Experimental Neutrino Physics III: Neutrinos as Tools

Diana Parno
Carnegie Mellon University

National Nuclear Physics Summer School, New Haven, CT

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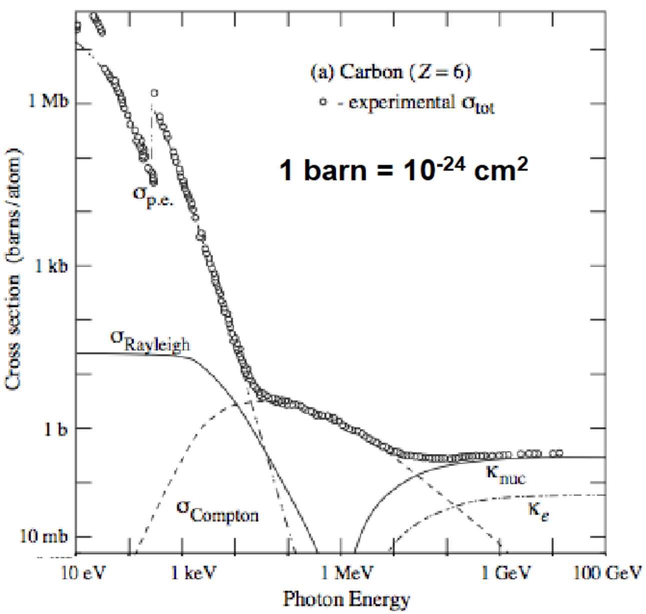
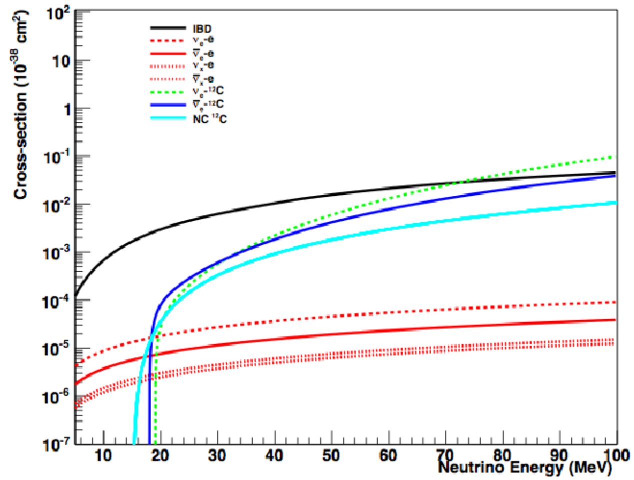
A Reminder: The **Weak** Force

Photon-matter cross-sections



~10^{-24} cm^2

Neutrino-matter cross-sections

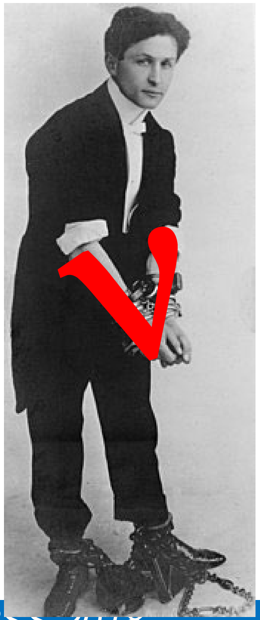


~10^{-40} cm^2

~16-17 orders of magnitude smaller

Slide: Kate Scholberg

- Neutrinos interact very, very rarely
- Hard to detect, *but ...*
- Neutrinos can escape from dense regions



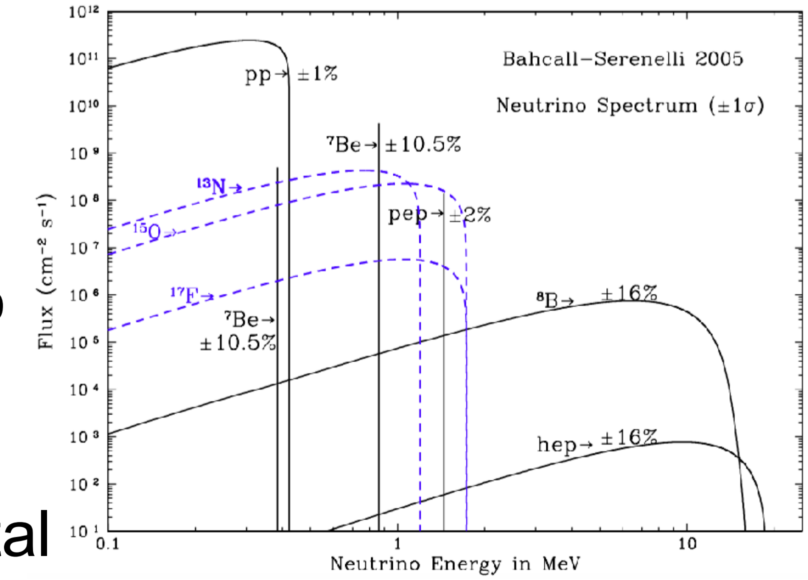
The Houdini of the particle world?

Outline

- Neutrinos for astrophysics
  - The Sun
  - Supernovae
  - Cosmic neutrino background
- Neutrinos for geology
- Neutrinos for nuclear physics

What's Inside the Sun?

- We've seen how solar neutrinos give access to what's happening in the core
- Photons give core information too
- **Abundance measurements:** Spectroscopic measurements of solar photosphere reveal elemental makeup
  - Need detailed 3D modeling of temperature, density
- **Helioseismology:** Doppler shifts in spectral reveal oscillations of gas, probing densities in different regions



Recommended review: *Alive and well: A short review about standard solar models*, Serenelli, EPJA 2016. **52**:78

Solar Abundance Problem

El.	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.60
Si	7.55	7.51
S	7.33	7.13
Fe	7.50	7.50
$(Z/X)_\odot$	0.0230	0.0180

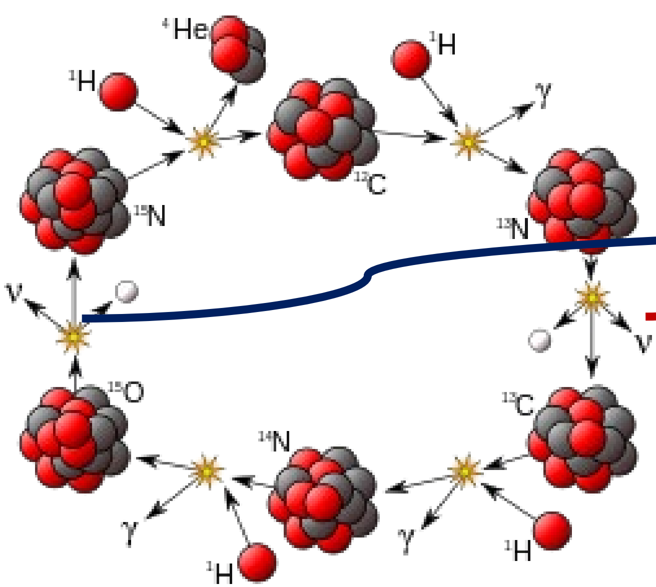
*Serenelli, EPJA **52** (2016) 78*

- In 2001, new 3D radiation hydrodynamic (3D-RHD) models (plus non-equilibrium models for line formation) yielded dramatic revision in heavy element abundances
  - 30% reduction in metal abundances relative to hydrogen!
- Spectroscopic abundance measurements no longer agree with helioseismology

- Also known as **solar metallicity problem**: to astronomers "metals" are any elements heavier than helium

A Need for Neutrinos

- CNO cycle responsible for ~1% of Sun's energy production
- If we know the CNO reaction rate, we also know CNO abundances in the core!
- Independent systematics from photon-based tools



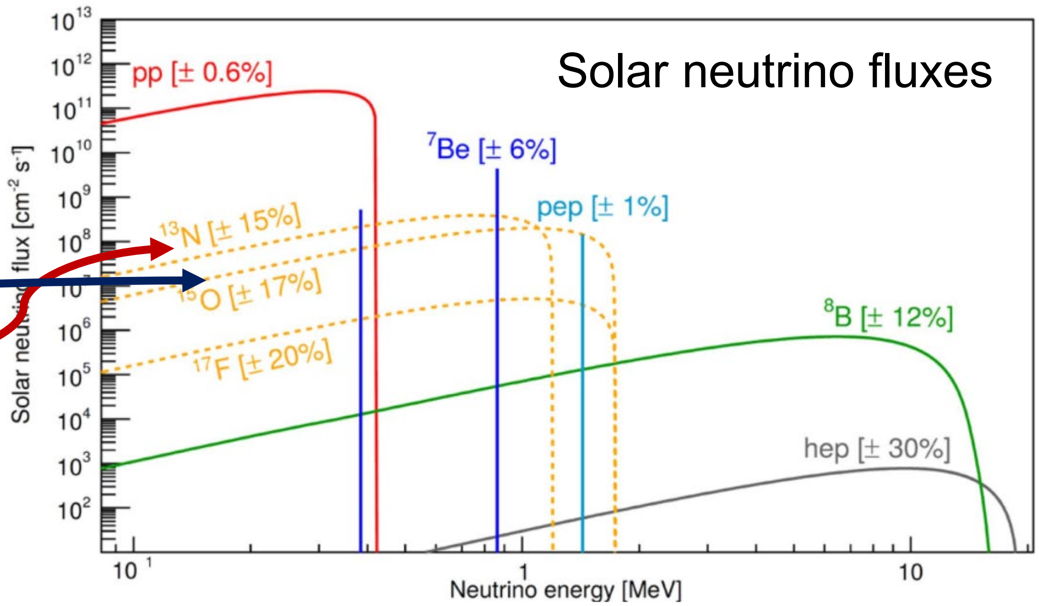
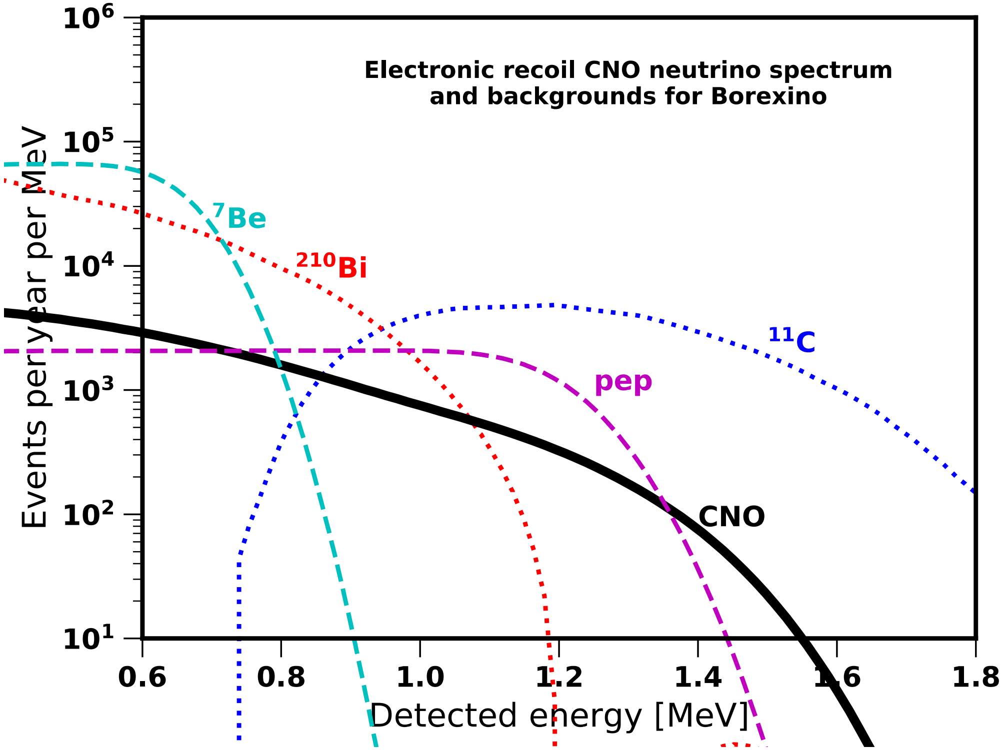


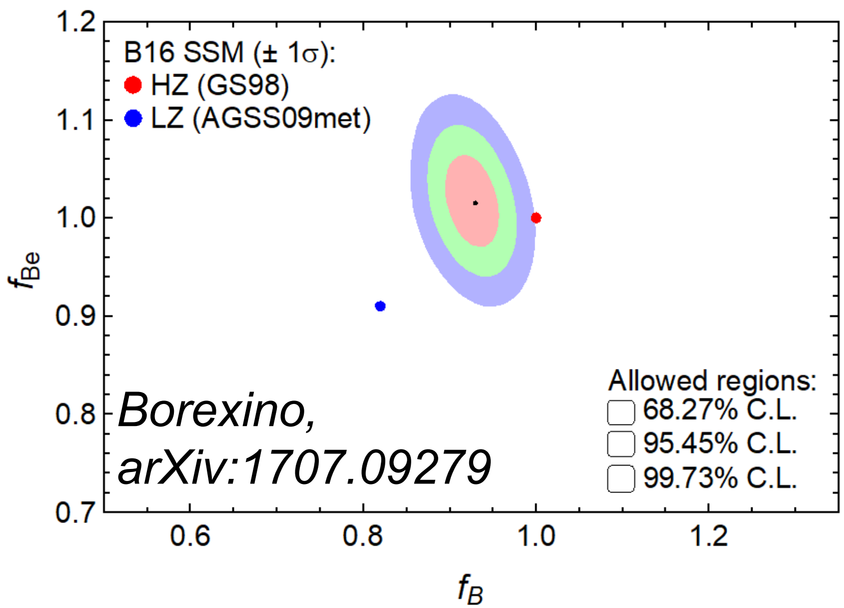
Image: Wikipedia

Searching for CNO Neutrinos



*Cerdeño et al JCAP **04** (2018) 037*

- CNO neutrinos sit under much more numerous *pep* neutrinos, near ^{210}Bi and ^{11}C backgrounds
- No discovery yet
- ^{7}Be, ^{8}B ν fluxes can't yet distinguish between SSMs

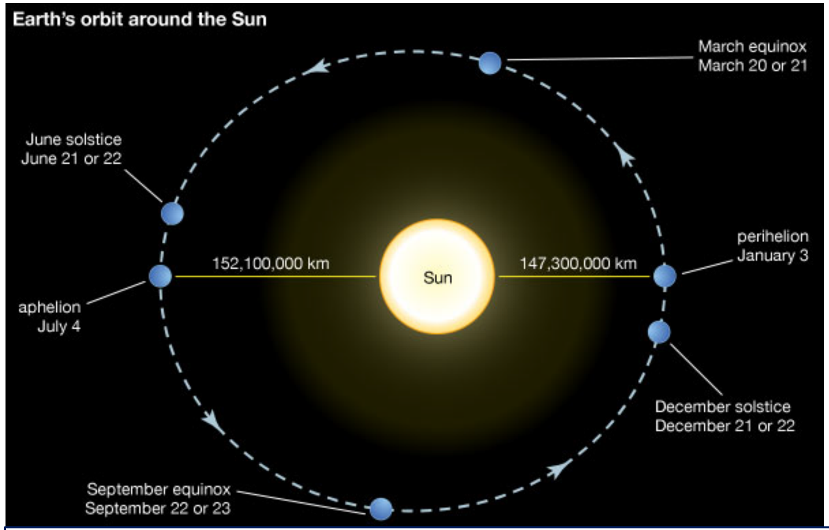


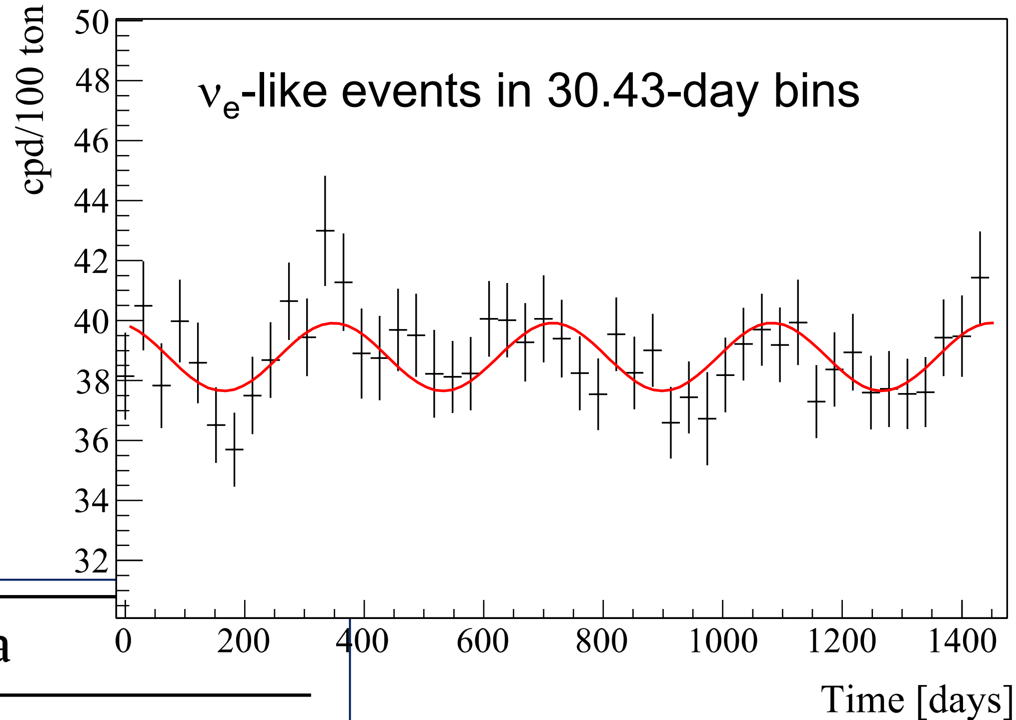
Borexino, arXiv:1707.09279

- Borexino, SNO+, ... could distinguish SSMs in 5-10 years of running – *with* tight background control

Sidebar: Borexino Precision

- Our solar orbit is an ellipse: Earth-Sun distance oscillates!
- Observing this effect requires precision and stability over multiple years



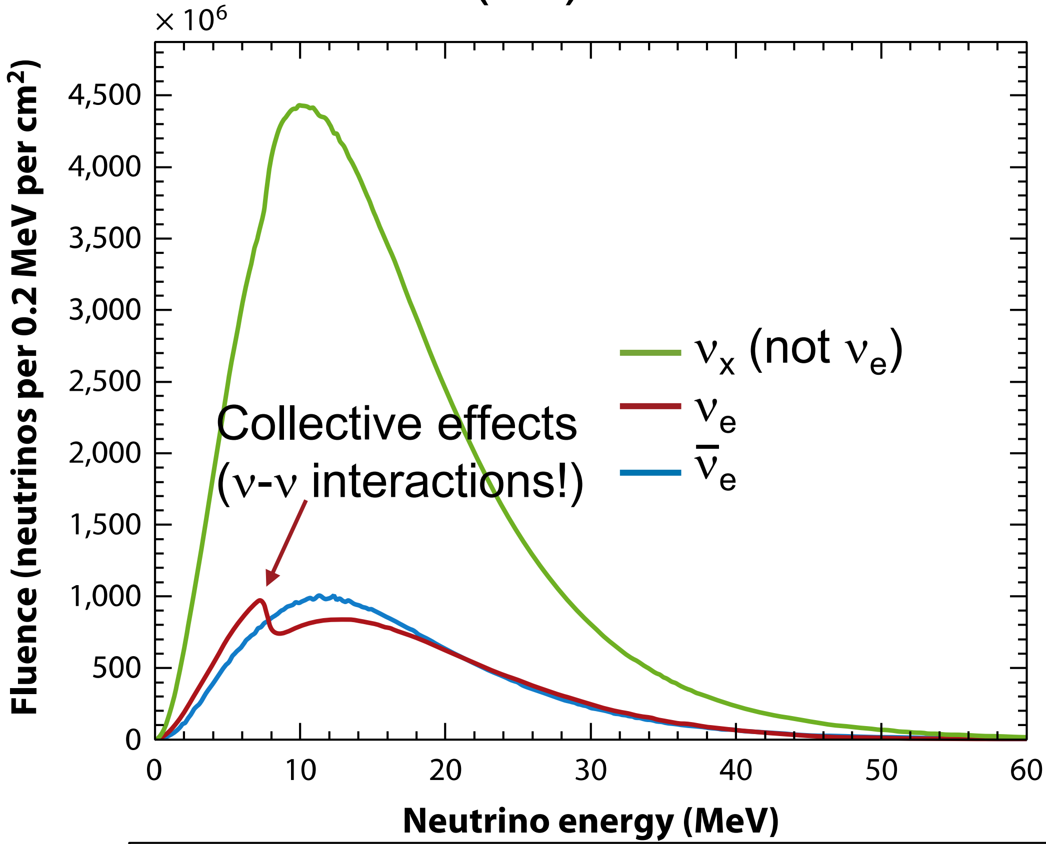


	Simulated data	Data
T [year]	0.95 ± 0.02	0.96 ± 0.05
ε	0.0155 ± 0.0025	0.0168 ± 0.0031
ϕ [day]	-12 ± 11	14 ± 22

Borexino, Astropart. Phys. ***92*** *(2017) 21*

Supernova Neutrinos

- A core-collapse supernova loses ~99% of its energy to neutrinos in $\mathcal{O}(10)$ s



- These neutrinos carry information about:
  - Core-collapse physics
  - r-process nucleosynthesis
  - Neutrino interactions in dense environments

Recommended review: *Supernova Neutrino Detection*, Scholberg, Annu. Rev. Nucl. Part. Sci. **62** (2012) 81

Who's Watching for Supernova νs?

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980–present
LVD	C_nH_{2n}	1	Italy	300	1992–present
Super-Kamiokande	H_2O	32	Japan	7,000	1996–present
KamLAND	C_nH_{2n}	1	Japan	300	2002–present
MiniBooNE[b]	C_nH_{2n}	0.7	USA	200	2002–present
Borexino	C_nH_{2n}	0.3	Italy	100	2007–present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007–present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE[b]	Ar	0.17	USA	17	Near future
NOνA[b]	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE with water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

Scholberg, Annu. Rev. Nucl. Part. Sci. ***62*** *(2012) 81*
Event estimates assume a supernova at 10 kpc

Very Early Warning System?

- When a very massive star starts carbon fusion, neutrino cooling becomes dominant
  - Cycles of carbon fusion and core contraction
  - Partial decoupling of core and envelope evolution
  - Very fast: 1000 years from C fusion onset to Fe core

> … Using Betelgeuse* as a likely progenitor, we find that a 3σ detection of pre-SN 2–90 hr before the collapse is possible.

*17-25 M_{solar}
197 ± 45 pc away

Pre-collapse
Logarithmic time
Model: Odrzywolek & Heger 2010

Post-collapse
Linear time
Model: Nakazato et al. 2013

KamLAND, ApJ ***818*** *(2016) 91*

Diffuse Supernova Background

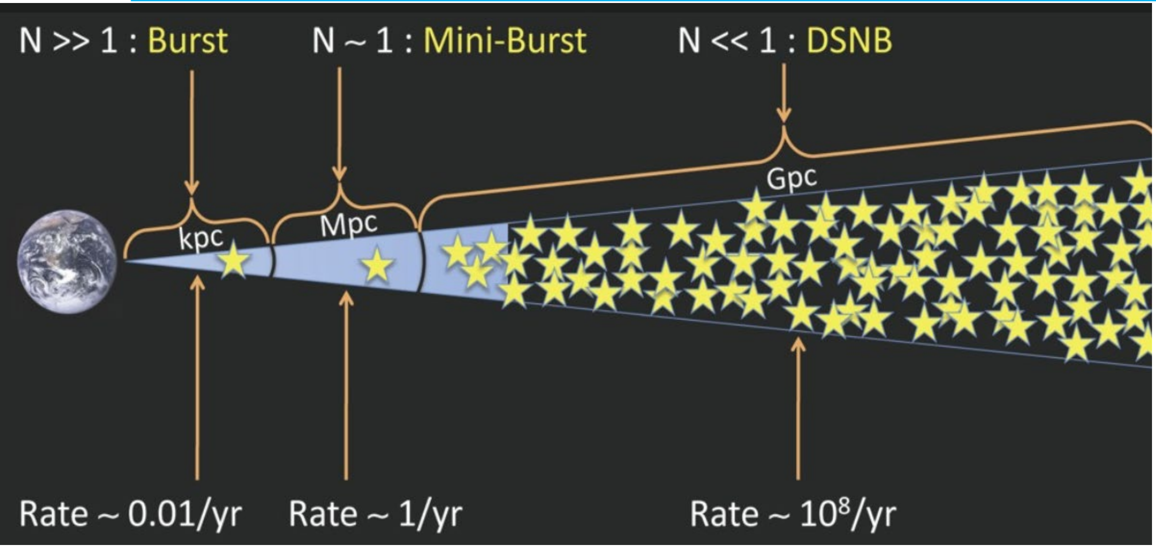


Figure: Basudeb Dasgupta, Neutrino 2018

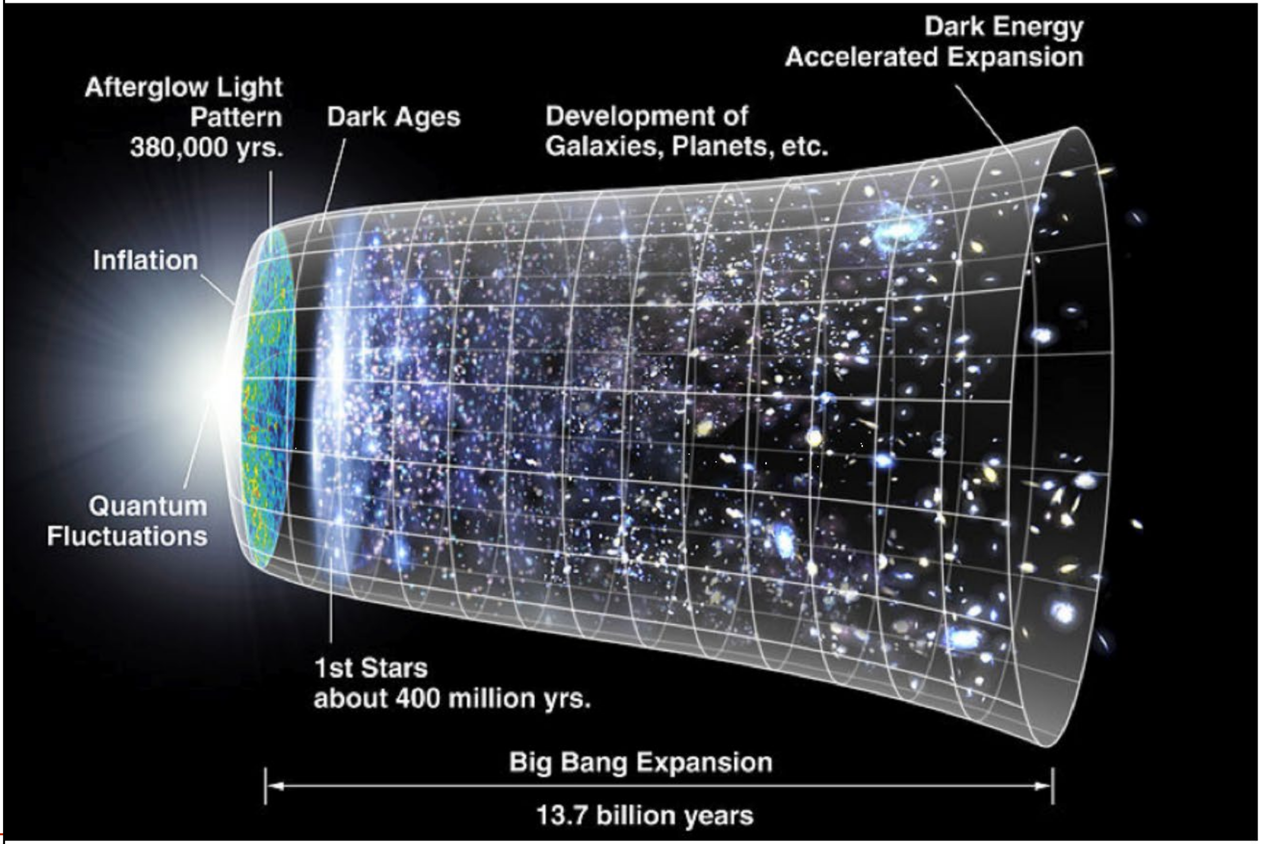
- Are supernova dynamics the same in older and younger populations of stars?
- Are supernova rates constant as the universe evolves?

- We will never observe neutrino bursts from faraway supernovae – but we can extract averaged energy spectra
- Next-generation neutrino-oscillation experiments (DUNE, Hyper-K, JUNO) should see this

Cosmic Neutrino Background

- a.k.a. relic neutrinos, CνB

Similar%to%CMB%photons,%except%neutrinos%show%the%universe%at% ~1%second%aÇer%the%Big%Bang.%



Es4mates:%

+Current+density:+
+++~300+/+cm^{3+}
+Current+temp:+
+++~1.95+K+
+
May+be+as+much+
mass+as+all+stars+
combined…+

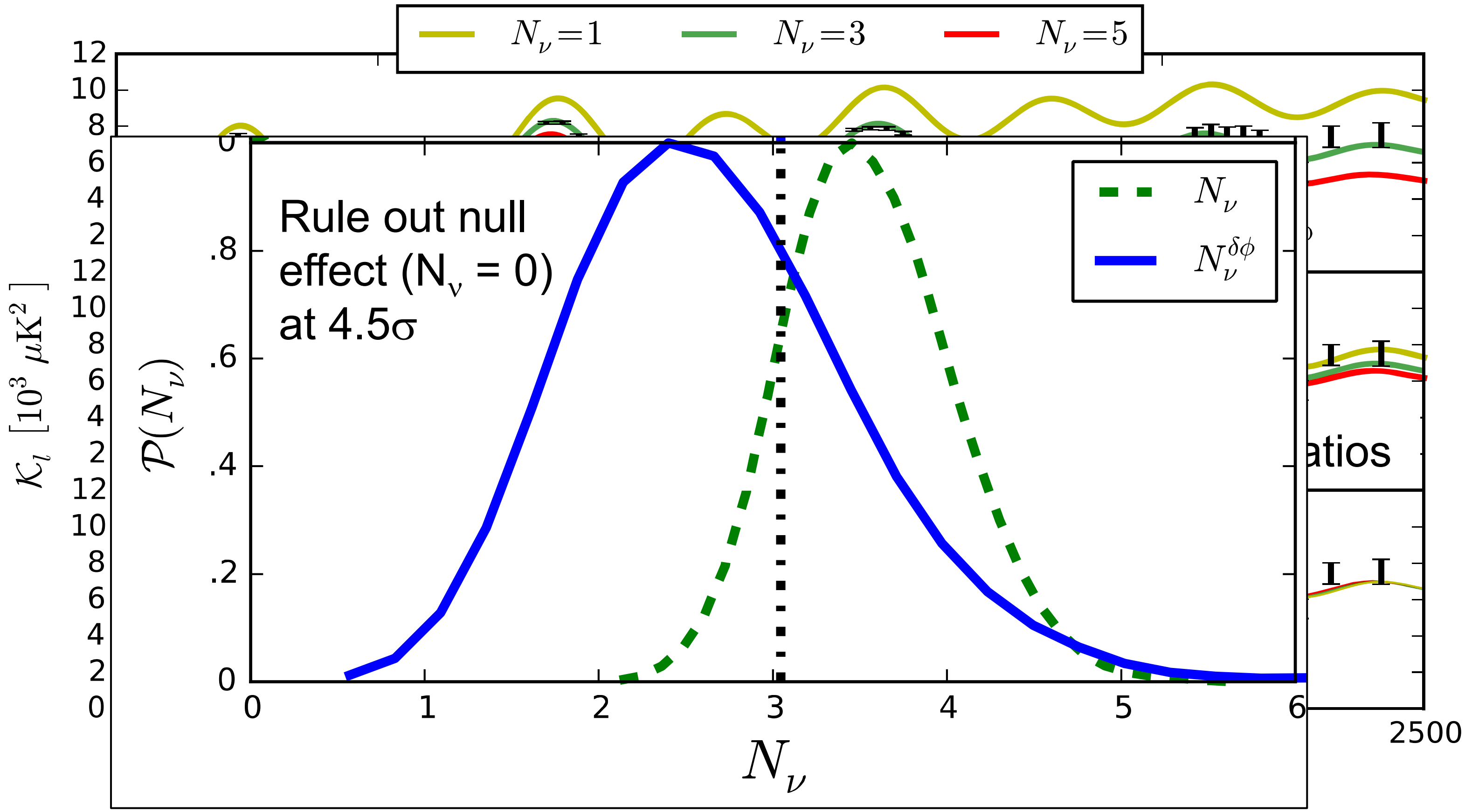
Slide: Dan Dwyer

Why Try to Measure the CνB?

- Test of physics at very early times / hot temperatures
  - CMB: t = 380,000 yrs after Big Bang
  - Big Bang nucleosynthesis: t = 1-20 minutes
  - CνB: t = 1 s
- Confirm crucial input to structure formation models
- Fabulous experimental challenge

Indirect Observation

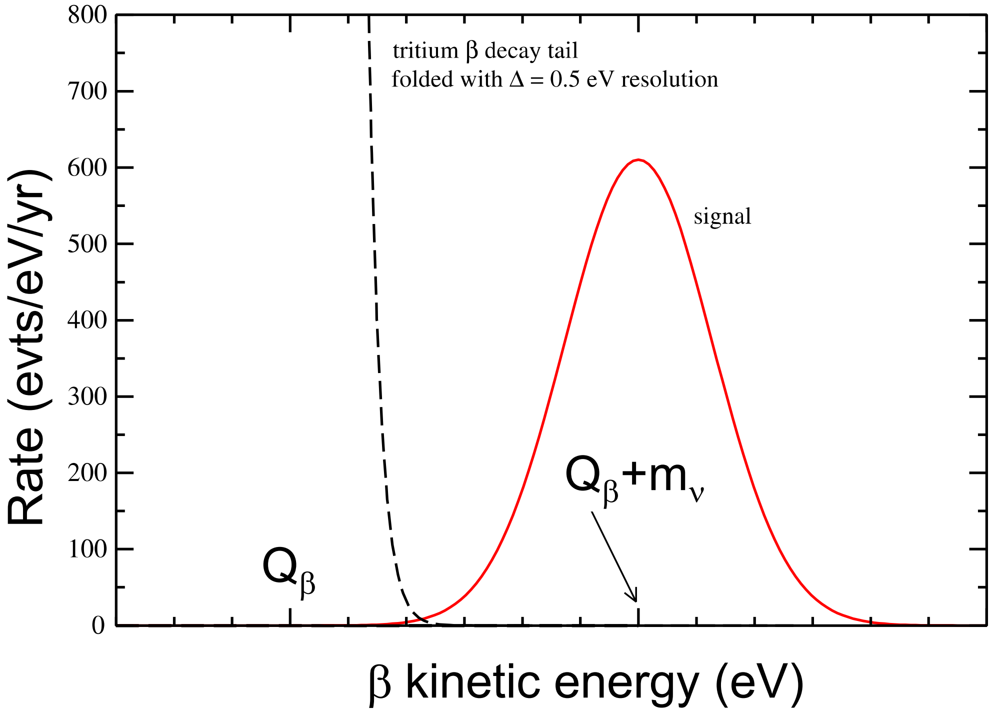
- CMB measurements probe plasma acoustic waves
- Gravitational influence of free-streaming νs gives phase shift



Follin et al., PRL 115 (2015) 091301, using Planck 2013 data

How to Measure the CνB

- Today, these neutrinos have tiny kinetic energy ~0.5 meV
- Conventional neutrino detectors will never see them!



Lazauskas, Vogel, Volpe, J. Phys. G ***35*** *(2008) 025001*

- One idea: Capture on β-decaying nuclei

$$\nu_e + {}^3H \rightarrow {}^3He + \beta$$

- Signature: Monoenergetic peak 2 neutrino masses above observed endpoint
- Requires: lots of ^3H, excellent energy resolution

Maybe you'll have a better idea!

Outline

- Neutrinos for astrophysics
- Neutrinos for geology
- Neutrinos for nuclear physics

Neutrinos Beneath Our Feet

- The Earth produces about ~44 TW of geothermal energy. Where does it come from?
  - Residual heat from planetary formation
  - Radioactive decays deep within the Earth

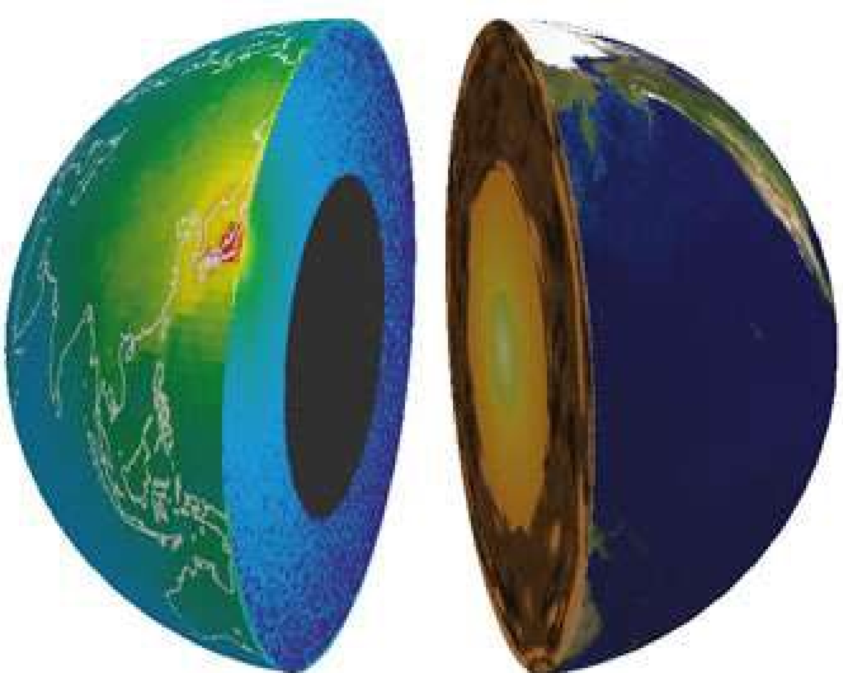
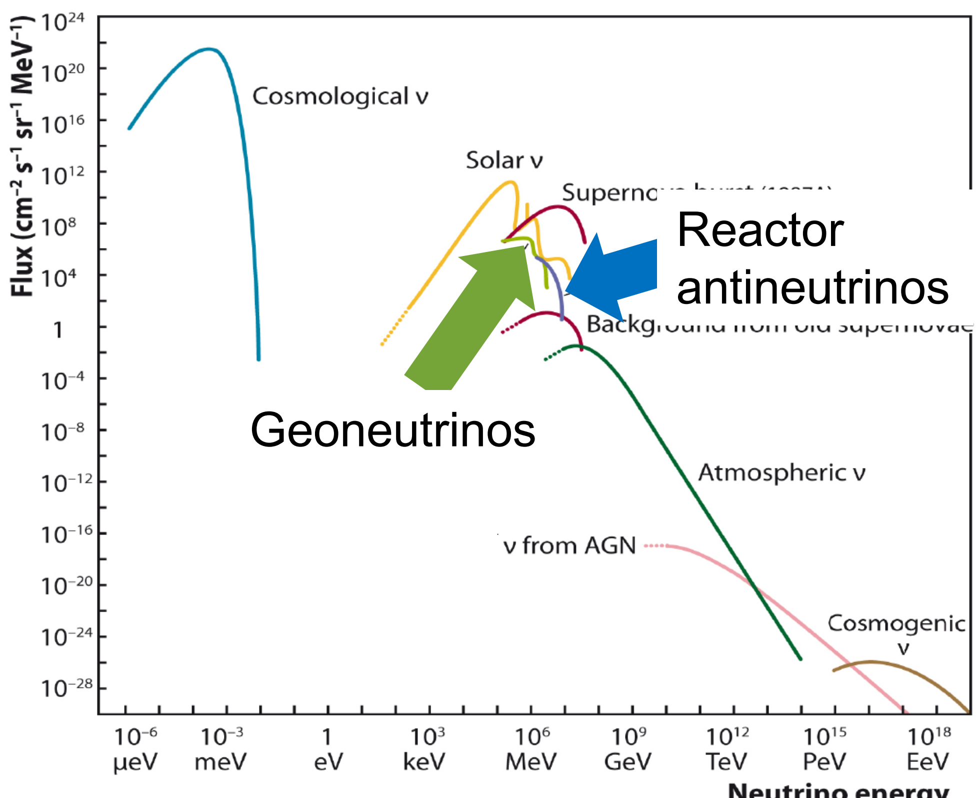
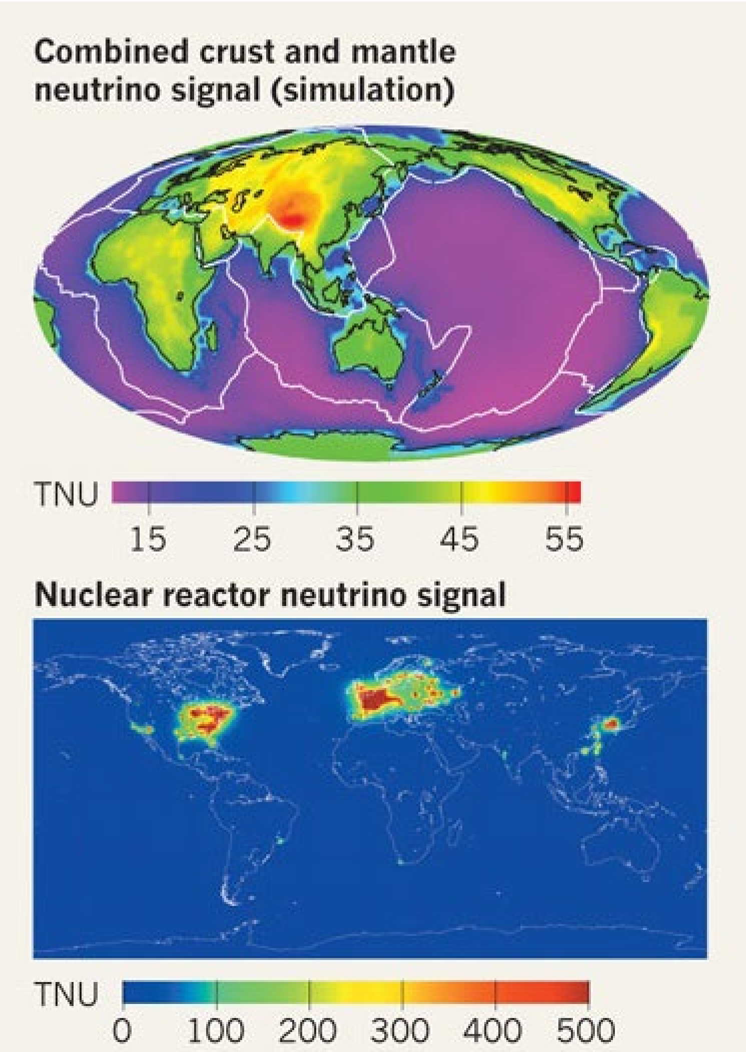


Image: Nature



Detecting Geoneutrinos

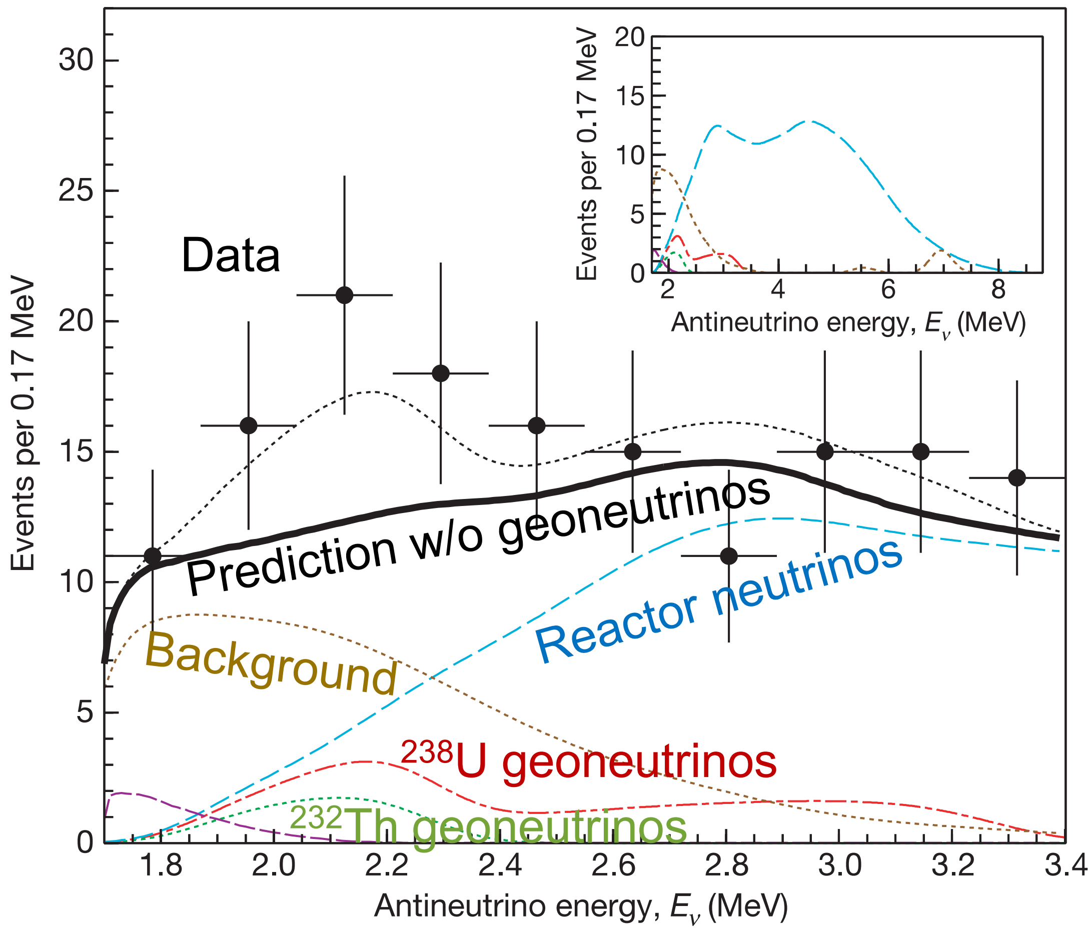


Images: Ondrej Šrámek, Barbara Ricci via Nature

- Large detector
- Low energy threshold
- Low backgrounds
- Separate geoneutrinos from reactor neutrinos
- Separate crustal neutrinos from mantle neutrinos
  - Need local geological models for crust/mantle boundary
  - Someday: an ocean-based geoneutrino detector?

First Discovery

- KamLAND (now host of KamLAND-Zen 0νββ experiment) in Japan



*KamLAND, Nature **436** (2005) 499*

Early Heat Models!

- More data from both KamLAND and Borexino are beginning to constrain geological models

- KamLAND* finds ~25-65% of Earth's heat due to radioactive decays

*KamLAND, Nat. Geoscience **4** (2011) 647*

- Borexino finds ~50-80% of Earth's heat due to radioactive decays
- It looks likely that Earth still retains primordial heat

*Borexino, PRD **92** (2015) 031101(R)*

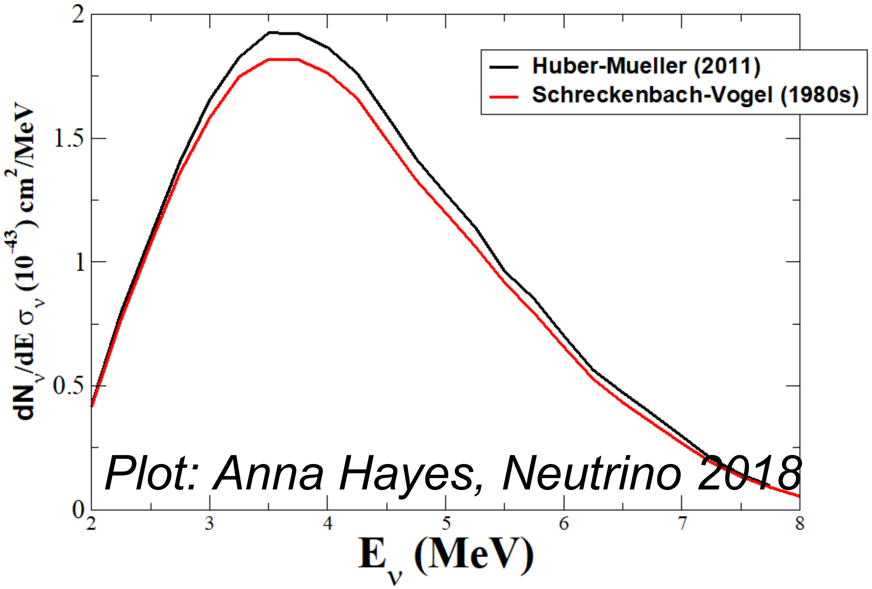
Recommended review of physics: *Geo-neutrinos*, Bellini et al., Prog. Part. Nucl. Phys. **73** (2013) 1 *(doesn't include most recent data)*

Outline

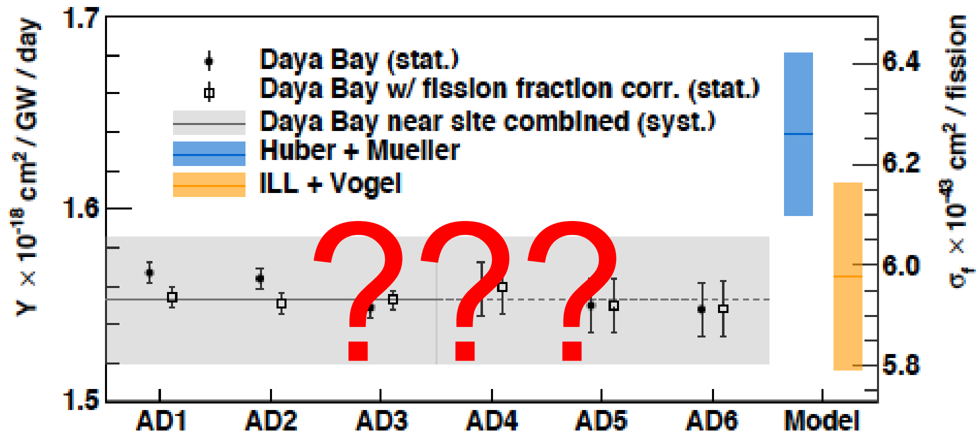
- Neutrinos for astrophysics
- Neutrinos for geology
- Neutrinos for nuclear physics
  - Reactor antineutrino spectra
  - Nonproliferation

Reactor Antineutrino Deficit

- A few years ago, reactor antineutrino flux predictions were updated ...

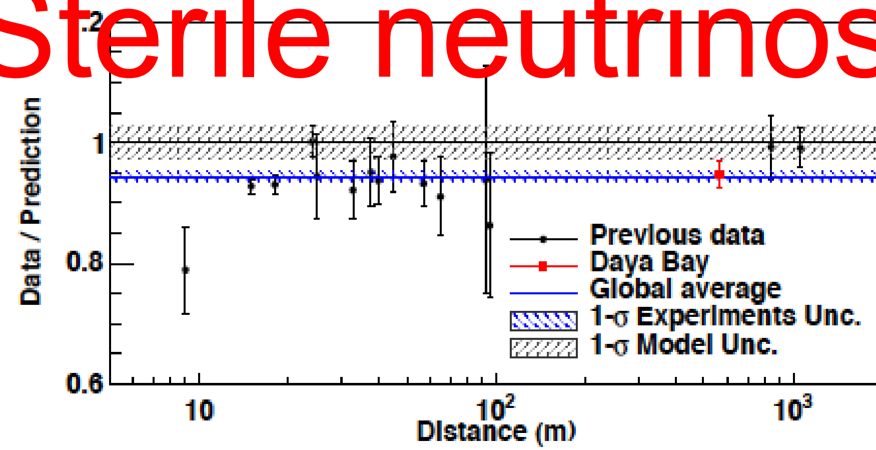


Plot: Anna Hayes, Neutrino 2018



???

Sterile neutrinos?



Daya Bay, PRL 116 (2016) 061801

RENO, DoubleChooz confirm

- Change reflects:
  - New data indicating more $\overline{\nu}_e$ from ^{238}U
  - Predicted E_ν increase for ^{235}U, ^{239}Pu, ^{241}Pu

Predicting a Reactor $\bar{\nu}$ Spectrum

Reactor thermal energy

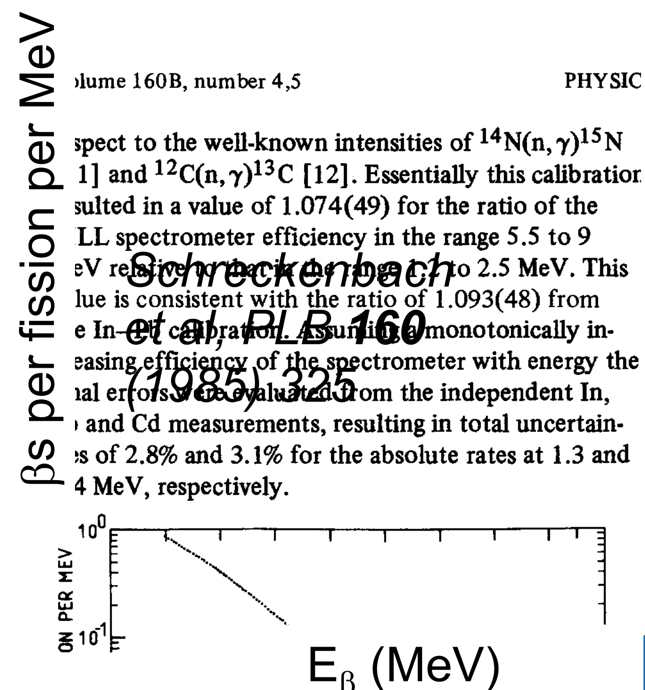
Relative fraction of fissions due to each isotope

Cumulative antineutrino spectrum (per fission)

$$S(E_\nu) = \frac{W_{\mathrm{th}}}{\Sigma_i (f_i/F) e_i} \Sigma_i \frac{f_i}{F} \left(\frac{\mathrm{d}N_i}{\mathrm{d}E_\nu} \right)$$

Thermal energy per fission

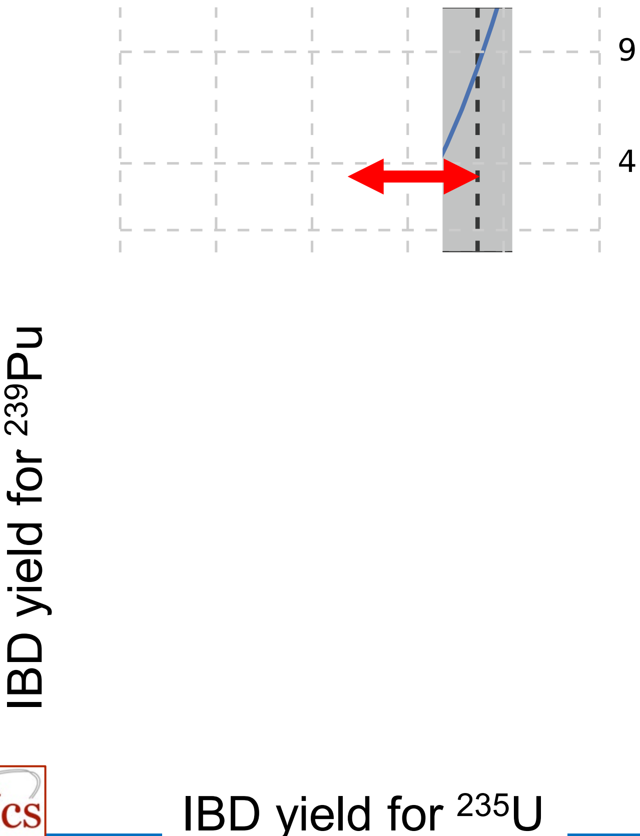
- **Ab initio summation method**
  - List all β-decay branches of all fission fragments
  - Sum up contributions to $\bar{\nu}$ spectrum
  - Need comprehensive, correct databases!
- **Conversion method**
  - Take measured β spectra from fission reactions (at ILL reactor in 1980s)
  - Infer $\bar{\nu}$ spectrum corresponding to each β spectrum



Back to Nuclear Physics

- Sterile neutrinos shouldn't prefer one β-decaying isotope over another (as long as both are above threshold)
- Fission isotope fractions in reactor cores evolve over time
  - ^{239}Pu fraction rises during operation; ^{235}U fraction falls

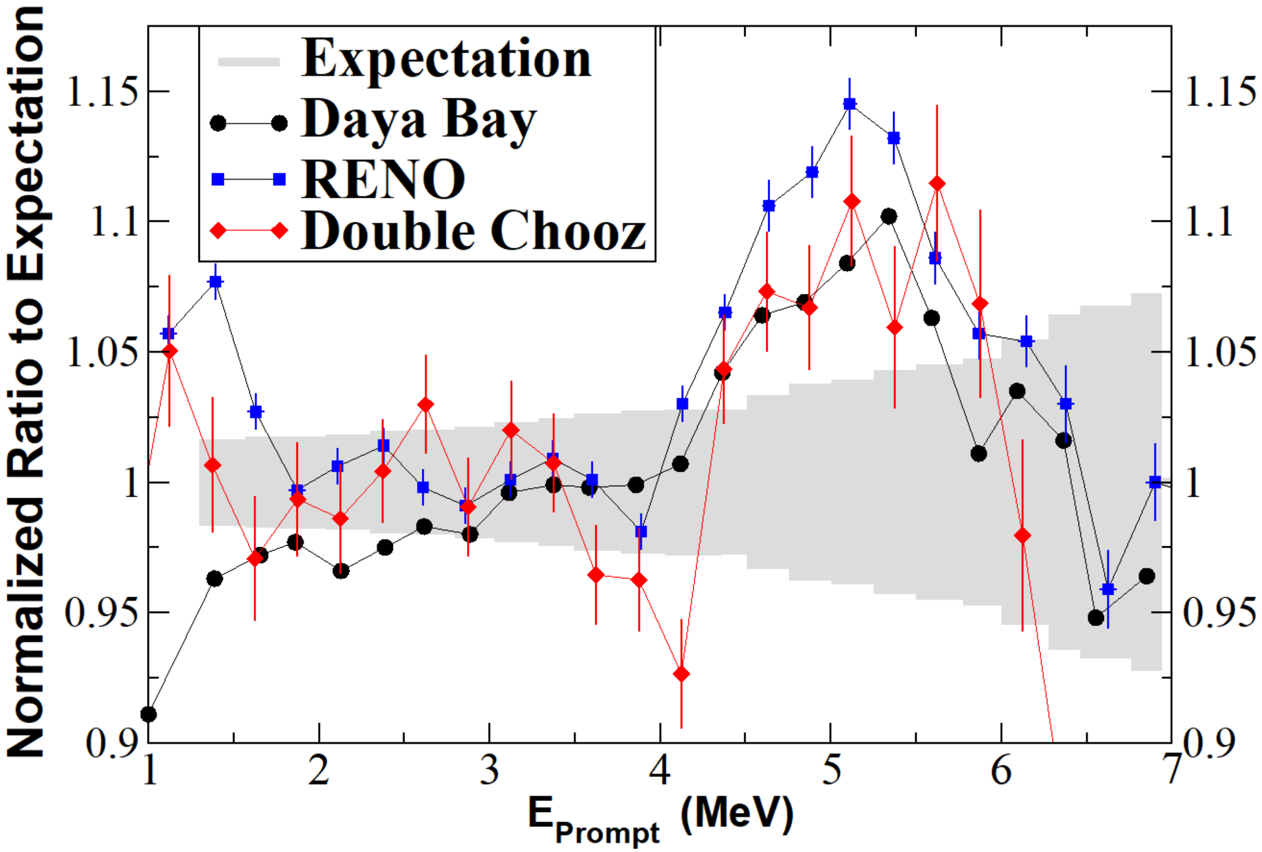
Daya Bay, PRL 118 (2017) 251801



- Something looks wrong with the predicted antineutrino flux for ^{235}U
- But ... it could be an error in model fit assumptions
- Daya Bay results don't rule out steriles (but do reduce significance of deficit)
- Stay tuned for results from research reactors

The 5-MeV "Bump"

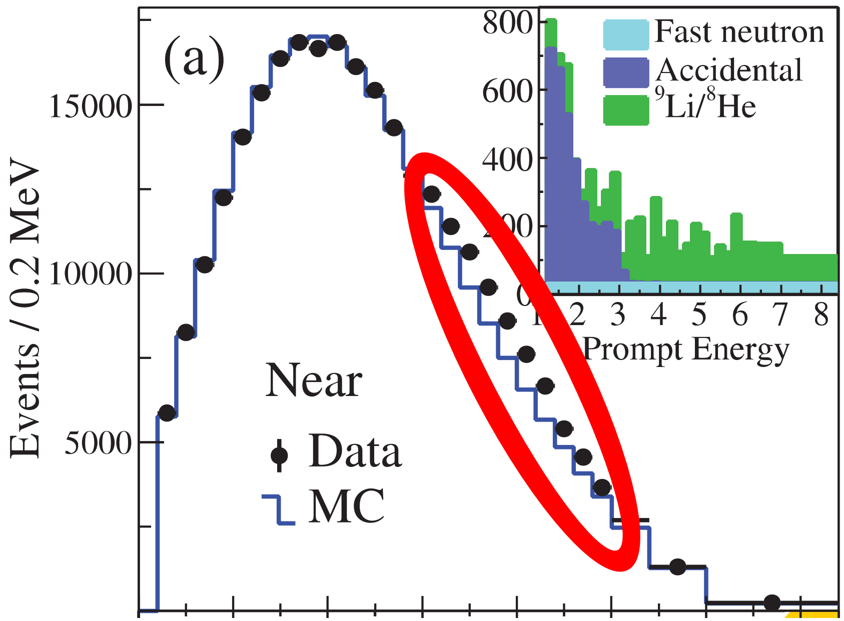
- All precision reactor neutrino experiments show a ~10% excess over spectral predictions at 4-6 MeV



Plot: Anna Hayes, Neutrino 2018

Sidebar: The Precision ν Era

- "Bump" evokes clear, bright resonances
- *This* bump appears on a steeply falling distribution – and it looks rather different

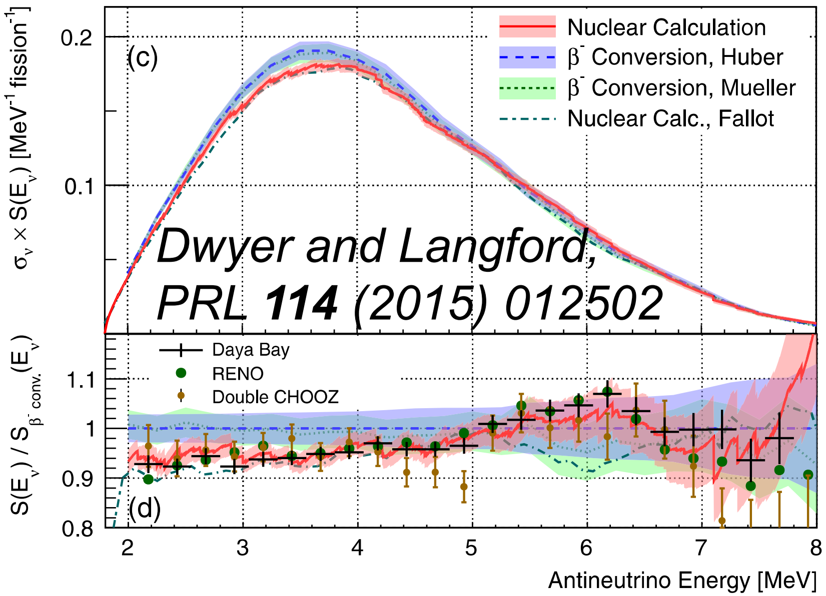


Two Lessons

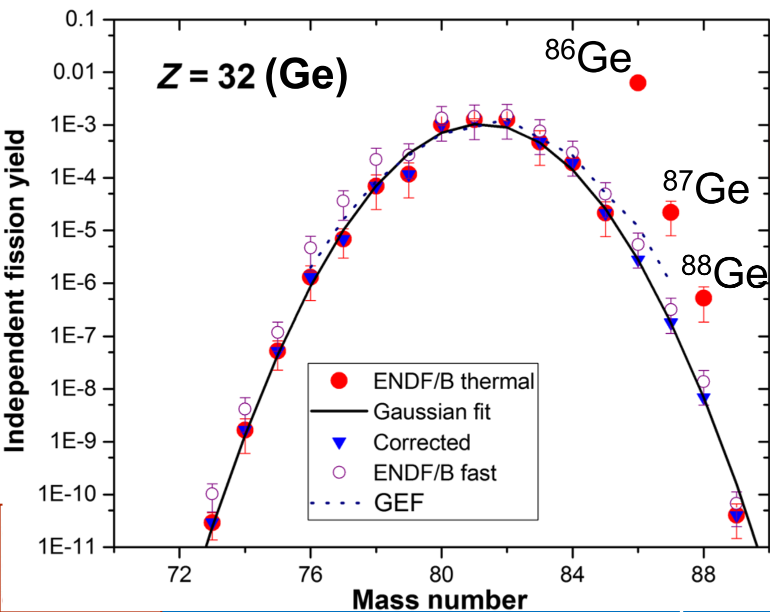
- Modern ν oscillation experiments are making discoveries requiring unprecedented statistics and precision!
- **Always look at the residuals**

RENO, PRL 116 (2016) 211801

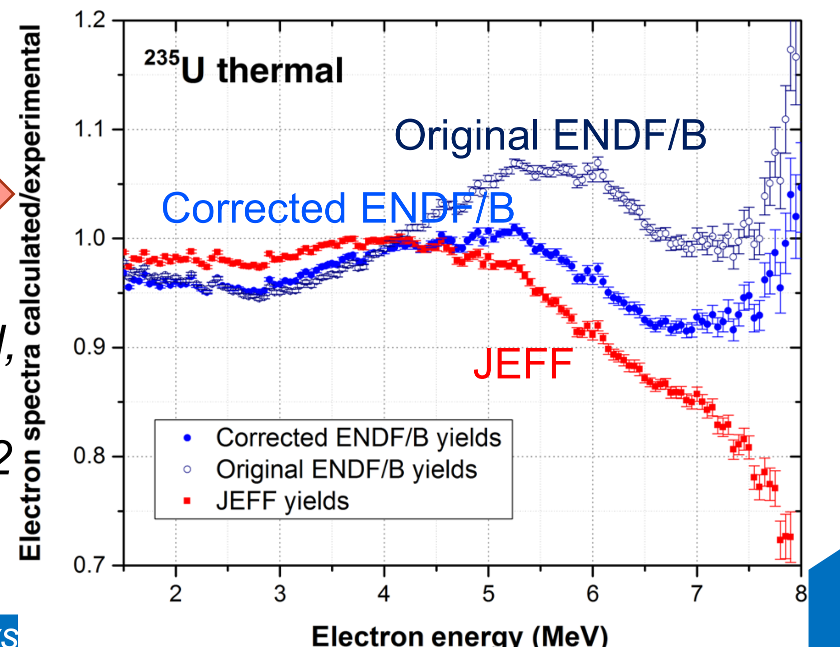
The Bump, Revisited



- Ab initio flux calculation (2015), using ENDF/B-VII.1 library, shows bump!
- But ... no bump when you use alternative JEFF-3.1 library
- This inspired a closer look at ENDF in 2016 ...



*Sonzogni et al, PRL **116** (2016) 132502*



What Does All This Mean?

- Measurements of reactor $\overline{\nu}_e$ spectra revealed significant discrepancies with model
- This could signal exciting new neutrino physics (steriles!)
- But it has also already revealed serious deficiencies with available nuclear data
  - (Maybe not surprising in catalogs compiled over decades...)
- Neutrino results are improving our understanding of nuclear fission

Recommended review: *Reactor Neutrino Spectra*, Hayes and Vogel, Annu. Rev. Nucl. Part. Sci. 2016. 66:219–44

Nuclear Nonproliferation

- Nuclear reactors have many uses
  - Neutrino sources for physics experiments
  - Clean electricity for individuals, industry, hospitals, ...
  - Making ^{239}Pu for nuclear bombs

- The world wants to know about:
  - Secret reactors?
  - Plutonium production at supposedly innocent reactors?
- Inspections require substantial cooperation

Neutrino Reactor Monitoring

- Neutrinos are the perfect informers
  - They come right from the core
  - Rates reveal on/off cycles (the β emitters are short-lived)
  - No power in the ‘verse can stop them
- Early work on WATCHMAN
  - kton water-Cerenkov detector with Gd doping (detect inverse β decay)
  - Monitor reactors within ~50 km
- For long-distance monitoring:
  - Larger water-Cerenkov detectors?
  - Small CEvNS detectors?
- Ideal case: A detector network for reactor-neutrino tomography

WATCHMAN conceptual design

To Summarize

- We've already heard how neutrinos are helping us revise and improve the Standard Model
  - See Friday's lectures; Michael Ramsey Musolf's lectures; Michelle Dolinski's seminar
- Neutrinos are also potent tools for answering questions from other areas of physics
  - Astronomy and cosmology
  - Geology
  - Nuclear physics and nonproliferation
- I've left out lots of other neat ideas, from elucidating cosmic-ray sources to measuring nuclear structure
- Maybe ***you***'ll add a new idea to this set!

Thank you for the great questions and discussions!