Oscillation-Independent Probes of Non-Standard Neutrino Interactions from Supernovae

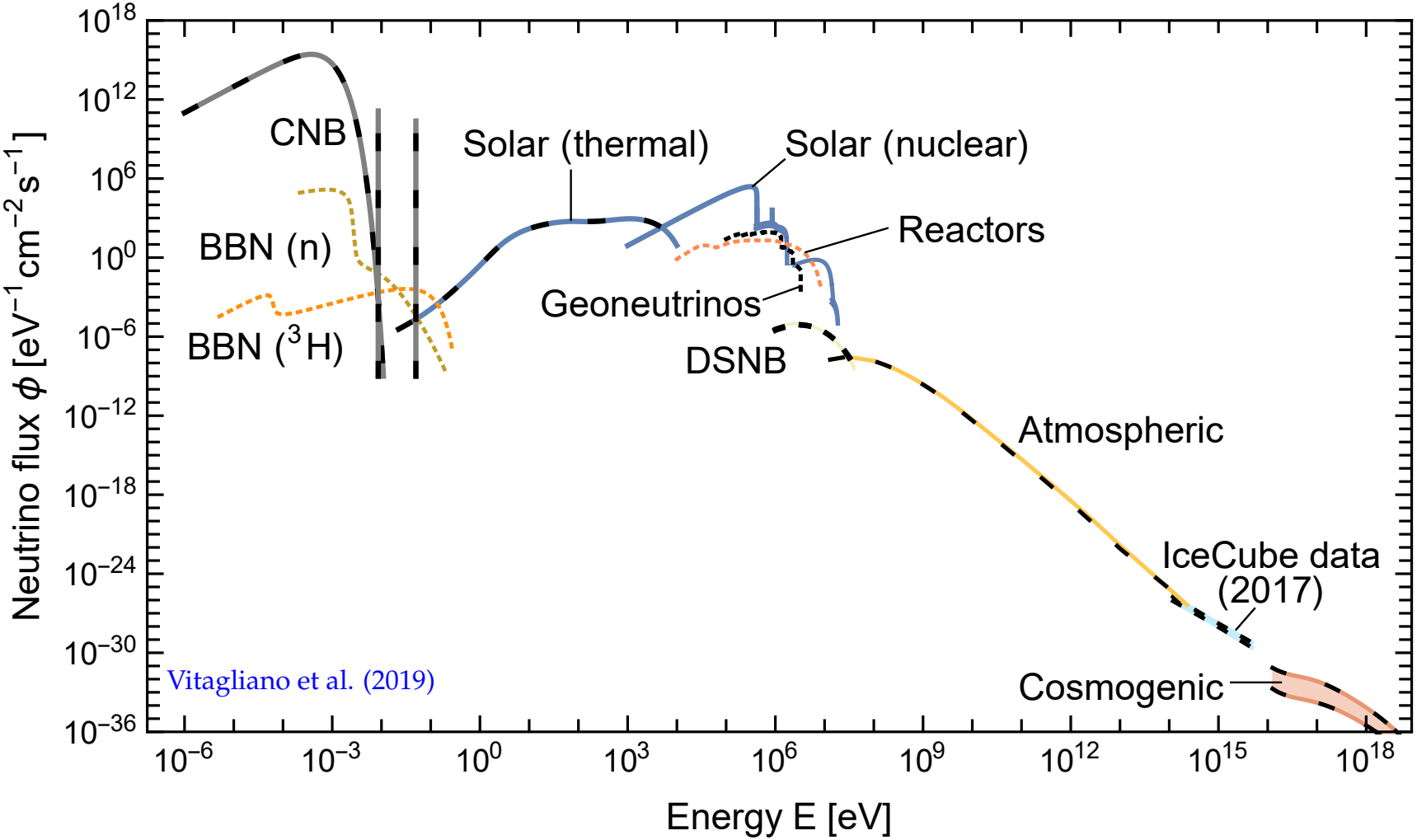
Anna M. Suliga
with Angela Beatty and Volodymyr Takhistov

Neutrino Theory Network Fellow
New York University

PACMAN at CCA, February 6, 2026

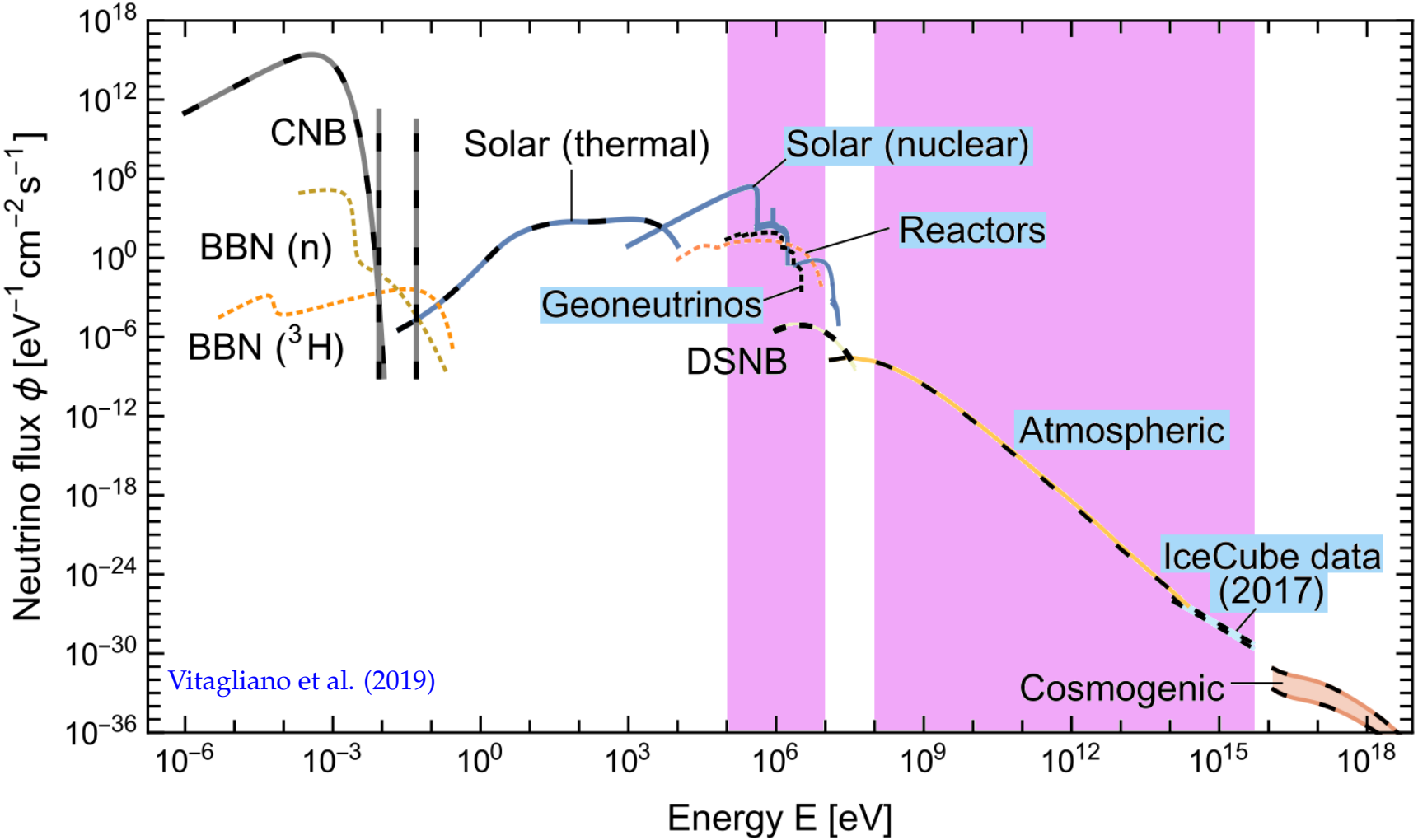
NYU

Why is studying astrophysical neutrinos crucial?



Free neutrino sources spanning nearly 25 decades in energy

Established track record of neutrino discoveries



Significant progress, but still room for new discoveries

Why is studying astrophysical neutrinos crucial?

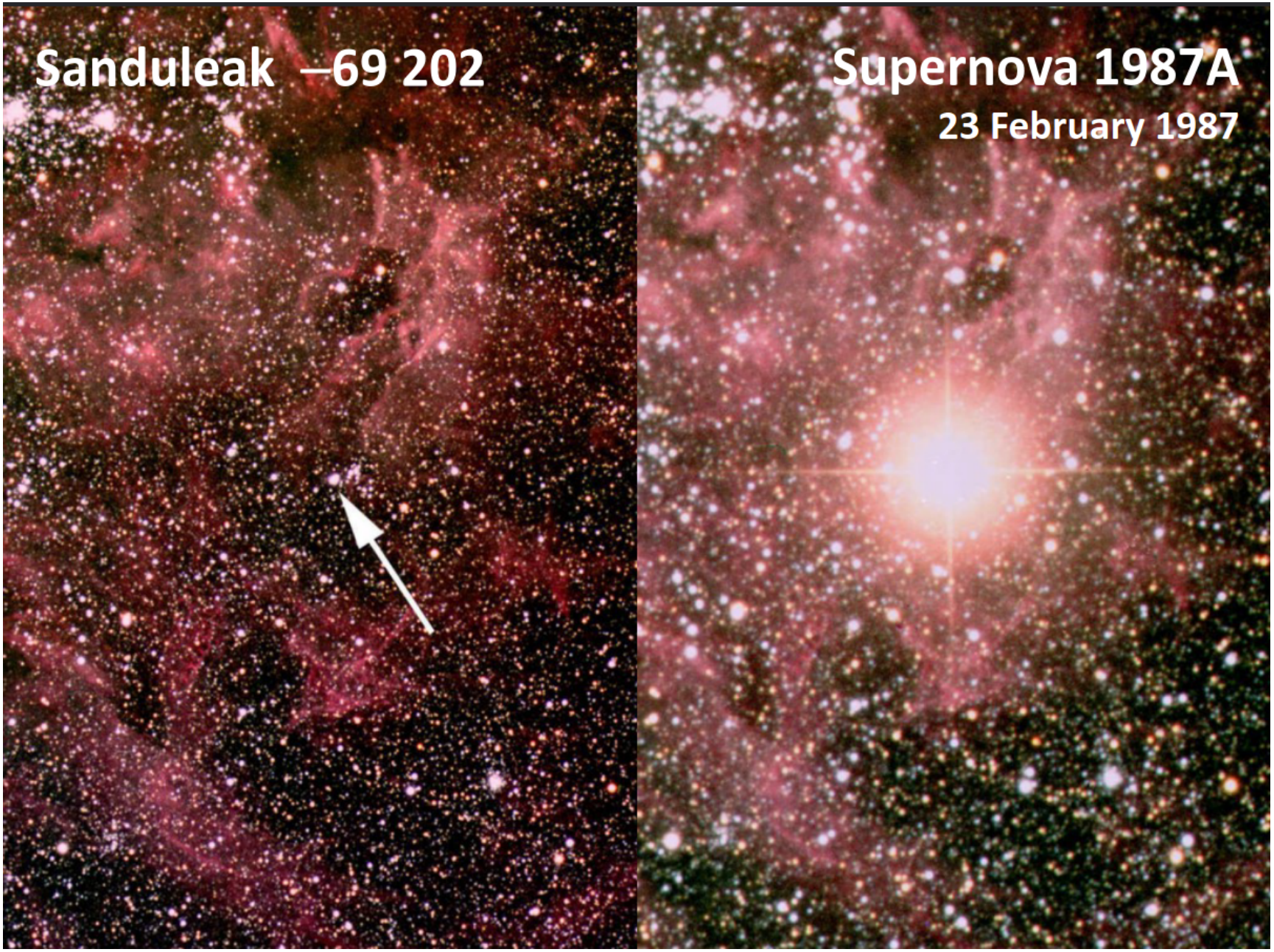
Benefits to the field of neutrino physics

- free sources spanning nearly 25 decades in energy
- established track record of neutrino discoveries
- test of physics in conditions not accessible on Earth
- complements terrestrial neutrino experimental efforts

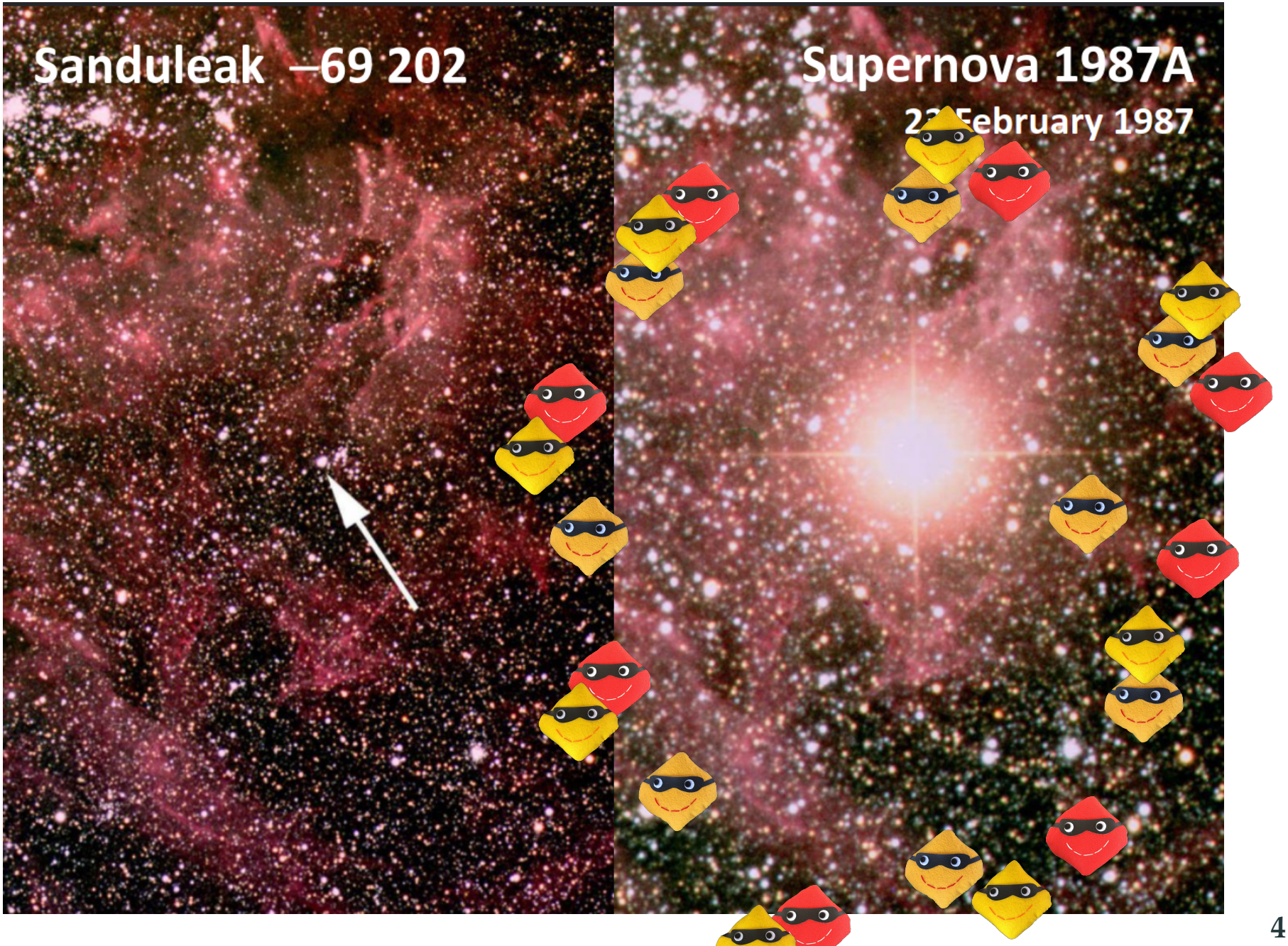
Benefits to the field of multimessenger astrophysics

- unveils physics of the sources
- experimentally and observationally timely

Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A



Hubble (2017)



JWST (2023)

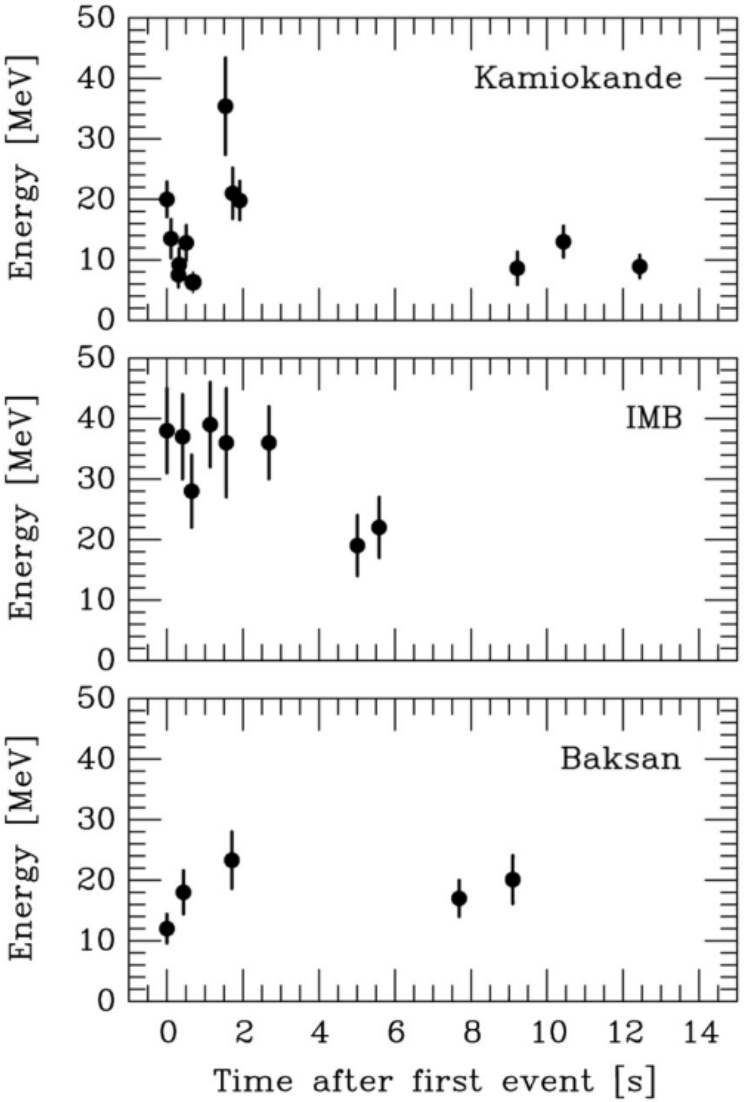
- Neutron star remnant

  Fransson et al. (2024)

- Binary system

  Morris & Podsiadlowski (2007), (2009)

Established track record of neutrino discoveries: SN 1987A



Courtesy of G. Raffelt



- Neutrino detection from SN 1987A:
  - confirmed the core-collapse scenario
  - 99% of the energy emitted in neutrinos
  - best limit at the time on the ν mass

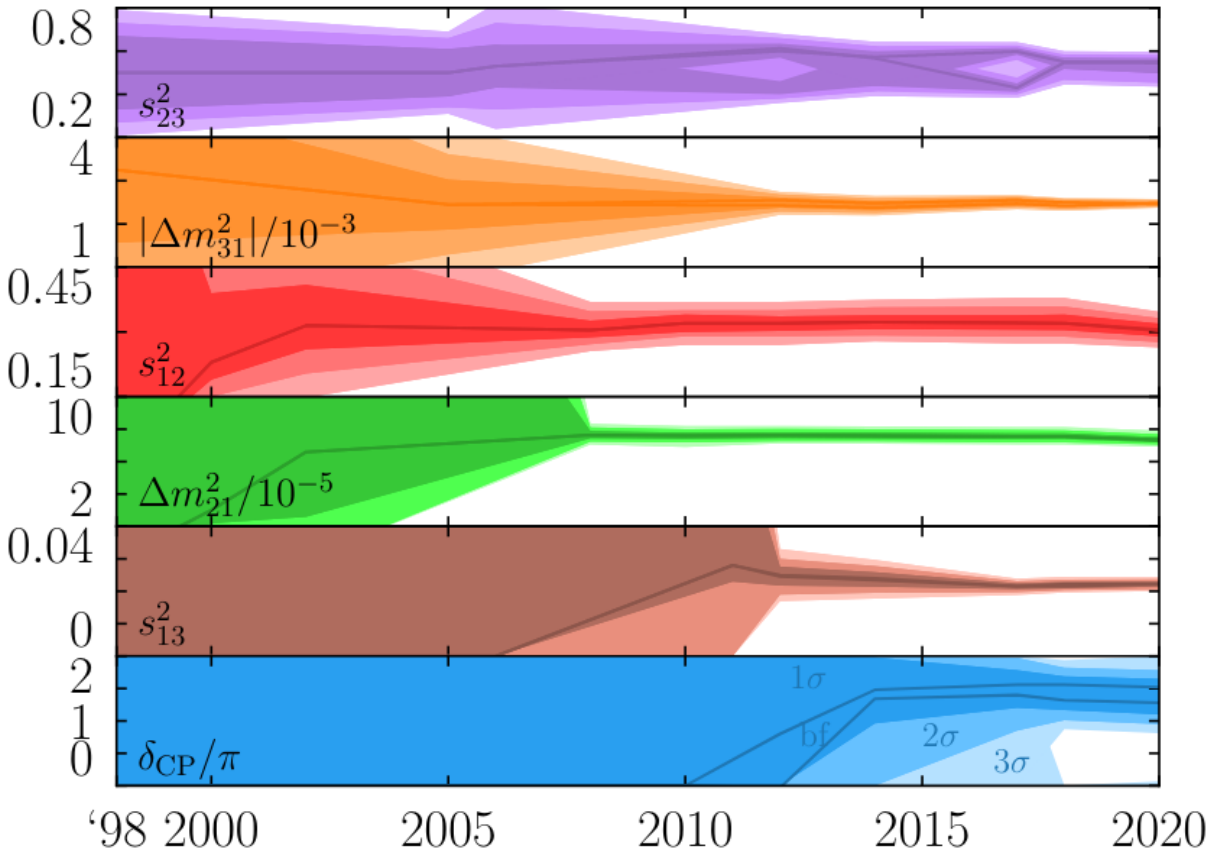
Towards Precise Neutrino Properties Measurements

We known now:

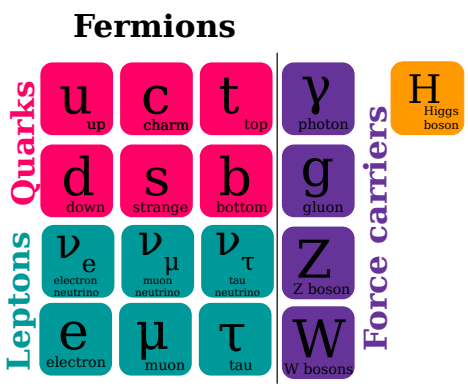
- large mixing angles
- non-zero masses

Remaining questions

- Majorana vs Dirac
- absolute masses
- degree of CP violation
- BSM connection



Snowmass Neutrino Frontier Report (2022)

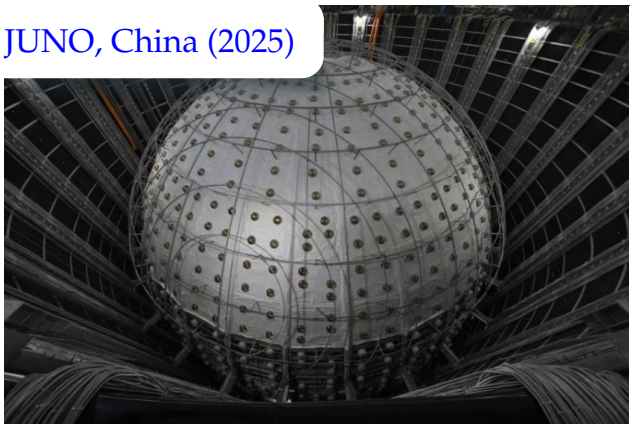


$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \qquad U = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix} \begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix} \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

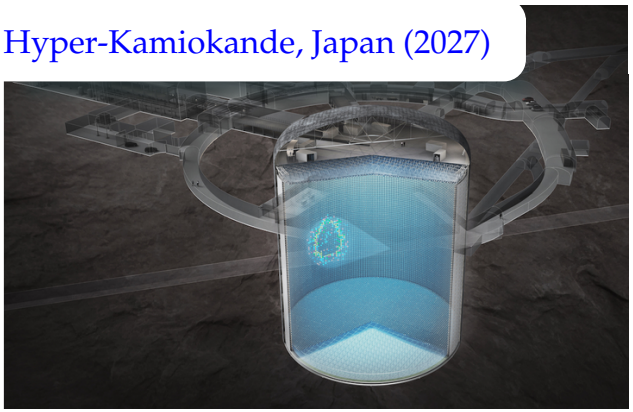
beam, atmospheric — beam, reactor — solar, reactor

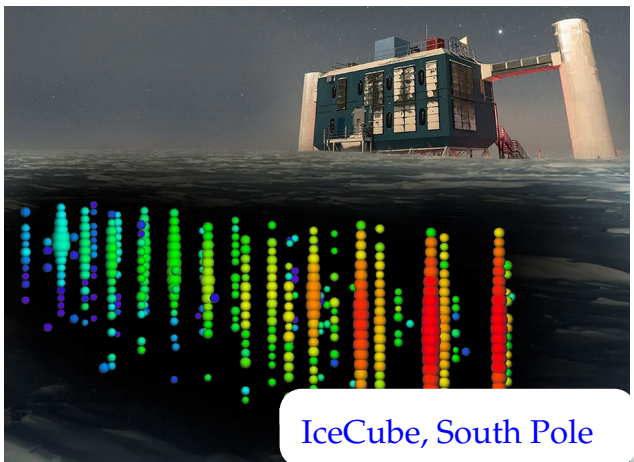
How to achieve full picture of neutrinos? All hands on deck!

JUNO, China (2025)



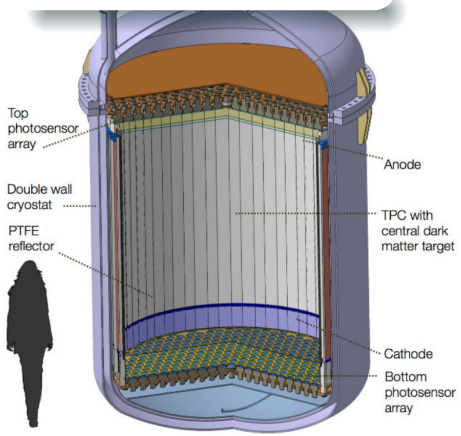
Hyper-Kamiokande, Japan (2027)





IceCube, South Pole

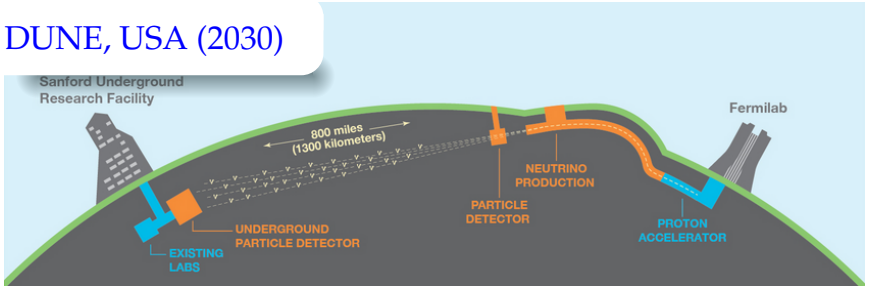
XLZD, DARWIN (20XX)



Rubin Observatory, Chile (2025)



DUNE, USA (2030)



- Many new experiments comimg online soon
- variety of approaches → superb sensitivity

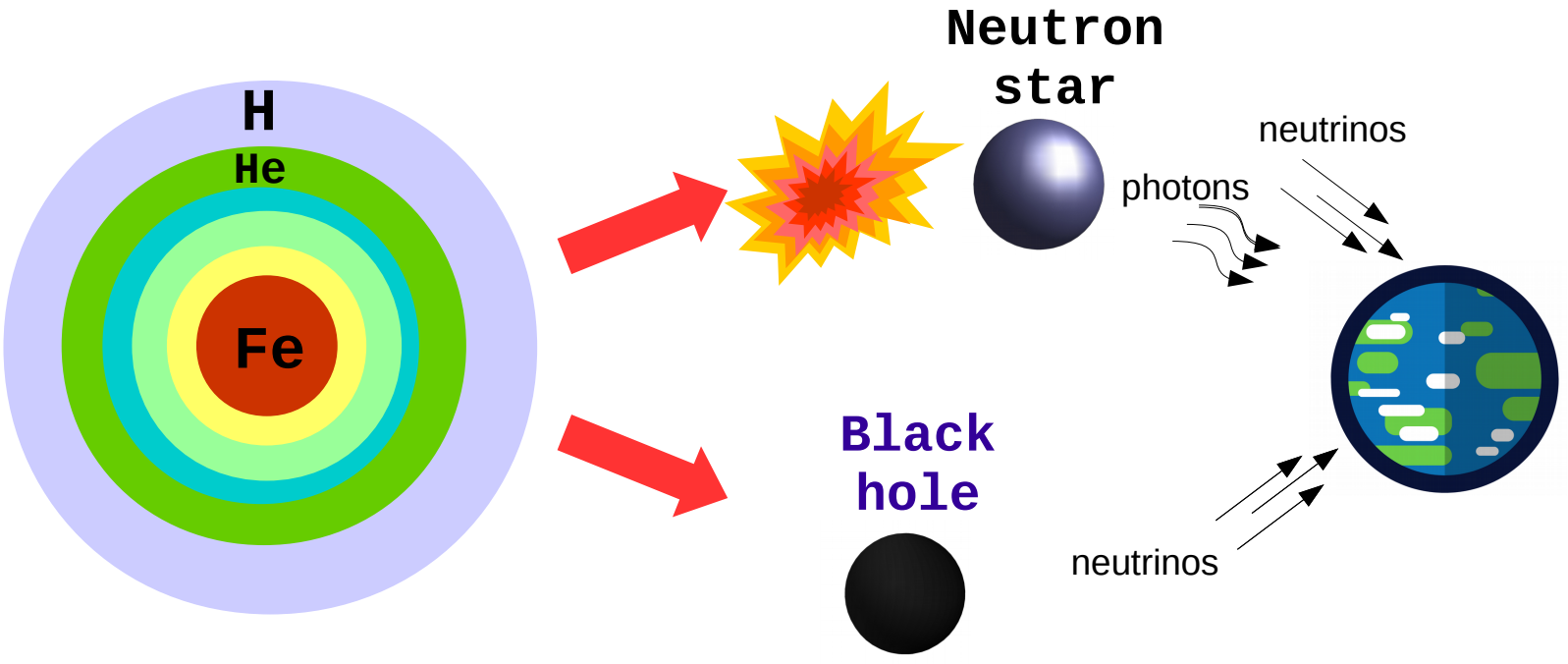
- Complementarity with:
  - reactor and accelerator searches
  - electromagnetic surveys
  - other astrophysical messengers

Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

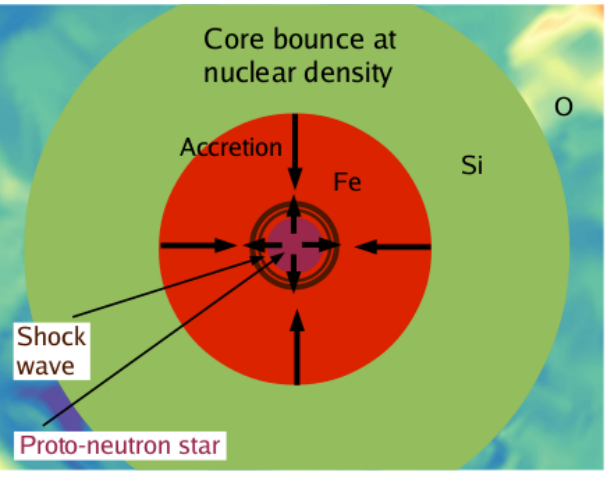
Neutrinos:

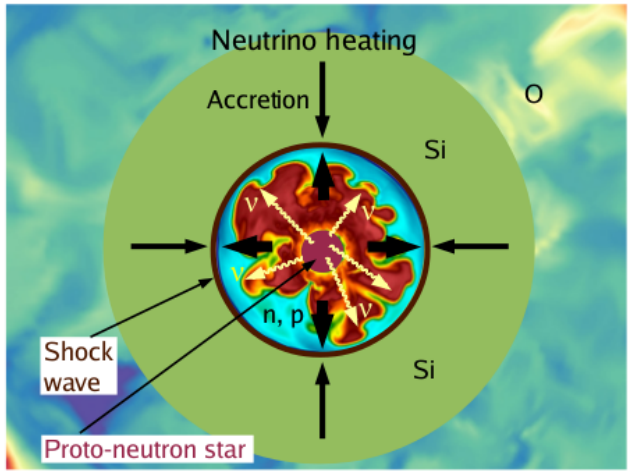
- $\sim 10^{58}$ of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only particles detectable from the collapse to a black hole

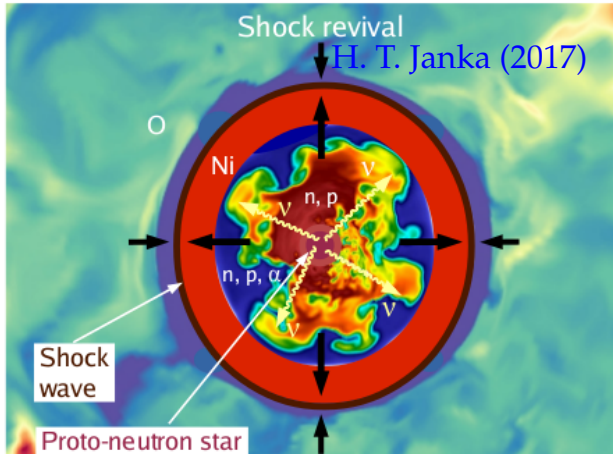


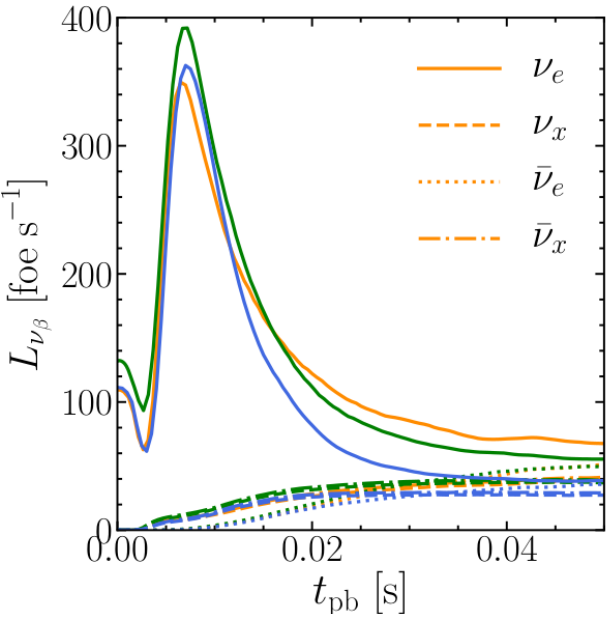
Different Phases of Supernova Explosion

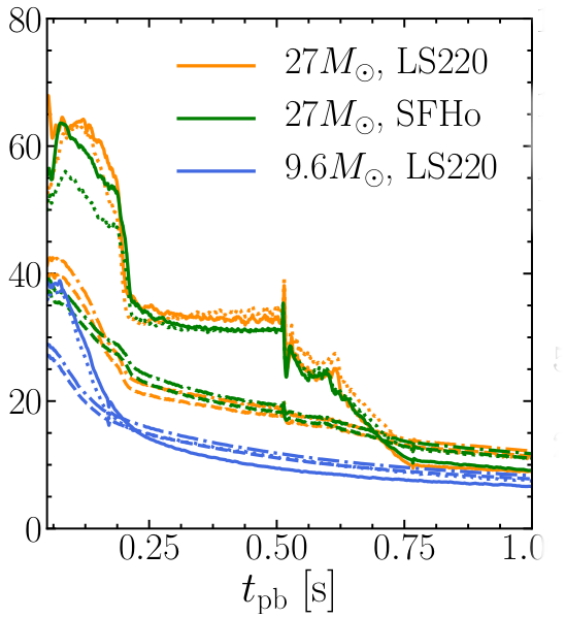
- Infall phase,
  ν_e burst $\sim$ 40 ms
- Accretion phase,
  $\sim$ 100 ms
- Cooling phase,
  $\sim$ 10 s

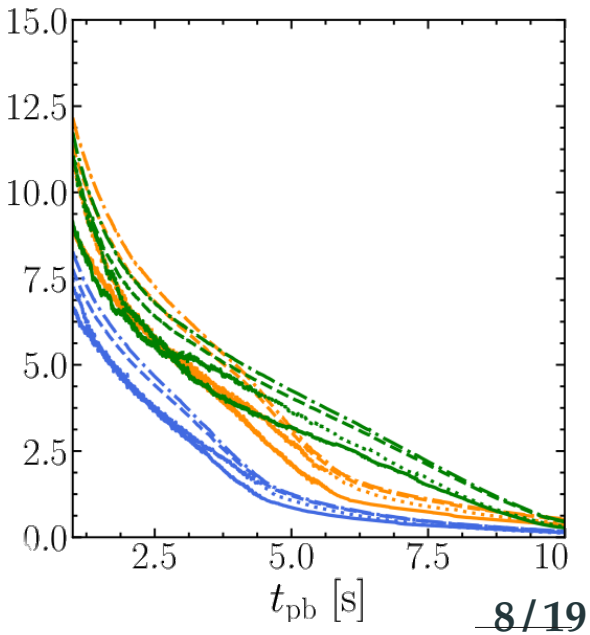












Why core-collapse supernovae are good physics probes?

Advantages

- extreme physical conditions not accessible on Earth
- within the reach of existing and upcoming detectors

What can we learn with a variety of detectors?

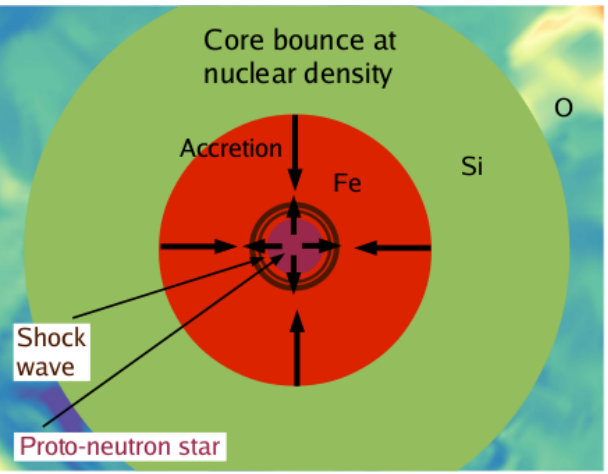
- explosion mechanism — Bethe & Wilson (1985), **AMS** et al. (2022)...
- nucleosynthesis — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino mixing — Balantekin & Fuller (2013), Siwach, **AMS**, Balantekin (2022)...
- non-standard physics — **AMS**, Tamborra, Wu (2020), **AMS** et al. (2024) ...

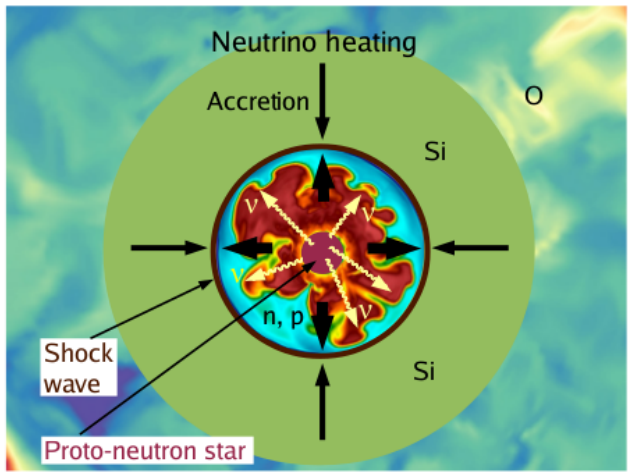
Neutrinos from Supernovae as Probes of New Physics

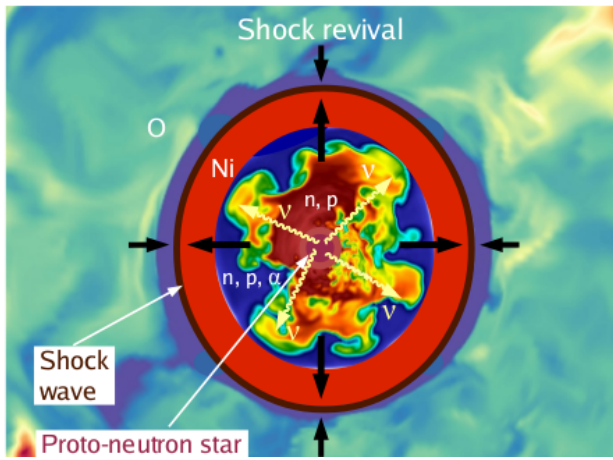
Different Phases of Supernova Explosion

- Infall phase,
  ν_e burst $\sim$ 40 ms
- Accretion phase,
  $\sim$ 100 ms
- Cooling phase,
  $\sim$ 10 s

H. T. Janka (2017)







New neutrino physics affects the core-collapse supernovae:

- change diffusion time $\rightarrow$ possible change in the star's fate
- changed diffusion time $\rightarrow$ changed duration of the neutrino signal
- new cooling channel $\rightarrow$ affects explosion probability

astrophysical feedback often ignored

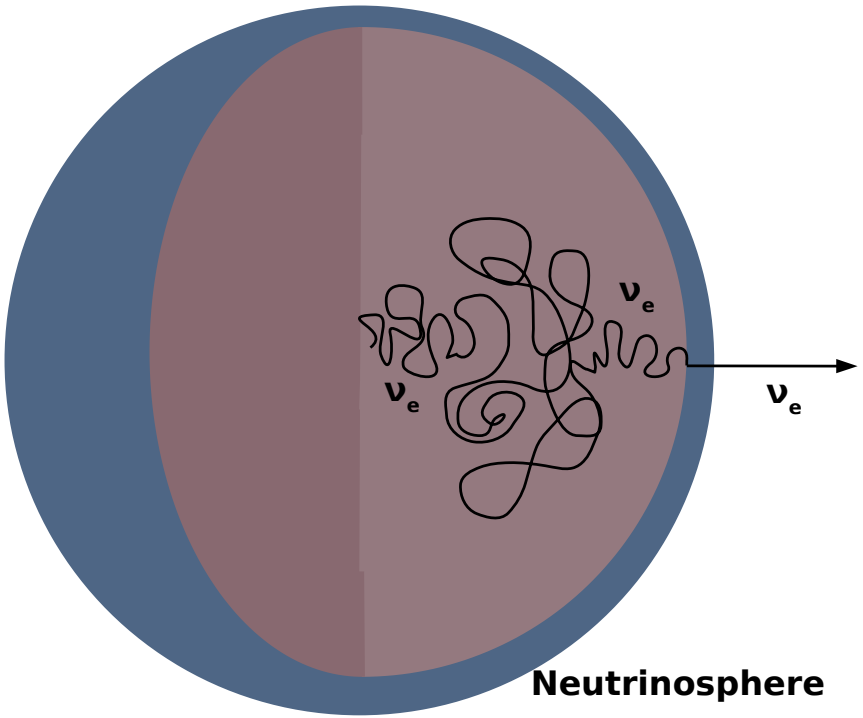
How astrophysical feedback affects the bounds on new physics?

Can we detect non-standard neutrino-quark interactions in supernova neutrino signal?

In collaboration with A. Beatty and V. Takhistov

arXiv: 2509.07856

Neutrino Trapping and $\beta-$equilibrium in the core



Neutrino trapping

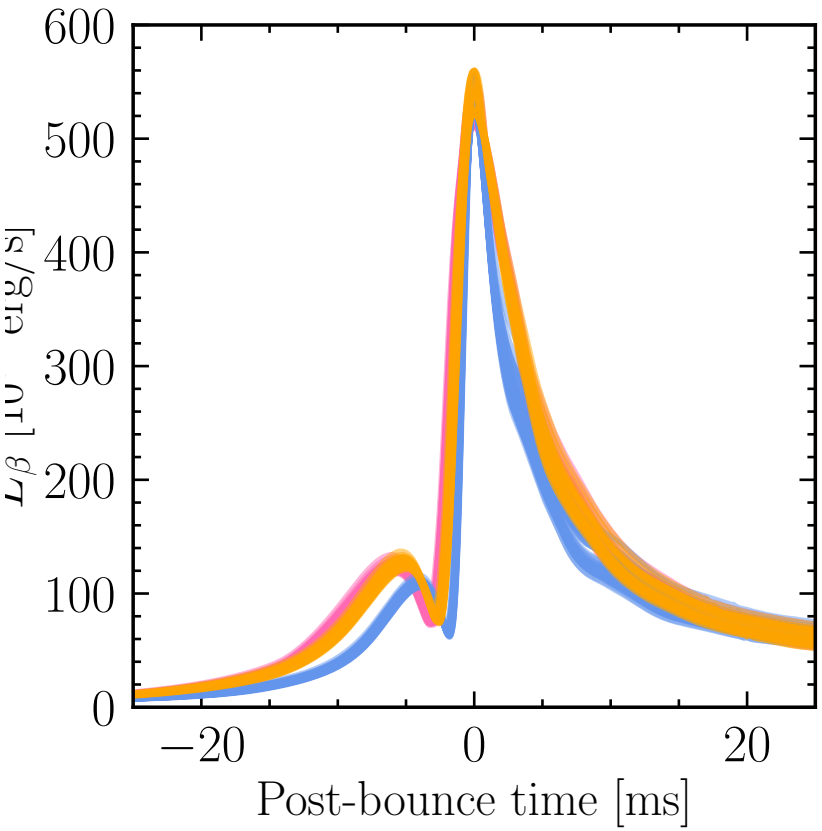
$$A(N,Z) + \nu \rightarrow A(N,Z) + \nu$$

β-equilibrium

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

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

Neutrino Trapping and $\beta-$equilibrium in the core



Neutrino trapping

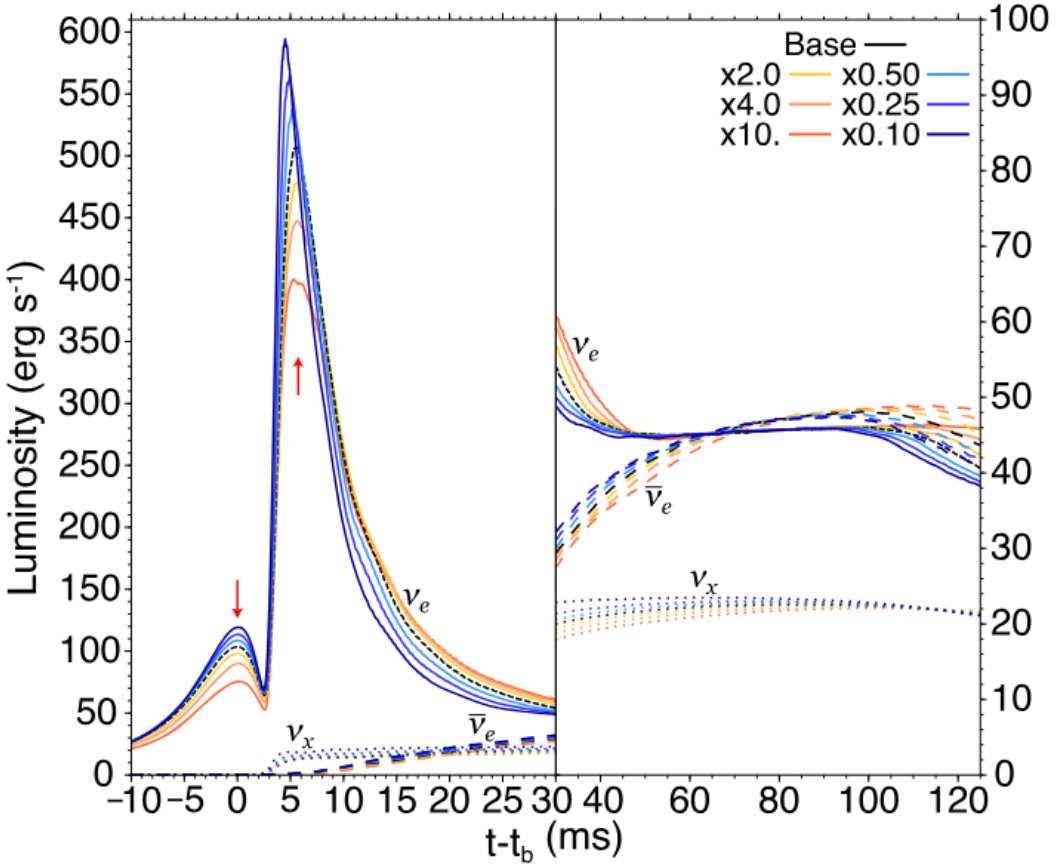
$$A(N,Z) + \nu \rightarrow A(N,Z) + \nu$$

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

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Neutrino Trapping and $\beta-$equilibrium in the core



Sullivan et al. (2016)

Neutrino trapping

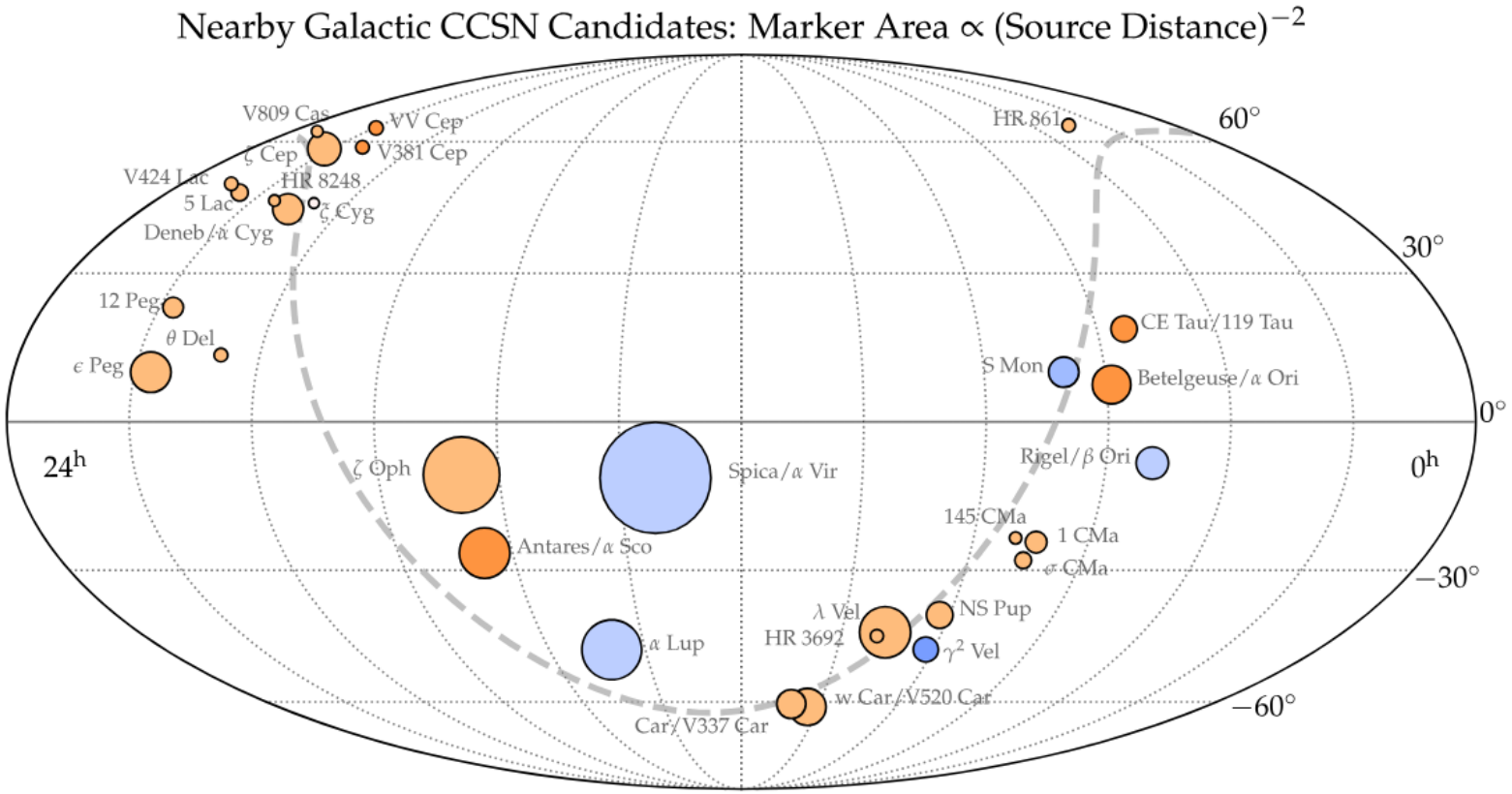
$$A(N,Z) + \nu \rightarrow A(N,Z) + \nu$$

β-equilibrium

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

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

Supernova-ready supergiant stars within ∼1 kpc of Earth



- ∼40 supernova-ready stars within 1 kpc
- best-known Betelgeuse at ∼ 0.2 kpc

SNEWS 2.0 (2021)

Non-standard neutrino-quark interactions

New Interaction Lagrangian

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F\varepsilon^{fV}_{\alpha\alpha}(\overline{\nu}_{\alpha L}\gamma^{\rho}\nu_{\alpha L})(\overline{f}\gamma_{\rho}f)$$

$$\varepsilon^{u(d)} = \varepsilon^{u(d)V}_{ee} = \varepsilon^{u(d)V}_{\mu\mu} = \varepsilon^{u(d)V}_{\tau\tau}$$

New Cross Sections

1. Coherent Elastic Neutrino-Nucleus Scattering

$$\frac{d\sigma_{\nu X}}{dE_r} \approx \frac{G_{\mathrm{F}}^2 m_X}{4\pi} Q_W^2 \left(1 - \frac{m_X E_r}{2E_\nu^2}\right) F^2(Q),$$

$$Q_W = -[N - Z(1 - 4\sin^2(\theta_W)]$$

with NSI $Q_W \to Q'_W = Q_W + Q_W^{\mathrm{NSI}}$

$$Q_W^{\mathrm{NSI}} = 2[Z(2\varepsilon^u + \varepsilon^d) + N(\varepsilon^u + 2\varepsilon^d)]$$

2. Elastic Neutrino-Proton Scattering

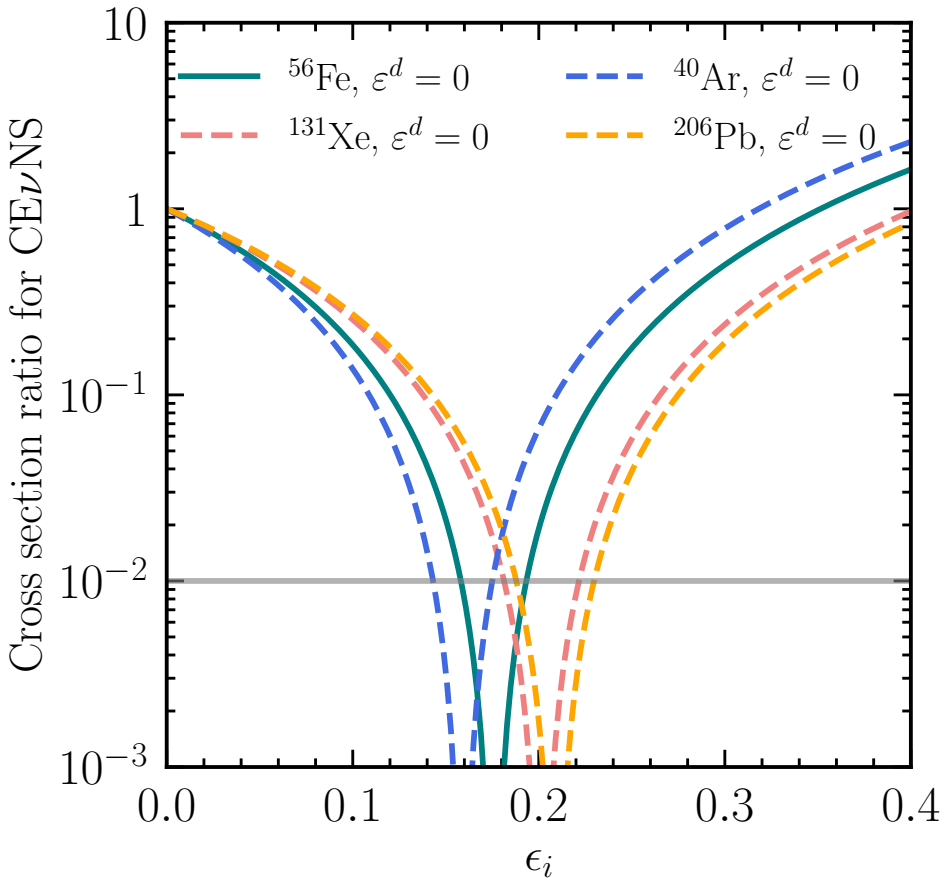
$$\frac{d\sigma_{\nu \mathrm{p}}}{dE_{\mathrm{p}}} \simeq \frac{G_{\mathrm{F}}^2 m_{\mathrm{p}}^2}{2\pi E_\nu^2}\left(BE_\nu^2 + C(E_\nu - E_{\mathrm{p}})^2 - Dm_{\mathrm{p}}E_{\mathrm{p}}\right)$$

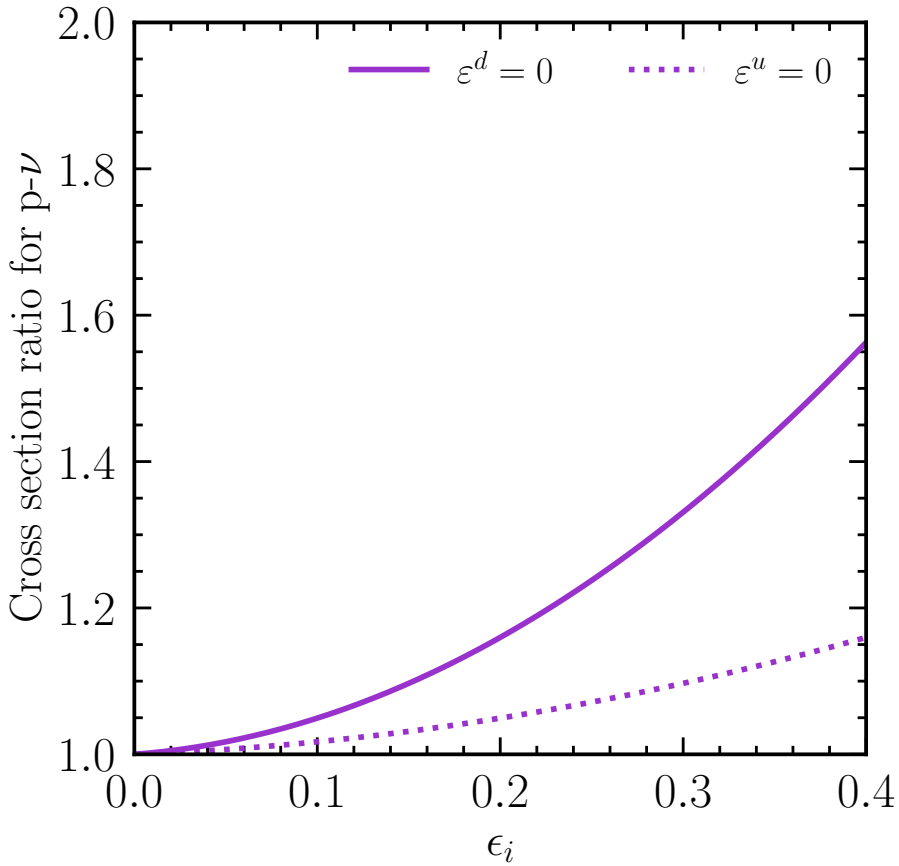
$$B = (c_V + c_A)^2, C = (c_V - c_A)^2, D = (c_V^2 + c_A^2)$$

with NSI $c_V \to c'_V = c_V + \varepsilon^p$

D. Z. Freedman (1973), L. Wolfenstein (1977), B. Dev et al. (2016), Huang et al. (2021)

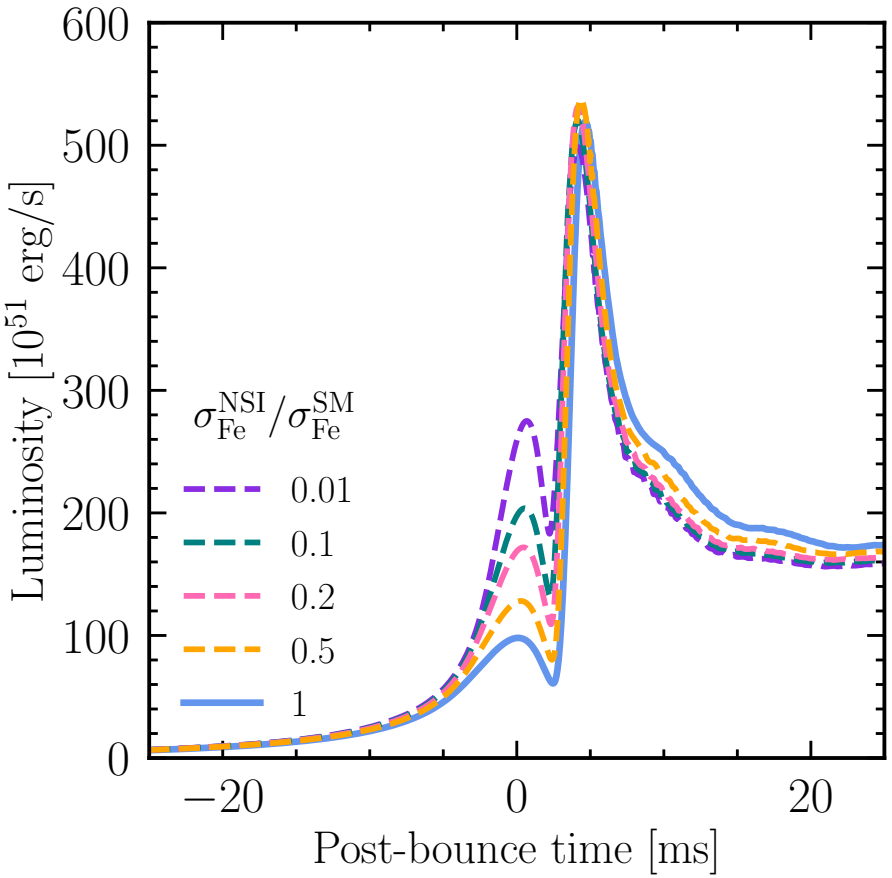
Cross-Section Changes

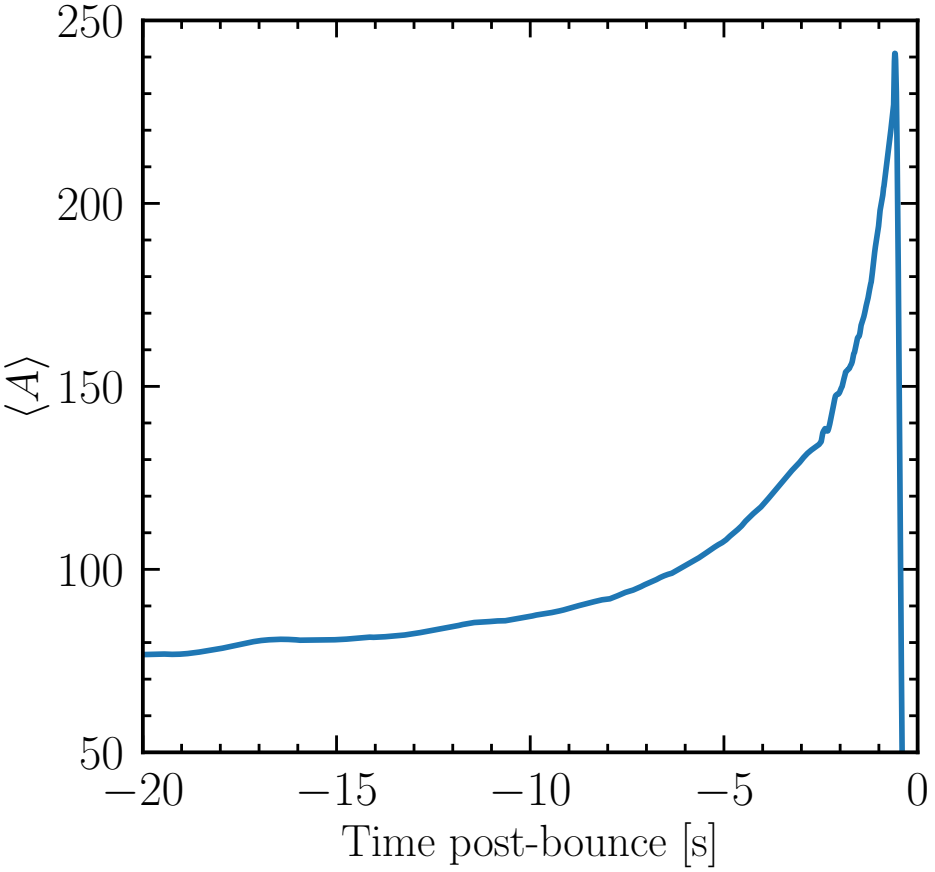




- Extreme changes for CEνNS
- Moderate changes for ν-p scattering

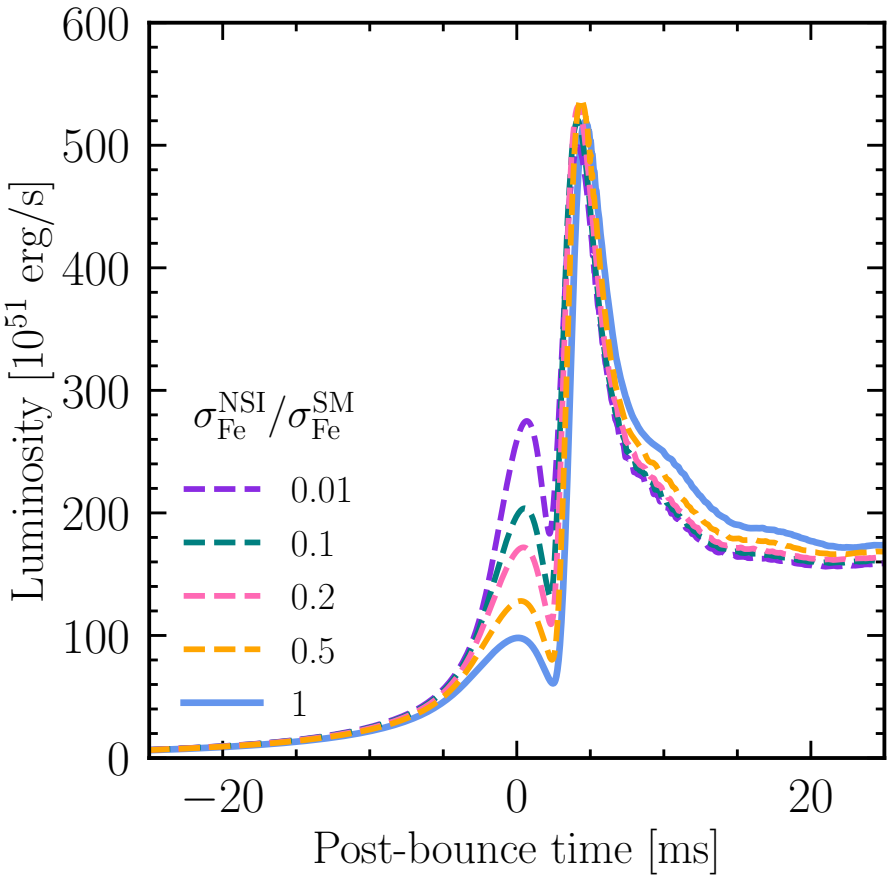
Changes in the neutrino signal: GR1D simulations

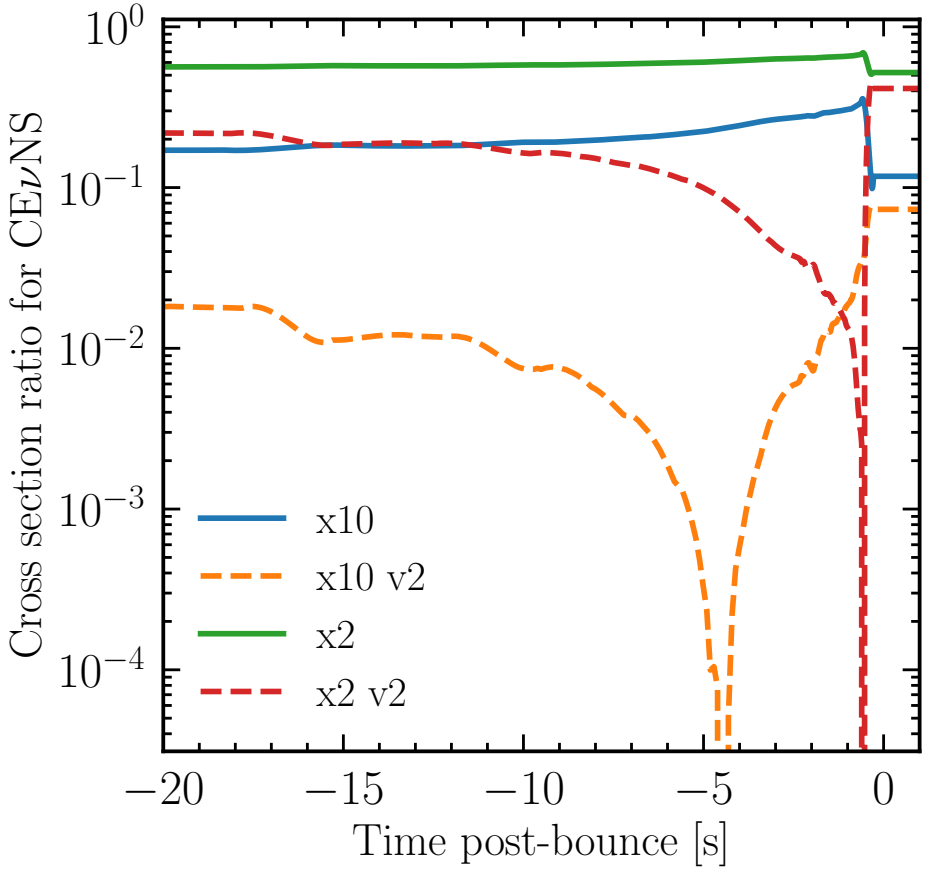




- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

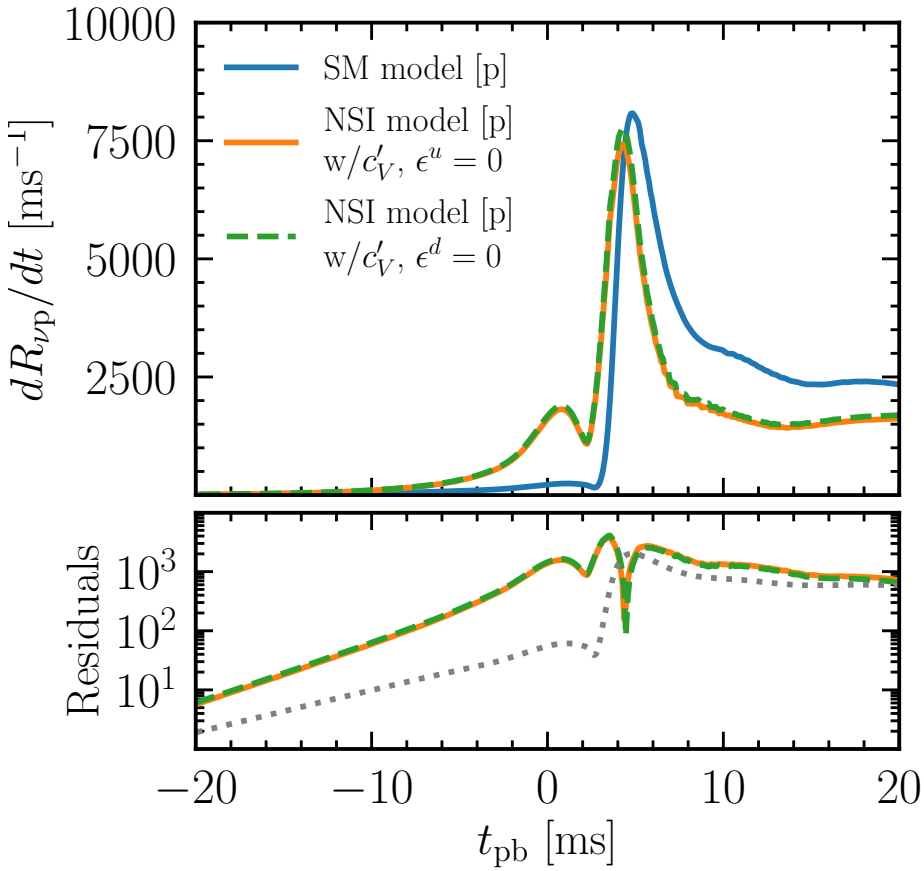
Changes in the neutrino signal: GR1D simulations

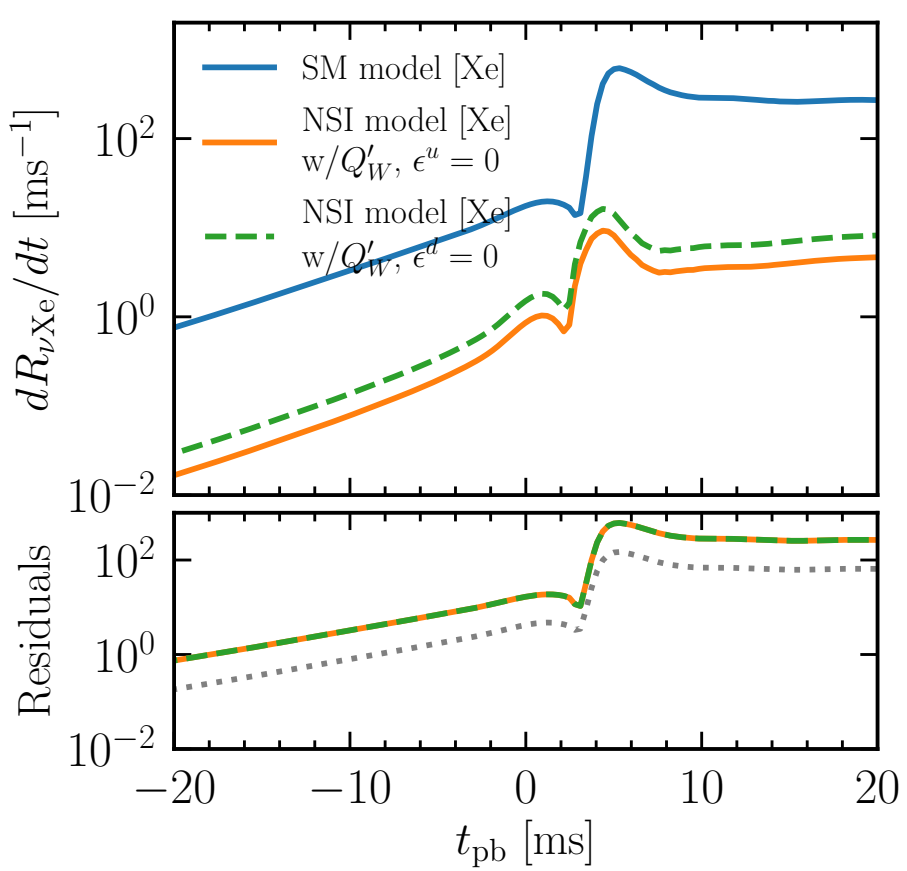




- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

Rates in JUNO and DM detectors for the Betelgeuse



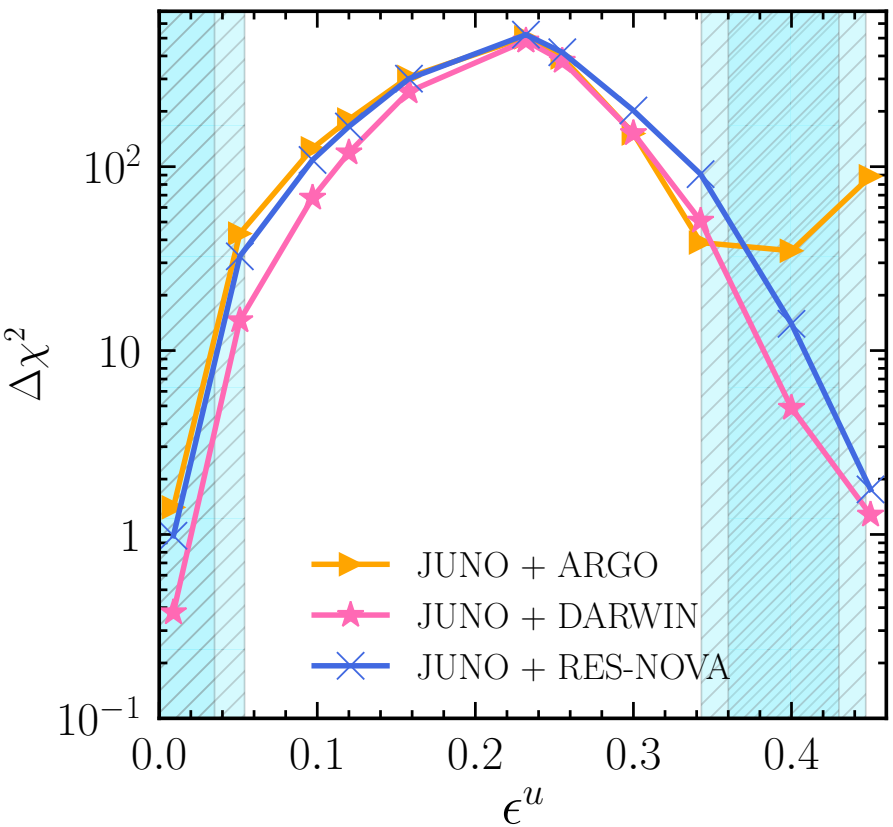


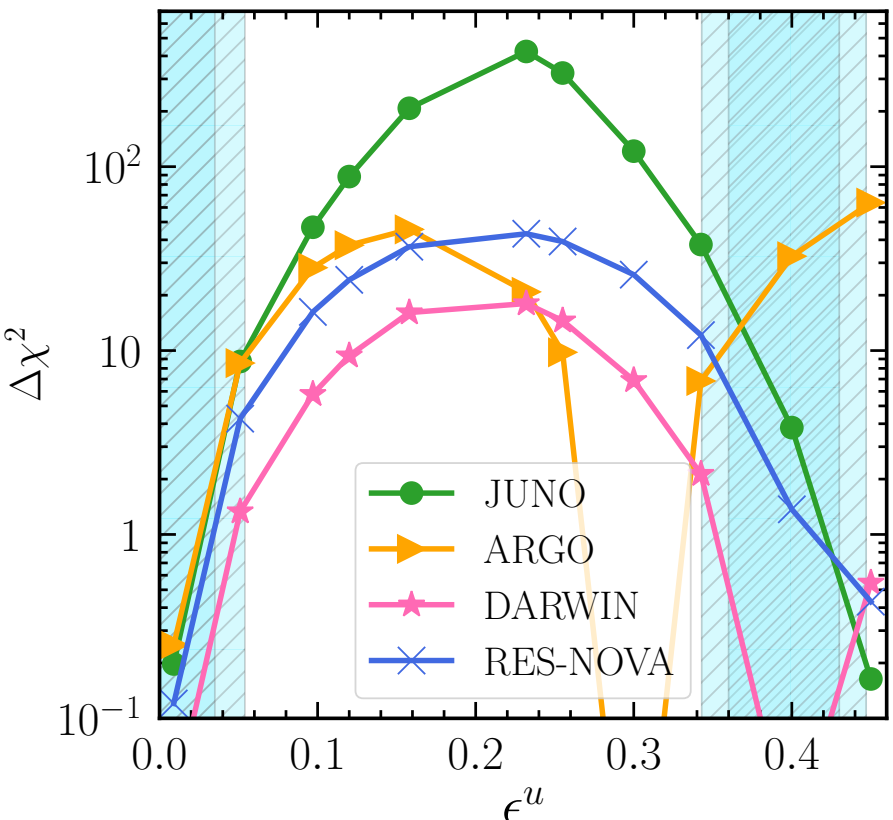
- JUNO - rate changed for the infall signal
- DARWIN - rate changed always
- approximately opposite effects

Detector (Target)	Volume (tons)	Energy Range (keV)
DARWIN (xenon)	40	1-50
RES-NOVA (lead)	465	1-50
ARGO (argon)	300	25-1,000
JUNO (protons)	20,000	200-10,000

Statistical Analysis

$$\Delta\chi^2 = \min_{x,y,z} \left\{ \frac{\left(N_{\rm J}^{\rm SM}\,(1+x)\,(1+y) - N_{\rm J}^{\rm NSI}\right)^2}{N_{\rm J}^{\rm SM}(1+x)(1+y)} + \frac{\left(N_{\rm DM}^{\rm SM}\,(1+x)\,(1+z) - N_{\rm DM}^{\rm NSI}\right)^2}{N_{\rm DM}^{\rm SM}(1+x)(1+z)} + \left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2 \right\}$$





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

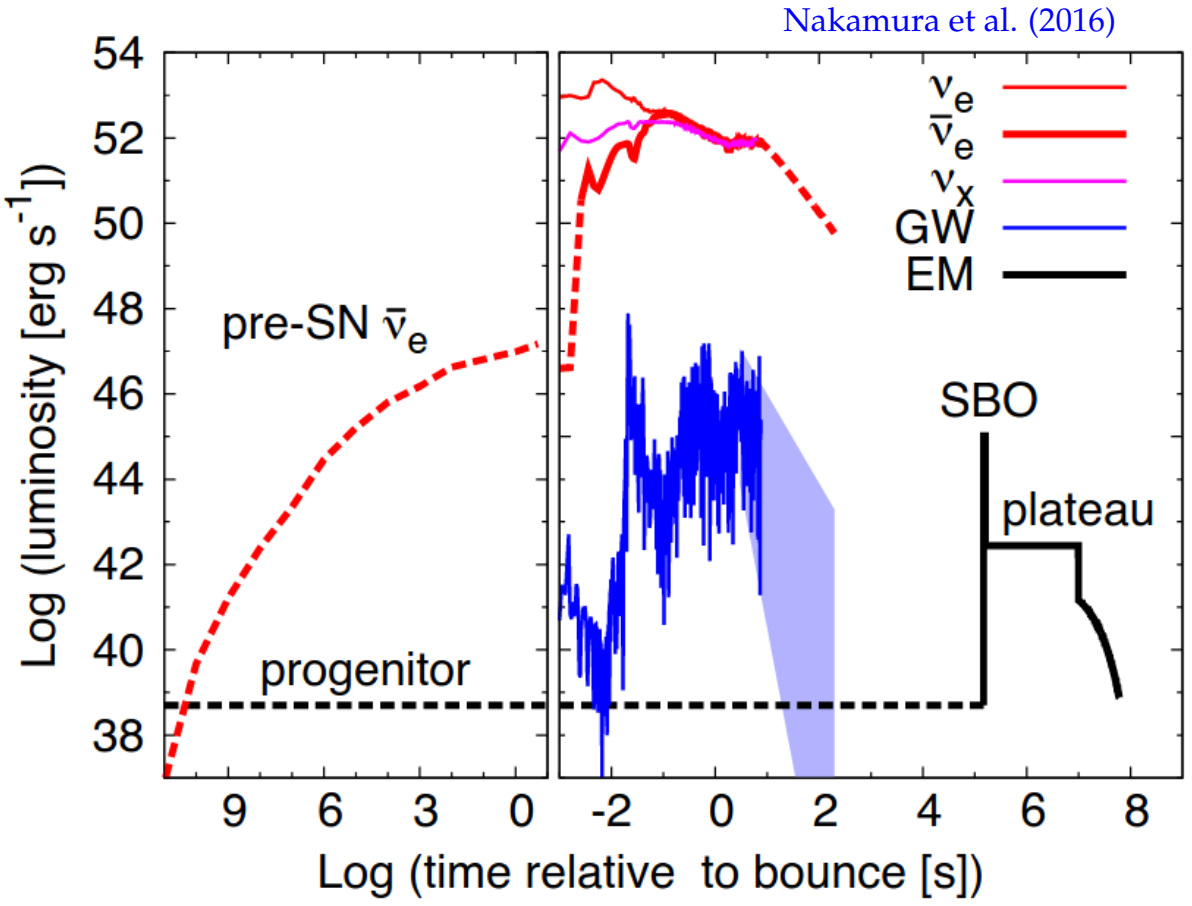
- brings us closer to fully understanding the physics inside the sources
- help us to probe potential new physics scenarios

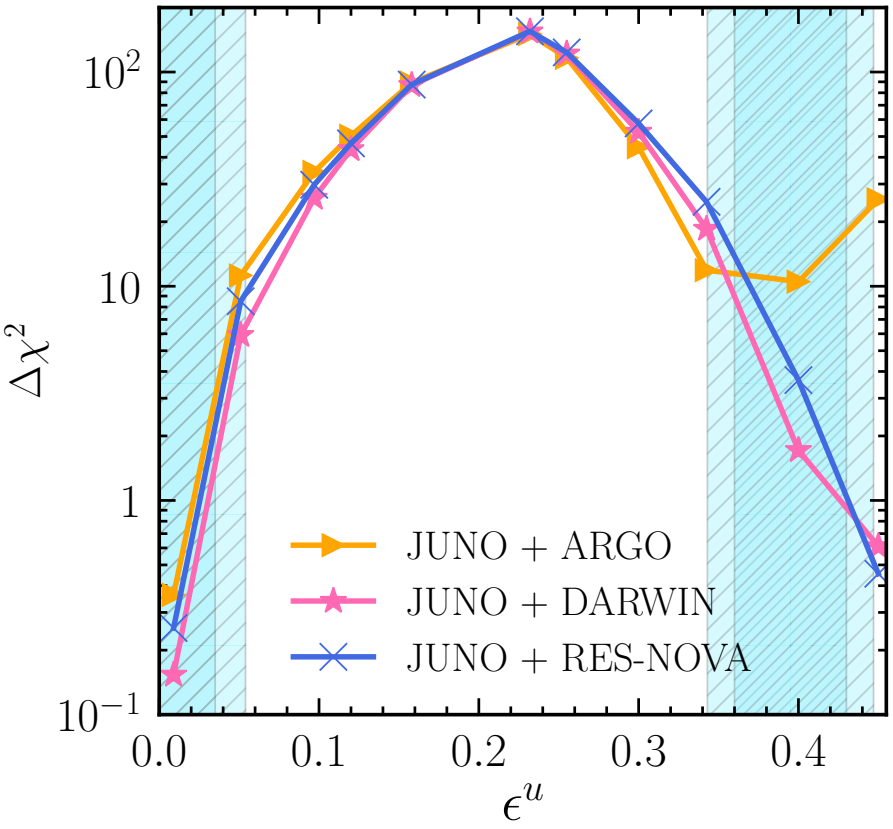
Exciting times ahead

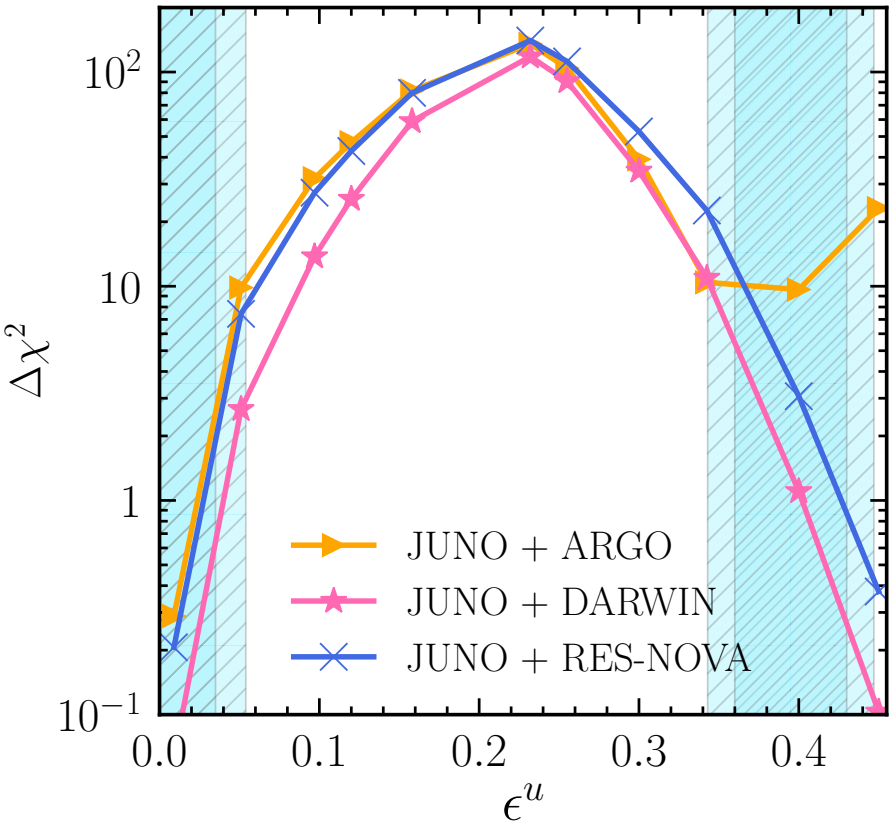
Thank you for the attention!

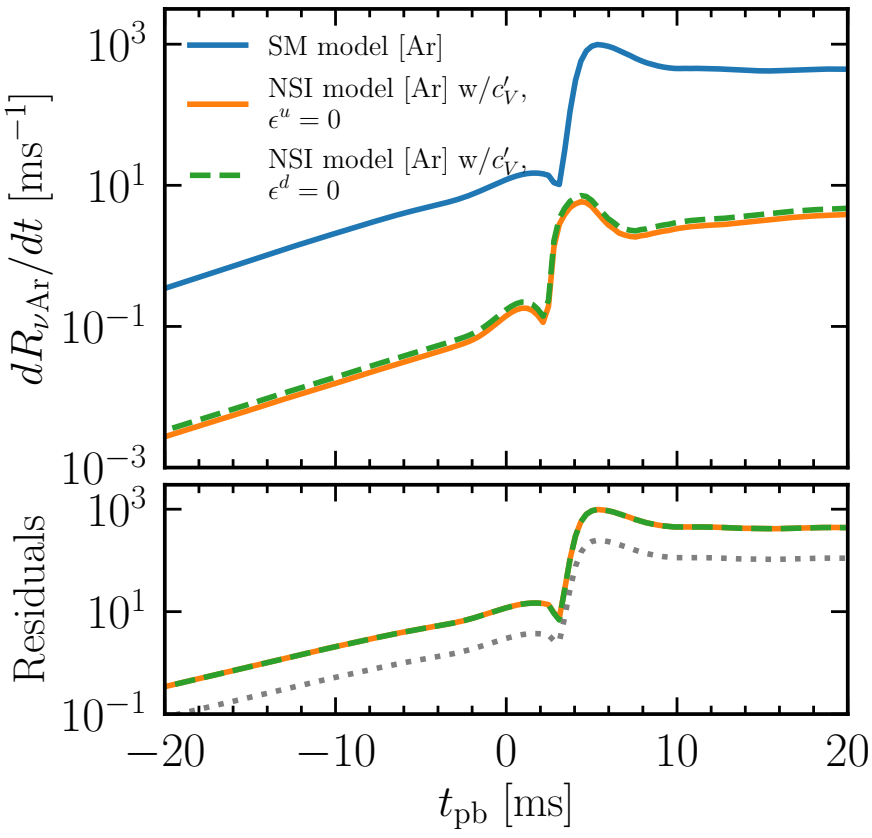
Backup

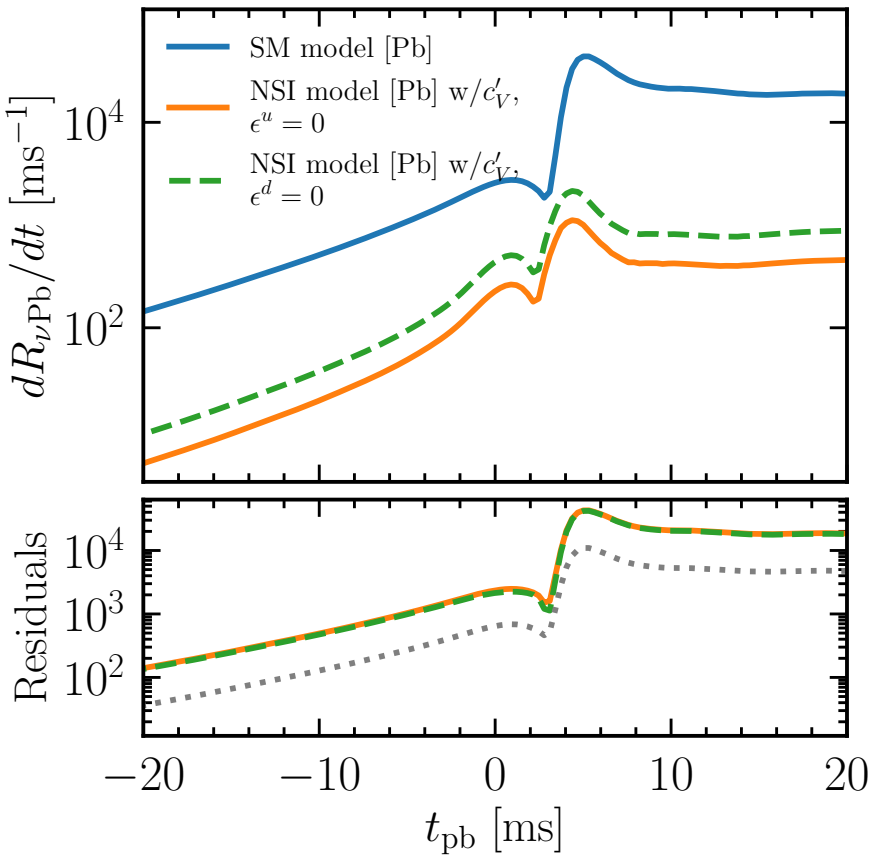
Core-Collapse Supernova Light Curve




10^2
10
1
10^{-1}
$\Delta\chi^2$
0.0
0.1
0.2
0.3
0.4
ϵ^u
JUNO + ARGO
JUNO + DARWIN
JUNO + RES-NOVA


10^2
10
1
10^{-1}
$\Delta\chi^2$
0.0
0.1
0.2
0.3
0.4
ϵ^u
JUNO + ARGO
JUNO + DARWIN
JUNO + RES-NOVA


SM model [Ar]
NSI model [Ar] w/c'_V, $\epsilon^u = 0$
NSI model [Ar] w/c'_V, $\epsilon^d = 0$
$dR_{\nu\mathrm{Ar}}/dt$ [ms^{-1}]
Residuals
t_{pb} [ms]


SM model [Pb]
NSI model [Pb] w/c'_V, $\epsilon^u = 0$
NSI model [Pb] w/c'_V, $\epsilon^d = 0$
$dR_{\nu\mathrm{Pb}}/dt$ [ms^{-1}]
Residuals
t_{pb} [ms]