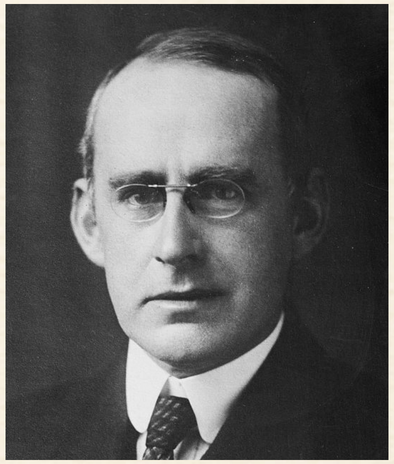
Astro- and Particle Physics Prospects of Solar and Supernova Neutrinos

Conference on Science at the Sanford Underground Research Facility,
May 12th, 2022

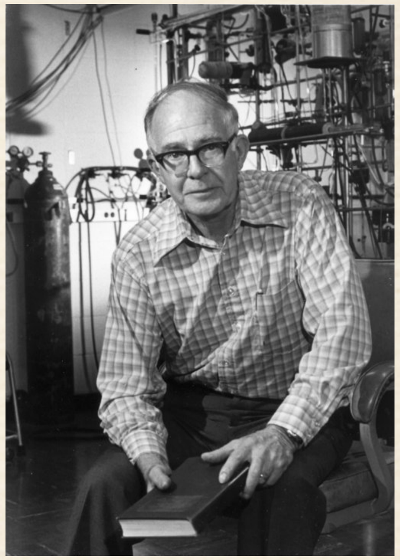
Michael Smy, University of California, Irvine

The Neutrino Probe and Probing the Neutrino

- neutrinos are interesting particles; due to their weak interactions, many properties are unknown or poorly known (e.g. mass)
- neutrinos are very weakly interacting, so neutrinos are good messengers from astrophysical objects (a super X-ray of these objects): stars are powered by nuclear fusion as demonstrated with neutrinos
- discuss two objects of interest:
    - the sun (for its own sake and as a model star)
    - core-collapse supernovae



Sir Arthur Eddington

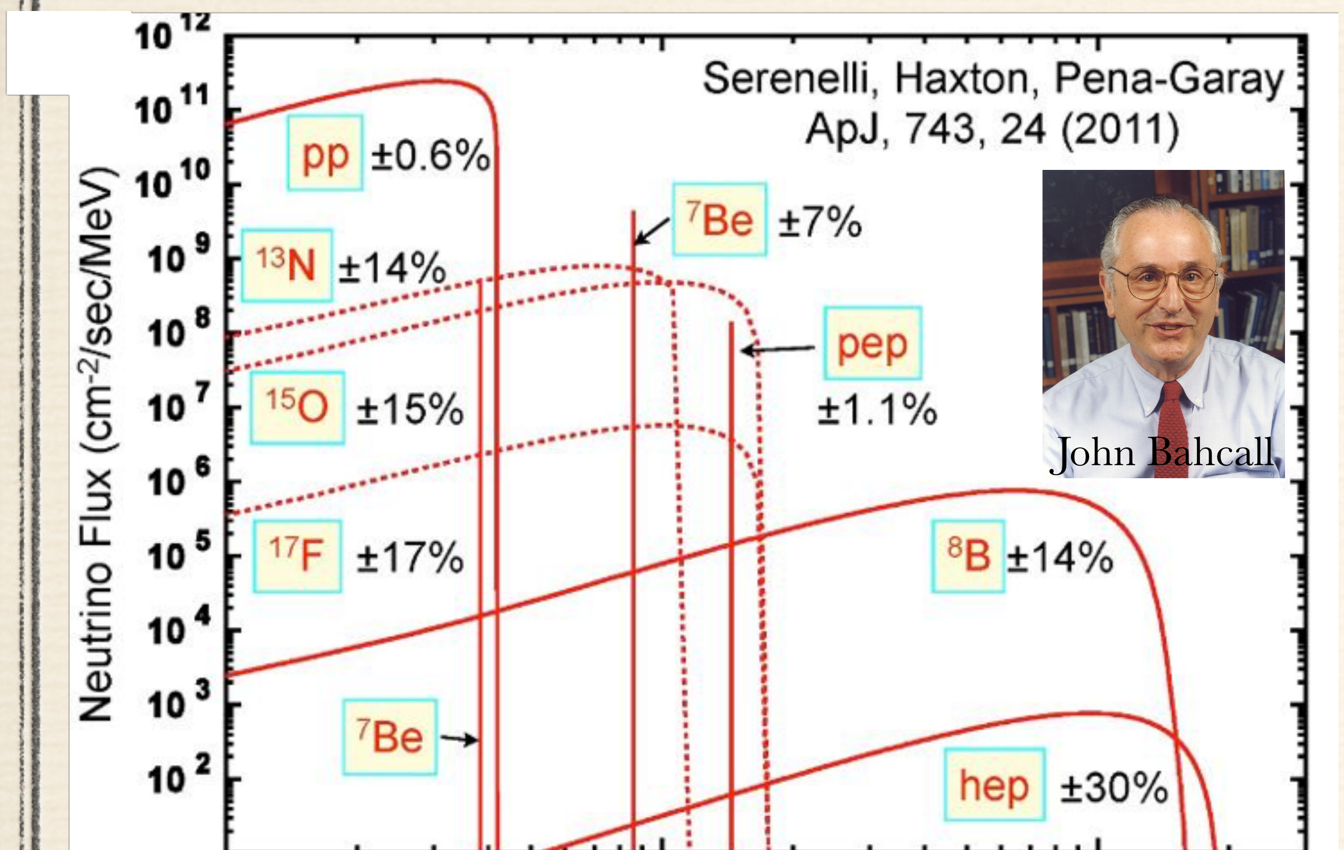


Raymond Davis Jr

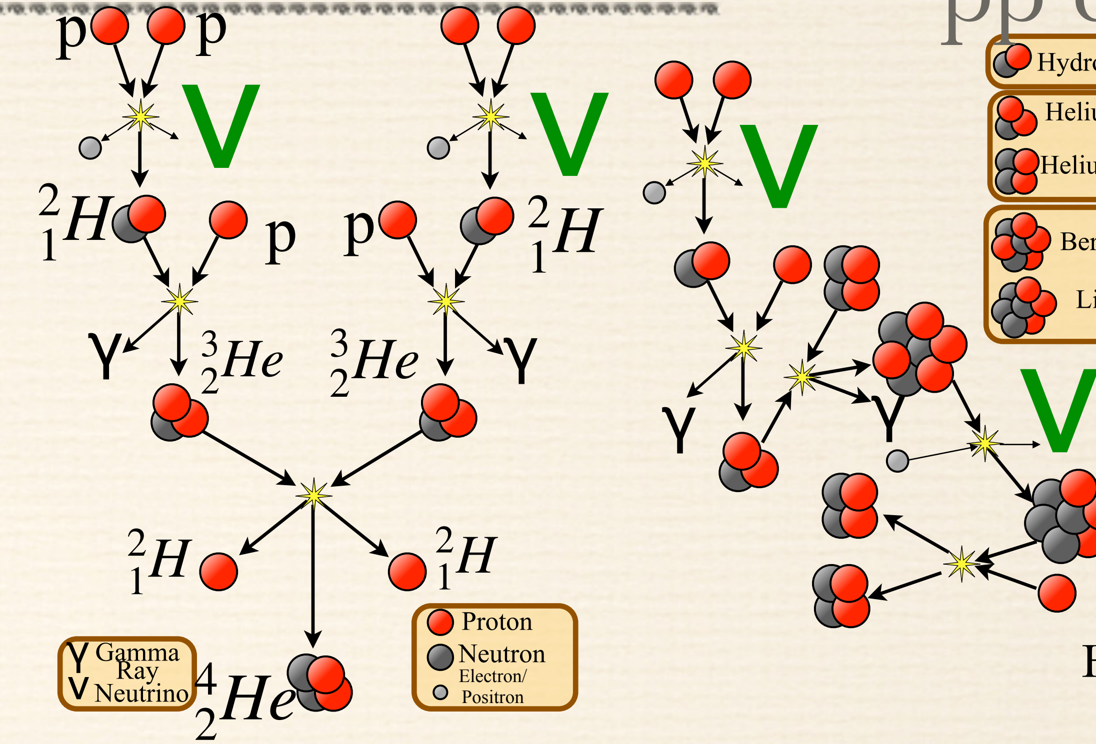
Michael Smy, UC Irvine

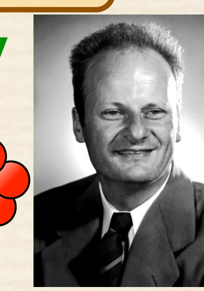
Solar Neutrinos

neutrino fluxes

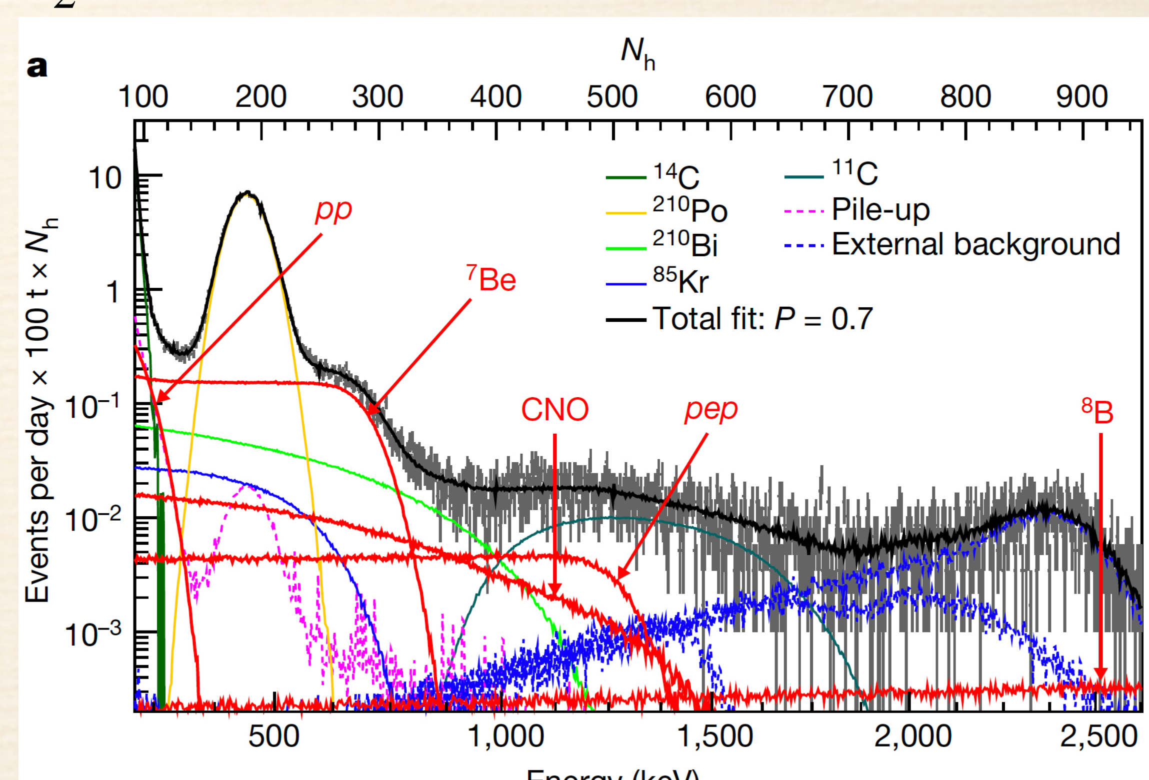


pp chain





Hans Bethe



Nature volume 562, pages 505–510 (2018)

- high matter density (~150 g/cm³ in the core)
- high magnetic fields (up to 3 kG)
- high flux
- direct product of solar energy production

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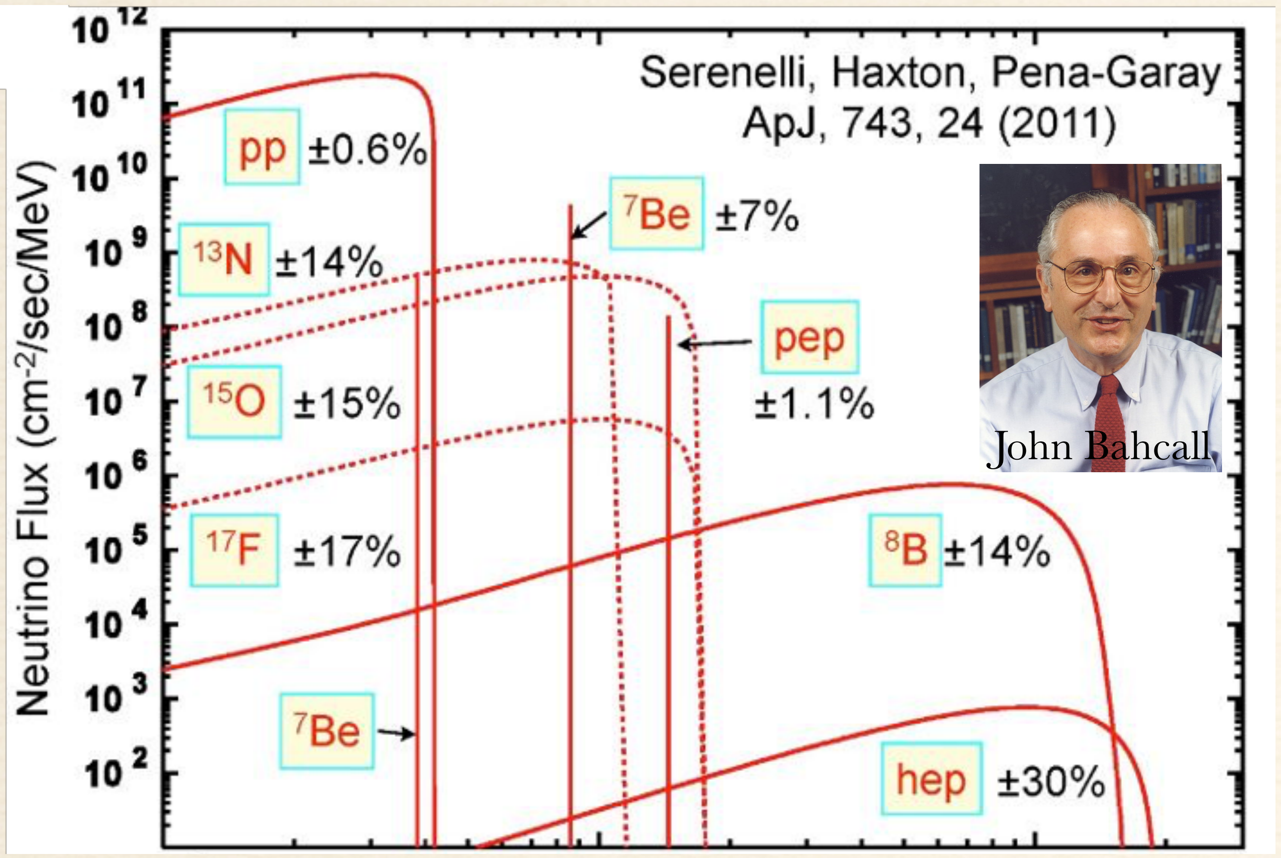
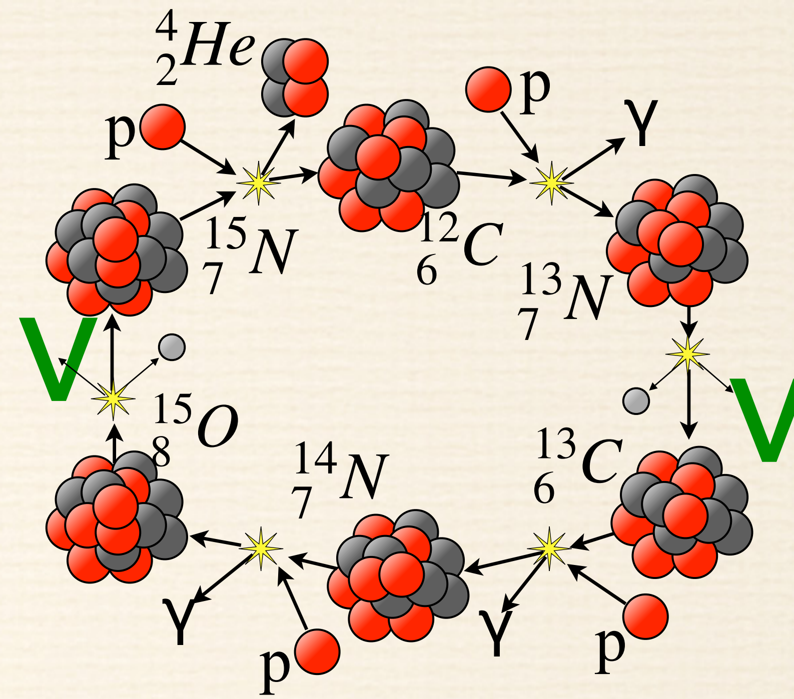
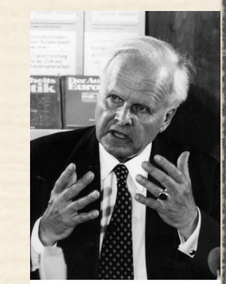
Solar Neutrinos

neutrino fluxes



CNO cycle





Carl-Friedrich von Weizsäcker

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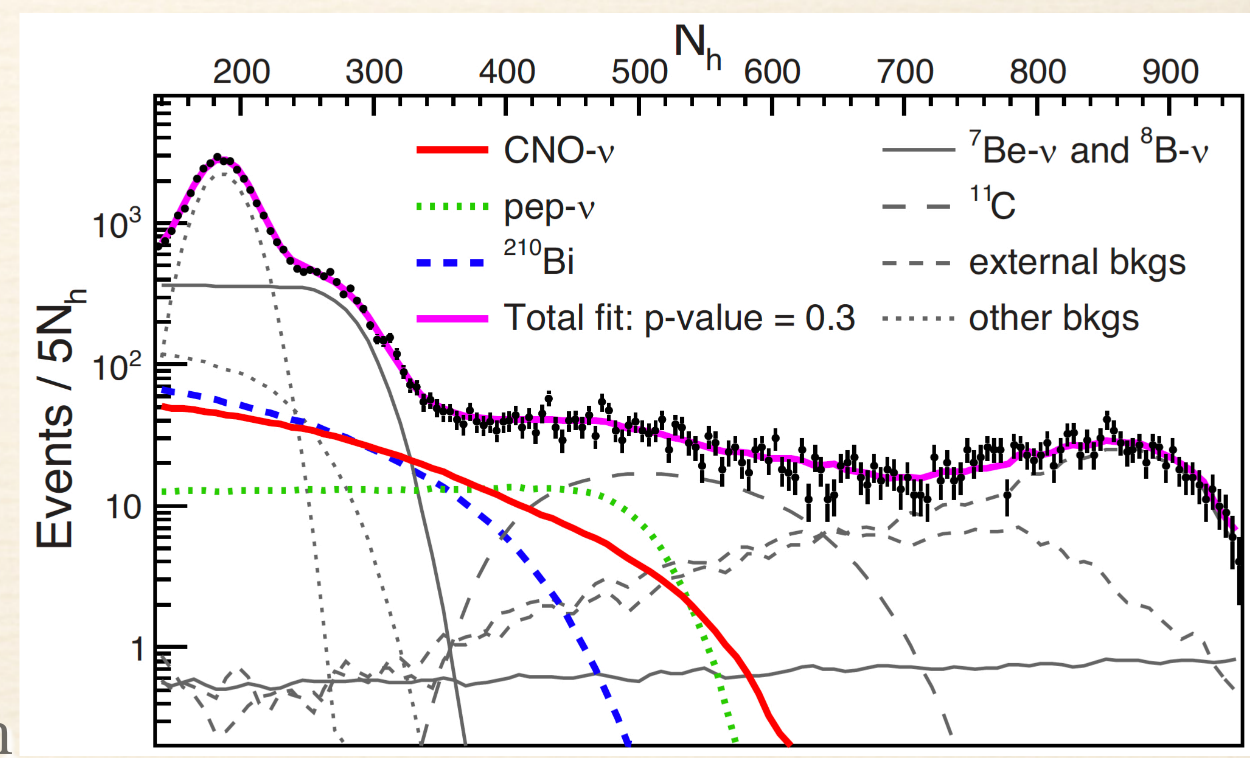
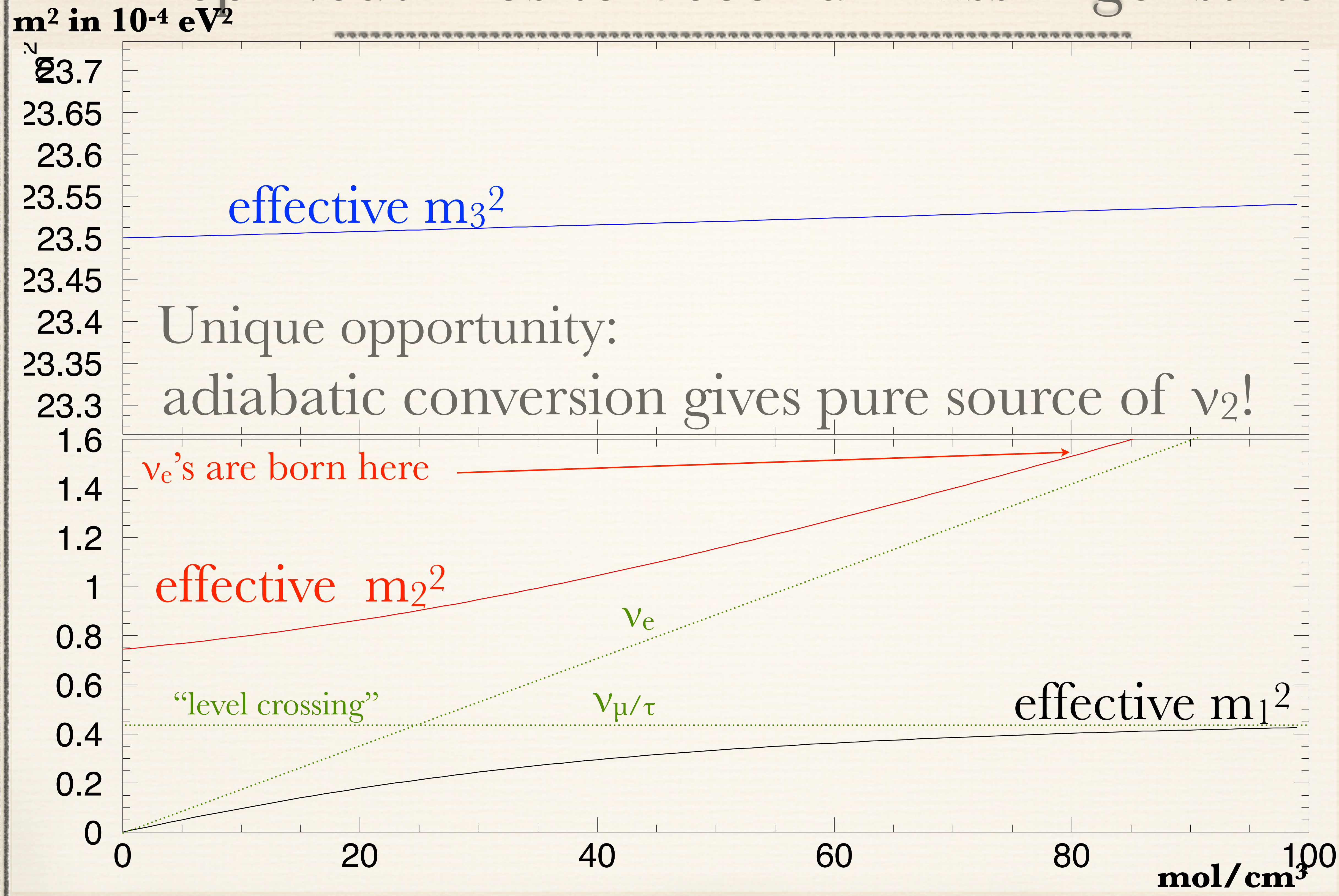


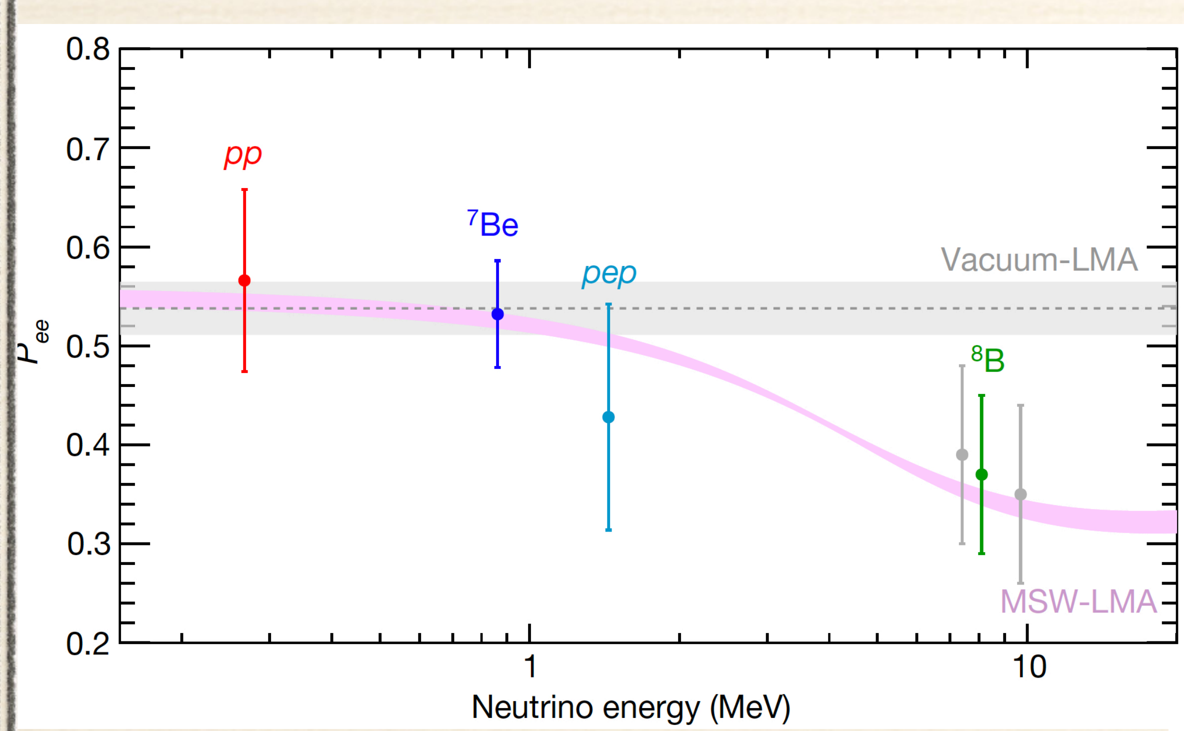
Nature volume 587, pages 577–582 (2020)

MSW Effect: Adiabatic Conversion of solar ^{8}B & hep Neutrinos to Second Mass Eigenstate

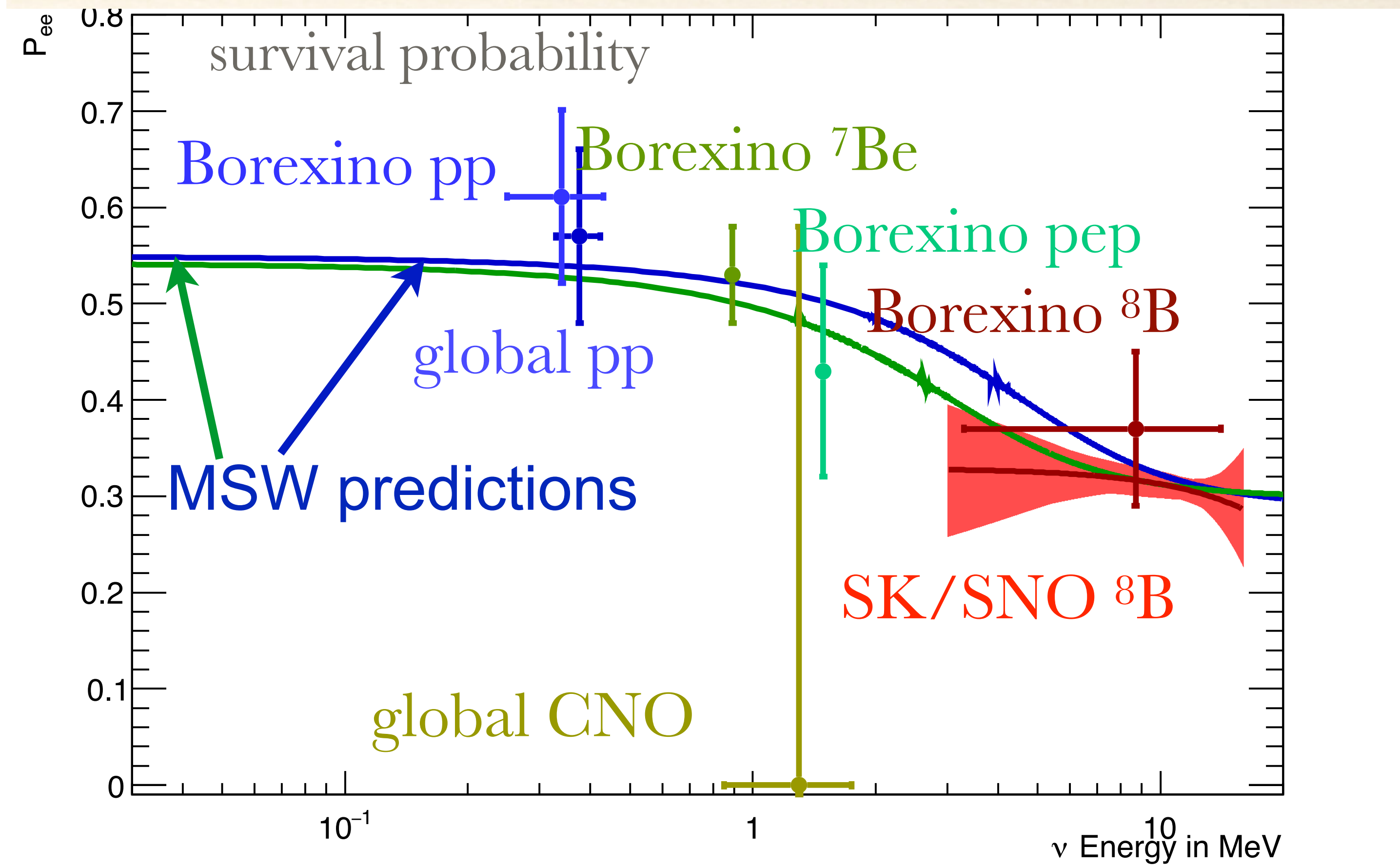


Study Energy Dependence of MSW Effect

- Borexino: compare measured (electron) neutrino fluxes with predictions from the solar model
- Super-Kamiokande and SNO: measure energy dependence of 8B (electron) neutrino flux and compare to total (active) ^{8}B neutrino flux measurement



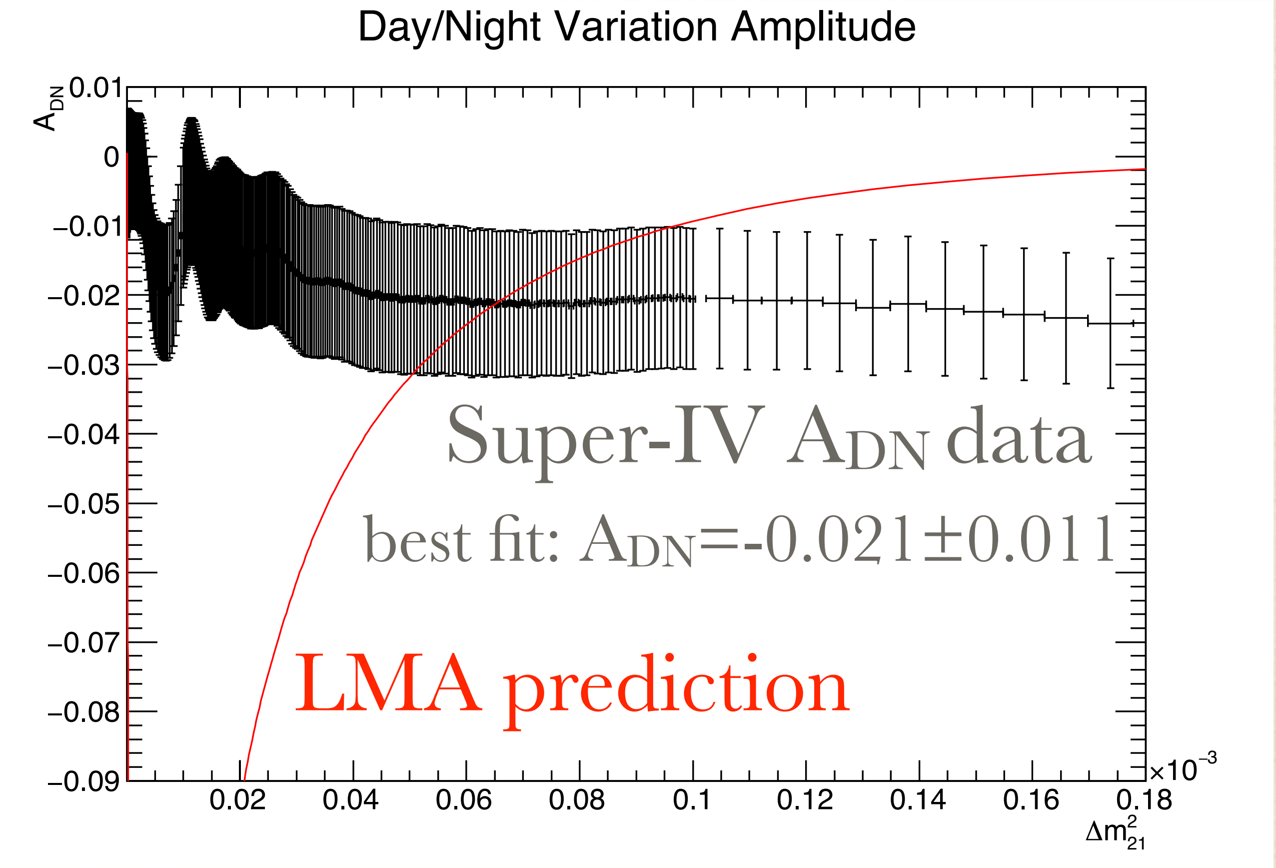
Nature volume 562, pages 505–510 (2018)



Directly Study Matter Effects on Neutrino Flavor Conversion

- the Earth matter density enters the solar beam every night
- the impact of that matter density is measured by comparing day (electron) flux to night-time (electron) flux: define asymmetry

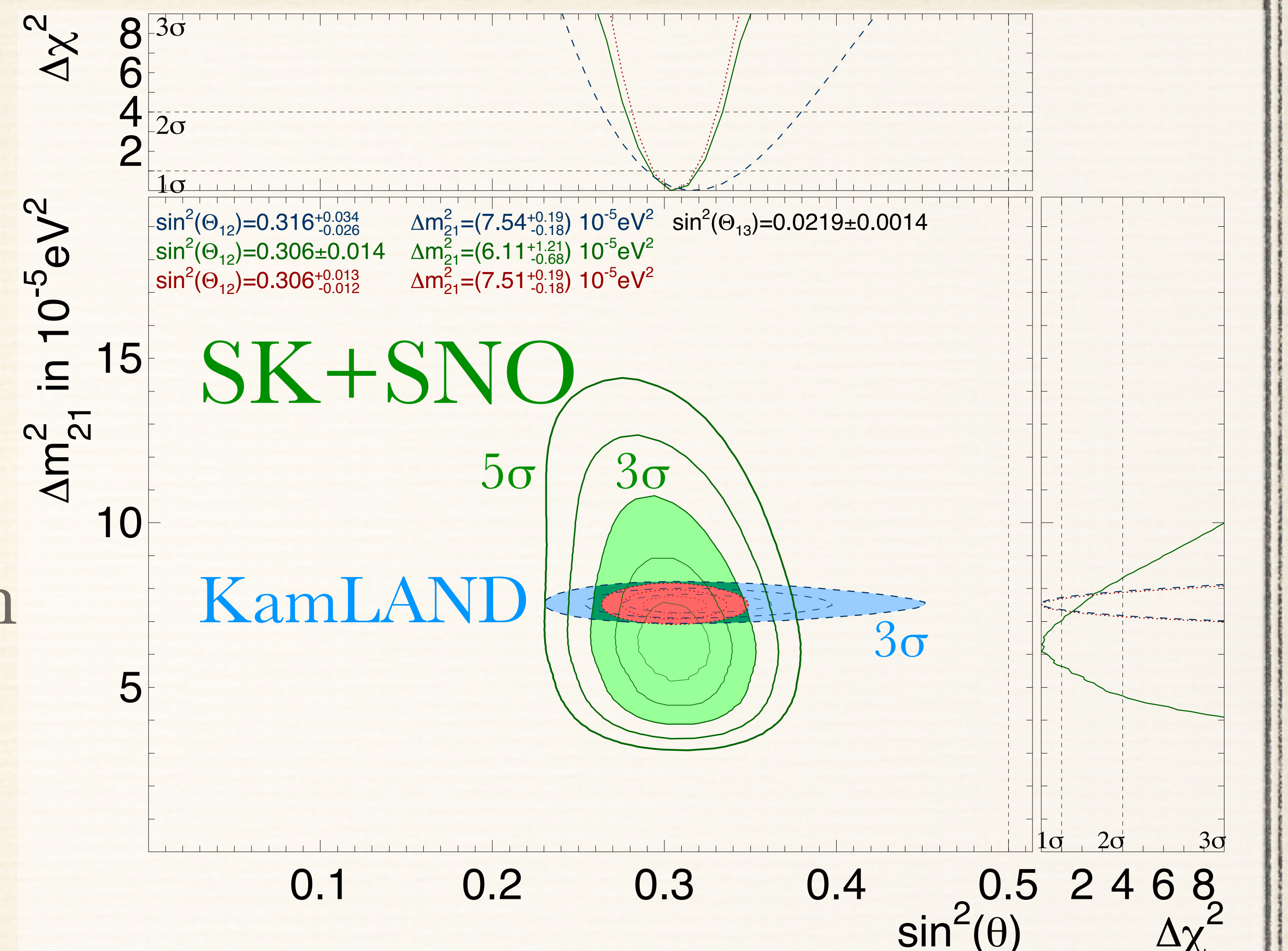
$$A_{DN} = \frac{\phi_{day} - \phi_{night}}{0.5\left(\phi_{day} + \phi_{night}\right)}$$



- for ^{8}B (and hep) solar neutrinos, a few % of electron-flavor regeneration is predicted (A_{DN}~-0.015)
- there is only a tiny impact for low energy solar neutrinos
- Borexino and SNO measured A_{DN} to be consistent with zero. Super-K saw a ~2.5σ indication for a negative A_{DN}

Test of CPT Invariance: Measure θ_{12}/θ_{13} and Δm^2_{12} with Neutrinos

- ultimately, reactor anti-neutrinos (JUNO!) will be best to determine those parameters
- however, since both measure a pure electron-flavor disappearance, a discrepancy in the survival probability P_{ee} between solar neutrino data and reactor anti-neutrinos implies CPT violation ⇒ a unique opportunity to test CPT
- Best constraints from Super-K and SNO (no solar model neutrino fluxes necessary)



perfect agreement in θ, Δm^2 agrees within 1.5σ

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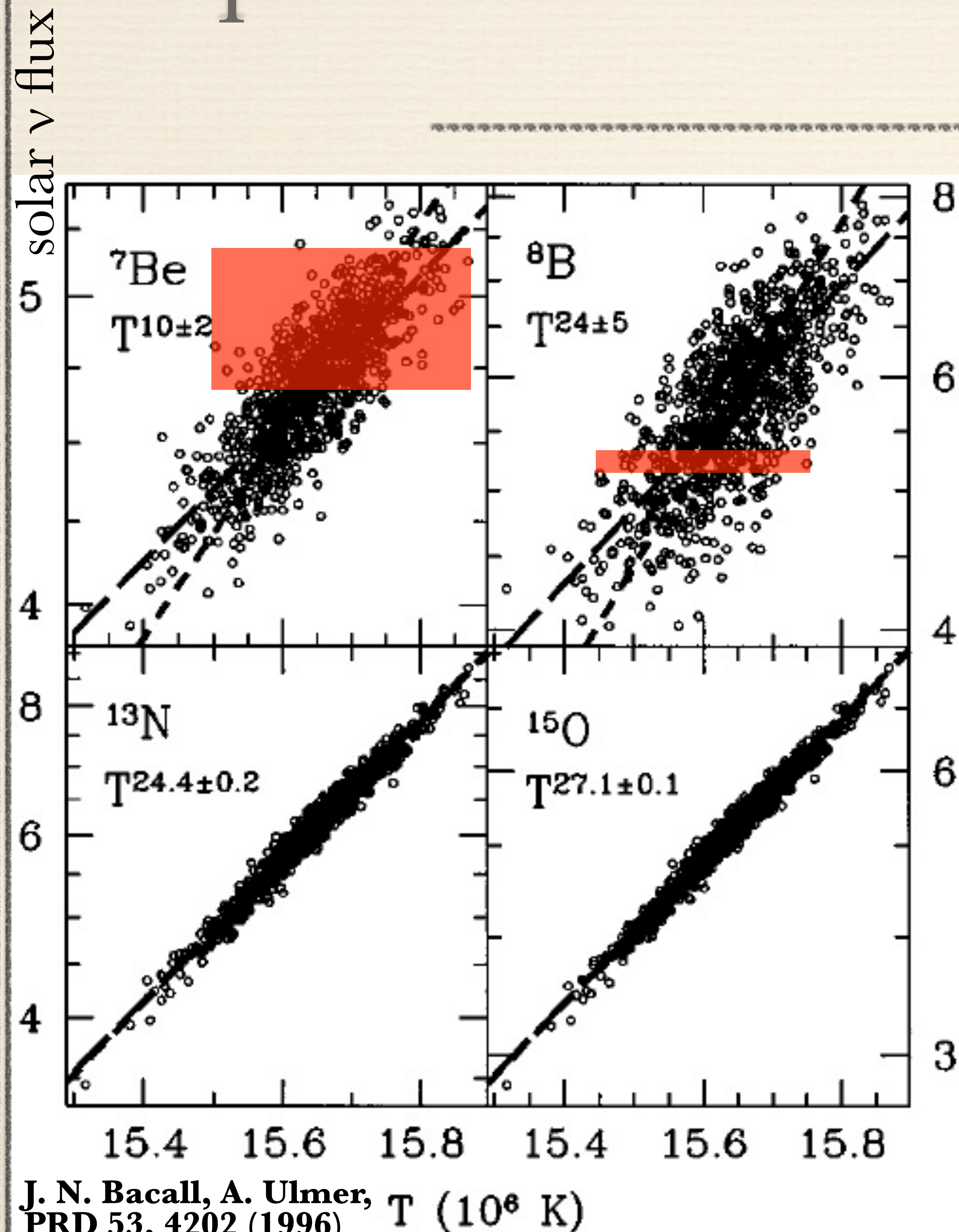
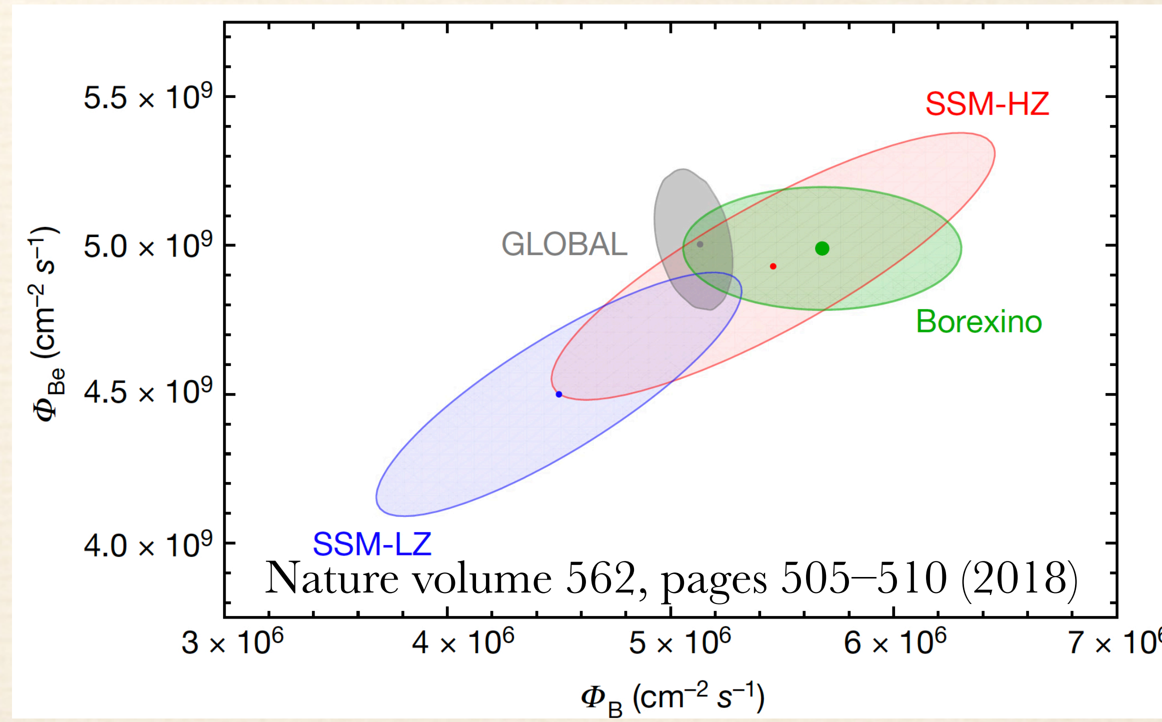
Temperature and Metallicity of the Sun



J. N. Bacall, A. Ulmer,
PRD 53, 4202 (1996)

- monitor solar core temperature with rare ^{8}B neutrinos
- comparison of ^{7}Be and ^{8}B has sensitivity to solar models, in particular metallicity
- CNO/pp data directly determines core metallicity



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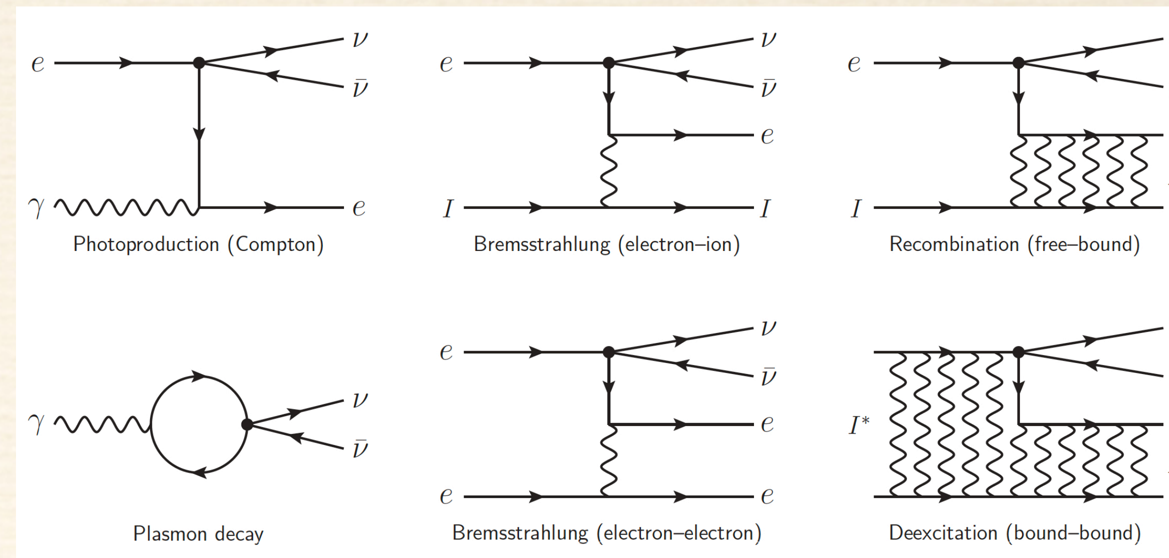
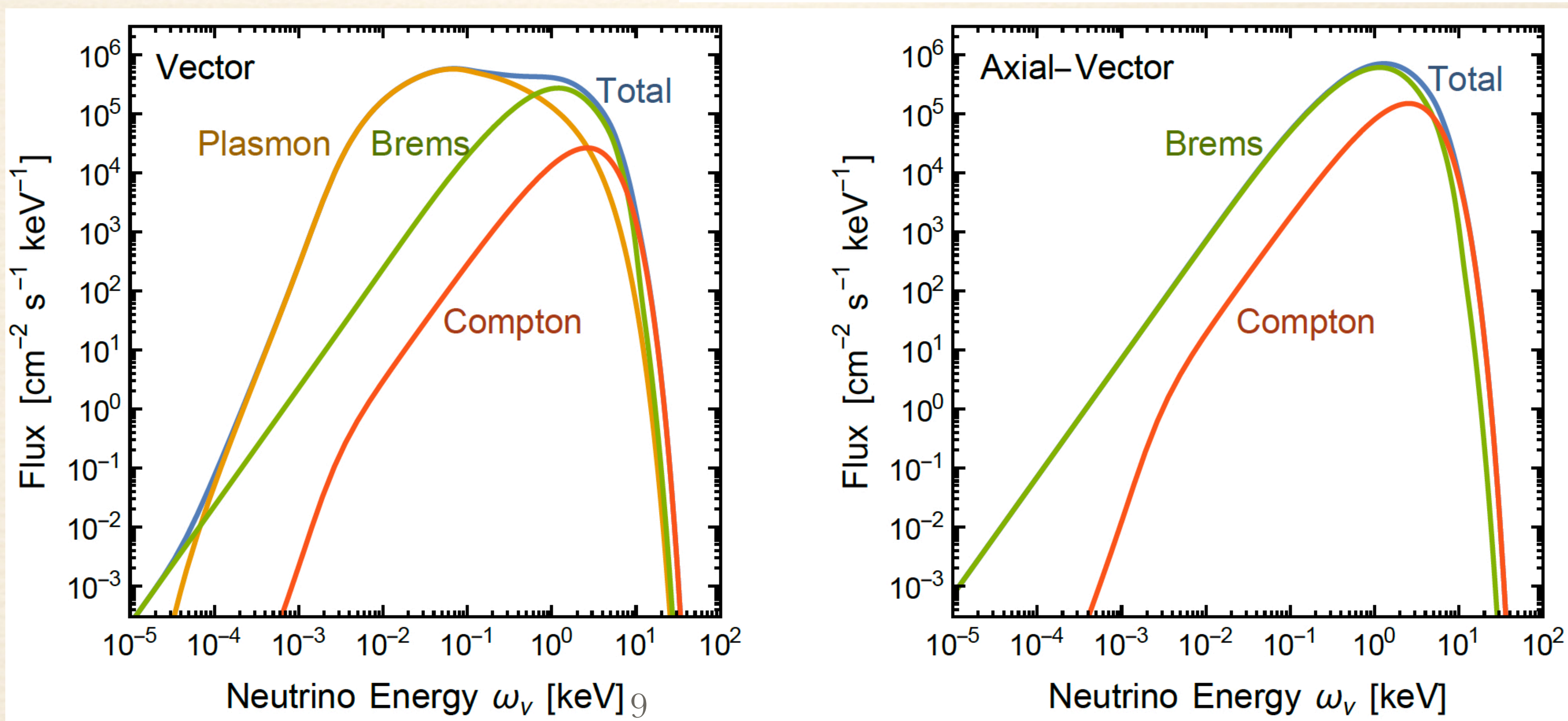
Thermal Solar Neutrinos

Vitagliano, Redondo, Raffelt: JCAP 12 (2017) 010

- study solar plasma with neutrinos
- really difficult: flux is O(^{8}B flux), but energy is lower by a factor of ~1000
- all neutrino flavors are produced





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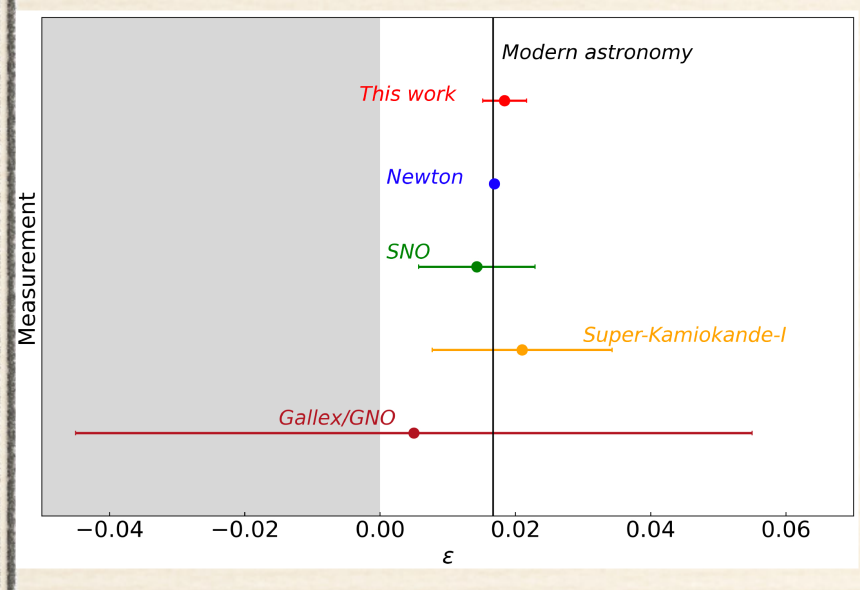
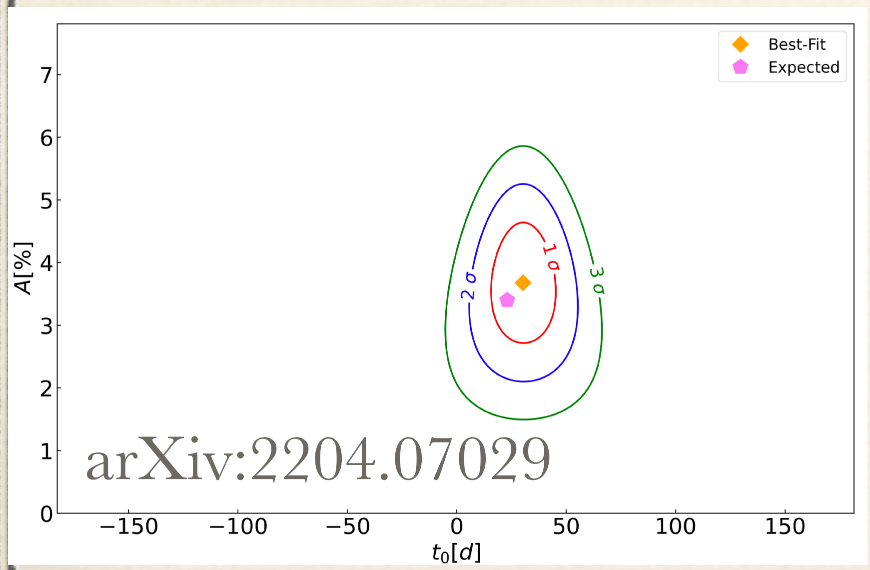
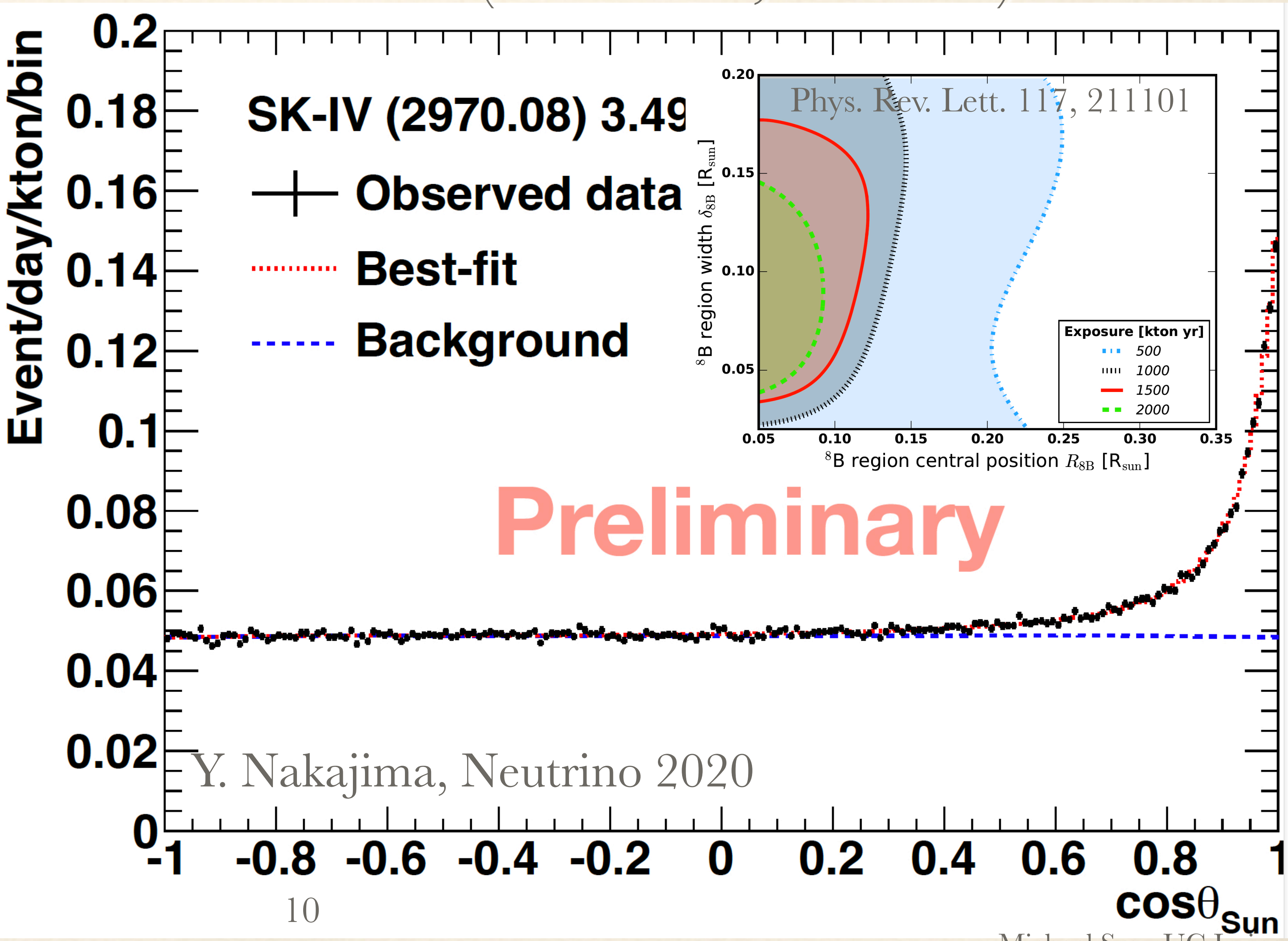
Do Solar Neutrinos Originate from the Sun?

- seasonal solar neutrino flux variation
- directional detection of solar neutrinos
- can attempt to detect size of solar core (PRL 117, 211101)

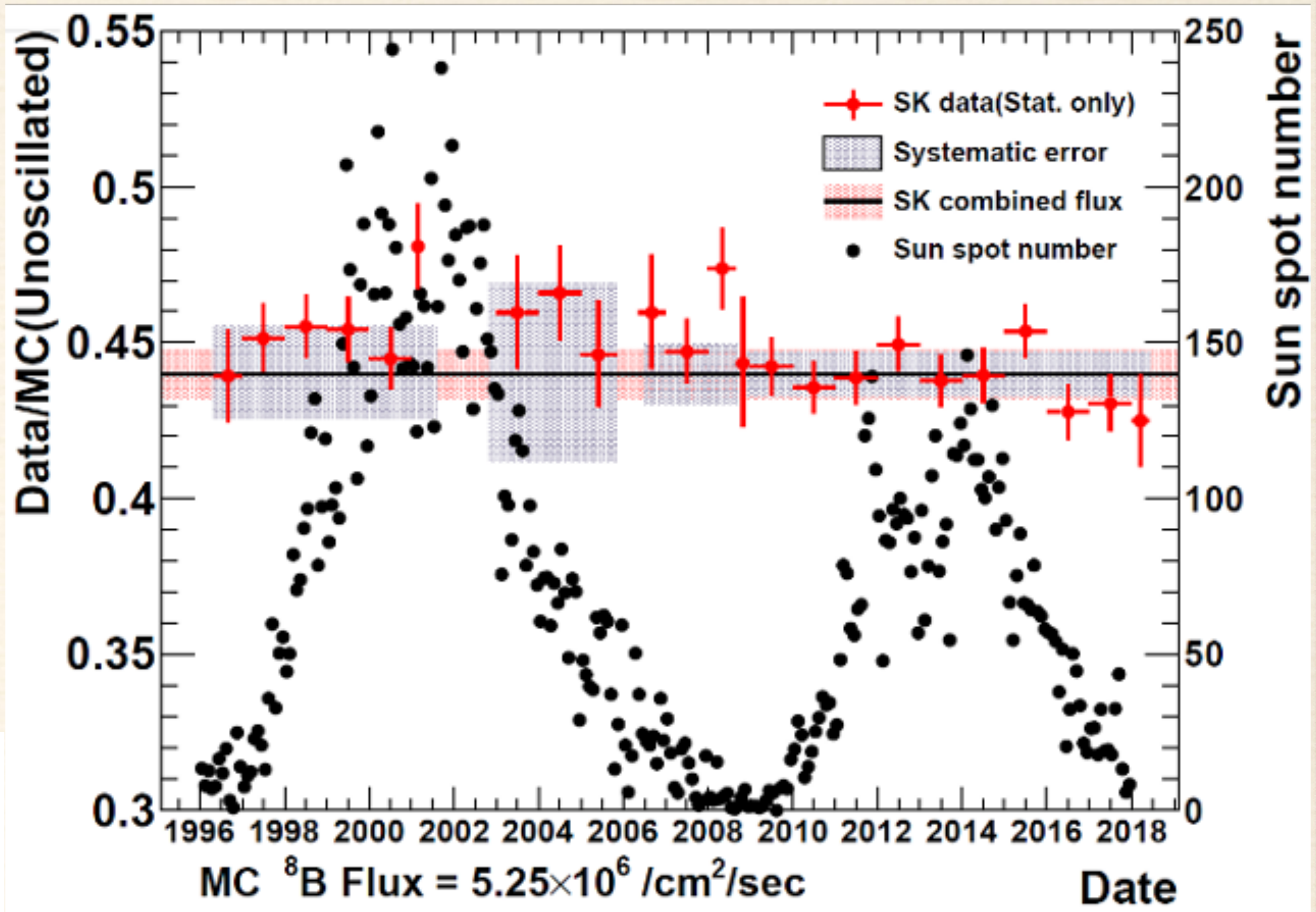






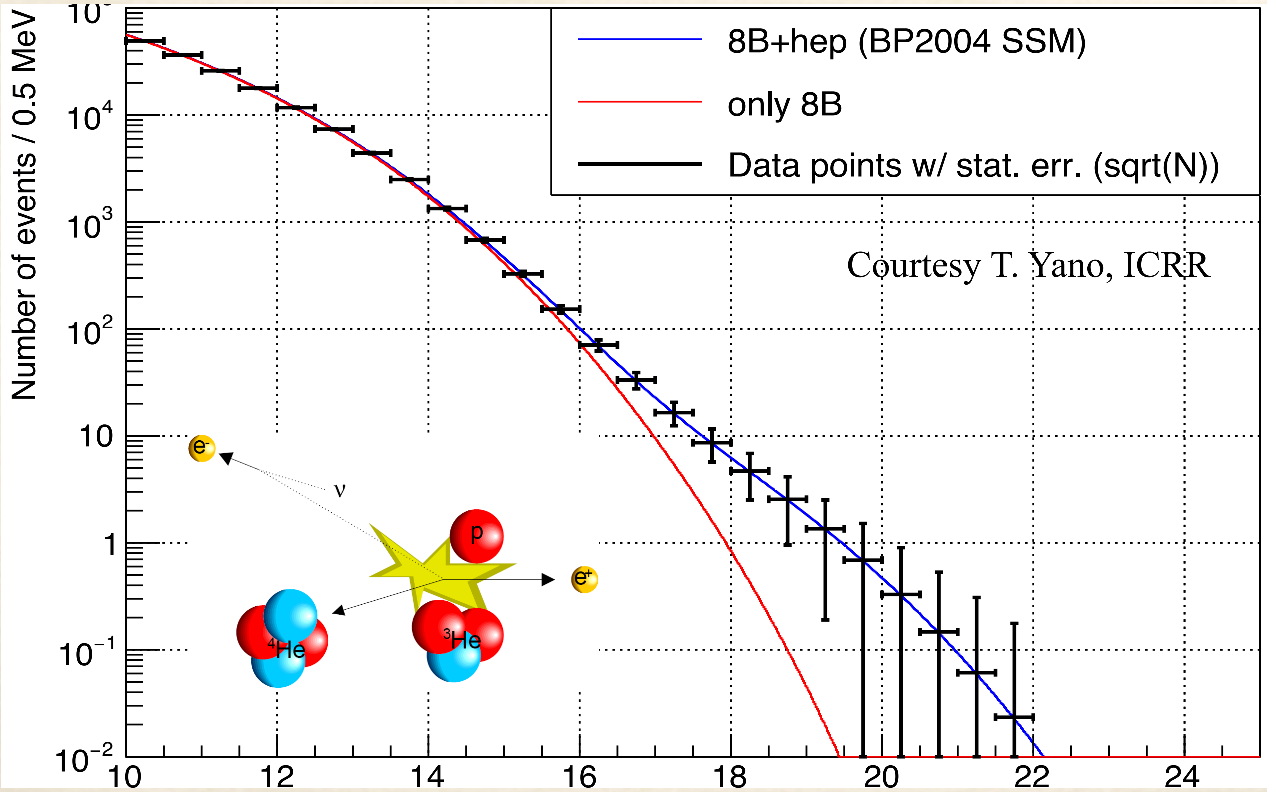
Monitoring Solar Burning, Solar hep Neutrinos

- high solar neutrino event rate at Hyper-K: ~130 events/day
- real-time monitoring of the solar reactor!



Y. Nakajima, Neutrino 2020

Detect hep Neutrinos in Hyper-K

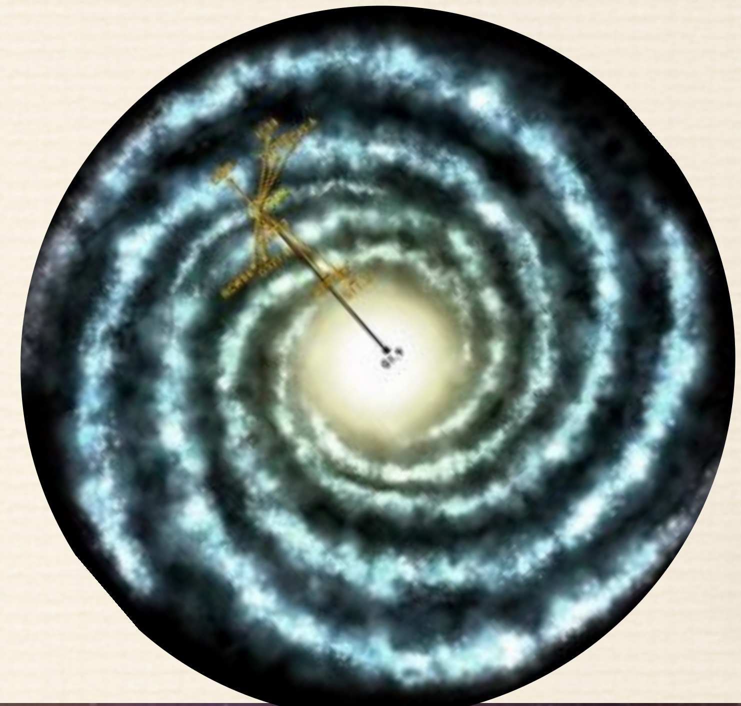


- last pp chain neutrino source that is unmeasured
- limits by Super-K and SNO
- Hyper-K has enough statistics

Neutrinos from Rare, Nearby (=Galactic) Core-Collapse (CC) Supernovae

- only six recorded CC explosions in ~1800 years in Milky Way (9 SN remnants in milky way)
- see only ~20%: ~2 CCSN/century

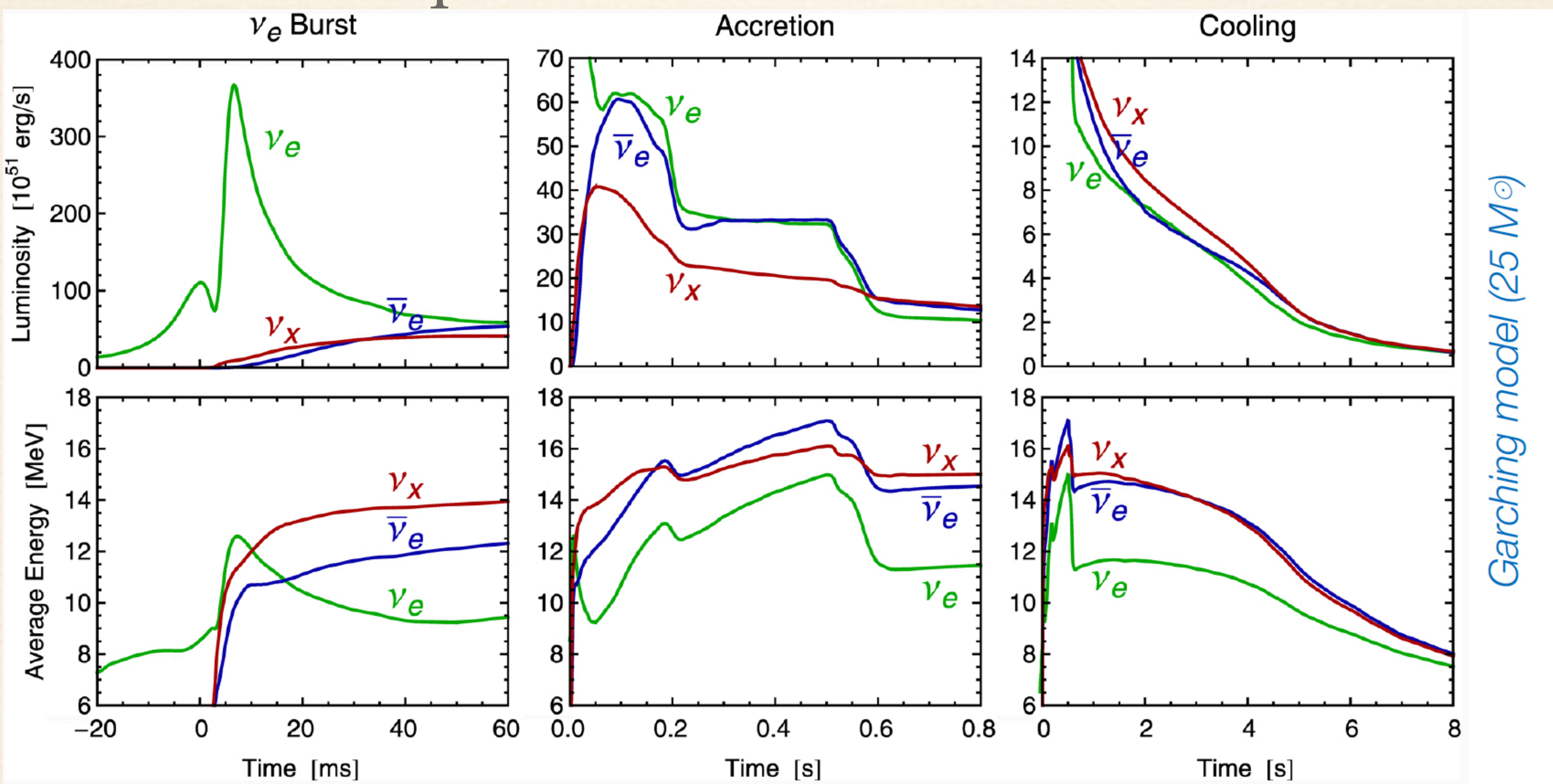
… and SN1885a (M31) SN 1987a (LMC)



from: M. Vagins, WATCHMAN meeting at Virginia Tech in 2013

Detection of Neutralization Burst

- begin (and reason) of core collapse
- pure electro flavor peak at short time scales



Neutronization burst

- Shock breakout
- De-leptonization of outer core layers

Accretion phase

- Shock stalls ~150 km
- Neutrinos powered by infalling matter

Cooling phase

- Cooling on neutrino diffusion time scale

July 4, 2018 Inés Gil-Botella I SN neutrino detection at DUNE

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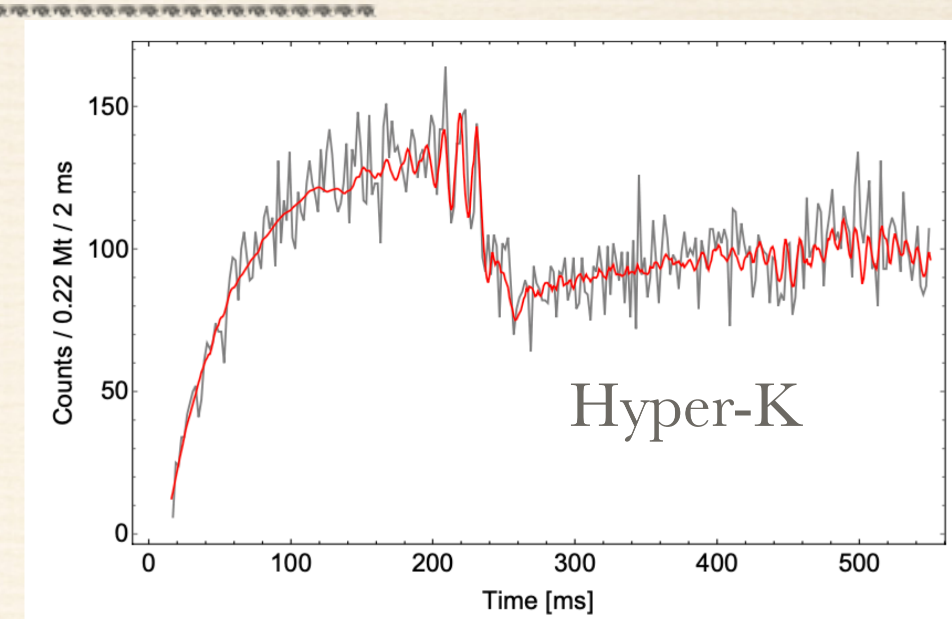
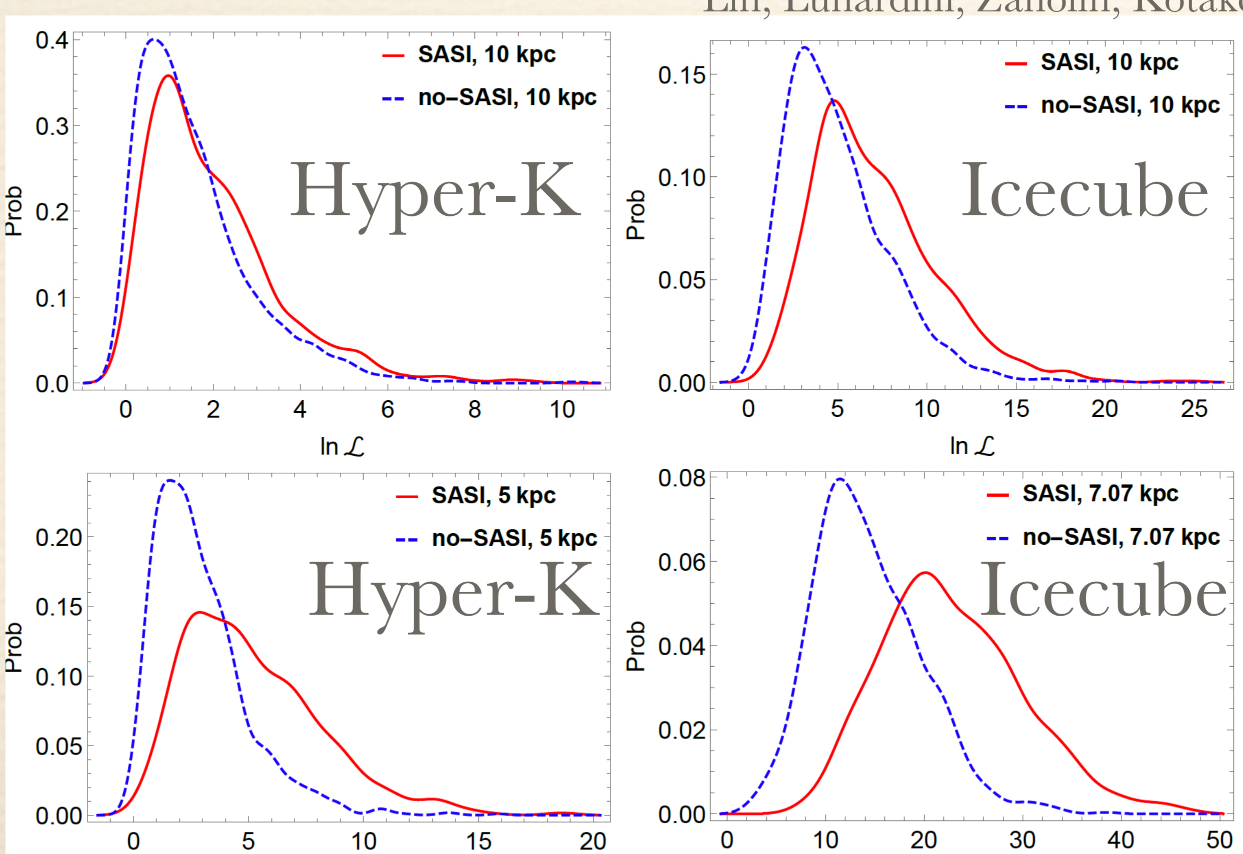
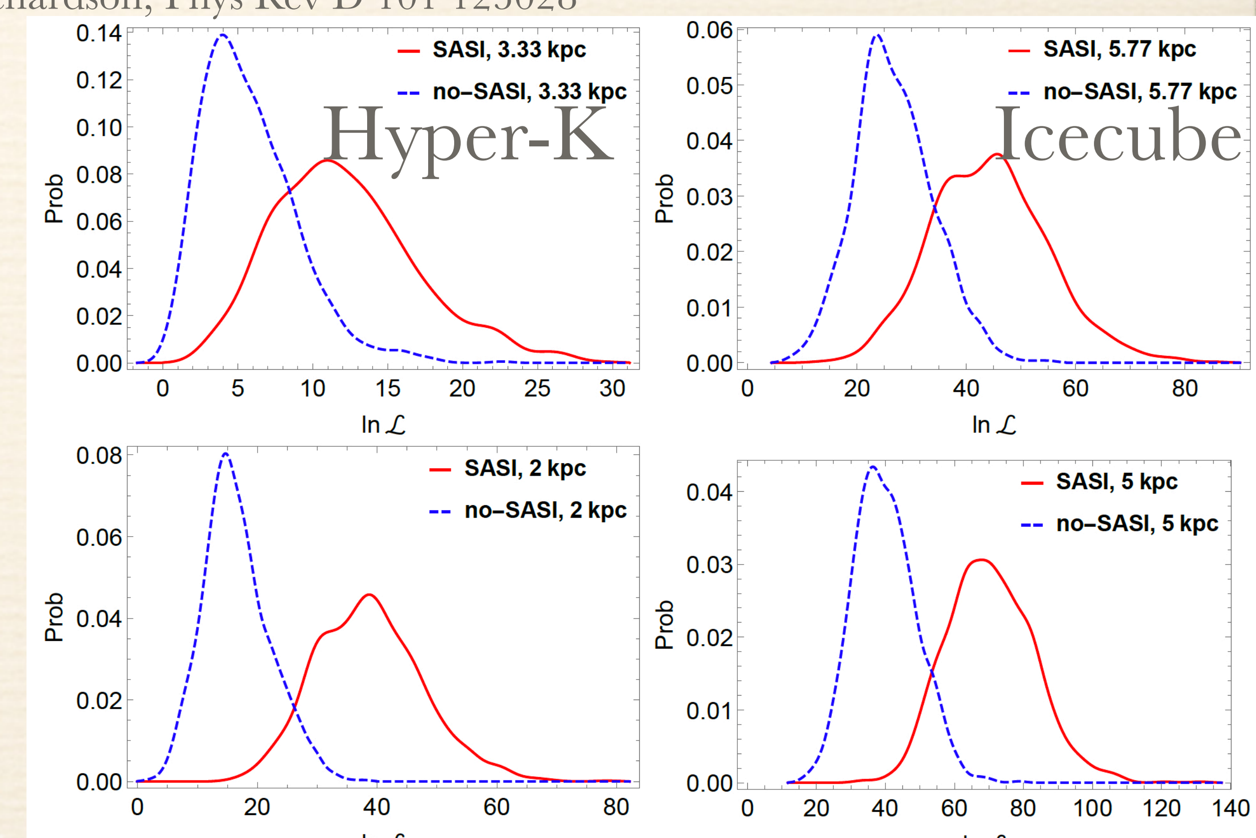
Understanding the Explosion Mechanism of Core Collapse Supernovae

- neutrinos drive the explosion, and 99% of the released energy of CC SN is in form of neutrinos
- example: observation of Standing Accretion Shock Instabilities using neutrinos:

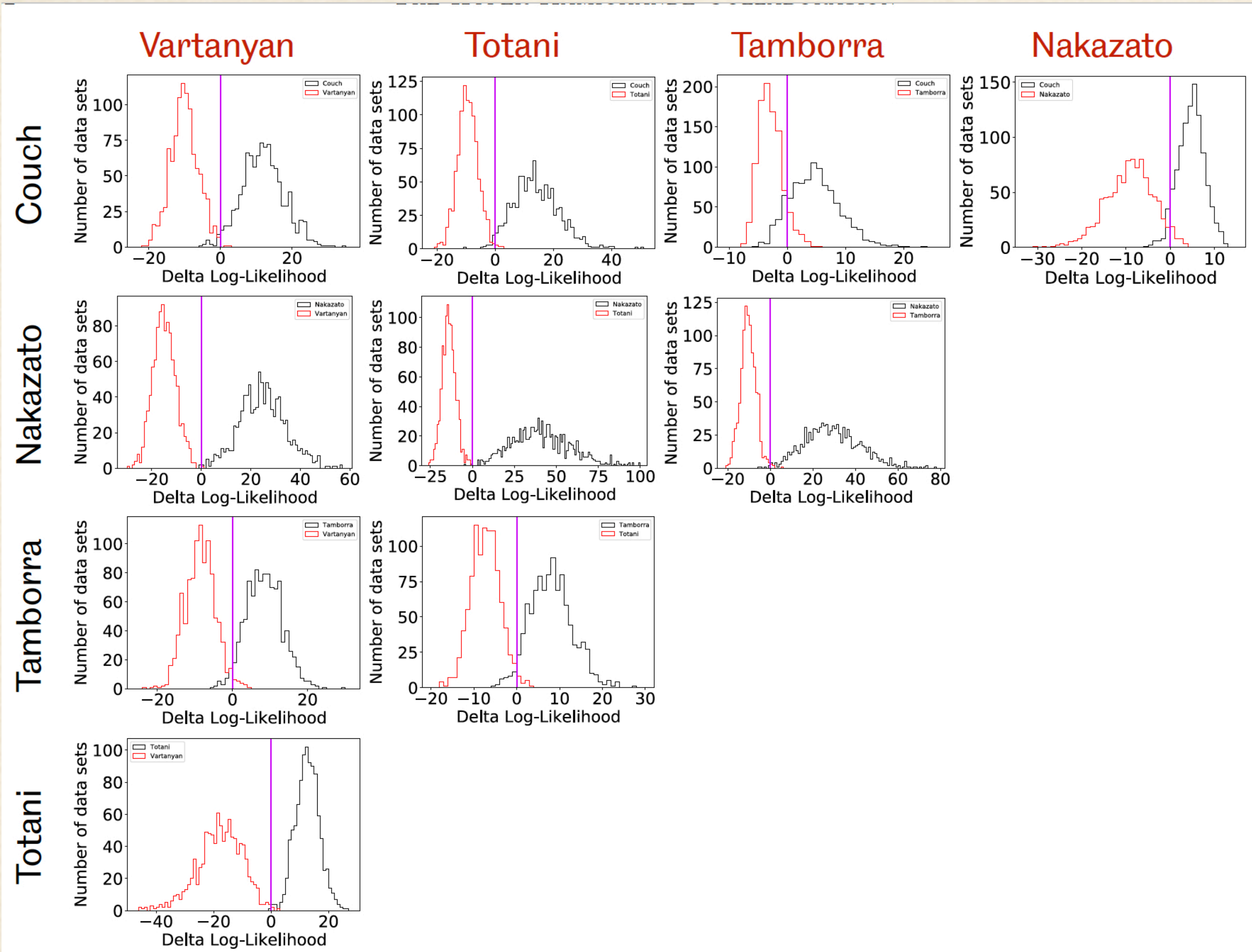


Lin, Lunardini, Zanolin, Kotake, Richardson, Phys Rev D 101 123028

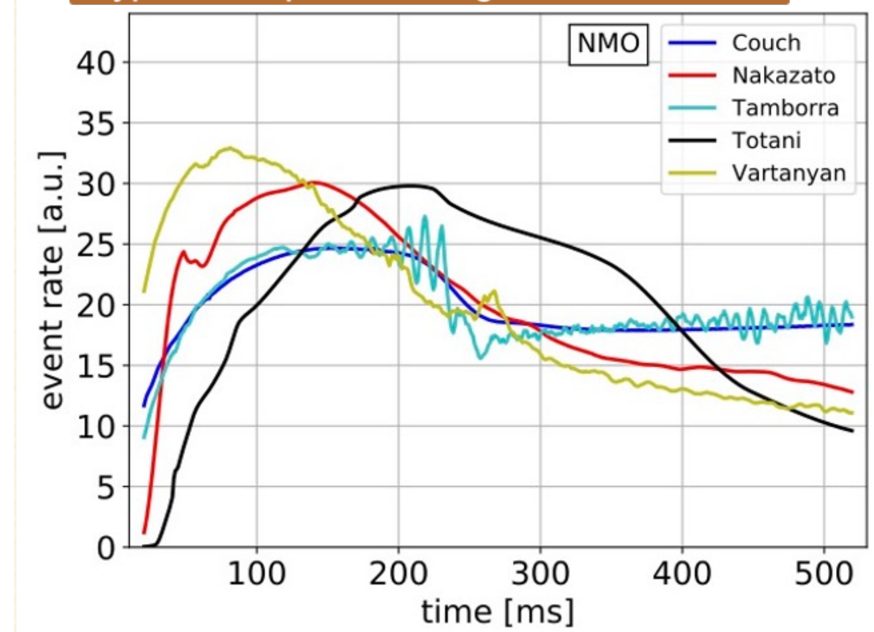




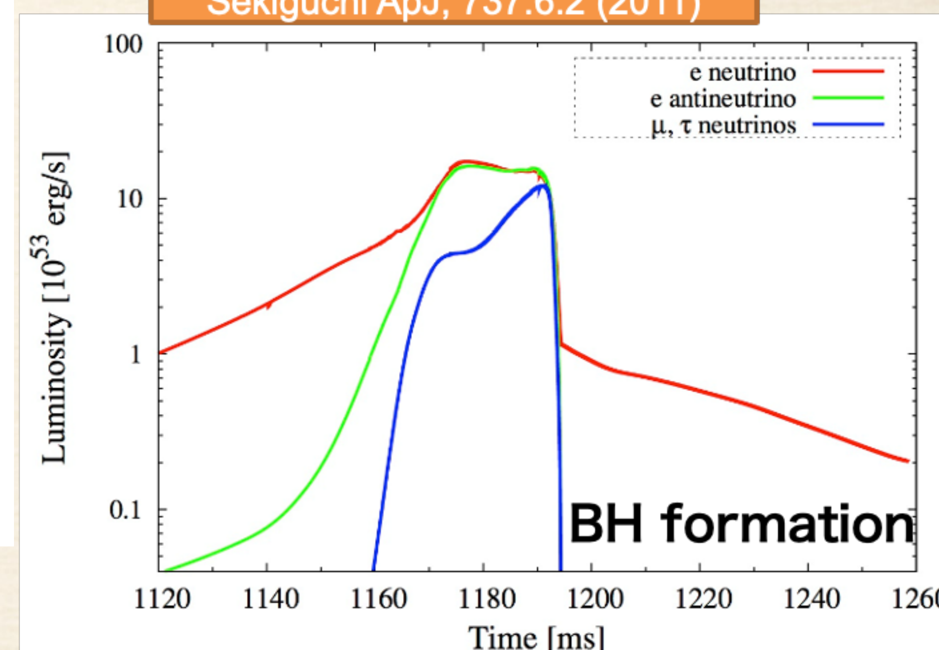
Understanding the Explosion Mechanism: Supernova Model Discrimination (Hyper-K)



Hyper-K, https://arxiv.org/abs/2101.05269



Sekiguchi ApJ, 737.6.2 (2011)



simulated 100 events for each model, NO, 20% photo-coverage

Courtesy T. Yano, ICRR

Understanding the Explosion Mechanism: Supernova Model Discrimination (Hyper-K)

Accuracy with which the true model can be identified, for 300 events per data set

Normal mass ordering.

Reconstructed Model (columns) / **True Model** (rows)

Normal	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**98.2**	0.2	1.6	0.0	0.0
Nakazato	0.1	**99.9**	0.0	0.0	0.0
Tamborra	1.6	0.0	**98.0**	0.2	0.2
Totani	0.0	0.0	0.0	**100.0**	0.0
Vartanyan	0.0	0.0	0.0	0.0	**100.0**

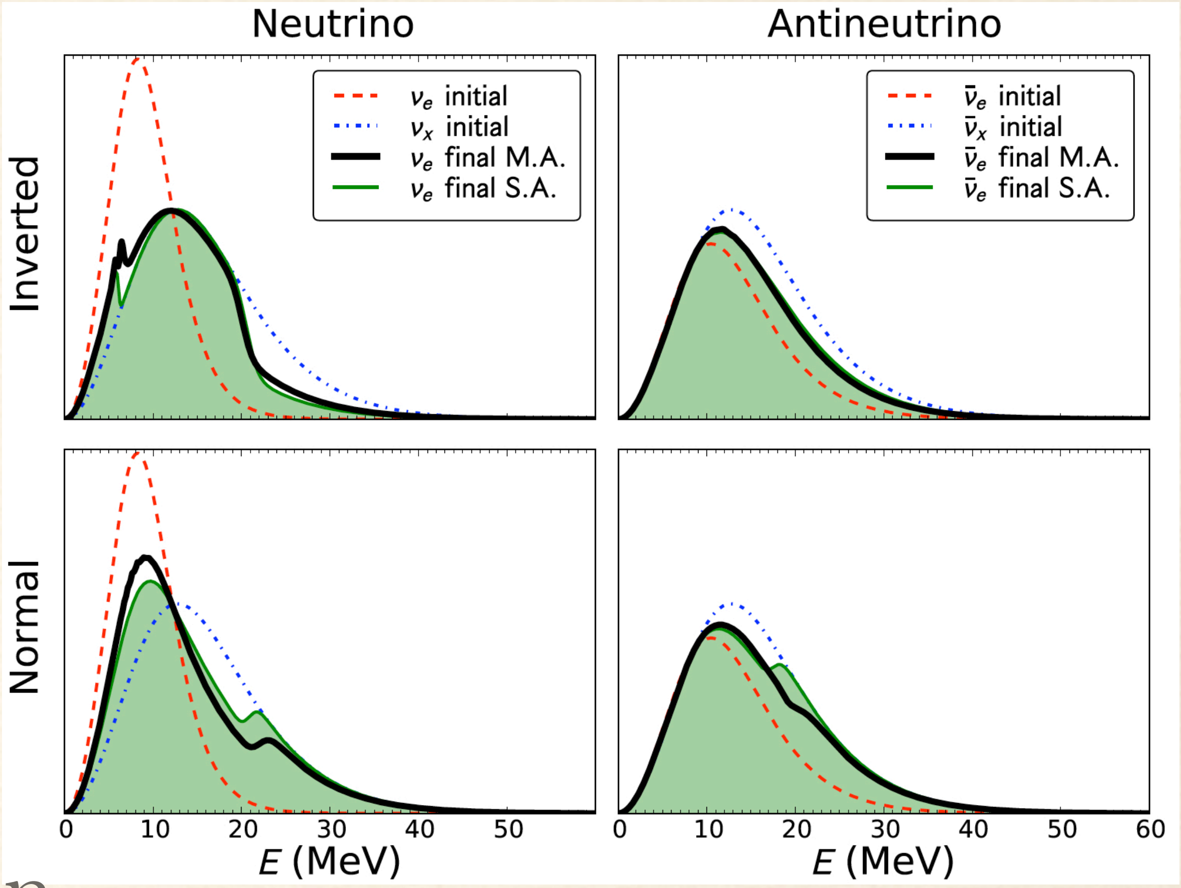
Inverted mass ordering.

Reconstructed Model (columns) / **True Model** (rows)

Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**99.9**	0.1	0.0	0.0	0.0
Nakazato	0.0	**100.0**	0.0	0.0	0.0
Tamborra	0.0	0.0	**97.4**	0.1	2.5
Totani	0.0	0.0	0.0	**100.0**	0.0
Vartanyan	0.0	0.0	0.8	0.0	**99.2**

Courtesy T. Yano, ICRR

Neutrino-Neutrino Interactions



Phys. Rev. Lett. 106 091101

- extreme test of our understanding of weak interactions
- only available in a core-collapse supernova (and at the big bang)
- "collective neutrino oscillations" to lead spectral swaps depending on neutrino/anti-neutrino and mass ordering
- also: 3 flavor MSW effects as matter densities go all the way to nuclear densities

Michael Smy, UC Irvine

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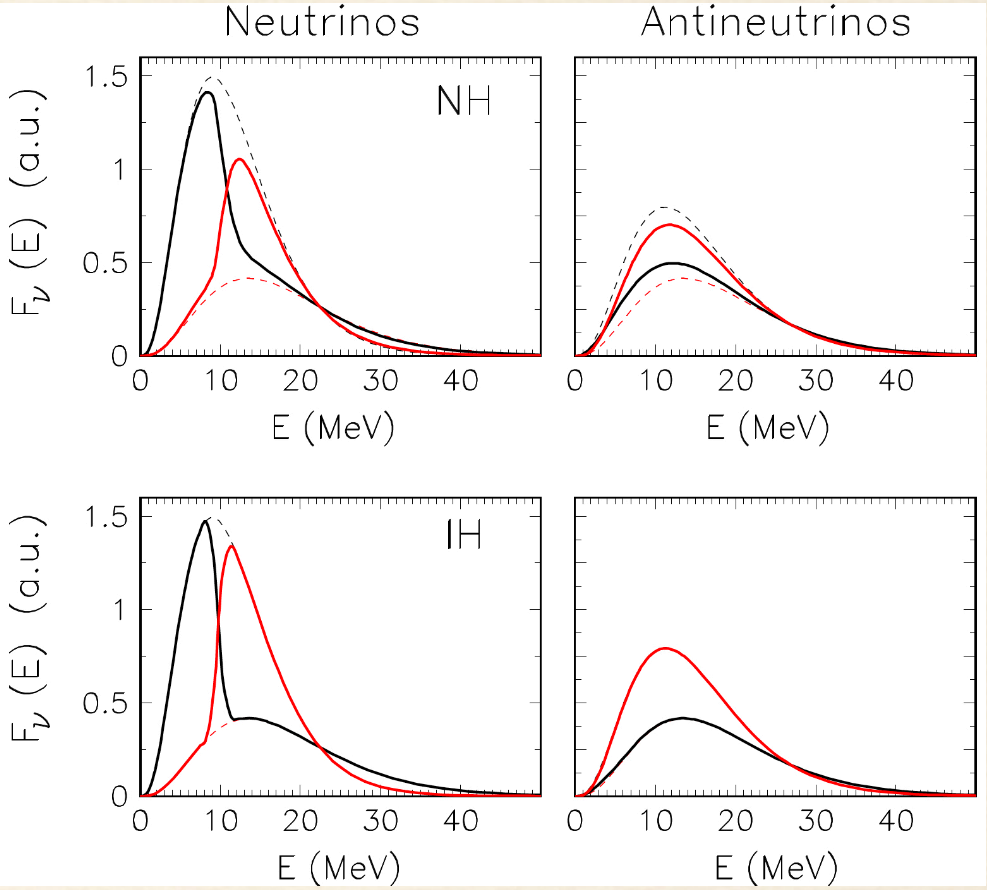

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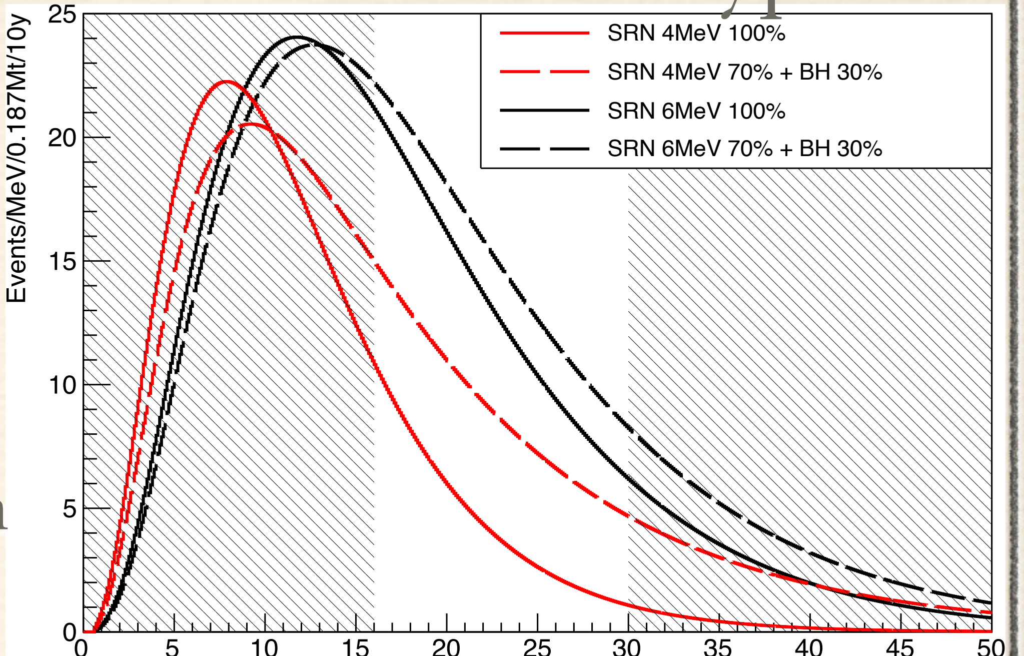
Phys. Rev. D90, 033004

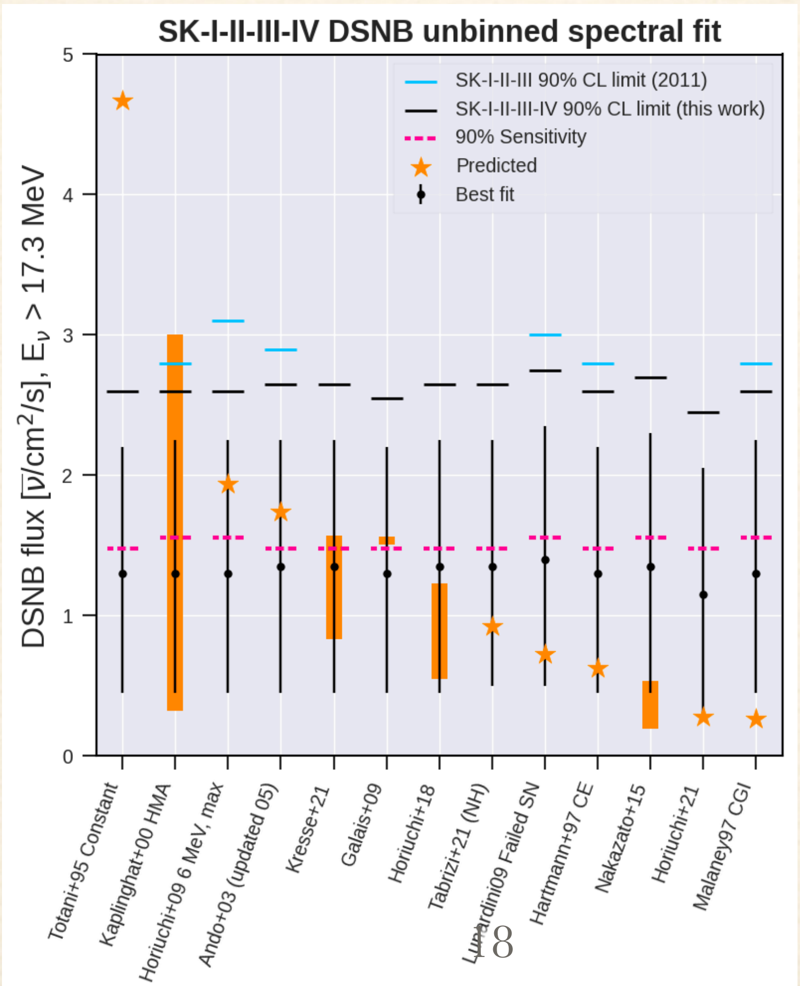
Distant Supernovae Neutrinos

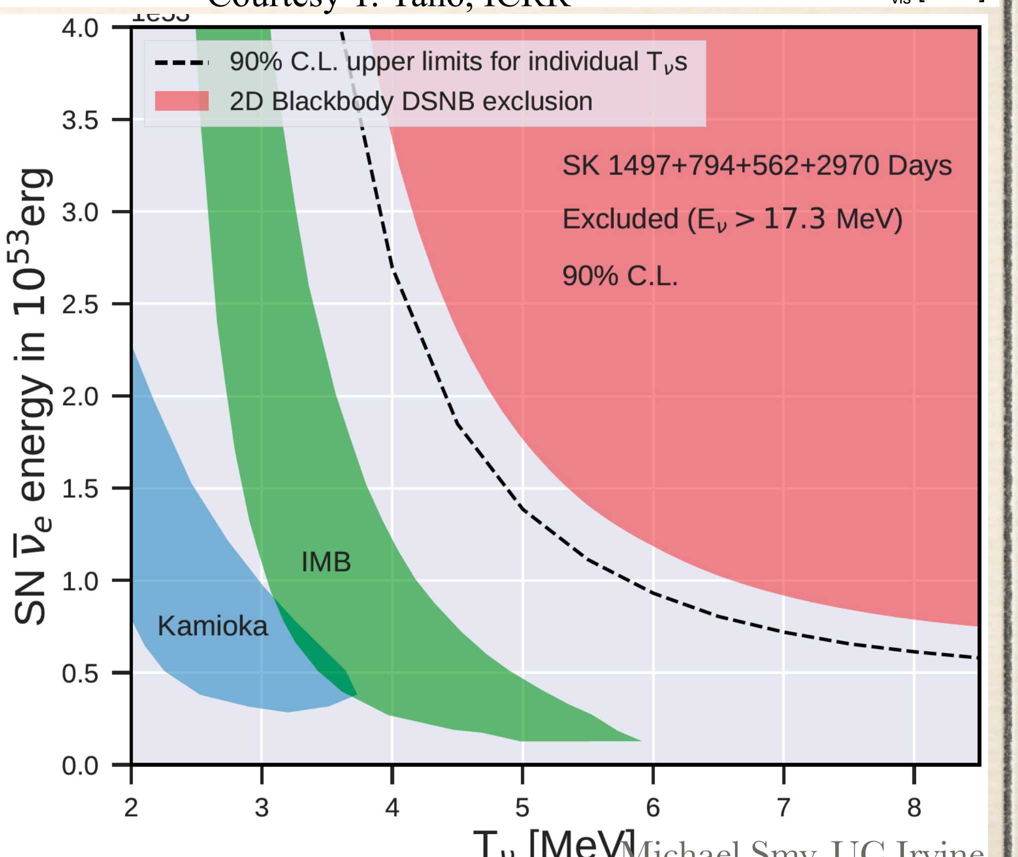
Hyper-K



Courtesy T. Yano, ICRR

- diffuse, constant ν flux of SN up to z~1:
  - test cosmic star formation history (factor of ~two discrepancy between expected and optically observed SN rate)
  - measure temperature of typical SN (from positron energy spectrum)
  - unusual supernova (optically dim and/or BH formation)
- SK-Gd and Juno will measure





Super-K
arXiv: 2109.11174

Conclusions

- solar neutrinos still offer many interesting physics topics, both in particle physics and astrophysics:
  - study MSW effect in detail, matter effects in a ν_2 beam, test CPT invariance by oscillation parameter comparison to reactor neutrino measurements, look for spin-flavor resonance
  - test solar model (e.g. metallicity, core temperature, core size), study pp-chain vs. CNO cycle, study solar plasma
- Core-collapse of supernovae is a very interesting astrophysical phenomenon and offer a unique environment to study neutrinos
  - neutronization, explosion mechanism, black hole/neutron star formation
  - neutrino-neutrino interactions, mass ordering, 3 flavor MSW