Core-collapse supernovae as probes of (not only) non-standard neutrino physics

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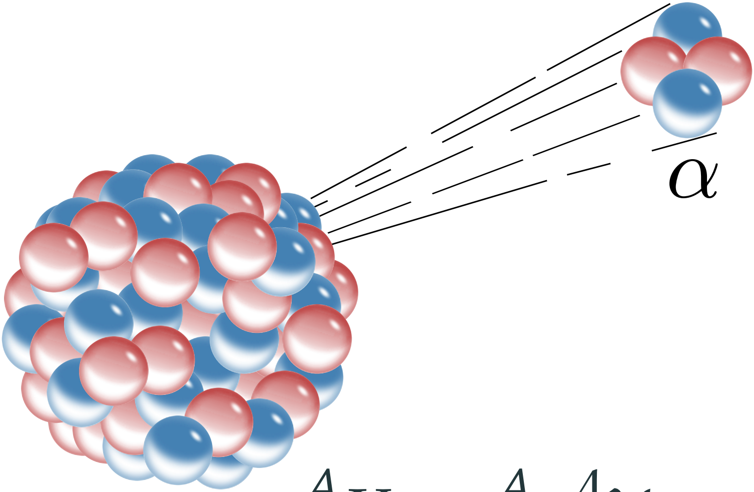
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Data interpretation 101 by W. Pauli

Alpha decay

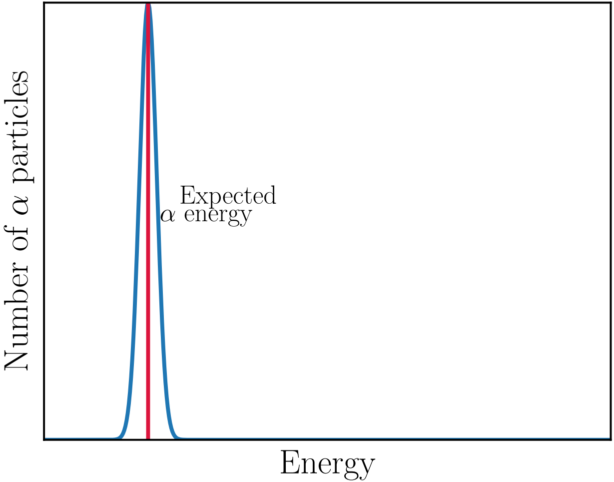


$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + \alpha$$

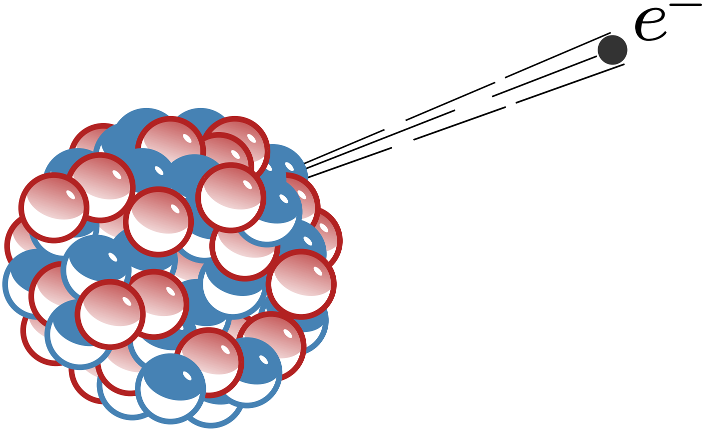
Wikipedia

Rutherford (1899), Gamow (1928)

Alpha decay - spectrum



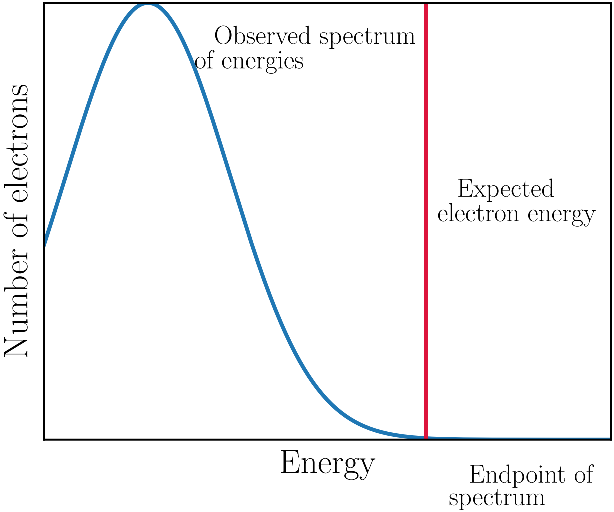
Beta decay



Wikipedia

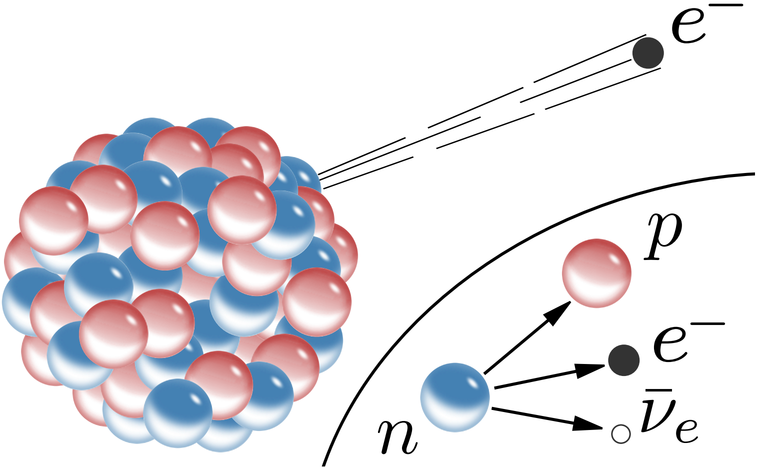
Rutherford (1899)

Beta decay - spectrum



Ellis, Chadwick, Mott (1920-1927)

Beta decay - explanation of the spectra



Wikipedia

Pauli (1930),
Beta+ decay Joliot, Joliot-Curie (1934)

How to detect a ghost?

Neutrino factories

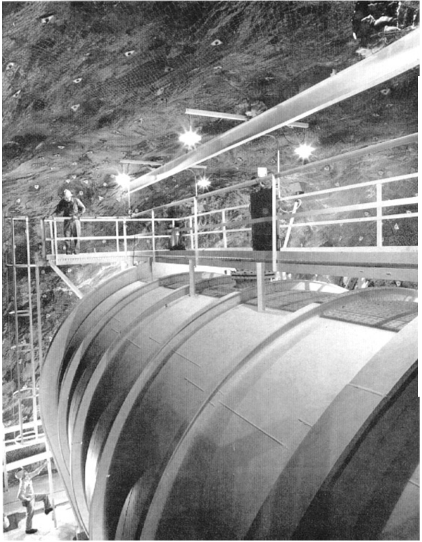
Kurzgesagt, Wikipedia

Neutrino factories

Neutrino factories

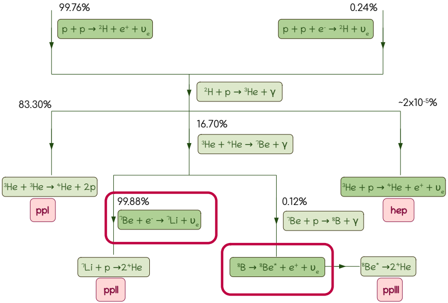
Homestake experiment - solar neutrino detector

Bahcall (1964), Davis(1964)



Fermilab picture archive

pp-chain



99.76%

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

0.24%

$p + p + e^{-} \rightarrow {}^{2}H + \nu_e$

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

83.30%

16.70%

~2×10^{-5}%

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

ppI

99.88%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

0.12%

${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

hep

${}^{7}Li + p \rightarrow 2\,{}^{4}He$

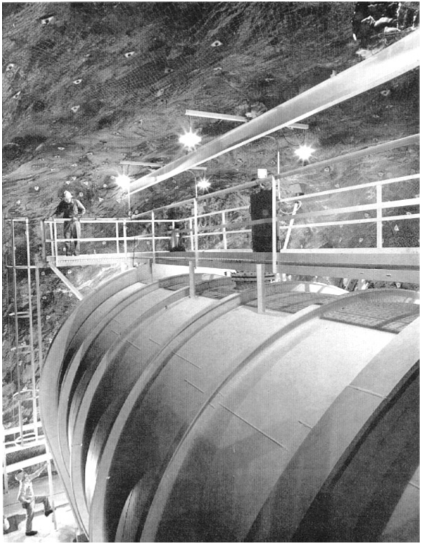
ppII

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

${}^{8}Be^{*} \rightarrow 2\,{}^{4}He$

ppIII

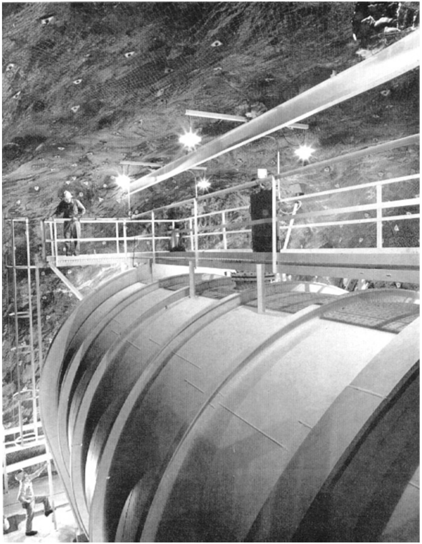
Homestake experiment - solar neutrino detector



Fermilab picture archive

1. BIG detector

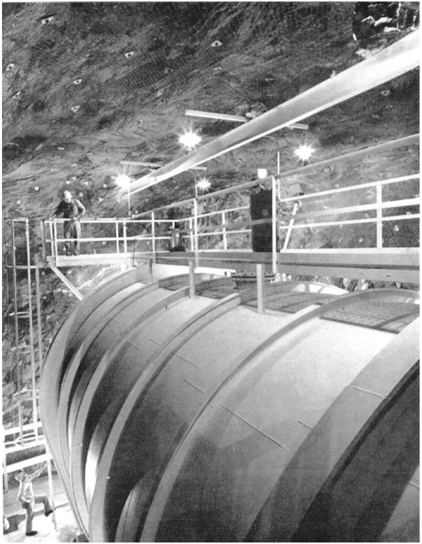
Homestake experiment - solar neutrino detector



Fermilab picture archive

1. BIG detector
2. isolate from other particles

Homestake experiment - solar neutrino detector



Fermilab picture archive

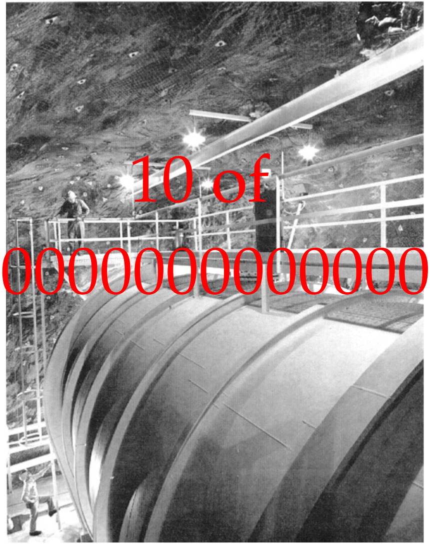
❶ BIG detector

❷ isolate from other particles

- 378,000 l of perchloroethylene (C_2Cl_4 ″dry-cleaning fluid″)
- 1.5 km underground

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

Homestake experiment - solar neutrino detector



Fermilab picture archive

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Solar Neutrino Problem

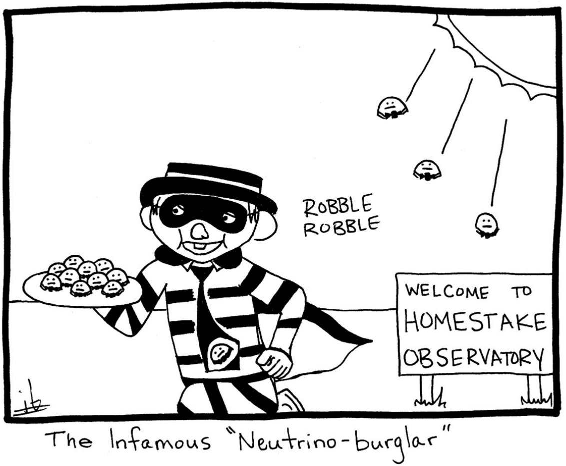
The number of detected neutrinos $\sim$ 3x smaller than expected

The Infamous "Neutrino-burglar"

Comic

Solar Neutrino Problem

The number of detected neutrinos $\sim$ 3x smaller than expected



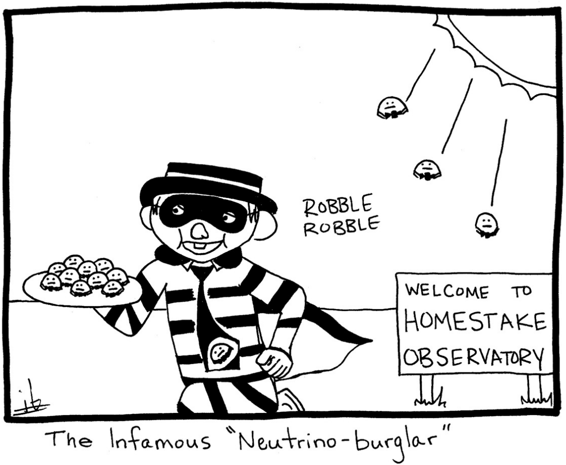
Plausible Solutions:

- Incorrect calculation
- Faulty detector
- New Physics

Comic

Solar Neutrino Problem

The number of detected neutrinos $\sim$ 3x smaller than expected



Plausible Solutions:

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Comic

Neutrino properties

Neutrino flavors

Neutrino flavors

Neutrino flavors

The Particle Zoo

Neutrino flavors

The Particle Zoo

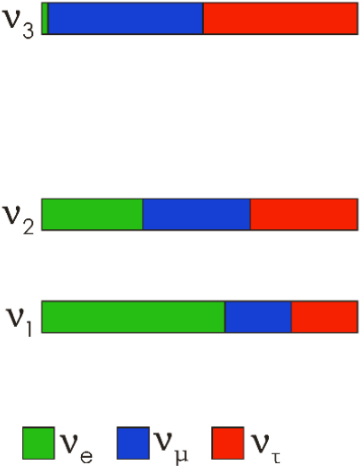
Neutrino flavors

The Particle Zoo

Neutrino flavors

The Particle Zoo

neutrino mass and flavor states



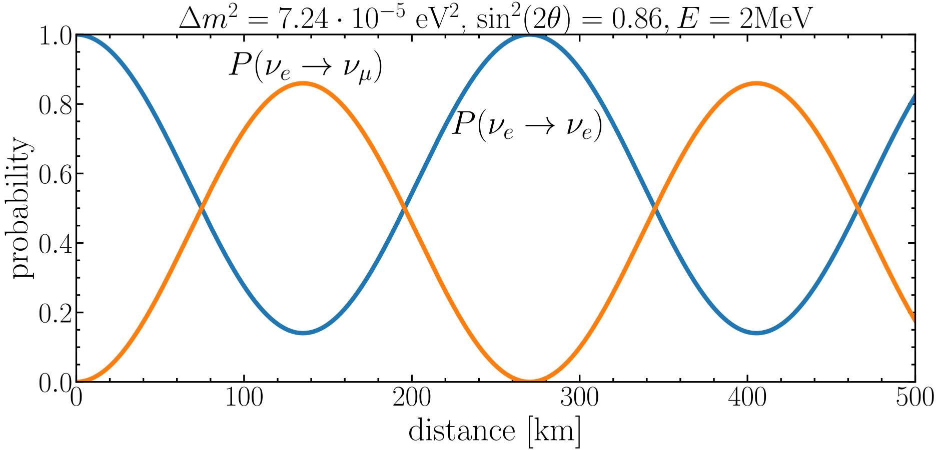
mass states $\neq$ flavor states

Neutrino oscillations in vacuum

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

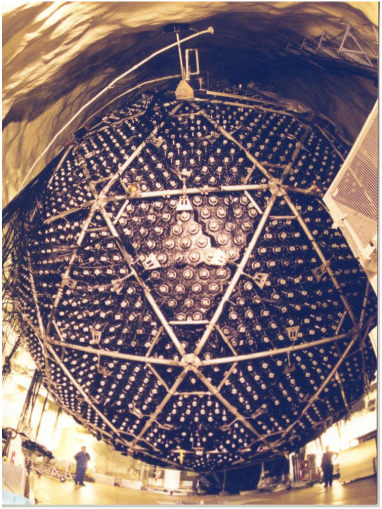
2ν mixing = easy dependence on

- mixing angle
- mass squared difference



All-neutrino-flavor sensitive detector

Sudbury Neutrino Observatory (SNO)



- 2.1 km underground
- filled with 1000 tonnes of heavy water
- sensitive to all neutrino flavors

$$\nu_e + \mathrm{D} \to \mathrm{p} + \mathrm{p} + e^-$$

$$\nu_x + \mathrm{D} \to \mathrm{p} + \mathrm{n} + \nu_x$$

$$\nu_x + e^- \to \nu_x + e^-$$

SNO

All-neutrino-flavor sensitive detector

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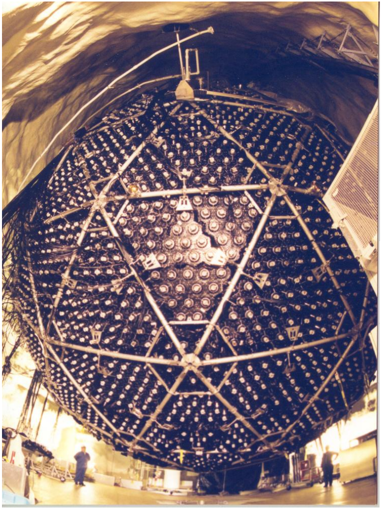
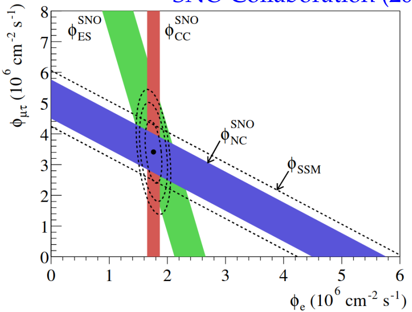


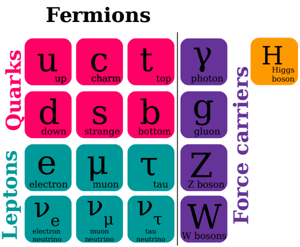
SNO

- 2.1 km underground
- filled with 1000 tonnes of heavy water
- sensitive to all neutrino flavors

SNO Collaboration (2002)

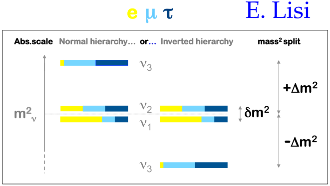


Neutrino flavor and mass states



flavor basis | mass basis

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$



E. Lisi

beam, atmospheric | beam, reactor | solar, reactor

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

is ν_s (ν_4) missing?

Pontecorvo (1957), Maki, Nakagawa, Sakata (1962)

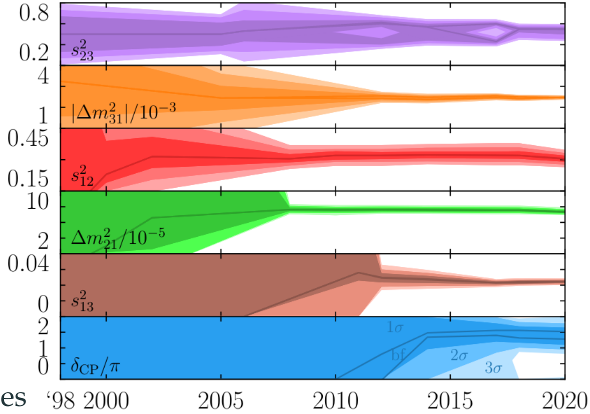
Towards Precise Neutrino Properties Measurements

Past measurements

- large mixing angles
- non-zero masses

Remaining questions

- Majorana vs Dirac
- absolute masses
- degree of CP violation
- some low-energy ν fluxes



Snowmass Neutrino Frontier Report

How to achieve it? All hands on deck

- Many new experiments comimg online soon, DUNE, JUNO, HK, SBND, DARWIN-LZ...
- variety of approaches → superb sensitivity

Why studying astrophysical neutrinos is crucial?

Benefits to the field of neutrino physics

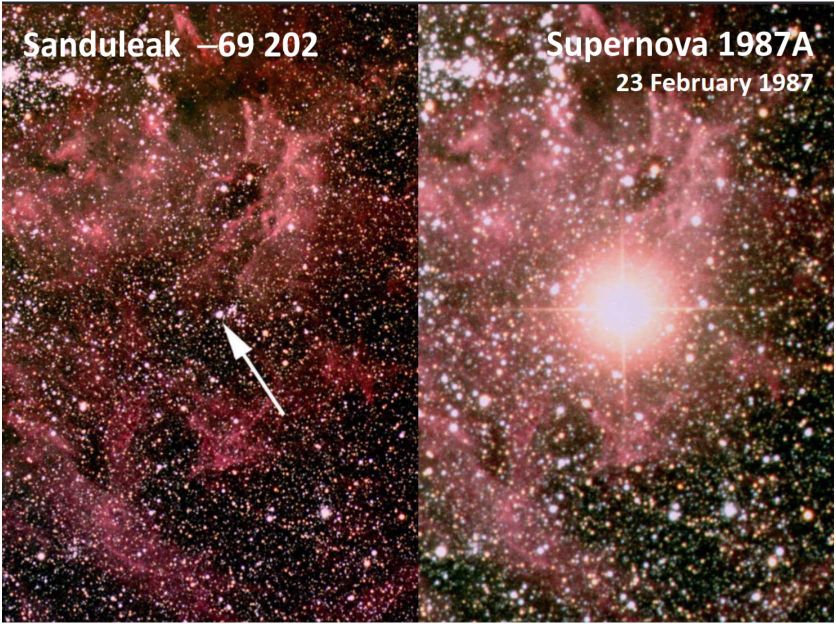
- free sources spanning over 20 decades in energy
- test of physics in the conditons not acessible on Earth
- established track record of neutrino discoveries
- complements terrestrial neutrino experminetal efforts

Benefits to the field of multimessenger astrophysics

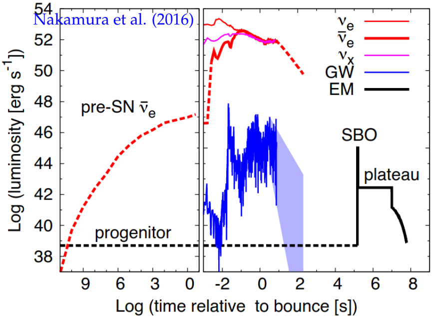
- unveils physics of the sources
- experminetally and observationally timely

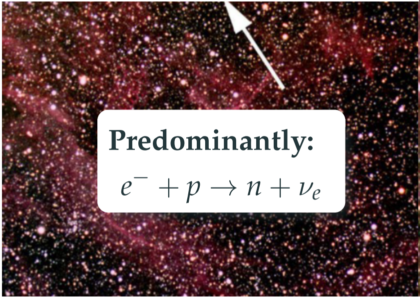
Core-collapse supernovae and neutrinos

Core-collapse supernova



Core-collapse supernova


Nakamura et al. (2016)

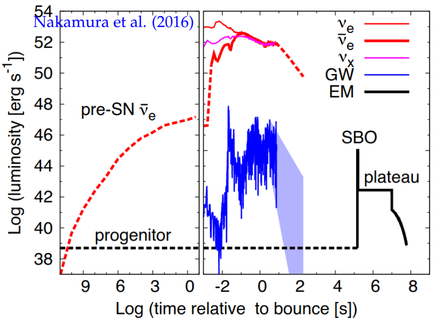


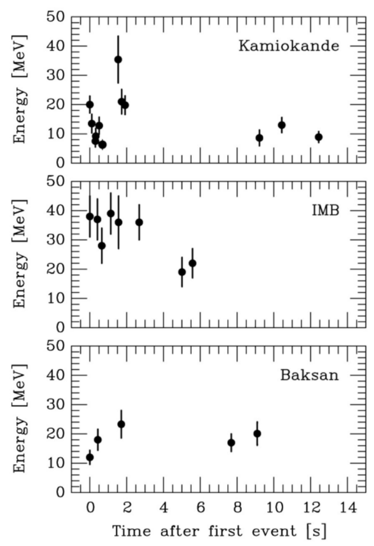
Predominantly:

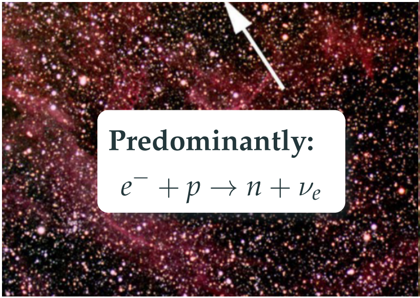
$$e^- + p \rightarrow n + \nu_e$$


Supernova 1987A
23 February 1987

Core-collapse supernova







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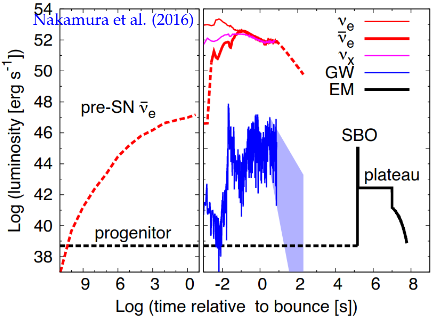
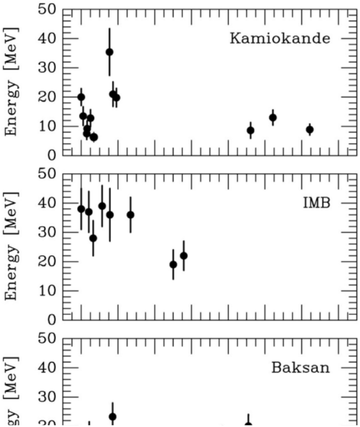




Early evolution matches models: Fiorillo et al. (2023)

Early evolution doesn’t match models: Li et al. (2023)

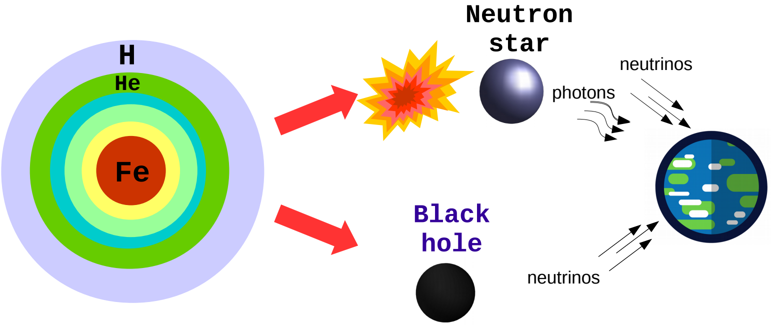
SK can discriminate models well: Migenda (2019)

Core-collapse supernova as an example neutrino source

Why are neutrinos important for a core-collapse supernova?

Neutrinos:

- $\sim 10^{58}$ of them emitted from a single core collapse
- only they (+ GW) can reveal the deep interior conditions
- only they (+ GW) are emitted from the collapse to a black hole



Earth image: Kurzgesagt

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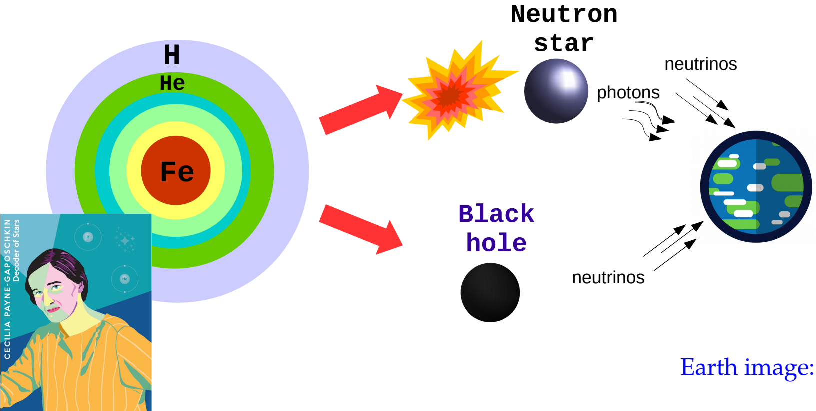


Earth image: Kurzgesagt

Why core-collapse supernovae are good physics probes?

Advantages

- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (SK, JUNO, XENON, PandaX...)

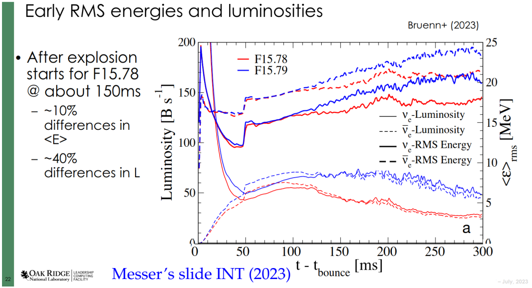
What can we learn with a variety of detectors?

• explosion mechanism	Bethe & Wilson (1985), Fischer et al. (2011)...
• yields of heavy elements	Woosley et al. (1994), Surman & McLaughlin (2003)...
• compact object formation	Warren et al. (2019), Li, Beacom et al. (2020)...
• neutrino flavor evolution	Balantekin & Fuller (2013), Tamborra & Shalgar (2020)...
• non-standard physics	McLaughlin et al. (1999), de Gouvêa et al. (2019) ...

Why such an exciting problem?

Synergy between many fields of physics

- nuclear physics
- hydrodynamics
- particle physics
- general relativity
- many-body physics
- dense matter



Early RMS energies and luminosities

Bruenn+ (2023)

- After explosion starts for F15.78 @ about 150ms
  - ~10% differences in <E>
  - ~40% differences in L

22

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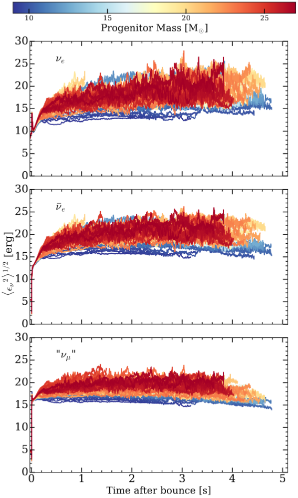
– July, 2023

Messer's slide INT (2023)

Vartanyan, Burrows (2023)



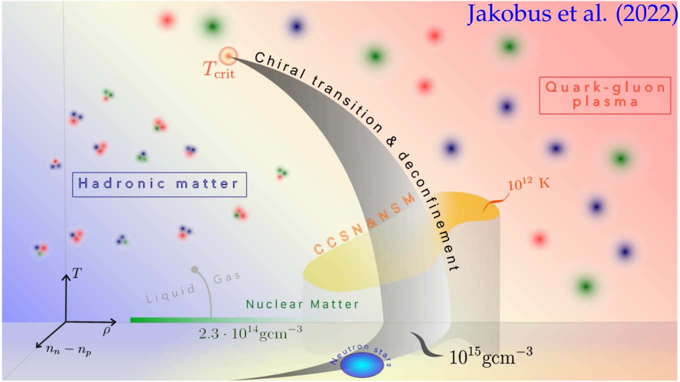
Phase transition to quark matter in core-collapse supernovae

In collaboration with T. Pitik, D. Heimsoth, and

A. B. Balantekin

Phys.Rev.D 106 (2022) 10, 103007

QCD phase diagram



Jakobus et al. (2022)

- Does the protocompact star contain non-leptonic degrees of freedom other than neutrons and protons?
- How to identify the presence of quark matter in astrophysical objects?

Quark matter in compact stars

Where the quark matter can appear in atrophysical objects?

- quark matter in accreting neutron stars
  Lin et al. (2006), Abdikamalov et al. (2008), Espino, Paschalidis (2021), ...
- in protoneutron stars after the CCSN explosion
  Pons et al. (2001), Keranen et al. (2004)
- in protocompact stars during early postbounce phase
  Gentile et al. (1993), Sagert et al. (2008), Fischer, Sagert et al. (2011) ...

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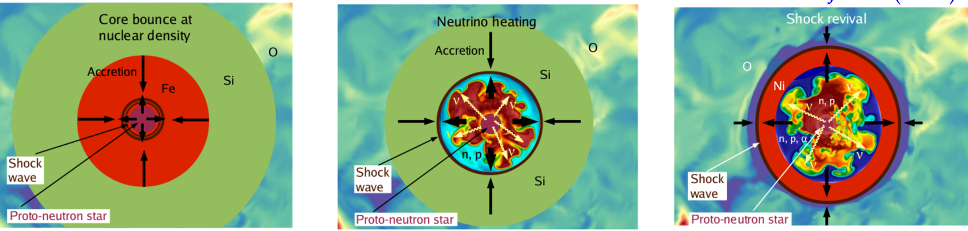
Different phases of core-collapse supernova explosion

- Infall phase, ν_e burst ~ 40 ms
- Accretion phase, ~ 100 ms
- Cooling phase, ~ 10 s

H. T. Janka (2017)



What drives the supernova supernova explosions?

- neutrino heating Colgate & White (1966), Bethe & Wilson (1985)
- magneto-rotational mechanism LeBlanc and Wilson (1970), Takiwaki et al. (2009)
- particles beyond the Standard Model Fuller et al. (2008), **AMS** et al. (2020) ...
- phase transition to quark matter Sagert et al. (2008)...

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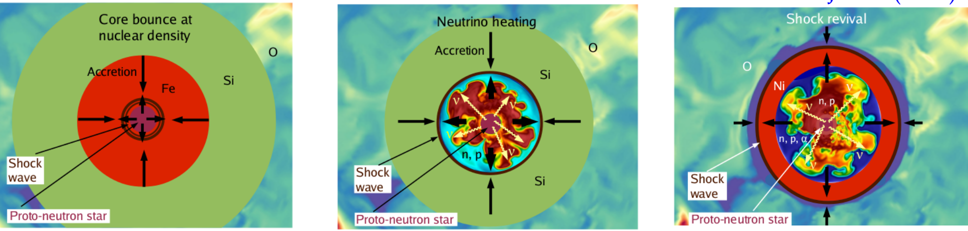

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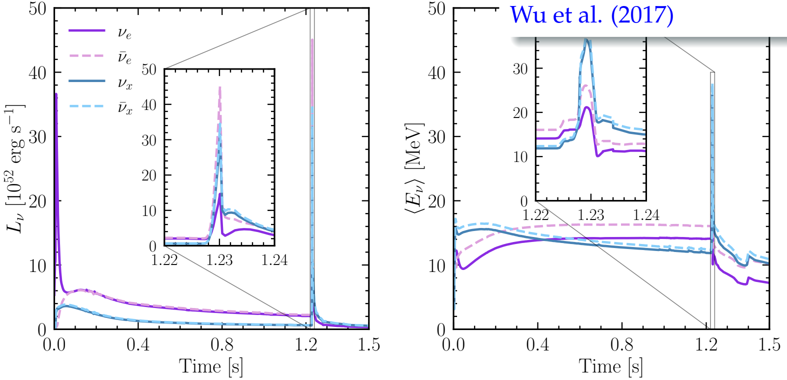
Neutrino Emission Properties from the QHPT CCSN

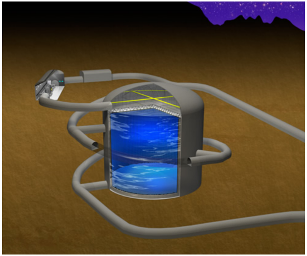


1D SN model Fischer, Bastian, Wu et al. (2017)

- second sharp neutrino burts dominated by $\bar{\nu}_e$
- non-exploding models can explode

Supernova neutrino detection

Hyper-Kamiokande (2027)



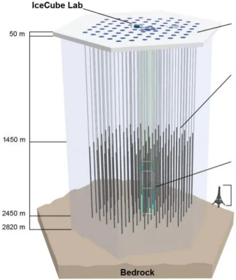
fiducial volume

217 kton

main detection channel

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

Ice-Cube Observatory



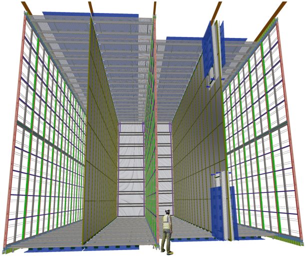
fiducial volume

3500 kton

main detection channel

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

DUNE (2030)



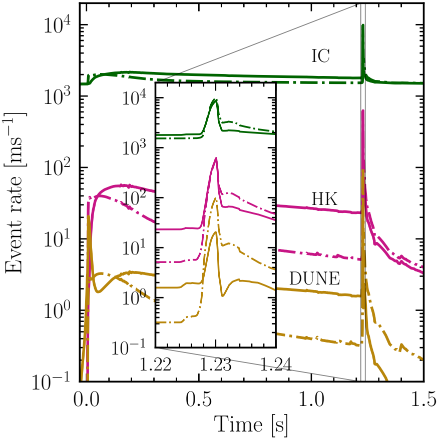
fiducial volume

40 kton

main detection channel

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

Neutrino Event Rates

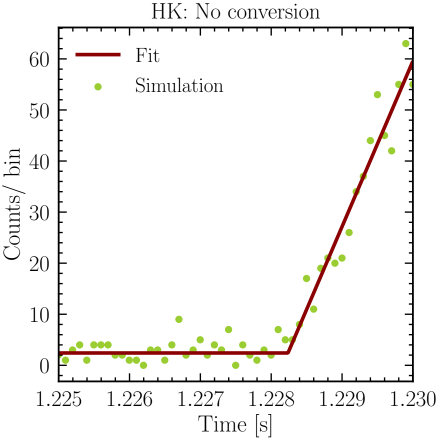


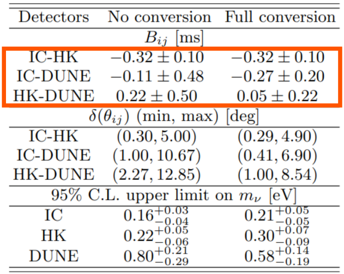
Impact of neutrino conversions

- Event rate in the antineutrino detectors comparable for both conversion scenarios
- Event rate in the neutrino detector larger for the full conversion case

$$R(t) = N_t \int_{E_\nu^{\min}}^{\infty} dE_\nu \int_{E_{\rm th}}^{E_{\max}} dE \; \varepsilon \sigma_i(E, E_\nu) \; F_{\nu_\beta}(E_\nu, t)$$

Timing the Neutrino Signal





Detectors	No conversion	Full conversion
	B_{ij} [ms]	
IC-HK	-0.32 ± 0.10	-0.32 ± 0.10
IC-DUNE	-0.11 ± 0.48	-0.27 ± 0.20
HK-DUNE	0.22 ± 0.50	0.05 ± 0.22
	$\delta(\theta_{ij})$ (min, max) [deg]	
IC-HK	$(0.30, 5.00)$	$(0.29, 4.90)$
IC-DUNE	$(1.00, 10.67)$	$(0.41, 6.90)$
HK-DUNE	$(2.27, 12.85)$	$(1.00, 8.54)$
	95% C.L. upper limit on m_ν [eV]	
IC	$0.16^{+0.03}_{-0.04}$	$0.21^{+0.05}_{-0.05}$
HK	$0.22^{+0.05}_{-0.06}$	$0.30^{+0.07}_{-0.09}$
DUNE	$0.80^{+0.21}_{-0.29}$	$0.58^{+0.14}_{-0.19}$

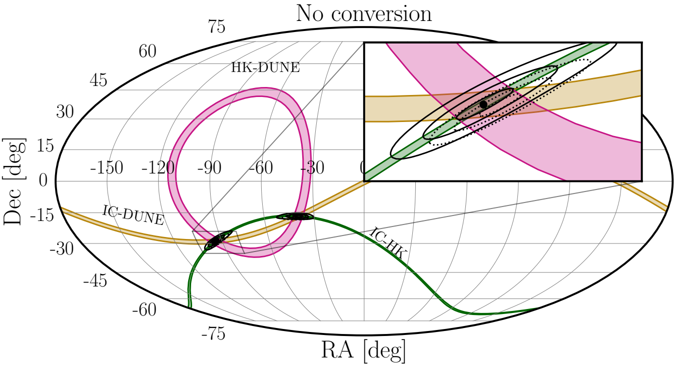
$$\Delta t_{ij}^{\text{true}} = \frac{(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{n}}{c} = \frac{D_{ij} \cos\theta}{c}$$

$$R_{\text{exp}} = \begin{cases} R_*, & \text{if } t < t_0 \\ R_* + a(t - t_0), & \text{otherwise} \end{cases},$$

$$\Delta t_{ij}^{\text{measured}} = \Delta t_{ij}^{\text{true}} + B_{ij}$$

Halzen and Raffelt (2009)

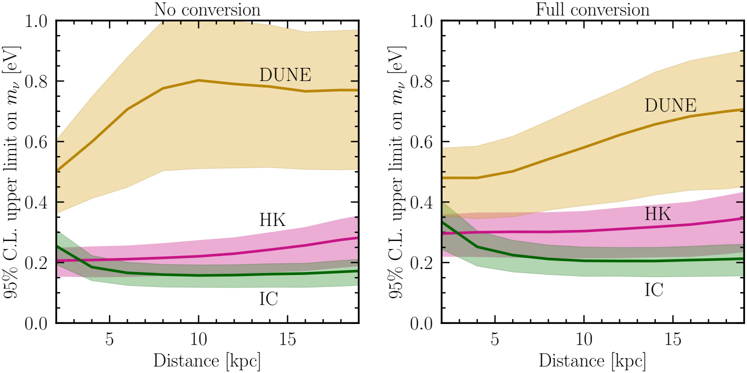
Determination of the CCSN localization



- improvement by 4.5-10 times compared to neutronization burst
- comparable results for black hole forming supernovae
- not far off from elastic scattering on electrons

Sensitivity to the Absolute Neutrino Mass

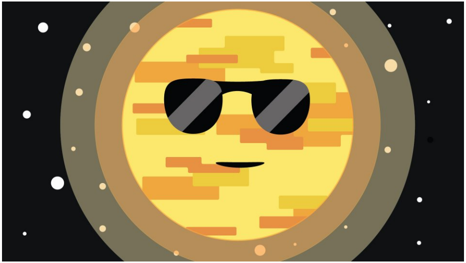
$$\Delta t \approx 5.15 \left(\frac{D}{10\ \mathrm{kpc}}\right) \left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^2 \left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2\ \mathrm{ms}$$

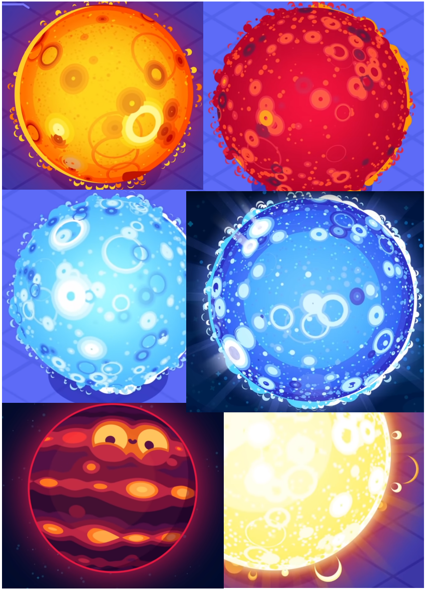


- up to $\sim$ 10x improvement compared to neutronization burst
- more stringent limits than from the laboratory experiments (0.8 eV)

Diffuse supernova neutrino background

Why focus only on a single rare event?





Single galactic SN event

- rare event
- precise infromation about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years

Images: Kurzgesagt

Diffuse supernova neutrino background

cosmological supernovae rate

fraction of black-hole-forming progenitors

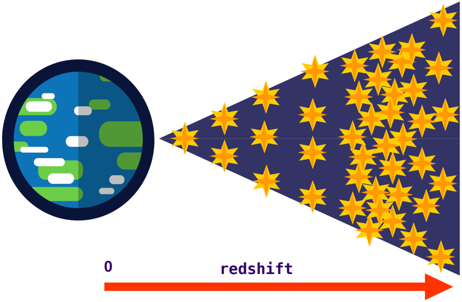
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\mathrm{CC-SN}}F_{\nu_\beta,\mathrm{CC-SN}}(E',M)+f_{\mathrm{BH-SN}}F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

- $R_{\mathrm{SN}}, f_{\mathrm{BH-SN}}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics

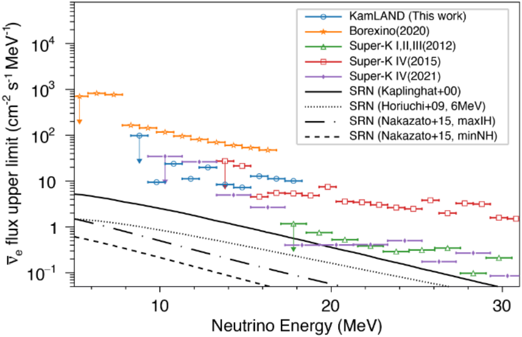


Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010),..

Recent reviews: Kresse et al. (2020), **AMS** (2022), Ando et al. (2023), ...

Diffuse supernova neutrino background: current limits

SK collab. (2021)



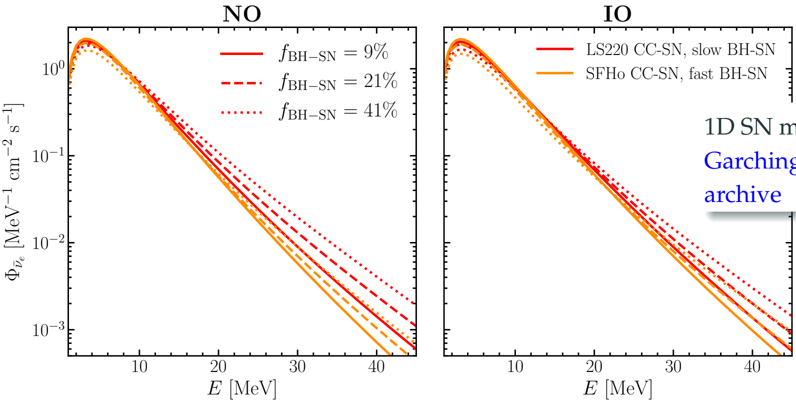
DSNB limits:

- $\bar{\nu}_e \approx 3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV SK collab. (2021), SK collab. (2023)

  soon detected by SK (Gd) Beacom, Vagins (2004) and JUNO JUNO collab. (2021)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu \epsilon [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)

  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)

The fraction of black-hole-forming progenitors



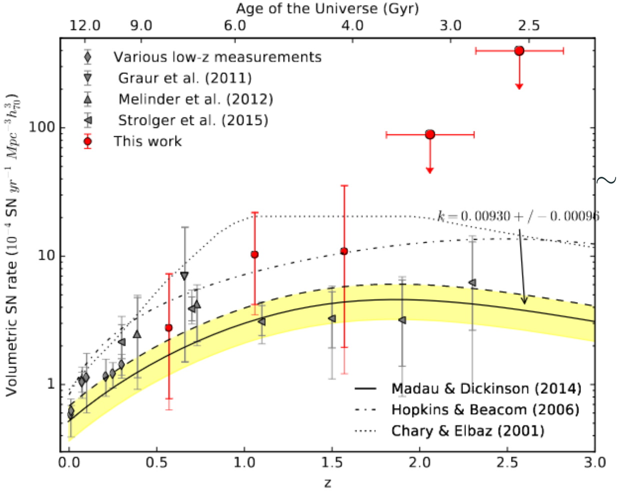
1D SN models
Garching group archive

Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above $\sim$ 15 MeV.

Lunardini (2009), Keehn, Lunardini (2010), Lunardini, Tamborra (2012), Priya, Lunardini (2017), Møller, **AMS** et al. (2018), Nakazato et al. (2018) Kresse et al. (2020), ...

Cosmological supernovae rate

Petrushevska et al (2016)



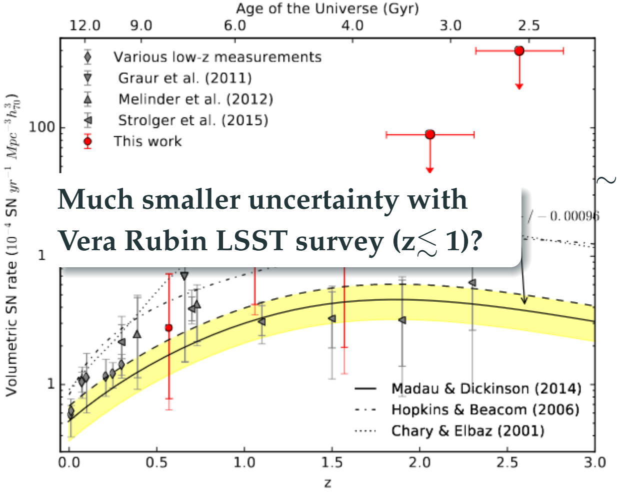
~ 1 SNe/s

The supernovae rate influences the normalization of the DSNB.

Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, **AMS**, Tamborra, Denton (2018), Nakazato et al. (2018), ...

Cosmological supernovae rate

Petrushevska et al (2016)



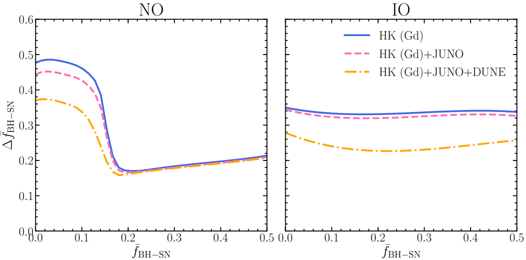
Much smaller uncertainty with Vera Rubin LSST survey (z$\lesssim$ 1)?

~ 1 SNe/s

The supernovae rate influences the normalization of the DSNB.

Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, **AMS**, Tamborra, Denton (2018), Nakazato et al. (2018), ...

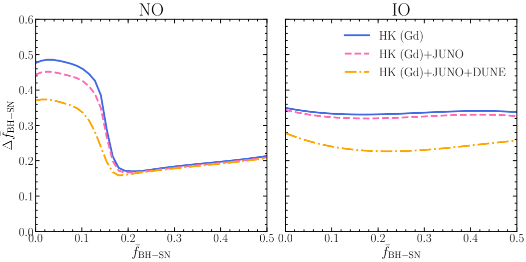
Expected 1σ uncertainty: fraction of BH forming progenitors



- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

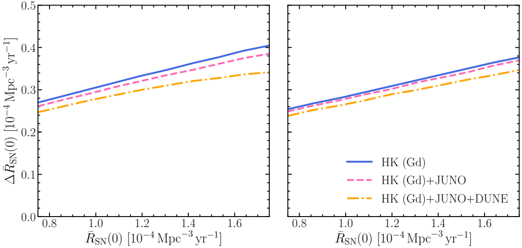
Møller, **AMS**, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

- Relative error of 20%-33% independent of the mass ordering.



Møller, **AMS**, Tamborra, Denton (2018)

Astrophysical uncertainties affecting the DSNB

- Neutrino Flux from an ”Average Supernova”

  Lunardini (2009), Lunardini & Tamborra (2012), Horiuchi et al. (2018), Kresse et al. (2018), ...
- Cosmological Supernovae Rate

  Beacom (2010), Horiuchi et al. (2011), Ando et al. (2023), ...
- Initial Mass Function

  Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)
- Fraction of Black-Hole-Forming Progenitors

  Lunardini (2009), Lien et al. (2010), Keehn & Lunardini (2012), Priya & Lunardini (2017), Møller, **AMS**, Tamborra, Denton (2018), Horiuchi et al. (2018), Kresse et al. (2018), ...
- Binary Interactions

  Horiuchi, Kinugawa, Takiwaki, Takahashi (2021)

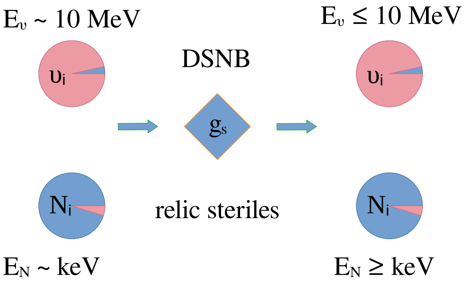
Non exhaustive list of references

Probing self-interacting sterile neutrino dark matter with the DSNB

In collaboration with B. Balantekin, G. Fuller, and A. Ray

Phys.Rev.D in 108 (2023) 12, 123011

KeV-mass sterile neutrino self-interactions



Resonant interaction
for sterile neutrinos
$\mathcal{L}^\phi = g_s \phi \nu_s \nu_s$

$$\sigma(E_\nu) = \frac{g_s^4}{4\pi}\frac{s}{(s-m_\phi^2)^2 + m_\phi^4\Gamma_\phi^2} \approx \frac{\pi g_s^2}{m_\phi^2} E_\nu \delta(E_R - E_\nu), \text{ where } E_R = m_\phi^2/2m_s$$

- sterile component in the DSNB ν_i interacts with the mostly sterile relic background of N_i

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

$$\phi_\alpha(E_\nu) \simeq \sum_{i=1}^{3} |U_{\alpha i}|^2 \int_0^{z_{\max}} dz \, \frac{P_i(E_\nu, z)}{H(z)} \times \, R_{\rm SN}(z) \, F^i_{\rm SN}\left(E_\nu(1+z)\right)$$

Probability of interaction

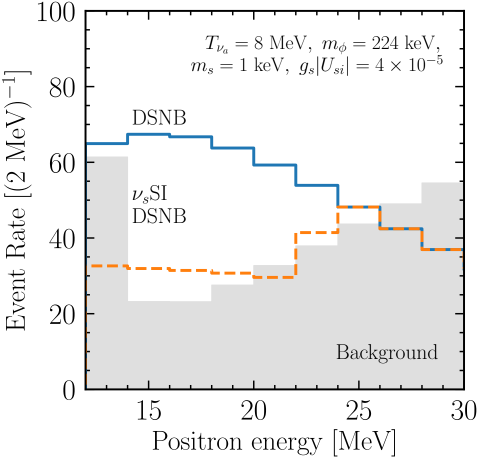
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

$$\tau_i(E_\nu, z) \simeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)}\Theta(z - z_R)$$

where $z_R = E_R/E_\nu - 1$,
interaction rate $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R)\sigma_R$,
and sterile neutrino number density $n_{\nu_s}(z_R) = n_{\nu_s}(1+z_R)^3$

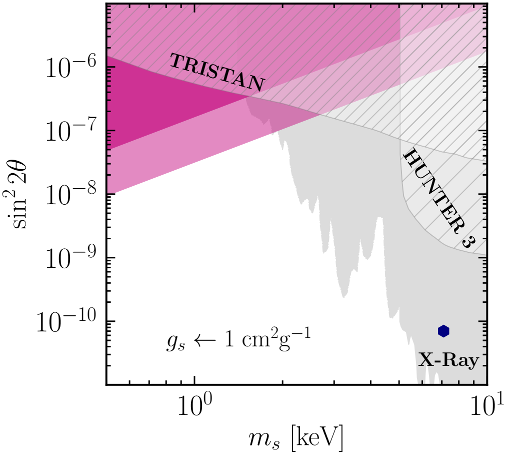
smilar studies for active neutrino self-interactions and eV-mass sterile neutrinos:
Goldberg et al. (2005), Baker et al. (2007), Farzan, Palomares-Ruiz (2014), Reno et al. (2018), Creque-Sarbinowski et al. (2021)

Secret neutrino interactions: DSNB



- **Sterile neutrino self-interactions may result in features in DSNB**

Sensitivity limits



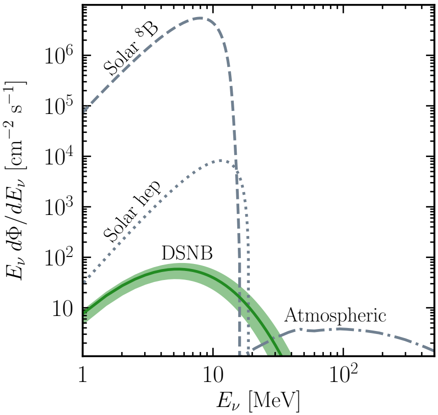
- **Overalap with the TRISTAN experiment paramater space**
- **Reduction of the astrophysical uncertainties helps but not by a lot**

Towards probing the DSNB in all flavors

In collaboration with J. Beacom, and I. Tamborra

Phys.Rev.D 105 (2022) 4, 043008

Can we detect the *x*-flavor DSNB? Maybe

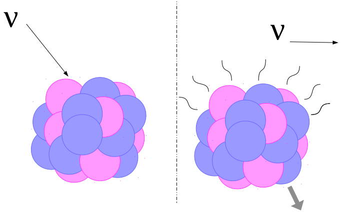


DSNB modeling:
Møller, **AMS**,
Tamborra, Denton
(2018)

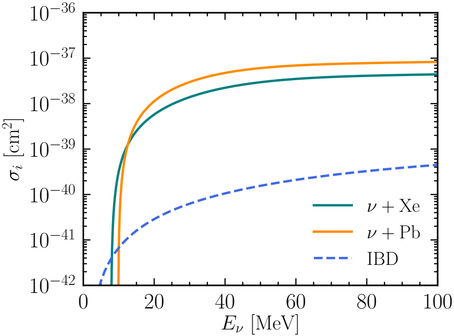
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

Vitagliano et al. (2019), Honda et al. (2011), Newstead et al. (2020)

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



$$\nu + T(A,Z) \to \nu + T(A,Z)$$



Cross section

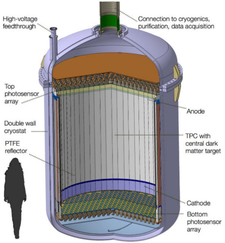
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q),\ \ Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

- coherently enhanced by the square of the neutron number
- flavor insensitive
- coherent up to $\sim$ 50 MeV

Freedman (1974),
Strigari (2009)

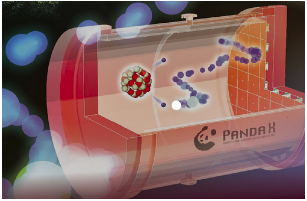
Current and future CEνNS detectors

XENONnT, DARWIN



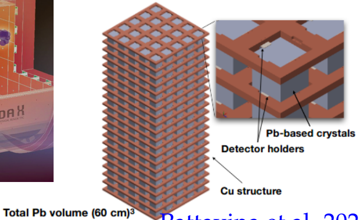
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

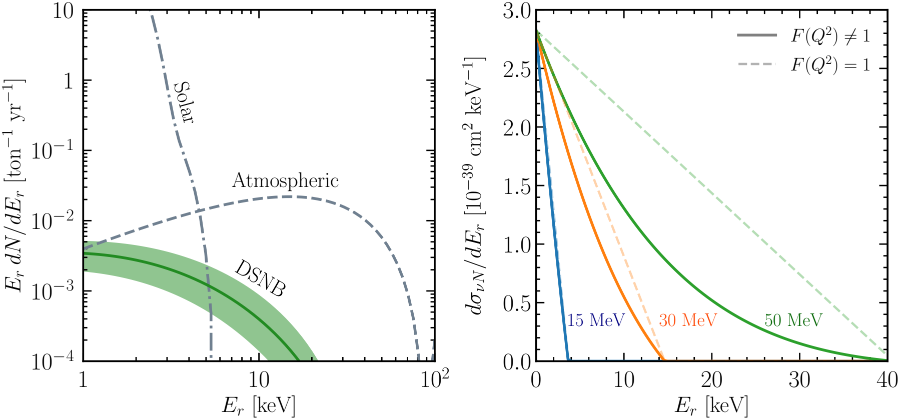
thresholds: $\mathcal{O}(1)$ keV

efficiency: $\sim$ 80-100%

Scattering rate

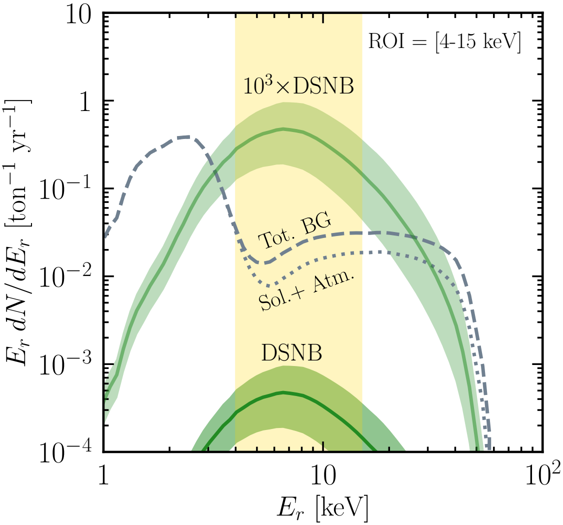
$$\frac{dR_{\nu N}}{dE_r dt} = N_T\, \epsilon(E_r) \int dE_\nu\, \frac{d\sigma_{\nu N}}{dE_r}\, \psi(E_\nu, t)\, \Theta(E_r^{\max} - E_r), \quad E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

Event rate in the xenon-based detector



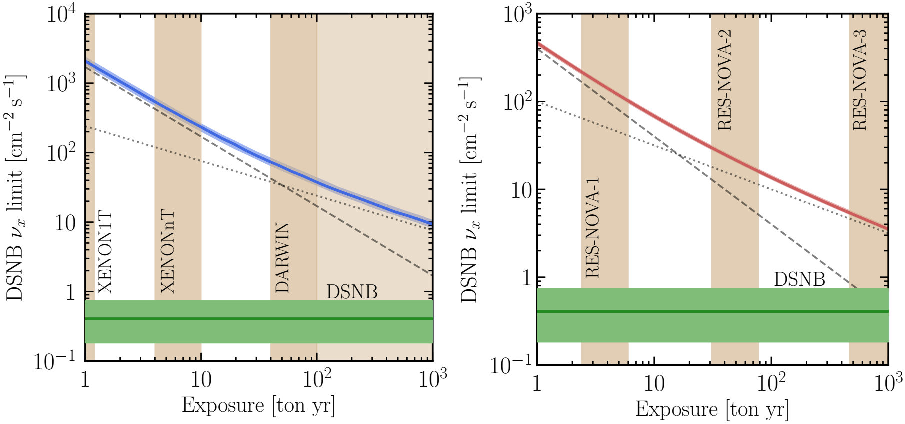
- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the *x*-flavor DSNB seems out of reach, BUT...

Can we improve the limits on the *x*-flavor DSNB? Yes



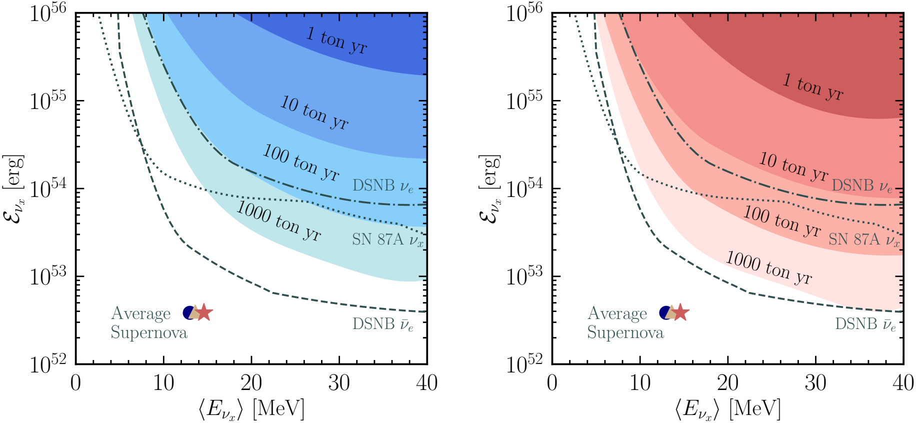
- Potential for an imporovement by $\gtrsim 1-2$ orders of magnitude

Sensitivity bounds on the normalization of the x-flavor DSNB



- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider windows at small exposures and narrower windows at large exposures

Sensitivity bounds on the x-flavor DSNB



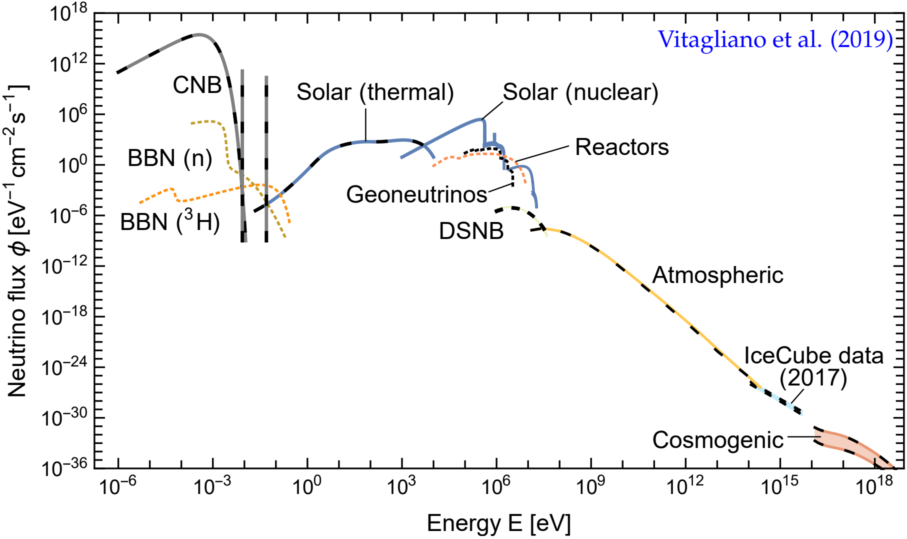
- Simple DSNB: all supernovae emit the same Fermi-Dirac ν_x spectrum
- Potential handle on the normalization and mean energy of the SN ν_x
- 1000 ton yr: limits comparable with current SK limit on $\bar{\nu}_e$ DSNB

Distinctive nuclear signatures of low-energy atmospheric neutrinos

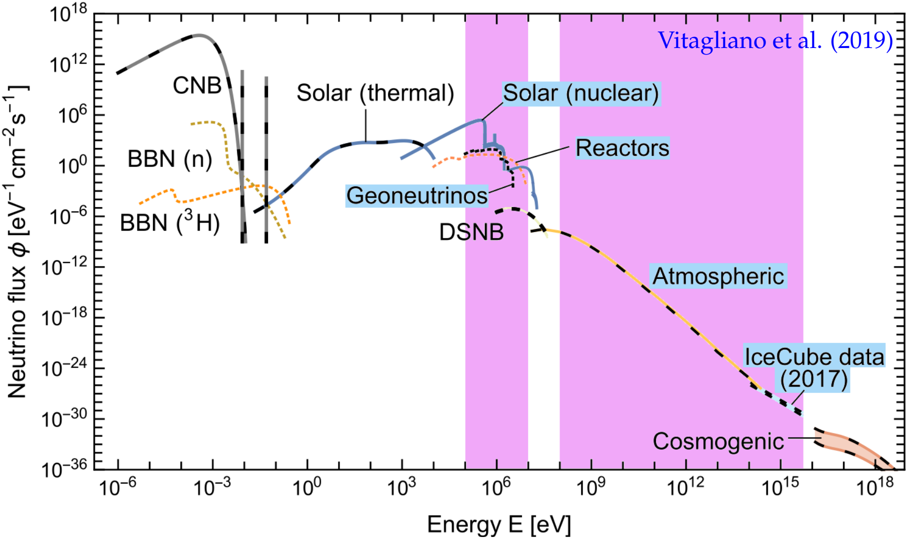
In collaboration with J. Beacom

Phys.Rev.D 108 (2023) 4, 043035

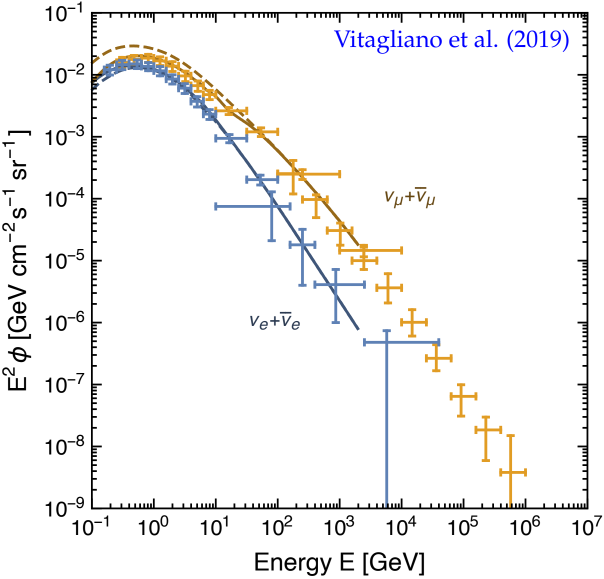
Grand Unified Neutrino Spectrum



Grand Unified Neutrino Spectrum - Detected Fluxes



Atmospheric neutrino measurements

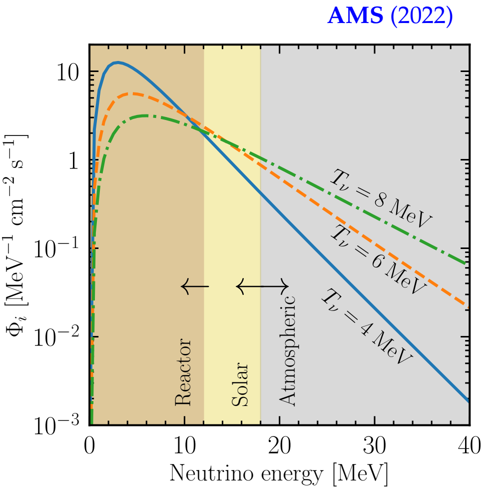


Data points from:

- Super-Kamiokande (SK)
  SK Collaboration (2015)
- Ice-Cube (IC)
  IC Collaboration (2015)

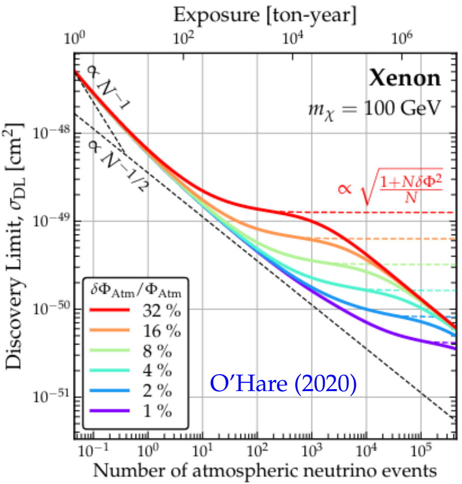
No measurements below 100 MeV

Diffuse Supernova Neutrino Background (DSNB)



- DSNB →
  isotropic and stationary
  guaranteed neutrino flux
  Guseinov (1967), Totani et al. (2009),
  Ando, Sato (2004), Lunardini (2009),
  Beacom (2010),..
- mitigating uncertainties in the atmopsheric neutrinos helps the discovery limits

Direct Dark Matter Detection Experiments - Neutrino Fog



O'Hare (2020)

- neutrino floor/fog → barrier for dark matter direct detection experiments Vergados & Ejiri (2008), Strigari (2009), Baudis et al. (2013), ...
- mitigating uncertainties in the atmopsheric neutrinos helps the discovery limits

Low-energy Atmospheric Neutrino Flux

Primary production channels

$\pi^+ \to \mu^+ + \nu_\mu;\ \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

$\pi^- \to \mu^- + \bar{\nu}_\mu;\ \mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

Non-oscillated flavor ratio

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Sources of uncertainty

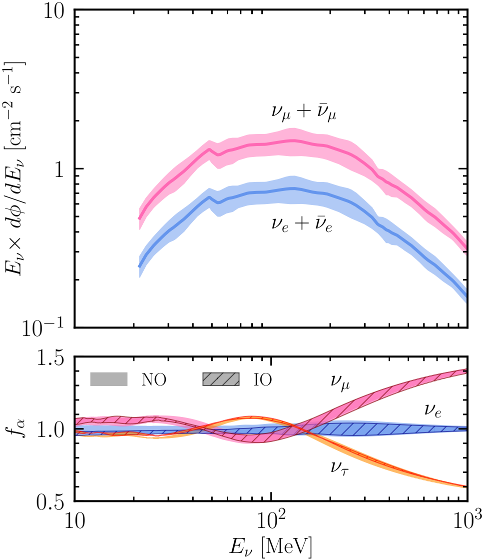
solar wind modulations

Earth's geomagnetic field

Oscillated flavor ratio

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

Past measurements: energies > 100 MeV



Neutrino flux: Zhuang (2021)

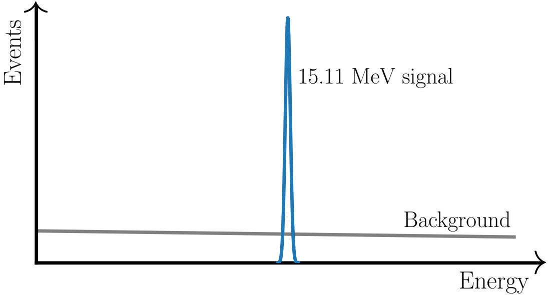
Mixing: NuCraft

Distinctive nuclear channels

Neutral current channels

$$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma,$$

$$\bar{\nu} + {}^{12}\mathrm{C} \to \bar{\nu} + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma,$$



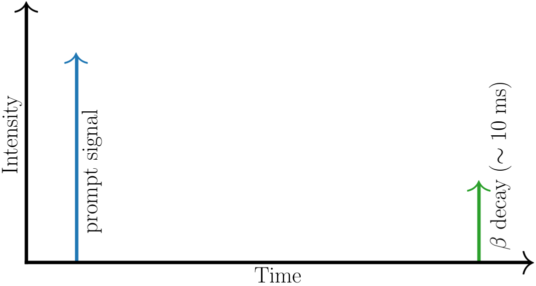
- instantaneous decay of ${}^{12}\mathrm{C}^*$
- emission of a monoenergetic γ

Distinctive nuclear channels

Charged current channels: $\nu_\mathbf{e}$

$$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$$ {}^{12}\mathrm{N}_{\mathrm{g.s.}} \rightarrow {}^{12}\mathrm{C} + e^+ + \nu_e,$$

$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$$ {}^{12}\mathrm{B}_{\mathrm{g.s.}} \rightarrow {}^{12}\mathrm{C} + e^- + \bar{\nu}_e.$$



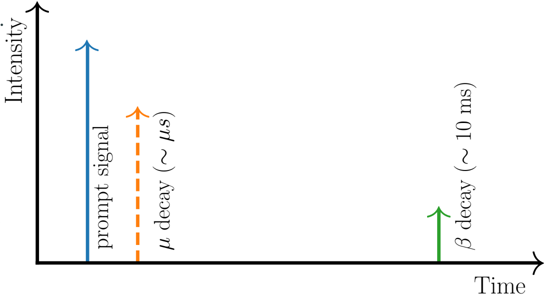
- coincidence detection of e^+ and e^-
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes → ν_e vs. $\bar{\nu}_e$ distinction

Distinctive nuclear channels

Charged current channels: ν_μ

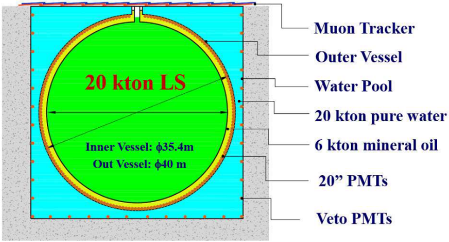
$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$

$$\bar{\nu}_\mu + {}^{12}\mathrm{C} \to \mu^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$



- coincidence detection of μ, its decay e and β-decay e
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes → ν_μ vs. $\bar{\nu}_\mu$ distinction
- triple vs. double coincidence detection → ν_e vs. ν_μ distinction

The Jiangmen Underground Neutrino Observatory (JUNO)

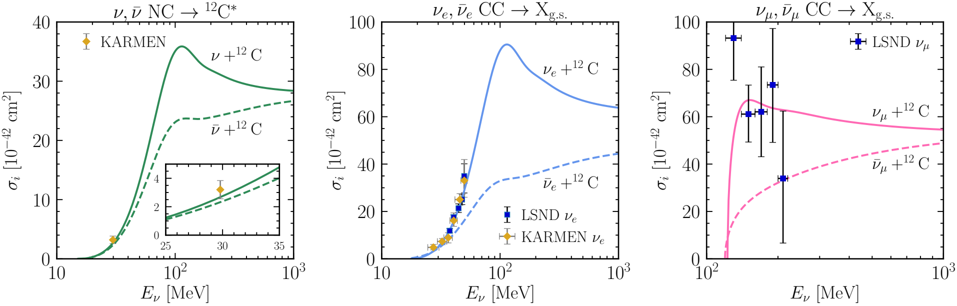


- large-scale carbon-based liquid scintilator detector
- soon operational ($\sim$ 2024)
- excelent energy resolution $\lesssim 3\%$
- excelent spatial resolution $\lesssim 10$ cm
- low backgrounds in the considerd channels

JUNO inclusive studies:
Cheng et al. (2020),
Cheng et al. (2020),
JUNO Collaboration (2022)

JUNO collabortation (2015), Sitsi (2022)

Cross section: elementary particle treatment (EPT)



- superallowed transitions from 0^+ to 1^+ states in A=12 triad
- the exclusive ν - ^{12}C cross sections measured only at low energies
- experimental data agrees well with the EPT treatment
- 5-40% difference with respect to, e.g., RPA calculations

Fukugita et al. (1988), Pourkaviani & Mintz (1990), Kubodera & Nozawa (1993), Engel et al. (1996), Kolbe (1996), Samana et al. (2010)

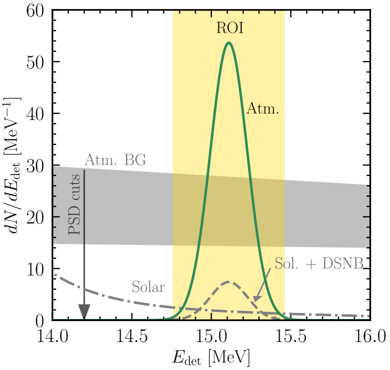
Atmospheric neutrino detection in JUNO

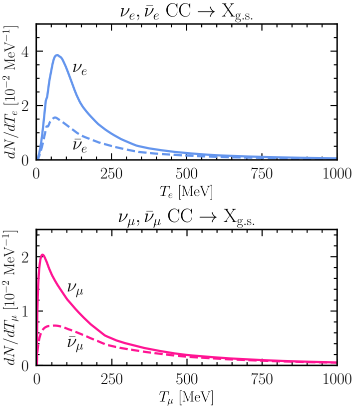
NC channel detection: single events

Irreducible BG: solar and DSNB ν

Reducible BG: atm. ν - p scattering

85 kton yr exposure → 25(40)% uncertainty of the atmospheric ν rate





CC channel detection: coincidence events

Irredicible BG: accidental coincidences

Rate per 85 kton yr: ∼0.0004

essentially background free channels

Conclusions

Astrophysical sources of MeV neutrinos

- can serve as powerful testing grounds in constraining new physics
- reliable limits, only when the sources are accurately modeled

Detection of astrophysical neutrino fluxes

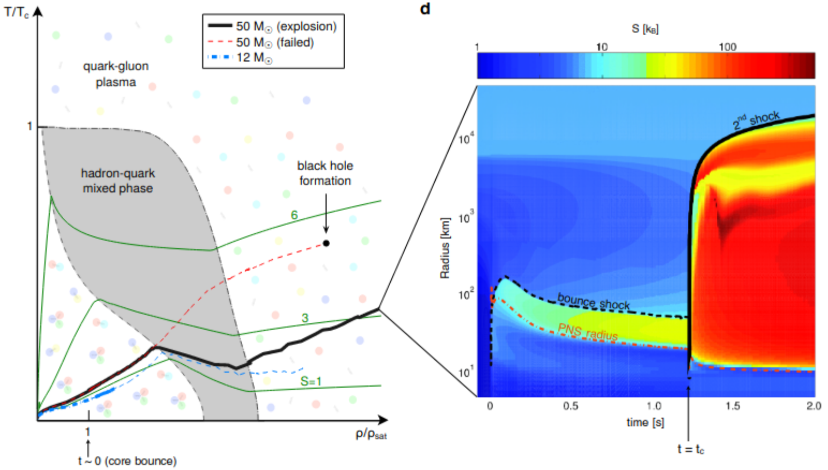
- brings us closer to fully understanding the physics inside the sources
- help us to rule out potential new physics scenarios

Exciting times ahead, a truly high statistic era of neutrino physics!

Thank you for the attention!

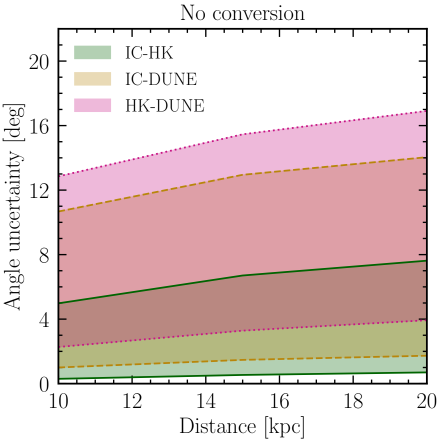
Backup Slides

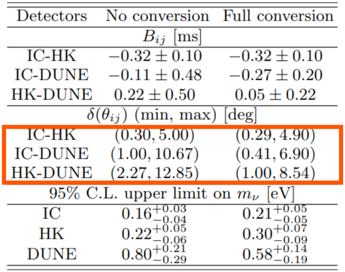
Quark deconfinement as a supernova explosion engine for massive blue supergiant stars



Fischer, Bastian, Wu et al. (2017)

Determination of the uncertainty of the CCSN localization



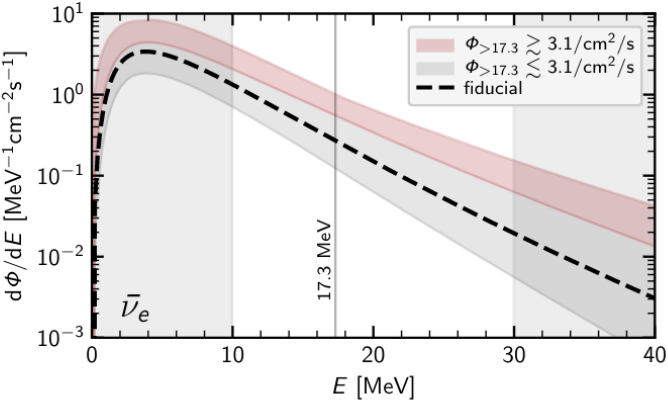


Detectors	No conversion	Full conversion
	B_{ij} [ms]	
IC-HK	-0.32 ± 0.10	-0.32 ± 0.10
IC-DUNE	-0.11 ± 0.48	-0.27 ± 0.20
HK-DUNE	0.22 ± 0.50	0.05 ± 0.22
	$\delta(\theta_{ij})$ (min, max) [deg]	
IC-HK	$(0.30, 5.00)$	$(0.29, 4.90)$
IC-DUNE	$(1.00, 10.67)$	$(0.41, 6.90)$
HK-DUNE	$(2.27, 12.85)$	$(1.00, 8.54)$
	95% C.L. upper limit on m_ν [eV]	
IC	$0.16^{+0.03}_{-0.04}$	$0.21^{+0.05}_{-0.05}$
HK	$0.22^{+0.05}_{-0.06}$	$0.30^{+0.07}_{-0.09}$
DUNE	$0.80^{+0.21}_{-0.29}$	$0.58^{+0.14}_{-0.19}$

$$\delta(\theta_{ij}) \approx \begin{cases} \delta(\cos\theta_{ij})/\sin\theta_{ij} & \text{if } \sin\theta_{ij} > \sqrt{\delta(\cos\theta_{ij})} \\ \sqrt{2\delta(\cos\theta_{ij})}, & \text{for } \theta_{ij} \ll \delta(\cos\theta_{ij}) \end{cases} .$$

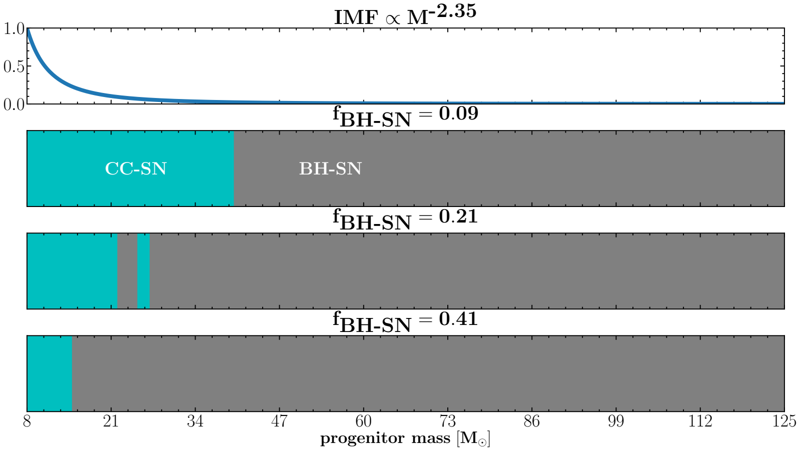
Astrophysical uncertainties affecting the DSNB

Kresse et al. (2020)



- models with the extreme combinations of parameters are disfavoured
  - large emission from black-hole-forming collapses and their fraction

The fraction of black-hole-forming progenitors

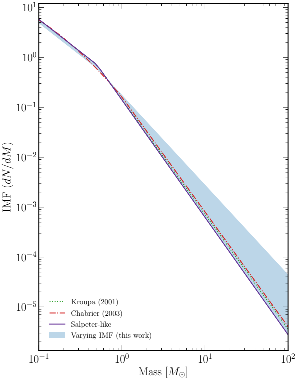


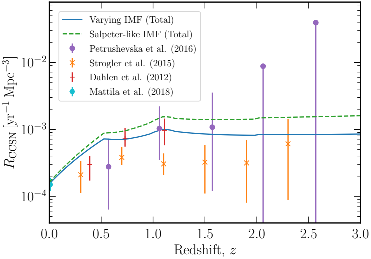
Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

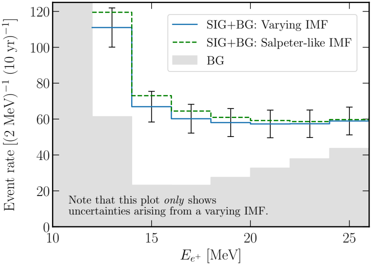
C. Lunardini (2009)

Ertl et al. 2015, Sukhbold et al.2015, Adams et al. 2016, Heger et al. 2001, Kochanek et al. 2001, Basinger et al. 2020, ...

Varying Initial Mass Function







- larger fraction of stars may evolve to black holes at high redshift
- changed rate of the core-collapse supernovae

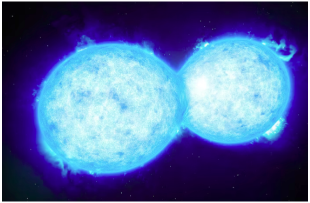
Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)

Binary interactions

Majority of massive stars have stellar companions and experience binary interactions Sana et al. 2012, Zapartas et al. 2020

Mass transfer

Mergers



Images: iflscience, Wiki

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Mass transfer

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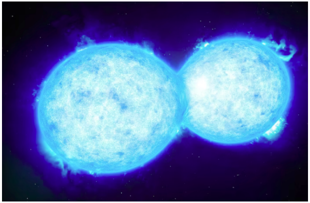
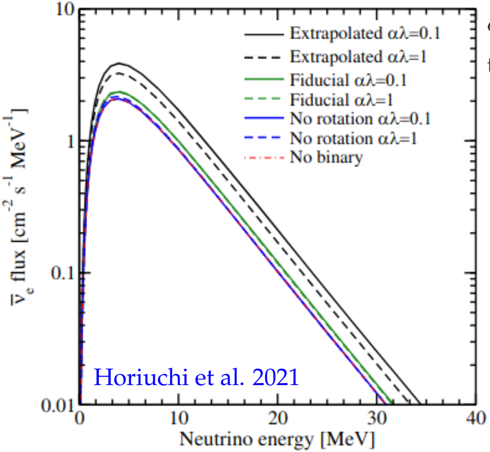


Effects on the stellar population Horiuchi et al. 2021

- change in mass due to mass transfer
- reduced progenitor counts
- increased progenitor counts

Images: iflscience, Wiki

Binary interactions: impact on DSNB

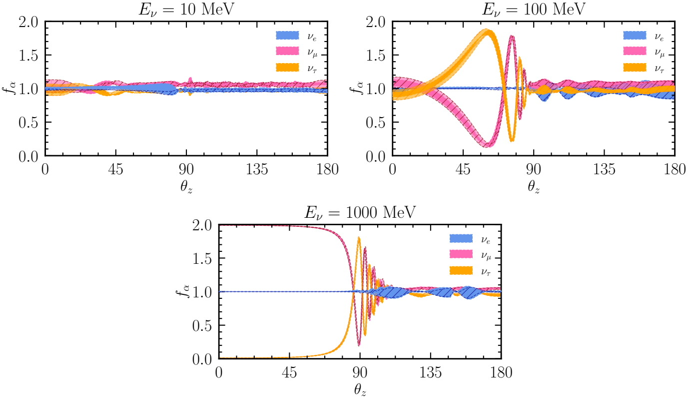


Horiuchi et al. 2021

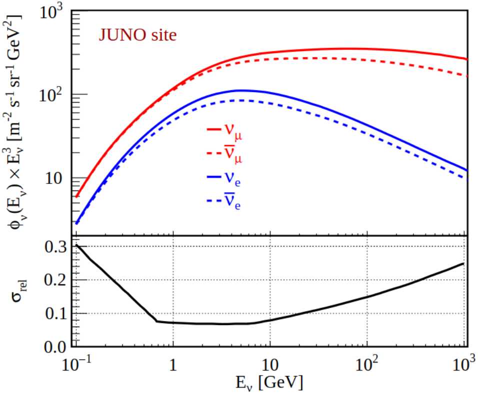
$\alpha\lambda$ - measure how hard it is to unbind the envelope

- enhancement $\leqslant 75\%$ compared to estimate w/o binary considerations
- core mass increases due to rotational effects
- more studies needed

Atmospheric neutrino oscillations



Relative uncertainty of atmospheric neutrinos



Cheng et al. (2022)

EPT cross sections

$$\sigma(E_\nu) = \frac{3G_F^2}{2\pi} F_A^2 (E'_\nu)^2 I \, , \quad \sigma(E_\nu) = \frac{3G_F^2}{\pi} \cos\theta_C^2 F_A^2 E_e p_e I \mathcal{F}^{\pm}(Z, E_e) \, , \tag{2}$$

$$I = \frac{1}{2}\int_{-1}^{1} dz f(\mathbf{q}^2) \left(A + B + C\right) \, , \tag{3}$$

$$f(\mathbf{q}^2) = \left(\frac{F_A(q)}{F_A}\right)^2 = \left(1 - \frac{1-\rho}{6(b|\mathbf{q}|)^2}\right)^2 \exp\left(-\frac{(b|\mathbf{q}|)^2}{2}\right) \, , \tag{4}$$

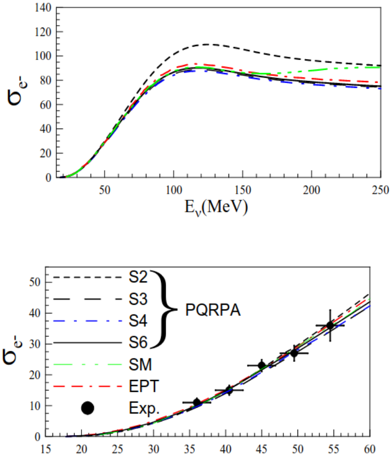
$$A = 1 - \frac{z}{3} \; \pm \; \frac{4}{3}(E_\nu + E'_\nu)(1 - 2\sin^2\theta_W)(1 - z)\, \frac{F_M}{F_A} \, , \tag{5}$$

$$B = \frac{2}{3}\left(E'_\nu E_\nu (1 - z^2) + (1 - z)\mathbf{q}^2\right)(1 - 2\sin^2\theta_W)^2 \left(\frac{F_M}{F_A}\right)^2 \, , \tag{6}$$

$$C = -\frac{2}{3}\Delta M (1 + z)\frac{F_T}{F_A} \; + \; \frac{1}{3}(1 + z)\mathbf{q}^2 \left(\frac{F_M}{F_A}\right)^2 \, . \tag{7}$$

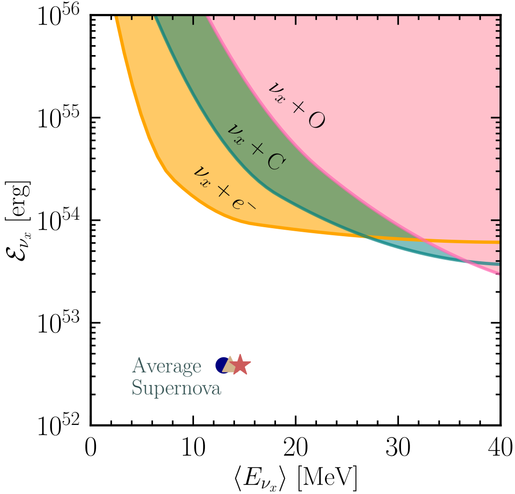
Fukugita et al. (1988)

CQRPA cross sections

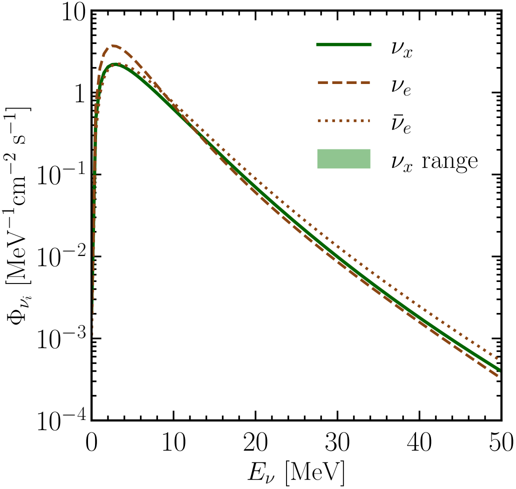


Samana et al. (2010)

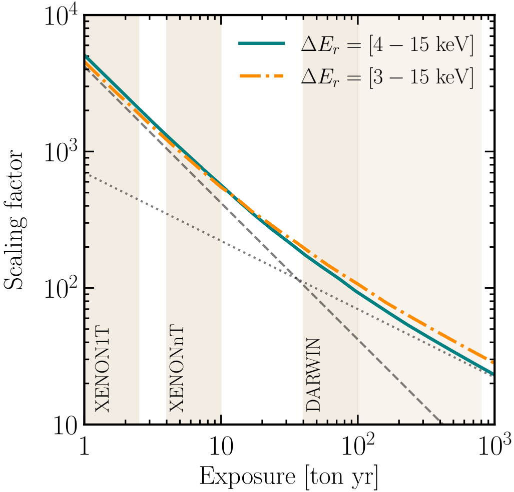
Limits from the SN 1987A



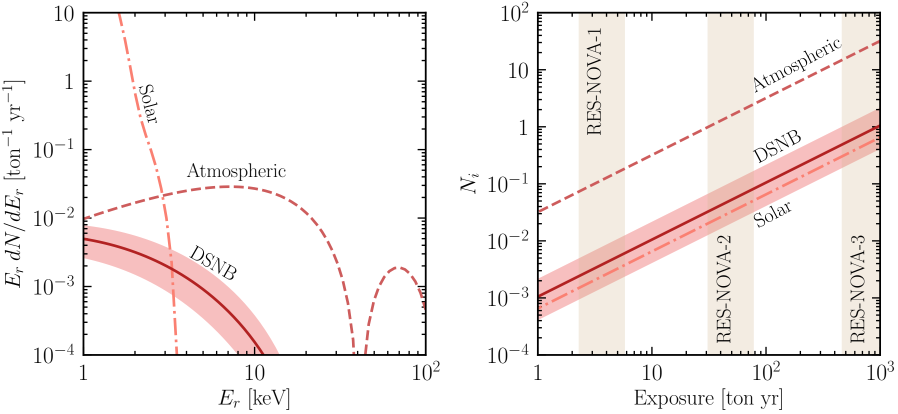
DSNB variability



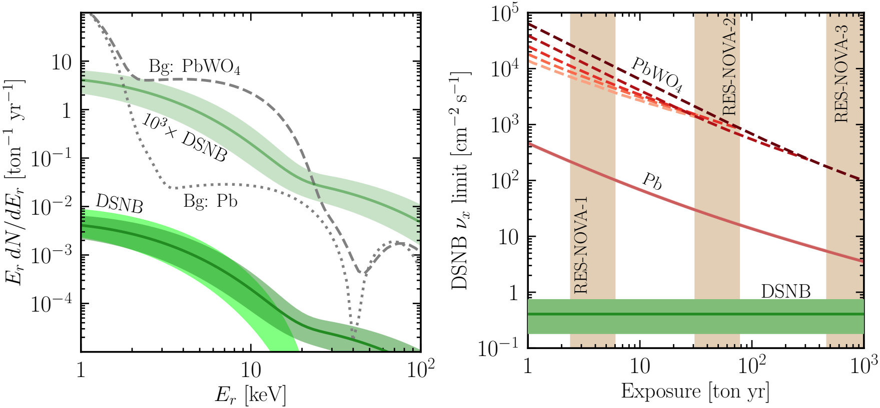
Sensitivity of the limits to a detection window



Event rate: lead detector



Event rate: lead crystals detector



Which part of the spectrum are CEνNS detectors sensitive to?