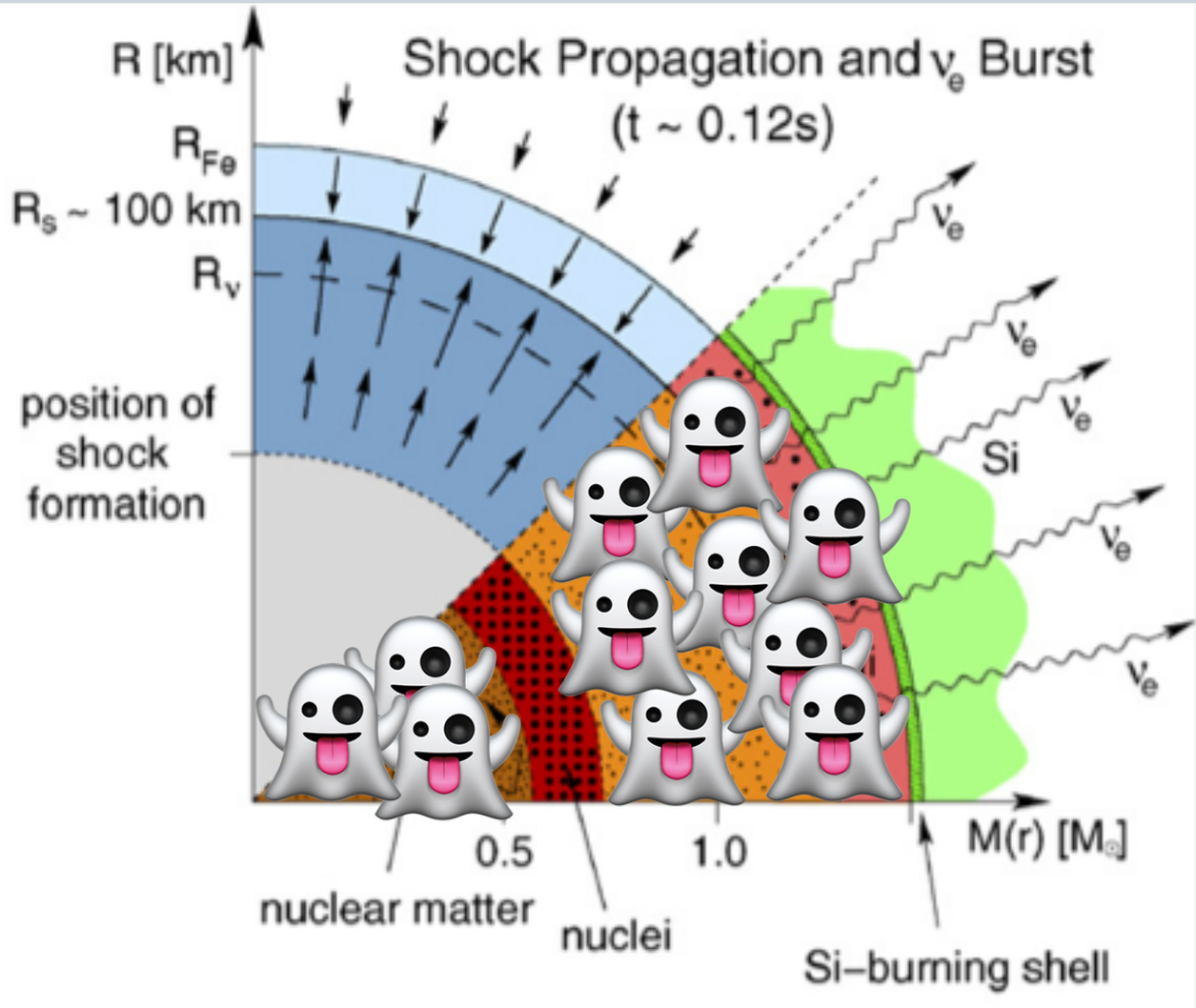

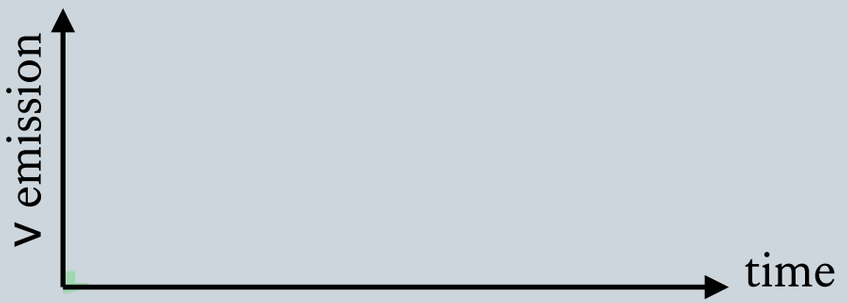

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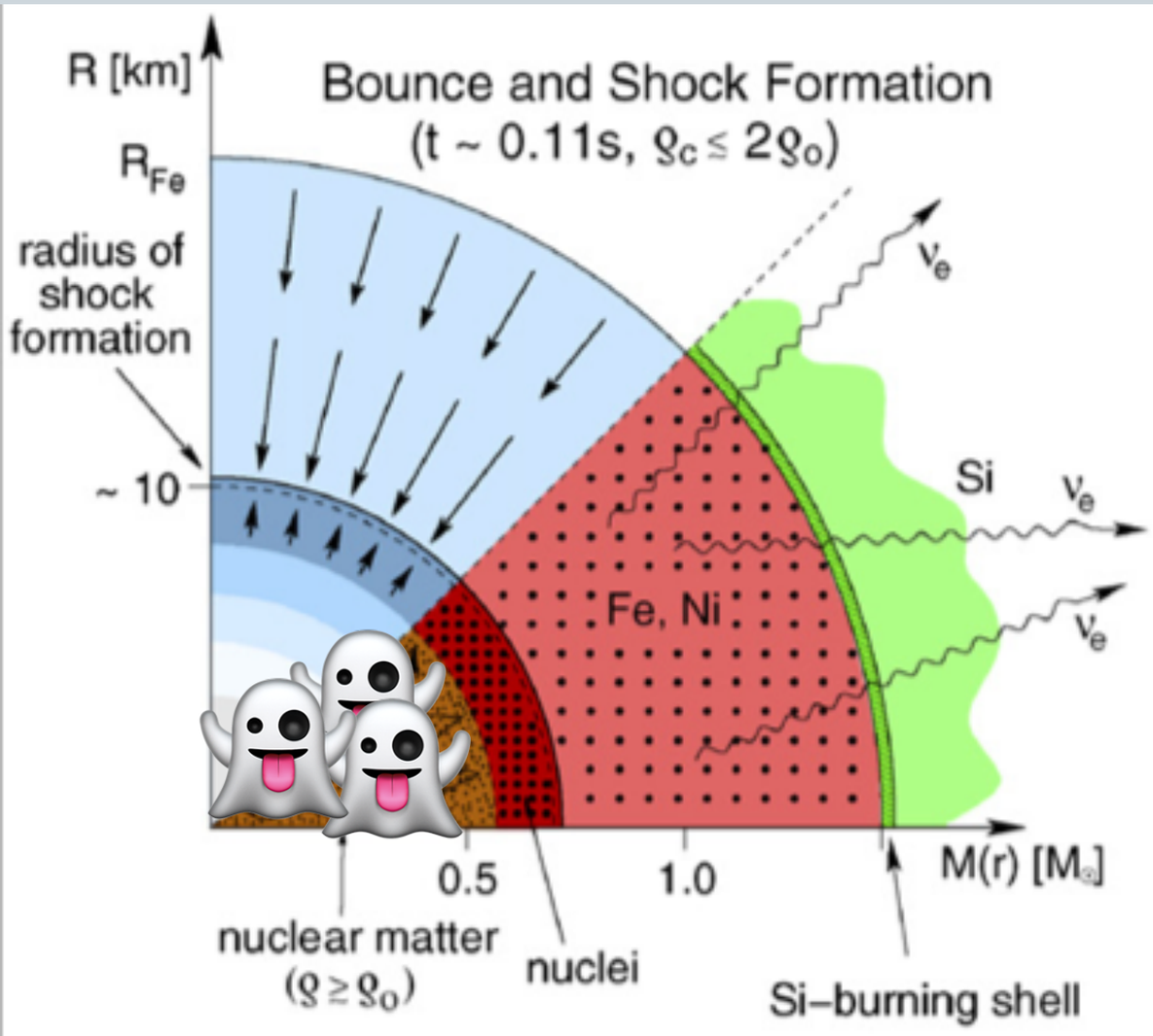
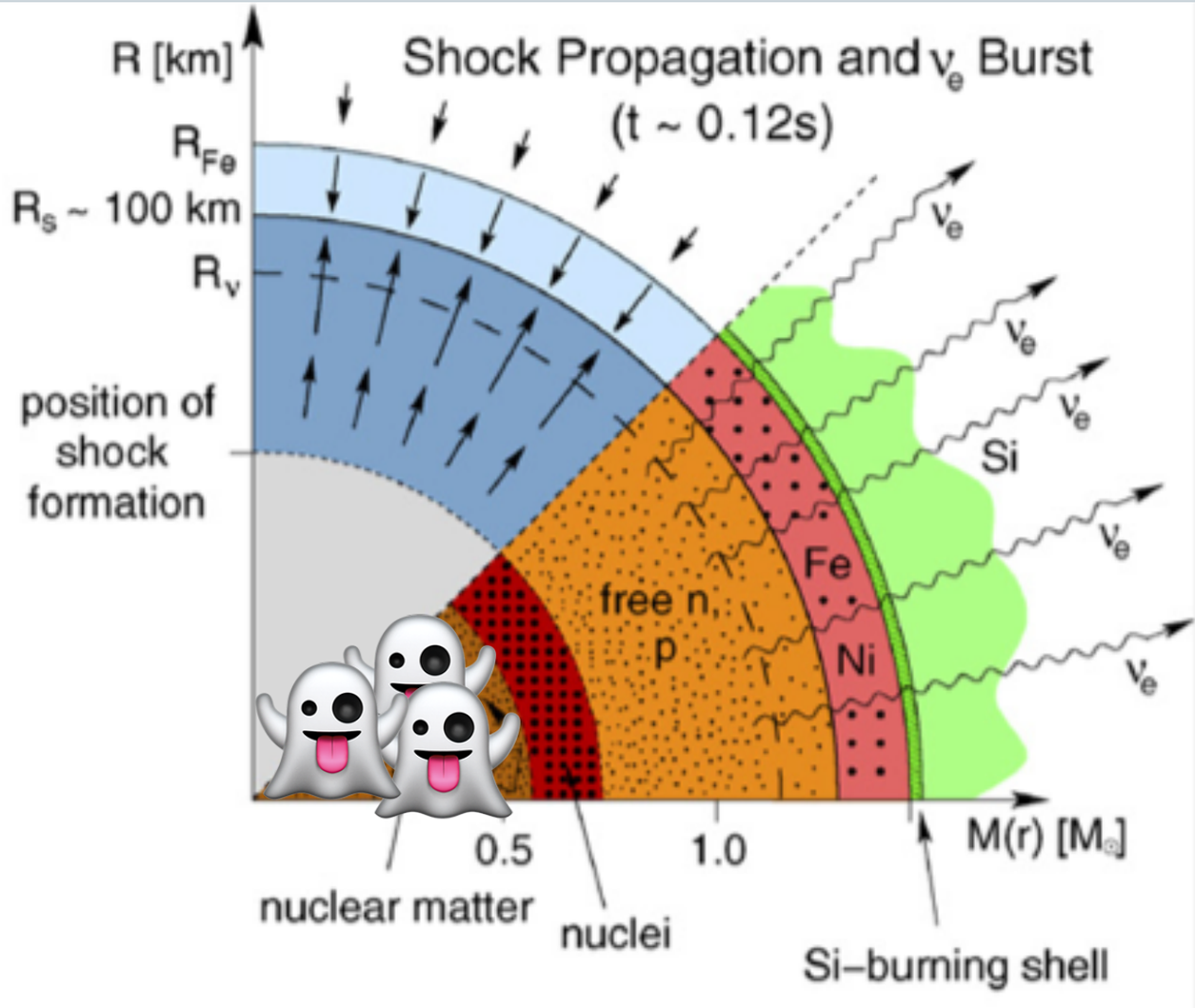
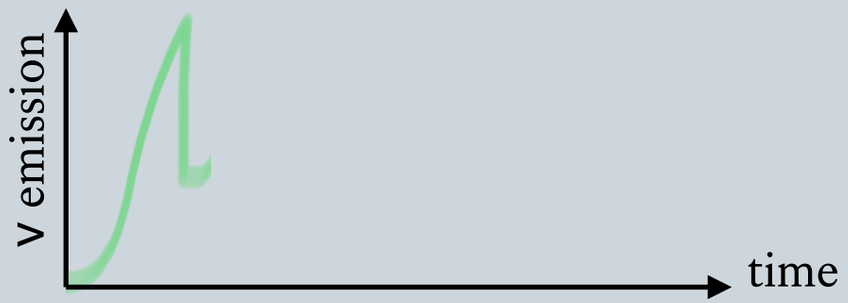
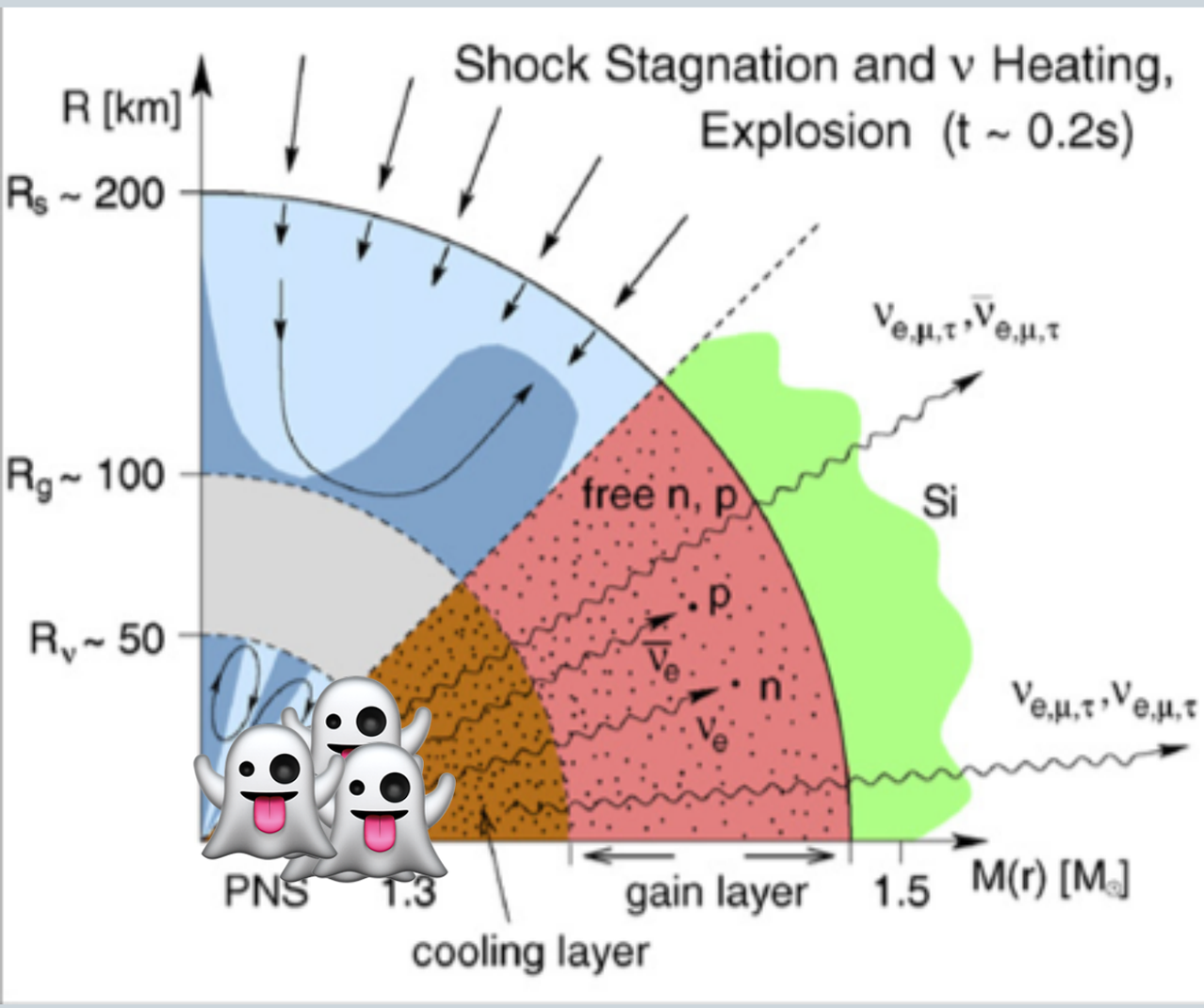


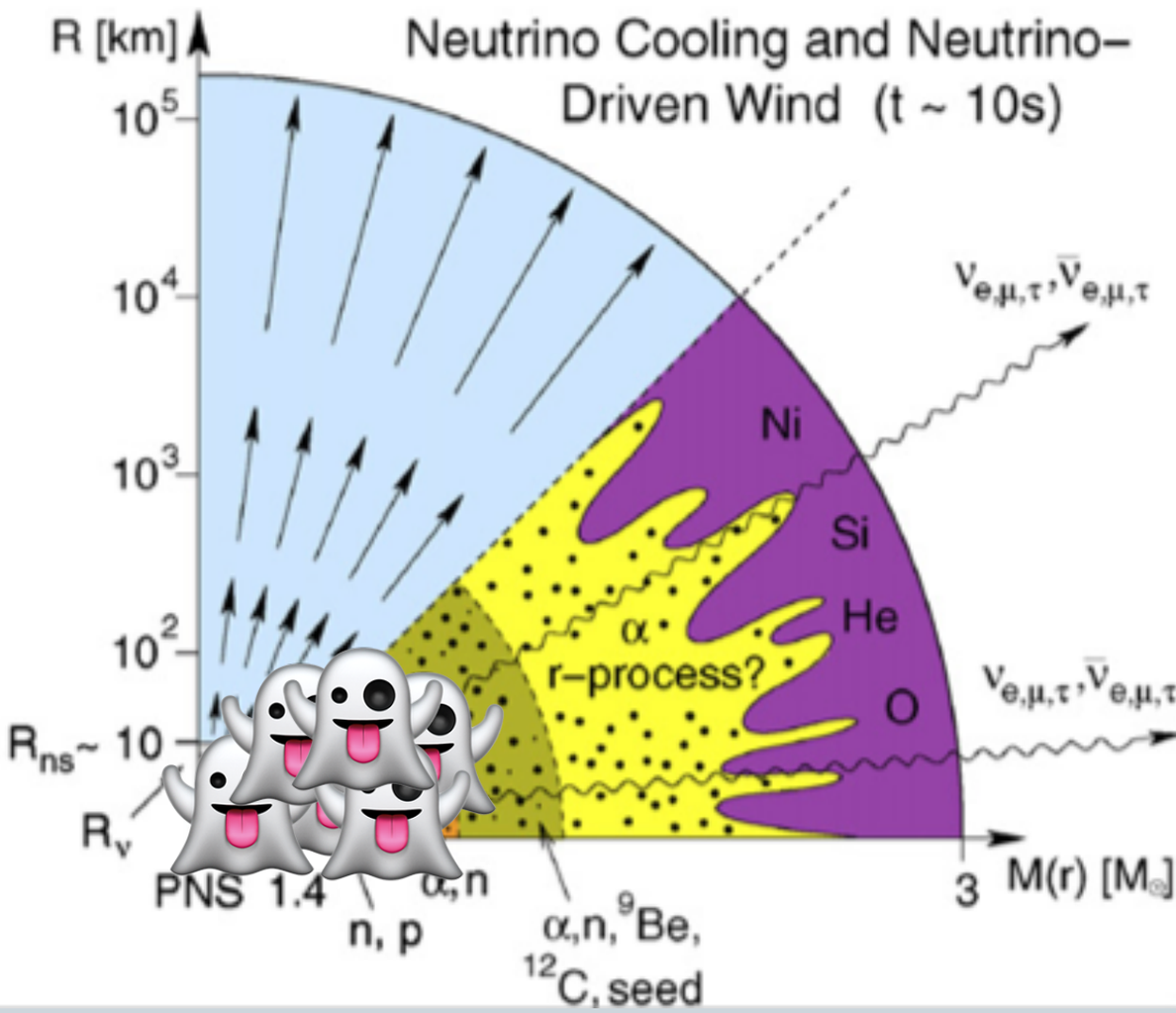


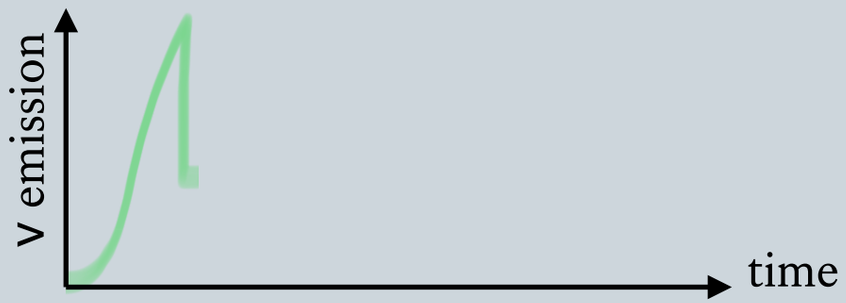


3) Shock Wave Is Restarted & Explodes

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







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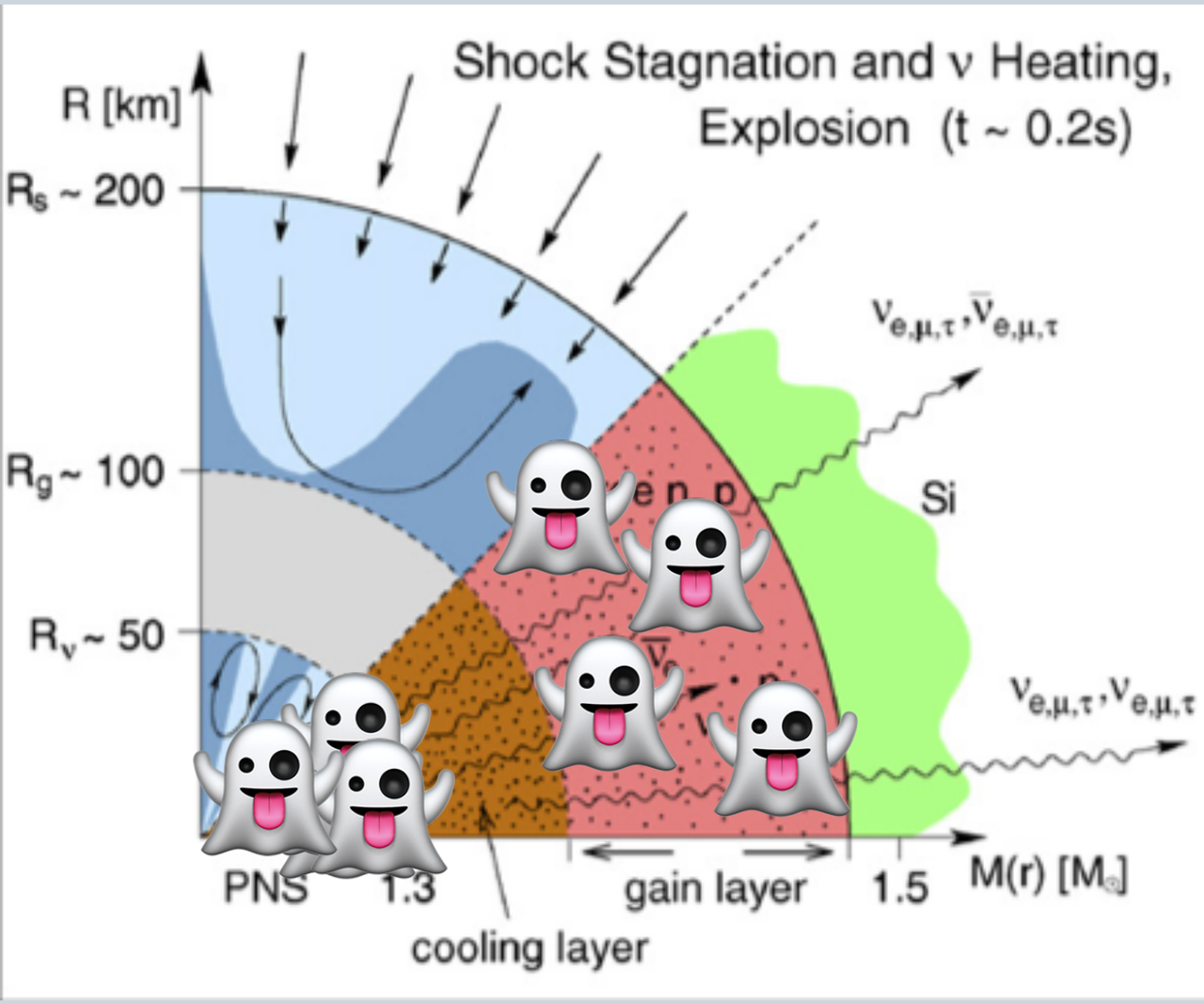

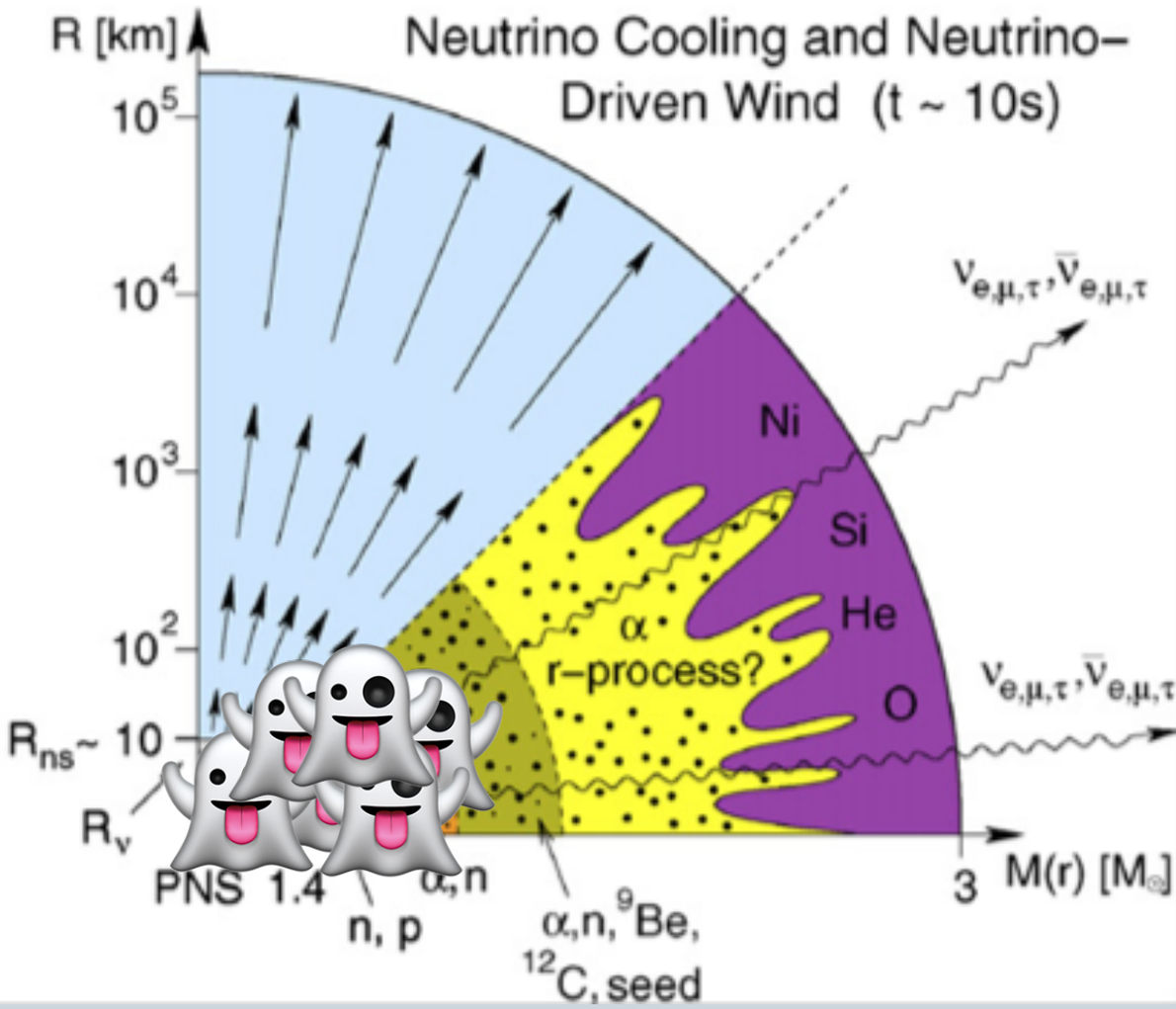

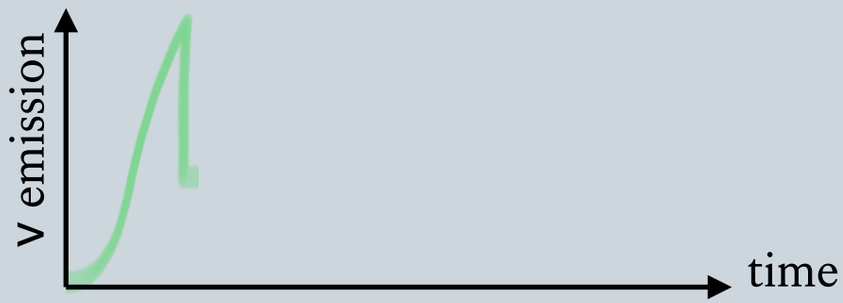

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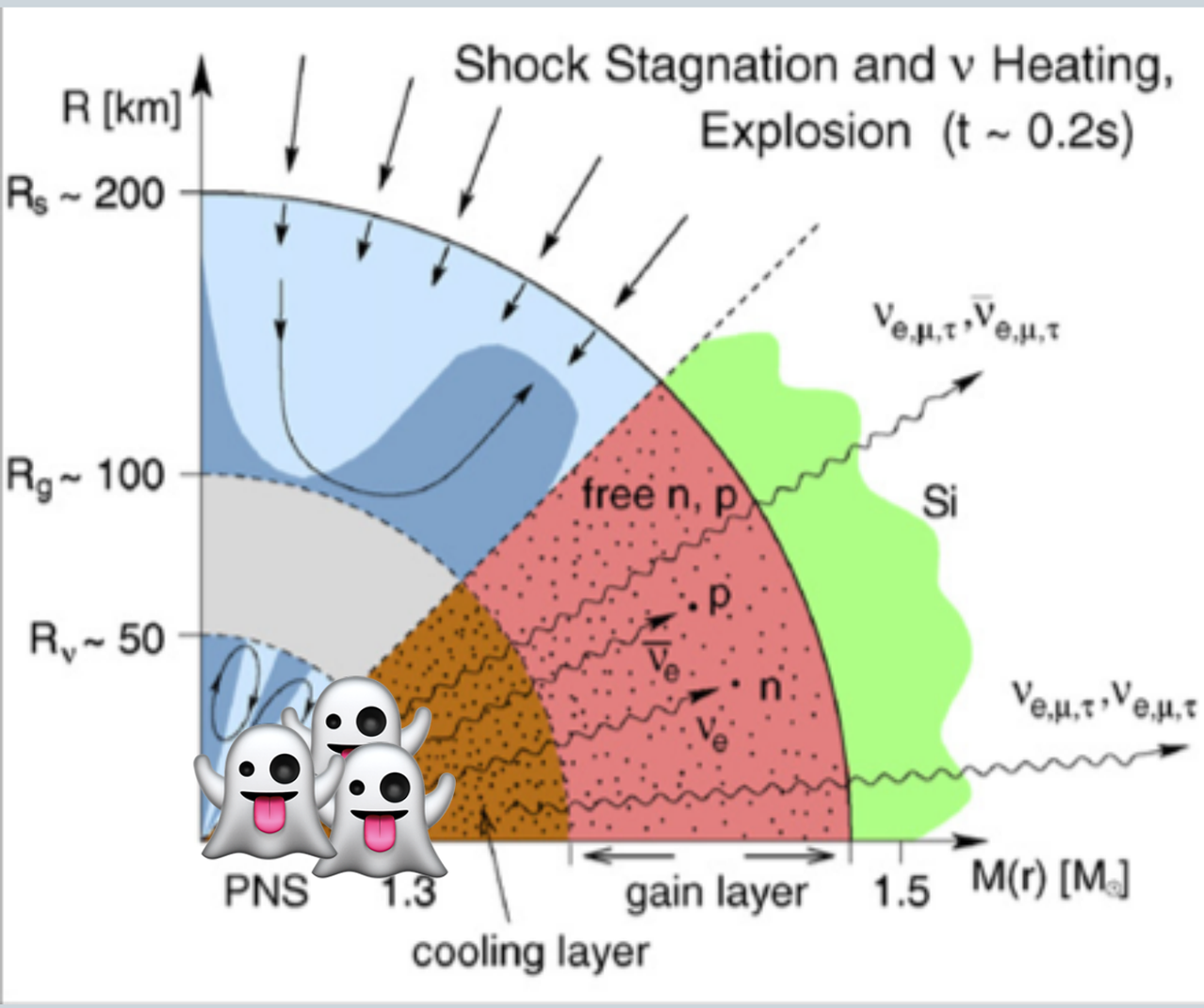

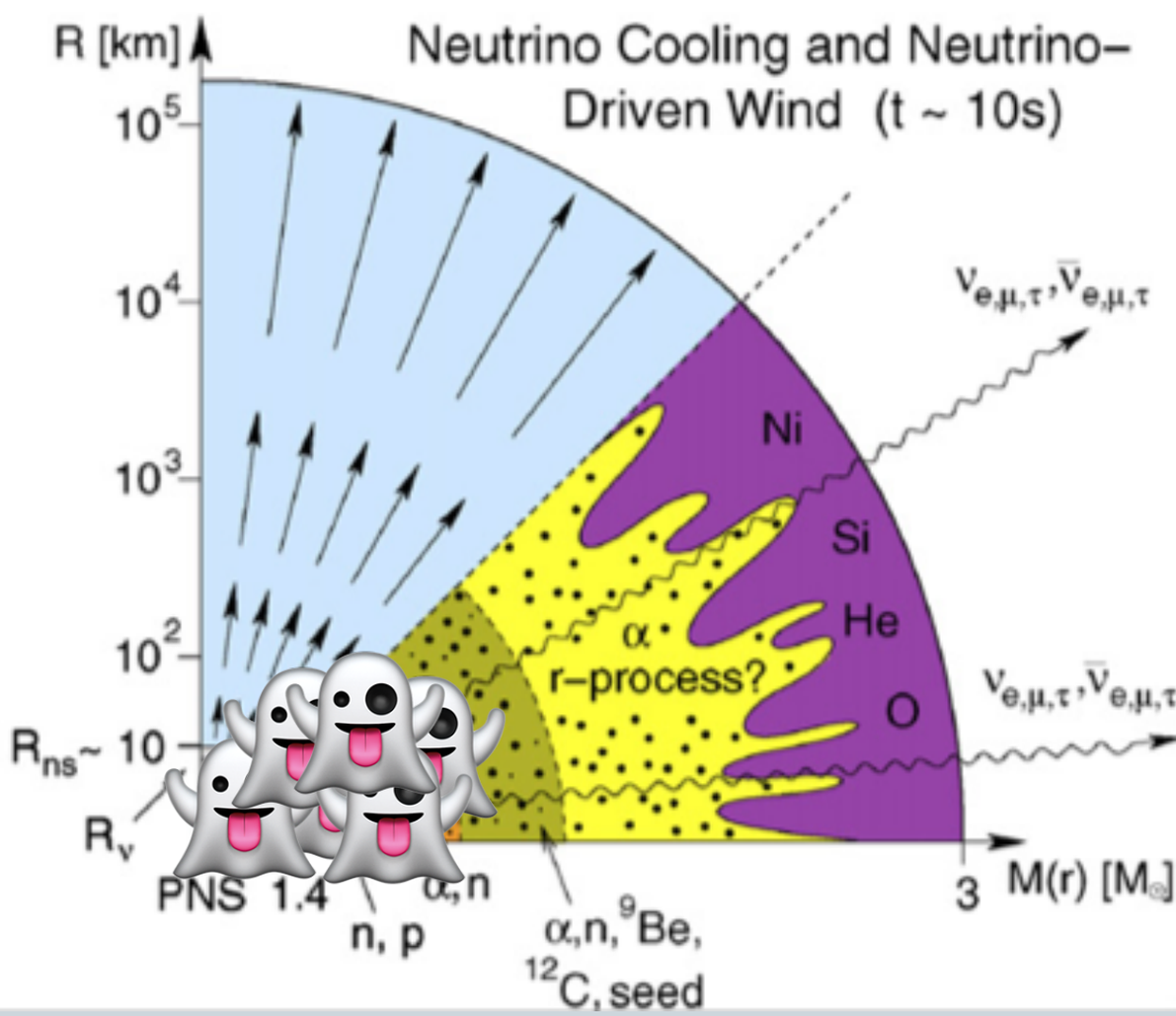

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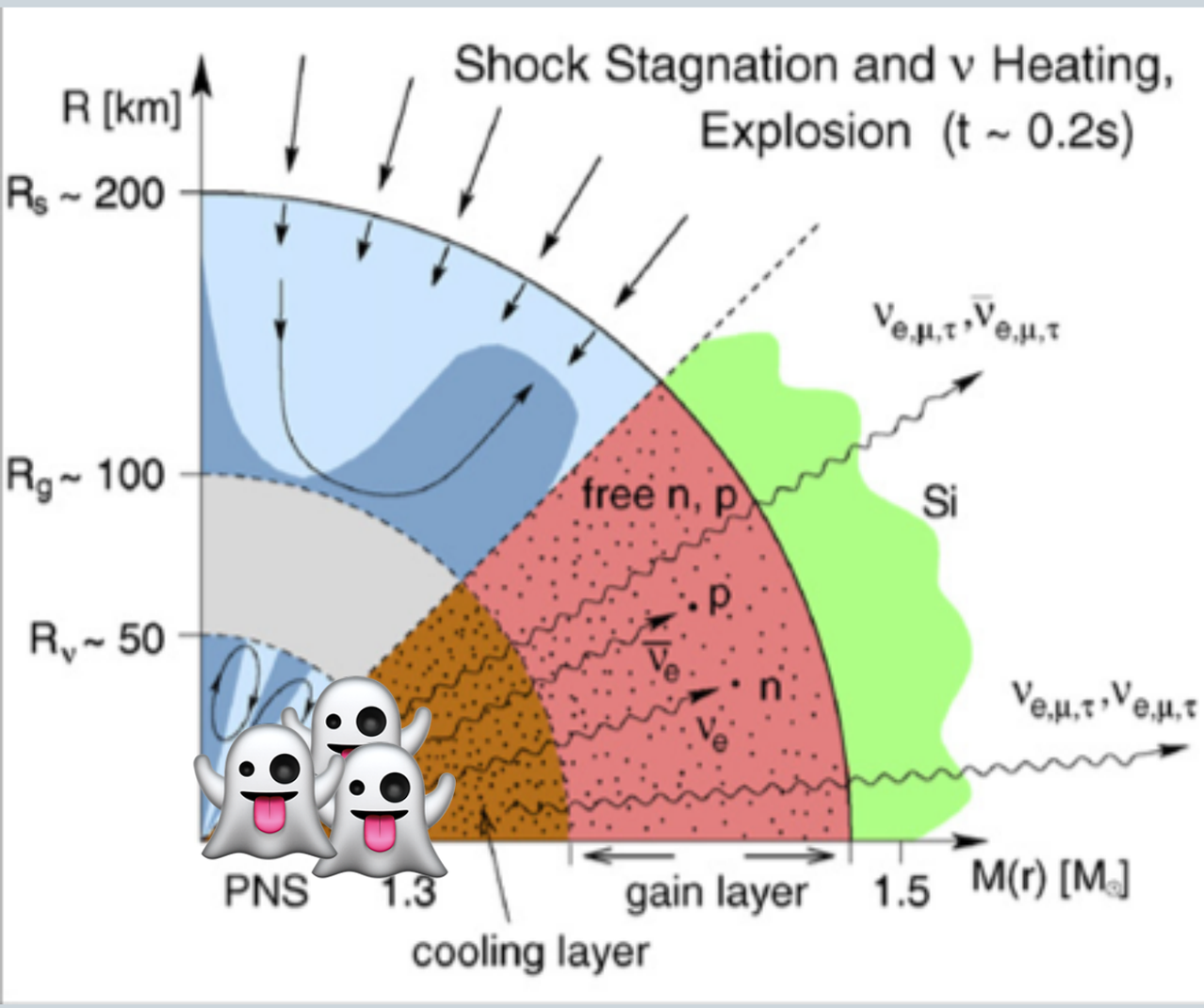
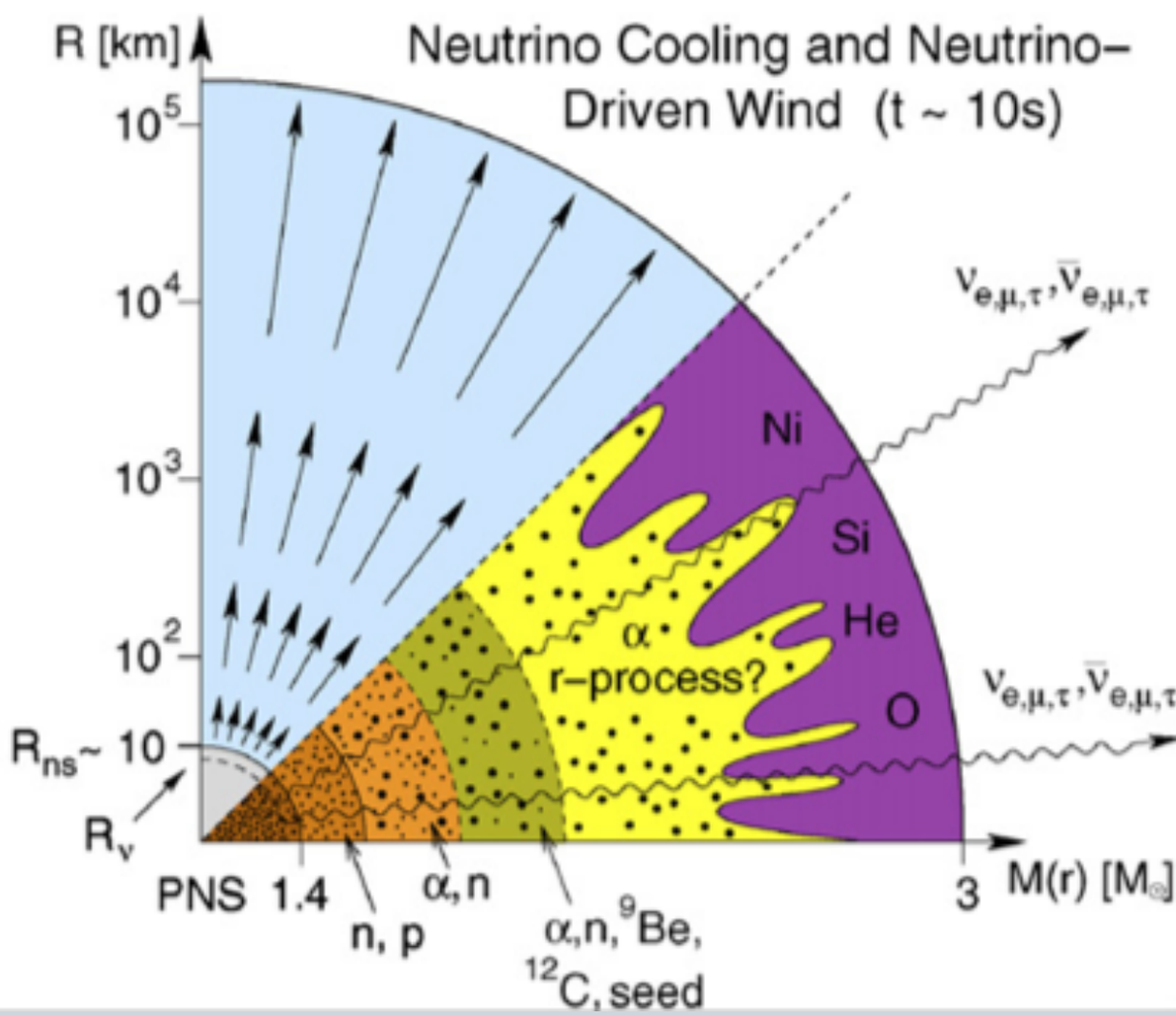
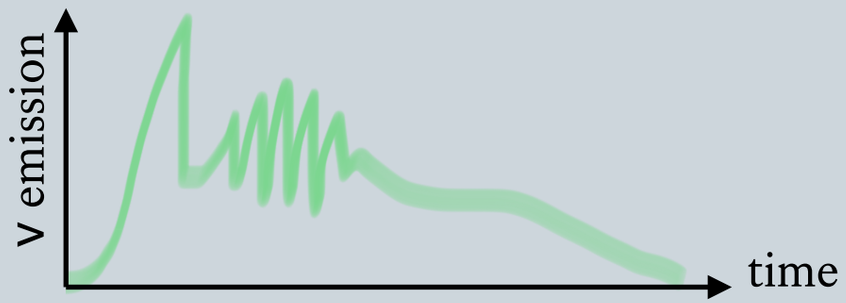


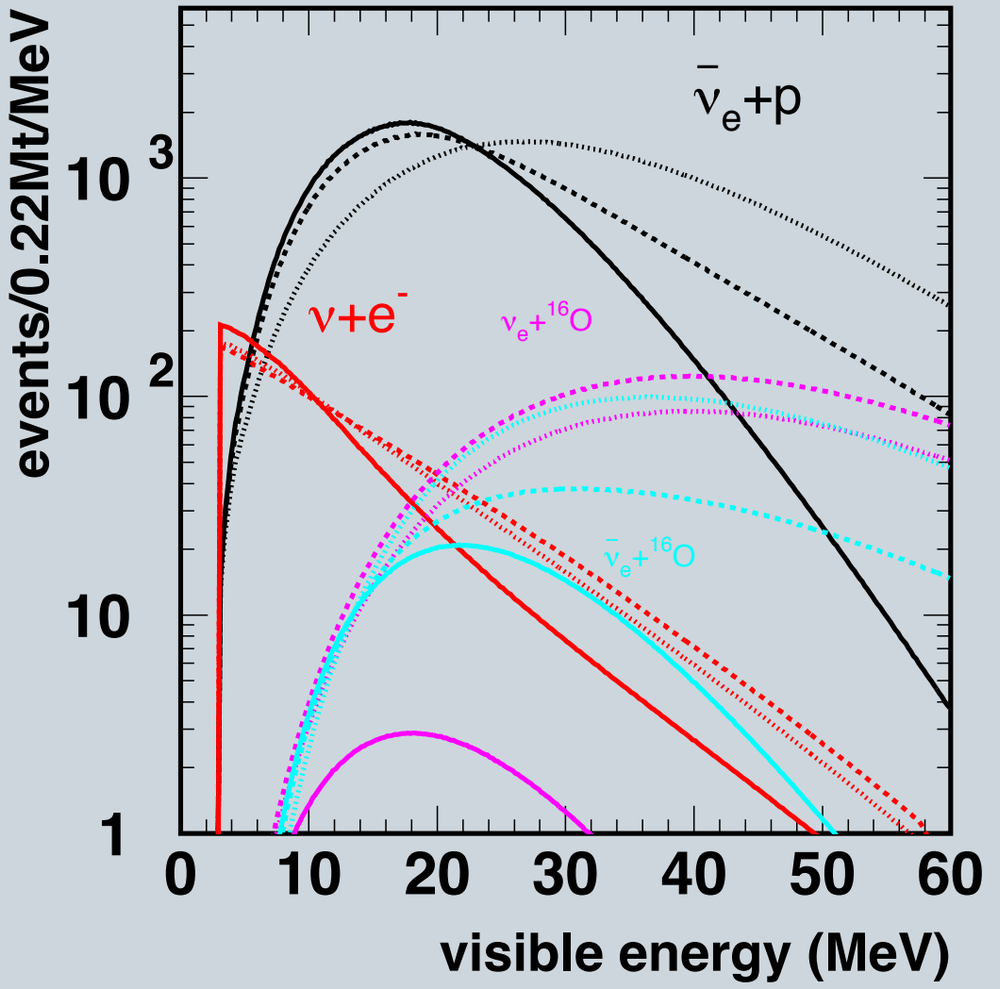


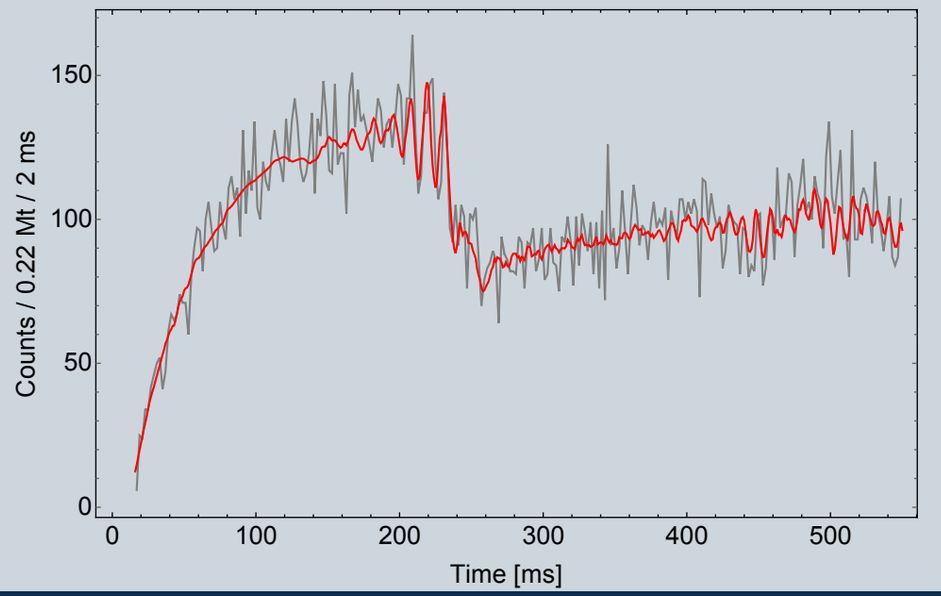


Supernova ν Burst

- At 10 kpc: 10^5–10^6 events in ~10 s
- Precise time & energy reconstruction on event-by-event basis
- Directionality: ~1° (via νe-scattering)
- Most sensitive to $\bar{\nu}_e$ (~90% of events from 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, JM arXiv:1609.04286)
  - Compare full t & E dependence (JM, arXiv:2002.01649 & 2101.05269)

- Use 5 supernova models
- Generated 1000 MC data sets per model
- Full detector simulation & reconstruction toolchain
- Unbinned likelihood function: Which model best matches the reconstructed t & E distribution?

Developed event generator:

- Precise cross sections
- Extensible (Water, LS, WbLS, ...)
- Open source: https://github.com/JostMigenda/sntools
- Accepted by JOSS (DOI:10.21105/joss.02877)

Identified as

True model: 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**

Identified as

True model: 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**

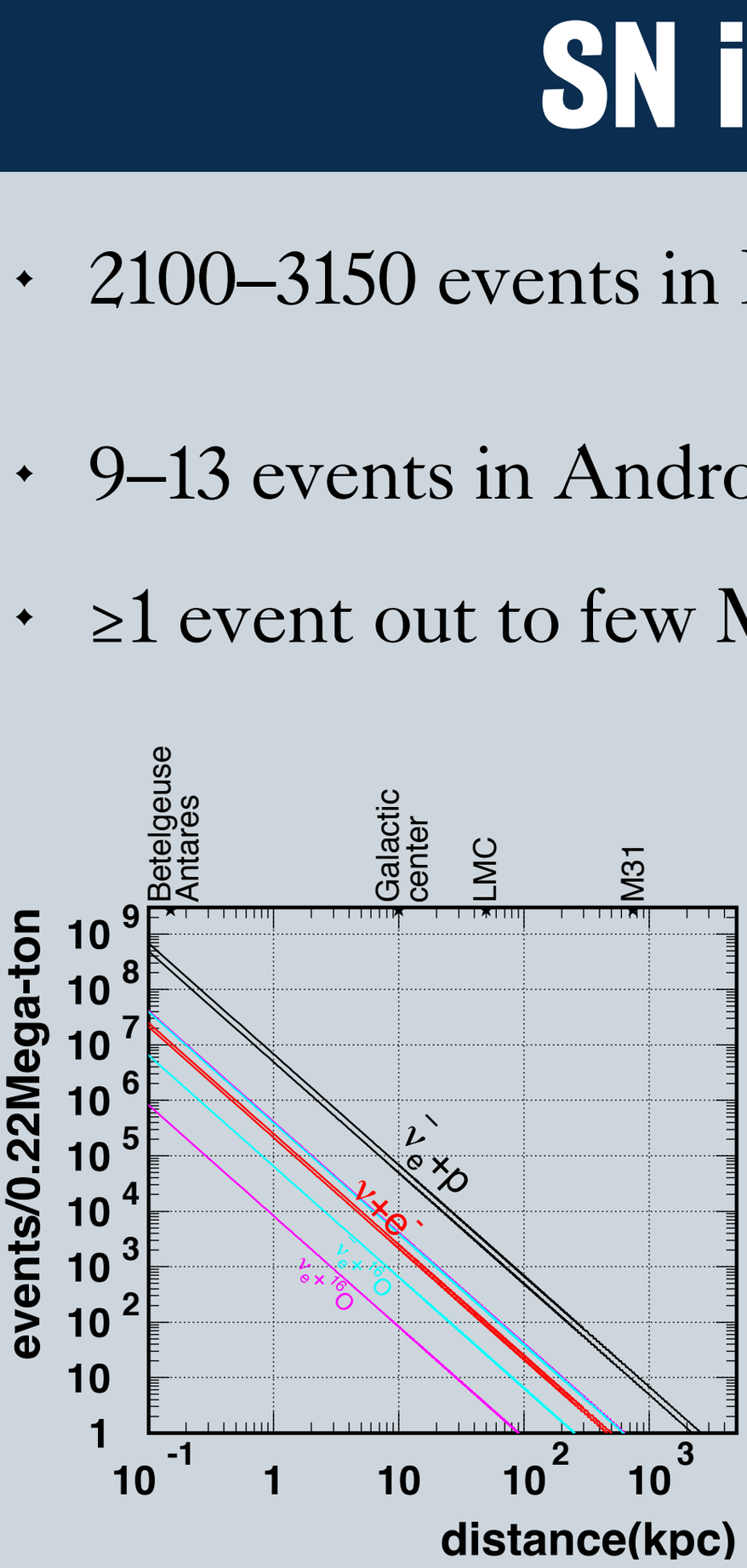
* during 20–520ms after core bounce, assuming Normal Ordering

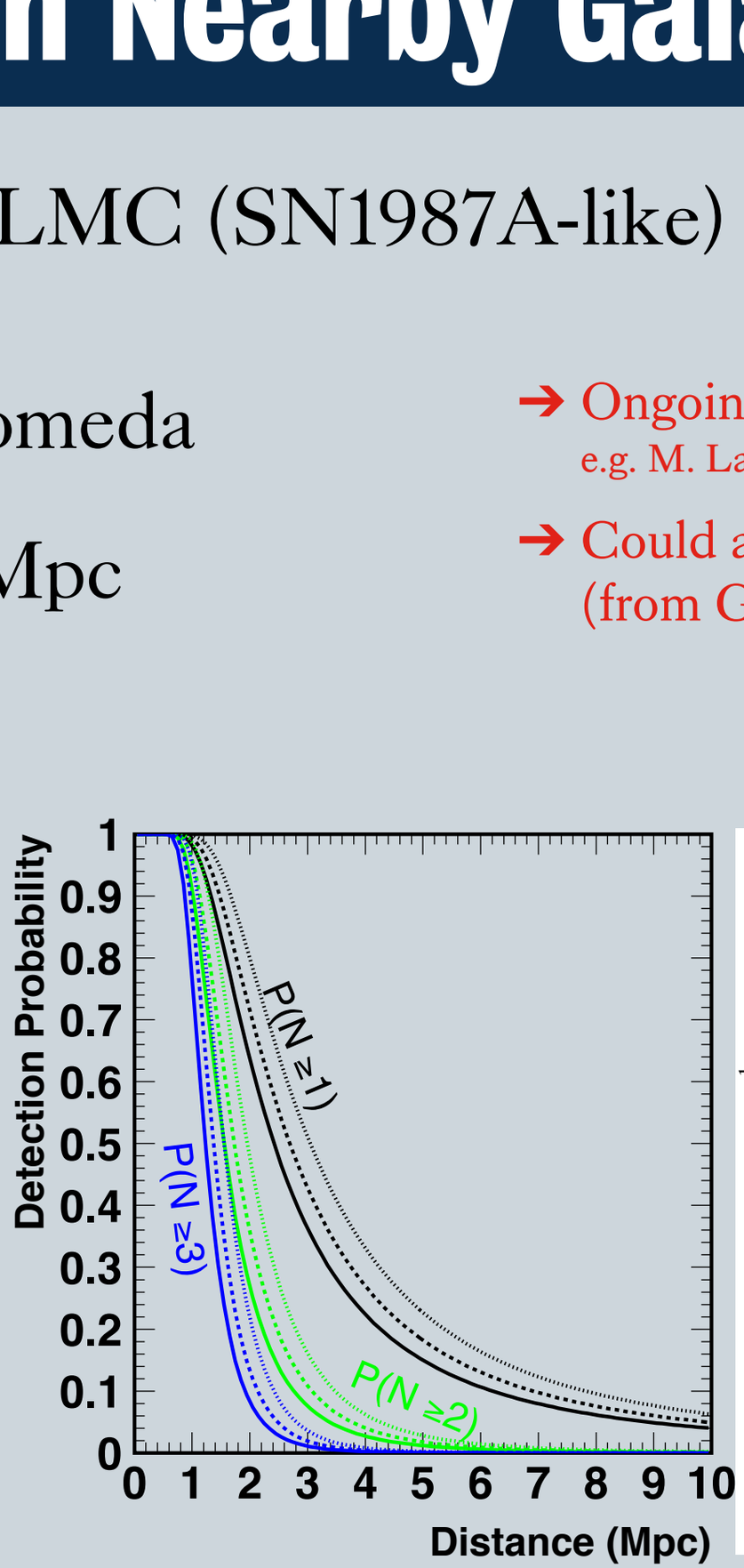
SN in Nearby Galaxy

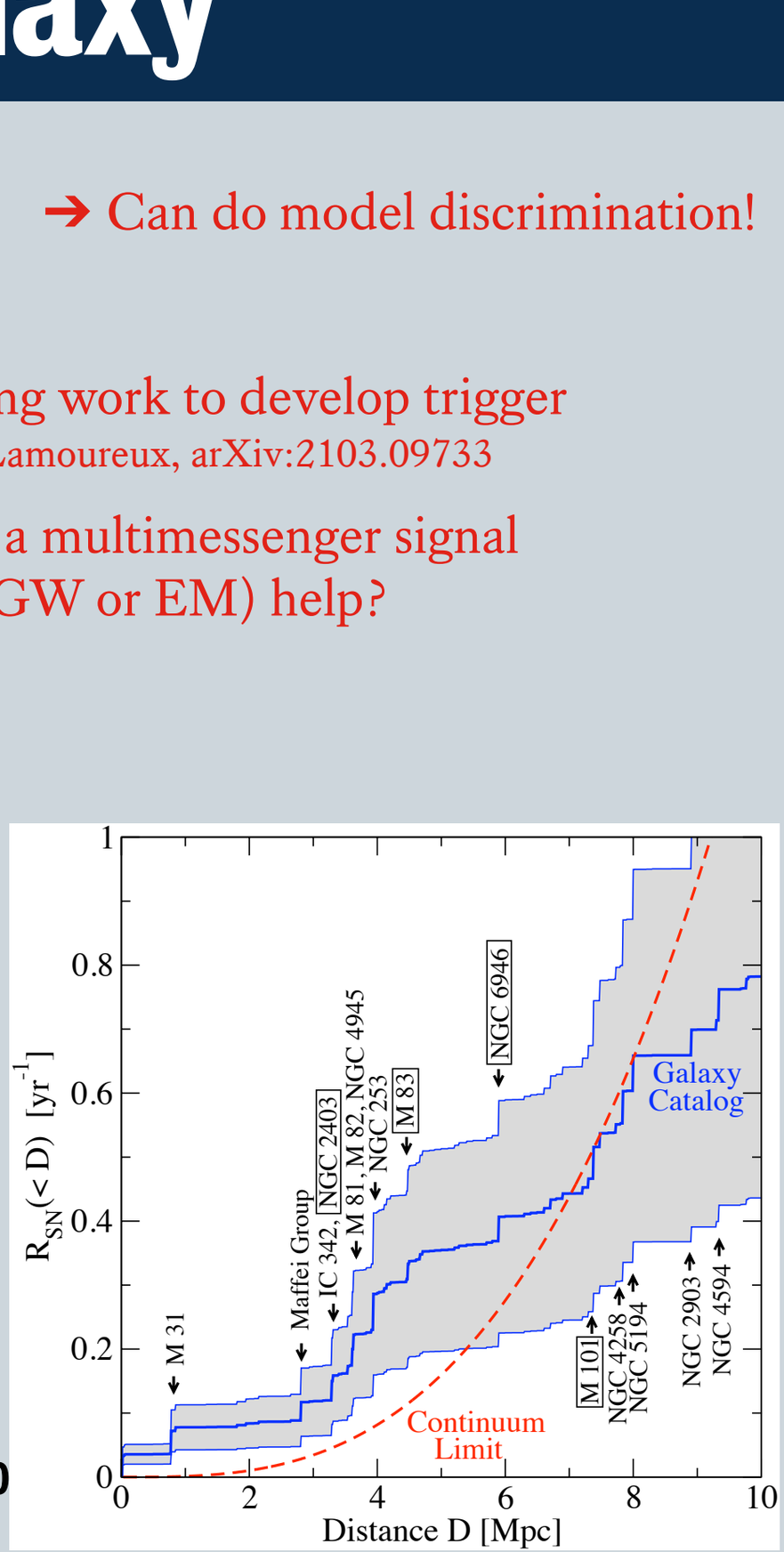
- 2100–3150 events in LMC (SN1987A-like) ➔ Can do model discrimination!
- 9–13 events in Andromeda
- ≥1 event out to few Mpc

➔ Ongoing work to develop trigger
e.g. M. Lamoureux, arXiv:2103.09733

➔ Could a multimessenger signal (from GW or EM) help?

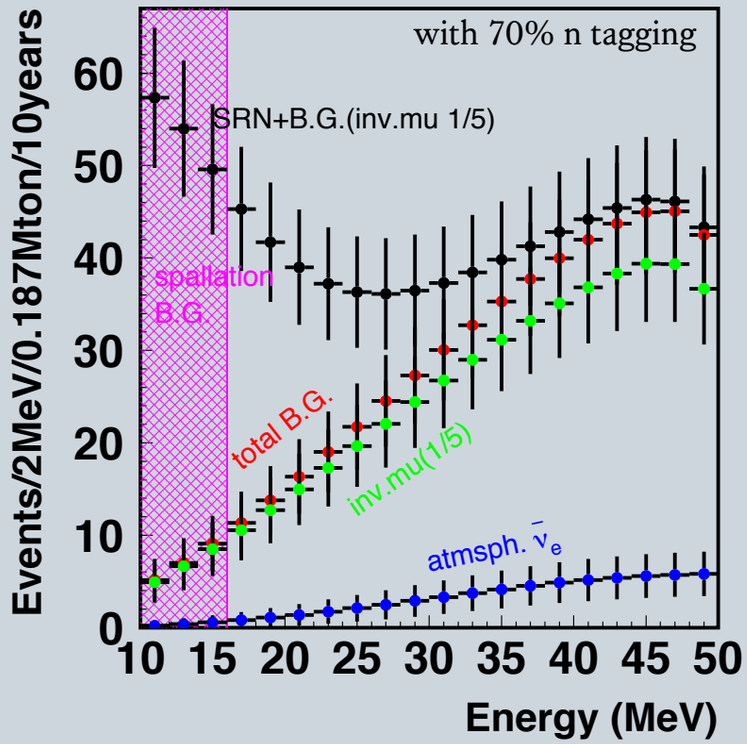


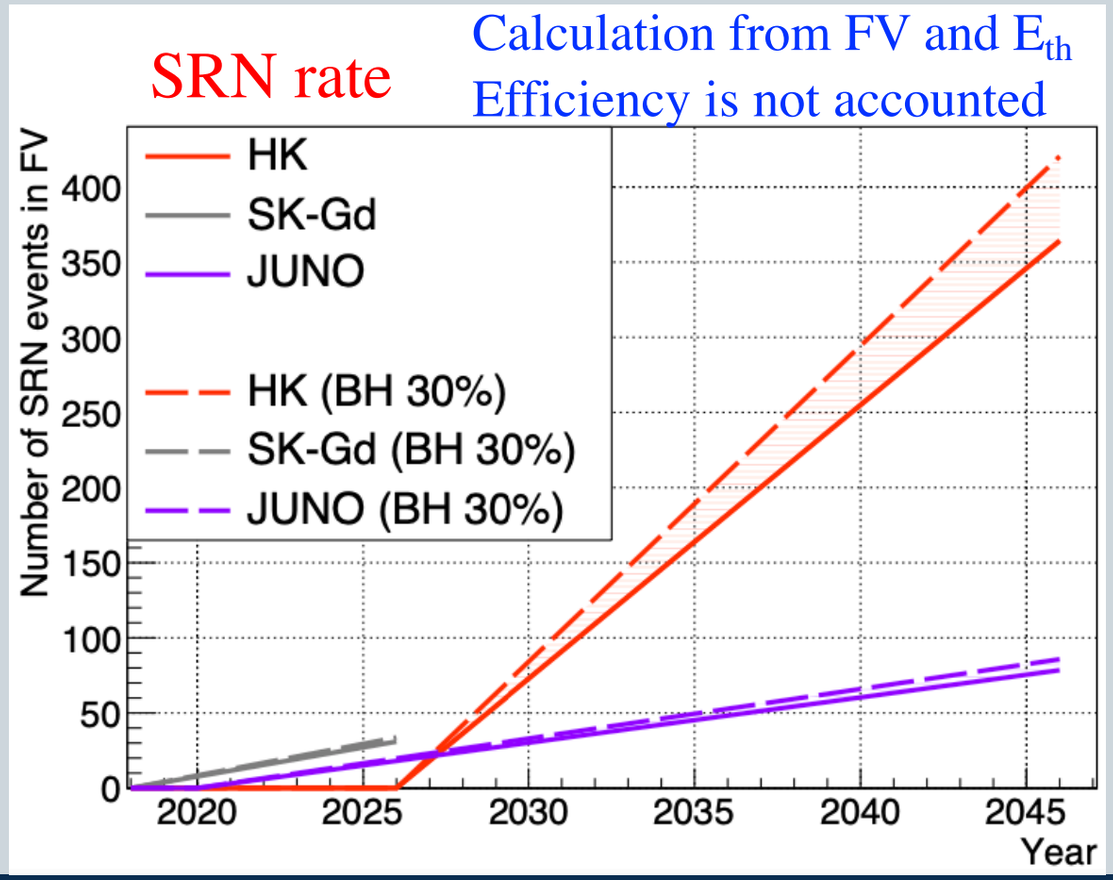


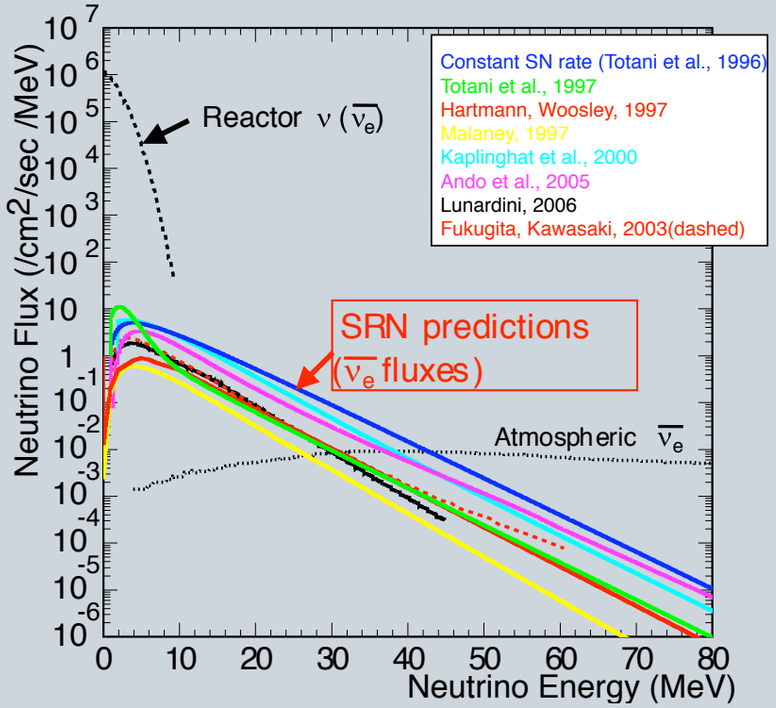


Supernova Relic Neutrinos

- 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







Summary

- HK is a next-generation underground water Cherenkov detector with a broad physics programme:
  - Proton decay searches surpassing 10^{35} years
  - Precision measurements of oscillation parameters (particularly CP violation & mass ordering) with long-baseline, atmospheric & solar neutrinos
  - Unprecedented statistics for neutrino astrophysics, e.g. solar, SN burst & relic neutrinos
- HK is officially approved in Japan
  - Construction has started & data taking begins in 2027
  - R&D to improve physics potential is ongoing (near detectors, photosensors & covers, electronics, outer detector, …)
  - New collaborators are welcome!