MDvDM 2024, January 8-11th 2024

Astrophysical neutrinos with paleo detectors

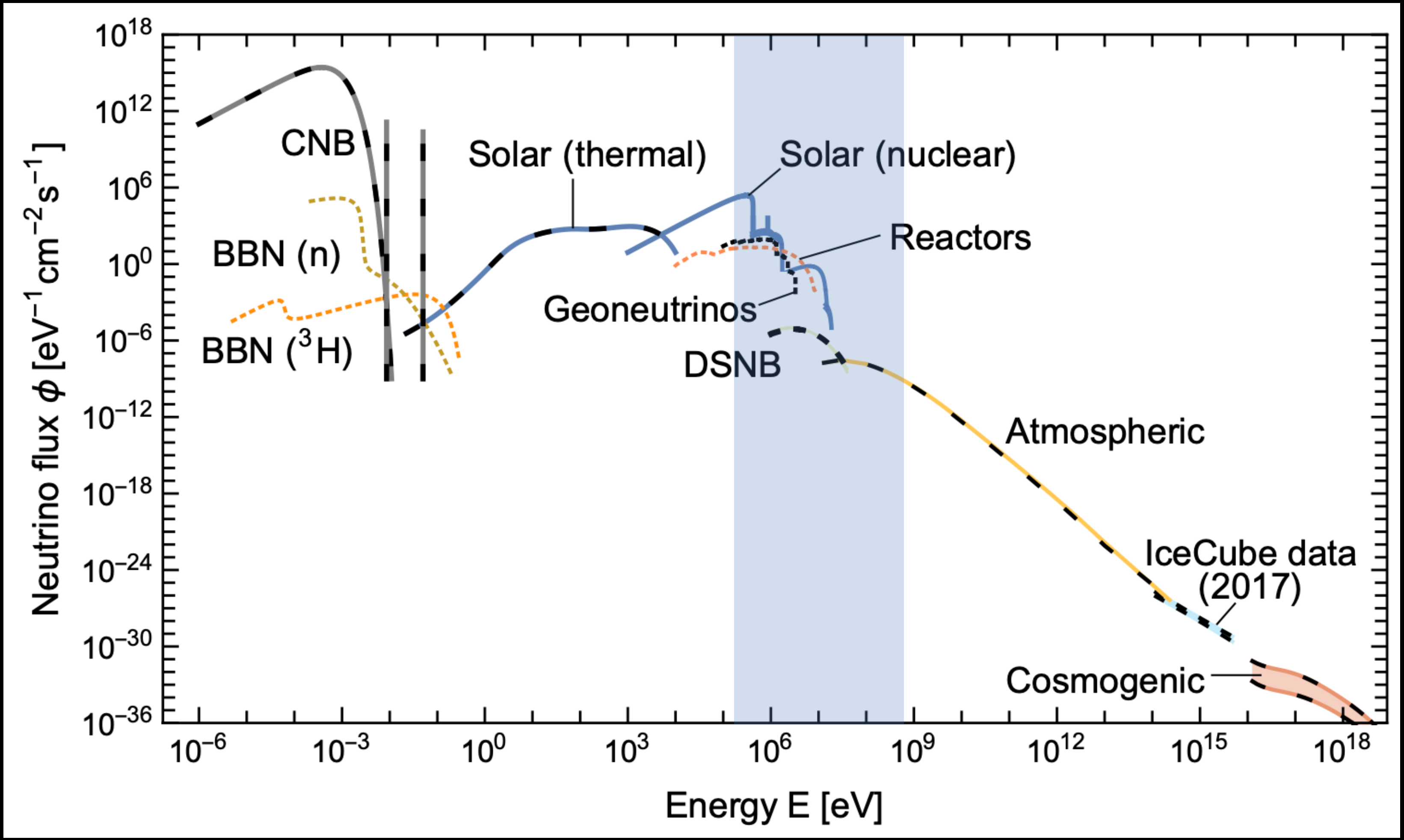
Shunsaku Horiuchi

Image credit: NASA/ESA

Astrophysical neutrino fluxes

Wide range of energies

Different source physics & detection strategies



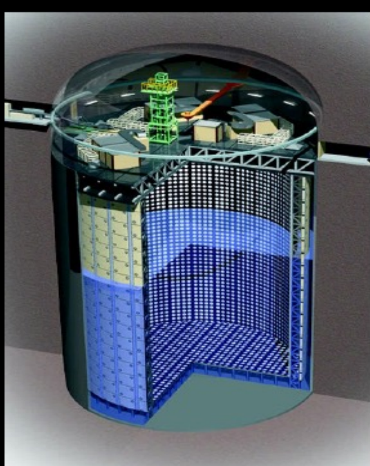
Vitagliano et al (2020)

Neutrino detection

- **Detector must be massive**
  Detectors are optically thin -- need large volumes
- **Detector must be "quiet"**
  Low natural radioactivity and lots of shielding
- **Detector better to have background rejection**
  Capabilities to distinguish signal and backgrounds

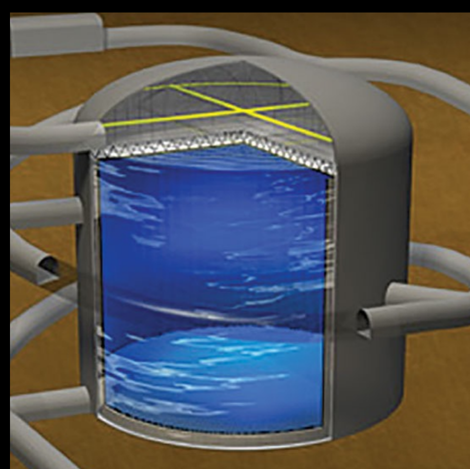
Paleo detectors: natural solid state nuclear track detectors, recording nuclear recoils over geological timescales

Super-Kamiokande

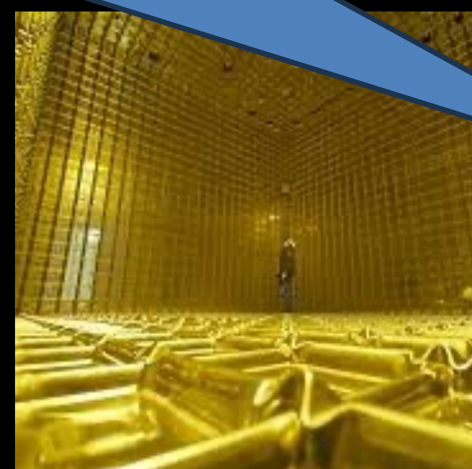


Water (doped)
Running

Hyper-Kamiokande



Water
Building



Liquid argon
Building

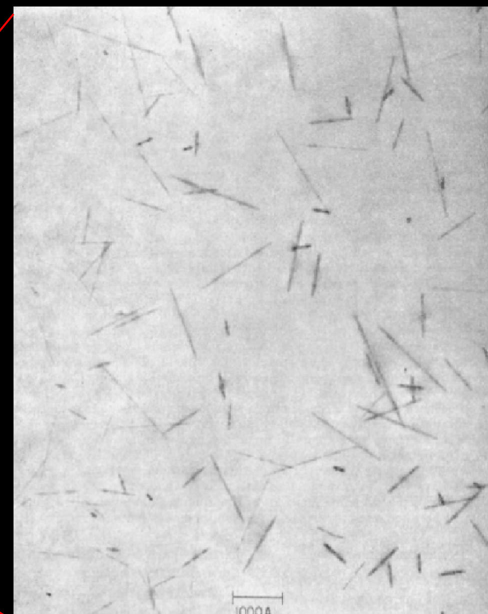
Mineral detectors

Rock mineral
R & D

Paleo detectors

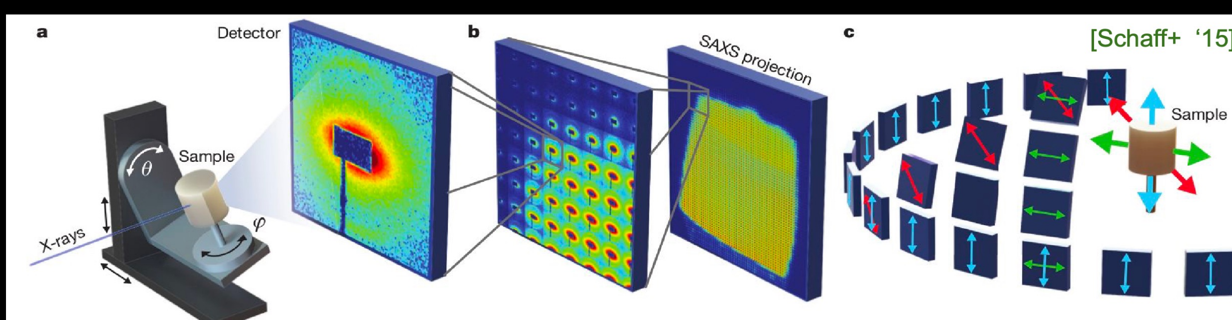
Recently revived as direct dark matter probes *Drukier et al (2019), Edwards et al (2019)*

Natural minerals as old as ~10^9 years



Permanent damage tracks carry information about recoils
= solid state nuclear track detectors

Microscopy: small angle X-ray scattering + computer tomography



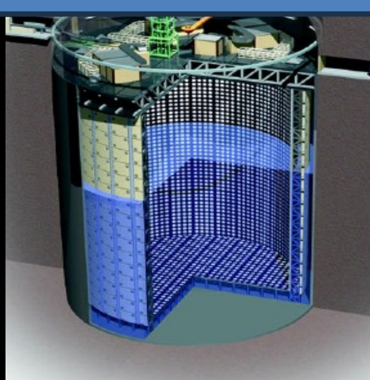
Modern readout technologies allow fast nm-resolution mapping of structures in macroscopic samples

Neutrino @ paleo detectors

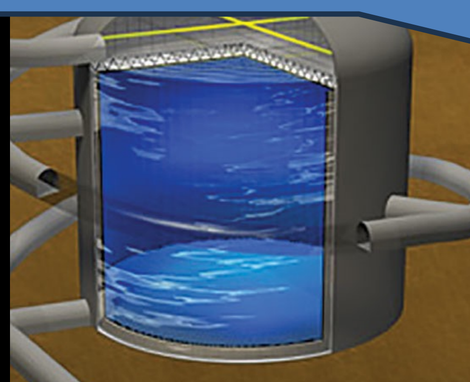
- **Detector must ~~be massive~~ have large exposure**
  Operate over geological timescales
- **Detector must be "quiet"**
  Low natural radioactivity: find samples
  Lots of shielding: sample from deep underground
- **Detector better to have background rejection**
  Added challenge due to being a passive detector without active background rejection

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

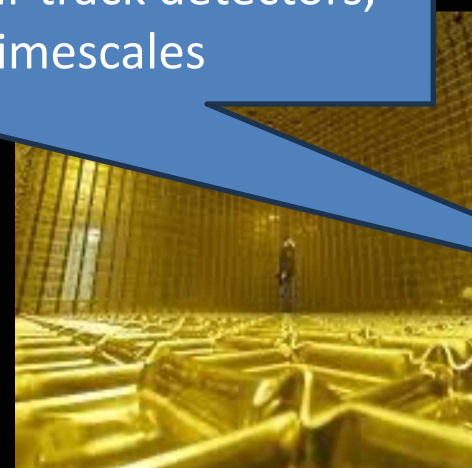
Mineral detectors



Water (doped)
Running

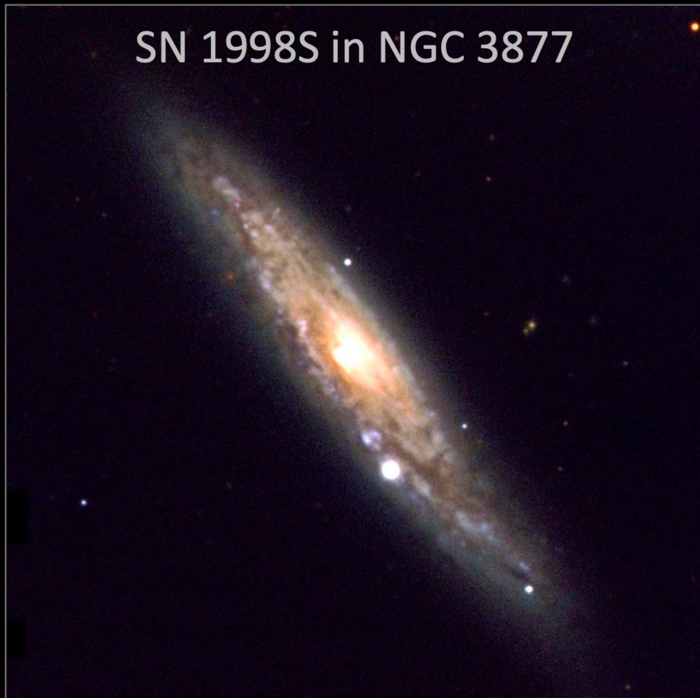


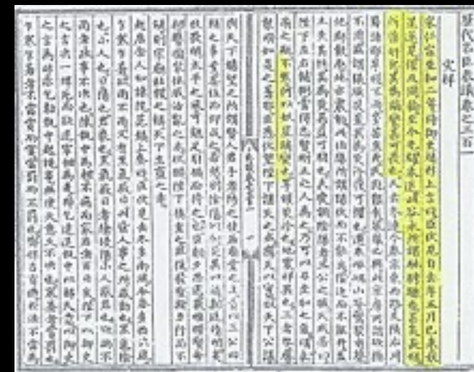
Water
Building

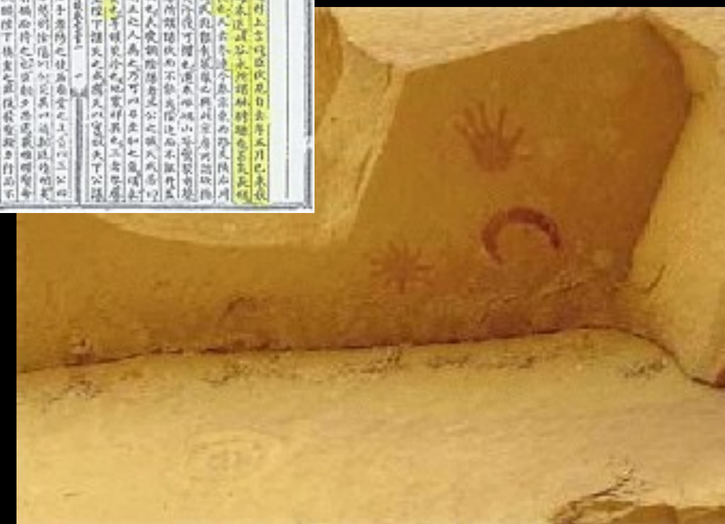


Liquid argon
Building

Rock mineral
R & D

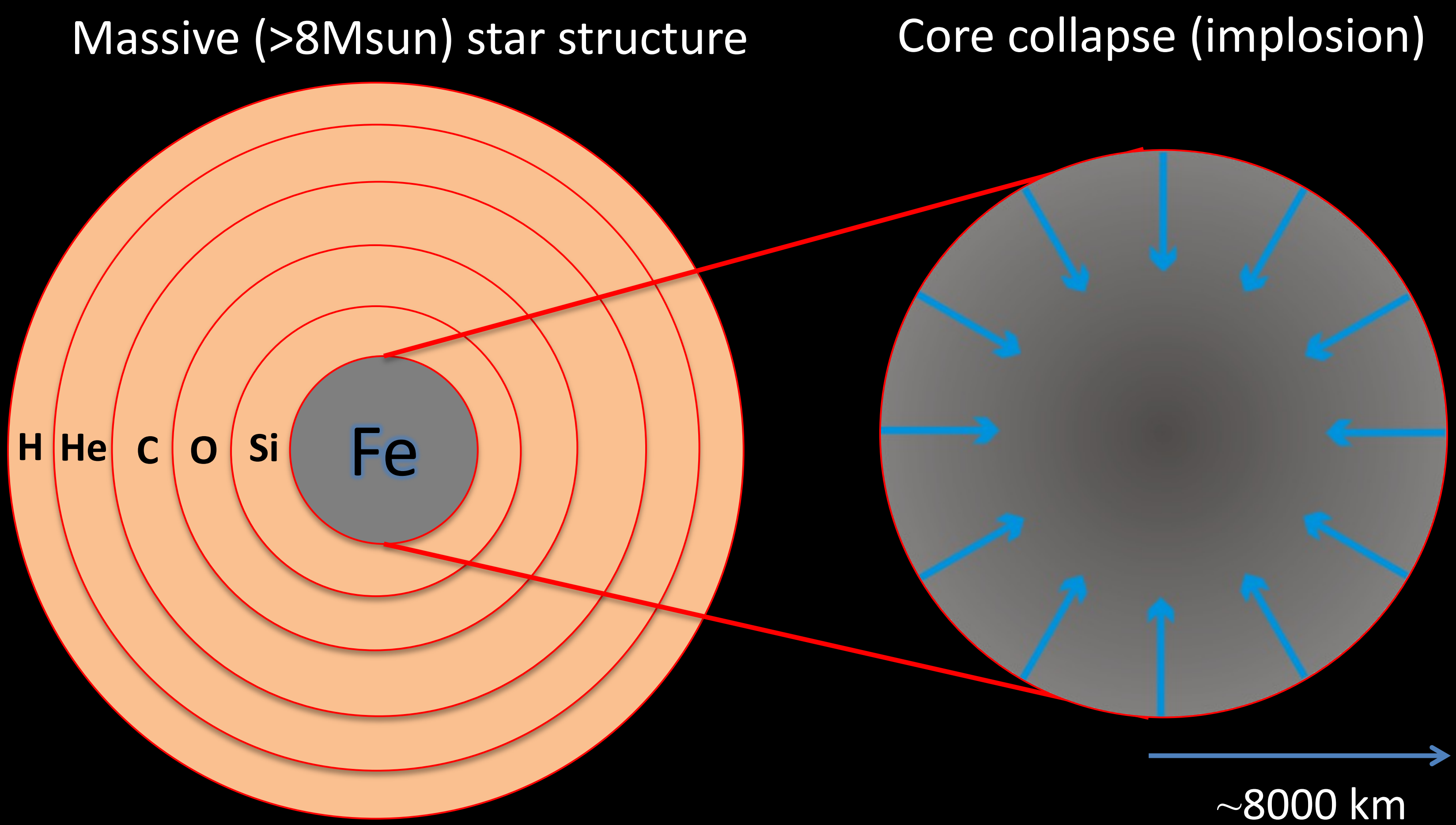






SUPERNOVA NEUTRINOS

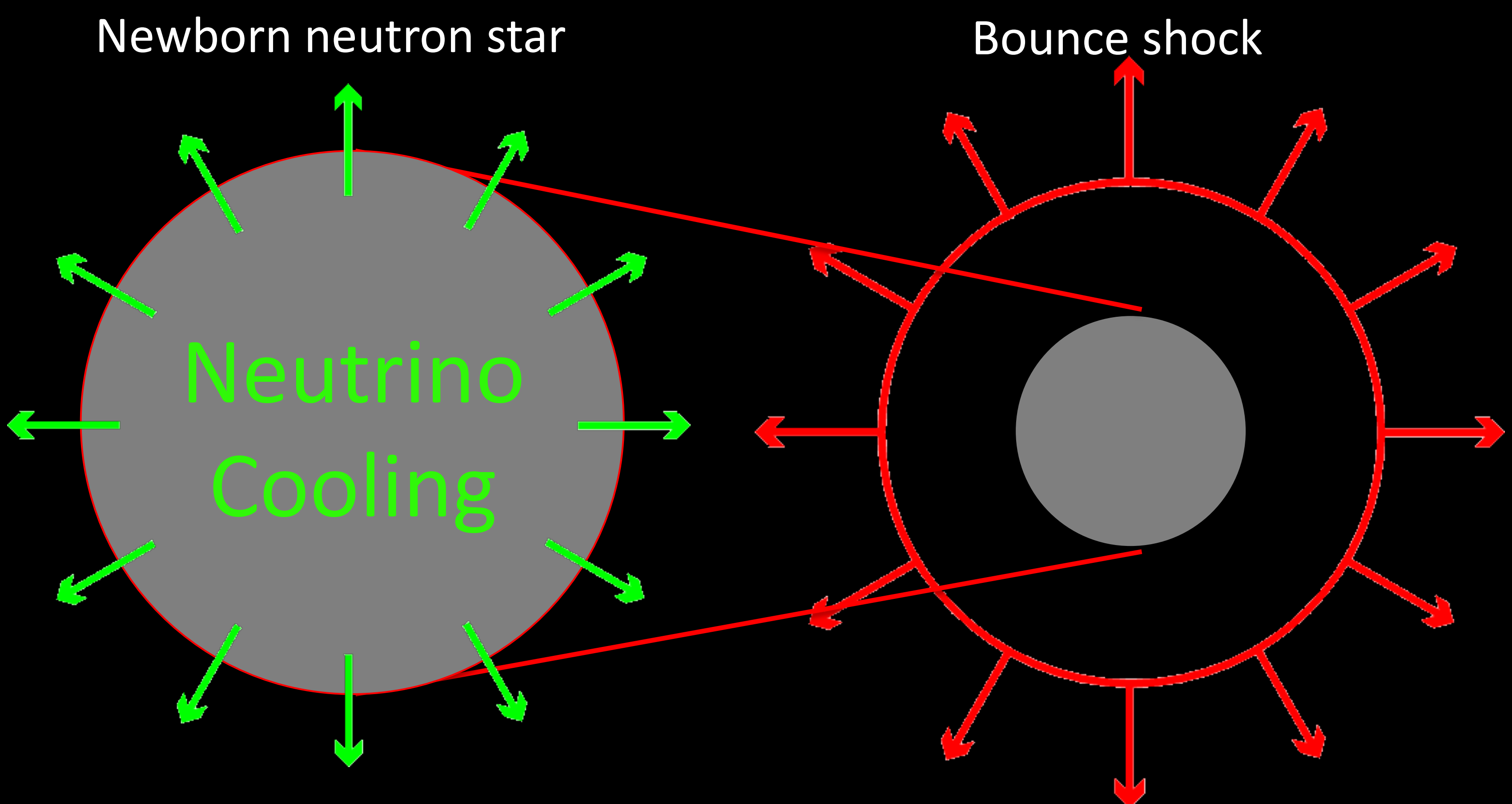
Under the hood



Shunsaku Horiuchi

(adapted from G. Raffelt's slides)

Under the hood

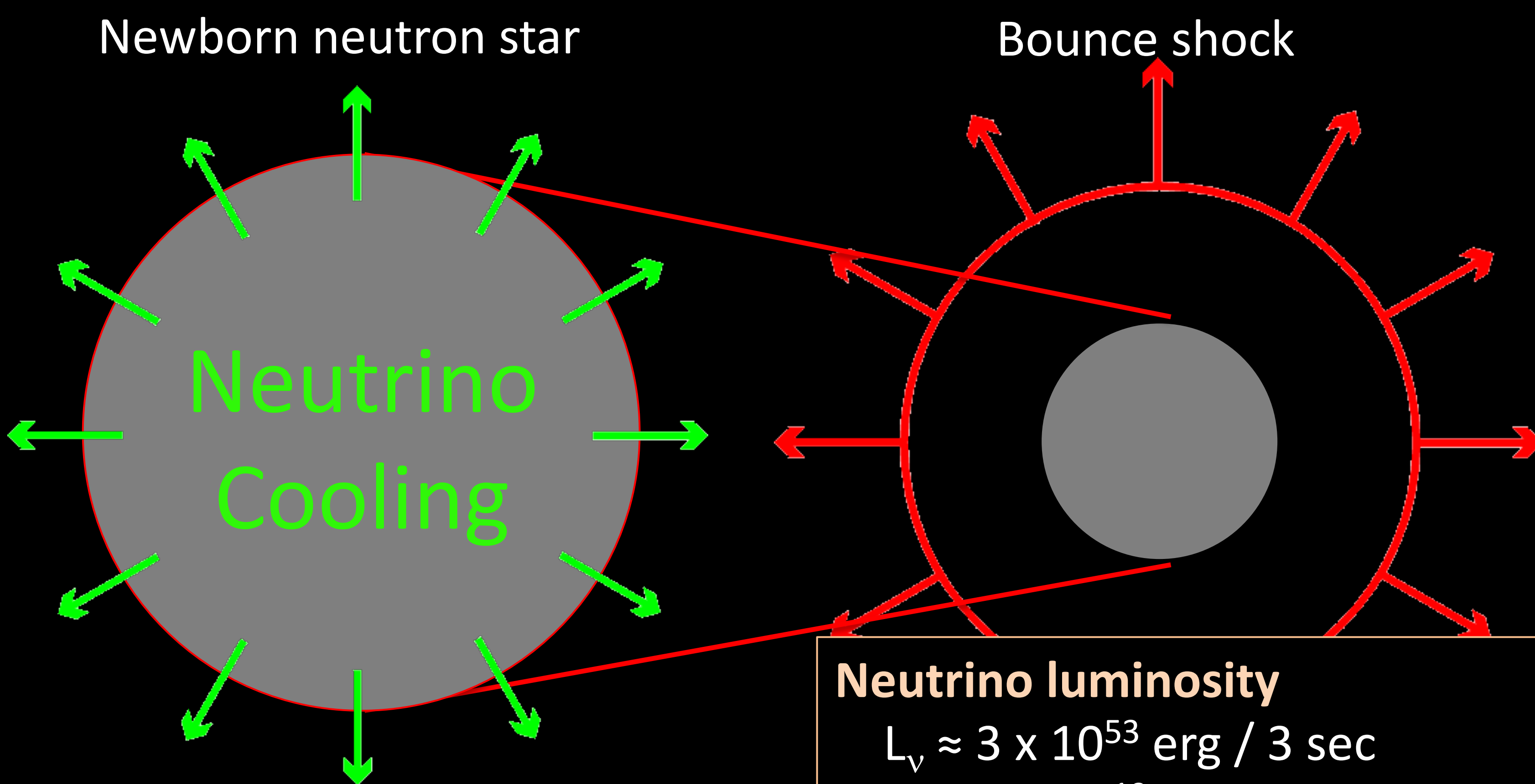


Energy budget ~ 3 x 10^{53} erg
99% into neutrinos
(~0.01% into photons)

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 x 10^{53} erg

99% into neutrinos

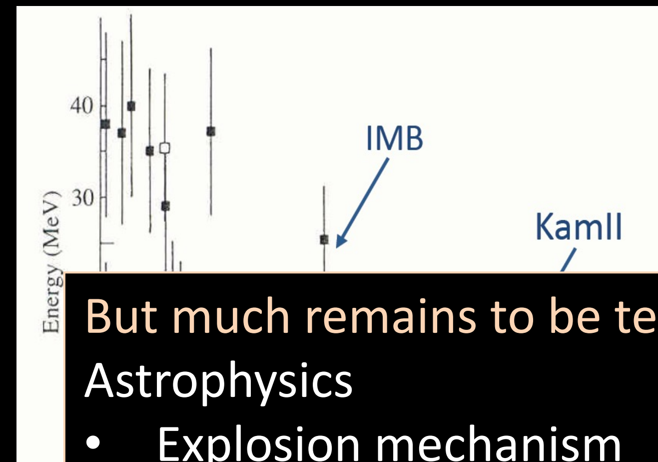
(~0.01% into photons)

(adapted from G. Raffelt's slides)

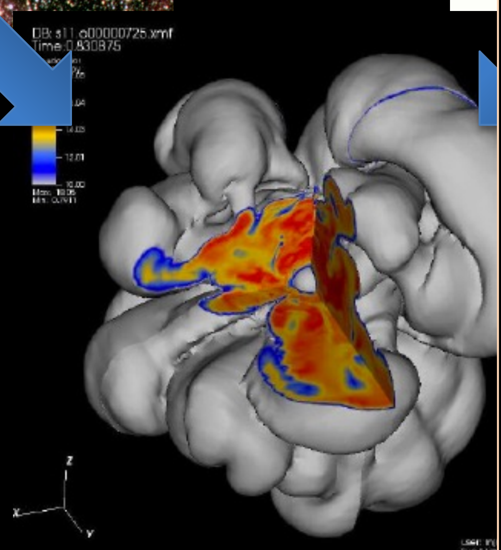
Where are we?

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



But much remains to be tested

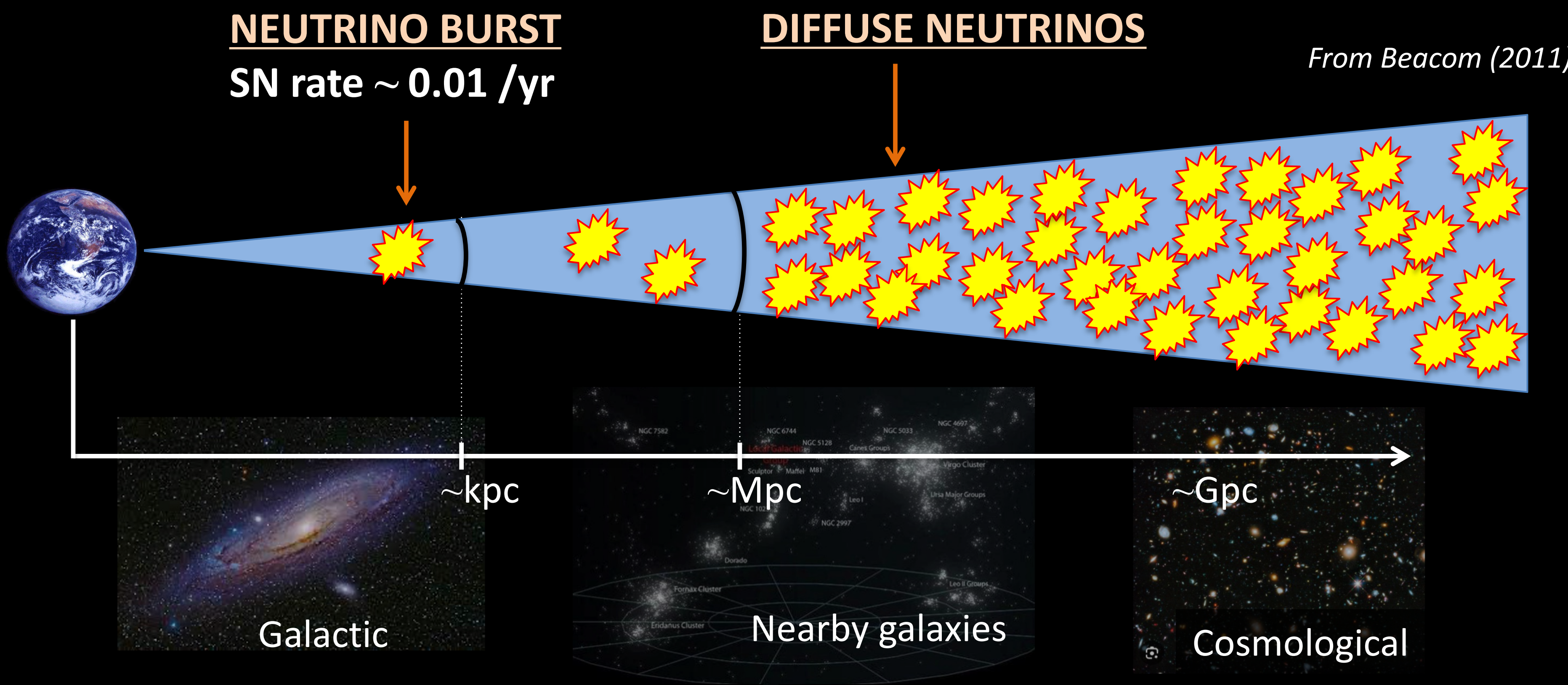
Astrophysics
- Explosion mechanism
- Instabilities
- Progenitor structure
- Black hole formation

Nuclear physics
- Equation of state
- Phase transitions

Particle physics
- Neutrino physics
- New particles

…and many, many more…

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?

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)

Milky Way: flavor sensitivity

nuebar flavor

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

IBD

nue flavor

$$\nu + e^- \rightarrow \nu + e^-$$

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

$$\nu_e + {}^{A}\mathrm{Pb} \rightarrow e^- + {}^{A}\mathrm{Bi}^*$$

nux flavor

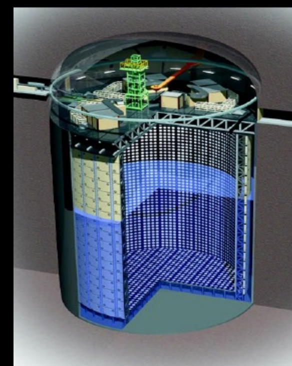
Must rely on NC…

$$\nu + e^- \rightarrow \nu + e^-$$

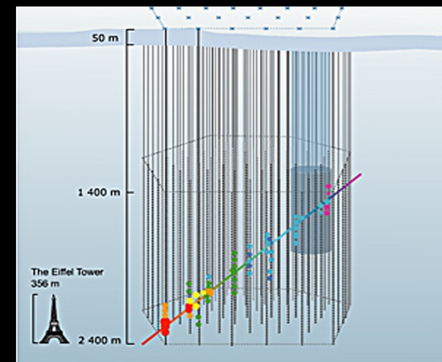
$$\nu + A \rightarrow \nu + A$$

CEvNS

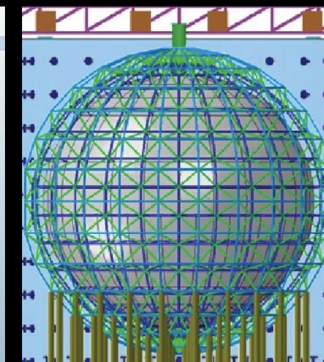
Water Cherenkov



Long String

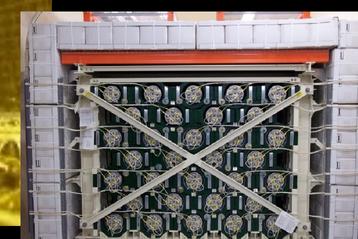


Scintillator

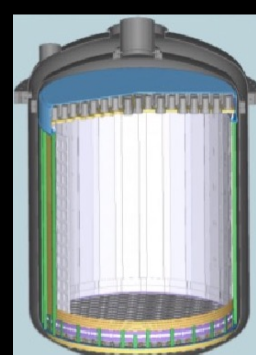


Liquid argon

Lead



Xenon



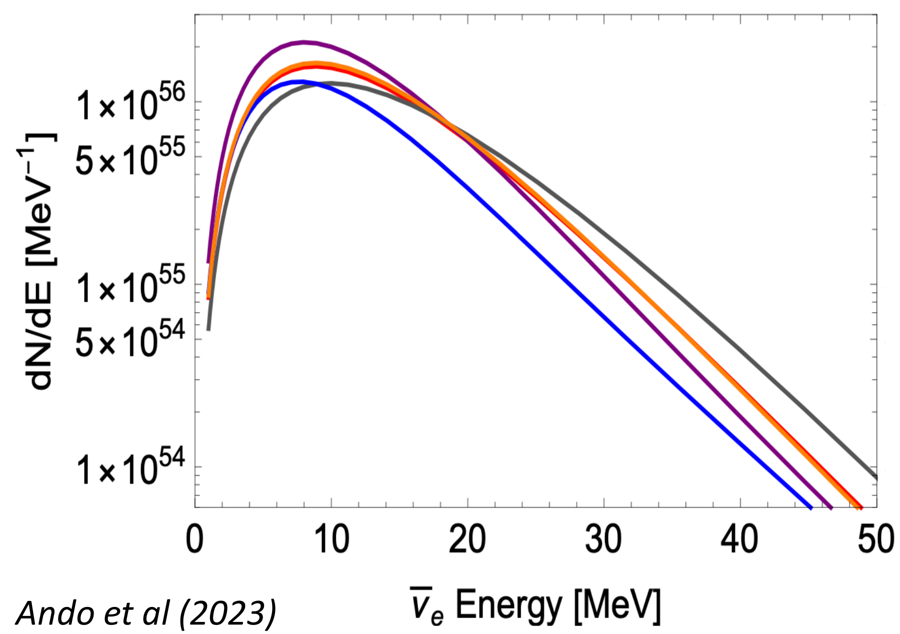
And now, mineral detectors
➔ Kate Scholberg's talk

Diffuse flux: model prediction

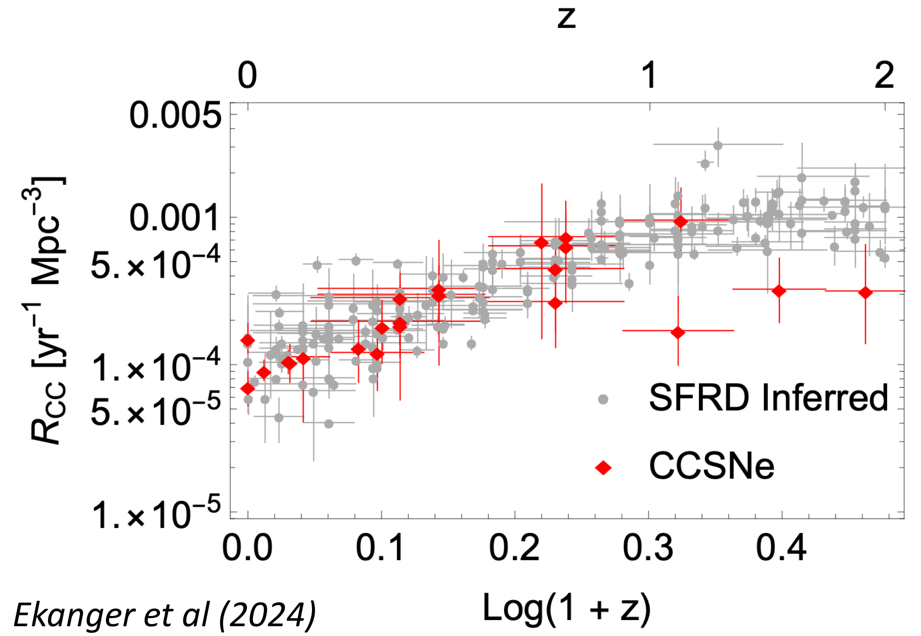
$$\text{Flux} = \int dz\, c \frac{dN}{dE'} (1+z) R_{CC}(z) \left| \frac{dt}{dz} \right|$$

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

Rate of massive star core collapse; directly observed



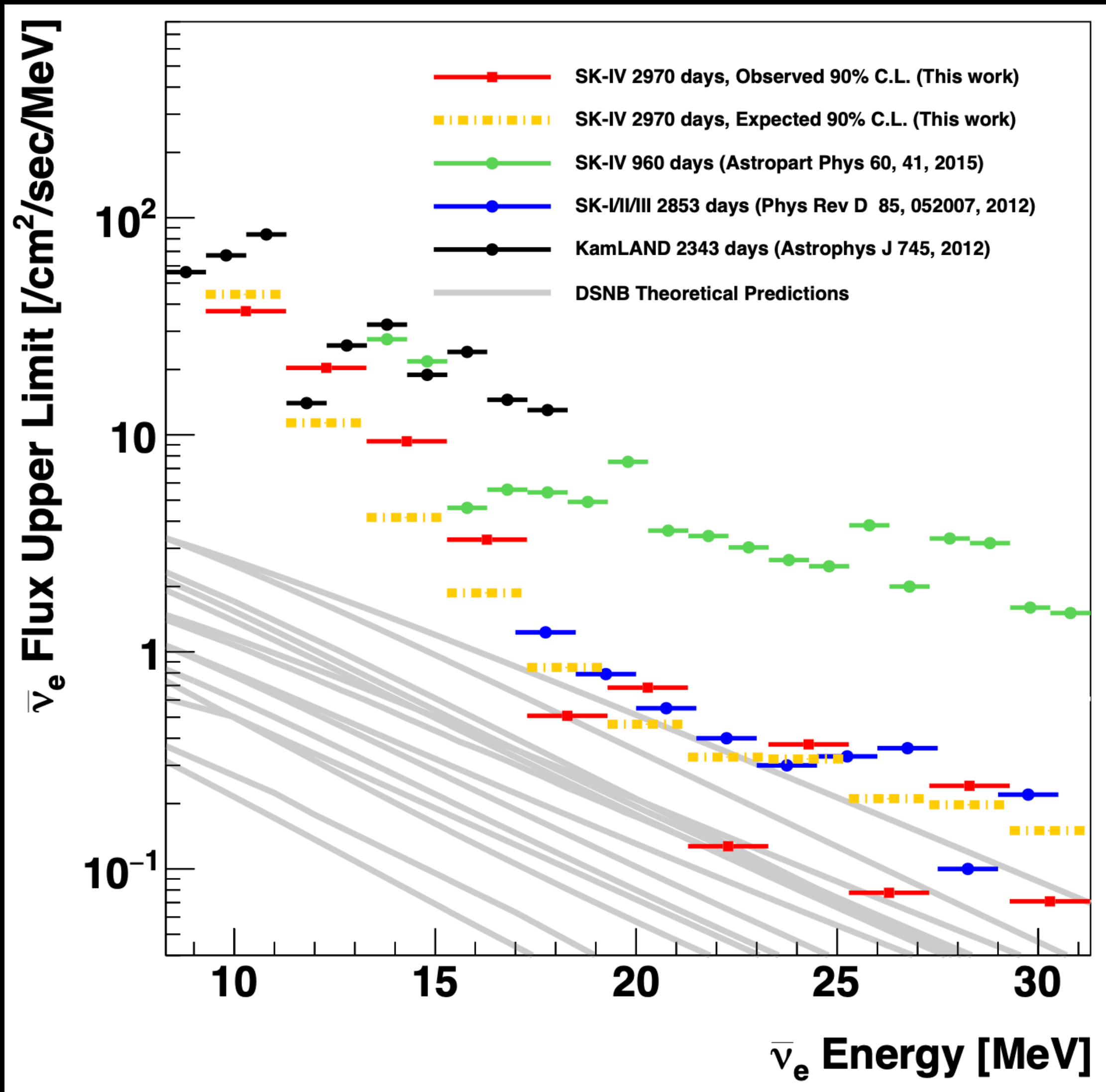
Ando et al (2023)

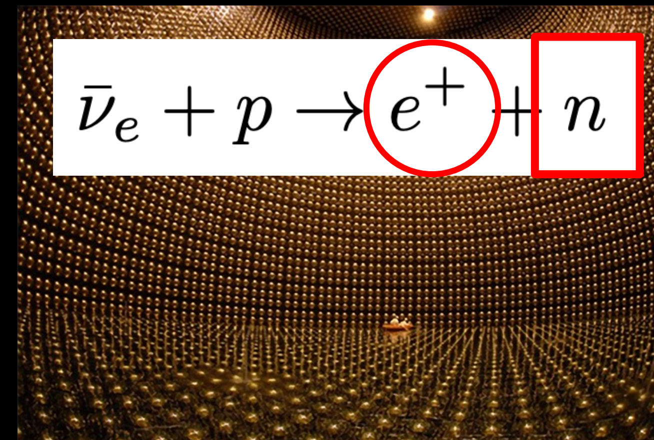


Ekanger et al (2024)

Diffuse supernova neutrino searches

Reaching factor of 2 of many predictions

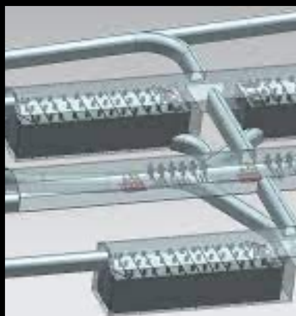




Capture on Gadolinium: proposed in 2003, after many R&D, Super-K was drained in 2018, refurbished, and doped by Gd in 2020

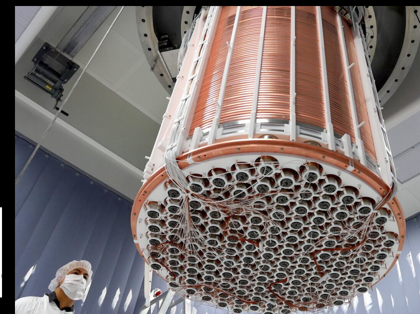
Beacom & Vagins (2004)
SK 2021 (arXiv:2109.00360)

Beyond nuebar flavor



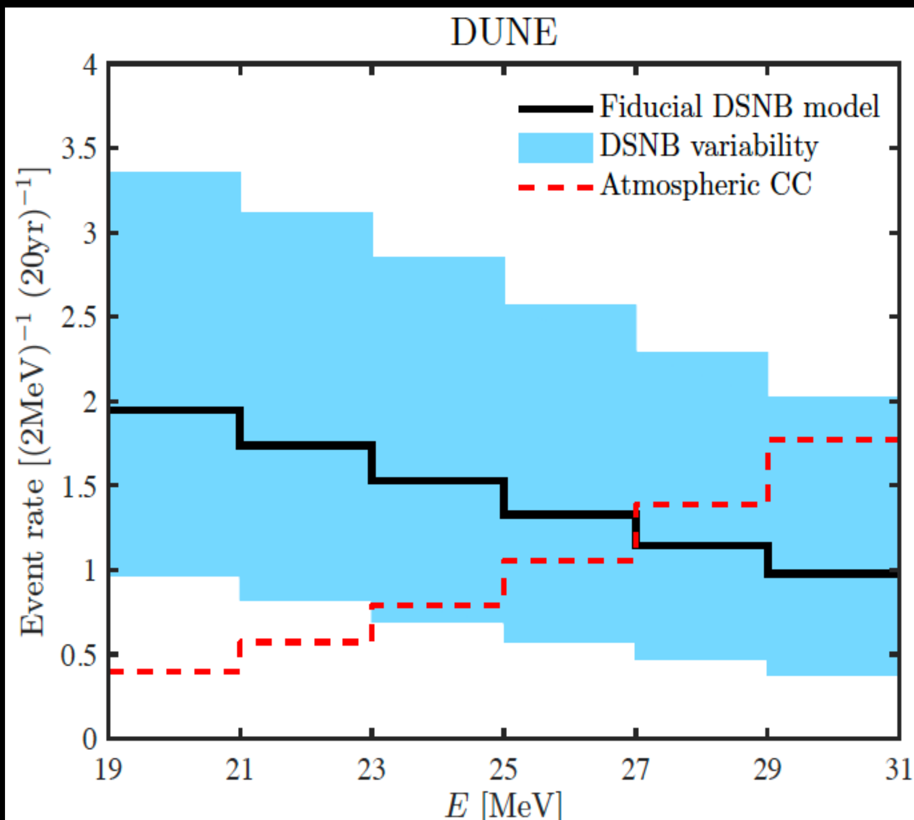
DUNE
- 40k ton lq Ar
- Signal & bkg studies

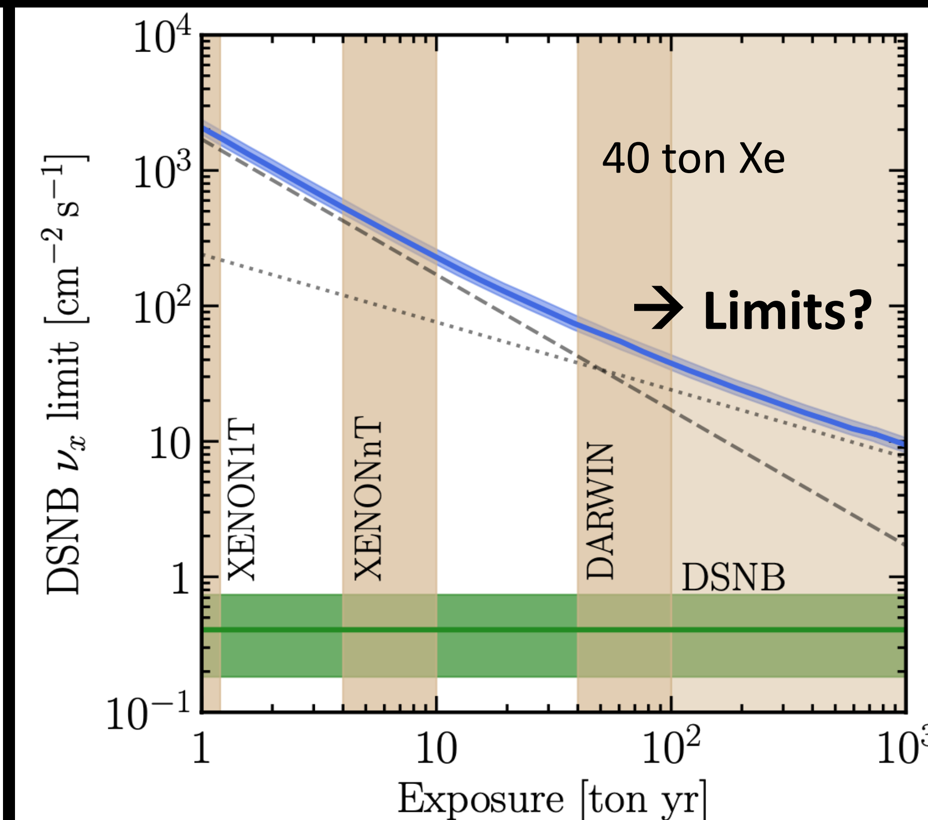
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



Direct DM detectors
- Xe or Ar targets
- Solar & atm. bkgs

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





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

Paleo detector: advantages

All flavors

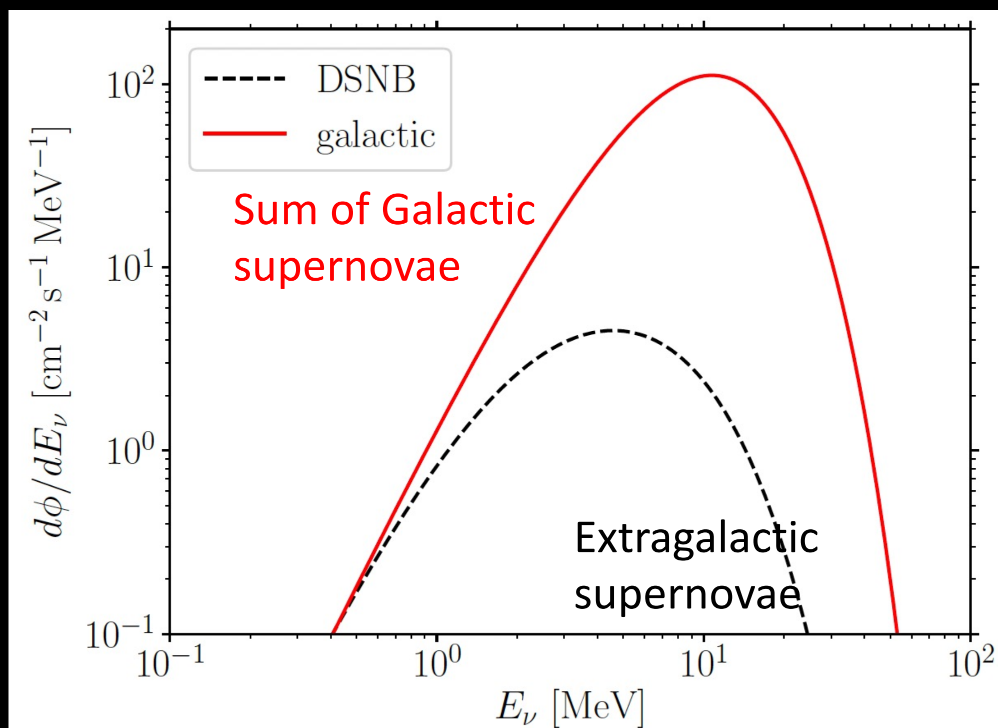
- CEνNS interaction for SN neutrino energies

Competitive exposure

- 100 grams over 10^9 years = 10^5 t year

Large, unique signal

- Duration >> inverse of Galactic supernova rate



Baum et al (2020)

Backgrounds, backgrounds, backgrounds…

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 → distinguish
- Neutrons from spontaneous fission, (a,n) reactions → find radiopure sample

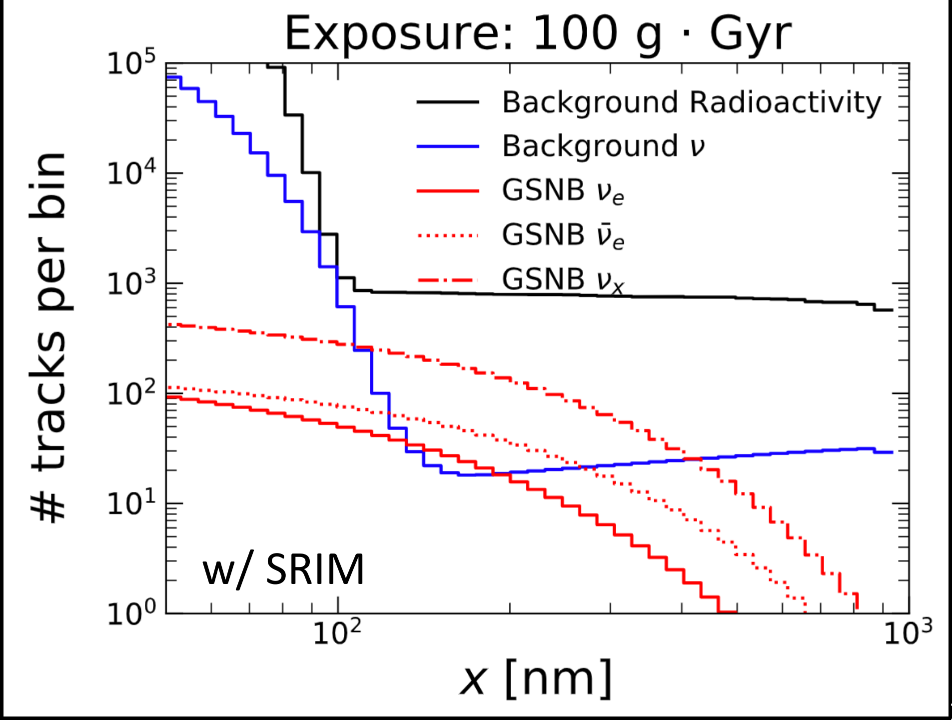
Other neutrinos:

- Atmospheric, solar

→ Cannot distinguish on event-by-event basis

→ Detection using wide-band track spectrum

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



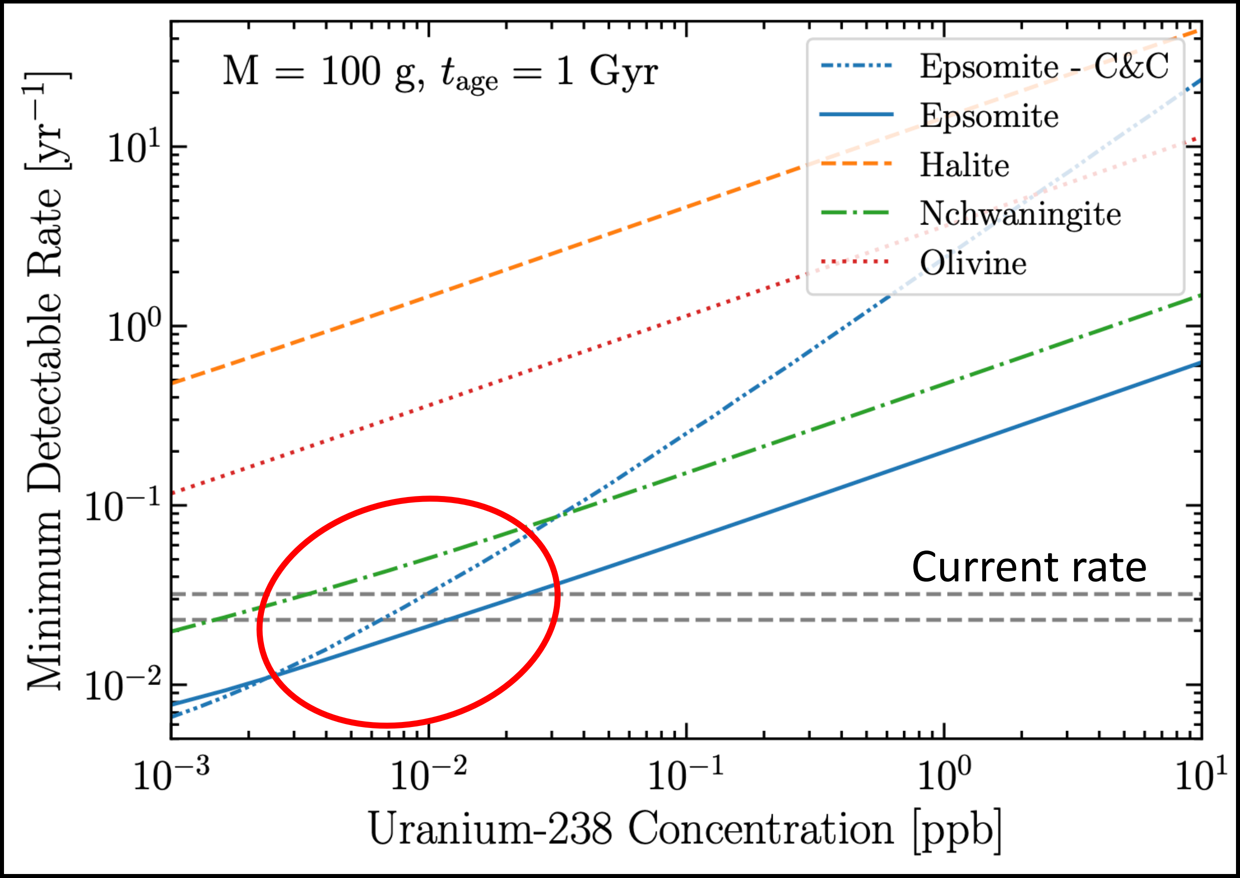
Baum et al (2022)

Supernova neutrino detection

Detection with sufficiently old & pure sample:

Smallest supernova rate that can be detected (3σ) is larger than present supernova rate

Baum et al (2020)

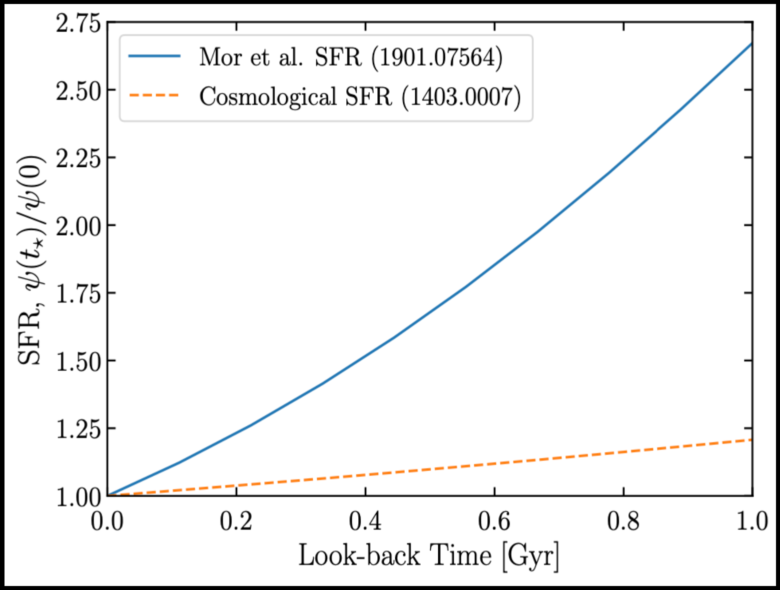


Halite -- NaCl
Epsomite -- $MgSO_4 \cdot 7(H_2O)$
Olivine -- $Mg_{1.6}Fe_{0.4}(SiO_4)$
Nchwaningite -- $Mn_2SiO_3(OH)_2 \cdot (H_2O)$

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

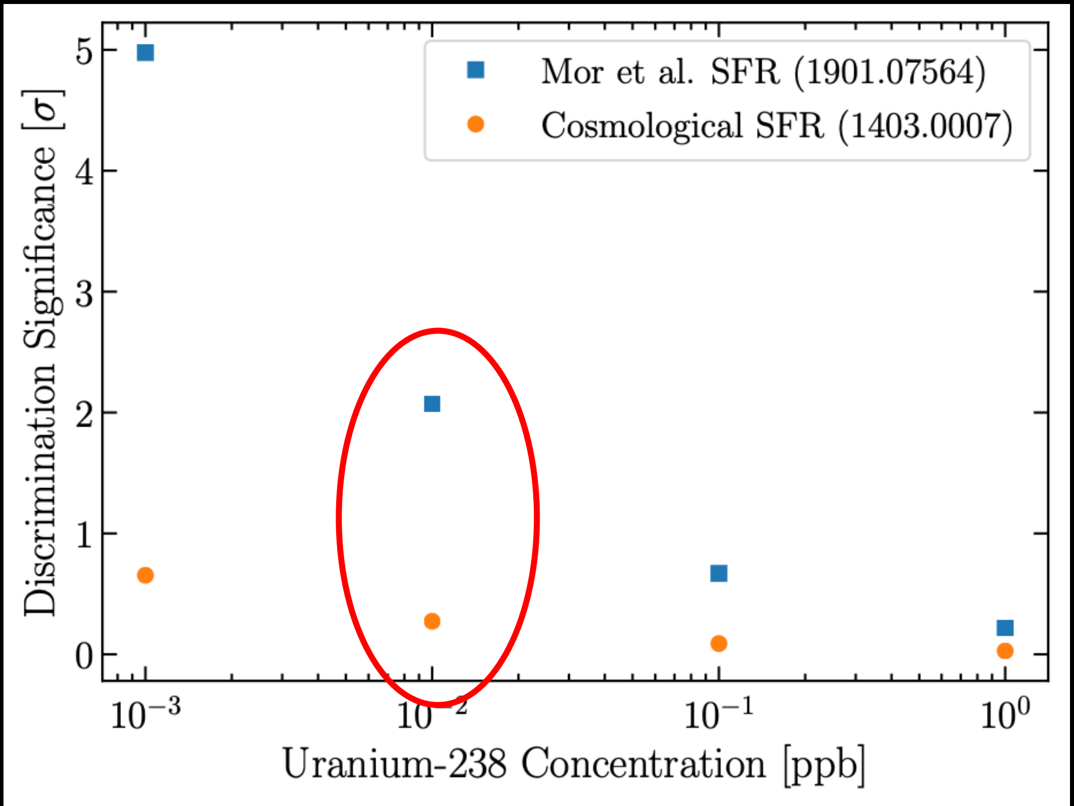
Probes of Milky Way models

Was Milky Way's star formation rate higher in the past?



Baum et al (2020)

➔ Sufficiently pure minerals can rule out constant rate model



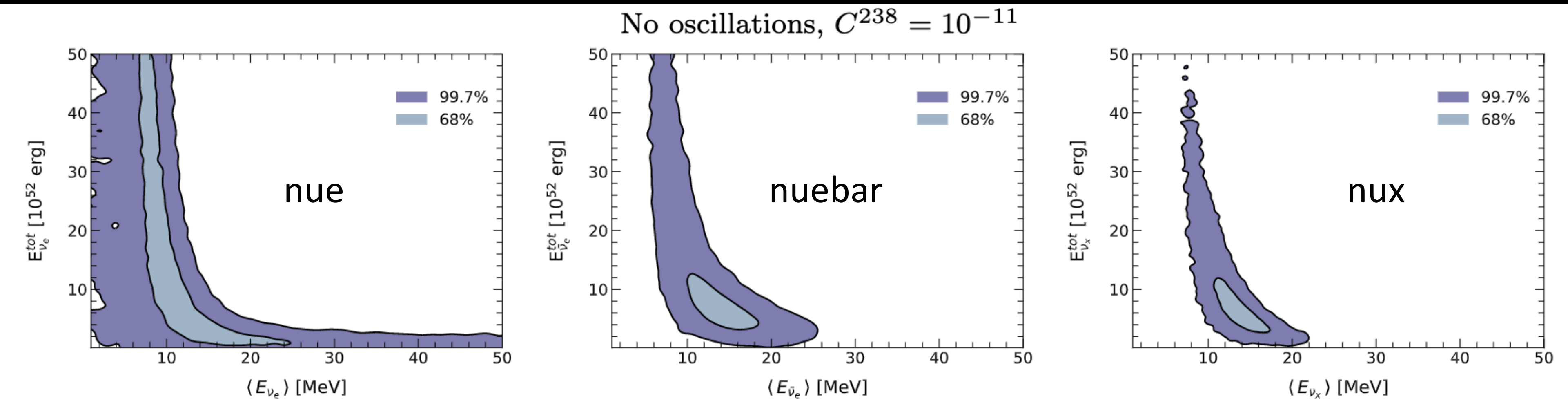
(10 paleo detectors, 100 g each, measuring integrated rates over 100, 200, 300, …10^3 Myr)

Probes of neutrino emissions

If Galactic supernova rate is known well…can test neutrino emissions

Combine with DSNB nuebar from HyperK and DSNB nue from DUNE → residual νx

→ Maybe only way to reveal the mean nux flux from many core collapses



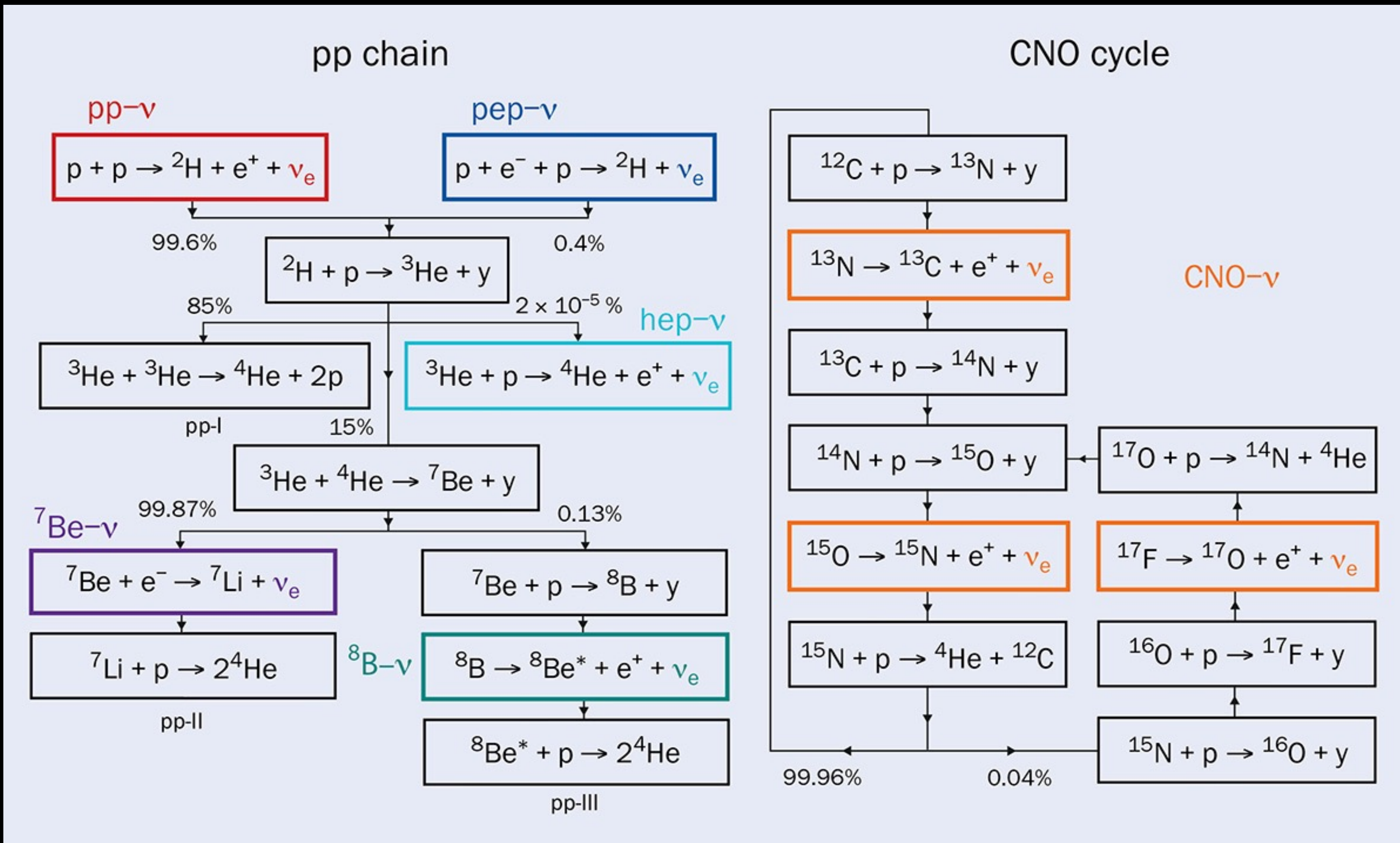
Baum et al (2022)

(100g of epsomite with 1 Gyr age + 20 yrs HyperK & DUNE run time)
(15nm track resolution)
(100% uncertainty on radiogenic & neutrino backgrounds)
(20% uncertainty on HK & DUNE backgrounds)
(10% uncertainty on DSNB flux & galactic rate)

SOLAR NEUTRINOS

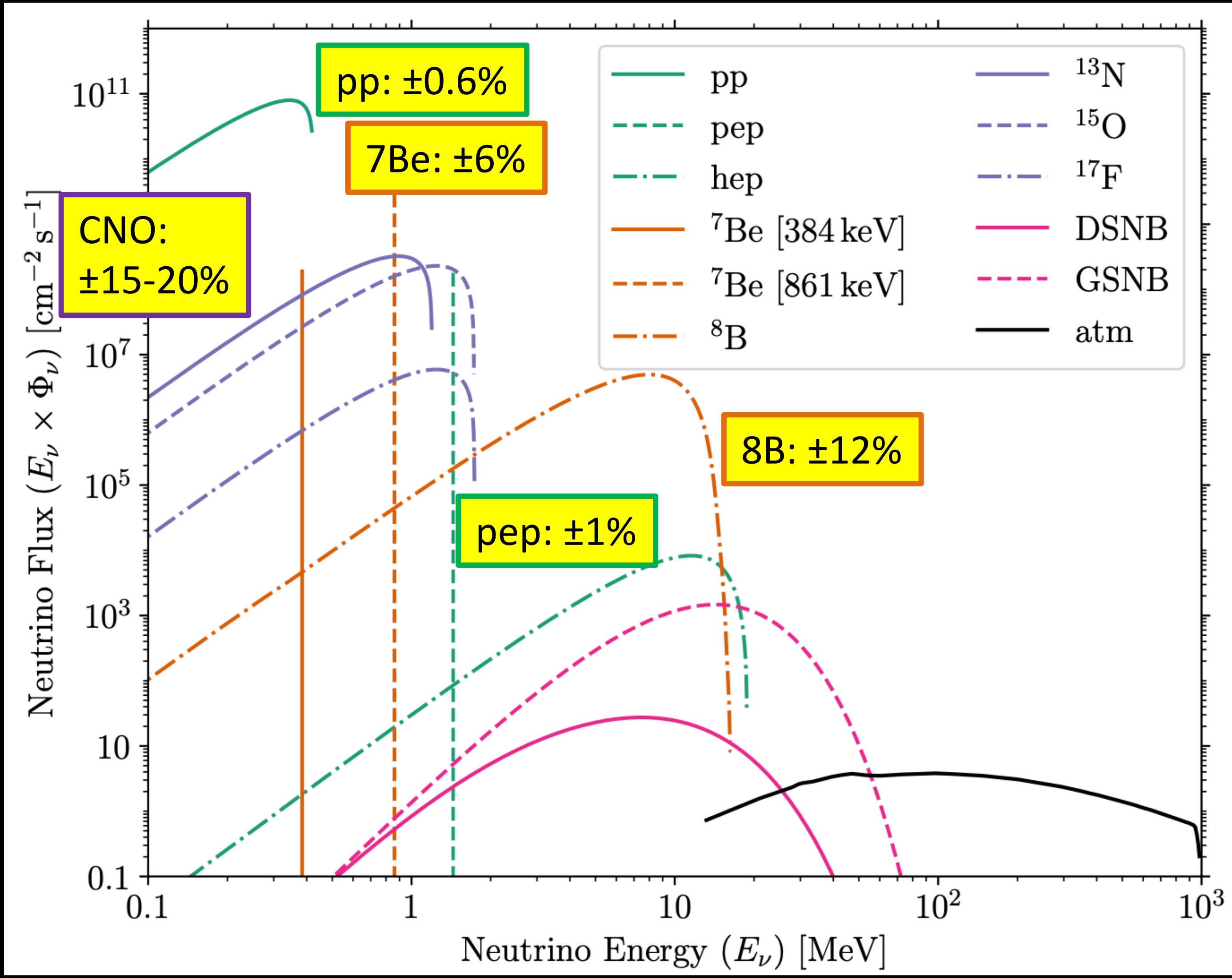
Solar neutrinos

Energy generation by fusion: neutrinos as energy sink



Standard solar model (SSM)

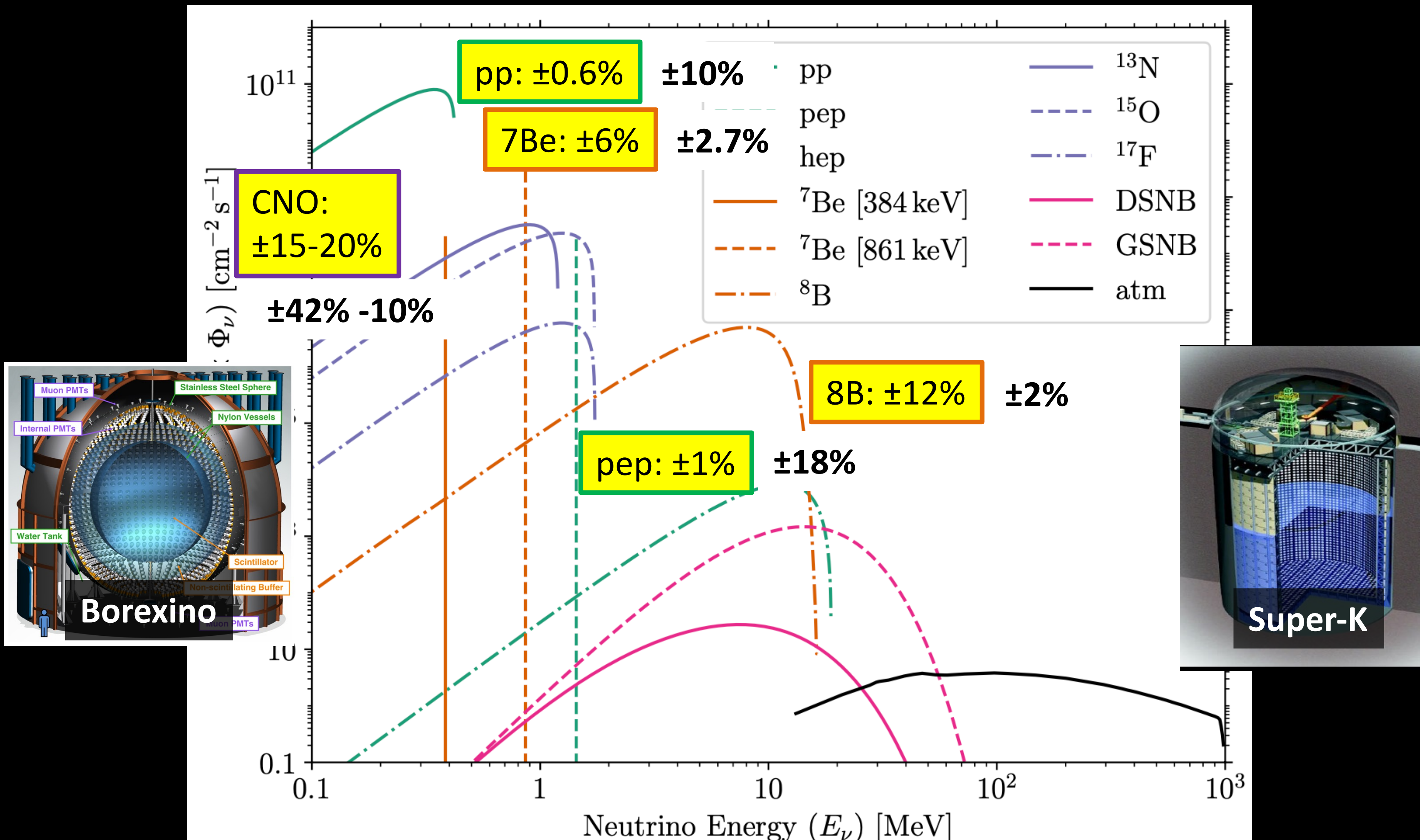
Provides stellar interior model → neutrino predictions



Baum et al 2022

Multiple measurements

Some recent measurement uncertainties



Baum et al 2022

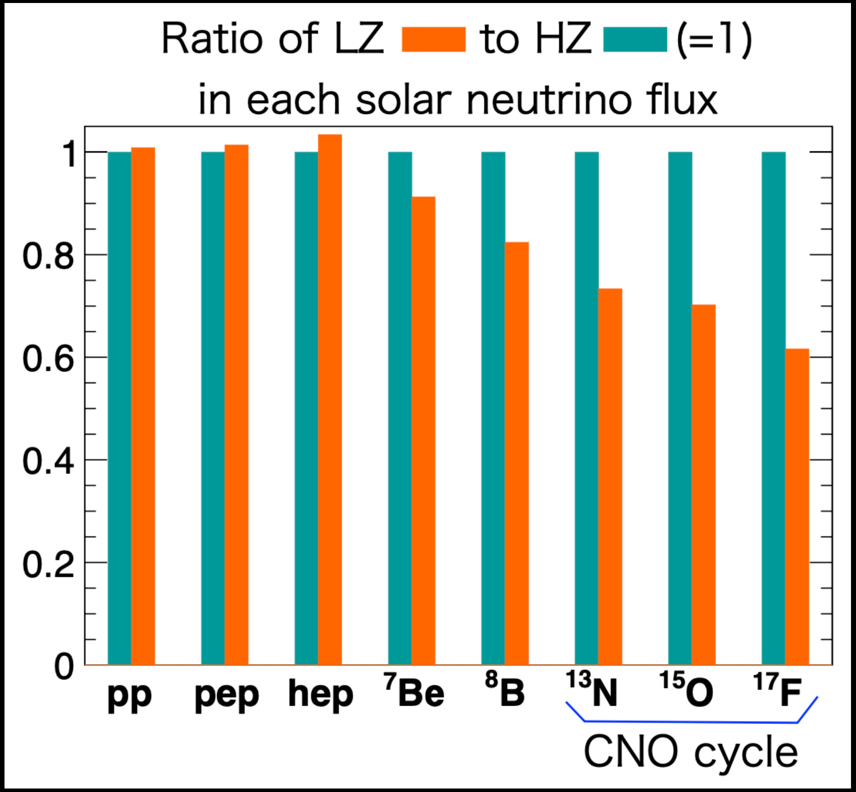
Breaking SSM assumptions

SSM: star is chemically homogeneous without further mass loss or gain

Solar metallicity problem : different metallicity SSMs and helioseismic constraints

- Z/X = 0.0229 (GS98) → HZ model, matches helioseismology
- Z/X = 0.0178 (AGSS09) → LZ model, doesn't match helioseismology

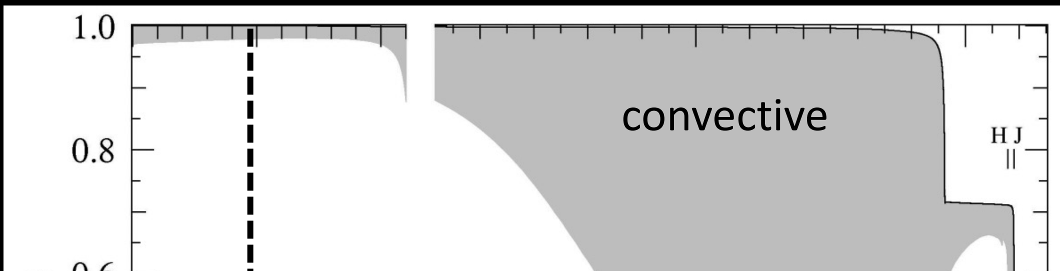
CNO neutrinos, which depend linearly on the core's metal abundance, is useful diagnostic

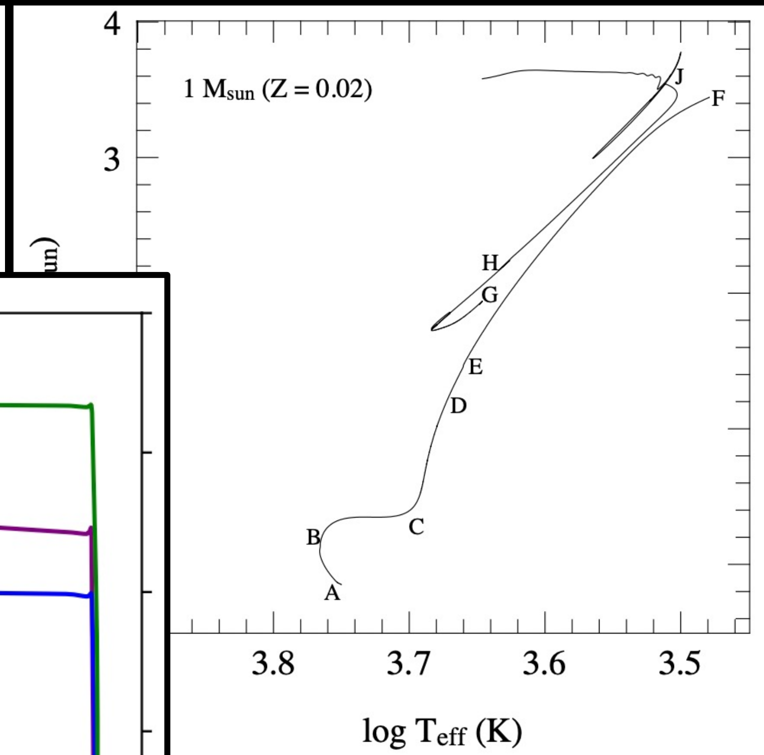


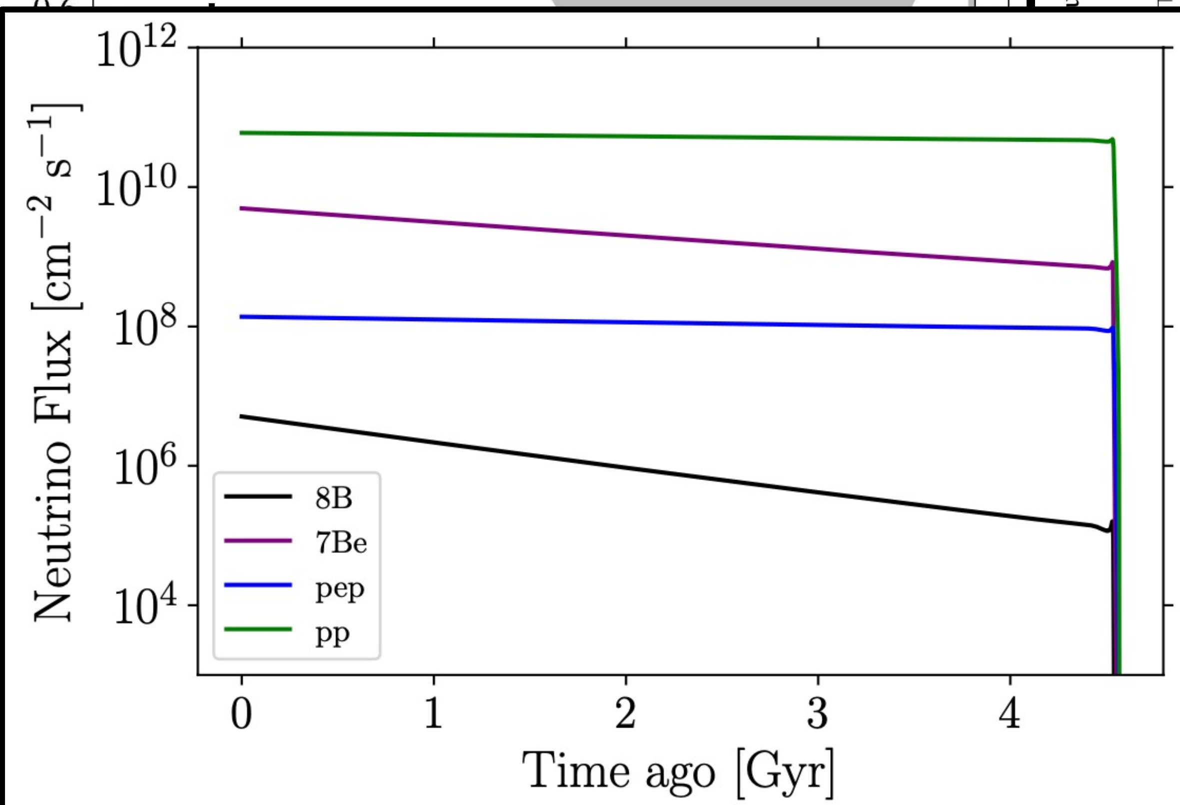
Vinyoles et al (2017)

Stability of the Sun

Hydrogen-burning ("main-sequence") → very stable







Evolution can be tracked by paleo detectors
→ Natalia Tapia-Arellano's talk

Tapia-Arellano & Horiuchi (2021)

Astrophysical neutrino summary

Astrophysical neutrino detection with paleo detectors

Challenges are similar to those of direct dark matter detection

Paleo detectors offer unique insights into astrophysics

Window into time-evolution over geological time scales, with competitive exposure

Supernova implications

Mineral detectors offer perhaps the best probe of heavy lepton neutrinos – both supernova burst neutrinos and diffuse supernova neutrinos

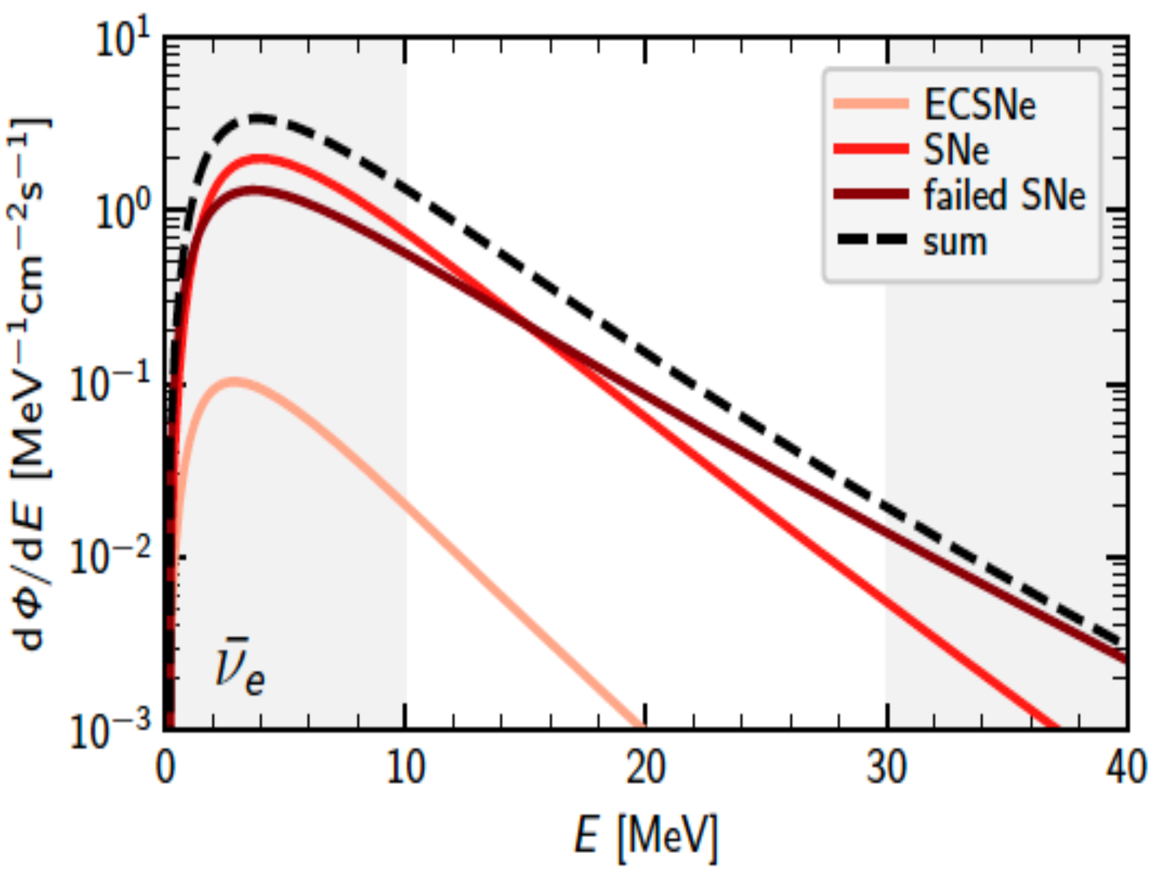
Solar implications

Unique probes of the time-evolution of our Sun over gigayears

Thank you

BACKUP

Prediction, including sub-populations



Kresse et al (2021)
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), Kresse et al (2021), Horiuchi et al (2021), Ashida & Nakazato (2022), Ekanger et al (2022), Ziegler et al (2023)

DSNB flux prediction
With multiple population

PyDSNB: a public code to estimate flux
https://github.com/shinichiroando/PyDSNB

Choice inputs:
- Hydro model
- Late-time model
- Initial mass function
- Dark collapse model
- Dark collapse fraction
- Neutrino mass hierarchy

Ando, Ekanger, Horiuchi, Koshio (2023)

Error budget

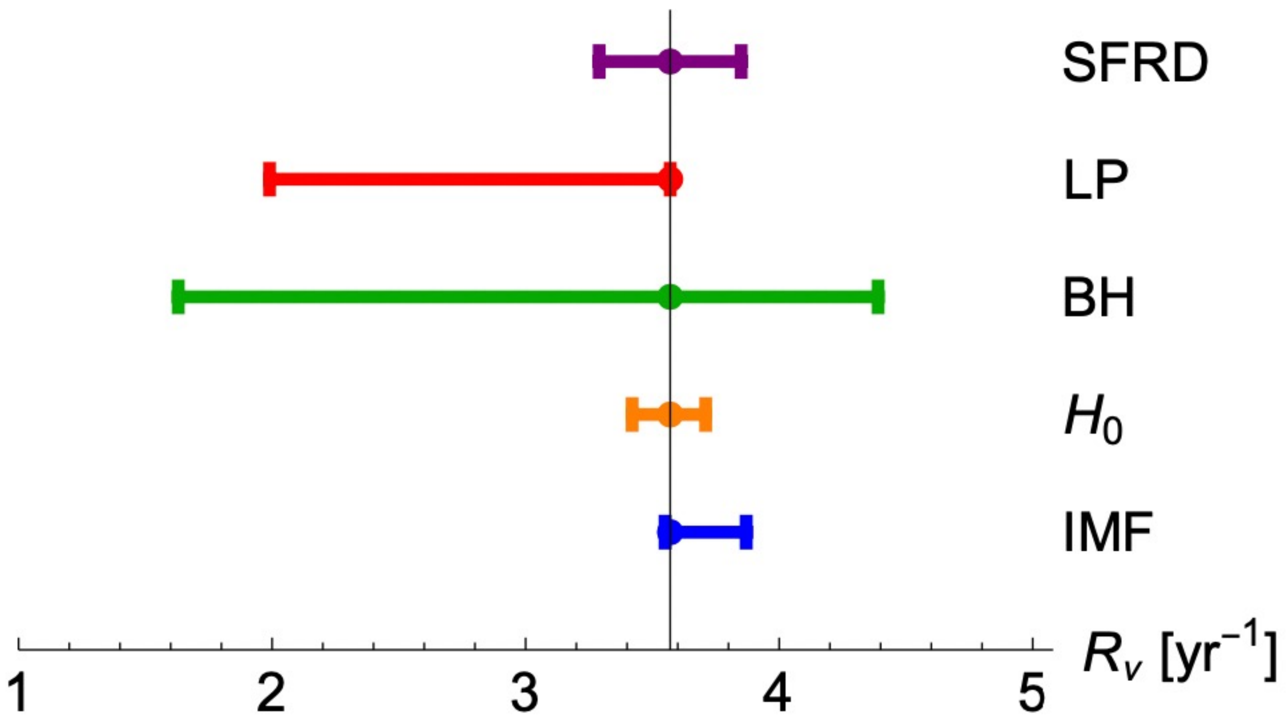
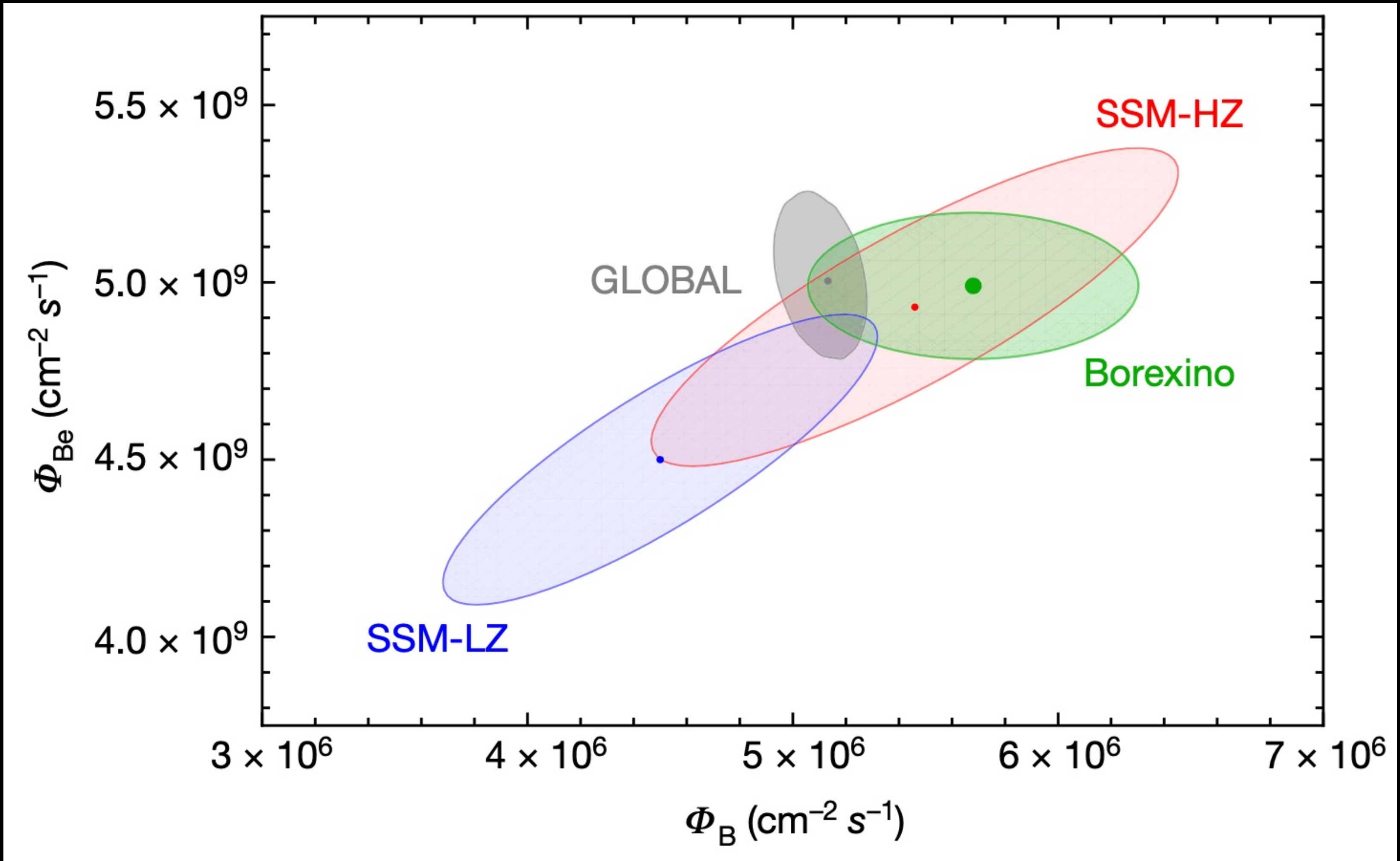


FIG. 6. Estimated errors of DSNB event rates for normal ordering at SK-Gd from SFRD measurements ('SFRD'), late-phase treatment ('LP,' Analytic or RenormLS), failed supernova modeling ('BH,' see Fig. 7), H_0, and IMF assumption ('IMF,' Chabrier, Salpeter A, or Baldry-Glazebrook). Quantitative values are given in Table II.


SSM-HZ
GLOBAL
Borexino
SSM-LZ
5.5×10^9
5.0×10^9
4.5×10^9
4.0×10^9
Φ_{Be} (cm^{-2} s^{-1})
3×10^6
4×10^6
5×10^6
6×10^6
7×10^6
Φ_B (cm^{-2} s^{-1})