Neutrinos from beyond the solar system

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Discovery potential at ~10 MeV scale

- Future astrophysical neutrino searches: energy windows

- The medium-energy window (~10-40 MeV): opportunities
  - Astrophysics
  - Particle physics

- Discussion

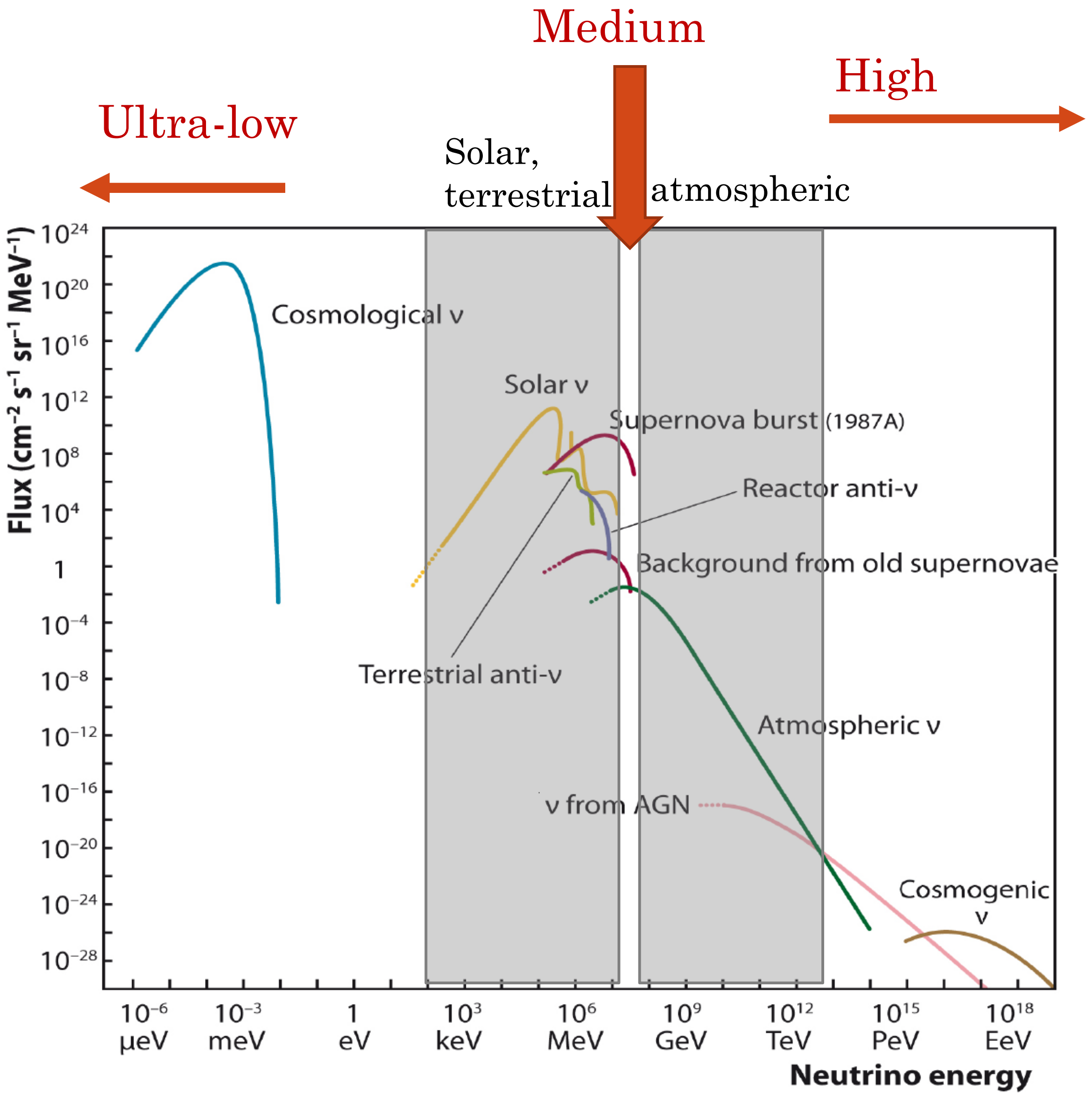
Future astrophysical neutrino searches: energy windows and detectors

Energy windows

- Looking for *continuous* astrophysical fluxes

- Solar, terrestrial and atmospheric neutrinos are *background!*

- Low-background regions:
  - Ultra-low (< eV)
  - Medium (~10 MeV)
  - High (> 10 TeV)

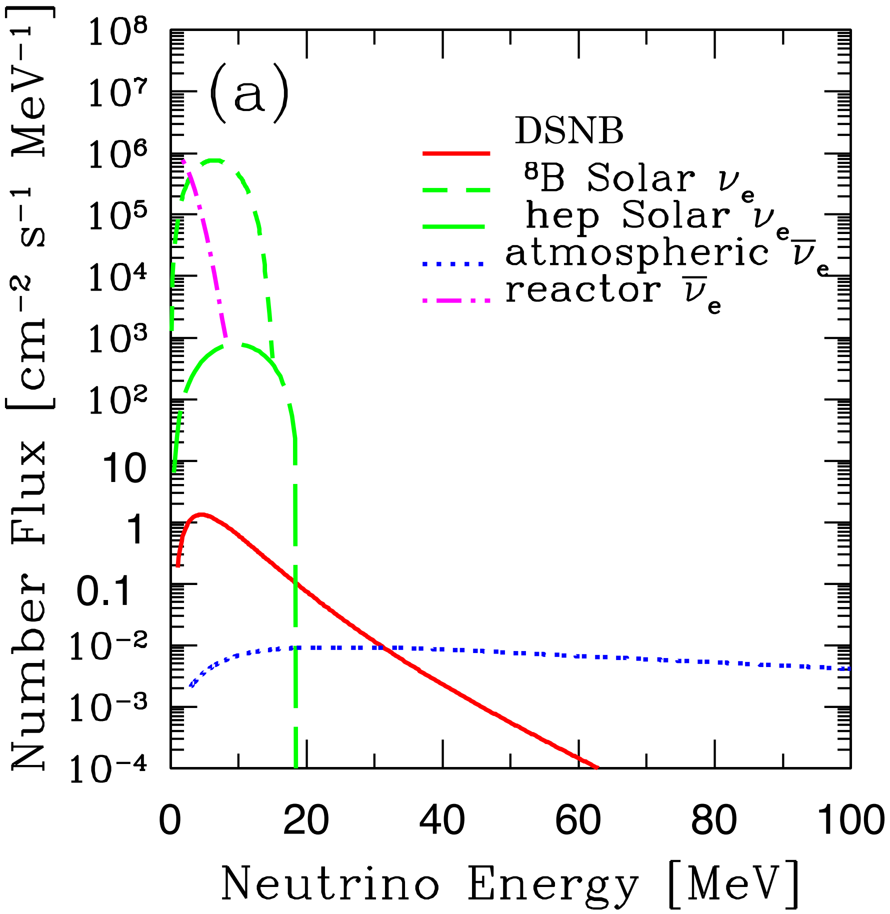


Katz, U.F. *et al.* Prog.Part.Nucl.Phys. 67 (2012) 651-704

The medium-energy window: 10-40 MeV

- Main goal: the ***Diffuse Supernova Neutrino Flux*** (or **B**ackground **DSNB**)

- SuperKamiokande bounds are background-limited
  - Atmospheric muons
  - Atmospheric NC
  - Spallation
  - …



Ando & Sato, New J.Phys. 6 (2004)

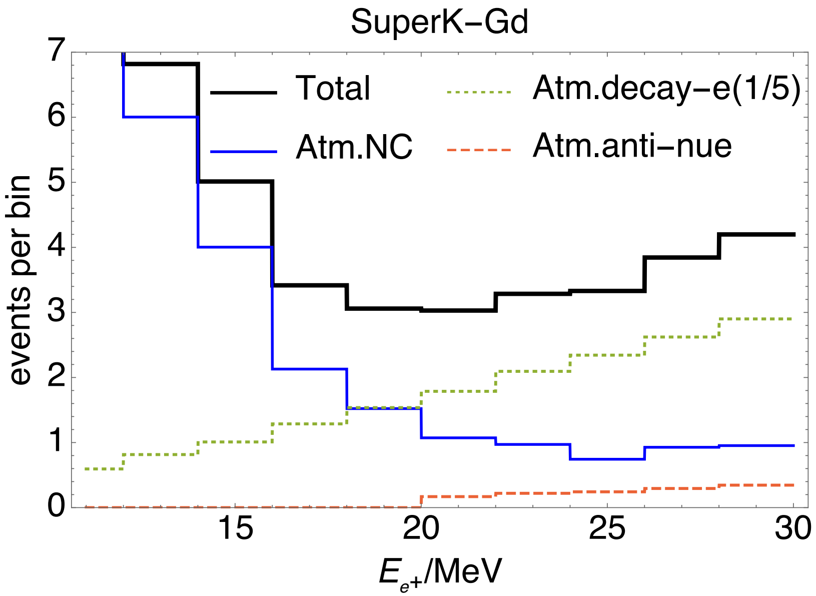
Under construction: large, *clean* detectors

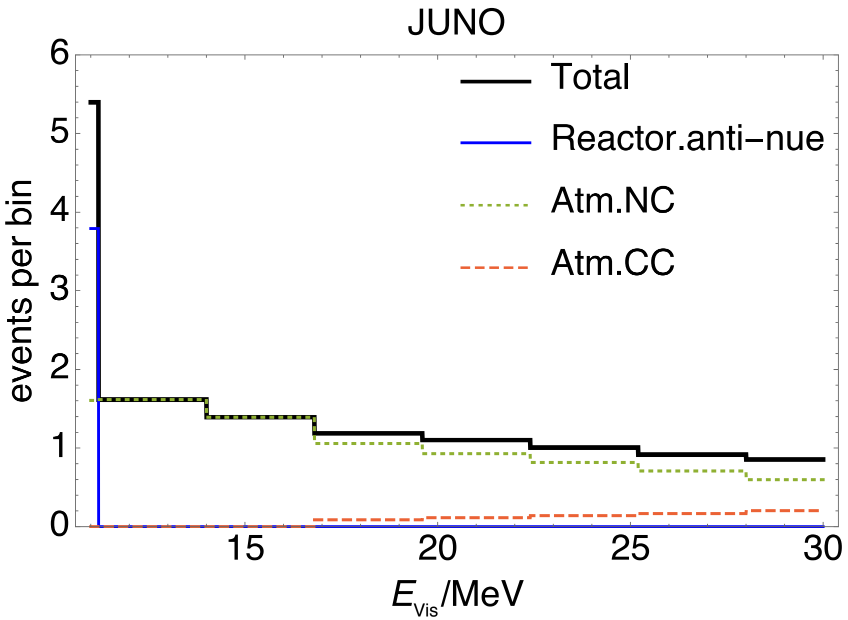
- Main channel: $\bar{\nu}_e + p \to n + e^+$
    - n-tagging is key!

- **SuperK-Gd** (50 kt)
    - Water + Gadolinium
    - *specifically* designed for medium-energy window

- **JUNO** (Jiangmen Underground Neutrino Observatory) (17 kt)
    - Liquid scintillator

Background-only, 10 years:





SuperK collab.; H. Kunxian, Ph.D. Thesis, Kyoto University.
An et al., J. Phys. G, 43 (2016) 030401

Figures from A. Priya and CL, JCAP 1711 (2017) no.11, 031

The medium-energy window: opportunities

Astrophysics

Physics of the DSNB

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{M_0}^{M_{\max}} \overset{\substack{\text{Progenitor mass}\\ \downarrow}}{dM} \int_0^{z_{\max}} dz\, \frac{\overset{\substack{\text{SN rate}\\ \downarrow}}{\dot{\rho}}_{SN}(z,M)\overset{\substack{\textit{Propagated}\text{ neutrino flux}\\ \downarrow}}{F}_{\nu_\beta}(E',M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

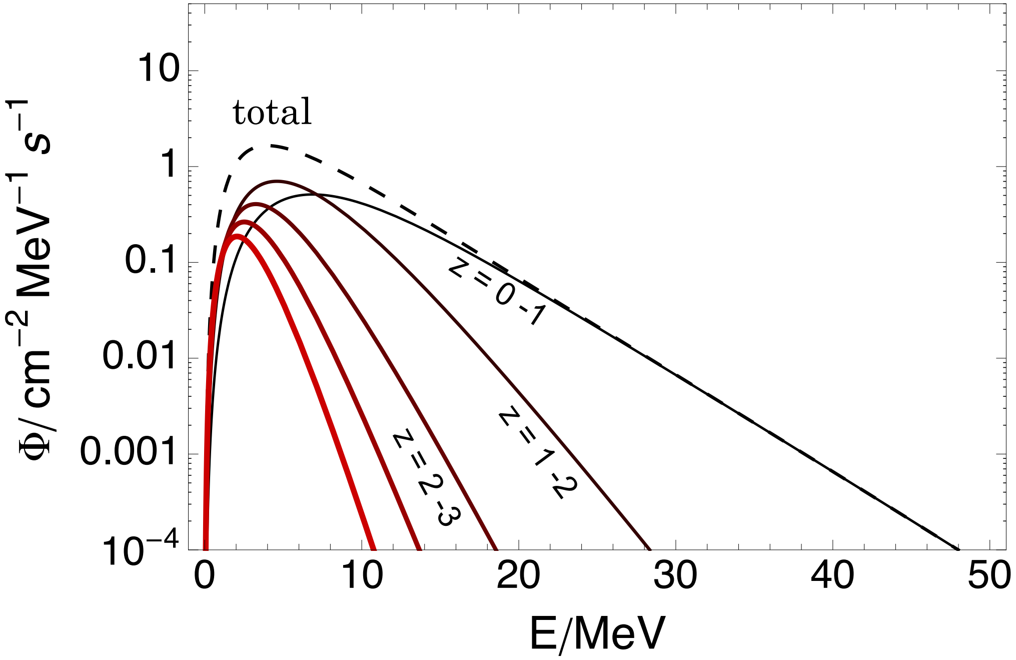
$$M_0 \simeq 8M_{sun}$$
$$M_{max} \simeq 125M_{sun}$$

- test neutrino emission scenario: $E_{tot} \sim 3\ 10^{53}$ ergs, quasi-thermal spectra, T ~ 3-6 MeV

- *Direct* test of rate of core collapse: more SNe in the past!
  - Tracks star formation rate, proportional to $(1+z)^3$

Why is the DSNB interesting?

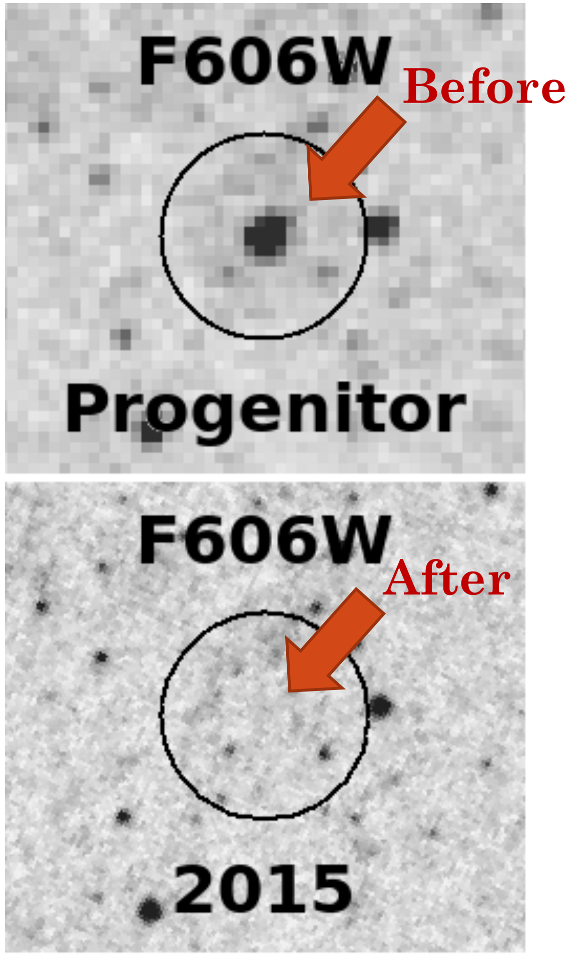
- *Continuous* flux, no waiting time!
  - Next SN neutrino detection after SN1987A?
- Strong *cosmological* component
- Gives image of the *whole* SN population
  - What is a *typical* neutrino emission?
  - Rare SN types?



Hypothesis: *failed* supernovae

- collapse *directly* into a black hole, *no explosion!*
  - ~10 - 40% of SN candidates
- Supported by:
  - numerical simulations
  - Problem of missing red supergiants
  - Evidence of a disappearing star (a "survey about nothing")

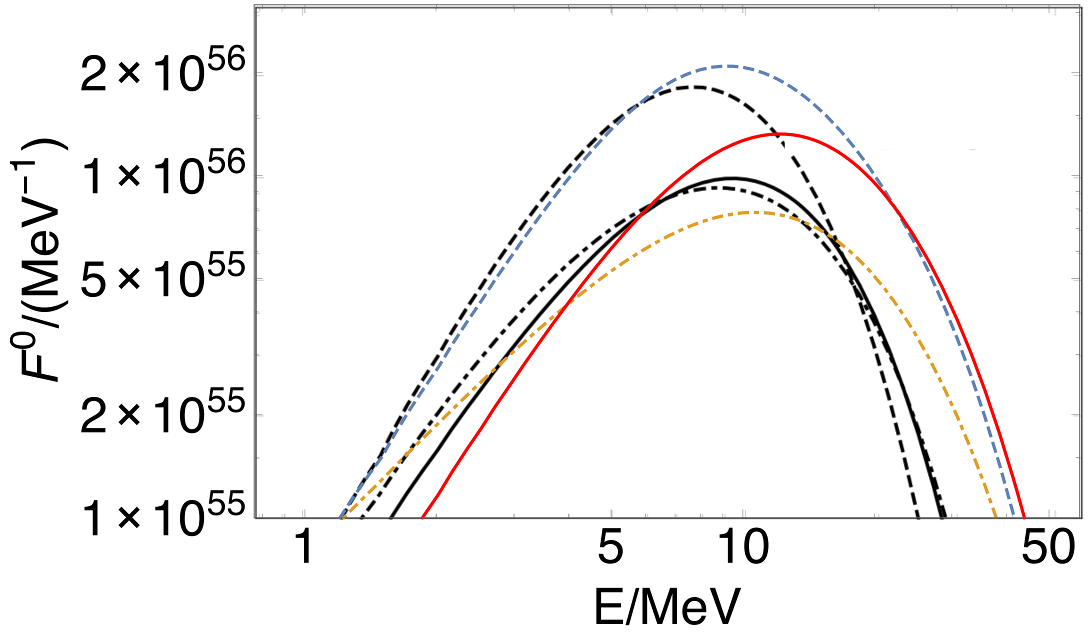
Horiuchi et al., MNRAS Lett. 445 (2014) L99
Kochanek, ApJ 785 (2014) 28
Kochanek et al. ApJ 684 (2008) 1336
Adams et al., MNRAS, 468, 4, p. 4968-4981



Adams et al., MNRAS, 468, 4, p. 4968-4981

Neutrinos from a failed supernova

- Failed supernovae are *brighter* in neutrinos
  - Higher luminosity, hotter spectrum

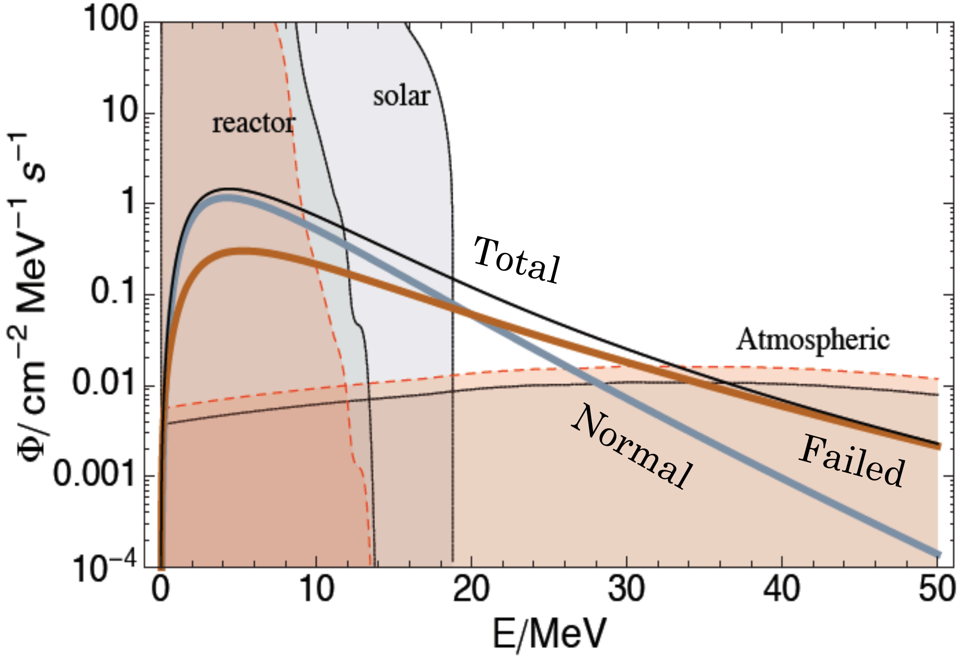


Simulation by Garching group, 2013.

Black: exploding SN, 11.2 Msun prog.;
Color: failed SN, 40 Msun prog.
dashed, solid, dot-dashed: ν_e, $\bar{\nu}_e$ and ν_x

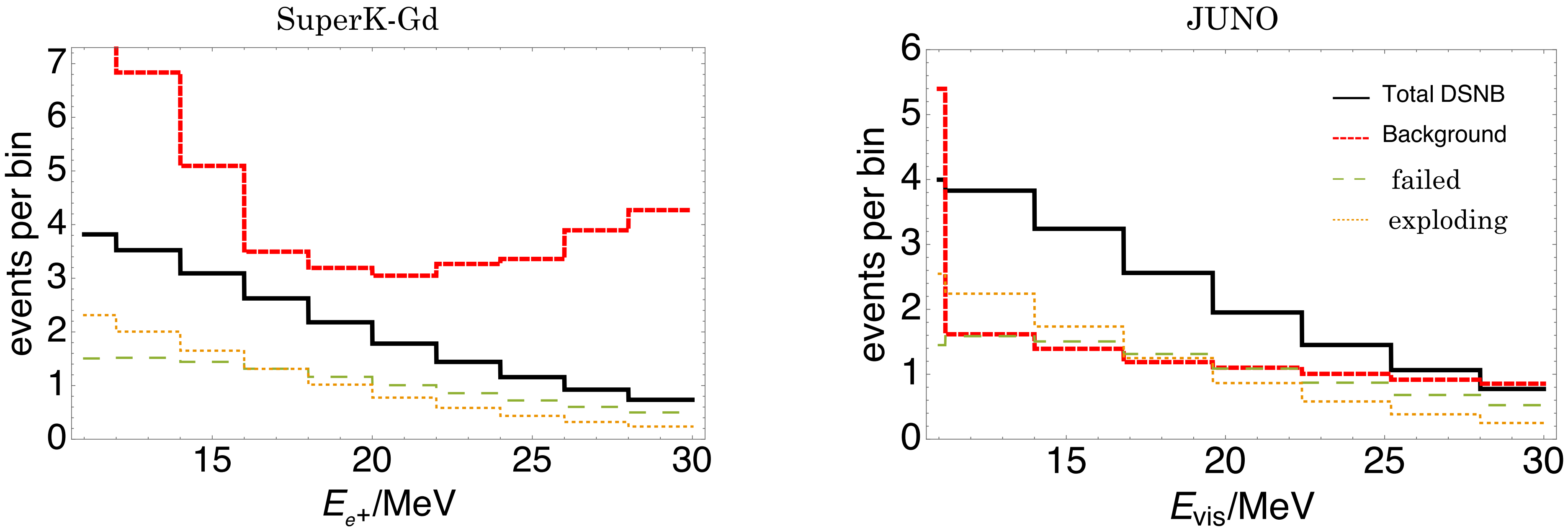
Figure from A. Priya and CL, JCAP 1711 (2017) no.11, 031

- Black-hole forming collapses can *dominate* the DSNB
  - If they account for ~30% or more of all SNe (i.e., all stars above ~ $20M_{sun}$)



CL, PRL 102 (2009);
Lien et al., PRD81 (2010);
Keehn & CL, PRD85 (2012);
Mathews et al., arXiv:1405.0458,
A. Priya and CL, JCAP 1711 (2017) no.11, 031

- Detectability:



A. Priya and CL, JCAP 1711 (2017) no.11, 031

The medium-energy window: opportunities

Particle physics

New physics effects

- **effects on the DSNB**
  - Propagation over *cosmological* distances!
  - Sensitive to new physics that builds up over time/distance: decay, absorption, etc.

- **Non-DSNB**: O(10) MeV neutrinos from other sources
  - Dark Matter annihilation/decay
  - Other

DSNB with neutrino decay

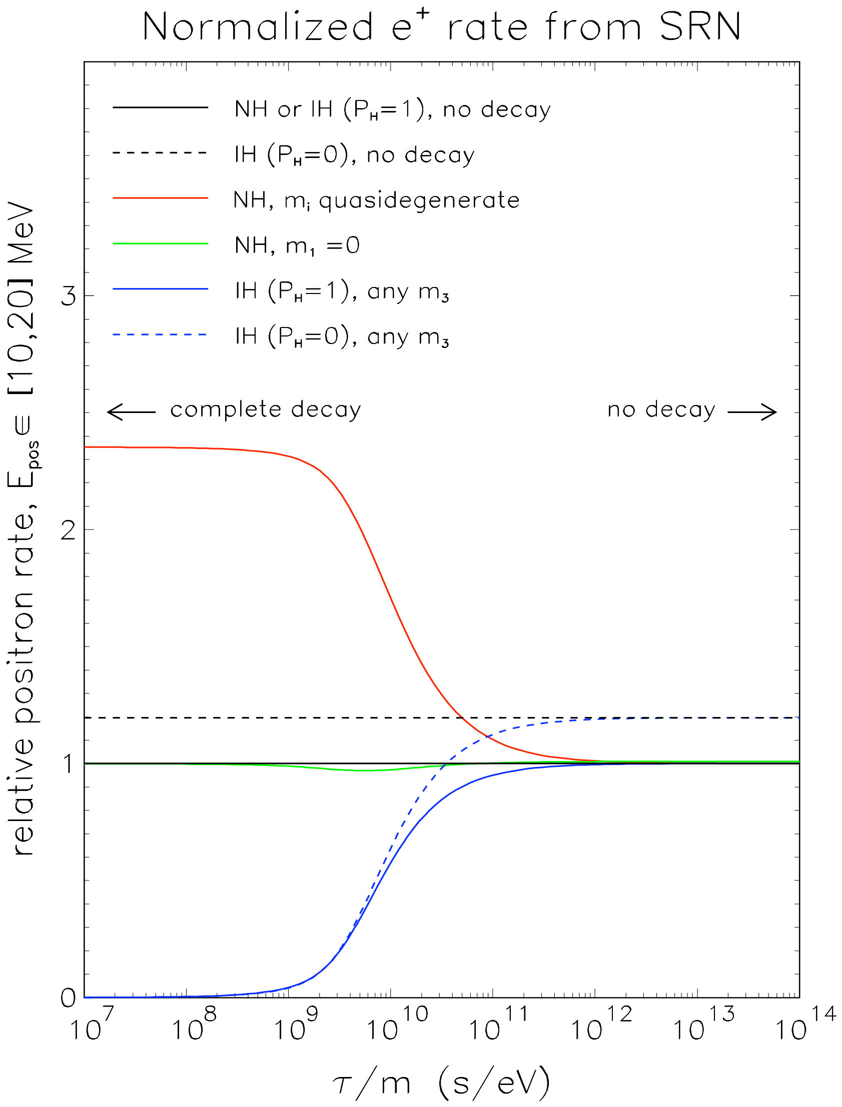
- invisible decay into the lightest mass eigenstate:
  - Enhancement or suppression of ν_e signal, depending on mass hierarchy

  - for complete decay:

hierarchy	meaning	ν_e mixing	effect on ν_e detection rate
Normal	$m_i \geq m_1$	$\lvert U_{e1} \rvert^2 \sim 0.68$	enhancement
Inverted	$m_i \geq m_3$	$\lvert U_{e3} \rvert^2 \sim 0.02$	suppression

$$f_{\mathrm{decay}}^{\mathrm{weak}} = \frac{3|U_{ei}|^2}{\sum_j |U_{ej}|^2} = \begin{cases} 3|U_{e1}|^2 \approx 2.03 & \mathrm{NH}\,,\ i=1 \\ 3|U_{e3}|^2 \approx 0.068 & \mathrm{IH}\,,\ i=3 \end{cases}$$

- Sensitivity to $\tau/m \sim 10^{10}$ s/eV
  - Current (model-independent): $\tau/m > 10^{5}$ s/eV



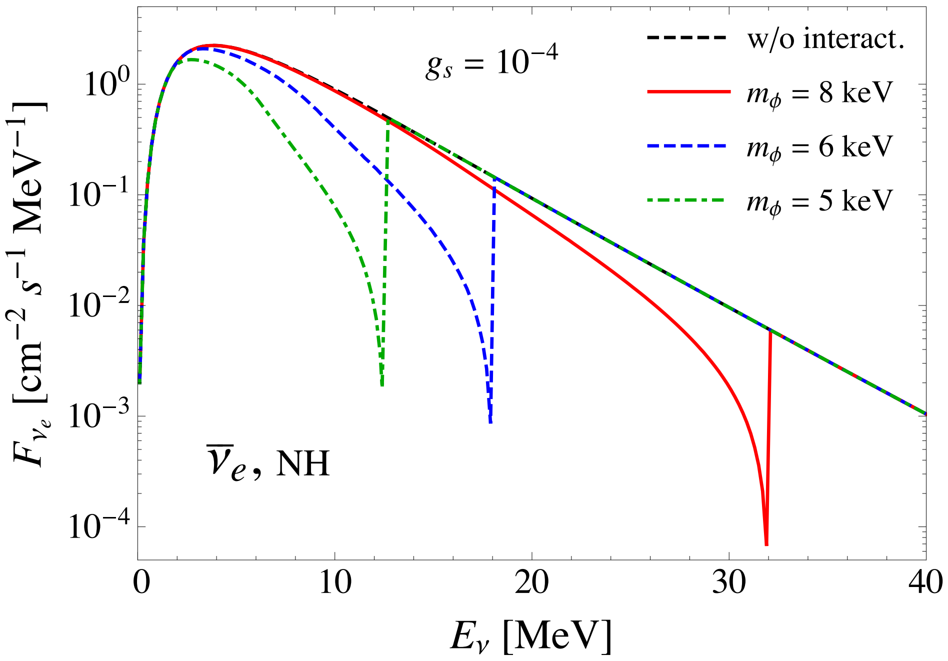
Ando, Phys. Lett. B 570 (2003) 11
Fogli, Lisi, Mirizzi and Montanino, Phys. Rev. D 70 (2004)

DSNB with neutrino absorption

- Dips due to resonant scattering on *light Dark Matter*, via *light mediators*
- Examples:
  - Scattering off the cosmological relic neutrino background, via Z' gauge bosons
  - Scattering off dark matter in models with radiatively-generated neutrino masses
  - Scattering off sterile neutrinos with “secret” interactions

Goldberg, Perez and Sarcevic, JHEP 11 (2006) 023
Baker, Goldberg, Perez and Sarcevic, Phys. Rev. D76 (2007) 063004
Farzan and Palomares-Ruiz, JCAP 1406 (2014) 014
Jeong, Palomares-Ruiz, Reno and Sarcevic, arXiv:1803.04541

- Dips are wide due to redshift distribution of SNe

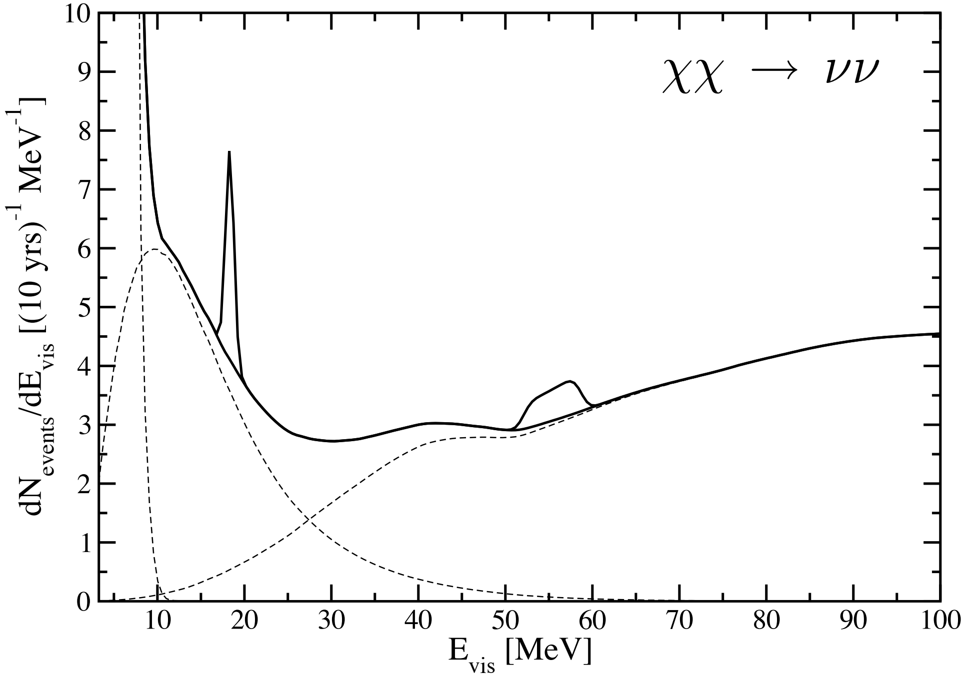


Jeong, Palomares-Ruiz, Reno and Sarcevic, arXiv:1803.04541

Non-DSNB: neutrinos from Dark Matter

- Annihilation of M ~ O(10-100) MeV DM into neutrinos
  - Galactic flux

- Secondaries from WIMP annihilation in the Sun



Palomares-Ruiz and Pascoli, Phys. Rev. D 77 (2008) 025025
Palomares-Ruiz, Phys. Lett. B 665 (2008) 50
Bernal, Martn-Albo and Palomares-Ruiz, J. Cosmol. Astropart. Phys. 1308 1928 (2013) 011

- WIMP decay into neutrinos in the Early Universe: $X \to \nu + Y$

$$Y_X \equiv \left[\frac{n_X}{s}\right]_{t \ll \tau_X}$$

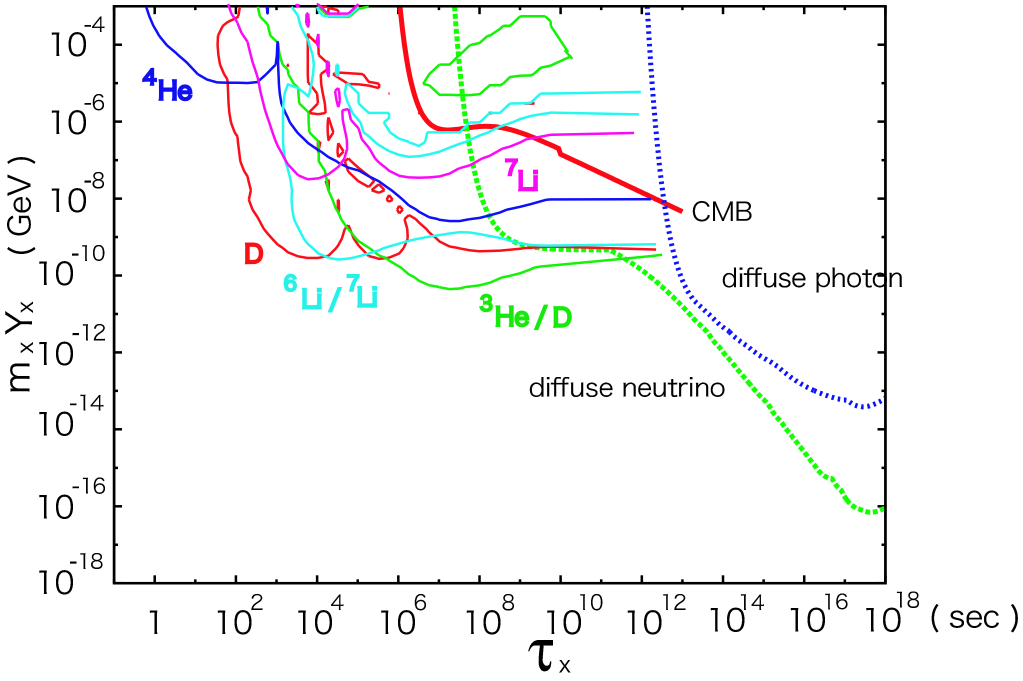
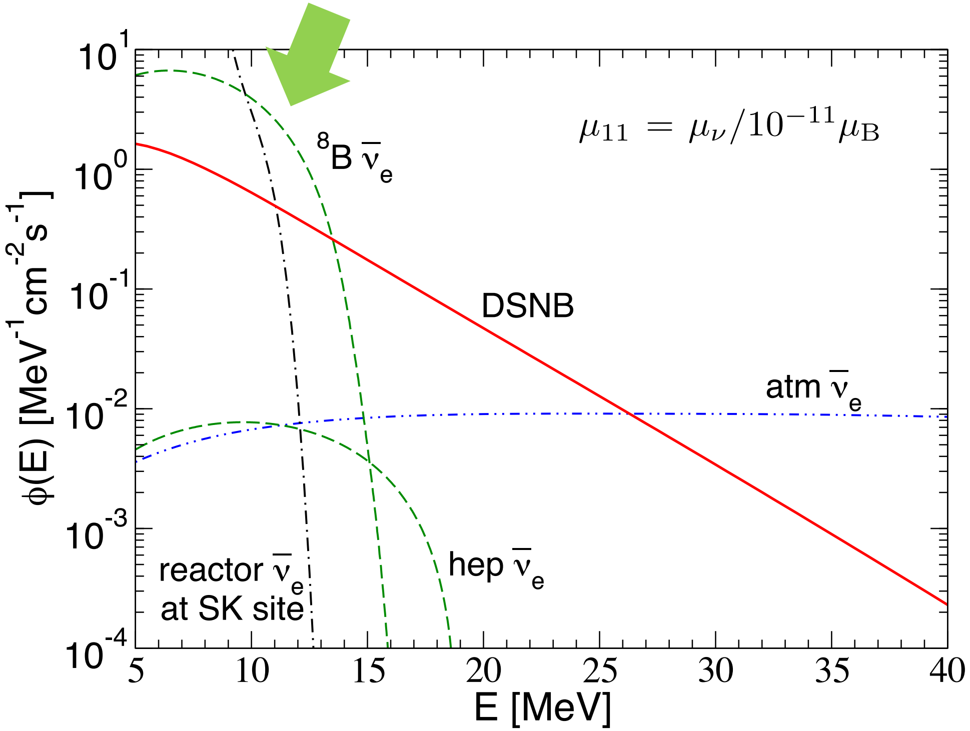


Figure 22. The constraints on the relic abundance of X from various observations with $m_X = 10\text{TeV}$ and $B_X = 10^{-3}$.

Kanzaki et al., Phys.Rev. D76 (2007) 105017

Solar antineutrinos

- Neutrino → antineutrino conversion due to transition magnetic moment
  - Spin-precession in solar magnetic field



Raffelt and Rashba, Phys.Atom.Nucl. 73 (2010) 609-613

Summary/discussion

- In ~5 years the DSNB might be discovered
  - Could be the *first* supernova neutrino detection since SN1987A
  - Could be the *oldest* neutrinos ever detected

- Image of supernova population up to cosmological distances
  - Dependence on progenitor mass? Redshift dependence? Failed supernovae?

- Strong spectrum distortions could reveal new neutrino couplings
  - Coupling to light Dark Matter? …

Backup

Physics of the DSNB

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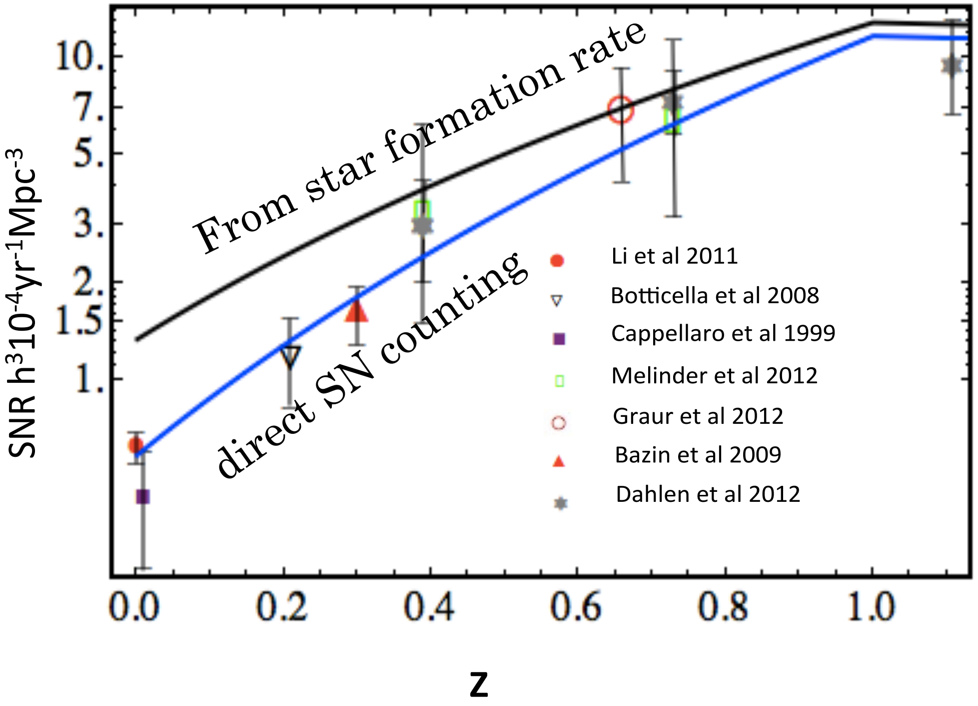

Hopkins and Beacom, ApJ. 651 (2006), Horiuchi et al., ApJ 738 (2011)