Low-Energy Astrophysics in Super- & Hyper-K

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they/them

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Agenda

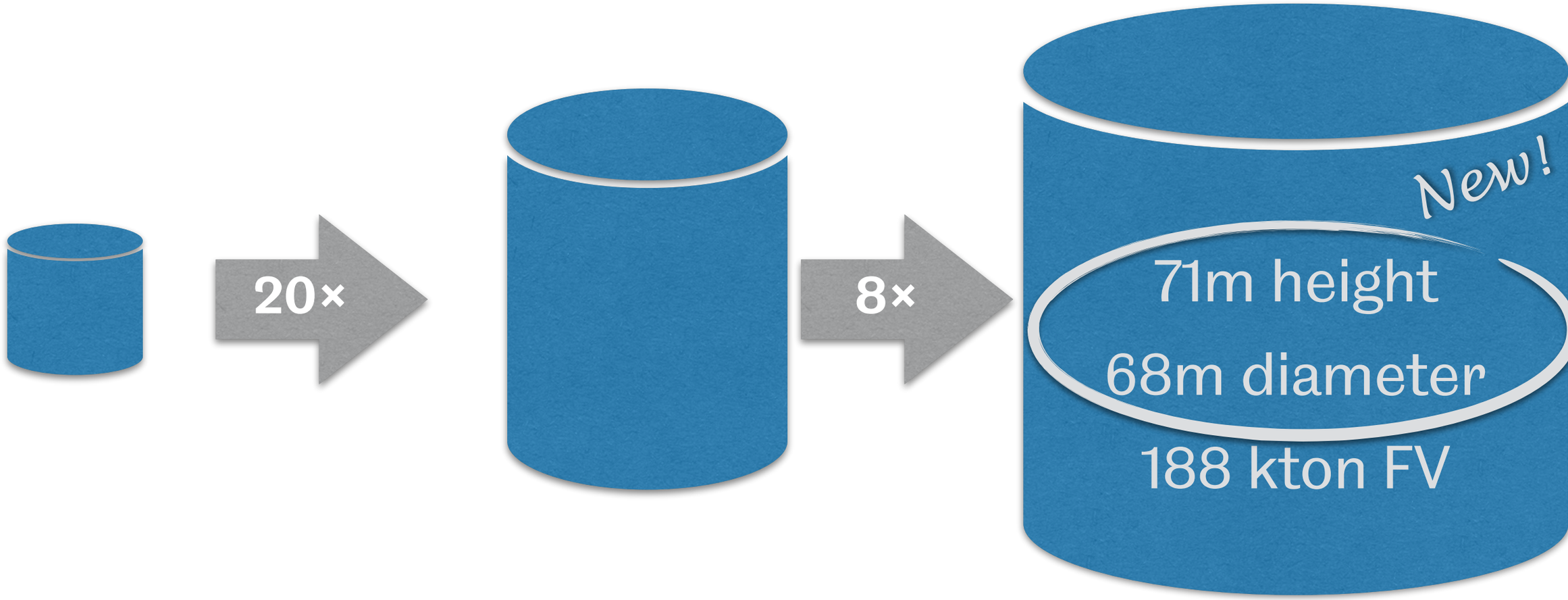
- SK-Gd and HK
- Solar Neutrinos
- Supernova Burst Neutrinos
- Supernova Relic Neutrinos (SRN/DSNB)

Three Generations

Kamiokande
1983–1996

Super-Kamiokande
1996–today (and beyond)

Hyper-Kamiokande
~2027–???



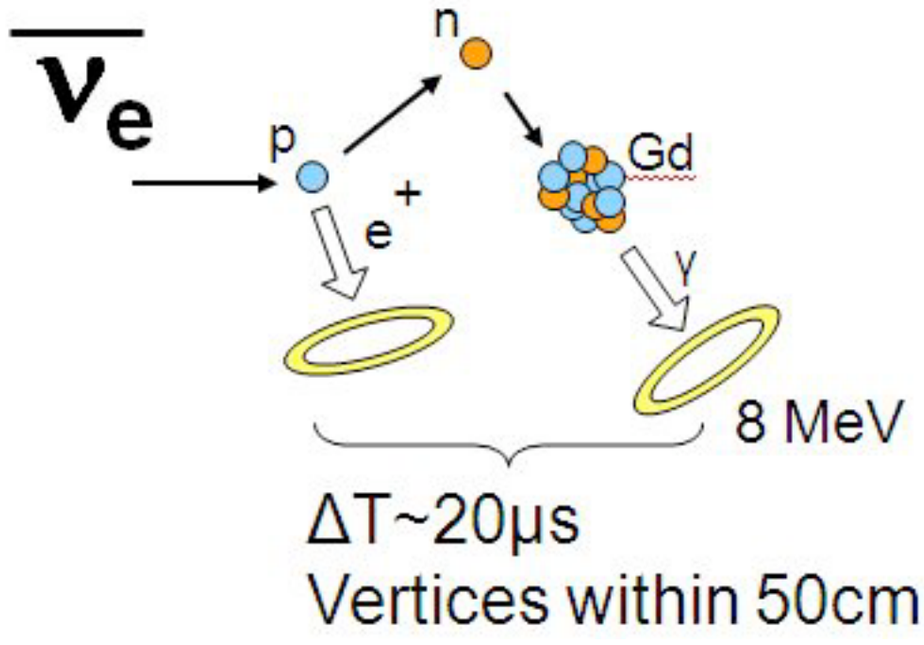

Koshiba, 2002


Kajita, 2015


TBD

Status of SK(-Gd)

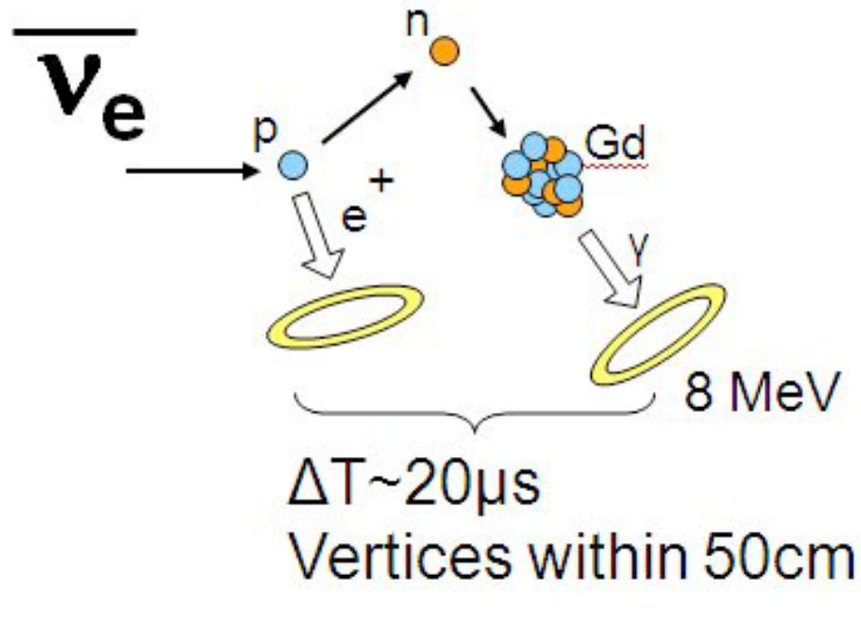
- SK-IV ended in June 2018
- refurbished to prepare for Gd loading
- running stably throughout 2019
- SK-Gd to start in 2020
  - Dissolve 0.02 % $Gd_2(SO_4)_3$ in the water (↗0.2% later)
  - 50% (↗90%) of neutrons capture on Gd
  - Based on experiences from EGADS



original proposal by Beacom, Vagins: PRL 93 (2004) 171101

Neutron Capture on H

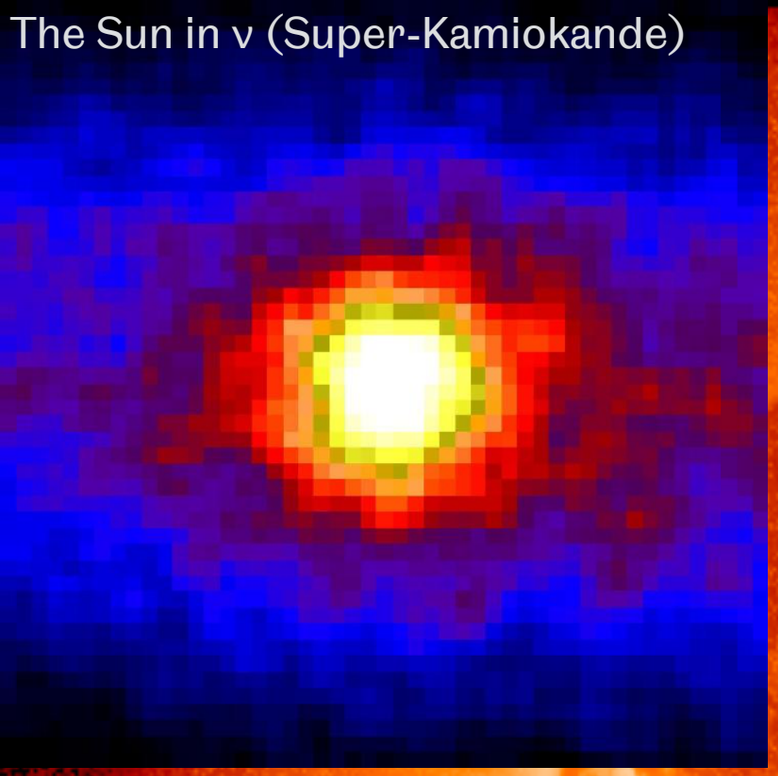
- 10^5× lower cross-section
  - Capture time: 200 μs
  - Energy: 2.2 MeV



- sub-threshold ➔ need advanced trigger to try to tag *some* n captures on H

- Low efficiency (17% in SK), but works
  - higher efficiency with better photosensors in HK?

Solar ν

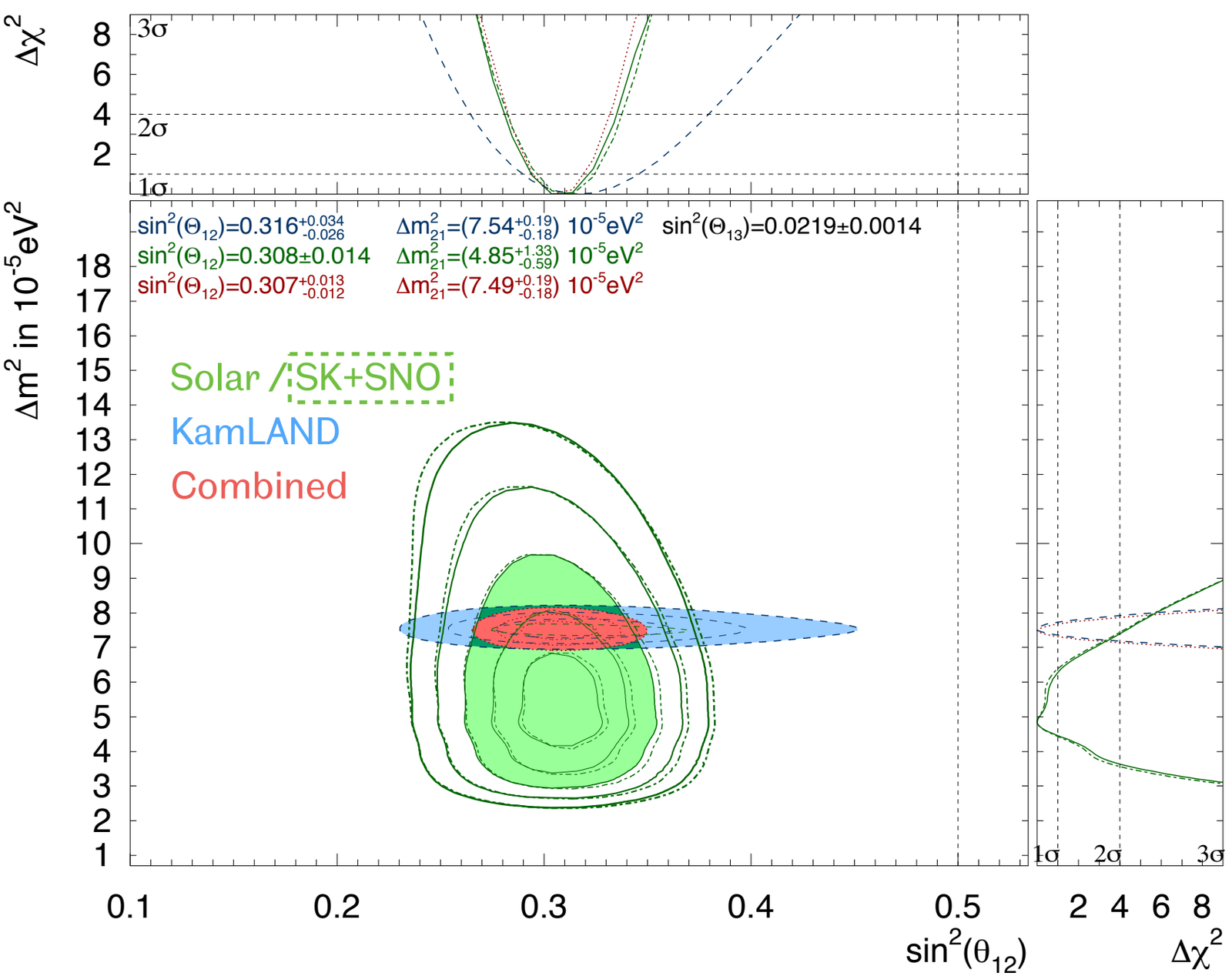


The Sun in ν (Super-Kamiokande)

The Sun in X-rays

http://rsd.gsfc.nasa.gov/rsd/images/yohkoh_l.gif

Oscillation Parameters



- SK: world's best measurement for neutrinos:

$$\Delta m^2_{21} = (4.8^{+1.5}_{-0.8}) \times 10^{-5}\,\mathrm{eV}^2$$

- >1.5 σ tension with KamLAND reactor anti-neutrino measurement!
- Agreement on θ_{12}

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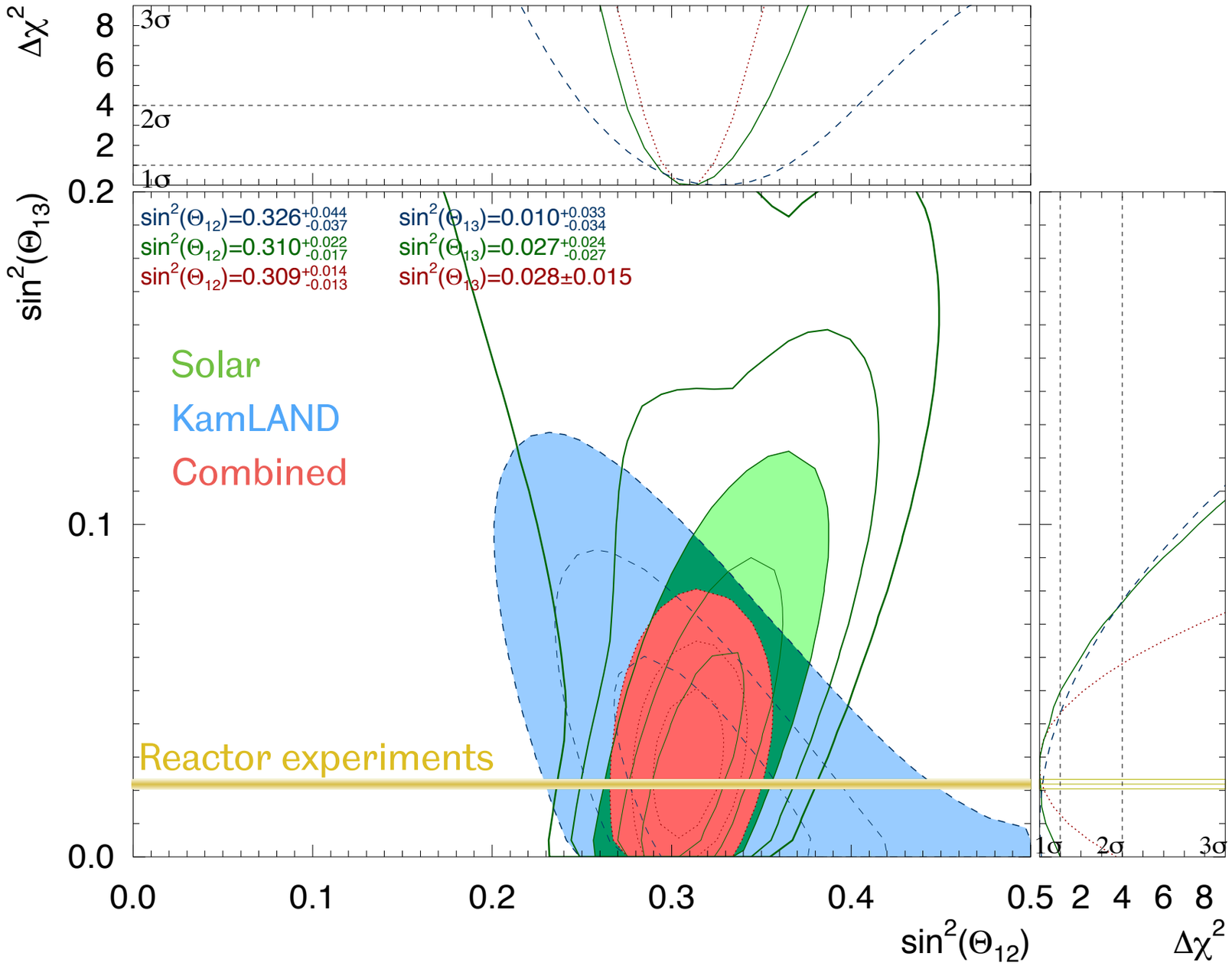

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- >1.5 σ tension with KamLAND reactor anti-neutrino measurement!
- Agreement on θ_{12}
- Low precision on θ_{13}

Day/Night Asymmetry

- At night, ν_e content in solar neutrinos is regenerated through MSW effect in Earth.

- SK combined result is at ~3σ:

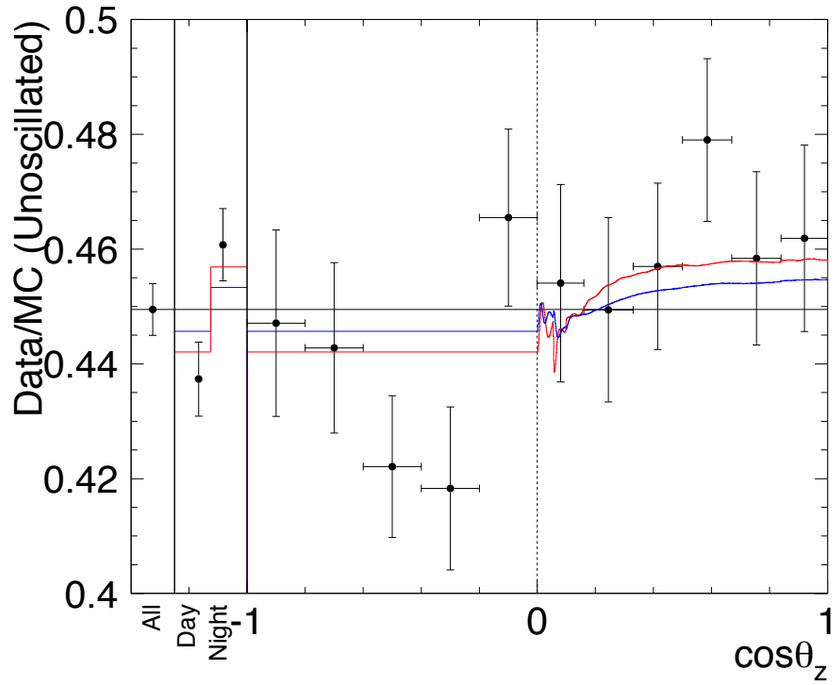
$$A_{\mathrm{DN}}^{\mathrm{fit,\ SK}} = (-3.3 \pm 1.0(\mathrm{stat.}) \pm 0.5(\mathrm{syst.}))\%$$

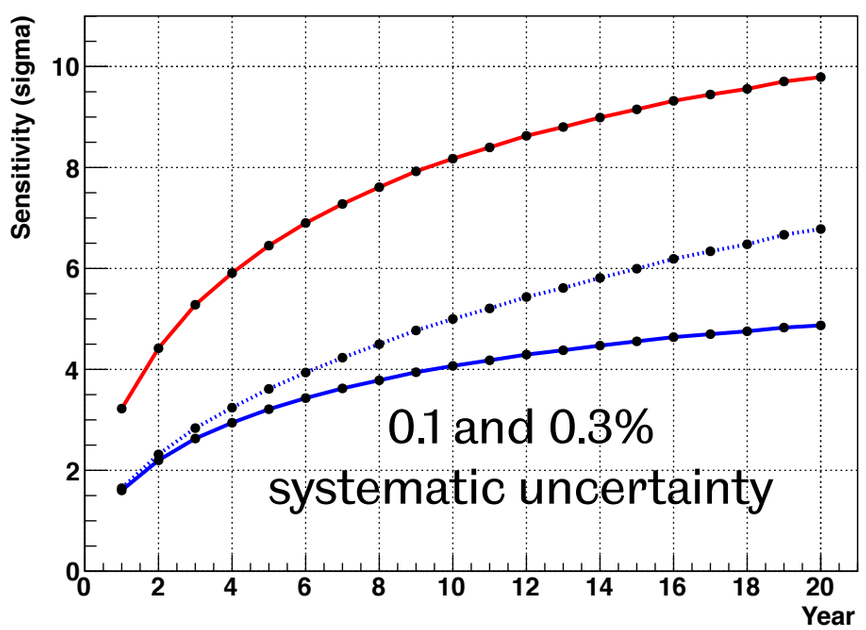
- KamLAND parameters predict:

$$A_{\mathrm{DN}}^{\mathrm{KamLAND}} = -1.7\,\% \ (\mathrm{expected})$$

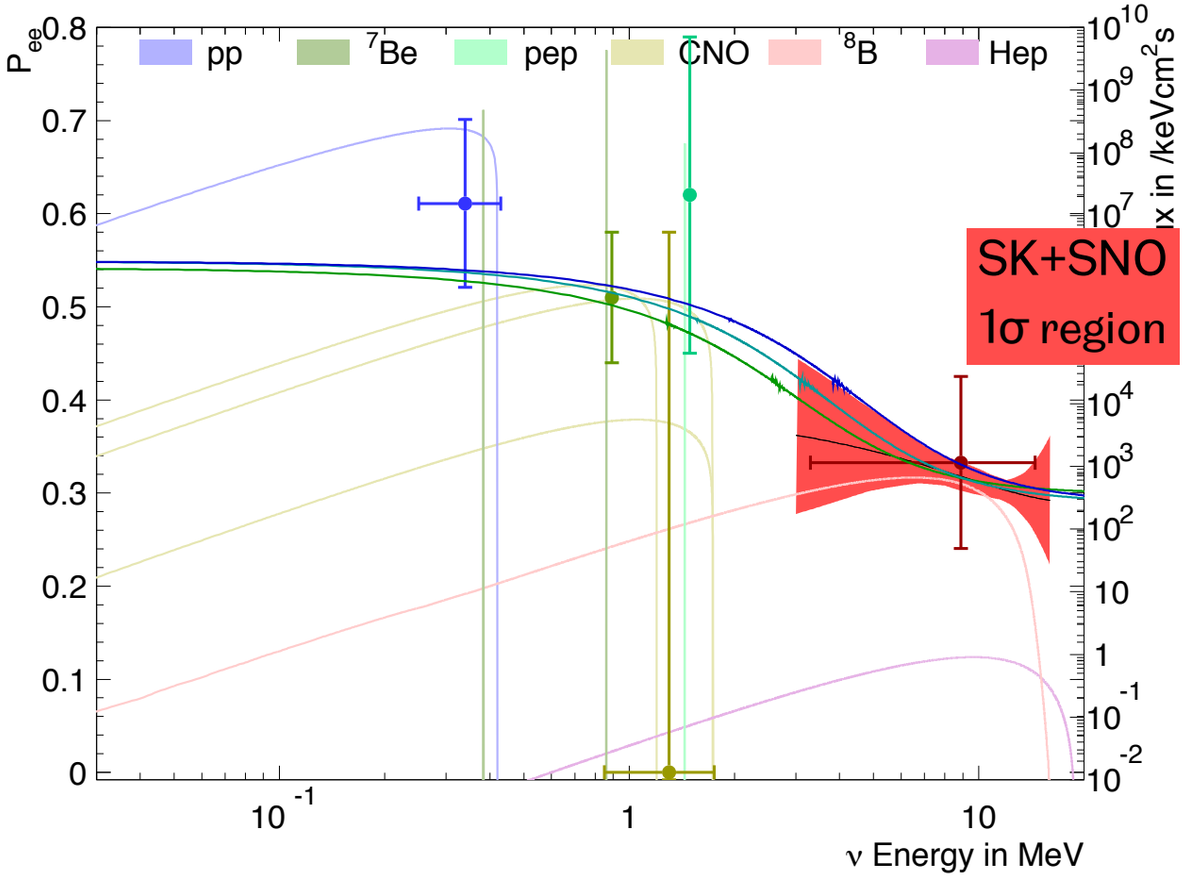
- in HK:
  - observation within 3 years
  - distinguish solar (ν_e) & reactor ($\bar{\nu}_e$) values at 3σ in ~5 years

$$A_{\mathrm{DN}} = \frac{\Phi_{\mathrm{D}} - \Phi_{\mathrm{N}}}{\frac{1}{2}(\Phi_{\mathrm{D}} + \Phi_{\mathrm{N}})}$$





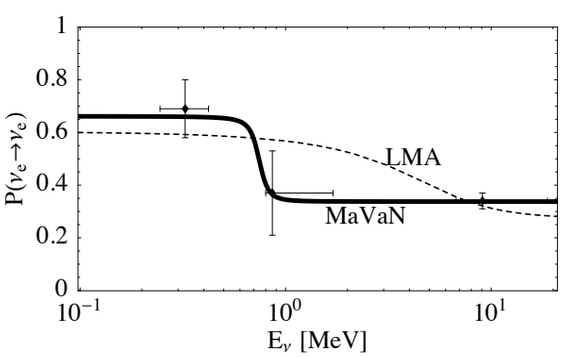
Spectral Upturn



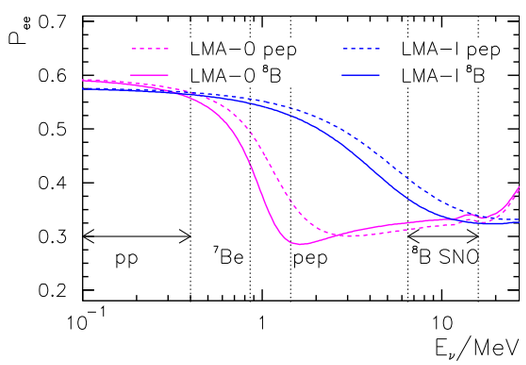
Vacuum oscillations dominate

MSW dominates

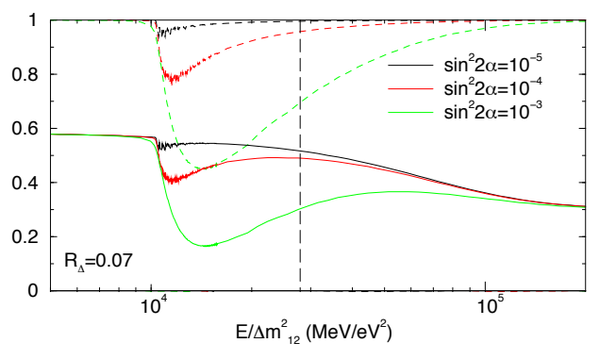
- Transition between vacuum & matter oscillations at ~5 MeV
- SK sensitivity: ~1σ level
- HK: 3–5σ in 10 years
- limit new physics that changes spectral shape



PRL 95, 211802 (2005)



Phys.Lett.B594, 347 (2004)



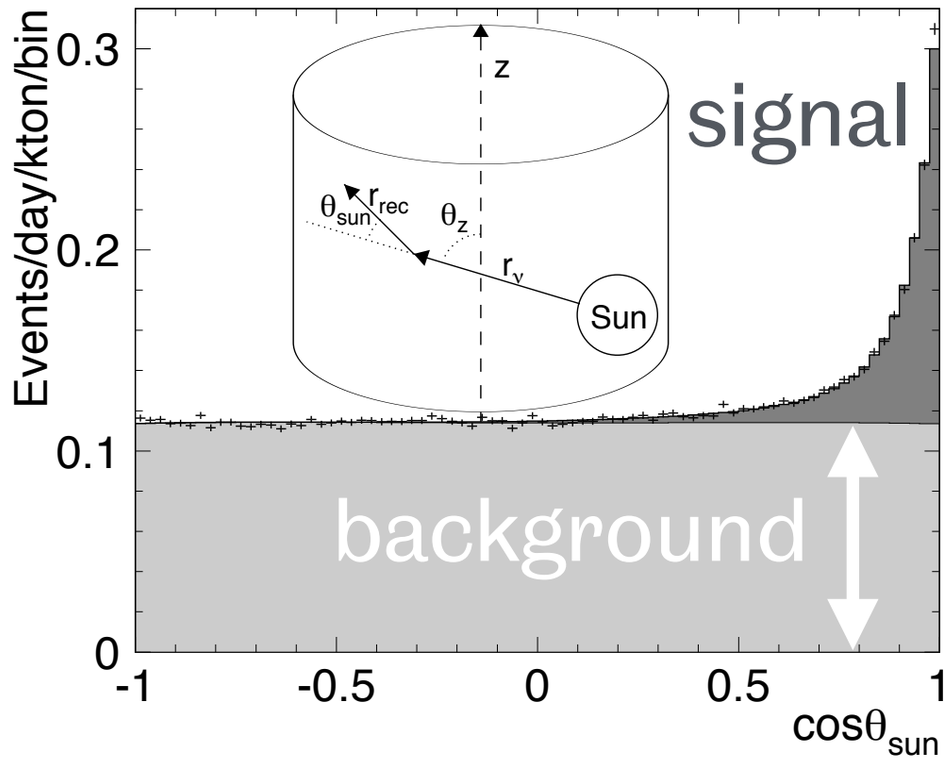
PRD 69, 113002 (2004)

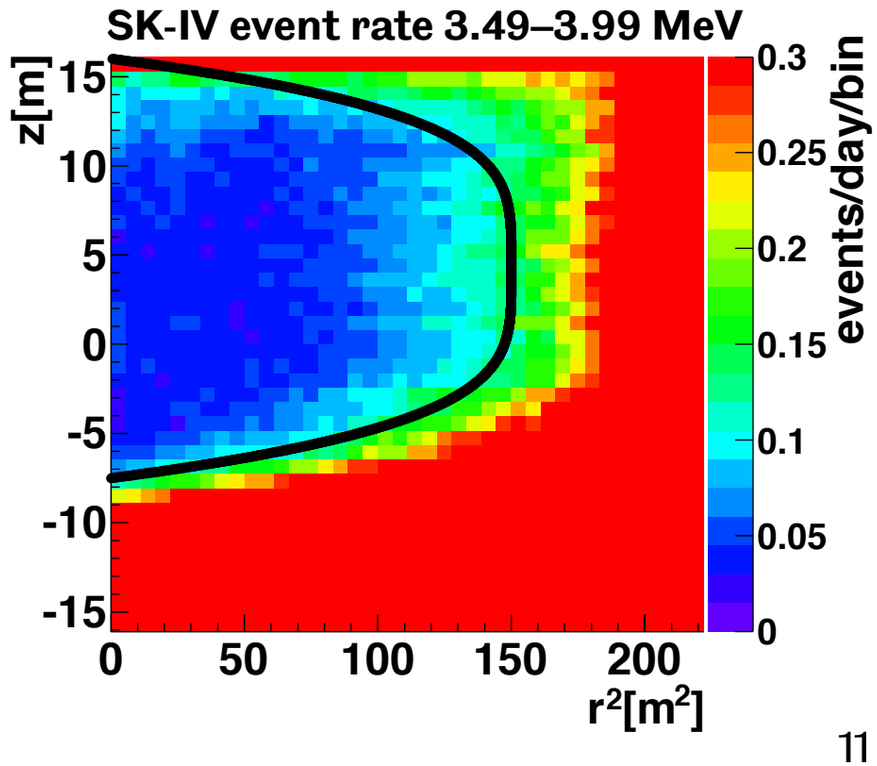
left to right:

- MaVaN
- NSI
- Sterile neutrinos

Solar Neutrinos in SK

- elastic scattering: $\nu + e \rightarrow \nu + e$ (no neutrons)
- 10–15 events per day at $E_{kin} \geq 3.49$ MeV
- overwhelmed by background (few neutrons)
  - ^{222}Rn decay products
  - impurities in PMTs
  - muon-induced spallation



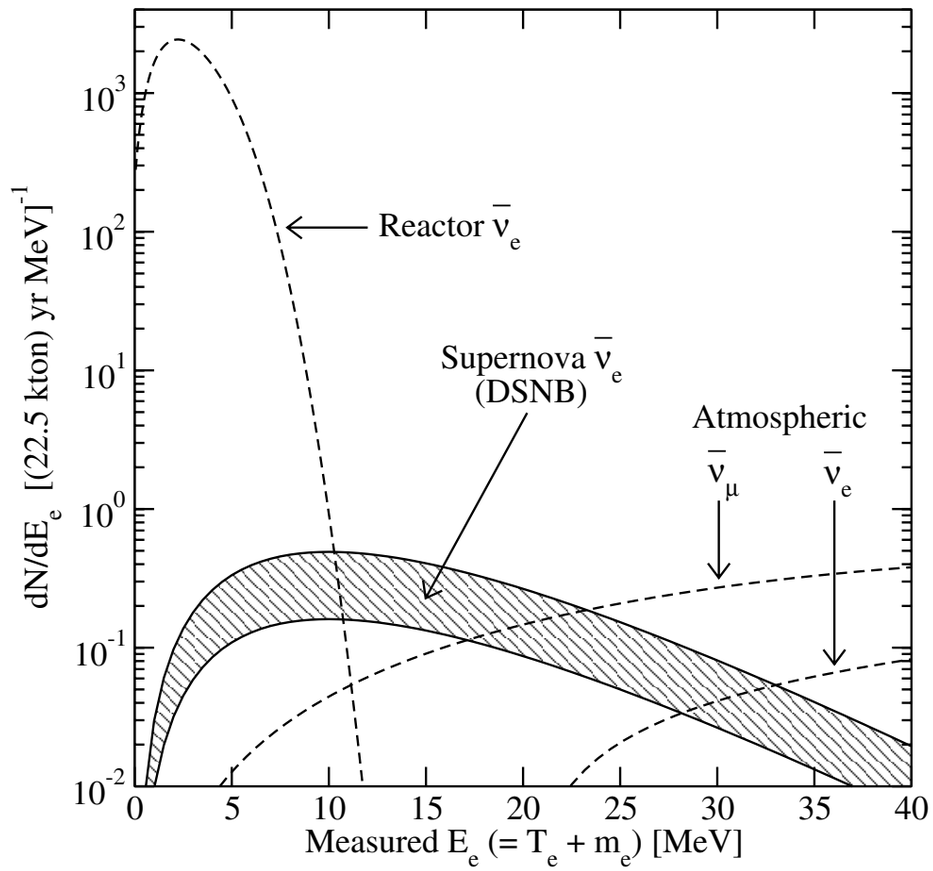


SK-IV solar ν paper: arXiv:1606.07538 / PRD94 (2016) 052010

Using n Tagging for Solar ν

- identify reactor $\overline{\nu}_e$
  - including sub-threshold via coincidence
  - minor "background" for solar ν, but cross-check for Δm^2_{21}
    - politics-dependent flux ... ¯_(ツ)_/¯

Beacom, Vagins: PRL 93 (2004) 171101



- expect ν_e only, can set limits on solar $\overline{\nu}_e$
  - $F_{\bar{\nu}_e} < 4.2 \cdot 10^{-4} F_{\nu_e}$ with n capture on H ➔ not competitive with KamLAND

- risk of introducing new background, from previously "invisible" neutrons?
  - not a problem, calculate Beacom & Vagins

Supernova* ν

* core-collapse SN

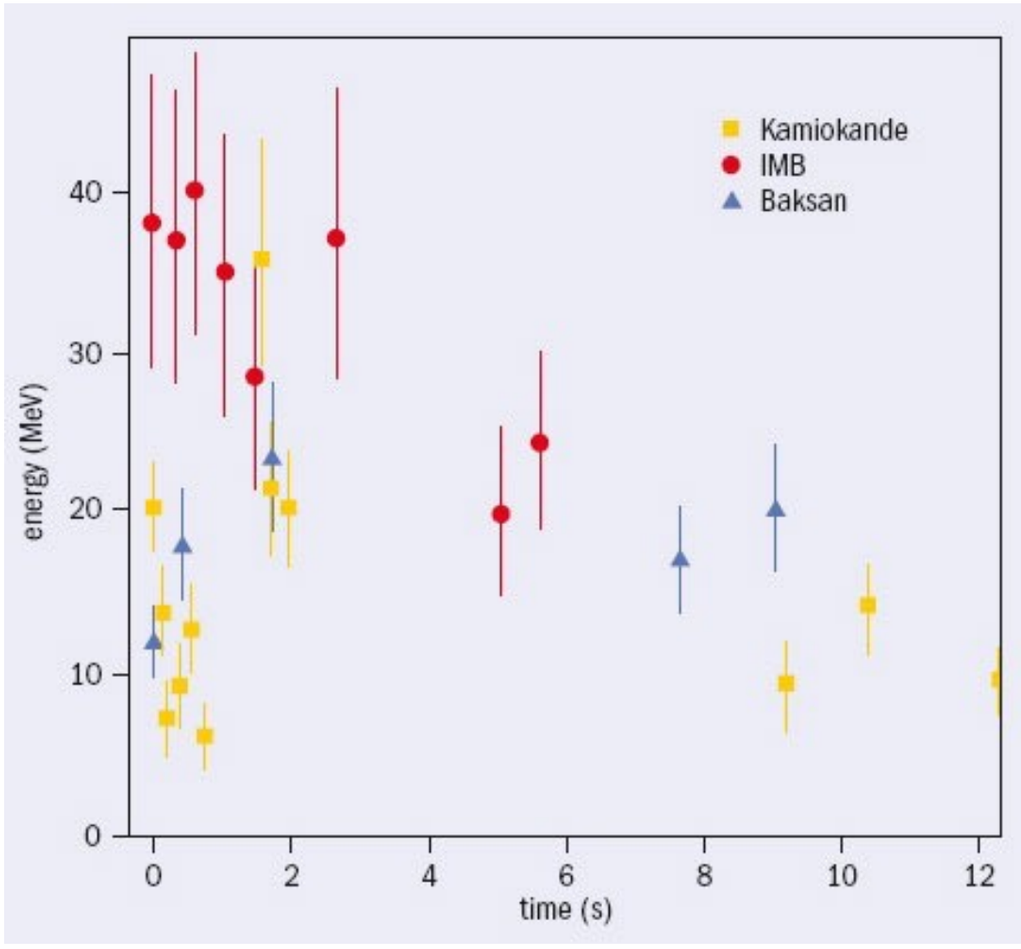
Crab Nebula, Remnant of SN 1054

NASA/ESA, https://commons.wikimedia.org/wiki/File:Crab_Nebula.jpg

What We (Think We) Know ...

- SN1987a: two dozen events, ~half of them in Kamiokande

- Confirmed basic picture:
  - ν burst ≈99% of energy
    - ~10^{53} erg, ~10^{58} ν
  - ν arrive ~hours before light



- Energy loss argument can constrain exotic particles

G. Raffelt, arXiv:hep-ph/9903472

- Simulations still limited by available computing power
  ➔ take any numbers with a grain of salt

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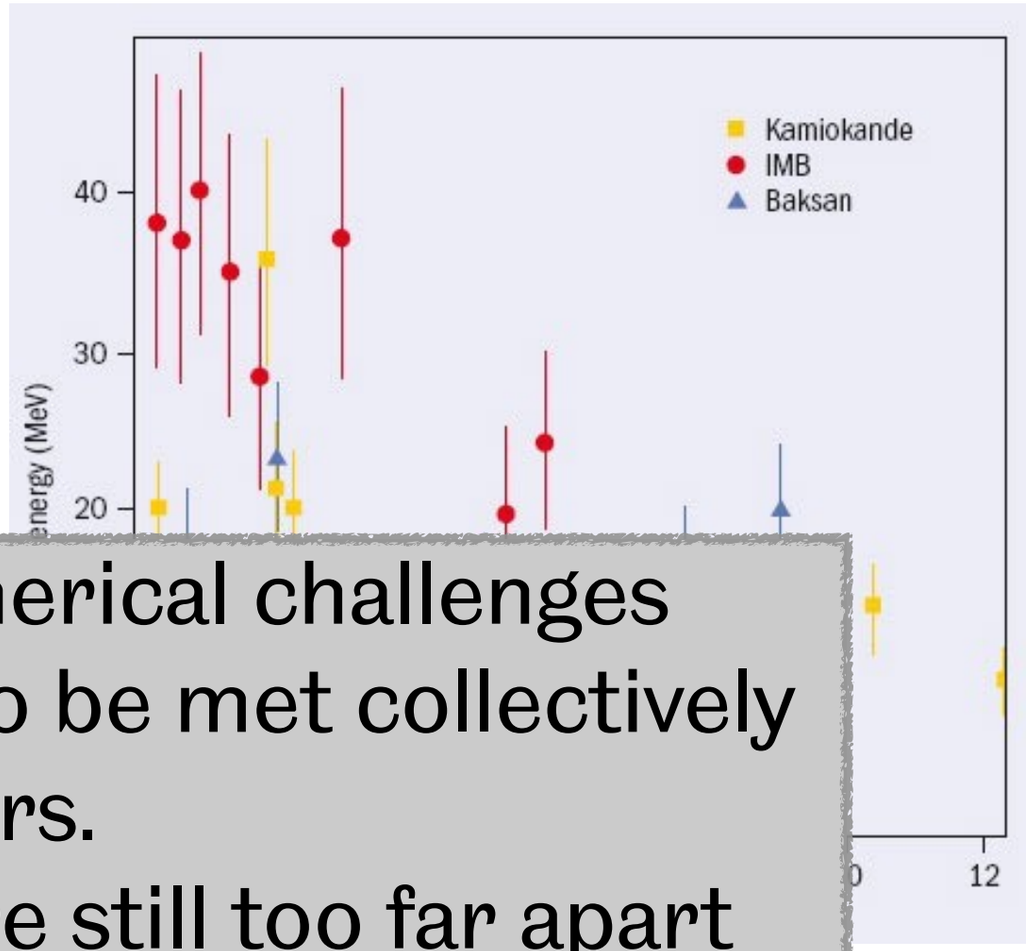

> "There is a rather long list of numerical challenges and code verification issues yet to be met collectively by the world's supernova modelers.
> The results of different groups are still too far apart to lend ultimate credibility to any one of them."
>
> — Skinner, Burrows, Dolence (arXiv:1512.00113)

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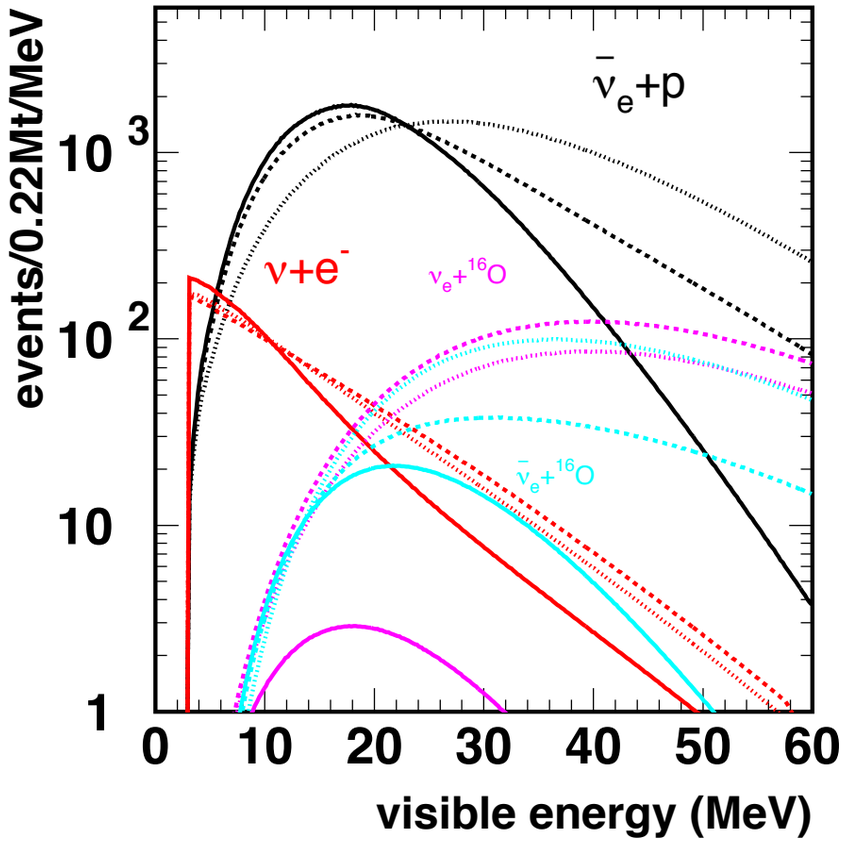
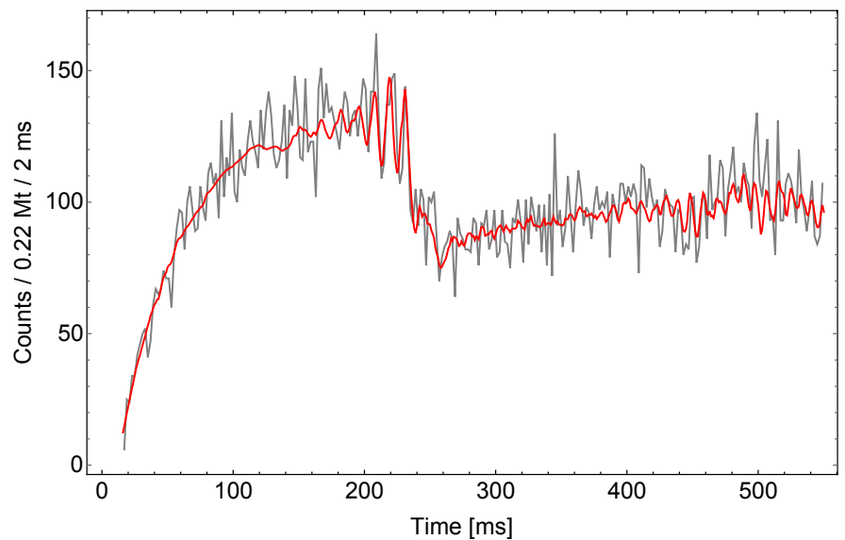
Supernova ν Burst at HK*

* for SK, scale linearly with detector volume

- at 10 kpc: **54 k – 90 k events** per tank (hierarchy-dependent) **in ~10 s**
- precise event-by-event **time & energy** information
- most sensitive to $\bar{\nu}_e$ (~90% **inverse beta decay** on H)
- Other interaction channels:
  - ν+e⁻ scattering
  - CC on ^{16}O (for ν_e and $\bar{\nu}_e$)
  - NC on ^{16}O





for ^{16}O channels, see Suzuki *et al.* arXiv:1807.02367

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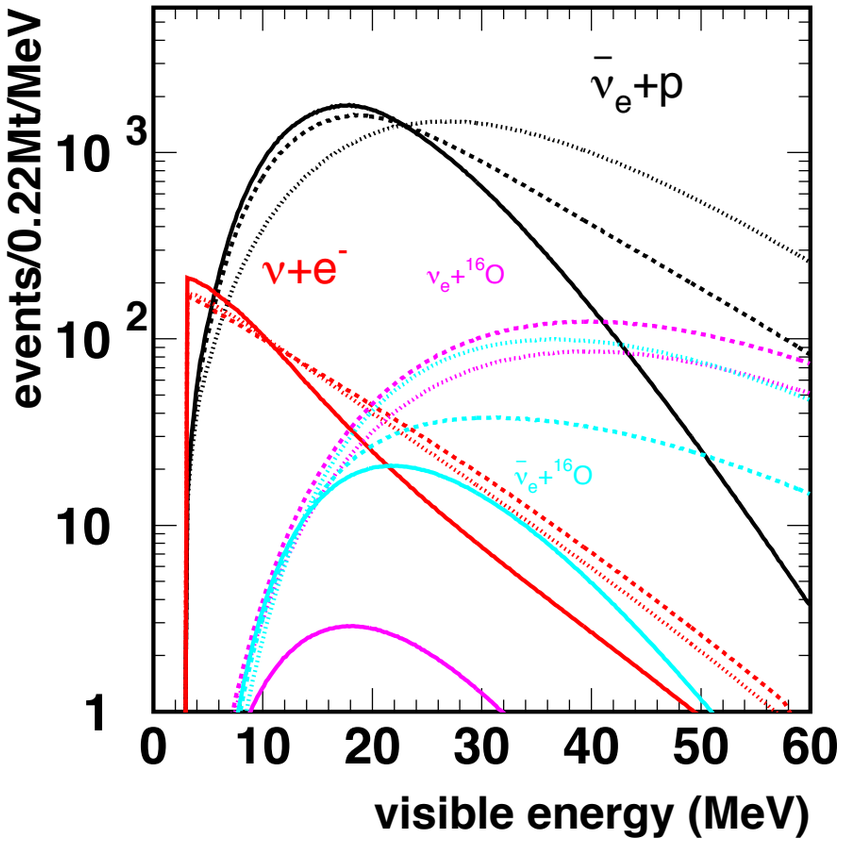
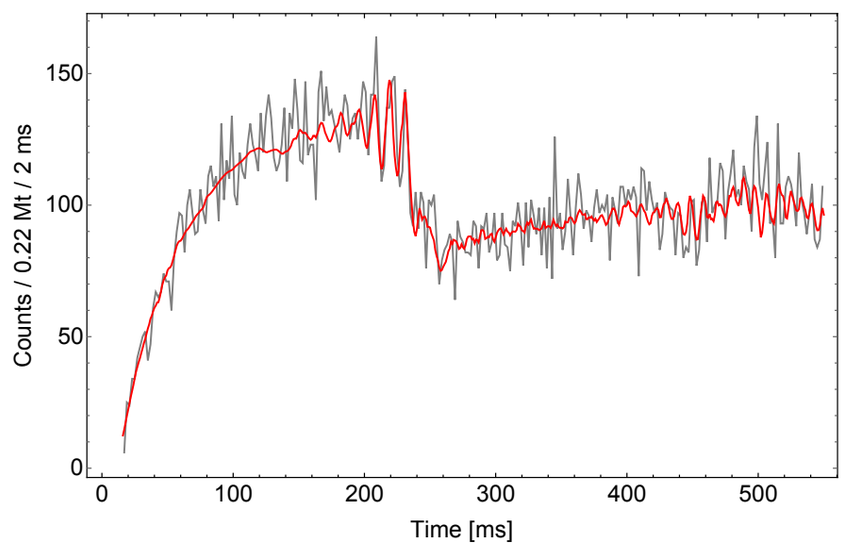
- precise event-by-event **time & energy** information
- most sensitive to $\bar{\nu}_e$ (~90% **inverse beta decay** on H) — neutrons!
- Other interaction channels:
  - ν+e⁻ scattering — no neutrons
  - CC on ^{16}O (for ν_e and $\bar{\nu}_e$)
  - NC on ^{16}O





for ^{16}O channels, see Suzuki *et al.* arXiv:1807.02367

Supernova ν Burst at HK*

* for SK, scale linearly with detector volume

- Pre-supernova neutrinos from Si burning (if distance <1 kpc)

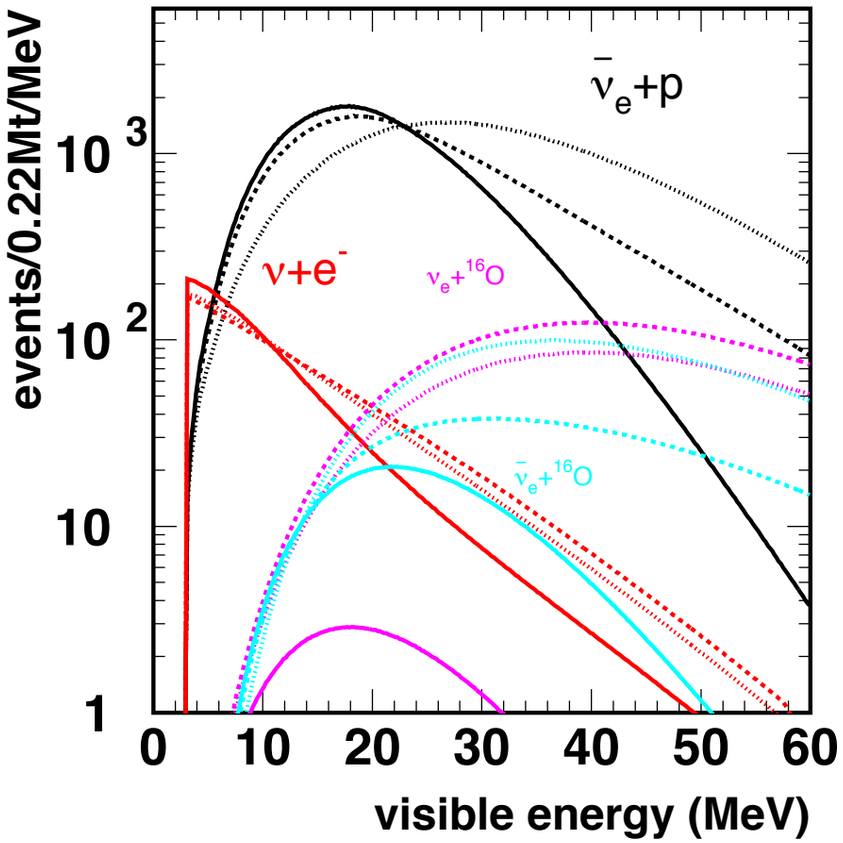
  (C. Simpson *et al.*, arXiv:1908.07551)

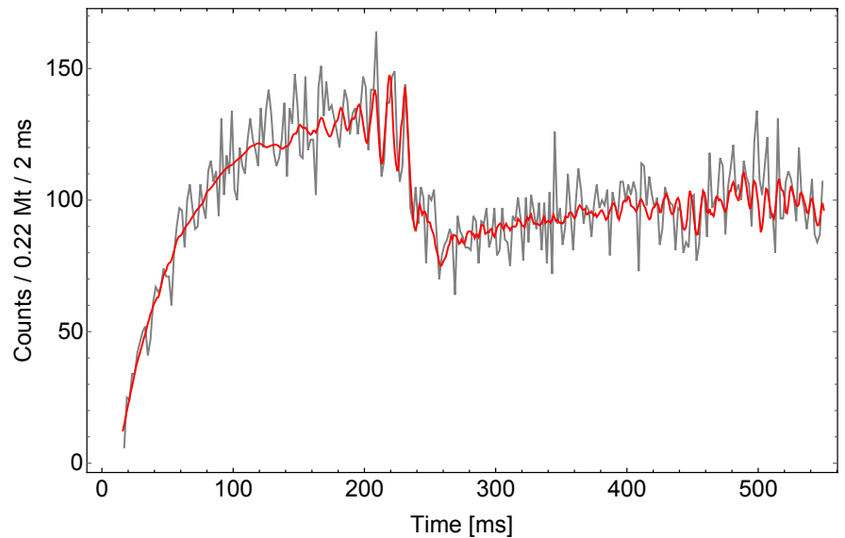
- Mass ordering determination

  (K. Scholberg, arXiv:1707.06384) ➔ uses initial ν_e burst

- Directionality: ~1° ($\nu+e^-$ scattering)
  - Useful for multi-messenger astronomy with SNEWS(2.0)

- explore details of SN explosion mechanism (e. g. the Standing Accretion Shock Instability – SASI)

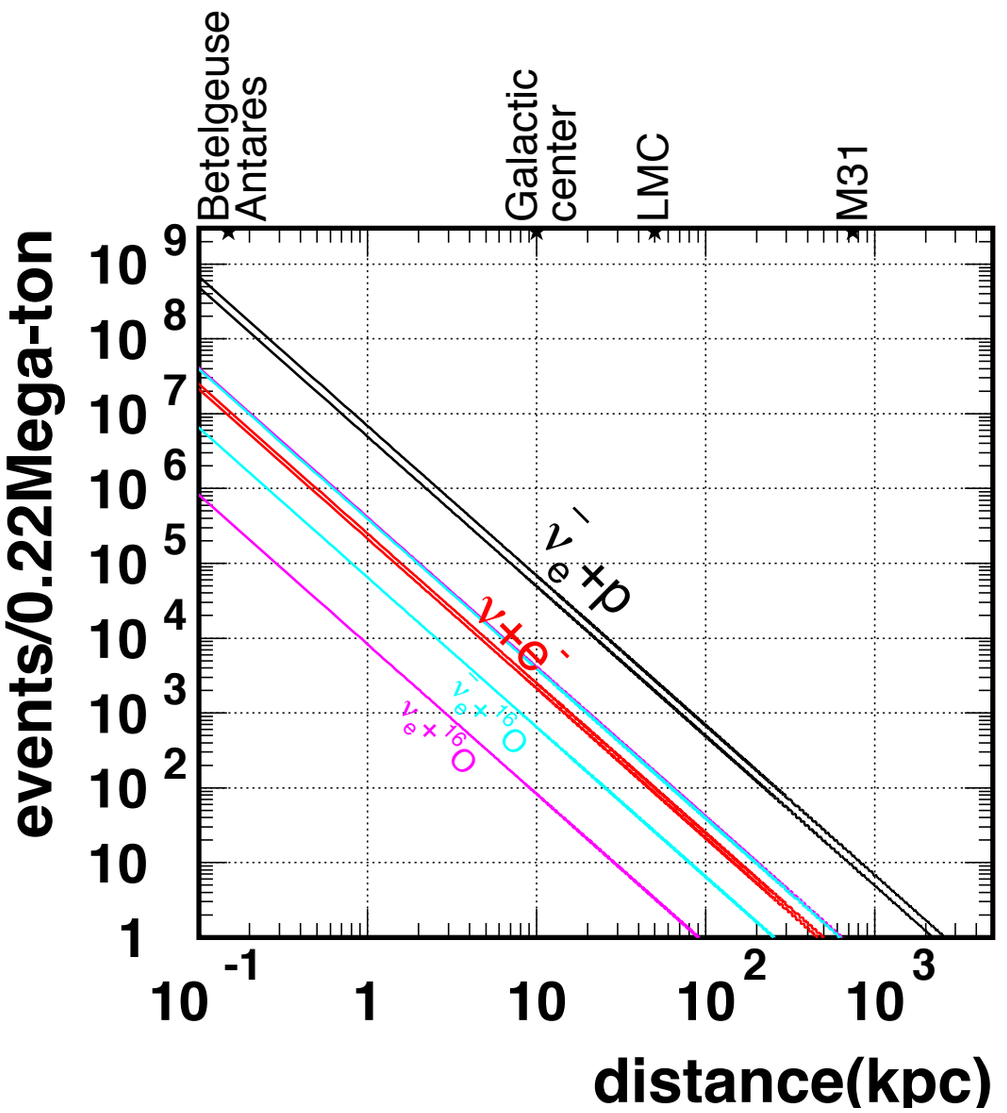


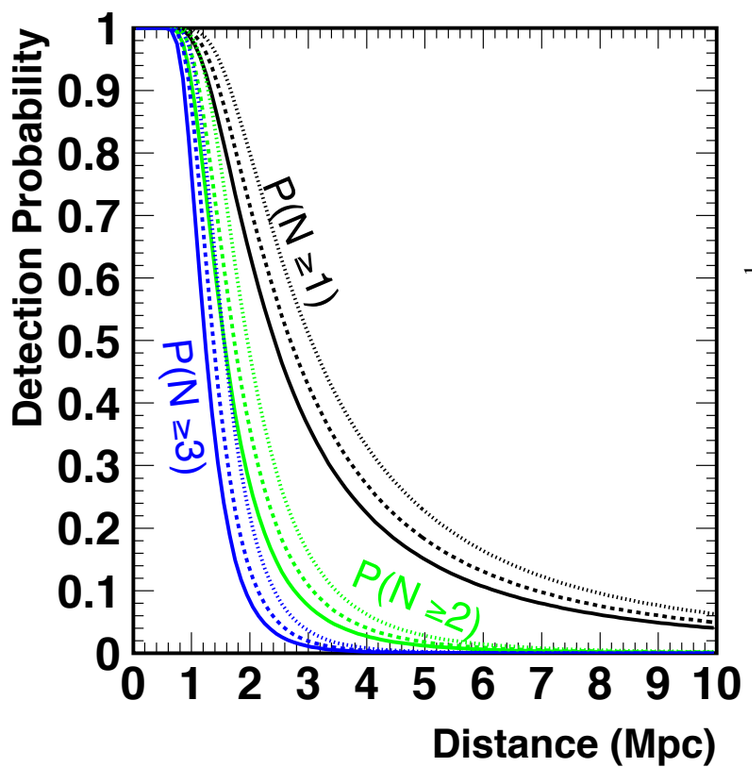


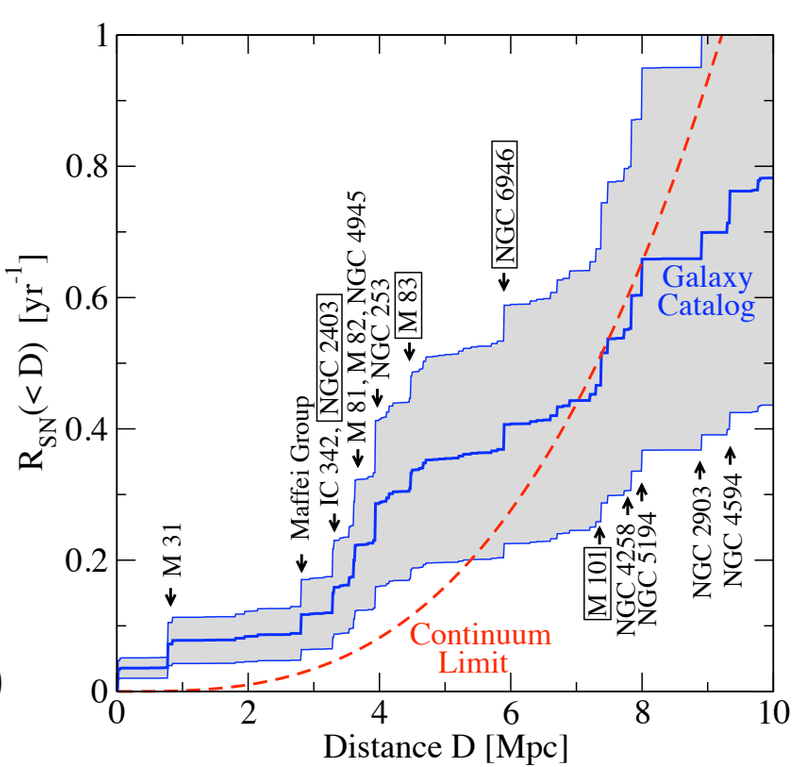
SN in Nearby Galaxy at HK

* for SK, scale linearly with detector volume

- 2100–3150 events in LMC (SN1987a-like)
- 9–13 events in Andromeda, (almost) all with n tag
  ➔ higher confidence of SN trigger
- ≥1 event out to few Mpc







➔ important test for SN simulations

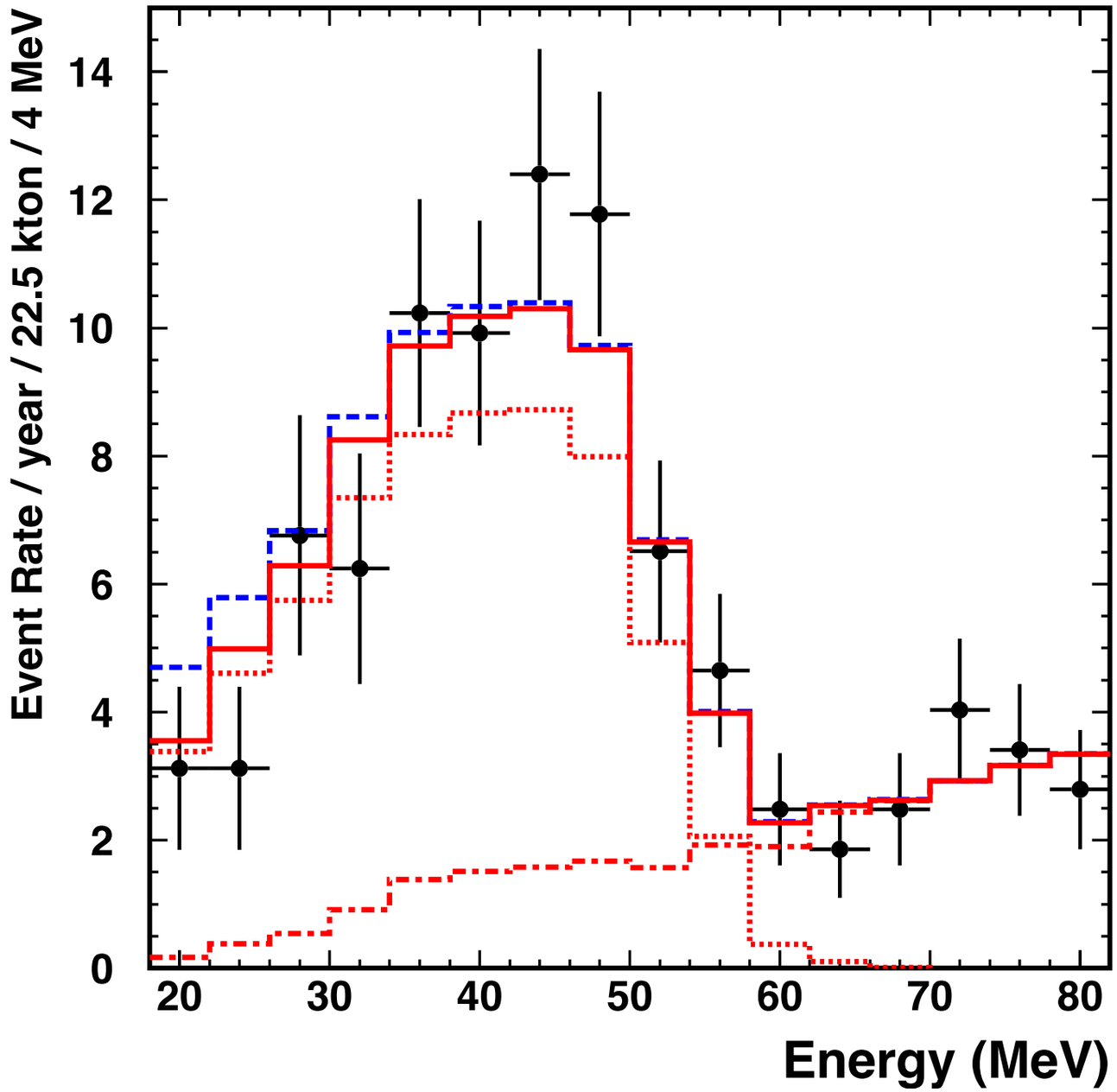
Supernova Relic ν

a.k.a. Diffuse Supernova ν Background (DSNB)

Crab Nebula, Remnant of SN 1054

NASA/ESA, https://commons.wikimedia.org/wiki/File:Crab_Nebula.jpg

First Modern SRN Search



E > 18 MeV ➔ upper limit of ~3× typical model predictions

Malek *et al.* (SK collaboration): PRL **90** (2003) 061101

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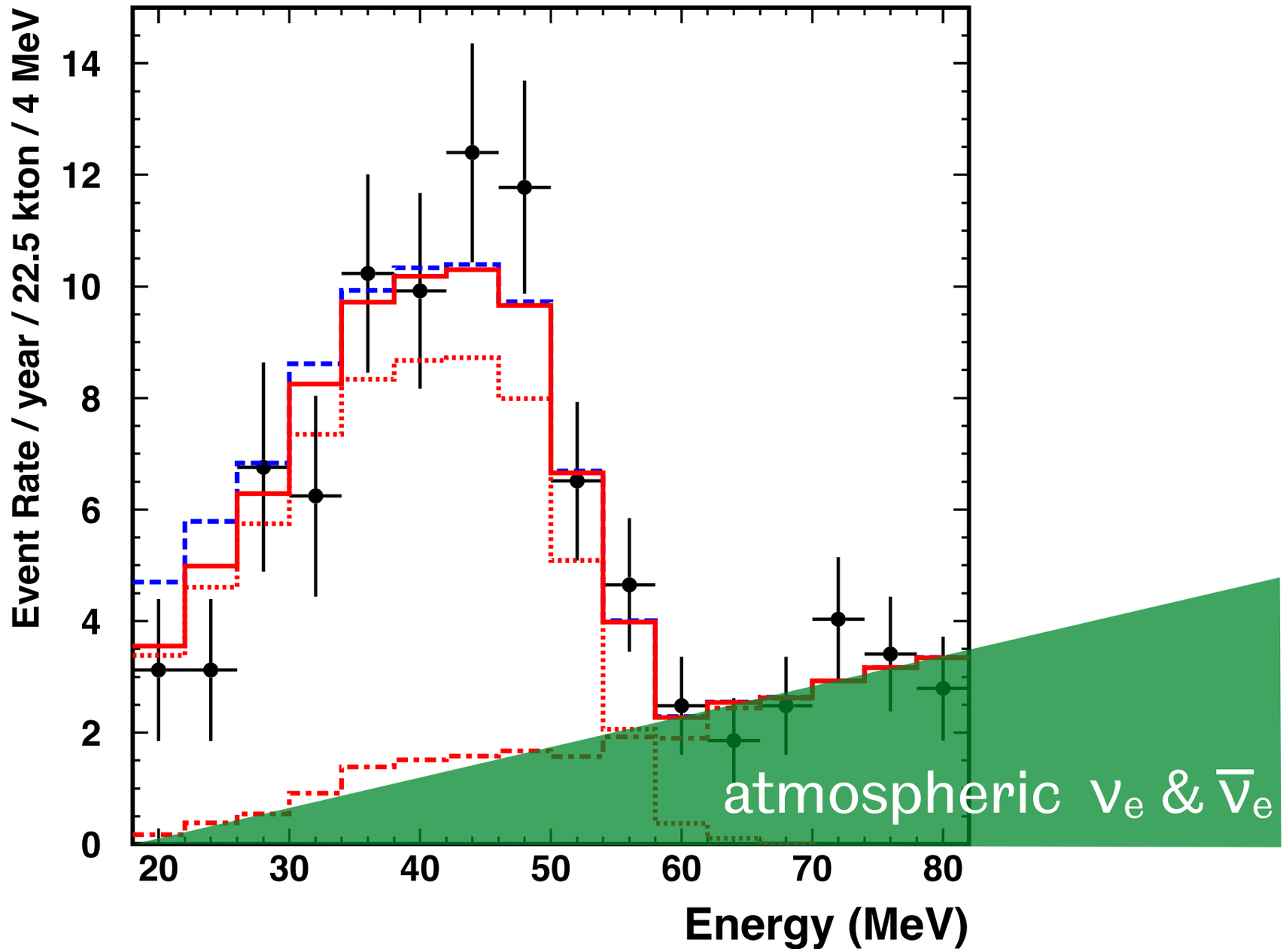

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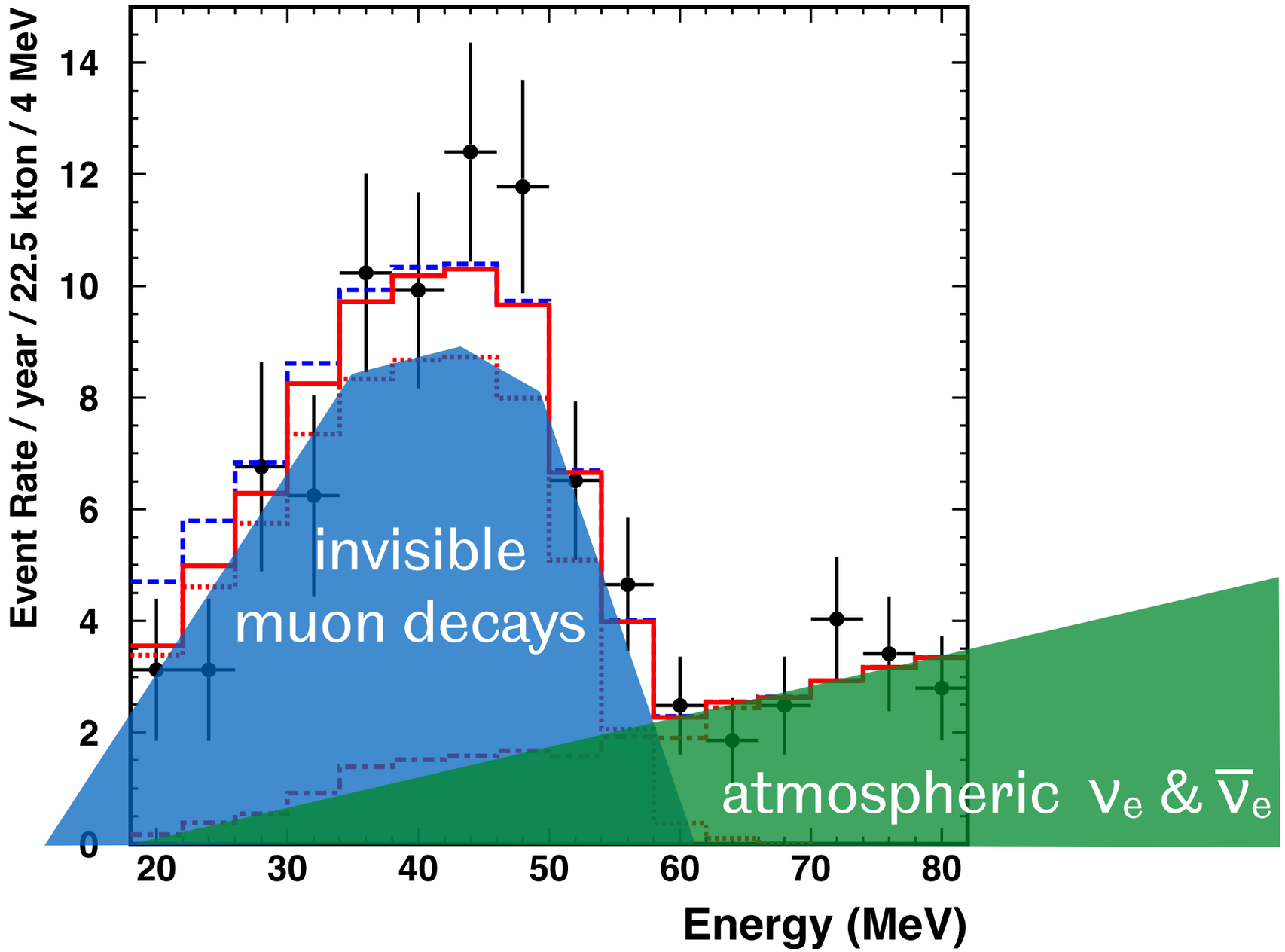

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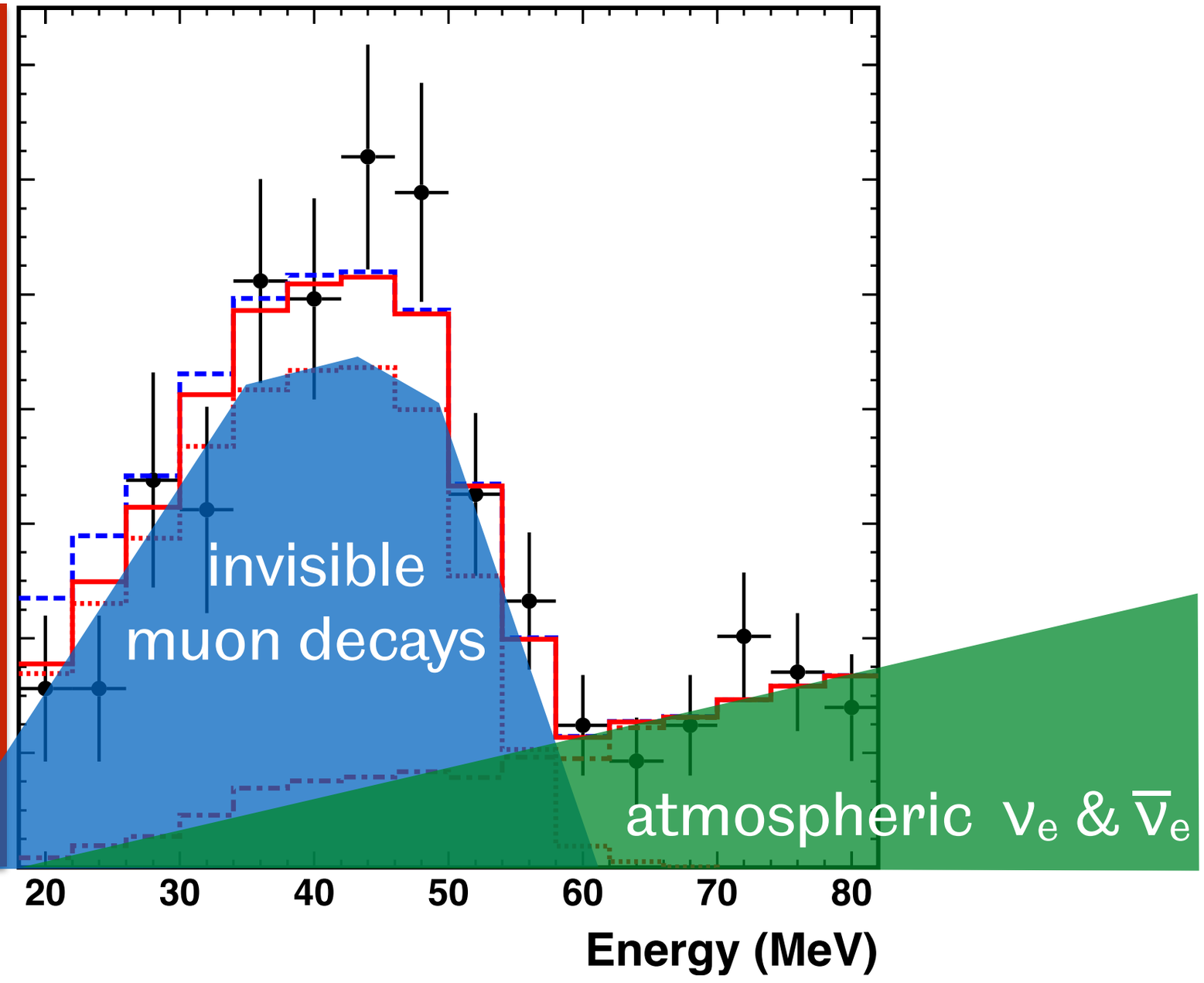
First Modern SRN Search

Muon-induced Spallation



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Reduce Spallation Background

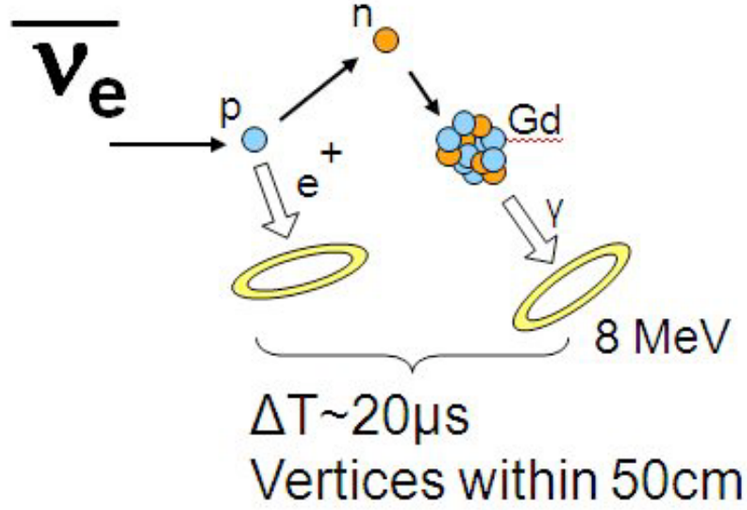
- SRN/DSNB observed in SK/HK overwhelmingly via IBD
  ➔ coincidence of e^+ and n

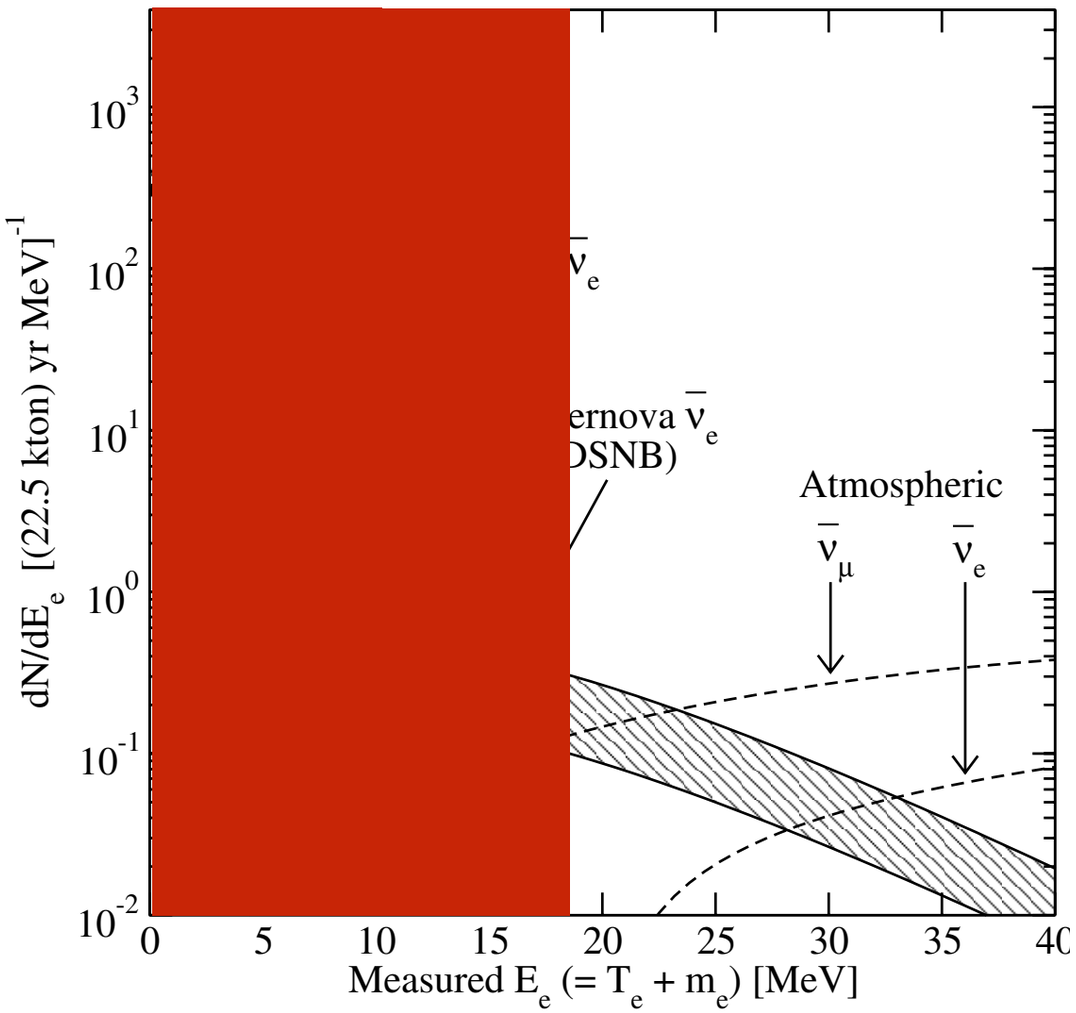
- spallation rarely produces coincidences

- n tagging can reduce threshold to ~10 MeV

- new irreducible* background: reactor $\overline{\nu}_e$

  * except politically





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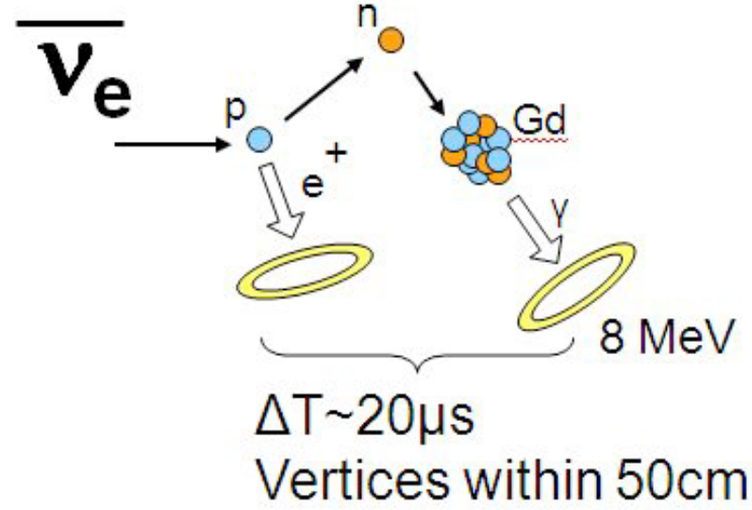
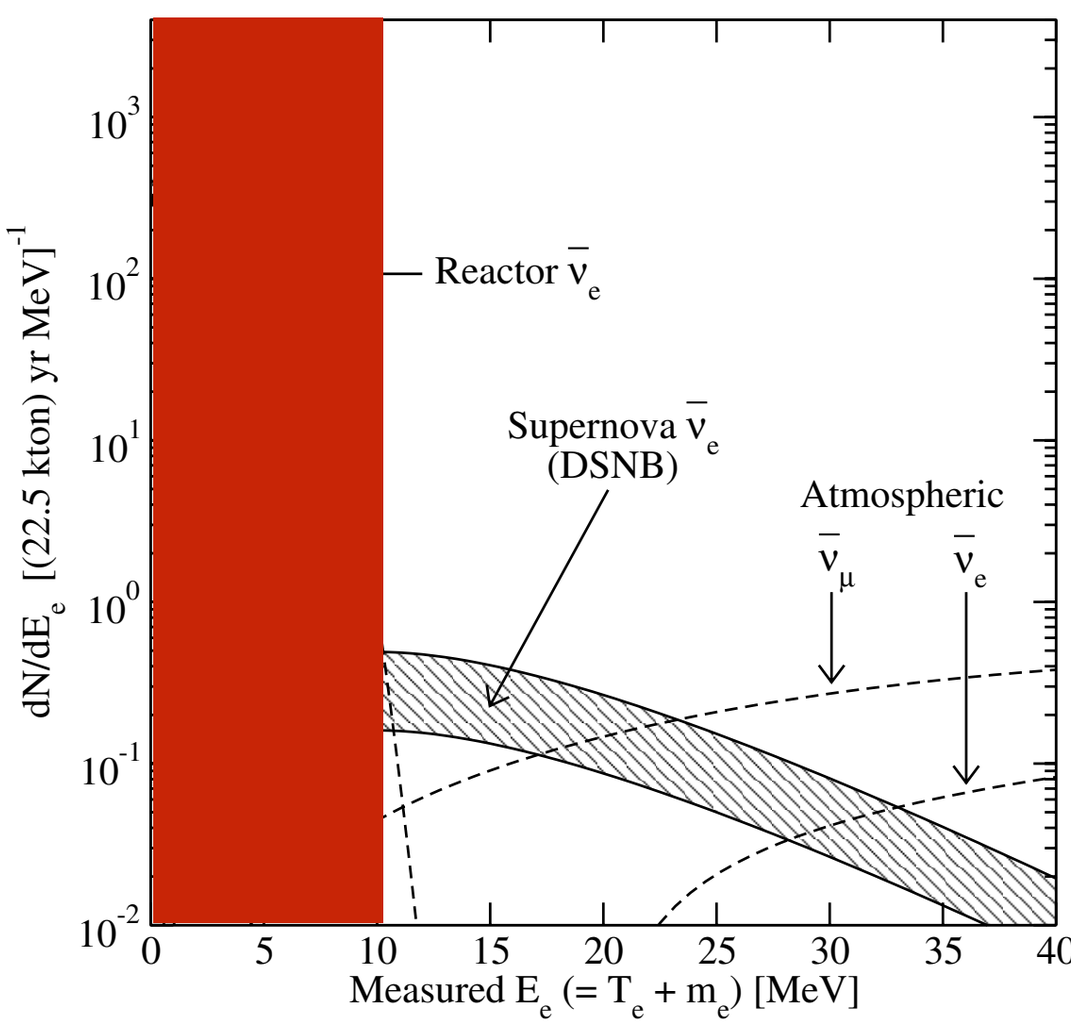
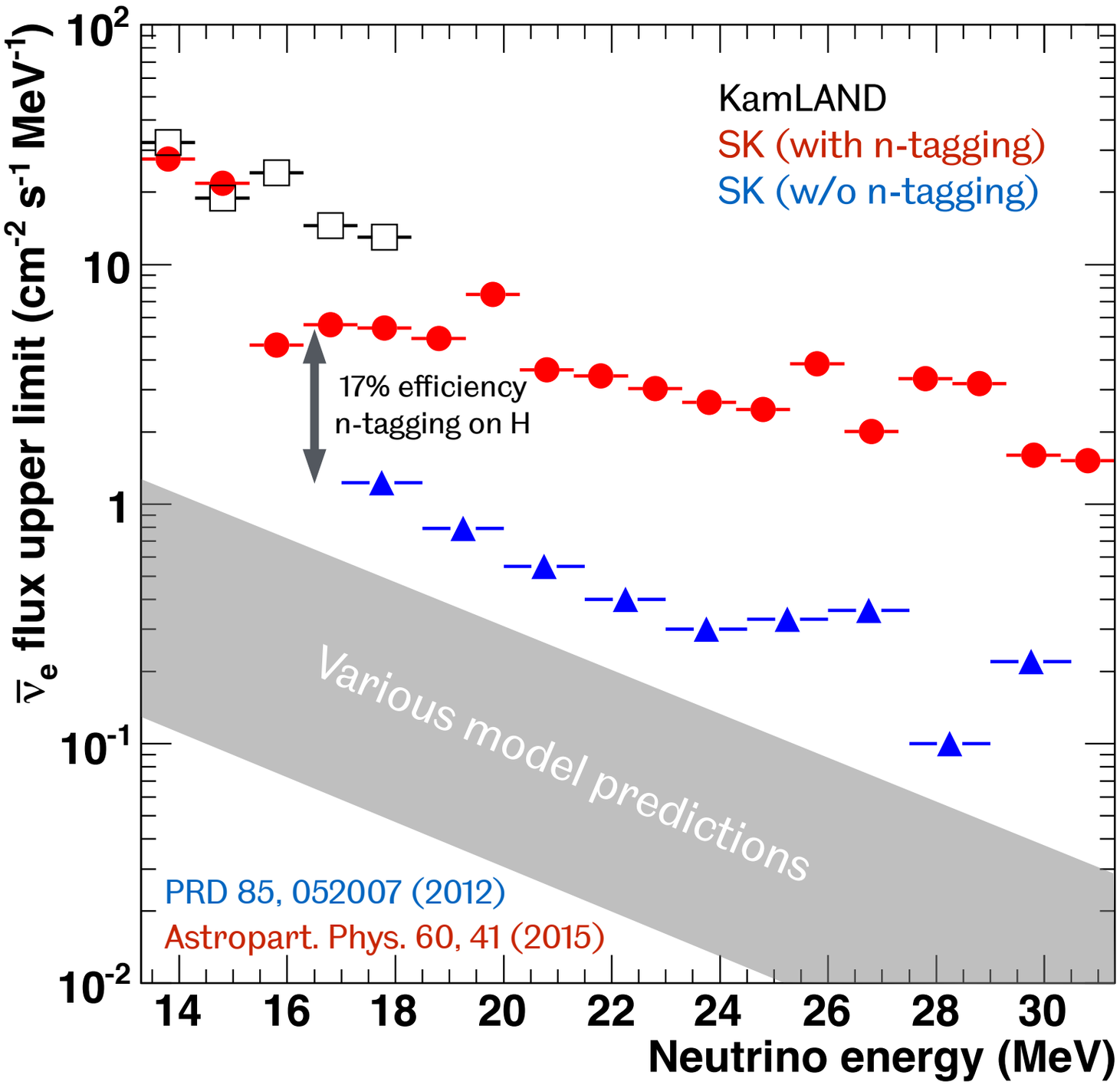




Beacom, Vagins: PRL 93 (2004) 171101

SRN Search with n-tagging on H



Conclusions

- SK-Gd is coming soon!
- Solar Neutrinos
  - minor improvements from n tagging
- Supernova Burst Neutrinos
  - separate interaction channels
  - better SN pointing, more accurate reconstruction of ν_e and $\overline{\nu}_e$ fluxes
  - pre-SN neutrinos from Si burning?
- Supernova Relic Neutrinos (SRN/DSNB)
  - reduce threshold from 18 to 10 MeV
  - first detection possible within few years

Backup Slides

^{16}O CC Partial Cross-Sections

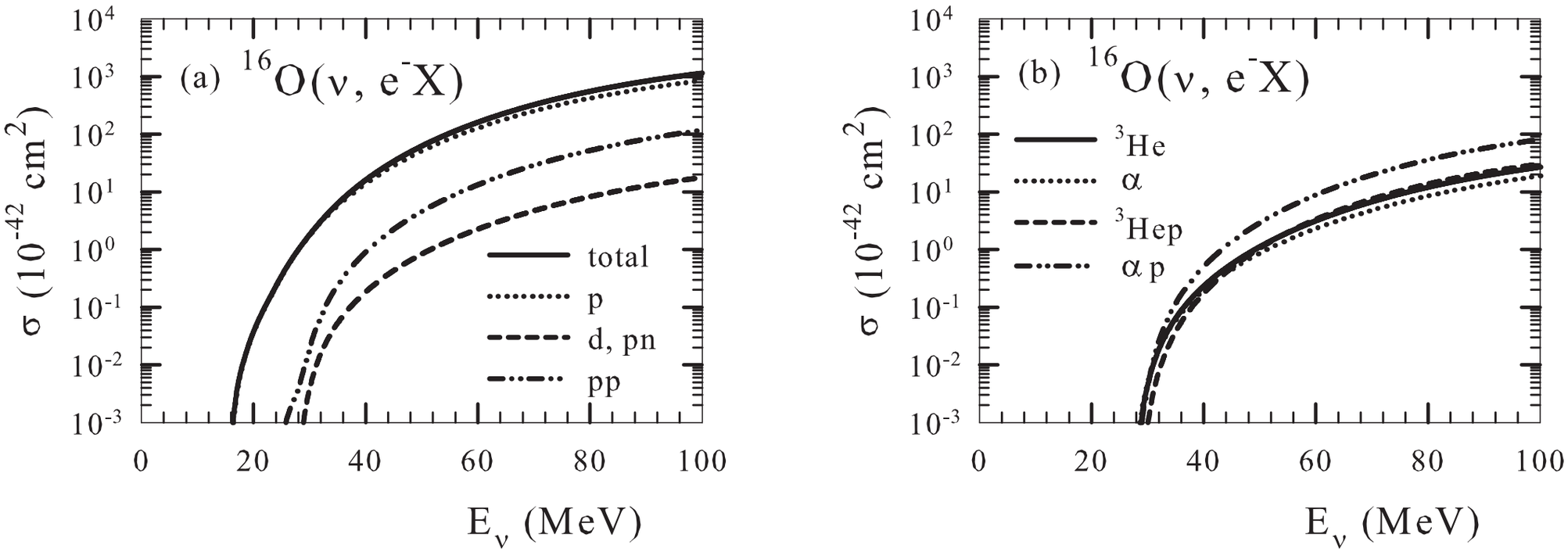


FIG. 6. Partial cross sections to various channels of ^{16}O (ν, e$^-$ X) as function of neutrino energy E_ν. (a) Cases for X =p, d and pn, and pp as well as the total cross section are shown. (b) Cases for X =^{3}He (and dp, ppn), α, ^{3}He p, and α p are shown.

^{16}O CC Partial Cross-Sections

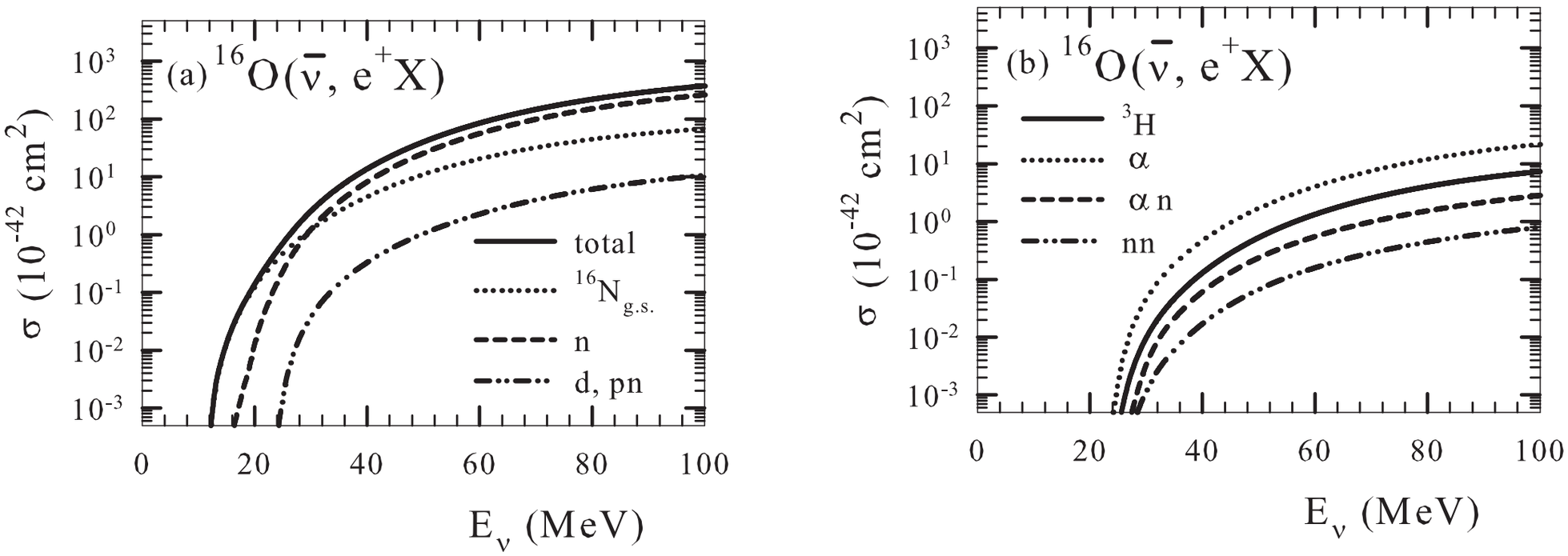


FIG. 7. The same as Fig. 6 for ^{16}O ($\bar{\nu}$, e$^+$X). (a) Cases for X =n, d and pn, and the transition to ^{16}N$_{g.s.}$ as well as the total cross section are shown (b) Cases for X =^{3}H (and dn, pnn), α, α n, and nn are shown.

^{16}O NC Partial Cross-Sections

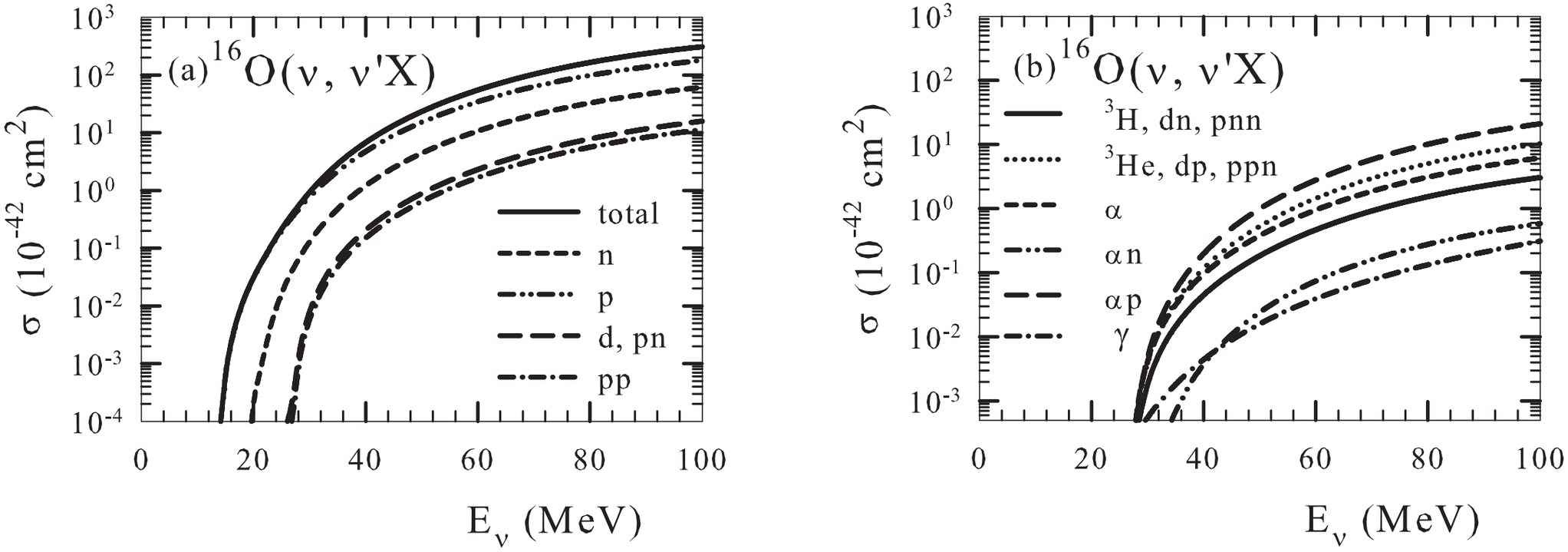


FIG. 8. The same as Fig. 6 for ^{16}O (ν, ν'X). (a) Cases for X =n. p. d and pn, and pp as well as the total cross section are shown. (b) Cases for X =^{3}H (and dn, pnn), ^{3}He (and dp, ppn), α, α n, α p, and γ are shown.

The Power of High Statistics @HK

- Detect *Hep* neutrinos $(^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + \mathrm{e}^+ + \nu_e)$
    - New PMTs: better E resolution reduces background from ^{8}B-ν that get reconstructed at too high E
        - Look for non-standard behaviour at higher energy
        - Different production region inside the sun

- Resolve production regions of ν inside the sun

  J. Davis: PRL 117, 211101 (2016) + talk 1 hour ago

- Sensitivity to shorter time variations
  (SK sees just O(10) events/day)

Supernova Relic Neutrinos @SK-Gd & HK

- SK-Gd: 1st observation (few evt/yr — equivalent to 3×SN1987a before HK starts)
- HK: hundreds of events in 20 years (even w/o Gd)
  ➔ measure spectrum & distinguish different models
- Can be combined with GW observations of BH binaries
  (J. Davis, M. Fairbairn: arXiv:1704.05073)
- Further improvements with 2nd HK-tank in Korea