Overview of Supernova Neutrinos

Jost Migenda
they/them

About Me

- Mainly work on Hyper-K and SNEWS 2.0
- Have dabbled in ...
  - Liquid Argon (DUNE)
  - Liquid Scintillator (LSC@Yemilab, arxiv:2309.13435)
  - WbLS (Theia)
- Maintainer of SNEWPY, SNOwGLoBES & sntools
- Writing a book on software tools for SN neutrinos

  → *Talk to me to get early drafts of chapters & Jupyter notebooks!*

Agenda

Linda, yesterday:

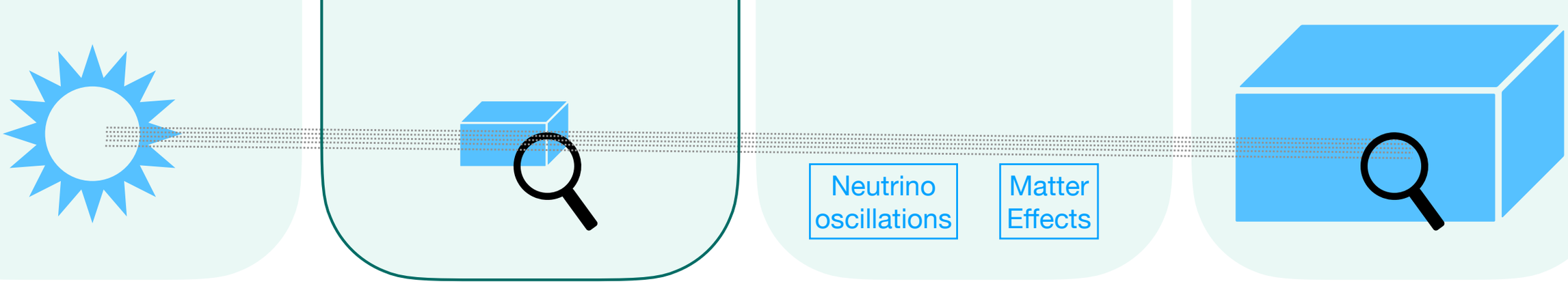
All neutrino oscillation experiments are the same…

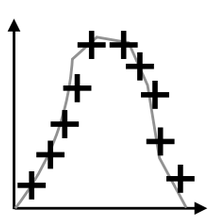
Produce neutrinos
[possibly all in the same flavour]

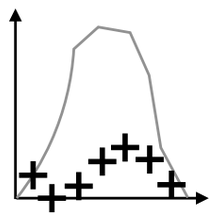
Check what you produced
[optional]

Propagate!
[a few km
to a few kpc]

Look for a deficit or excess!







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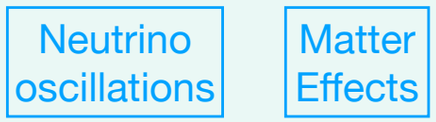

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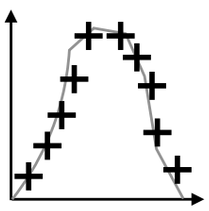

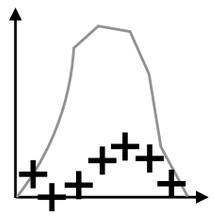

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S O F T W A R E

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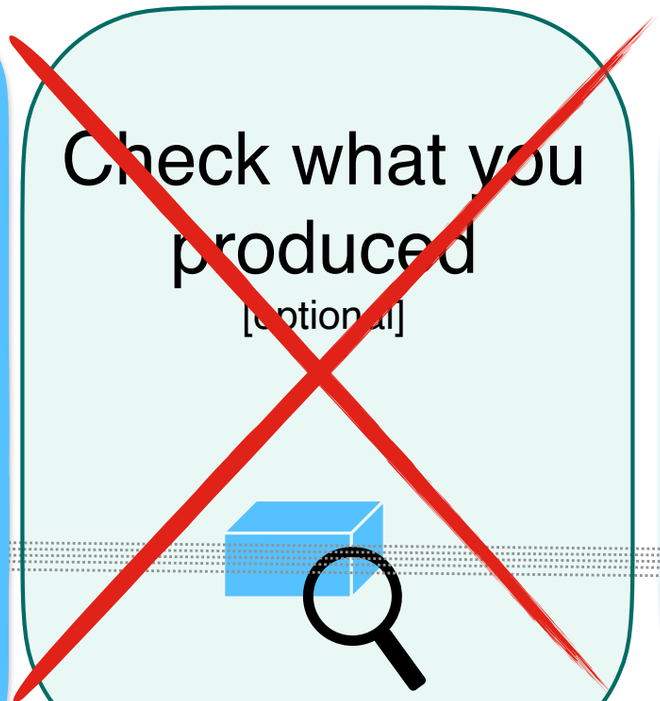

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Neutrino oscillations

Matter Effects

Look for ~~a deficit~~ or excess!

SOFTWARE

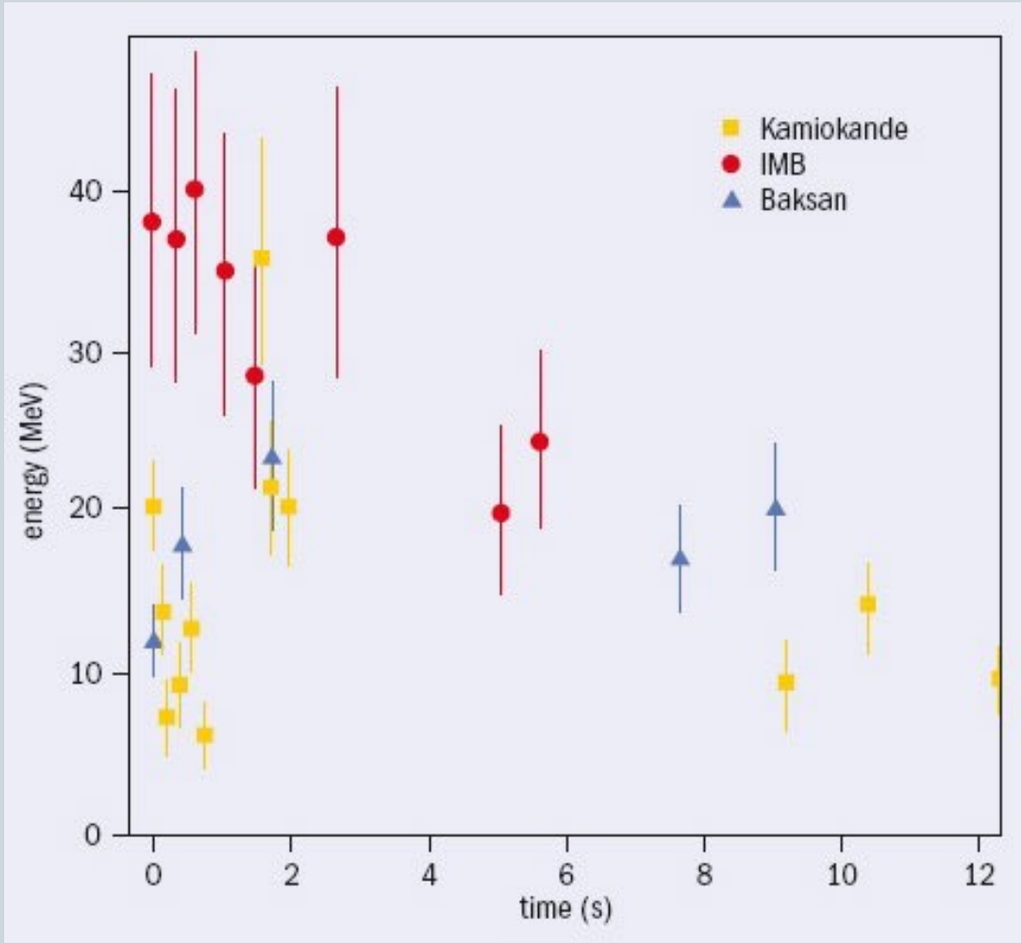
Production

- Stellar evolution before core-collapse is a whole separate field
  - See e.g. codes like TULIPS (E. Laplace), BPASS (J.J. Eldridge, E. Stanway *et al.*), MESA
  - Note: "20 M_{sol} progenitor" refers to Zero Age Main Sequence (ZAMS) mass—relation to pre-explosion structure of progenitor is complicated …
    - Common progenitors e.g. by Woosley & Heger, Sukhbold et al.
- Alternative mechanisms (ECSN, PISN, Ia) are beyond the scope of this talk!

What We (Think We) Know …

- SN1987A: two dozen events in Kamiokande, IMB, Baksan

- 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

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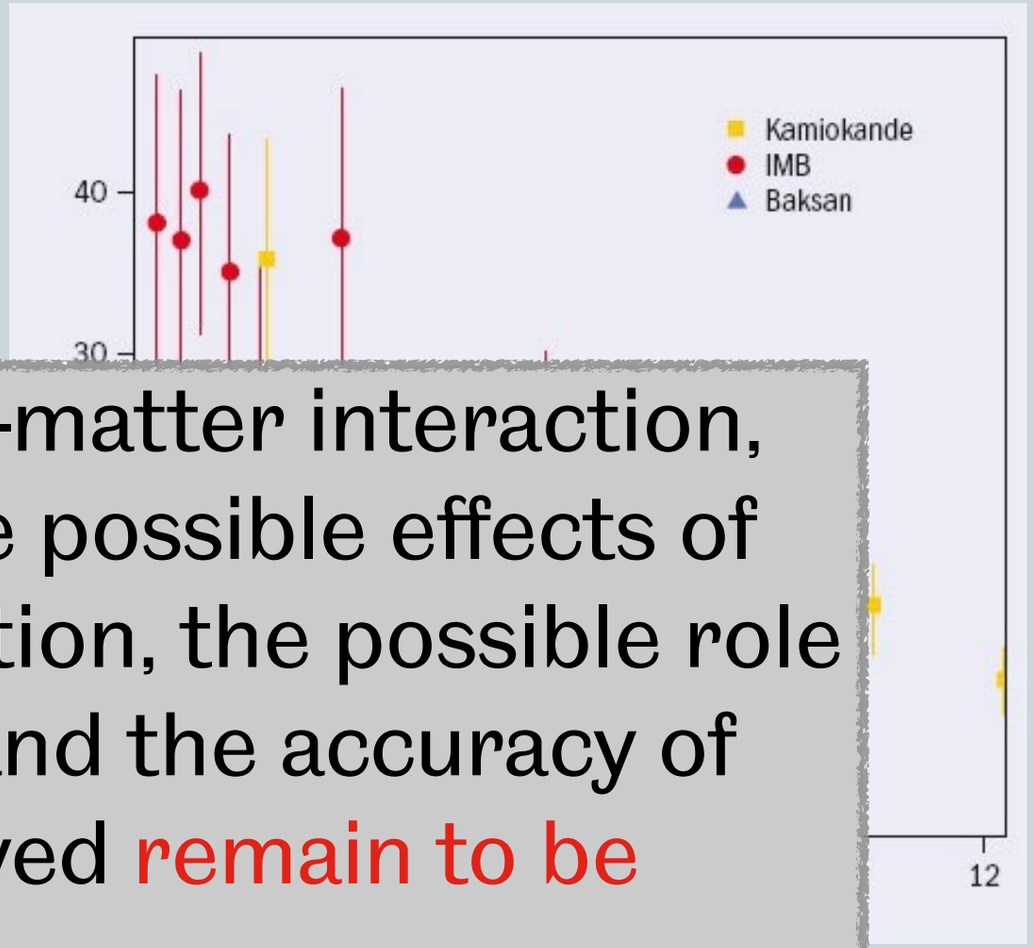

"issues concerning the neutrino–matter interaction, the nuclear equation of state, the possible effects of neutrino oscillations, grid resolution, the possible role of rotation and magnetic fields, and the accuracy of the numerical algorithms employed remain to be resolved."

— Wang, Vartanyan, Burrows, Coleman (arXiv:2207.02231)

9903472

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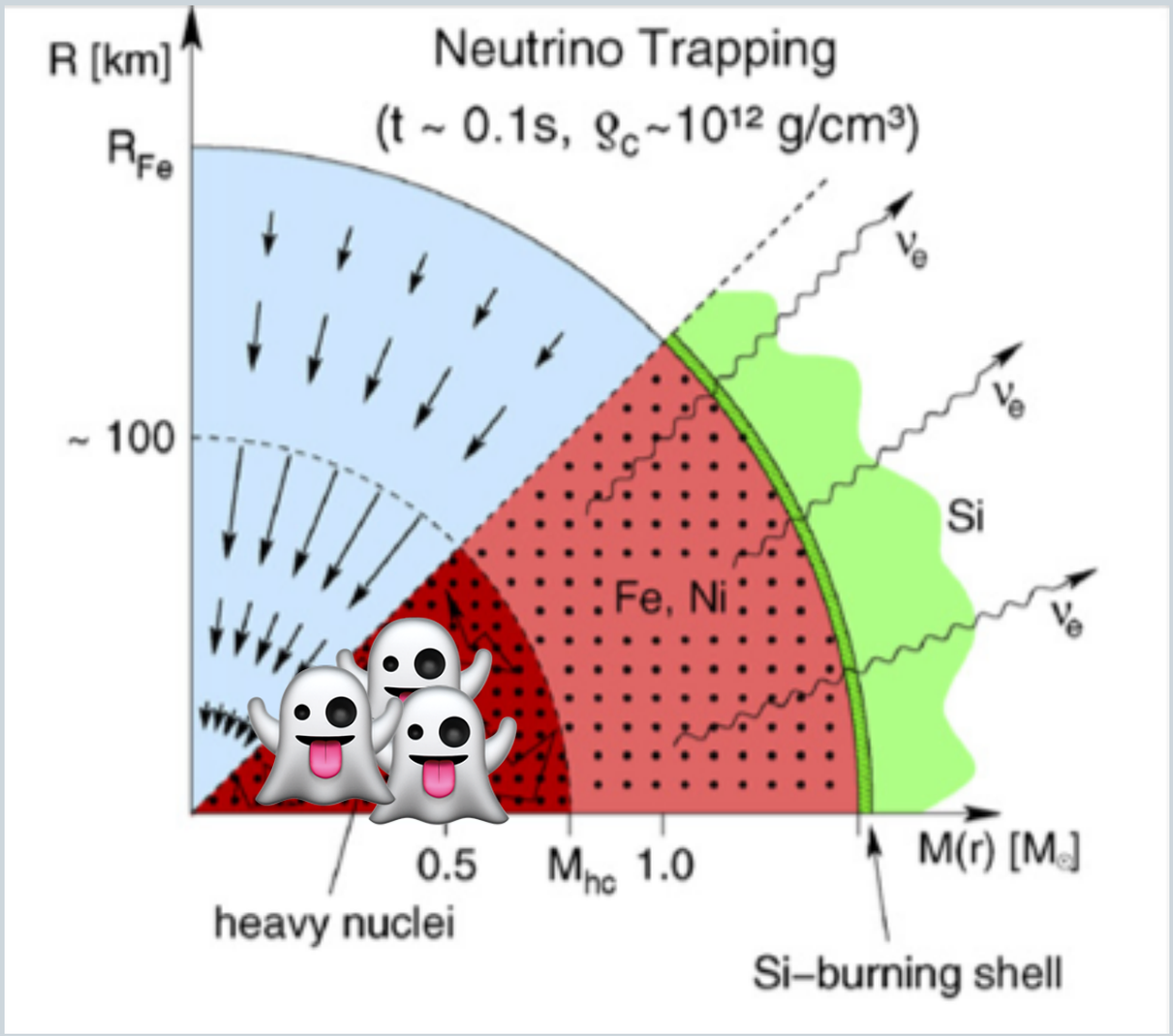
1) The Star Collapses



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

2) A Shock Wave Forms

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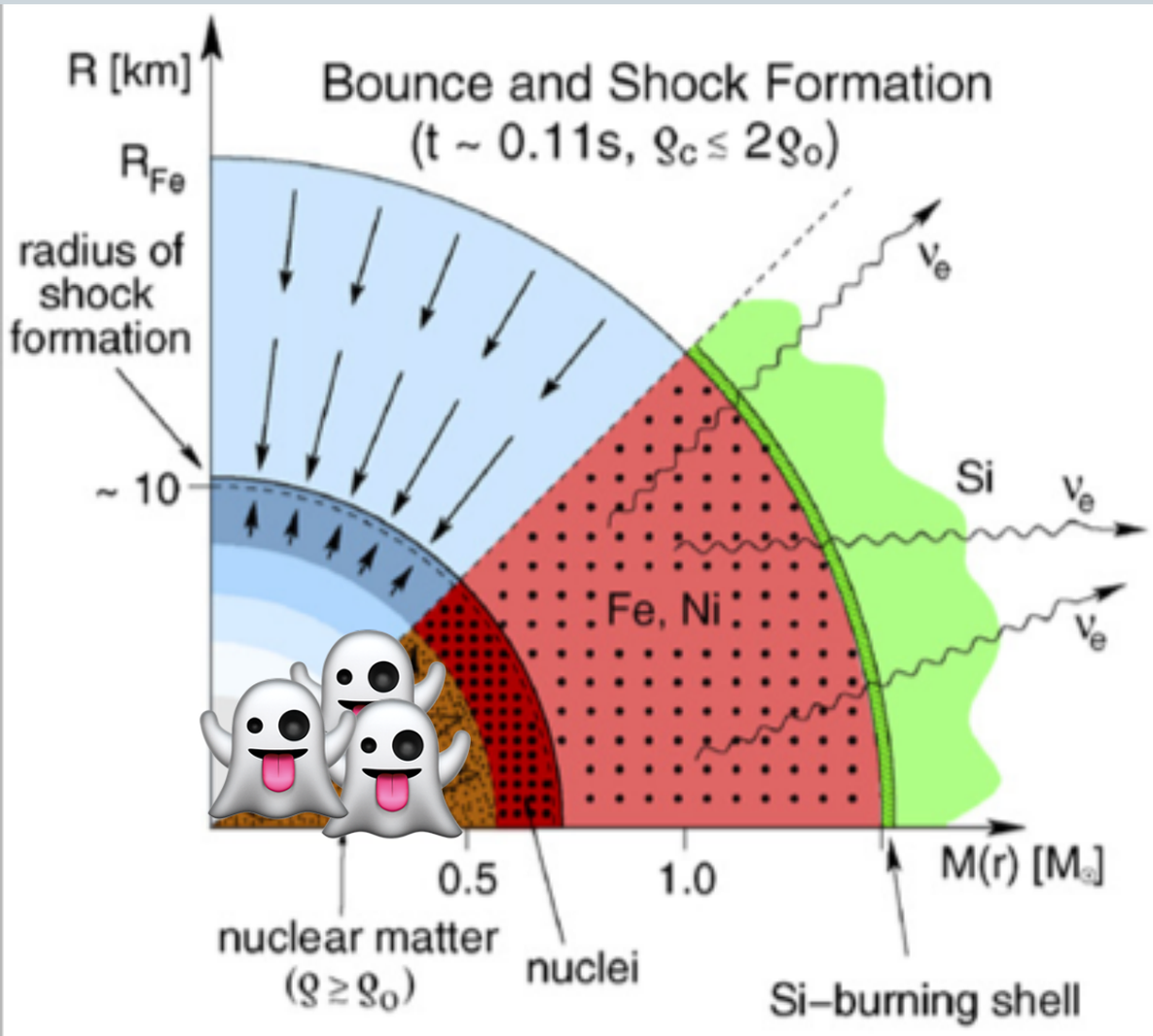

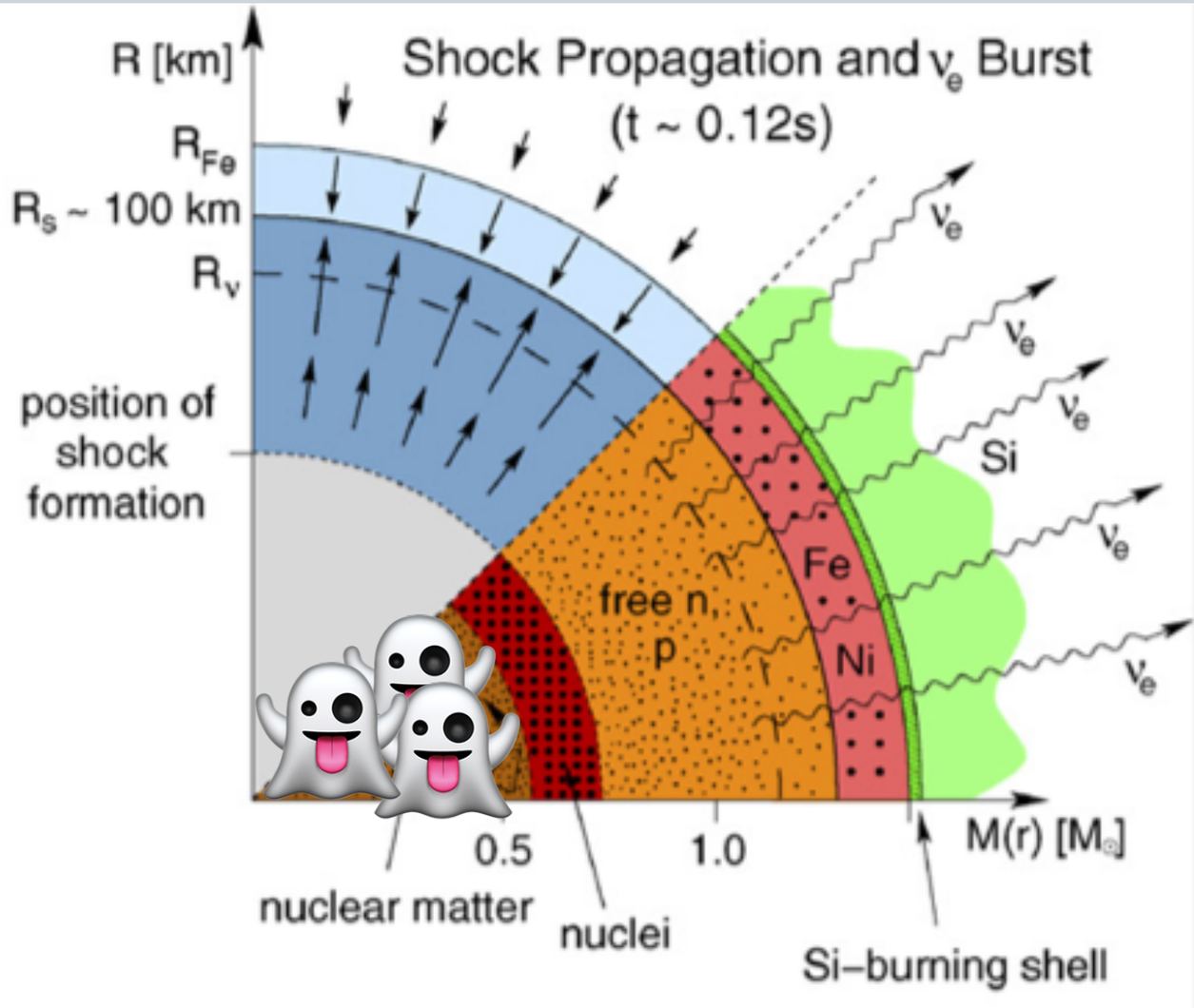

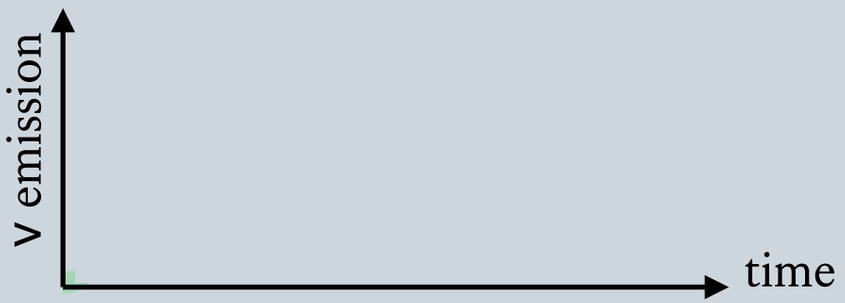

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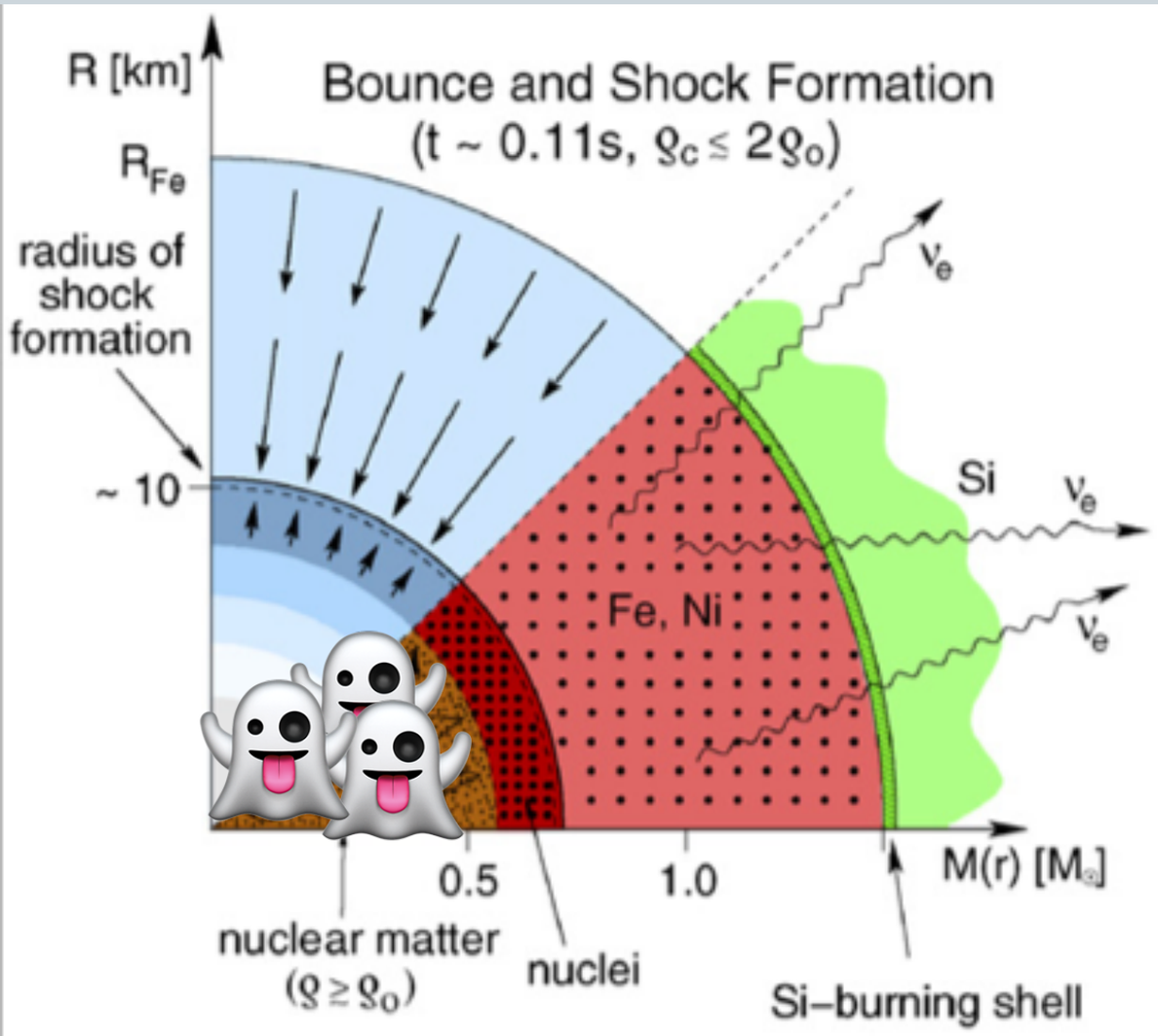

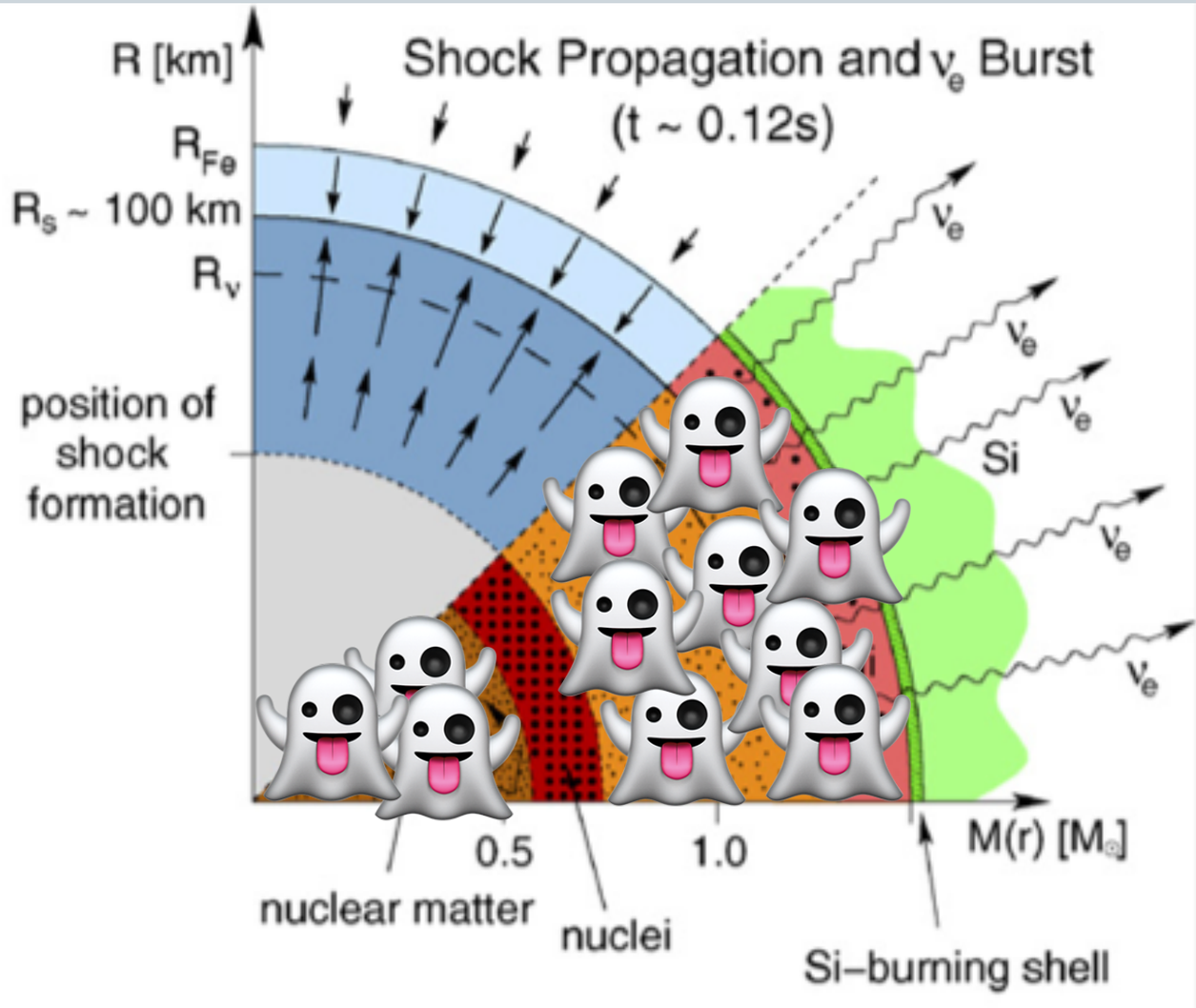

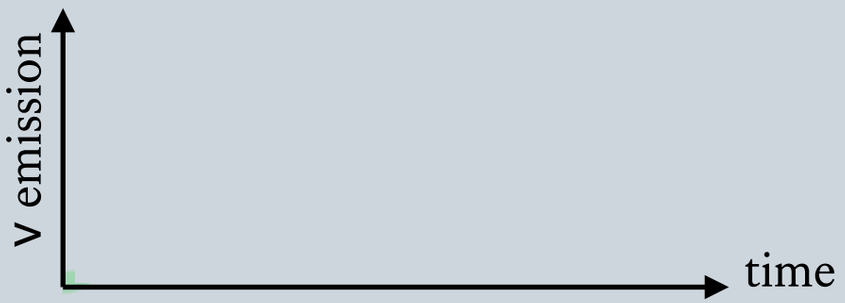

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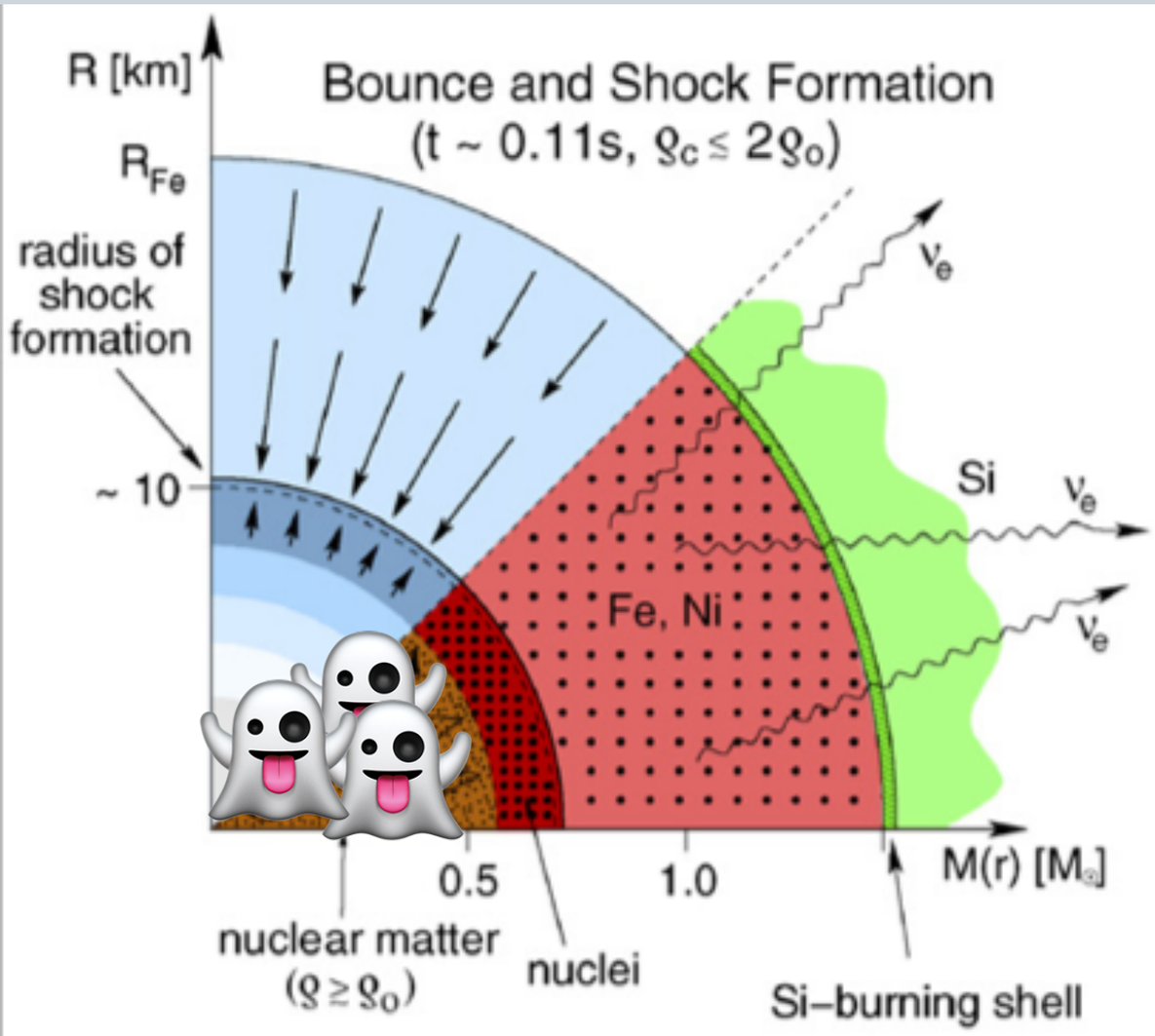

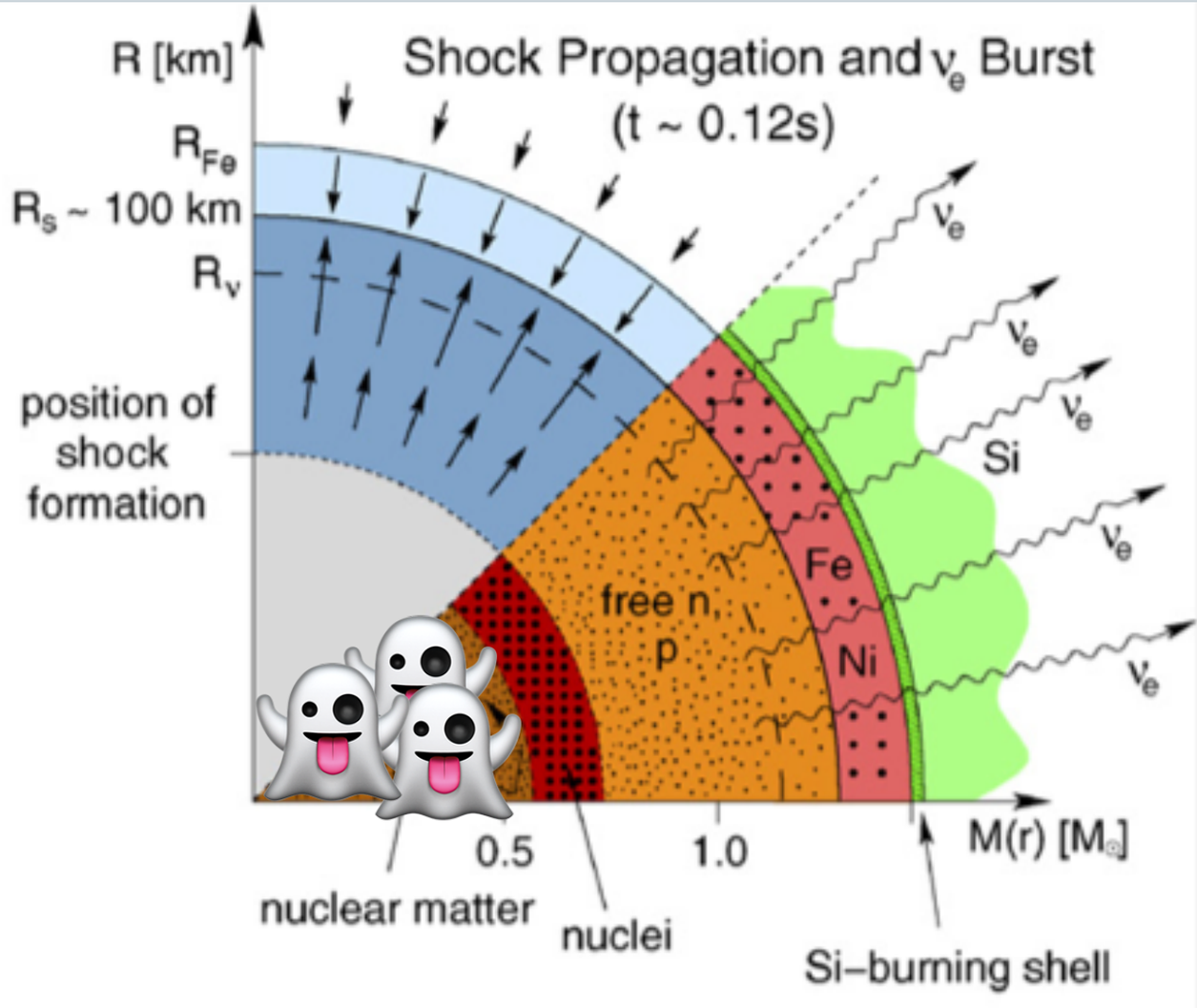

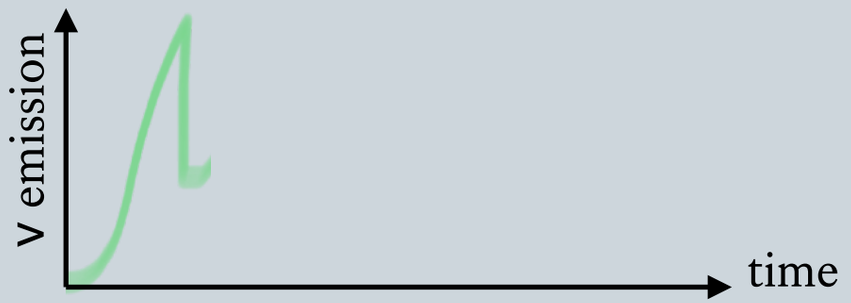

3) Shock Wave Is Restarted & Explodes

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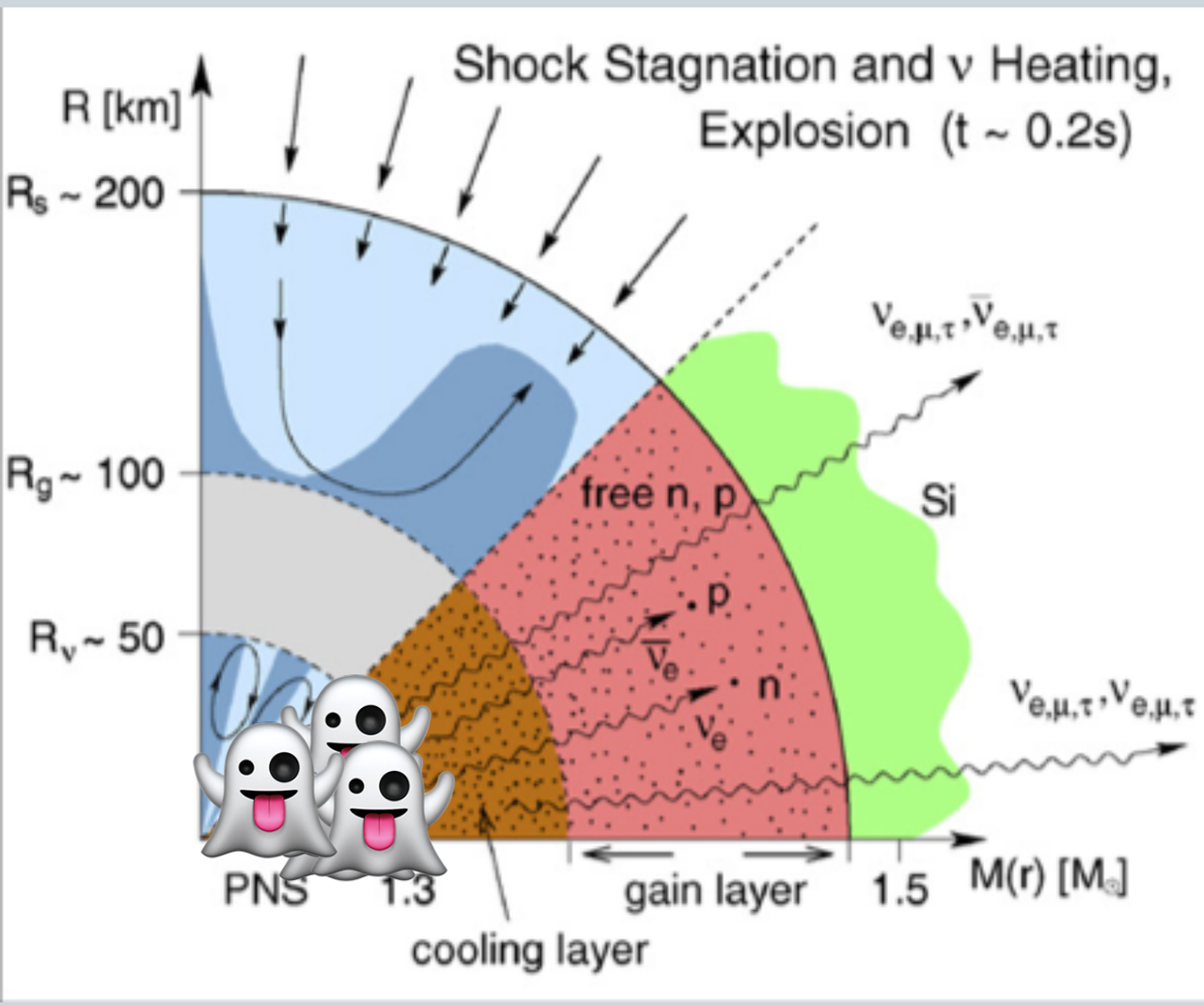

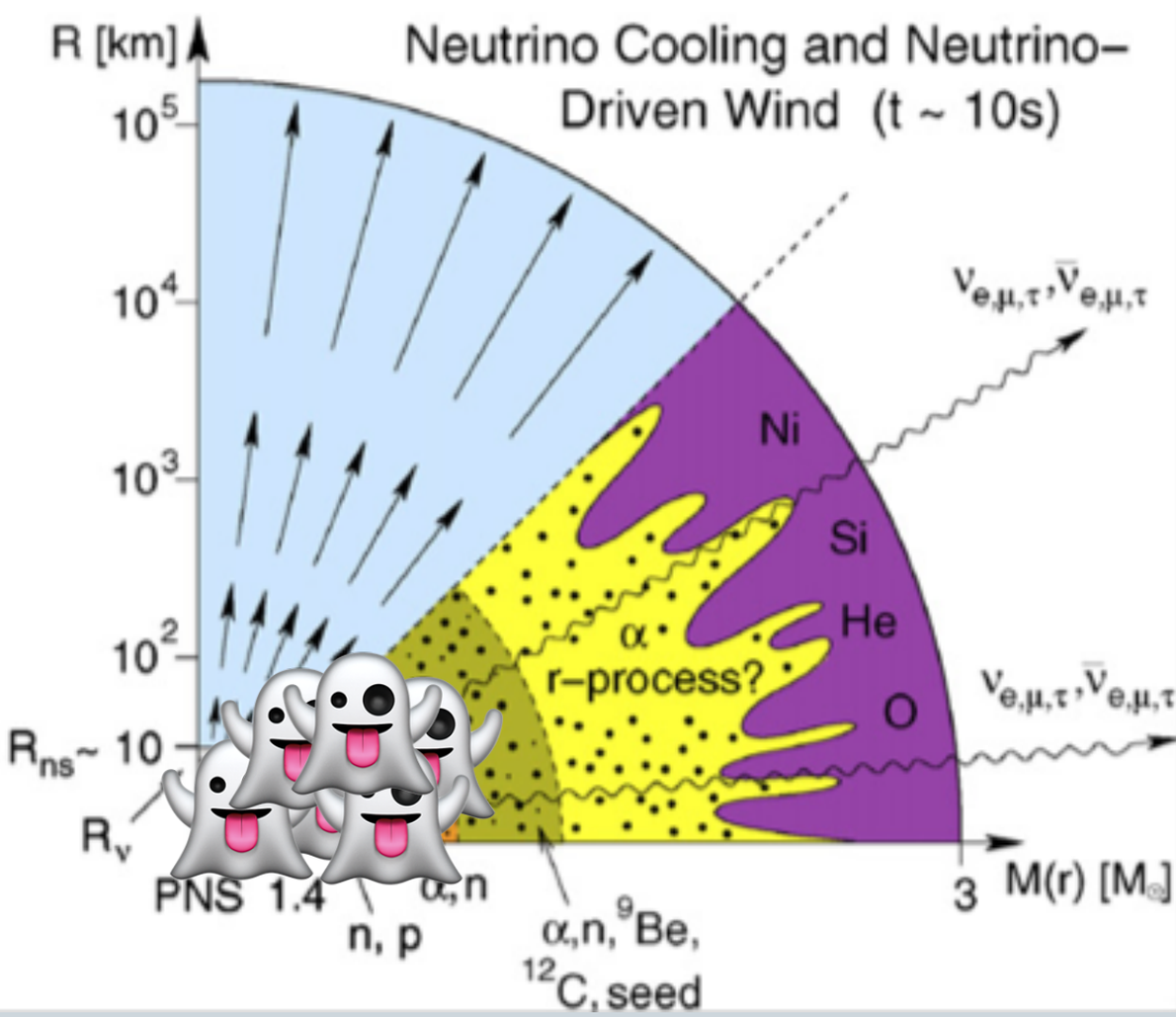

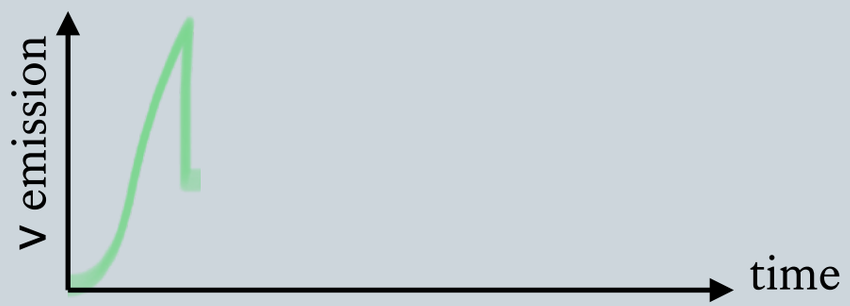

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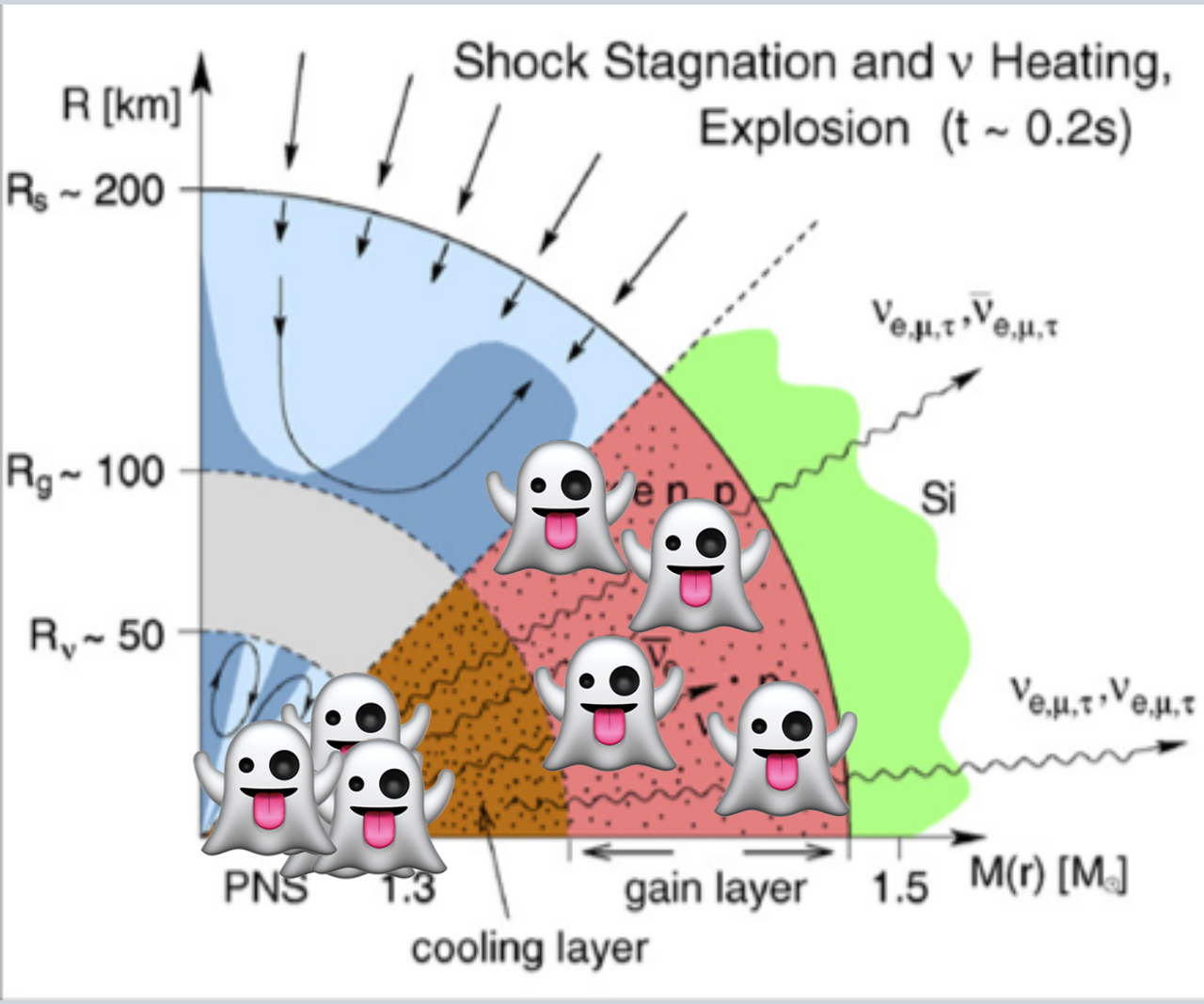

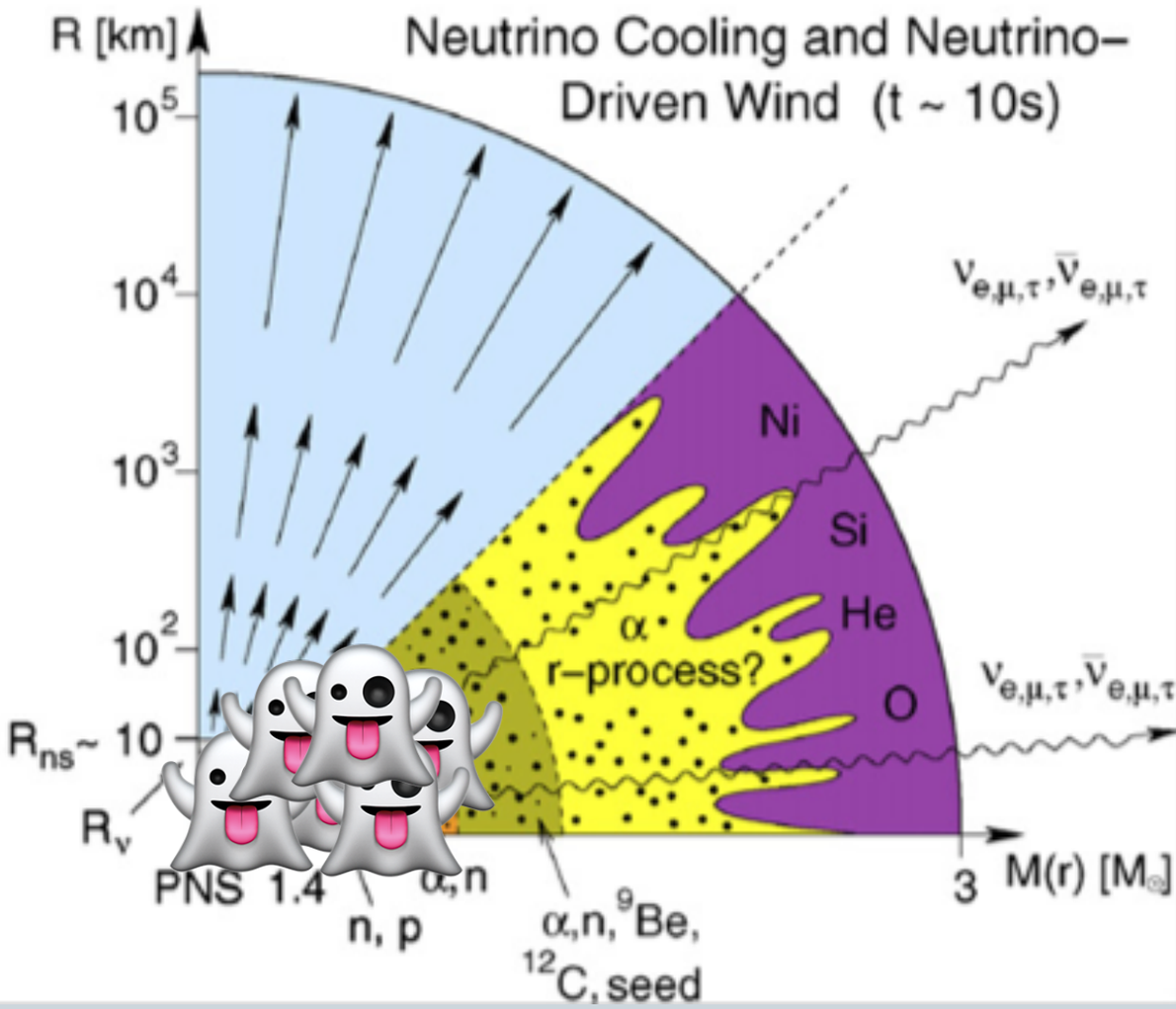

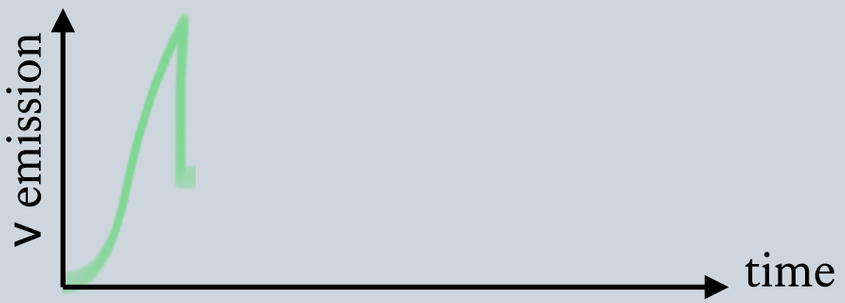

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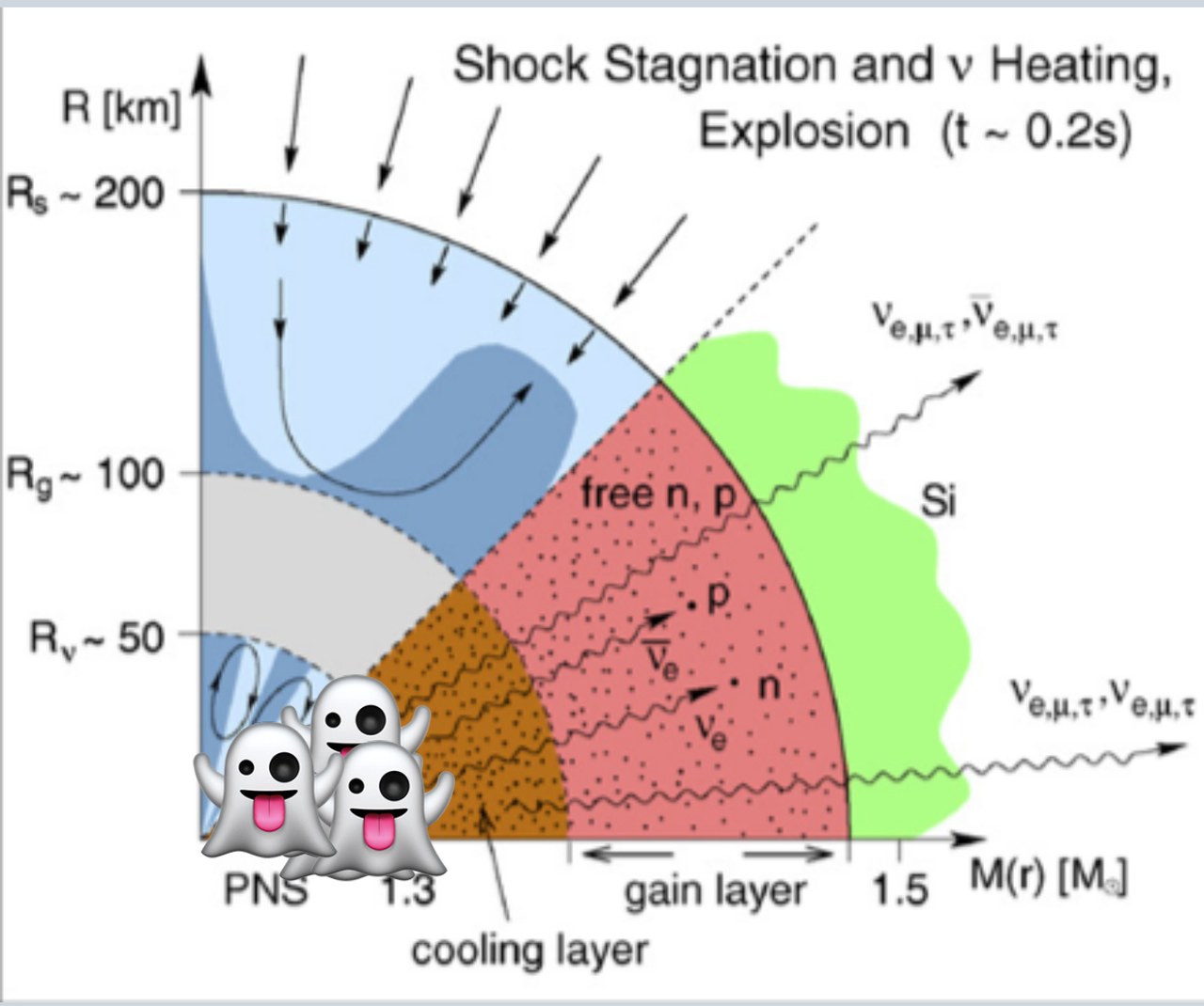

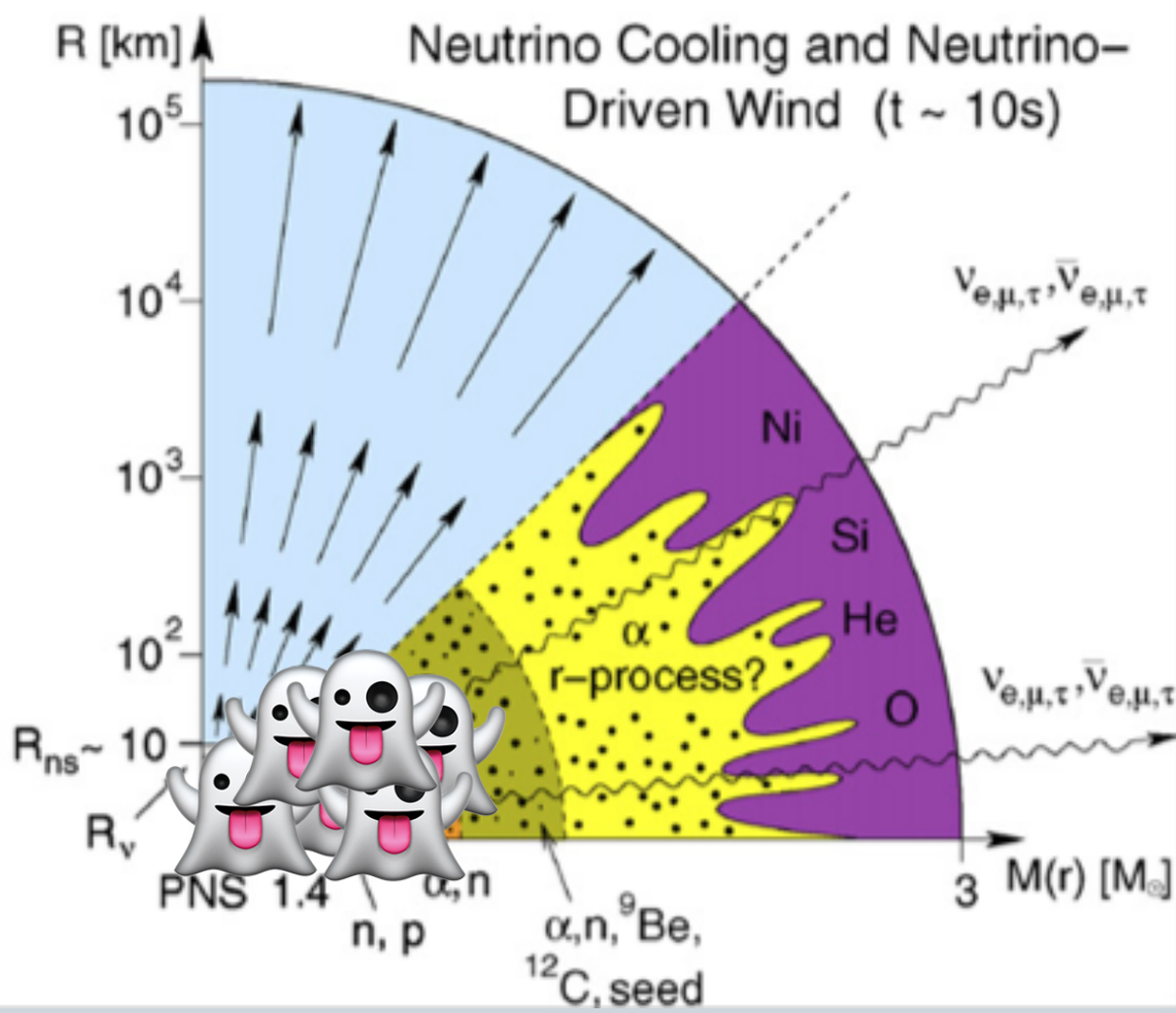

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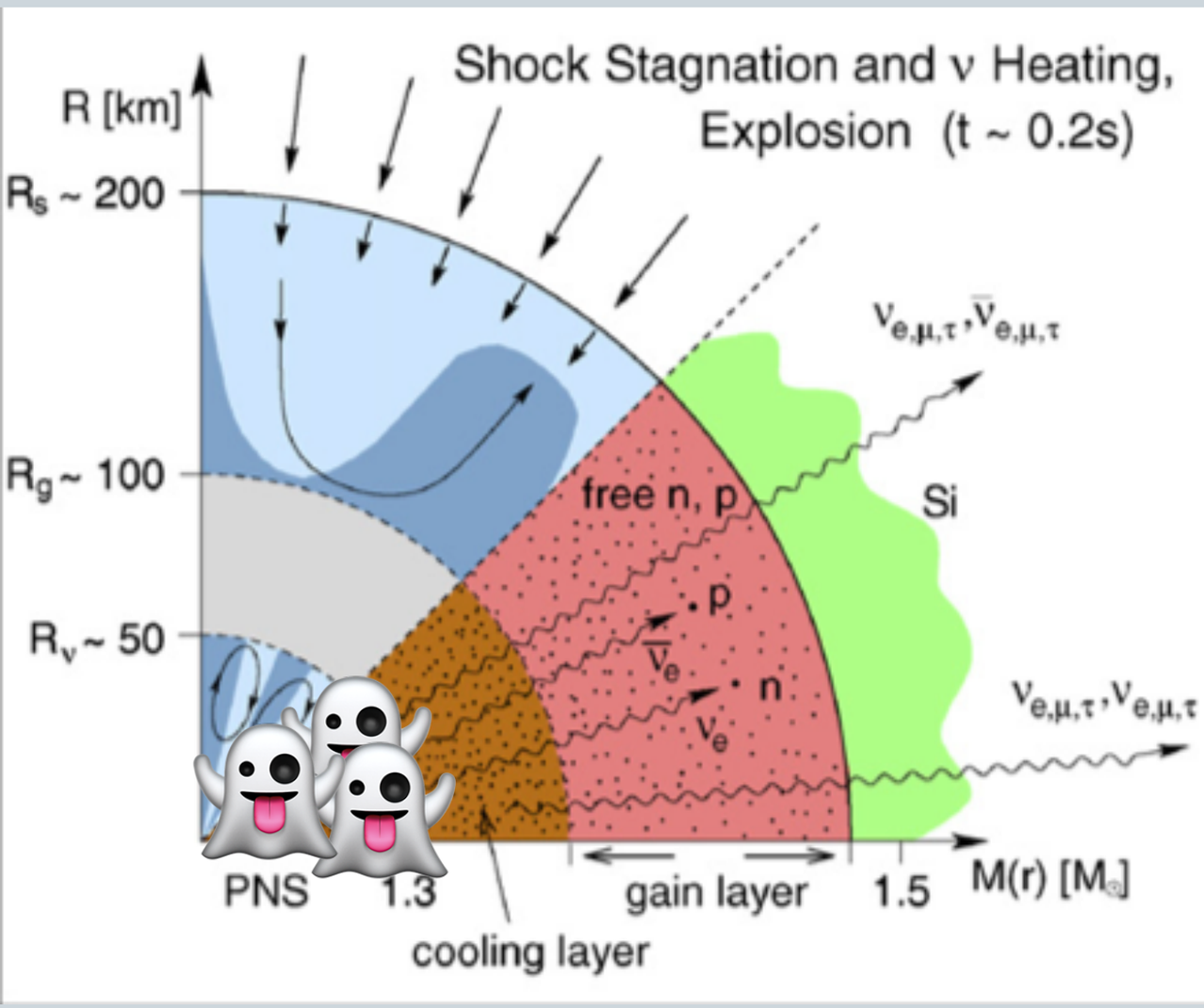

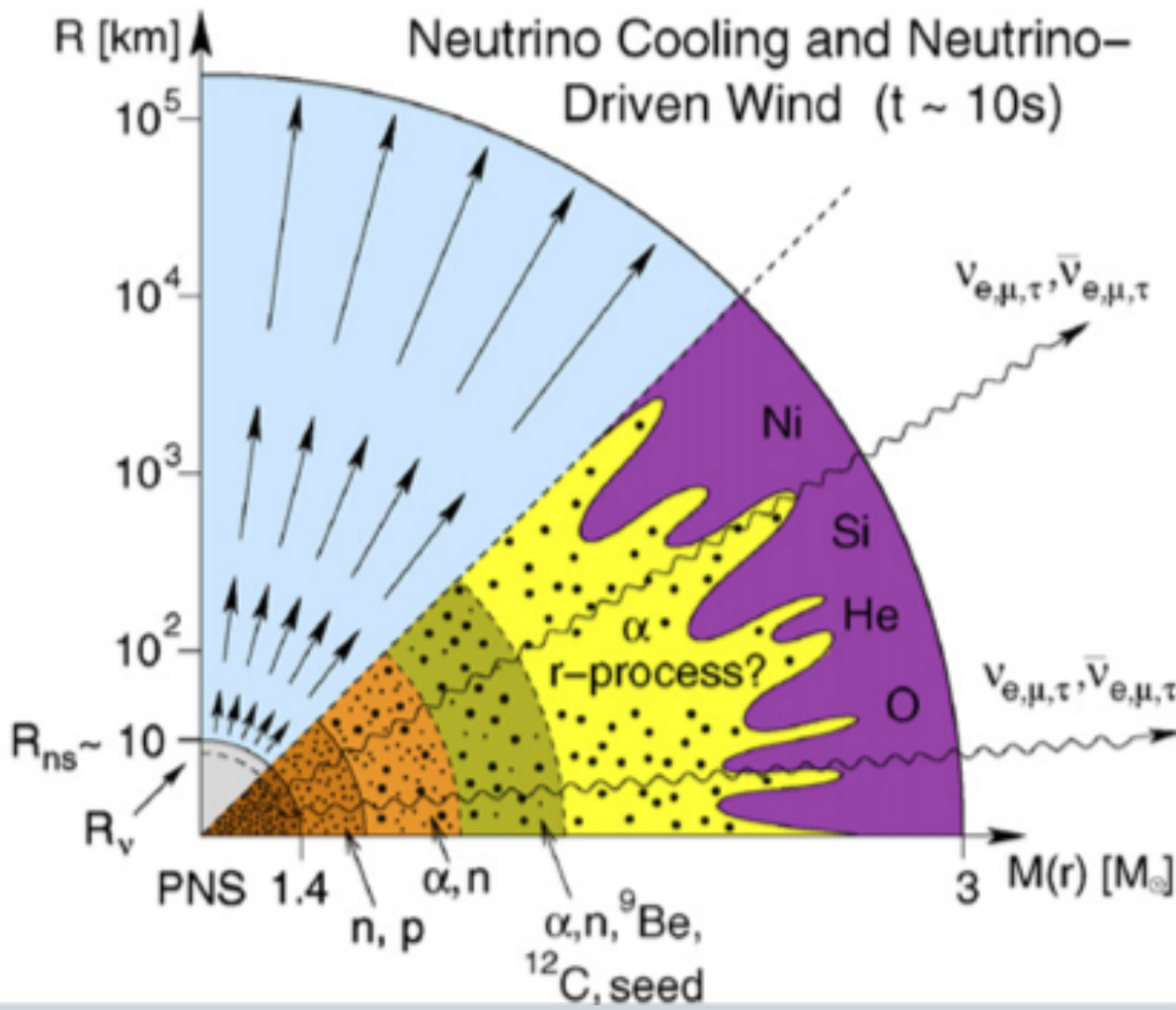

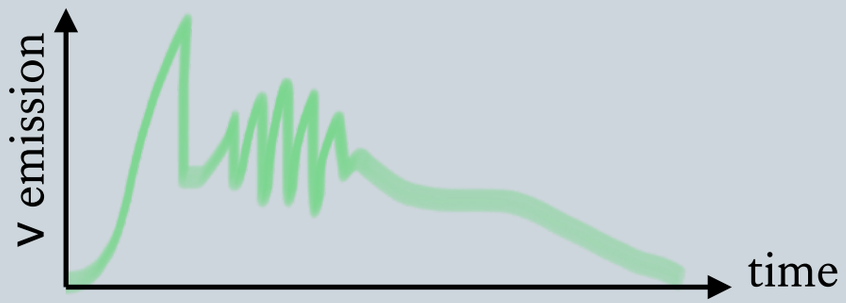

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Neutrino oscillations

Matter Effects

Look for ~~a deficit~~ or excess!

~~SOFTWARE~~

Agenda

- Fast flavor conversion
  ($\nu - \nu$ interactions lead to flavor transformations on ~cm scales, see e.g. arXiv:2301.11938 and refs therein)
- Adiabatic MSW (as seen in solar neutrinos) with normal or inverted mass ordering
- Non-adiabatic MSW because of shock wave
- Your favorite exotic scenario: NSI, steriles, ν decay, ...
- Earth matter effect

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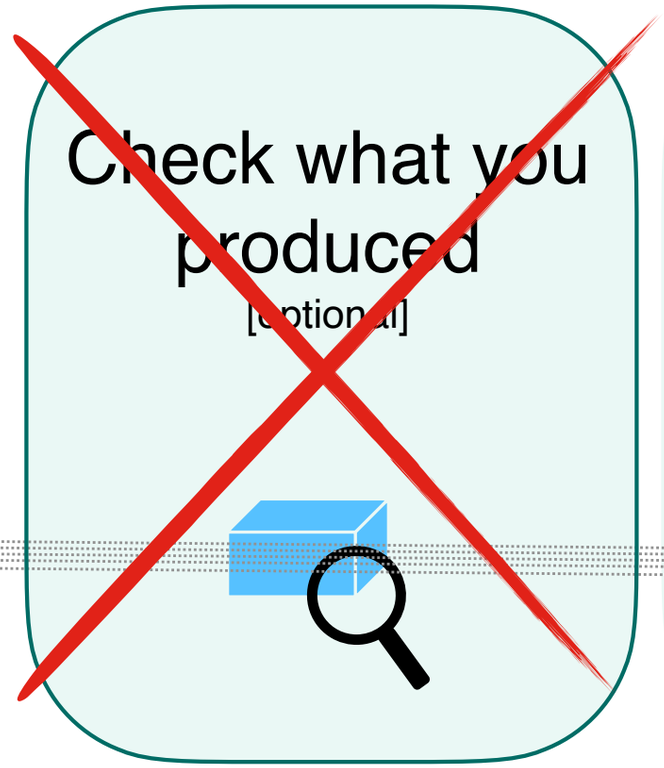

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S O F T W A R E

Neutrino Interactions

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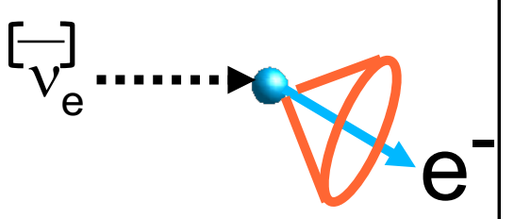
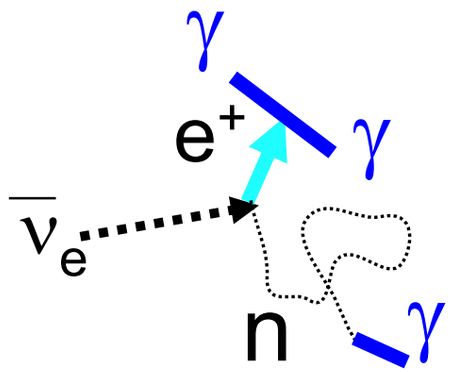
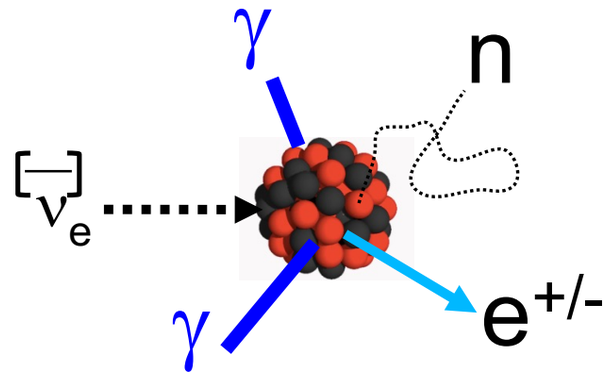
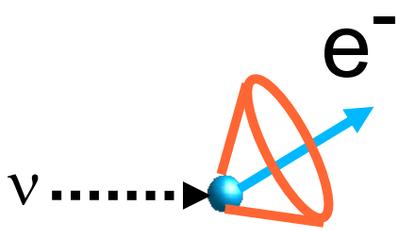
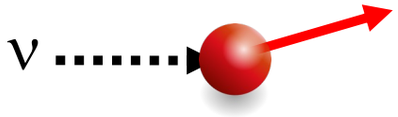
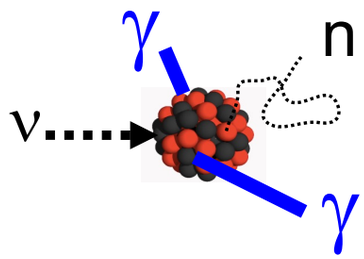
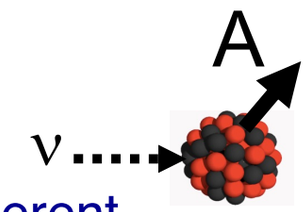
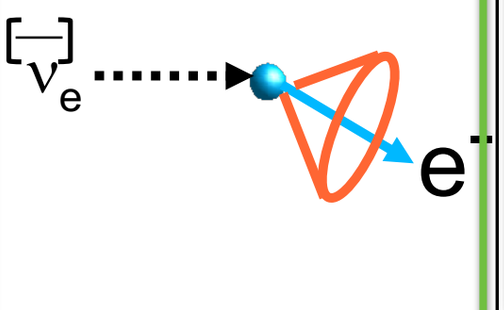
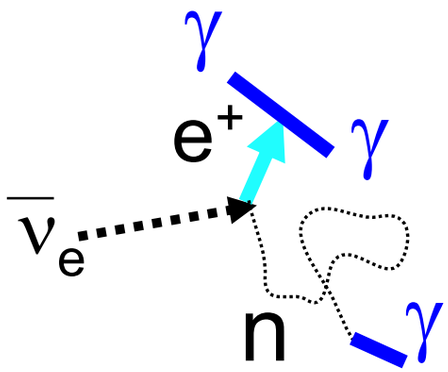
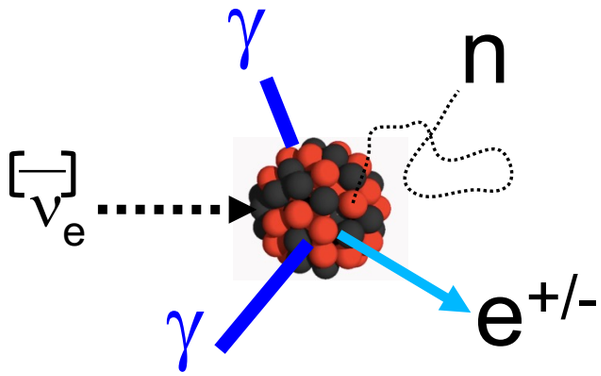
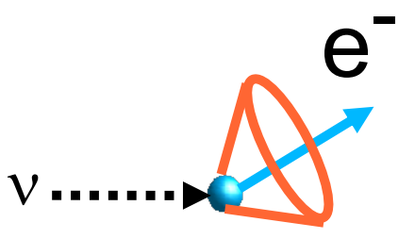
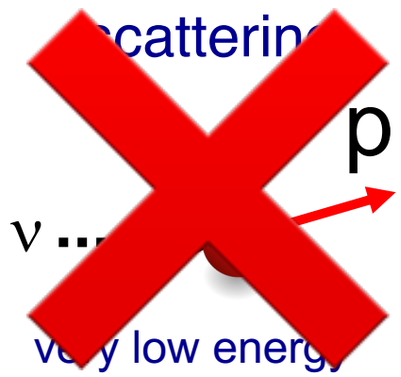
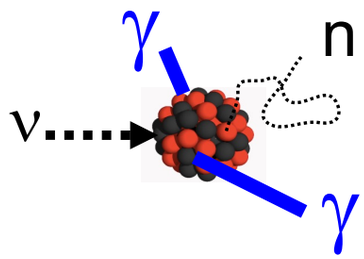
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

Slide from Kate Scholberg, SN@LNGS 2023

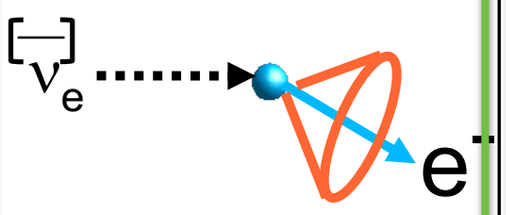
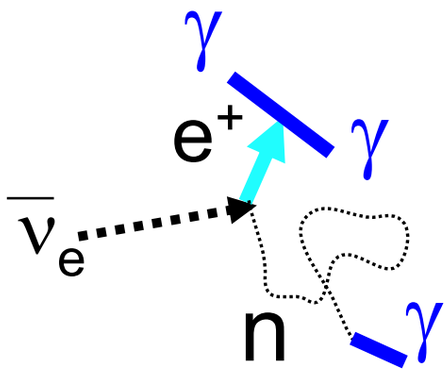
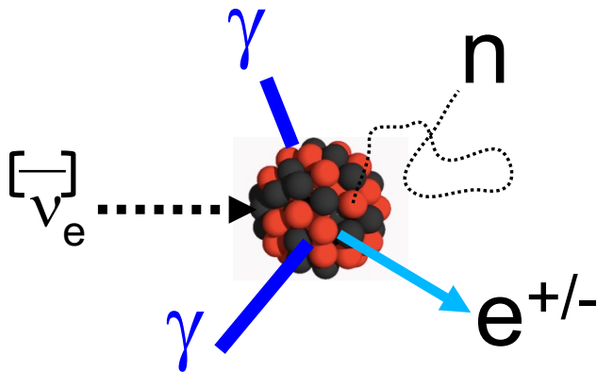
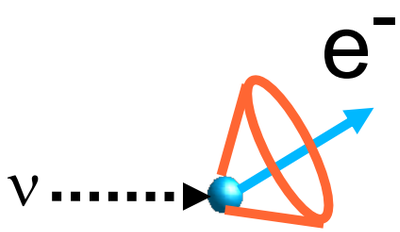
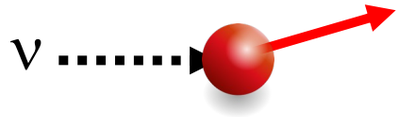
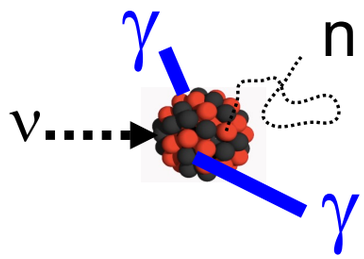
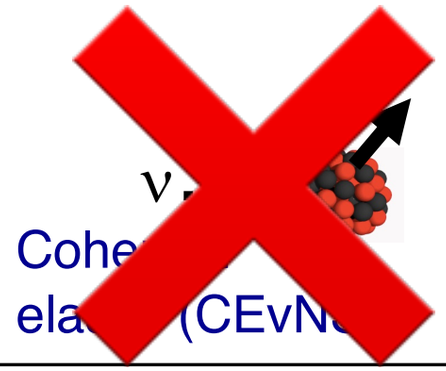
Water Cherenkov Detectors

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

e.g. SK, HK, IceCube*, KM3NeT*

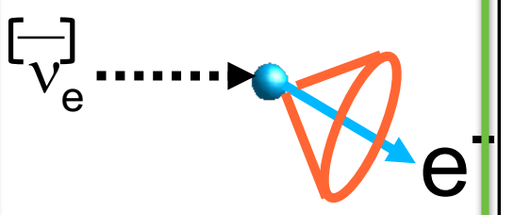
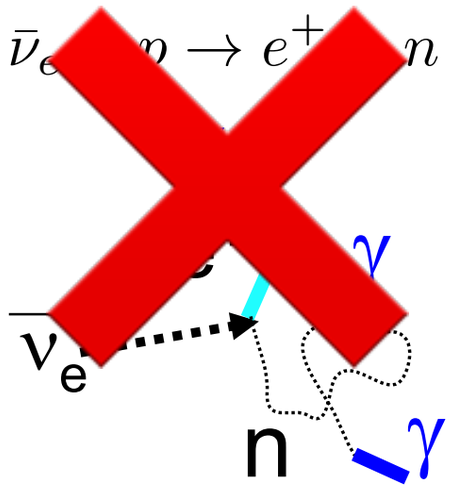
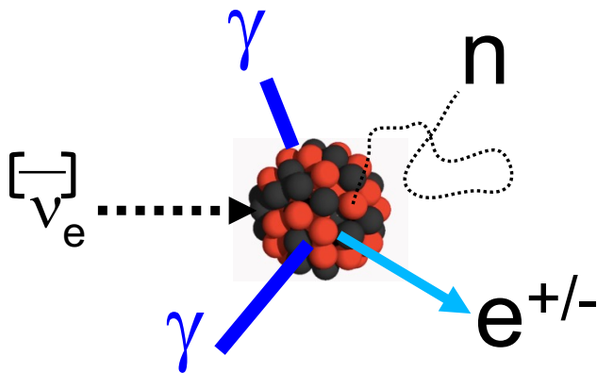
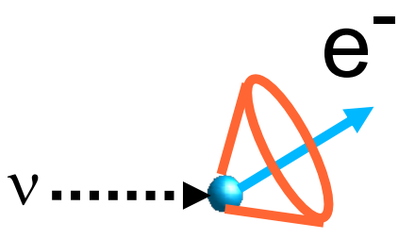
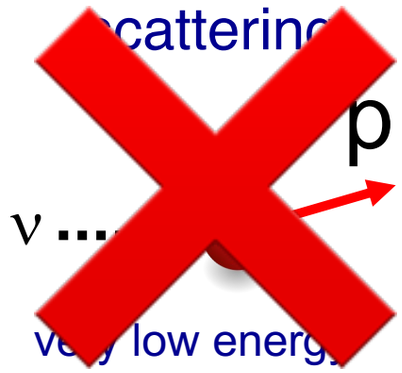
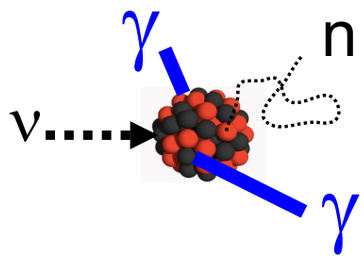
* rate-only, can't reconstruct individual events

Liquid Scintillator Detectors

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Cohe… ela… (CEvN…

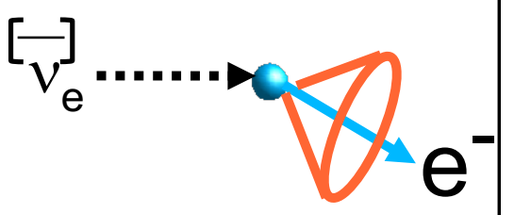
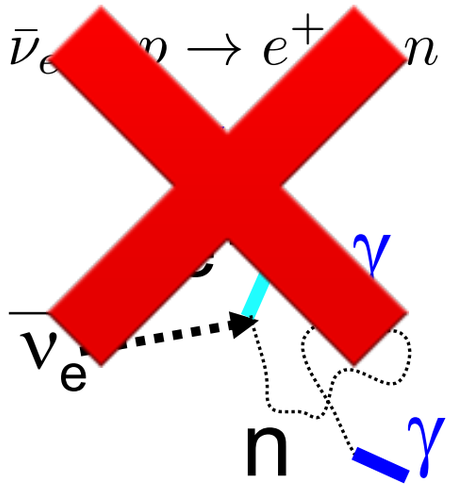
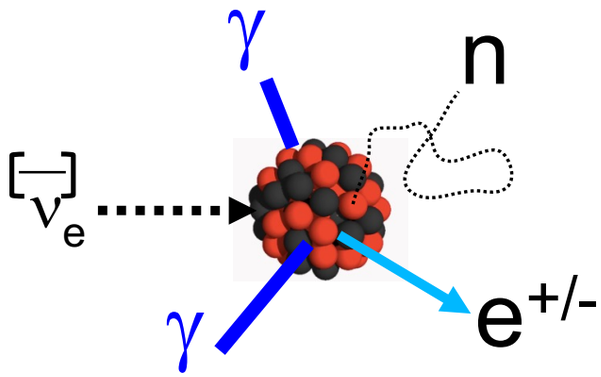
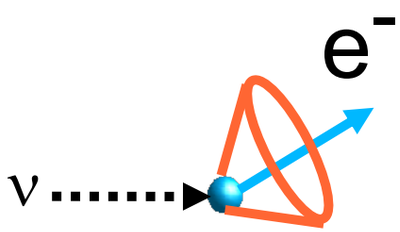
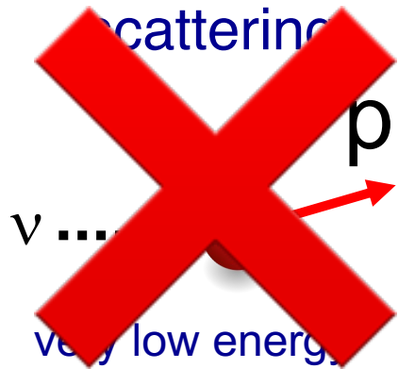
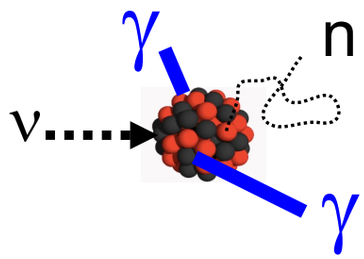
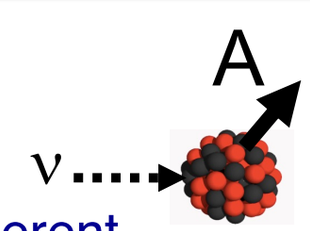
e.g. SNO+, JUNO

Liquid Argon Detectors

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

e.g. DUNE

Direct Dark Matter Detectors

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

e.g. XENONnT, LZ, DS-20k

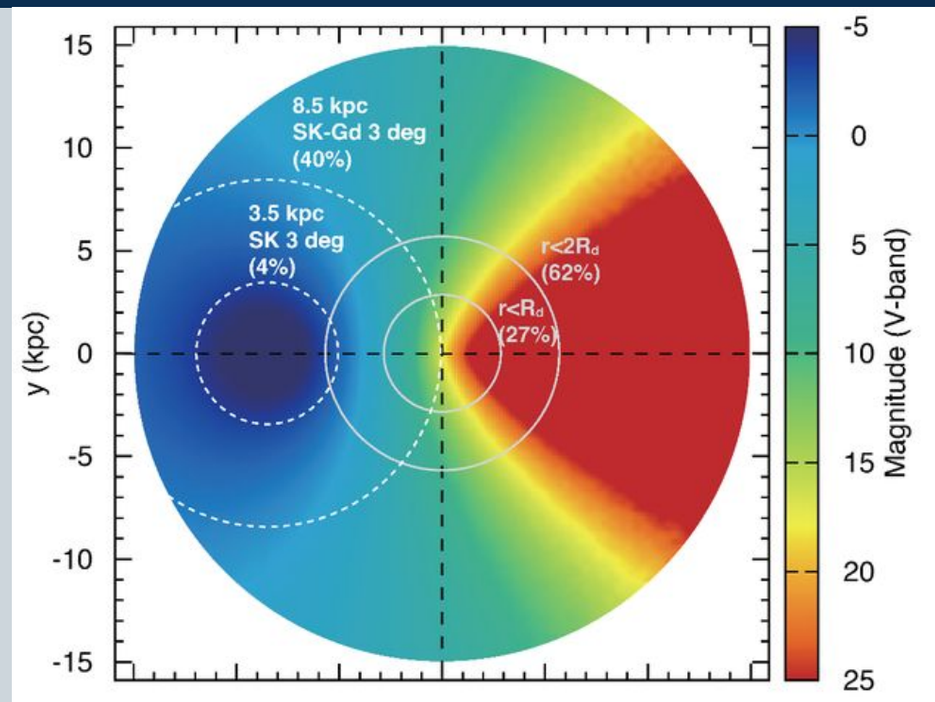
Lang et al. arXiv:1606.09243

All Together Now!

- … and various other detector types/materials
- Exploiting complementarity of different detectors will be essential for disentangling flavour transformations; e.g. we could get …
  - $\bar{\nu}_e$ from Hyper-K
  - ν_e from DUNE
  - $\sum \nu$ from JUNO ($\nu - p$ scattering) & DARWIN

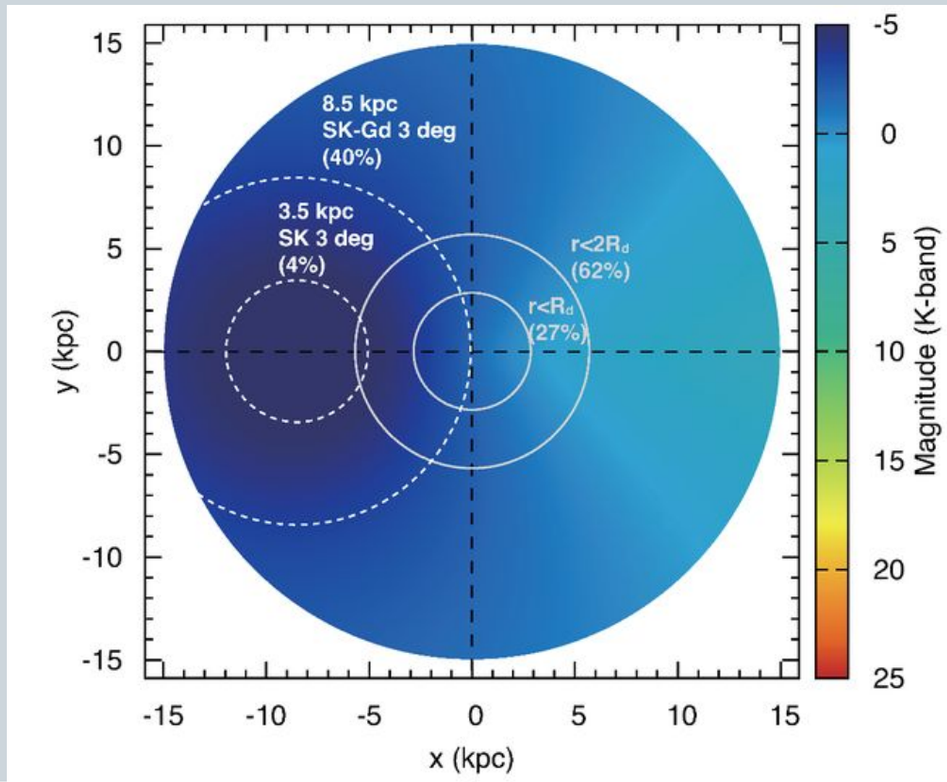
What Can We Learn?

- Directionality ➔ next slides!
- Distance may affect optimal follow-up strategy
  - Dust obscuration near GC ➡️
  - Compare with list of candidate stars (arXiv:2307.08785)
    - From $1/r^2$ scaling or advanced methods
- SN Model Discrimination with just a few 100 events
  - First developed in HK (JM, arXiv:2002.01649)
  - Also possible in LS (arXiv:2301.08079), LAr, … as long as you have per-event time & energy information!
- Exotic events, e.g. black-hole formation, type Ia, …



arXiv:1602.03028

⬆️ Optical Near-IR ⬇️



Supernova Pointing

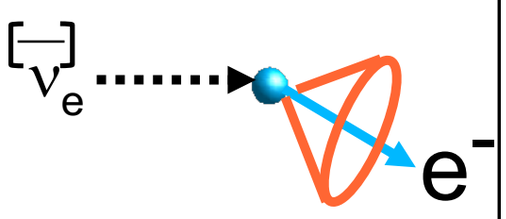
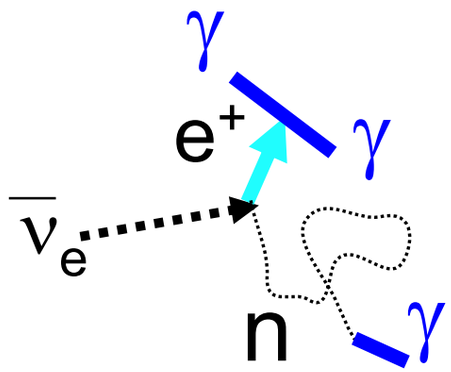
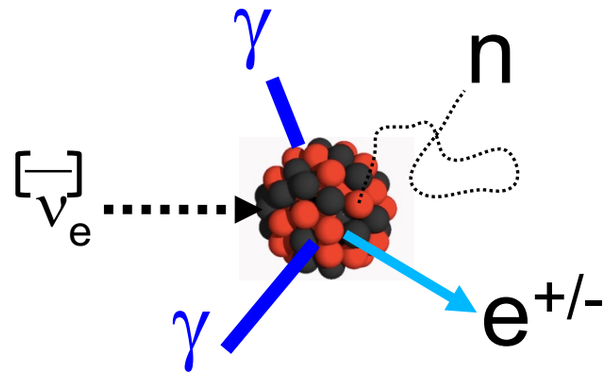
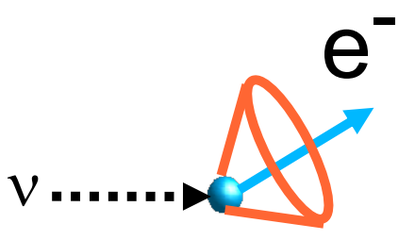
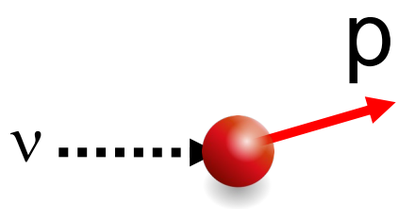
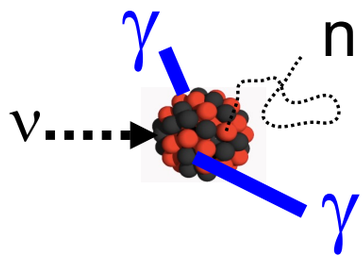
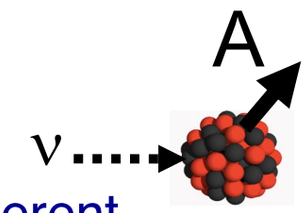
- Determining the SN direction is essential
  - For alerting astronomers & enabling multi-wavelength observations of the shock-breakout
  - If failed SN: search for disappearing progenitor
    - Reconstruct size of earth matter effect
- Multiple methods
  - Anisotropic neutrino interactions
  - Triangulation by multiple detectors

  } *this talk*
  - Oscillations patterns? High-E ν within ~hours?

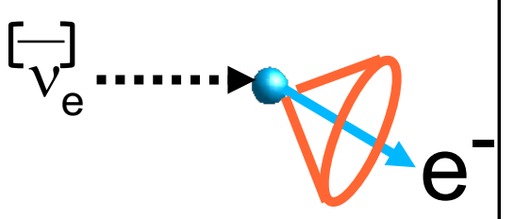
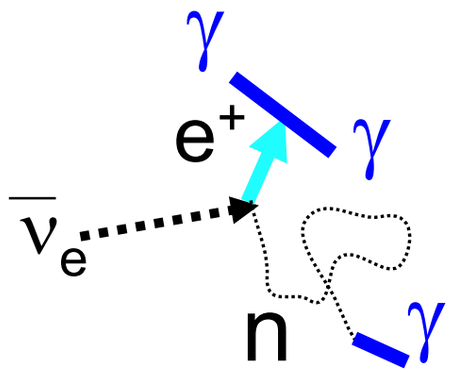
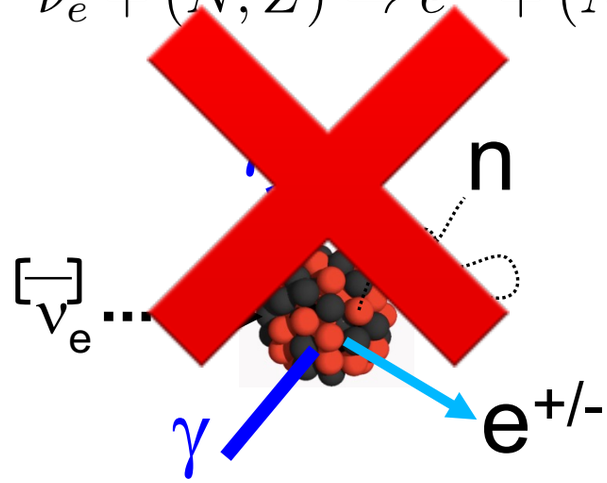
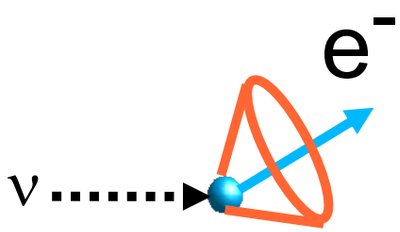
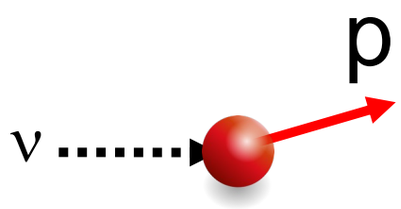
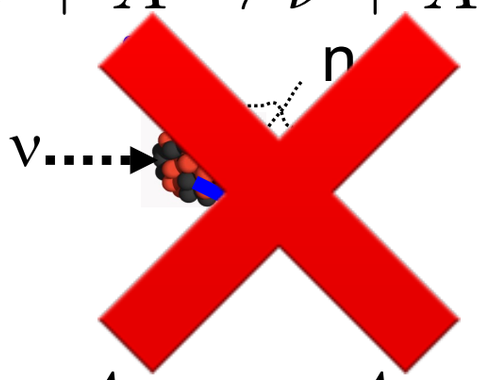
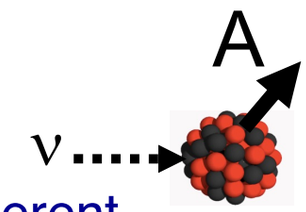
e.g. Scholberg *et al.*
PRD81 (2010) 043007

PRD68 093013; PRD97, 081307; ApJ 945, 98

Anisotropic Interactions?

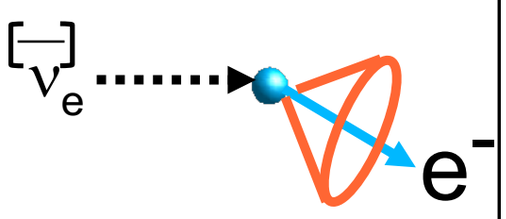
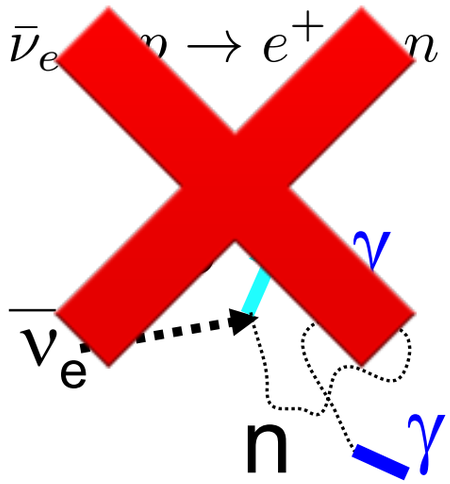
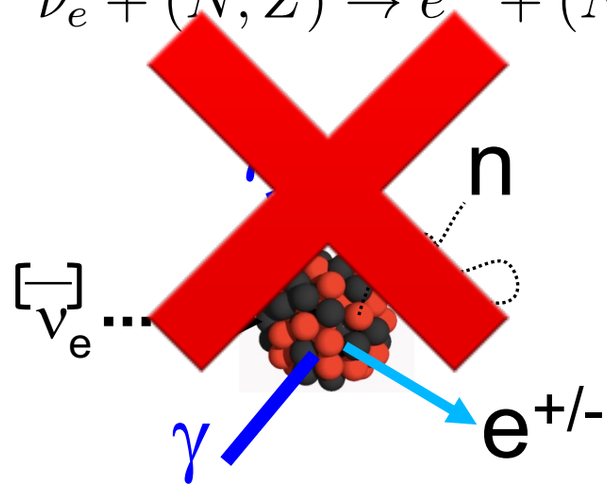
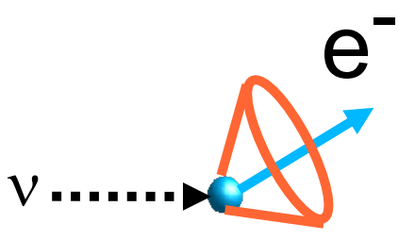
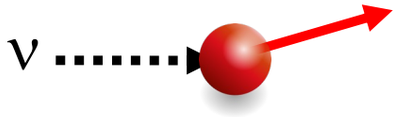
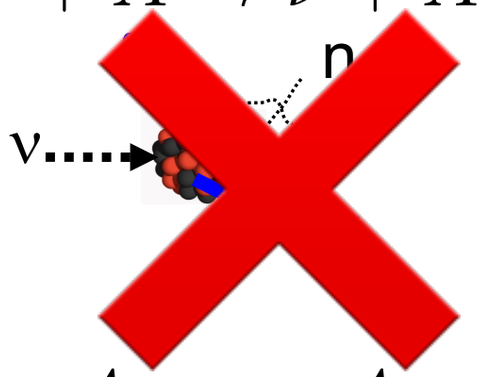
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

Anisotropic Interactions?

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

Cross section poorly understood, low statistics

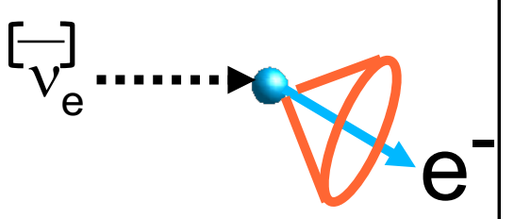
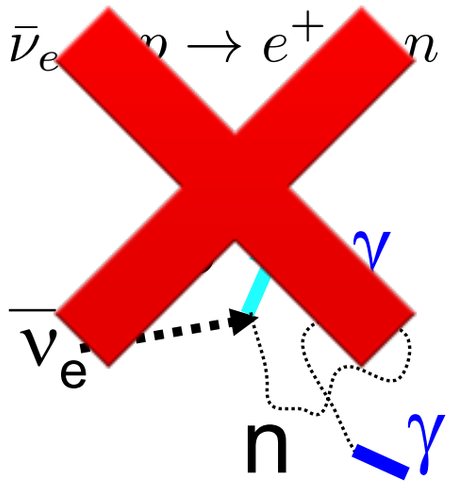
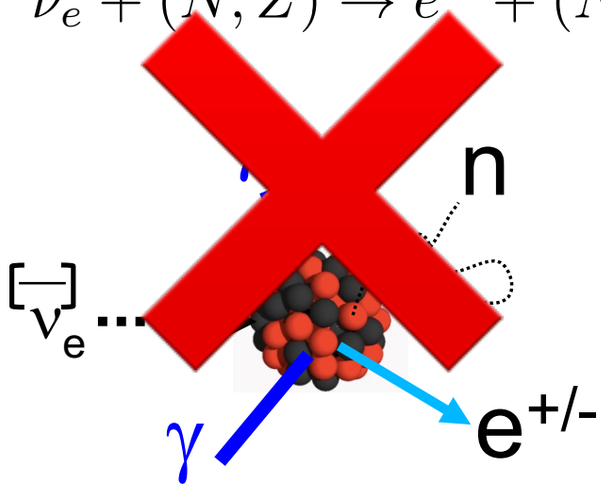
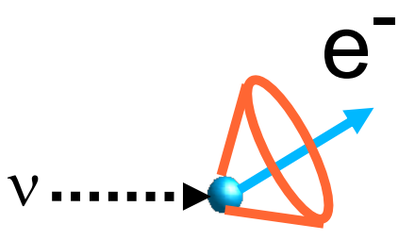
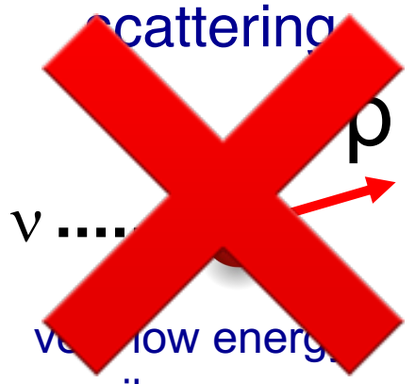
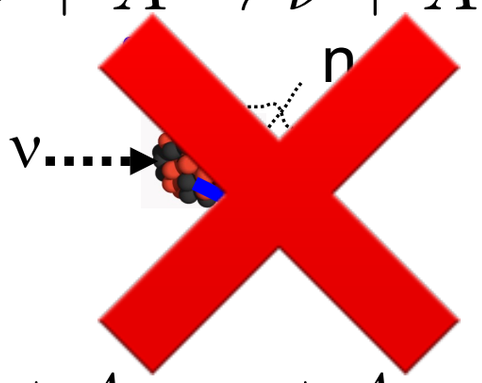
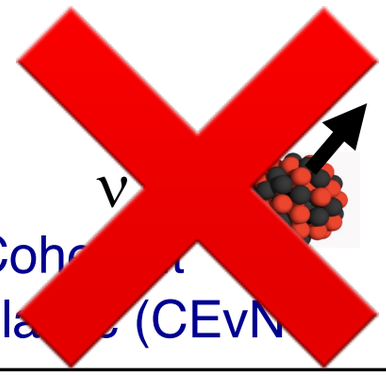
Anisotropic Interactions?

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$ Coherent elastic (CEvNS)

Low anisotropy, hard to reconstruct full final state

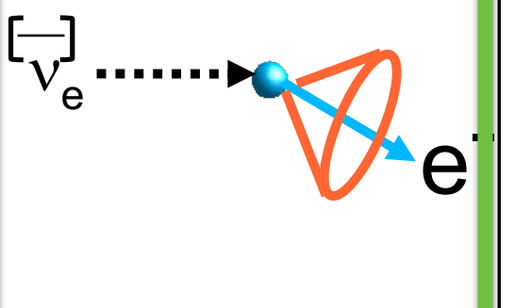
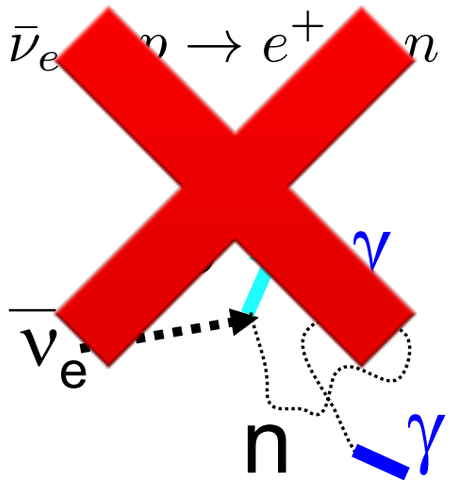
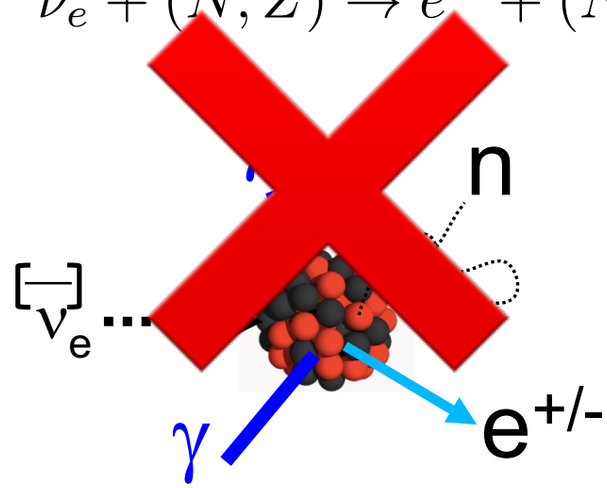
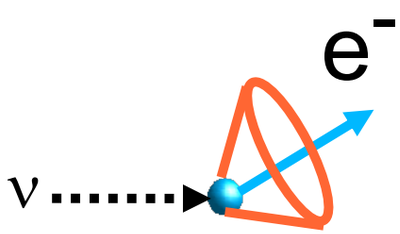
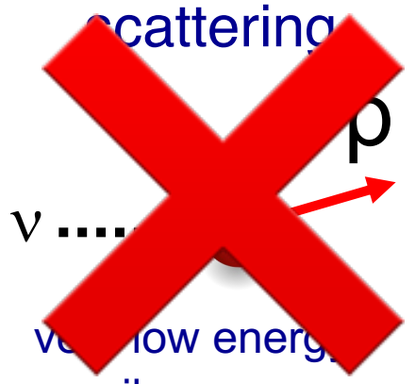
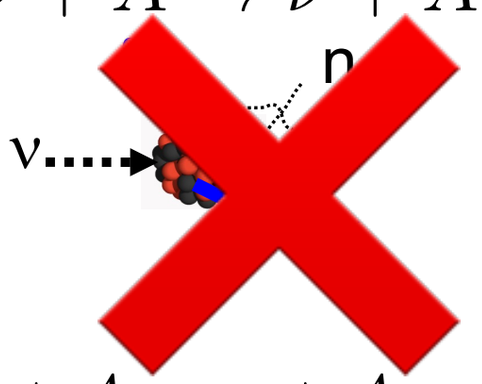
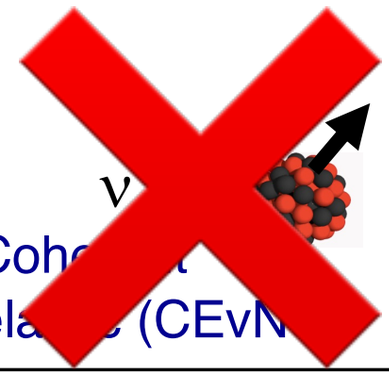
But see Fischer et al., arXiv:1504.05466

Anisotropic Interactions?

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvN

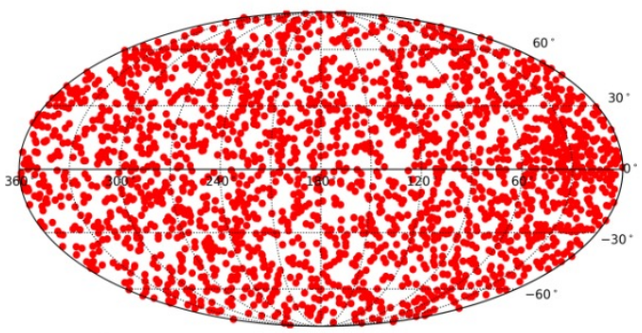
High anisotropy, but experimentally hard due to very low energy

Anisotropic Interactions?

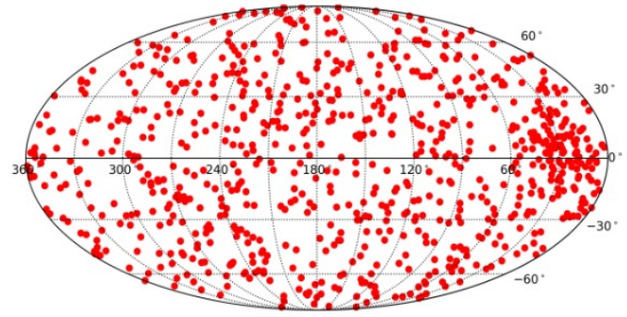
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  Very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

High anisotropy & available in all detectors, but subdominant channel

Pointing in Super-K



SN burst events w/o IBD tagging
(10kpc simulation)

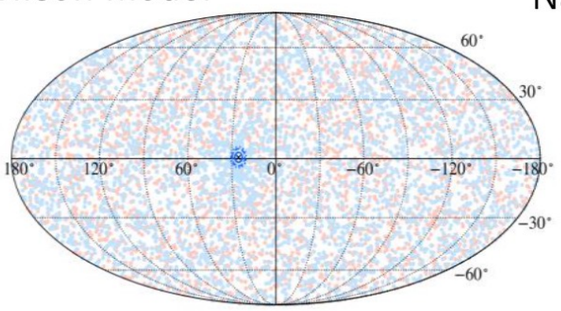


Tagged IBD events are removed

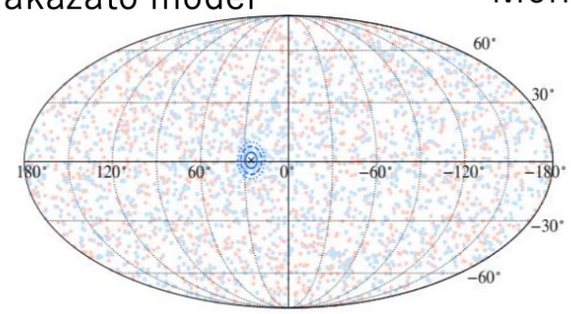
SN burst events w/ 72% IBD events tagged/removed
(10kpc simulation) (Expected with 0.1% Gd)

Detailed MC study showed that the direction pointing accuracy is 3-7 degrees at 10 kpc with IBD tagging (Gd 0.03 wt%) among several models and neutrino oscillation assumption.

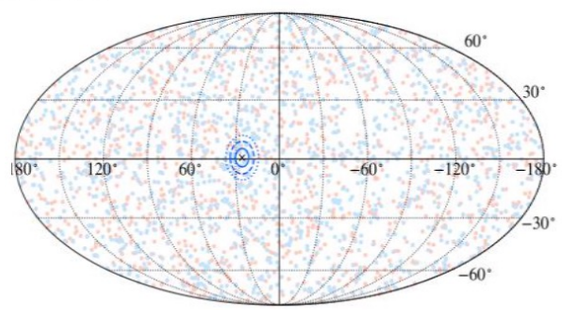
Wilson model



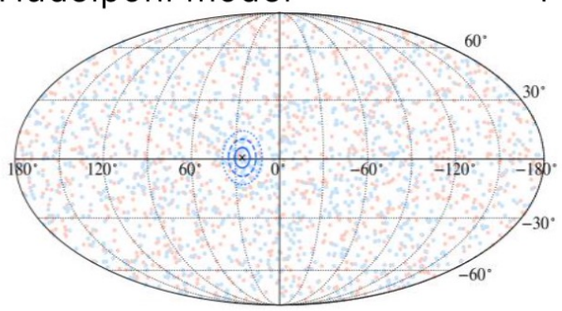
Nakazato model



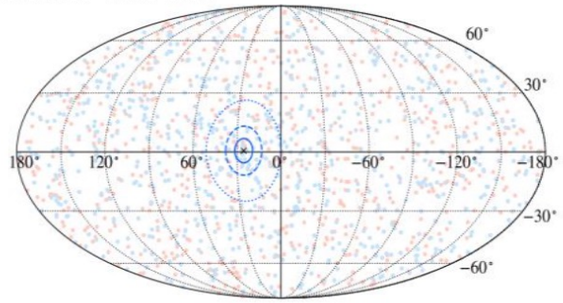
Mori model



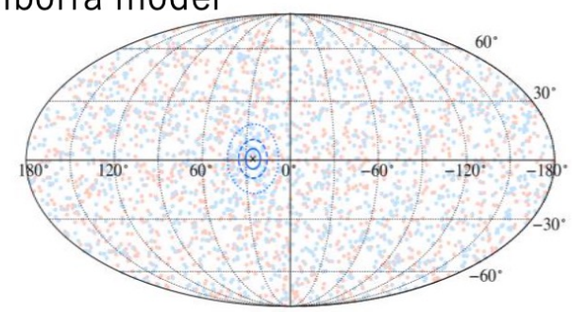
Hudelpohl model



Fischer model



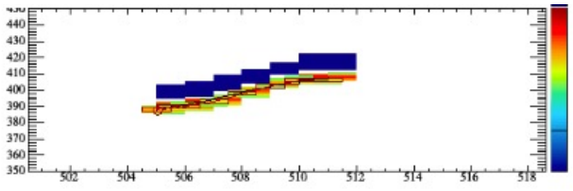
Tamborra model



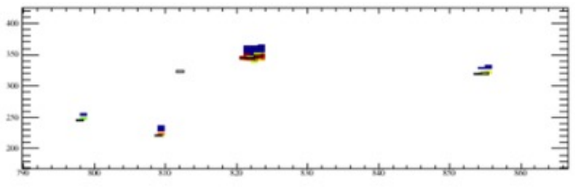
From Takedaさん, SN@LNGS workshop

Pointing in DUNE

$\nu + e$

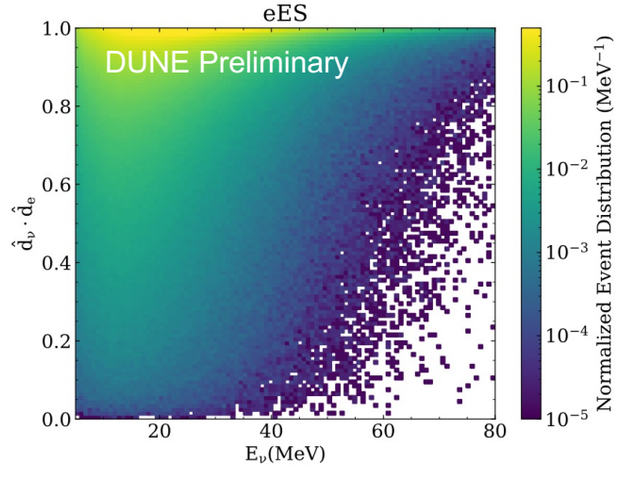


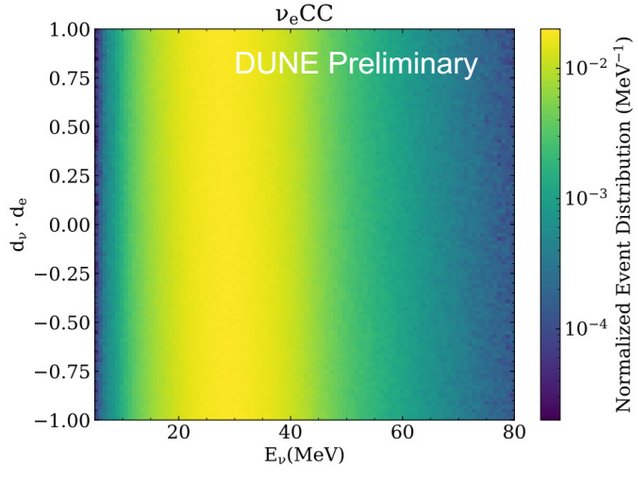
10.25 MeV electron



20.25 MeV neutrino

ν_e CC





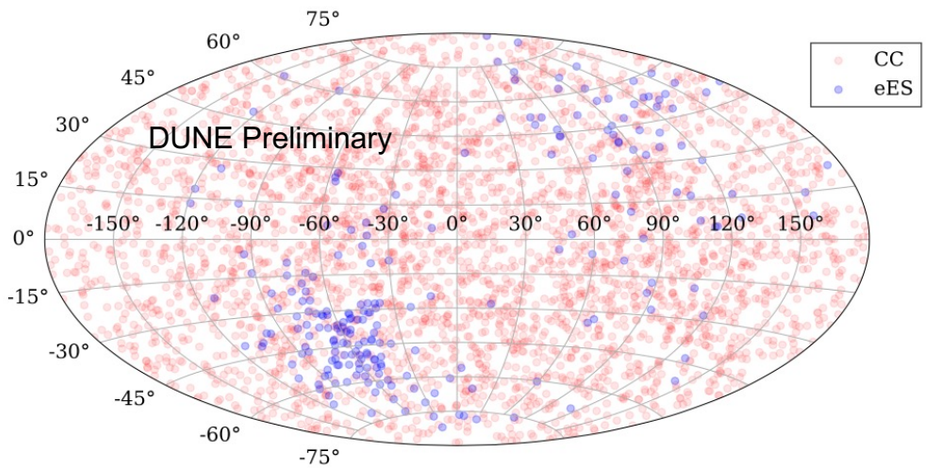
Work by:
James Shen
Janina Hekenmüller
Josh Queen

Forward-pointed
~300 events/40 kt @10 kpc

Quasi-isotropic*
~3000 events/40 kt @10 kpc

* potential for Fermi/GT separation

Note direction ambiguity, can only be resolved statistically



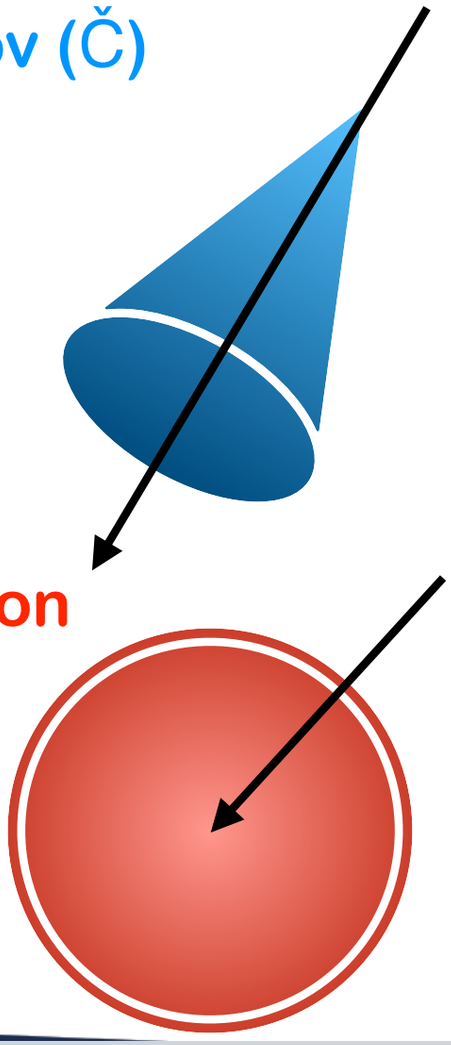
directional signal on an ~isotropic background

Figures from Kate Scholberg, SN@LNGS workshop

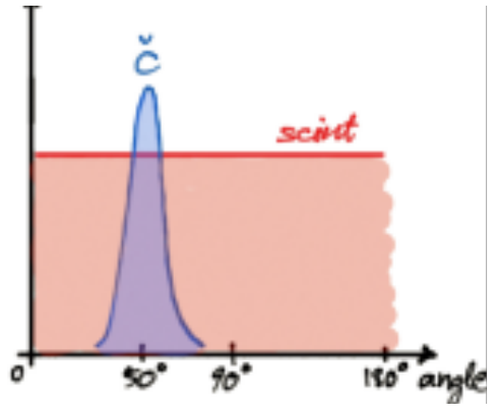
Pointing in (Wb)LS

Cherenkov (Č)

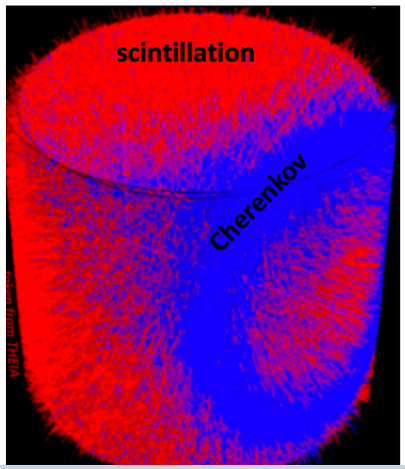
Scintillation



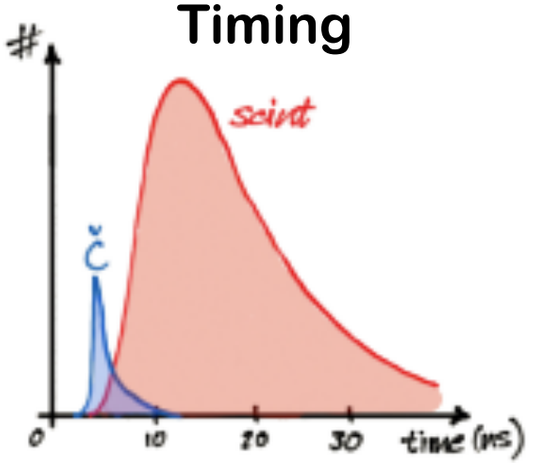
Angular distribution



Angular resolution

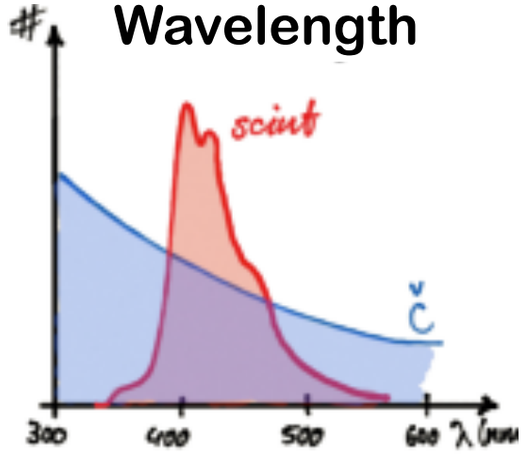


Timing



Large area picosecond photodetectors LAPPDs (~70 ps TTS) or other fast photodetectors

Wavelength

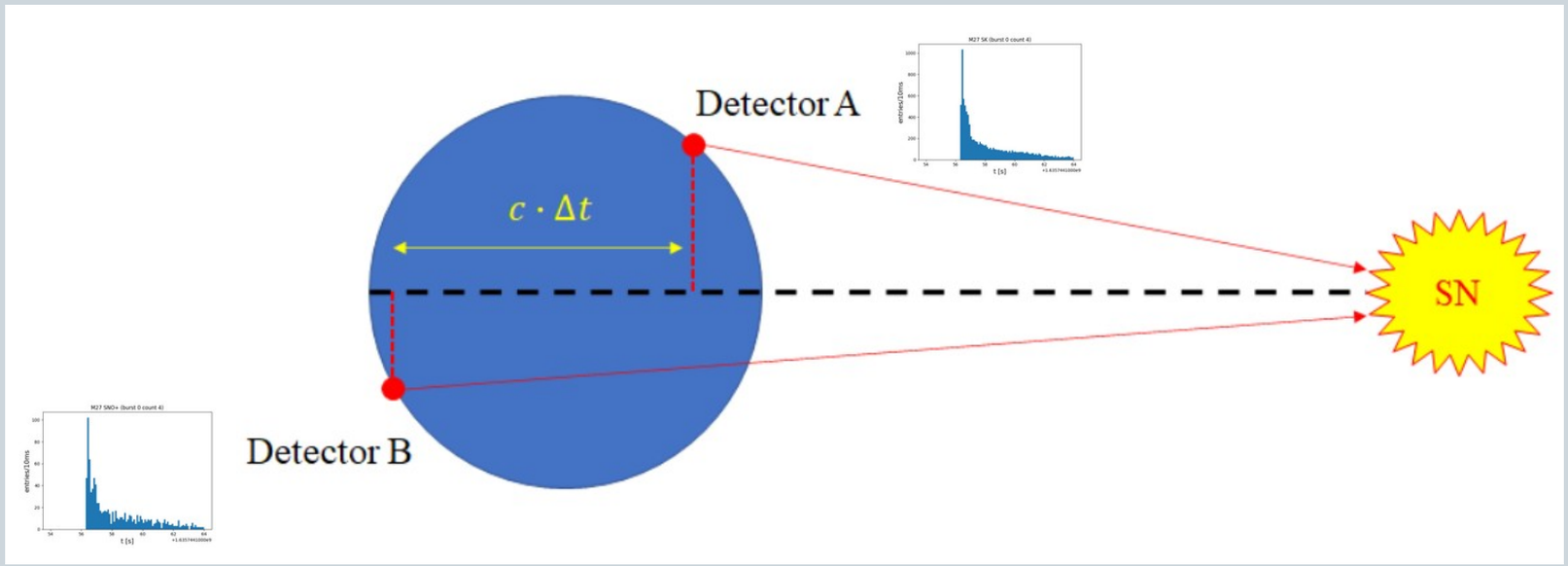


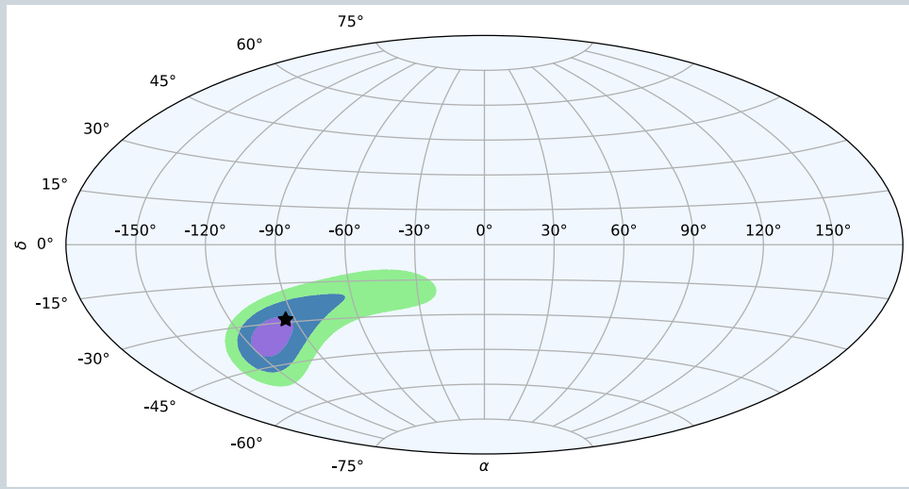
- Dichroic filters
- Red-sensitive PMTs
- Filtering

- Cherenkov/scintillation light separation possible in principle, but very tricky to do in a realistic detector
- First demonstrations in Borexino (statistical only, arXiv:2112.11816) and SNO+ (slow scintillator, arXiv:2309.06341)
- Significant R&D program towards THEIA

Figure from Zara Bagdasarian

Triangulation

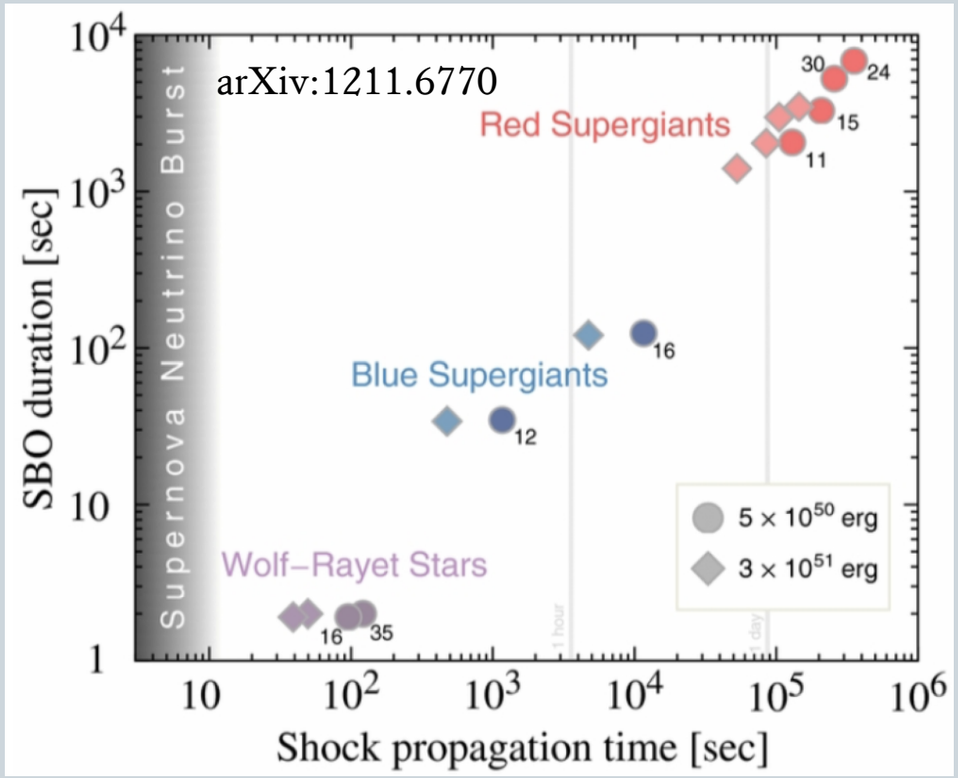




arXiv:1909.03151 (HK+IC+JUNO+DUNE)
See also PRD60, 033007; PRD88, 085010; JCAP 1804, 025; arXiv:1904.11461; arXiv:2003.04864; ...

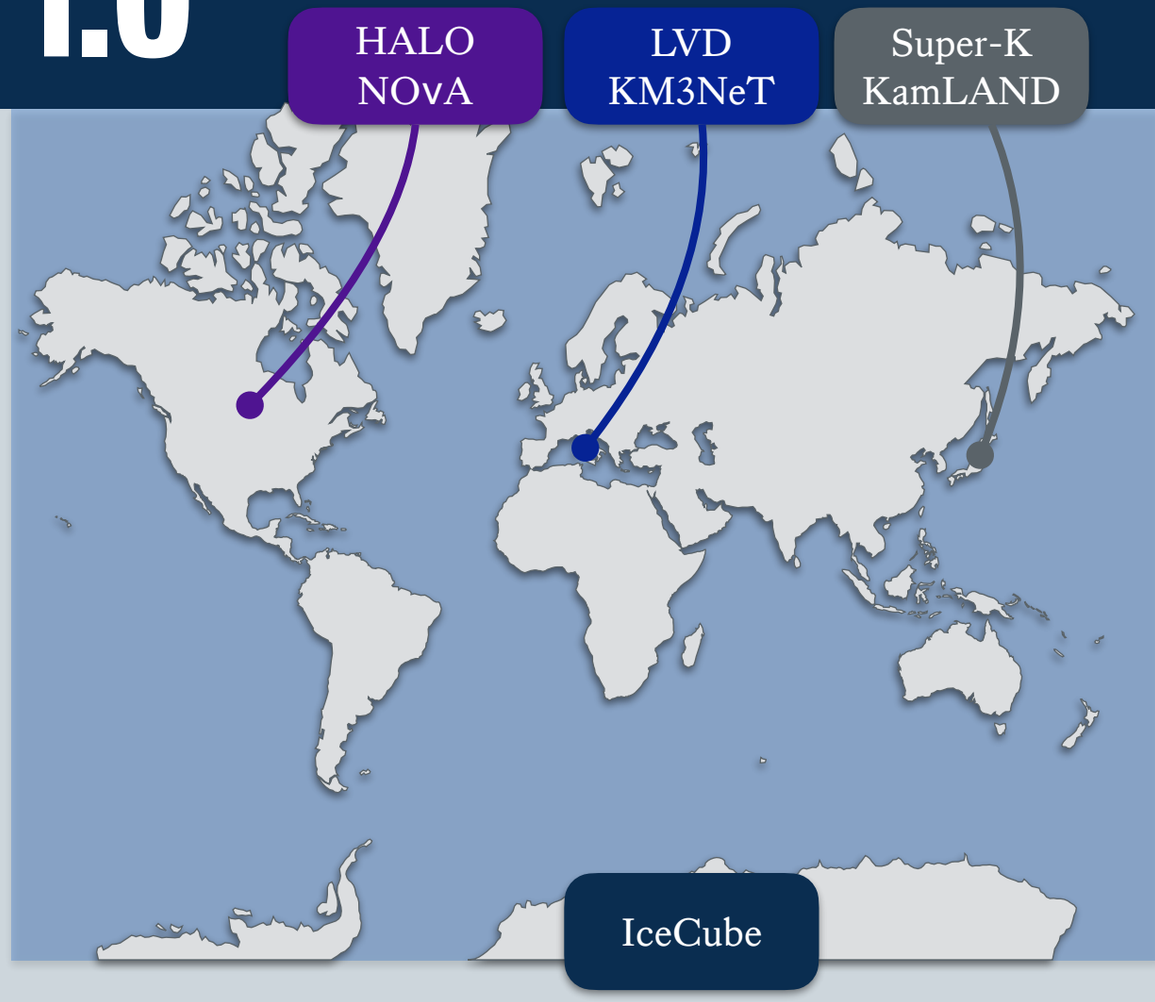
- Simple in principle, but hard to do in practice
  - Earth diameter is ~40 ms ➔ need O(1) ms accuracy per detector, which requires high statistics
  - Systematics: e.g. DUNE (ν_e) & HK ($\bar{\nu}_e$) see different time structure
- Less accurate (≳10°, depending on detectors, direction, SN model, ...)
- But much faster! (Only need to reconstruct time of first few events)

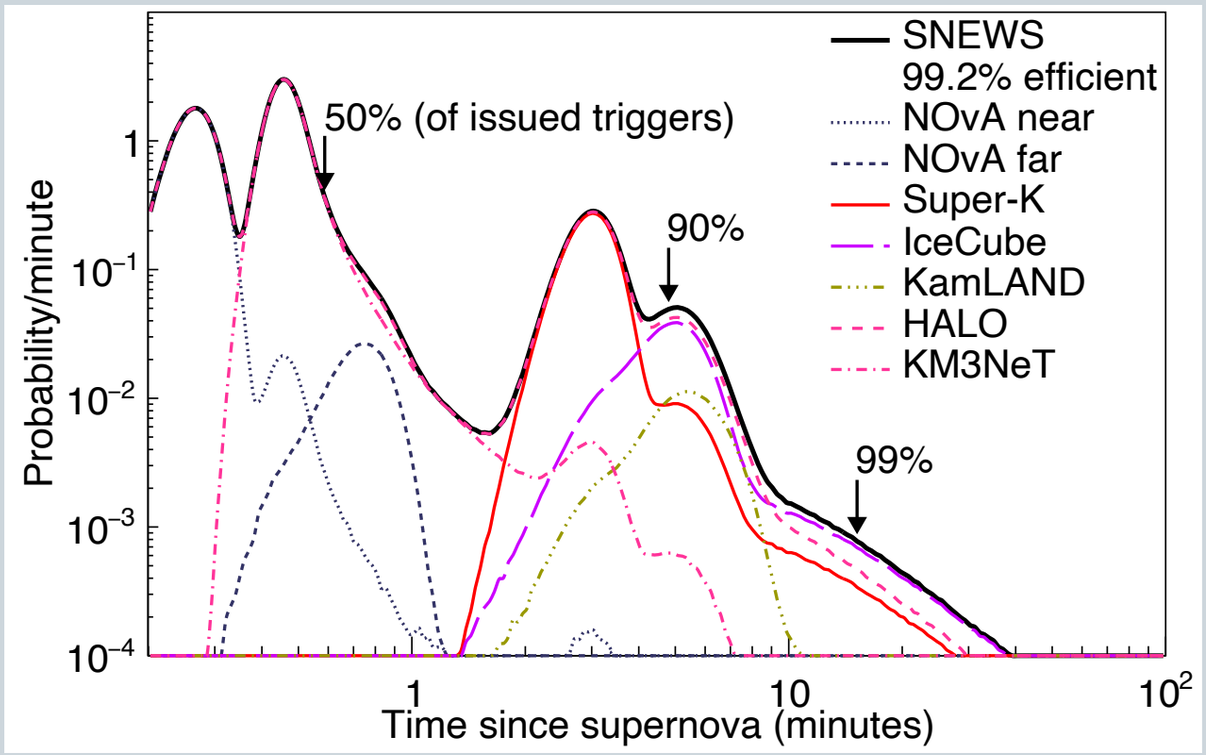
10-30 ms (!) in JUNO



SNEWS 1.0

- SuperNova Early Warning System looks for coincident event bursts
- Started >20 years ago, running in automated mode since 2005
- 2022: 7 participating detectors →





"3 P's" of a good alert *(K.Scholberg, 2000)*

✅ Prompt: send alert within ~min

❌ Pointing: *(left up to individual experiments)*

✅ Positive: false-alarm rate < 1 per 100 years

limiting factor

SNEWS 2.0

- Since 2019: re-imagined SNEWS for today's new age of multi-messenger astronomy (arXiv:2011.00035 / DOI:10.1088/1367-2630/abde33)

- Basic implementation works, first experiments sending data & discussing MoUs

- Regular "fire drills", working with astronomy community for monitoring candidates & developing optimal follow-up strategy

- Move from "3P's" to "3F's" of a good alert:

✅ Prompt

❌ Pointing

✅ Positive

✅ Fast

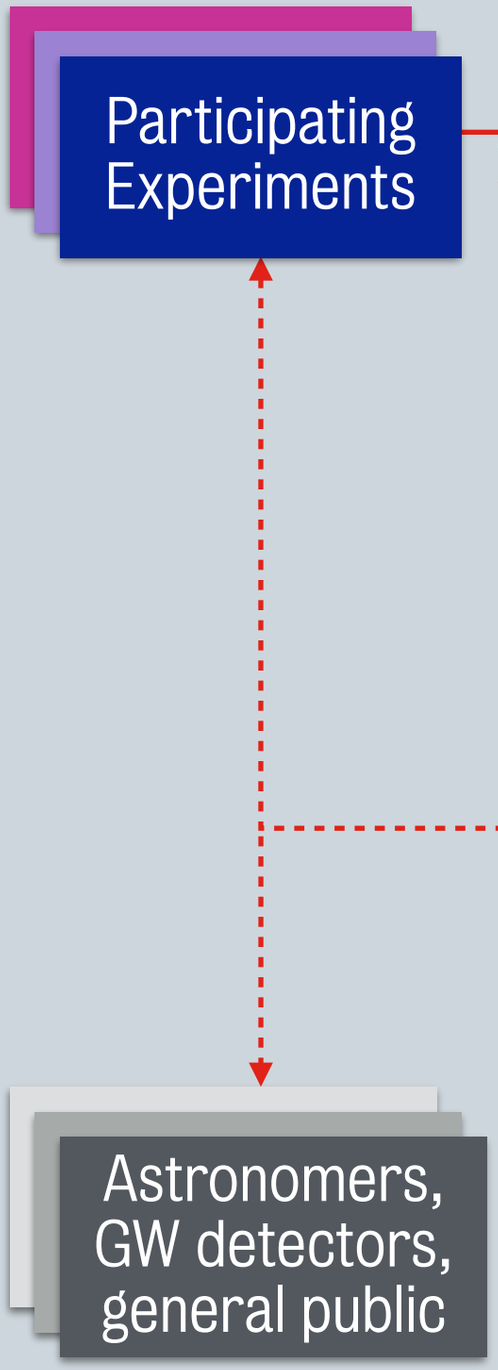
✅ Full-featured

✅ FAR

Better alerts if experiments share more data (optional!)

No more "boy who cried wolf"

SNEWS 2.0 Software Overview



Publicly available on GitHub:

- SNEWS Publishing Tools
- Online analysis tools
- SNEWPY

Agenda

Even applies to supernova neutrino experiments:

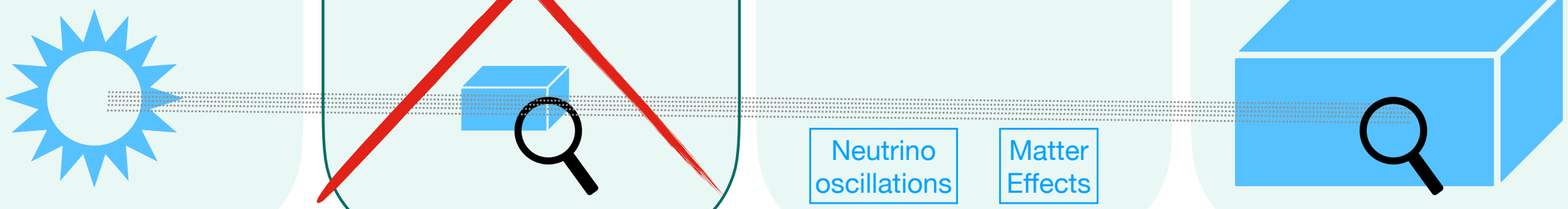
All neutrino ~~oscillation~~ experiments are the same…

Produce neutrinos
[possibly all in the same flavour]

~~Check what you produced~~
~~[optional]~~

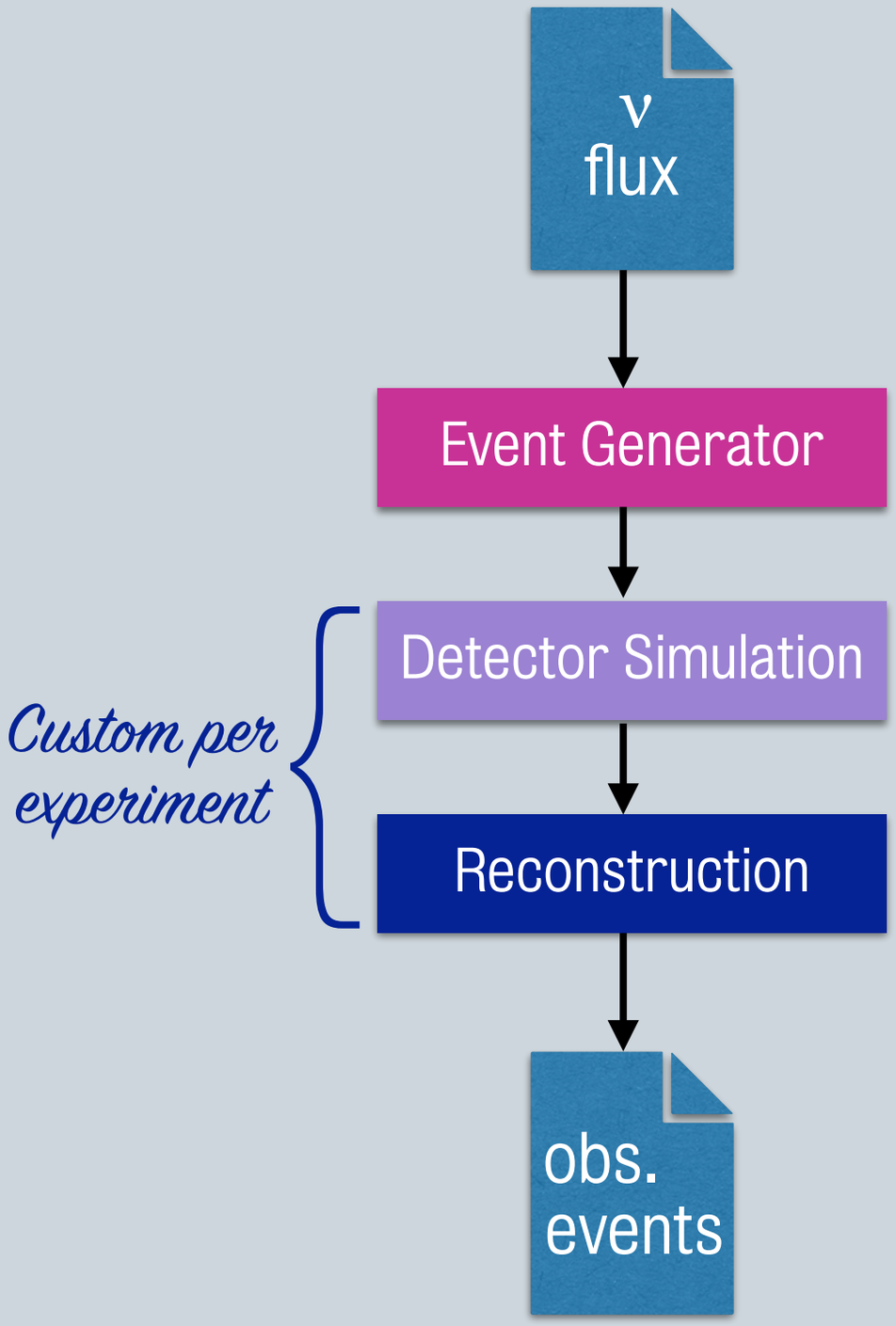
Propagate!
[~~a few km~~ to a few kpc]

Look for ~~a deficit~~ or excess!



SOFTWARE

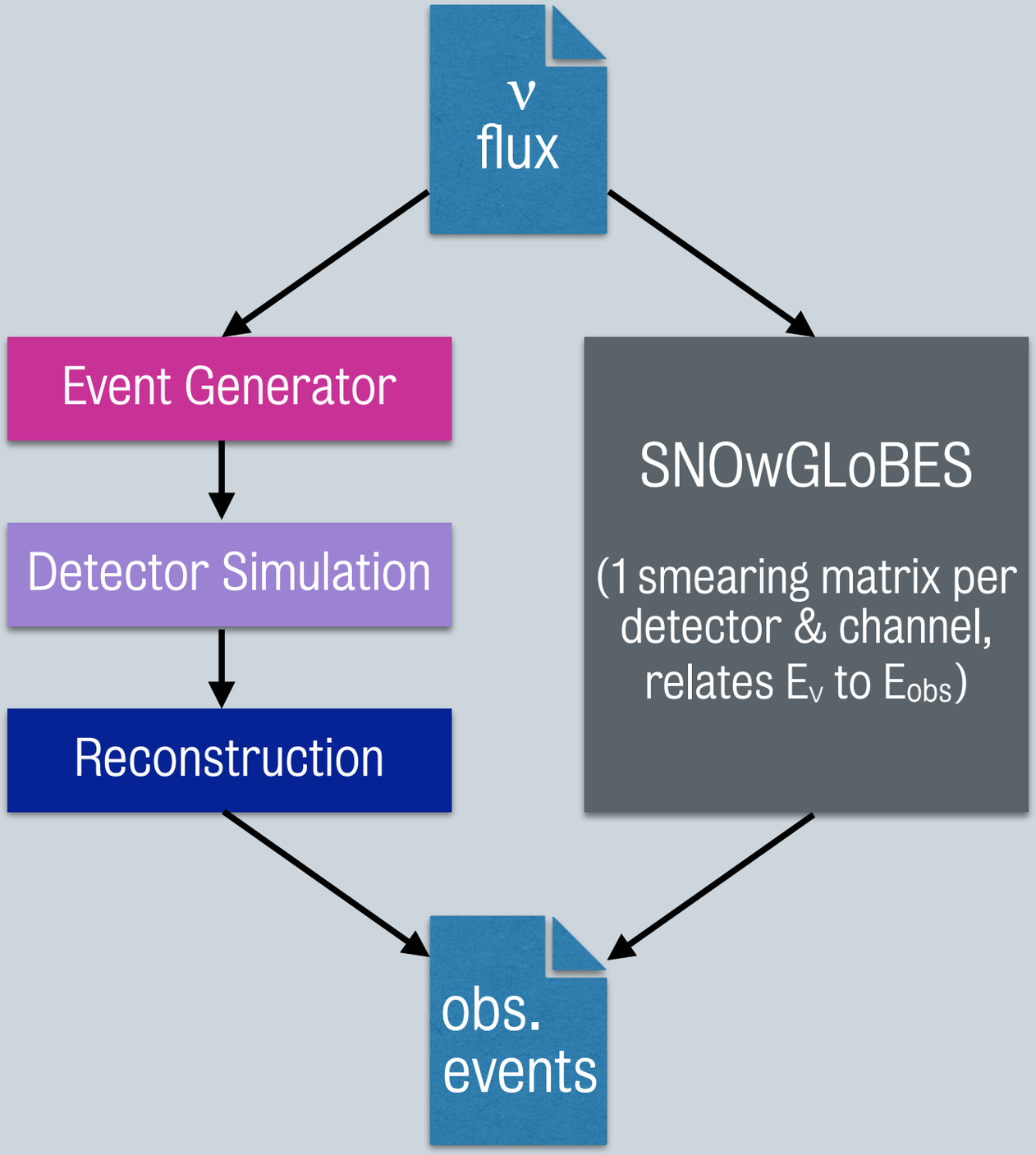
Determining the Detector Response



- Implement cross sections, energy & angular distribution of outgoing particles, and more

- Existing event generators
  - MARLEY (mainly Ar)
  - sntools (H_2O, LS, WbLS)
  - *… and some proprietary ones*

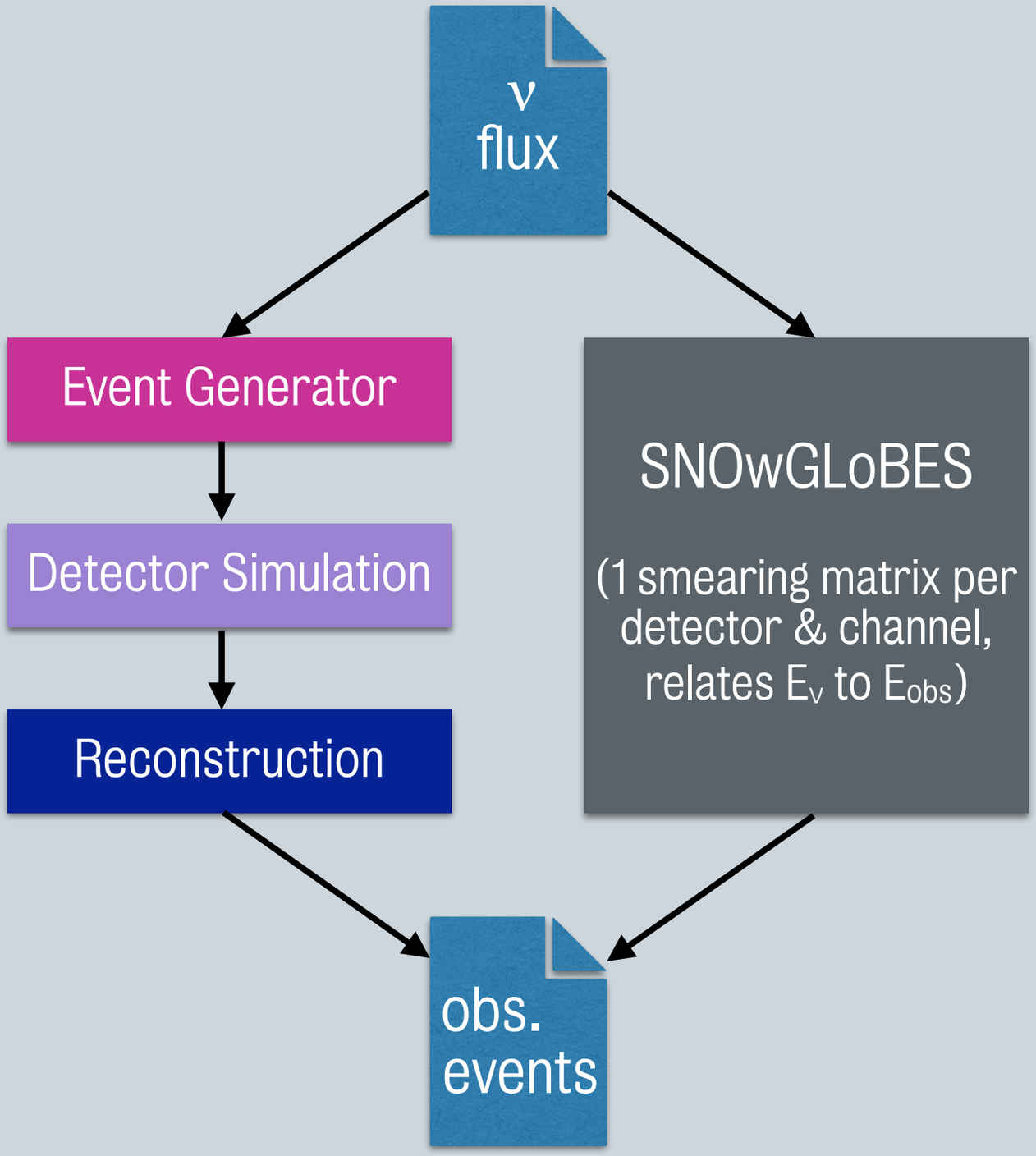
Determining the Detector Response



- github.com/SNOwGLoBES/snowglobes
- Orders of magnitude faster & covers *many* use cases
- Still need event generator for advanced studies (e.g. directionality, n capture)

Determining the Detector Response

Where to get fluxes from different SN models?



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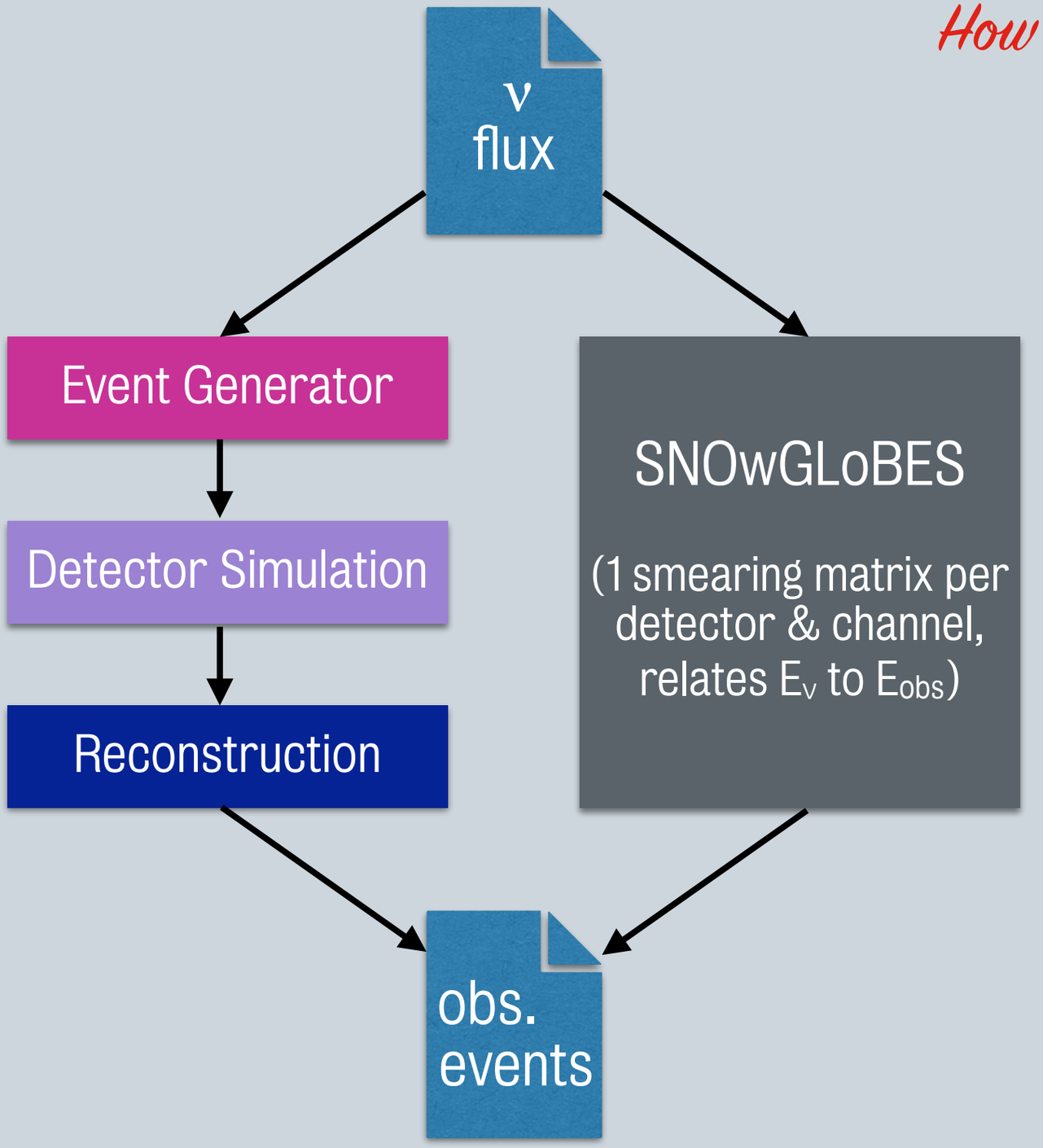

How to apply transformations to ν flux before reaching the detector?

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Determining the Detector Response

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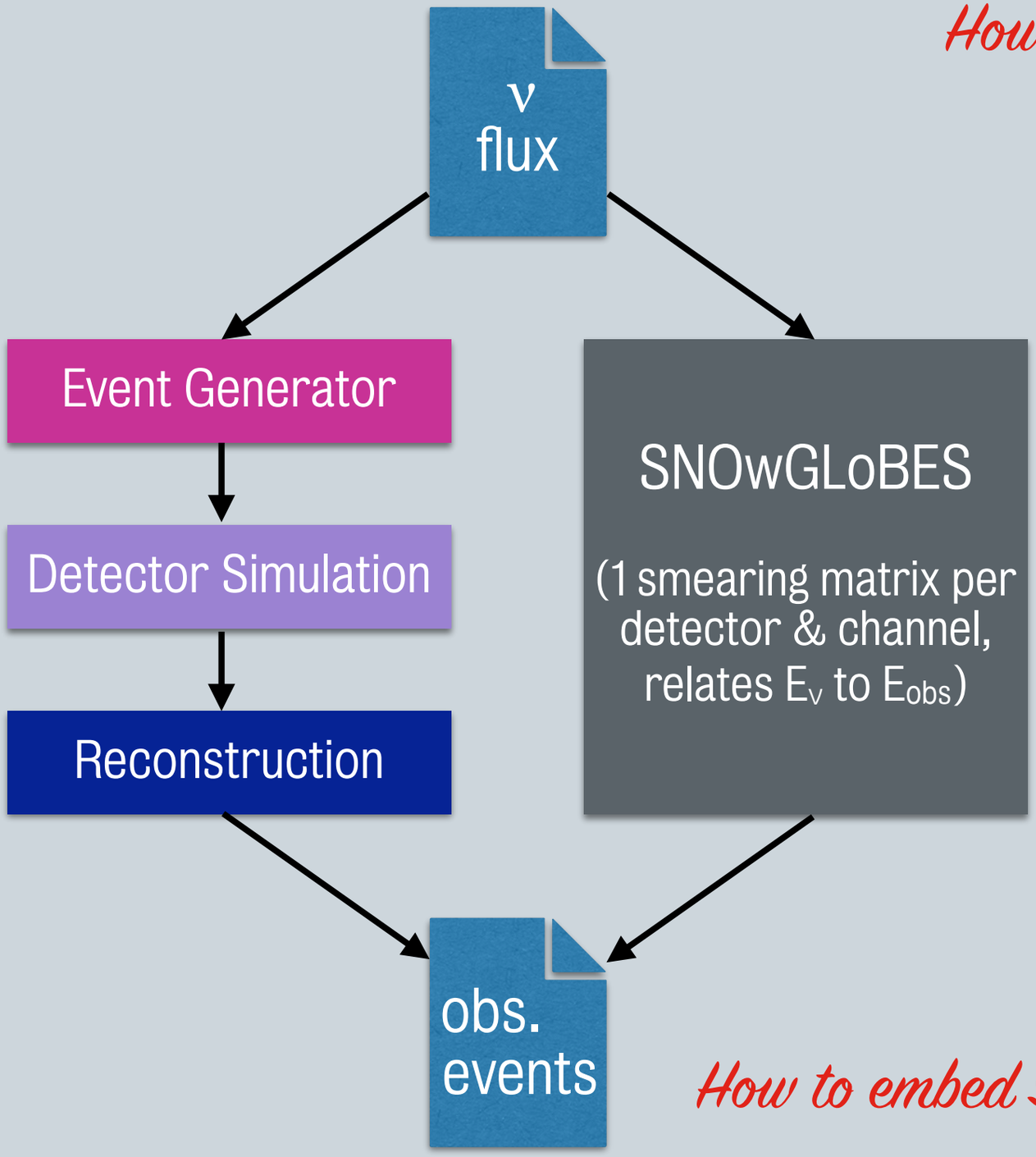

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How to embed SNOwGLoBES in a Python-based workflow?

SNEWPY Offers ...

Where to get fluxes from different SN models?

- ... a simple and unified interface to hundreds of supernova simulations.

How to apply transformations to ν flux before reaching the detector?

- ... a large library of flavor transformations that relate neutrino fluxes produced in the supernova to those reaching a detector on Earth.

How to embed SNOwGLoBES in a Python-based workflow?

- ... and a Python interface to SNOwGLoBES to integrate into your existing workflows.

ApJ 925 (2022) 107
JOSS 6 (2021) 03772
github.com/SNEWS2/snewpy

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Can use these in your code!

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ApJ 925 (2022) 107
JOSS 6 (2021) 03772
github.com/SNEWS2/snewpy

Integrating SNEWPY in sntools

- sntools: event generator for SN neutrinos in water Cherenkov & liquid scintillator detectors
- Used by Hyper-K, SNO+, JUNO, THEIA & more …
- Open Source:
  - github.com/JostMigenda/sntools
  - JOSS paper: DOI:10.21105/joss.02877
- Integrates SN models & flavor transformations from SNEWPY
  - For devs: Save work & eliminate major source of bugs
  - For users: Smooth transition from quick initial estimates (SNOwGLoBES) to advanced analyses (sntools)

Similar for IceCube's ASTERIA generator (DOI:10.5281/zenodo.3926834)

Usage of SNEWPY

- SNEWS-internally
- By other software (e.g. sntools, ASTERIA)
- In non-SNEWS papers:

DOI:10.1051/epjconf/202328005002

Exploiting synergies between neutrino telescopes for the next galactic core-collapse supernova

Meriem Bendahman[1,3], *Anne-Cécile* Buellet[2], *Matteo* Bugli[2], *Joao* Coelho[1], *Alexis* Coleiro[1], *Gwenhaël* de Wasseige[1], *Sonia* El Hedri[1,*], *Thierry* Foglizzo[2], *Davide* Franco[1], *Isabel* Goos[1], *Jérôme* Guilet[2], *Antoine* Kouchner[1], *Yahya* Tayalati[3], *Alessandra* Tonazzo[1], *Cristina* Volpe[1]

arXiv:2203.05141

Neutrino Echos following Black Hole Formation in Core-Collapse Supernovae

Samuel Gullin,[1] Evan P. O'Connor,[1] Jia-Shian Wang,[2] and Jeff Tseng[2]

[1] *The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova, SE-106*

[2] *Department of Physics, Oxford University, Oxfor*

arXiv:2109.13242

Detectability of hadron-quark phase transition in neutrino signals of failing core-collapse supernova

Zidu Lin,[1] Shuai Zha,[2] Evan P. O'Connor,[3] and Andrew W. Steiner[1,4]

[1] *Department of Physics and Astronomy, University of Tennessee Knoxville*

[2] *Tsung Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China*

in Centre, Department of Astronomy, , AlbaNova, SE-106 91 Stockholm, Sweden

ion, Oak Ridge National Laboratory

Dated: March 11, 2022)

Uncovering the neutrino mass ordering with the next galactic core-collapse supernova neutrino burst using water Cherenkov detectors

César Jesús-Valls[1,*]

[1] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

arXiv:2210.11676

That input file contains the flux of ν_μ *or* ν_τ and *not* the sum of both!

Software matters!

Based on three real examples I have witnessed.

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Based on three real examples I have witnessed.

Software Matters!

- Software can make or break a physics result!
  - If we all write the same code from scratch, we waste time & produce more bugs!
  - Less physics & worse physics!

- SNEWPY offers shared & well-tested implementations for common tasks
  - Easy to integrate into custom tools → enables smooth transition from quick estimates (SNOwGLoBES) to advanced analyses (e.g. sntools)
  - Have a new SN model? New flavour transformation? Make them easily available to everyone!

Talk to me for early drafts of book chapters & Jupyter notebooks!

Conclusions

- "All neutrino ~~oscillation~~ experiments are the same" … but SNν experiments have some special features

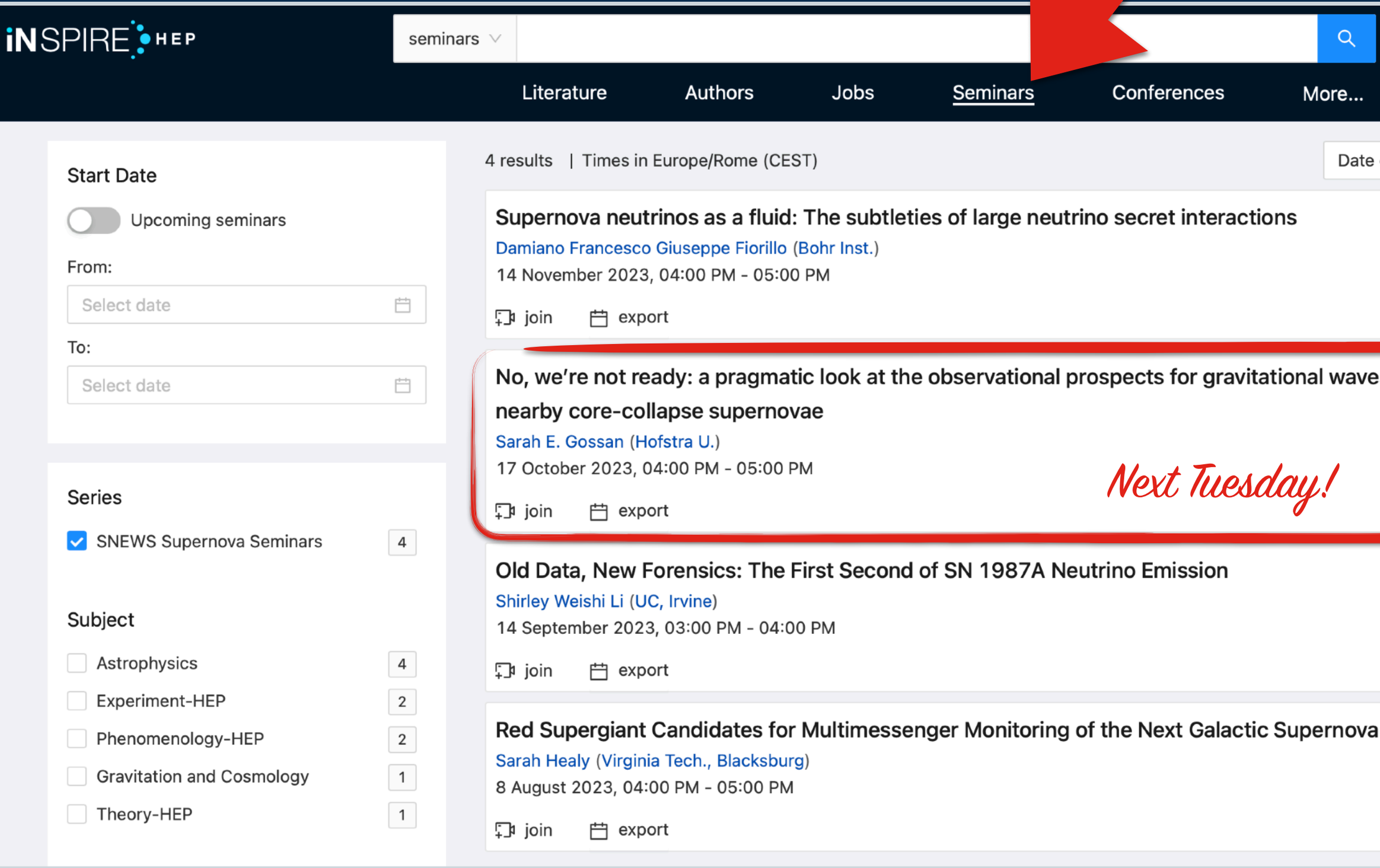
- Next galactic SN is a once-in-a-lifetime opportunity; we need to fully exploit complementarity between different detectors

- SNEWS 2.0 brings together SNν community, astronomers & GW experiments for multi-messenger observations

- Software matters! Use established open-source tools & do not re-invent the wheel!

- Please join the public Supernova Seminar Series!

Conclusions



- Please join the public Supernova Seminar Series!

Backup Slides

Follow-Up: A New Era

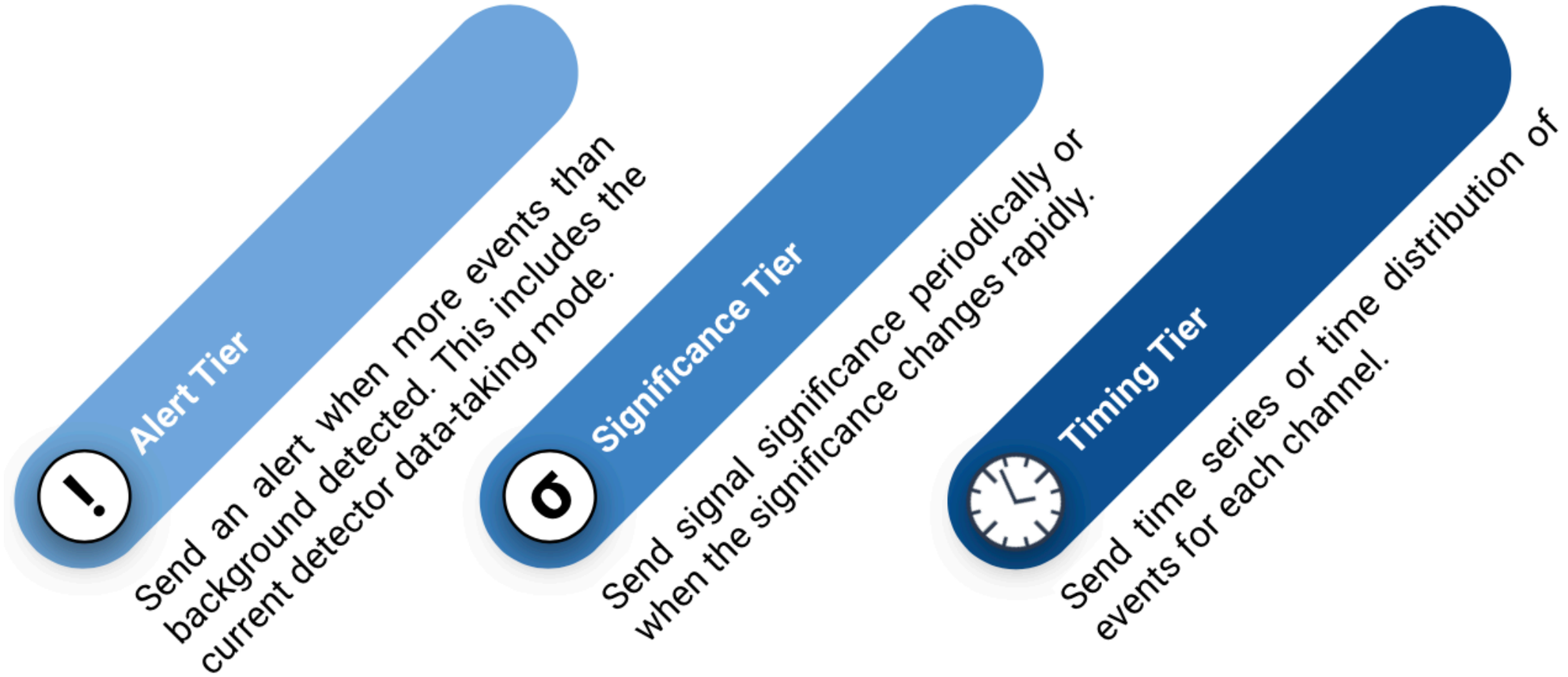
- 1997: ATel & GCN started distributing alerts
  - Human-readable, unstructured, via mailing list
  - Good strategy for SNEWS 1.0
- Today: up to 10^7 alerts per night (LSST)
  - Specialized brokers distribute & filter alerts for end users, large degree of automation
  - Many robotic & fully automated telescopes
- SNEWS is important forum to bring neutrino & astronomy communities together and prepare follow-up strategy

  ➔ Ensure maximal science output!

SNEWS 🤝 Astronomy Community

- GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts, arXiv:2008.03962)
  - Network of 25 telescopes, “coordinates telescope observations of transient sources with large localization uncertainties”
- AAVSO (American Association of Variable Star Observers, aavso.org)
  - Network of “amateur” astronomers in 100+ countries, archive database with ~10^6 observations/year, can send out alerts with observation requests to members
    - Amateur astronomers often more flexible (e.g. photometry in different observation bands, spectra, higher cadence, larger FOV, …)
    - Starting campaign to regularly observe SN candidate list
- REFITT (Recommender Engine for Intelligent Transient Tracking, arXiv:2003.08943)
  - AI-based engine to plan & coordinate follow-up strategy, taking into account available facilities (wavelengths, sensitivity, current weather, …)
- *… and more!*

Participating in SNEWS 2.0



Effectively SNEWS 1.0

Experiments can share more data to enable more new features

Experiments can start simple and join more tiers over time!

SNEWS 2.0

- Since 2019: re-imagined SNEWS for today's new age of multi-messenger astronomy (arXiv:2011.00035 / DOI:10.1088/1367-2630/abde33)

- Basic implementation works, first experiments sending data & discussing MoUs

- Regular "fire drills", working with astronomy community for monitoring candidates & developing optimal follow-up strategy

- Move from "3P's" to "3F's" of a good alert:

✅ Prompt

❌ Pointing

✅ Positive

✅ Fast

✅ Full-featured

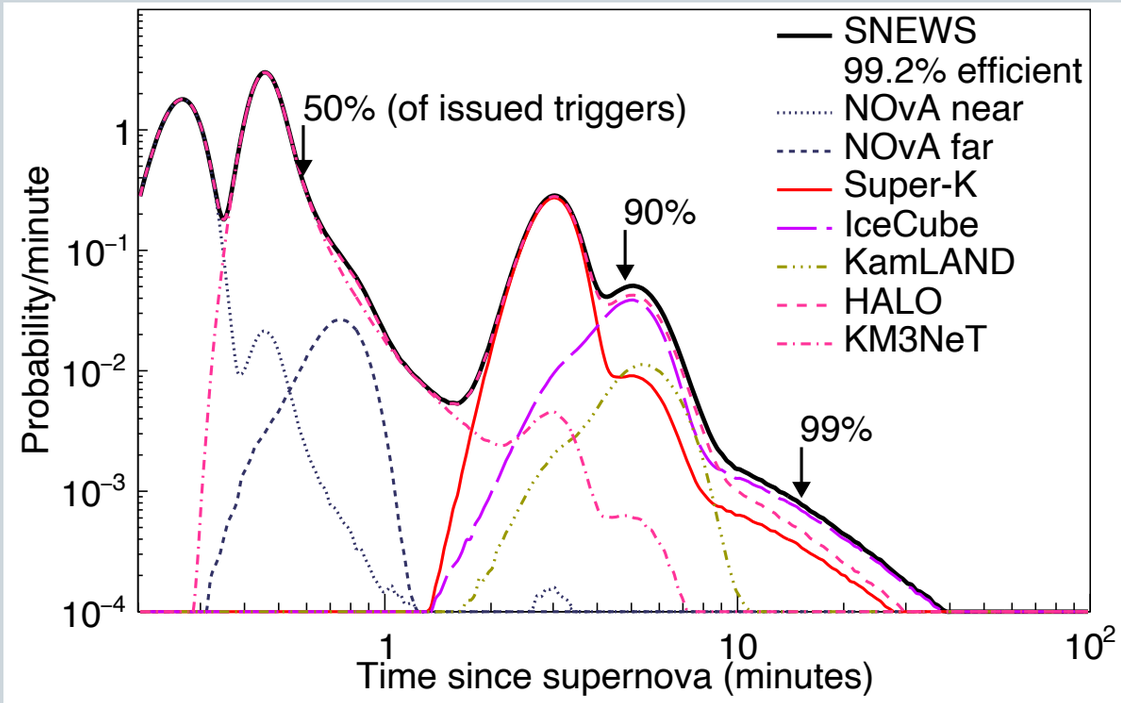
✅ FAR

Better alerts if experiments share more data (optional!)

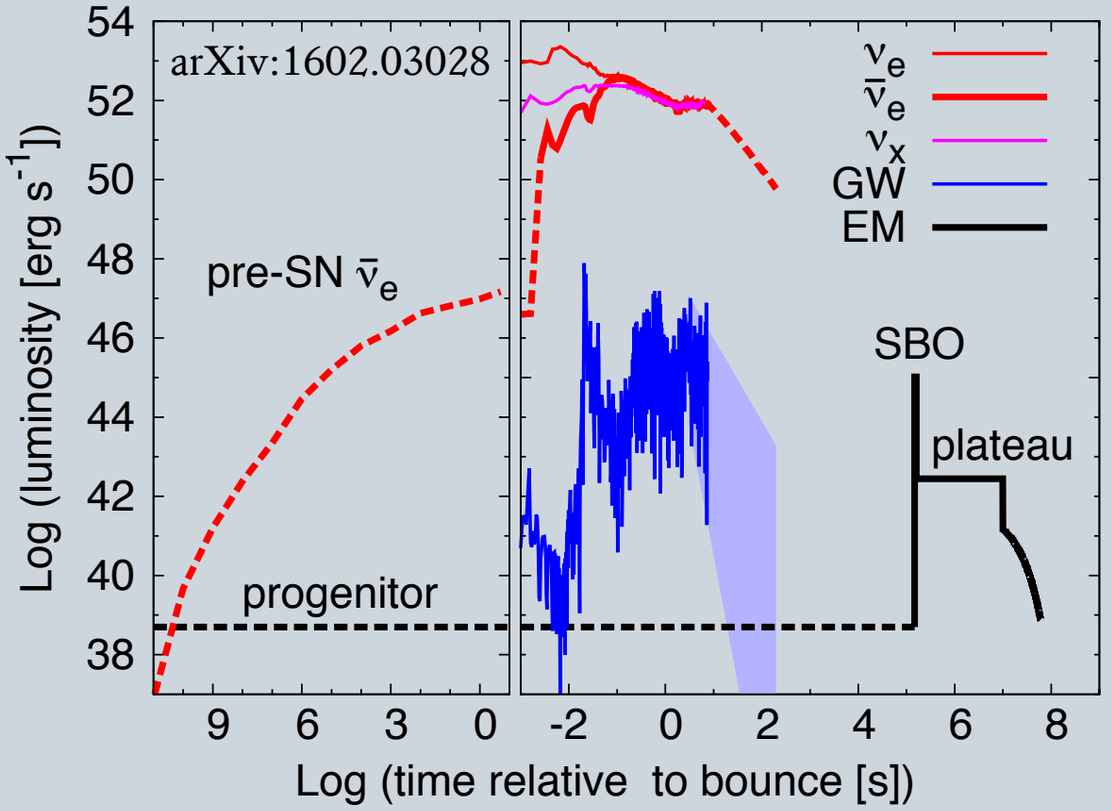
No more "boy who cried wolf"

✅ Fast

- Lower latency
  - More flexible SNEWS policy
  - DAQ design of individual experiments is important



- Pre-supernova neutrino alert
  - ~hours warning from Si burning
  - KamLAND already shares significance, some other experiments are sensitive
  - Low statistics ➔ severely distance limited (<1 kpc)

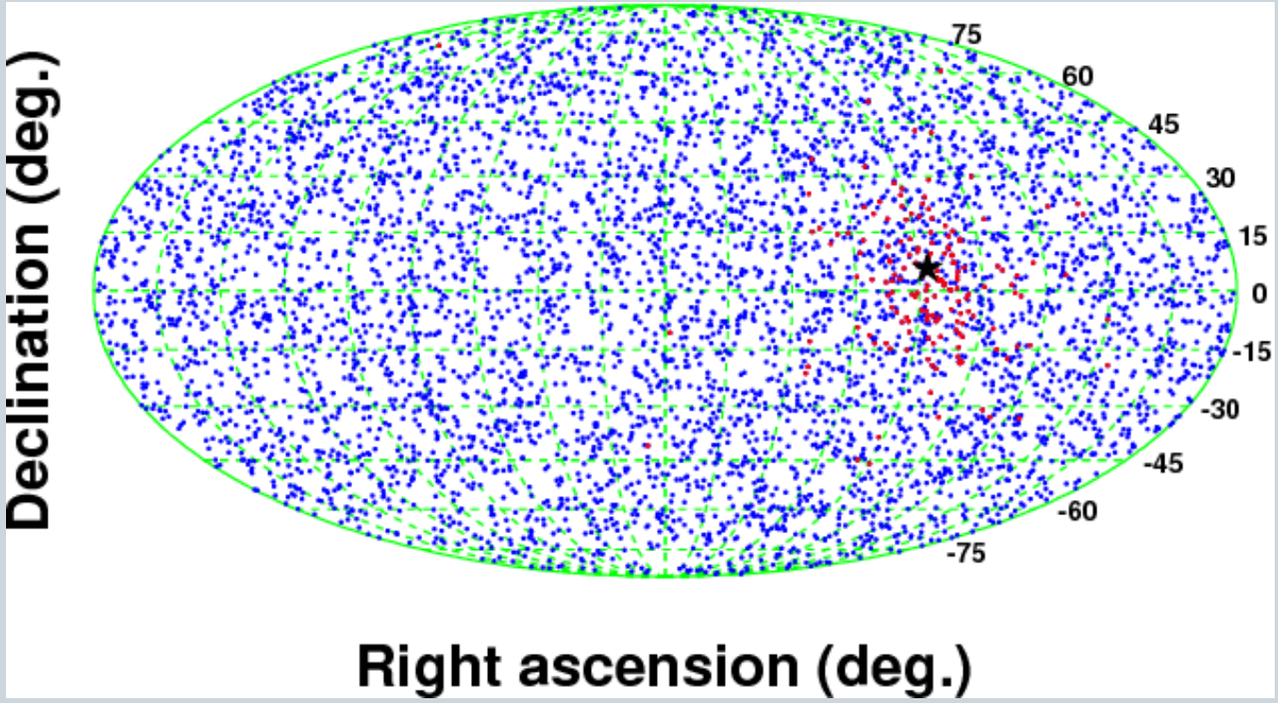


✅ Full-Featured

- Want to know as much additional information as possible to inform follow-up strategy
  - Pointing (“3 P’s”)
  - Distance
  - Event type
  - …

✅ Full-Featured

- Two ways to determine direction
  - Directional information from reconstructed events
  - Triangulation between different experiments



SK: IBD + ^{16}O-CC (blue) and e scattering (red) events, arXiv:1601.04778

- Mainly from ν-e scattering in WCh detectors
- Good accuracy (e.g. Super-K: ~5° at 10 kpc)
- Slow, requires full event reconstruction
- Up to each experiment, SNEWS can combine info from detectors & progenitor lists

✅ Full-Featured

- Two ways to determine direction
  - Directional information from reconstructed events
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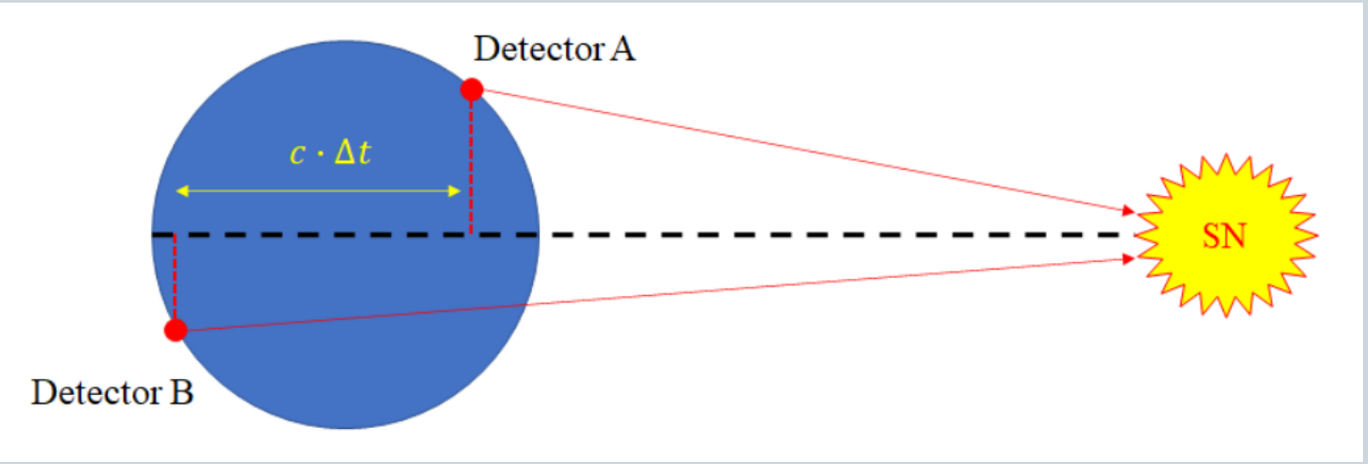
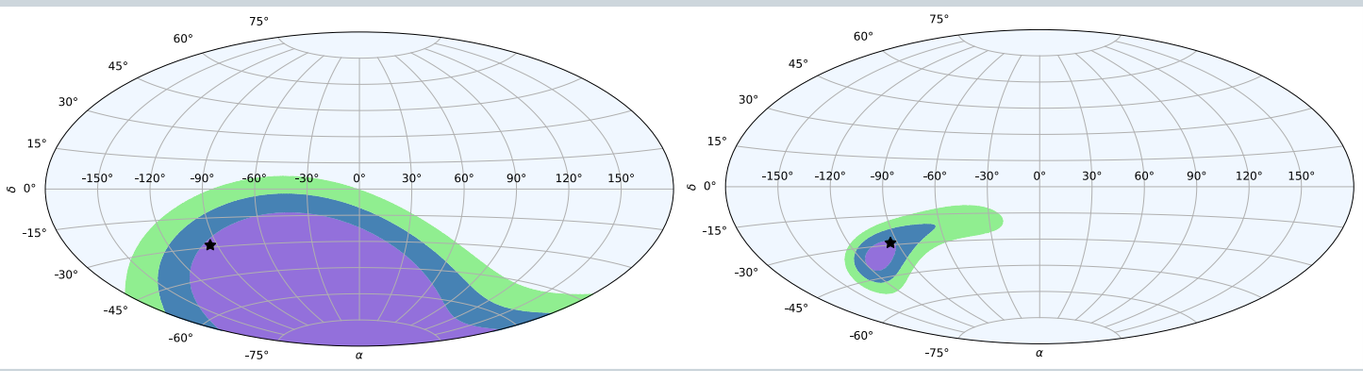




⬆️ SK+IC

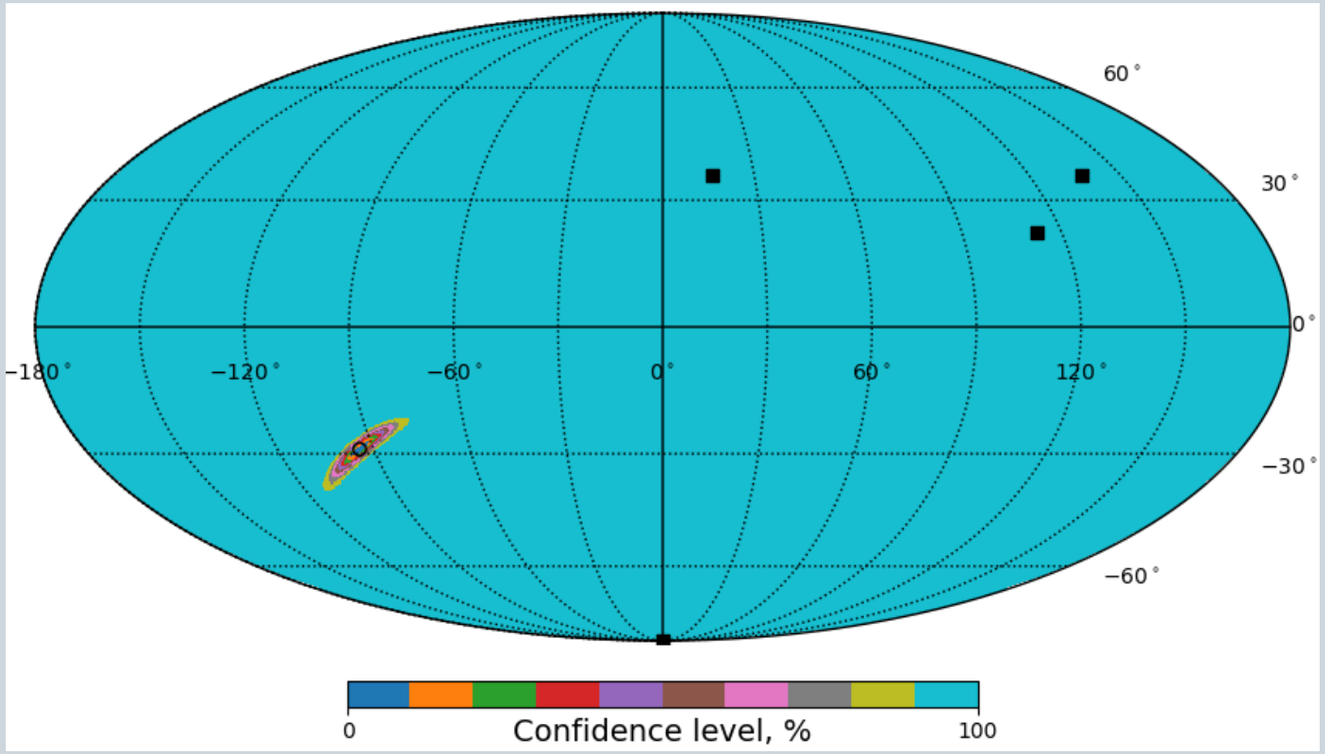
arXiv:1909.03151

⬆️ HK+IC+JUNO+DUNE

- Arrival time difference up to ~40 ms between detectors
- If clocks synchronised & common definition of t_0, can identify direction
- Less precise, but very fast
- Identify suitable telescopes, start slewing

✅ Full-Featured

- Two ways to determine direction
  - Directional information from reconstructed events
  - Triangulation between different experiments



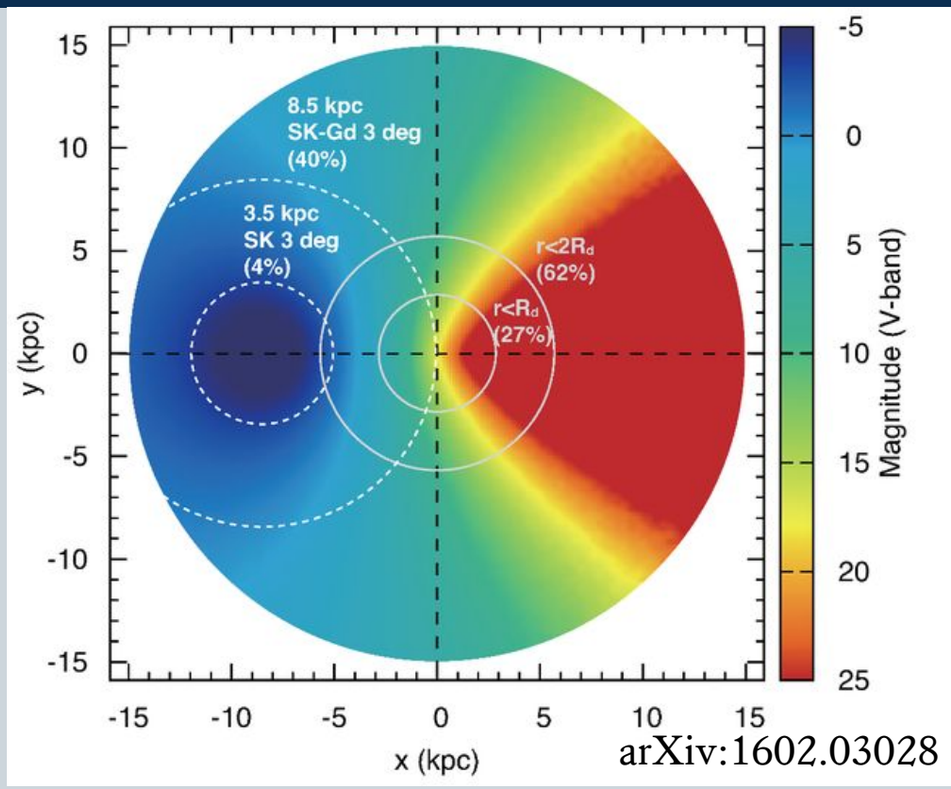
IC+ARCA+HK+JUNO (arXiv:2003.04864)

- Instead of just t_0, use time series matching to improve accuracy
- Similar experiments only (e.g. IBD-dominated)
- Rapid changes in flux (e.g. BH cut-off) very powerful

✅ Full-Featured

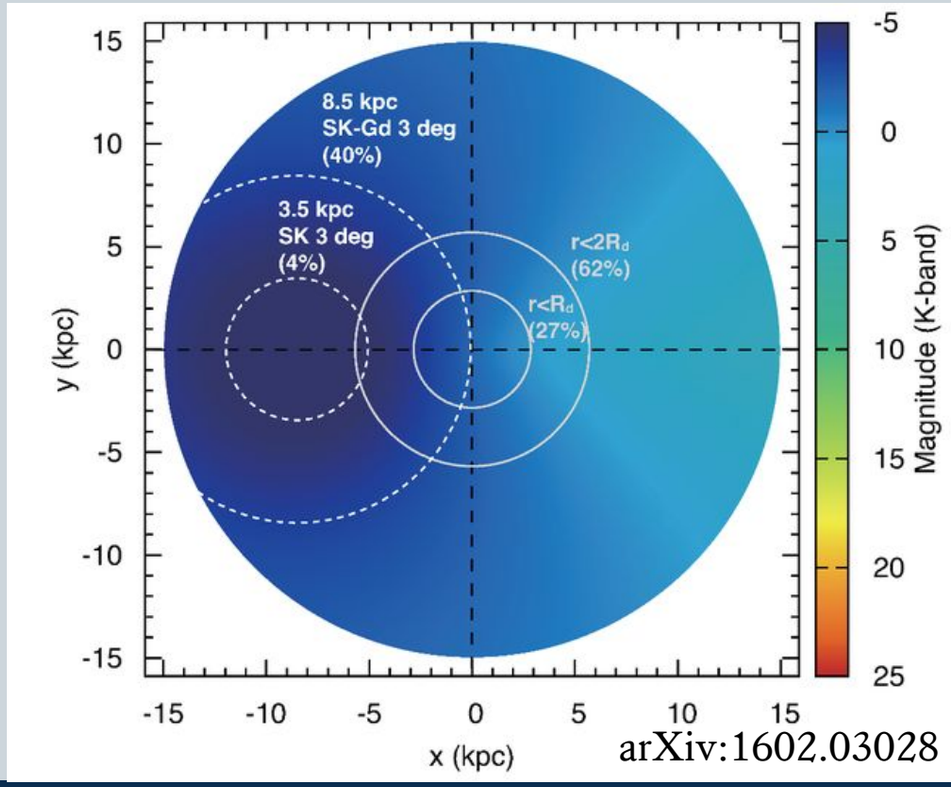
- Distance may affect the optimal observation strategy
  - Dust obscuration near GC
  - If close: direction may let us create "shortlist" of candidate stars
  - Estimate from event rate

(or in more advanced ways, see supplementary slides)



- Event type
  - Sudden cut-off in ν signal can indicate black hole formation
  - Identify non-core-collapse events? (SN Ia, PISN, binary merger, …)

⬆ Optical Near-IR ⬇



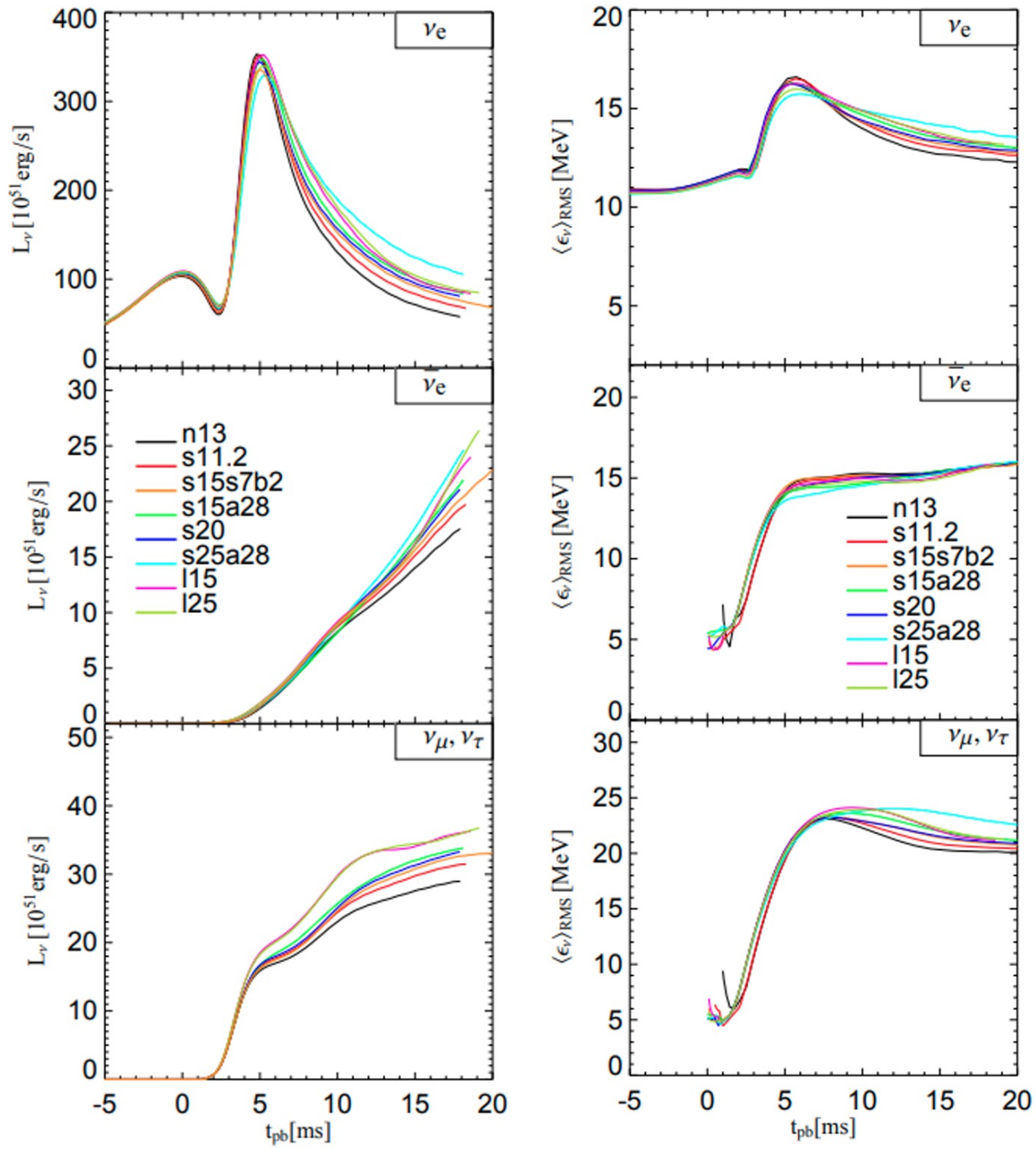
✅ FAR

- GW alerts have demonstrated that it's fine to send out uncertain alerts if false alarm rate is included
  - No "Boy who cried wolf" effect
    - Astronomers can set their own FAR threshold
- Allowing higher FAR enables sensitivity at farther distance, e.g. for LMC & exotic transients

Distance

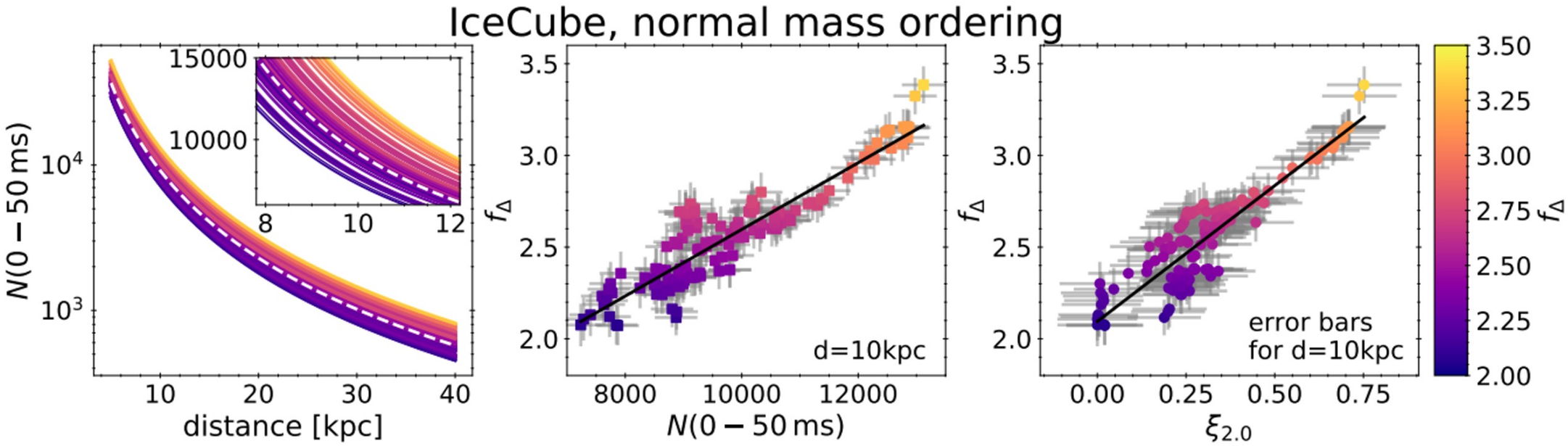
Kachelriess et al., PRD71 (2005) 063003

- Neutronization burst (ν_e) self-limited by electron captures
  - Potential standard candle, stable vs progenitor mass
  - Yield can be used to estimate distance to SN
- 1MT water Cherenkov detector
  - Average 112 EES events at 10kpc
  - 5% uncertainty on distance
- SNO+ and JUNO should also get a sizable number of proton elastic scattering events



Distance

- Anti-ν_e yield ratio of (100,150)ms / (0,50)ms related to “compactness”
  - Can also be related to mass → similar sensitivity, smaller detectors using IBD



Segerlund et al., arxiv:2101.10624 (2021)