INSTITUTE for NUCLEAR THEORY

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

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Astrophysical neutrinos
and the origin of the elements
July 27, 2023

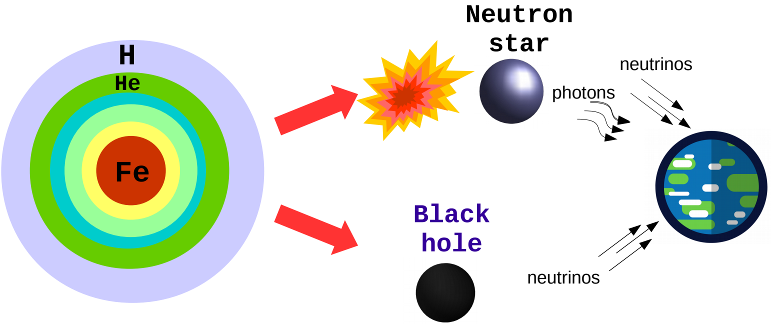
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

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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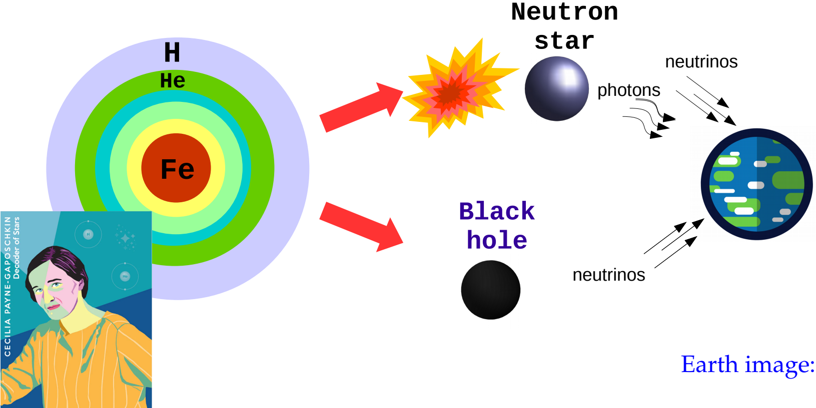
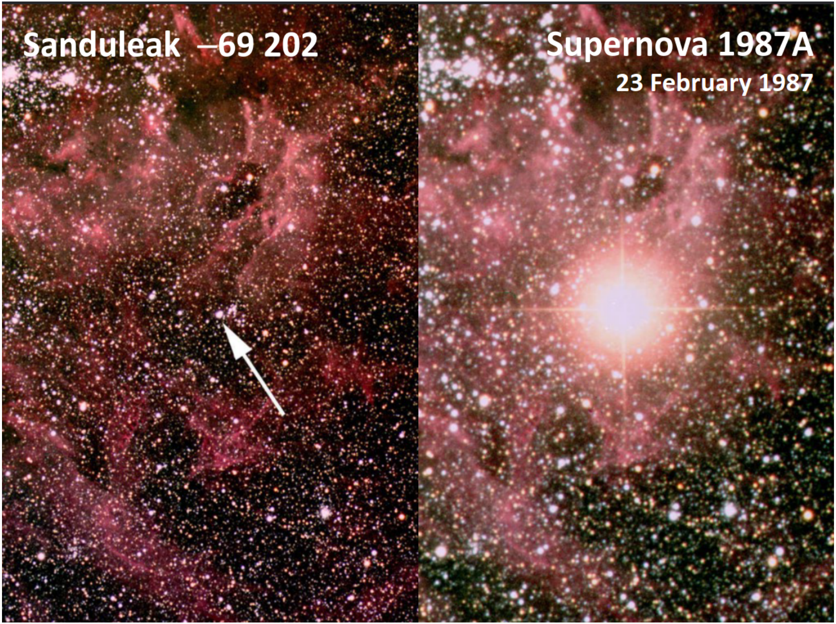


Earth image: Kurzgesagt

Observation of neutrinos from core-collapse supernova



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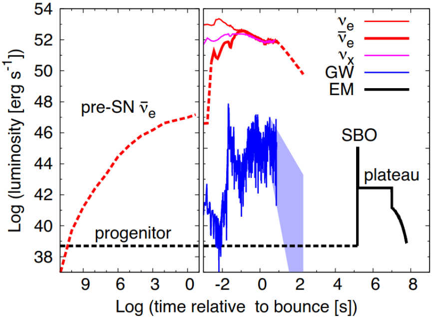

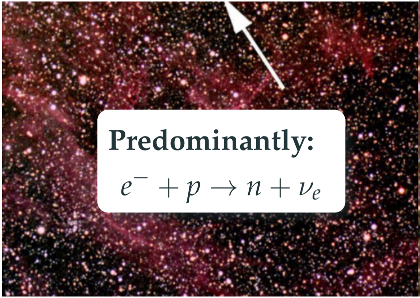

Predominantly:

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

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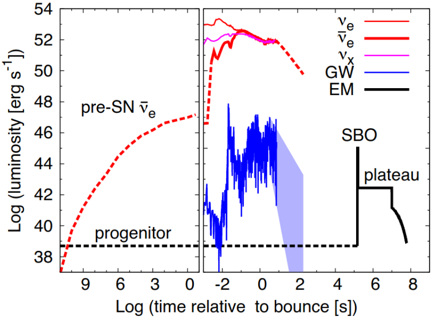

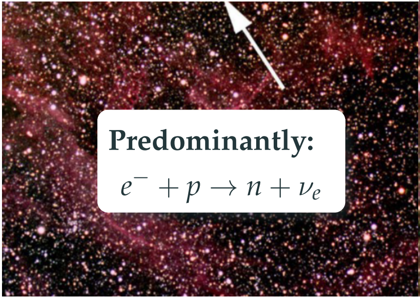

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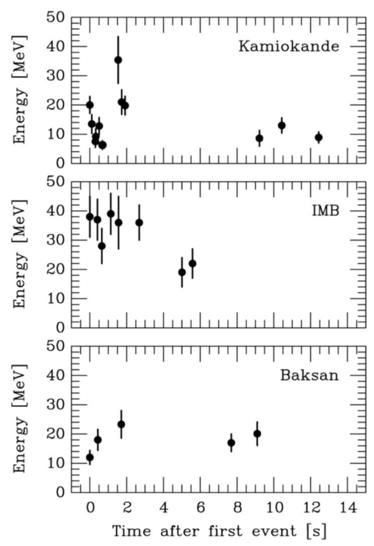

Why core-collapse supernovae are good physics probes?

Advantages

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

What can we learn with a variety of detectors?

- explosion mechanism
- yields of heavy elements
- compact object formation
- neutrino mixing
- non-standard physics

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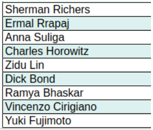

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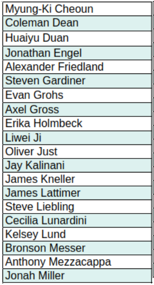

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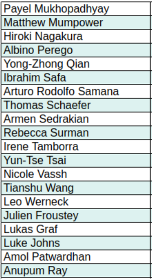

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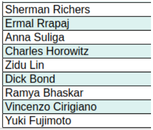

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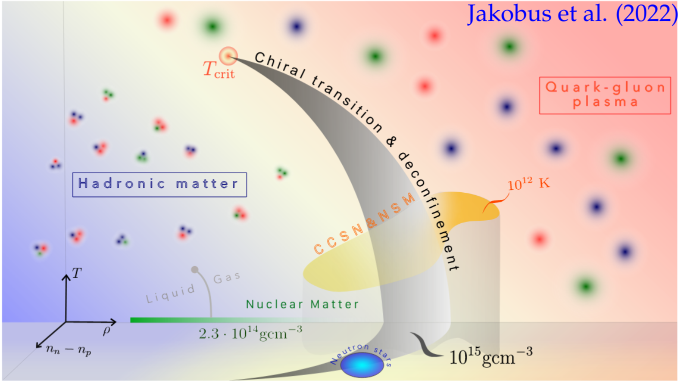
Phase transition to quark matter in core-collapse supernovae

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

A. B. Balantekin

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

QCD phase diagram



- 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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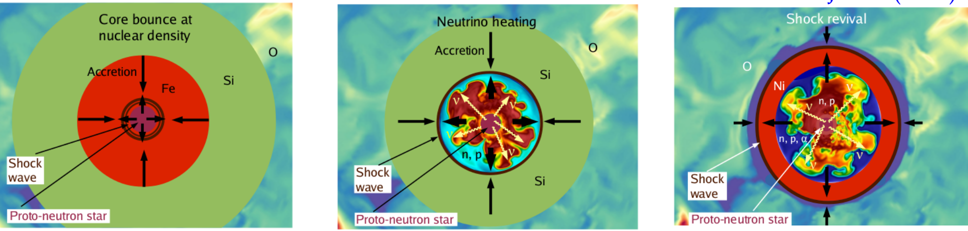
Different phases of core-collapse supernova explosion

- 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, Tamborra, Wu (2
- phase transition to quark matter Sagert et al. (2008)...

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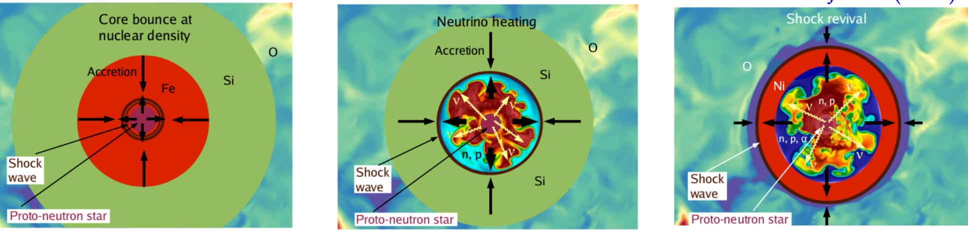

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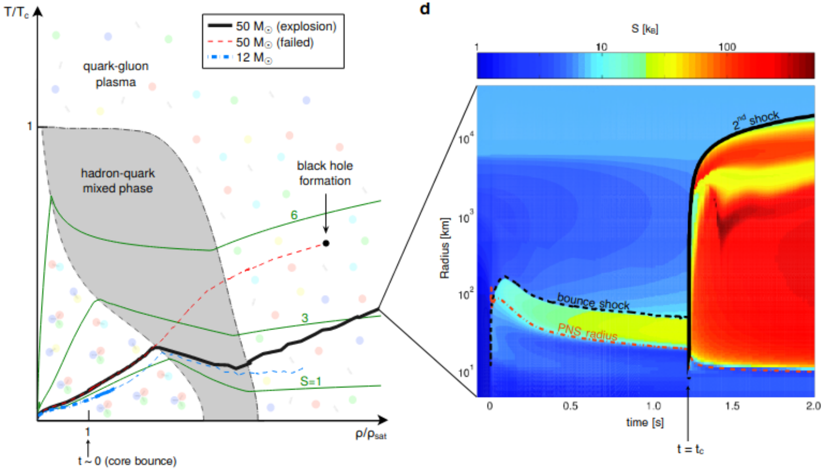
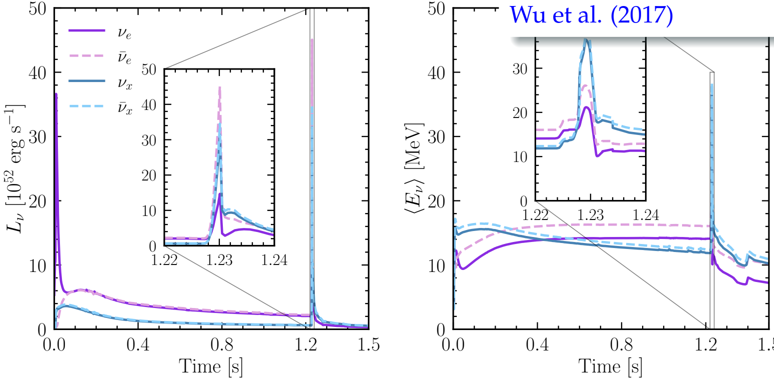
Quark deconfinement as a supernova explosion engine for massive blue supergiant stars



Fischer, Bastian, Wu et al. (2017)

Neutrino Emission Properties from the QHPT CCSN

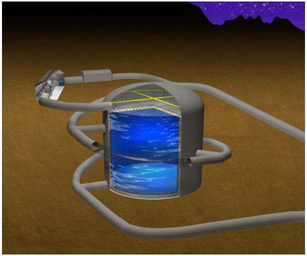


1D SN model Fischer, Bastian, Wu et al. (2017)

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

Supernova neutrino detection

Hyper-Kamiokande (2027)



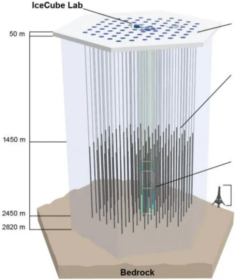
fiducial volume

217 kton

main detection channel

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

Ice-Cube Observatory



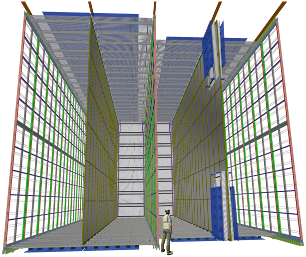
fiducial volume

3500 kton

main detection channel

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

DUNE (2030)



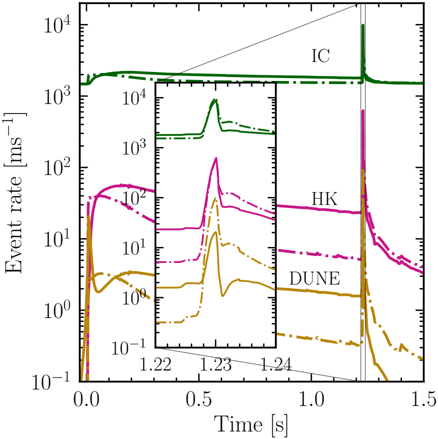
fiducial volume

40 kton

main detection channel

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

Neutrino Event Rates

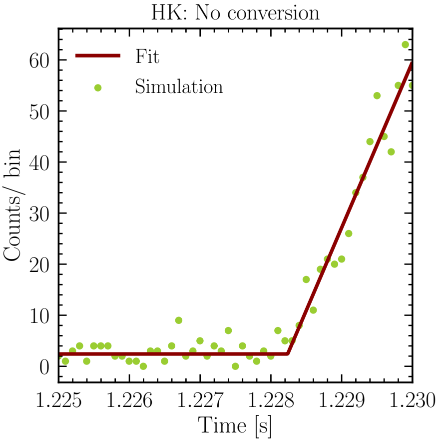


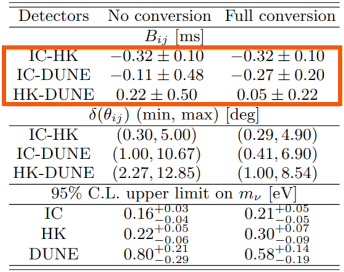
Impact of neutrino conversions

- 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	$0.80^{+0.21}_{-0.29}$	$0.58^{+0.14}_{-0.19}$

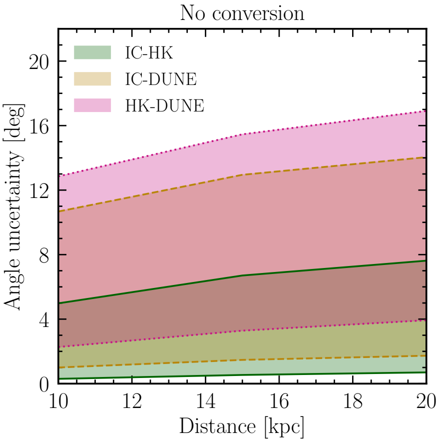
$$\Delta t_{ij}^{\text{true}} = \frac{(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{n}}{c} = \frac{D_{ij} \cos\theta}{c}$$

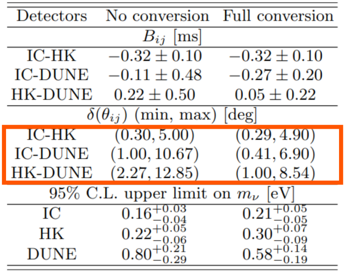
$$R_{\text{exp}} = \begin{cases} R_*, & \text{if } t < t_0 \\ R_* + a(t - t_0), & \text{otherwise} \end{cases},$$

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

Halzen and Raffelt (2009)

Determination of the uncertainty of the CCSN localization





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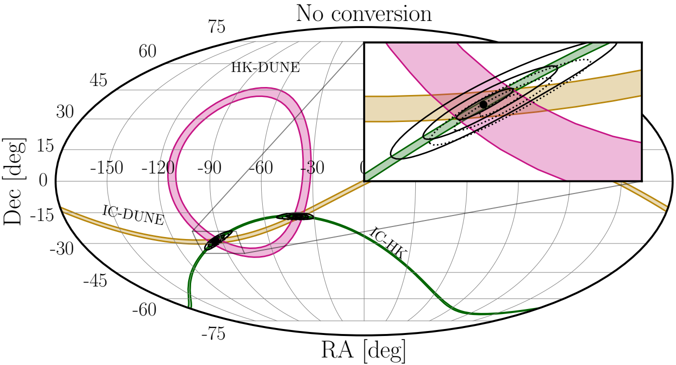
$$\delta(\theta_{ij}) \approx \begin{cases} \delta(\cos\theta_{ij})/\sin\theta_{ij} & \text{if } \sin\theta_{ij} > \sqrt{\delta(\cos\theta_{ij})} \\ \sqrt{2\delta(\cos\theta_{ij})}, & \text{for } \theta_{ij} \ll \delta(\cos\theta_{ij}) \end{cases} .$$

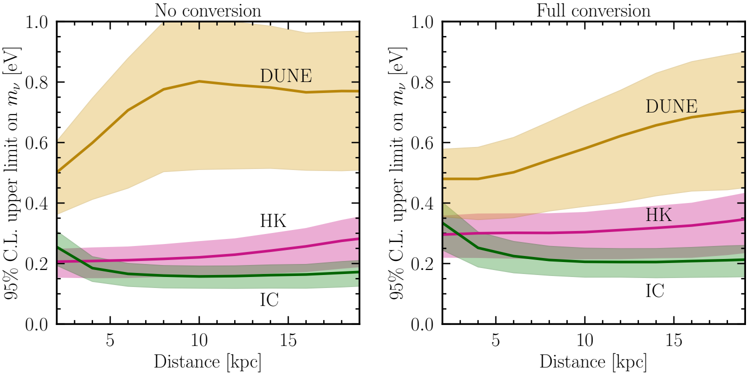
Determination of the CCSN localization



- 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

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



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

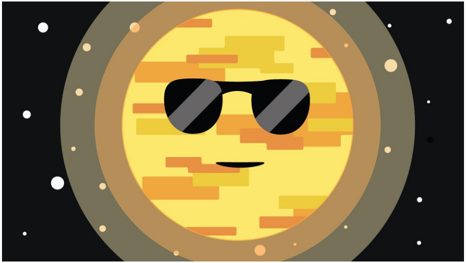
Conclusions: Quark-hadron phase transition in CCSNe

- QCD phase transition in the collapsing star can:
    - produce second core bounce
    - result in release of a second sharp neutrino burst
    - lead to some *r*-process elements production

- Detection of the phase transition induced neutrino burst:
    - indicates the QCD phase transition in supernova
    - improves the precision of the supernova triangulation
    - sets competitive limits on the neutrino mass

Why focus only on a single rare event?

Single event vs. multiple events

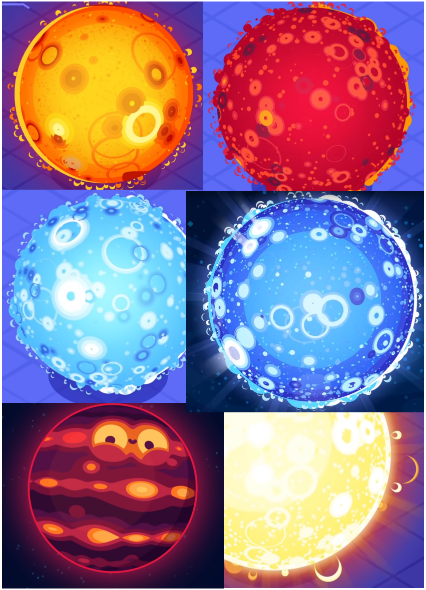


Single galactic SN event

- 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

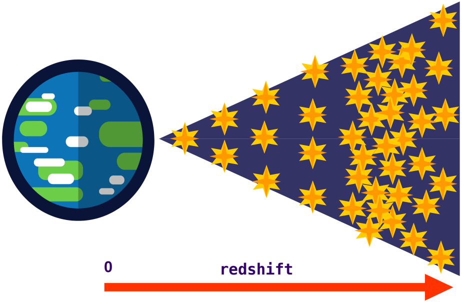
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\mathrm{CC-SN}}F_{\nu_\beta,\mathrm{CC-SN}}(E',M)+f_{\mathrm{BH-SN}}F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

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

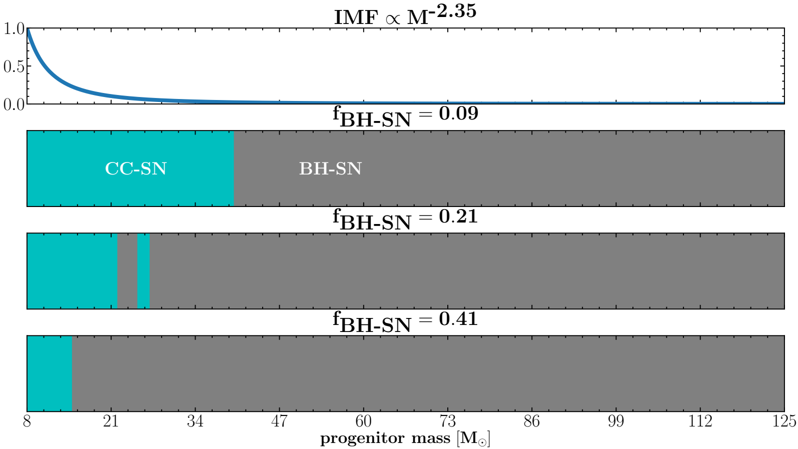


Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010),...

Very recent reviews: Kresse et al. (2020), AMS (2022), Ando et al. (2023), ...

Astrophysical uncertainties

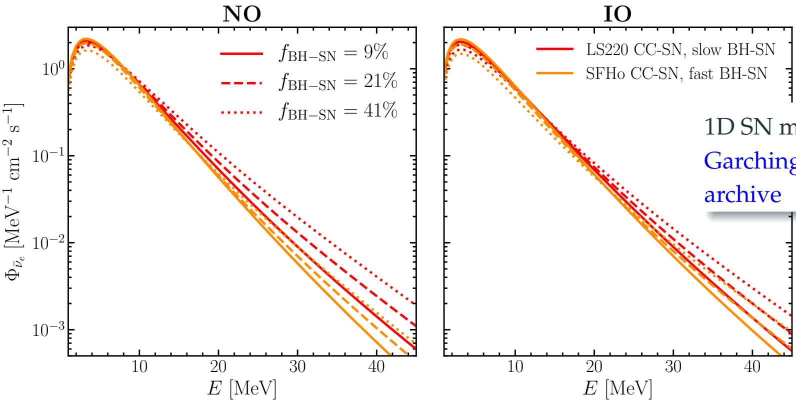
The fraction of black-hole-forming progenitors



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

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

The fraction of black-hole-forming progenitors

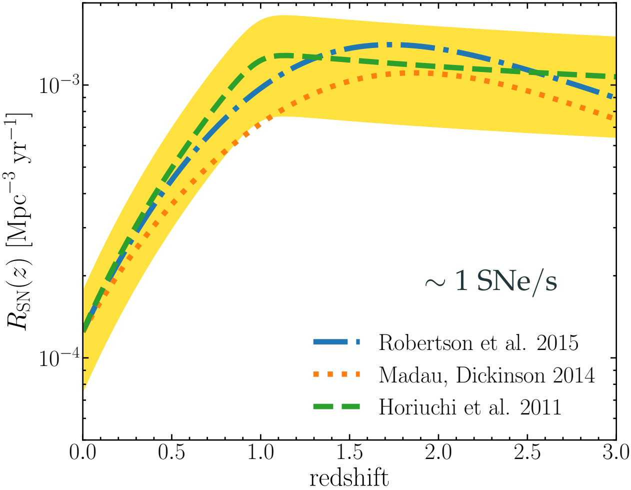


1D SN models
Garching group archive

Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV. Lunardini (2009)

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

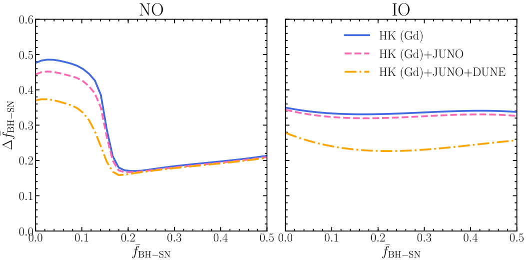
Cosmological supernovae rate



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), ...

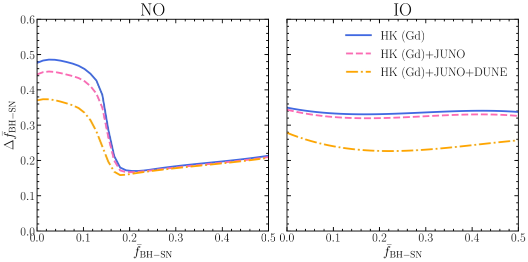
Expected 1σ uncertainty: fraction of BH forming progenitors



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

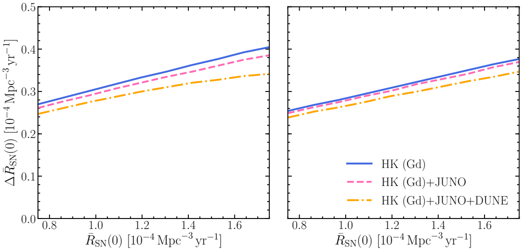
Møller, AMS, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



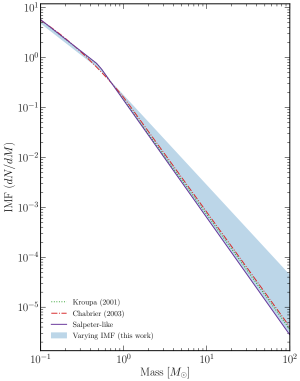
- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

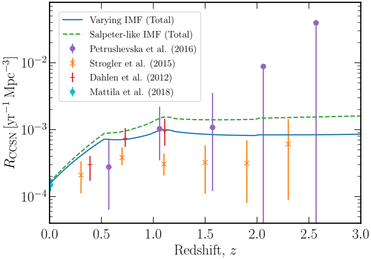
- Relative error of 20%-33% independent of the mass ordering.

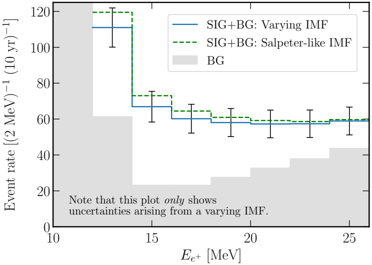


Møller, AMS, Tamborra, Denton (2018)

Varying Initial Mass Function







Note that this plot *only* shows uncertainties arising from a varying IMF.

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

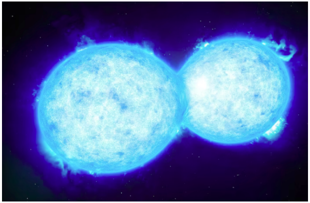
Ziegler, Edwards, AMS, Tamborra, Horiuchi, Ando, Freese (2022)

Binary interactions

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

Mass transfer

Mergers



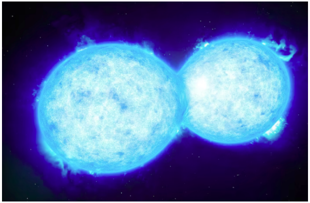
Images: iflscience, Wiki

Binary interactions

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

Mass transfer

Mergers

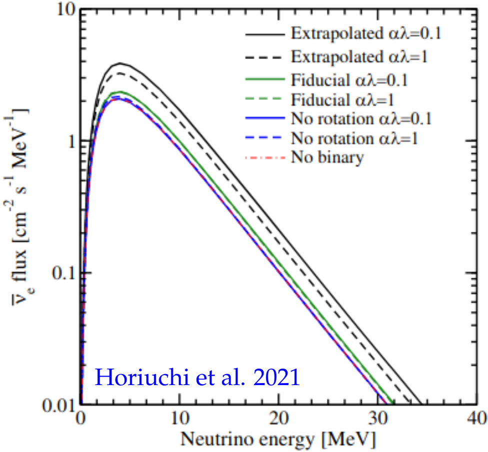


Effects on the stellar population Horiuchi et al. 2021

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

Images: iflscience, Wiki

Binary interactions: impact on DSNB



$\alpha\lambda$ - 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

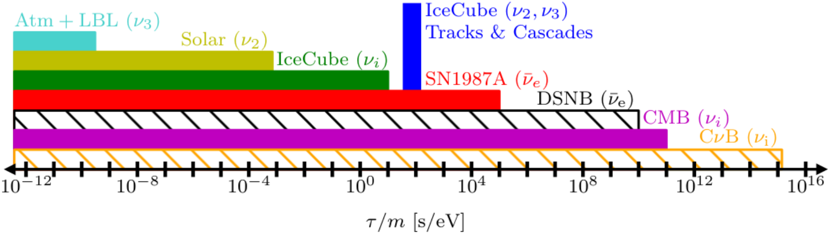
BSM scenarios affecting DSNB

Neutrino decay

Active neutrinos are massive and masses are not identical

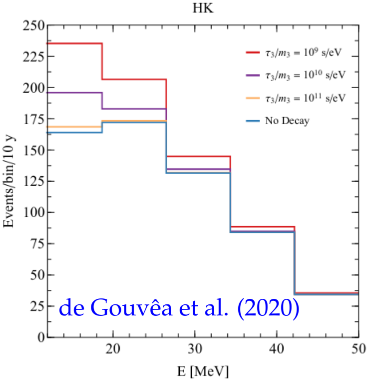
- SM decays are loop supressed
- lifetimes ≫ age of the Universe

If neutrinos have BSM interactions they can decay faster

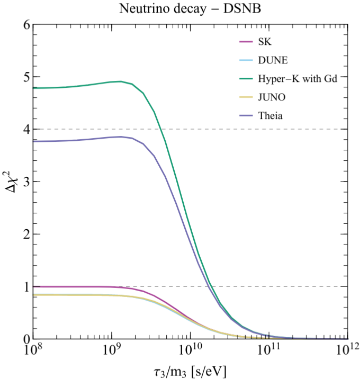


Abdullahi, Denton (2020)

Neutrino decay: impact on DSNB



de Gouvêa et al. (2020)

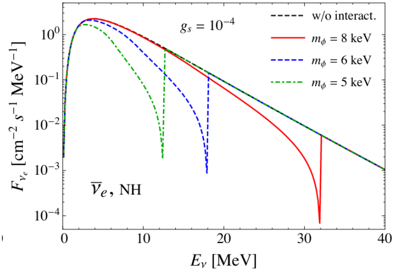


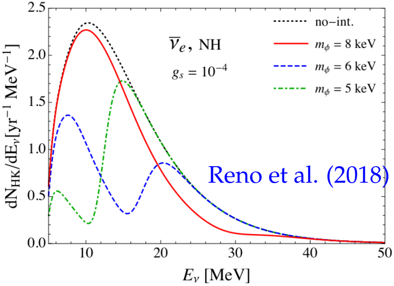
Exact detector features depend on

- Mass ordering
- Dirac vs Majorana nature
- details of the BSM model

Ando et al. 2003, Fogli et al. 2004, de Gouvêa et al. 2020, Tabrizi & Horiuchi (2020), Ivanez-Ballesteros & Volpe (2023),...

Secret neutrino interactions: impact on DSNB





Reno et al. (2018)

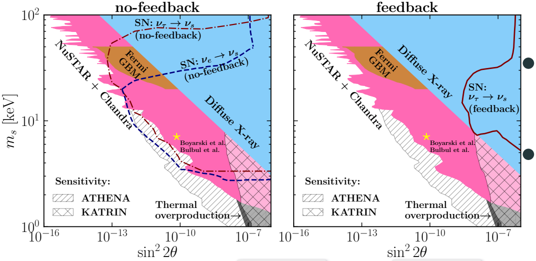
DSNB interactions with

- cosmic relic neutrinos
  Goldberg et al. (2005), Baker et al. (2007), Reno et al. (2018)
- dark matter Farzan, Palomares-Ruiz (2014)

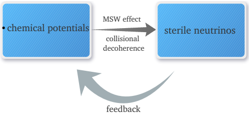
result in spectral features in DSNB

BSM impacting neutrinos inside CCSN

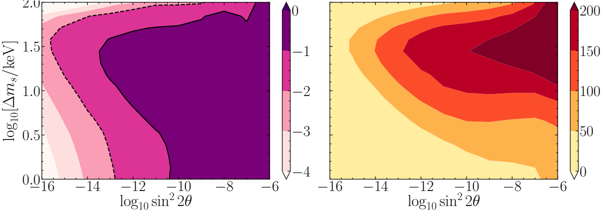
KeV sterile neutrinos



- The inclusion of feedback: reduction of the excluded region
- CC-SNe cannot exclude any region the DM parameter space

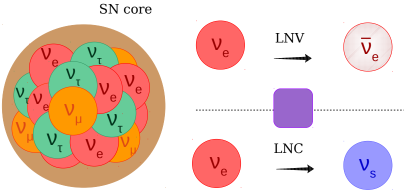


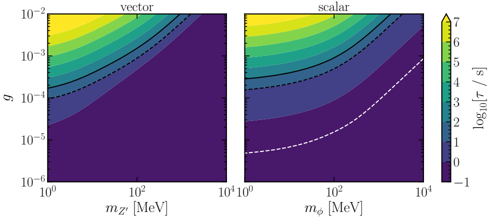
- The inclusion of feedback: growth of asymmetries
- Neutrino spectrum affected



Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Abazajian et al. (2001), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), AMS et al. (2019, 2020), Syvolap et al. (2019), Ray & Qian (2023)

Non-standard coherent scattering in the supernova core





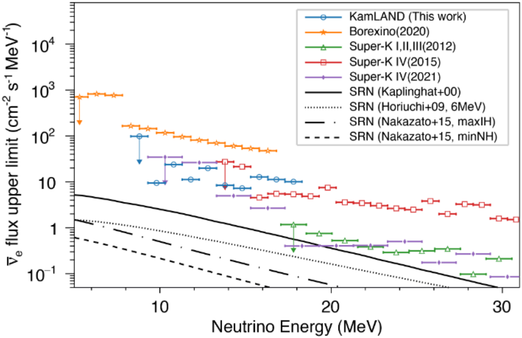
- prolonged diffusion time → possible change in the star's fate
- prolonged diffusion time → changed duration of the neutrino signal
- LNC scalar mediator → new cooling channel due to ν_R

Kolb & Turner (1987), Fuller et al. (1988) Farzan et al.(2018), Heurtier & Zhang (2016), Shalgar et al. (2019), AMS & Tamborra (2020), Reddy & Zhou(2021)

Current limits on the DSNB

Diffuse supernova neutrino background: current limits

Abe et al. (2021)



DSNB limits:

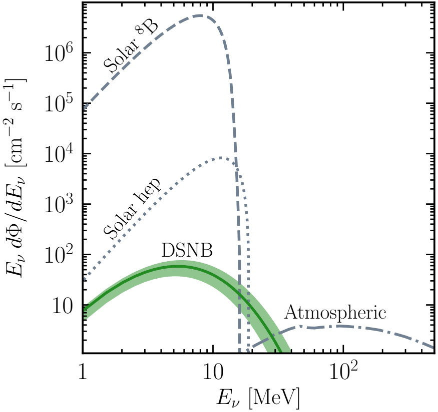
- $\bar{\nu}_e \approx 3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV Giampaolo et al. (2021), SK collab. (2021) soon detected by SK (Gd) Beacom, Vagins (2004) and JUNO JUNO collab. (2021)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu \in [22.9, 36.9\ \mathrm{MeV}]$ Mastbaum et al. (2020) possibly detectable by DUNE Zhu et al. (2019)

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

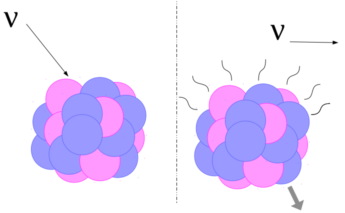


DSNB modeling:
Møller, AMS, Tamborra, Denton (2018)

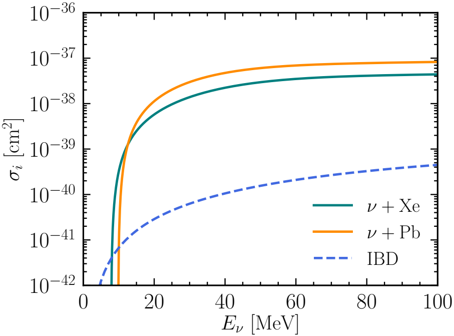
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750$ cm^{-2} s^{-1} for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

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

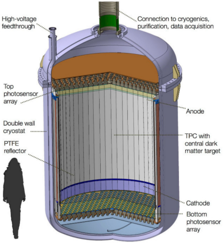
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q),\ \ Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

Freedman (1974)

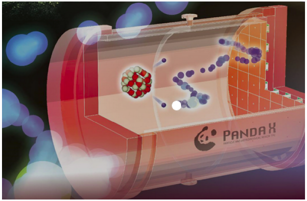
Current and future CEνNS detectors

XENONnT, DARWIN



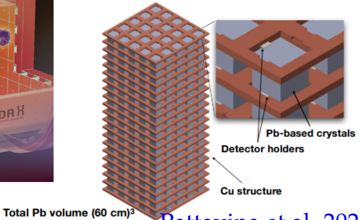
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

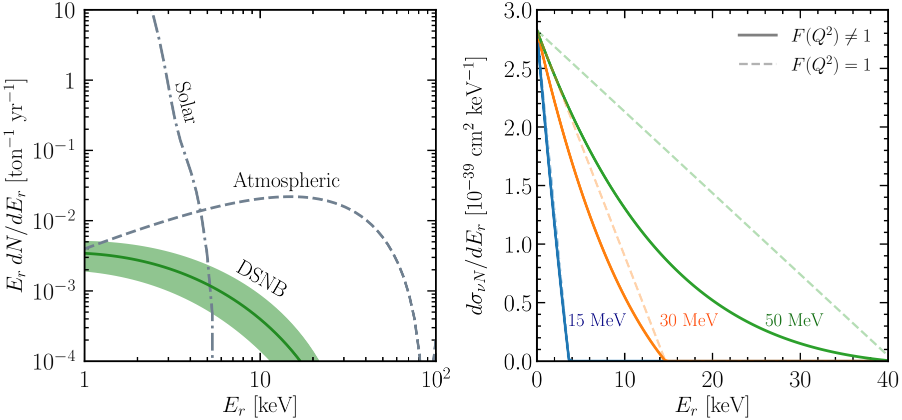
thresholds: $\mathcal{O}(1)$ keV

efficiency: $\sim$ 80-100%

Scattering rate

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

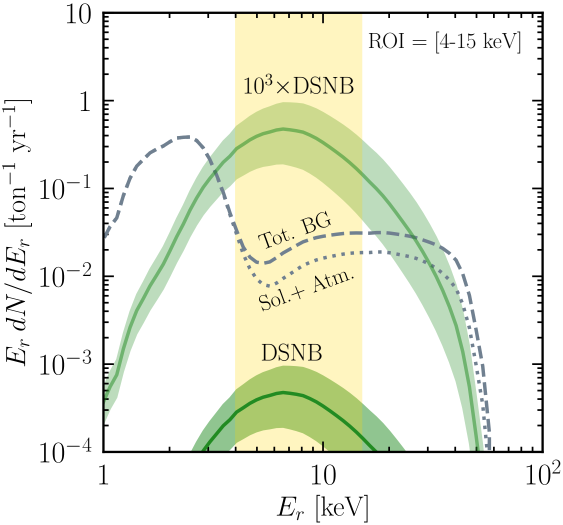
Event rate in the xenon-based detector



- 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?

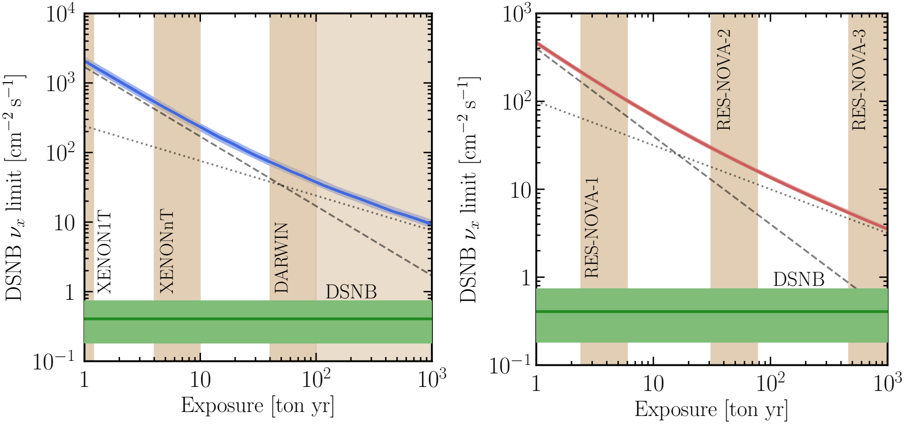
YES: Scaled event rate in the xenon-based detector



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

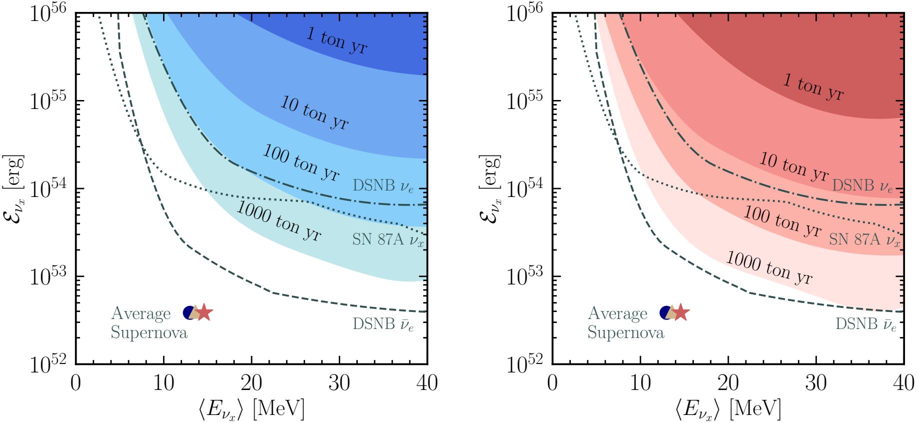
Sensitivity bounds on the x-flavor DSNB

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

Conclusions

Diffuse supernova neutrino background

- $\bar{\nu}_e$: soon to be detected by SK + Gd, JUNO
- ν_e: posssibly detectable by DUNE
- ν_x:
  - XENON1T, PandaX-4T yield similar limits to the one from SK
  - CEνNS detectors can improve the existing limits $\gtrsim 100$

Improved limits on the *x*-flavor DSNB

- help us to rule out potential non-standard scenarios
- bring us closer to understaning the supernova physics

Conclusions

Core-collapse supernovae

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

Detection of astrophysical neutrino fluxes

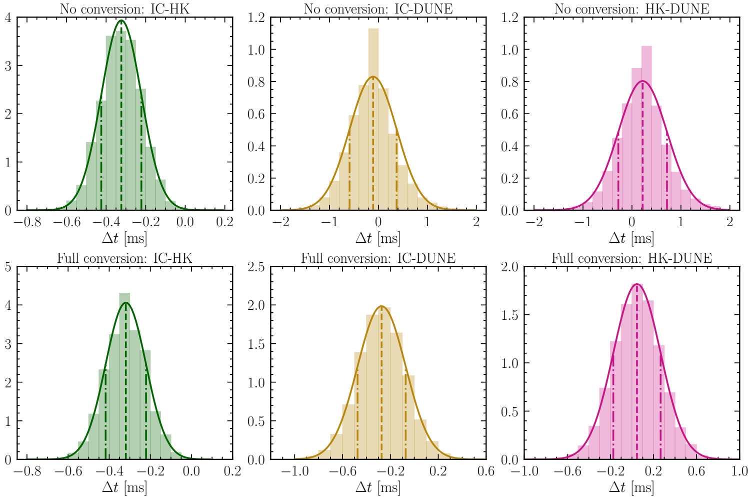
- brings us closer to fully understanding the physics inside the sources
- help us to probe potential new physics scenarios

Exciting times ahead

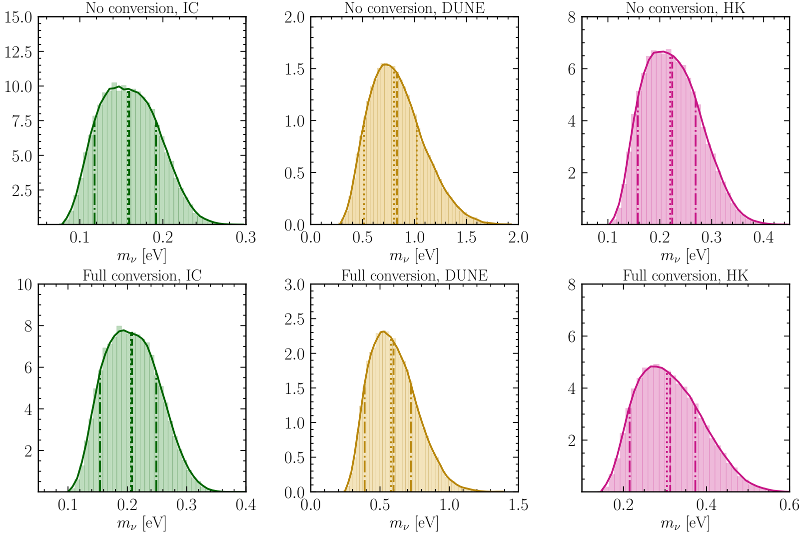
Thank you for the attention!

Backup

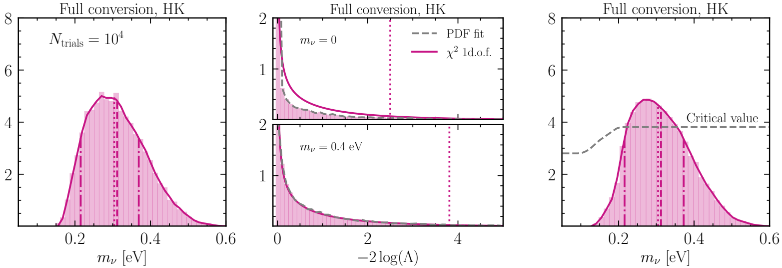
Histograms: Timing the neutrino signal



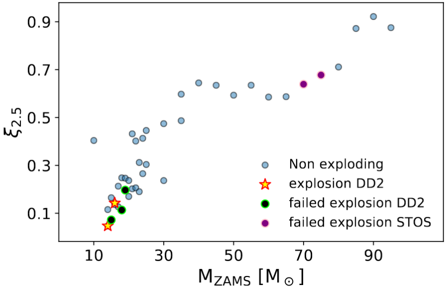
Histograms: neutrino mass limit



Relaxing Wilk's theorem approximation



The Role of the QCD Phase Transition in CCSNe



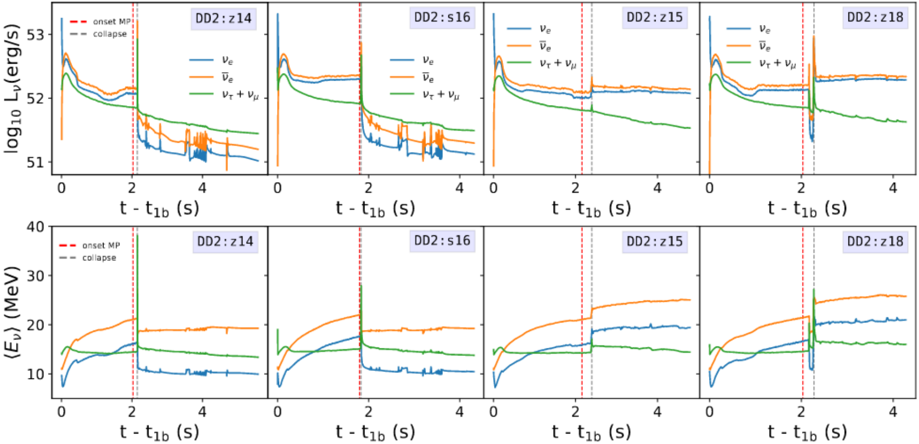
Compactness parameter

$$\xi_M = \frac{M/M_\odot}{r(M)/1000\ \mathrm{km}}$$

- Three equations of state: DD2F (1st order PT, Gibbs), STOS-B145 (1st order PT, Maxwellian), and CMF (smooth crossover)
- Sucessful explosions only for 2 models in DD2F
- Failed explosions in DD2F and STOS-B145

Pia Jakobus et al. (2022)

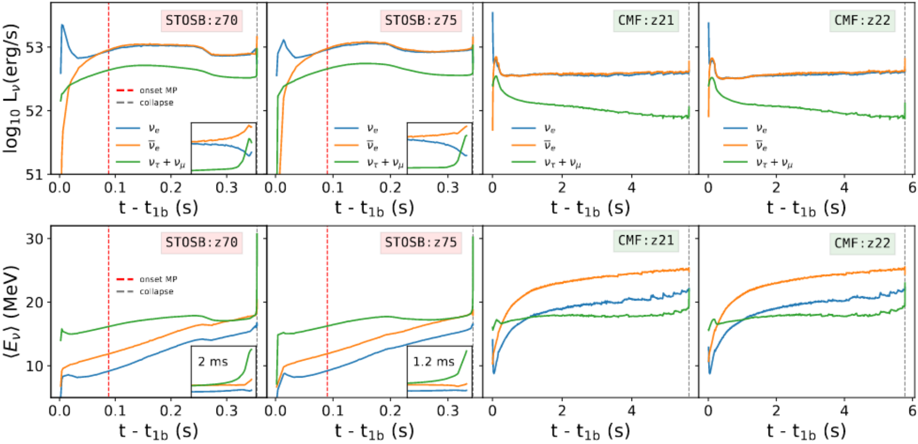
Neutino signals: DD2F



- Low explosion energies $\sim 10^{50}$ erg
- Majority of models have second bounce 37/40
- Failed explosions only for zero metallicity

Pia Jakobus et al. (2022)

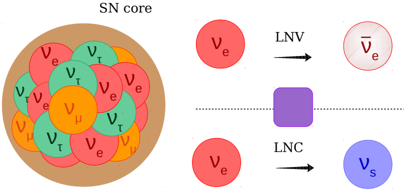
Neutino signals: STOS-B145, CMF

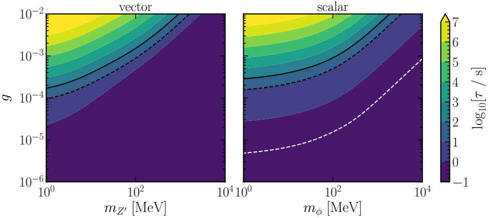


- Relatively small increase in luminosity during 2nd bounce
- No models successfuly explode
- No 2nd bounces in the CMF models

Pia Jakobus et al. (2022)

Non-standard coherent scattering in the supernova core

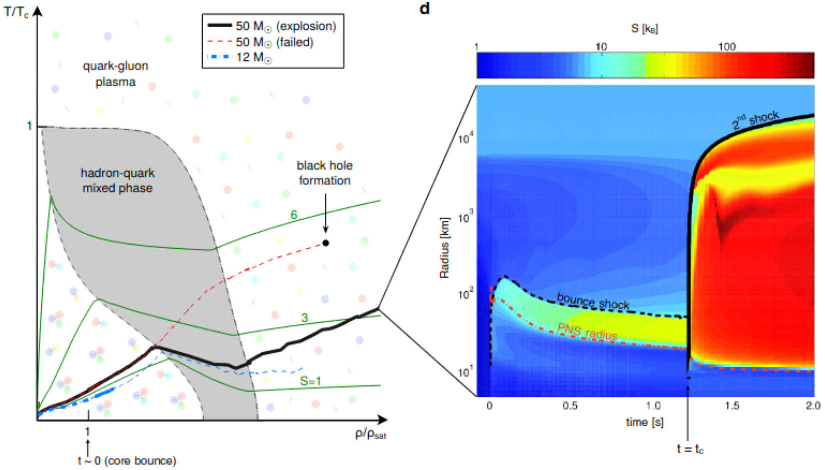




- prolonged diffusion time → possible change in the star's fate
- prolonged diffusion time → changed duration of the neutrino signal
- LNC scalar mediator → new cooling channel due to ν_R

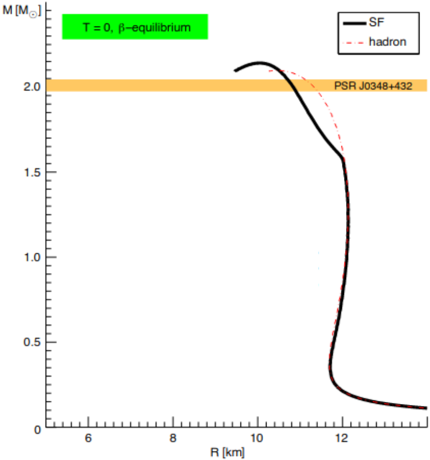
Kolb & Turner (1987), Fuller et al. (1988) Farzan et al.(2018), Heurtier & Zhang (2016), Shalgar et al. (2019), AMS & Tamborra (2020), Reddy & Zhou(2021)

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



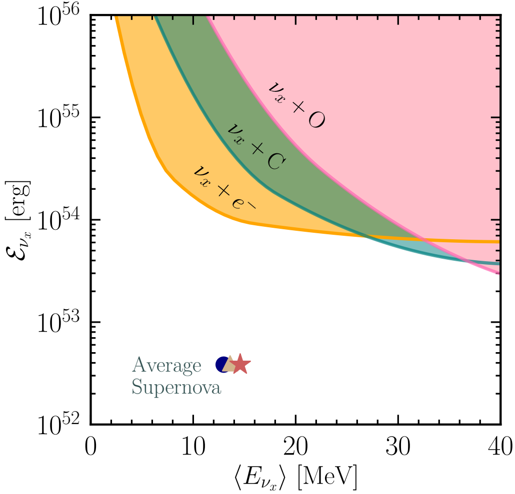
Fisher et al. (2017)

or mas-

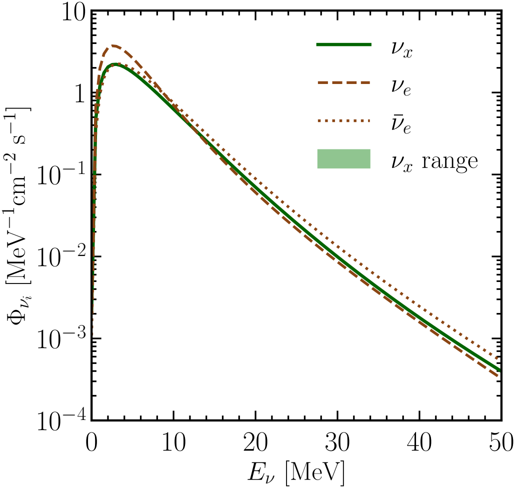


Fisher et al. (2017)

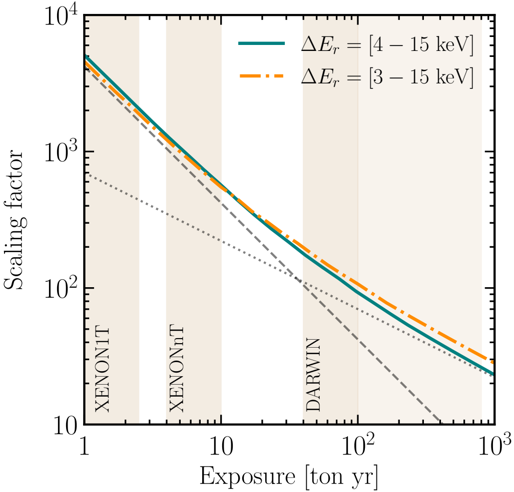
Limits from the SN 1987A



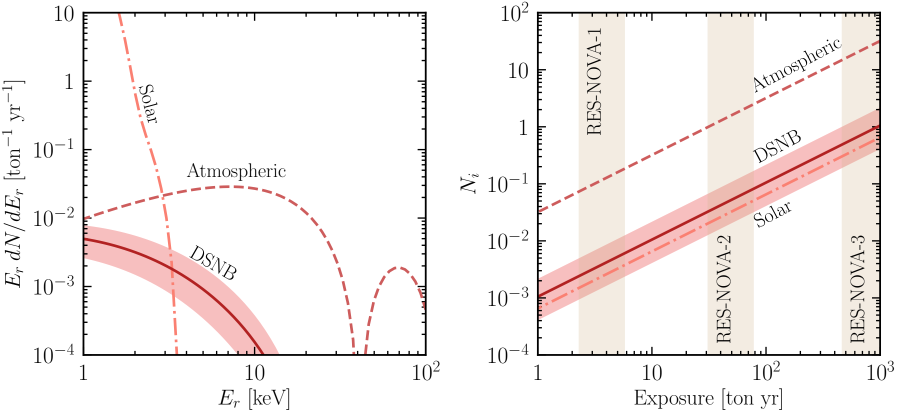
DSNB variability



Sensitivity of the limits to a detection window



Event rate: lead detector



Which part of the spectrum are CEνNS detectors sensitive to?