MDvDM 2025, May 22nd 2025

Astrophysical: supernova neutrino overview

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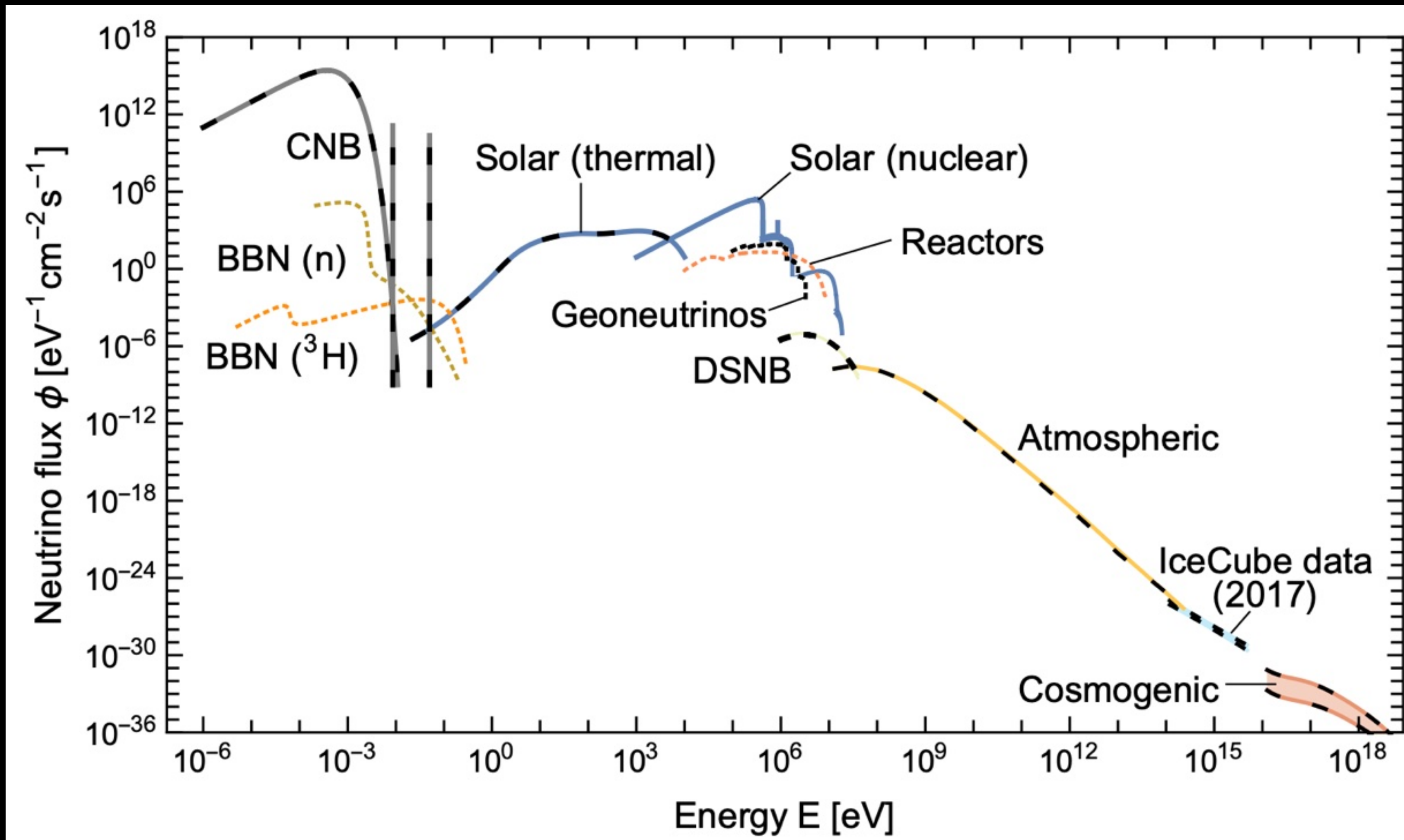
Virginia Tech, Kavli IPMU

Image credit: NASA/ESA

Neutrinos @Earth

Many different sources, energies, physics & detection strategies



Vitagliano et al (2020)

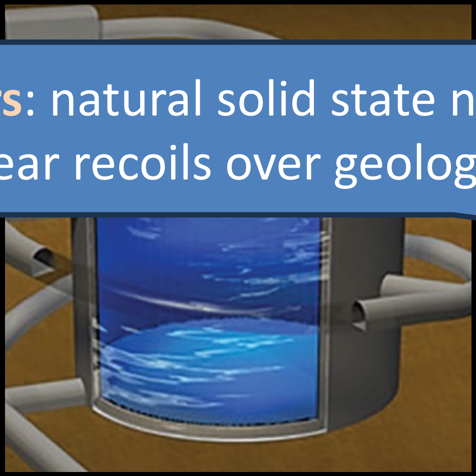
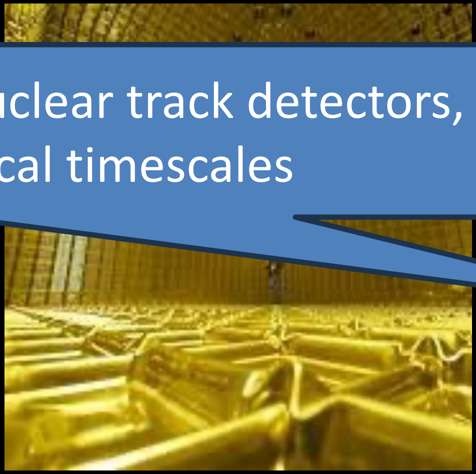
Neutrino detection

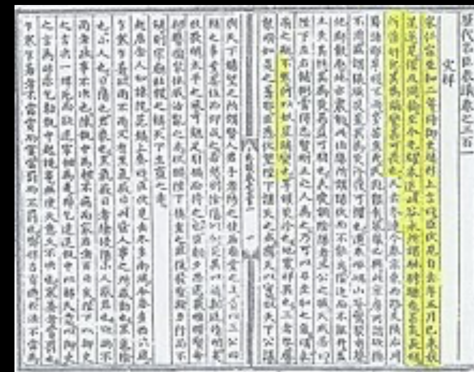
- **Detector must be massive**
  Need large volumes
- **Detector must be "quiet"**
  Low radioactivity, shielding
- **Detector better to have back**
  Distinguish signal and backgrounds

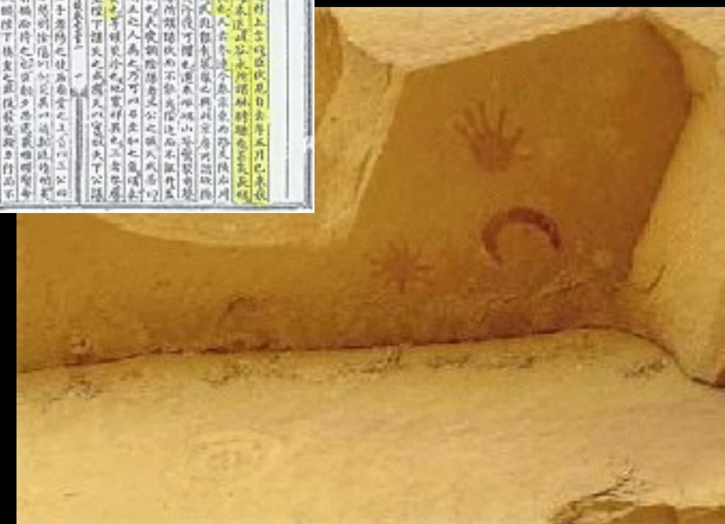
Need large exposures

sample from underground

Paleo detectors: natural solid state nuclear track detectors, recording nuclear recoils over geological timescales

JUNO	Hyper-Kamiokande	DUNE	Mineral detectors
			
Scintillator *Imminent*	Water *Building*	Liquid argon *Building*	Rock mineral *R & D*





SUPERNOVA NEUTRINOS

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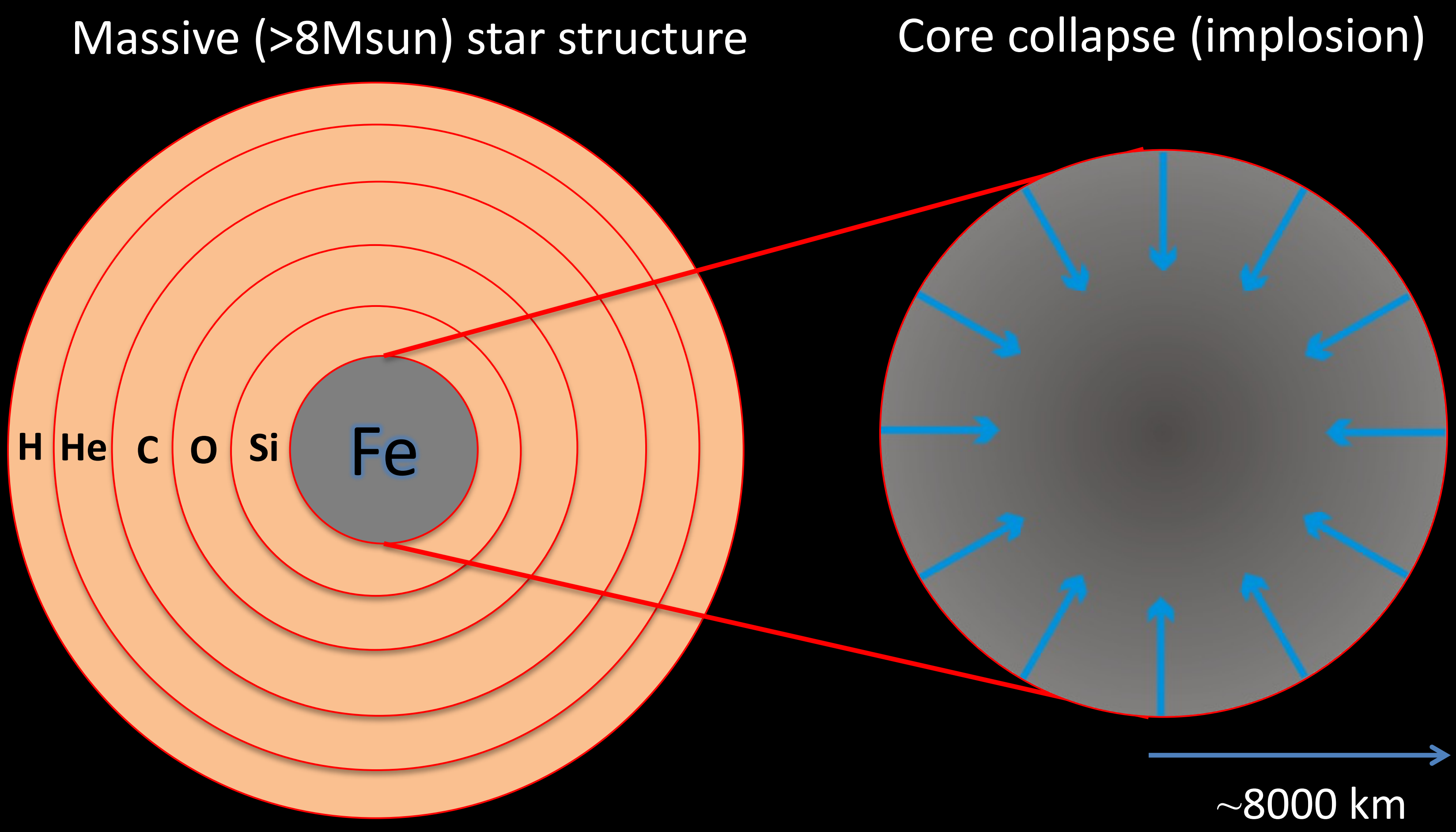
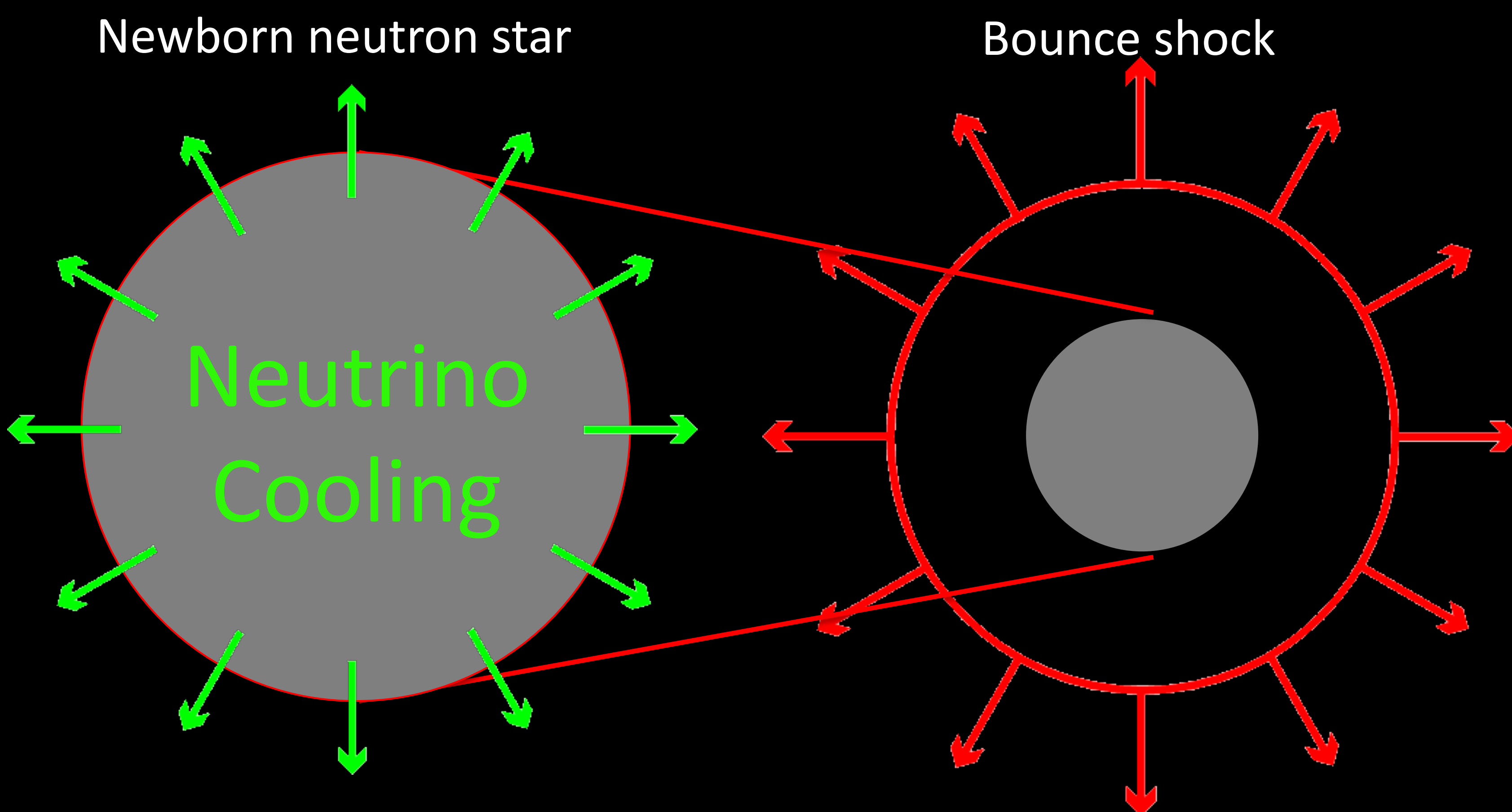
Under the hood



(adapted from G. Raffelt's slides)

Under the hood

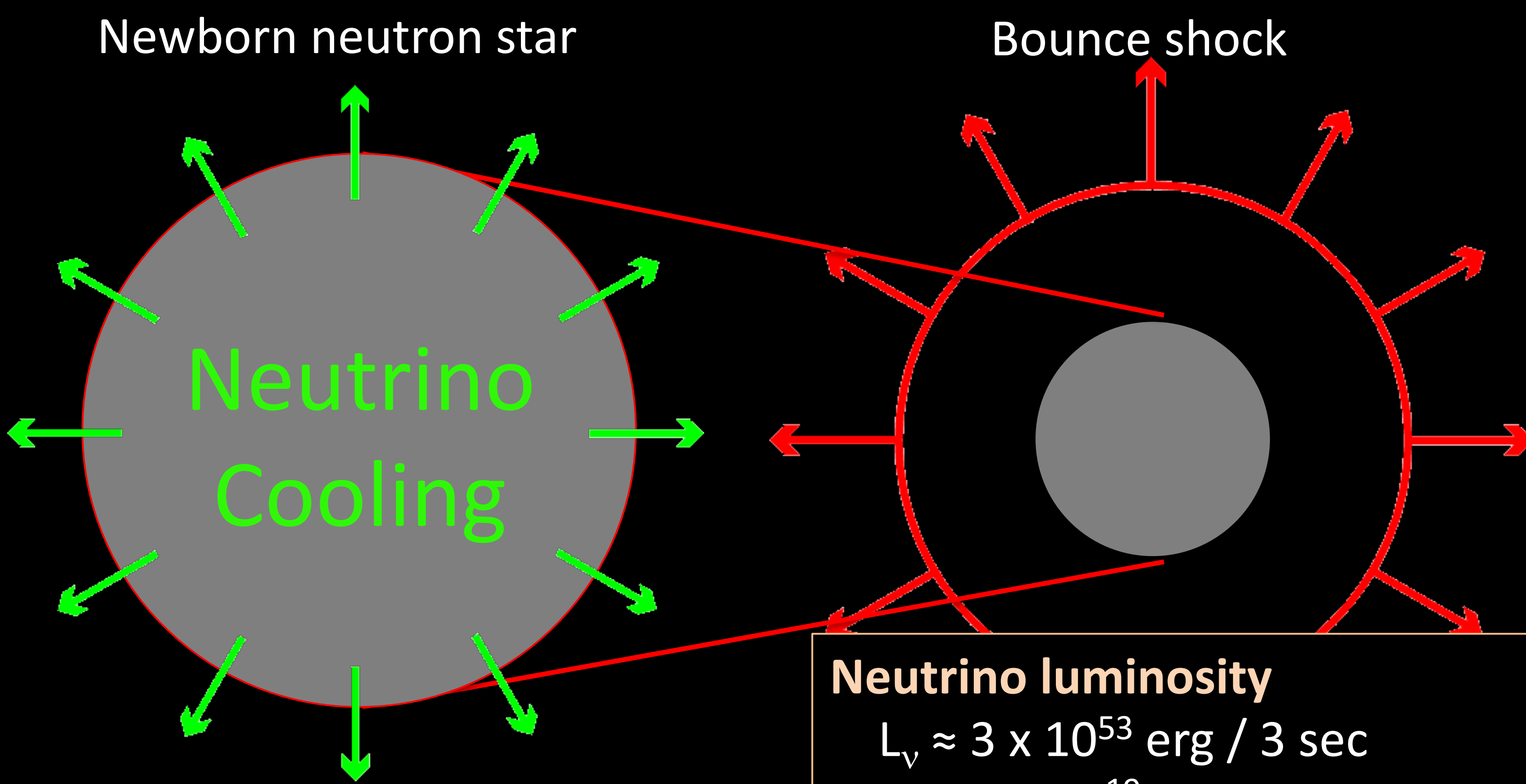


Energy budget ~ 3 x 10^{53} erg
99% into neutrinos
(~0.01% into photons)

R: 8000 km → ~20 km
ρ: ~10^{9} g cm^{-3} → ~10^{14} g cm^{-3}
T: ~10^{10} K → ~30 MeV

(adapted from G. Raffelt's slides)

Under the hood



Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

$\approx 3 \times 10^{19}\ L_{SUN}$

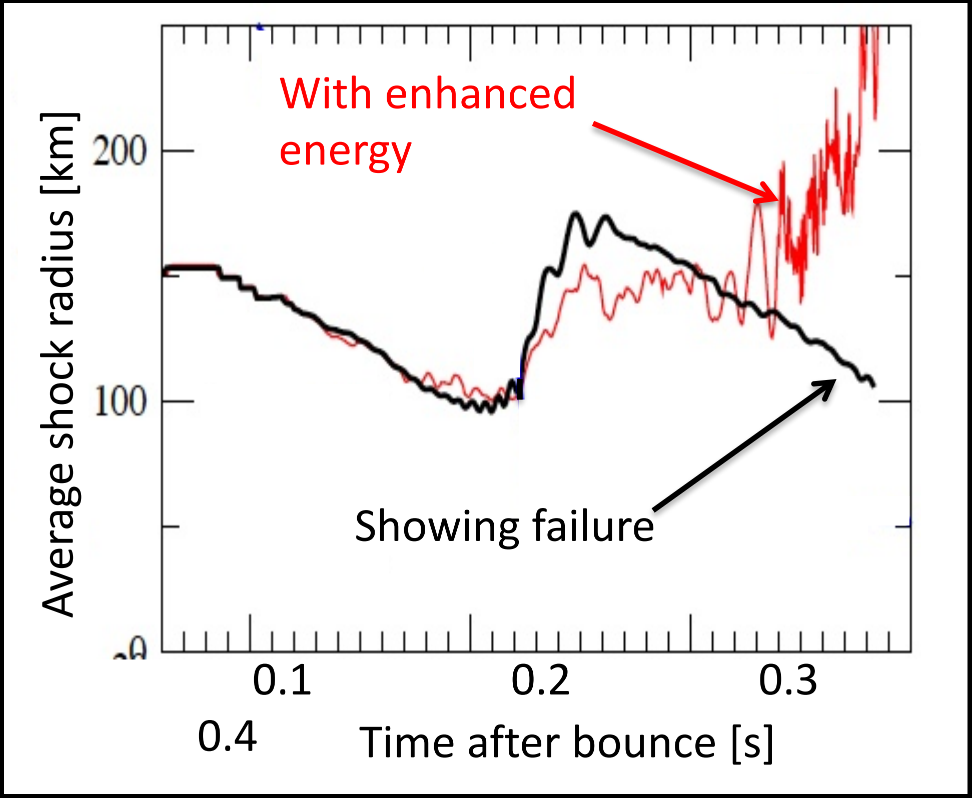
While it lasts, it outshines the entire visible Universe

<u>Energy budget</u> ~ 3×10^{53} erg
99% into neutrinos
(~0.01% into photons)

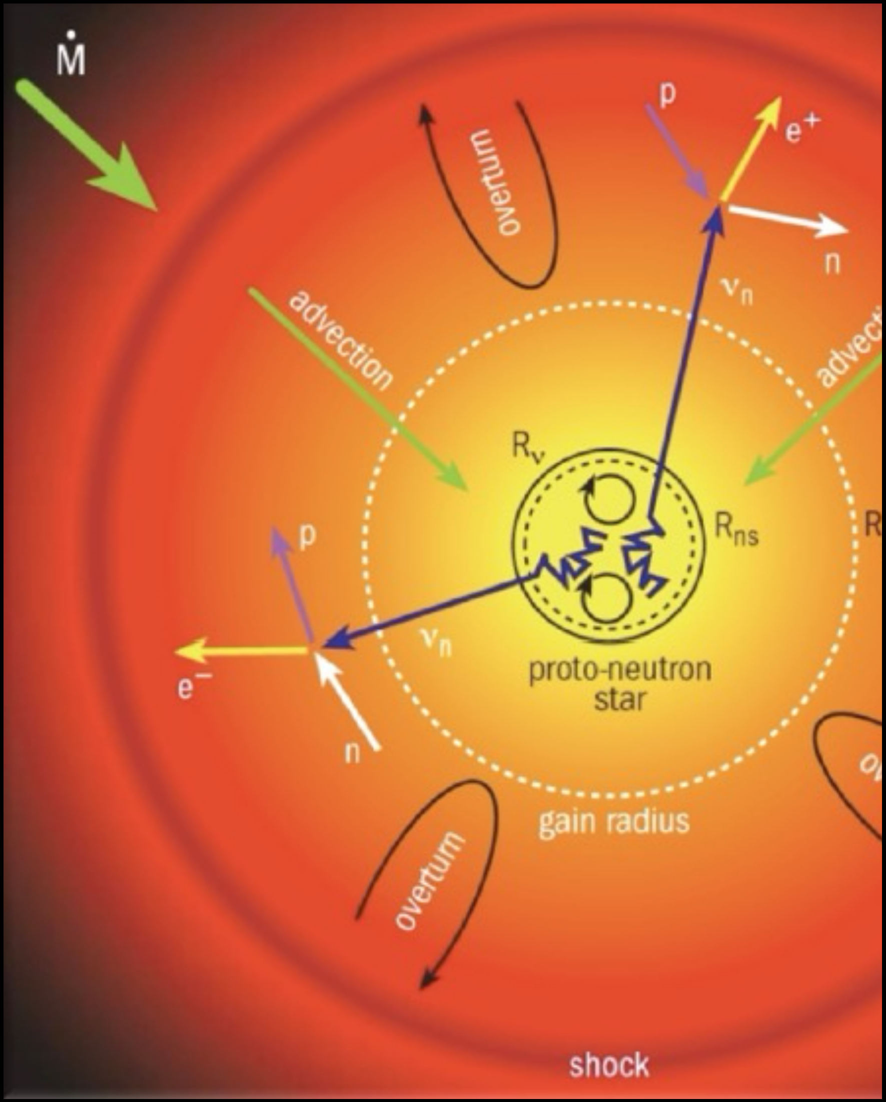
(adapted from G. Raffelt's slides)

No prompt explosion

The problem:
The bounce shock loses energy and stalls at ~150 km, eventually gets overwhelmed by infalling mass and collapses



Hanke et al (2014)



(Image from B. Messner)

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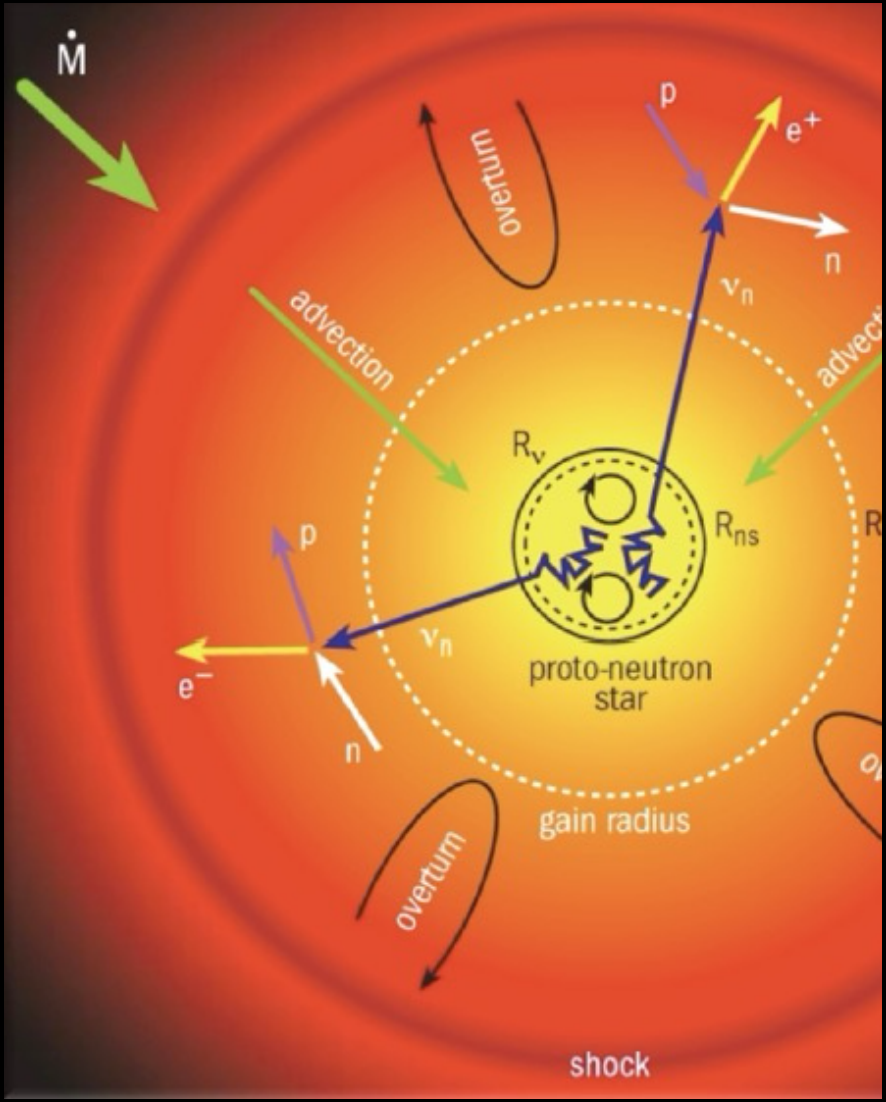
Explosion mechanisms

The problem:
The bounce shock loses energy and stalls at ~150 km, eventually gets overwhelmed by infalling mass and collapses

Many proposed solutions:

1. Neutrino mechanism *E(neutrino)*
   Wilson (1985), …
2. Phase transition *E(gravity)*
   Migdal et al (1971), …
3. Magneto-rotational *E(rotation)*
   Bisnovatyi-Kogan (1976), …
4. *Others, e.g., exotic neutrinos*
   Kainulainen et al (1991), …



(Image from B. Messner)

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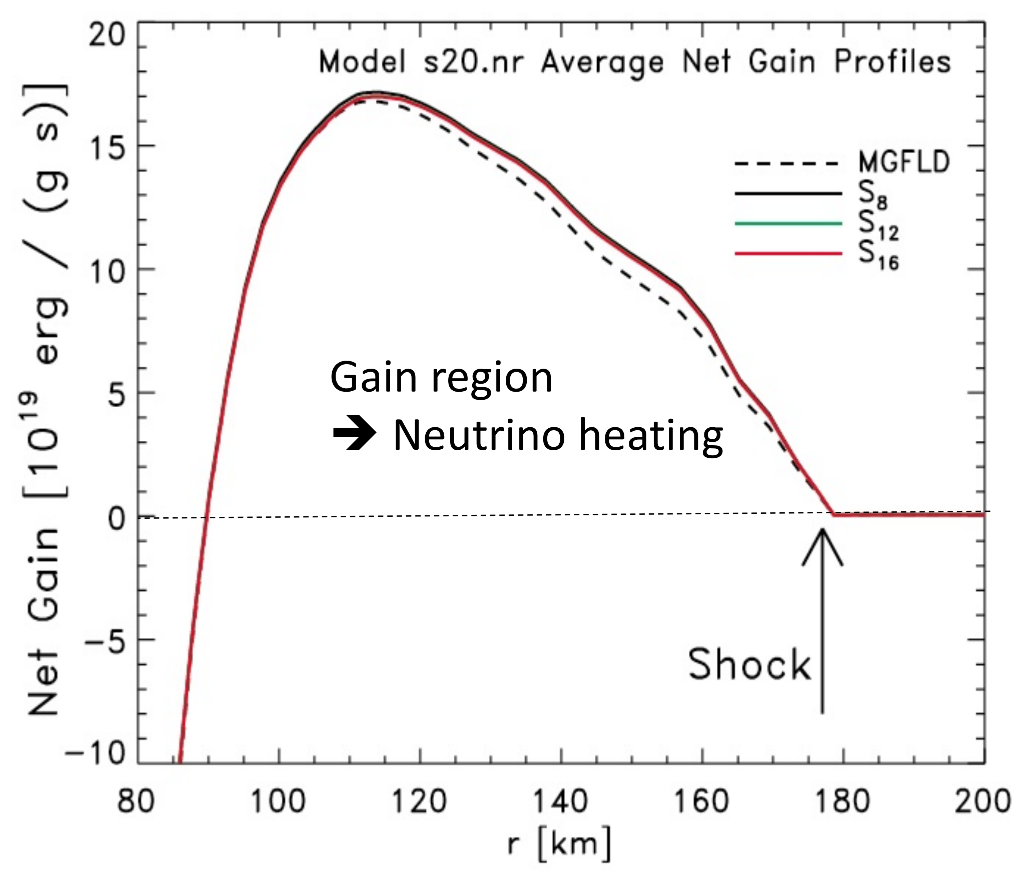
Why are neutrinos so crucial?

Energy source & transfer
Neutrinos cause both energy gain and cooling, but there is a region of net deposition of energy



Why are neutrinos so crucial?

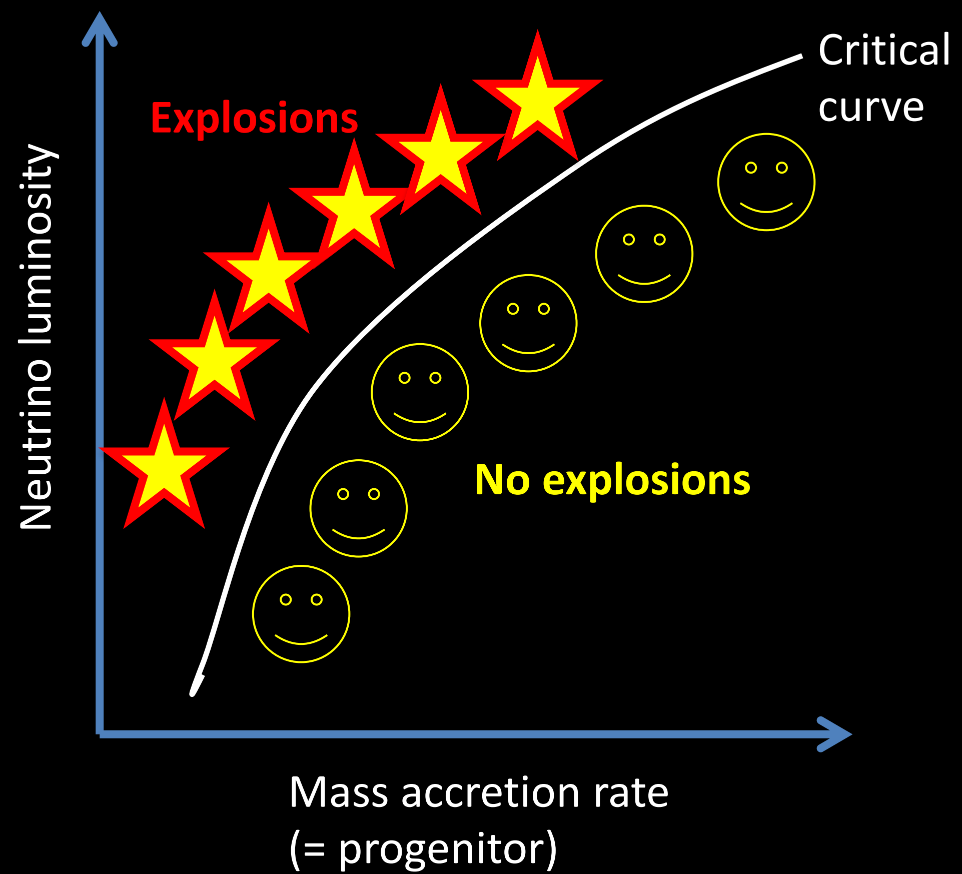
Energy source & transfer

Neutrinos cause both energy gain and cooling, but there is a region of net deposition of energy

Neutrino-powered explosions

Many simulations indicate neutrino heating is efficient enough to trigger explosions

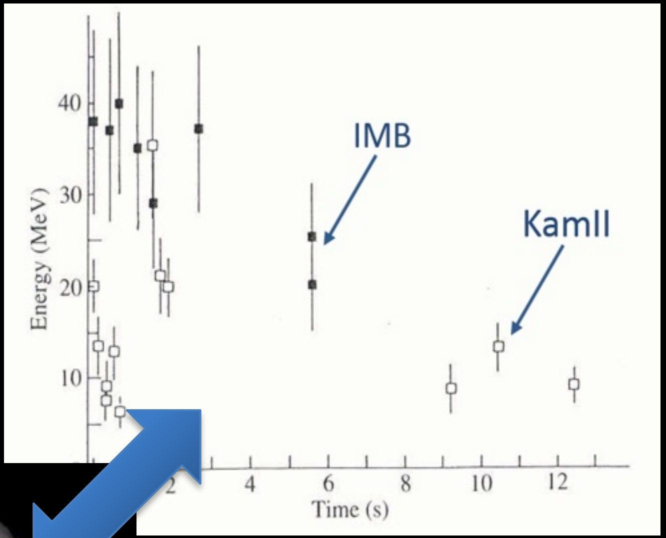
e.g., Fukuoka-NAOJ group, Garching group, MSU-Stockholm group, Oakridge group, Princeton group,

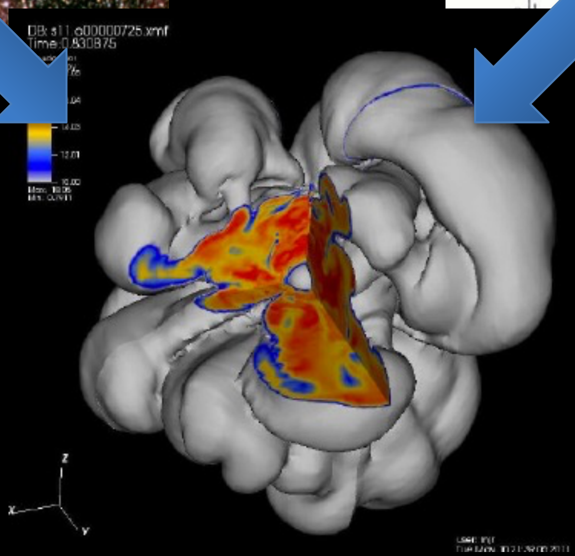


SN1987A: Rosetta stone

1987: Massive star explodes as Type II supernova

10 – 40 MeV neutrino signal lasting ~10 s





Theory: core collapse, emits neutrinos, launches shock, causes supernova explosion

Some implications

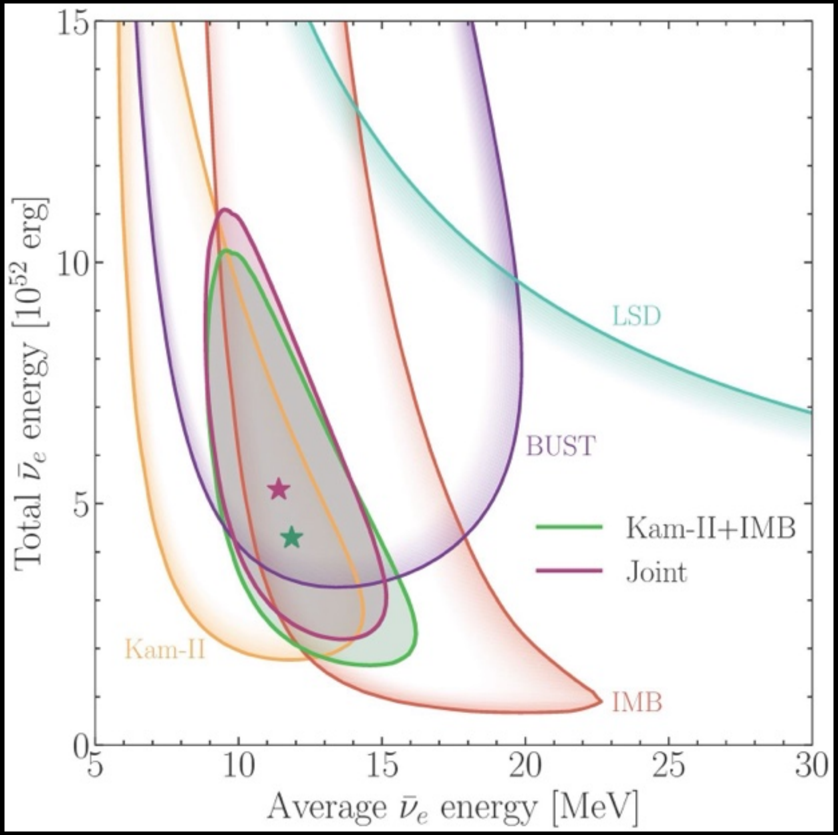
What did it tell us?

- The general picture is correct: massive stars explode as supernovae, emitting most of its energy released as neutrinos
- New physics doesn't affect neutrino emission and cooling at O(1) level

But so much remains

- Explosion mechanism
- Instabilities
- Black hole formation
- Equation of state
- Phase transitions
- New physics

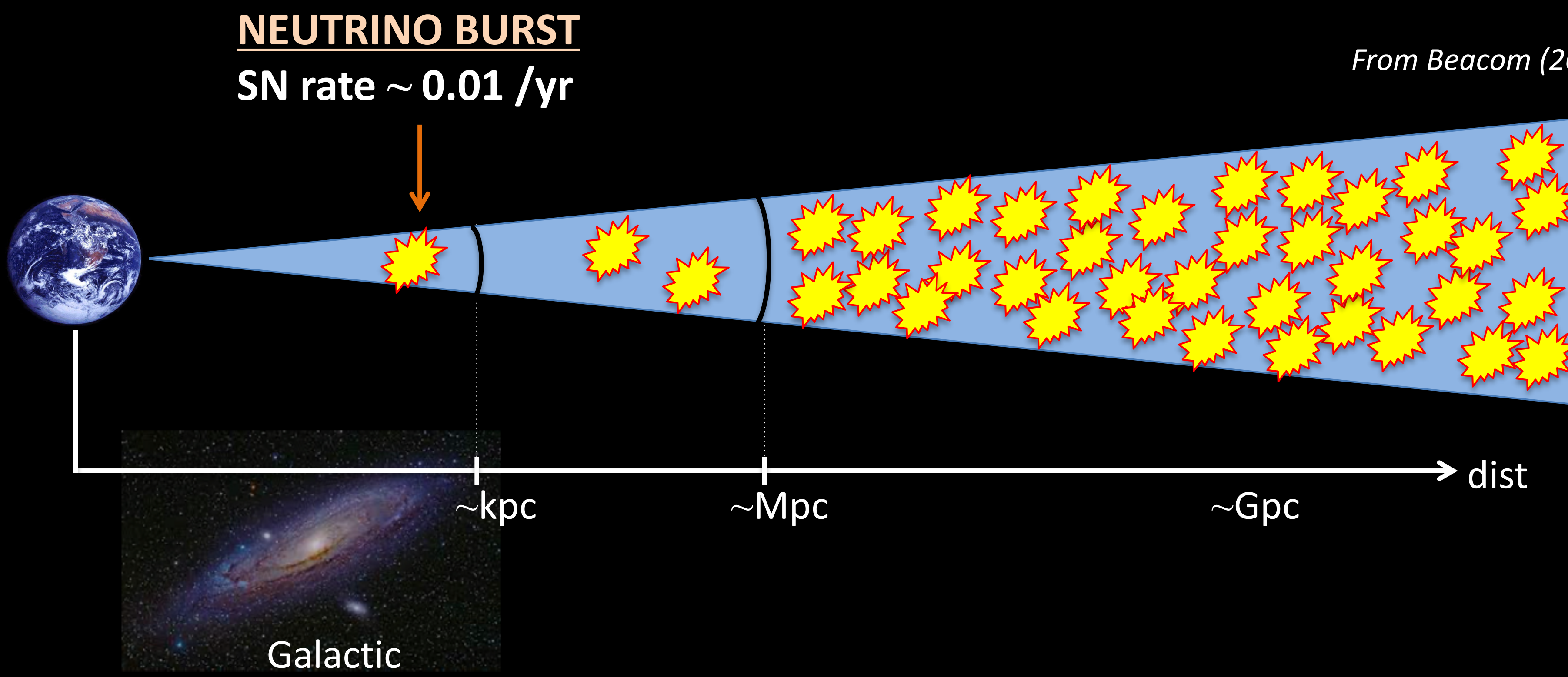
...and much more



Fiorillo et al (2023)
Many others, eg Li et al (2023), Vissani (2015)

Supernova neutrino detection frontiers

From Beacom (2011)



Features:

- Wait For nature's cooperation
- Precision multi-messenger observations on 1 progenitor
- Surprises?

Milky Way: detection ready

High number of neutrino detections expected from a Galactic core collapse

Experiment	Type	Mass (kt)	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	—	250	—
XENONnT	Xe/any ν	0.006	Italy	56	106	—
LZ	Xe/any ν	0.007	USA	65	123	—
PandaX-4T	Xe/any ν	0.004	China	37	70	—

SNEWS (2022)

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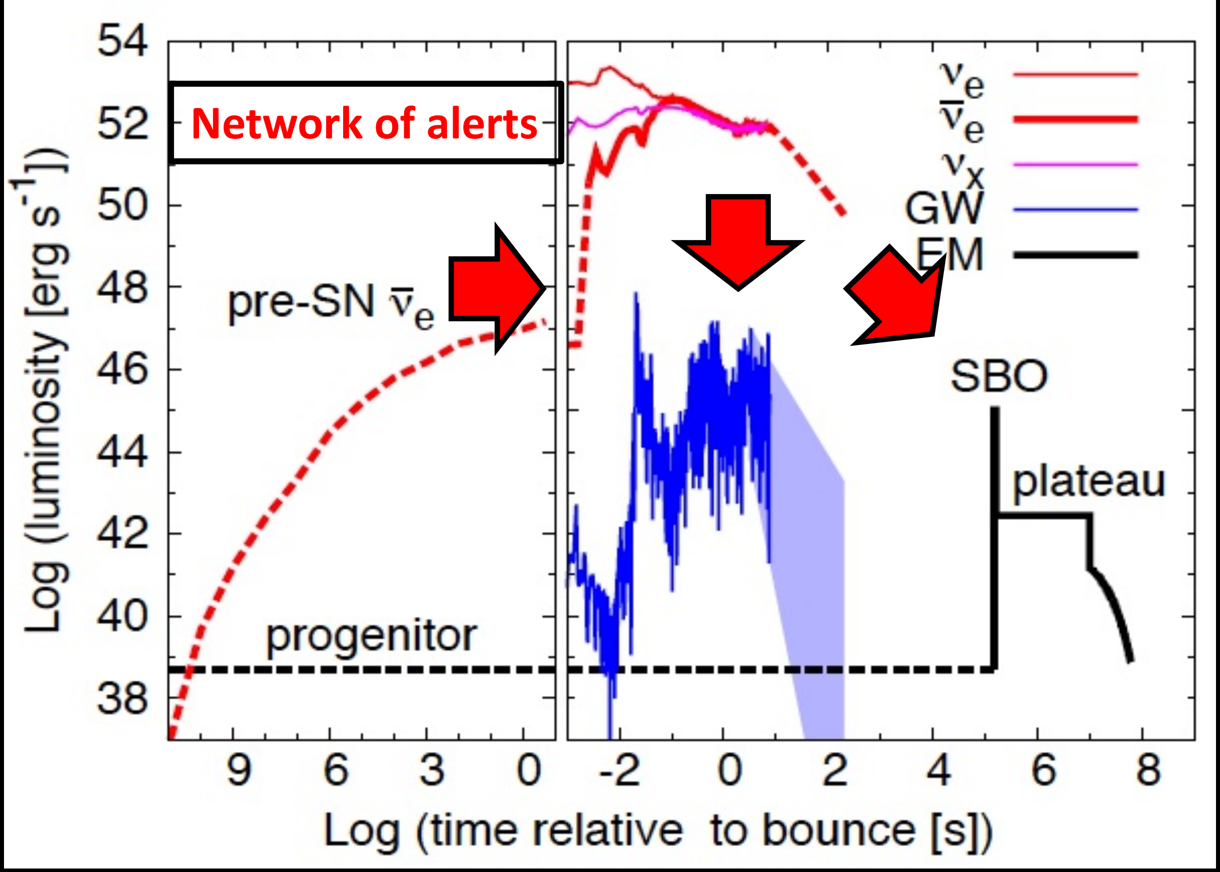
The multi-messenger context

Supernova neutrinos come with gravitational waves and photons, each revealing unique complementary information:



Nakamura, Horiuchi et al (2016)

But...Galactic supernova rate is ~1.5 per century

→ Need to be well prepared!

SNEWS2.0 brings neutrino detectors for the new age of multi-messenger astronomy:

SNEWS SUPERNOVA EARLY WARNING SYSTEM

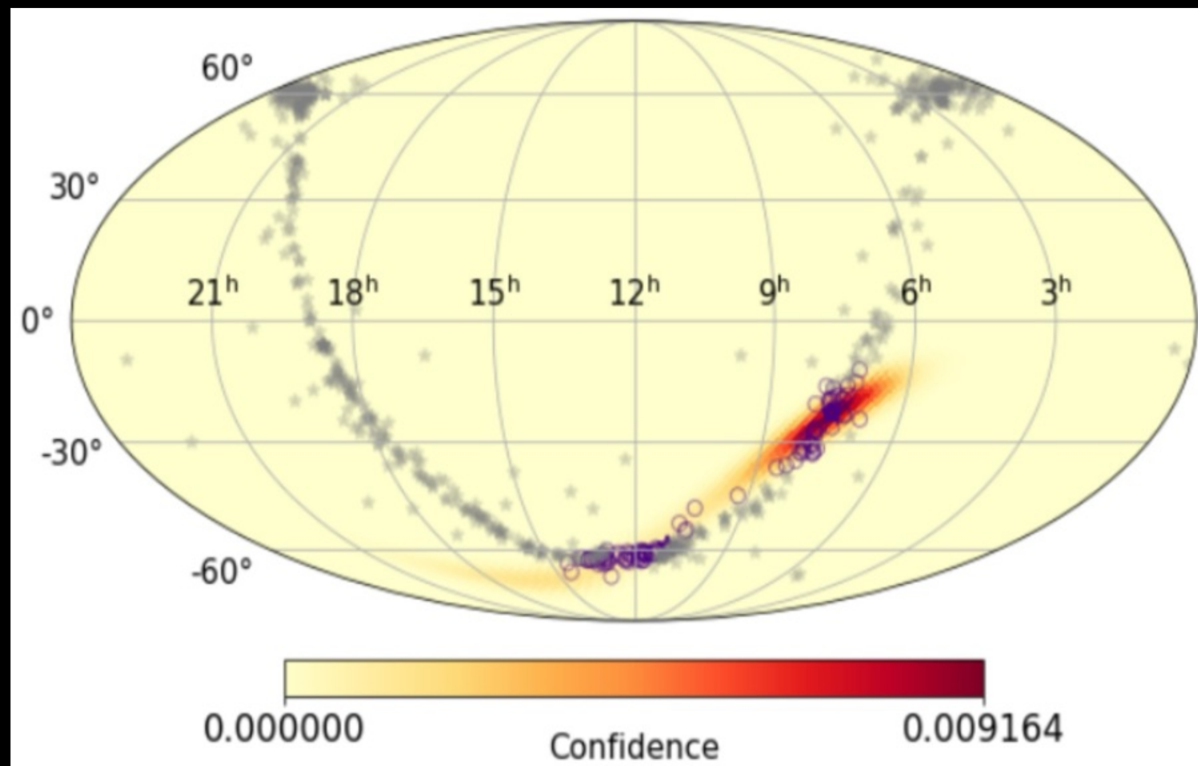
(everyone can sign up for alerts! https://snews2.org/)

Neutrino pointing

Prompt and automated <u>alert</u> in under 1 hr	Neutrino <u>timing</u> for coincident searches	<u>Pointing</u> with neutrino triangulation	<u>Monitoring</u> and <u>coordination</u> with EM follow-up

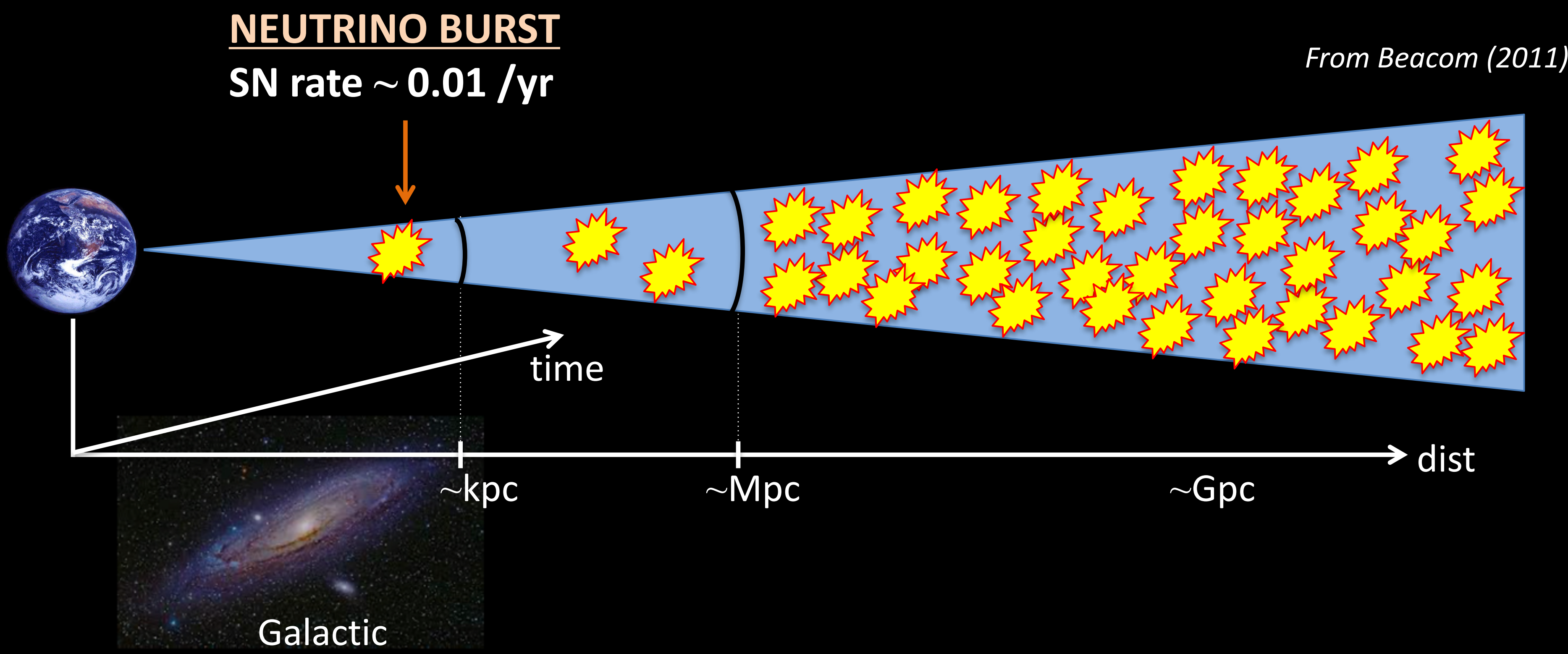
1) Monitor candidates
↓
2) Neutrino burst
↓
3) Triangulation & alert
↓
4) Follow-up

→ Eg: 500+ supernova progenitor candidates, down to 2 with neutrino burst info.



Healy, Horiuchi, et al (2023)

Supernova neutrino detection frontiers



Features:

- Wait For nature’s cooperation
- Precision multi-messenger observations on 1 progenitor
- Surprises?

Paleo detector: advantages

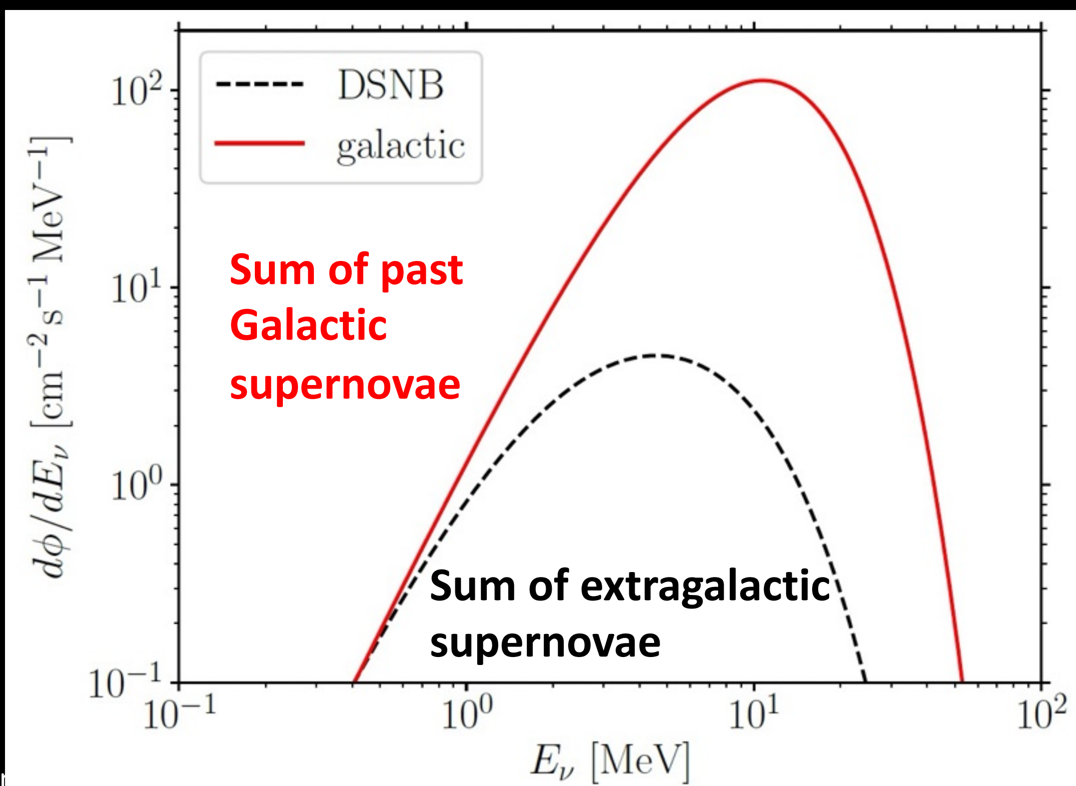
Large, unique signal

Data taking >> inverse of Galactic supernova rate (~few per century)

No waiting! Signal is already there.

All flavors! CEνNS interaction for SN neutrino energies

Competitive exposure! 100 grams over 10^9 years = 10^5 t yr

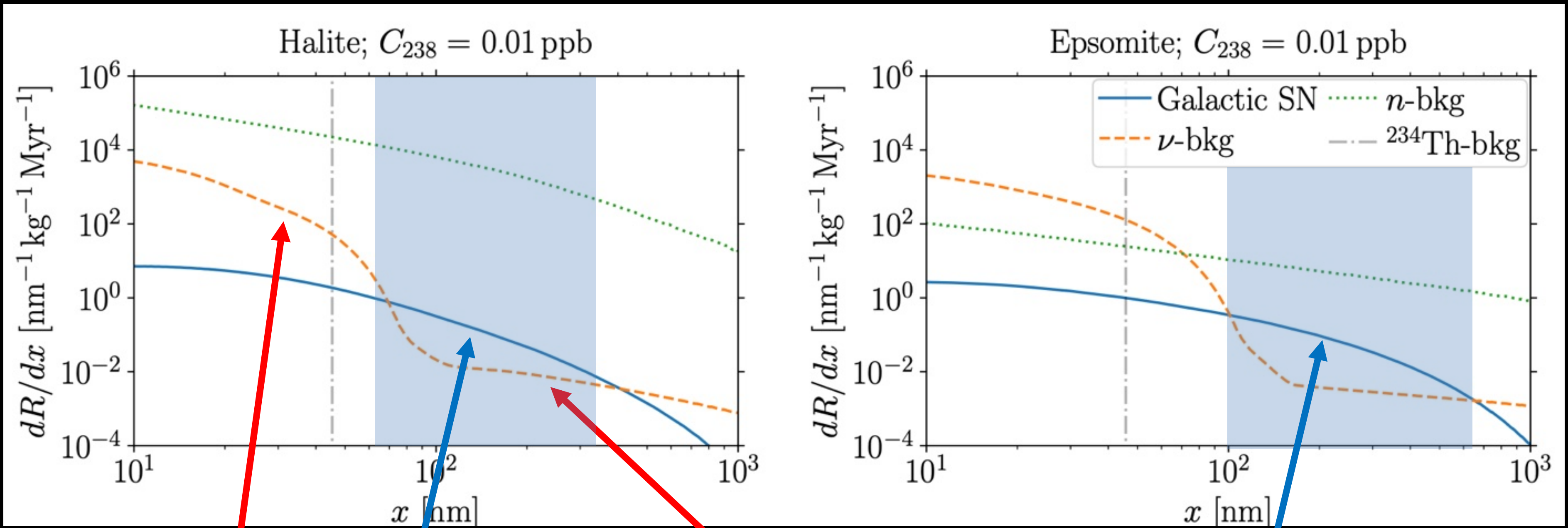


- Model the neutrino spectrum
- Assume target mineral
- Estimate damaga track spectra (SRIM)
- Background considerations
- Track reconstruction assumptions

Baum et al (2020)

Track spectra

Supernova neutrino window: consideration of other neutrinos & backgrounds



Baum et al (2020)

Solar neutrinos

Atmospheric neutrinos

Signal region

Exact region depends on chemical makeup of targets

Backgrounds in passive detectos:

→ Cannot distinguish on track-by-track basis
→ Search using wide-band track spectrum

Main backgrounds considered

Natural defects:

- Single sites or stretches across sample → distinguish

Cosmogenic:

- Muons negligible by ~5 km → sample from deep underground

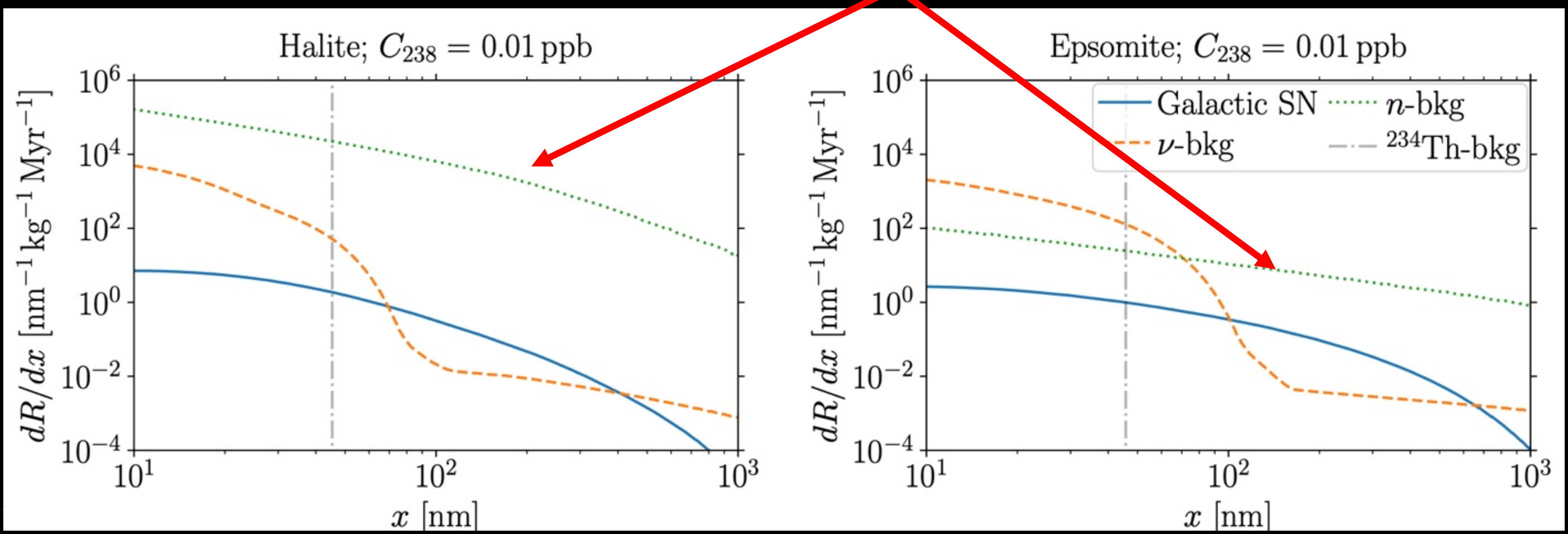
Radiogenic:

- ^{238}U decay chain localized → mostly distinguish
- Neutrons from spontaneous fission, (α,n) reactions → find radiopure sample

Other neutrinos:

- Atmospheric, solar

Uncertainty of neutron backgrounds critical (assumed 1%)



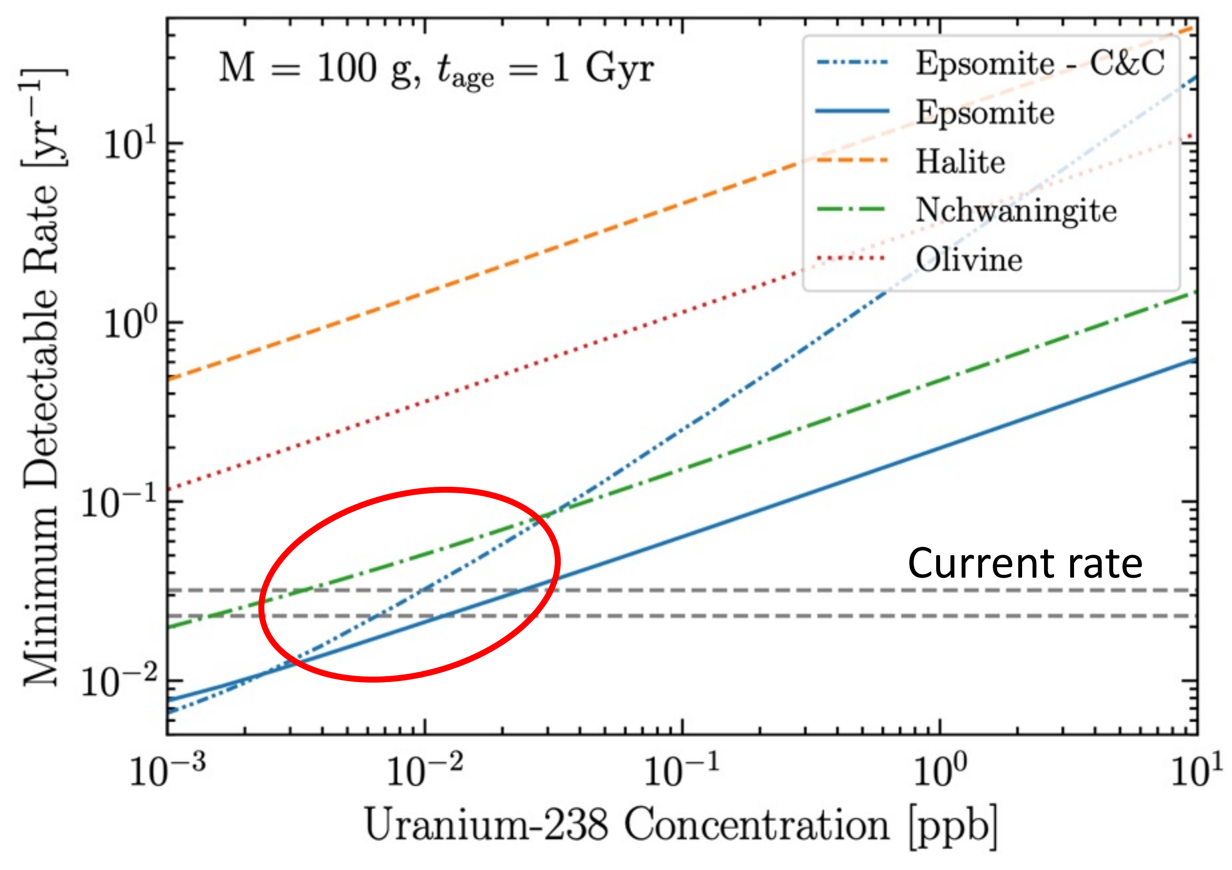
Supernova neutrino detection

Detection with sufficiently old & pure sample:

- *Age: 1 Gys*
- *Mass: 100 g*
- *Pure: ~0.01 ppb*

→ Depending on the past supernova rate, paleo detectors can be used to detected past neutrinos

(good minerals composed of intermediate mass nuclei, small (α,n) reactions, low ^{238}U, and contain hydrogen)



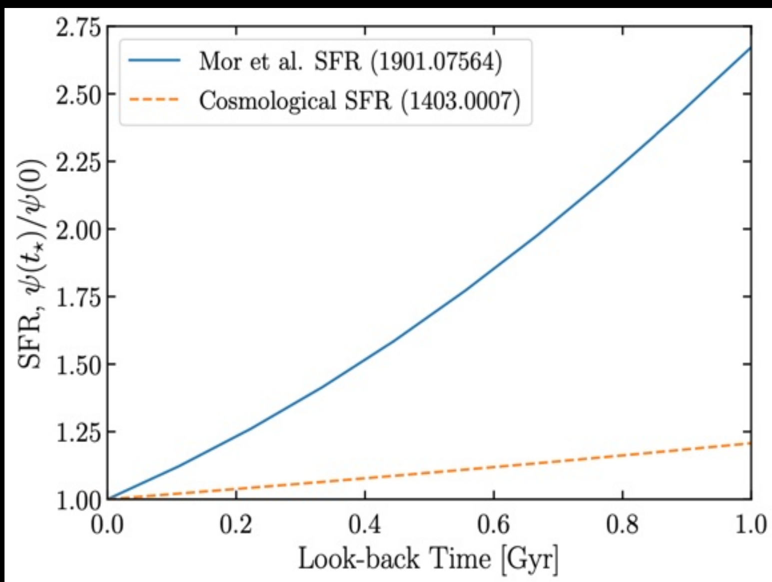
Baum et al (2020)

Halite -- NaCl
Epsomite -- $MgSO_4 \cdot 7(H_2O)$
Olivine -- $Mg_{1.6}Fe_{0.4}(SiO_4)$
Nchwaningite -- $Mn_2SiO_3(OH)_2 \cdot (H_2O)$

(15nm track resolution)
(1% uncertainty on radiogenic backgrounds)
(100% uncertainty on neutrino backgrounds)

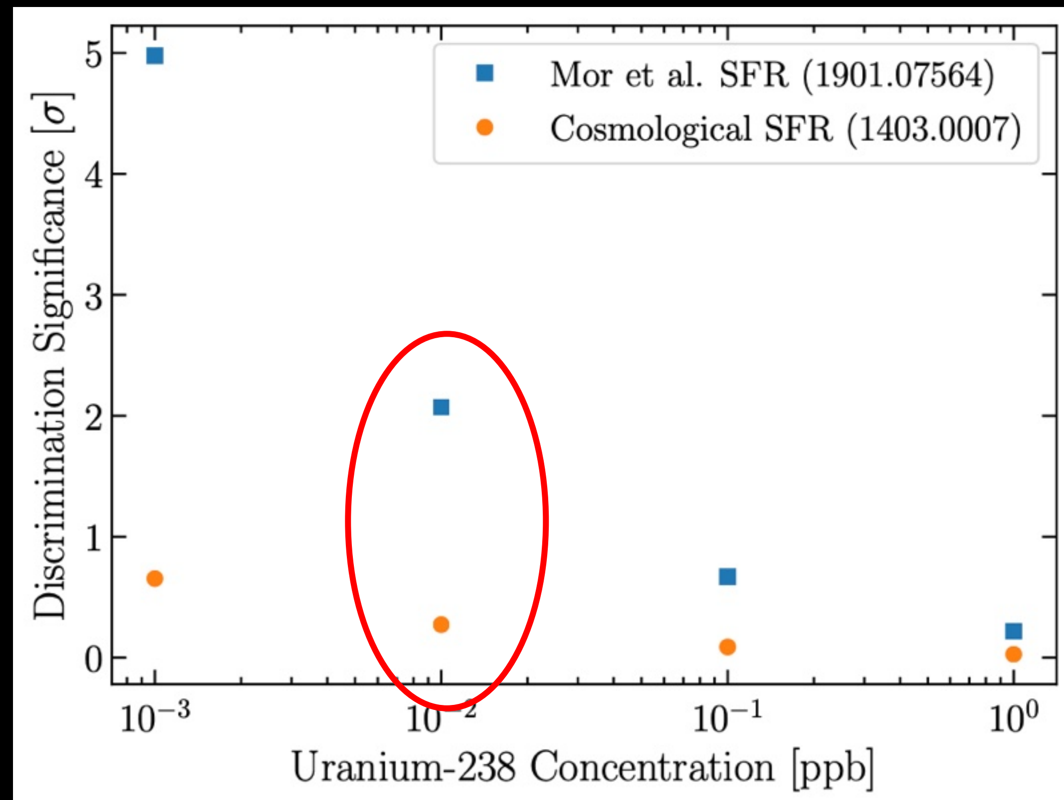
How high was the past supernova rate?

Was Milky Way's star formation rate higher in the past?
Quite possibly, but uncertain.



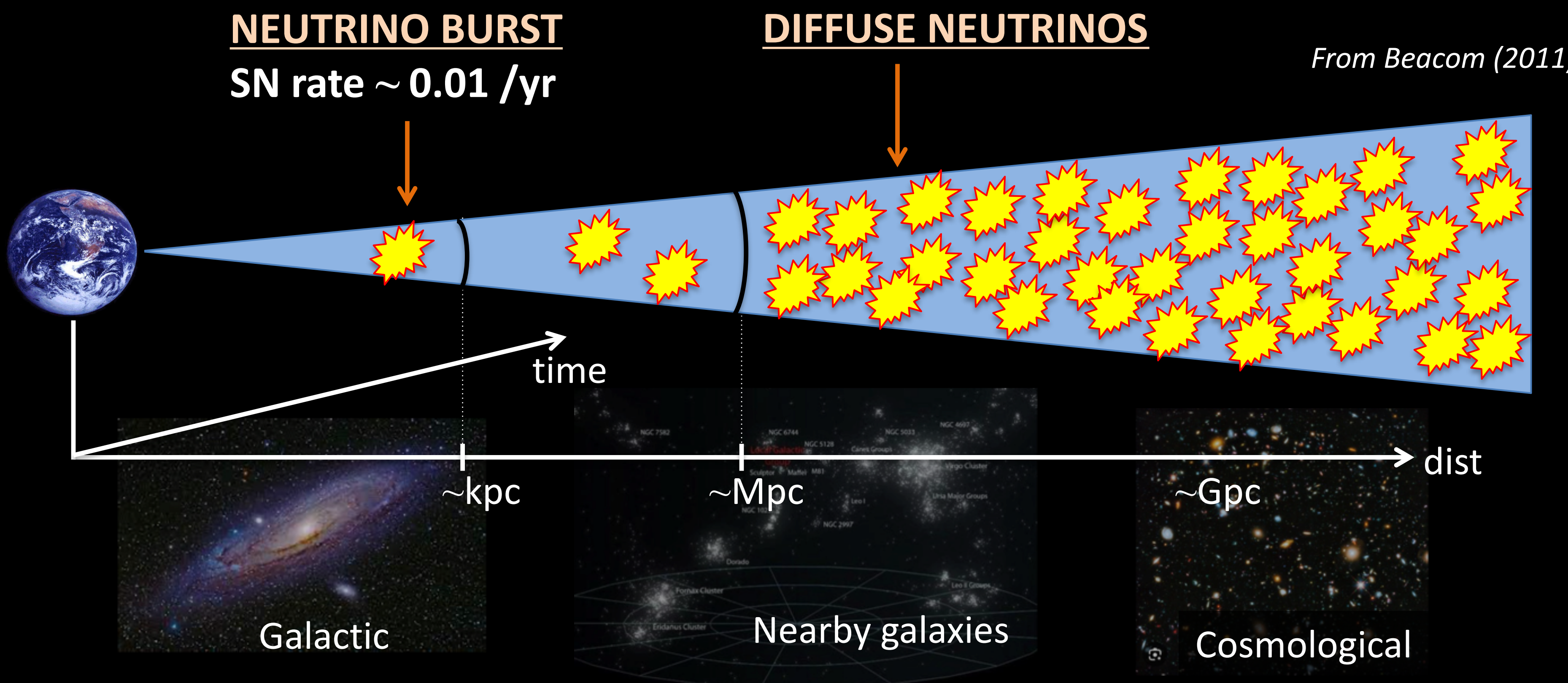
Baum et al (2020)

➔ **Sufficiently pure minerals can rule out constant supernova rate model**



(10 paleo detectors, 100 g each, measuring integrated rates over 100, 200, 300, …, 1000 Myr)

Supernova neutrino detection frontiers



Features:
- Wait For nature's cooperation
- Precision multi-messenger observations on 1 progenitor
- Surprises?

Features:
- Guaranteed signal (no waiting)
- Many progenitors, population studies
- Cosmological distances
- Surprises?

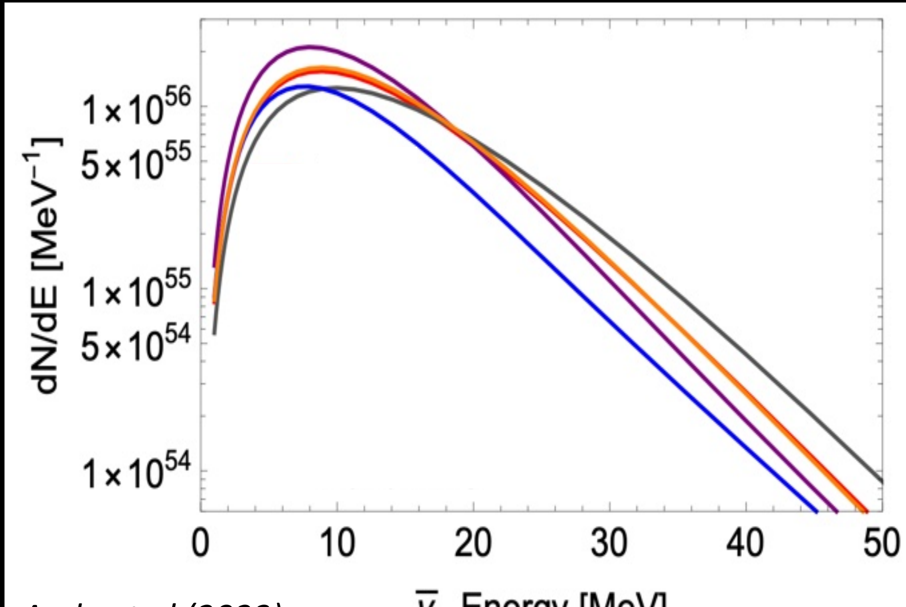
Shunsaku Horiuchi

Diffuse flux: model prediction

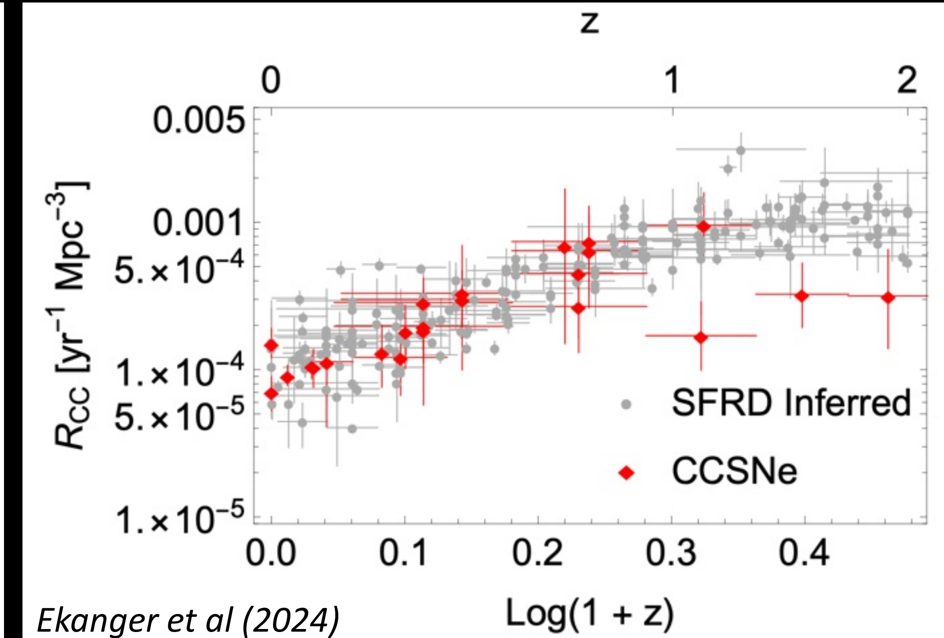
$$DSNB = \int dz\, c \frac{dN}{dE'} (1+z) R_{CC}(z) \left| \frac{dt}{dz} \right|$$

Time-integrated neutrino emission; detected in SN1987A, predicted by simulations

Rate of massive star core collapse; directly observed



Ando et al (2023)



Ekanger et al (2024)

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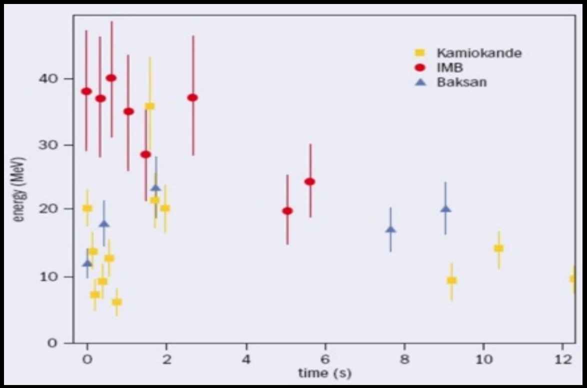
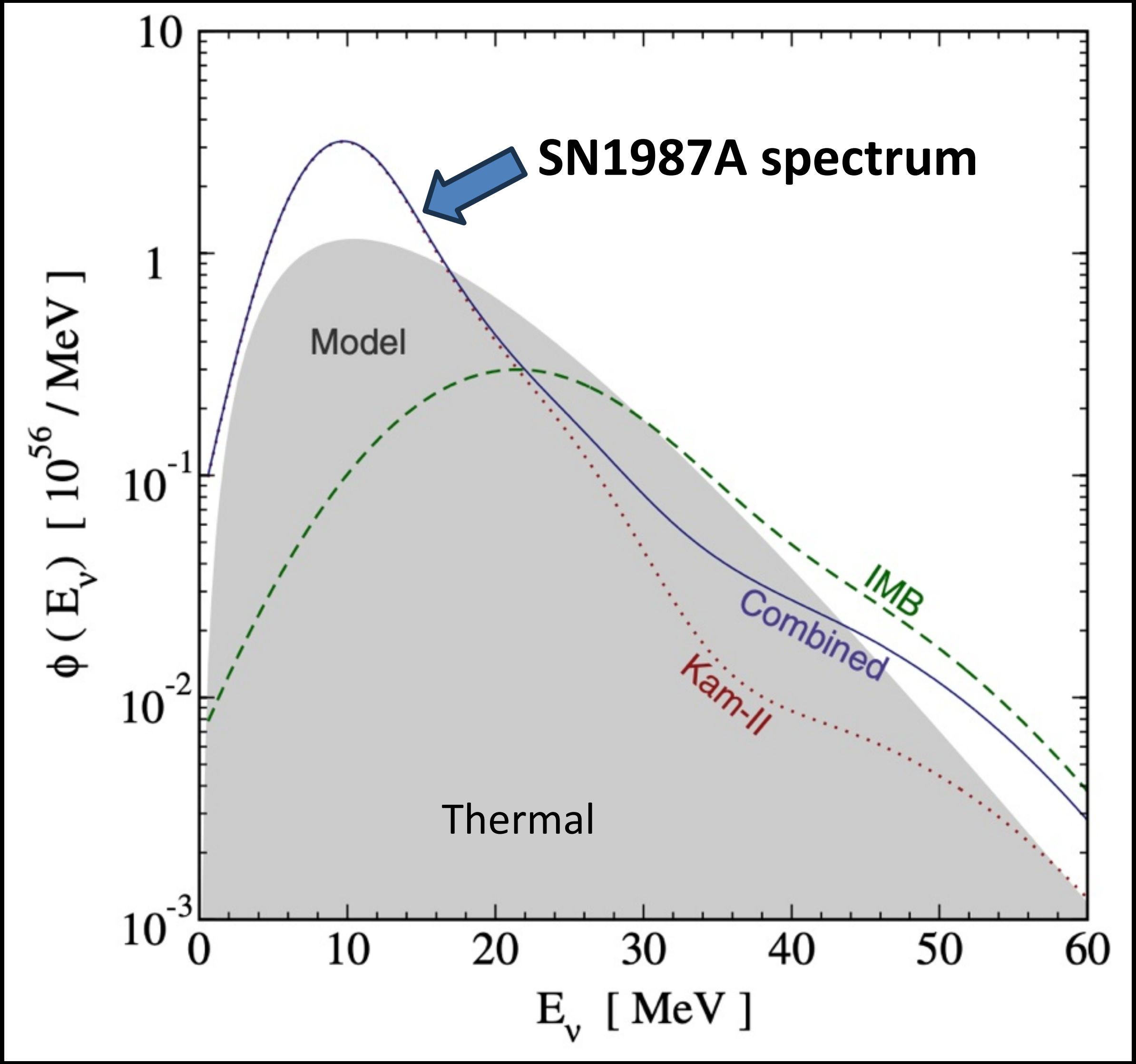
Guidance from SN1987A

Look to SN1987A for guidance: the only data set, not quite perfect match





Yuksel & Beacom (2007); also Krauss (1987), Bahcall (1987), Vissani (2015), others

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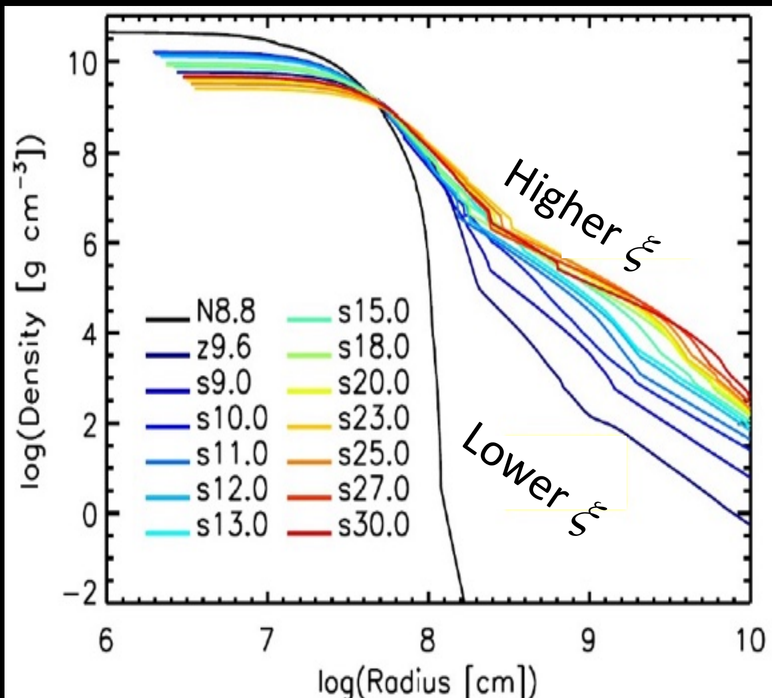
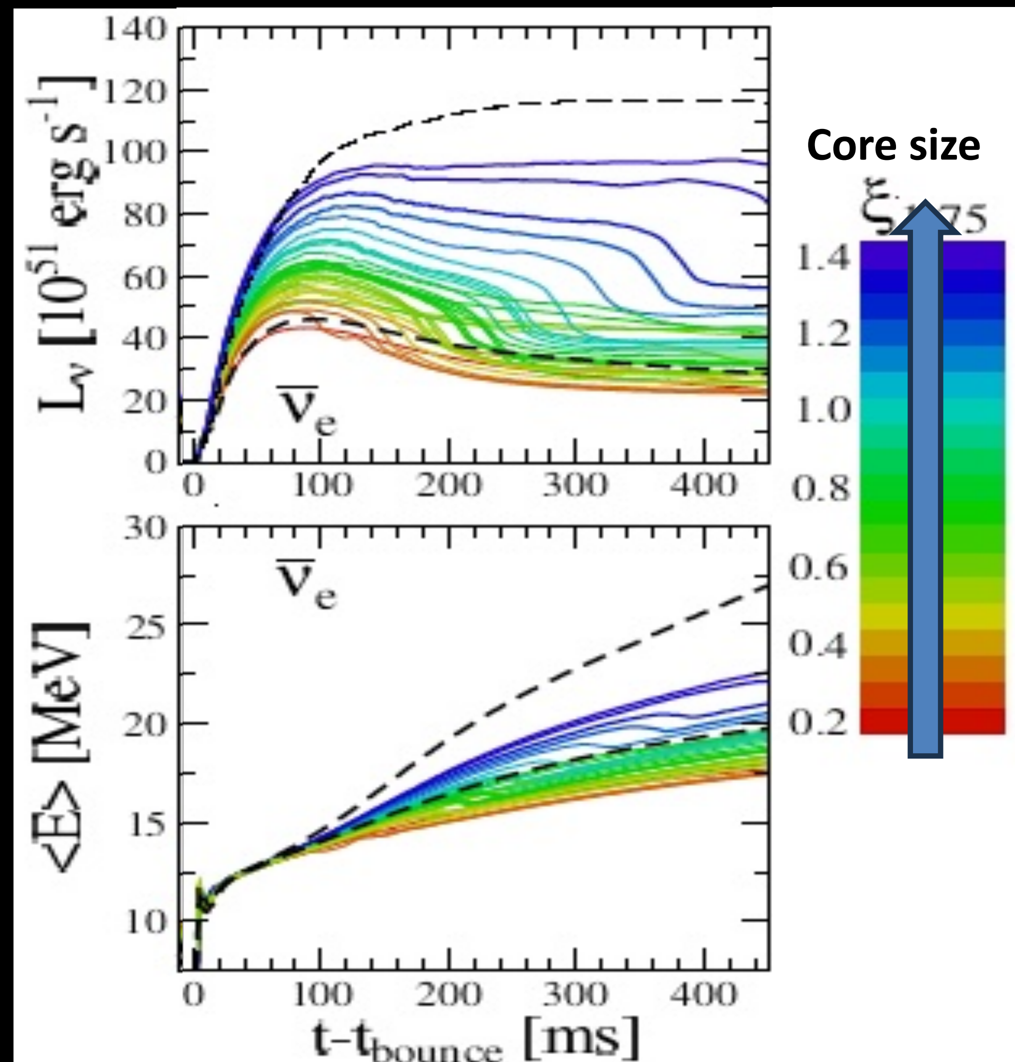
Not standard candles

Look to simulations for guidance: neutrino emission depends on progenitor



$$\xi_M = \frac{M/M_\odot}{R(M_{\mathrm{bary}} = M)/1000\,\mathrm{km}}\bigg|_t$$



O'Connor & Ott (2013)
See Nakamura et al (2014), Horiuchi et al (2016)
for 2D version

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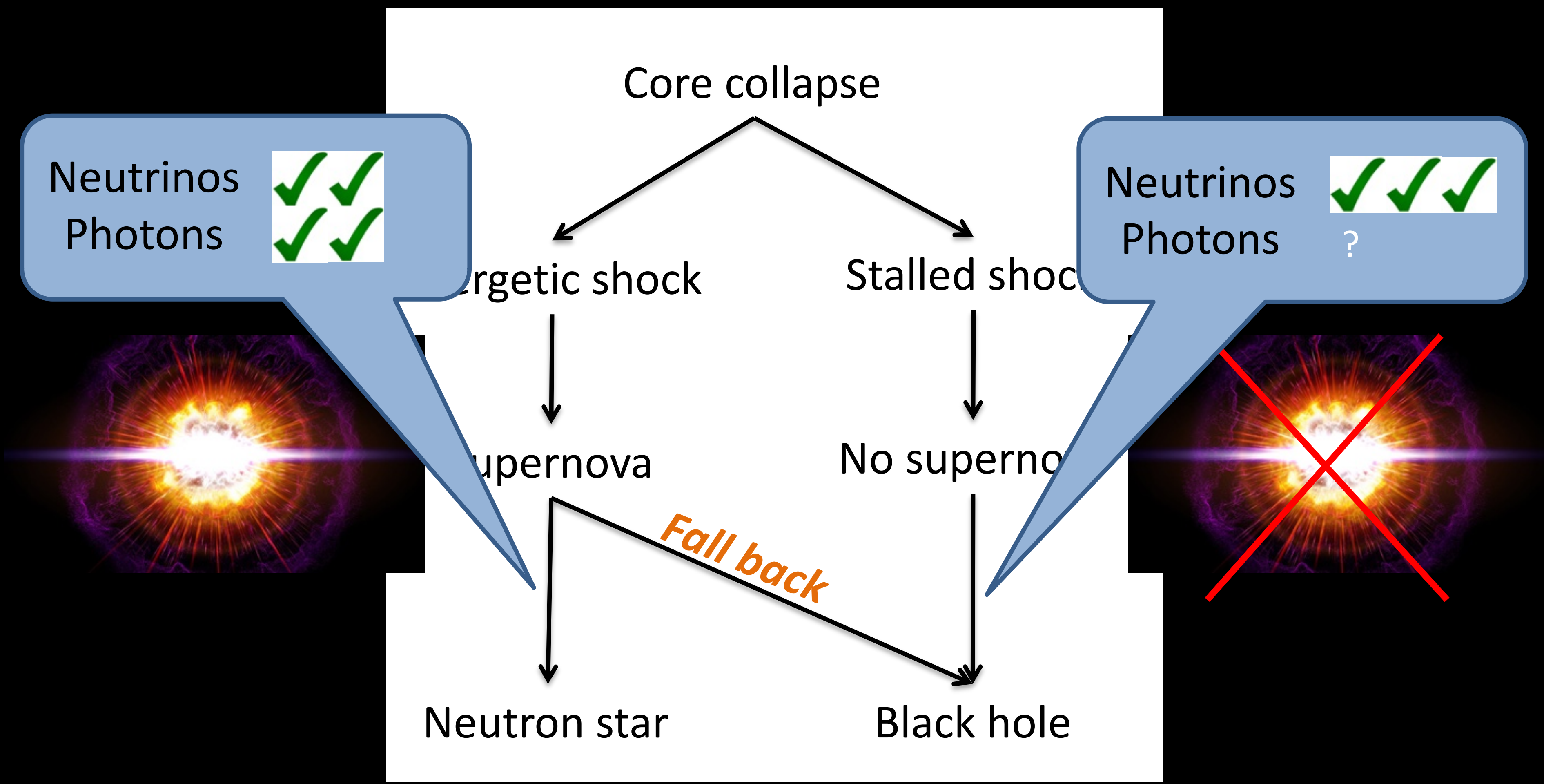
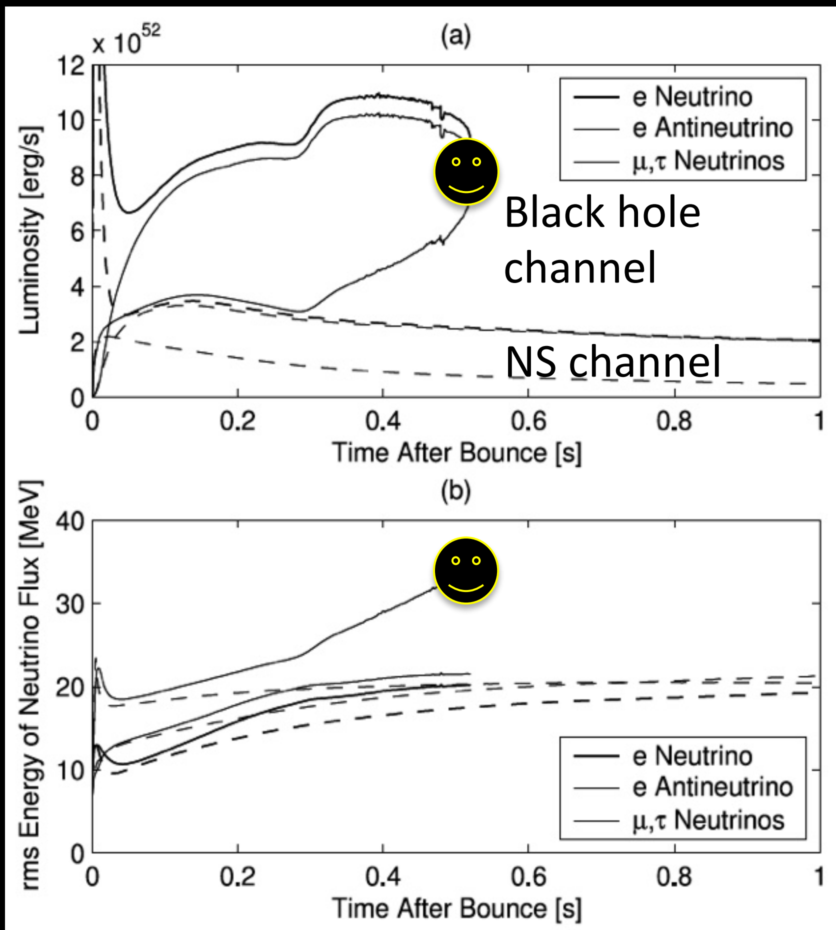
Extreme: collapse to black holes



Black hole channel simulations

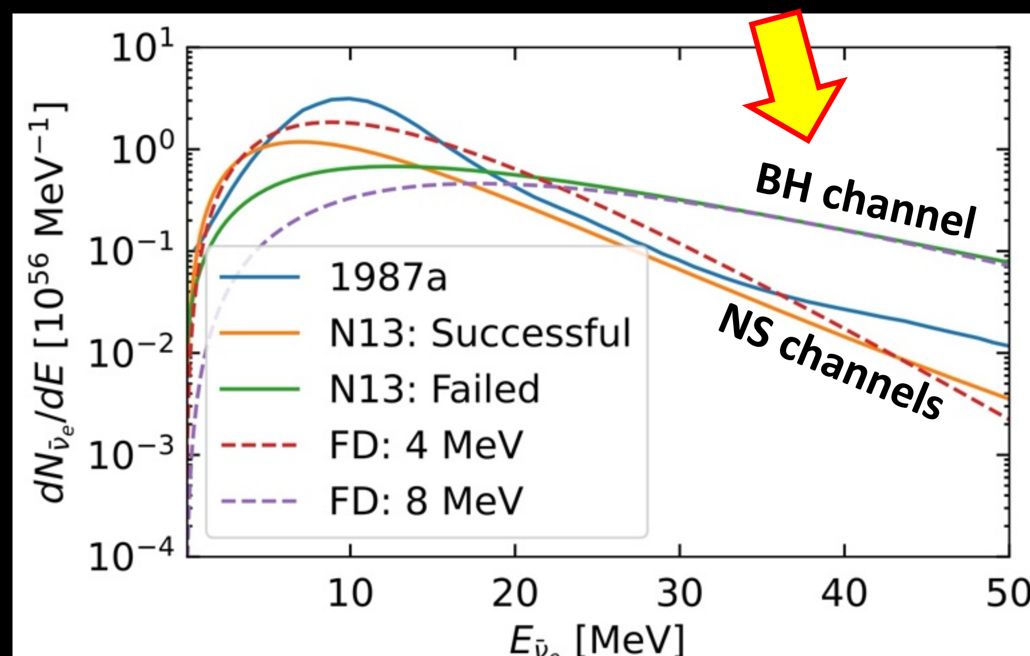
Look to simulations for guidance: collapse to black hole are different



Liebendoerfer et al (2004); many others

- Neutrino luminosities all rise quickly ☺
- Some neutrino energies rise ☺
- Then abruptly terminate ☹

➔ **When time-integrated, shows a systematically higher-energy spectrum**

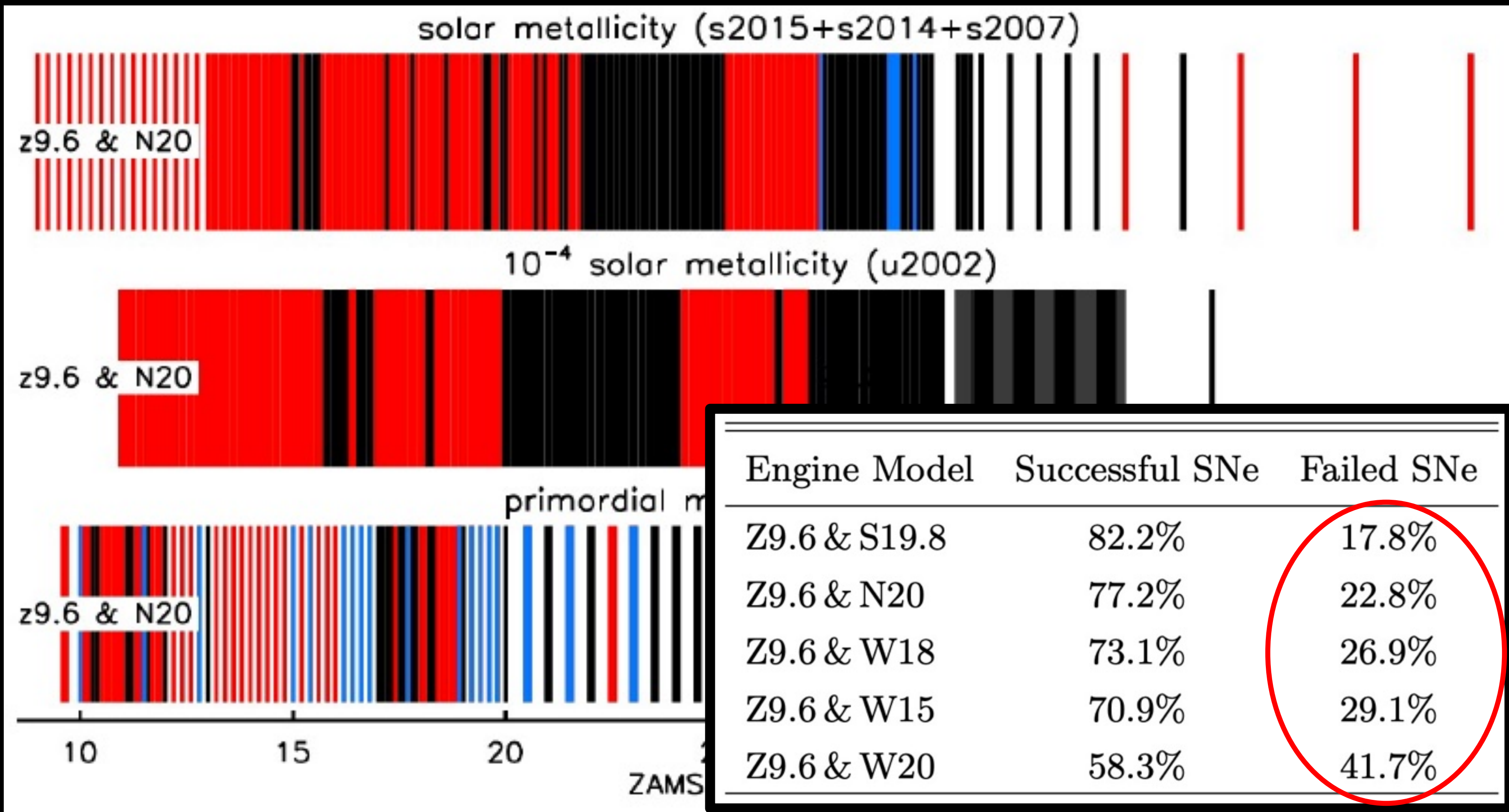


Ando, Ekanger, Horiuchi, Koshio (2023)

Systematic simulation insights

Neutrino mechanism predicts islands of successful explosions & implosions

Exact mass ranges subject to large uncertainties → **more works ongoing**



Engine Model	Successful SNe	Failed SNe
Z9.6 & S19.8	82.2%	17.8%
Z9.6 & N20	77.2%	22.8%
Z9.6 & W18	73.1%	26.9%
Z9.6 & W15	70.9%	29.1%
Z9.6 & W20	58.3%	41.7%

Janka 2017; based on Ertl et al (2016); see also Ugliano et al (2012), Sukhbold et al (2016), Pejcha & Thompson (2015), Mueller et al (2016), Sukhbold & Adams (2019), Kresse et al (2021)

Shunsaku Horiuchi

Diffuse supernova neutrino flux predictions

Winning solution

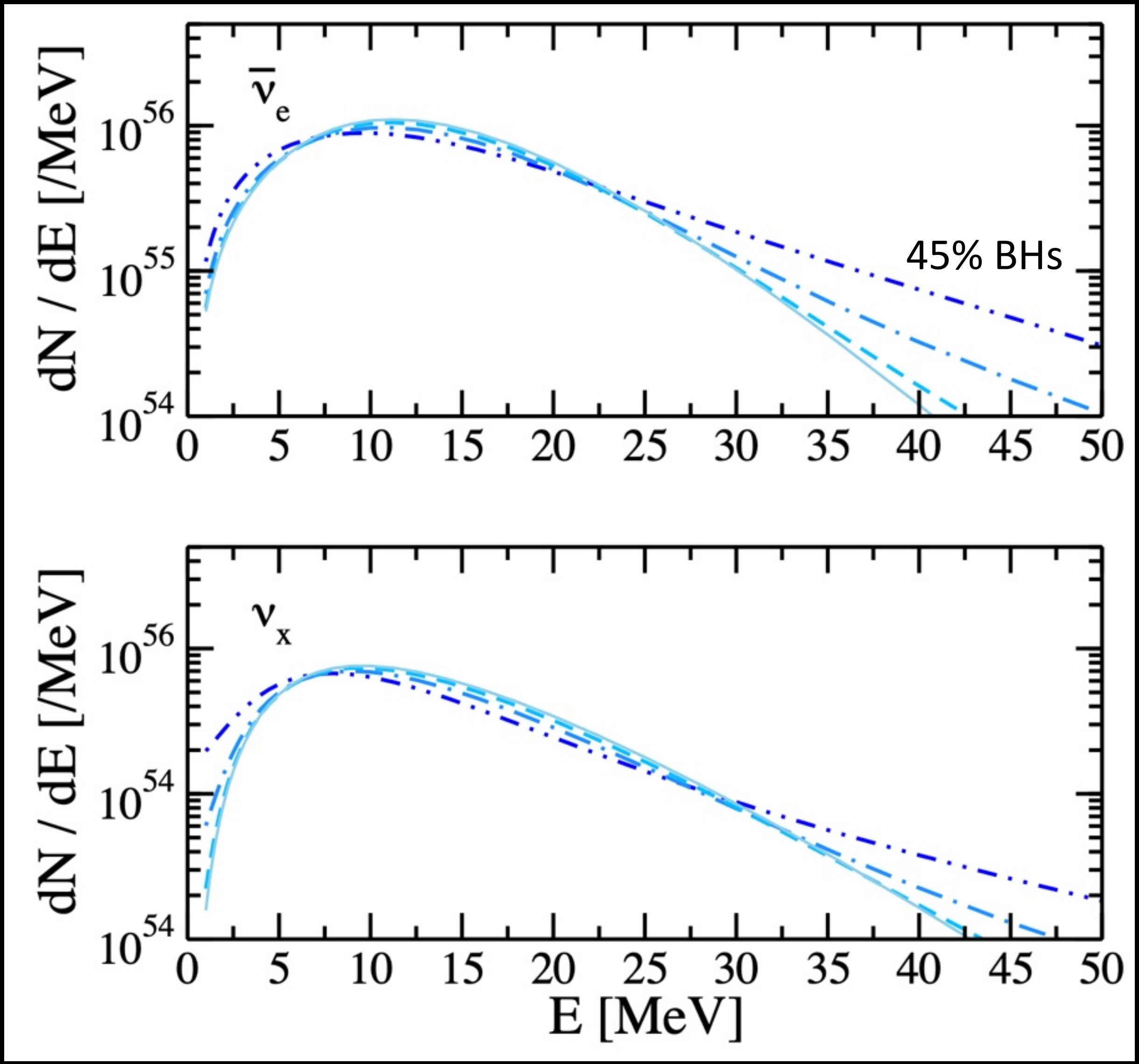
Black hole formation emits lots of neutrinos

+

Black hole formation may not be rare

→ Detecting the diffuse supernova neutrino flux will reveal universal collapse to black holes

See also: Lunardini (2009), Lien et al (2010), Yang & Lunardini (2011), Keehnn & Lunardini (2012), Nakazato (2013), Mathews et al (2014), Yuksel & Kistler (2015), Nakazato et al (2015), Hidaka et al (2016), Priya & Lunardini (2017), Moller et al (2018), Horiuchi et al (2018), Sing & Rentala (2021), Horiuchi et al (2021), Ashida & Nakazato (2022), Ekanger et al (2022), Ziegler et al (2023)



Horiuchi et al (2018)

PyDSNB

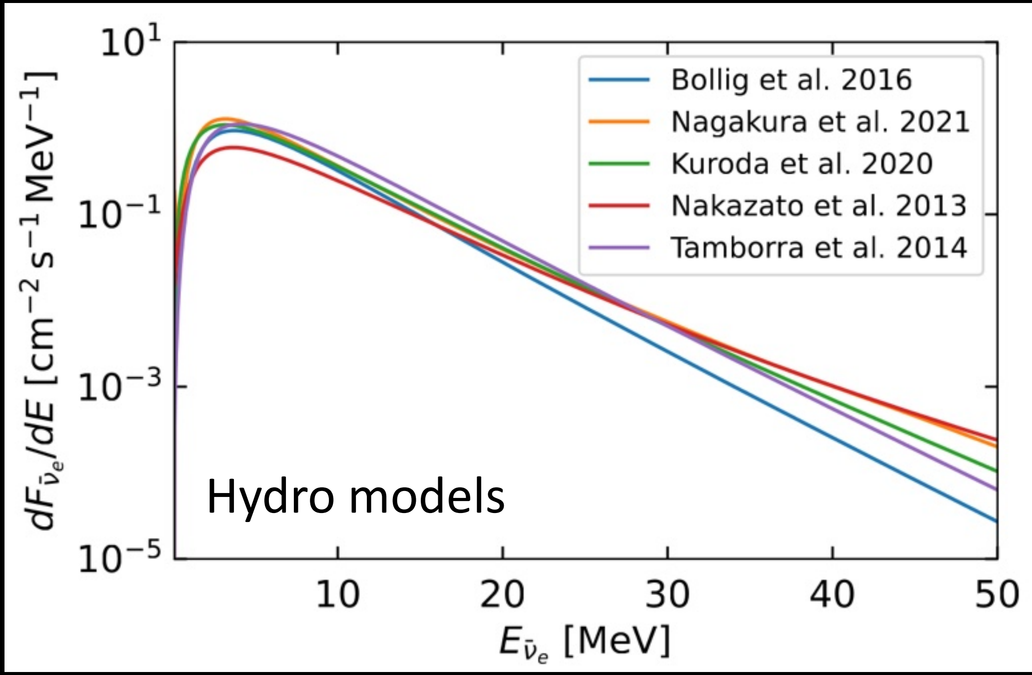
Public code to estimate DSNB
https://github.com/shinichiroando/PyDSNB
(in process of merging to snewpy)

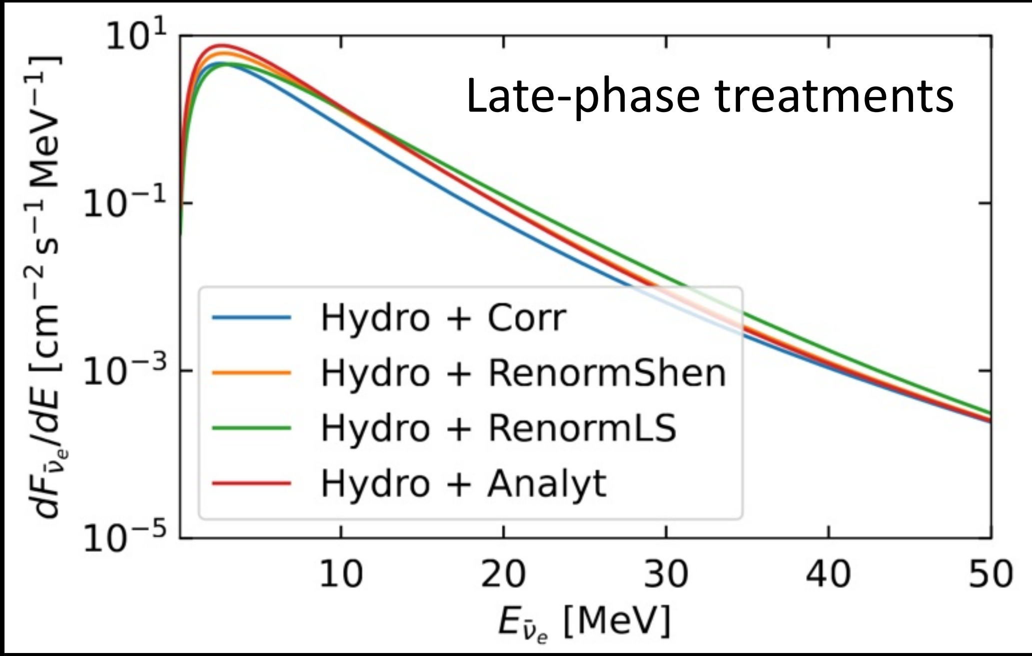
Input choices:

- Hydro model (x5) + FermiDirac
- Late-time estimate method (x4)
- Initial mass function
- Failed (BH) fraction
- Failed (BH) model
- MSW + neutrino mass hierarchy

Some future plans:

- New CCSN rate estimates
- Binary models
- Accretion models
- Beyond MSW oscillations





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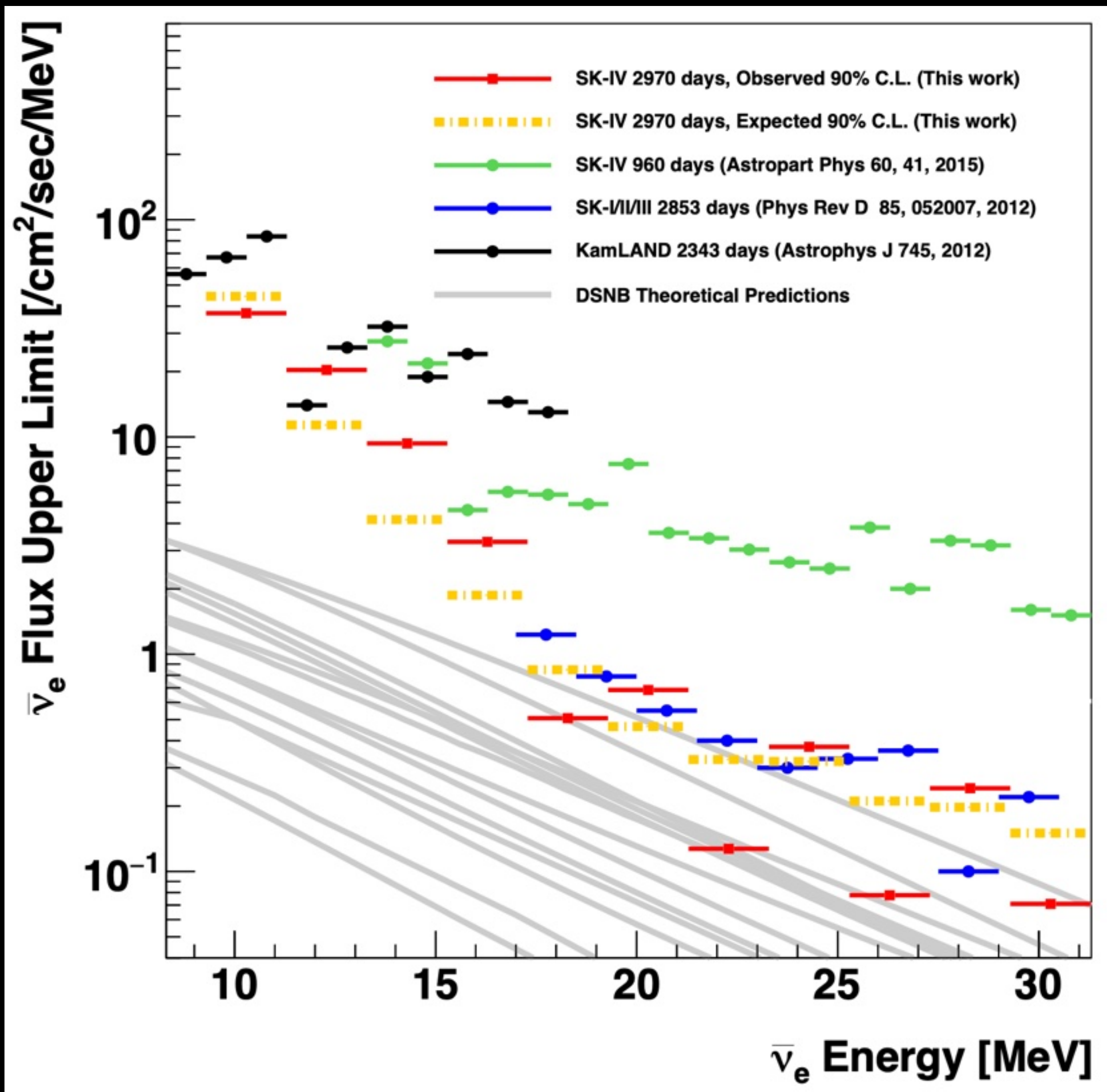
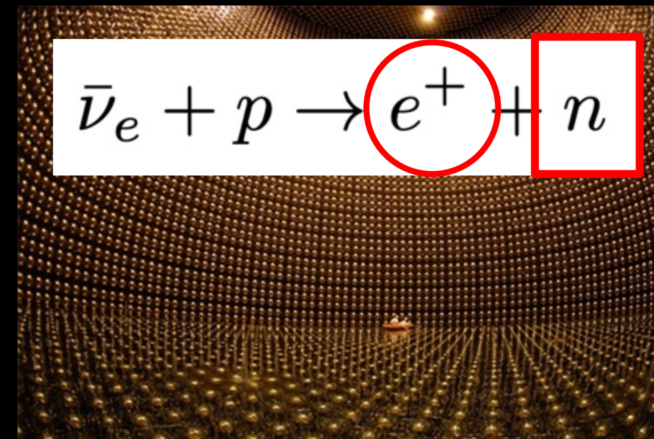
Diffuse supernova neutrino searches

Reaching factor of 2 of many predictions





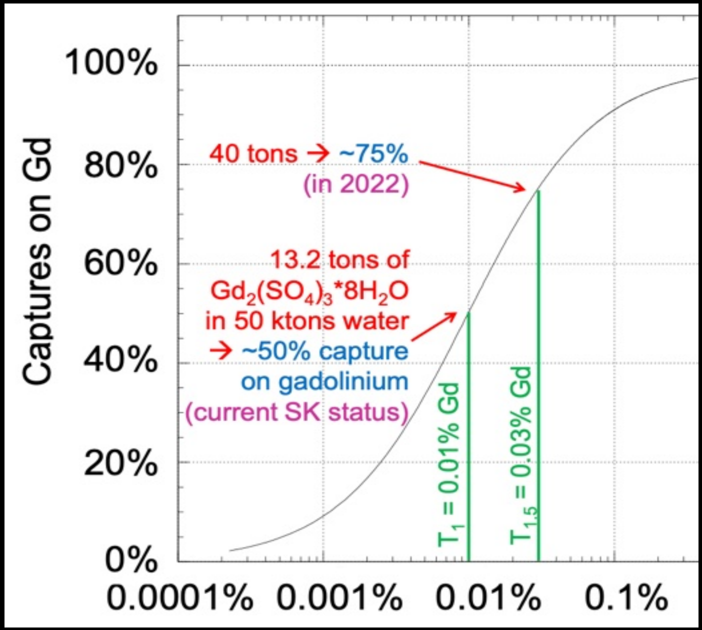
Capture on Gadolinium: proposed in 2003, after many R&D, Super-K was drained in 2018, refurbished, and doped by Gd in 2020

Beacom & Vagins (2004)
SK 2021 (arXiv:2109.00360)

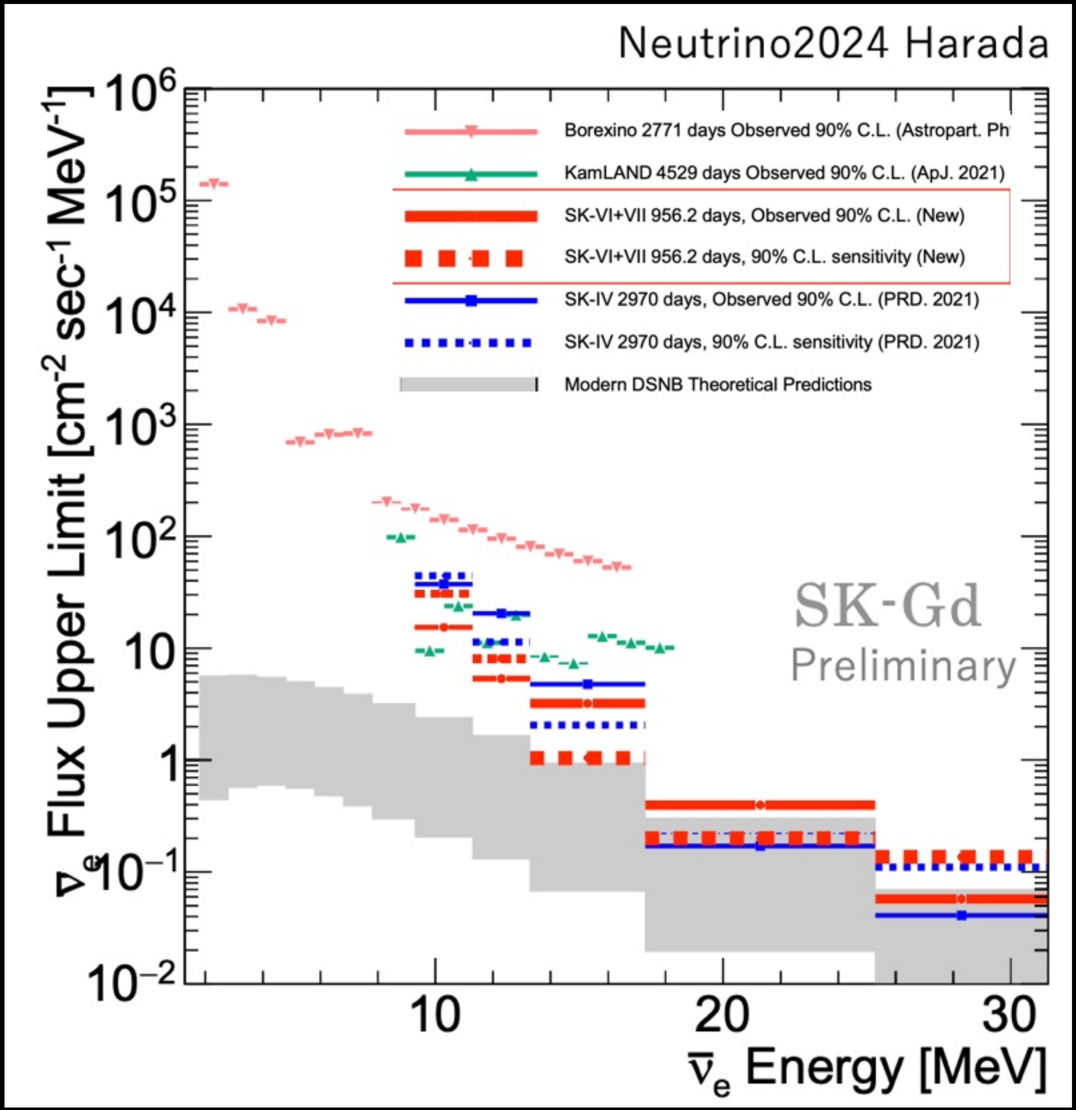
SK-VI: successful Gd performance

Already comparable with ~10 years of pre-Gd result

SuperK with 0.01% Gd by mass
→ ~50% captures on Gd
(approx. doubled cf pre-Gd)



Gd by mass percentage



SuperK (in prep)

Shunsaku Horiuchi

Future? Beyond nuebar flavor

DUNE

40k ton lq Ar

Signal & bkg studies ongoing

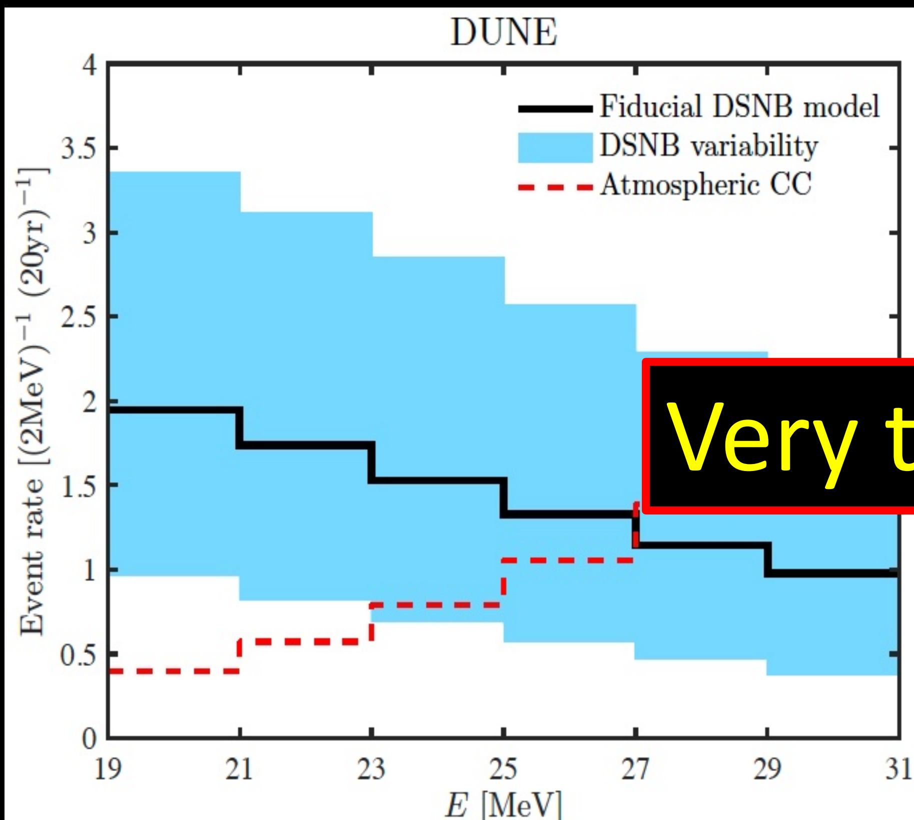
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

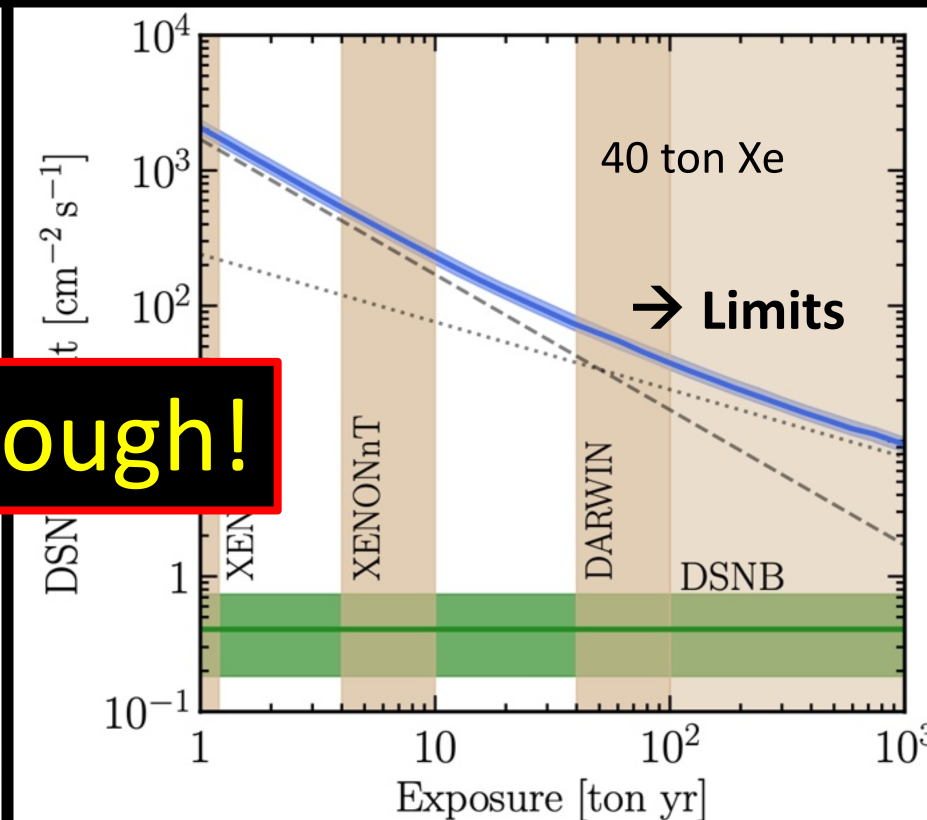
Direct DM detectors

Xe or Ar targets

Solar & atm. ν bkgs

$$\nu + A \rightarrow \nu + A$$





Very tough!

Moller et al (2018) *Suliga et al (2022)*

Shunsaku Horiuchi

Paleo detector: advantages

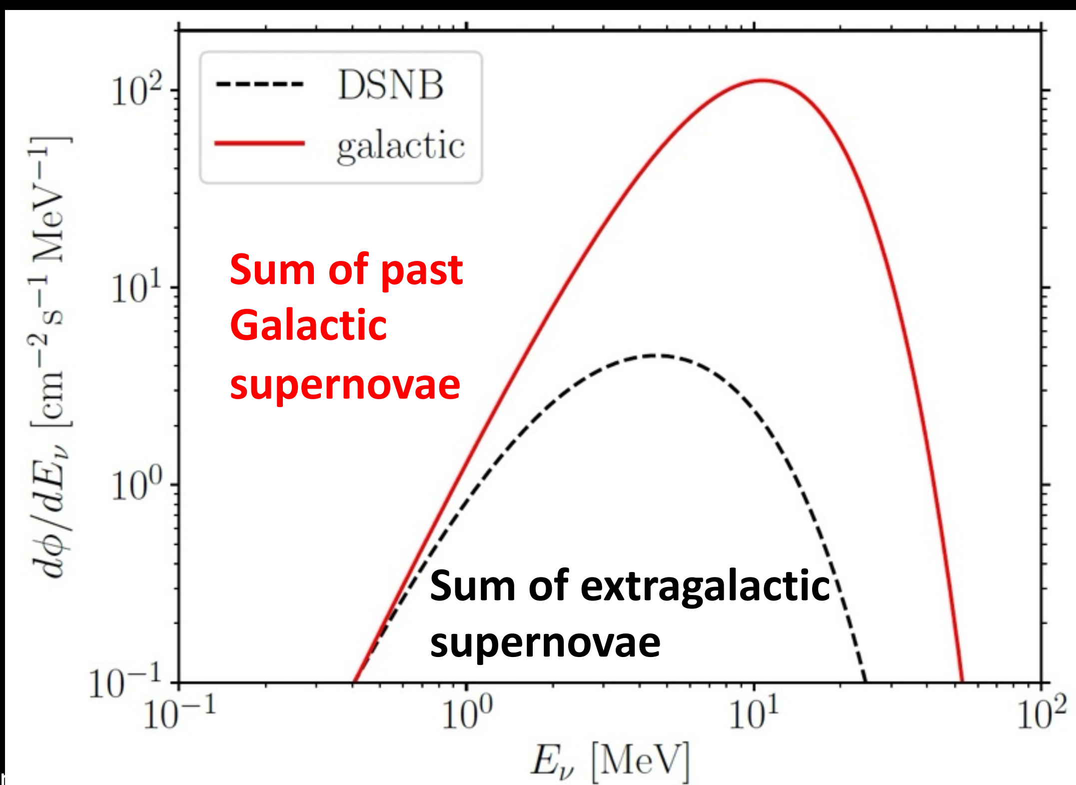
Large, unique signal

Operation duration >> inverse of Galactic supernova rate (~few per century)

All flavors CEνNS interaction for SN neutrino energies

Competitive exposure 100 grams over 10^9 years = 10^5 t yr

(cf SK: 22kton over years ~ 10^5 t yr)



What if we knew the Galactic supernova rate, to some accuracy? Plausibly, by modeling the billions of stars observed by eg Gaia, or by simulations of Galactic archeology

Baum et al (2020)

Extracting supernova physics

Signal prediction

- Model the neutrino spectrum
- Assume target mineral
- Estimate damaga track spectra (SRIM)
- Background considerations
- Track reconstruction setup

→ **Heavy-flavor neutrinos dominate the signal & tracks**

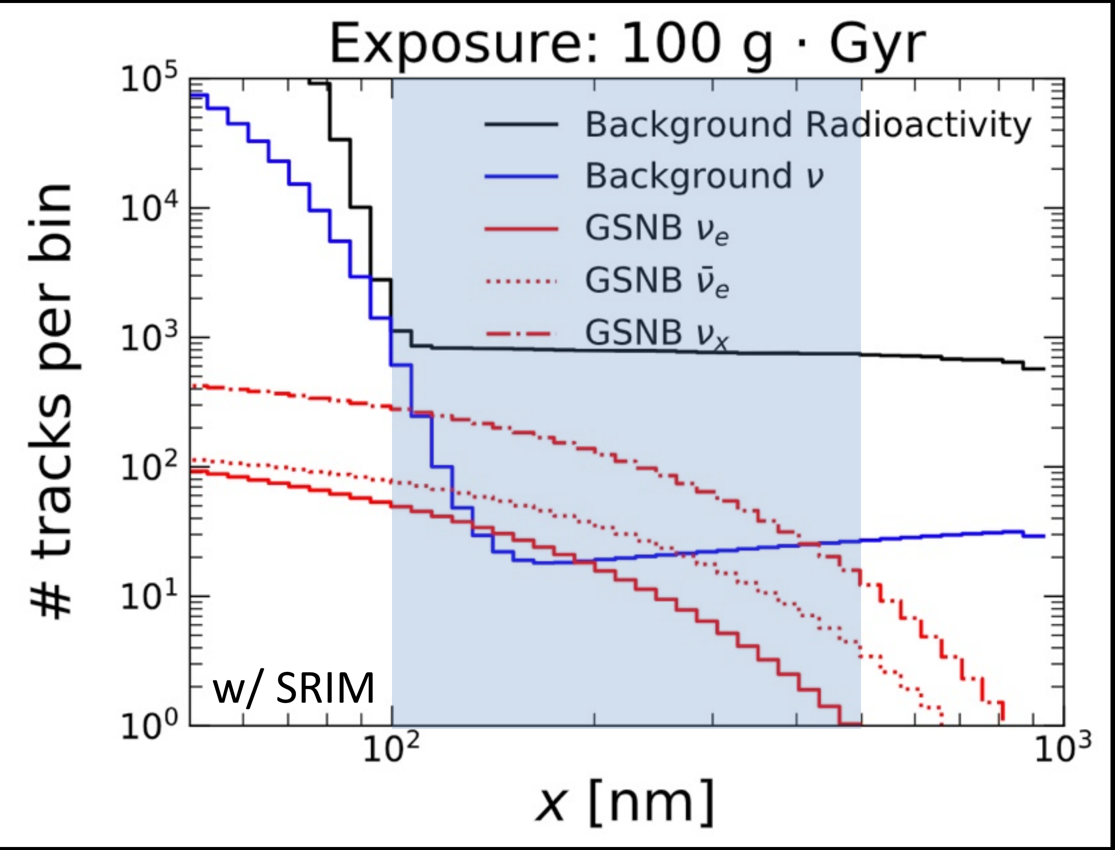
eg, in 100-500 nm:

$N_{bkg} \sim 10^5$
$N_{nux} \sim 10^3$ ➔ $\sim 6\sigma$

Much depends on accuracy of knowledge of backgrounds (neutrons)

Use best target from Baum et al (2020)

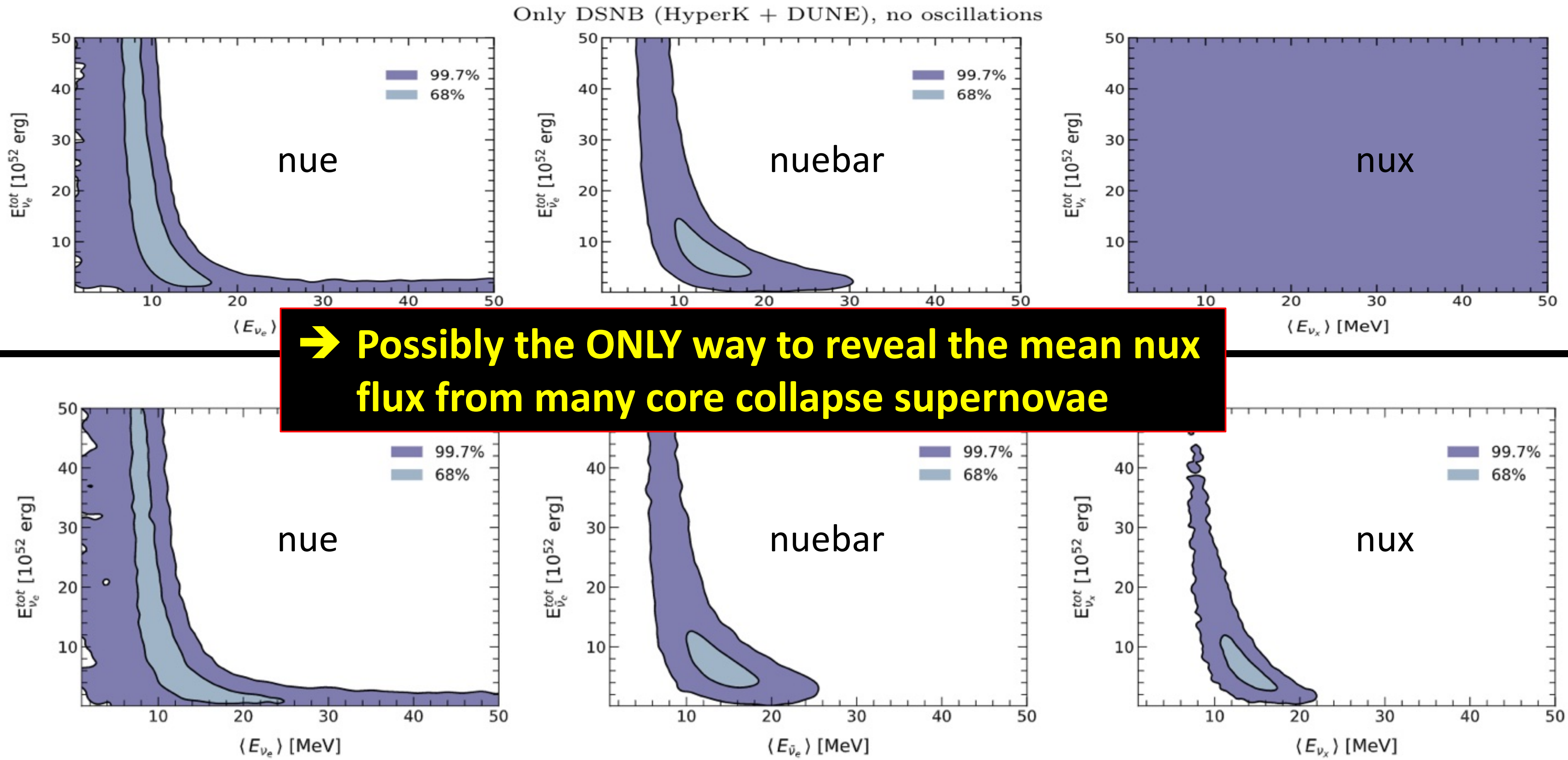
Epsomite $[\mathrm{Mg(SO_4)\cdot 7(H_2O)}]$



Baum et al (2022)

Probes of neutrino emissions

DSNB only: Hyper-K & DUNE, 20 years operation. Add 100g paleo detector aged 1 Gyr



➔ **Possibly the ONLY way to reveal the mean nux flux from many core collapse supernovae**

Baum et al (2022)

(100g of epsomite with 1 Gyr age, 15nm track resolution)
(100% uncertainty on radiogenic & solar neutrino backgrounds)
(20% uncertainty on HK & DUNE backgrounds)
(10% uncertainty on extragalactic & galactic supernova rates)

Shunsaku Horiuchi

Supernova neutrino summary

Astrophysical neutrinos

Pesky background for eg dark matter searches

Are rich and related to key physics within supernovae

Supernovae and mineral detectors

Paleo detectors offer new ways to find supernova neutrinos, with unique information for supernova physics.

- **Mineral detectors offer a new way to study supernovae in the Milky Way's past**
- **Mineral detectors are perhaps the best hope of probing the heavy lepton neutrinos in vast numbers of supernovae**

Thank you!