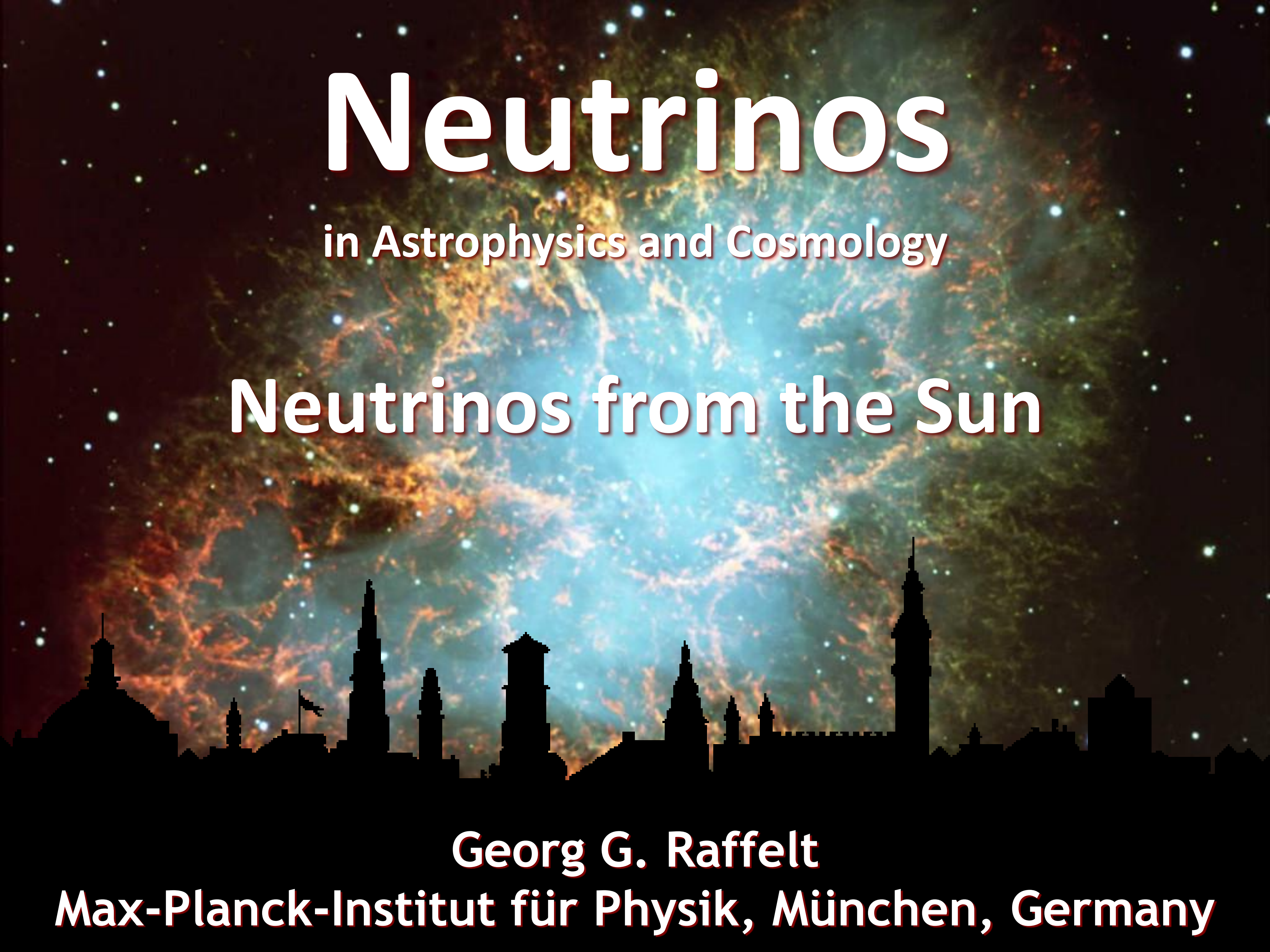


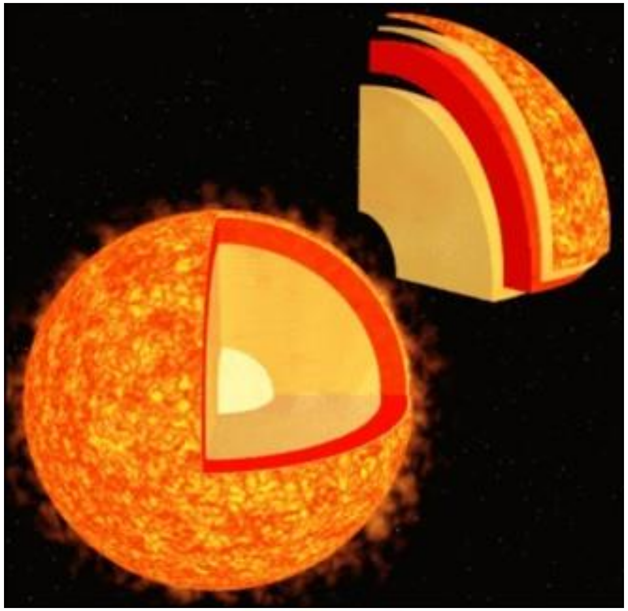
Neutrinos

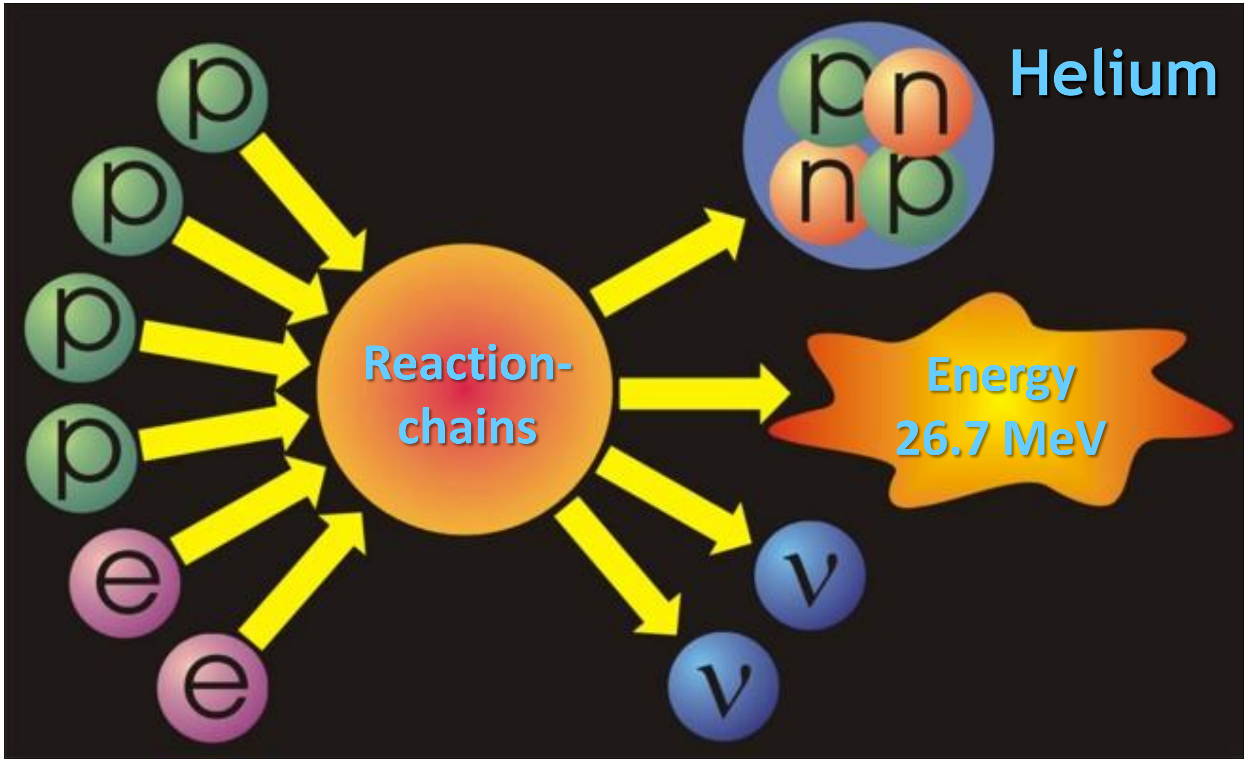
in Astrophysics and Cosmology

Neutrinos from the Sun

Georg G. Raffelt
Max-Planck-Institut für Physik, München, Germany

Neutrinos from the Sun

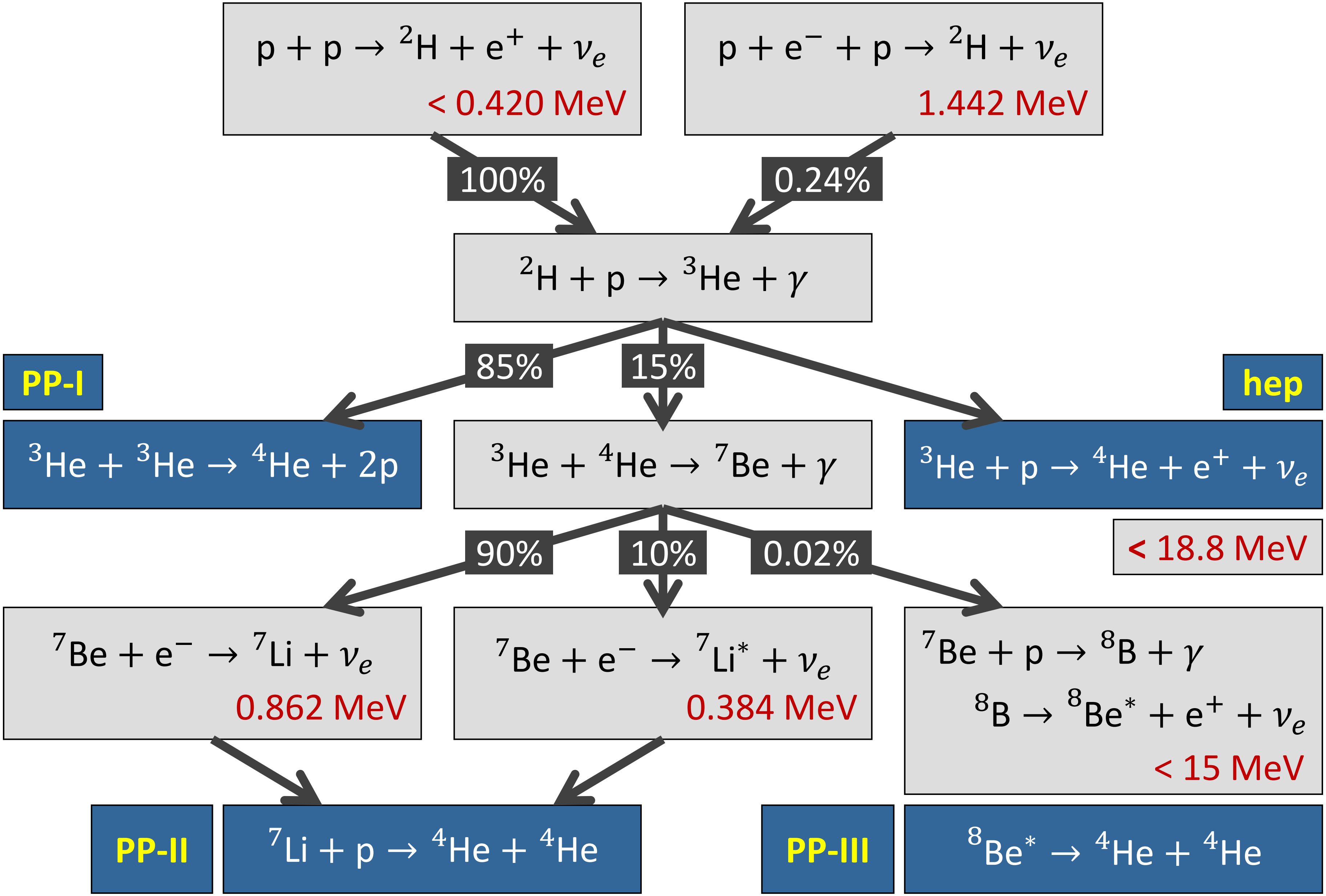




Solar radiation: 98 % light (photons)
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

Hans Bethe (1906–2005, Nobel prize 1967)
Thermonuclear reaction chains (1938)

Hydrogen Burning: Proton-Proton Chains



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

< 0.420 MeV

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

1.442 MeV

100%

0.24%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

15%

PP-I

hep

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

< 18.8 MeV

90%

10%

0.02%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

0.862 MeV

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li}^* + \nu_e$

0.384 MeV

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

< 15 MeV

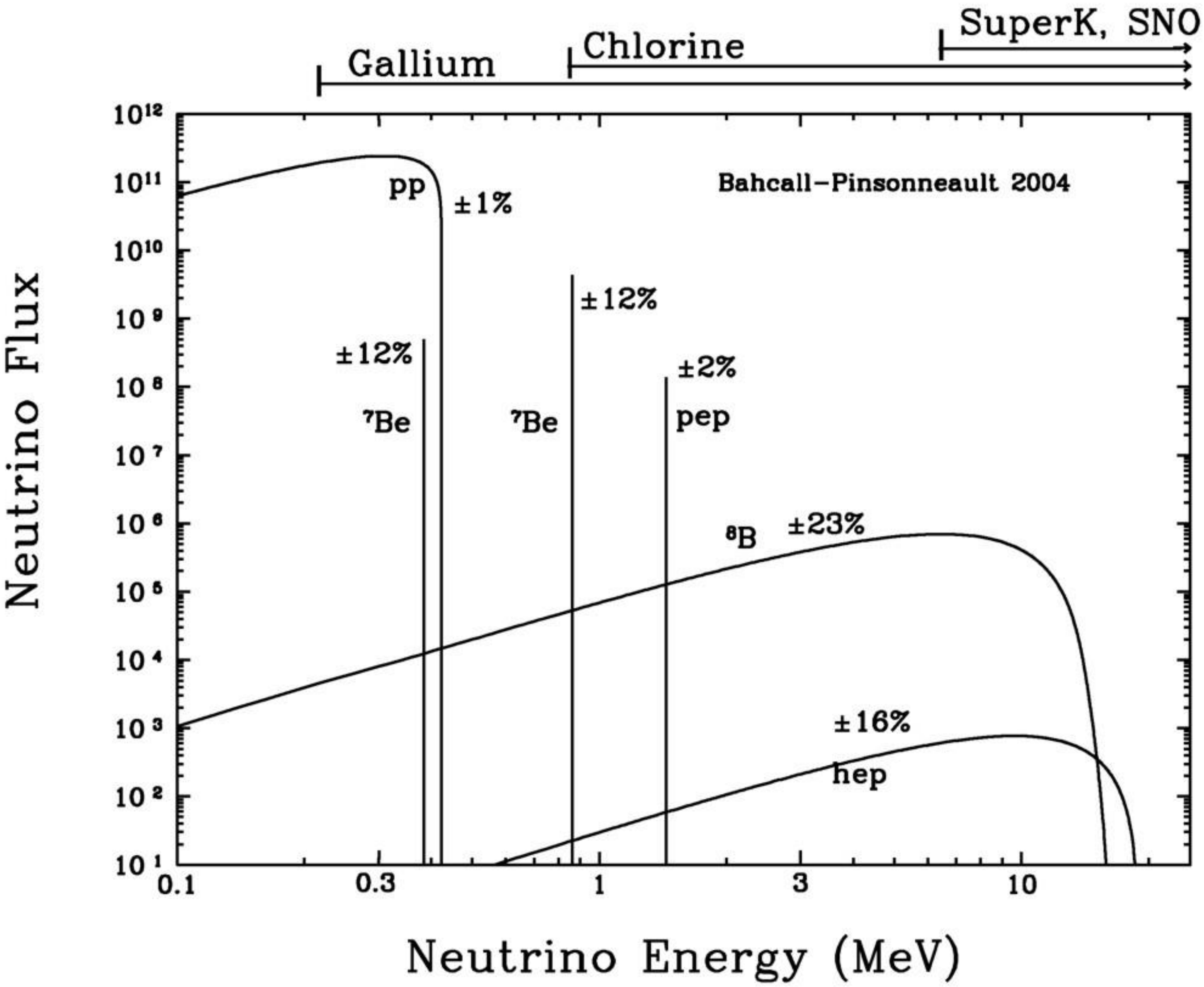
PP-II

${}^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

PP-III

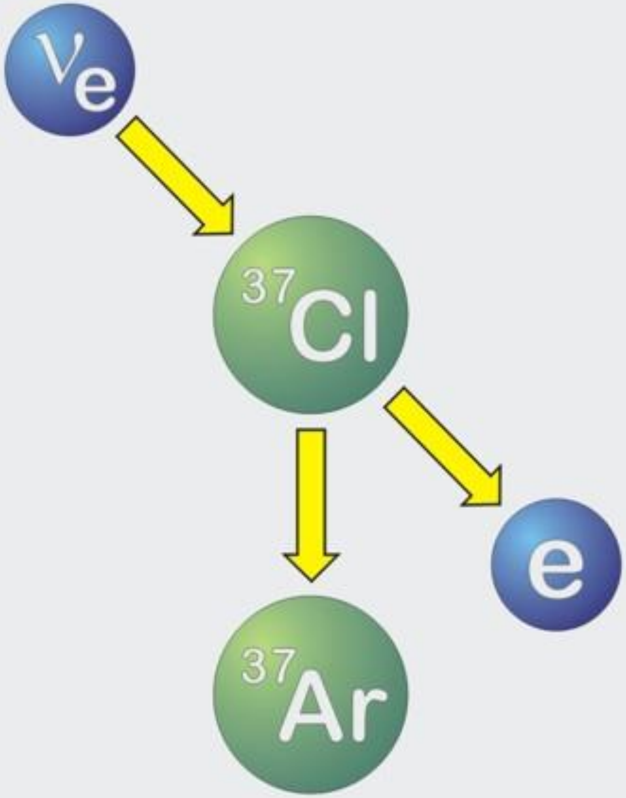
${}^8\mathrm{Be}^* \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$

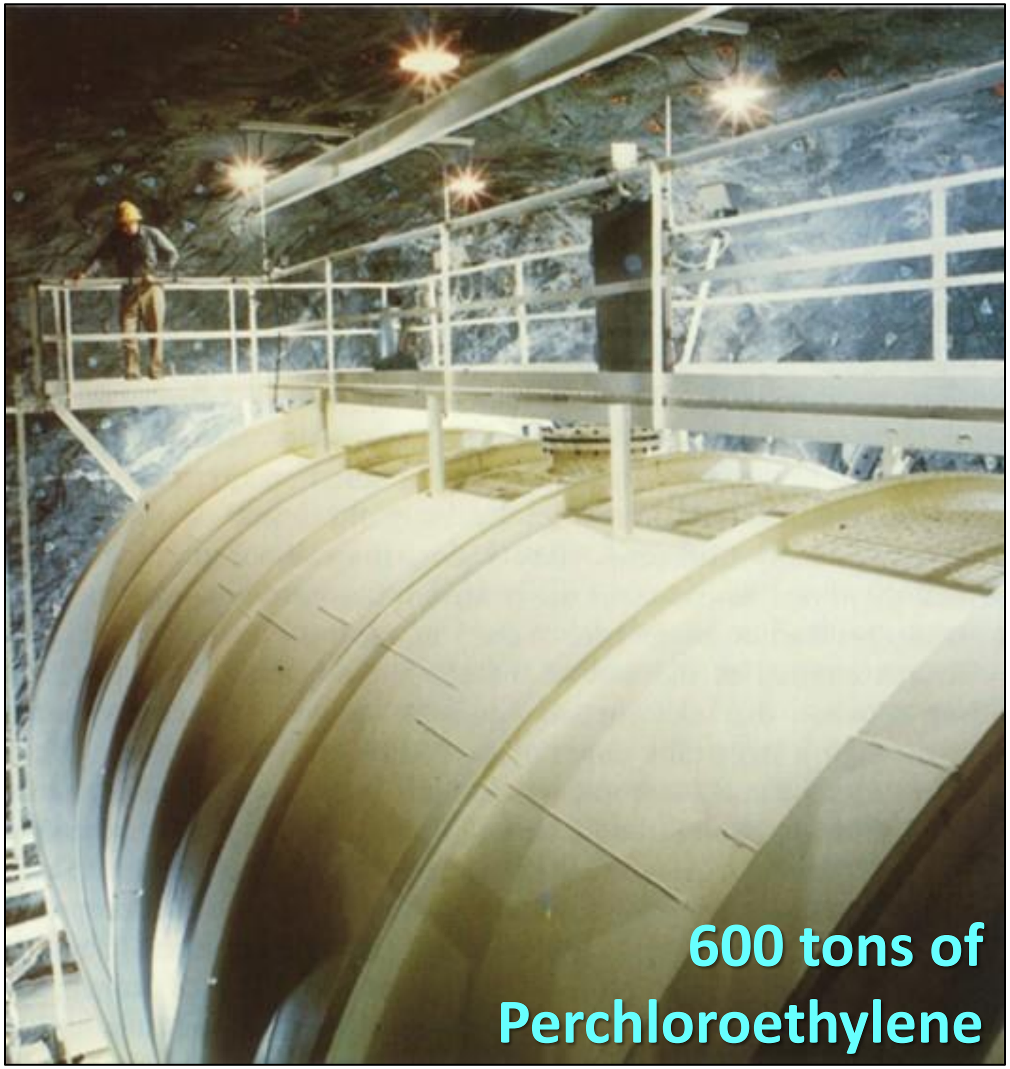
Solar Neutrino Spectrum



First Measurement of Solar Neutrinos

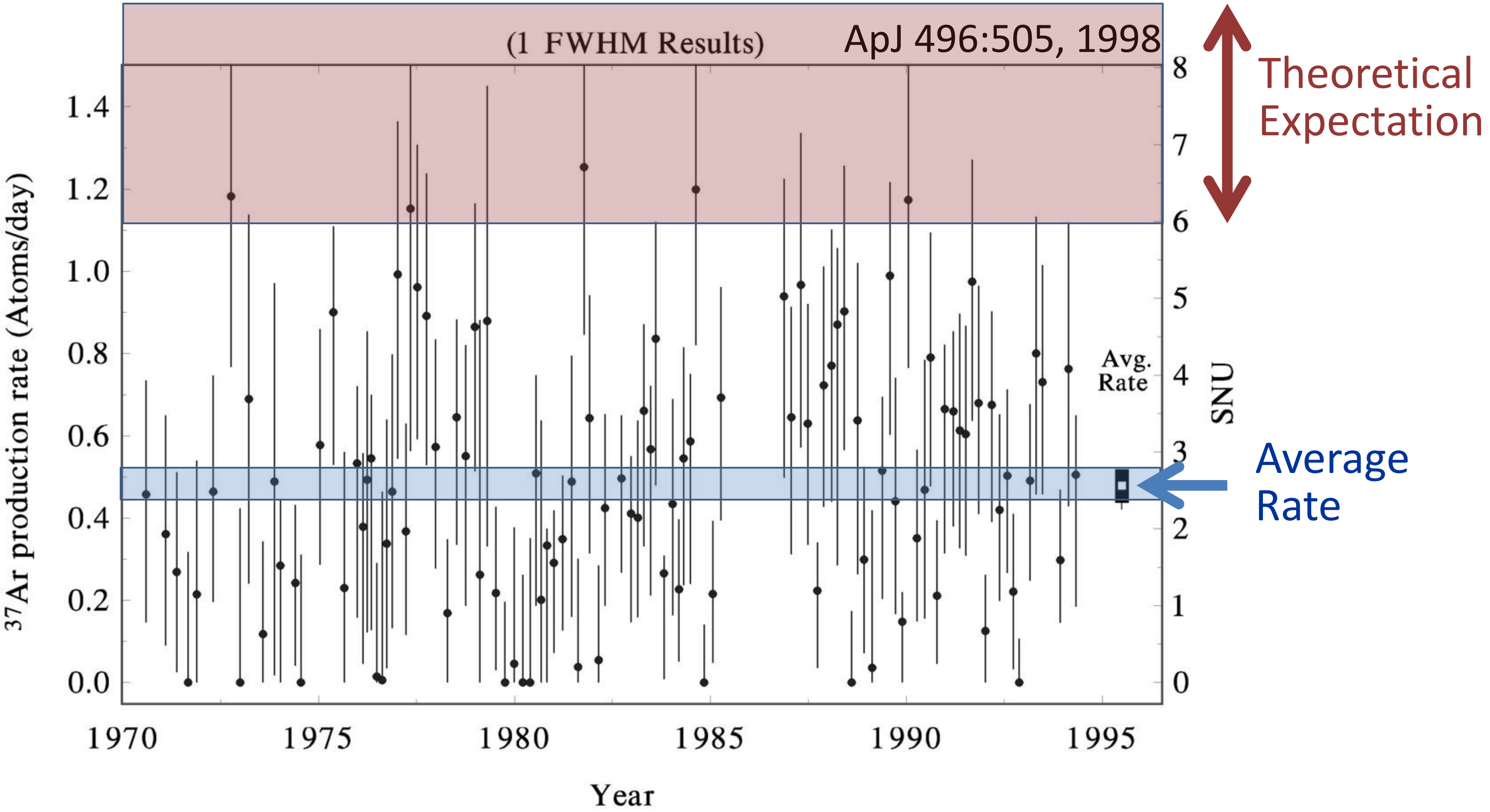
Inverse beta decay of chlorine




600 tons of Perchloroethylene

Homestake solar neutrino observatory (1967–2002)

Results of Chlorine Experiment (Homestake)



Average (1970–1994) $2.56 \pm 0.16_{\text{stat}} \pm 0.16_{\text{sys}}$ **SNU**

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

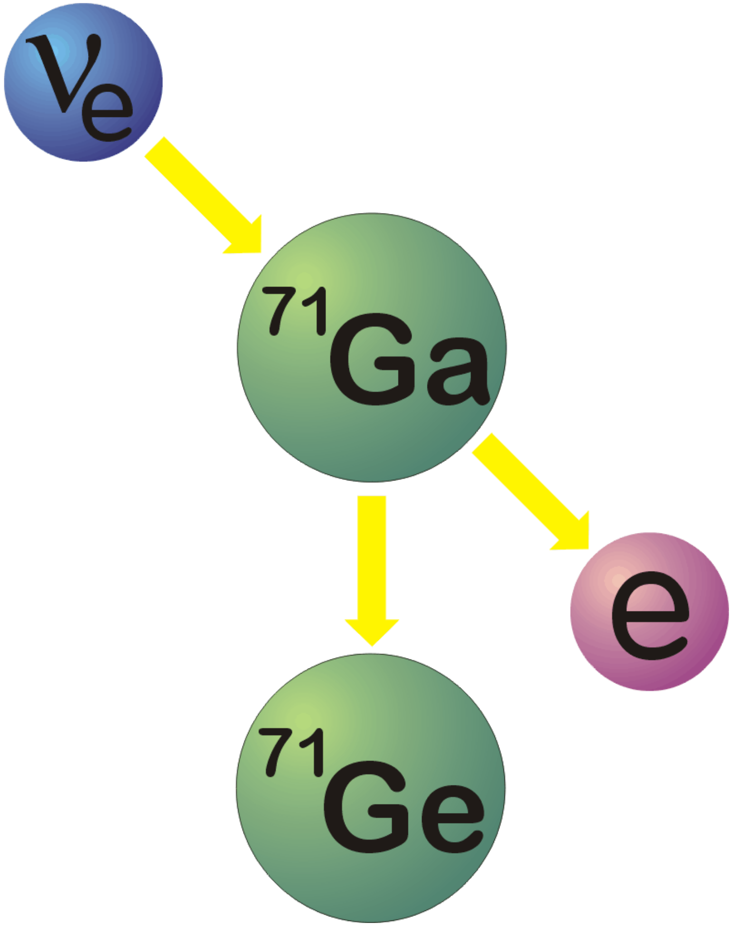
Theoretical Prediction 6–9 SNU

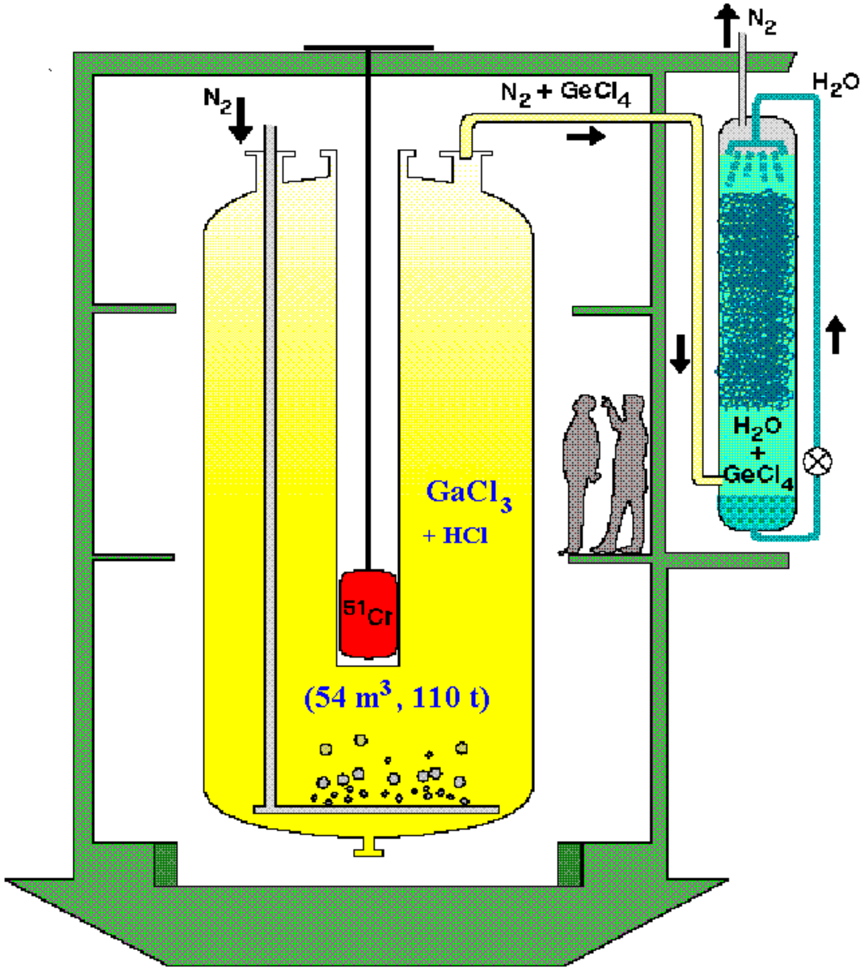
“Solar Neutrino Problem” since 1968

GALLEX/GNO and SAGE

Inverse Beta Decay

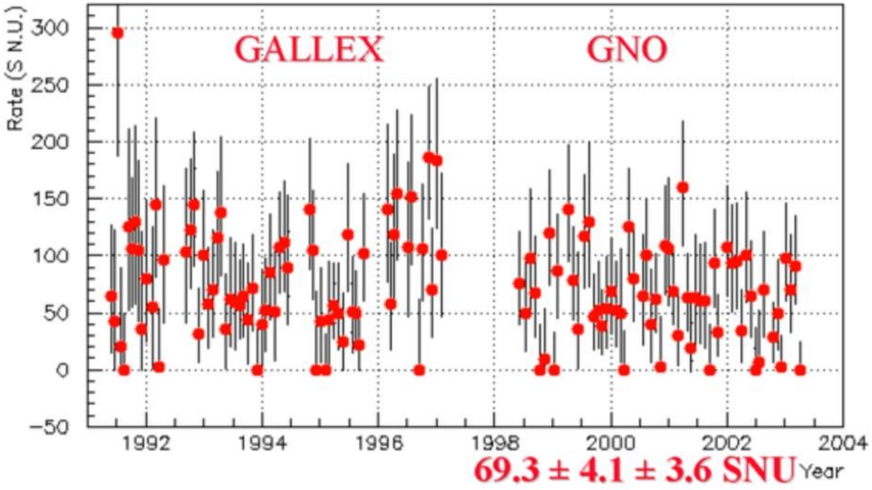
Gallium → Germanium



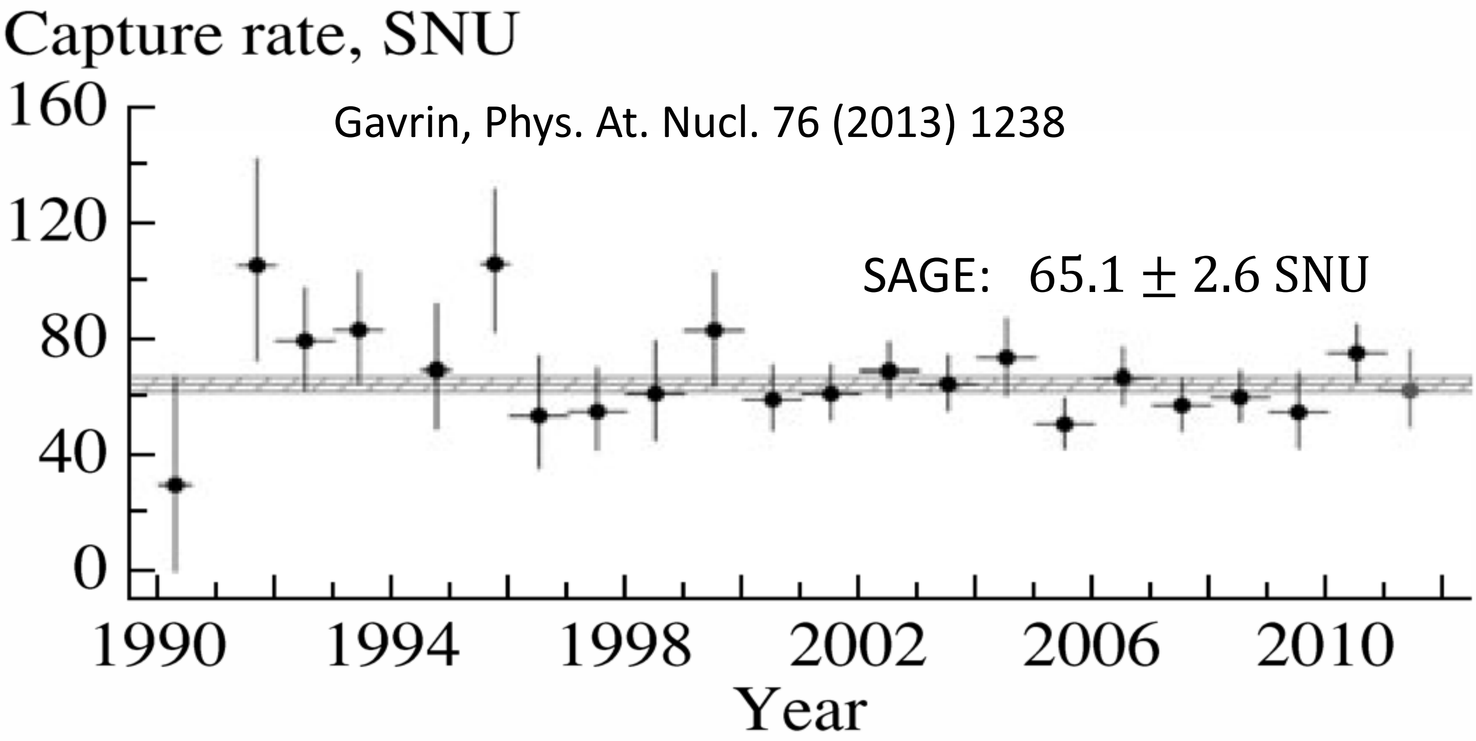


GALLEX/GNO (1991–2003)

Gallium Results



Shown at Neutrino 2006

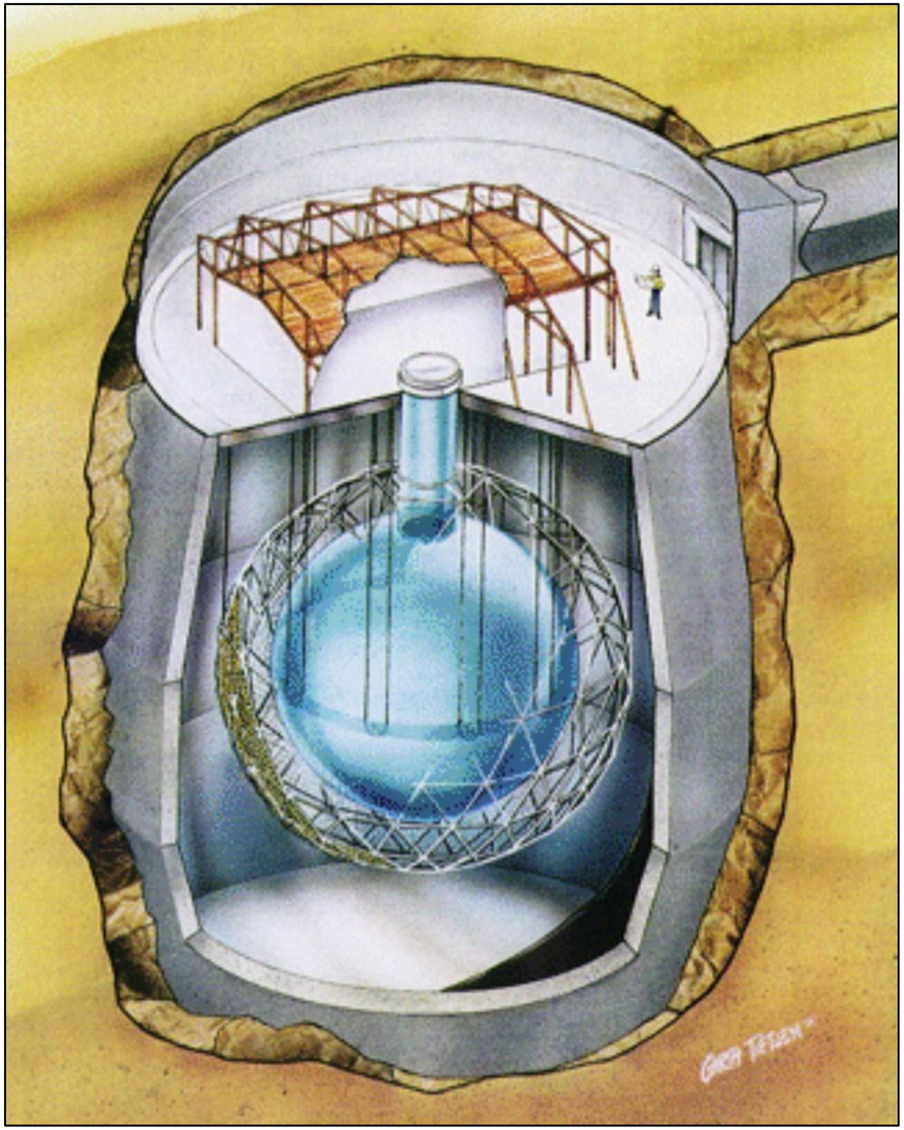


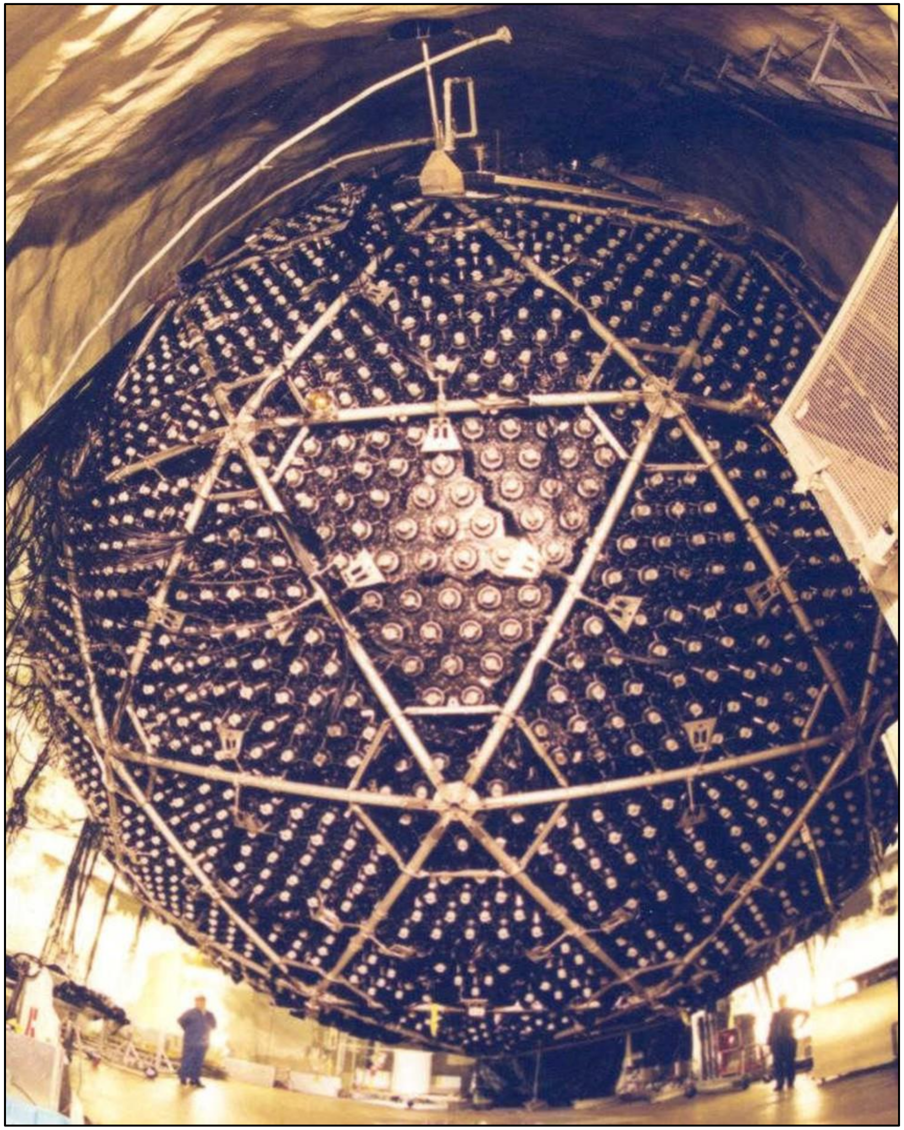
Gavrin, Phys. At. Nucl. 76 (2013) 1238

SAGE: 65.1 ± 2.6 SNU

Sudbury Neutrino Observatory (SNO) 1999–2006

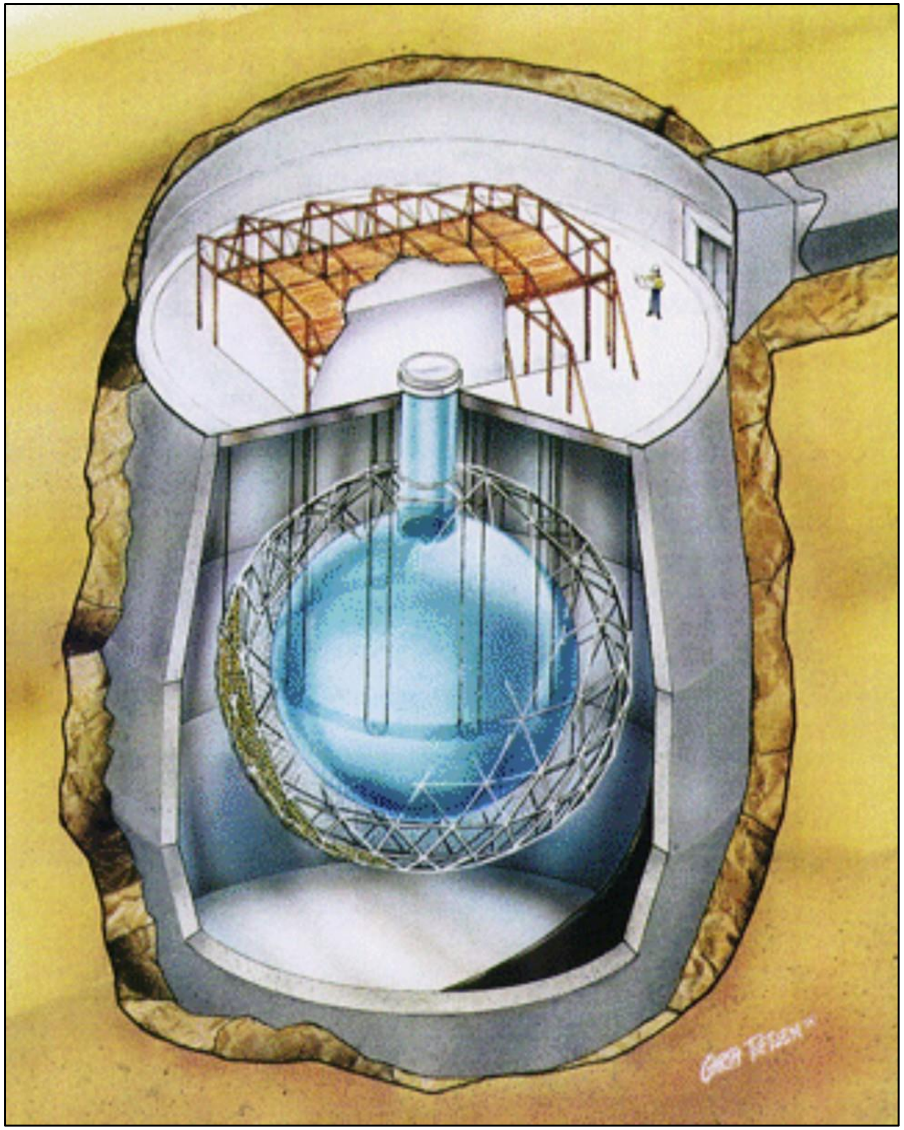
1000 tons of heavy water

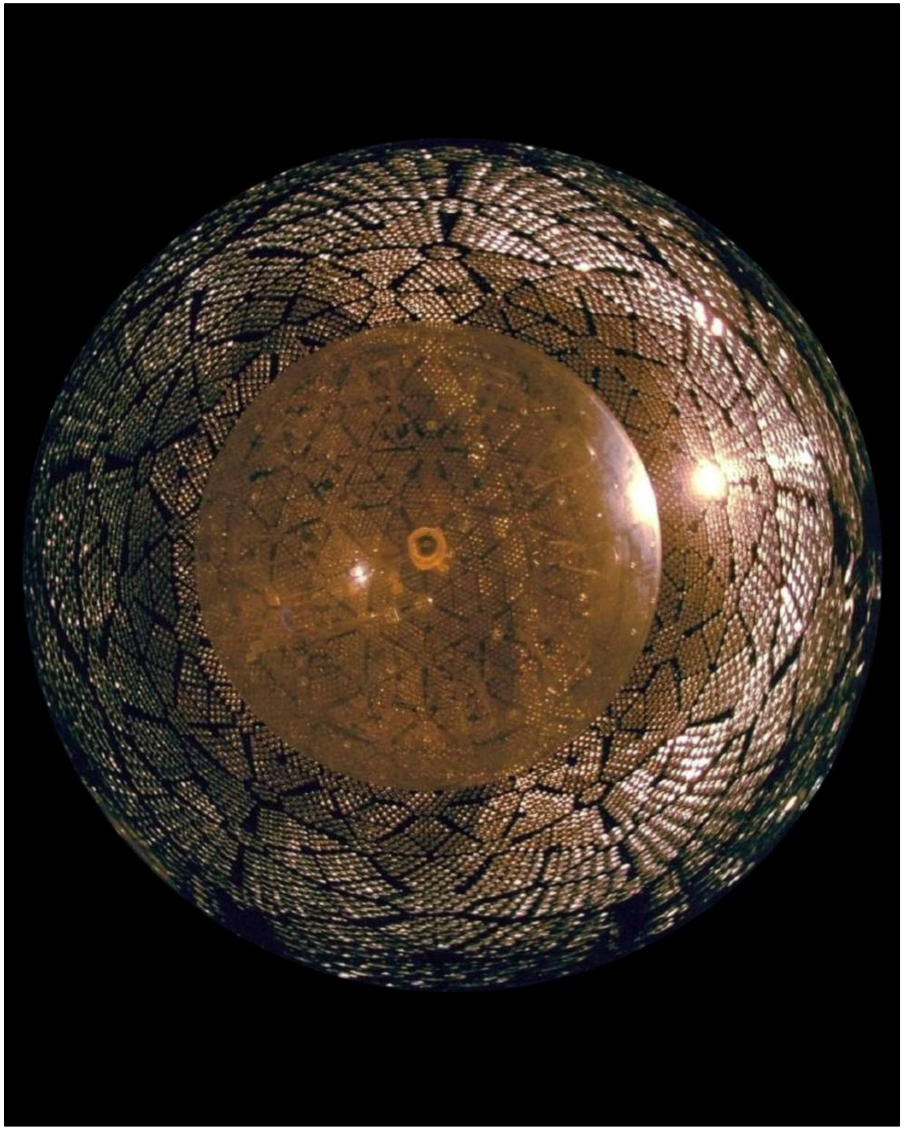




Sudbury Neutrino Observatory (SNO) 1999–2006

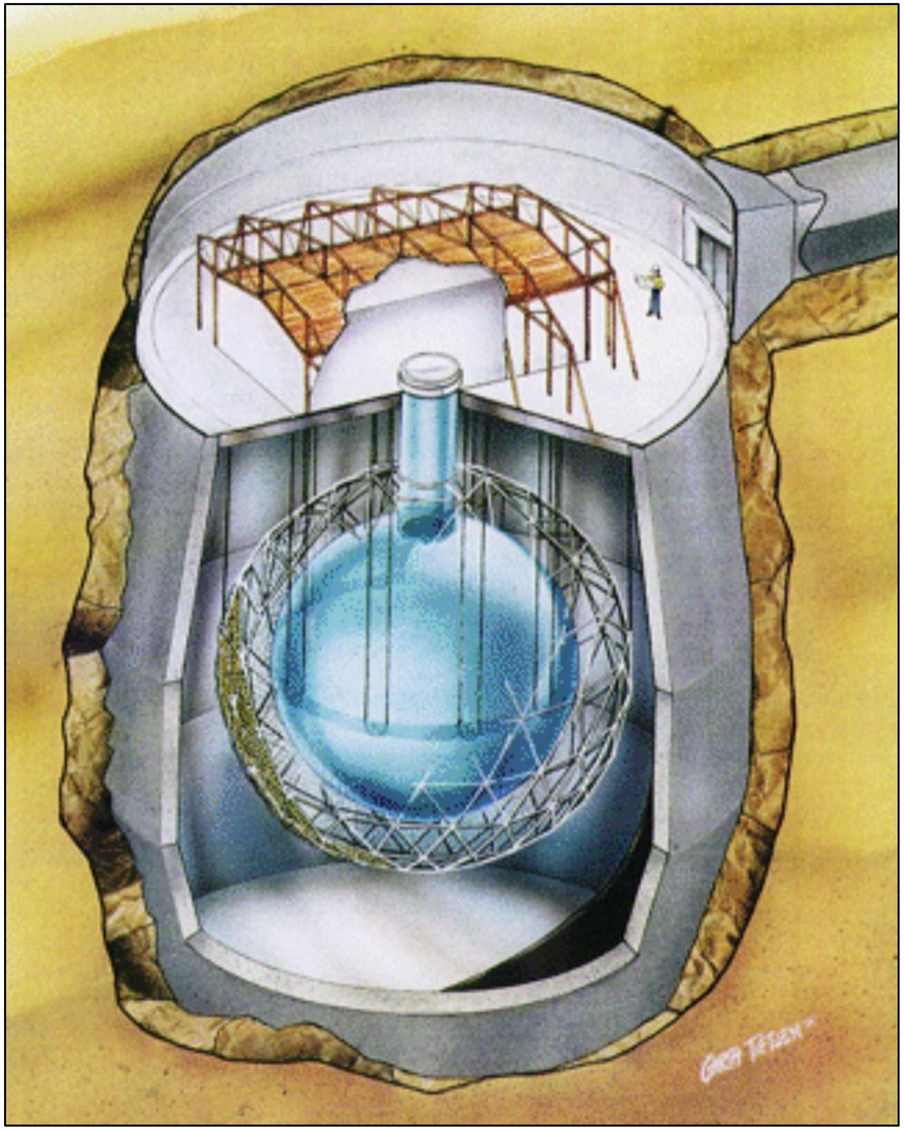
1000 tons of heavy water





Sudbury Neutrino Observatory (SNO) 1999–2006

1000 tons of heavy water



Normal (light) water

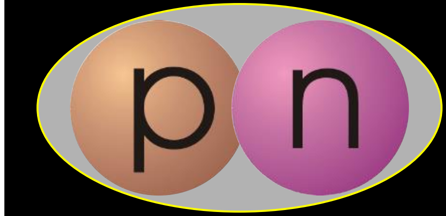
H_20

Heavy water

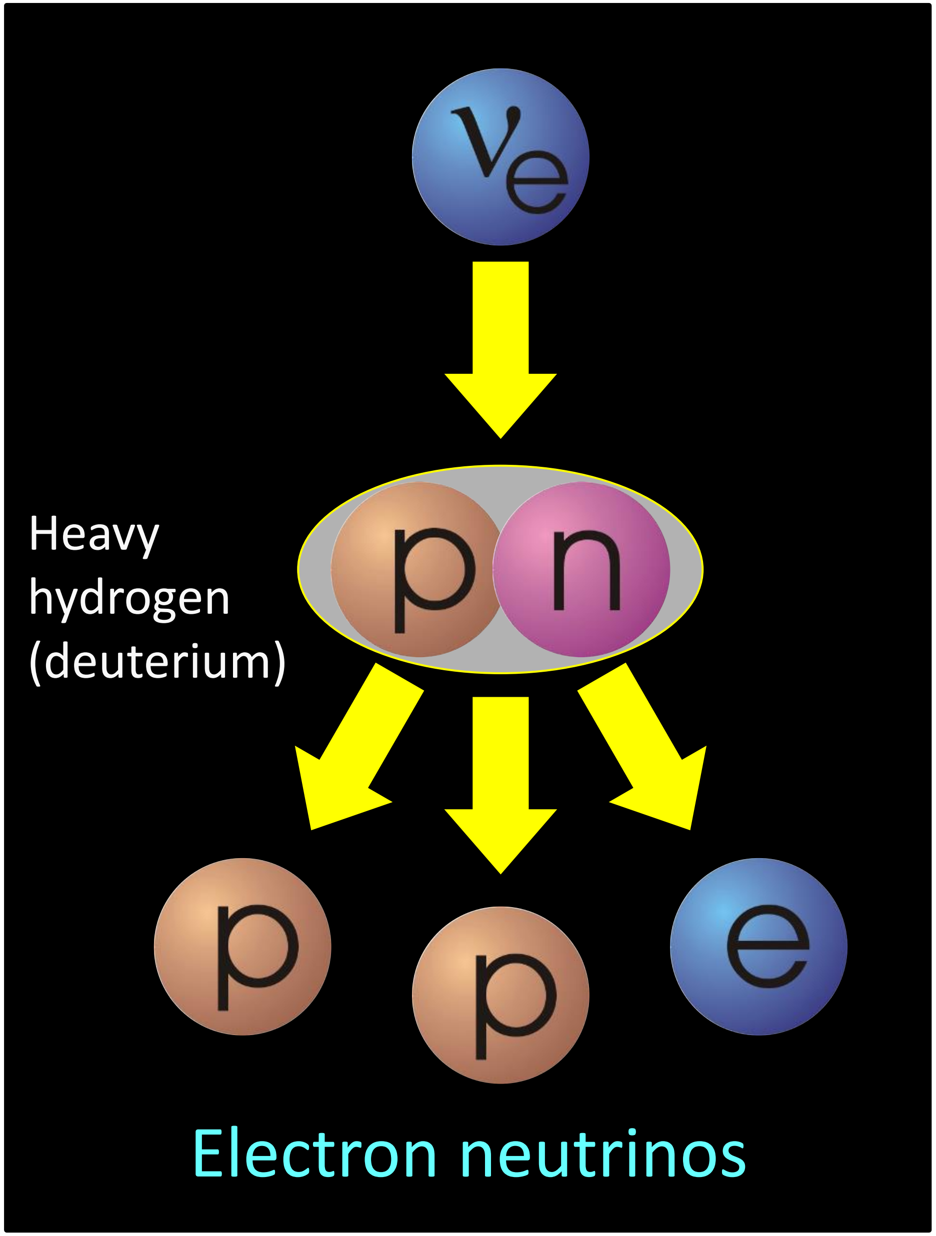
D_20

Nucleus of hydrogen (proton)

Nucleus of heavy hydrogen (deuterium)

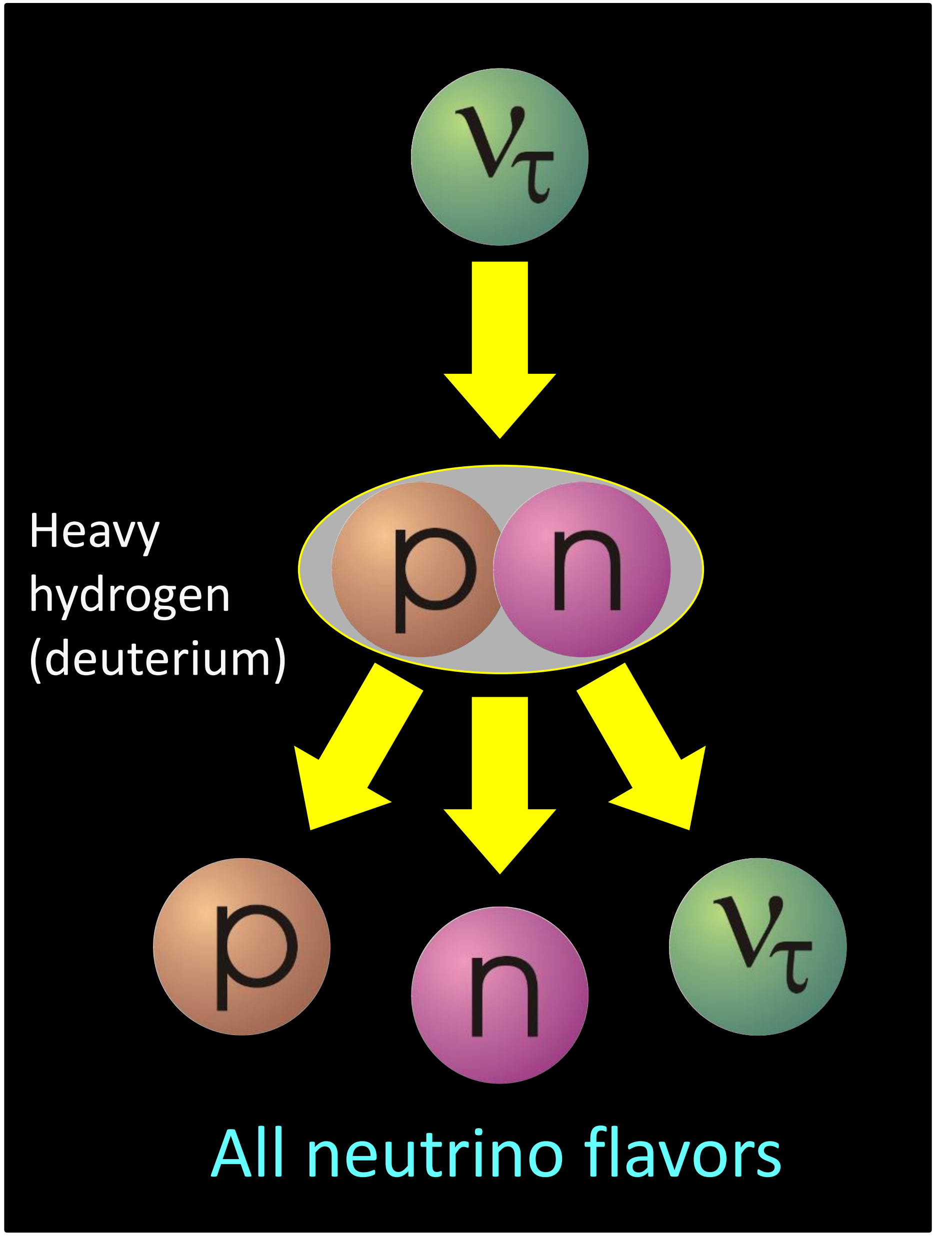


Sudbury Neutrino Observatory (SNO) 1999–2006



Heavy hydrogen (deuterium)

Electron neutrinos



Heavy hydrogen (deuterium)

All neutrino flavors

Missing Neutrinos from the Sun

Electron-Neutrino Detectors | **All Flavors**

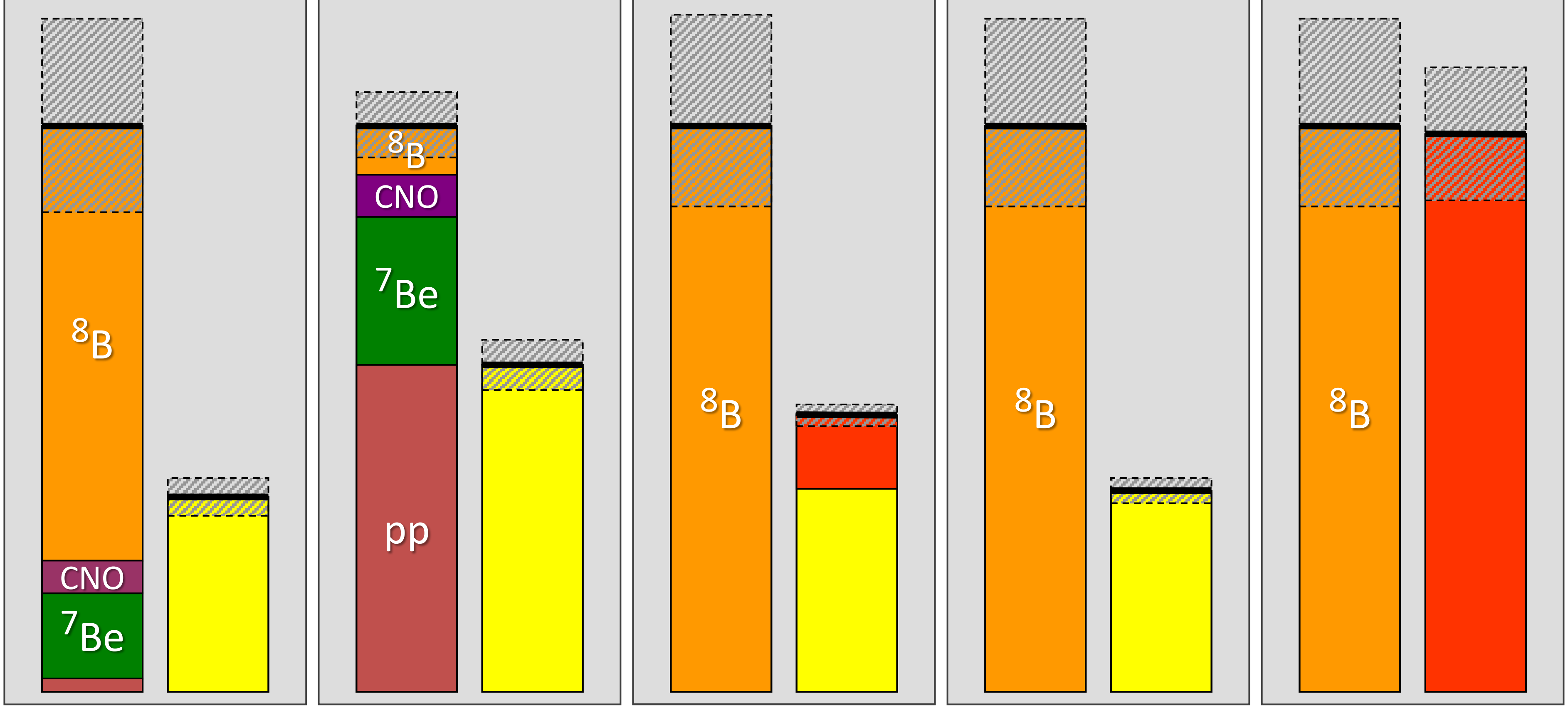
Chlorine

Gallium

Water
$\nu + e^- \rightarrow \nu + e^-$

Heavy Water
$\nu_e + d \rightarrow p + p + e^-$

Heavy Water
$\nu + d \rightarrow p + n + \nu$



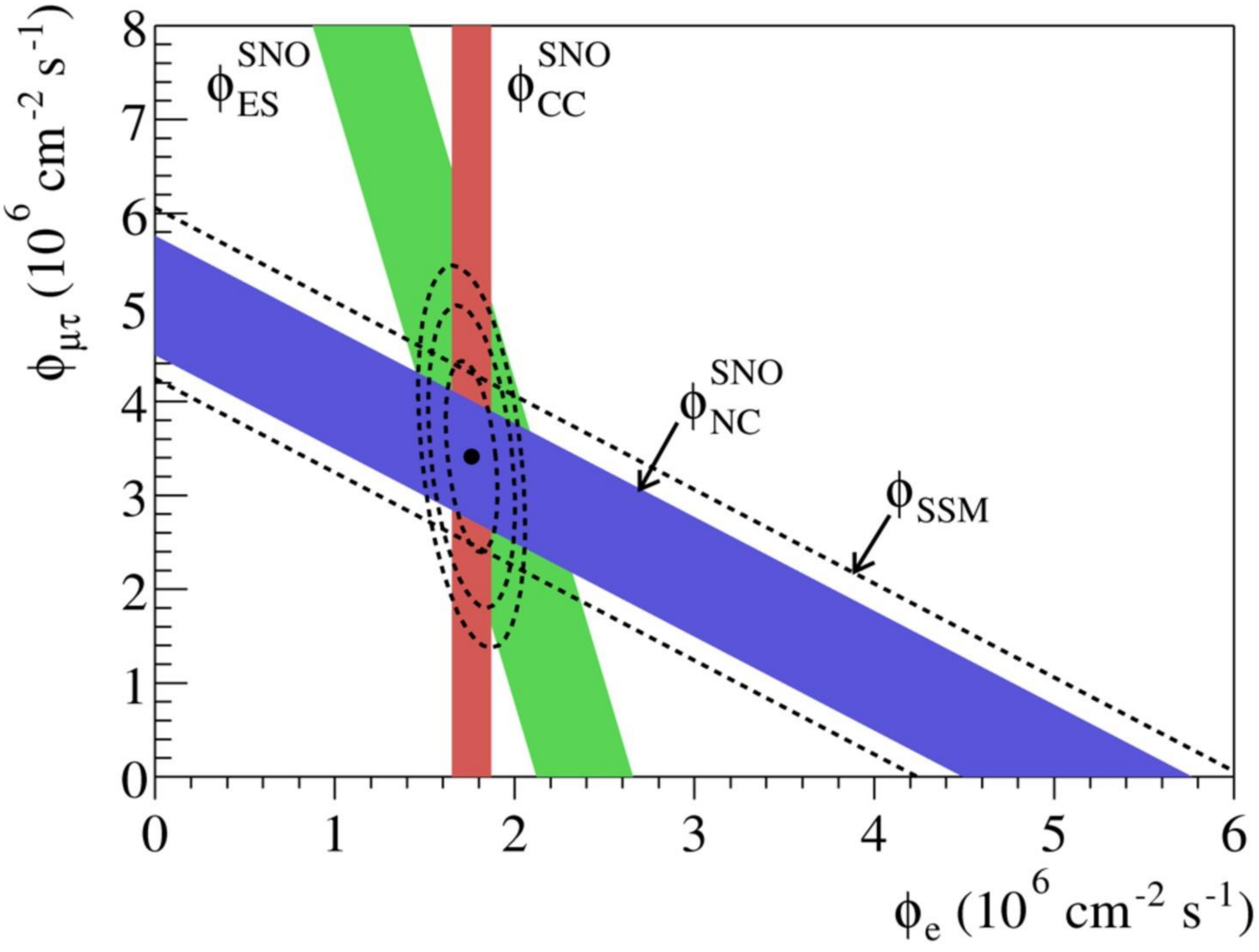
Homestake

Gallex/GNO
SAGE

(Super-)
Kamiokande

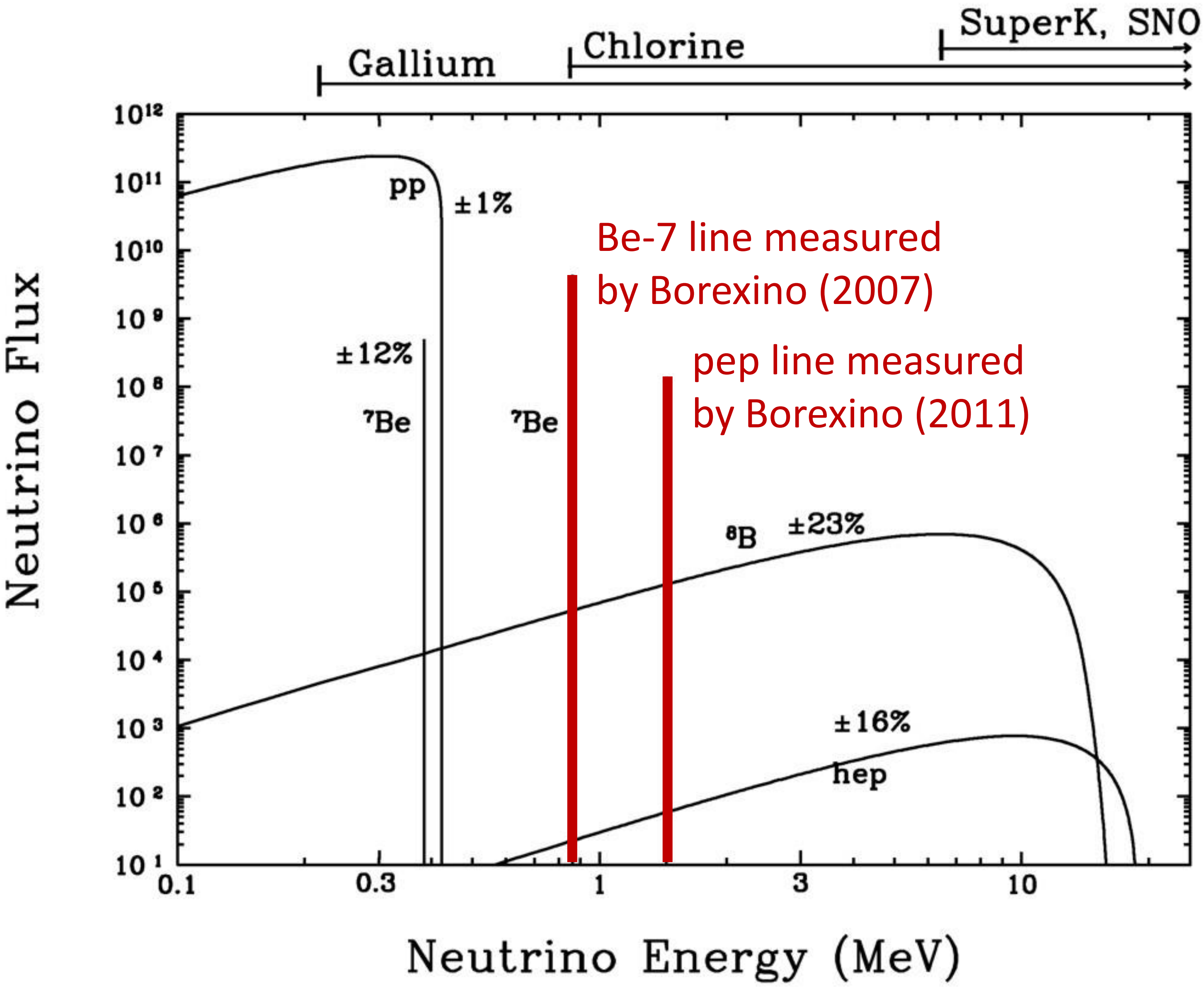
SNO

Charged and Neutral-Current SNO Measurements



Ahmad et al. (SNO Collaboration), PRL 89:011301,2002
(nucl-ex/0204008)

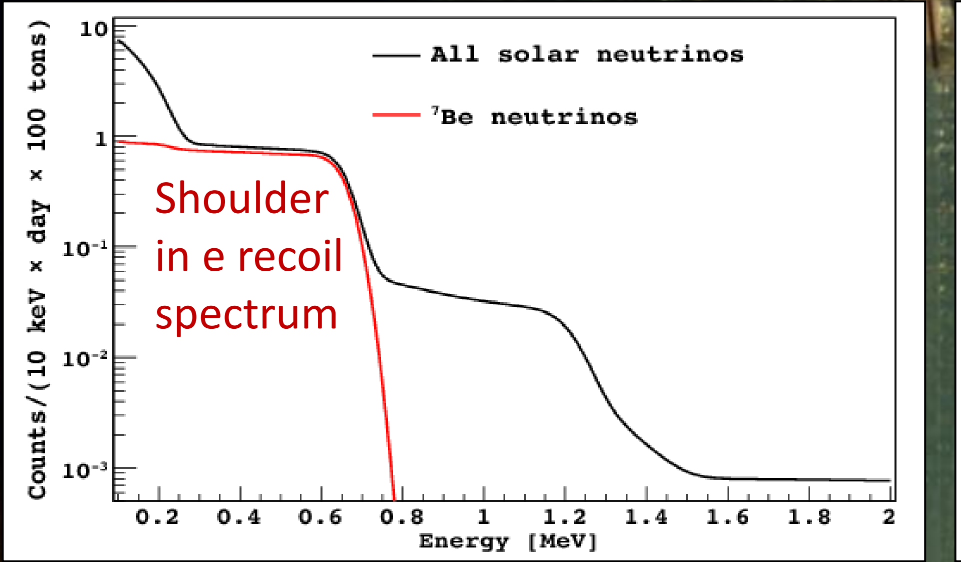
Solar Neutrino Spectrum



Be-7 line measured by Borexino (2007)

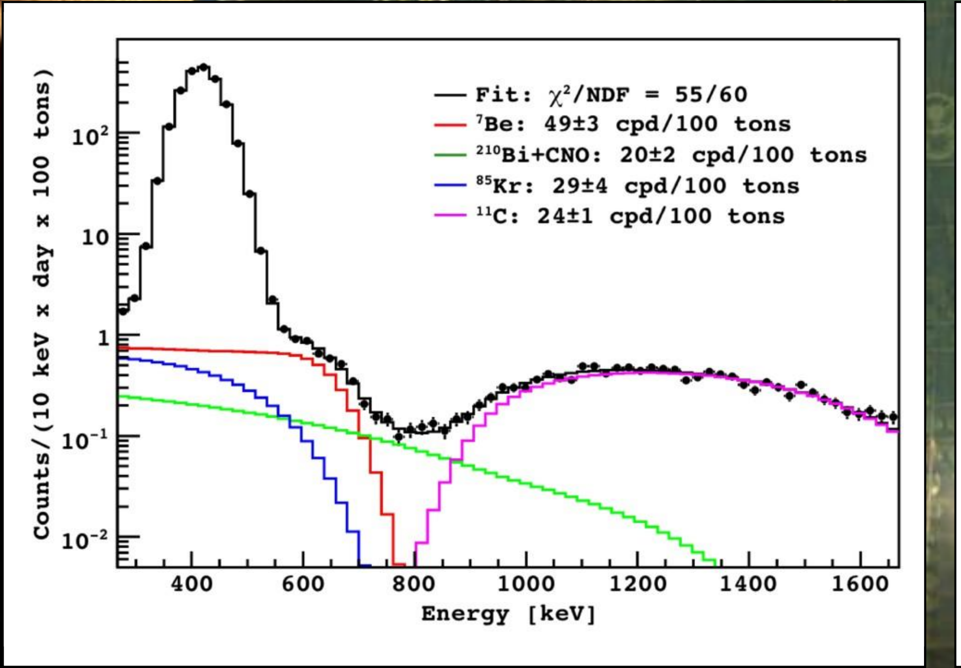
pep line measured by Borexino (2011)

Solar Neutrino Spectroscopy with BOREXINO



Shoulder in e recoil spectrum

- Neutrino electron scattering
- Liquid scintillator technology (~ 300 tons)
- Low energy threshold (~ 60 keV)
- Online since 16 May 2007



- Expected without flavor oscillations

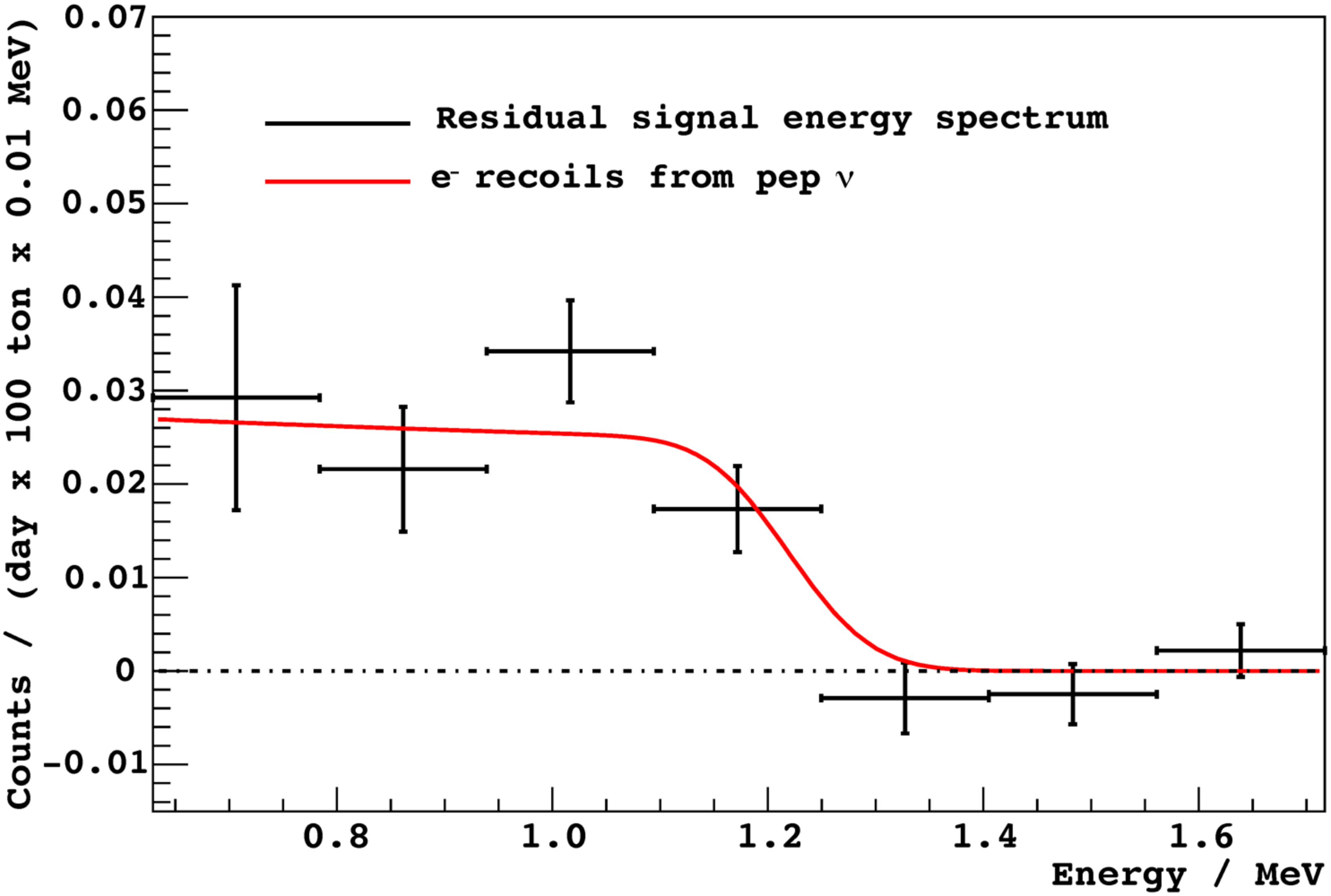
  75 ± 4 counts/100 t/d
- Expected with oscillations

  49 ± 4 counts/100 t/d
- BOREXINO result (May 2008)

  $49 \pm 3_{stat} \pm 4_{sys}$ cnts/100 t/d

  arXiv:0805.3843 (25 May 2008)

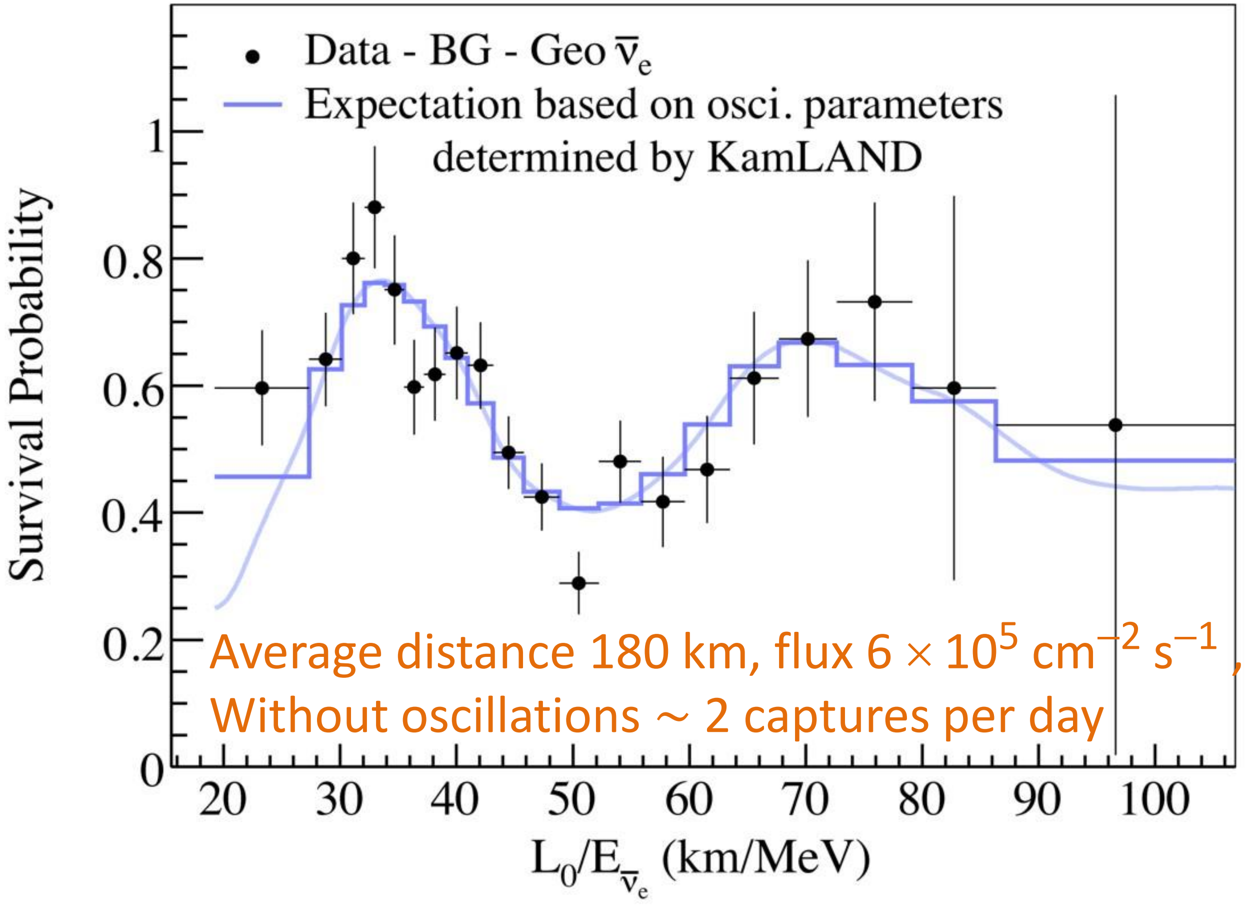
pep Neutrinos in Borexino



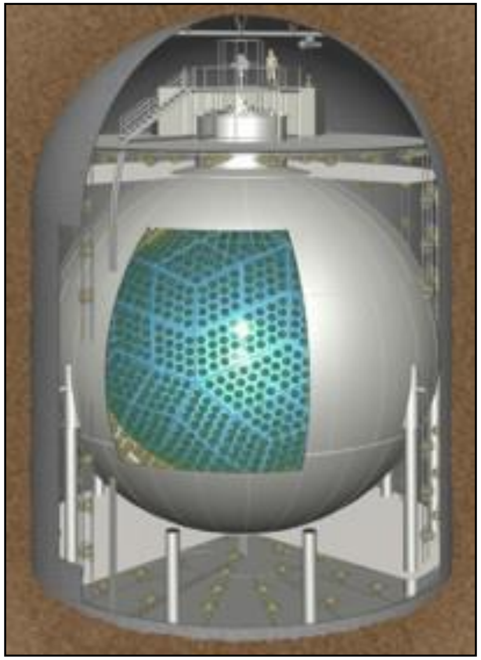
Borexino Collaboration, arXiv:1110.3230v1

Oscillation of Reactor Neutrinos at KamLAND (Japan)

Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E

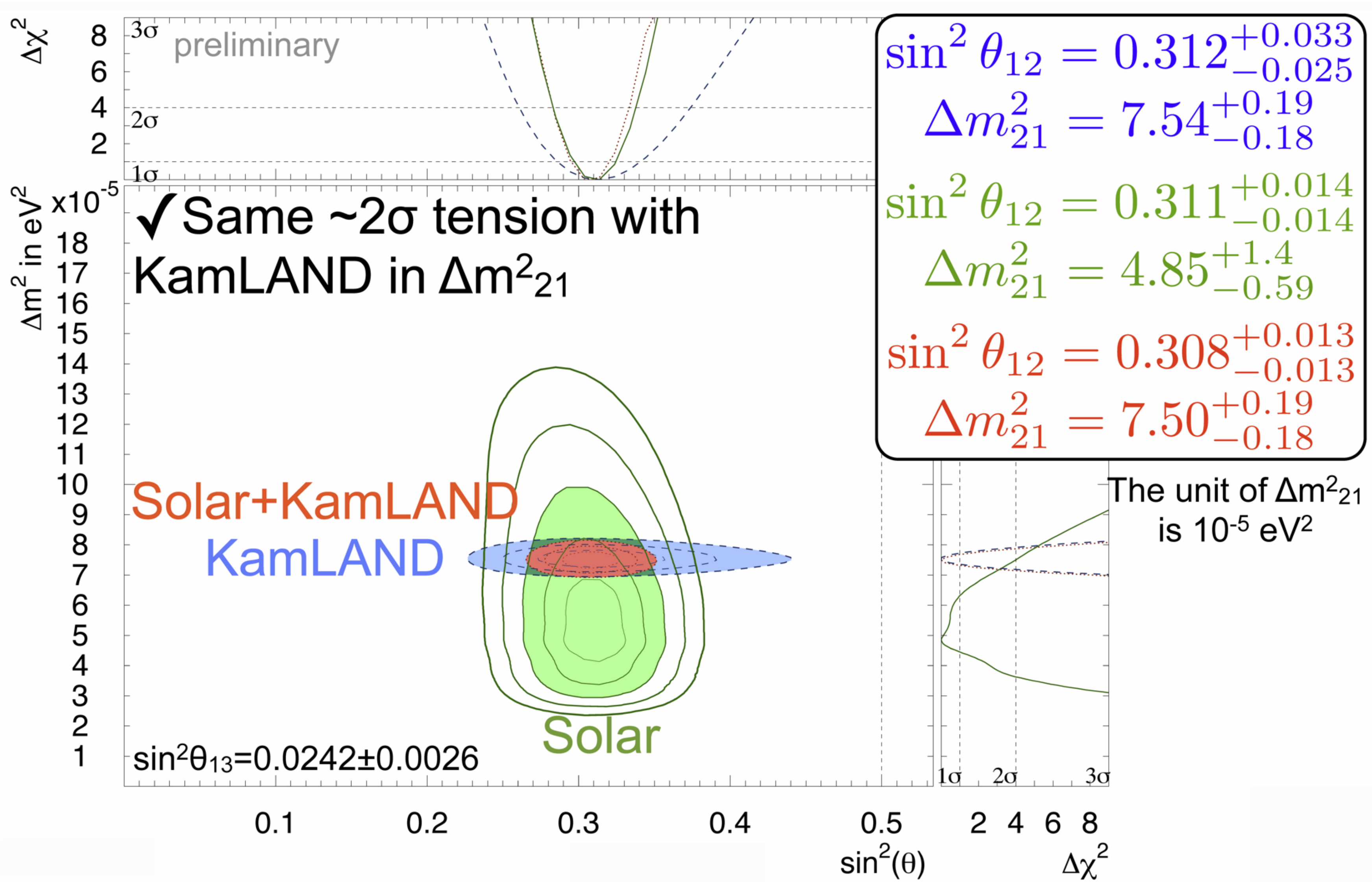


Average distance 180 km, flux 6×10^5 cm^{-2} s^{-1},
Without oscillations ~ 2 captures per day



KamLAND Scintillator detector (1000 t)

Best-fit "solar" oscillation parameters



✓Same ~2σ tension with KamLAND in Δm^2_{21}

$\sin^2\theta_{13}=0.0242\pm0.0026$

$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$
$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

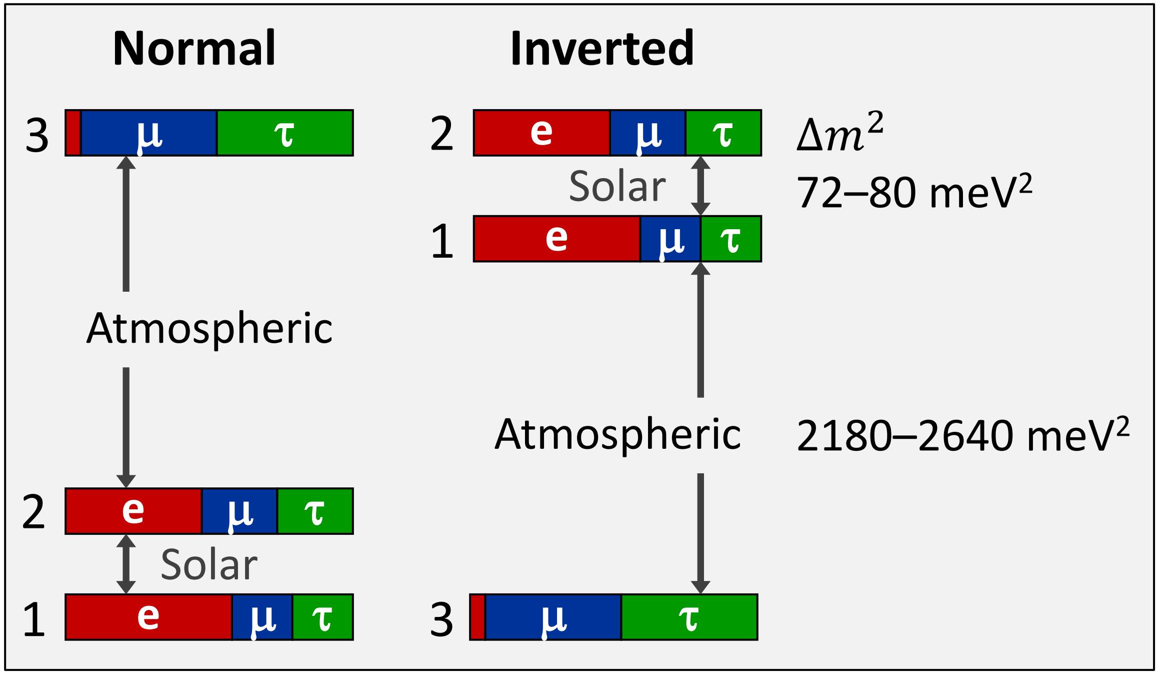
The unit of Δm^2_{21} is 10^{-5} eV^2

Yusuke Koshio at Neutrino 2014

Three-Flavor Neutrino Parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ\\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 11^\circ\\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{33^\circ < \theta_{12} < 37^\circ\\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for}\\ 0\nu2\beta\ \text{decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Tasks and Open Questions

- Precision for all angles
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Matter Effect on Flavor Oscillations in the Sun

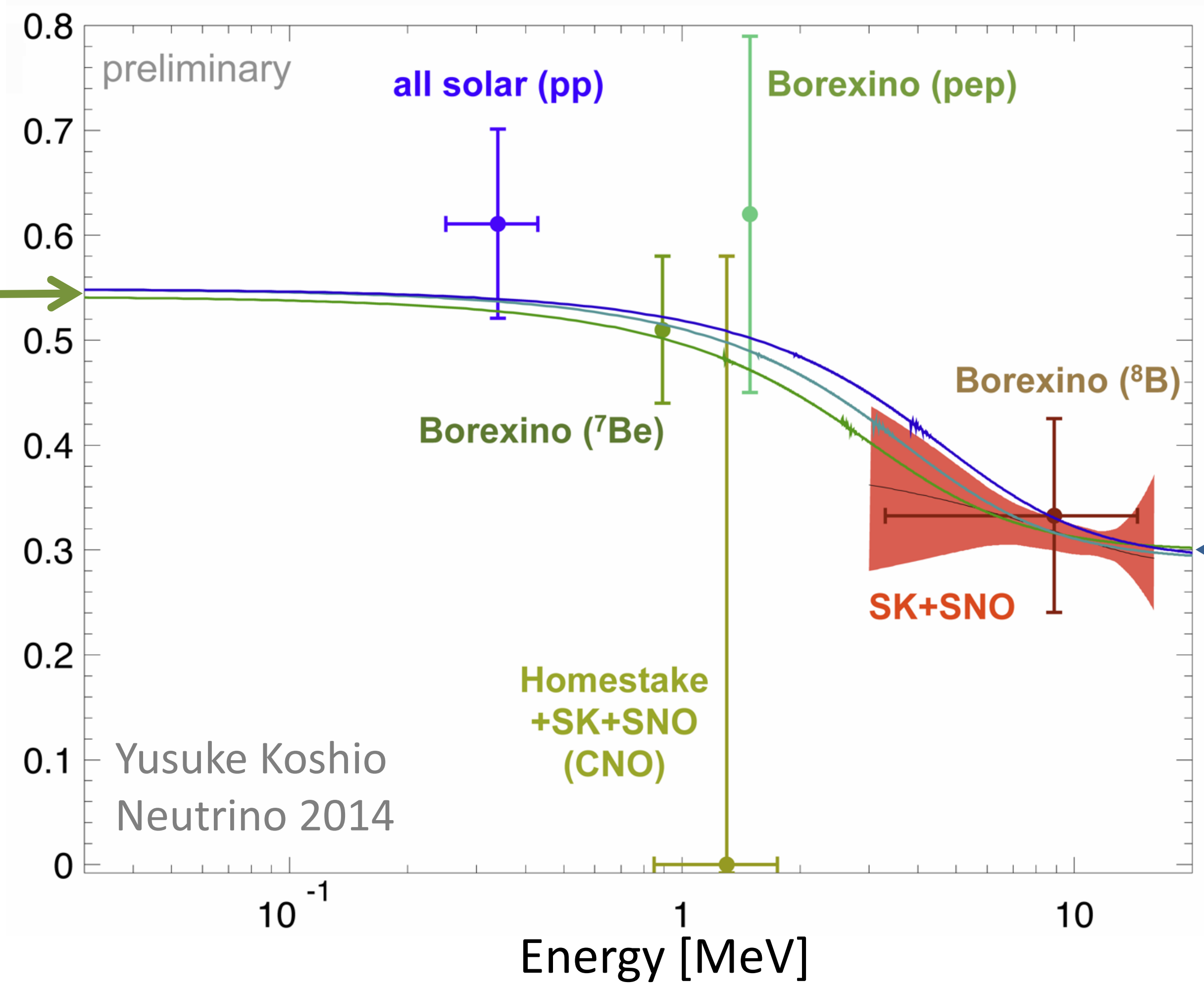
Low energy (E ≲ 1 MeV)
Phase-averaged vacuum oscillations

High energy (E ≳ 5 MeV)
MSW conversion

$1-\frac{1}{2}\sin^2 2\Theta_{12}$

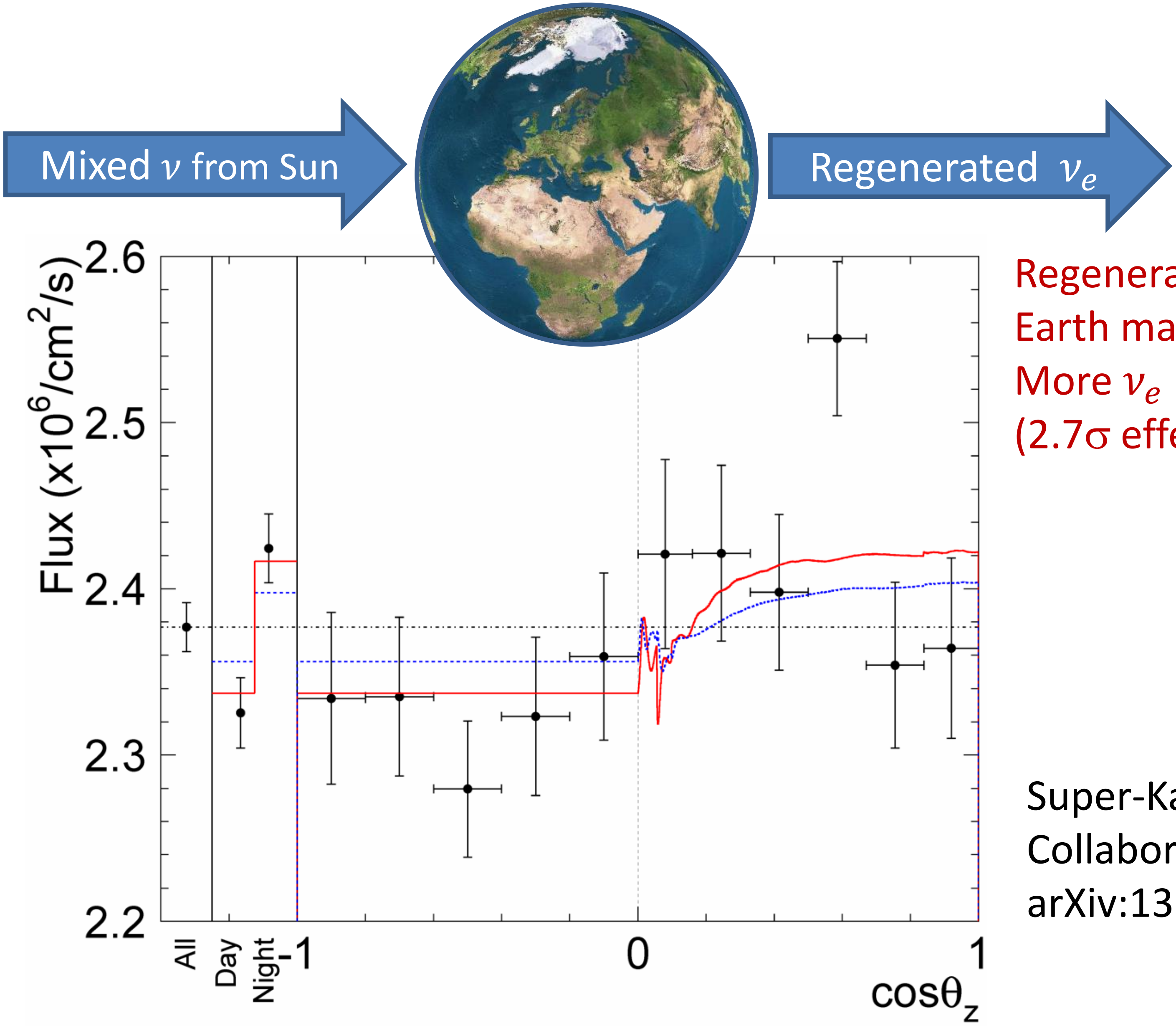
ν_e survival probability

$\sin^2\Theta_{12}$



Yusuke Koshio
Neutrino 2014

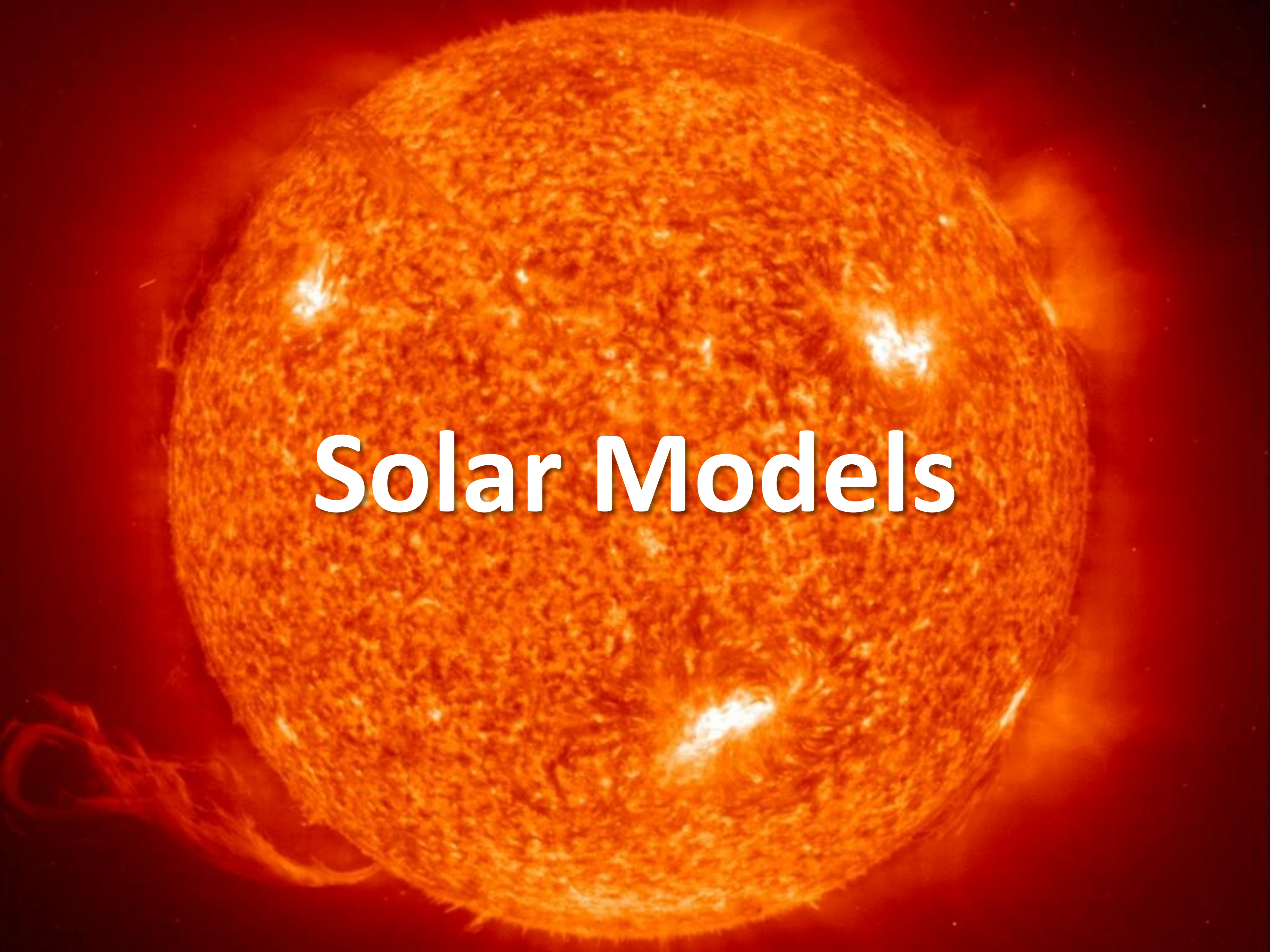
Neutrinos are Brighter at Night


Mixed ν from Sun

Regenerated ν_e

Regeneration by Earth matter effect: More ν_e at night! (2.7σ effect)

Super-Kamiokande Collaboration arXiv:1312.5176



Solar Models

Equations of Stellar Structure

Assume spherical symmetry and static structure (neglect kinetic energy)
Excludes: Rotation, convection, magnetic fields, supernova-dynamics, …

Hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{G_N M_r \rho}{r^2}$$

Energy conservation

$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

Energy transfer

$$L_r = \frac{4\pi r^2}{3\kappa\rho} \frac{d(aT^4)}{dr}$$

Literature

- Clayton: Principles of stellar evolution and nucleosynthesis (Univ. Chicago Press 1968)
- Kippenhahn & Weigert: Stellar structure and evolution (Springer 1990)

r	Radius from center
P	Pressure
G_N	Newton’s constant
ρ	Mass density
M_r	Integrated mass up to r
L_r	Luminosity (energy flux)
ϵ	Local rate of energy generation $[\mathrm{erg\,g^{-1}s^{-1}}]$ $\epsilon = \epsilon_{\mathrm{nuc}} + \epsilon_{\mathrm{grav}} - \epsilon_\nu$
κ	Opacity $\kappa^{-1} = \kappa_\gamma^{-1} + \kappa_{\mathrm{c}}^{-1}$
κ_γ	Radiative opacity $\kappa_\gamma \rho = \langle \lambda_\gamma \rangle_{\mathrm{Rosseland}}^{-1}$
κ_{c}	Electron conduction

Constructing a Solar Model: Fixed Inputs

Solve stellar structure equations with good microphysics, starting from a zero-age main-sequence model (chemically homogeneous) to present age

Fixed quantities		
Mass	$M_\odot = 1.989 \times 10^{33}$ g 0.1%	Kepler's 3rd law
Age	$t_\odot = 4.57 \times 10^{9}$ yrs 0.5%	Meteorites

Quantities to match		
Luminosity	$L_\odot = 3.842 \times 10^{33}$ erg s^{-1} 0.4%	Solar constant
Radius	$R_\odot = 6.9598 \times 10^{10}$ cm 0.1%	Angular diameter
Metals/hydrogen ratio	$(Z/X)_\odot = 0.0229$	Photosphere and meteorites

Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

Constructing a Solar Model: Free Parameters

3 free parameters

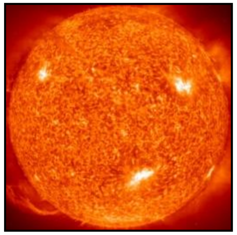
- Convection theory has 1 free parameter:
  Mixing length parameter α_{MLT}
  determines the temperature stratification where convection is not adiabatic (upper layers of solar envelope)

- 2 of 3 quantities determining the initial composition:
  X_{ini}, Y_{ini}, Z_{ini} (linked by $X_{\mathrm{ini}} + Y_{\mathrm{ini}} + Z_{\mathrm{ini}} = 1$).
  Individual elements grouped in Z_{ini} have relative abundances given by solar abundance measurements (e.g. GS98, AGS05)

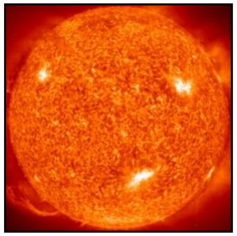
- Construct 1 $M_\odot$ initial model with X_{ini}, Z_{ini}, $Y_{\mathrm{ini}} = 1 - X_{\mathrm{ini}} - Z_{\mathrm{ini}}$ and α_{MLT}
- Evolve for the solar age $t_\odot$
- Match $(Z/X)_\odot$, $L_\odot$ and $R_\odot$ to better than 10^{-5}

Adapted from A. Serenelli’s lectures at Scottish Universities Summer School in Physics 2006

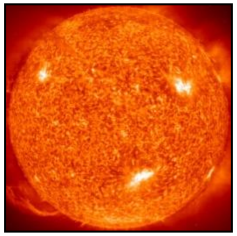
Standard Solar Model Output Information



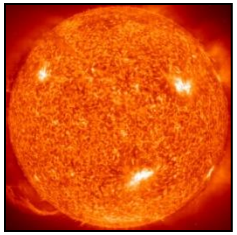
Eight neutrino fluxes:
Production profiles and integrated values



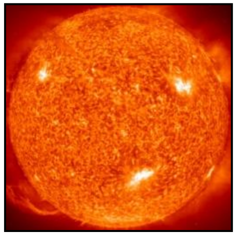
Chemical profiles $X(r)$, $Y(r)$, $Z_i(r)$
$\rightarrow$ electron and neutron density profiles



Thermodynamic quantities as a function of radius:
T, P, density ρ, sound speed c



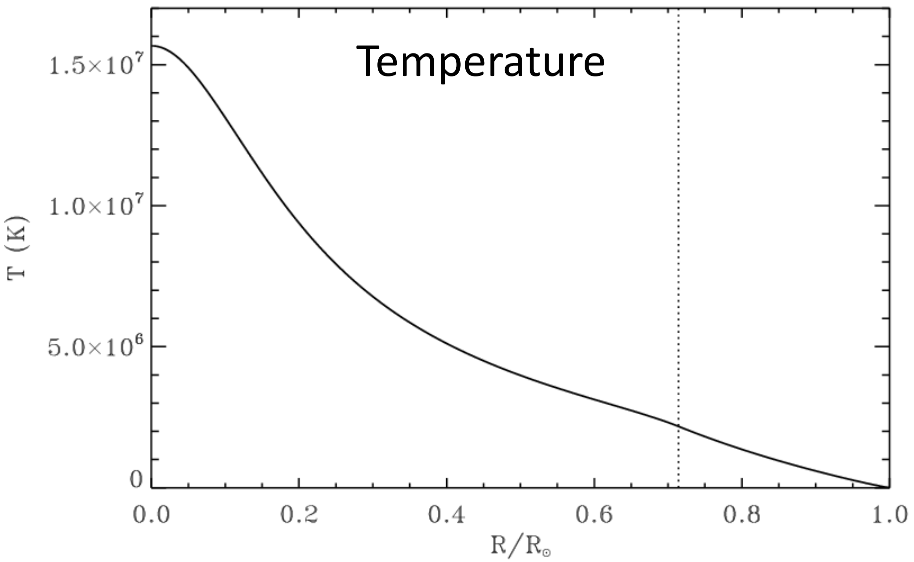
Surface helium abundance Y_{surf}
(Z/X and $1 = X + Y + Z$ leave 1 degree of freedom)

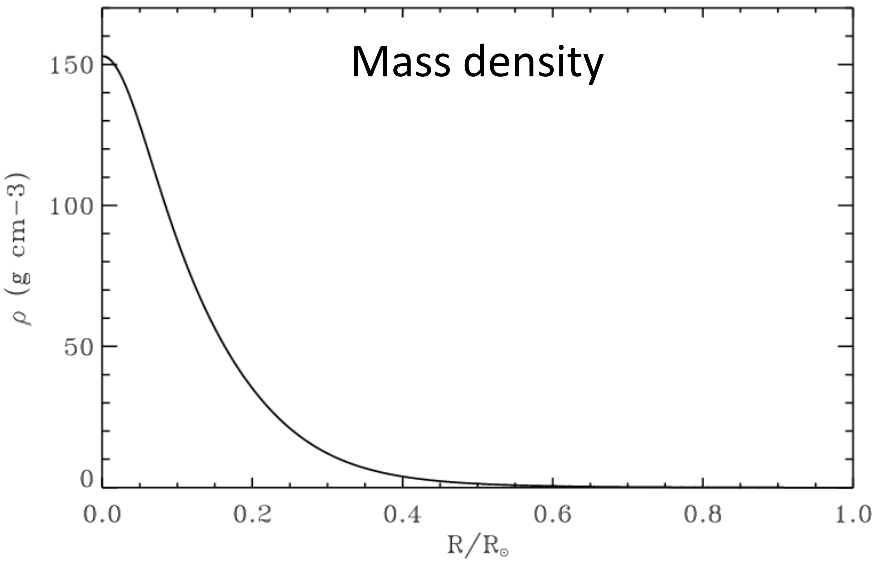


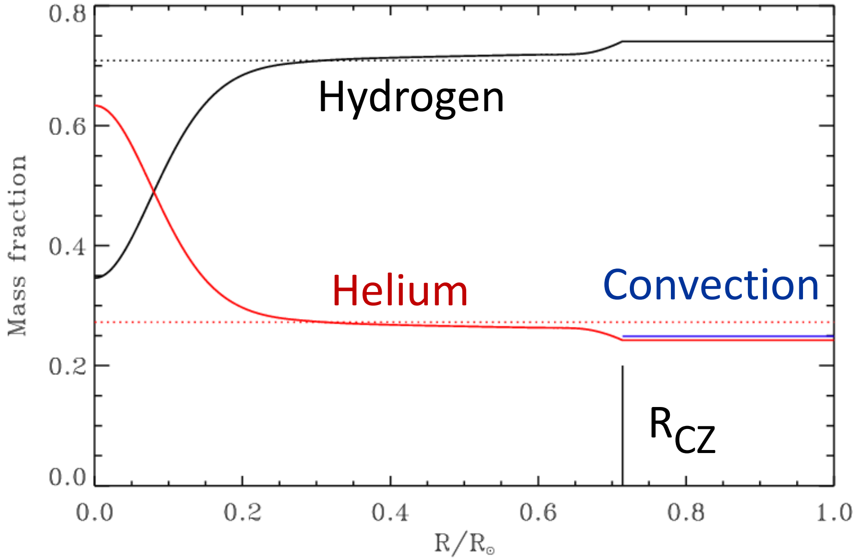
Depth of the convective envelope R_{CZ}

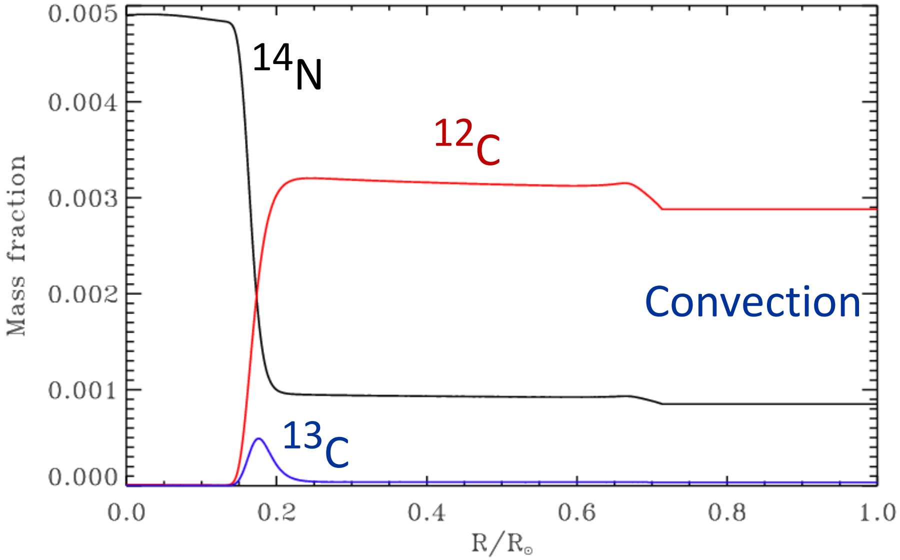
Adapted from A. Serenelli’s lectures at Scottish Universities Summer School in Physics 2006

Standard Solar Model: Internal Structure

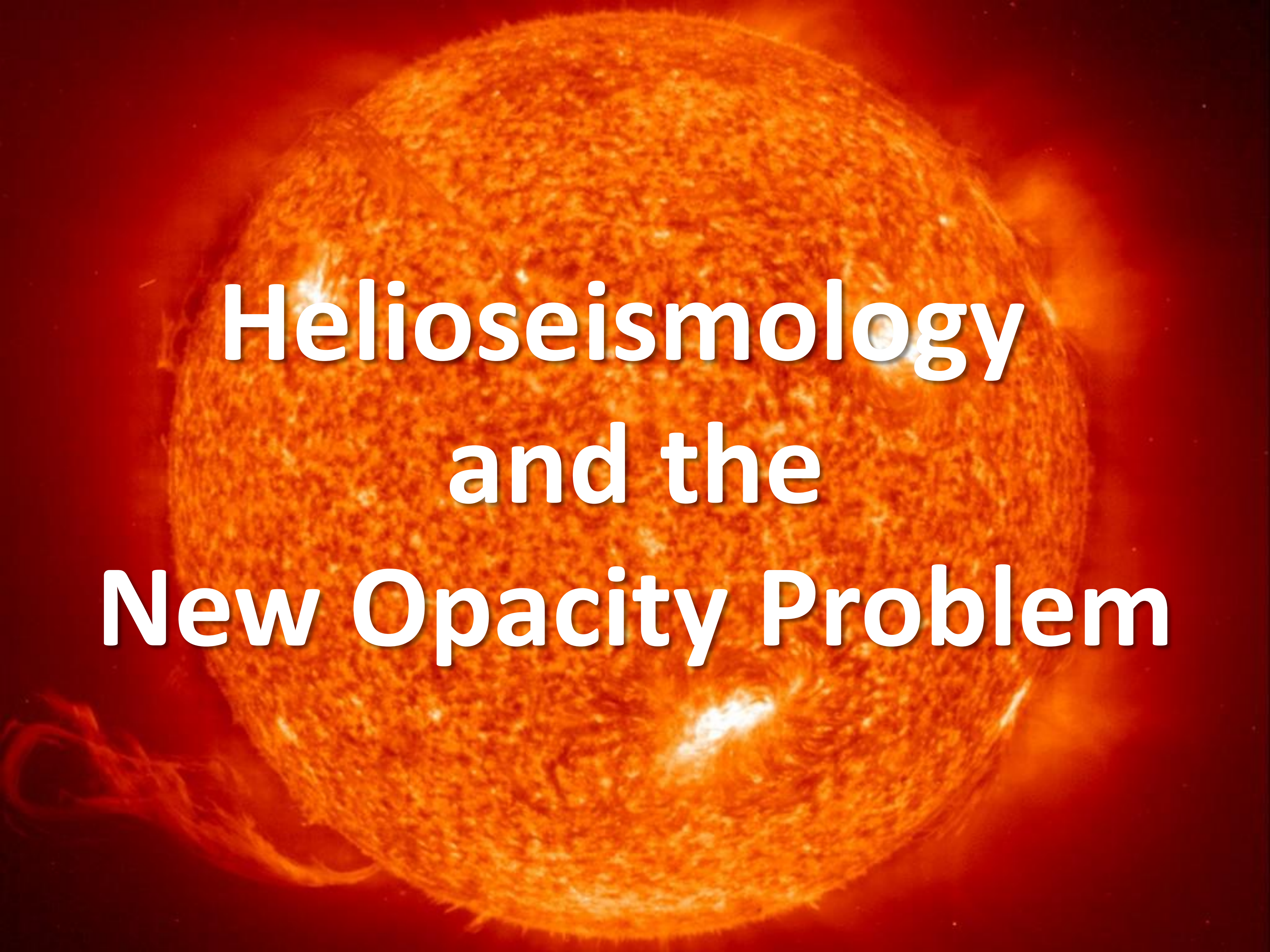






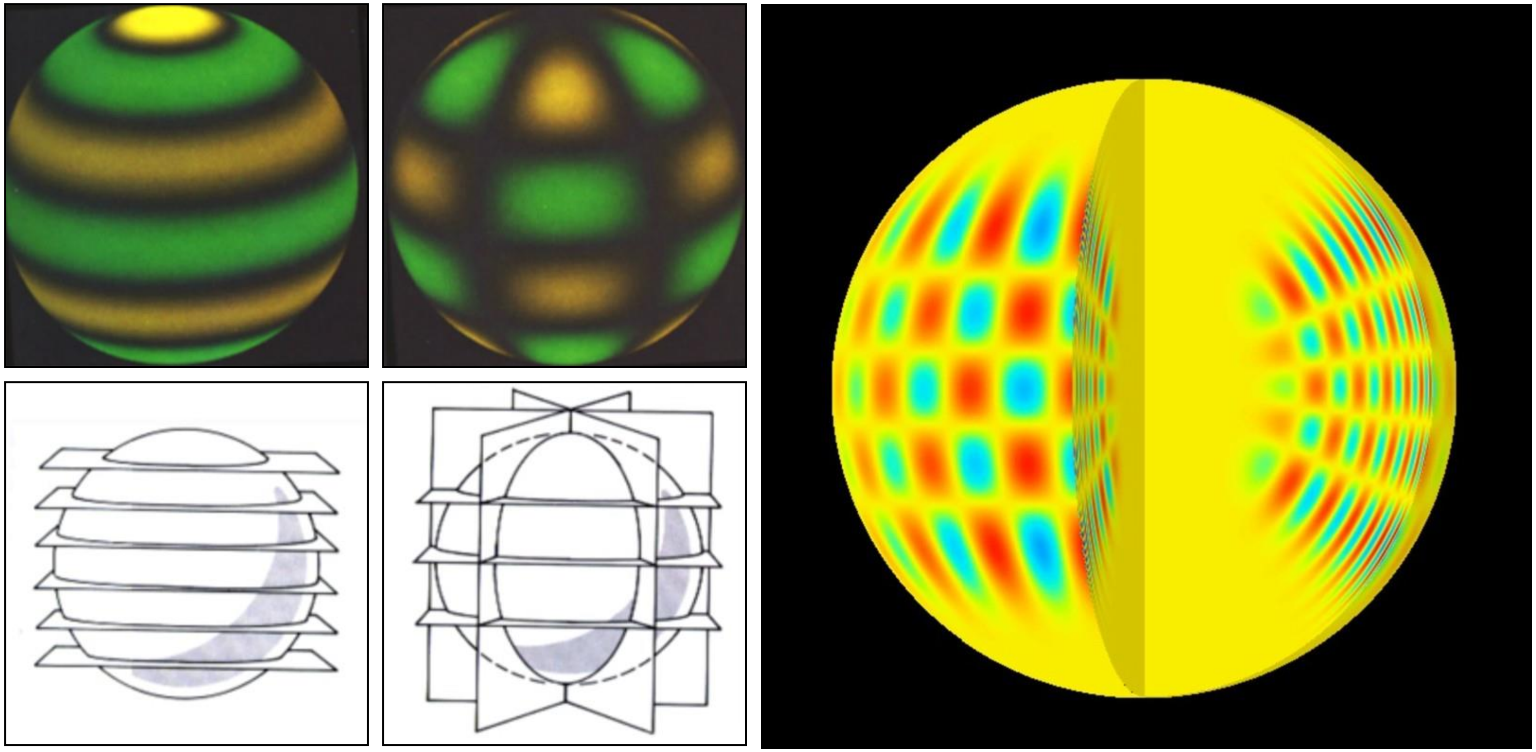


Helioseismology and the New Opacity Problem



Helioseismology: Sun as a Pulsating Star

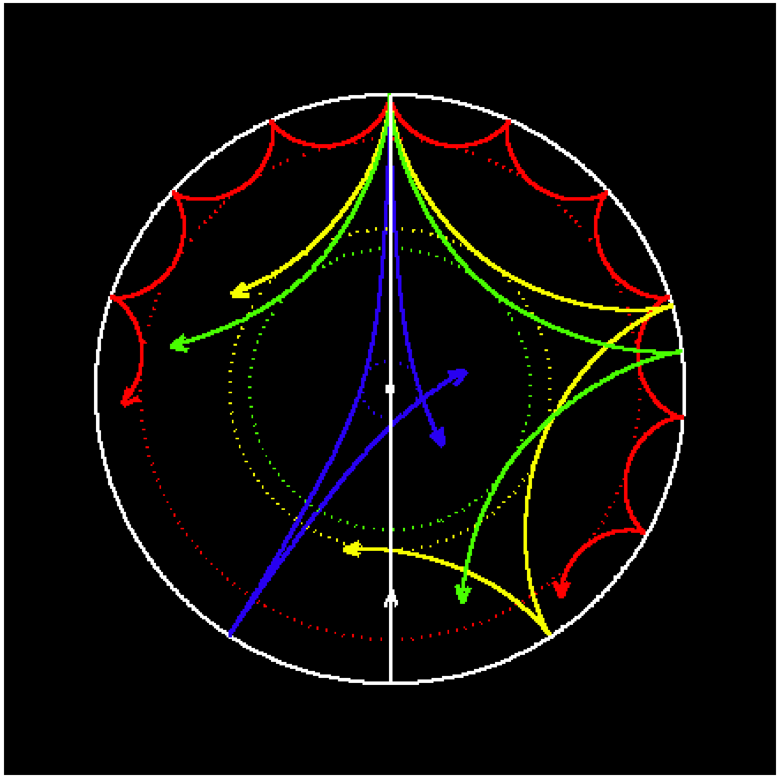
- Discovery of oscillations: Leighton et al. (1962)
- Sun oscillates in > 10^5 eigenmodes
- Frequencies of order mHz (5-min oscillations)
- Individual modes characterized by radial n, angular ℓ and longitudinal m numbers



Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

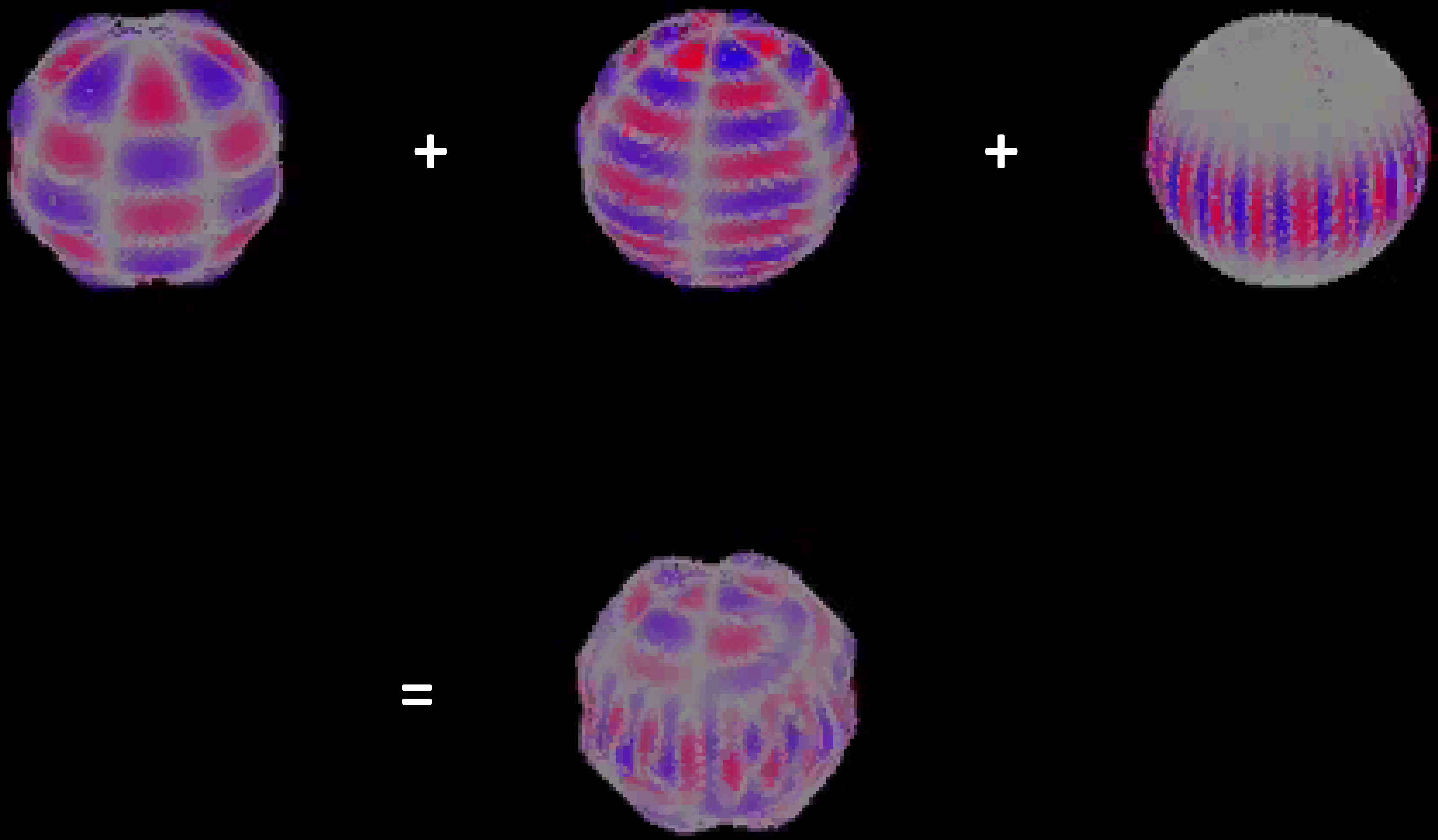
Helioseismology: p-Modes

- Solar oscillations are acoustic waves
  (p-modes, pressure is the restoring force)
  stochastically excited by convective motions
- Outer turning-point located close to temperature inversion layer
- Inner turning-point varies, strongly depends on ℓ (centrifugal barrier)



Credit: Jørgen Christensen-Dalsgaard

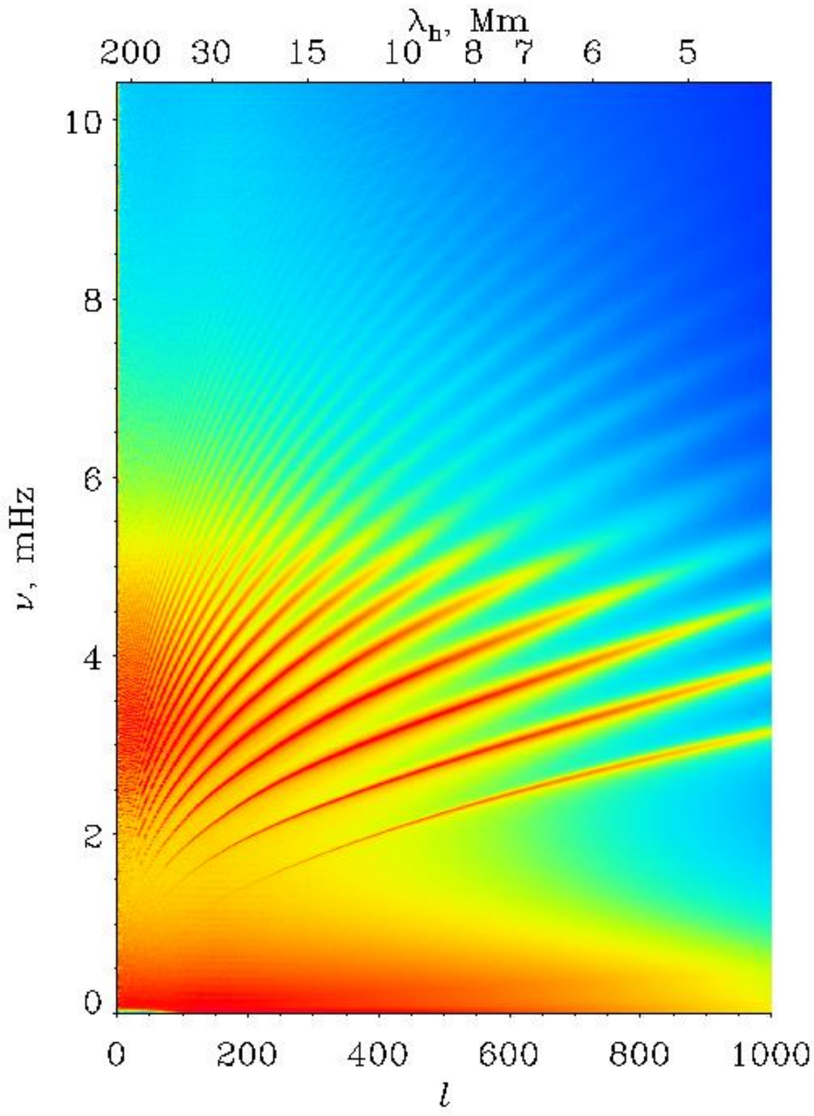
Examples for Solar Oscillations



http://astro.phys.au.dk/helio_outreach/english/

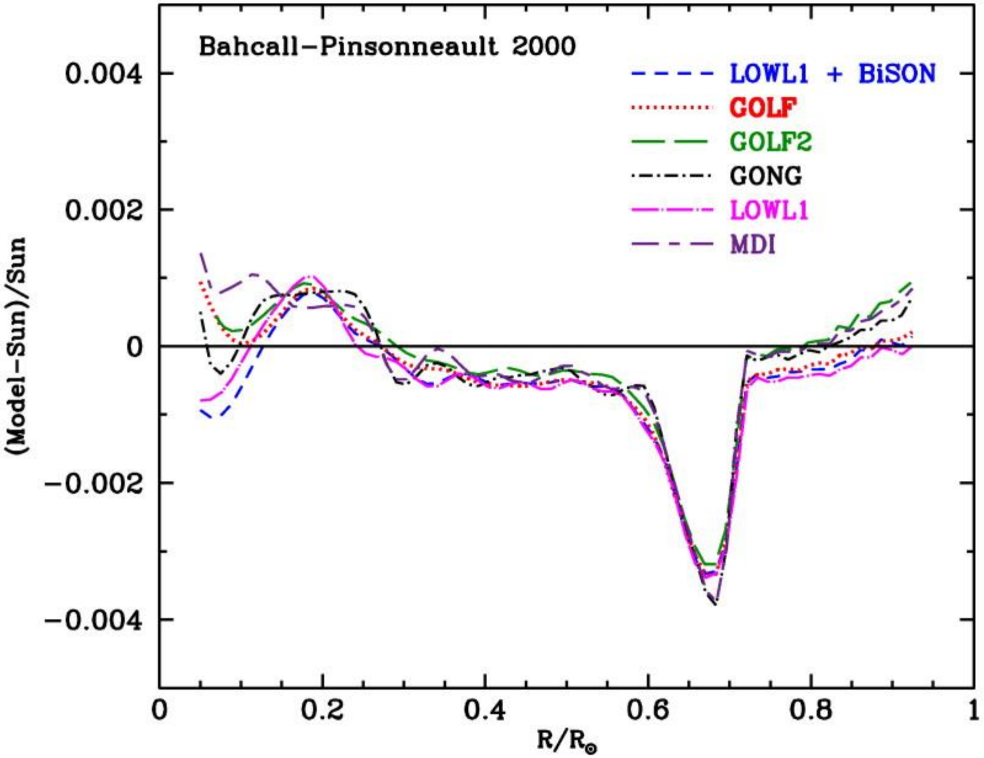
Helioseismology: Observations

- Doppler observations of spectral lines measure velocities of a few cm/s
- Differences in the frequencies of order mHz
- Very long observations needed. BiSON network (low-l modes) has data for ~ 5000 days
- Relative accuracy in frequencies is 10^{-5}



Helioseismology: Comparison with Solar Models

- Oscillation frequencies depend on ρ, P, g, c
- Inversion problem:
  From measured frequencies and from a reference solar model determine solar structure
- Output of inversion procedure: $\delta c^2(r)$, $\delta\rho(r)$, R_{CZ}, Y_{SURF}



Relative sound-speed difference between helioseismological model and standard solar model

New Solar Opacities (Asplund, et al. 2005, 2009)

- Large change in solar composition:
  Mostly reduction in C, N, O, Ne
- Results presented in many papers by the “Asplund group”
- Summarized in Asplund, Grevesse, Sauval & Scott (2009)

Authors	$(Z/X)_\odot$	Main changes (dex)
Grevesse 1984	0.0277	
Anders & Grevesse 1989	0.0267	$\Delta C = -0.1$, $\Delta N = +0.06$
Grevesse & Noels 1993	0.0245	
Grevesse & Sauval 1998	0.0229	$\Delta C = -0.04$, $\Delta N = -0.07$, $\Delta O = -0.1$
Asplund, Grevesse & Sauval 2005	0.0165	$\Delta C = -0.13$, $\Delta N = -0.14$, $\Delta O = -0.17$ $\Delta Ne = -0.24$, $\Delta Si = -0.05$
Asplund, Grevesse, Sauval & Scott (arXiv:0909.0948, 2009)	0.0178	

Adapted from A. Serenelli’s lectures at Scottish Universities Summer School in Physics 2006

Origin of Changes

Spectral lines from solar photosphere and corona	• **Improved modeling** 3D model atmospheres MHD equations solved NLTE effects accounted for in most cases • **Improved data** Better selection of spectral lines Previous sets had blended lines (e.g. oxygen line blended with nickel line)
Meteorites	• **Volatile elements** do not aggregate easily into solid bodies e.g. C, N, O, Ne, Ar only in solar spectrum • **Refractory elements** e.g. Mg, Si, S, Fe, Ni both in solar spectrum and meteorites meteoritic measurements more robust

Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

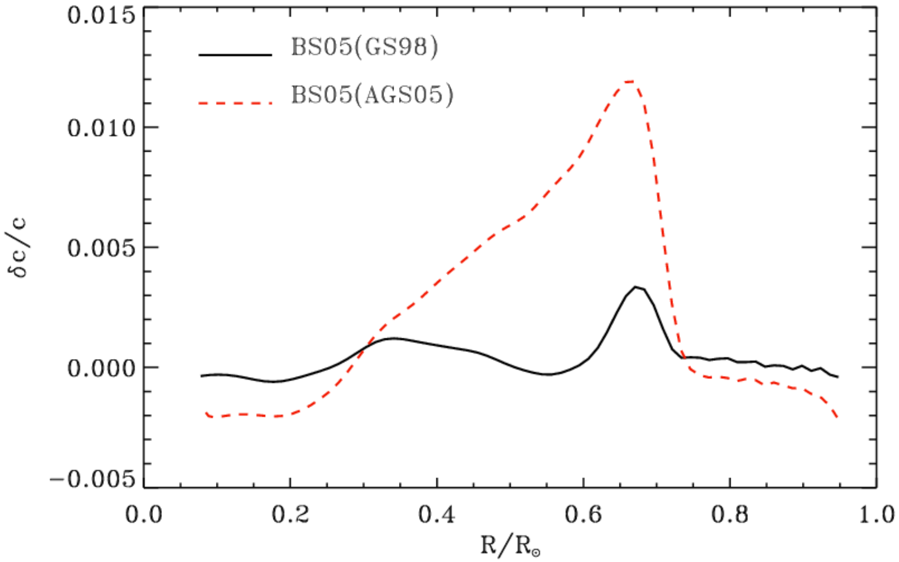
Consequences of New Element Abundances

What is good	• Much improved modeling • Different lines of same element give same abundance (e.g. CO and CH lines) • Sun has now similar composition to solar neighborhood
New problems	• Agreement between helioseismology and SSM very much degraded • Was previous agreement a coincidence?

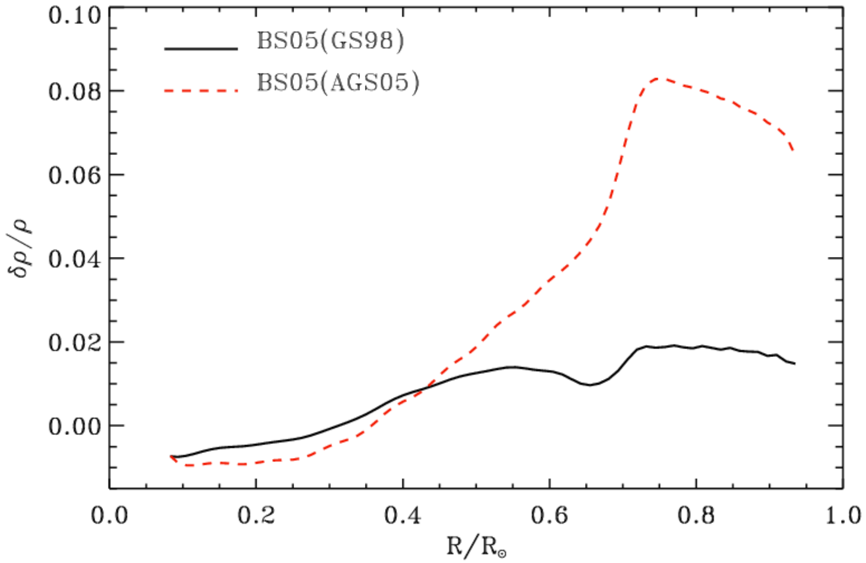
Adapted from A. Serenelli’s lectures at Scottish Universities Summer School in Physics 2006

Standard Solar Model 2005: Old and New Opacity

Sound Speed



Density



	Old: BS05 (GS98)	New: BS05 (ASG05)	Helioseismology
R_{CZ}	0.713	0.728	0.713 ± 0.001
Y_{SURF}	0.243	0.229	0.2485 ± 0.0035
<δc>	0.001	0.005	—
<δr>	0.012	0.044	—

Adapted from A. Serenelli’s lectures at Scottish Universities Summer School in Physics 2006

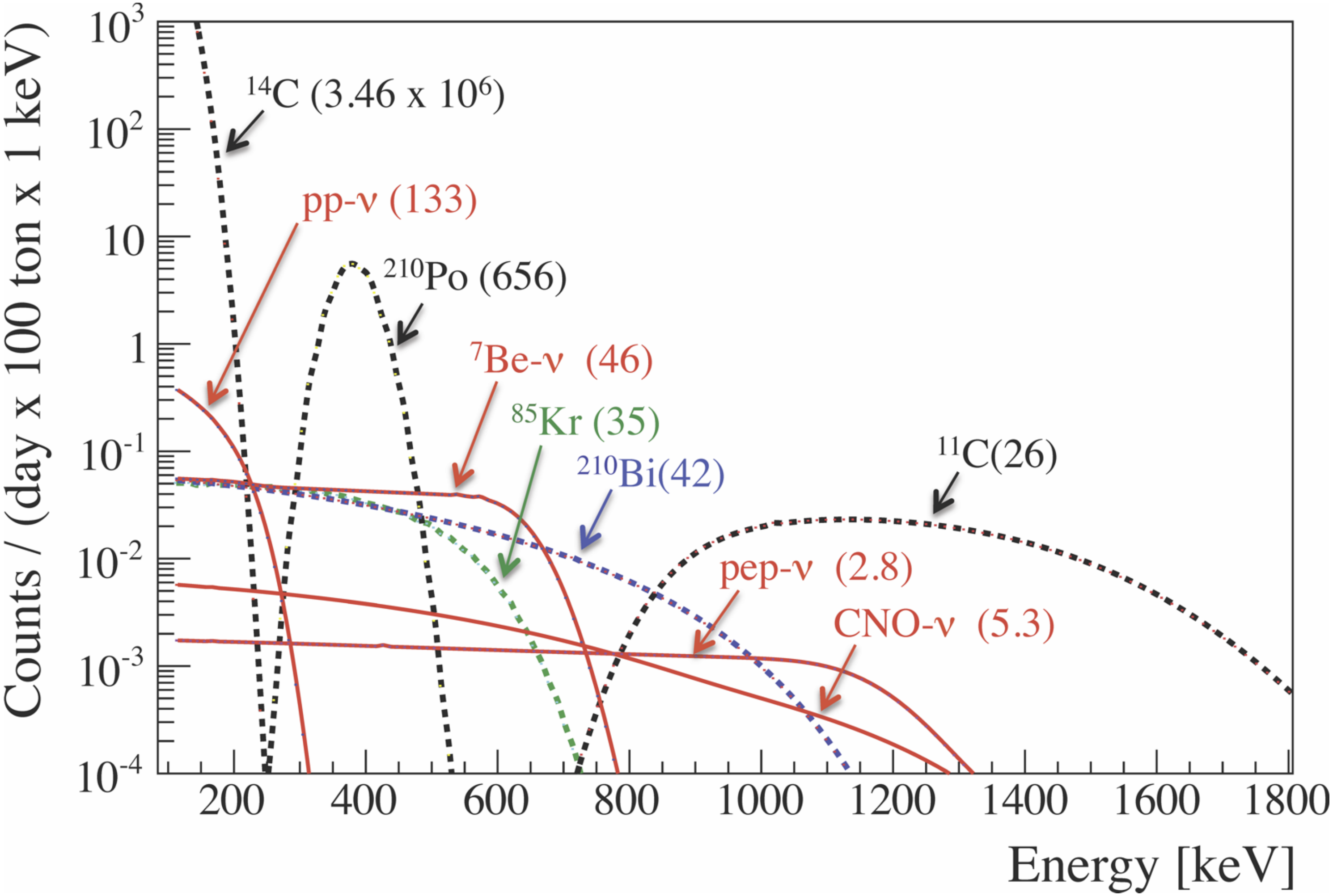
Old and New Neutrino Fluxes

	Old: (GS98)		New: (AGSS09)		Best Measurements	
	Flux $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	Error %	Flux $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	Error %	Flux $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	Error %
pp	5.98×10^{10}	± 0.6	6.03×10^{10}	± 0.6	6.05×10^{10}	± 0.6
pep	1.44×10^{8}	± 1.1	1.47×10^{8}	± 1.2	1.46×10^{8}	± 1.2
hep	8.04×10^{3}	± 30	8.31×10^{3}	± 30	18×10^{3}	± 45
^{7}Be	5.00×10^{9}	± 7	4.56×10^{9}	± 7	4.82×10^{9}	± 4.5
^{8}B	5.58×10^{6}	± 14	4.59×10^{6}	± 14	5.0×10^{6}	± 3
^{13}N	2.96×10^{8}	± 14	2.17×10^{8}	± 14	$< 6.7 \times 10^{8}$	
^{15}O	2.23×10^{8}	± 15	1.56×10^{8}	± 15	$< 3.2 \times 10^{8}$	
^{17}F	5.52×10^{6}	± 17	3.40×10^{6}	± 16	$< 59 \times 10^{6}$	

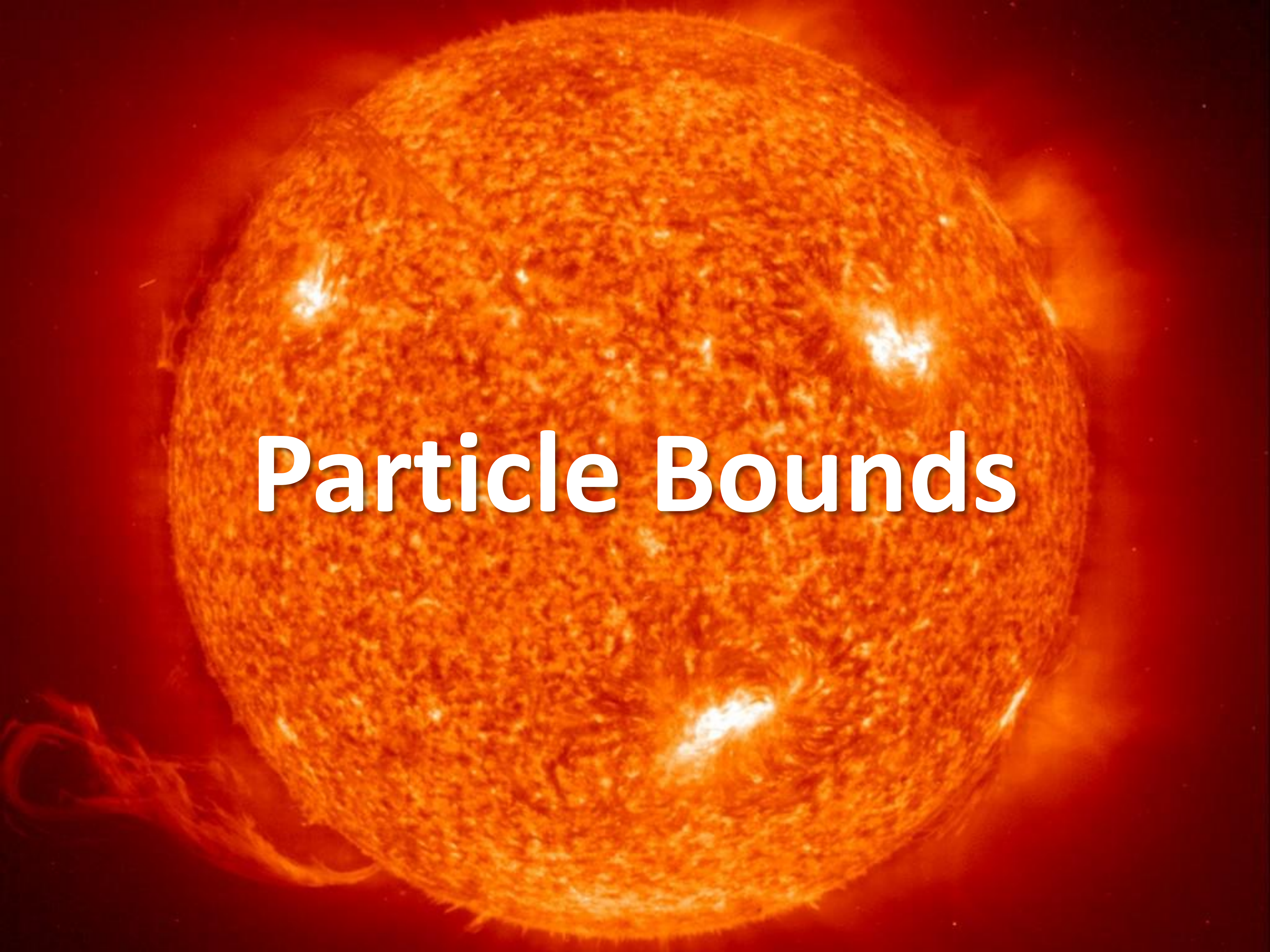
- Directly measured 7-Be (Borexino) and 8-B (SNO) fluxes are halfway between models
- CN fluxes depend linearly on abundances, measurements needed

Prospect for CNO Flux Measurements

CNO neutrino measurements require excellent background reduction/subtraction
Not achievable in Borexino in near future. Perhaps in SNO+ ?



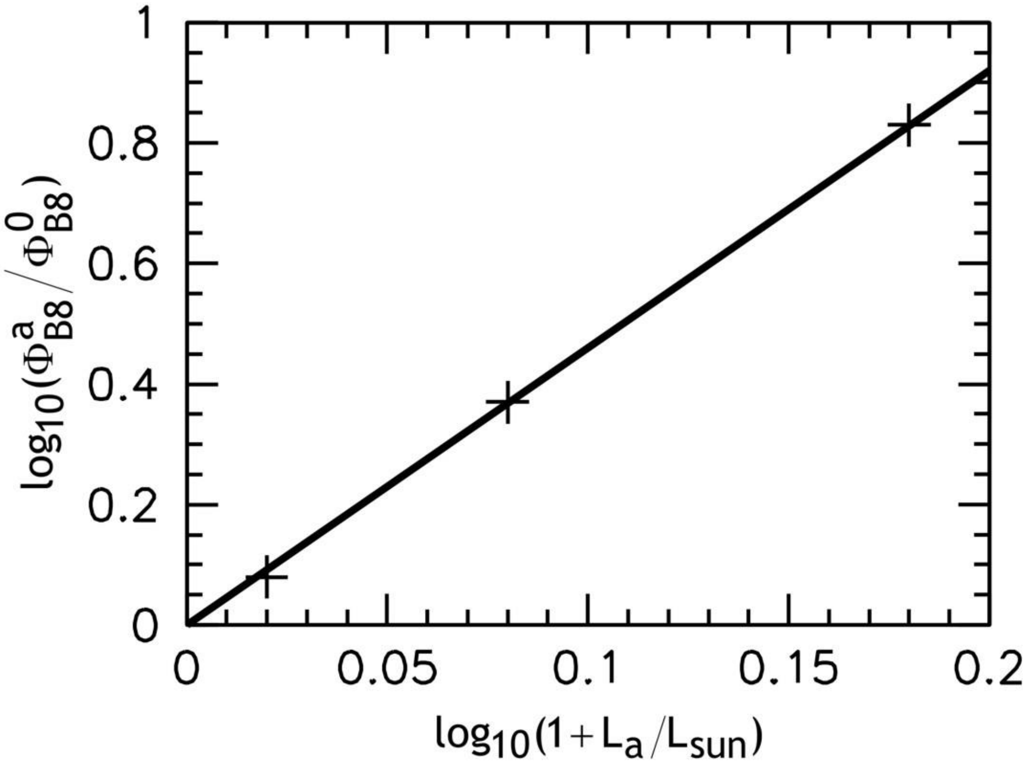
Borexino Collaboration, arXiv:1308.0443



Particle Bounds

Solar Neutrino Limit on Solar Energy Losses

Self-consistent models of the present-day Sun provide a simple power-law connection between a new energy loss L_a (e.g. axions) and the all-flavor solar neutrino flux from the B8 reaction as measured by SNO



$$\Phi^a_{\mathrm{B8}} = \Phi^0_{\mathrm{B8}} \left(\frac{L_\odot + L_a}{L_\odot}\right)^{4.6}$$

Solar model prediction and SNO measurements imply roughly

$$L_a \lesssim 0.10\ L_\odot$$

Gondolo & Raffelt, arXiv:0807.2926

Schlattl, Weiss & Raffelt, hep-ph/9807476

Hidden Photons (HPs)

New U(1) gauge boson (HP) with small mass m and kinetic mixing parameter χ

$$\mathcal{L} = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{m^2}{2}B_\mu B^\mu - \frac{\chi}{2}A_{\mu\nu}B^{\mu\nu}$$

Normal photons oscillate into HPs, lose coherence by collisions, HPs escape from Sun

Dispersion relation of longitudinal plasmons to lowest order independet of k

$$\omega_\mathrm{L} = \omega_\mathrm{Pl} = \left(\frac{4\pi\alpha n_e}{m_e}\right)^{1/2}$$ (Plasma frequency)

At any position in the Sun, L-plasmons with

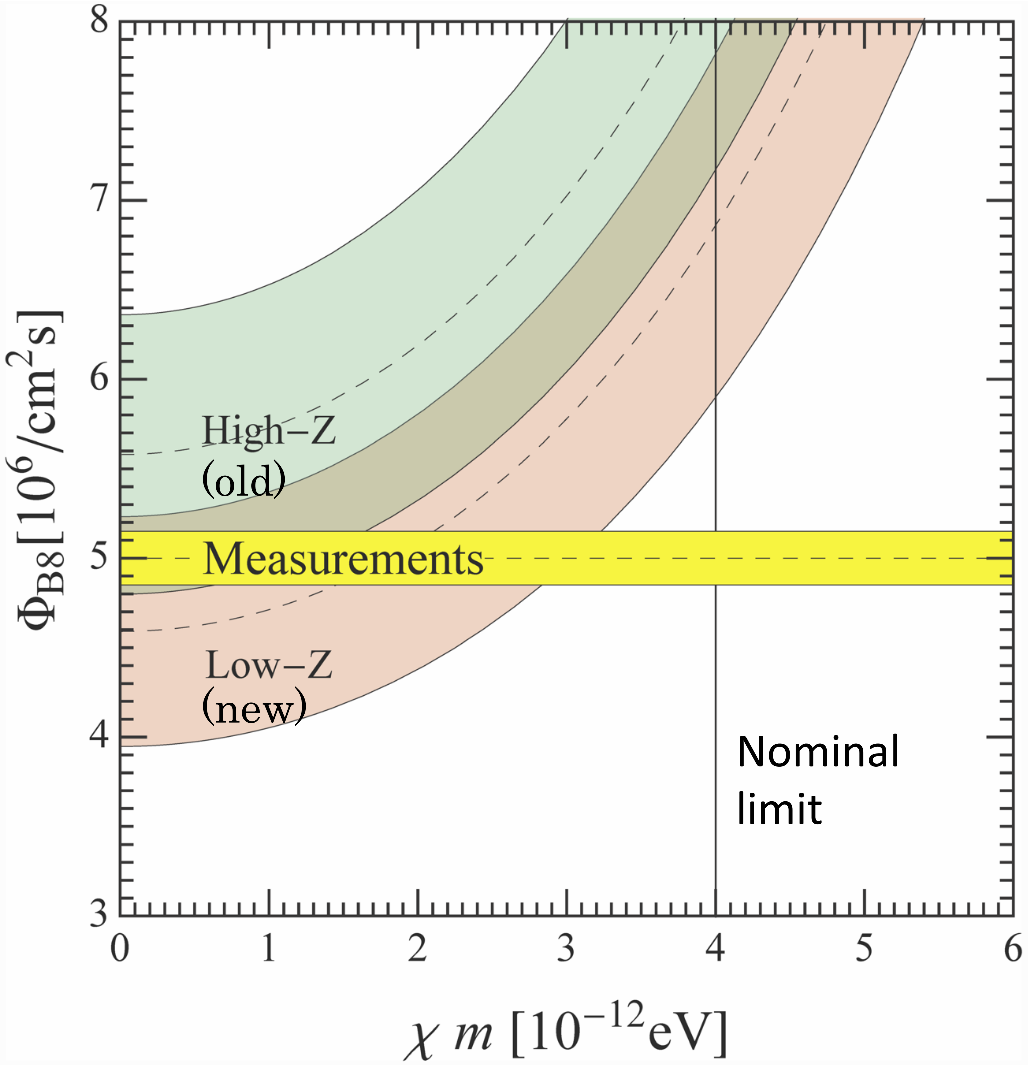
$$k_L = \sqrt{\omega_L^2 - m^2}$$

match HP dispersion relation: Resonant conversion!

$$\Gamma_\mathrm{HP}^\mathrm{prod}(\omega) = \frac{\chi^2 m^2}{e^{\omega/T}-1}\,\frac{\omega^2\Gamma_\mathrm{L}}{\left(\omega^2-\omega_\mathrm{Pl}^2\right)^2+(\omega\Gamma_\mathrm{L})^2} \sim \frac{\chi^2 m^2}{e^{\omega/T}-1}\,\frac{\pi}{2}\delta(\omega-\omega_\mathrm{Pl})$$

(Redondo, arXiv:0801.1527. An, Pospelov & Pradler, arXiv:1302.3884.
Redondo & Raffelt, arXiv:1305.2920)

Solar Hidden Photon Constraints



Energy loss in hidden photons (HPs) in solar plasma

$$Q_{\mathrm{HP}} = \chi^2 m^2 \frac{\alpha\, T\, n_e}{m_e}$$

Solar energy loss

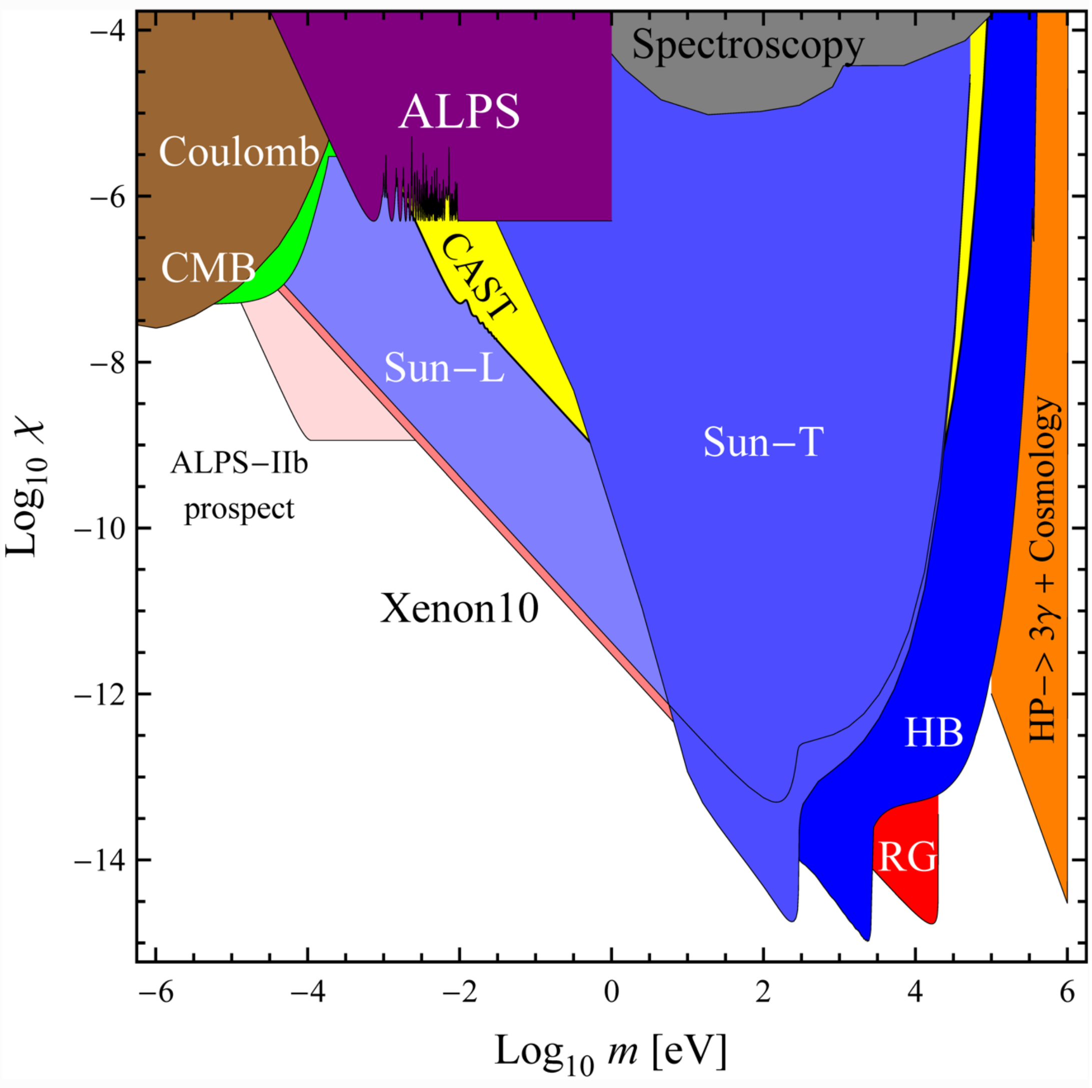
$$L_{\mathrm{HP}} = \chi^2 \left(\frac{m}{\mathrm{eV}}\right)^2 5.7 \times 10^{21} L_\odot$$

Nominal limit

$$\chi\, m < 4 \times 10^{-12}\ \mathrm{eV}$$

Redondo & Raffelt, arXiv:1305.2920

Summary of Hidden Photon Limits



Redondo & Raffelt, arXiv:1305.2920

Search for Solar Axions

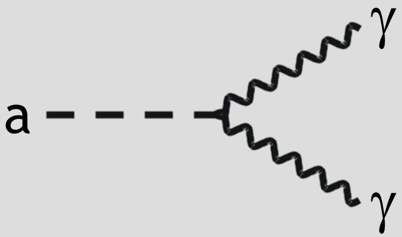
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by
Peccei-Quinn mechanism

$\rightarrow$ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are “invisible”
and very light

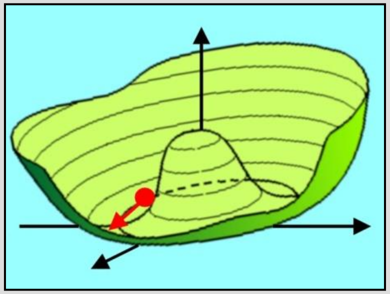
Solar and Stellar Axions

Axions thermally produced in stars,
e.g. by Primakoff production

- Limits from avoiding excessive energy drain
- Solar axion searches (CAST, Sumico)

Cosmology

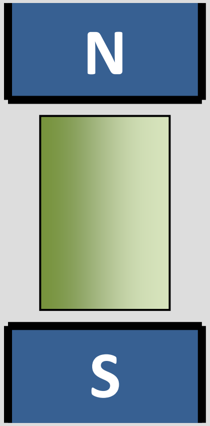
In spite of small mass, axions are born
non-relativistically
(non-thermal relics)



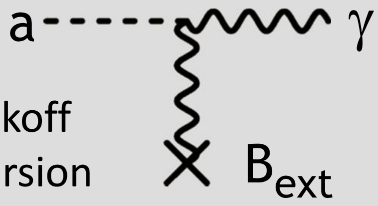
Cold dark matter
candidate

$m_a \sim 10\ \mu\mathrm{eV}$ or even smaller

Search for Axion Dark Matter

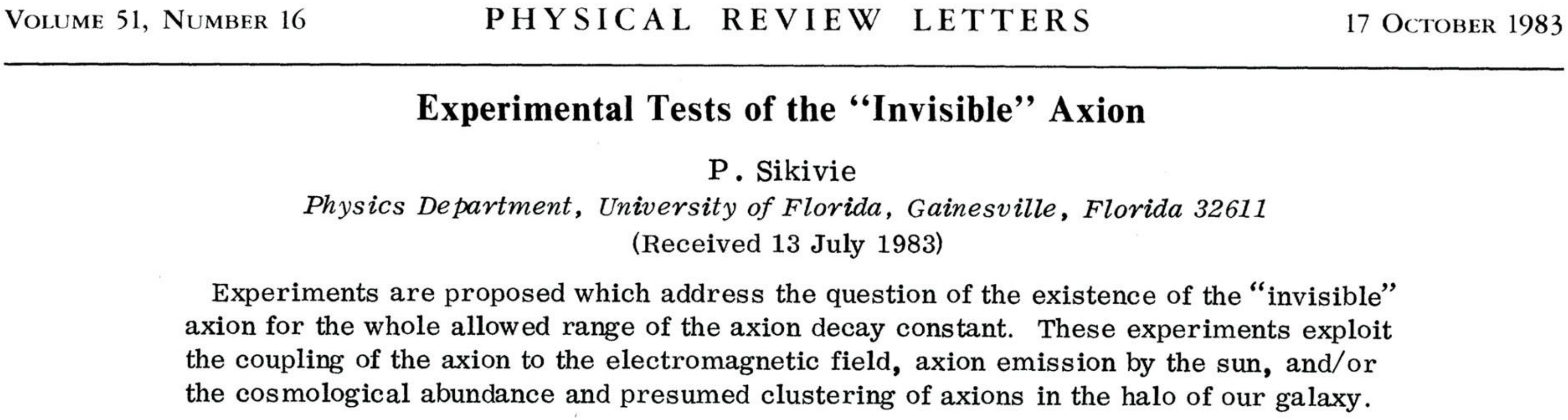


Microwave resonator
(1 GHz = 4 μeV)



Primakoff
conversion

ADMX-LF (UW Seattle)
ADMX-HF (Yale)



VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

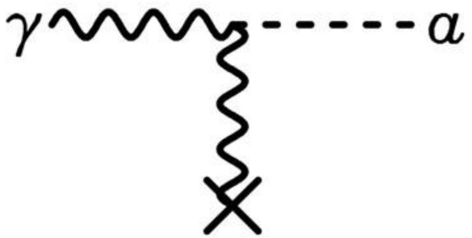
P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611

(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:

Axion-photon transition in external static E or B field
(Originally discussed for π^0
by Henri Primakoff 1951)



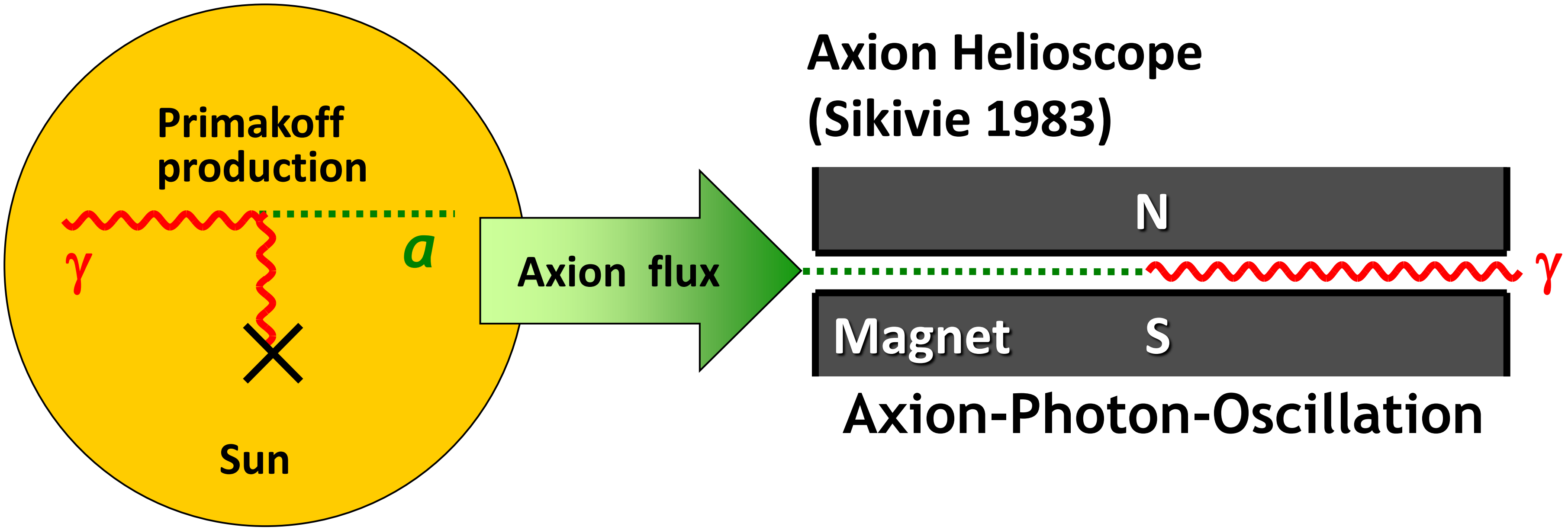
Pierre Sikivie:

Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

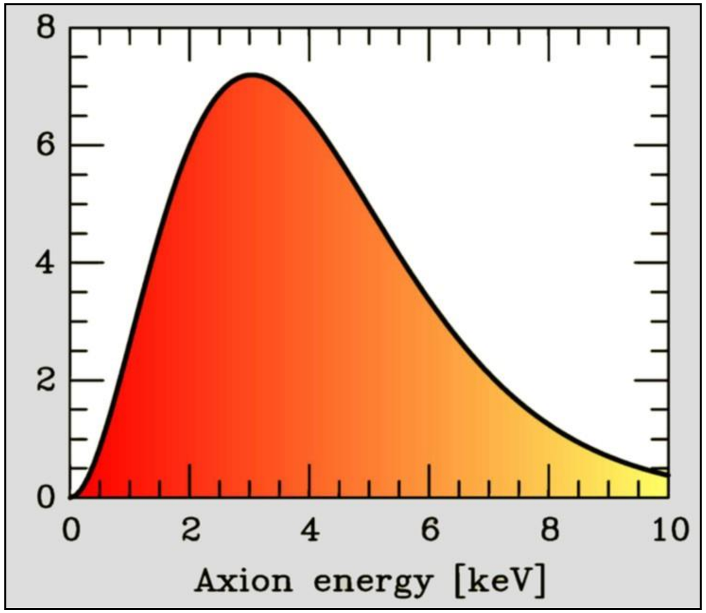
- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with
  A microwave resonant cavity

Search for Solar Axions

Axion Helioscope (Sikivie 1983)



Axion-Photon-Oscillation



- Tokyo Axion Helioscope (“Sumico”)
  (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST)
  (Data since 2003)

Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, CDMS ...)

Axion-Photon-Transitions as Particle Oscillations

Raffelt & Stodolsky, PRD 37 (1988) 1237

Stationary Klein-Gordon equation for coupled a-γ-system

Photon refractive and birefringence effects (Faraday rotation, Cotton-Mouton-effect)

$$\left[\omega^2+\nabla^2+2\omega^2\begin{pmatrix} n_\perp-1 & n_F & 0\\ n_F & n_\parallel & \frac{g_{a\gamma}B}{2\omega}\\ 0 & \frac{g_{a\gamma}B}{2\omega} & -\frac{m_a^2}{2\omega^2}\end{pmatrix}\right]\begin{pmatrix}A_\perp\\ A_\parallel\\ a\end{pmatrix}=0$$

Axion-photon transitions

- Axions roughly like another photon polarization state
- In a homogeneous or slowly varying B-field, a photon beam develops a coherent axion component

CERN Axion Solar Telescope (CAST)

Extending to higher mass values with gas filling

Axion-photon transition probability

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

Axion-photon momentum transfer

$$q = \left|\frac{m_a^2 - m_\gamma^2}{2E}\right|$$

Transition is suppressed for $qL \gtrsim 1$

Gas filling: Give photons a refractive mass to restore full transition strength

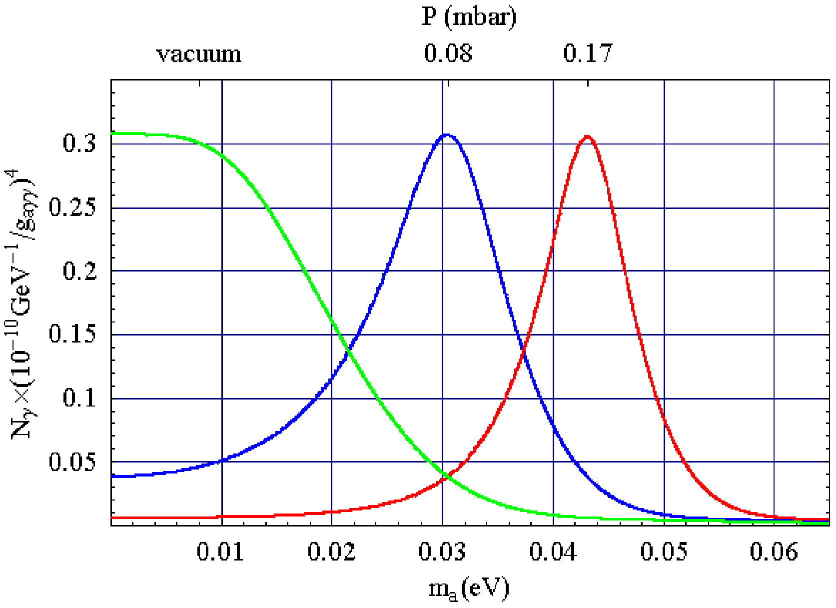
$$m_\gamma^2 = \frac{4\pi\alpha}{m_e}\, n_e$$

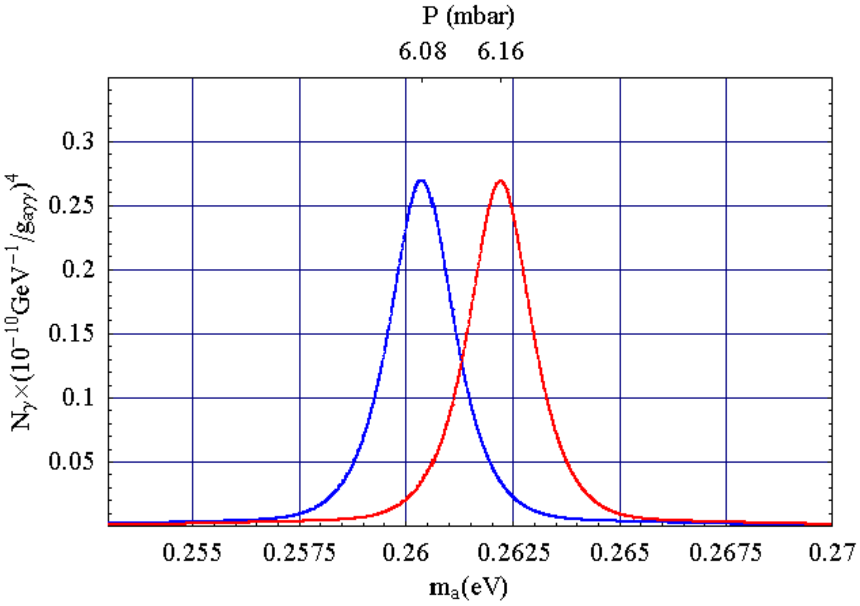
$$m_\gamma = 28.9\ \mathrm{eV}\left(\frac{Z}{A}\,\rho_{\mathrm{gas}}\right)^{1/2}$$

He-4 vapour pressure at 1.8 K is

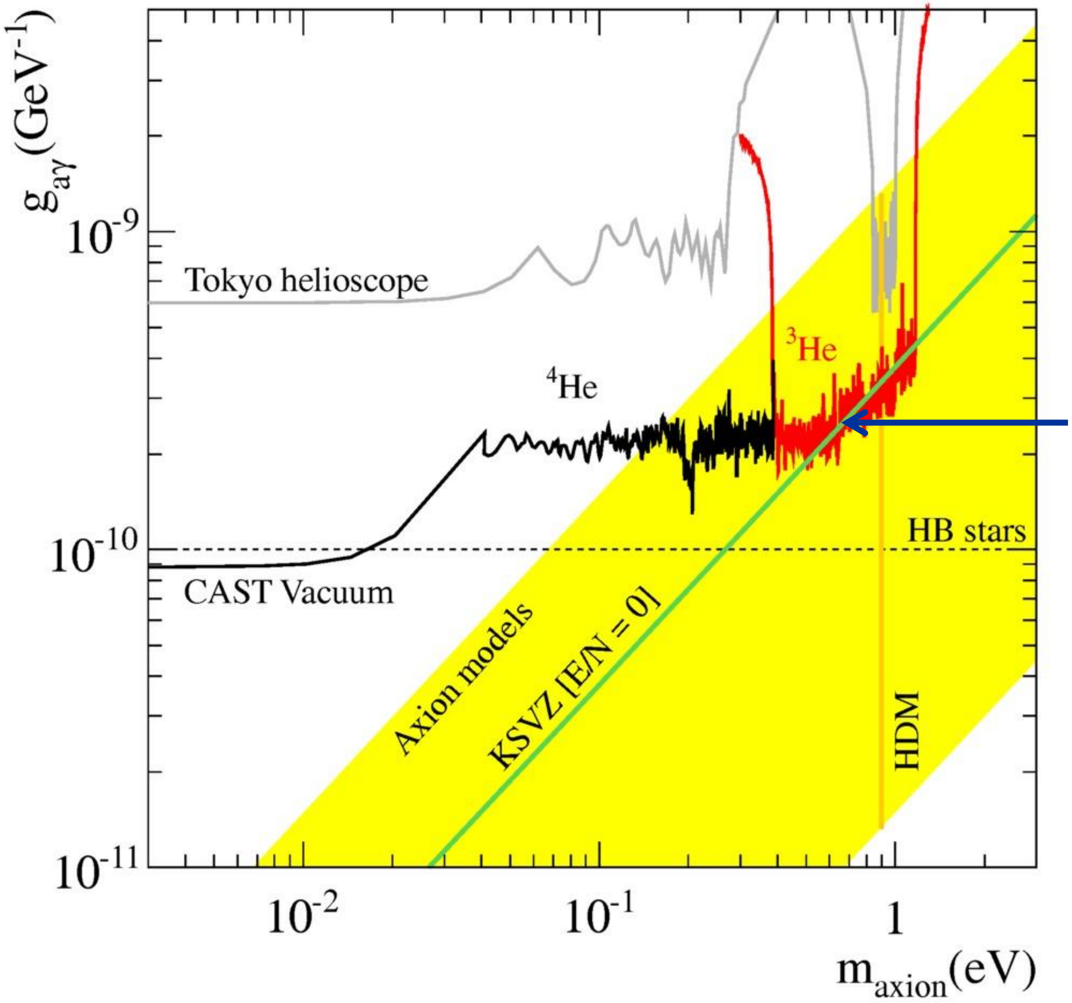
$$\rho \approx 0.2 \times 10^{-3}\ \mathrm{g\,cm^{-3}}$$

$$m_\gamma = 0.26\ \mathrm{eV}$$





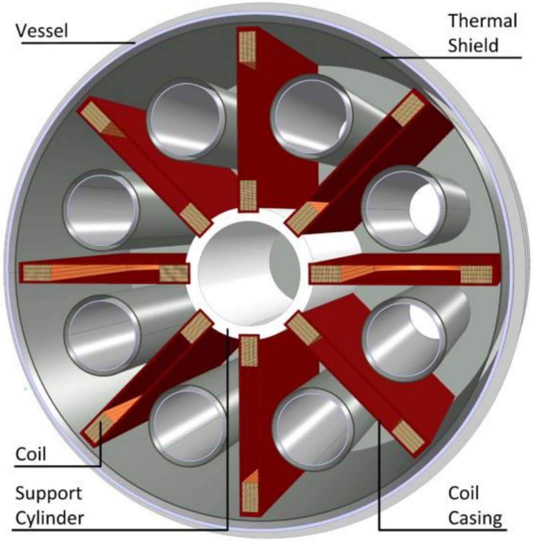
Helioscope Limits

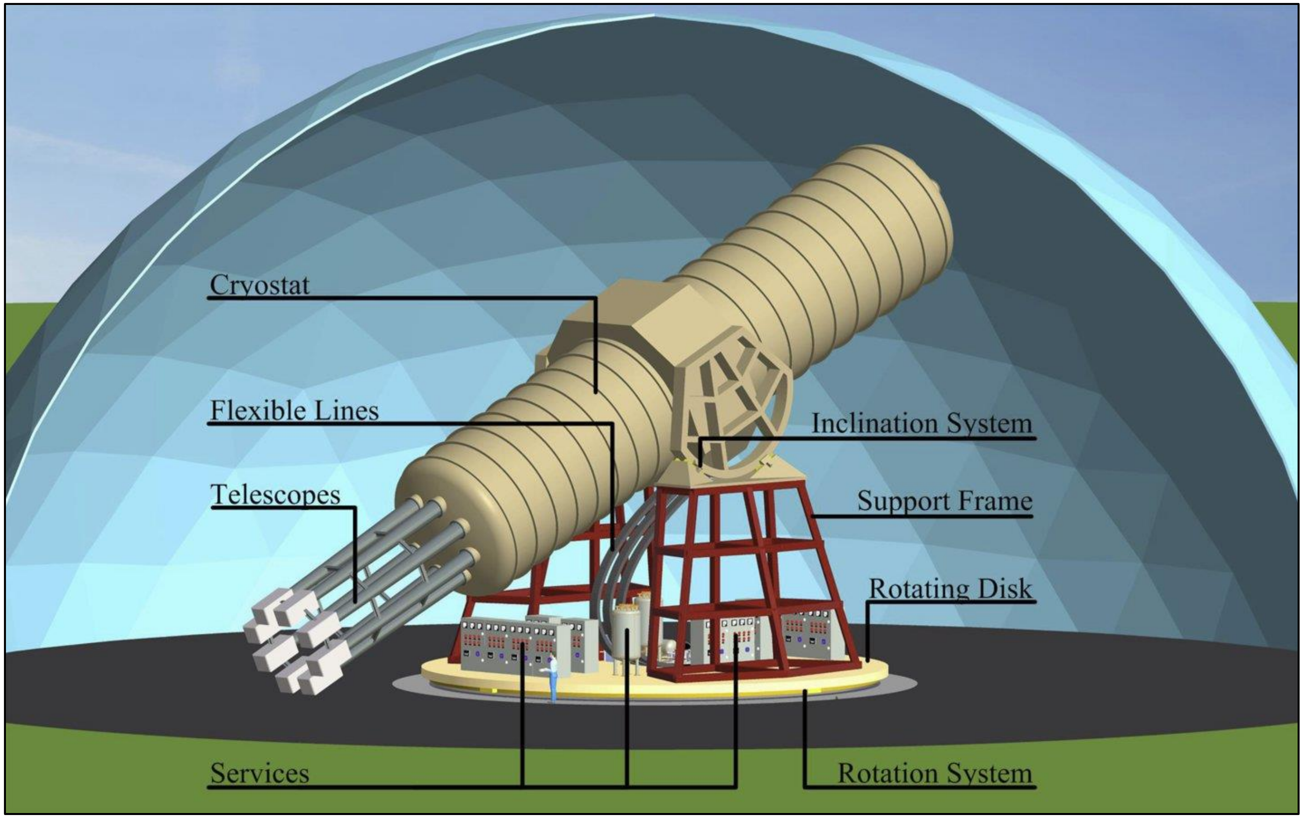


First experimental crossing of the KSVZ line

CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): JCAP 0902 (2009) 008
CAST-II results (He-3 filling): PRL 107: 261302 (2011) and in preparation (2013)

Next Generation Axion Helioscope (IAXO) at CERN





Need new magnet w/
- Much bigger aperture: $\sim 1\ \mathrm{m}^2$ per bore
- Lighter (no iron yoke)
- Bores at T_{room}

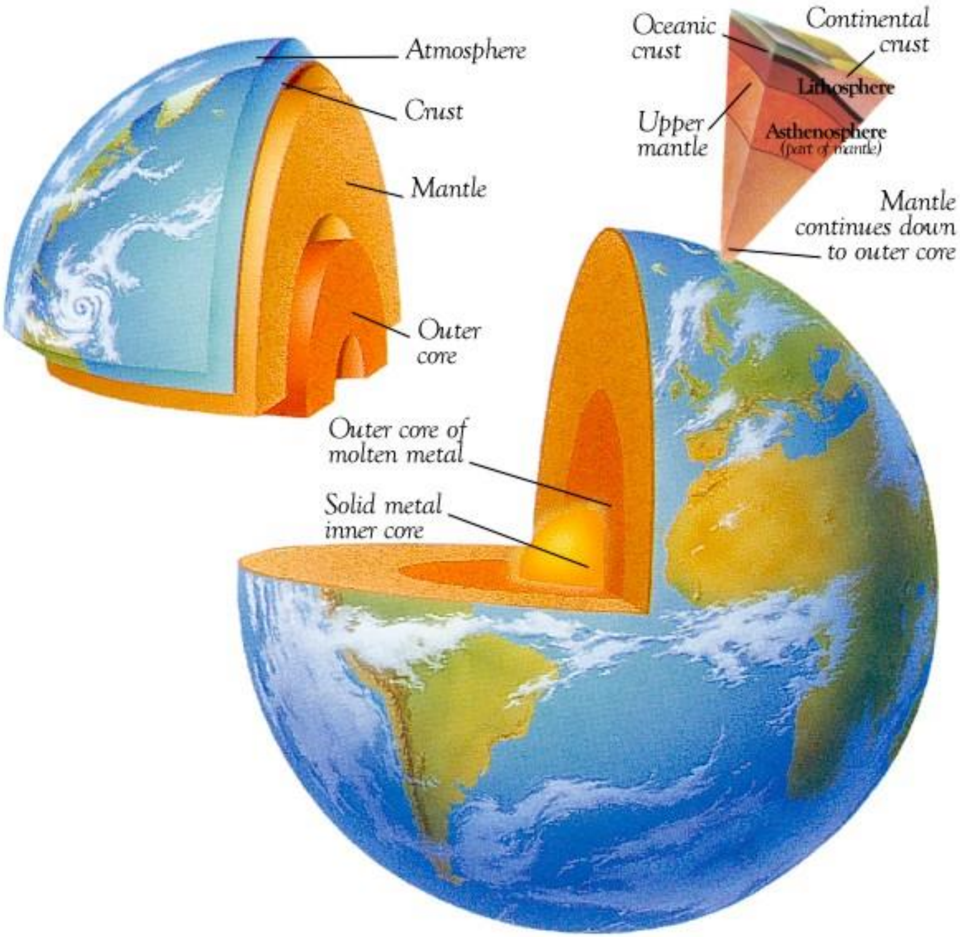
- Irastorza et al.: Towards a new generation axion helioscope, arXiv:1103.5334
- Armengaud et al.: Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233

Geo Neutrinos

Geo Neutrinos: What is it all about?

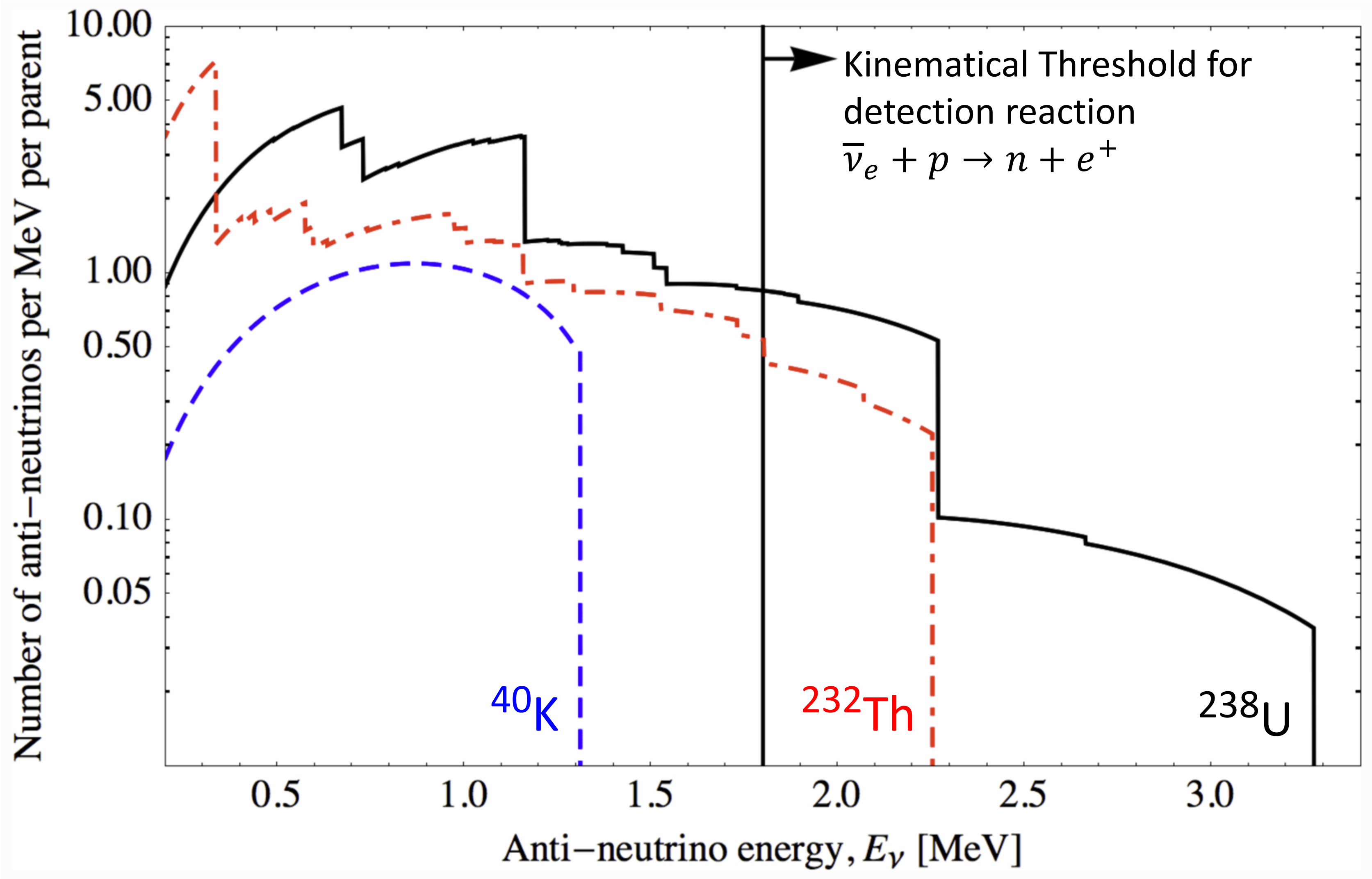
We know surprisingly little about the Earth's interior

- Deepest drill hole ~ 12 km
- Samples of crust for chemical analysis available (e.g. vulcanoes)
- Reconstructed density profile from seismic measurements
- Heat flux from measured temperature gradient 30–44 TW (Expectation from canonical BSE model ~ 19 TW from crust and mantle, nothing from core)



- Neutrinos escape unscathed
- Carry information about chemical composition, radioactive energy production or even a hypothetical reactor in the Earth's core

Geo Neutrino Spectrum

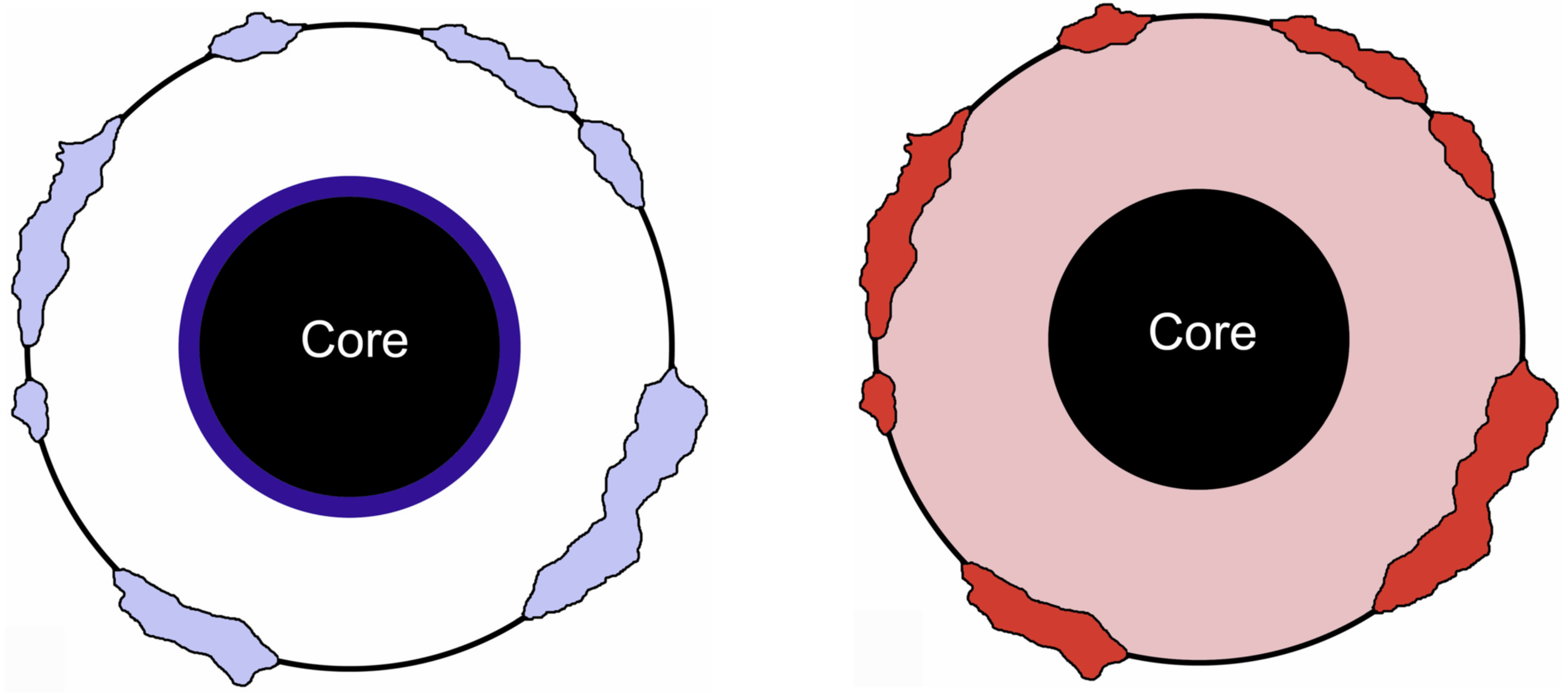


Kinematical Threshold for detection reaction
$\overline{\nu}_e + p \rightarrow n + e^+$

Bellini, Ianni, Ludhova, Mantovani & McDonough, arXiv:1310.3732

Extreme Geo Neutrino Fluxes

Schematic radioactive element distribution for fixed heat flux



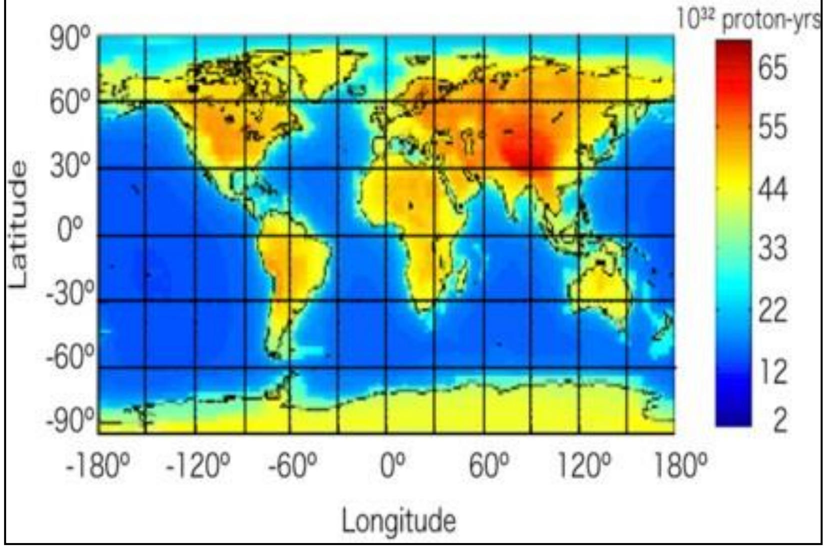
Minimal neutrino flux
at detector

Maximal neutrino flux
at detector

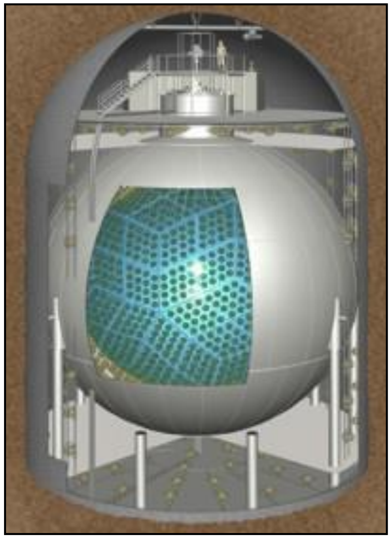
Bellini, Ianni, Ludhova, Mantovani & McDonough, arXiv:1310.3732

Geo Neutrinos

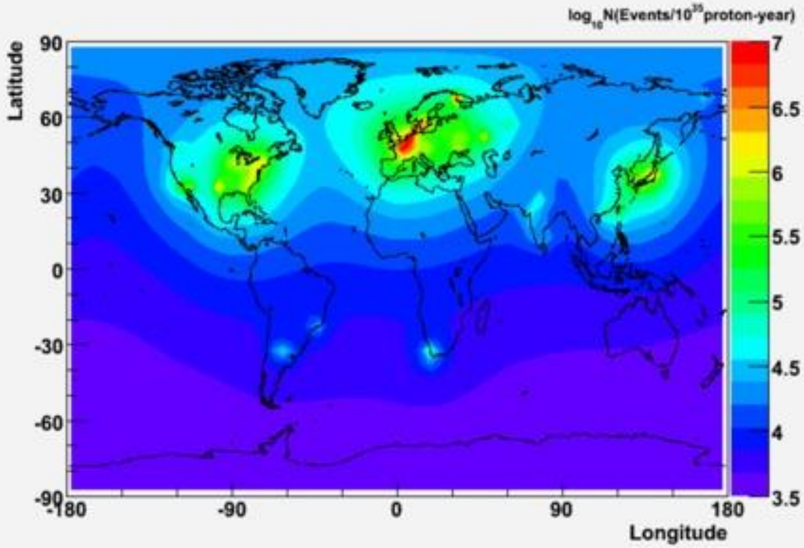
Expected Geoneutrino Flux

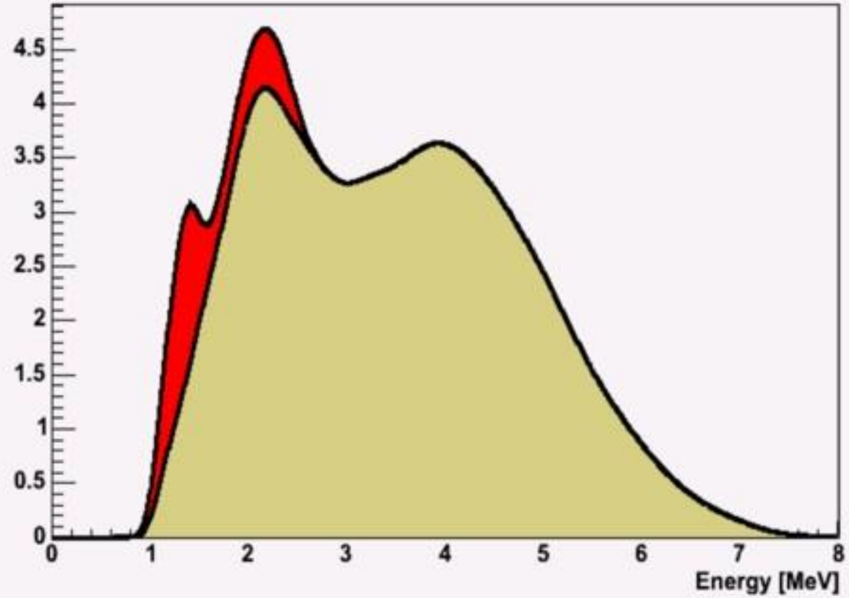


KamLAND Scintillator-Detector (1000 t)

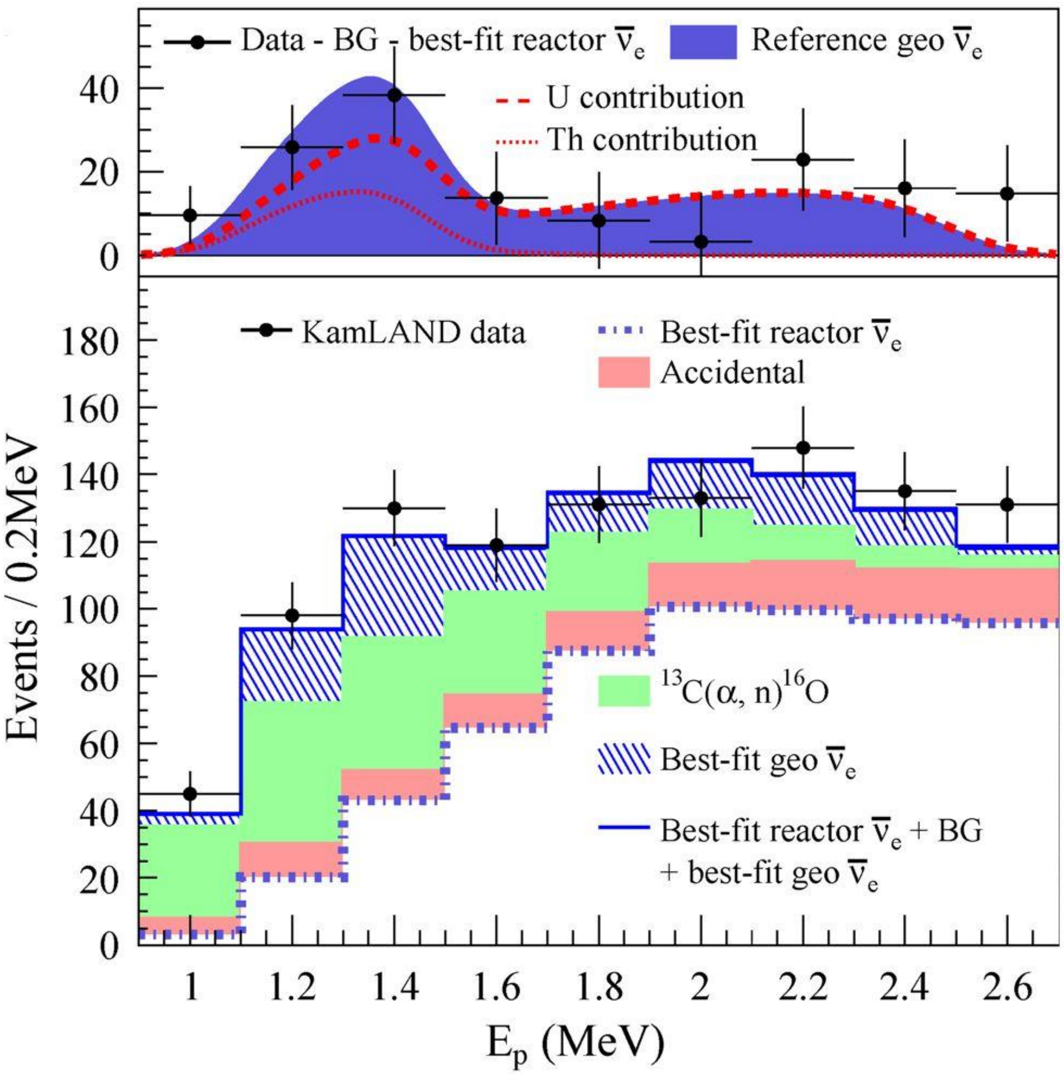


Reactor Background





KamLAND Geo-Neutrino Flux



116^{+28}_{-27} Geoneutrino events
(U/Th = 3.9 fixed)

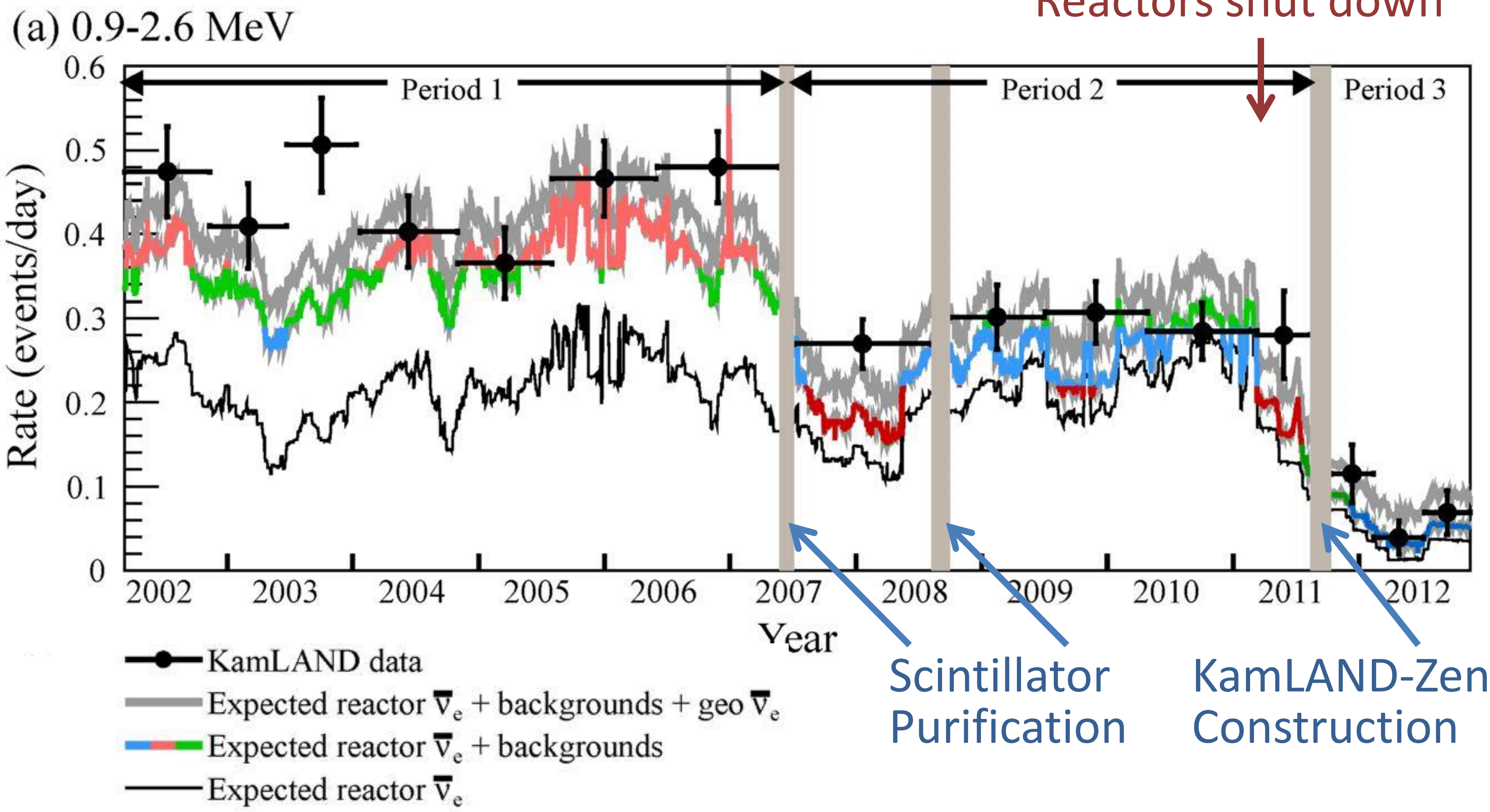
Separately free fitting:
U 116 events
Th 8 events

Beginning of
neutrino geophysics!

KamLAND Collaboration, arXiv:1303.4667 (2013)

Reactor On-Off KamLAND Data

2011 Earthquake
Reactors shut down

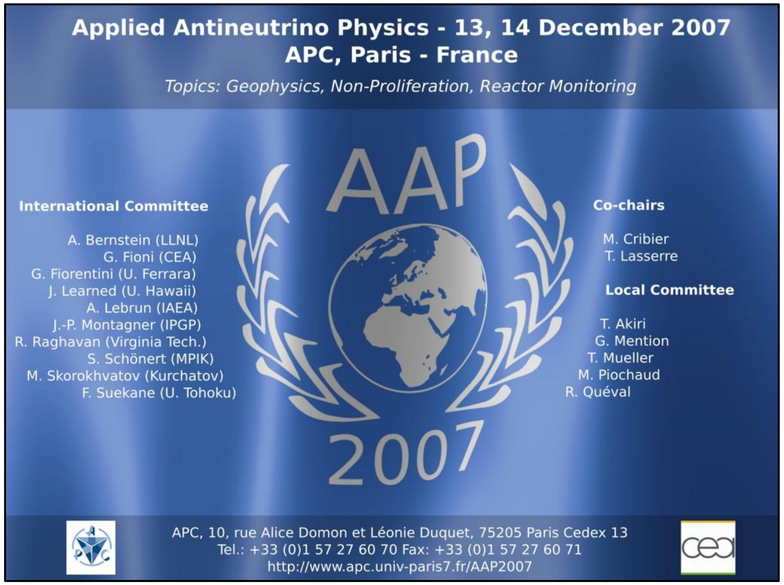


Scintillator
Purification

KamLAND-Zen
Construction

KamLAND Collaboration, arXiv:1303.4667 (2013)

Applied Anti-Neutrino Physics (AAP)



Applied Antineutrino Physics - 13, 14 December 2007
APC, Paris - France

Topics: Geophysics, Non-Proliferation, Reactor Monitoring

AAP 2007

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Applied Anti-Neutrino Physics (AAP)
Annual Conference Series since 2004

- Neutrino geophysics
- Reactor monitoring ("Neutrinos for Peace")

IAEA
International Atomic Energy Agency
Atoms For Peace

- Relatively small detectors can measure nuclear activity without intrusion
- Of interest for monitoring by International Atomic Energy Agency (Monitors fissile material in civil nuclear cycles)