ISAPP 2017, Arenzano, Italy, 13–24 June 2017

Astrophysical Neutrinos

Georg G. Raffelt

Max-Planck-Institut für Physik, München, Germany

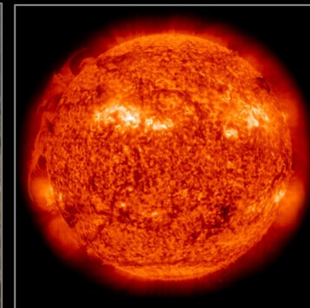
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

elusives
neutrinos, dark matter & dark energy physics

SFB 1258 Neutrinos Dark Matter Messengers

Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors

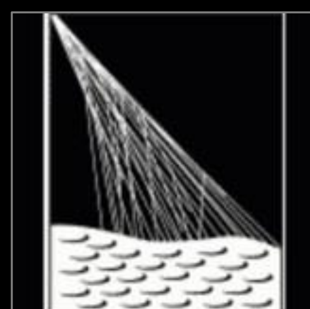


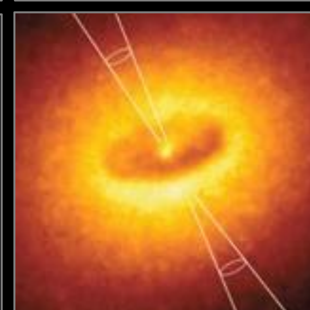
Sun ✓

✓ Particle Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓

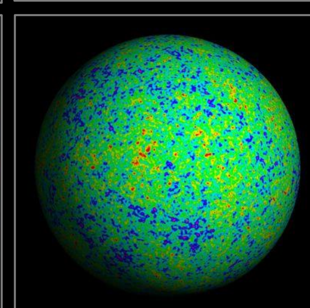
✓ Earth Atmosphere
(From Cosmic Rays)





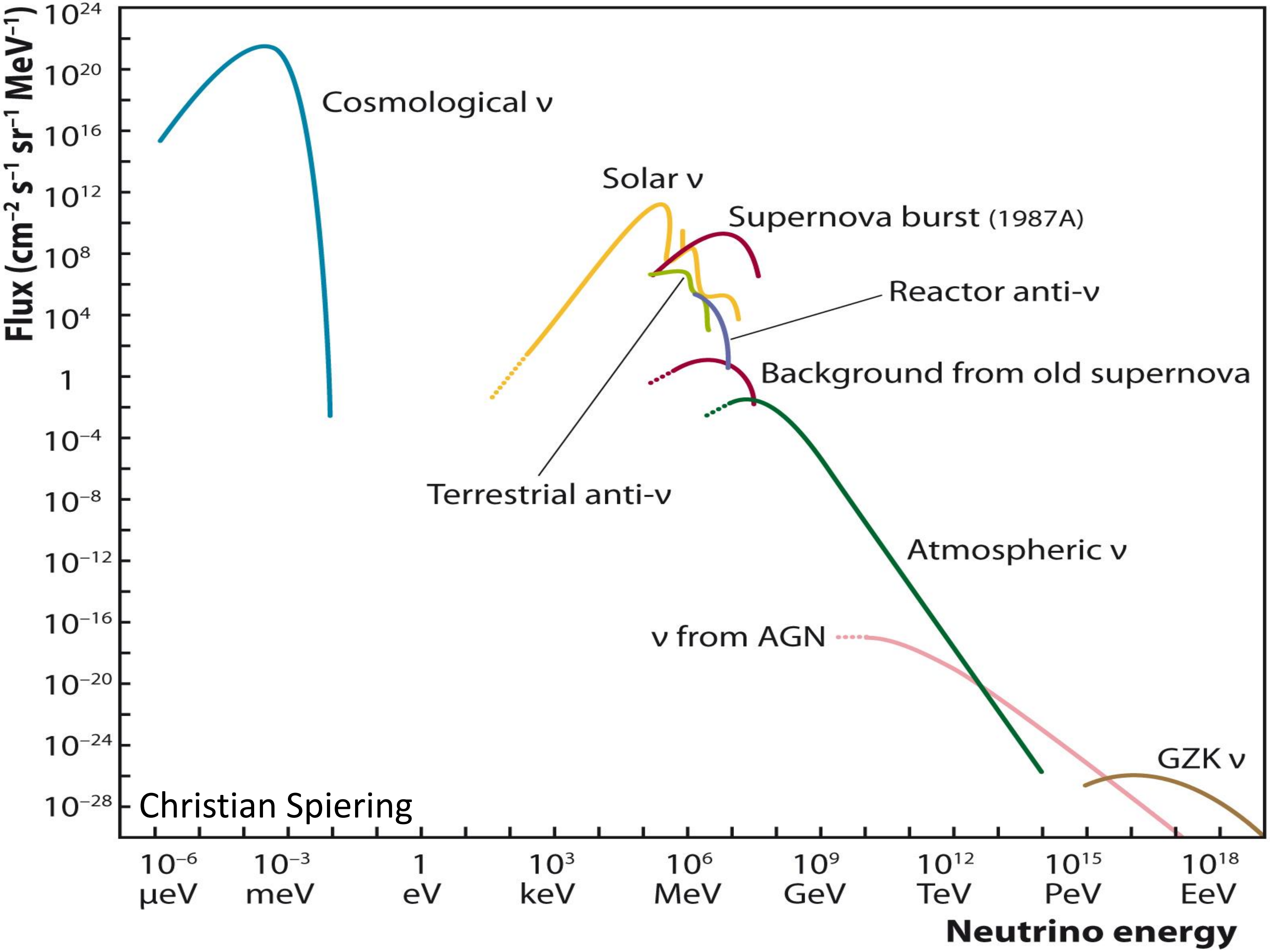
Astrophysical
Accelerators ✓

✓ Earth Crust
(Natural Radioactivity)

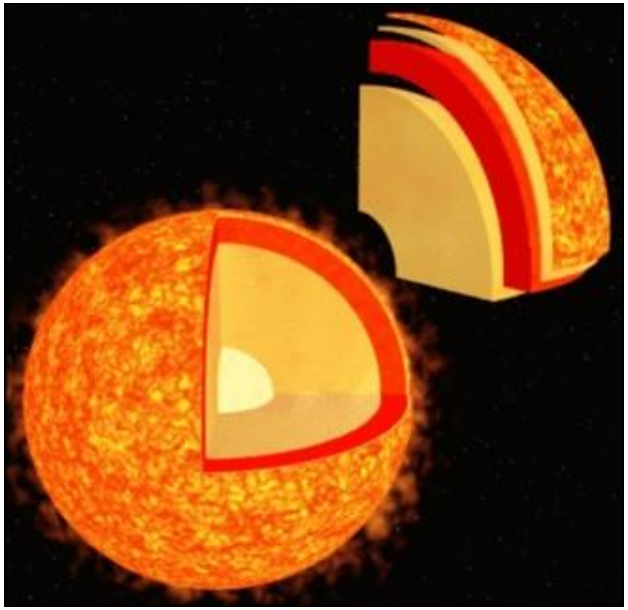


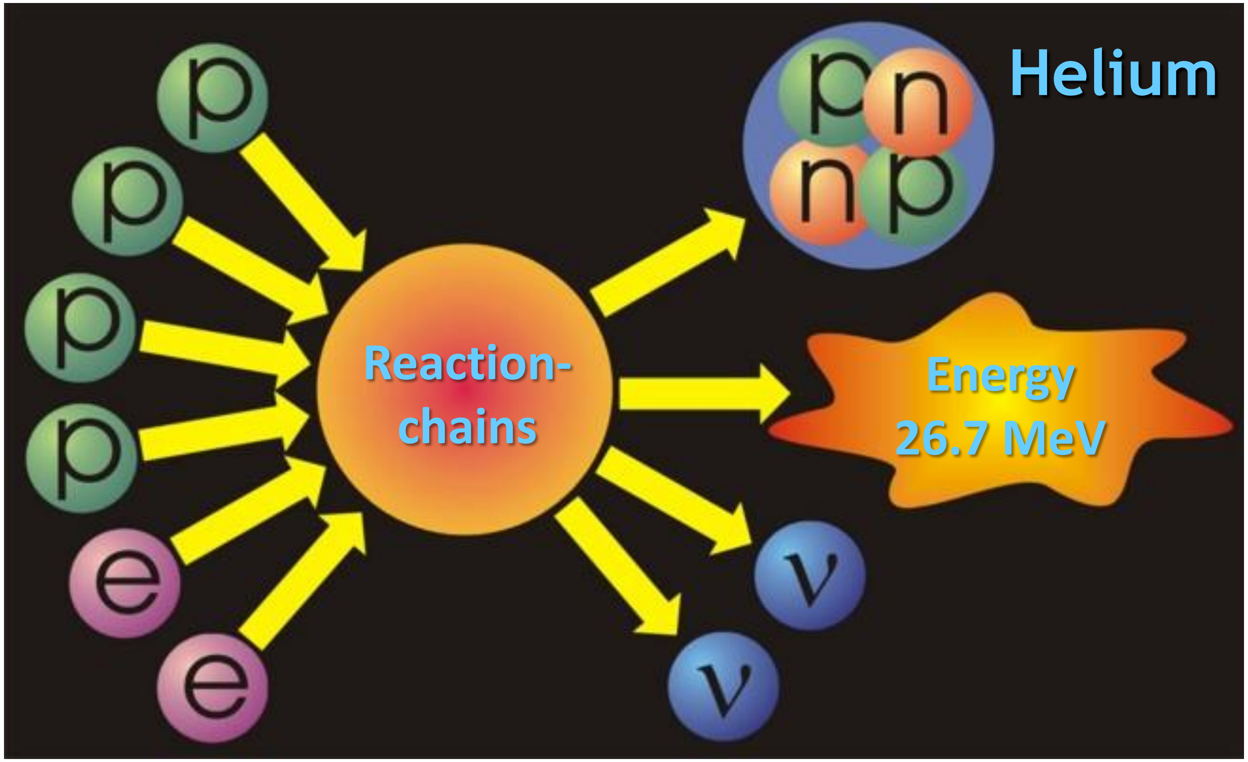
Cosmic Big Bang
(Today 336 ν/cm^3)
Indirect Evidence

Grand Unified Neutrino Spectrum



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)

Bethe's Classic Paper on Nuclear Reactions in Stars

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. && \end{aligned} \quad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

No neutrinos from nuclear reactions in 1938 …

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

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Predicting Neutrinos from Stars

The Possible Role of Neutrinos in Stellar Evolution

It can be considered at present as definitely established that the energy production in stars is caused by various types of thermonuclear reactions taking place in their interior. Since these reaction chains usually contain the processes of β-disintegration accompanied by the emission of high speed neutrinos, and since the neutrinos can pass almost without difficulty through the body of the star, we must assume that a certain part of the total energy produced escapes into interstellar space without being noticed as the actual thermal radiation of the star. Thus, for example, in the case of the carbon-nitrogen cycle in the sun, about 7 percent of the energy produced is lost in the form of neutrino radiation. However, since, in such reaction chains, the energy taken away by neutrinos represents a definite fraction of the total energy liberation, these losses are of but secondary importance for the problem of stellar equilibrium and evolution.

More detailed calculations on this collapse process are now in progress.

G. Gamow

The George Washington University,
Washington, D. C.,

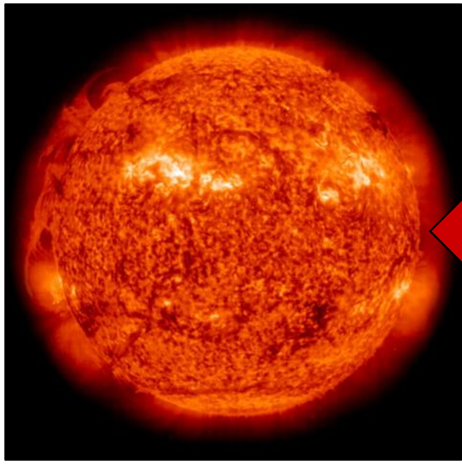
M. Schoenberg*

University of São Paulo,
São Paulo, Brazil,
November 23, 1940.

* Fellow of the Guggenheim Memorial Foundation. Now in Washington, D. C.

Phys. Rev. 58:1117 (1940)

Sun Glasses for Neutrinos?

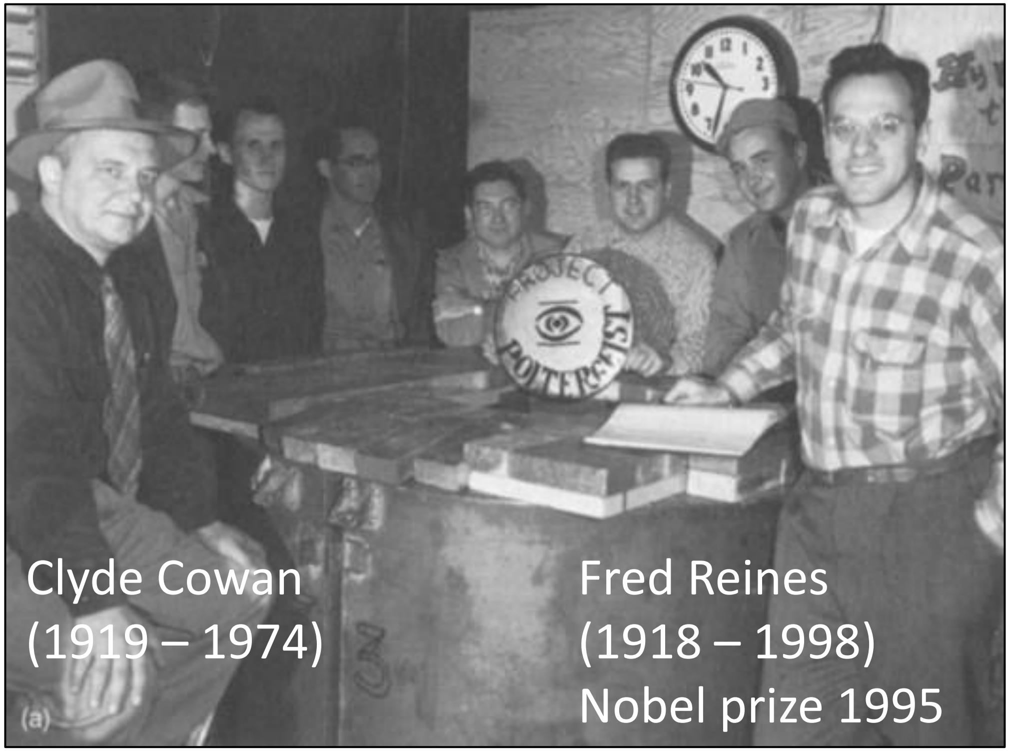


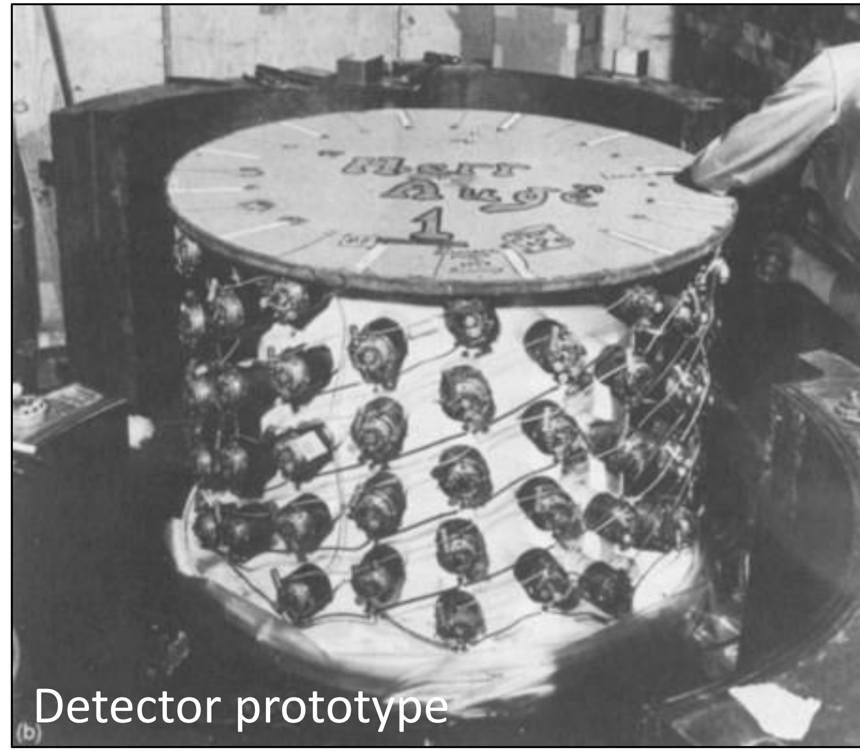
8.3 light minutes

Several light years of lead needed to shield solar neutrinos

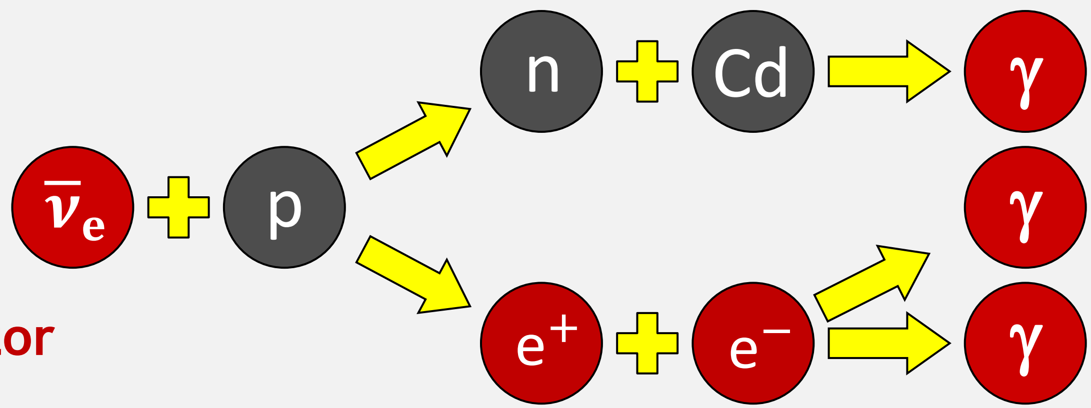
Bethe & Peierls 1934:
… this evidently means that one will never be able to observe a neutrino.

First Detection (1954 – 1956)



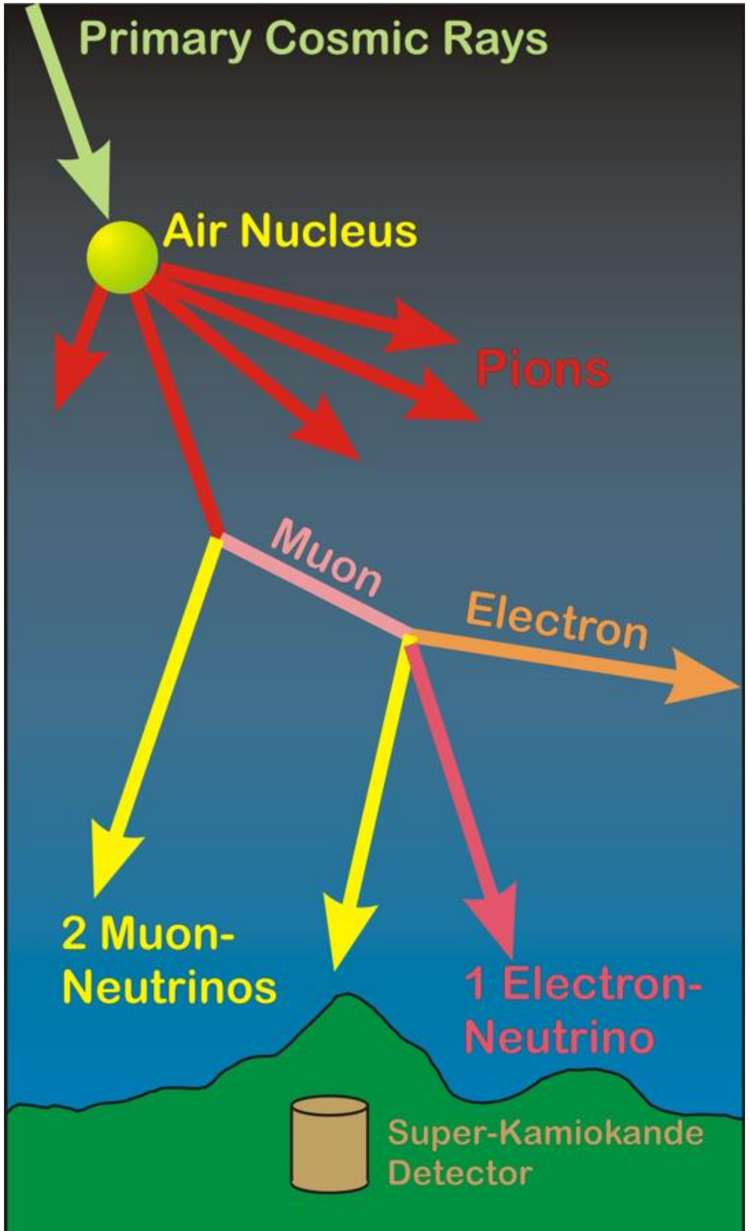


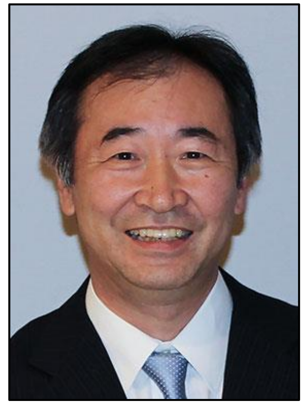
Anti-Electron Neutrinos from Hanford Nuclear Reactor



3 Gammas in coincidence

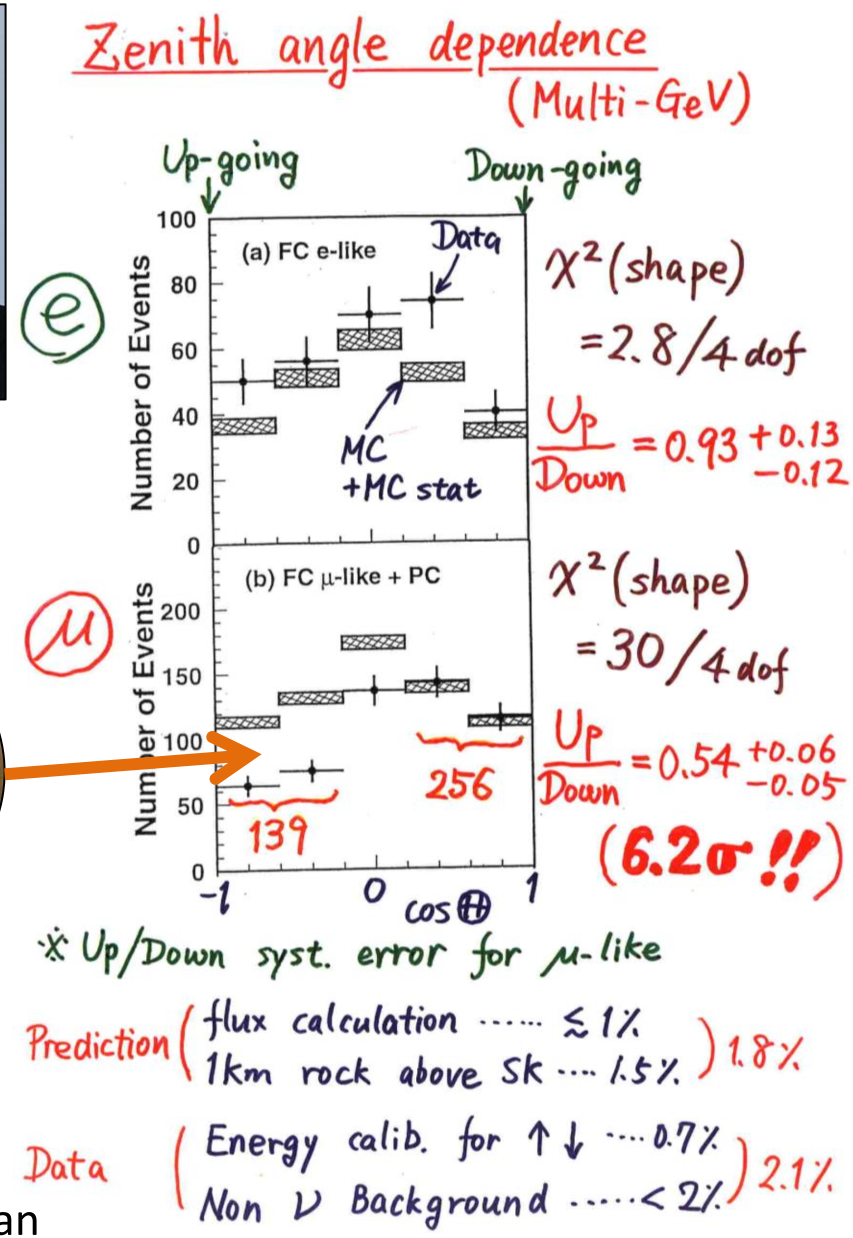
Atmospheric Neutrinos





T. Kajita
Univ. Tokyo

2015



Neutrino 1998
Takayama, Japan

Heisenberg 1936

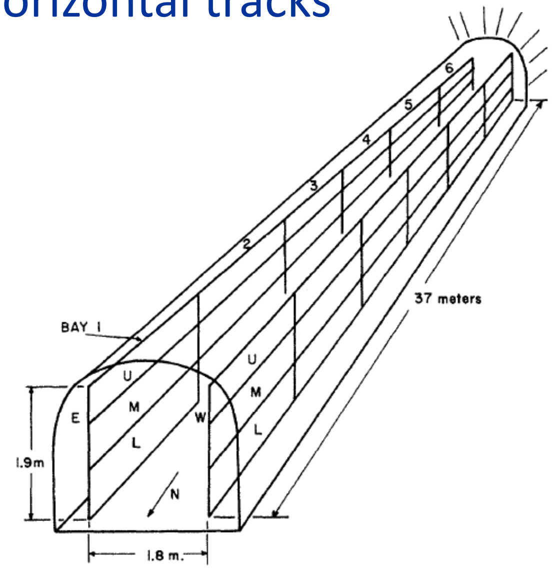
Instead [of protons and neutrons] Pauli's hypothetical 'neutrinos' should contribute substantially to the penetrating radiation. This is because in each shower ... neutrinos should be generated which then would lead to the generation of small secondary showers. The cross section for the generation of these secondary showers would likely not be much smaller than 10^{-26} cm². Contrary to the low-energy neutrinos from β decay one should be able to detect the energetic neutrinos from cosmic rays via their interactions.

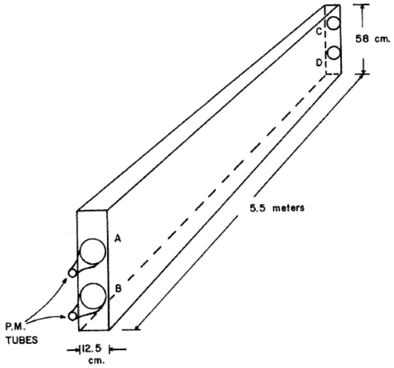
Werner Heisenberg
Zur Theorie der Schauerbildung in der Höhenstrahlung
Zeitschrift für Physik 101 (1936) 533

Detection of First Atmospheric Neutrinos 1965

Chase-Witwatersrand-Irvine (CWI) Coll.
Mine in South Africa, 8800 mwe

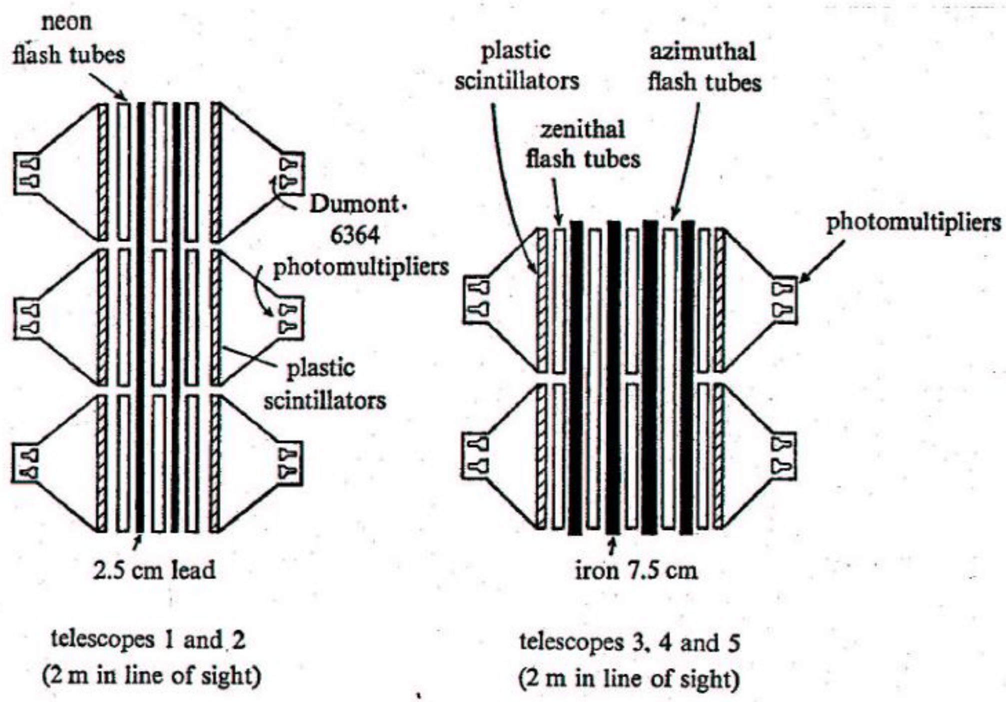
- Liquid scintillator
- Horizontal tracks

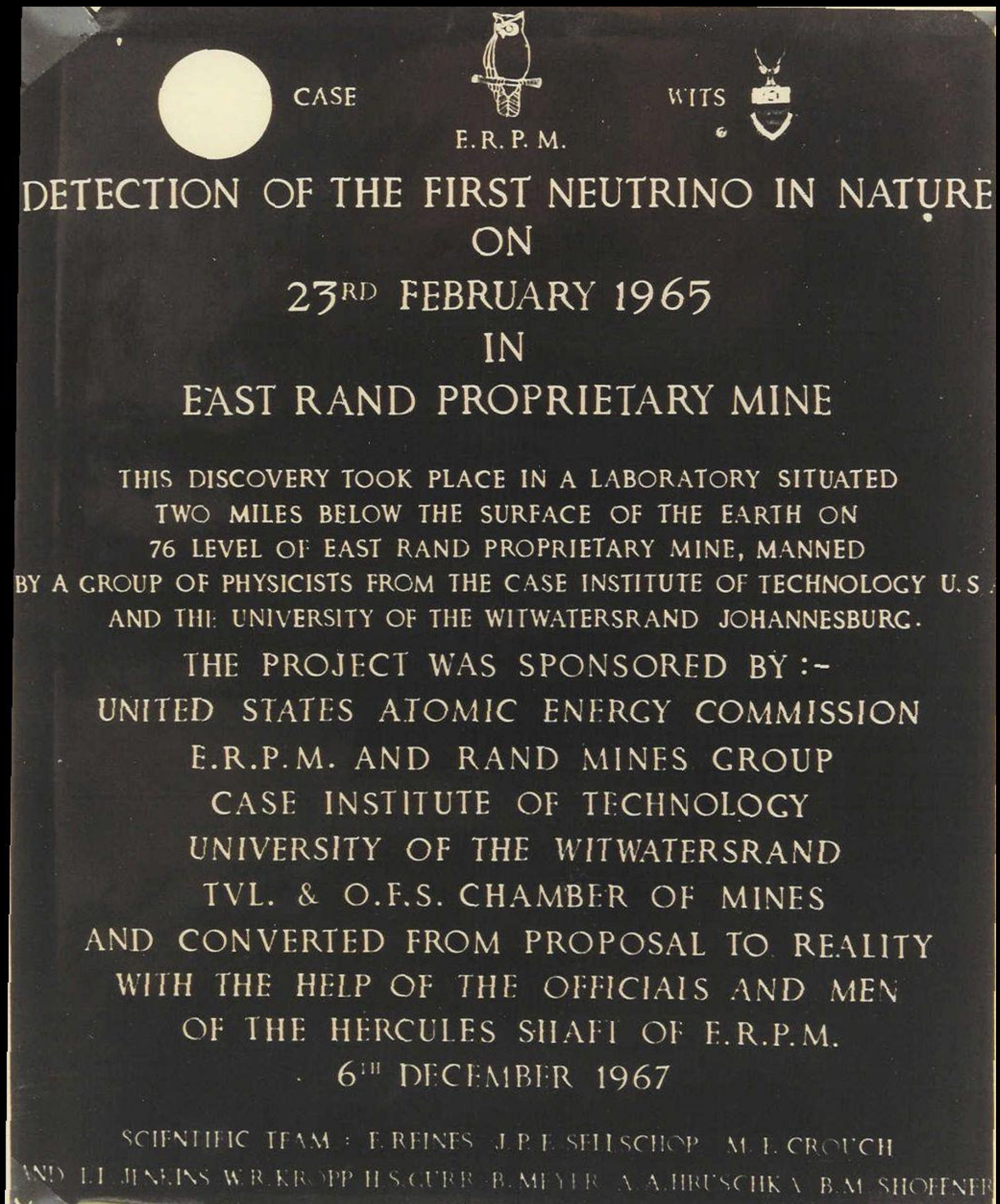




Kolar Gold Field (KGF) Collaboration
(Japan-India-UK group), 7500 mwe

- Plastic scintillator
- Flash tubes

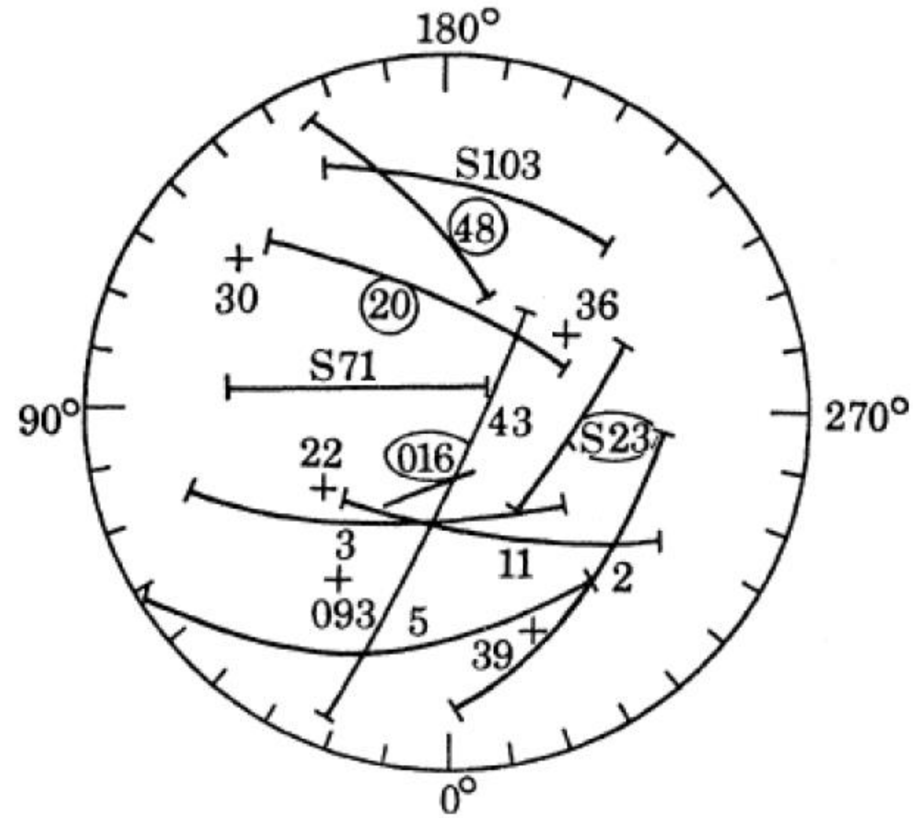



CASE
E.R.P.M.
WITS
DETECTION OF THE FIRST NEUTRINO IN NATURE
ON
23RD FEBRUARY 1965
IN
EAST RAND PROPRIETARY MINE
THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED
TWO MILES BELOW THE SURFACE OF THE EARTH ON
76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED
BY A GROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOGY U.S.A.
AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG.
THE PROJECT WAS SPONSORED BY :-
UNITED STATES ATOMIC ENERGY COMMISSION
E.R.P.M. AND RAND MINES GROUP
CASE INSTITUTE OF TECHNOLOGY
UNIVERSITY OF THE WITWATERSRAND
TVL. & O.F.S. CHAMBER OF MINES
AND CONVERTED FROM PROPOSAL TO REALITY
WITH THE HELP OF THE OFFICIALS AND MEN
OF THE HERCULES SHAFT OF E.R.P.M.
6TH DECEMBER 1967
SCIENTIFIC TEAM : F. REINES J.P.F. SELLSCHOP M.F. CROUCH
AND T.L. JENKINS W.R. KROPP H.S. GURR B. MEYER A.A. HRUSCHKA B.M. SHOFFNER

First Neutrino Sky Map

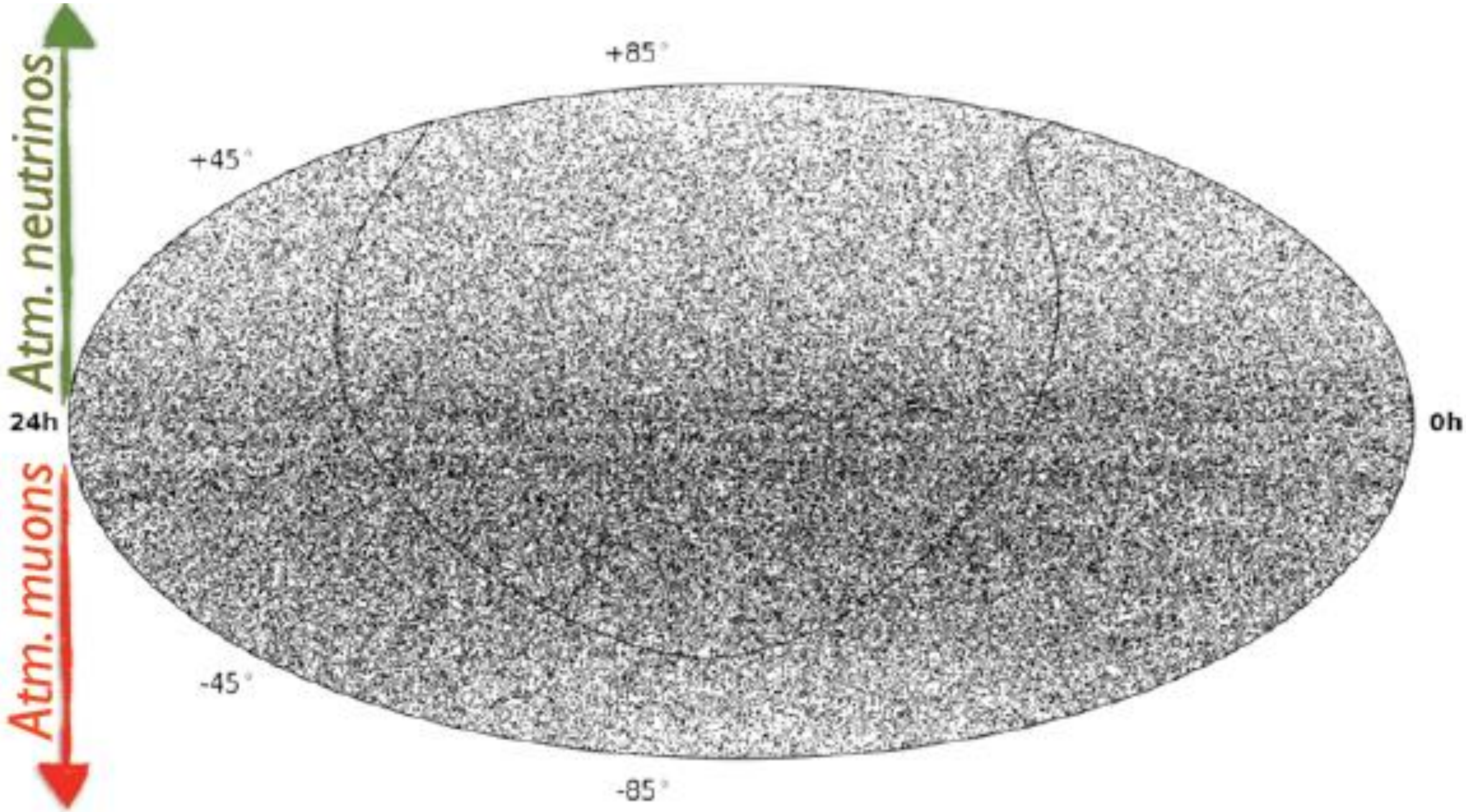
The first neutrino sky map with the celestial coordinates of 18 Kolar Gold Field neutrino events

(Krishnaswamy et al. 1971)



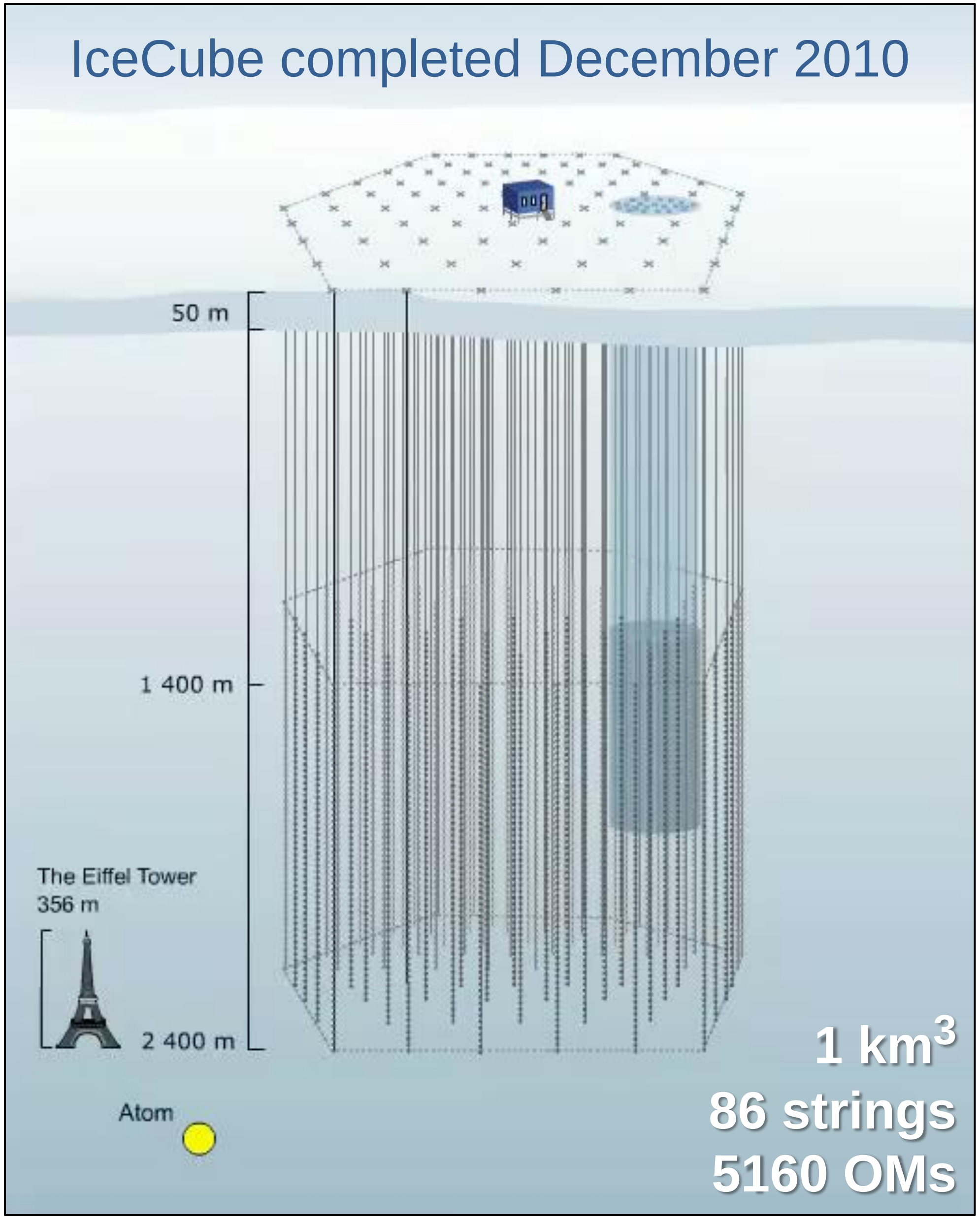
Due to uncertainties in the azimuth, the coordinates for some events are arcs rather than points. The labels reflect the numbers and registration mode of the events (e.g. S for spectrograph). Only for the ringed events the sense of the direction of the registered muon is known.

IceCube (40 & 59 strings) Skymap



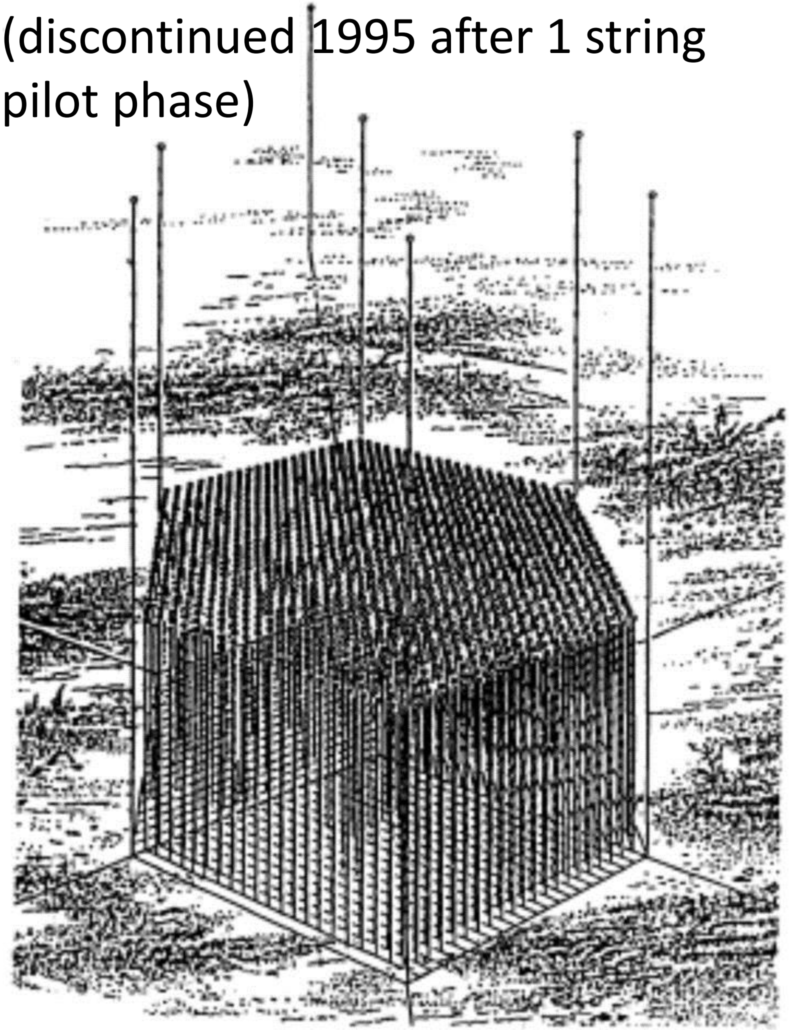
Total events: 43339 (upgoing) and 64230 (downgoing)
Livetime: 348 days (IC59) and 375 days (IC40)

IceCube Neutrino Telescope at the South Pole

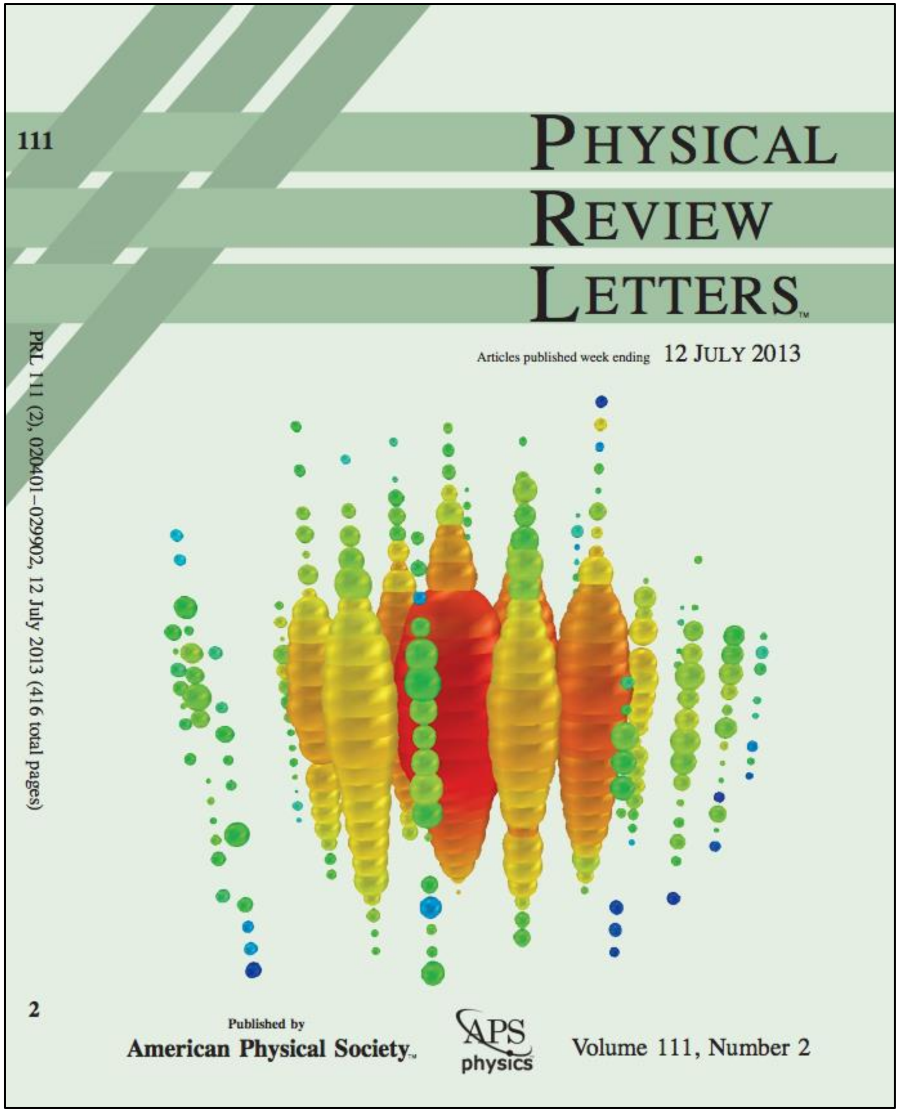


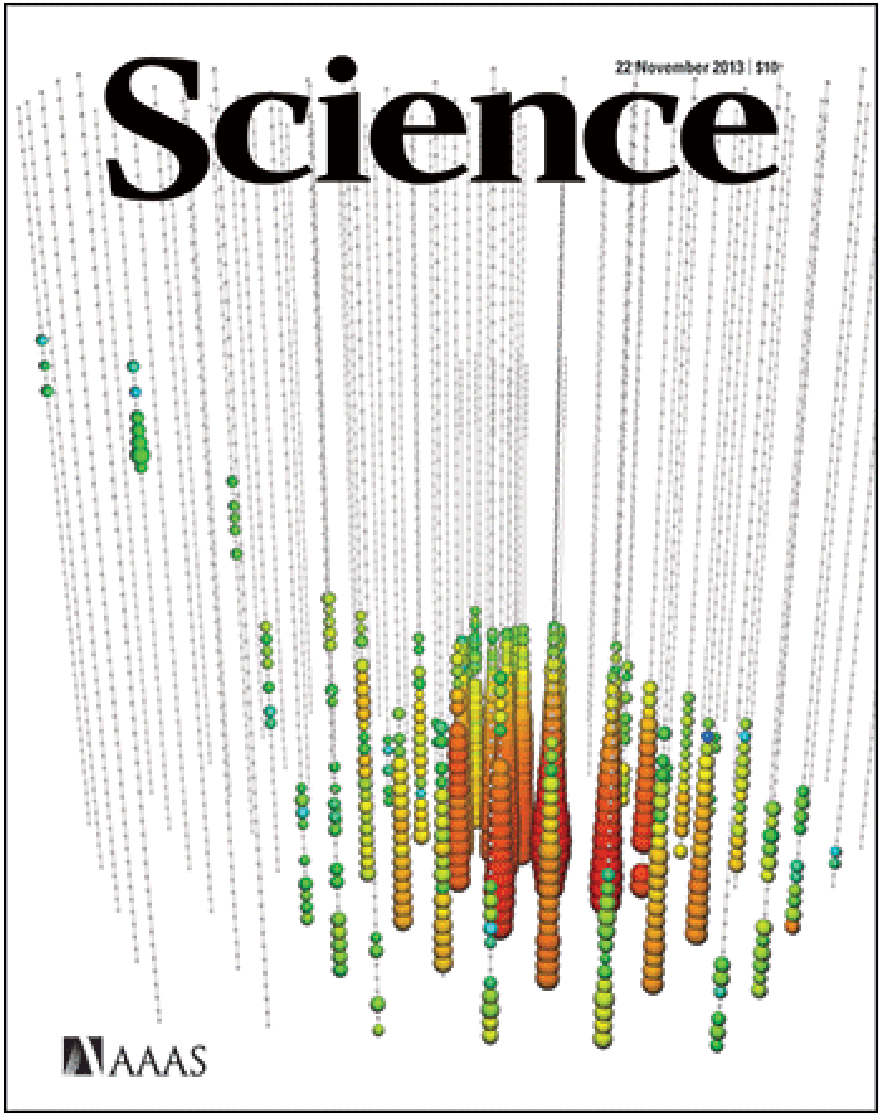
Idea for DUMAND under sea Cherenkov detector (1978)

1.26 km^3, 22 698 Optical Modules (discontinued 1995 after 1 string pilot phase)

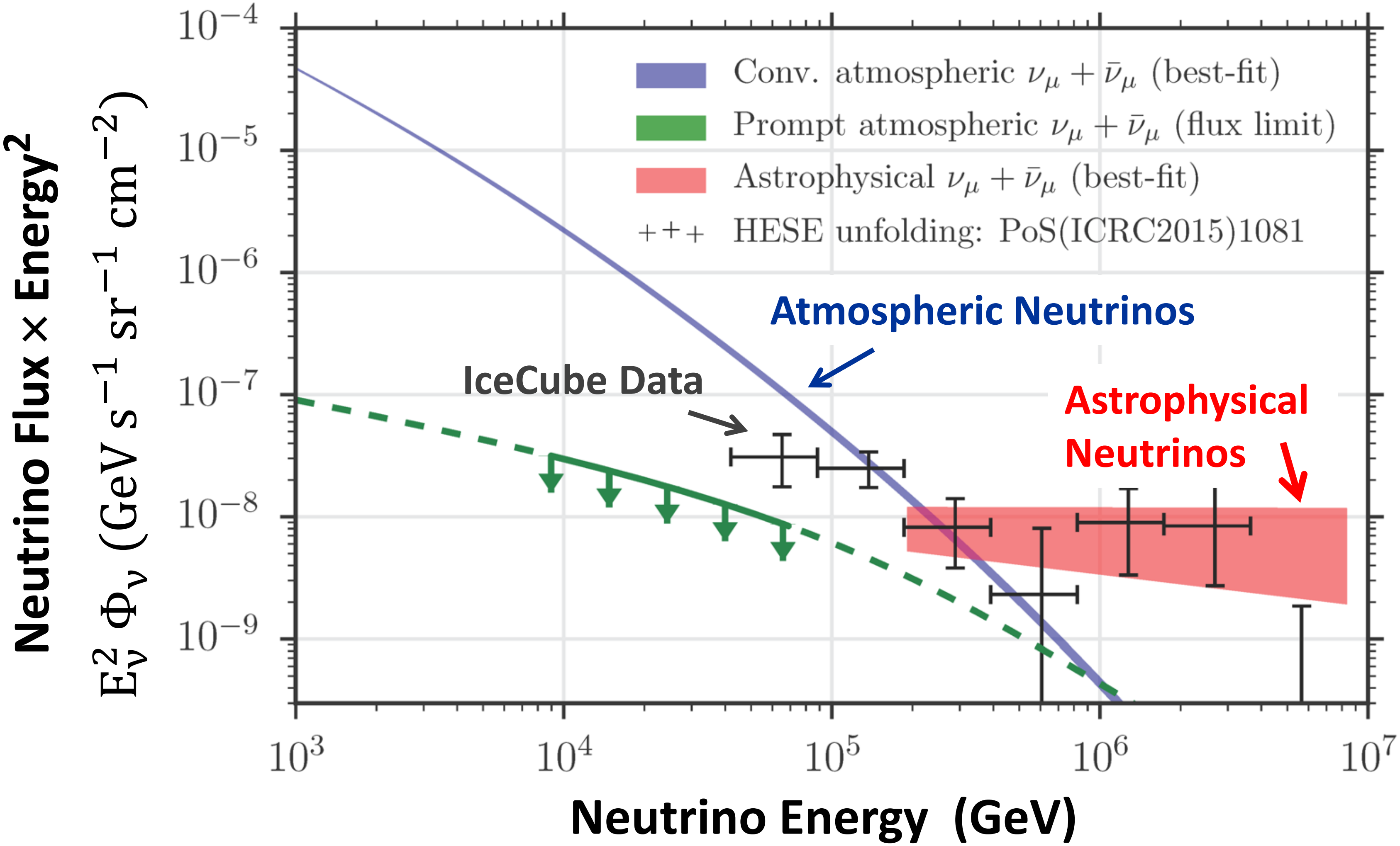


Detection of The Year (2013)



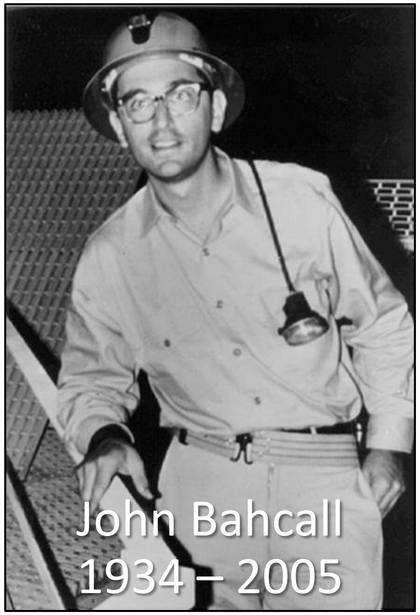


Diffuse Astrophysical High-Energy Neutrinos



IceCube Collaboration, arXiv:1702.05244

Proposing the First Solar Neutrino Experiment



SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^1\text{H}(p, e^+\nu)^2\text{H}(p,\gamma)^3\text{He}$ and terminated by the following sequences: (i) $^3\text{He}(^3\text{He}, 2p)^4\text{He}$; (ii) $^3\text{He}(\alpha,\gamma)^7\text{Be}(e^-\nu)^7\text{Li}(p,\alpha)^4\text{He}$; and (iii) $^3\text{He}(\alpha,\gamma)^7\text{Be}(p,\gamma)^8\text{B}(e^+\nu)^8\text{Be}^*(\alpha)^4\text{He}$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) $^{37}\text{Cl}(\nu_{\text{solar}}, e^-)^{37}\text{Ar}$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

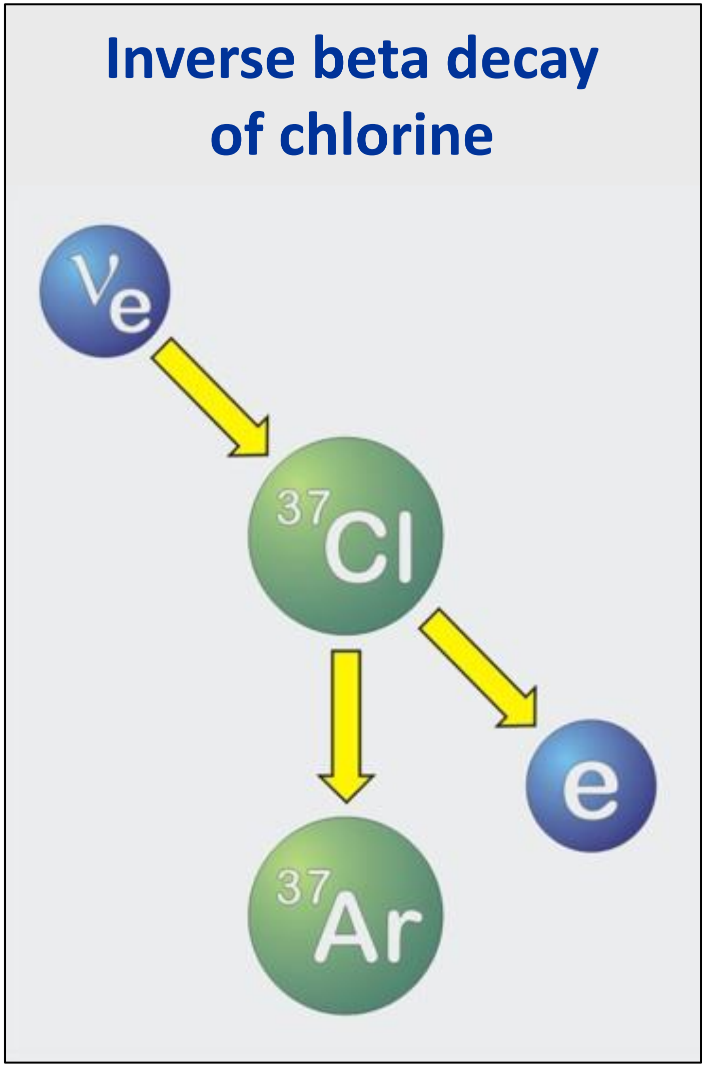
Volume 12, Number 11 PHYSICAL REVIEW LETTERS 16 March 1964

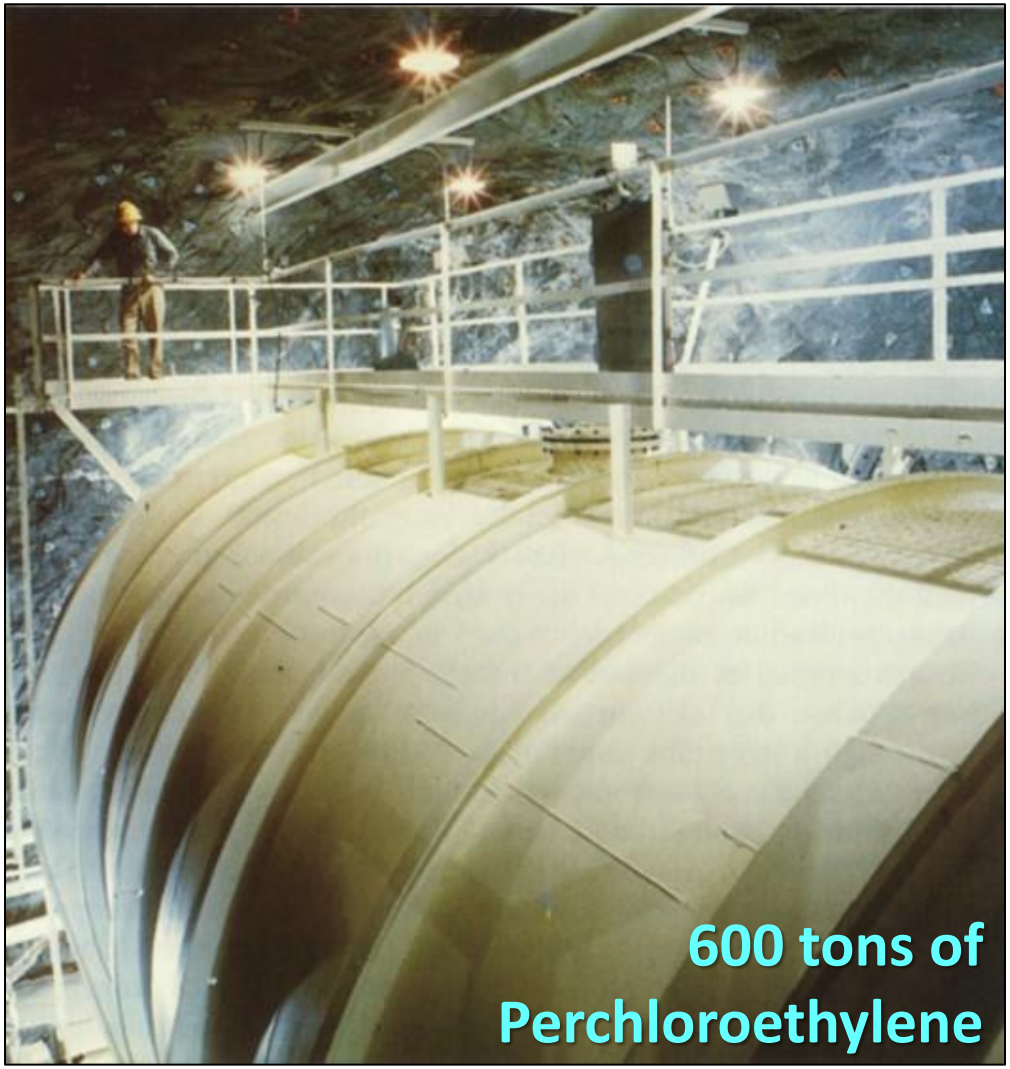
SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These 3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1}$.

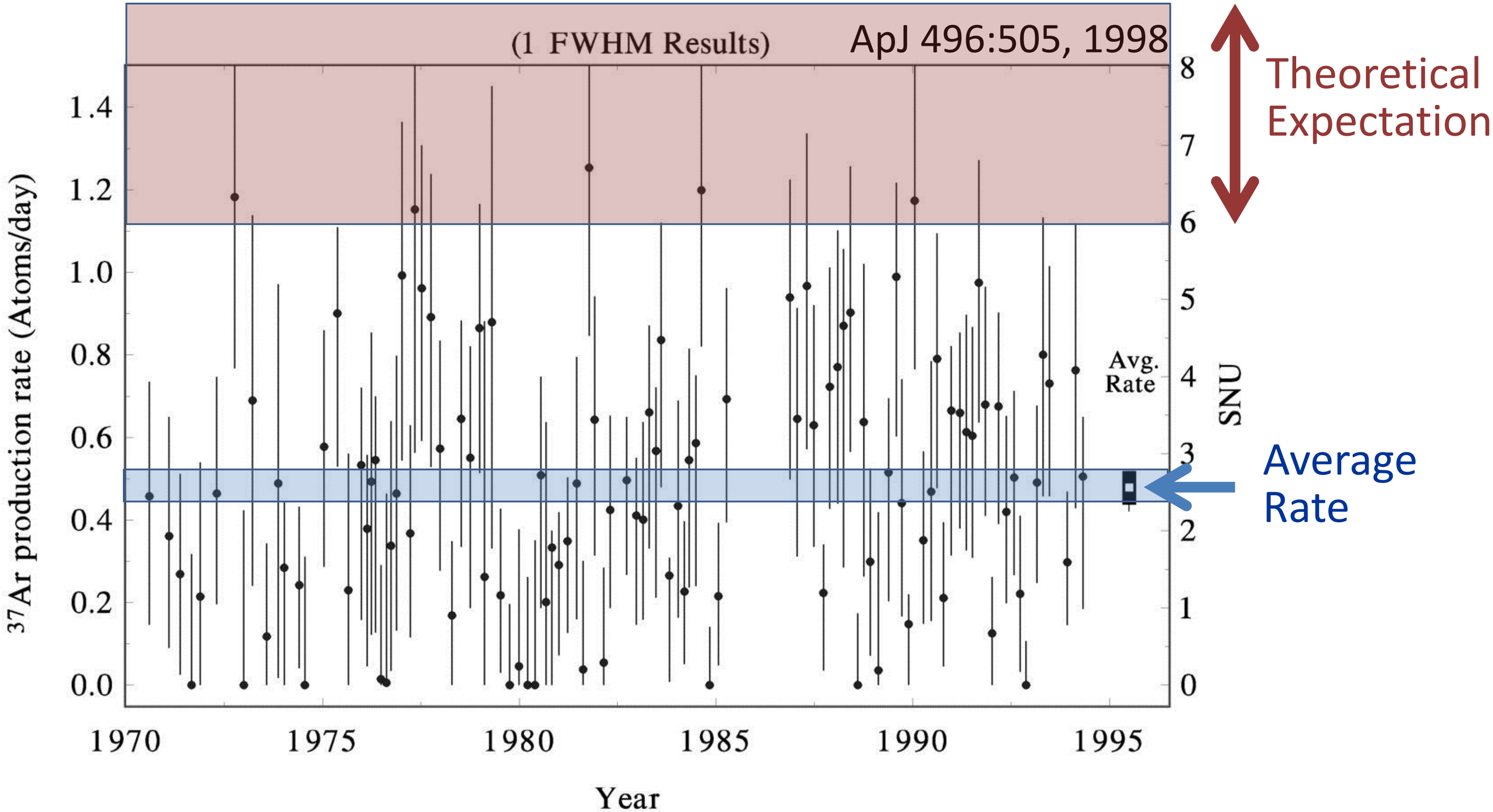
First Measurements of Solar Neutrinos





Homestake solar neutrino observatory (1967–2002)

Results of Chlorine Experiment (Homestake)



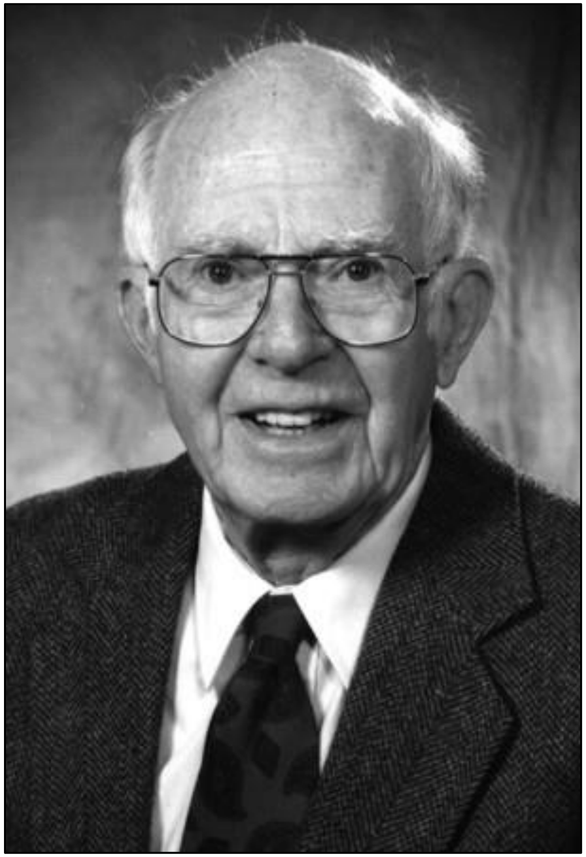
Average (1970–1994) **$2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU**

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

Theoretical Prediction 6–9 SNU

“Solar Neutrino Problem” since 1968

2002 Physics Nobel Prize for Neutrino Astronomy



Ray Davis Jr.
(1914–2006)

Masatoshi Koshiba
(*1926)

“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

Volume 28B, number 7 PHYSICS LETTERS 20 January 1969

NEUTRINO ASTRONOMY AND LEPTON CHARGE

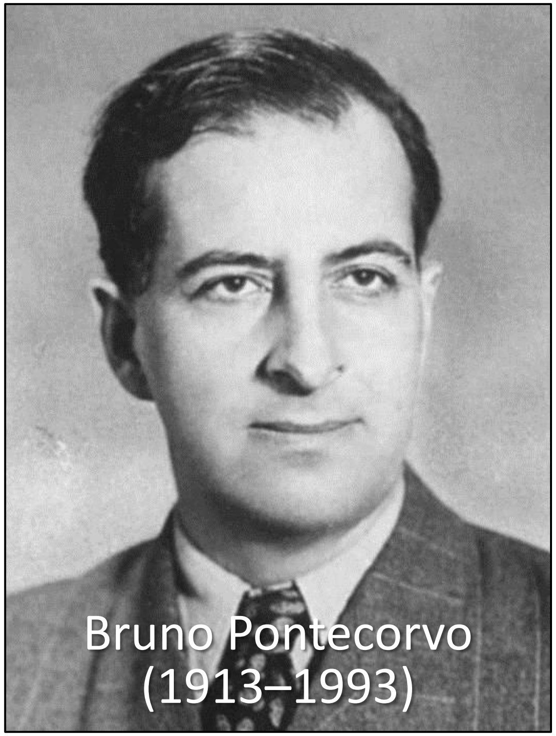
Learning about astrophysical sources with neutrinos

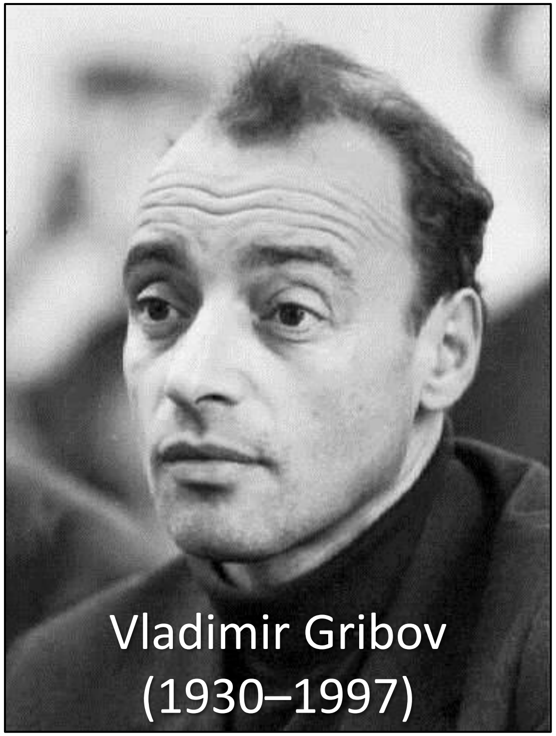
Learning about neutrinos from astrophysics and cosmology

V. GRIBOV* and B. PONTECORVO
Joint Institute for Nuclear Research, Dubna, USSR

Received 20 December 1968

It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^0 \rightleftarrows \tilde{K}^0$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

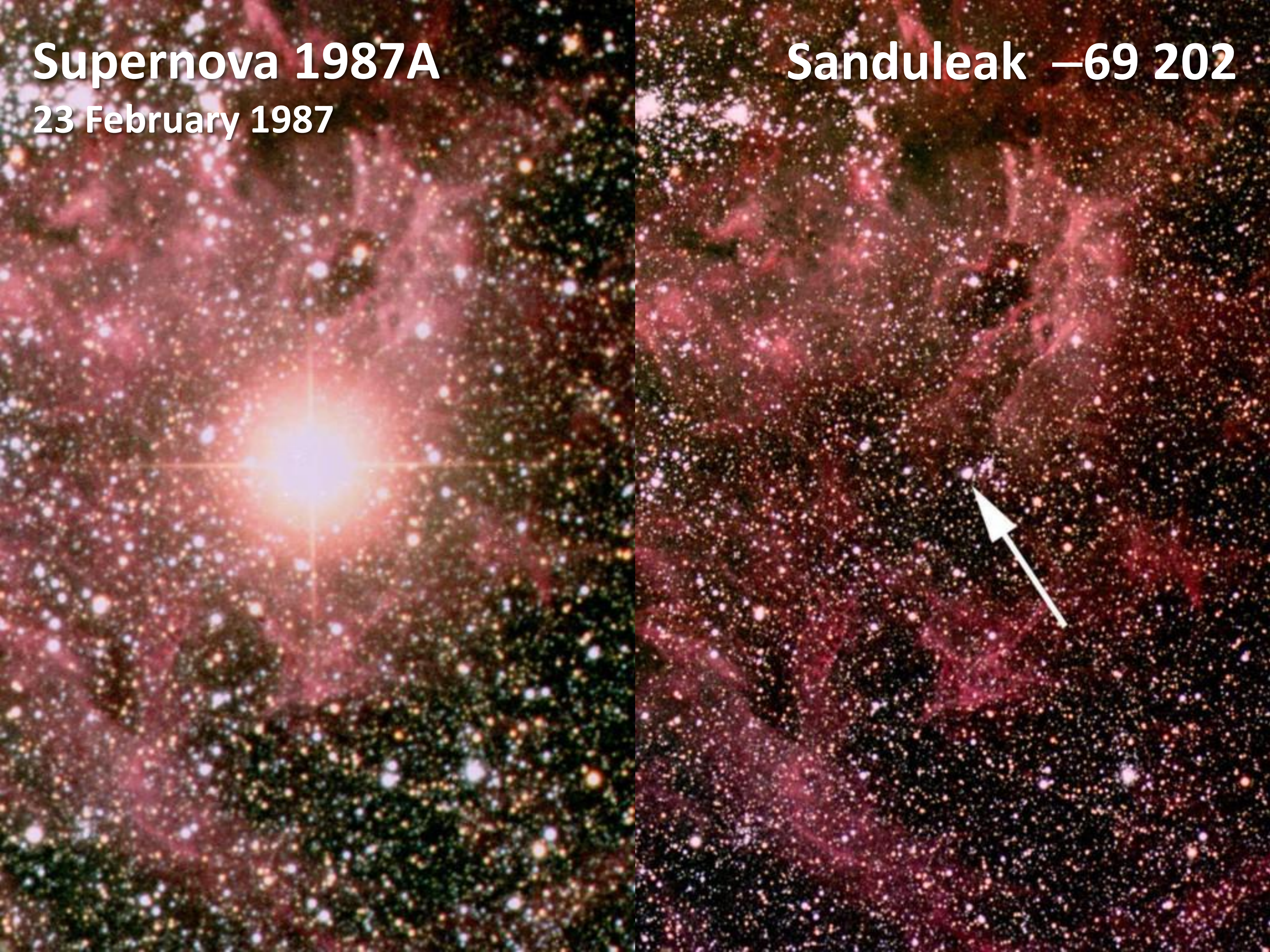





Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)

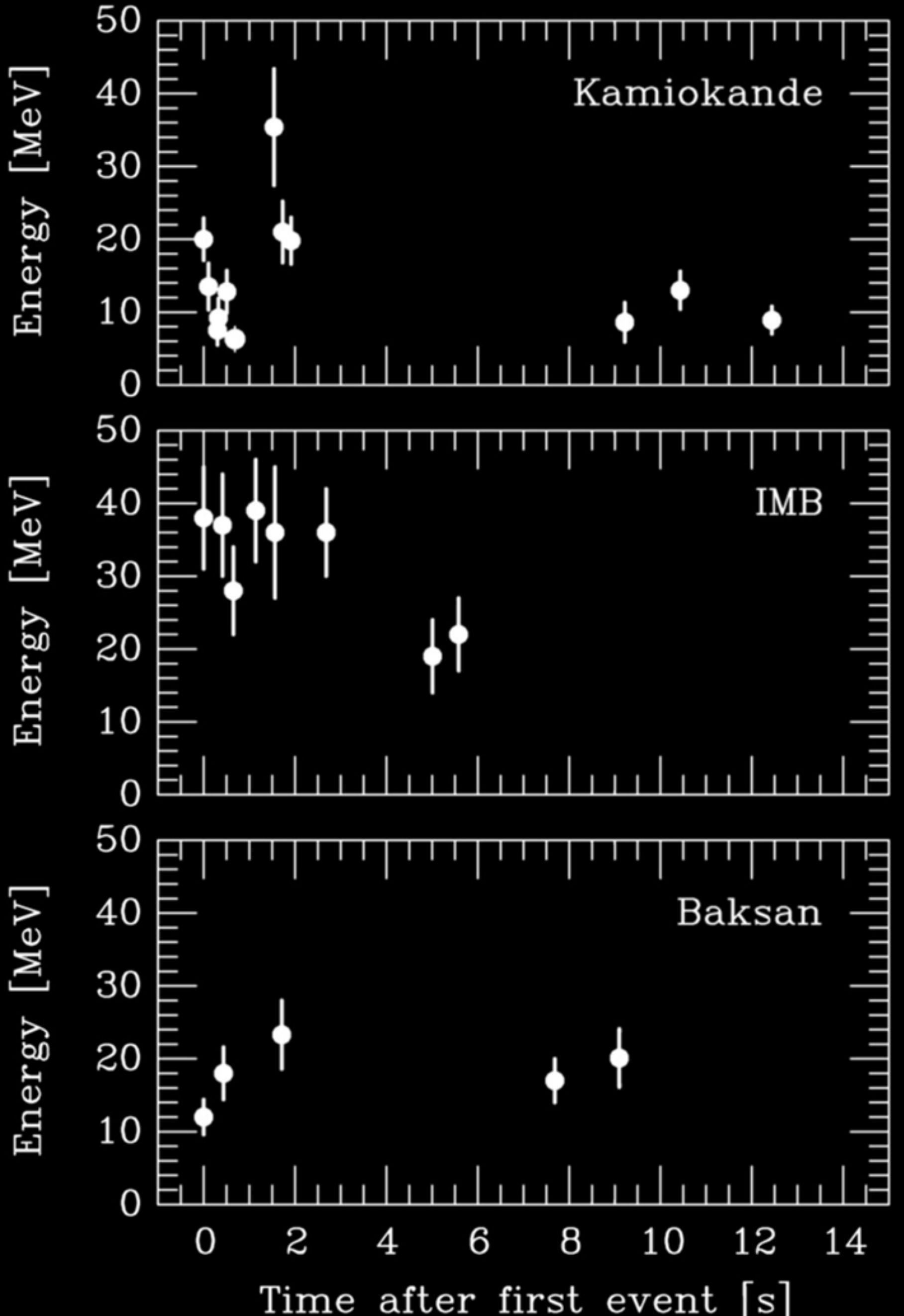

Tarantula Nebula


Sanduleak –69 202

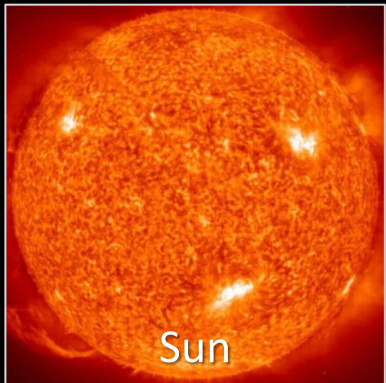

Supernova 1987A
23 February 1987
Sanduleak –69 202

Supernova 1987A

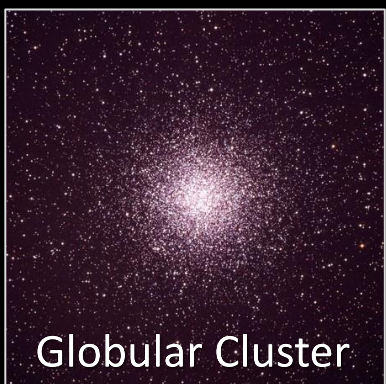
23 February 1987



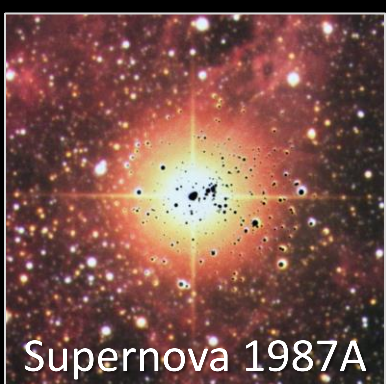
Neutrinos and the Stars



- Strongest local neutrino flux
- Long history of detailed measurements
- Crucial for flavor oscillation physics
- Resolve solar metal abundance problem in future?
- Use Sun as source for other particles (especially axions)

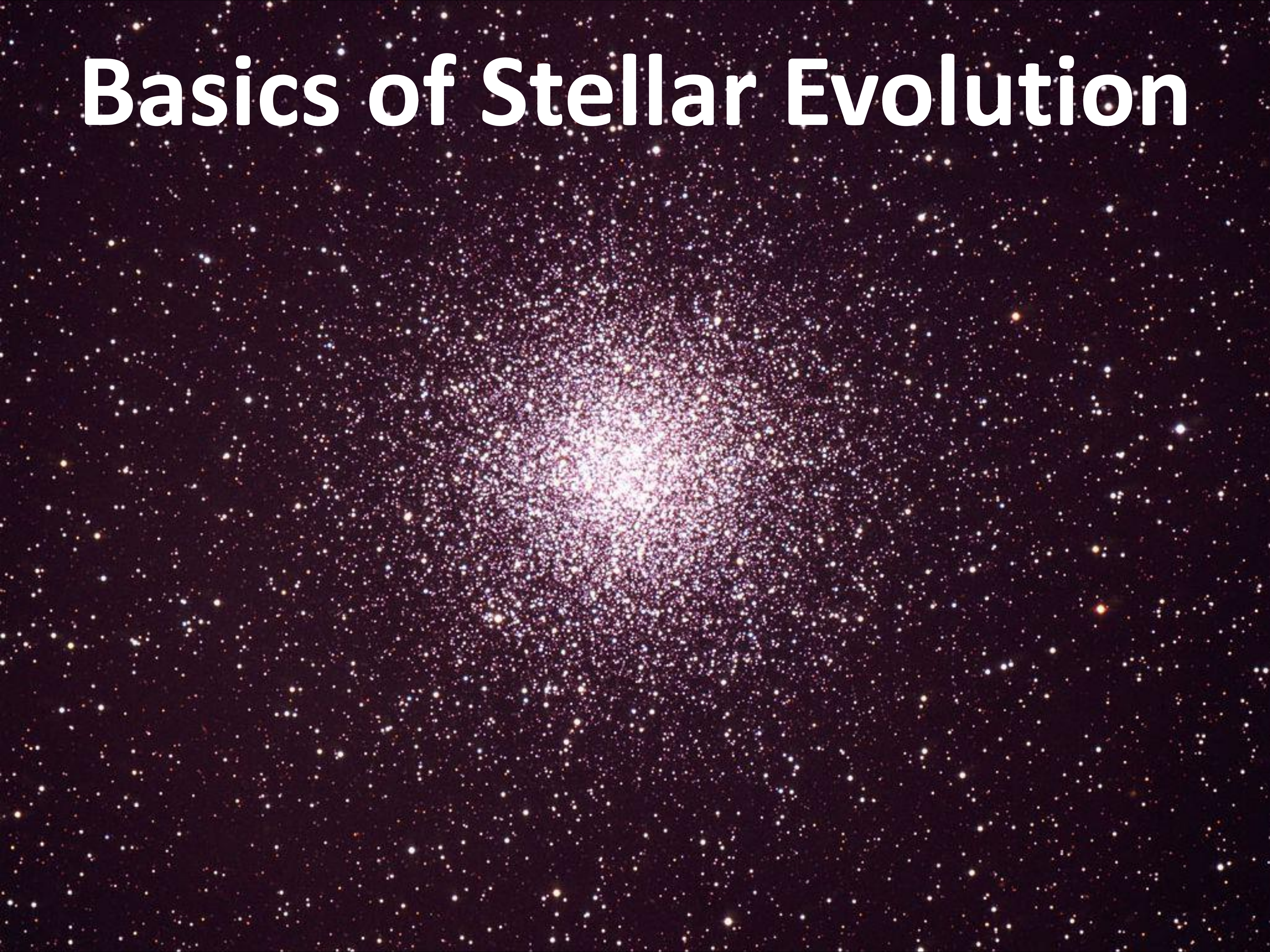


- Neutrino energy loss crucial in stellar evolution theory
- Backreaction on stars provides limits,
  e.g. neutrino magnetic dipole moments



- Collapsing stars most powerful neutrino sources
- Once observed from SN 1987A
- Provides well-established particle-physics constraints
- Next galactic supernova: learn about astrophyiscs of core collapse
- Diffuse Supernova Neutrino Background (DSNB) is detectable

Basics of Stellar Evolution



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

Convection in Main-Sequence Stars

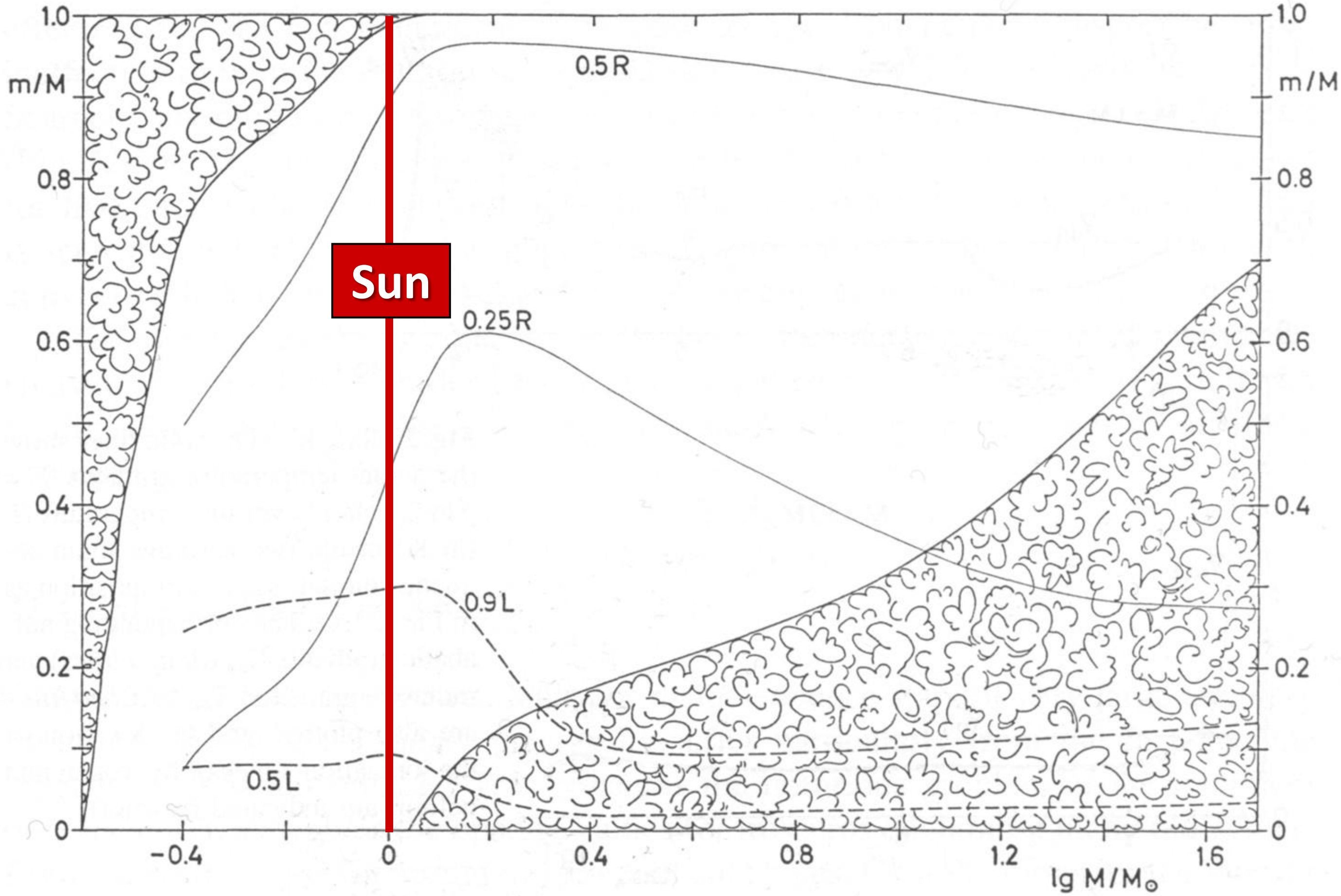


Fig. 22.7. The mass values m from centre to surface are plotted against the stellar mass M for the same zero-age main-sequence models as in Fig. 22.1. "Cloudy" areas indicate the extension of convective zones inside the models. Two solid lines give the m values at which r is 1/4 and 1/2 of the total radius R. The dashed lines show the mass elements inside which 50% and 90% of the total luminosity L are produced

Kippenhahn & Weigert, Stellar Structure and Evolution

Virial Theorem and Hydrostatic Equilibrium

Hydrostatic equilibrium

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

Integrate both sides

$$\int_0^R dr\,4\pi r^3 P' = -\int_0^R dr\,4\pi r^3 \frac{G_N M_r \rho}{r^2}$$

L.h.s. partial integration
with $P = 0$ at surface R

$$-3\int_0^R dr\,4\pi r^2 P = E_{\rm grav}^{\rm tot}$$

Monatomic gas: $P = \frac{2}{3} U$
(U density of internal energy)

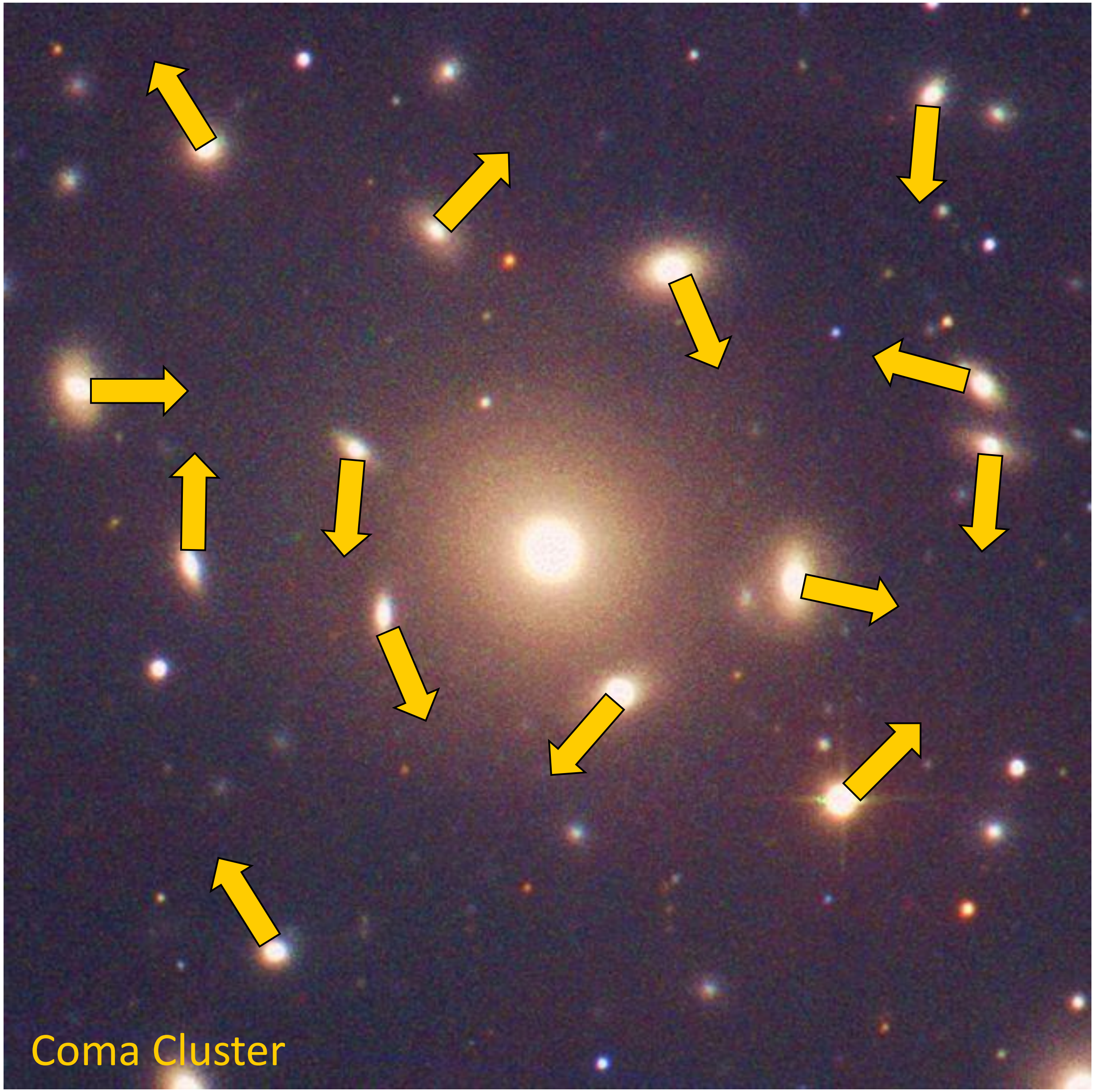
$$U^{\rm tot} = -\frac{1}{2} E_{\rm grav}^{\rm tot}$$

Average energy of single
"atoms" of the gas

$$\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm grav}\rangle$$

Virial Theorem:
Most important tool to study
self-gravitating systems

Dark Matter in Galaxy Clusters



A gravitationally bound system of many particles obeys the virial theorem

$$2\langle E_{\rm kin}\rangle = -\langle E_{\rm grav}\rangle$$

$$2\left\langle\frac{mv^2}{2}\right\rangle = \left\langle\frac{G_N M_r m}{r}\right\rangle$$

$$\langle v^2\rangle \approx G_N M_r \langle r^{-1}\rangle$$

Velocity dispersion from Doppler shifts and geometric size

Total Mass

Virial Theorem Applied to the Sun

Virial Theorem $\langle E_{\mathrm{kin}} \rangle = -\frac{1}{2} \langle E_{\mathrm{grav}} \rangle$

Approximate Sun as a homogeneous sphere with

Mass $M_{\mathrm{sun}} = 1.99 \times 10^{33}\mathrm{g}$

Radius $R_{\mathrm{sun}} = 6.96 \times 10^{10}\mathrm{cm}$

Gravitational potential energy of a proton near center of the sphere

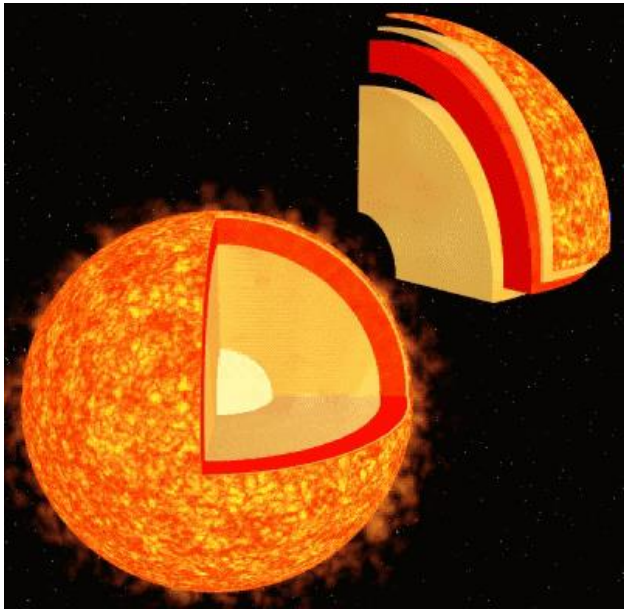
$$\langle E_{\mathrm{grav}} \rangle = -\frac{3}{2} \frac{G_N M_{\mathrm{sun}} m_p}{R_{\mathrm{sun}}} = -3.2\ \mathrm{keV}$$

Thermal velocity distribution

$$\langle E_{\mathrm{kin}} \rangle = \frac{3}{2} k_{\mathrm{B}} T = -\frac{1}{2} \langle E_{\mathrm{grav}} \rangle$$

Estimated temperature

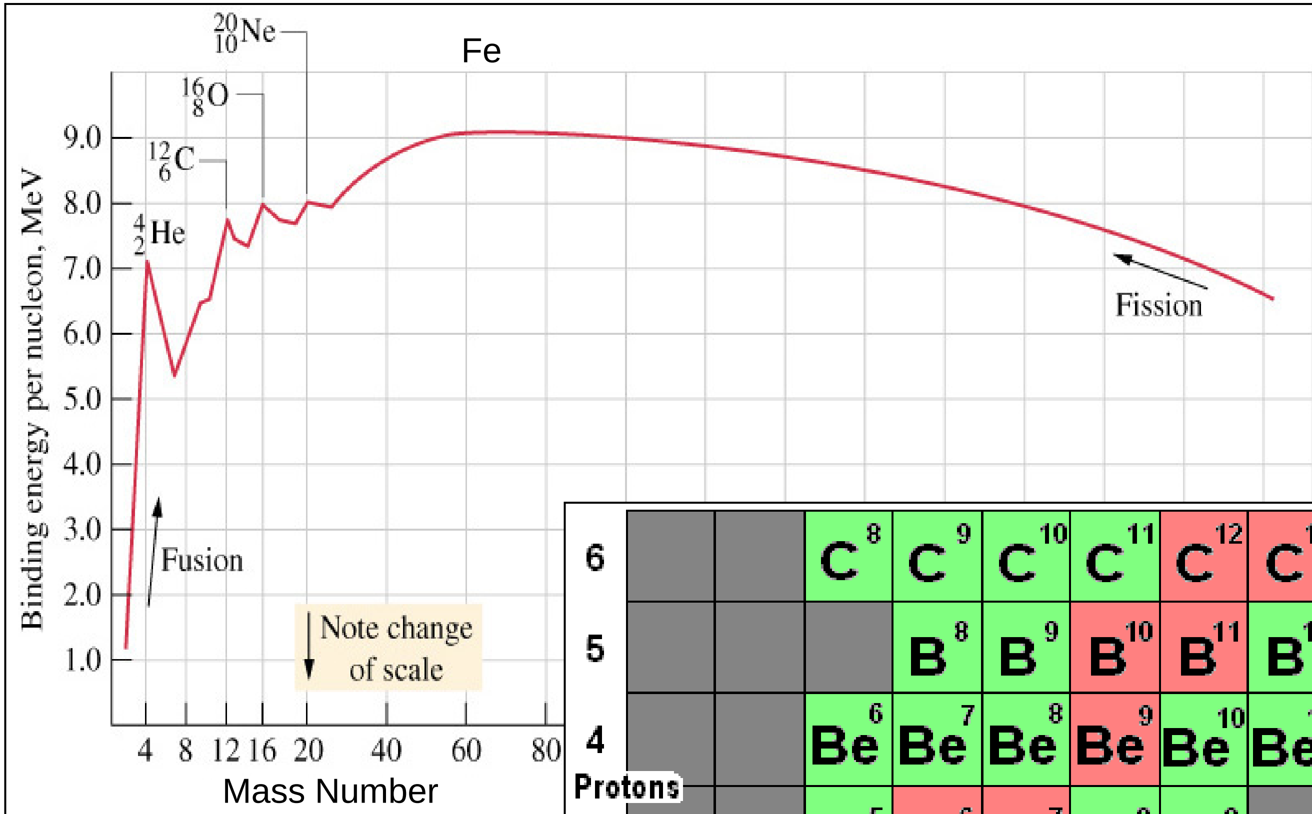
$$T = 1.1\ \mathrm{keV}$$

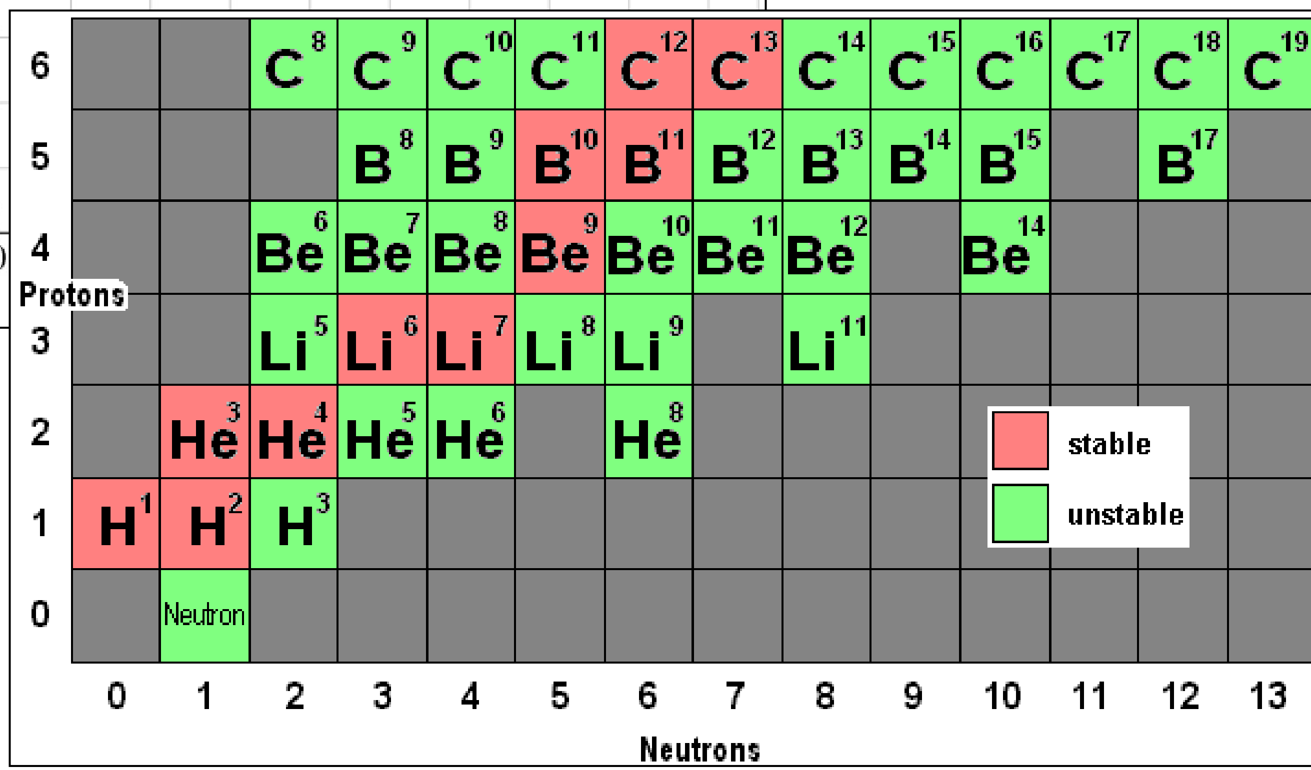


Central temperature from standard solar models

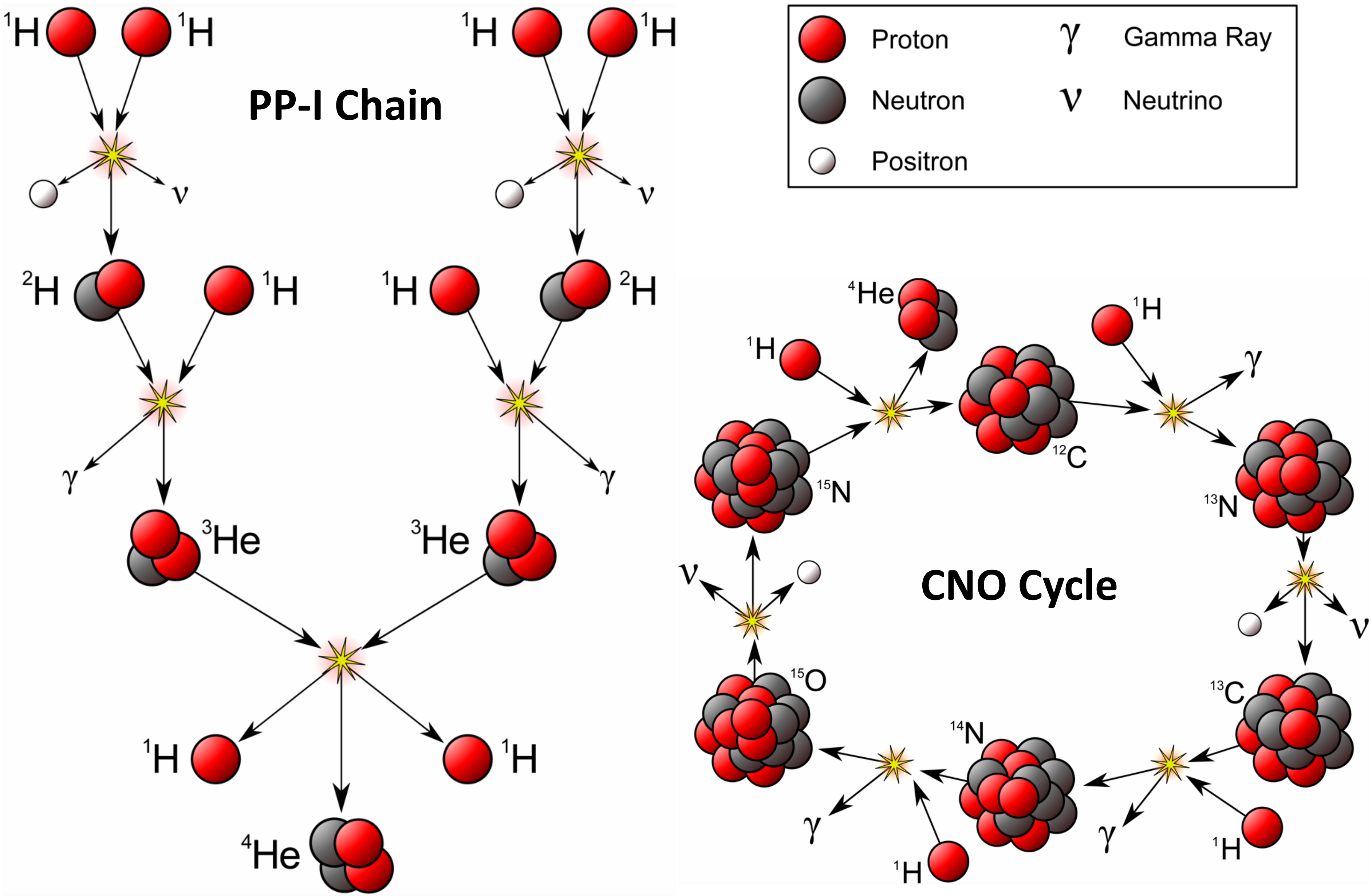
$$T_{\mathrm{c}} = 1.56 \times 10^{7}\mathrm{K} = 1.34\ \mathrm{keV}$$

Nuclear Binding Energy





Hydrogen Burning



Thermonuclear Reactions and Gamow Peak

Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling

Tunneling probability

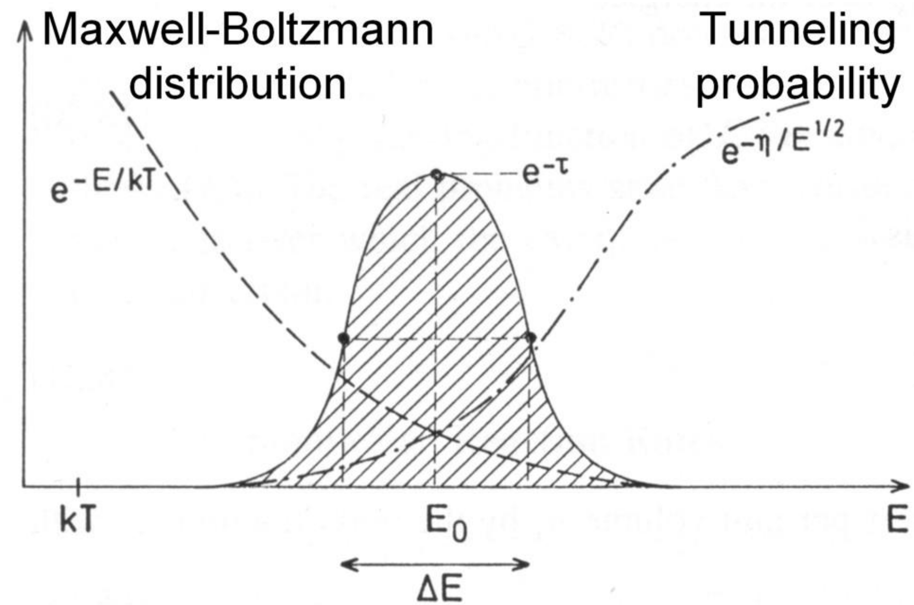
$$p \propto E^{-1/2} e^{-2\pi\eta}$$

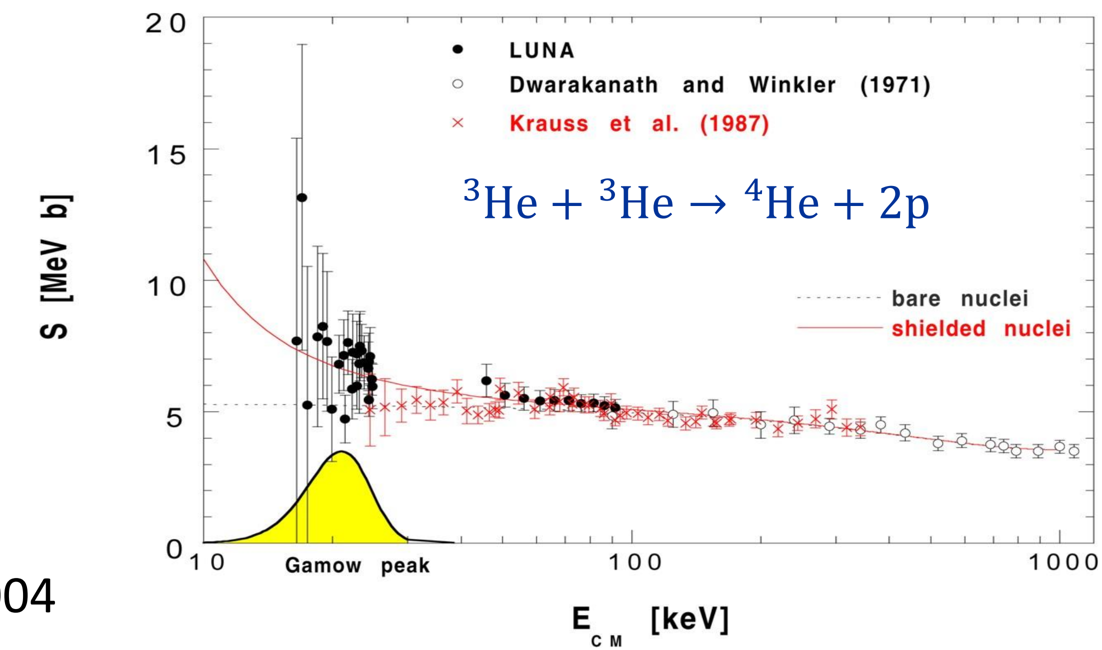
where the Sommerfeld parameter is

$$\eta = \left(\frac{m}{2E}\right)^{1/2} Z_1 Z_2 e^2$$

Parameterize cross section with astrophysical S-factor

$$S(E) = \sigma(E)\, E\, e^{2\pi\eta(E)}$$





LUNA Collaboration, nucl-ex/9902004

Main Nuclear Burning Stages

Hydrogen burning $4\mathrm{p} + 2\mathrm{e}^- \to {}^4\mathrm{He} + 2\nu_e$

- Proceeds by pp chains and CNO cycle
- No higher elements are formed because no stable isotope with mass number 8
- Neutrinos from $\mathrm{p} \to \mathrm{n}$ conversion
- Typical temperatures: 10^7 K (~1 keV)

Helium burning

$${}^4\mathrm{He} + {}^4\mathrm{He} + {}^4\mathrm{He} \leftrightarrow {}^8\mathrm{Be} + {}^4\mathrm{He} \to {}^{12}\mathrm{C}$$

"Triple alpha reaction" because ${}^8\mathrm{Be}$ unstable, builds up with concentration $\sim 10^{-9}$

$${}^{12}\mathrm{C} + {}^4\mathrm{He} \to {}^{16}\mathrm{O}$$
$${}^{16}\mathrm{O} + {}^4\mathrm{He} \to {}^{20}\mathrm{Ne}$$

Typical temperatures: 10^8 K (~10 keV)

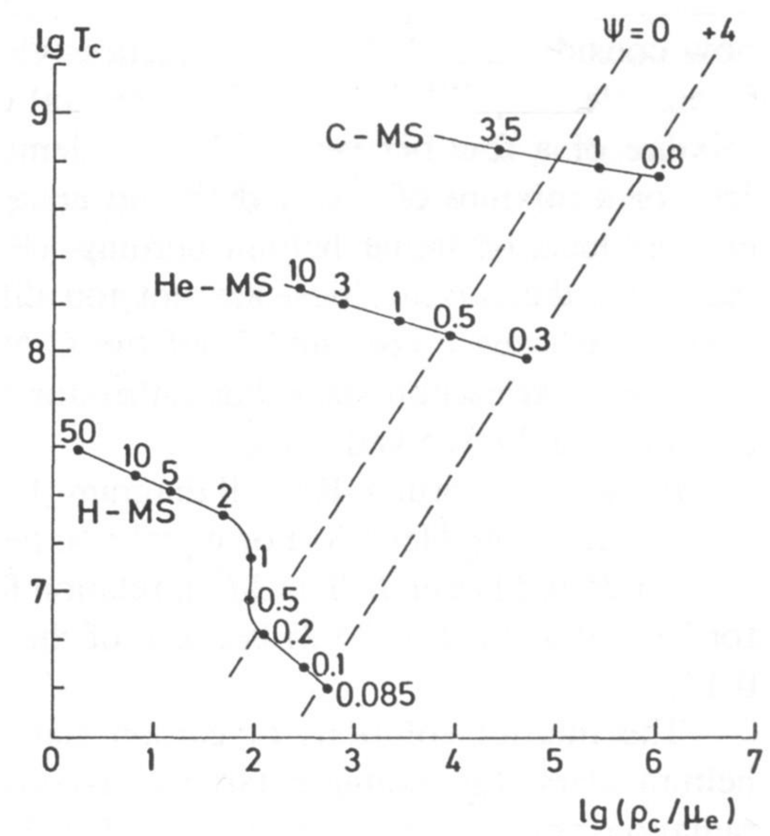
Carbon burning

Many reactions, for example

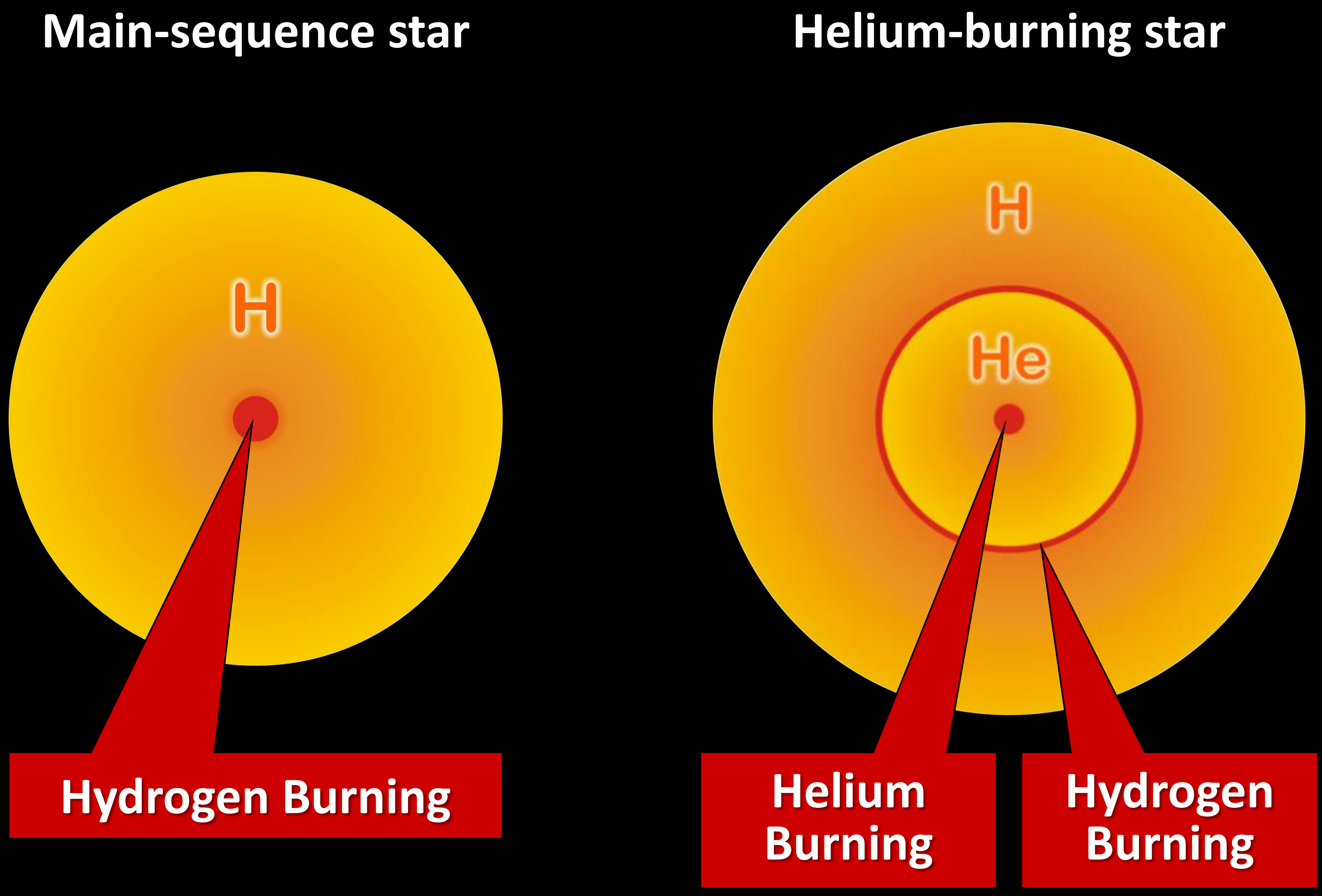
${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \to {}^{23}\mathrm{Na} + \mathrm{p}$ or ${}^{20}\mathrm{Ne} + {}^4\mathrm{He}$ etc

Typical temperatures: 10^9 K (~100 keV)

- Each type of burning occurs at a very different T but a broad range of densities
- Never co-exist in the same location



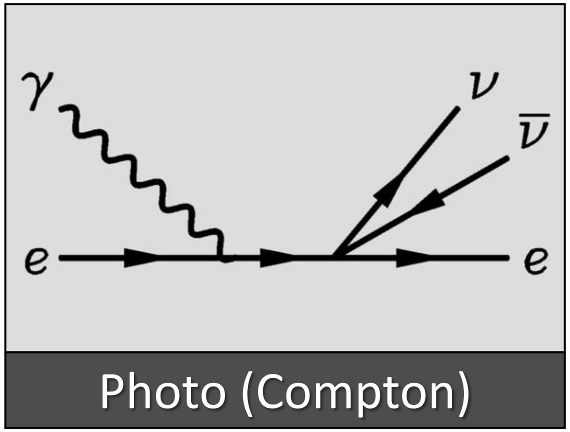
Hydrogen Exhaustion

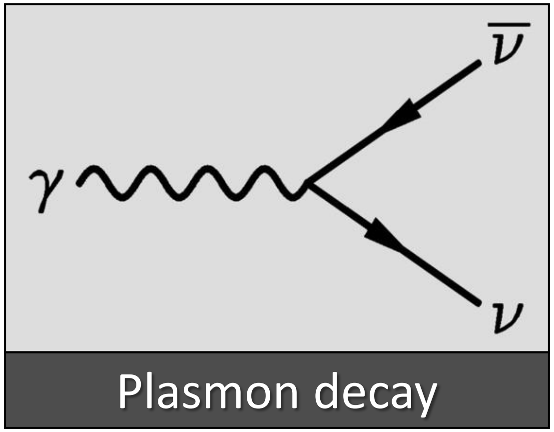


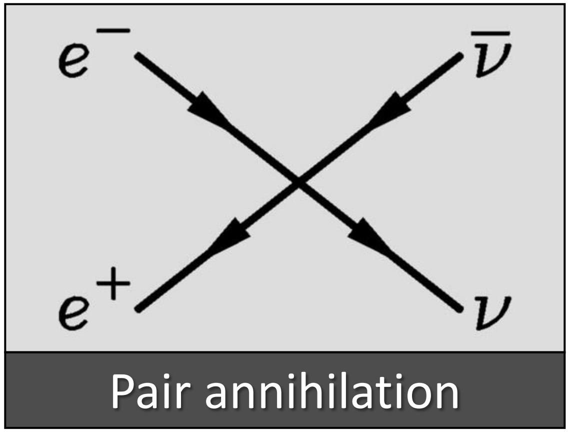
Burning Phases of a 15 Solar-Mass Star

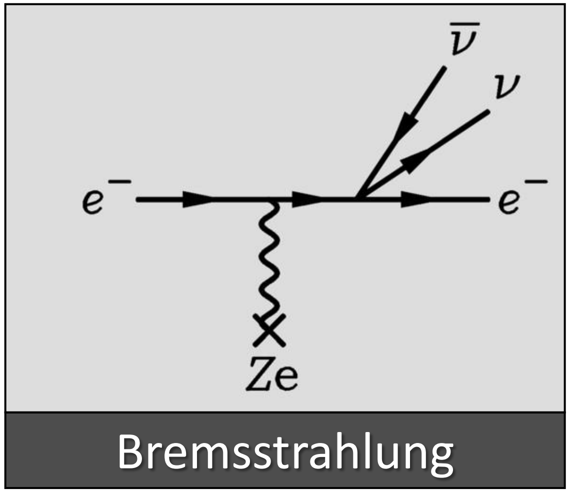
Burning Phase		Dominant Process	T_c [keV]	ρ_c [g/cm^3]	L_γ [10^4 L_{sun}]	L_ν/L_γ	Duration [years]
	Hydrogen	$H \to He$	3	5.9	2.1	–	1.2×10^7
	Helium	$He \to C, O$	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
	Carbon	$C \to Ne, Mg$	53	1.7×10^5	8.6	1.0	6.3×10^3
	Neon	$Ne \to O, Mg$	110	1.6×10^7	9.6	1.8×10^3	7.0
	Oxygen	$O \to Si$	160	9.7×10^7	9.6	2.1×10^4	1.7
	Silicon	$Si \to Fe, Ni$	270	2.3×10^8	9.6	9.2×10^5	6 days

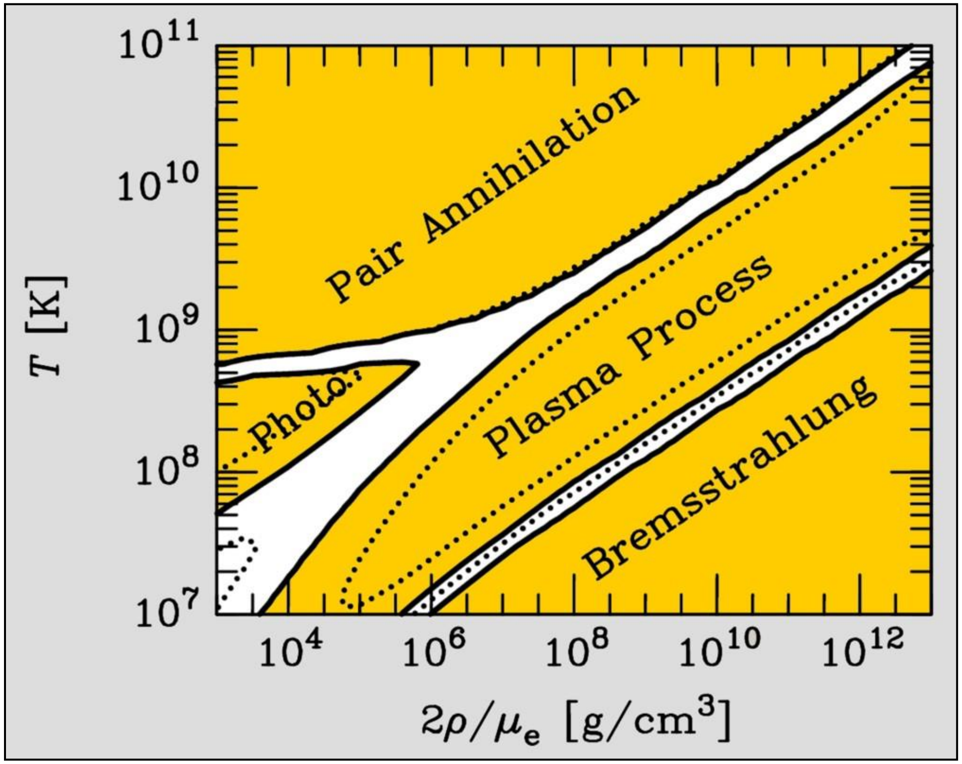
Neutrinos from Thermal Processes











These processes were first discussed in 1961–63 after V–A theory

Neutrinos from Thermal Processes

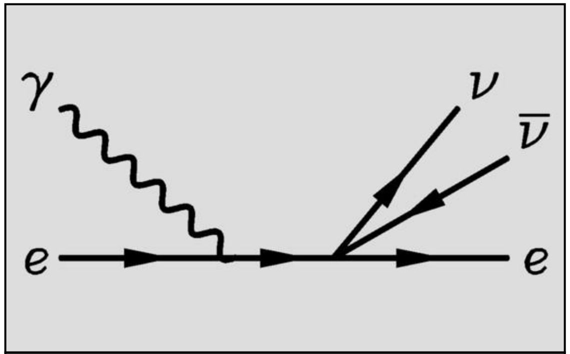
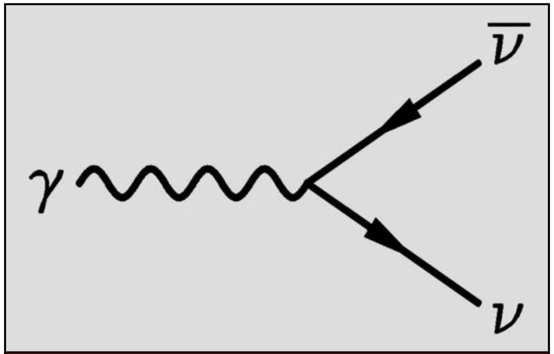
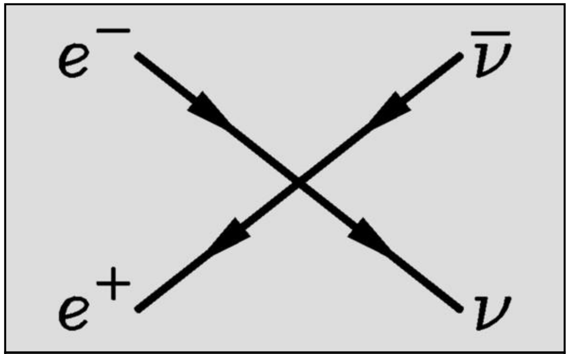


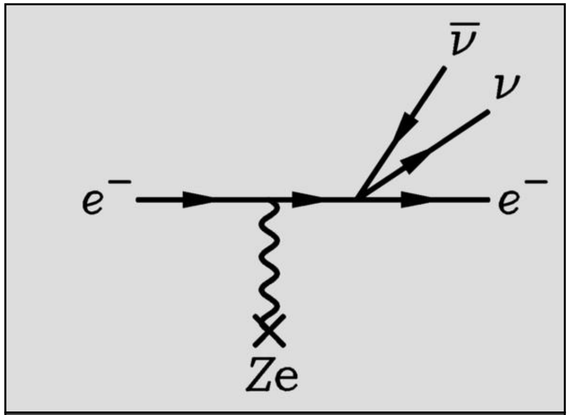
Photo (Compton)



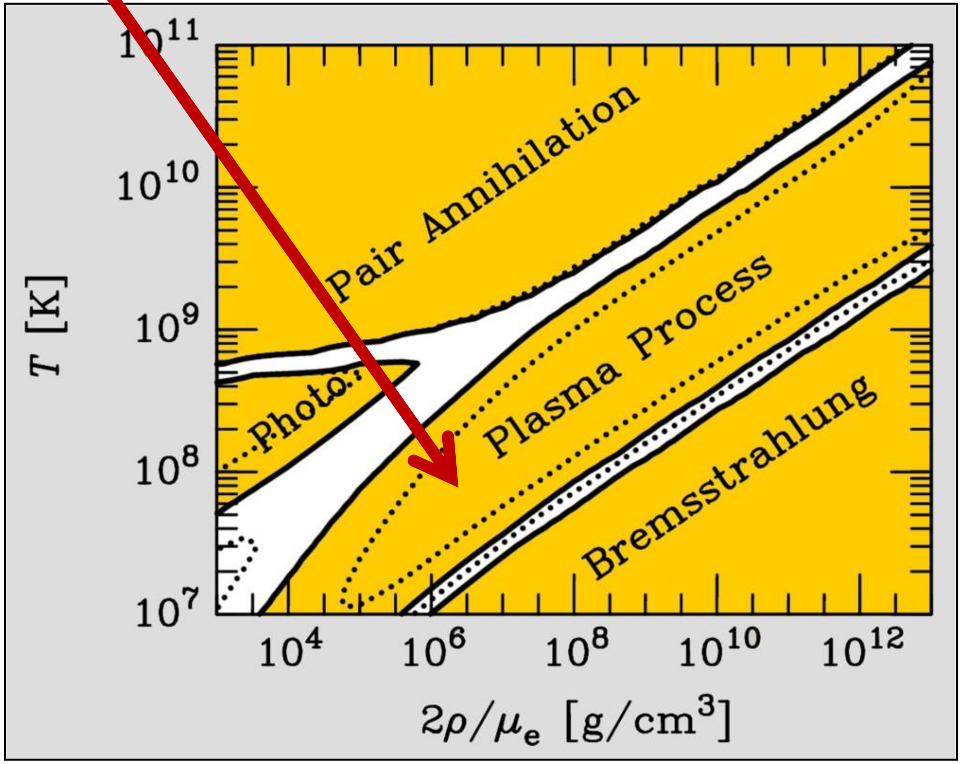
Plasmon decay



Pair annihilation

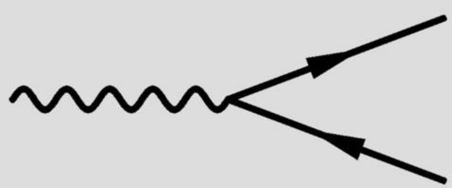
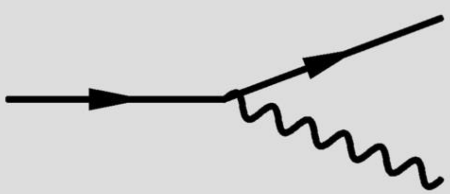


Bremsstrahlung

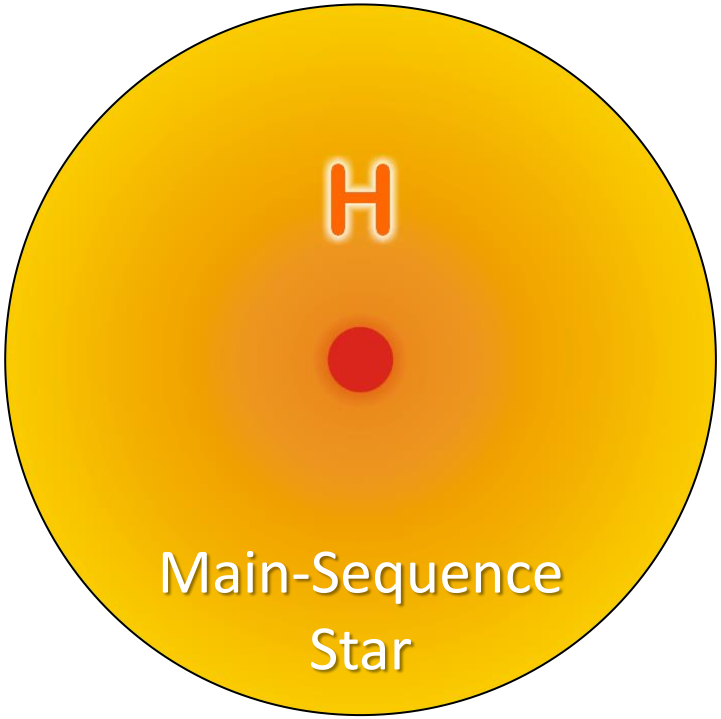


These processes were first discussed in 1961–63 after V–A theory

Plasmon Decay vs. Cherenkov Effect

Photon dispersion in a medium can be	"Time-like" $\omega^2 - k^2 > 0$	"Space-like" $\omega^2 - k^2 < 0$
Refractive index n ($k = n\,\omega$)	$n < 1$	$n > 1$
Example	• Ionized plasma • Normal matter for large photon energies	Water ($n \approx 1.3$), air, glass for visible frequencies
Allowed process that is forbidden in vacuum	Plasmon decay to neutrinos $\gamma \to \nu\bar{\nu}$ 	Cherenkov effect $e \to e + \gamma$ 

Self-Regulated Nuclear Burning



Virial Theorem: $\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm grav}\rangle$

Small Contraction
→ Heating
→ Increased nuclear burning
→ Increased pressure
→ Expansion

Additional energy loss ("cooling")
→ Loss of pressure
→ Contraction
→ Heating
→ Increased nuclear burning

Hydrogen burning at nearly fixed T
→ Gravitational potential nearly fixed:
$G_{\rm N}M/R \sim \text{constant}$
→ $R \propto M$ (More massive stars bigger)

Degenerate Stars ("White Dwarfs")

Assume temperature very small
$\to$ No thermal pressure
$\to$ Electron degeneracy is pressure source

Pressure ~ Momentum density × Velocity

- Electron density $n_e = p_\mathrm{F}^3/(3\pi^3)$
- Momentum p_F (Fermi momentum)
- Velocity $v \propto p_\mathrm{F}/m_e$
- Pressure $P \propto p_\mathrm{F}^5 \propto \rho^{5/3} \propto M^{5/3}R^{-5}$
- Density $\rho \propto MR^{-3}$

Hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{G_\mathrm{N} M_r \rho}{r^2}$$

With $dP/dr \sim -P/R$ we have

$$P \propto G_\mathrm{N} M \rho R^{-1} \propto G_\mathrm{N} M^2 R^{-4}$$

Inverse mass radius relationship

$$R \propto M^{-1/3}$$

$$R = 10{,}500\ \mathrm{km} \left(\frac{0.6\, M_\odot}{M}\right)^{1/3} (2Y_e)^{5/3}$$

(Y_e electrons per nucleon)

For sufficiently large stellar mass M, electrons become relativistic

- Velocity = speed of light
- Pressure

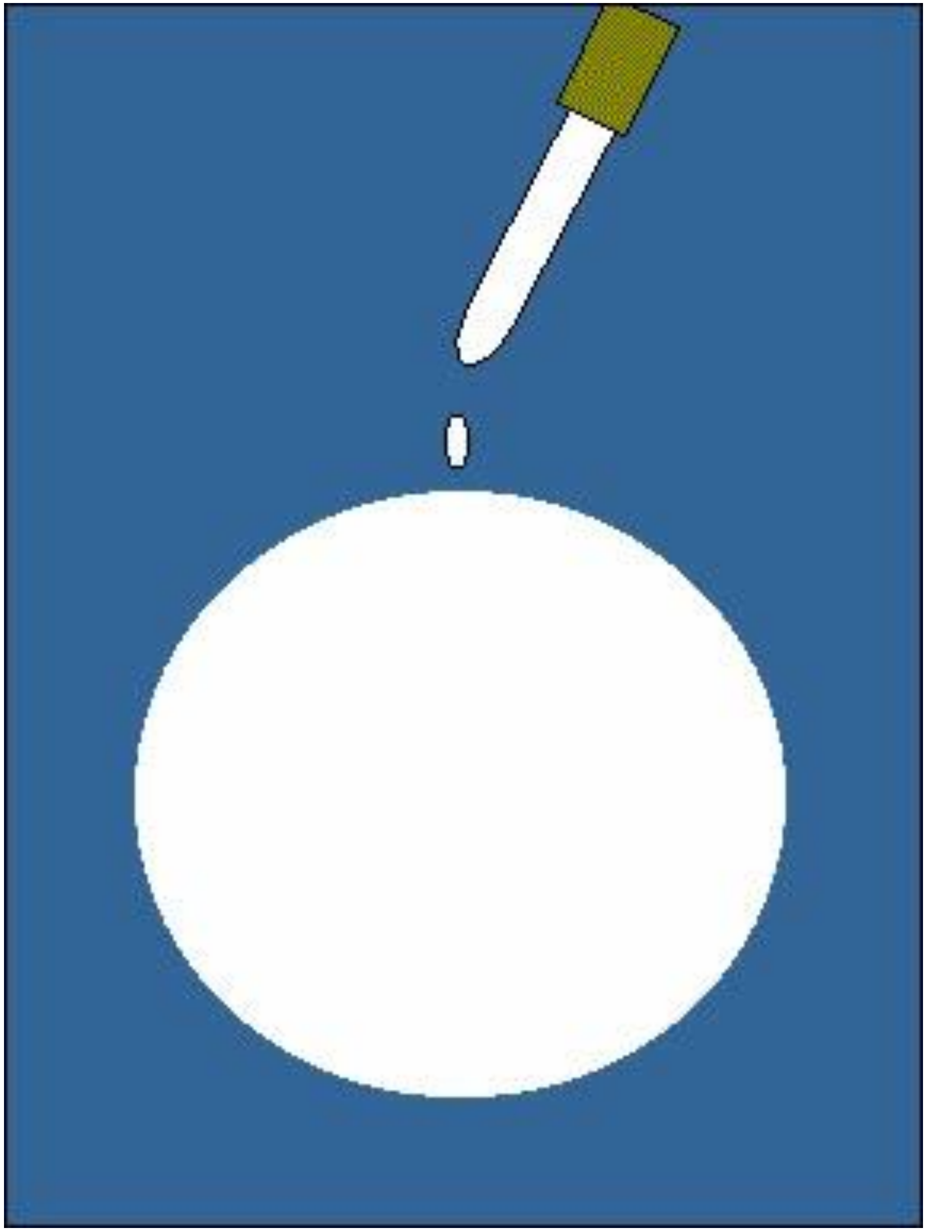
$$P \propto p_\mathrm{F}^4 \propto \rho^{4/3} \propto M^{4/3}R^{-4}$$

No stable configuration

Chandrasekhar mass limit

$$M_\mathrm{Ch} = 1.457\, M_\odot\, (2Y_e)^2$$

Degenerate Stars ("White Dwarfs")



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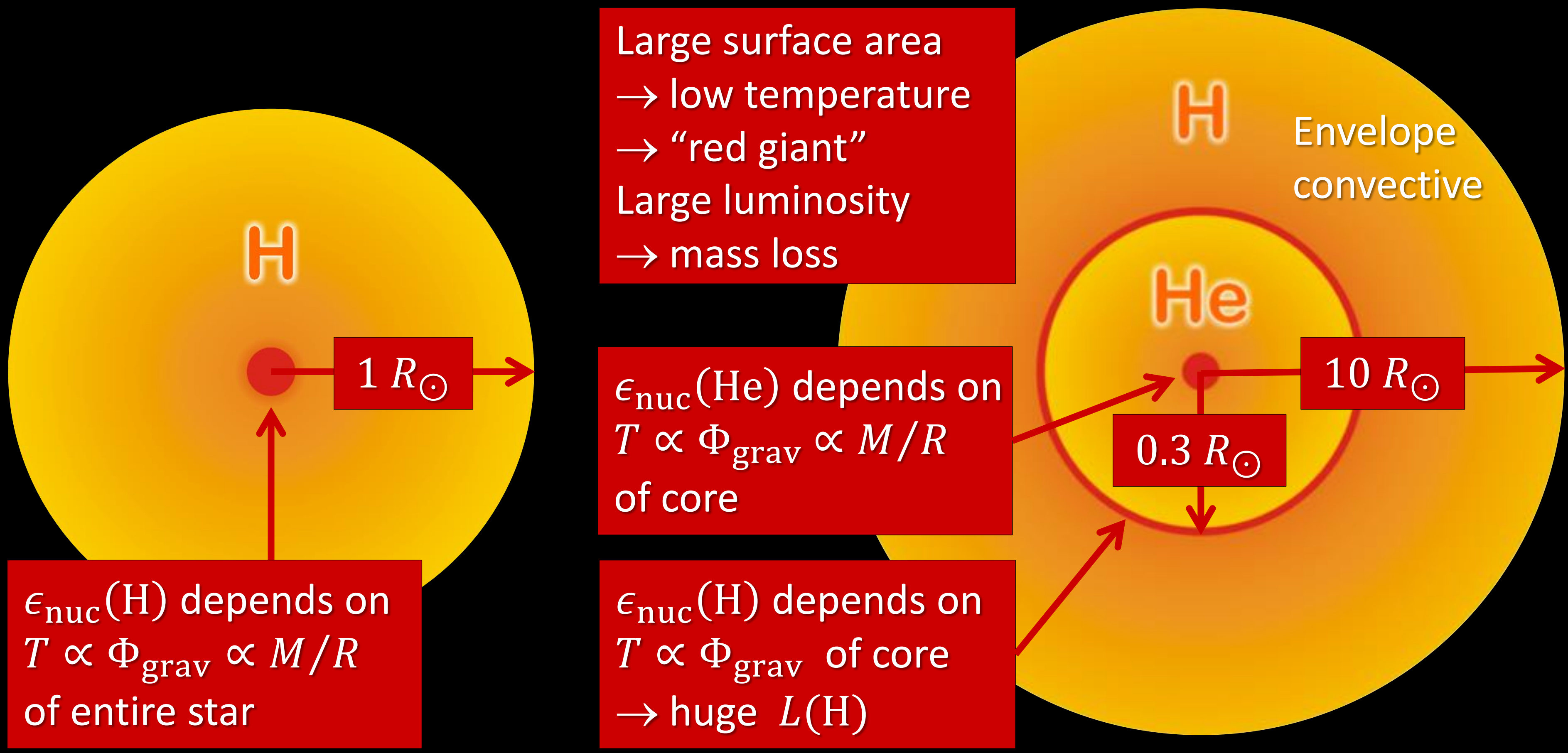
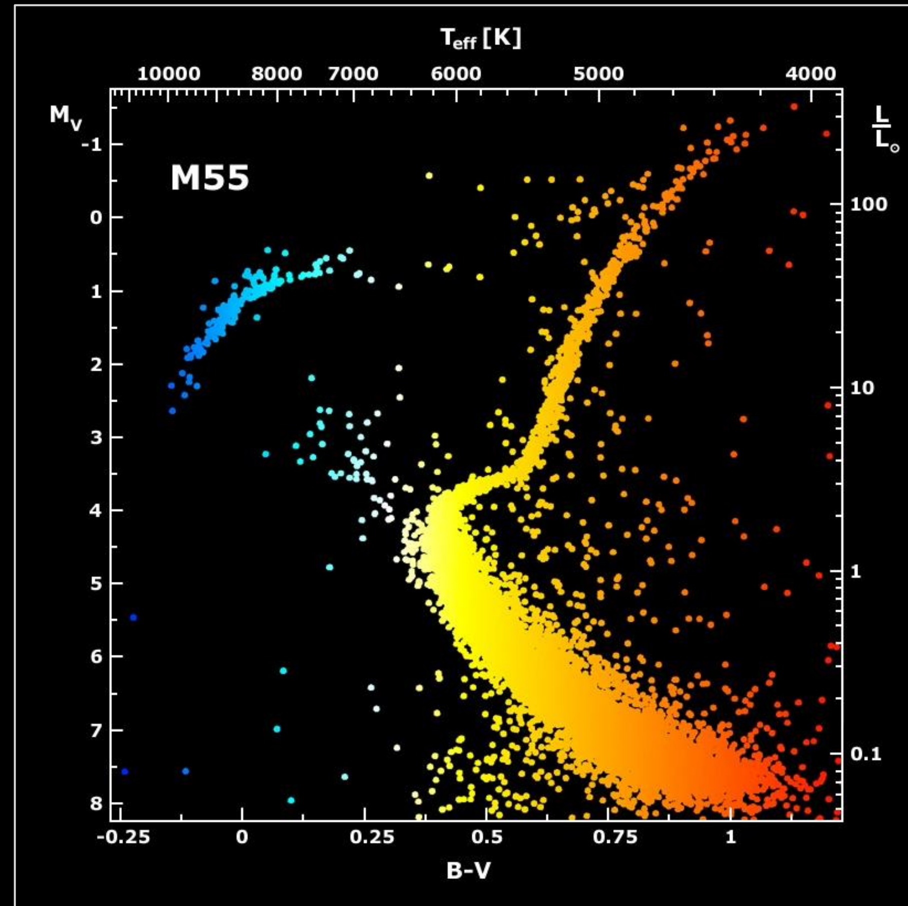
Giant Stars

Main-sequence star $1M_\odot$
(Hydrogen burning)

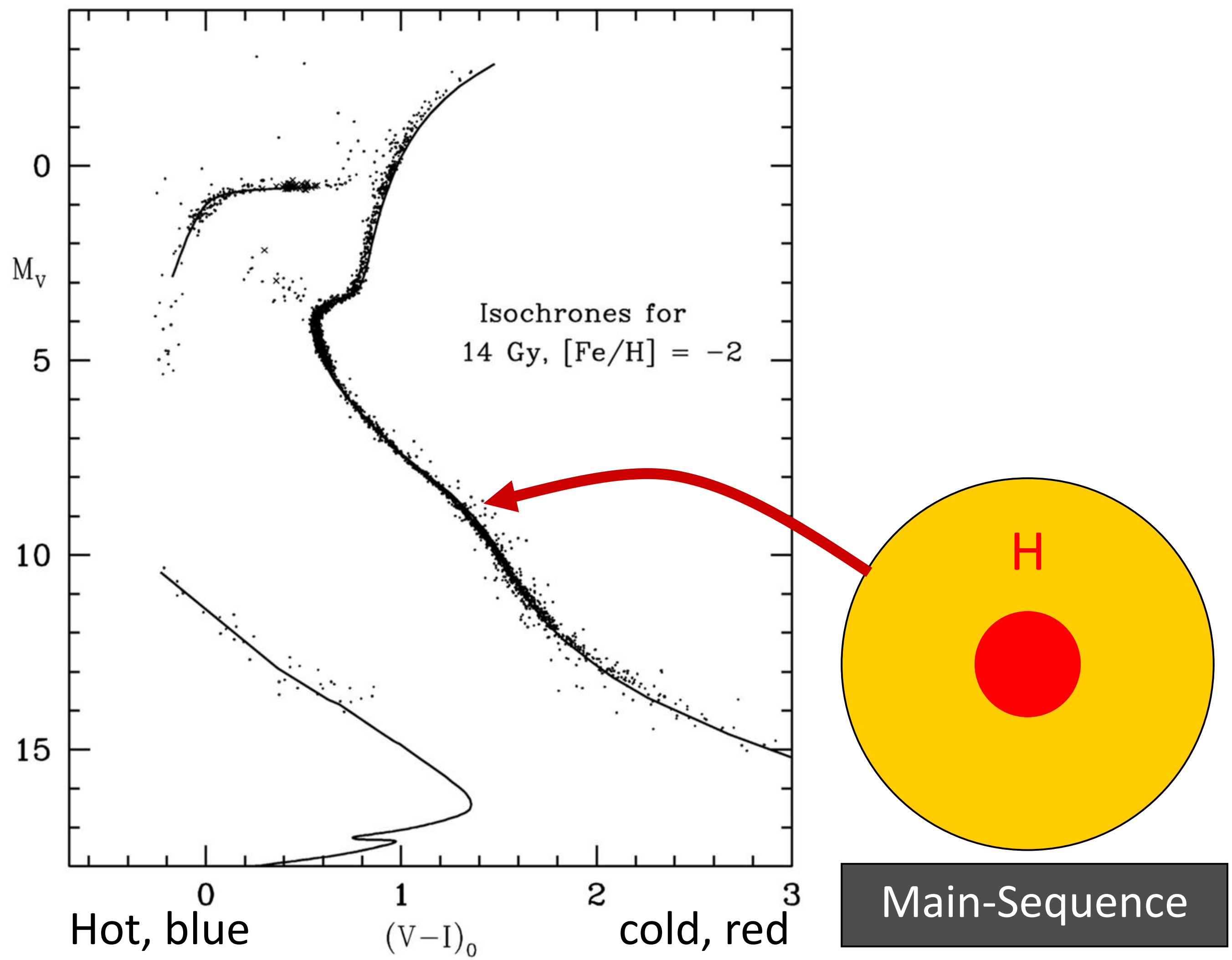
Helium-burning star $1M_\odot$



Galactic Globular Cluster M55



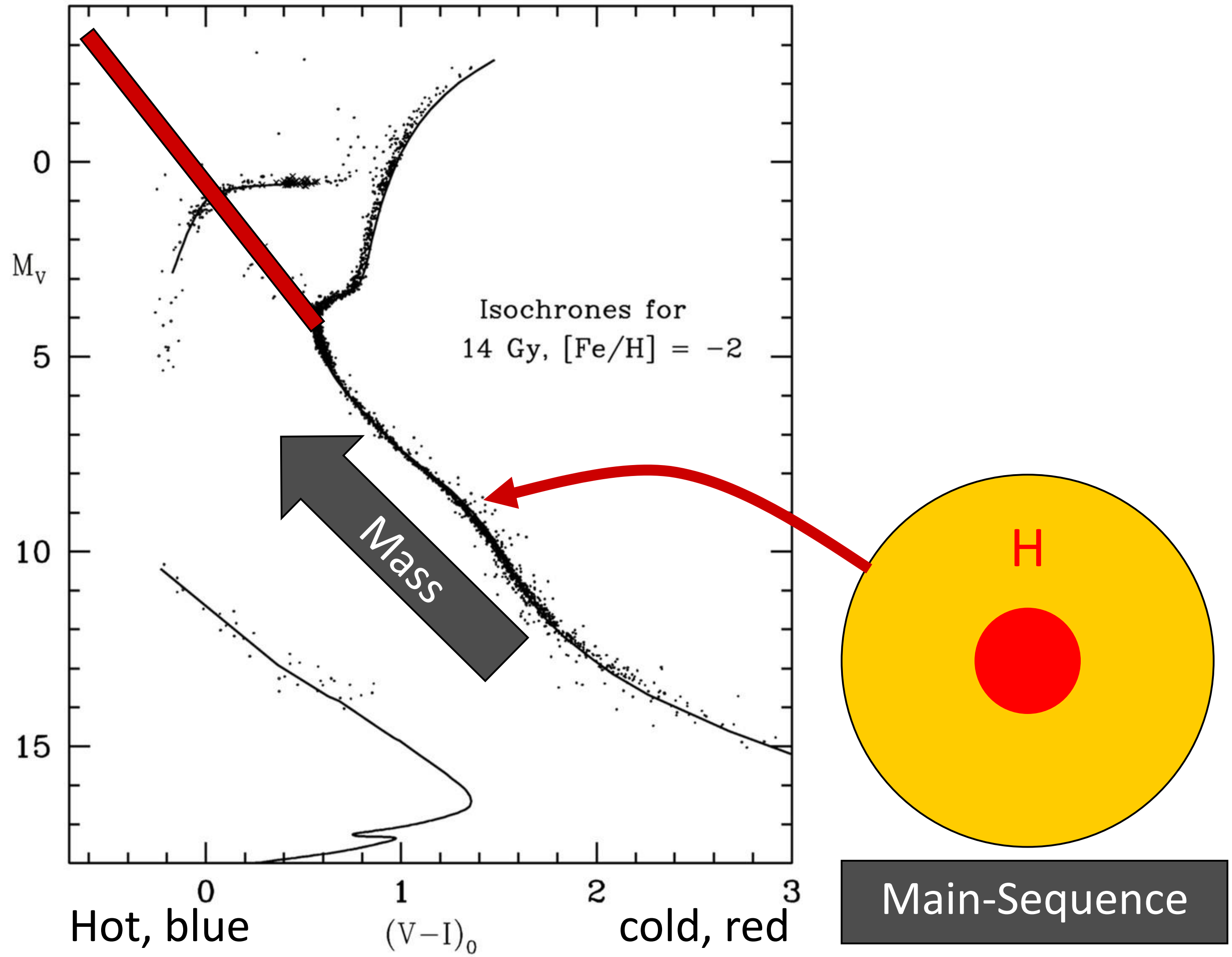
Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters

- Stars with M so large that they have burnt out in a Hubble time
- No new star formation in globular clusters



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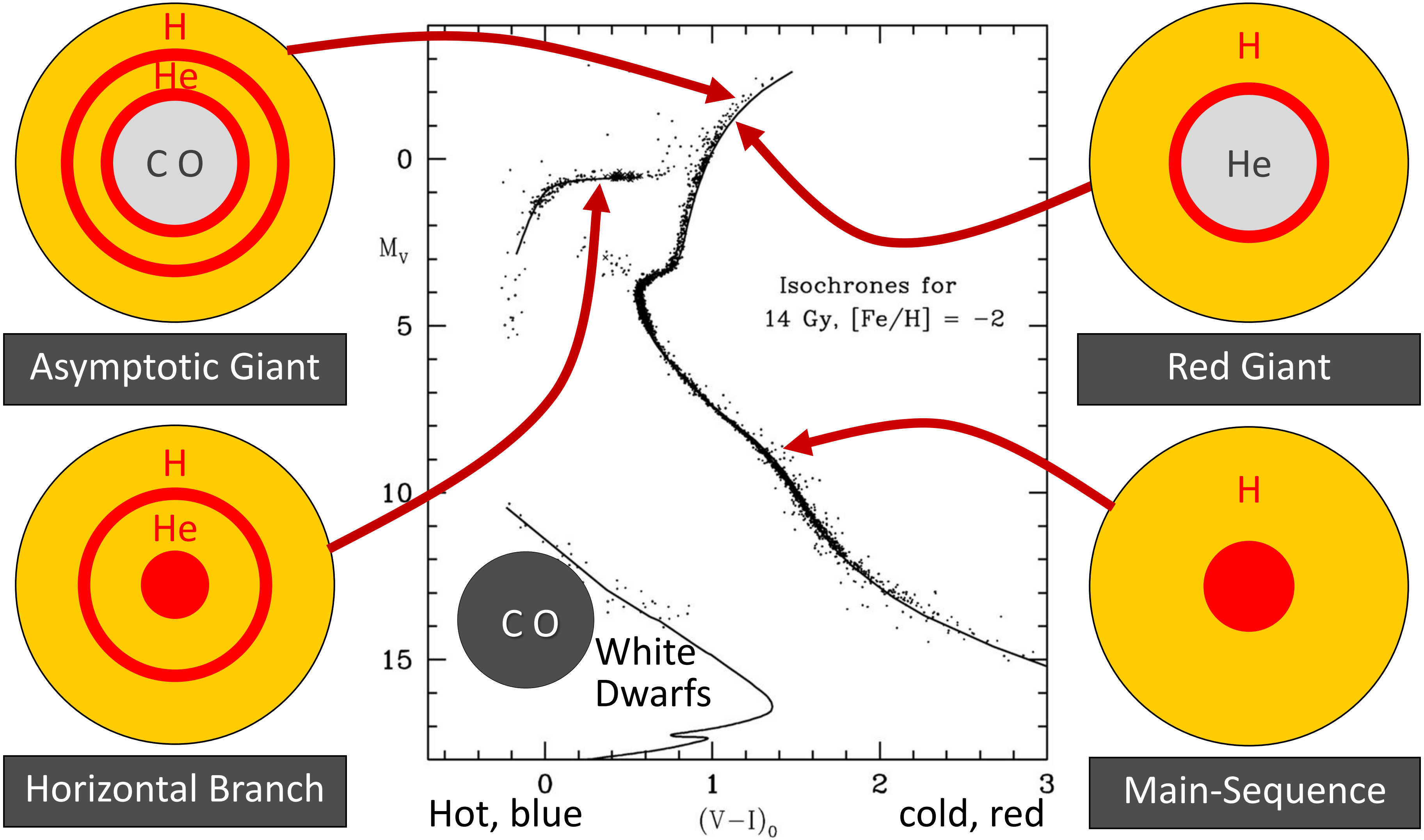
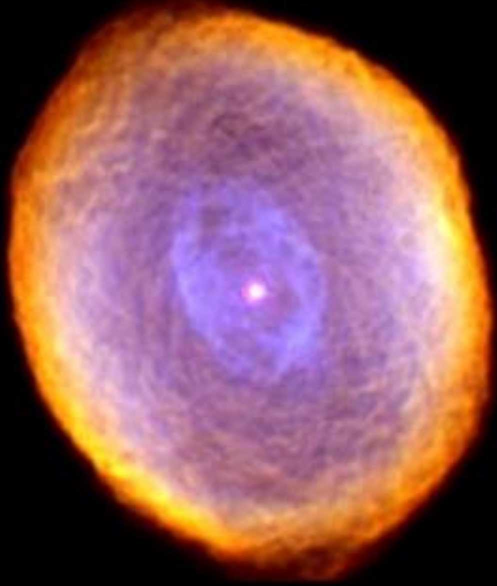
Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Planetary Nebulae

Hour Glass Nebula



Planetary Nebula IC 418

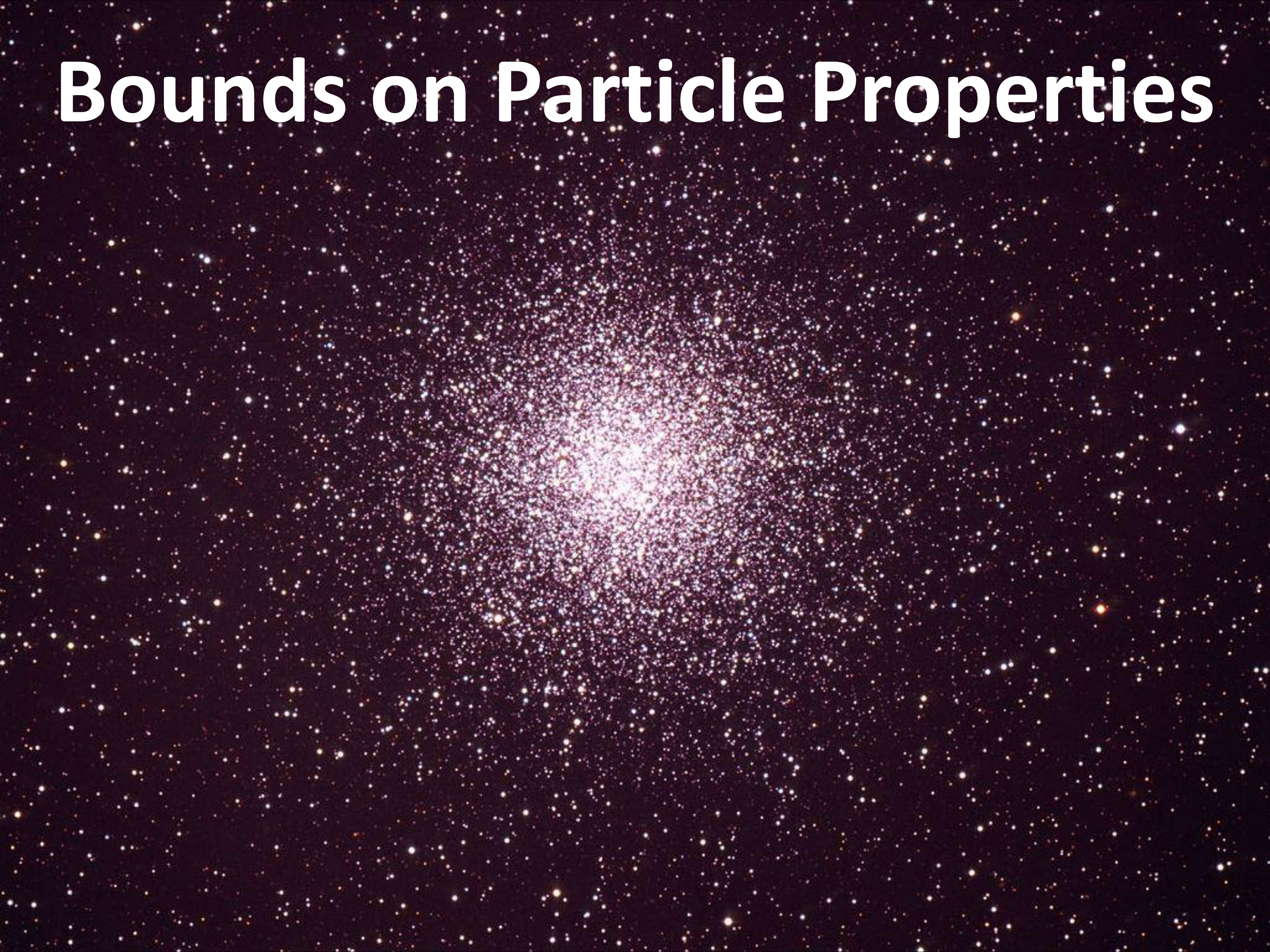
Eskimo Nebula

Planetary Nebula NGC 3132

Evolution of Stars

$M < 0.08\ M_{sun}$	Never ignites hydrogen → cools ("hydrogen white dwarf")		Brown dwarf
$0.08 < M \lesssim 0.8\ M_{sun}$	Hydrogen burning not completed in Hubble time		Low-mass main-squence star
$0.8 \lesssim M \lesssim 2\ M_{sun}$	Degenerate helium core after hydrogen exhaustion		• Carbon-oxygen white dwarf • Planetary nebula
$2 \lesssim M \lesssim 5–8\ M_{sun}$	Helium ignition non-degenerate		
$8\ M_{sun} \lesssim M < ???$	All burning cycles → Onion skin structure with degenerate iron core	Core collapse supernova	• Neutron star (often pulsar) • Sometimes black hole • Supernova remnant (SNR), e.g. crab nebula

Bounds on Particle Properties



PHYSICAL REVIEW VOLUME 132, NUMBER 3 1 NOVEMBER 1963

Electromagnetic Properties of the Neutrino

JEREMY BERNSTEIN* AND MALVIN RUDERMAN†
Department of Physics, New York University, New York, New York

AND

GERALD FEINBERG‡
Department of Physics, Columbia University, New York, New York
(Received 11 June 1963)

In this note we make a detailed survey of the experimental information on the neutrino charge, charge radius, and magnetic moment. Both weak-interaction data and astrophysical results can be used to give precise limits to these quantities, independent of the supposition that the weak interactions are charge conserving.

I. INTRODUCTION

MOST physicists now accept the prospect that there are two neutrinos—ν_e and ν_μ—identical except for interaction (ν_e couples weakly with electrons and ν_μ with muons) and that these neutrinos have the simplest properties compatible with existing experimental evidence; i.e., zero mass, charge, electric, and magnetic dipole moments. However, the weak interactions have produced so many surprises that it is worthwhile, from time to time, to study the *experimental* limits that have been set on these quantities. In this note we present a systematic survey of the properties of the two neutrinos that can be inferred from experiment.

II. PROPERTIES

We begin by listing the properties of the neutrinos to

tritium experiments give

$$m_{\nu_e} < 200 \text{ eV}, \tag{2}$$

and the experiments are consistent with $m_{\nu_e}=0$.

(2) ν_μ: The mass of the muon neutrino is the least well known of the parameters associated with either neutrino. The best measurements of it come from the energy-momentum balance in π decay. The experiment of Barkas *et al.*[3] gives[4]

$$m_{\nu_\mu} < 3.5 \text{ MeV}. \tag{3}$$

The reason for this uncertainty lies in the kinematic fact that the small neutrino mass is given as the difference between measured quantities of order 1. In the $\pi \to \mu + \nu$ decay, the accuracy with which the neutrino mass can be determined is given by

Neutrino Electromagnetic Form Factors

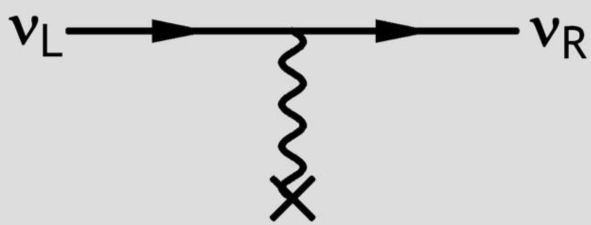
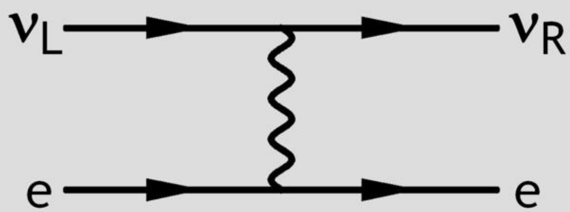
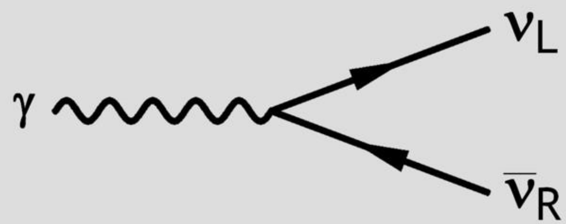
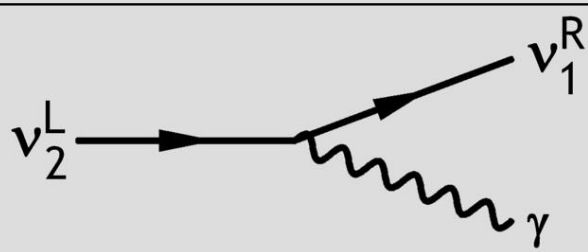
Effective coupling of electromagnetic field to a neutral fermion

$$
\begin{aligned}
L_{\text{eff}} = & -F_1 \overline{\Psi}\gamma_\mu \Psi\, A^\mu && \text{Charge } e_\nu = F_1(0) = 0 \\
& -G_1 \overline{\Psi}\gamma_\mu\gamma_5 \Psi\, \partial_\nu F^{\mu\nu} && \text{Anapole moment } G_1(0) \\
& -\frac{1}{2} F_2\, \overline{\Psi}\sigma_{\mu\nu} \Psi\, F^{\mu\nu} && \text{Magnetic dipole moment } \mu = F_2(0) \\
& -\frac{1}{2} G_2\, \overline{\Psi}\sigma_{\mu\nu}\gamma_5 \Psi\, F^{\mu\nu} && \text{Electric dipole moment } \varepsilon = G_2(0)
\end{aligned}
$$

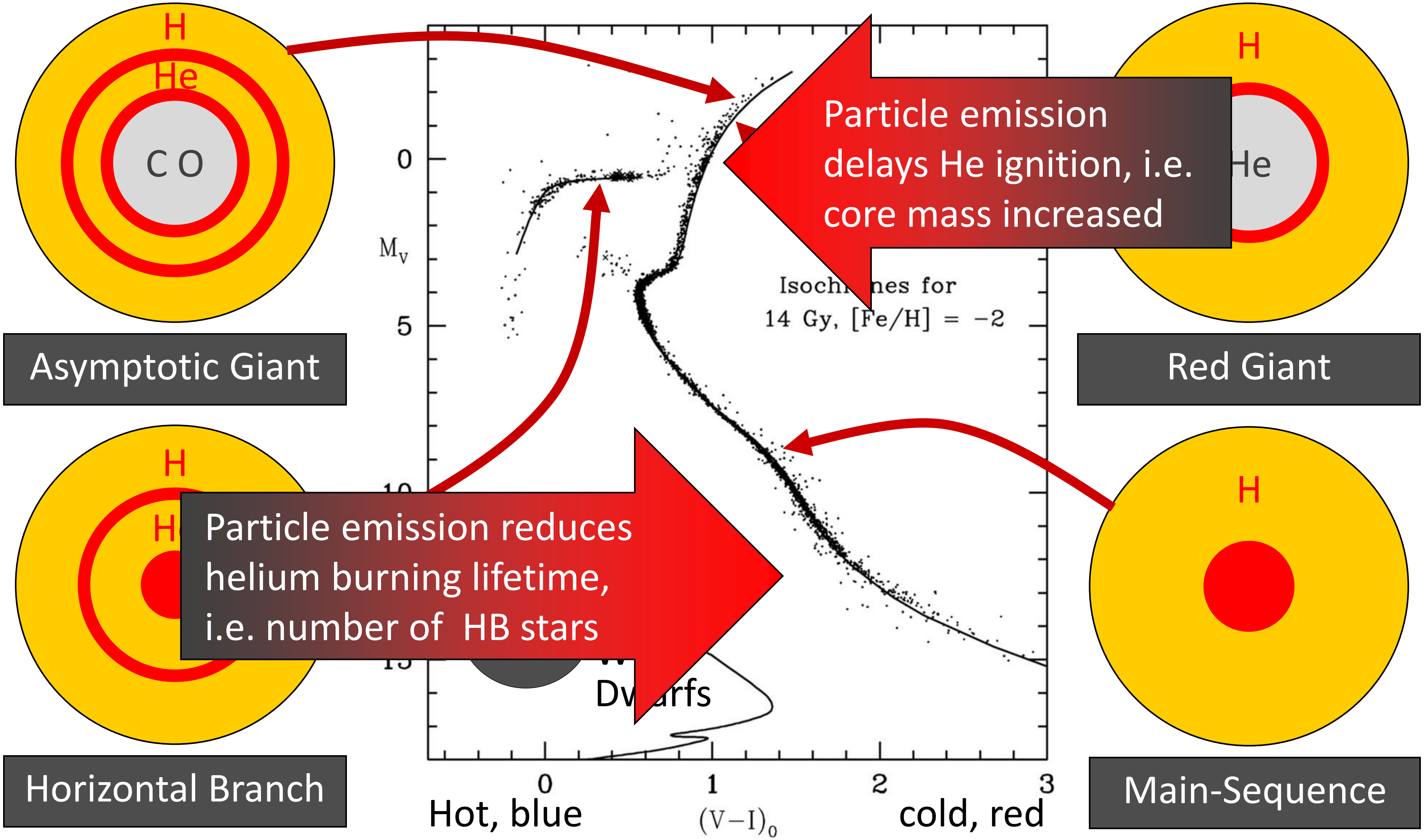
- Charge form factor $F_1(q^2)$ and anapole $G_1(q^2)$ are short-range interactions if charge $F_1(0) = 0$
- Connect states of equal helicity
- In the standard model they represent radiative corrections to weak interaction

- Dipole moments connect states of opposite helicity
- Violation of individual flavor lepton numbers (neutrino mixing)
  $\rightarrow$ Magnetic or electric dipole moments can connect different flavors or different mass eigenstates ("Transition moments")
- Usually measured in "Bohr magnetons" $\mu_B = e/2m_e$

Consequences of Neutrino Dipole Moments

Spin precession in external E or B fields		$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix} = \begin{pmatrix}0 & \mu_\nu B_\perp\\ \mu_\nu B_\perp & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix}$
Scattering	$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(C_V + C_A)^2 + (C_V - C_A)^2\left(1-\frac{T}{E}\right)^2 + (C_V^2 - C_A^2)\frac{m_e T}{E^2}\right] + \alpha\mu_\nu^2\left(\frac{1}{T}+\frac{1}{E}\right)$ 	T electron recoil energy
Plasmon decay in stars		$\Gamma = \frac{\mu_\nu^2}{24\pi}\,\omega_{\rm pl}^3$
Decay or Cherenkov effect		$\Gamma = \frac{\mu_\nu^2}{8\pi}\left(\frac{m_2^2 - m_1^2}{m_2}\right)^3$

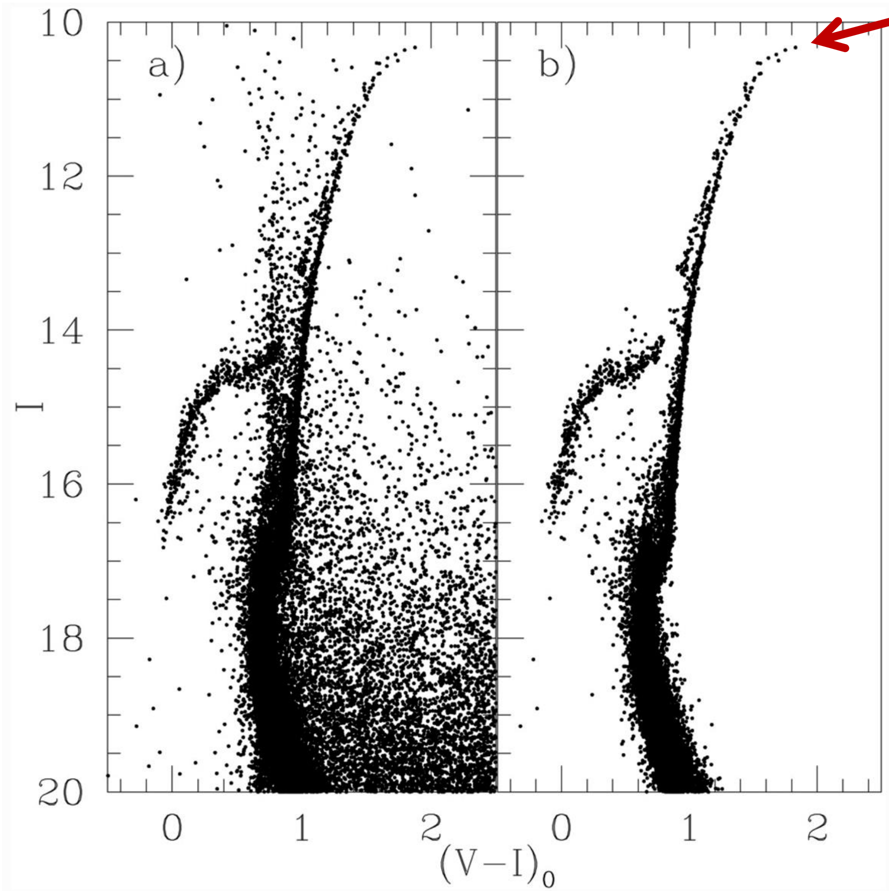
Color-Magnitude Diagram for Globular Clusters



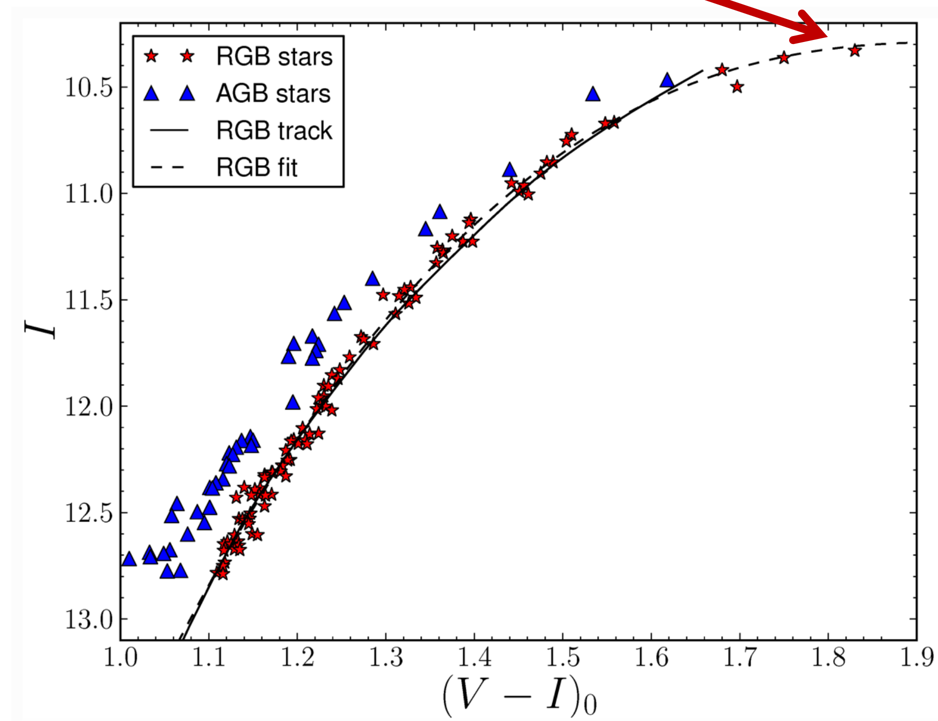
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram of Globular Cluster M5

Brightest red giant
measures nonstandard energy loss



CMD (a) before and (b) after cleaning

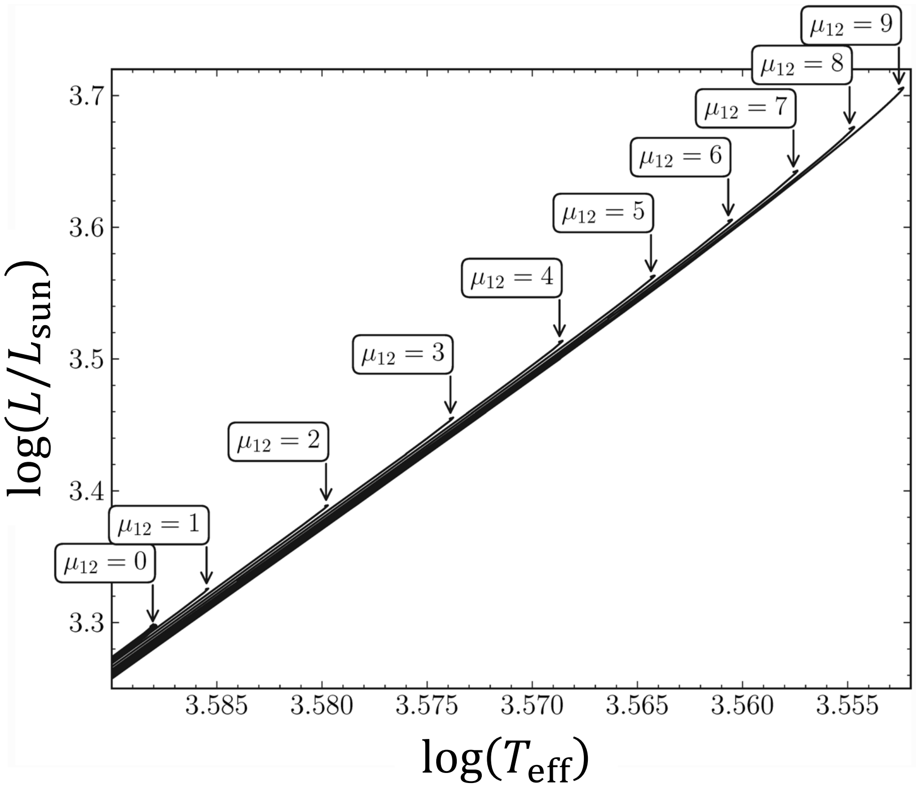


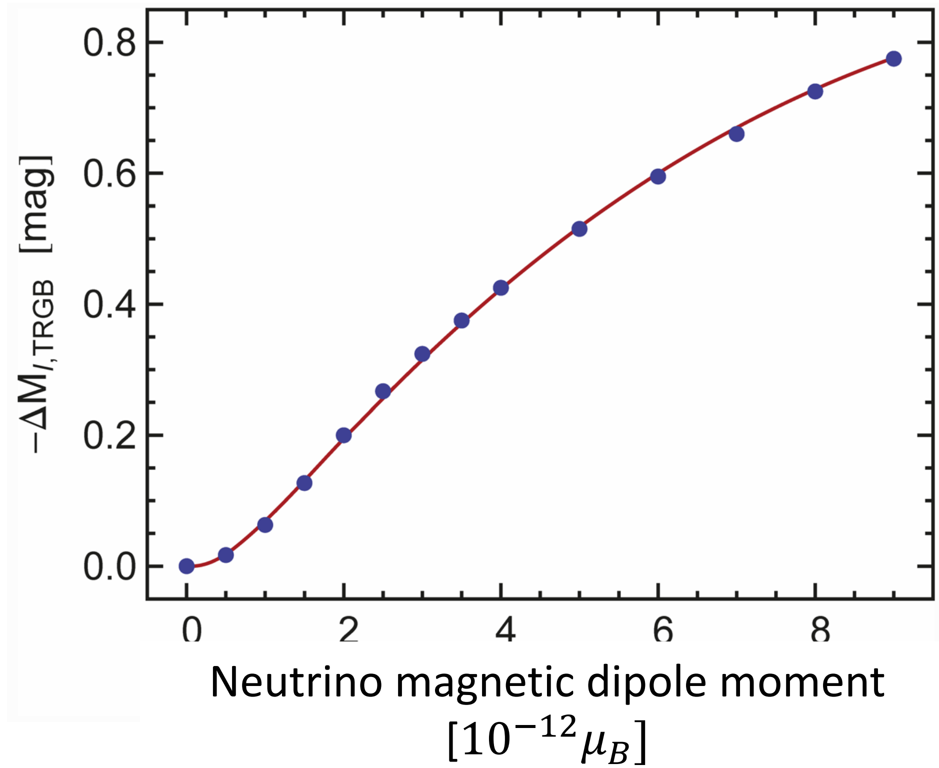
CMD of brightest 2.5 mag of RGB

Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

Helium Ignition for Low-Mass Red Giants

Brightness increase at He ignition by nonstanderd neutrino losses

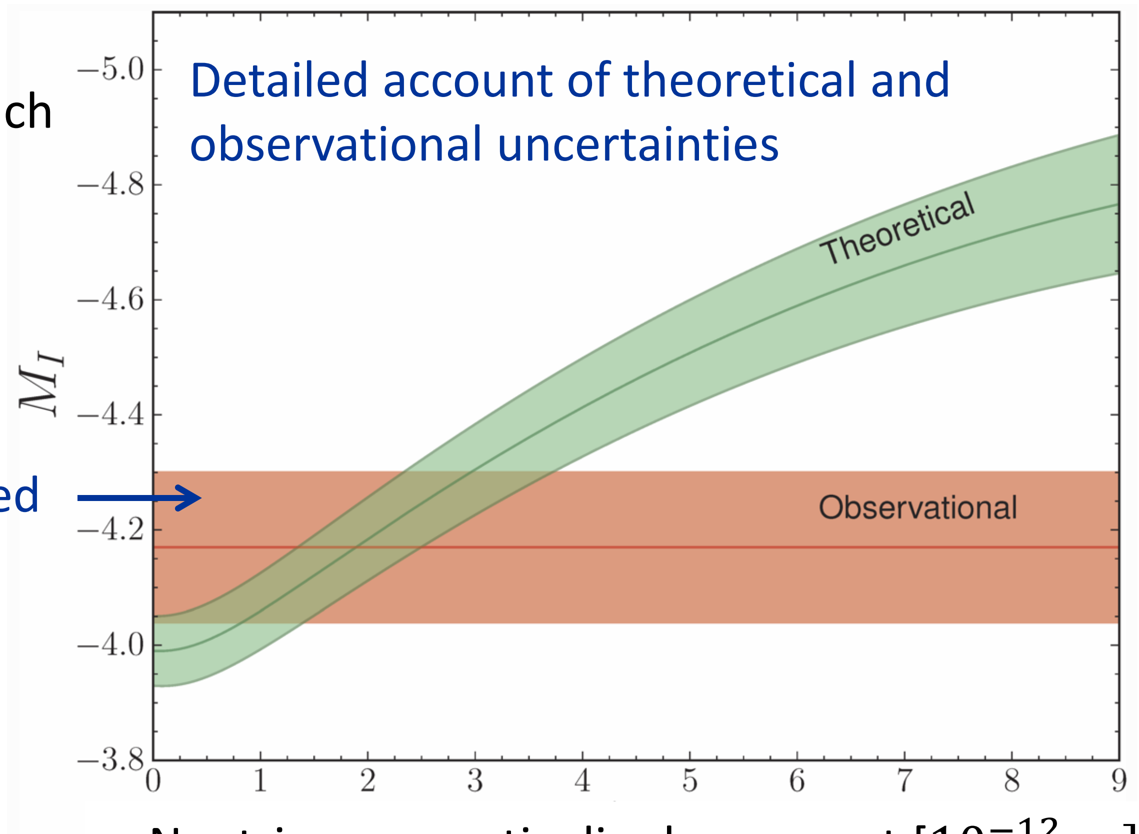




Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

Neutrino Dipole Limits from Globular Cluster M5

I-band brightness
of tip of red-giant brach
[magnitudes]



- Uncertainty dominated by distance
- Can be improved in future (GAIA mission)

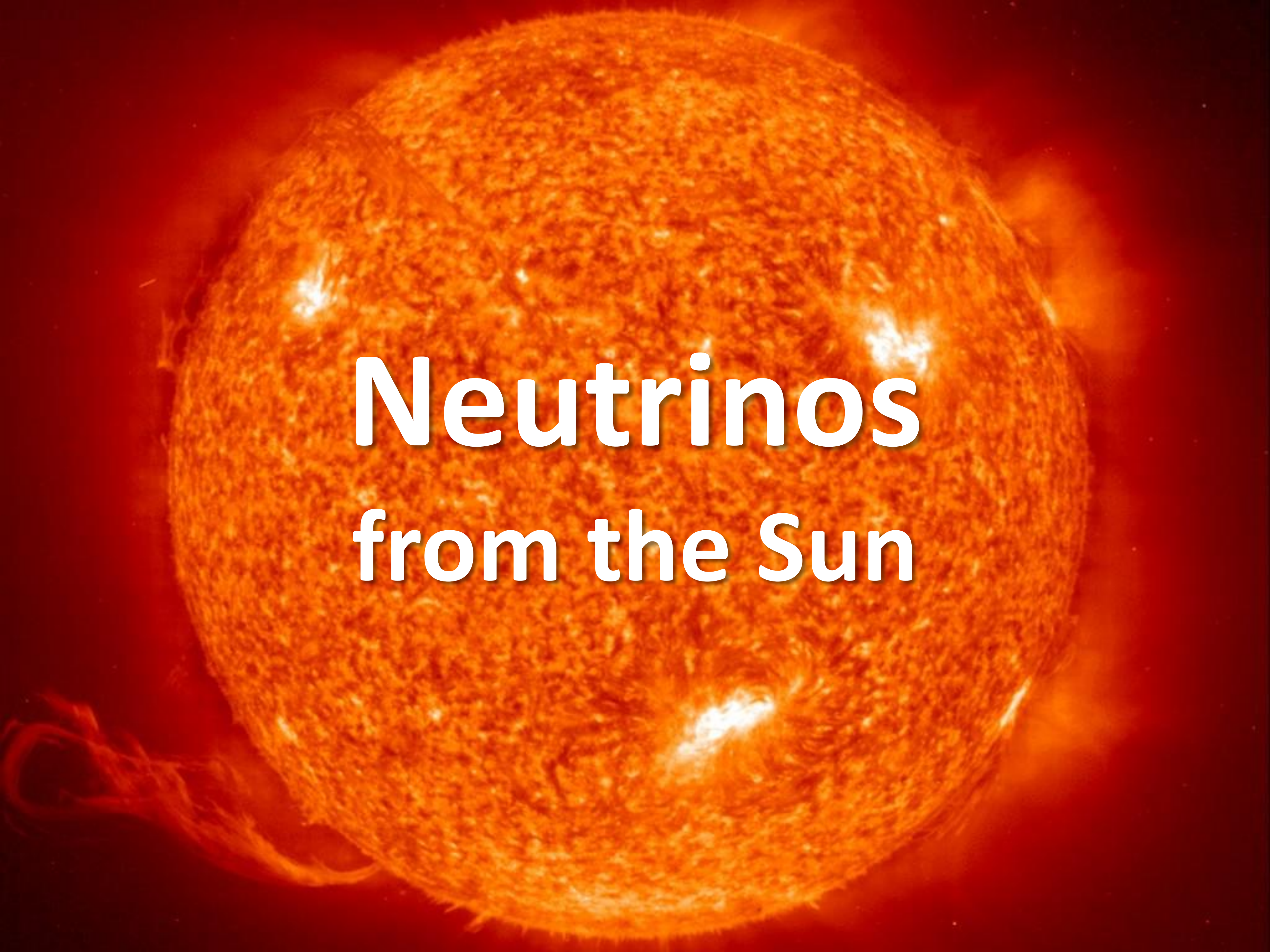
Neutrino magnetic dipole moment $[10^{-12}\mu_B]$

Most restrictive limit on neutrino electromagnetic properties

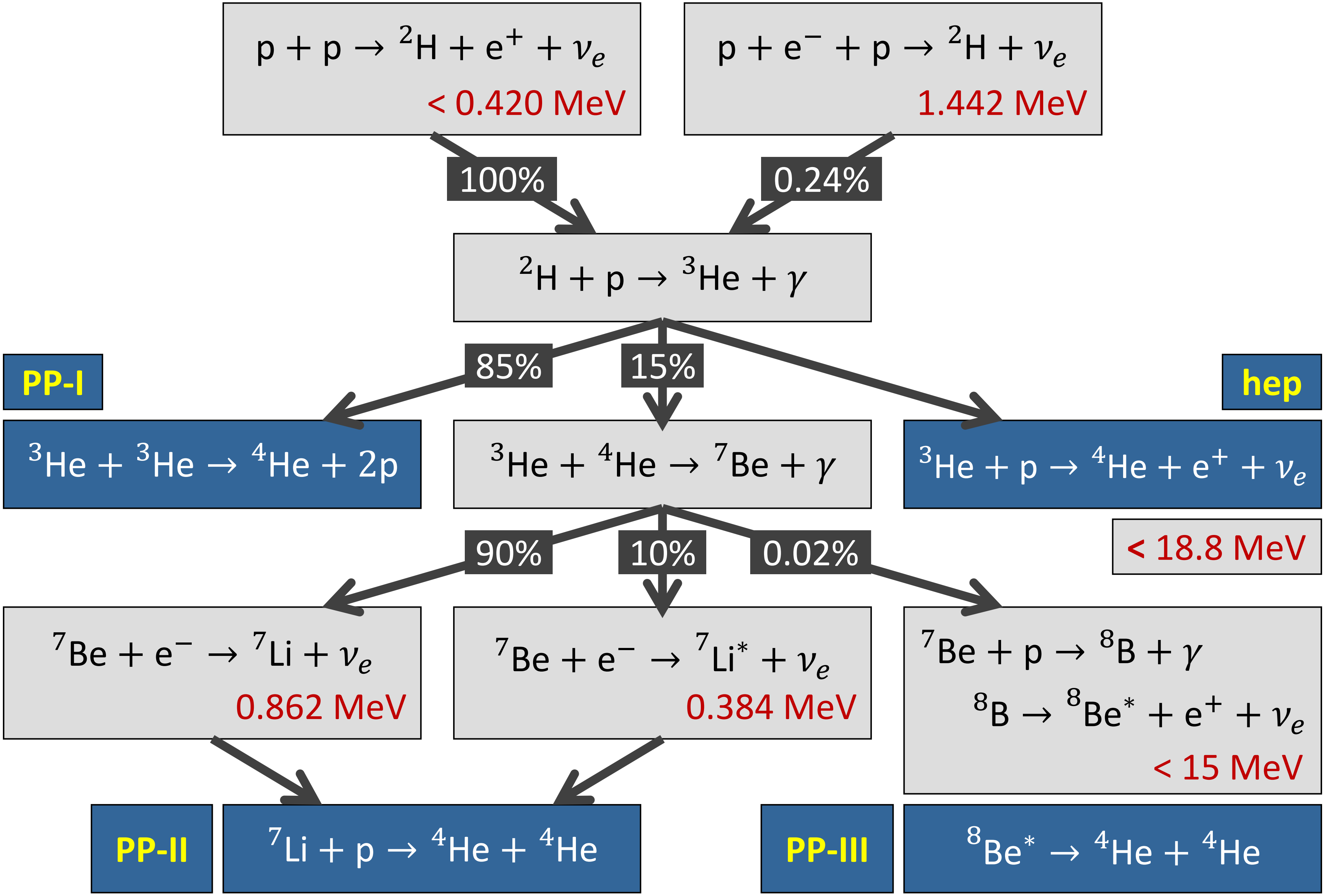
$$\mu_\nu < \begin{cases} 2.6 \times 10^{-12}\mu_B & (68\%\ \mathrm{CL}) \\ 4.5 \times 10^{-12}\mu_B & (95\%\ \mathrm{CL}) \end{cases}$$

Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

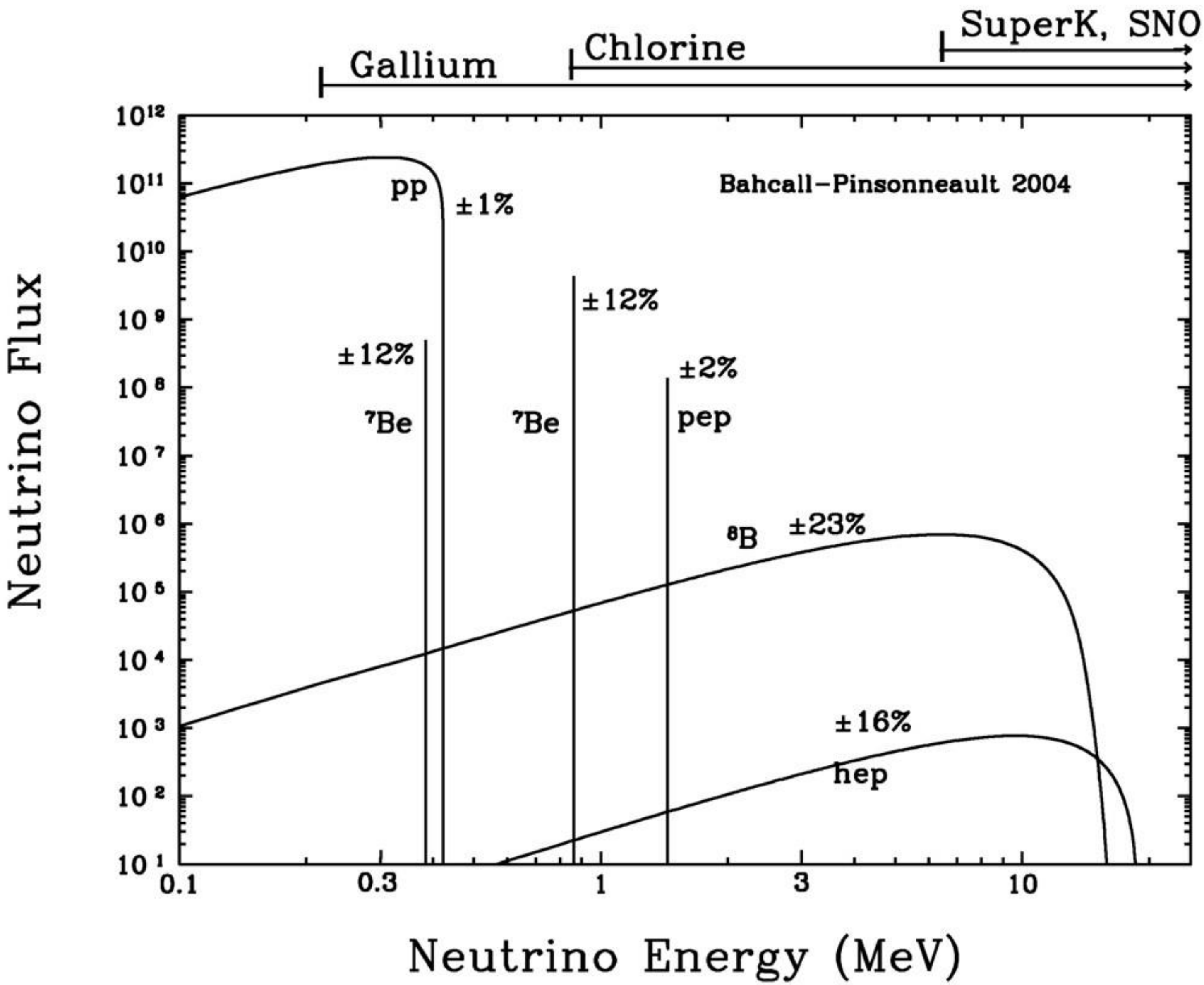
Neutrinos from the Sun



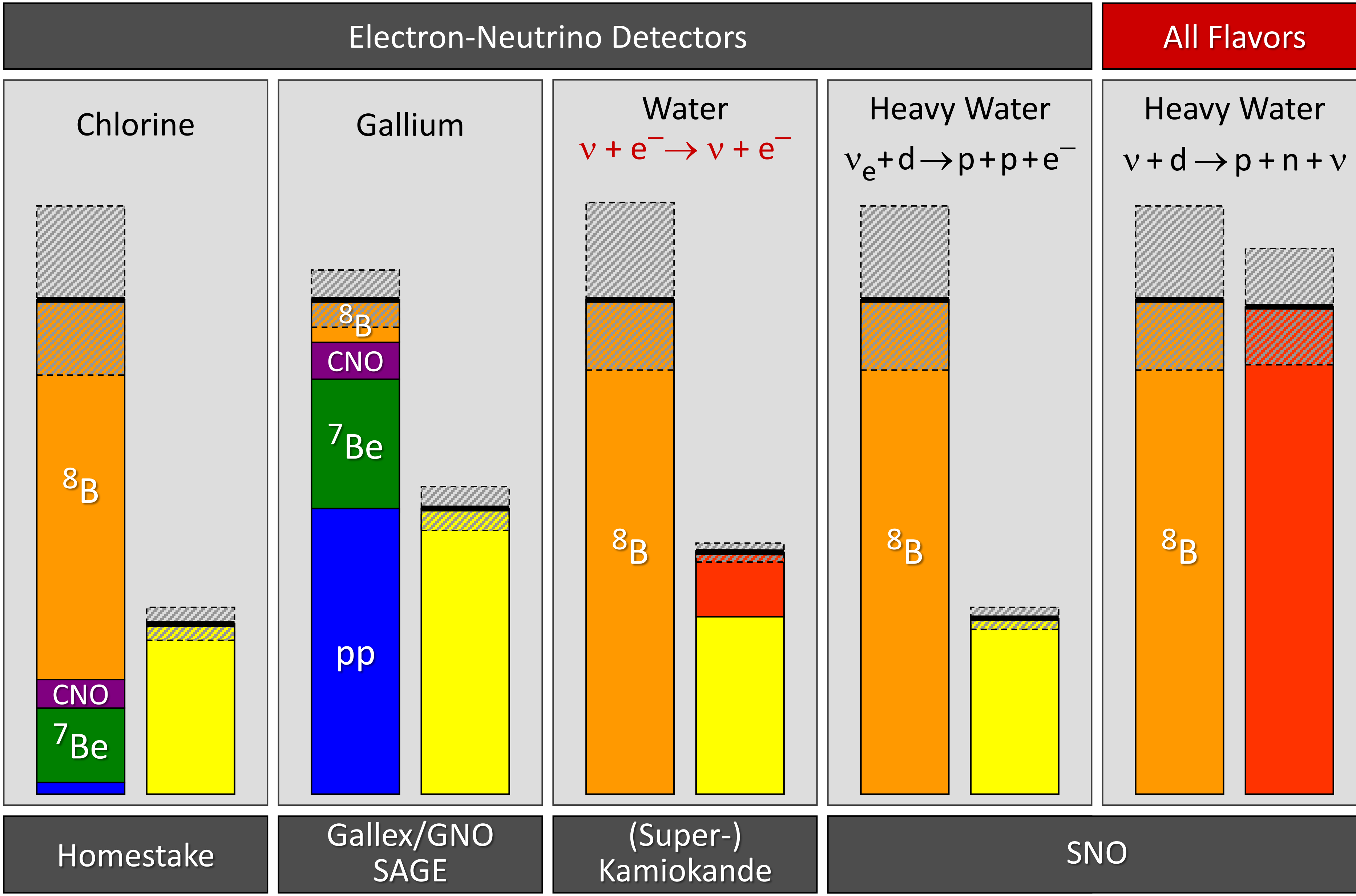
Hydrogen Burning: Proton-Proton Chains



Solar Neutrino Spectrum



Missing Neutrinos from the Sun



VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

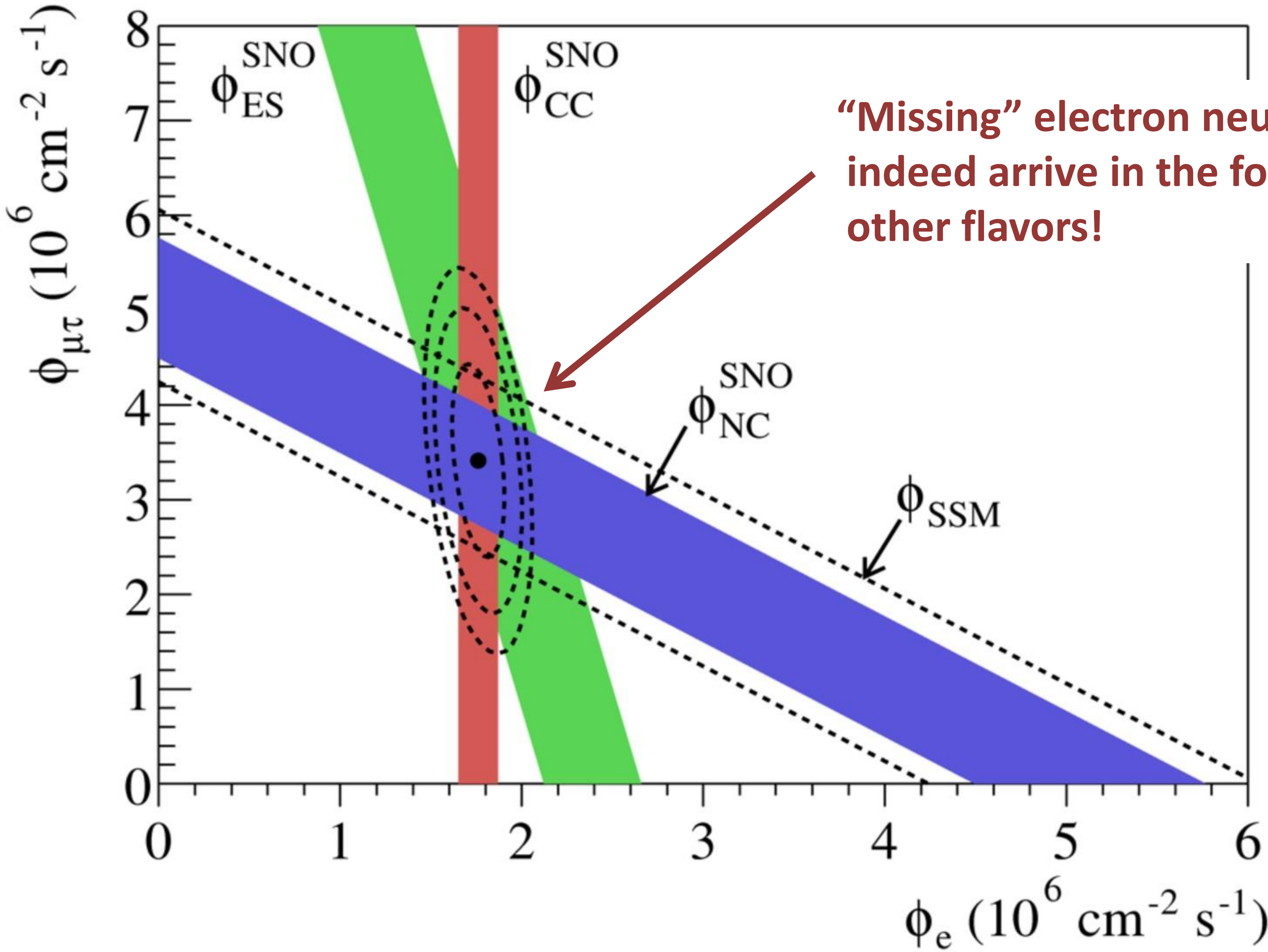
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

Herbert Hwa Chen
(1942–1987)

- Proposal to use heavy water as target (1984)
- Sensitive to all neutrino flavors
- Heavy water available on loan from the Canadian strategic reserve of CANDU reactor program
- Formation of Sudbury Neutrino Observatory project (SNO)
- After H. Chen had passed away (7 Nov 1987), leadership taken over by Art McDonald (then Princeton)
- Measurement of full solar neutrino flux 2002
- Nobel prize 2015 for Art McDonald

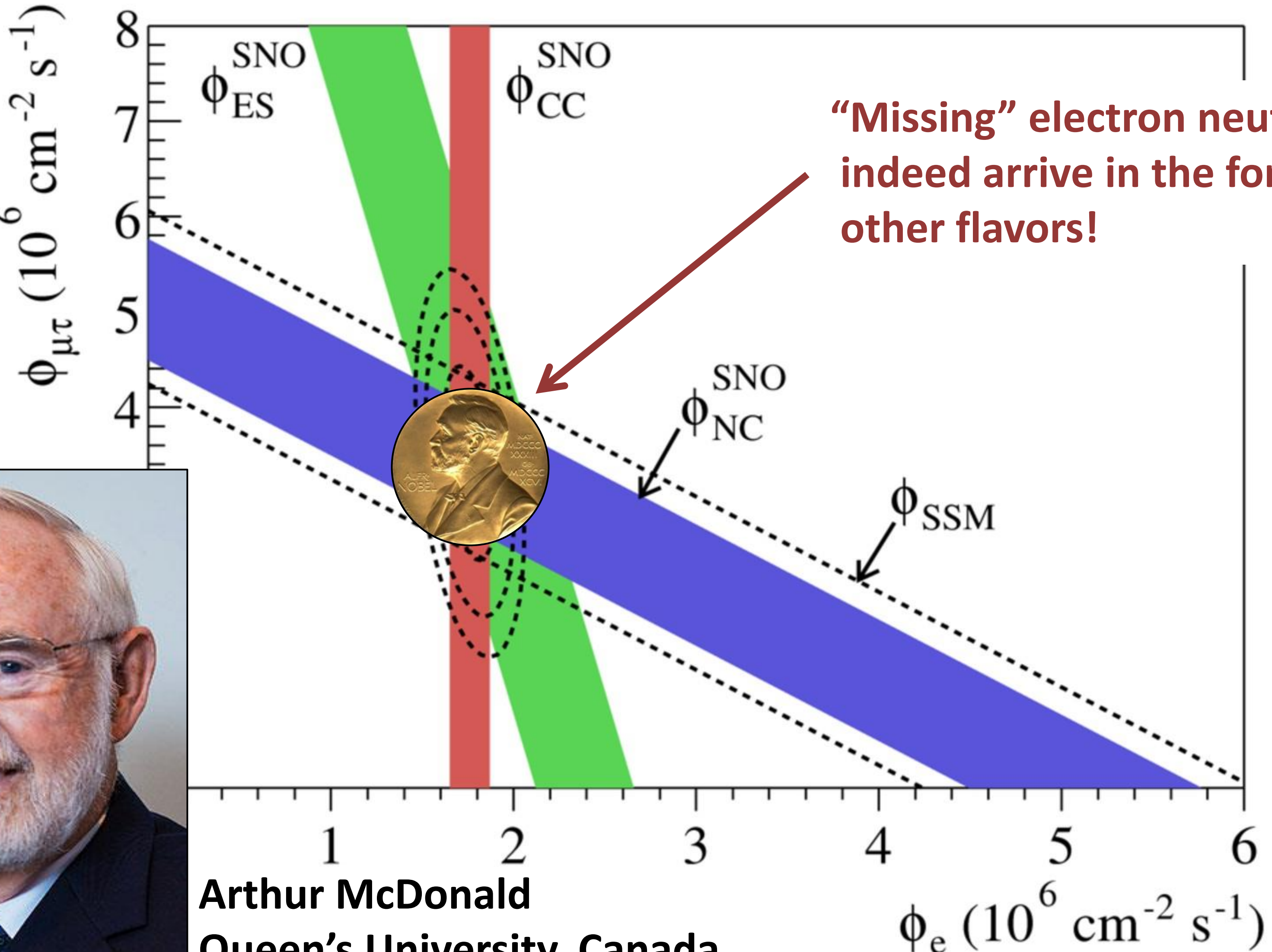
Sudbury Neutrino Observatory (SNO) Results 2002



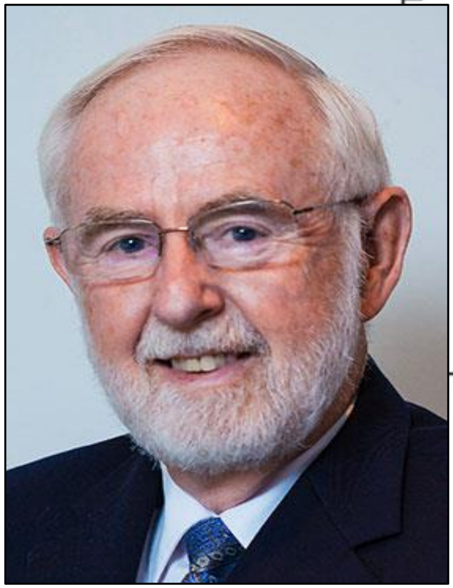
"Missing" electron neutrinos indeed arrive in the form of other flavors!

Phys. Rev. Lett. 89:011301, 2002 (http://arXiv.org/abs/nucl-ex/0204008)

Sudbury Neutrino Observatory (SNO) Results 2002



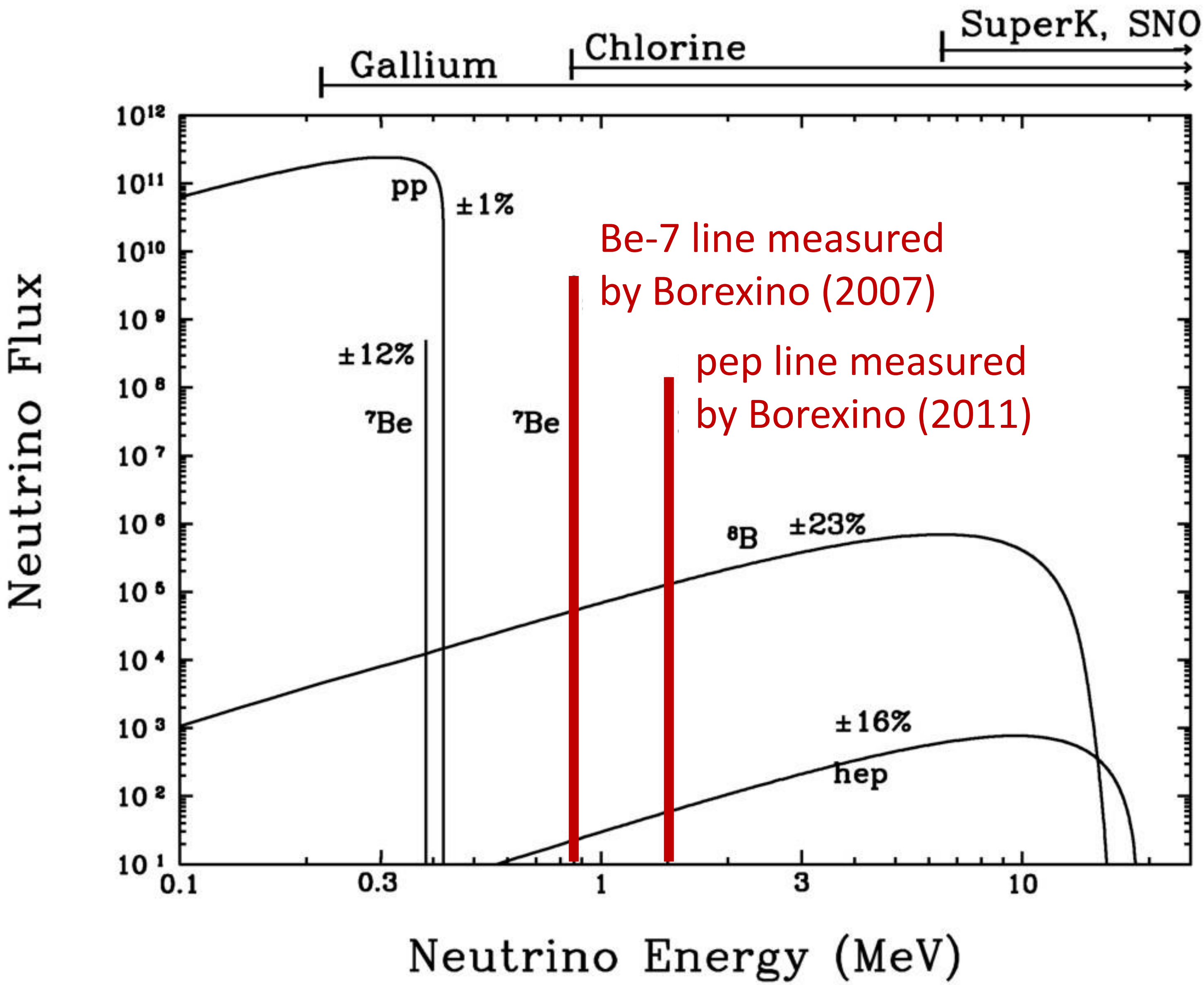
"Missing" electron neutrinos indeed arrive in the form of other flavors!

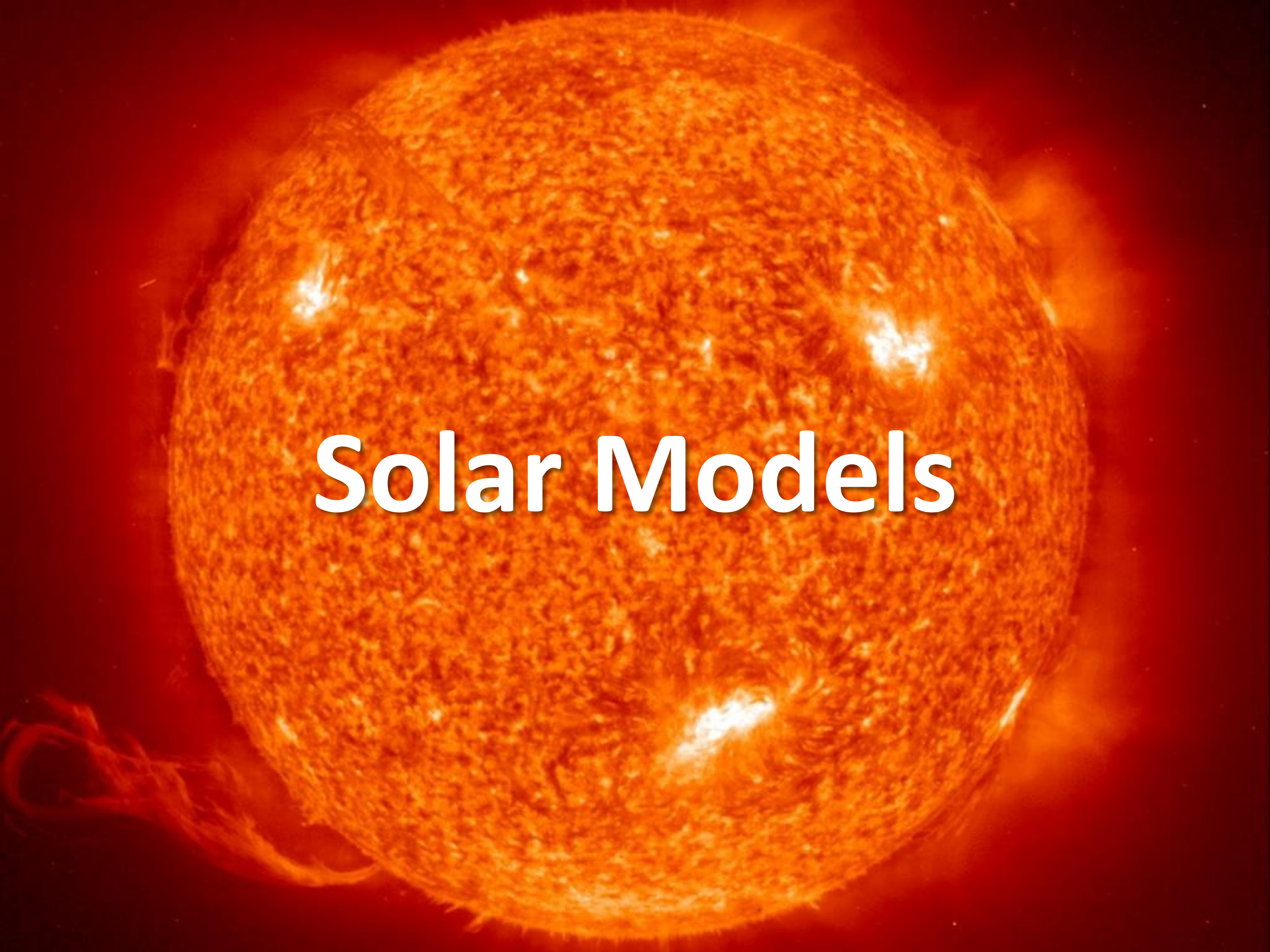


Arthur McDonald
Queen's University, Canada

Phys. Rev. Lett. 89:011301, 2002 (http://arXiv.org/abs/nucl-ex/0204008)

Solar Neutrino Spectrum




Solar Models

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

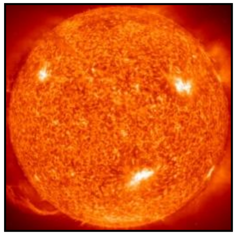
3 free parameters

- 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 $X_{ini} + Y_{ini} + Z_{ini} = 1$).
  Individual elements grouped in Z_{ini} have relative abundances given by solar abundance measurements (e.g. GS98, AGS05)

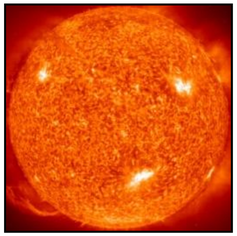
- Construct 1 $M_\odot$ initial model with X_{ini}, Z_{ini}, $Y_{ini} = 1 - X_{ini} - Z_{ini}$ and α_{MLT}
- Evolve for the solar age $t_\odot$
- Match $(Z/X)_\odot$, $L_\odot$ and $R_\odot$ to better than 10^{-5}

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

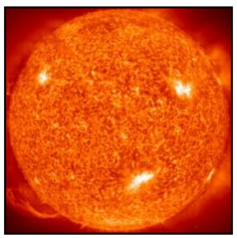
Standard Solar Model Output Information



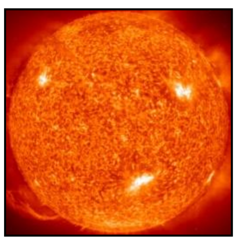
Eight neutrino fluxes:
Production profiles and integrated values



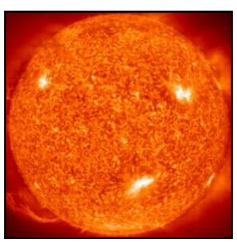
Chemical profiles $X(r)$, $Y(r)$, $Z_i(r)$
$\rightarrow$ electron and neutron density profiles



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



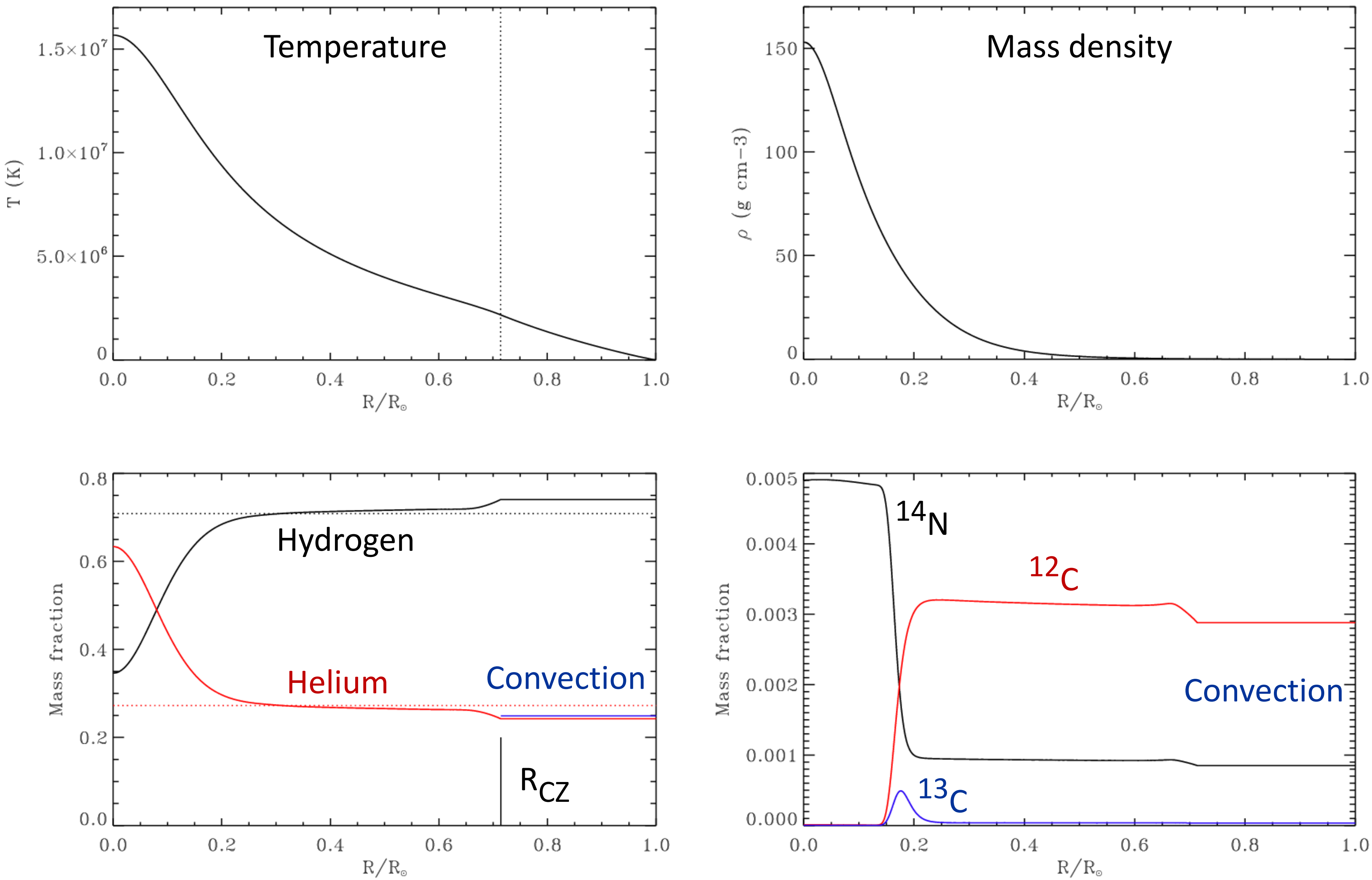
Surface helium abundance Y_{surf}
(Z/X and $1 = X + Y + Z$ leave 1 degree of freedom)



Depth of the convective envelope R_{CZ}

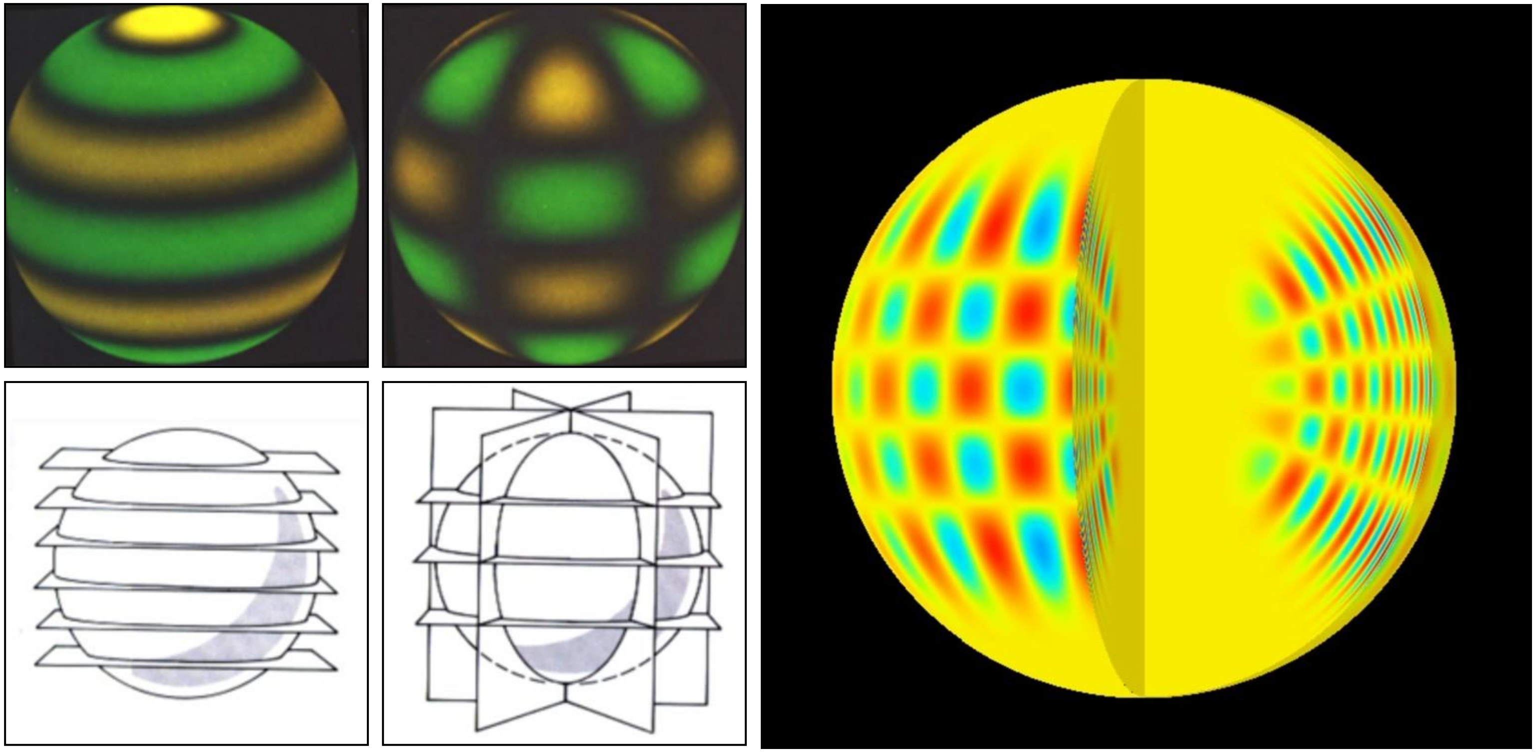
Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

Standard Solar Model: Internal Structure



Helioseismology: Sun as a Pulsating Star

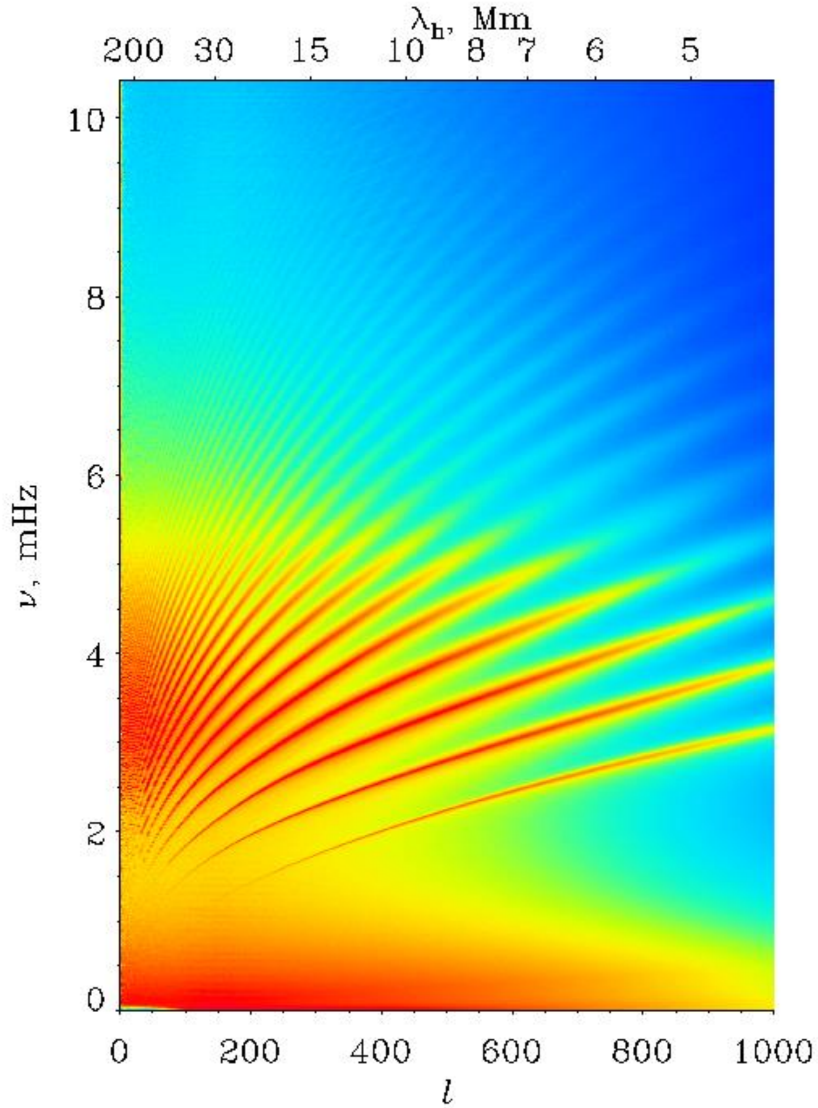
- Discovery of oscillations: Leighton et al. (1962)
- Sun oscillates in > 10^5 eigenmodes
- Frequencies of order mHz (5-min oscillations)
- Individual modes characterized by radial n, angular ℓ and longitudinal m numbers



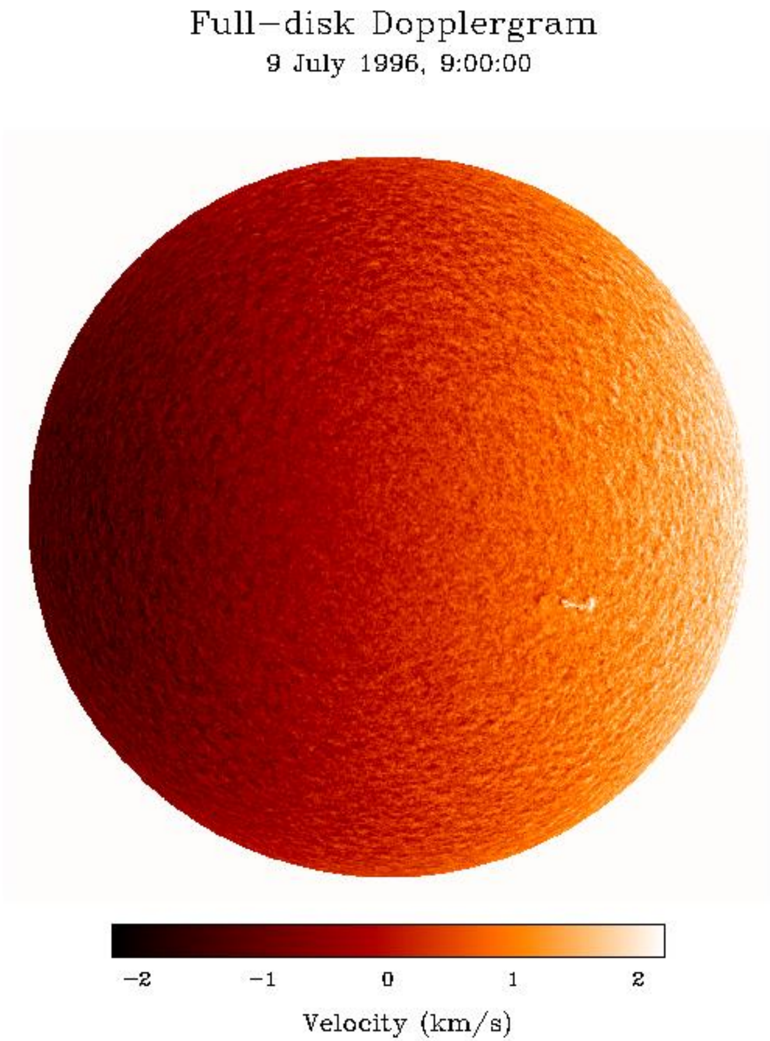
Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

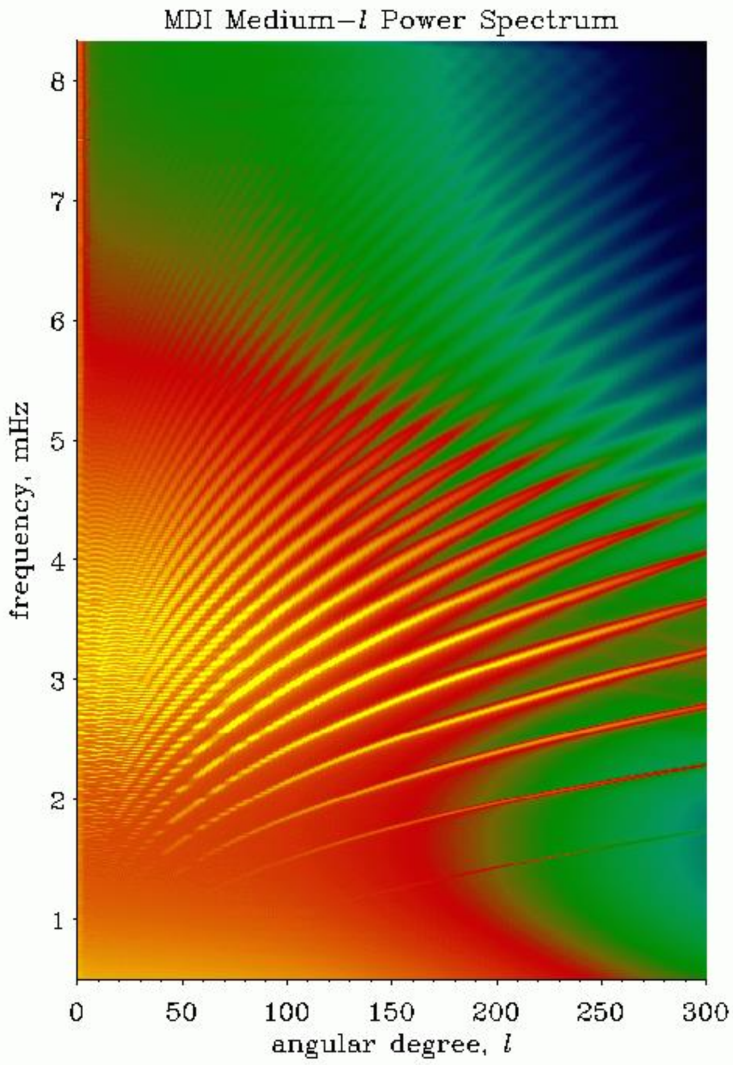
Helioseismology: Observations

- 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}



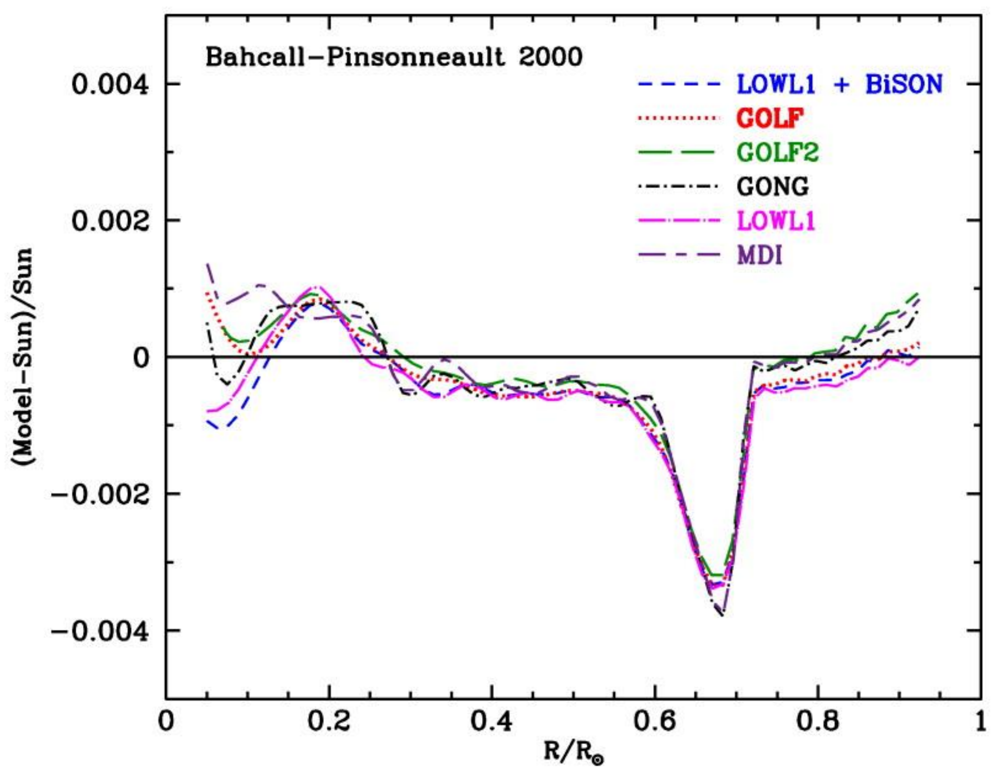
Full-Disk Dopplergram of the Sun





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)

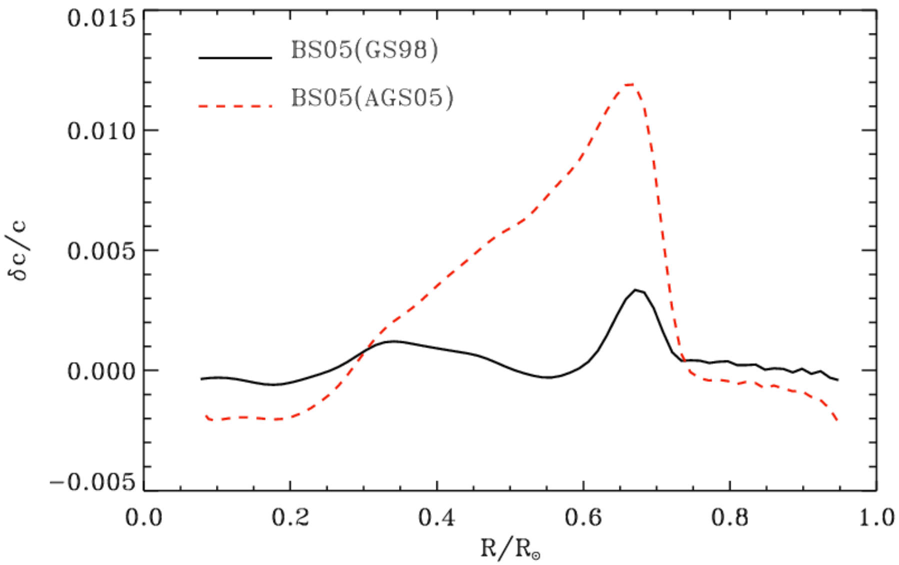
- Large change in solar composition:
  Mostly reduction in C, N, O, Ne
- Results presented in many papers by the "Asplund group"
- Summarized in Asplund, Grevesse, Sauval & Scott (2009)

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	

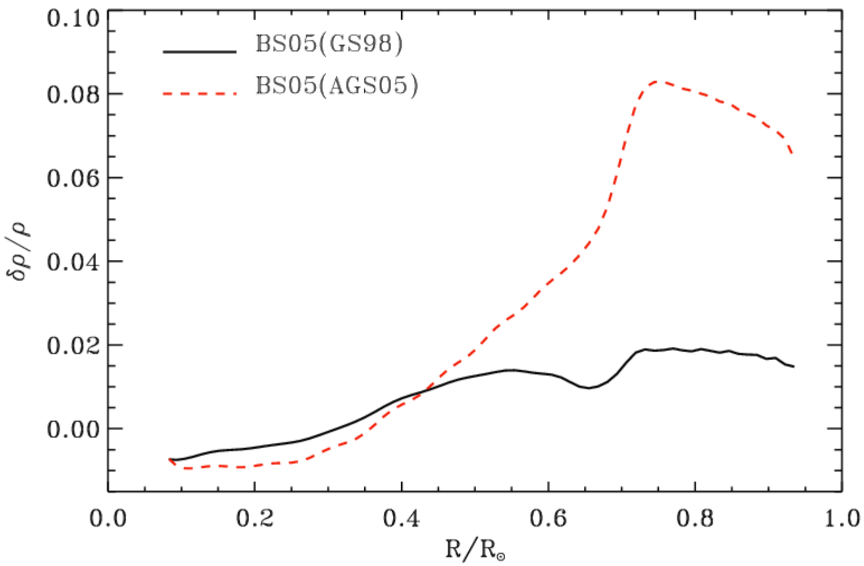
Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

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

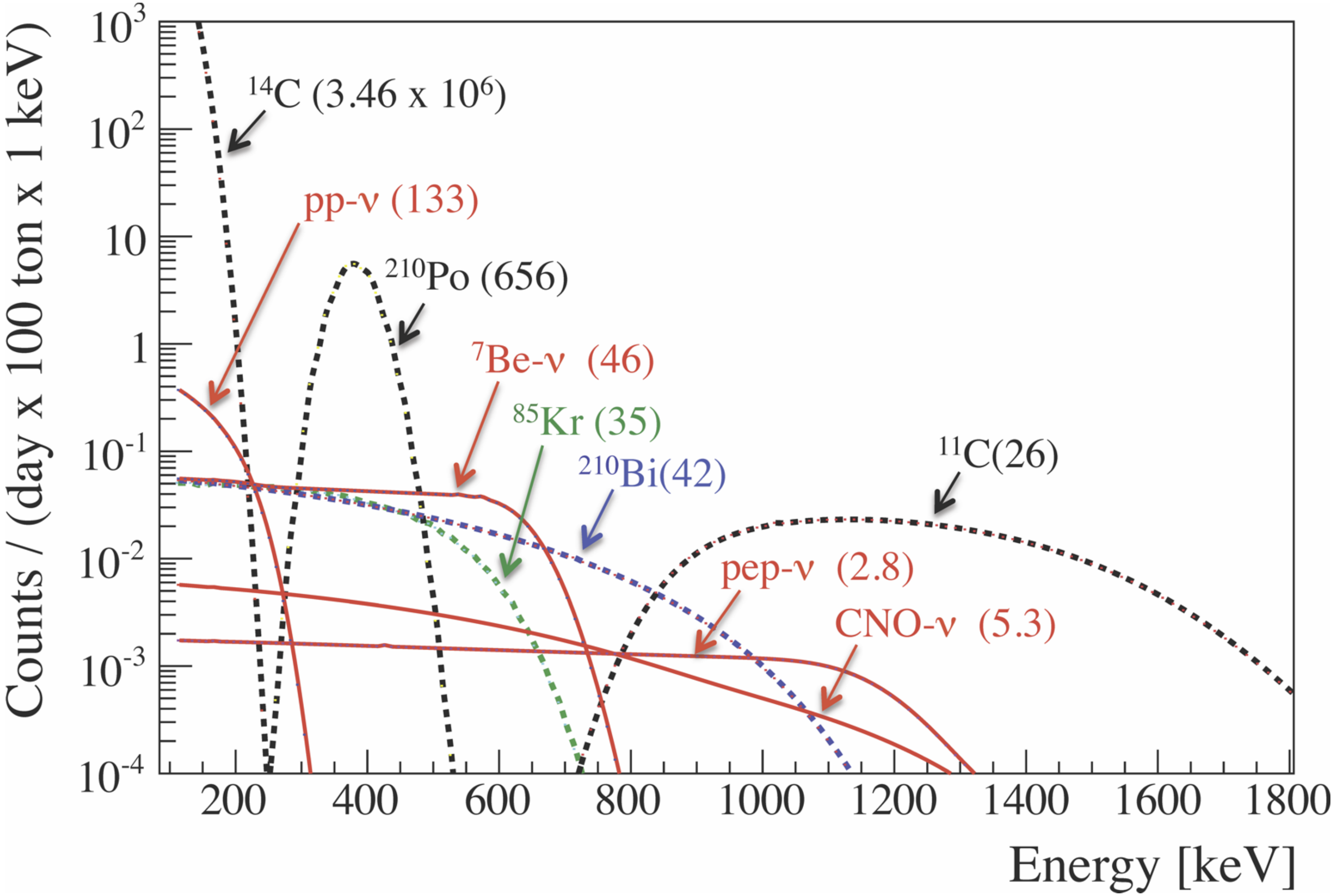
Old and New Neutrino Fluxes

	Old: (GS98)		New: (AGSS09)		Best Measurements	
	Flux cm^{-2} s^{-1}	Error %	Flux cm^{-2} s^{-1}	Error %	Flux cm^{-2} 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
Probably not achievable in Borexino in near future. Perhaps in SNO+ ?



Borexino Collaboration, arXiv:1308.0443


Axion Bounds
and Searches

PHYSICAL REVIEW D VOLUME 18, NUMBER 6 15 SEPTEMBER 1978

Astrophysical bounds on the masses of axions and Higgs particles

Duane A. Dicus and Edward W. Kolb*

Center for Particle Theory, The University of Texas, Austin, Texas 78712

Vigdor L. Teplitz†

Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

Robert V. Wagoner

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 27 April 1978)

Lower bounds on the mass of a light scalar (Higgs) or pseudoscalar (axion) particle are found in three ways: (1) by requiring that their effect on primordial nucleosynthesis not yield a deuterium abundance outside present experimental limits, (2) by requiring that the photons from their decay thermalize and not distort the microwave background, and (3) by requiring that their emission from helium-burning stars (red giants) not disrupt stellar evolution. The best bound is from (3); it requires the axion or Higgs-particle mass to be greater than about 0.2 MeV.

The first process considered is the Primakoff process,[16] $\gamma + Z \to \phi + Z$, shown in Fig. 2. The cross section for this process near threshold is

$$|v|\sigma = 64\pi\alpha Z^2 \frac{\omega\Gamma(\phi\to 2\gamma)}{m_\phi^{\,2}} \frac{(\omega^2 - m_\phi^{\,2})^{1/2}(\omega - m_\phi)}{(m_\phi^{\,2} - 2\omega m_\phi)^2}, \tag{7}$$

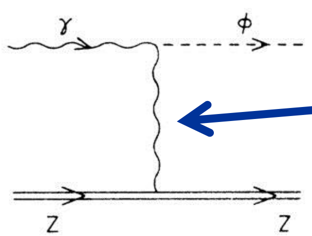
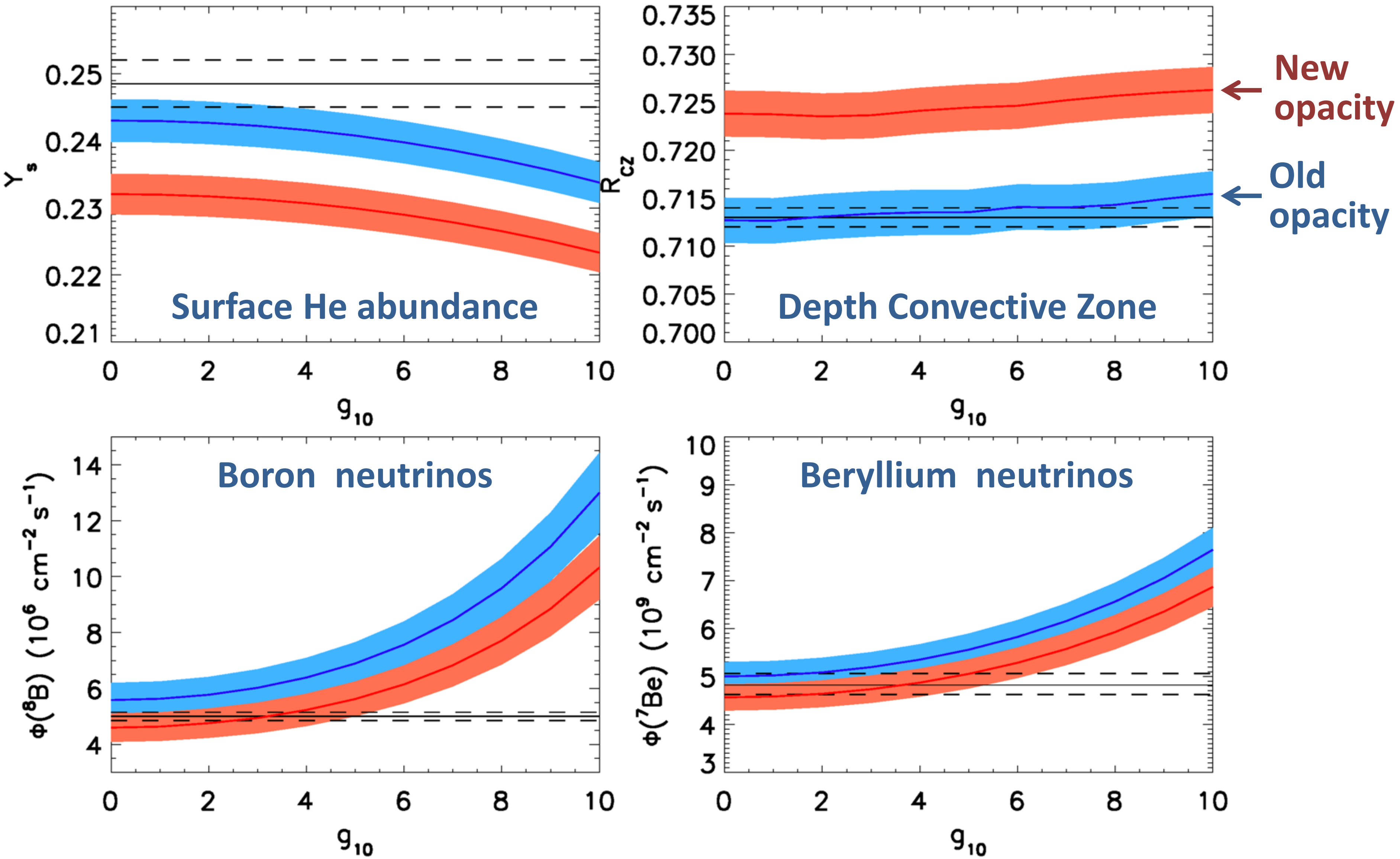


FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

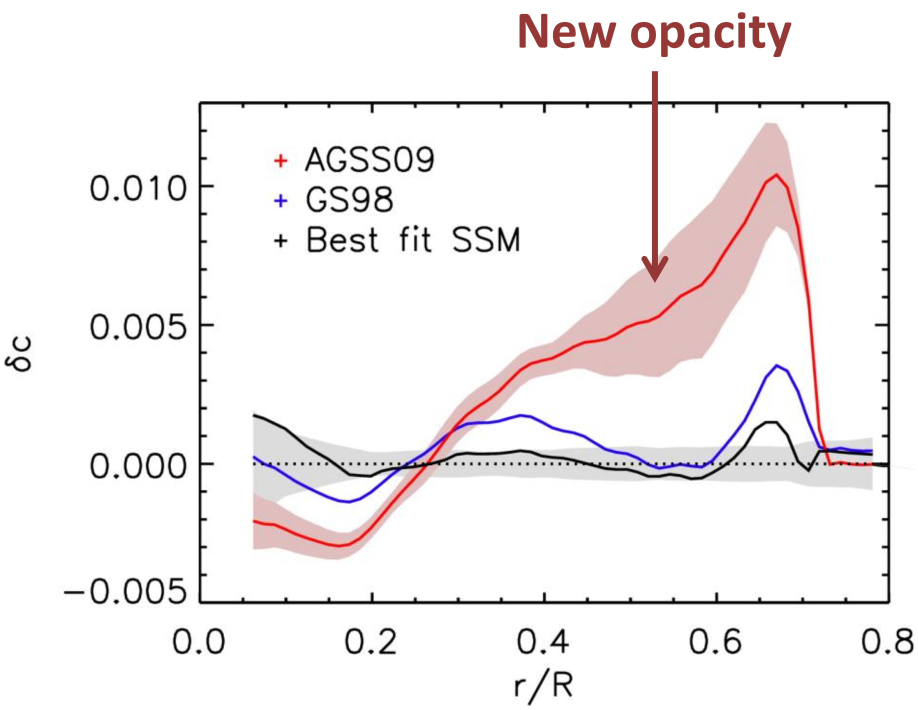
First discussion of Primakoff effect for WW axions ($m_a \gg T$)

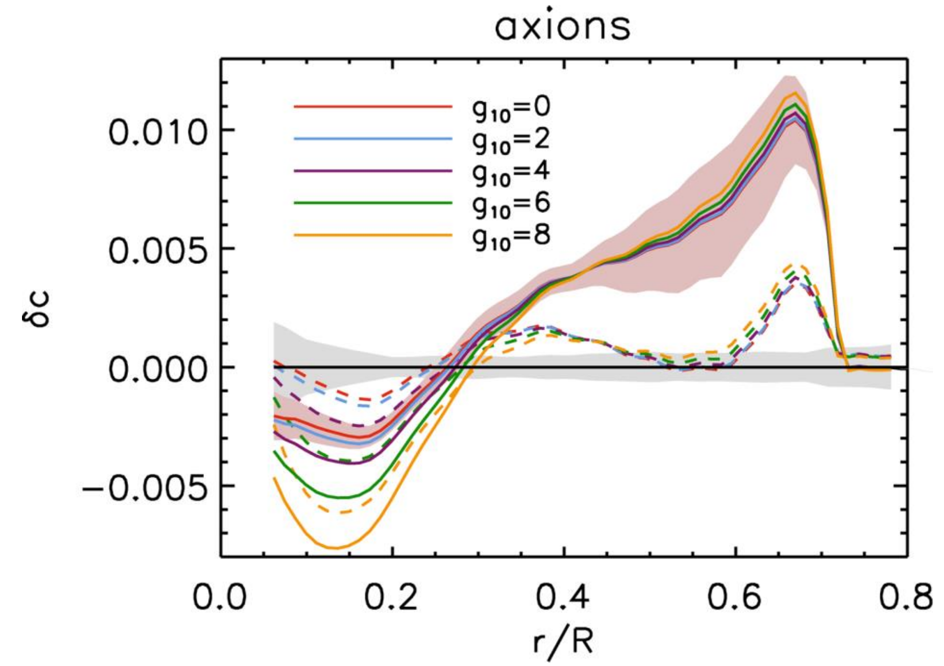
For "invisible axions" ($m_a \ll T$) screening effects crucial (G.R., PRD 33, 897:1986)

Solar Observables Modified by Axion Losses



Solar Sound-Speed Variation

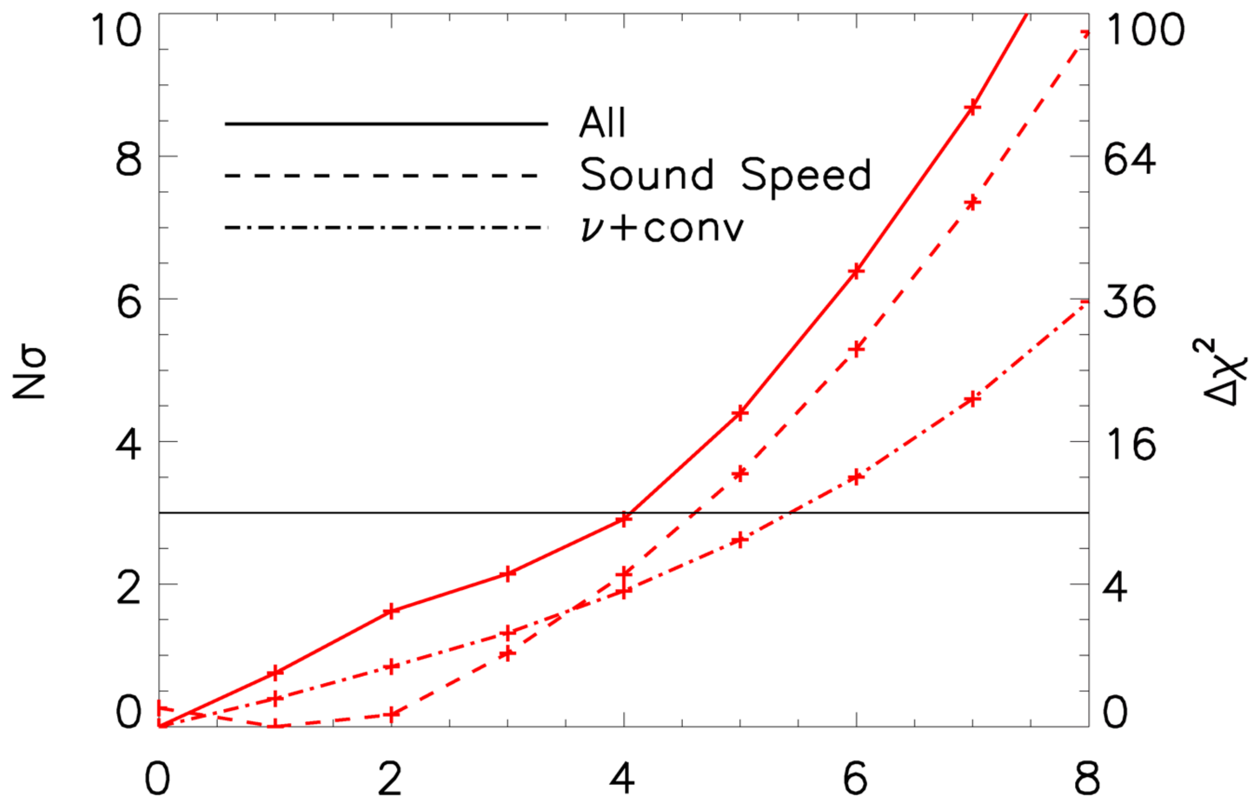




New energy loss makes disagreement with seismic observations worse, especially in the central regions

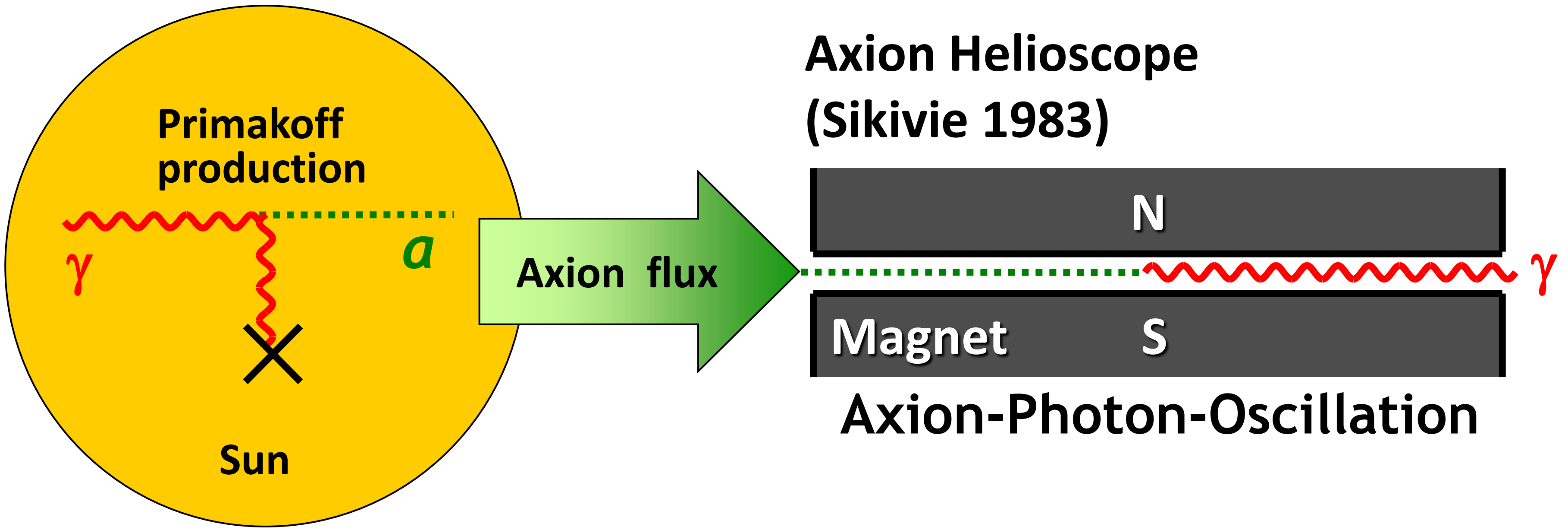
Global Fit from Solar Observables

Allow all input parameters to float, including chemical composition, and marginalize except for axion losses



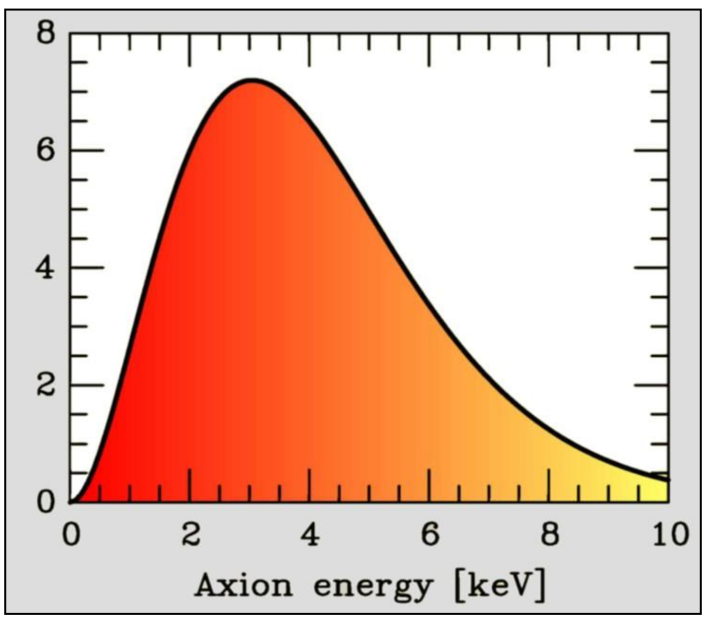
$$g_{10} = g_{a\gamma} \times 10^{10}\ \text{GeV}$$

Search for Solar Axions



Axion Helioscope
(Sikivie 1983)

Axion-Photon-Oscillation

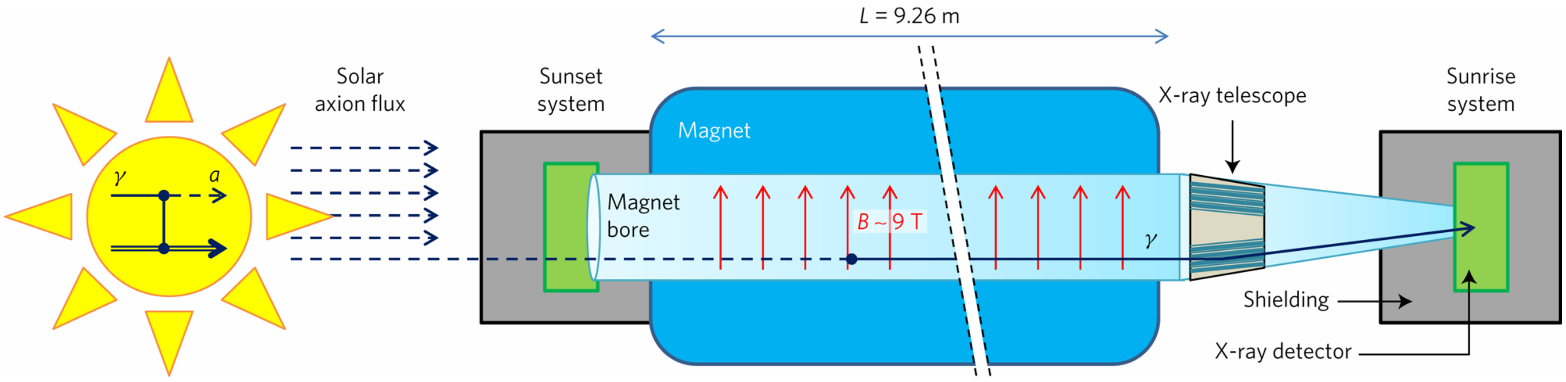


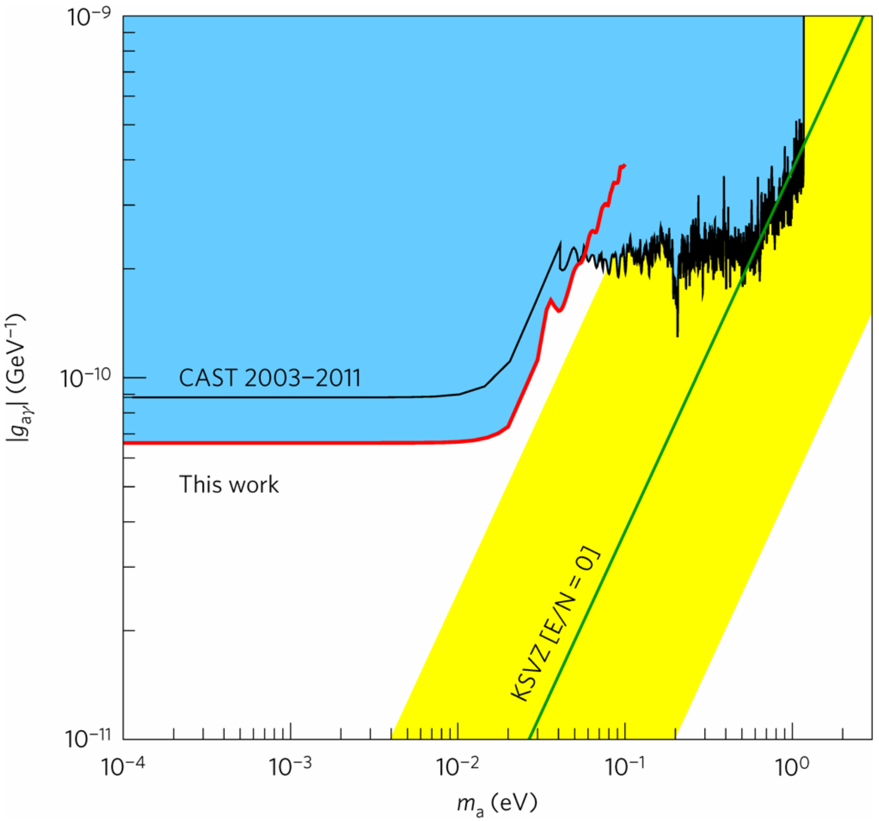
- Tokyo Axion Helioscope ("Sumico") (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

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

CERN Axion Solar Telescope (CAST)

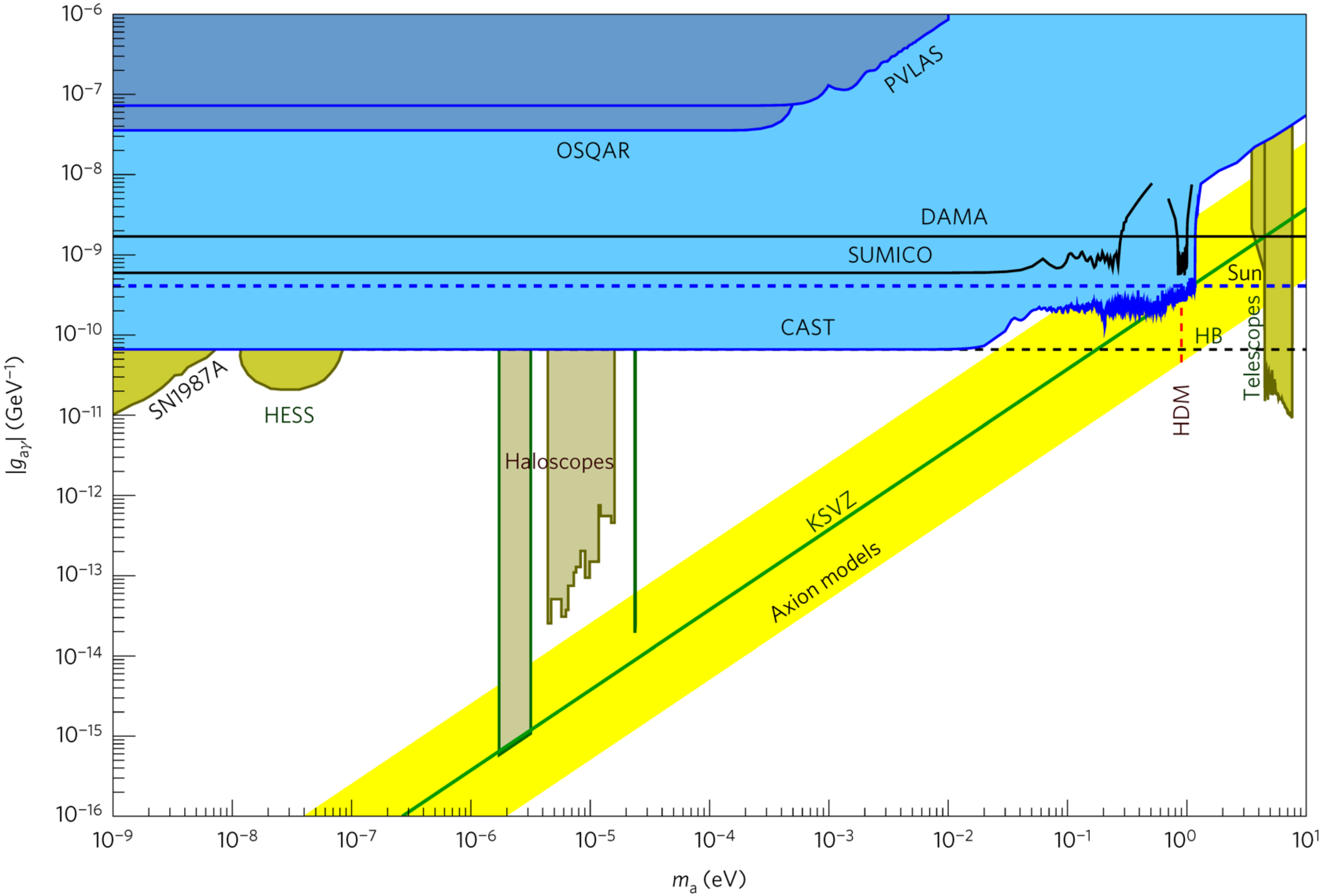
Helioscope Limits





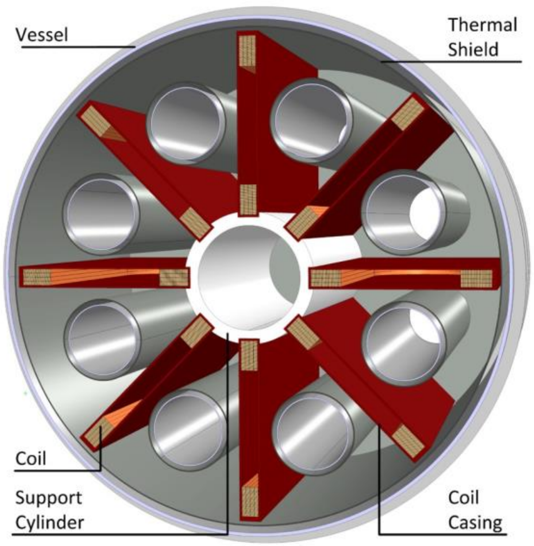
Latest CAST limits on axion-photon interaction
Nature Physics 13 (2017) 584
arXiv:1705.02290

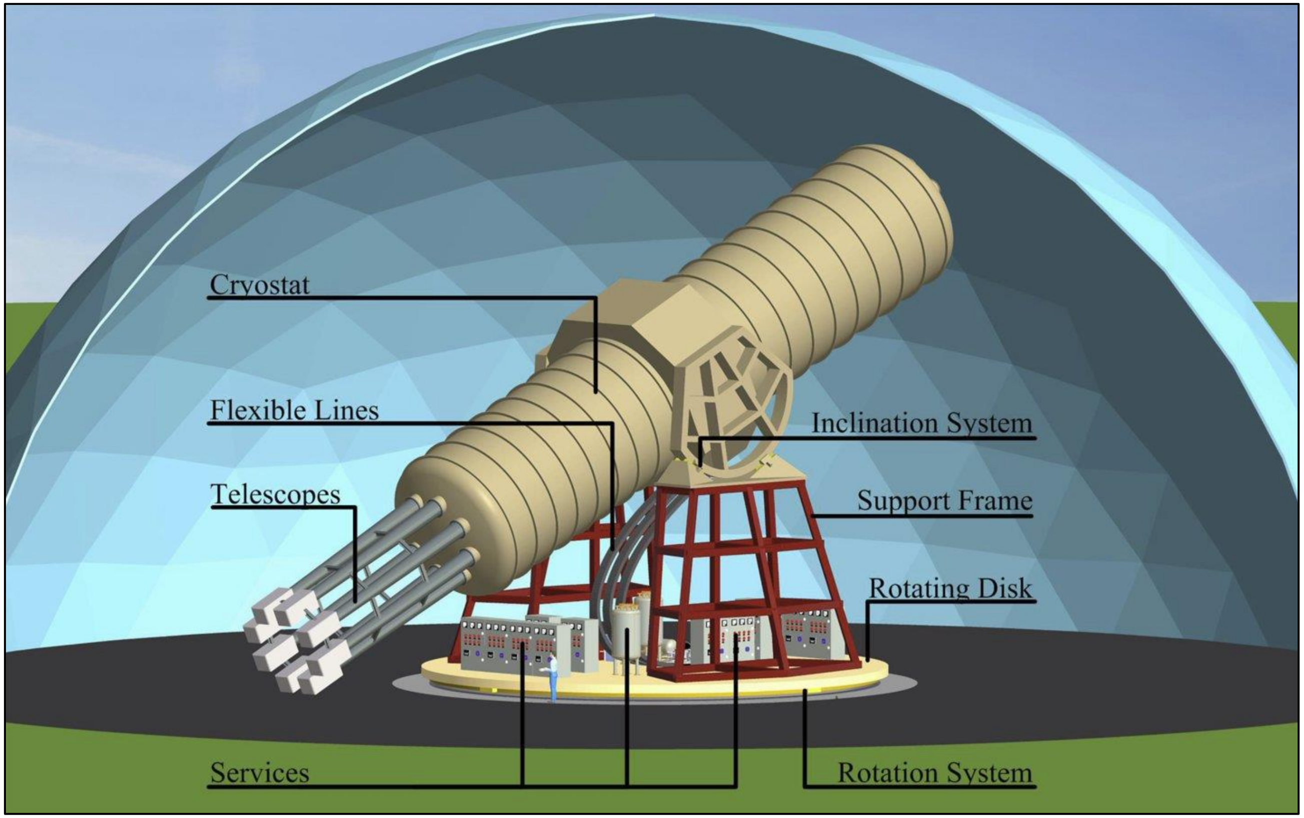
Limits on Axion-Like Particles (ALPs)



CAST Collaboration, Nature Physics 13 (2017) 584 [arXiv:1705.02290]

Next Generation Axion Helioscope (IAXO)





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

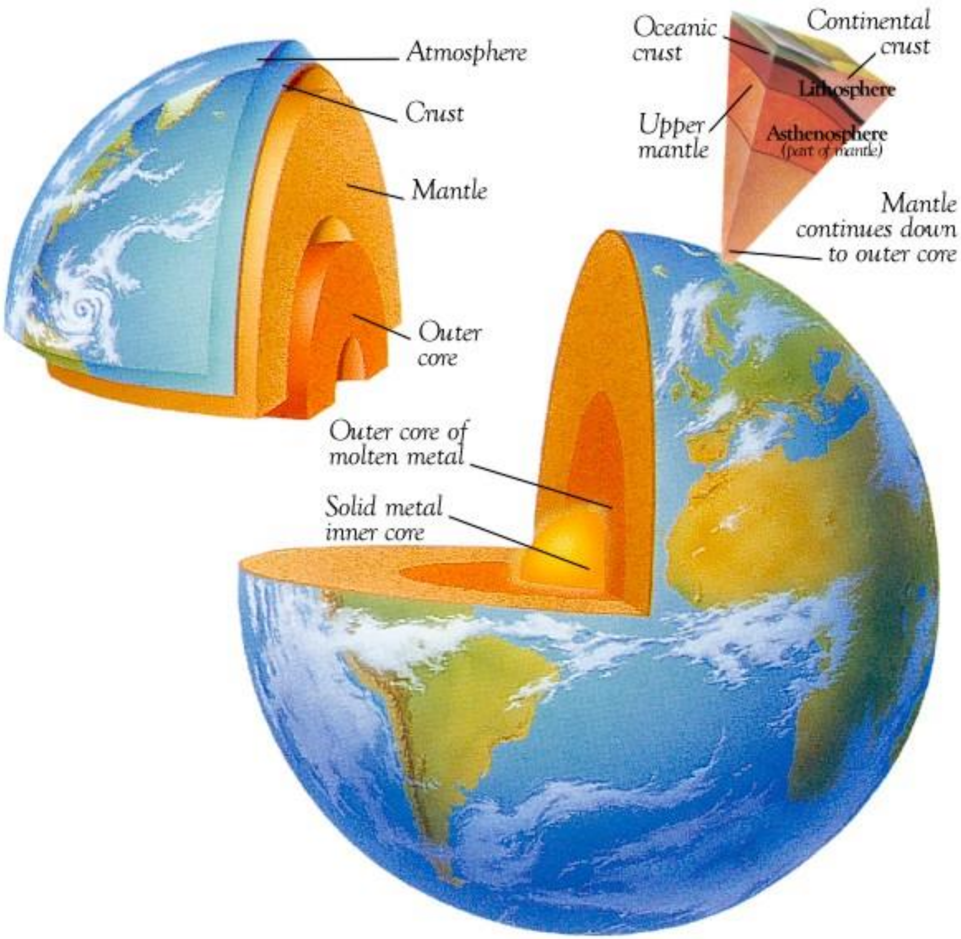
- Irastorza et al.: Towards a new generation axion helioscope, arXiv:1103.5334
- Armengaud et al.: Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233

Geo-Neutrinos

Geo Neutrinos: What is it all about?

We know surprisingly little about the Earth's interior

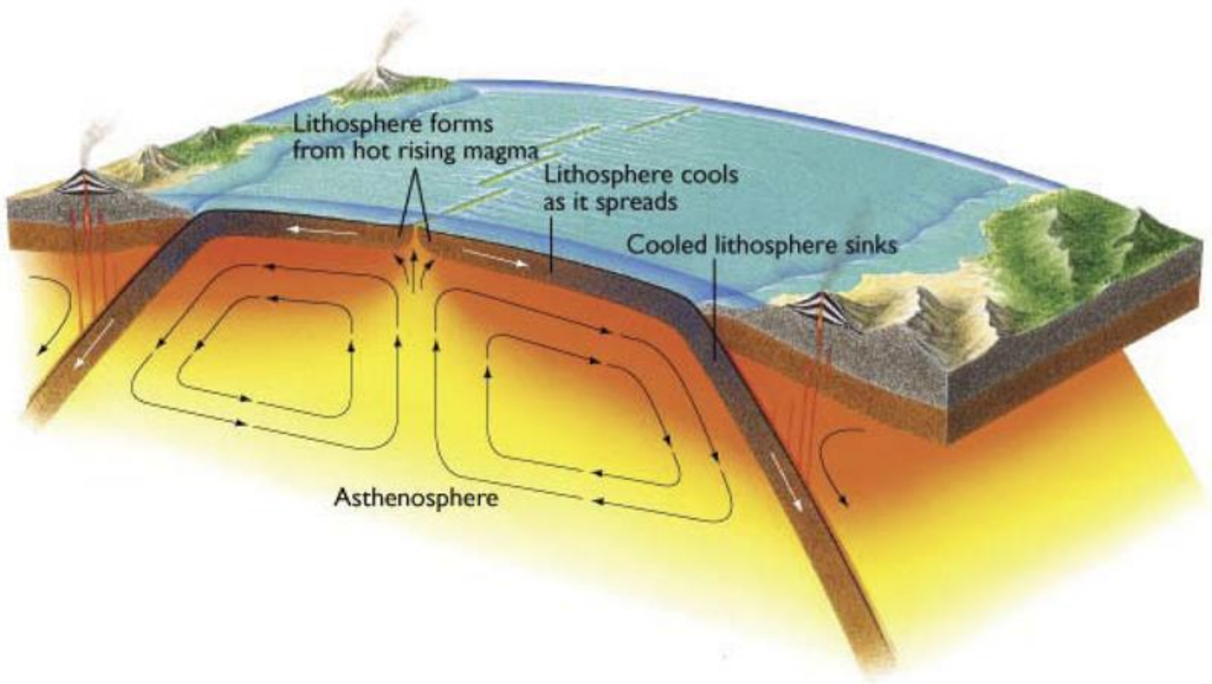
- Deepest drill hole ~ 12 km
- Samples of crust for chemical analysis available (e.g. vulcanoes)
- Reconstructed density profile from seismic measurements
- Heat flux from measured temperature gradient 30–44 TW (Expectation from canonical BSE model ~ 19 TW from crust and mantle, nothing from core)

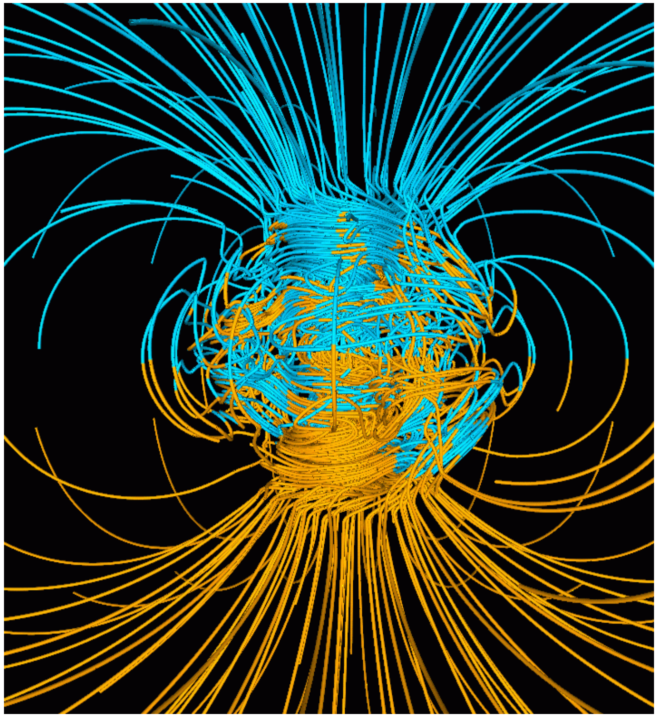


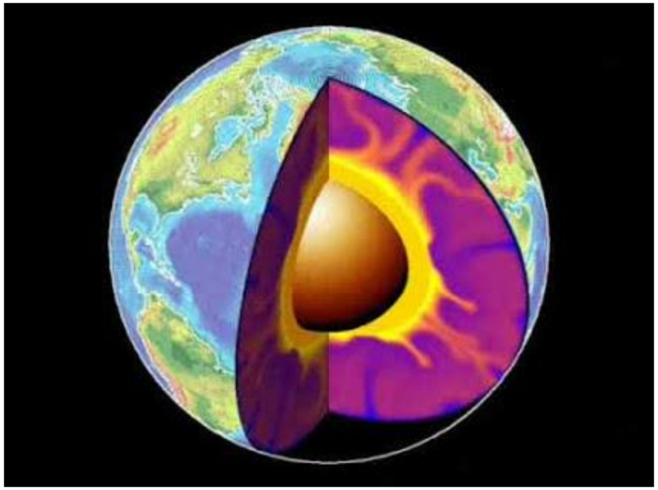
- Neutrinos escape unscathed
- Carry information about chemical composition, radioactive energy production or even a hypothetical reactor in the Earth's core

Plate Tectonics, Convection, Geo-Dynamo

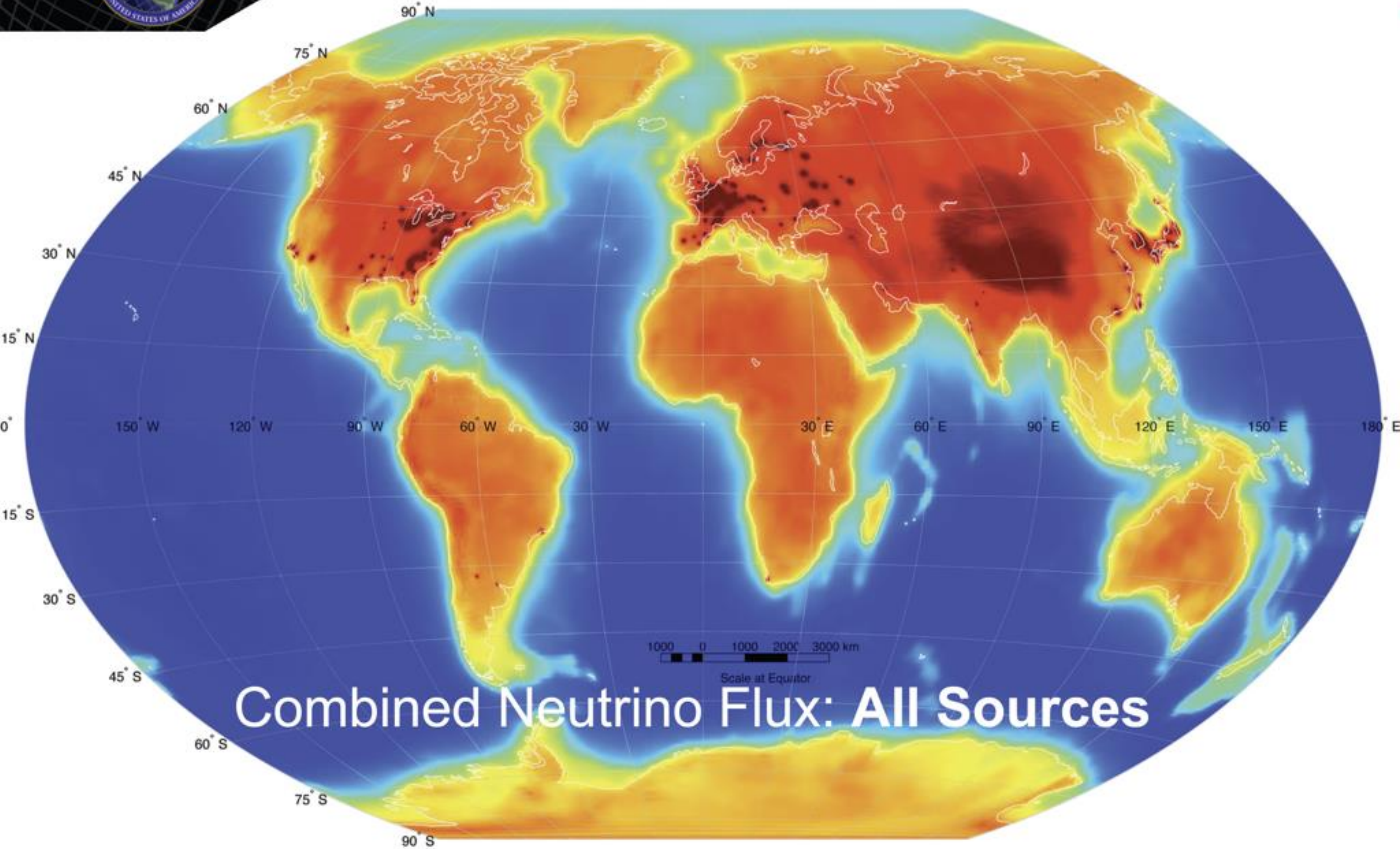
- Potassium-40 (Half life 1.25 billion years)
- Thorium-232 (14 billion years)
- Uranium-238 (4.5 billion years)

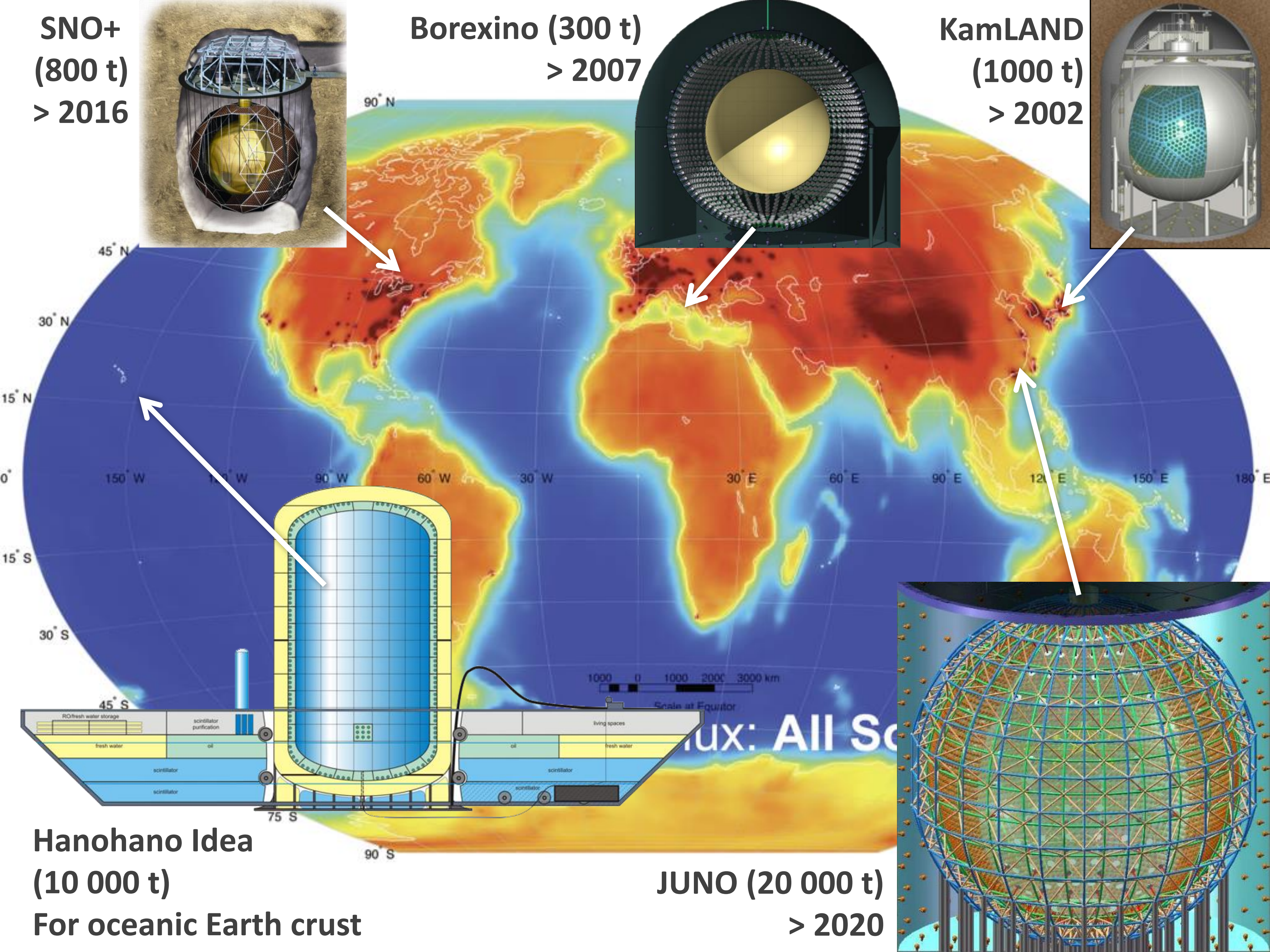




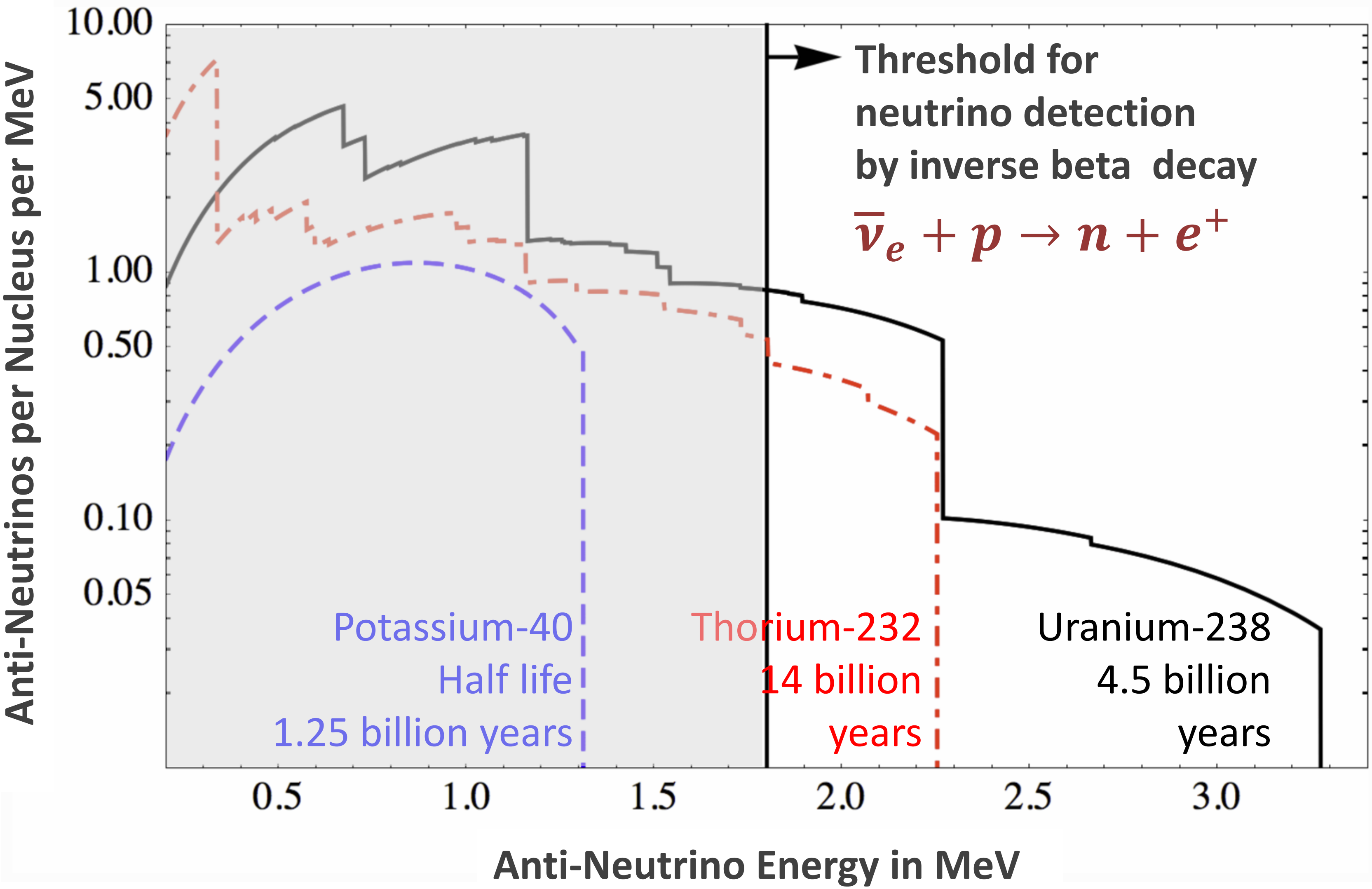


Radioactive decays provide the engine!


90° N
75° N
60° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
90° S
150° W
120° W
90° W
60° W
30° W
30° E
60° E
90° E
120° E
150° E
180° E
1000 0 1000 2000 3000 km
Scale at Equator
Combined Neutrino Flux: All Sources

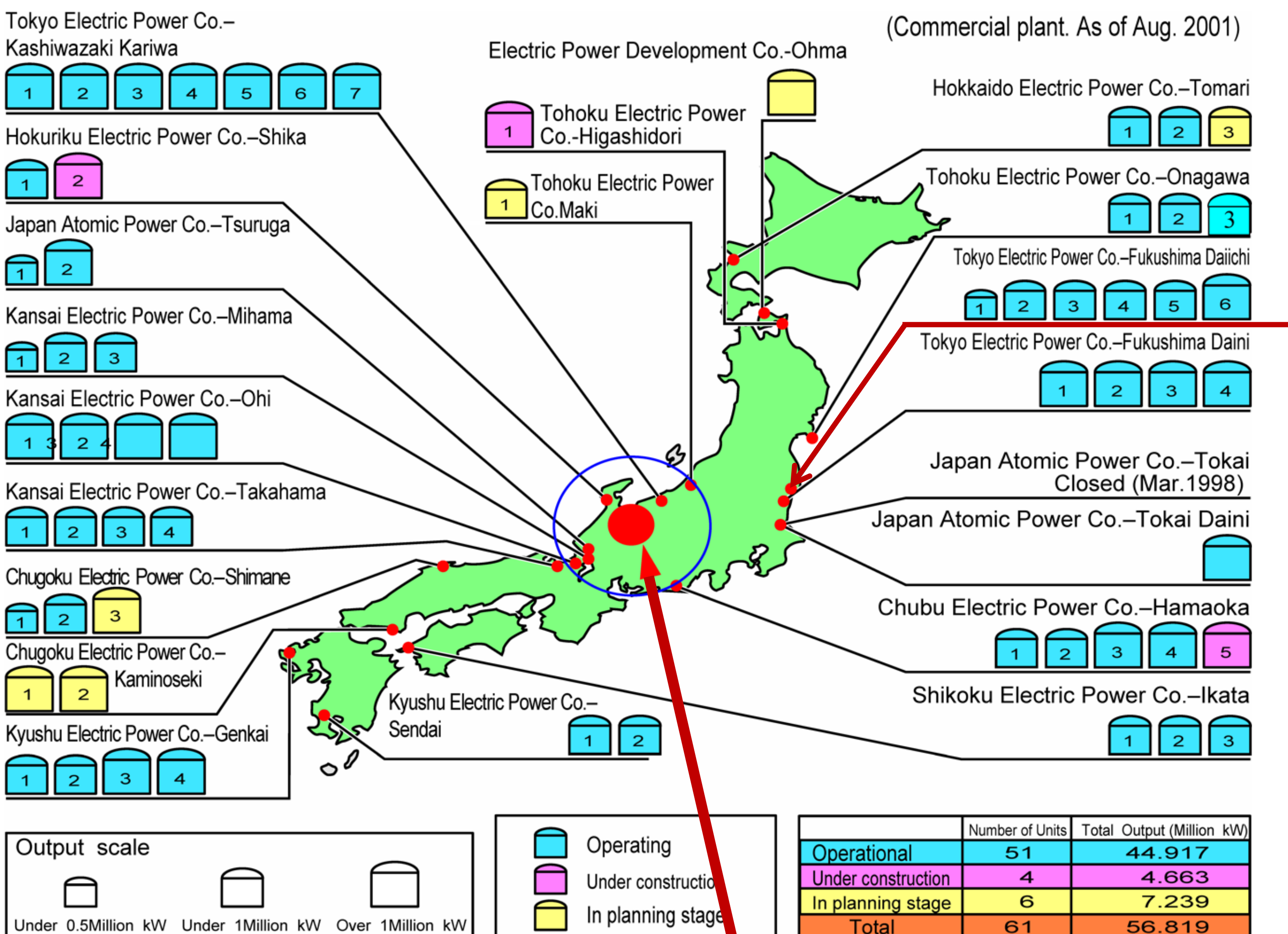

SNO+
(800 t)
> 2016
Borexino (300 t)
> 2007
KamLAND
(1000 t)
> 2002
90° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
75° S
90° S
150° W
90° W
60° W
30° W
30° E
60° E
90° E
150° E
180° E
1000 0 1000 2000 3000 km
Scale at Equator
RO/fresh water storage
scintillator purification
living spaces
fresh water
oil
scintillator
Hanohano Idea
(10 000 t)
For oceanic Earth crust
JUNO (20 000 t)
> 2020

Energy Spectrum of Geo-Neutrinos



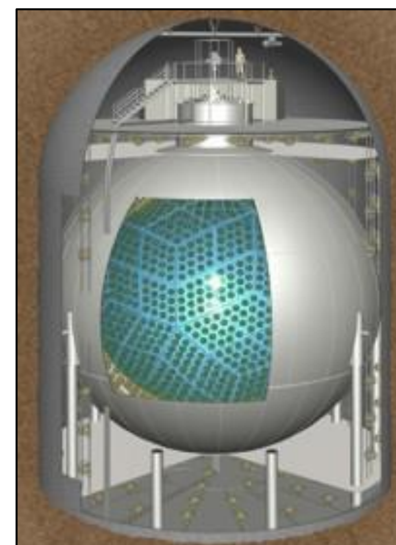
Bellini, Ianni, Ludhova, Mantovani & McDonough, http://arXiv.org/abs/1310.3732

Nuclear Reactors in Japan and KamLAND Detector

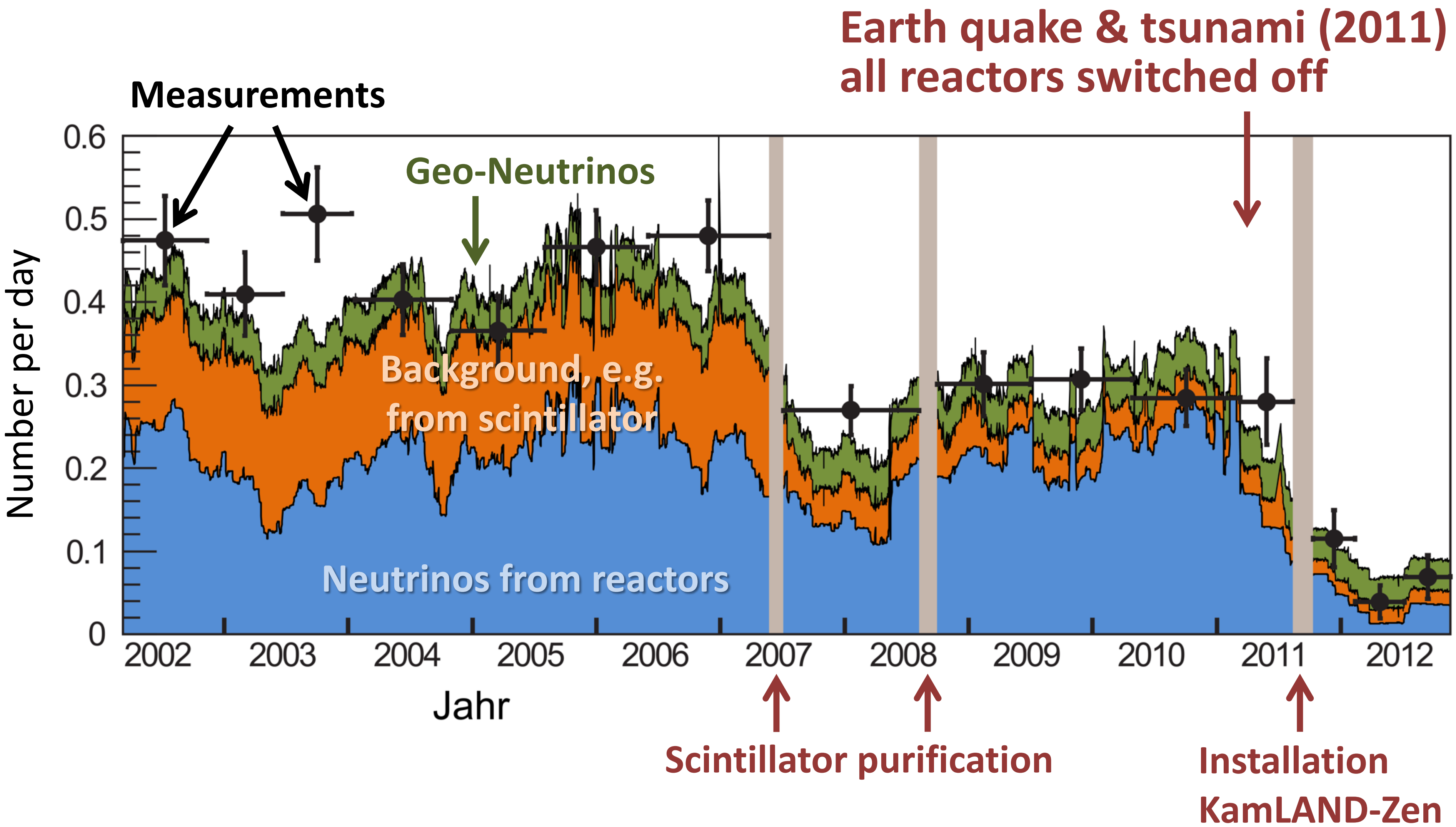


	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	6	7.239
Total	61	56.819

KamLAND neutrino detector (1000 t scintillator)



Reactor- und Geo-Neutrinos in KamLAND (Japan)

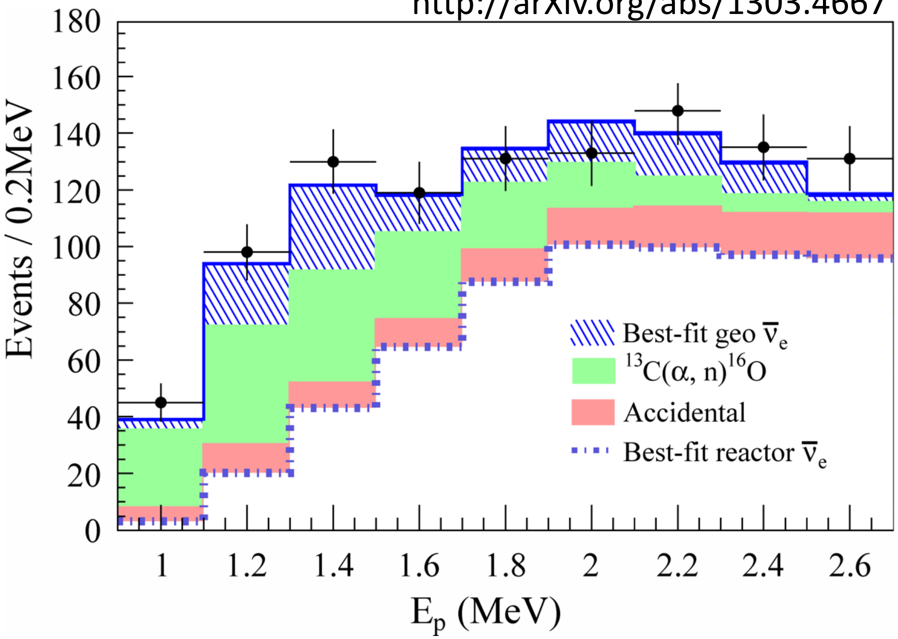


KamLAND Collaboration (2013), http://arXiv.org/abs/1303.4667

Geo-Neutrino Measurements

KamLAND (Japan)

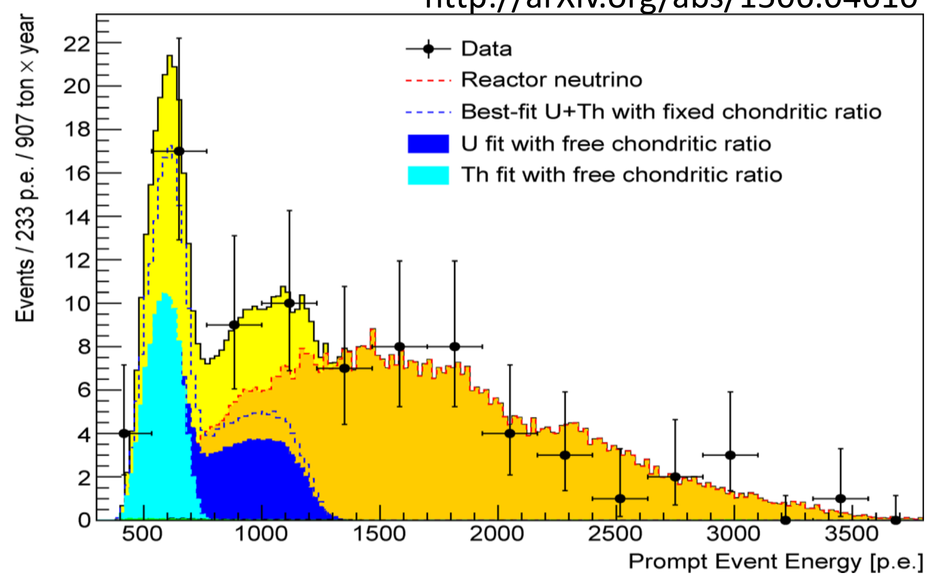
http://arXiv.org/abs/1303.4667



116^{+28}_{-27} **Geo-Neutrinos**

Borexino (Gran Sasso, Italy)

http://arXiv.org/abs/1506.04610



24^{+7}_{-6} **Geo-Neutrinos**

Neutrino Geoscience 2015 Paris

Beginnings of geophysics with neutrinos!

http://www.ipgp.fr/fr/evenements/neutrino-geoscience-2015-conference