Detections Prospects of the DSNB w/ Simulations and Star Formation Measurements

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CNP Day 2023

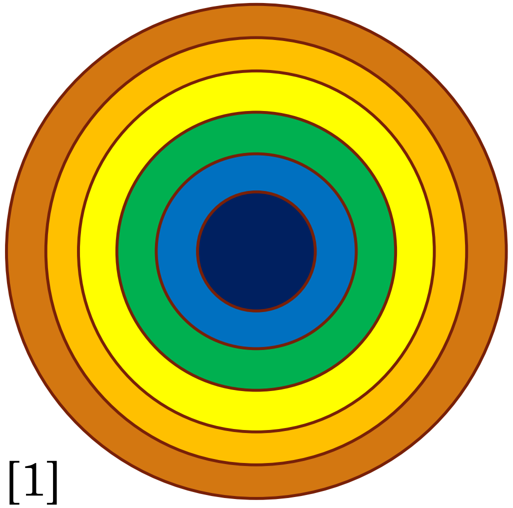
Outline

The Center for Neutrino Physics

1. CCSNe and neutrinos
2. DSNB modeling ingredients
   - Neutrino emission spectra from simulations
   - Core collapse rate from measurements
   - Neutrino detectors
3. Detection prospects

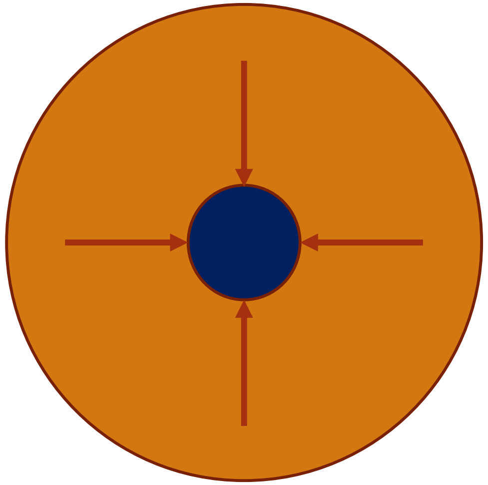
CCSNe and Neutrinos

Core-collapse supernova (CCSN)



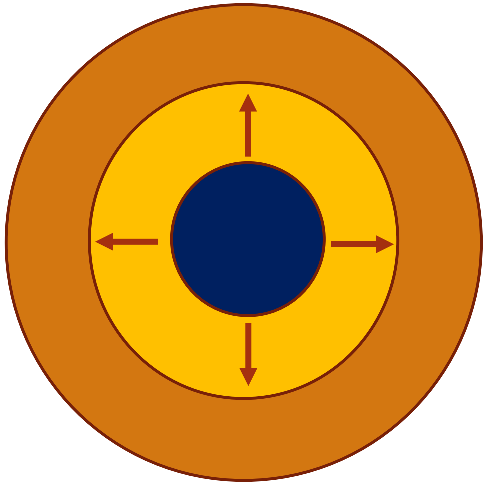
[1]

>8 $M_\odot$, Iron fused in core, radiation pressure decreases

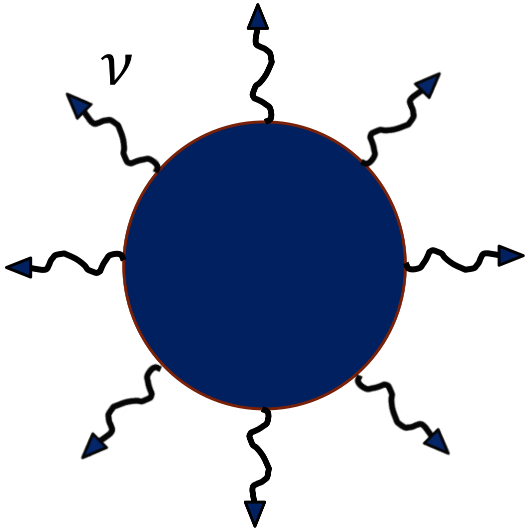


~1.4 $M_\odot$ core collapses, $e^- + p \rightarrow n + \nu_e$, neutron degeneracy

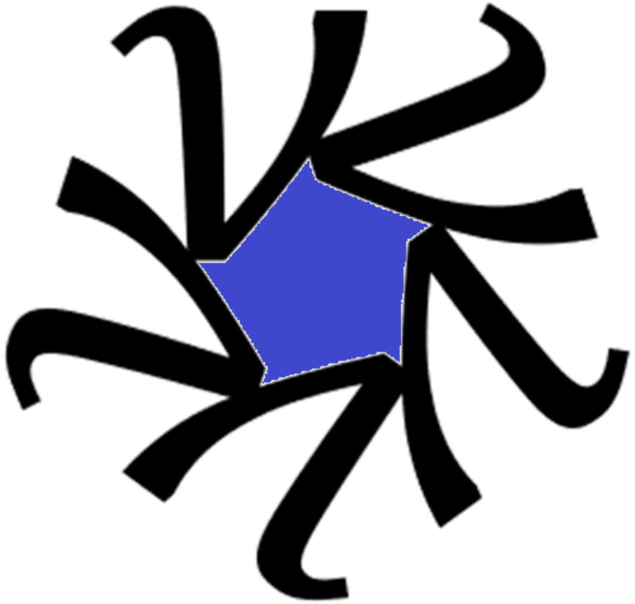
Infalling material bounces off core, pressure shock wave



Neutrinos revive shock, cooling protoneutron star

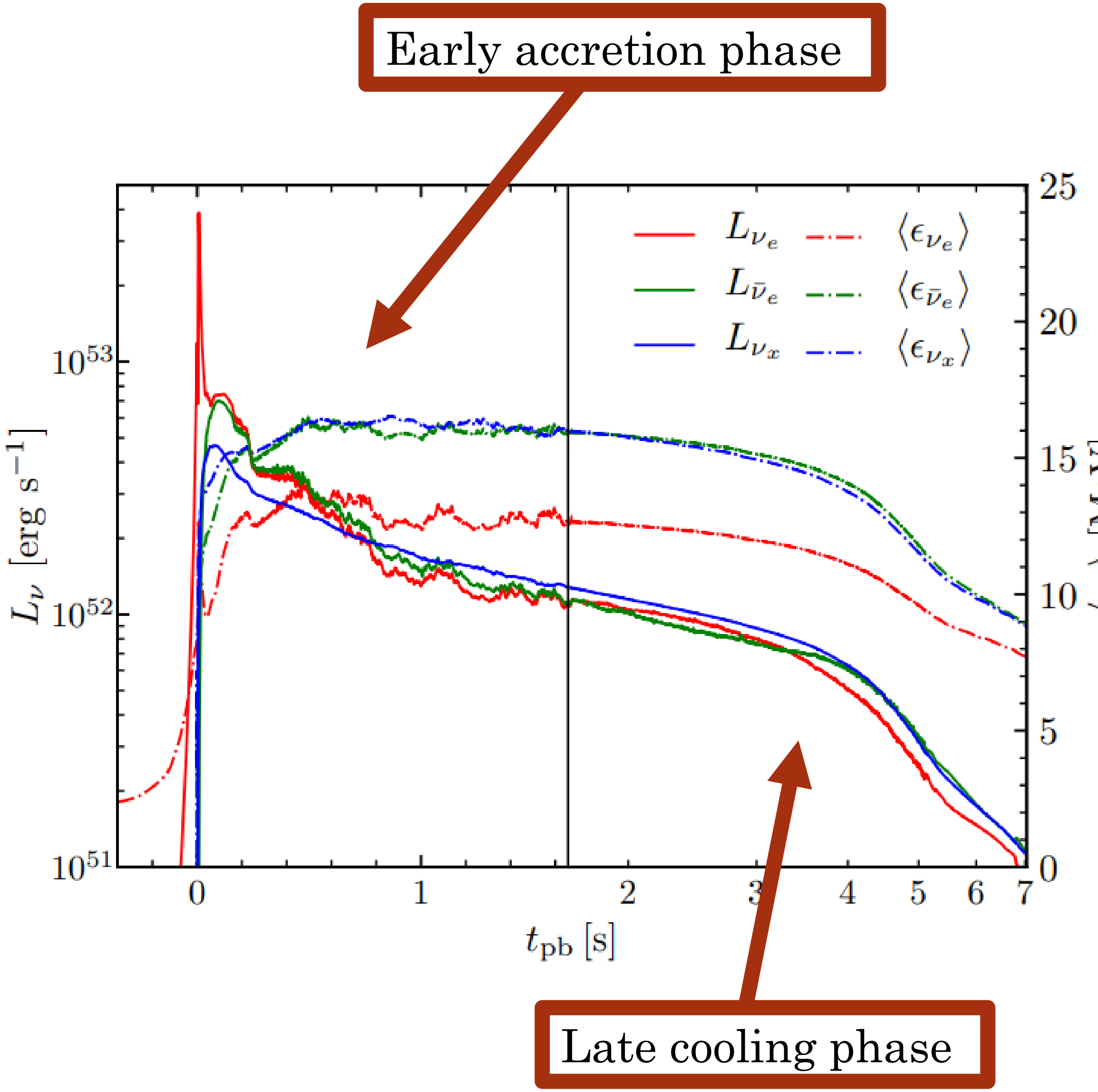


[1] Burrows and Vartanyan 2021



Neutrinos from CCSNe

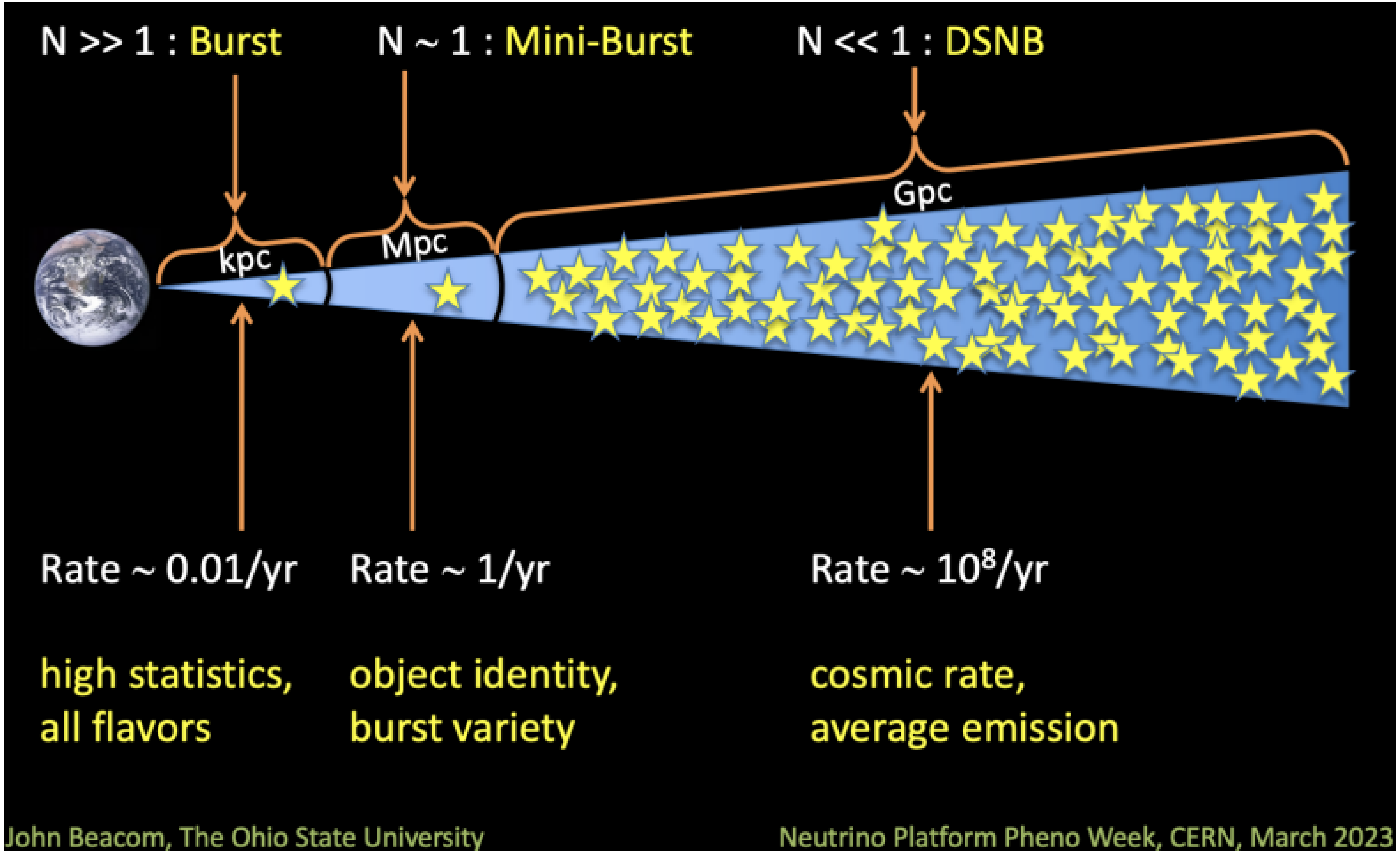
- $\mathcal{O}(10)$ MeV neutrinos emitted over ~10s
  - Approx thermal emission
  - Accretion → higher energy neutrinos
  - PNS cooling → lower energy neutrinos
  - **> 50% of energy liberated** in cooling phase



[1]

[1] Bollig+ 2021

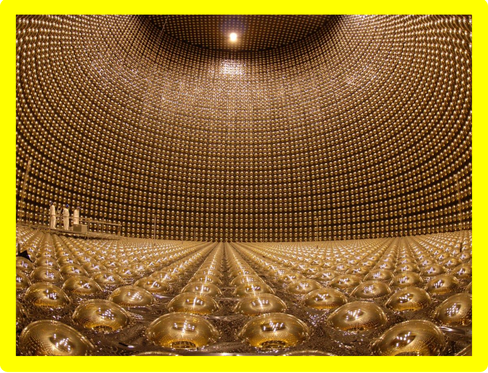
CCSNe give rise to the DSNB

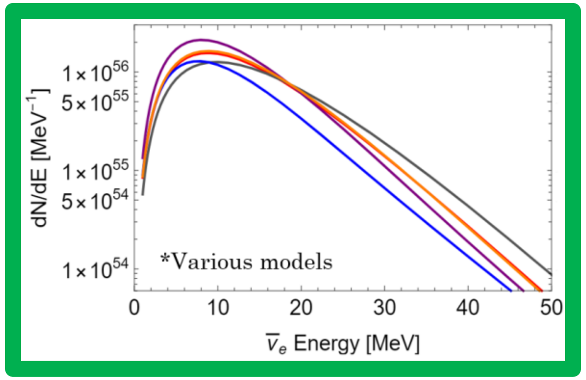


DSNB Modeling Ingredients

DSNB modeling ingredients

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





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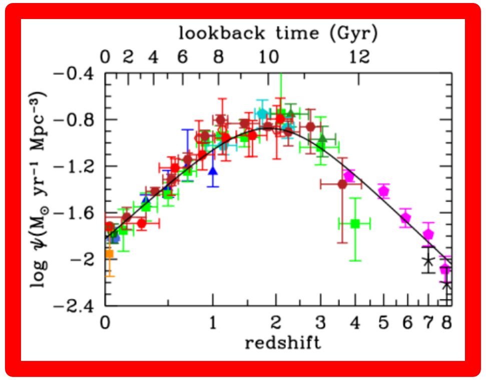

[2]

[1] **Ekanger**+ 2022, Impact of late-time neutrino emission on the DSNB
[2] Madau and Dickinson 2014

DSNB modeling ingredients

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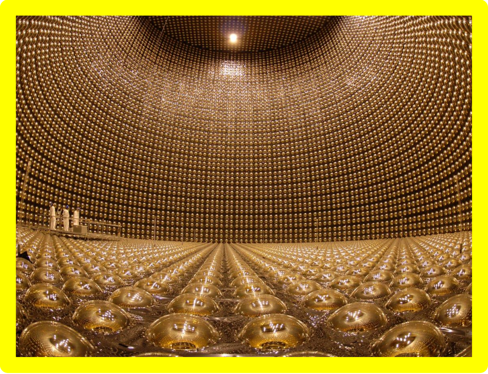

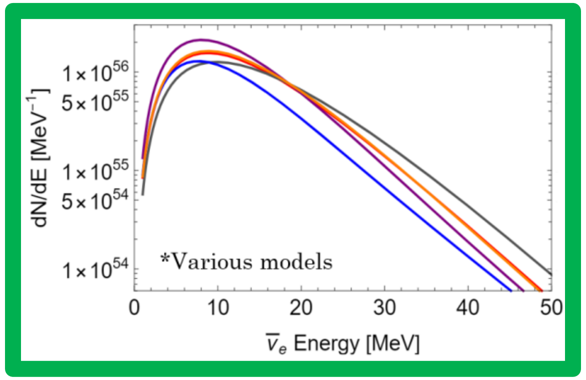

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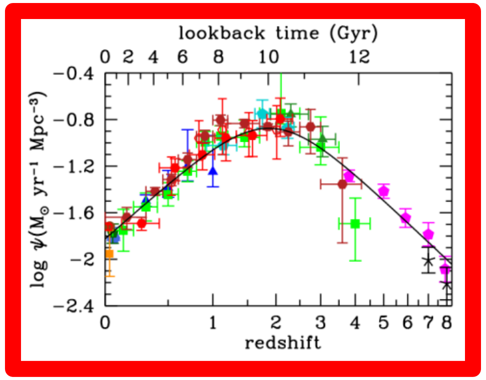
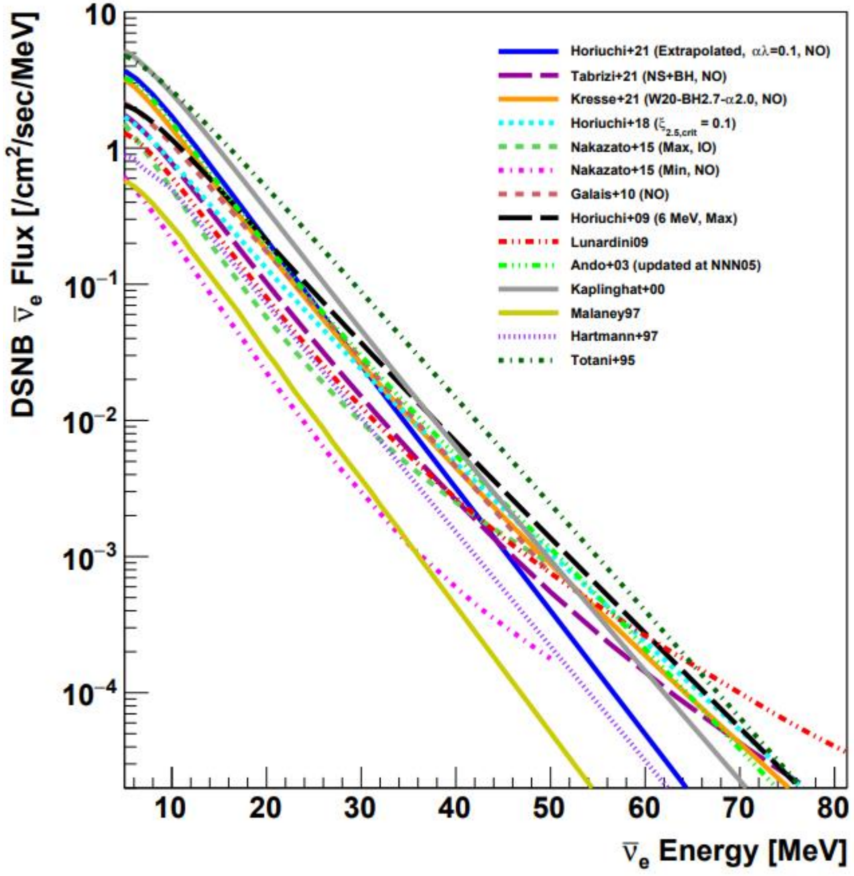


[2]

Factor of ~10 in overall flux predictions



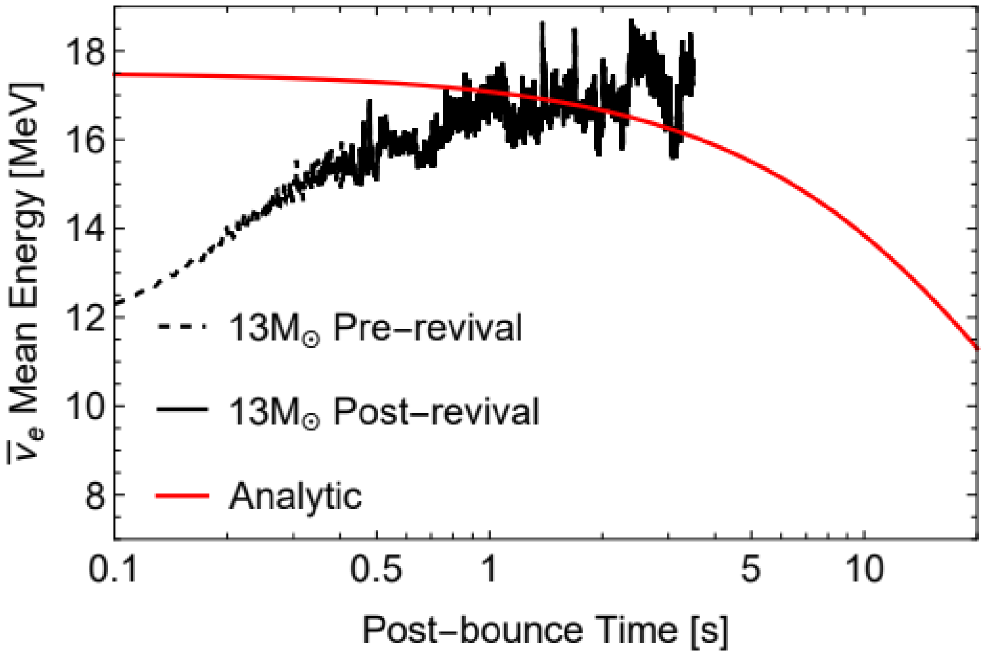
[3]

[1] **Ekanger**+ 2022, Impact of late-time neutrino emission on the DSNB
[2] Madau and Dickinson 2014
[3] Abe+ 2011

Updating neutrino emission modeling

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

[1], [2]



- Tune analytic function to simulation data
- **~5s sim data** + >5s analytic function
- Done for many progenitors

[1] **Ekanger**+ 2022, Impact of late-time neutrino emission on the DSNB
[2] **Ekanger**+ 2023, DSNB with up-to-date SFR measurements and long-term multi-D SN simulations

Updating rate of core collapse

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

- Directly measuring difficult, rely on indicators of star formation rate: $\mathbf{SFRD} \propto \mathbf{R_{CC}}$

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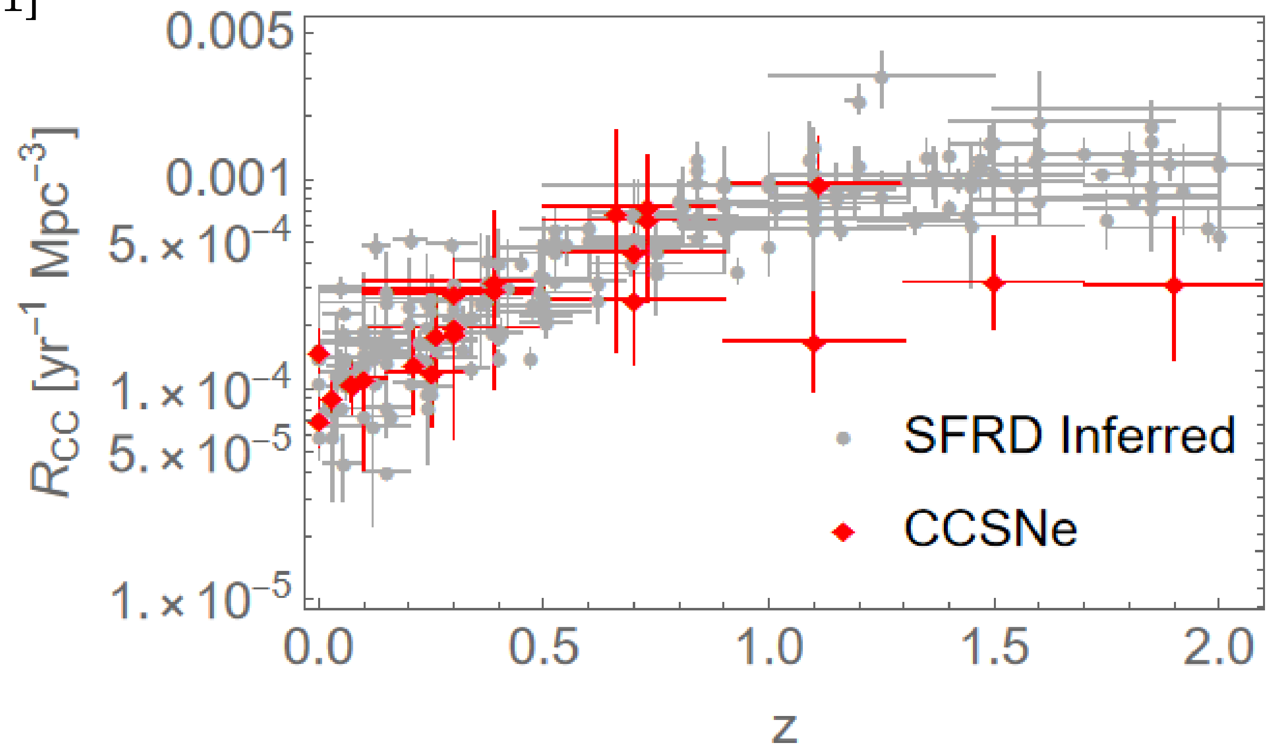

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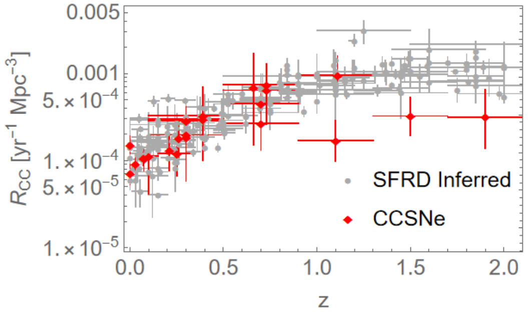
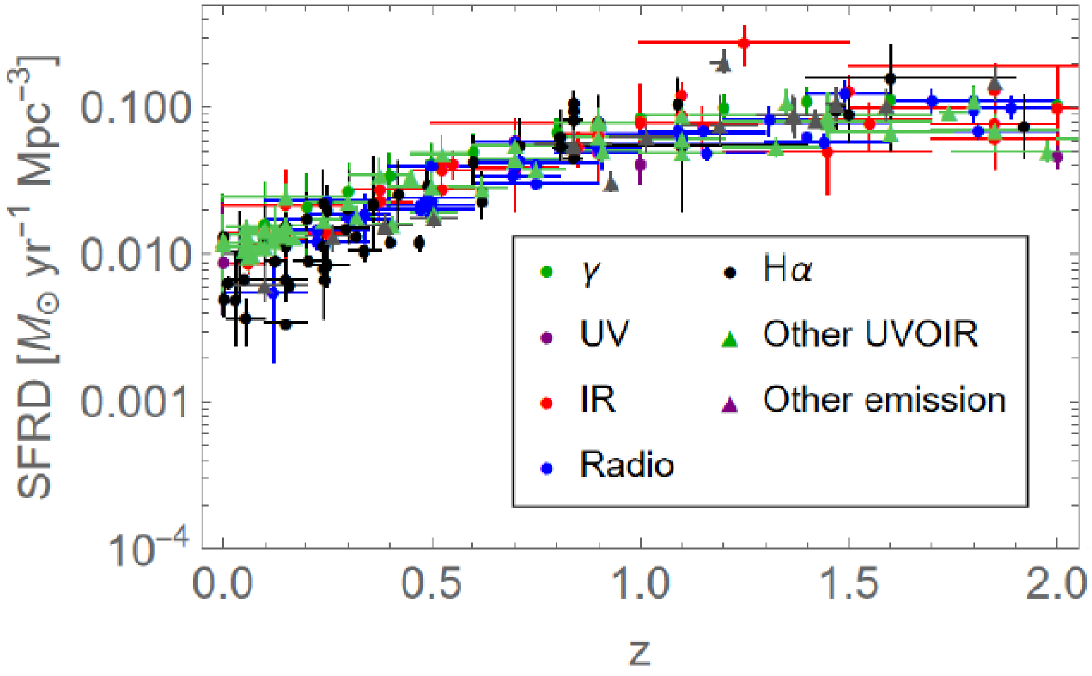


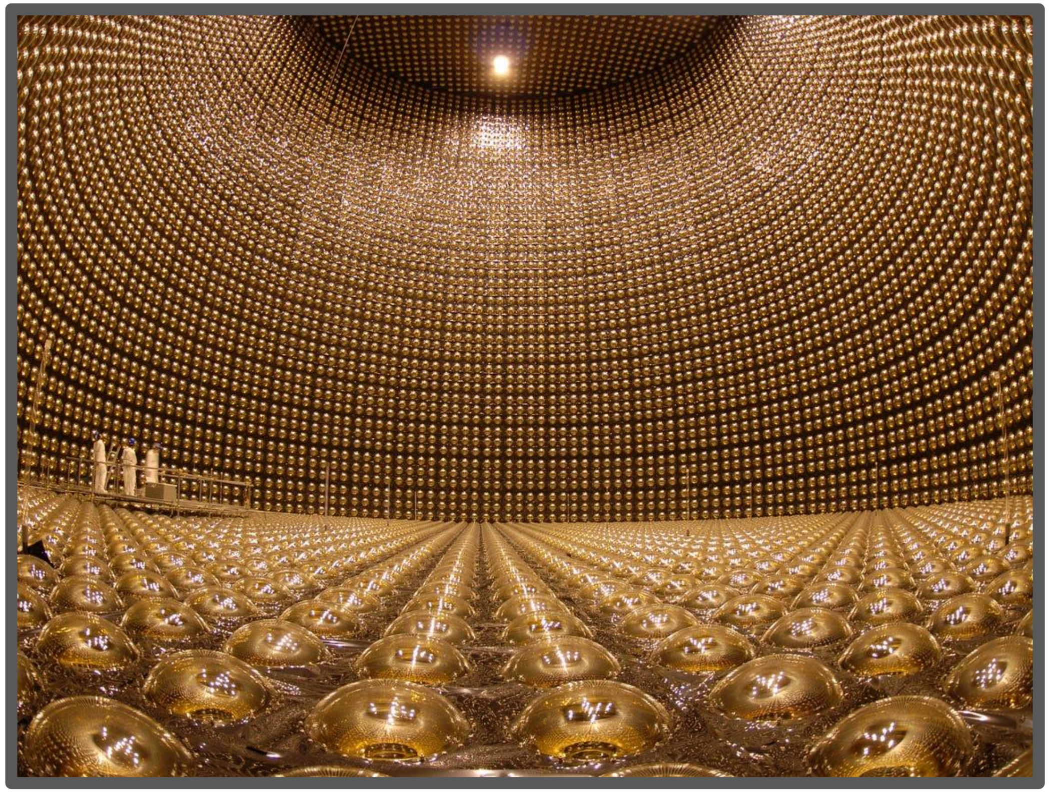


[1] **Ekanger**+ 2023, DSNB with up-to-date SFR measurements and long-term multi-D SN simulations

Detecting the DSNB

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

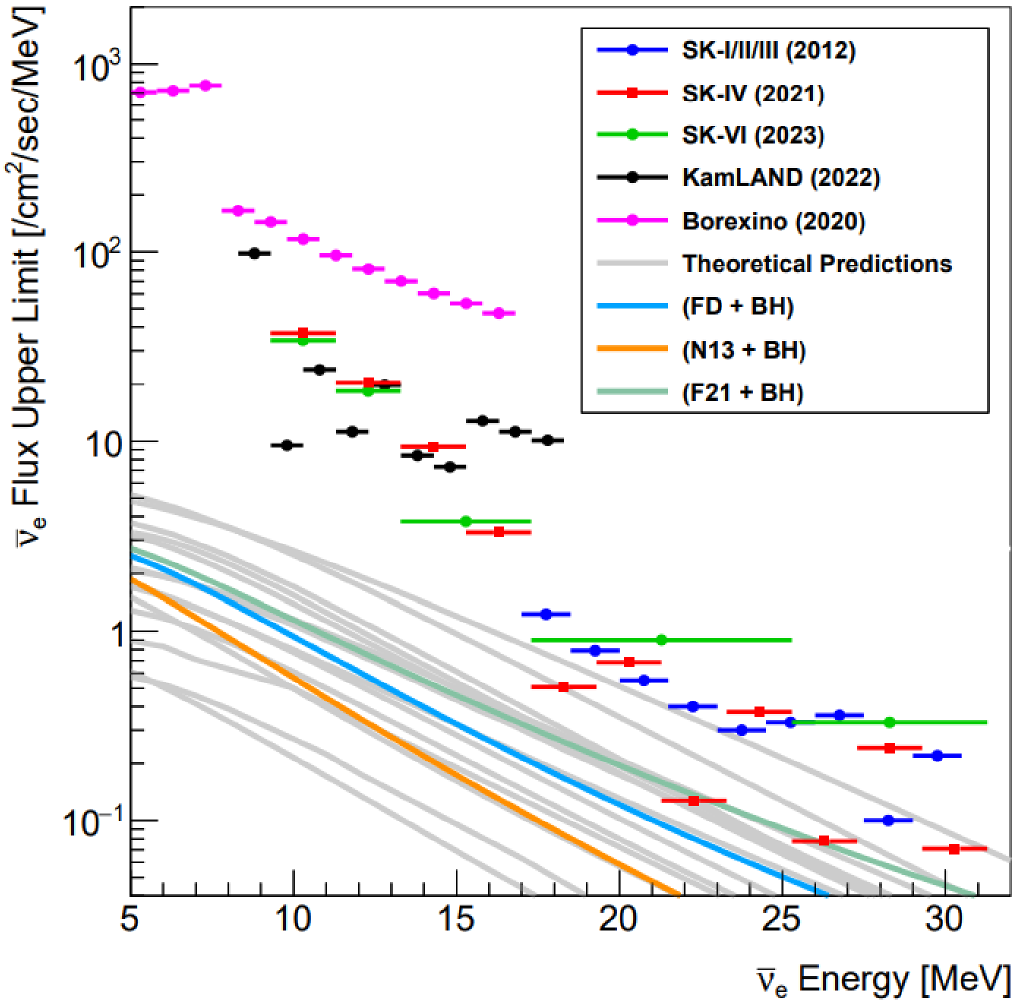
- Super Kamiokande (SK), water Cherenkov
- IBD: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - *Gadolinium upgrade (SK-Gd)
- $\boldsymbol{\sim 3\ \mathrm{yr}^{-1}, \sim 5\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}}$



Detection Prospects

Recent limits

[1]



- SK-Gd probing most optimistic models
- Publicly available Python code to estimate the DSNB flux
  - Green, Blue, Orange created with code

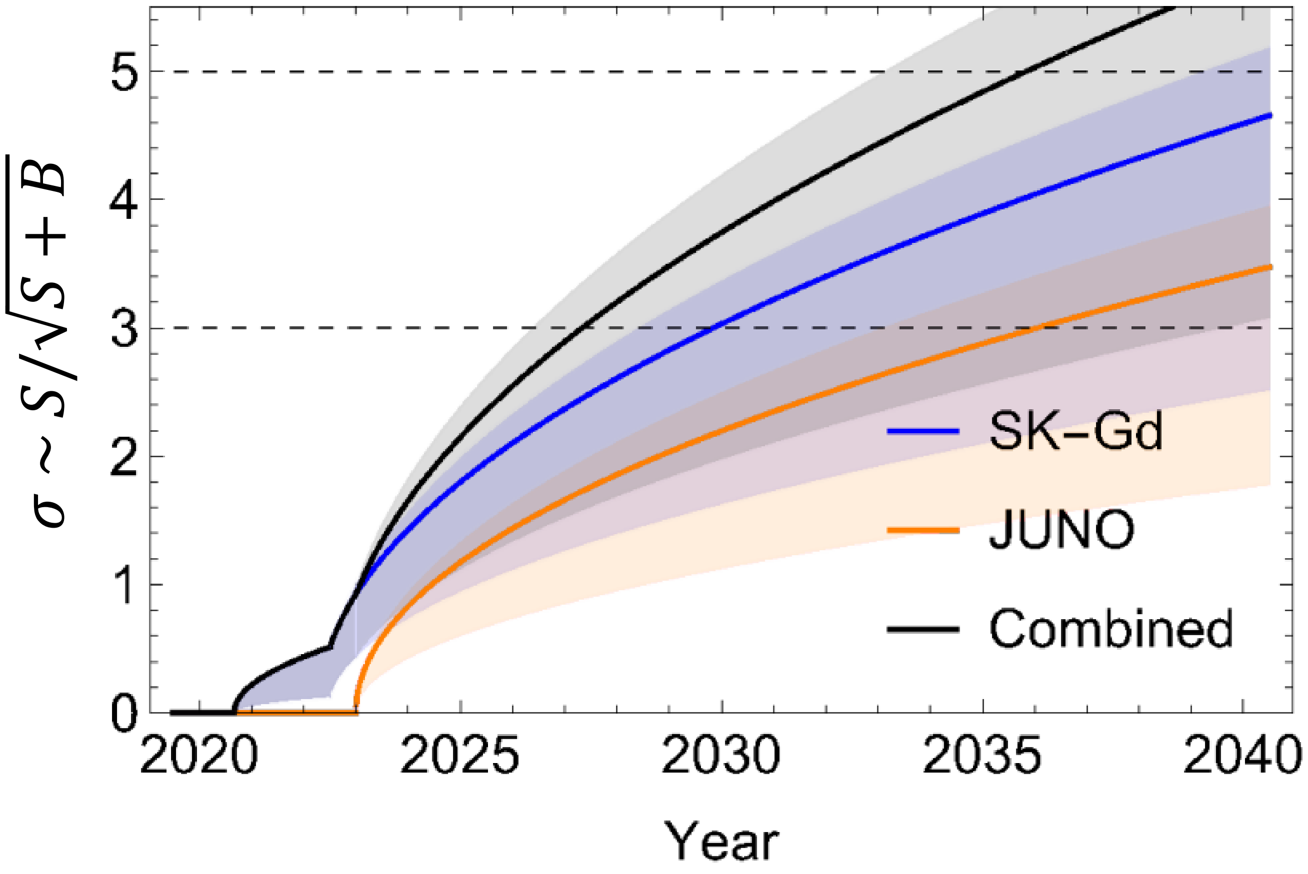
'PyDSNB'

[1] Ando, **Ekanger**+ 2023, Diffuse neutrino background from past CCSNe

Projecting DSNB detection

- SK-Gd and JUNO currently running
- Large uncertainties
- Reducing background rate
- Potential detection by 2030
  - Significant by 2035

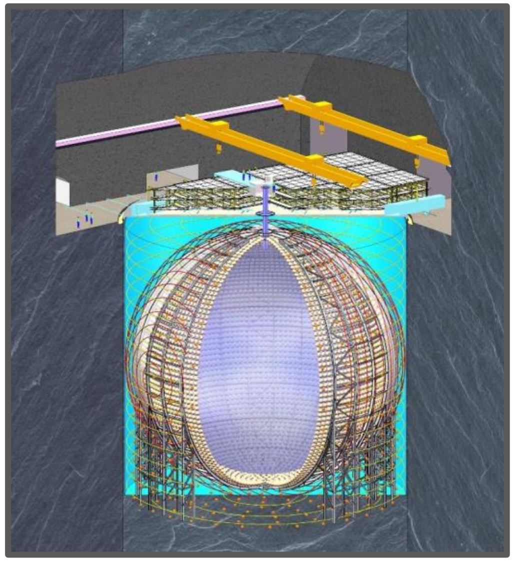
[1]



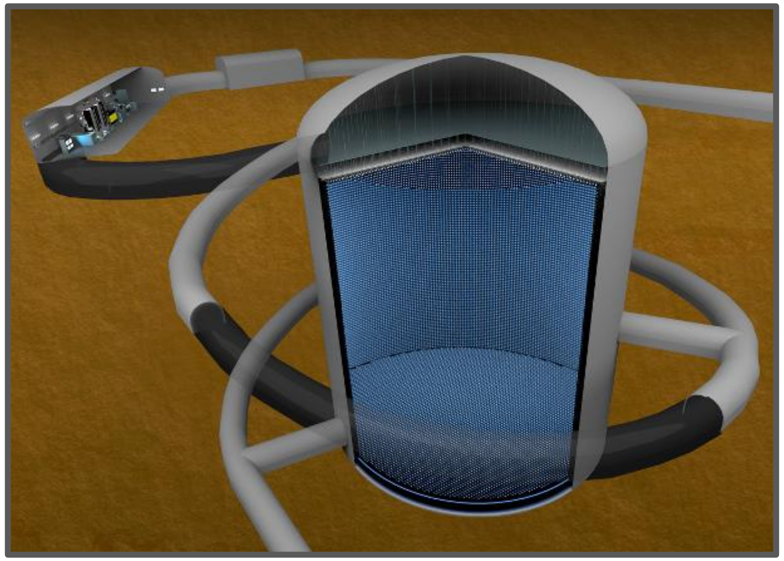
[1] **Ekanger+** 2023, DSNB with up-to-date SFR measurements and long-term multi-D SN simulations

Additional neutrino experiments

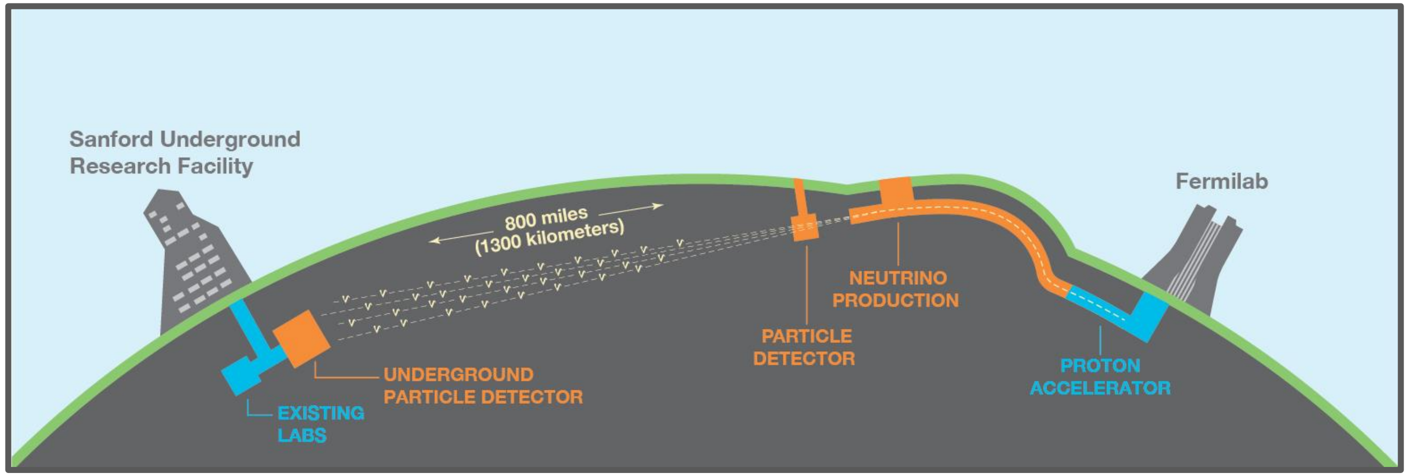
JUNO:
-Running
-Backgrounds



HK:
-Scaled-up SK
-SK techniques
-Gd?



DUNE:
-Cross section
-Backgrounds



Summary

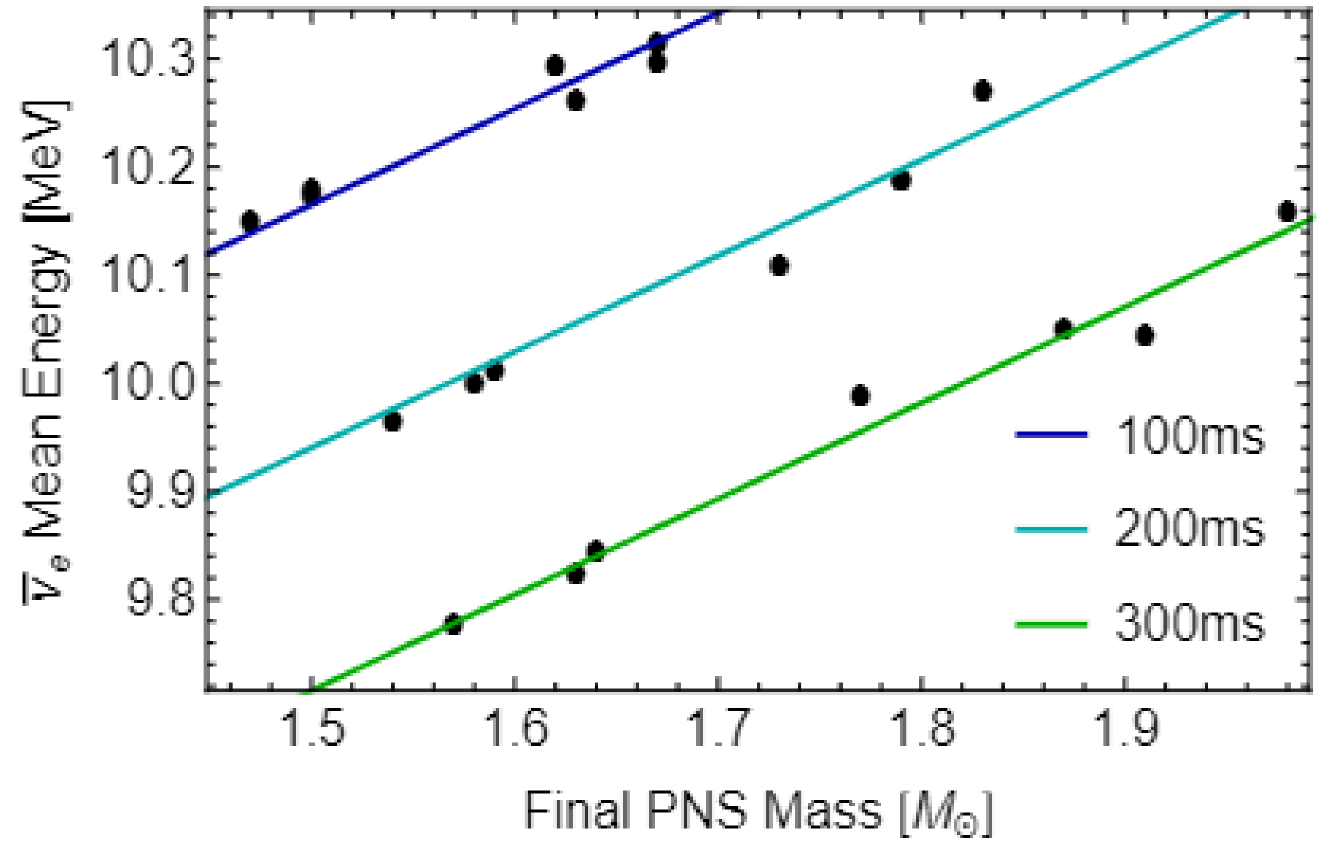
Summary

- Diffuse signal of ~10 MeV neutrinos from SNe → DSNB
- Updated DSNB modeling
  - Simulations and analytic techniques → neutrino emission
  - Star formation rate measurements → core collapse rate
- Detection on the horizon with current and future detectors
  - **SK-Gd + JUNO** → **2030s**, also HK, DUNE

Backup Slides

Correlation method for late phase

- Correlation with long term 1D simulations



Detector stats and SFRD database

- SK-Gd (22.5 kton, 9.3 – 31.3 MeV)

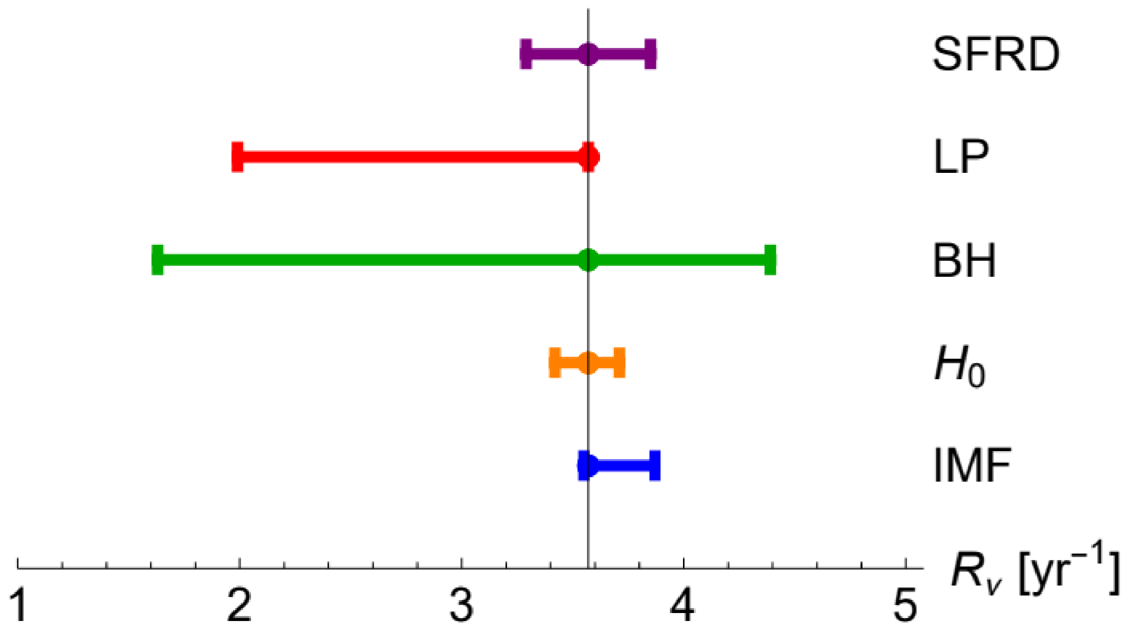
	Ordering	Fiducial	SFRD err	LP err	BH err
R_ν	NO	3.57	$^{+0.28}_{-0.28}$	$^{+0.00}_{-1.58}$	$^{+0.82}_{-1.94}$
[yr^{-1}]	IO	2.85	$^{+0.28}_{-0.28}$	$^{+0.00}_{-1.07}$	$^{+0.17}_{-1.30}$
ϕ	NO	5.10	$^{+0.40}_{-0.40}$	$^{+0.00}_{-2.04}$	$^{+0.50}_{-2.70}$
[$\text{cm}^2\ \text{s}^{-1}$]	IO	4.10	$^{+0.40}_{-0.40}$	$^{+0.00}_{-1.36}$	$^{+0.20}_{-1.92}$

- JUNO, HK, DUNE

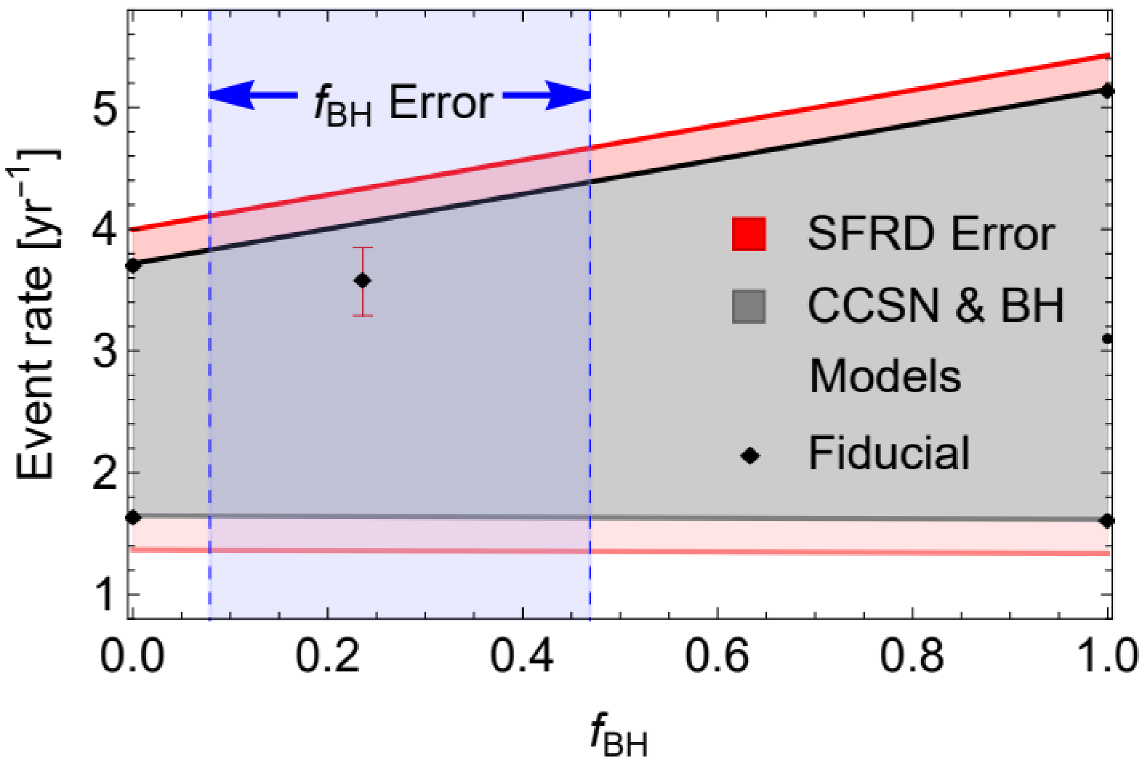
	Ordering	Mass	E_ν	R_ν	ϕ
		[kton]	[MeV]	[yr^{-1}]	[$\text{cm}^2\ \text{s}^{-1}$]
JUNO	NO (IO)	17	12-30	2.07 (1.65)	2.17 (1.73)
HK	NO (IO)	187	20-30	7.70 (6.10)	4.10 (3.20)
HK-Gd	NO (IO)	187	10-30	27.60 (22.00)	36.50 (29.10)
DUNE	NO (IO)	40	16-40	5.70 (5.30)	1.81 (1.73)

SFRD database

Error plots



SFRD
LP
BH
H_0
IMF
R_ν [yr^{-1}]
1
2
3
4
5



f_{BH} Error
SFRD Error
CCSN & BH Models
Fiducial
Event rate [yr^{-1}]
f_{BH}
0.0
0.2
0.4
0.6
0.8
1.0
1
2
3
4
5

Detection rate equation

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

where $E' = E(1+z)$ and $|dz/dt| = H_0(1+z)[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$.

To account for neutrino emission from both successful and failed supernovae, we compute the total flux as the sum:

$$\left.\frac{d\phi}{dE}\right|_{\mathrm{tot}} = (1 - f_{\mathrm{BH}}) \left.\frac{d\phi}{dE}\right|_{\mathrm{s}} + f_{\mathrm{BH}} \left.\frac{d\phi}{dE}\right|_{\mathrm{f}}, \quad (5)$$

where subscripts s and f indicate successful and failed supernova, respectively. We also consider the Mikheyev-Smirnov-Wolfenstein (MSW) effect for neutrino oscillations:

$$\frac{d\phi}{dE}^{\mathrm{obs}}_{\nu_e} \approx \begin{cases} \frac{d\phi}{dE}_{\nu_x} & \text{(NO)}, \\ \frac{d\phi}{dE}_{\nu_e} \sin^2\theta_{12} + \frac{d\phi}{dE}_{\nu_x} \cos^2\theta_{12} & \text{(IO)}, \end{cases} \quad (6)$$

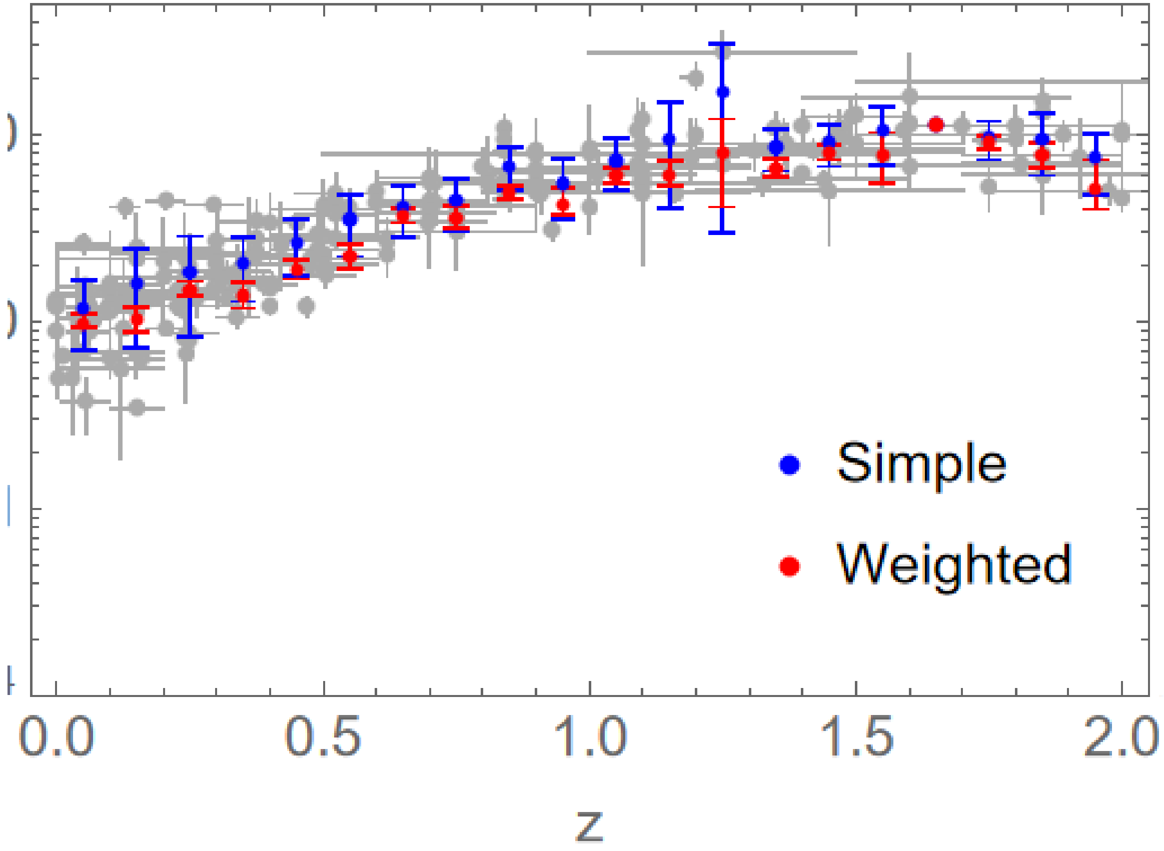
$$\frac{d\phi}{dE}^{\mathrm{obs}}_{\bar{\nu}_e} \approx \begin{cases} \frac{d\phi}{dE}_{\bar{\nu}_e} \cos^2\theta_{12} + \frac{d\phi}{dE}_{\nu_x} \sin^2\theta_{12} & \text{(NO)}, \\ \frac{d\phi}{dE}_{\nu_x} & \text{(IO)}, \end{cases} \quad (7)$$

where NO and IO are the normal and inverted mass orderings, respectively, $\cos^2\theta_{12} \approx 0.7$, and $\sin^2\theta_{12} \approx 0.3$

SFRD binning

- Simple and weighted averages

[1]



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SK-Gd upgrade