Georg Raffelt, Max-Planck-Institut für Physik, München

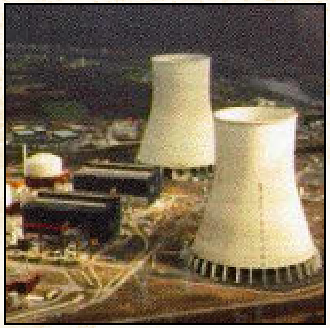
Astroparticle Physics 2:

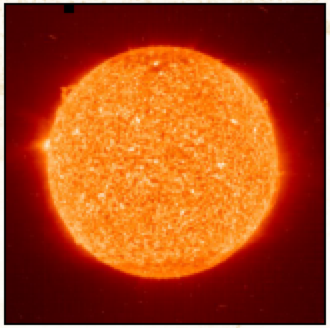
Neutrino Astrophysics

IMPRS Inauguration Course
13-19 October 2005, München, Germany

Where do Neutrinos Appear in Nature?

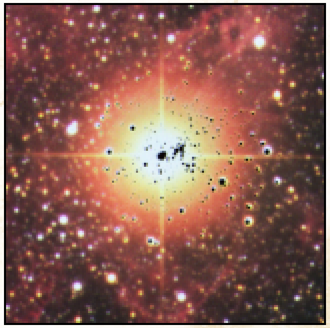
✓ Nuclear Reactors





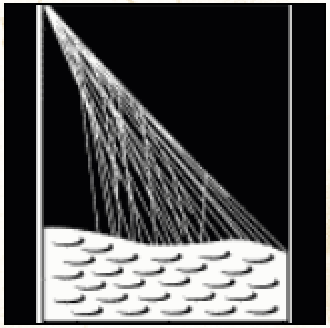
Sun ✓

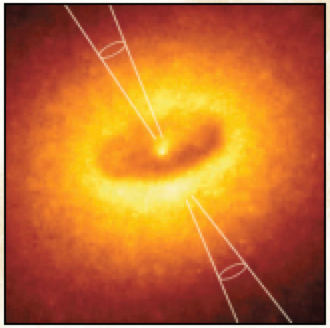
✓ Particle Accelerators



Supernovae
(Stellar Collapse)
SN 1987A ✓

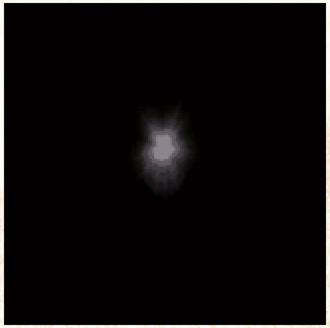
✓ Earth Atmosphere
(Cosmic Rays)





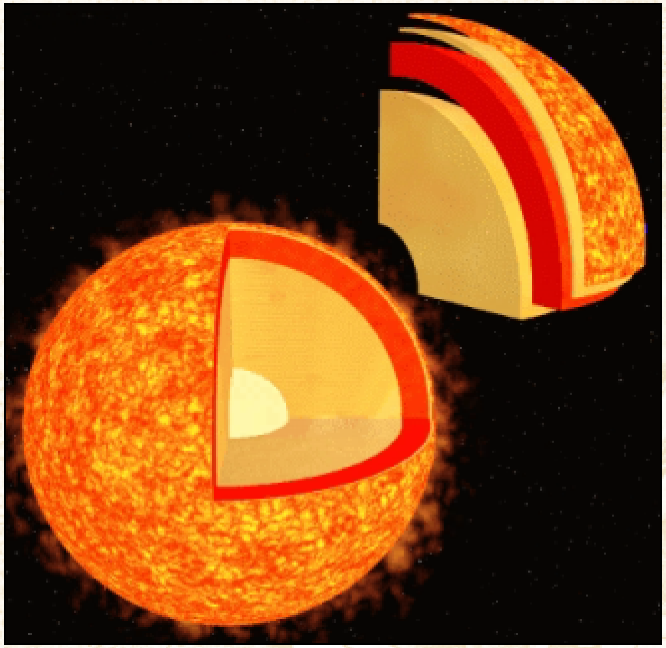
Astrophysical
Accelerators Soon ?

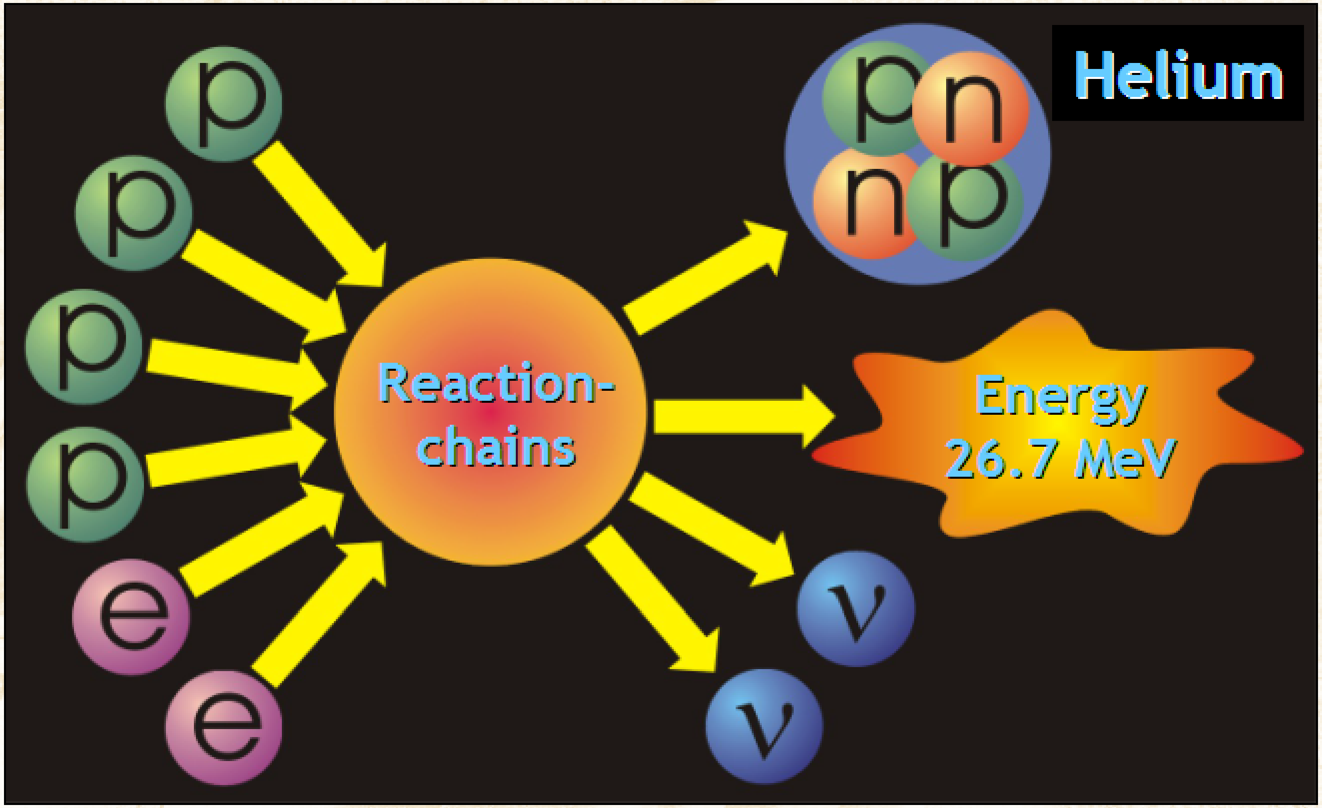
✓ Earth Crust
(Natural
Radioactivity)



Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Neutrinos from the Sun

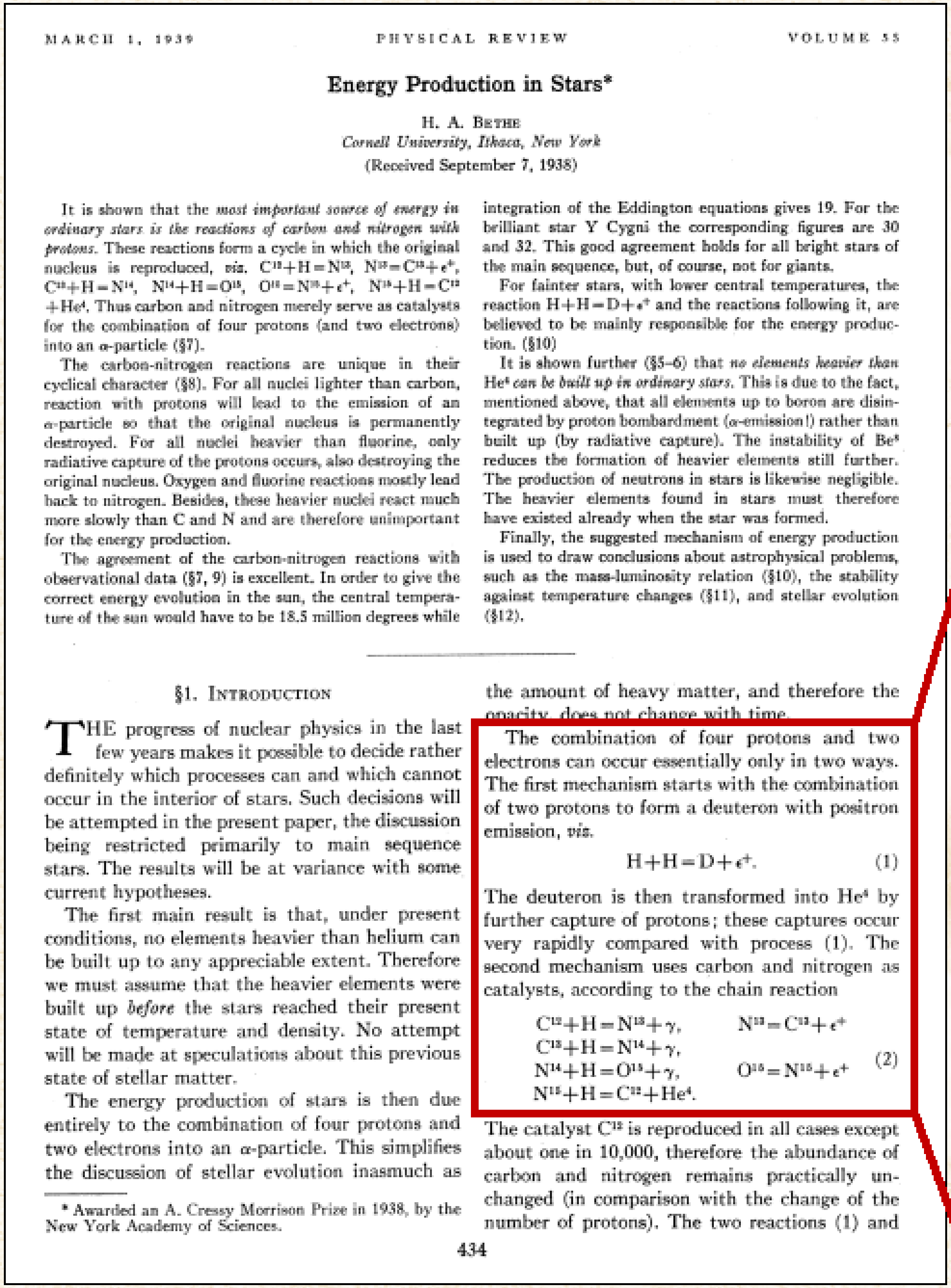




Solar radiation: 98 % light
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

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.*

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

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

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

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

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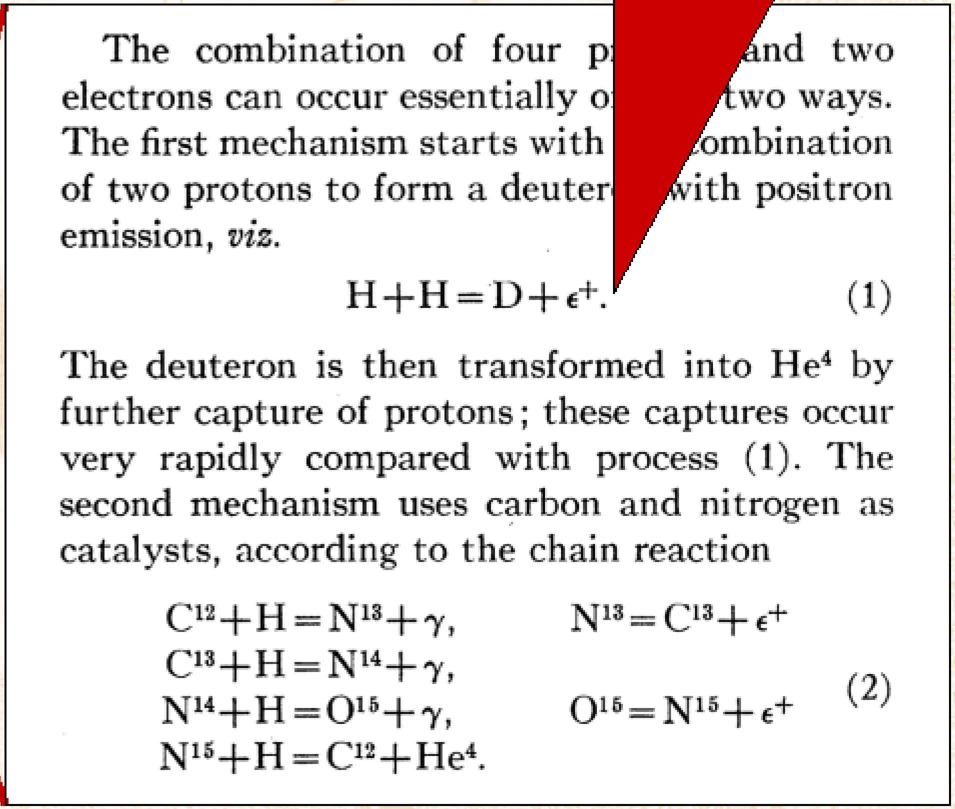
* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

No neutrinos
from nuclear reactions
in 1938 ...



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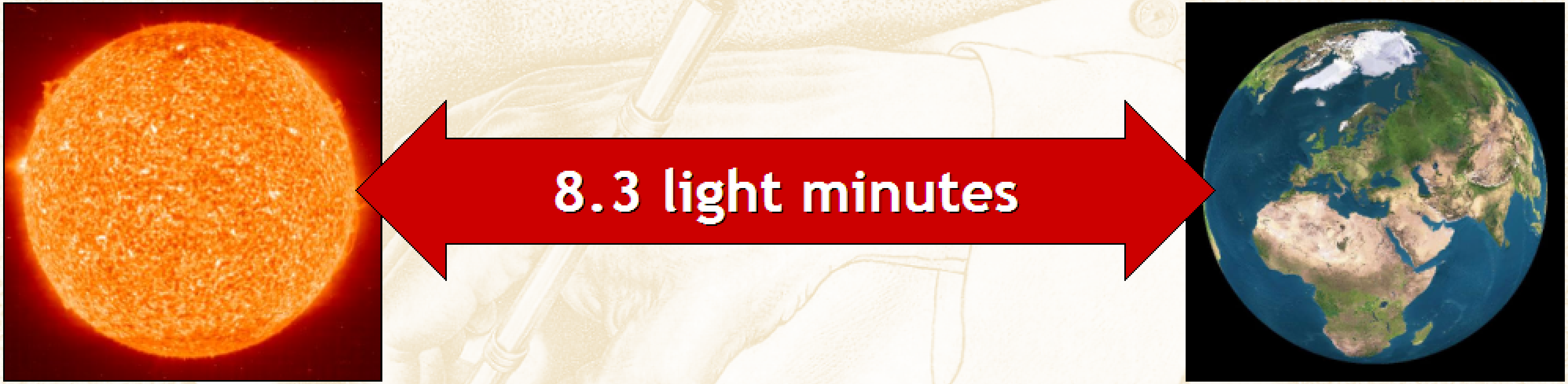
Sun Glasses for Neutrinos?



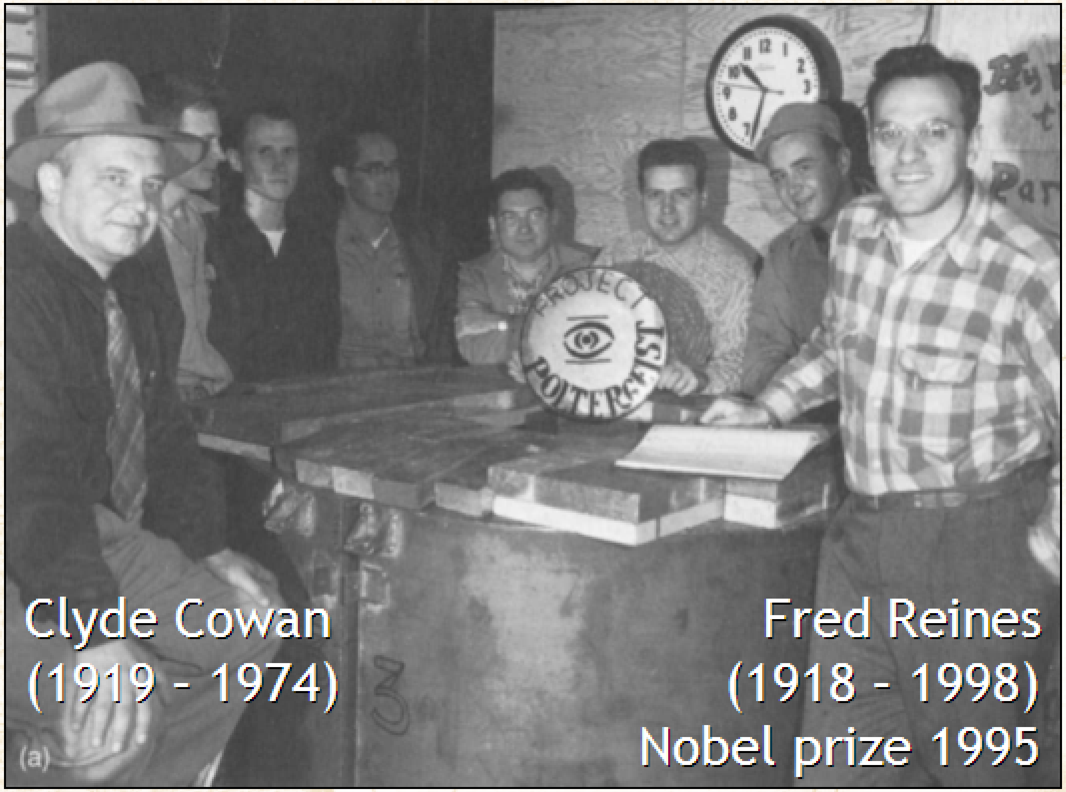
8.3 light minutes

1000 light years of lead needed to shield solar neutrinos

Bethe & Peierls 1934:

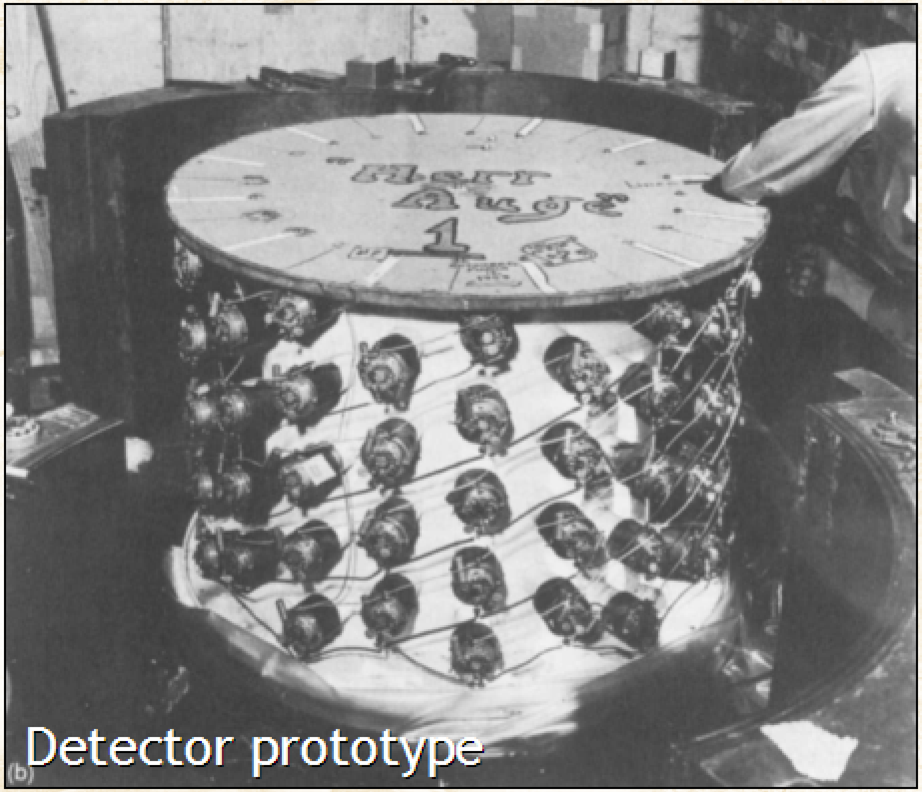
"... this evidently means that one will never be able to observe a neutrino."

First Detection (1954 - 1956)



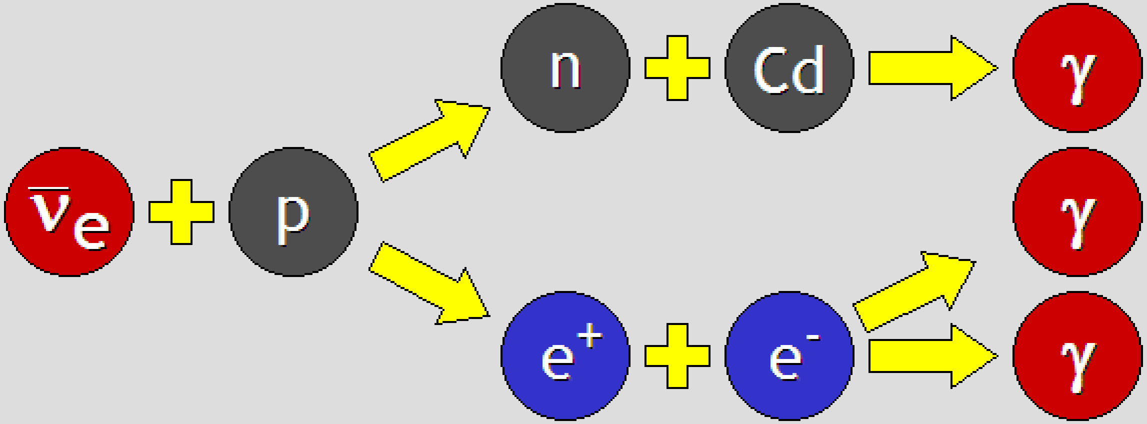
Clyde Cowan
(1919 - 1974)

Fred Reines
(1918 - 1998)
Nobel prize 1995



Detector prototype

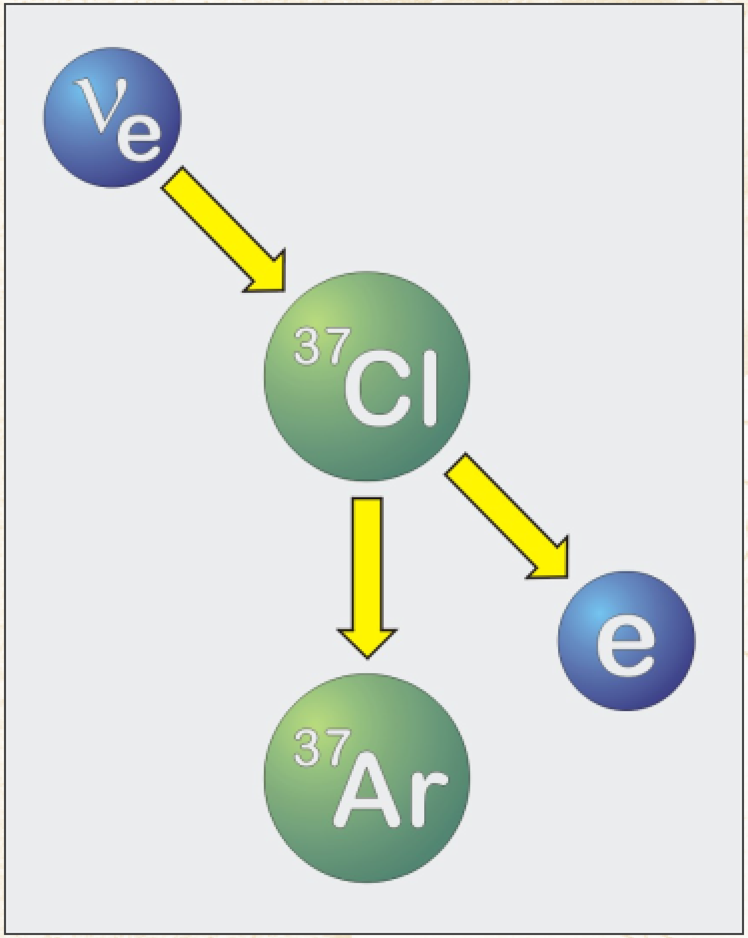
Anti-Electron Neutrinos from Hanford Nuclear Reactor

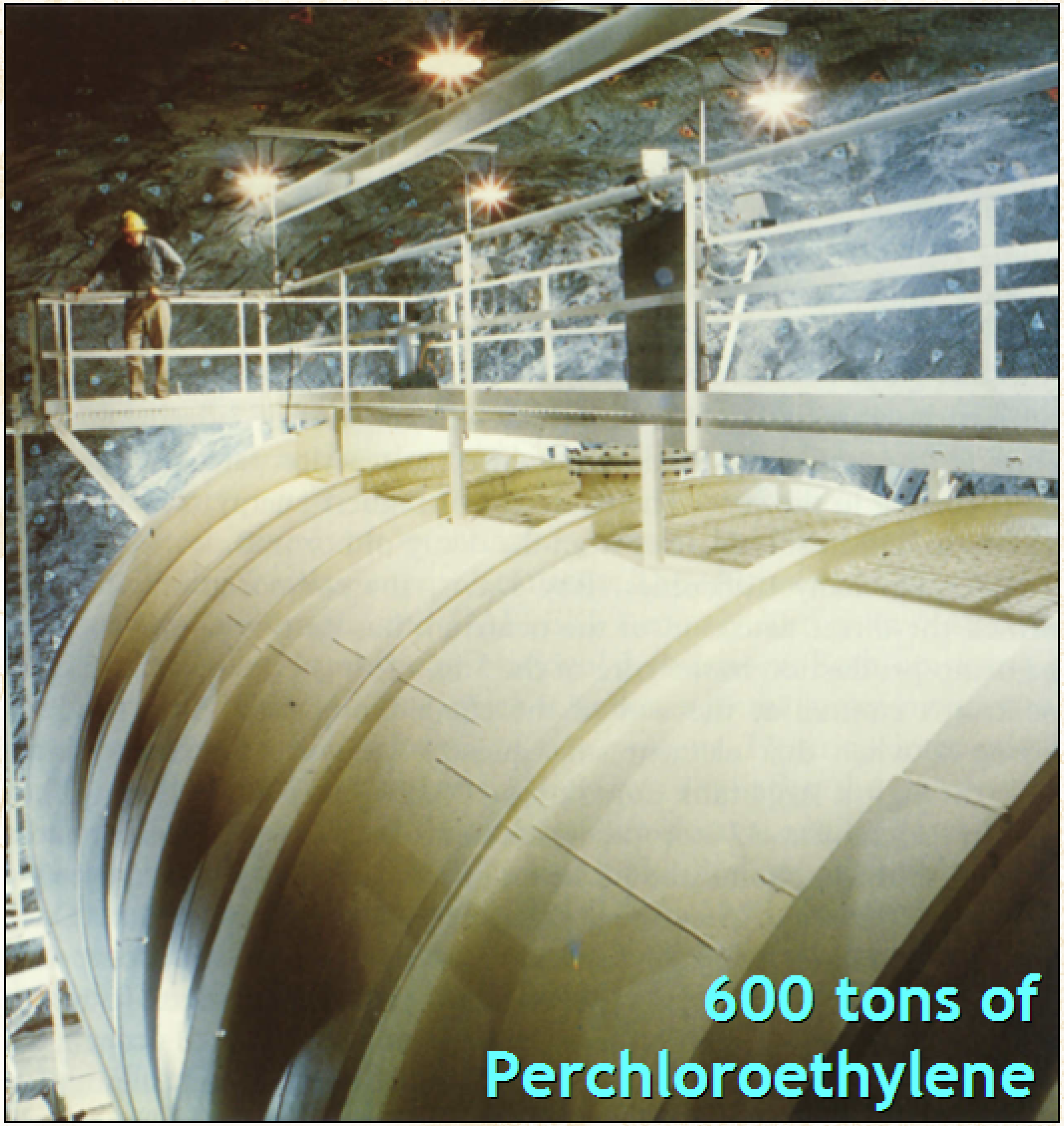


3 Gammas in coincidence

First Measurement of Solar Neutrinos

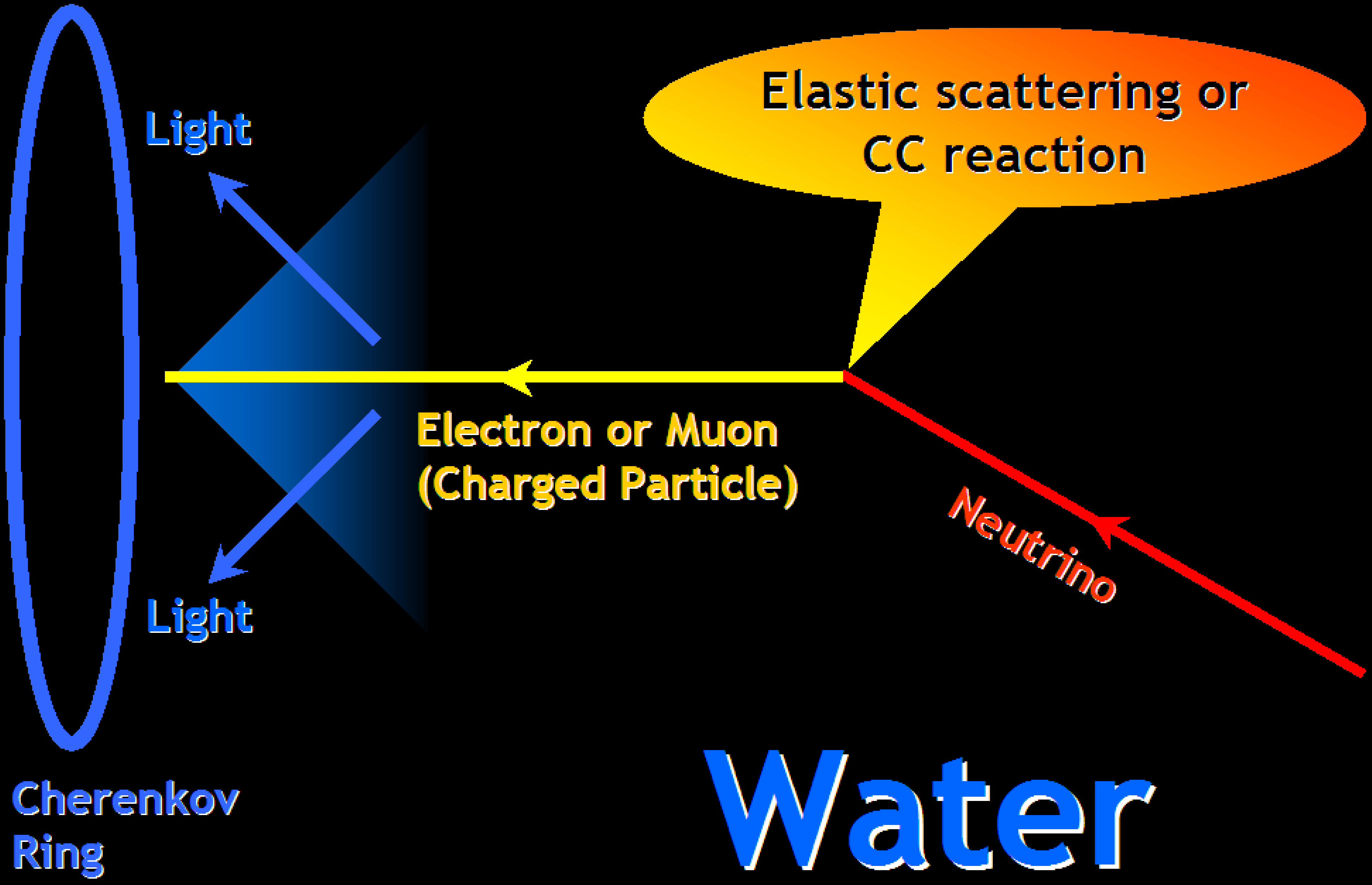
Inverse beta decay of chlorine



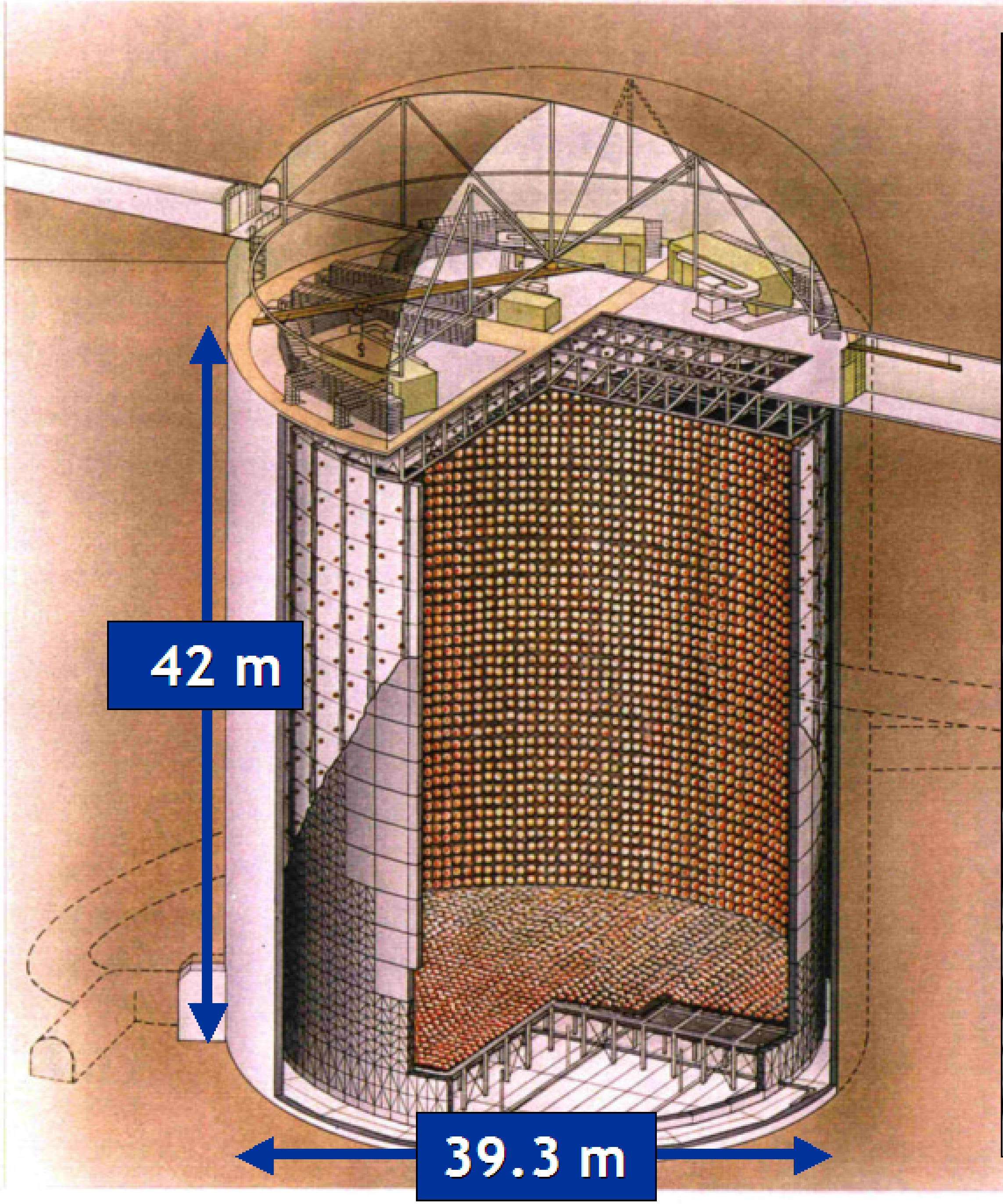


Homestake solar neutrino observatory (1967–2002)

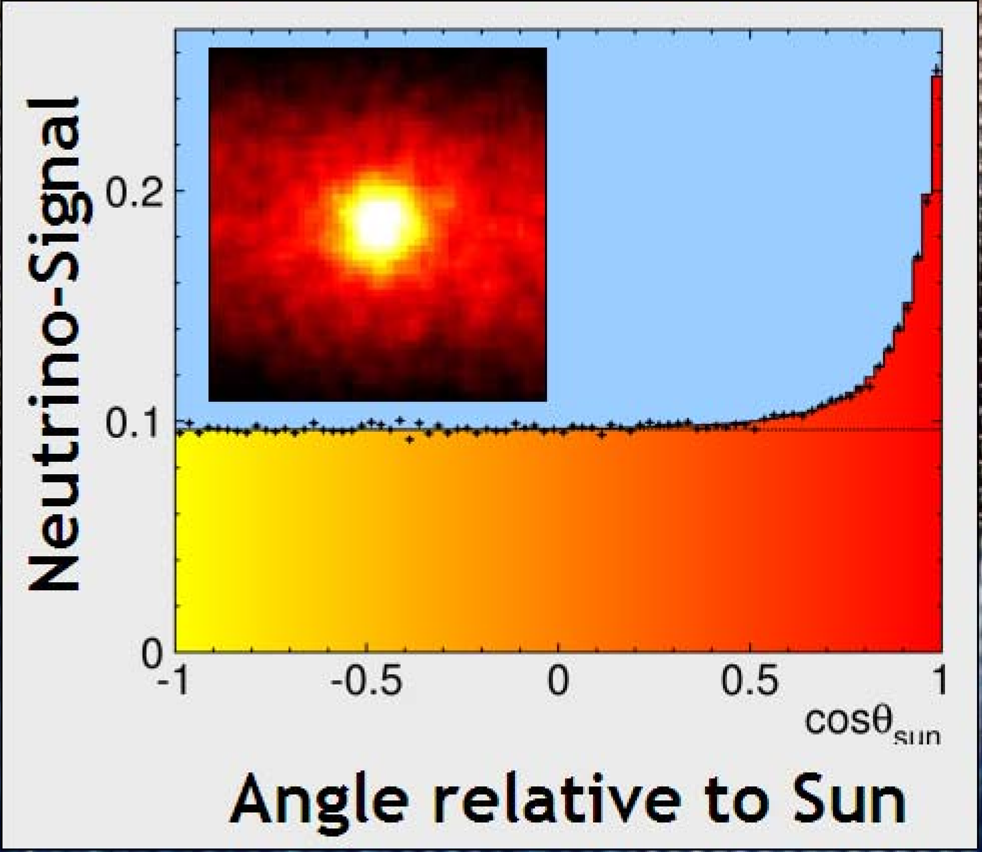
Cherenkov Effect

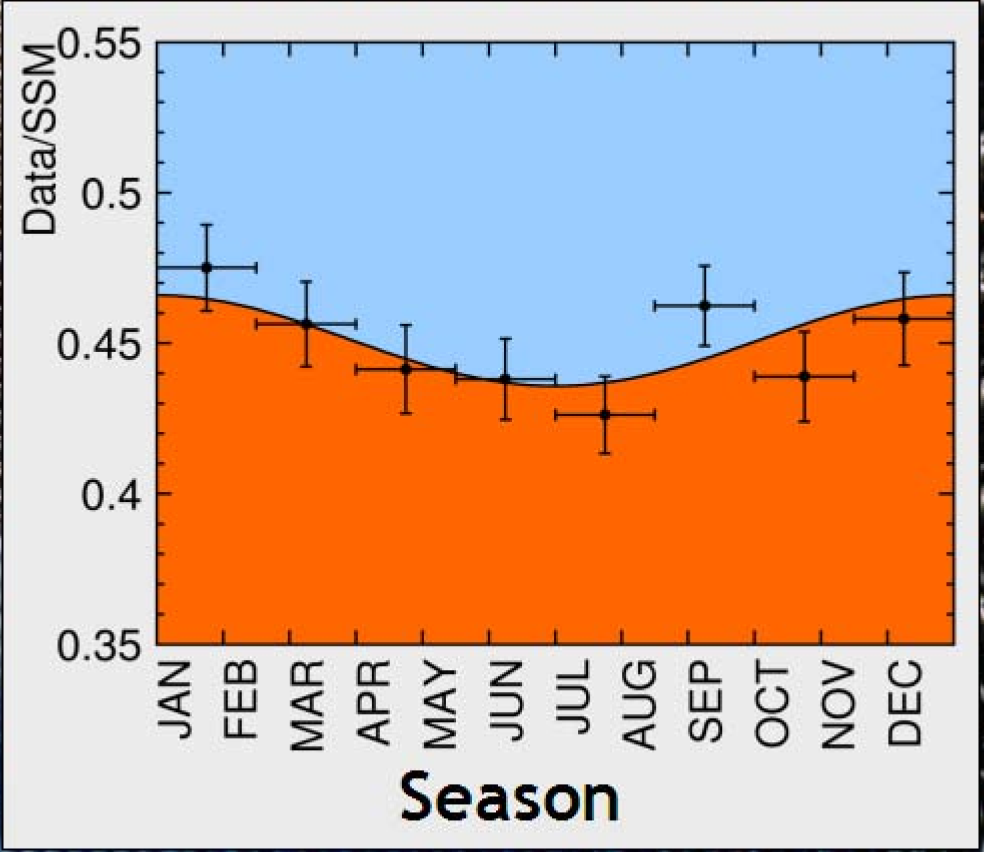


Super-Kamiokande Neutrino Detector



Super-Kamiokande: Sun in the Light of Neutrinos





Three-Flavor Neutrino Parameters

Atmospheric/K2K	CHOOZ	Solar/KamLAND	2σ ranges
$37^\circ < \theta_{23} < 54^\circ$	$\theta_{13} < 11^\circ$	$30^\circ < \theta_{12} < 36^\circ$	hep-ph/0405172

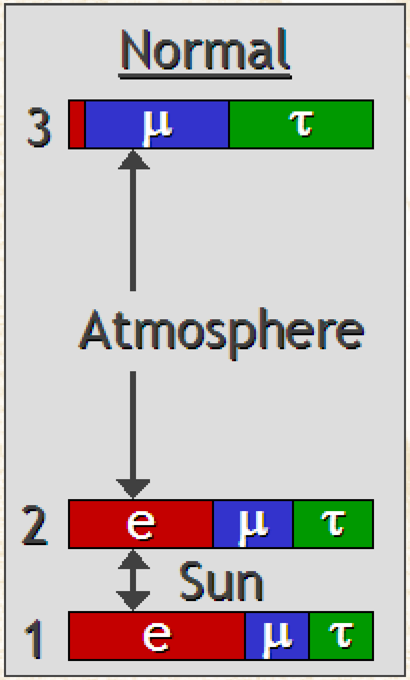
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

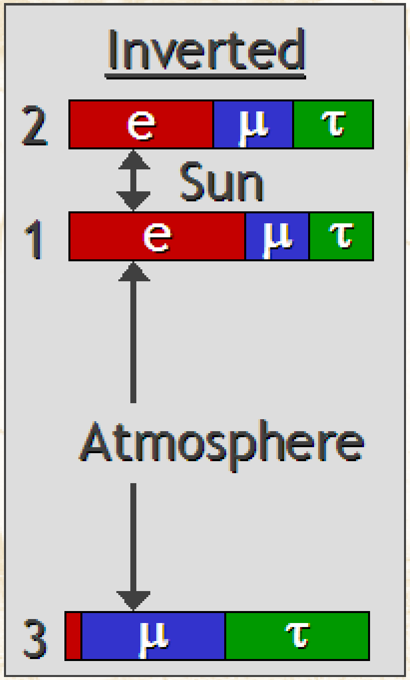
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

Solar
75–92

Atmospheric
1400–3000

$\Delta m^2/\mathrm{meV}^2$

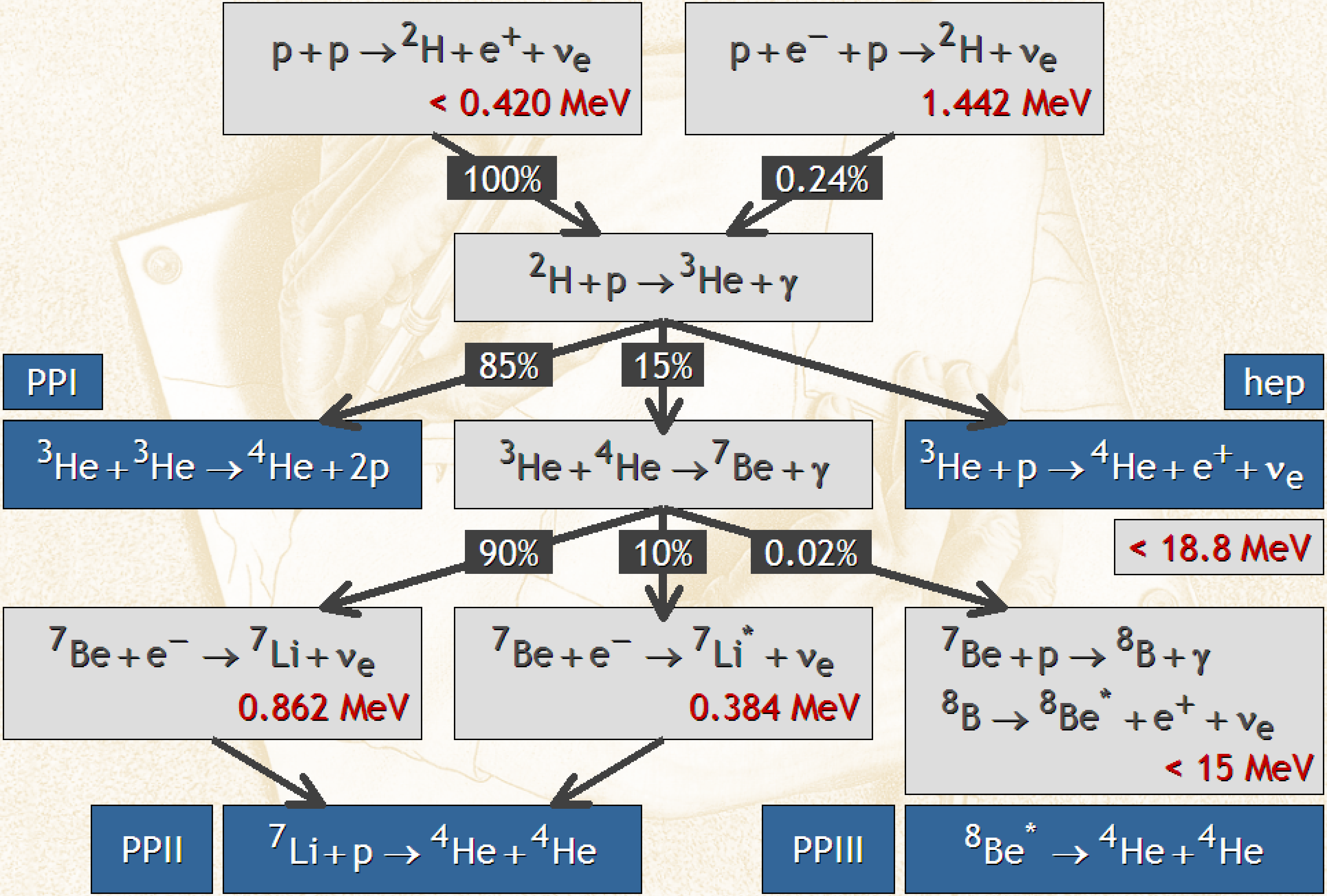




Tasks and Open Questions

- Precision for θ_{12} and θ_{23}
- How large is θ_{13}?
- CP-violating phase δ?
- Mass ordering?
  (normal vs inverted)
- Absolute masses?
  (hierarchical vs degenerate)
- Dirac or Majorana?

Hydrogen burning: Proton-Proton Chains



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

< 0.420 MeV

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

1.442 MeV

100%

0.24%

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

85%

15%

PPI

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

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

hep

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

< 18.8 MeV

90%

10%

0.02%

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

0.862 MeV

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

0.384 MeV

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

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

< 15 MeV

PPII

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

PPIII

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

Neutrinos from Thermal Plasma Processes

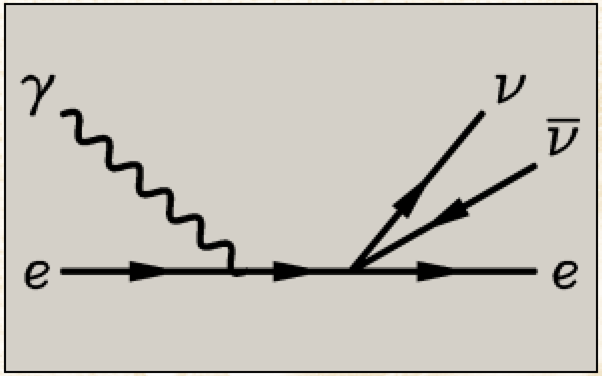
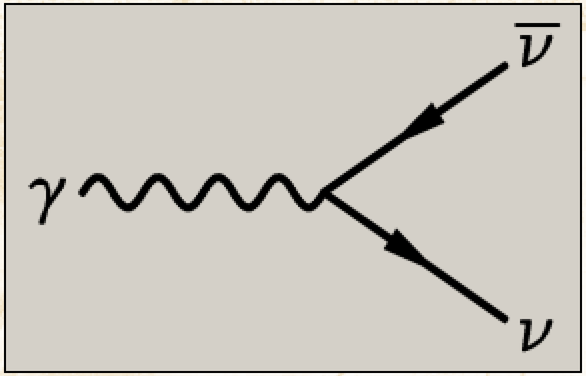
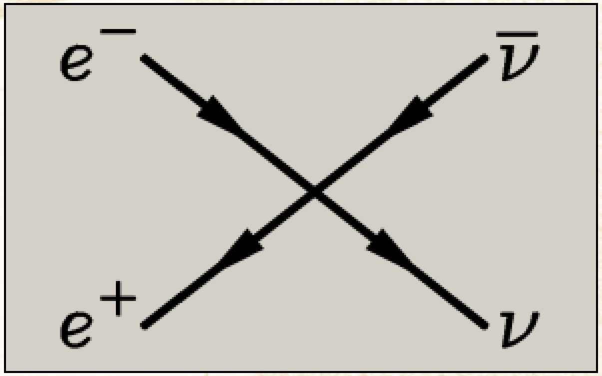


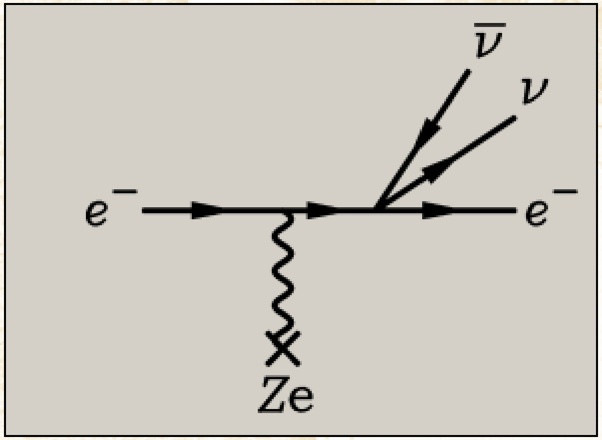
Photo (Compton)



Plasmon decay

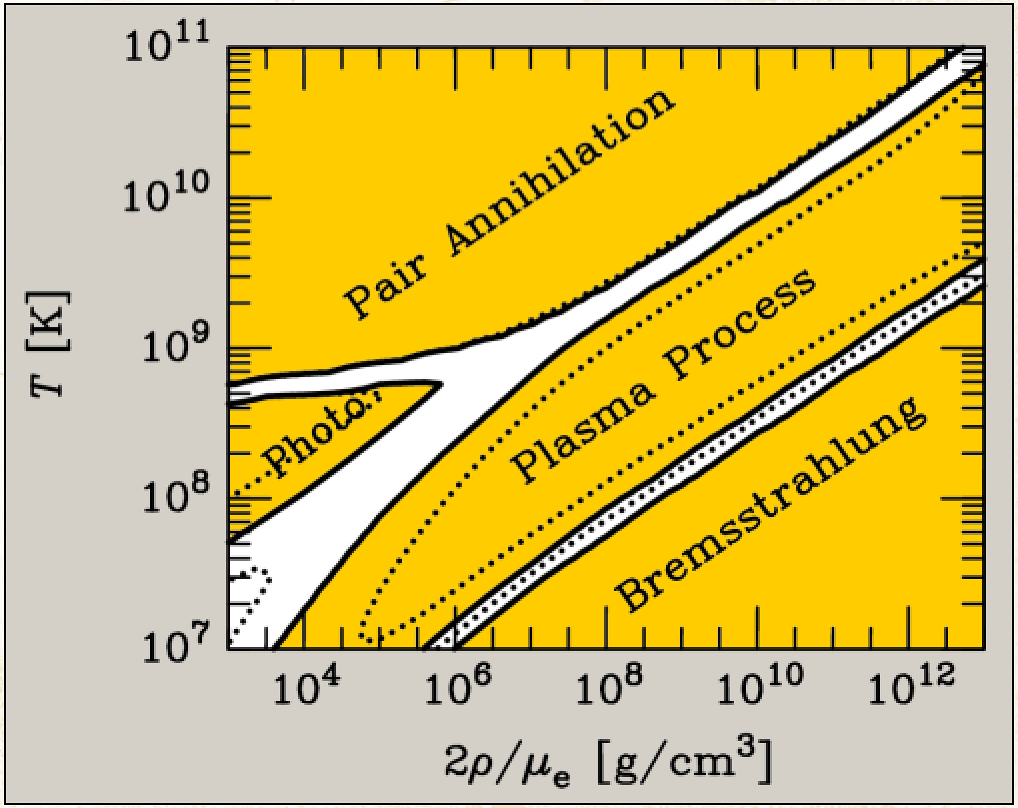


Pair annihilation



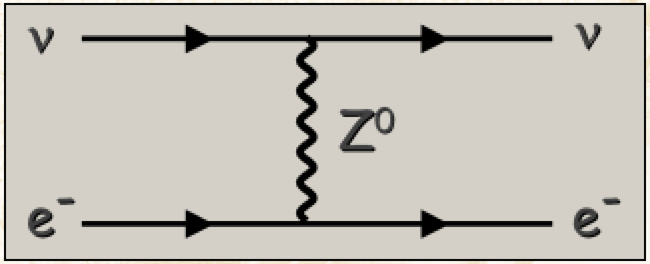
Bremsstrahlung

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

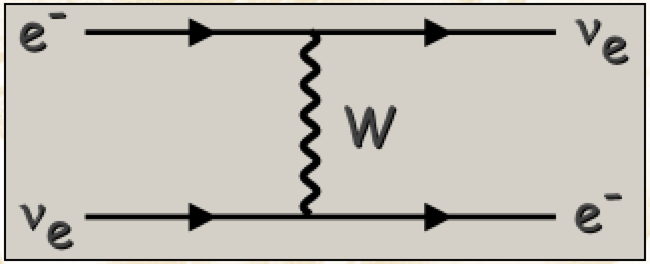


Effective Neutrino Neutral-Current Couplings

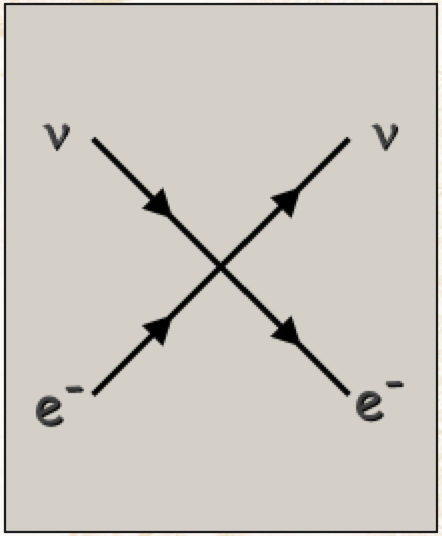
Neutral current



Charged current



$E \ll M_{W,Z}$



Effective four fermion coupling

$$H_{\rm int} = \frac{G_F}{\sqrt{2}}\,\overline{\Psi}_f\gamma_\mu(C_V - C_A\gamma_5)\Psi_f\;\overline{\Psi}_\nu\gamma^\mu(1-\gamma_5)\Psi_\nu$$

Neutrino	Fermion	C_V	C_A
ν_e	Electron	$+\frac{1}{2}+2\sin^2\Theta_W \approx 1$	$+\frac{1}{2}$
ν_μ, ν_τ		$-\frac{1}{2}+2\sin^2\Theta_W \approx 0$	$-\frac{1}{2}$
ν_e, ν_μ, ν_τ	Proton	$+\frac{1}{2}-2\sin^2\Theta_W \approx 0$	$+\frac{1.26}{2}$
	Neutron	$-\frac{1}{2}$	$-\frac{1.26}{2}$

$G_F =$
$1.166 \times 10^{-5}\,\mathrm{GeV}^{-2}$
$\sin^2\Theta_W = 0.231$

Solar Neutrinos from Compton Process

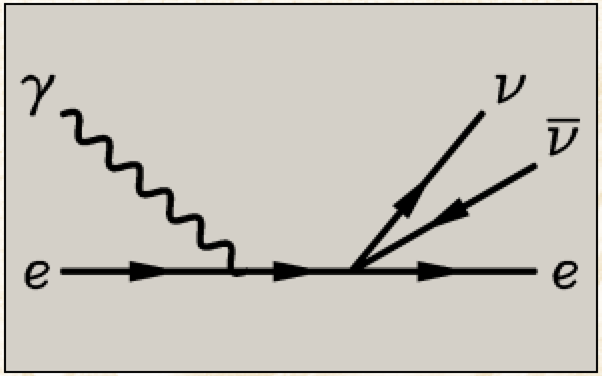


Photo (Compton)

Cross section (non-relativistic limit)

$$\sigma = \frac{32}{105}\,\frac{\alpha G_F^2 m_e^2}{(4\pi)^2}\,(C_V^2 + 5C_A^2)\left(\frac{E_\gamma}{m_e}\right)^4$$

$$\sum_{\text{flavors}} \sigma = 1.34\times10^{-55}\,\text{cm}^2\left(\frac{E_\gamma}{10\,\text{keV}}\right)^4$$

Volume energy loss rate

$$Q_{\nu\overline{\nu}} = n_e \int \frac{2\,d^3\vec{p}_\gamma}{(2\pi)^3}\,\frac{E_\gamma \sum \sigma}{e^{E_\gamma/T} - 1}$$

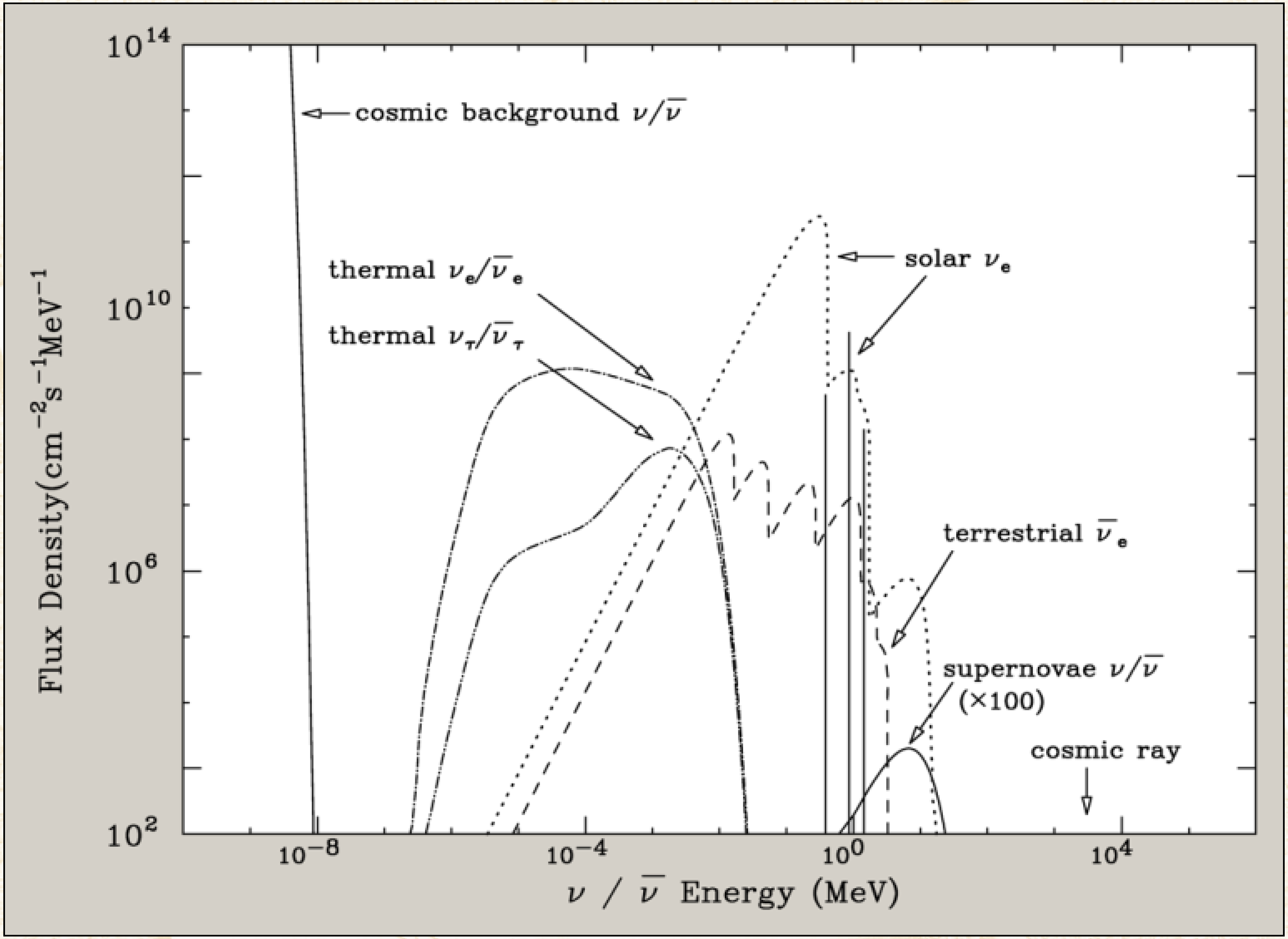
Energy loss rate per unit mass

$$\varepsilon_{\nu\overline{\nu}} = \frac{Q_{\nu\overline{\nu}}}{\rho} = 2.5\times10^{-8}\,\frac{\text{erg}}{\text{g s}}\,Y_e\left(\frac{T}{\text{keV}}\right)^8$$

To be compared with nuclear energy generation rate in the Sun

$$\langle \varepsilon_{\text{nuc}} \rangle = \frac{L_{\text{sun}}}{M_{\text{sun}}} = \frac{4\times10^{33}\,\text{erg/s}}{2\times10^{33}\,\text{g}} = 2\,\frac{\text{erg}}{\text{g s}} = 2\times10^{-7}\,\frac{\text{Watts}}{\text{g}} = \frac{200\,\text{Watts}}{\text{kilo-ton}}$$

Thermal vs. Nuclear Neutrinos from Sun



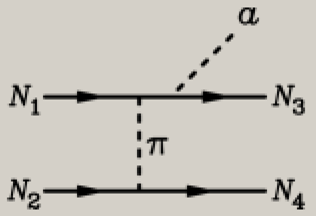
Haxton & Lin, The very low energy solar flux of electron and heavy-flavor neutrinos and anti-neutrinos, nucl-th/0006055

Axion or Graviton Emission Processes in Stars

Nucleons

$$\frac{C_N}{2f_a}\,\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a$$

Nucleon Bremsstrahlung



Photons

$$\frac{C_e}{2f_a}\,\overline{\Psi}_e\gamma_\mu\gamma_5\Psi e\,\partial^\mu a$$

Primakoff

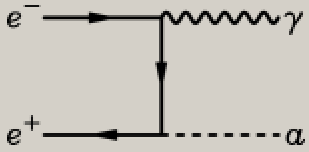
Electrons

$$C_\gamma\,\frac{\alpha}{2\pi f_a}\,\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

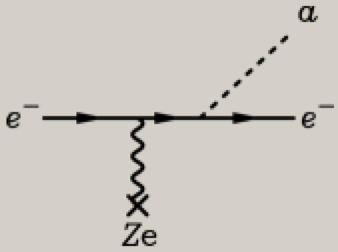
$$= -C_\gamma\,\frac{\alpha}{2\pi f_a}\,\vec{E}\cdot\vec{B}\,a$$

Compton

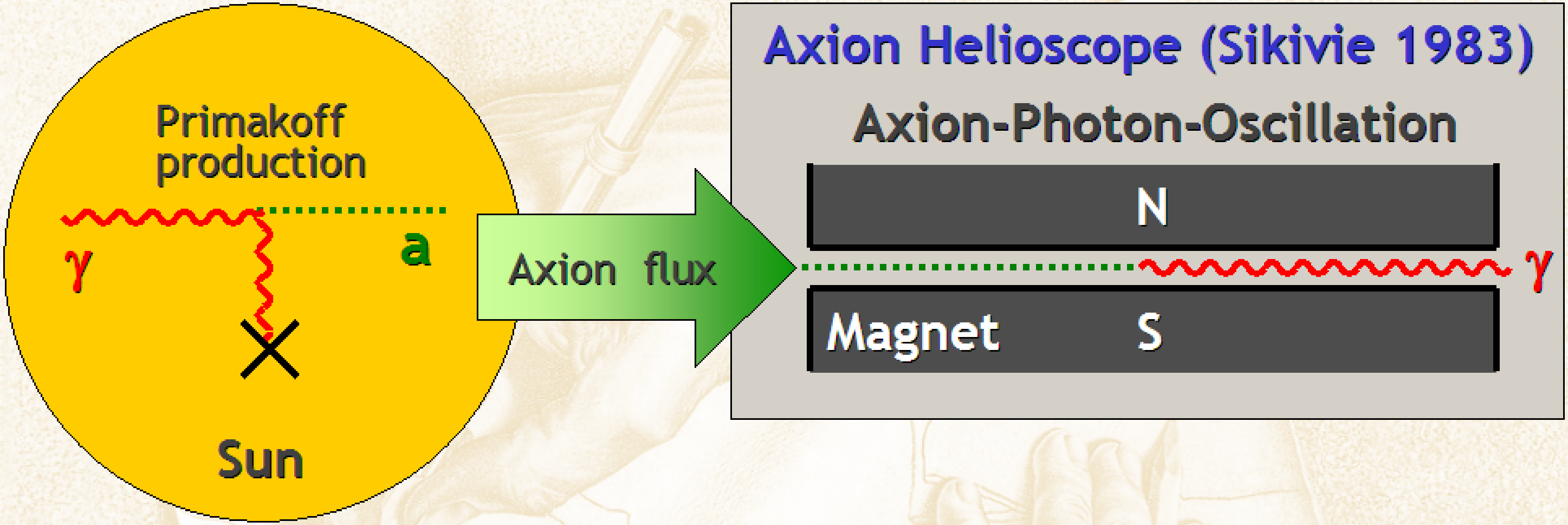
Pair Annihilation



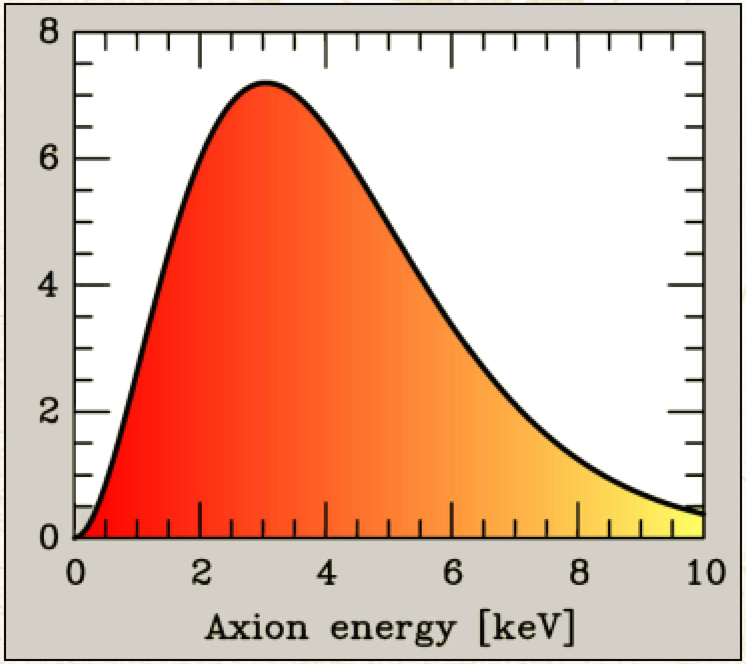
Electromagnetic Bremsstrahlung



Search for Solar Axions



Axion Helioscope (Sikivie 1983)



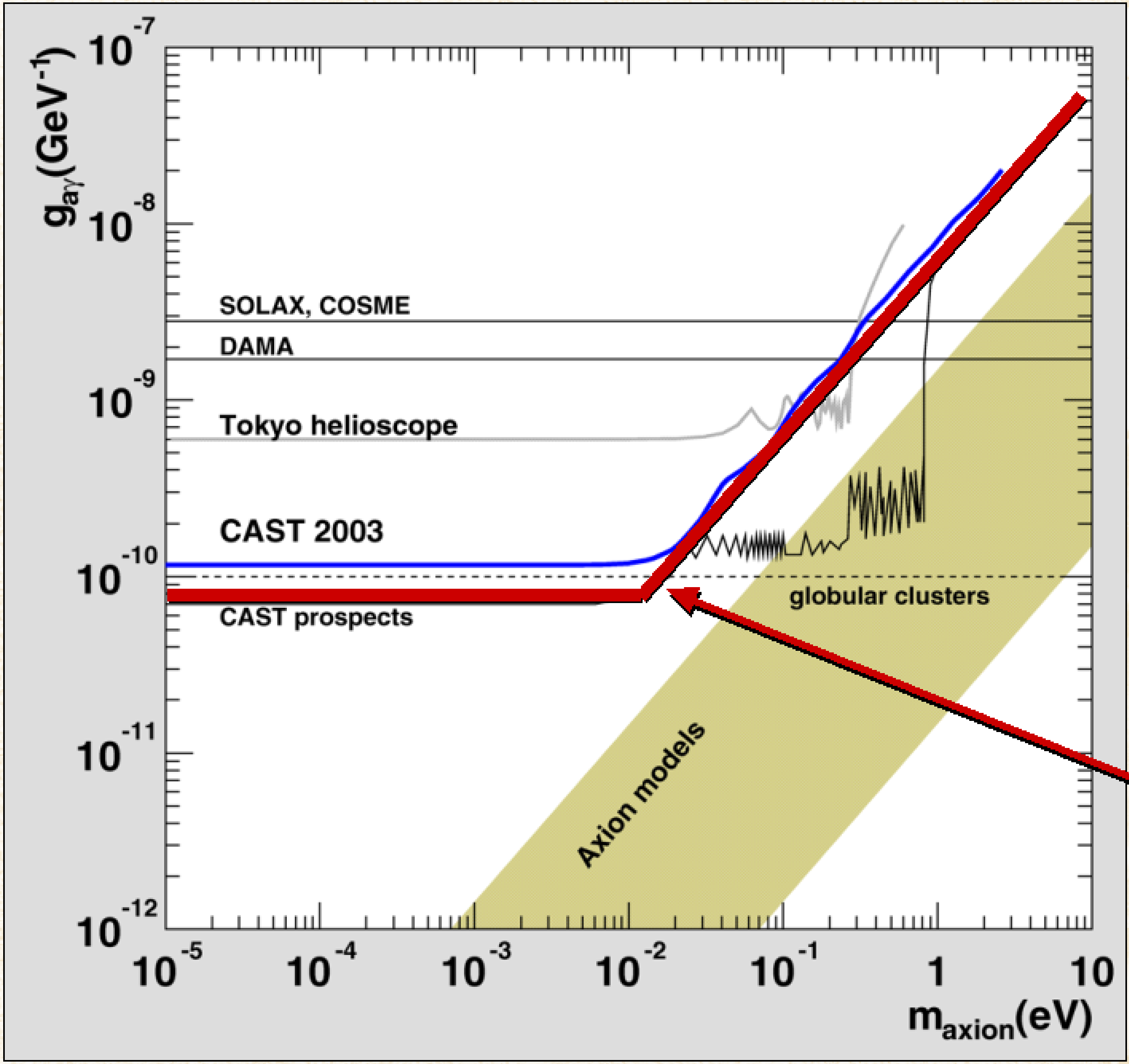
- ➔ Tokyo Axion Helioscope (Results since 1998)
- ➔ CERN Axion Solar Telescope (CAST) (Data since 2003)

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

Recent Picture of CAST

CAST Movie

CAST Exclusion Range (2003 Data)



CAST Collaboration:

First results from the CERN Axion Solar Telescope (CAST)

Submitted to PRL (hep-ex/0411033)

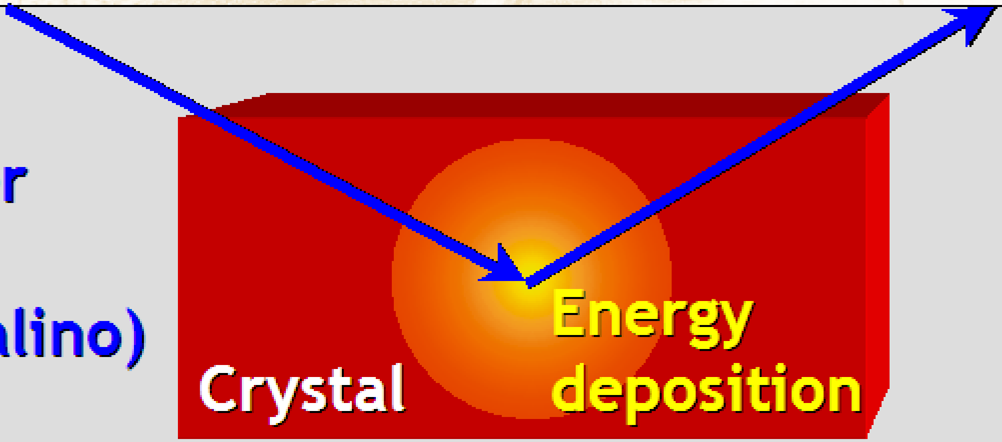
Anticipated sensitivity with 2004 data

- Additional exposure
- Solar image of x-ray telescope better known and stability control:
  Use smaller spot on CCD

Search for Neutralino Dark Matter

Direct Method (Laboratory Experiments)

Galactic dark matter particle (e.g.neutralino)



Crystal

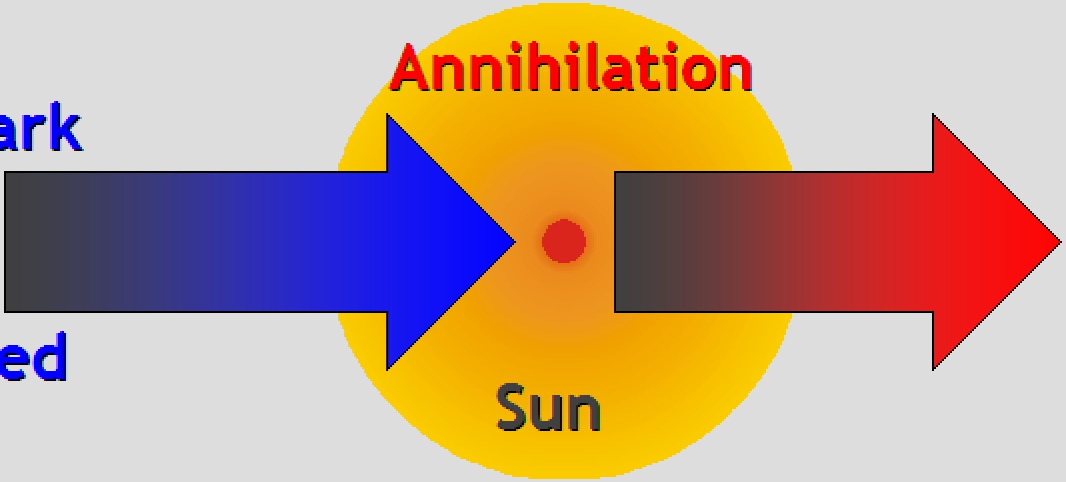
Energy deposition

Recoil energy (few keV) is measured by

- Ionisation
- Scintillation
- Cryogenic

Indirect Method (Neutrino Telescopes)

Galactic dark matter particles are accreted

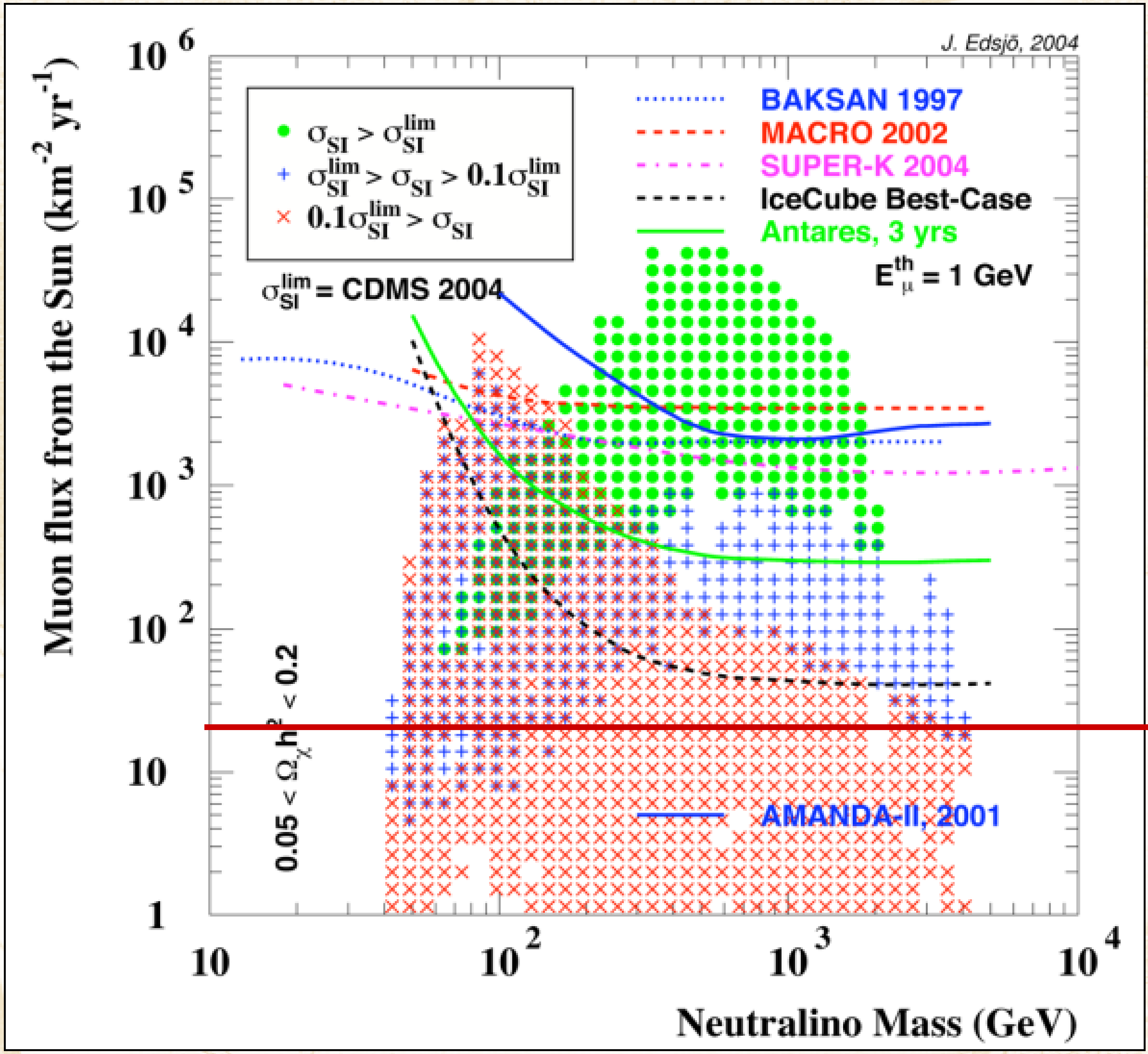


Annihilation

Sun

High-energy neutrinos (GeV-TeV) can be measured

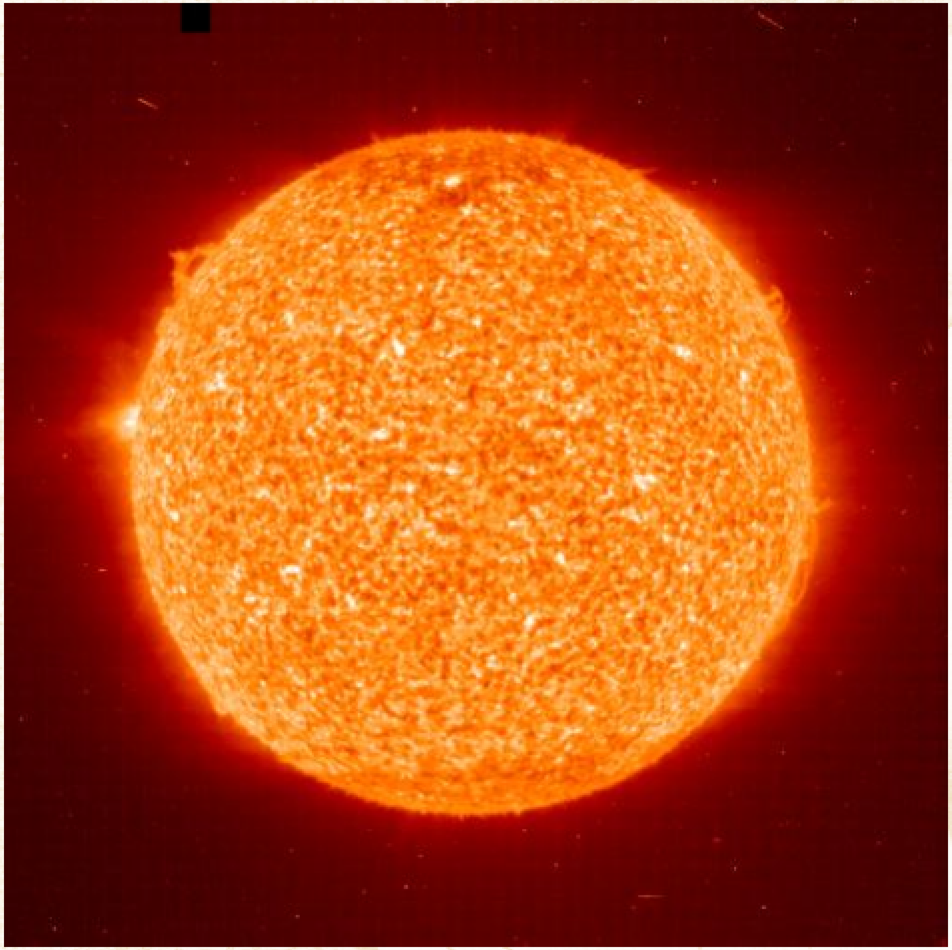
Muon Flux from WIMP Annihilation in the Sun



Background from Sun

Need a km^3 water Cherenkov detector to reach solar background

Solar Neutrinos



Thermal plasma reactions
E ~ 1 eV - 30 keV
No apparent way to measure

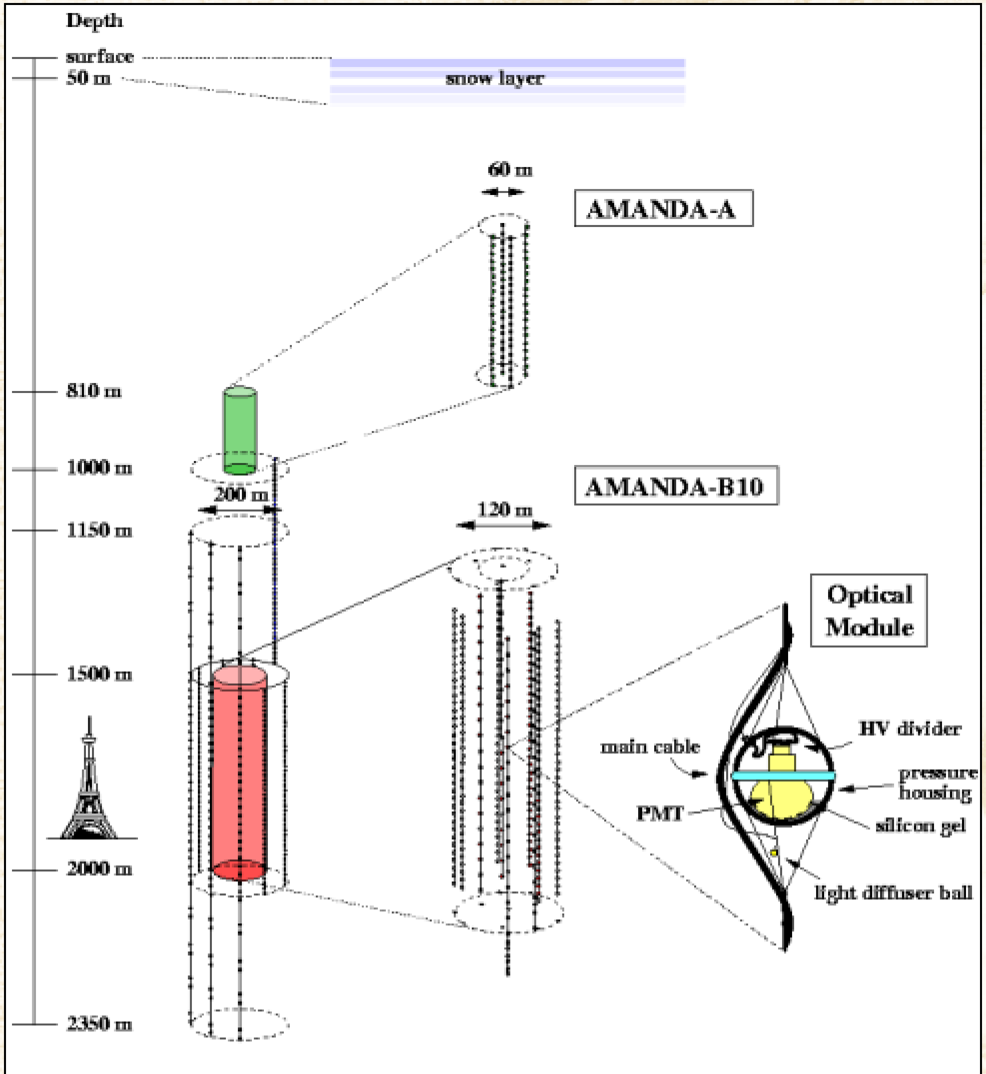
Nuclear burning reactions
E ~ 0.1 - 15 MeV
Routine detailed measurements

Cosmic-ray interactions in the Sun
E ~ 10 - 10^9 GeV
Future high-E neutrino telescopes (?)

Dark matter annihilation in the Sun
E ~ GeV - TeV (?)
Future high-E neutrino telescopes (?)

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)

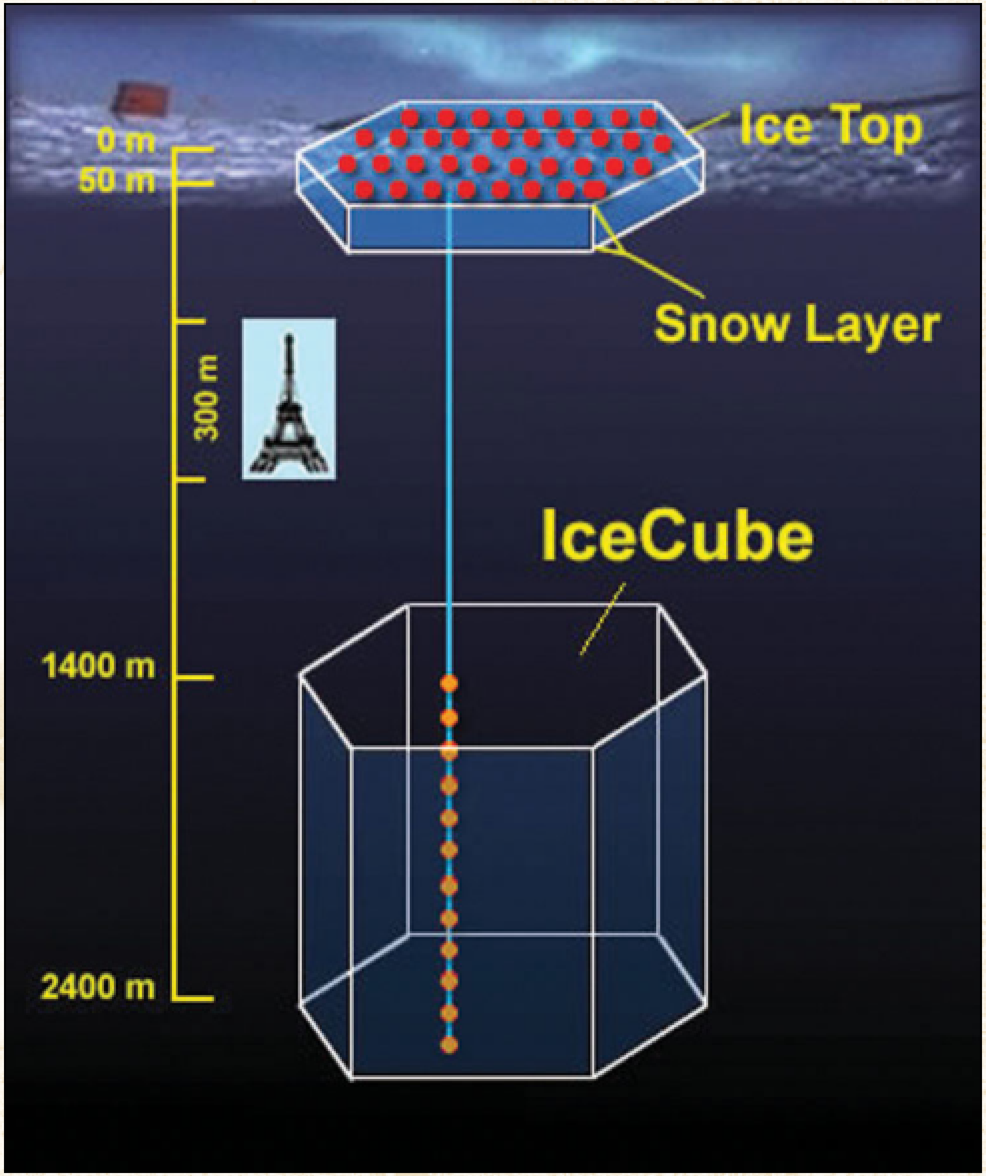


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

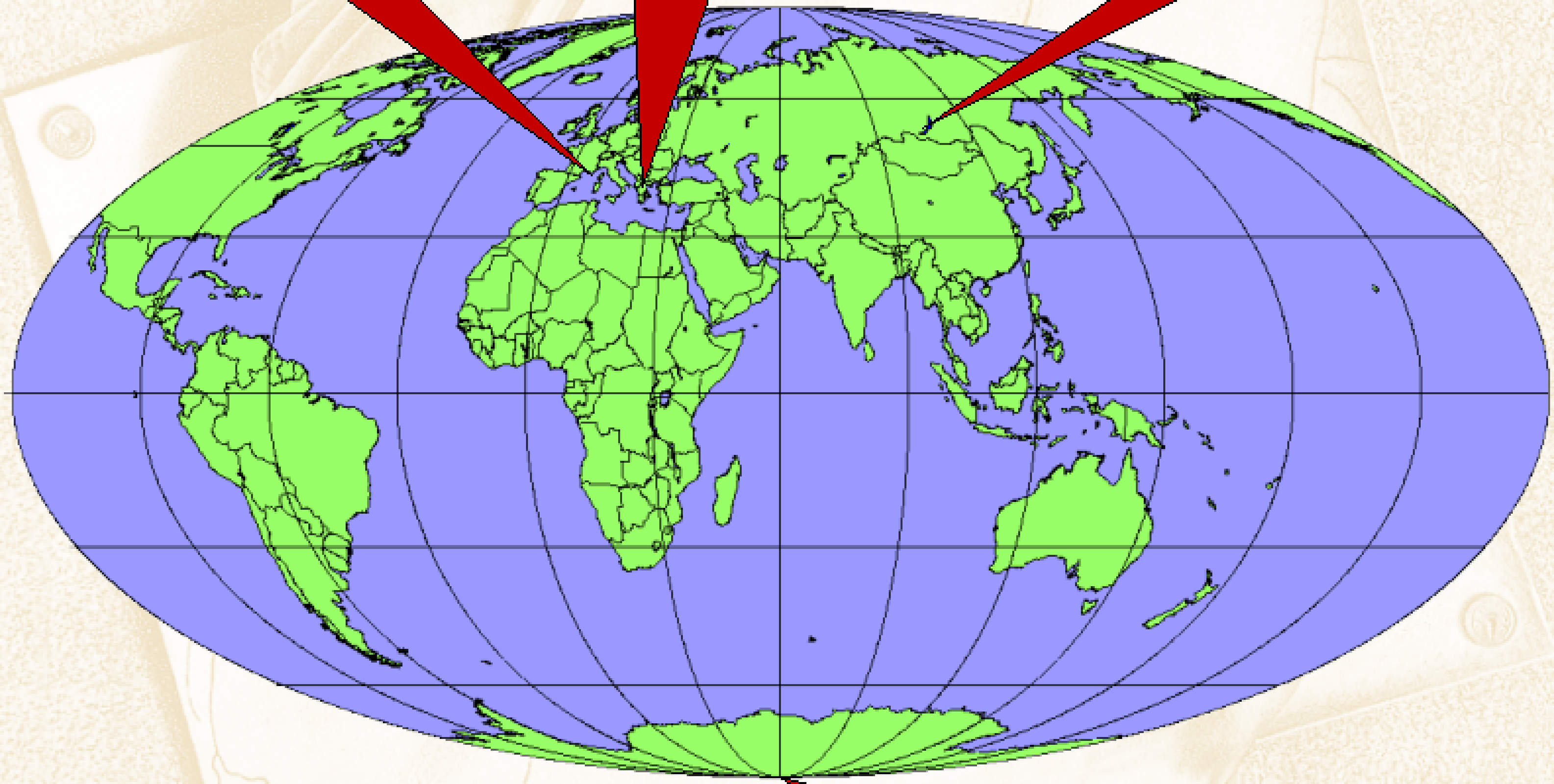
zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Future IceCube (1 km^3, 4800 PMTs)



High-Energy Neutrino Telescopes



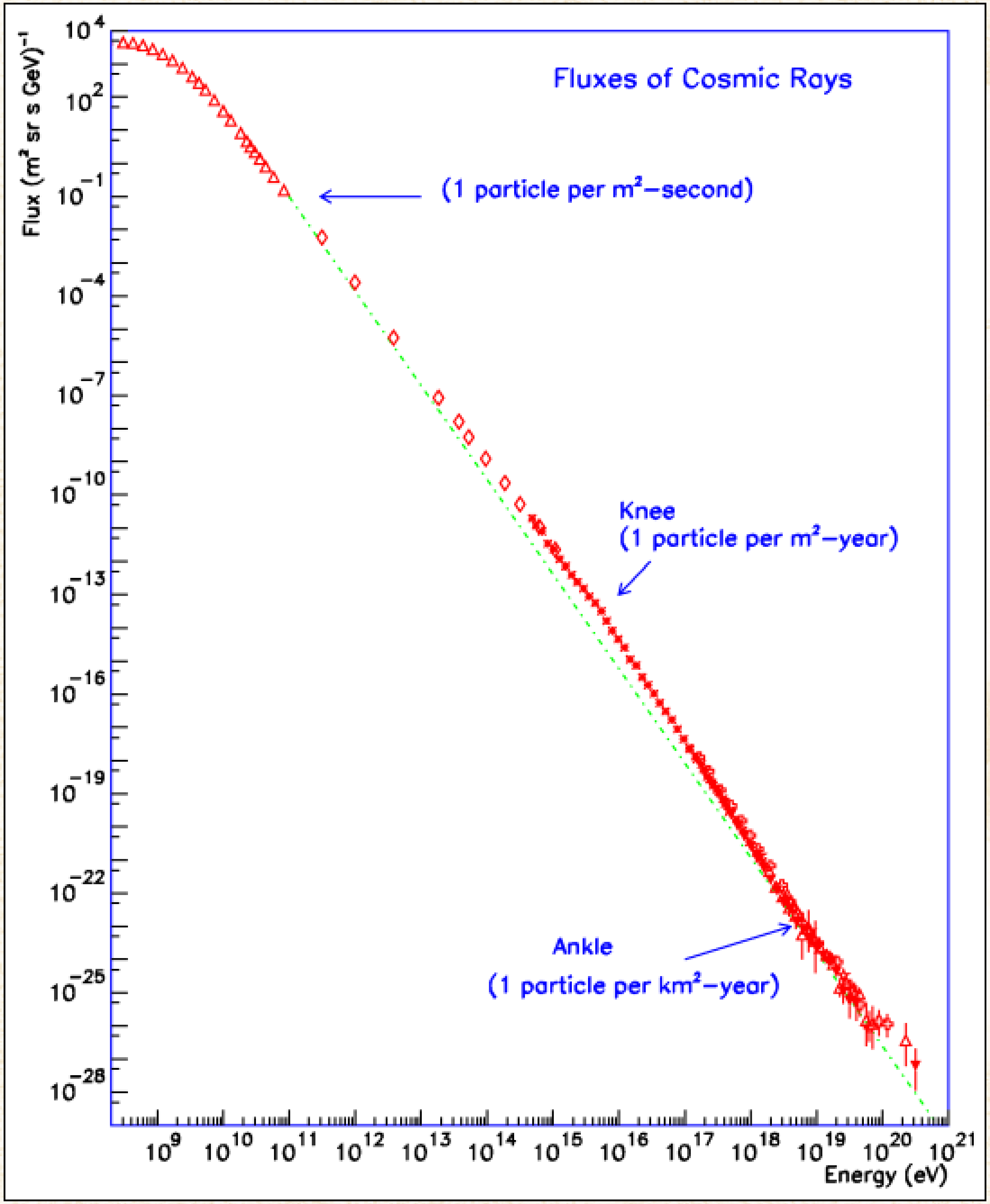
Antares Project

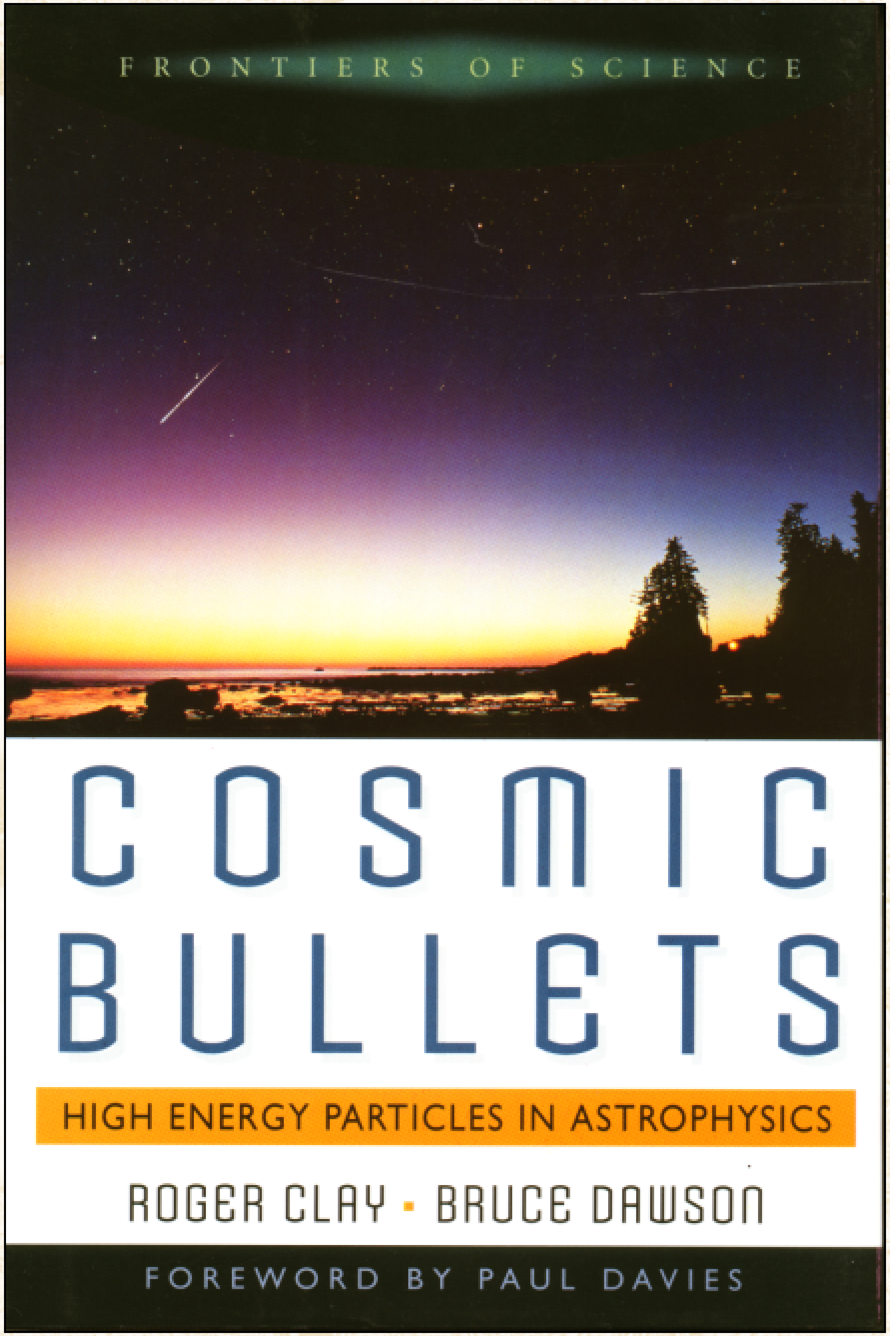
Nestor Project

Baikal 200 PMTs

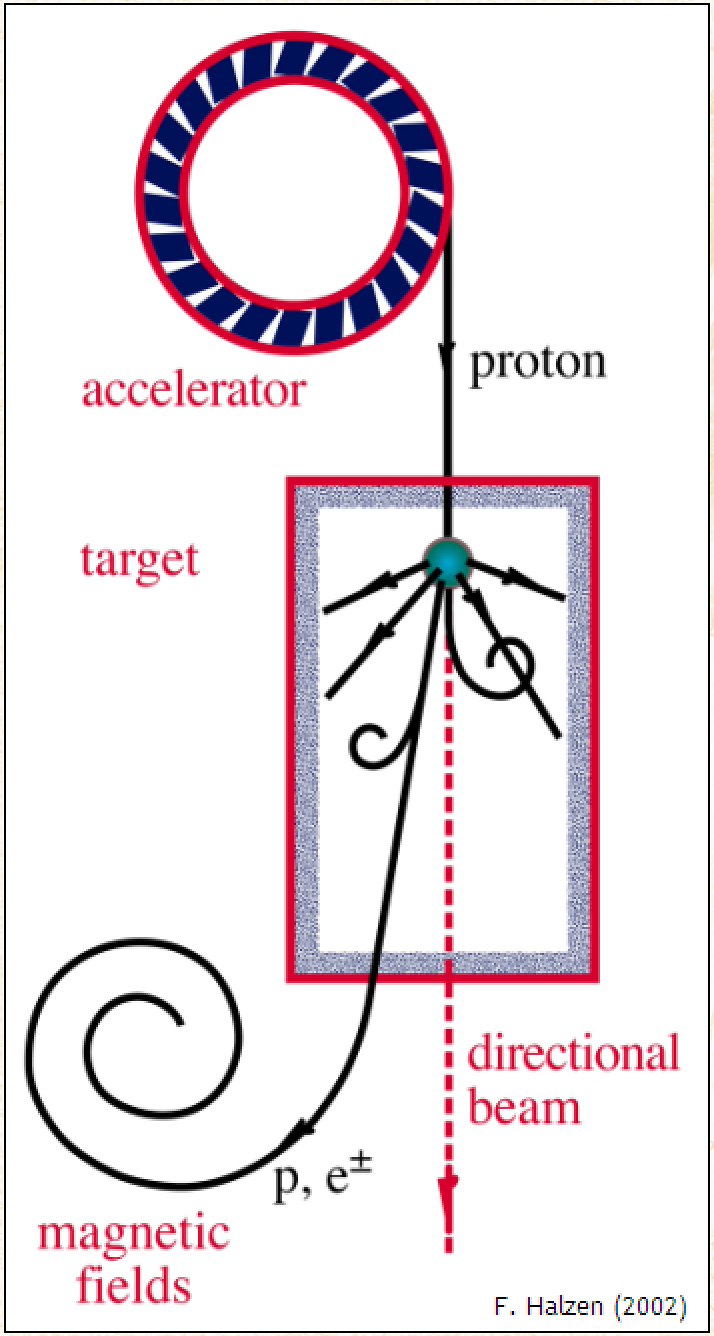
Amanda II, 800 PMTs IceCube Project

Global Cosmic Ray Spectrum

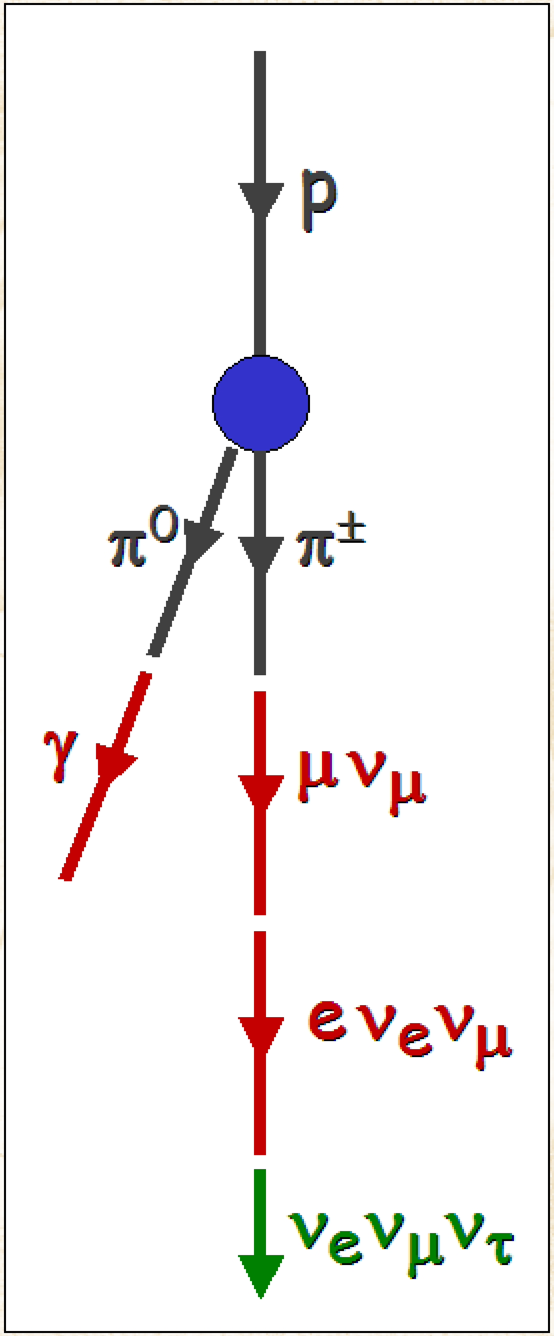




Neutrino Beams: Heaven and Earth



F. Halzen (2002)

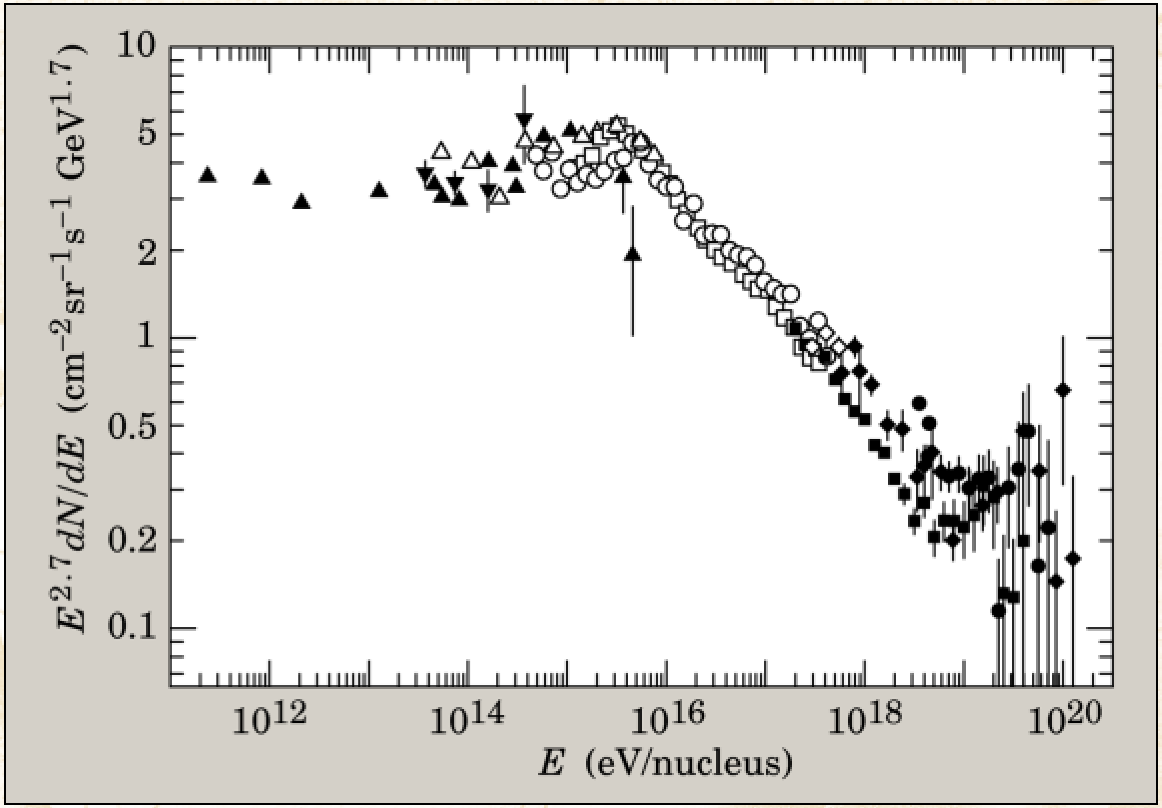


Target:
Protons or Photons

Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

Gamma-, Neutrino- and Proton-Astronomy



Cosmic-ray spectrum × $E^{2.7}$

What are the sources ?

TeV γ astronomy

Photon mean free path < few 10 Mpc

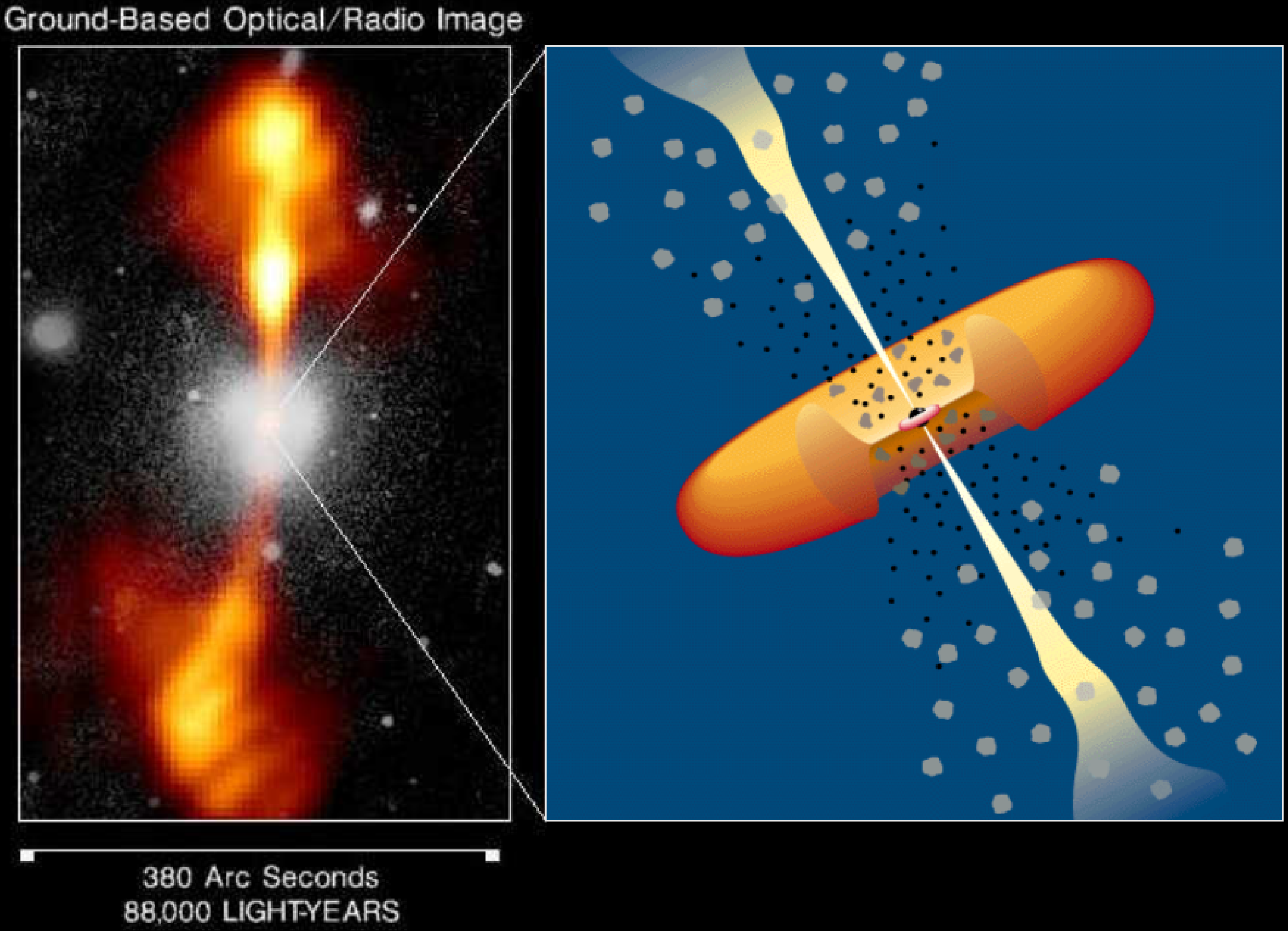
Proton magnetic field deflection

GZK cutoff

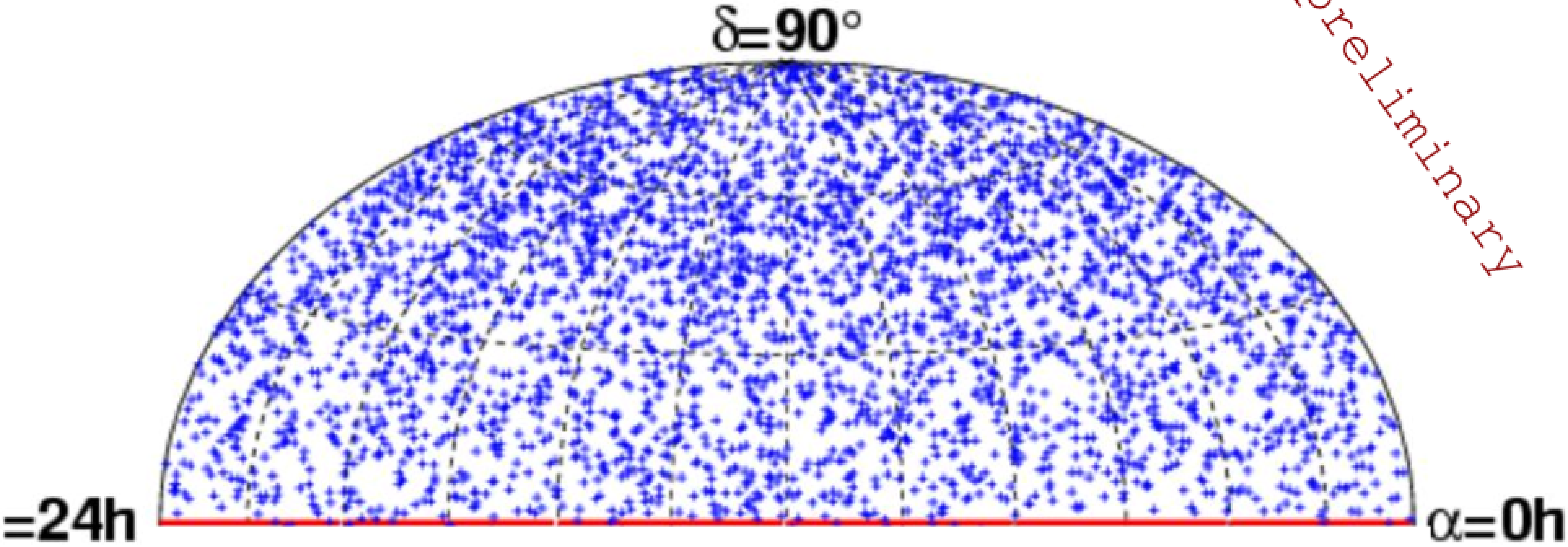
Opportunity for neutrino astronomy

- Point back to sources
- No absorption (reach across the universe)

Core of the Galaxy NGC 4261



Neutrino Sky at AMANDA (2000-2003)



preliminary

3329 ν events in 2000-03 data (807 days)

(sensitivity ~3 higher as 2000)

S.Schlenstedt, Zeuthen Workshop, 4-5 Oct 2005

Neutrinos in Ordinary Stars

Neutrinos from Thermal Plasma Processes

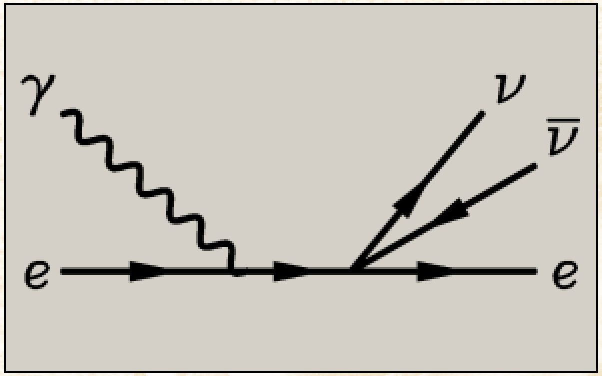
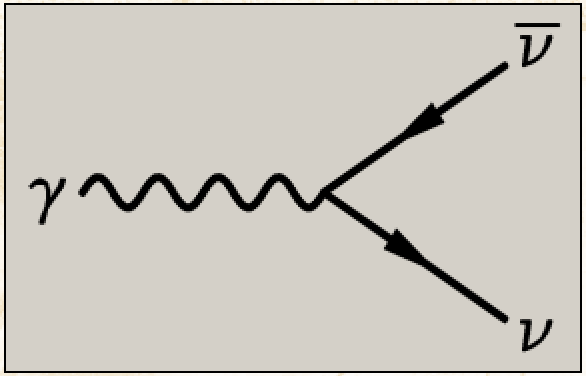
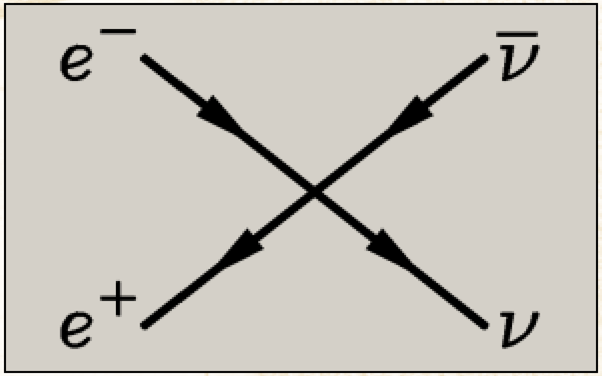


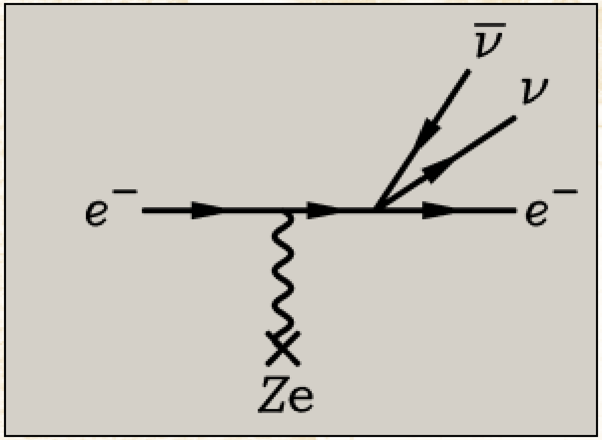
Photo (Compton)



Plasmon decay

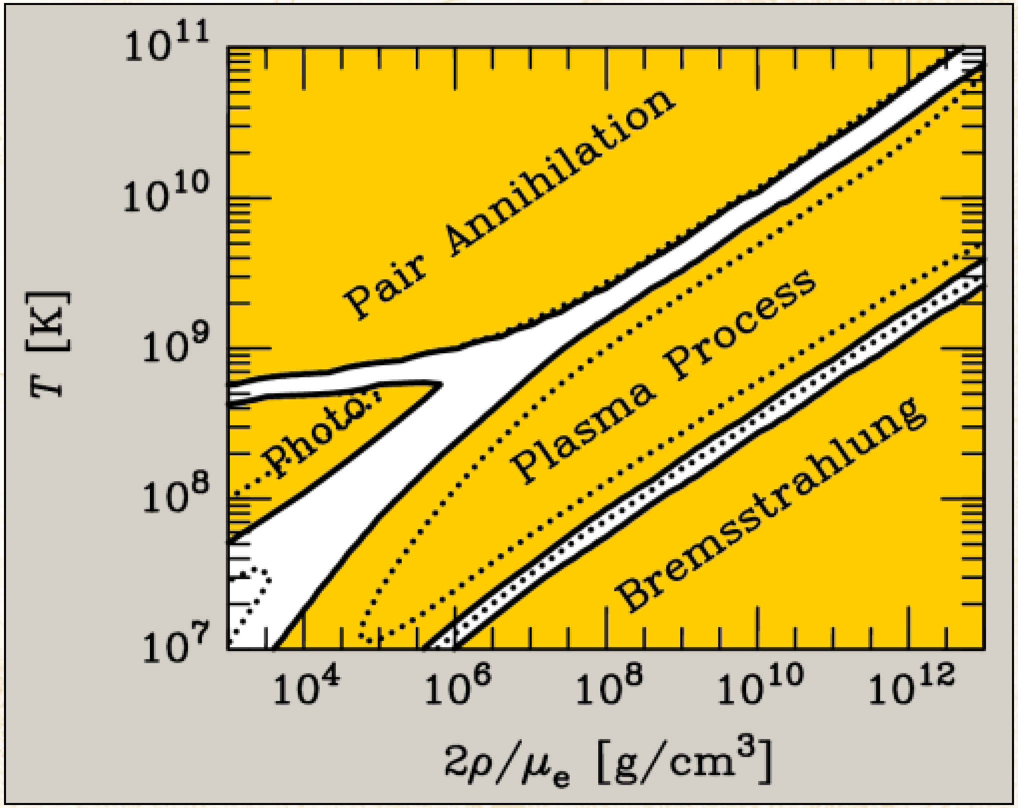


Pair annihilation

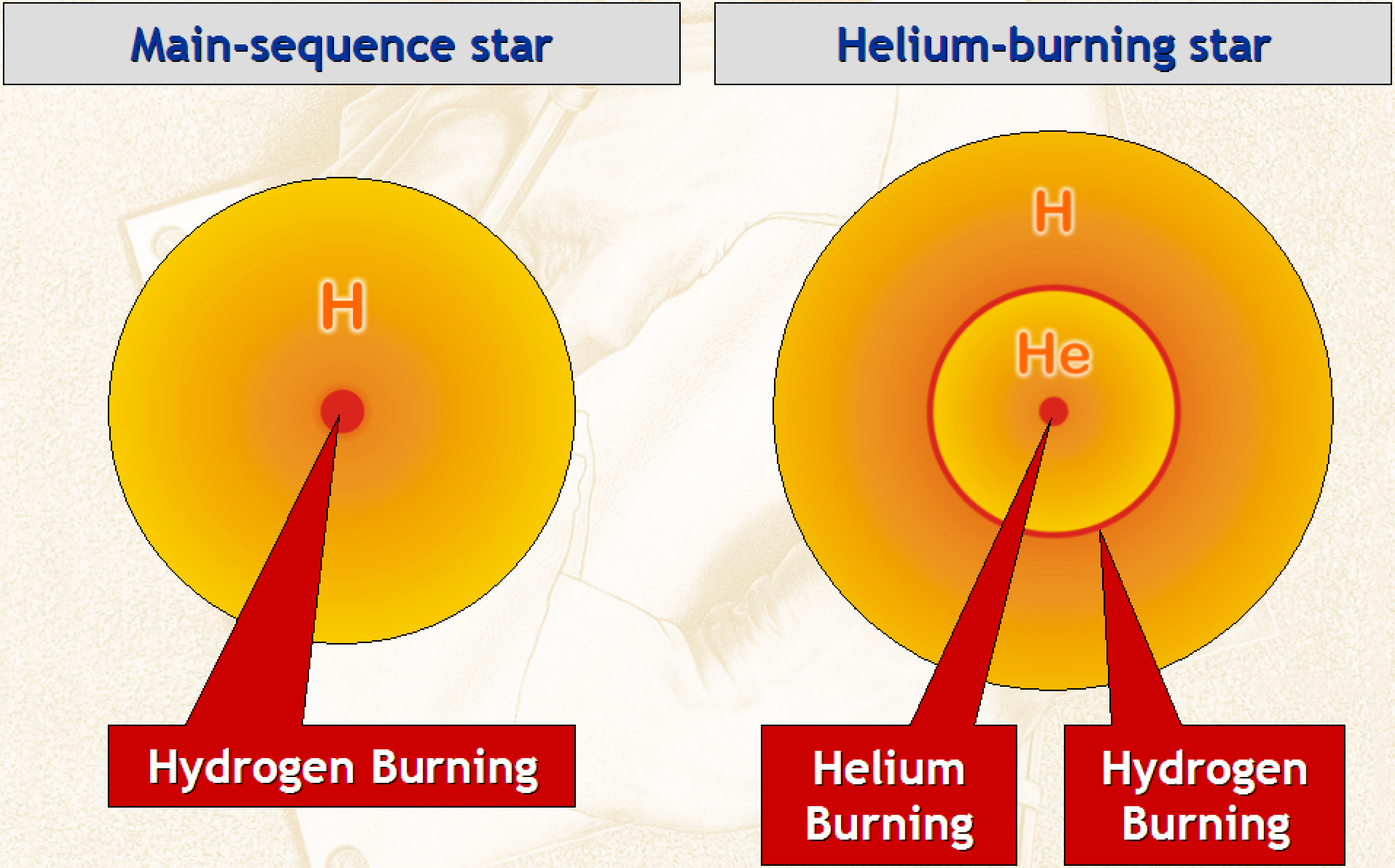


Bremsstrahlung

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



Hydrogen Exhaustion



Main-sequence star

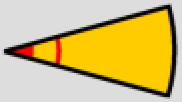
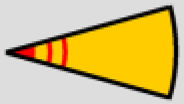
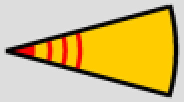
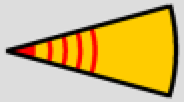
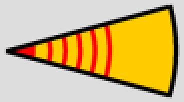
Helium-burning star

Hydrogen Burning

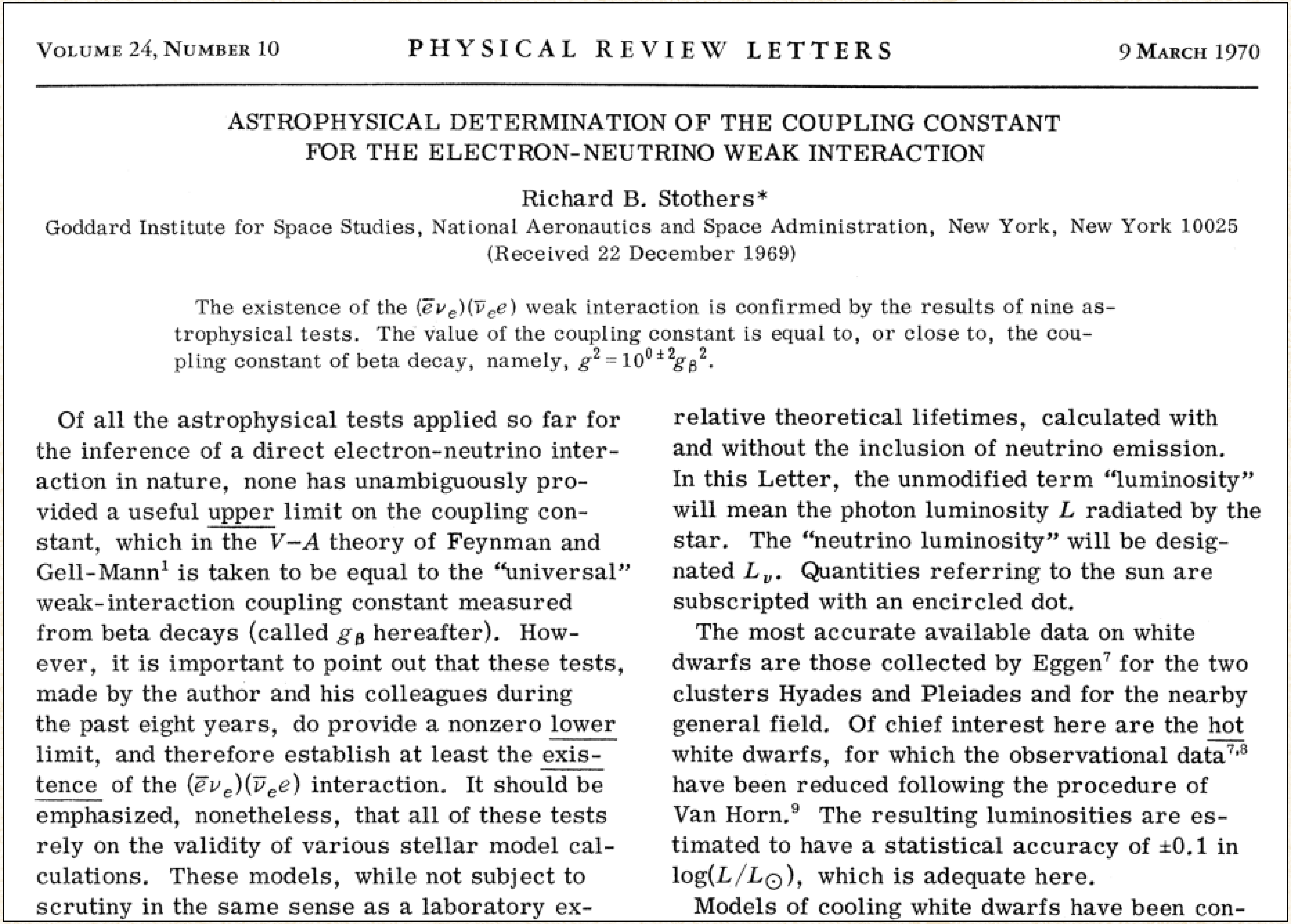
Helium Burning

Hydrogen Burning

Burning Phases of a 15 Solar-Mass Star

Burning Phase		Dominant Process	T_c [keV]	ρ_c [g/cm³]	L_γ [10^4 L_{sun}]		Duration [years]
						L_ν/L_γ	
	Hydrogen	H → He	3	5.9	2.1	–	1.2×10^7
	Helium	He → C, O	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
	Carbon	C → Ne, Mg	53	1.7×10^5	8.6	1.0	6.3×10^3
	Neon	Ne → O, Mg	110	1.6×10^7	9.6	1.8×10^3	7.0
	Oxygen	O → Si	160	9.7×10^7	9.6	2.1×10^4	1.7
	Silicon	Si → Fe, Ni	270	2.3×10^8	9.6	9.2×10^5	6 days

Existence of Direct Neutrino-Electron Coupling



VOLUME 24, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1970

ASTROPHYSICAL DETERMINATION OF THE COUPLING CONSTANT FOR THE ELECTRON-NEUTRINO WEAK INTERACTION

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Goddard Institute for Space Studies, National Aeronautics and Space Administration, New York, New York 10025

(Received 22 December 1969)

The existence of the $(\bar{e}\nu_e)(\bar{\nu}_e e)$ weak interaction is confirmed by the results of nine astrophysical tests. The value of the coupling constant is equal to, or close to, the coupling constant of beta decay, namely, $g^2 = 10^{0\pm2} g_\beta^2$.

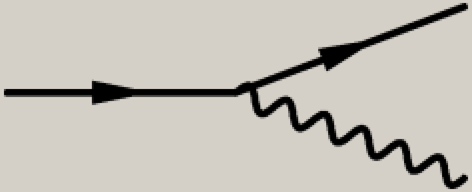
Of all the astrophysical tests applied so far for the inference of a direct electron-neutrino interaction in nature, none has unambiguously provided a useful upper limit on the coupling constant, which in the $V-A$ theory of Feynman and Gell-Mann[1] is taken to be equal to the "universal" weak-interaction coupling constant measured from beta decays (called g_β hereafter). However, it is important to point out that these tests, made by the author and his colleagues during the past eight years, do provide a nonzero lower limit, and therefore establish at least the existence of the $(\bar{e}\nu_e)(\bar{\nu}_e e)$ interaction. It should be emphasized, nonetheless, that all of these tests rely on the validity of various stellar model calculations. These models, while not subject to scrutiny in the same sense as a laboratory ex-

relative theoretical lifetimes, calculated with and without the inclusion of neutrino emission. In this Letter, the unmodified term "luminosity" will mean the photon luminosity L radiated by the star. The "neutrino luminosity" will be designated L_ν. Quantities referring to the sun are subscripted with an encircled dot.

The most accurate available data on white dwarfs are those collected by Eggen[7] for the two clusters Hyades and Pleiades and for the nearby general field. Of chief interest here are the hot white dwarfs, for which the observational data[7,8] have been reduced following the procedure of Van Horn.[9] The resulting luminosities are estimated to have a statistical accuracy of ±0.1 in $\log(L/L_\odot)$, which is adequate here.

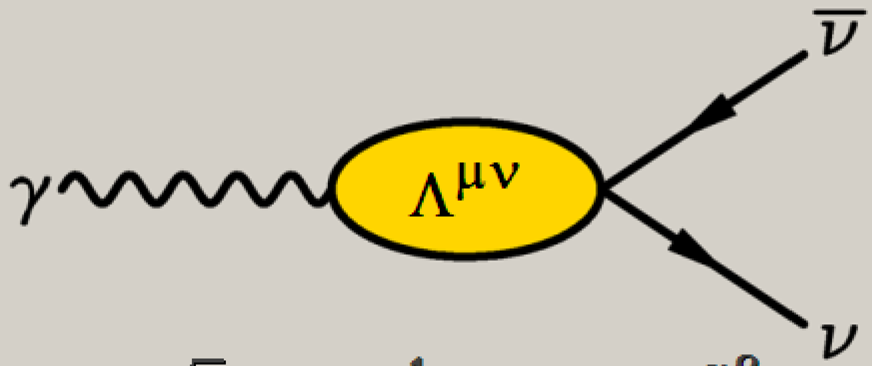
Models of cooling white dwarfs have been con-

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 $e \to e + \gamma$ 

Neutrino-Photon-Coupling in a Plasma

Neutrino effective in-medium coupling



$$L_{\rm eff} = -\sqrt{2}G_F\bar\Psi\gamma_\alpha\tfrac{1}{2}(1-\gamma_5)\Psi\Lambda^{\alpha\beta}A_\beta$$

For vector-current analogous to photon polarization tensor

$$\Lambda_V^{\mu\nu}(K) = 4eC_V\int\frac{d^3\vec p}{2E(2\pi)^3}\left[f_{e^-}(\vec p)+f_{e^+}(\vec p)\right]\frac{(PK)^2g^{\mu\nu}+K^2P^\mu P^\nu-(PK)(P^\mu K^\nu+K^\mu P^\nu)}{(PK)^2-\frac{1}{4}(K^2)^2}$$

$$= \frac{C_V}{e}\Pi_V^{\mu\nu}(K)$$

$$\Lambda_A^{\mu\nu}(K) = 2ieC_A\varepsilon^{\mu\nu\alpha\beta}\int\frac{d^3\vec p}{2E(2\pi)^3}\left[f_{e^-}(\vec p)-f_{e^+}(\vec p)\right]\frac{K^2P_\alpha K_\beta}{(PK)^2-\frac{1}{4}(K^2)^2}$$

Usually negligible

Neutrino Dipole Moments

Effective coupling of electromagnetic field to a neutral fermion

$$
\begin{aligned}
L_{\text{eff}} = & -F_1 \bar{\psi} \gamma_\mu \psi A^\mu \\
& -G_1 \bar{\psi} \gamma_\mu \gamma_5 \psi \partial_\nu F^{\mu\nu} \\
& -\tfrac{1}{2} F_2 \bar{\psi} \sigma_{\mu\nu} \psi F^{\mu\nu} \\
& -\tfrac{1}{2} G_2 \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}
\end{aligned}
$$

Charge $e_\nu = F_1(0) = 0$

Anapole moment $G_1(0)$

Magnetic dipole moment $\mu = F_2(0)$

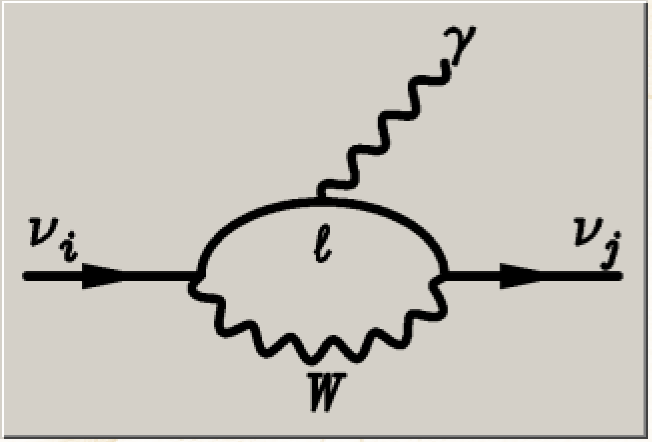
Electric dipole moment $\varepsilon = G_2(0)$

- 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 chirality
- In standard model they represent radiative corrections to weak interaction

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

Standard Dipole Moments for Massive Neutrinos

In standard electroweak model, neutrino dipole and transition moments are induced at higher order



Massive neutrinos ν_i $(i = 1,2,3)$, mixed to form weak eigenstates

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i} \nu_i$$

Explicit evaluation for Dirac neutrinos
(Magnetic moments μ_{ij}
electric moments ε_{ij})

$$\mu_{ij} = \frac{e\sqrt{2}G_F}{(4\pi)^2}(m_i + m_j) \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* f\left(\frac{m_\ell}{m_W}\right)$$

$$\varepsilon_{ij} = \ldots (m_i - m_j) \ldots$$

$$f\left(\frac{m_\ell}{m_W}\right) = -\frac{3}{2} + \frac{3}{4}\left(\frac{m_\ell}{m_W}\right)^2 + O\left(\left(\frac{m_\ell}{m_W}\right)^4\right)$$

Standard Dipole Moments for Massive Neutrinos

Diagonal case
(Magnetic moments
of Dirac neutrinos)

$$\mu_{ii} = \frac{3e\sqrt{2}G_F}{(4\pi)^2} m_i = 3.20 \times 10^{-19} \mu_B \frac{m_i}{\mathrm{eV}} \qquad \mu_B = \frac{e}{2m_e}$$

$$\varepsilon_{ii} = 0$$

Off-diagonal case
(Transition moments)

First term in
$f(m_\ell/m_W)$ does not
contribute
("GIM cancellation")

$$\mu_{ij} = \frac{3e\sqrt{2}G_F}{4(4\pi)^2} (m_i + m_j) \left(\frac{m_\tau}{m_W}\right)^2 \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \left(\frac{m_\ell}{m_\tau}\right)^2$$

$$= 3.96 \times 10^{-23} \mu_B \frac{m_i + m_j}{\mathrm{eV}} \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \left(\frac{m_\ell}{m_\tau}\right)^2$$

$$\varepsilon_{ij} = \ldots (m_i - m_j) \ldots$$

Largest neutrino mass eigenstate $0.05\ \mathrm{eV} < m < 0.7\ \mathrm{eV}$
For Dirac neutrino expect

$$1.6 \times 10^{-20} \mu_B < \mu_\nu < 2.2 \times 10^{-19} \mu_B$$

Plasmon Decay And Stellar Energy Loss Rates

Assume photon dispersion relation like a massive particle (nonrelativistic plasma)

$$E_\gamma^2 - p_\gamma^2 = \omega_{\rm pl}^2 = \frac{4\pi\alpha n_e}{m_e}$$

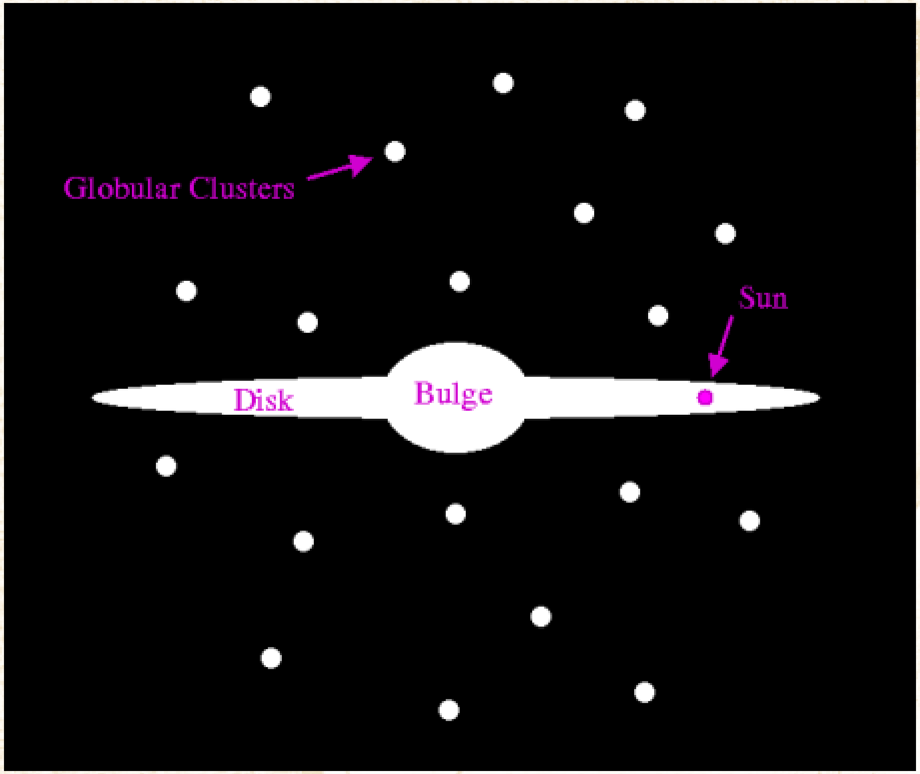
Decay rate of photon (transverse plasmon) with energy E_γ

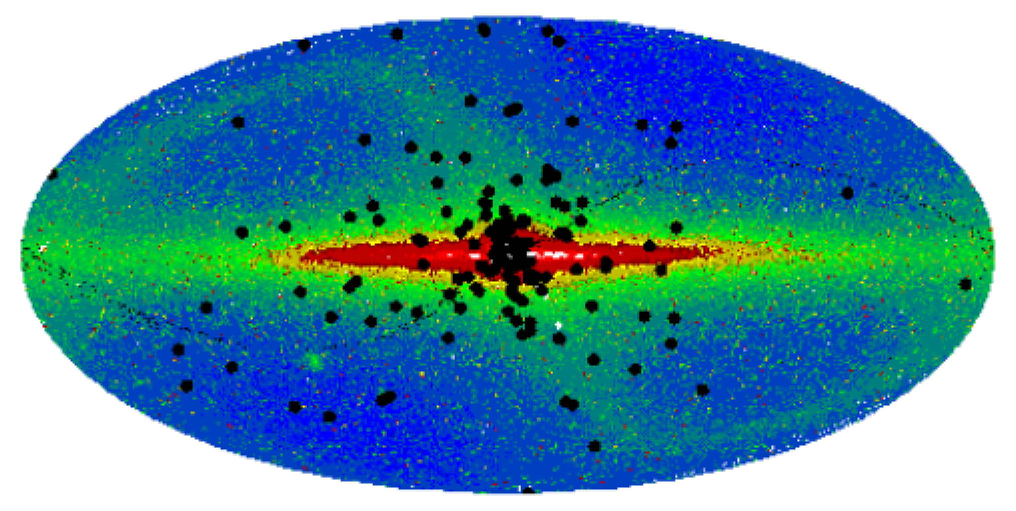
$$\Gamma(\gamma\to\nu\bar\nu) = \frac{4\pi}{3}\frac{1}{E_\gamma}\times\begin{cases} \alpha_\nu\left(\omega_{\rm pl}^2/4\pi\right) & \text{Millicharge} \\ \frac{\mu_\nu^2}{2}\left(\omega_{\rm pl}^2/4\pi\right)^2 & \text{Dipole moment} \\ \frac{C_V^2 G_F^2}{\alpha}\left(\omega_{\rm pl}^2/4\pi\right)^3 & \text{Standard model} \end{cases}$$

Energy-loss rate of stellar plasma (temperature T and plasma frequency $\omega_{\rm pl}$)

$$Q(\gamma\to\nu\bar\nu) = \int\frac{2d^3\vec{p}}{(2\pi)^3}\frac{E_\gamma\Gamma}{e^{E_\gamma/T}-1} = \frac{8\zeta_3}{3\pi}T^3\times\begin{cases} \alpha_\nu\left(\omega_{\rm pl}^2/4\pi\right) \\ \frac{\mu_\nu^2}{2}\left(\omega_{\rm pl}^2/4\pi\right)^2 \\ \frac{C_V^2 G_F^2}{\alpha}\left(\omega_{\rm pl}^2/4\pi\right)^3 \end{cases}$$

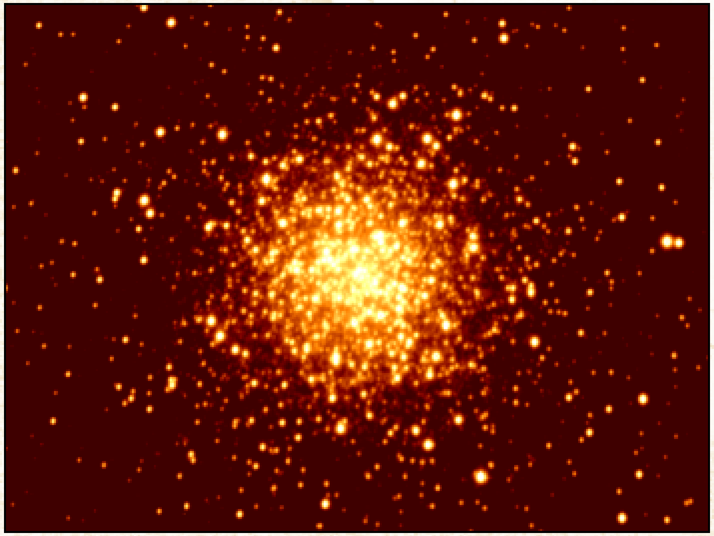
Globular Clusters of the Milky Way





http://www.dartmouth.edu/~chaboyer/mwgc.html

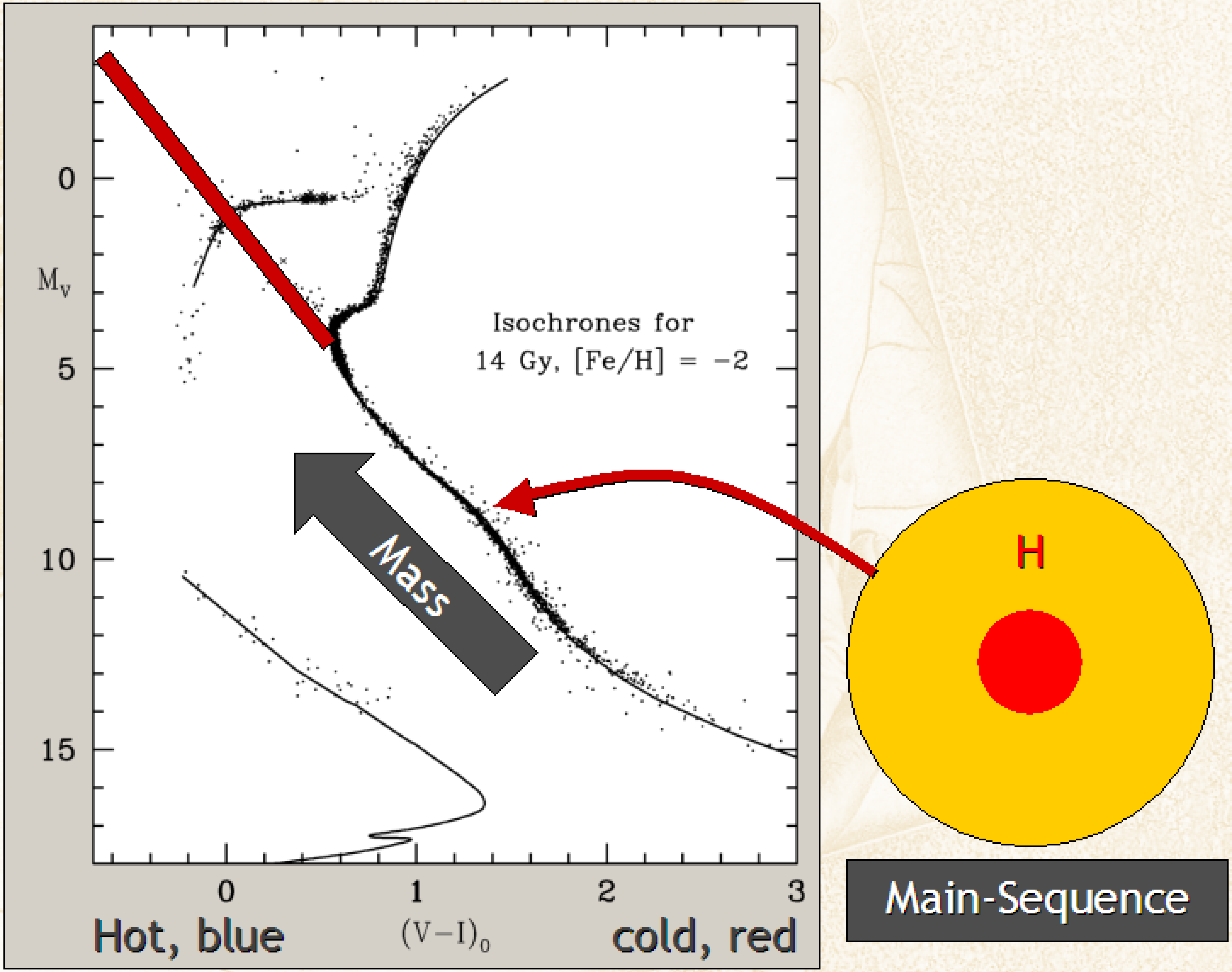
Globular clusters on top of the FIRAS 2.2 micron map of the Galaxy



The galactic globular cluster M3

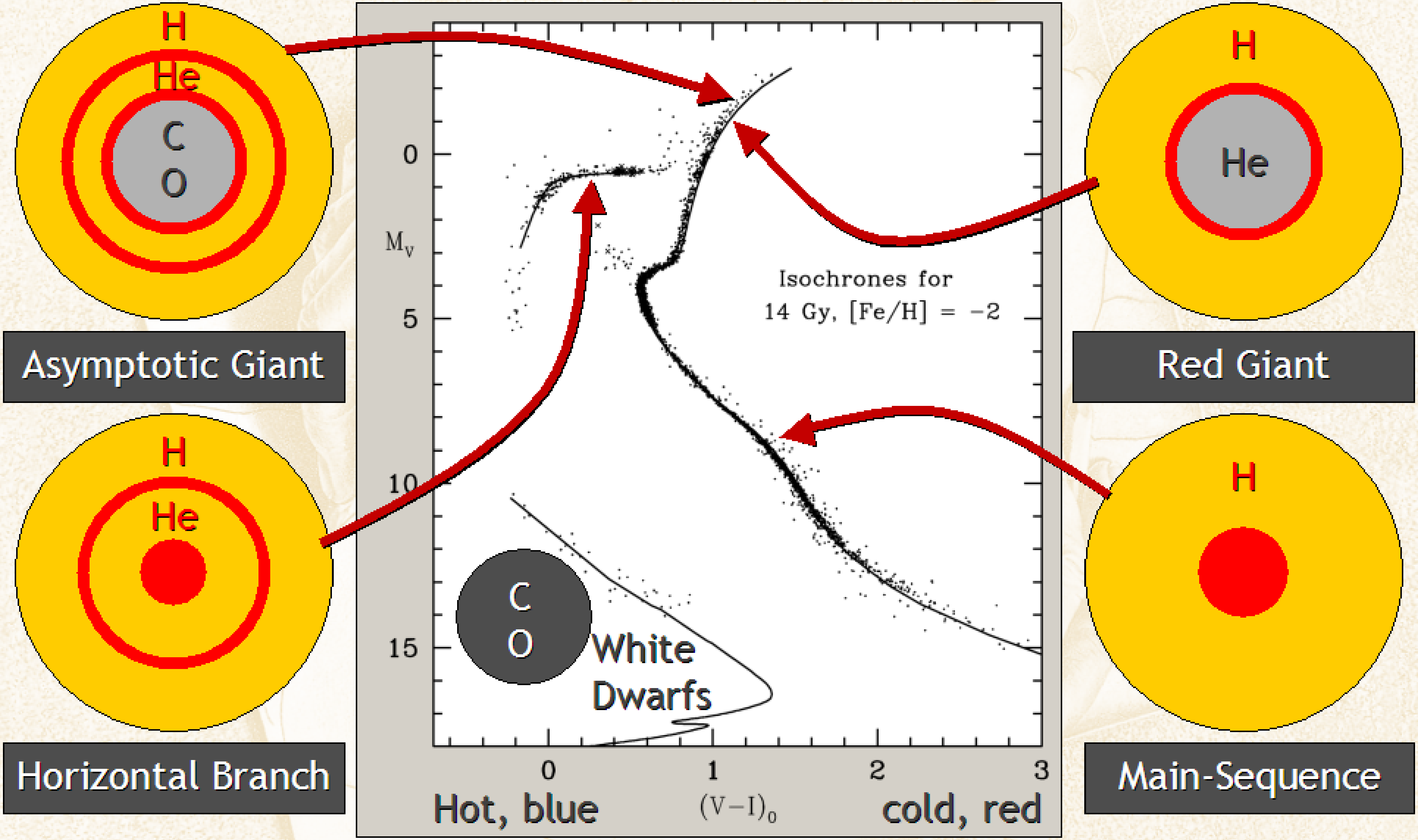
Color-Magnitude Diagram for Globular Clusters

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



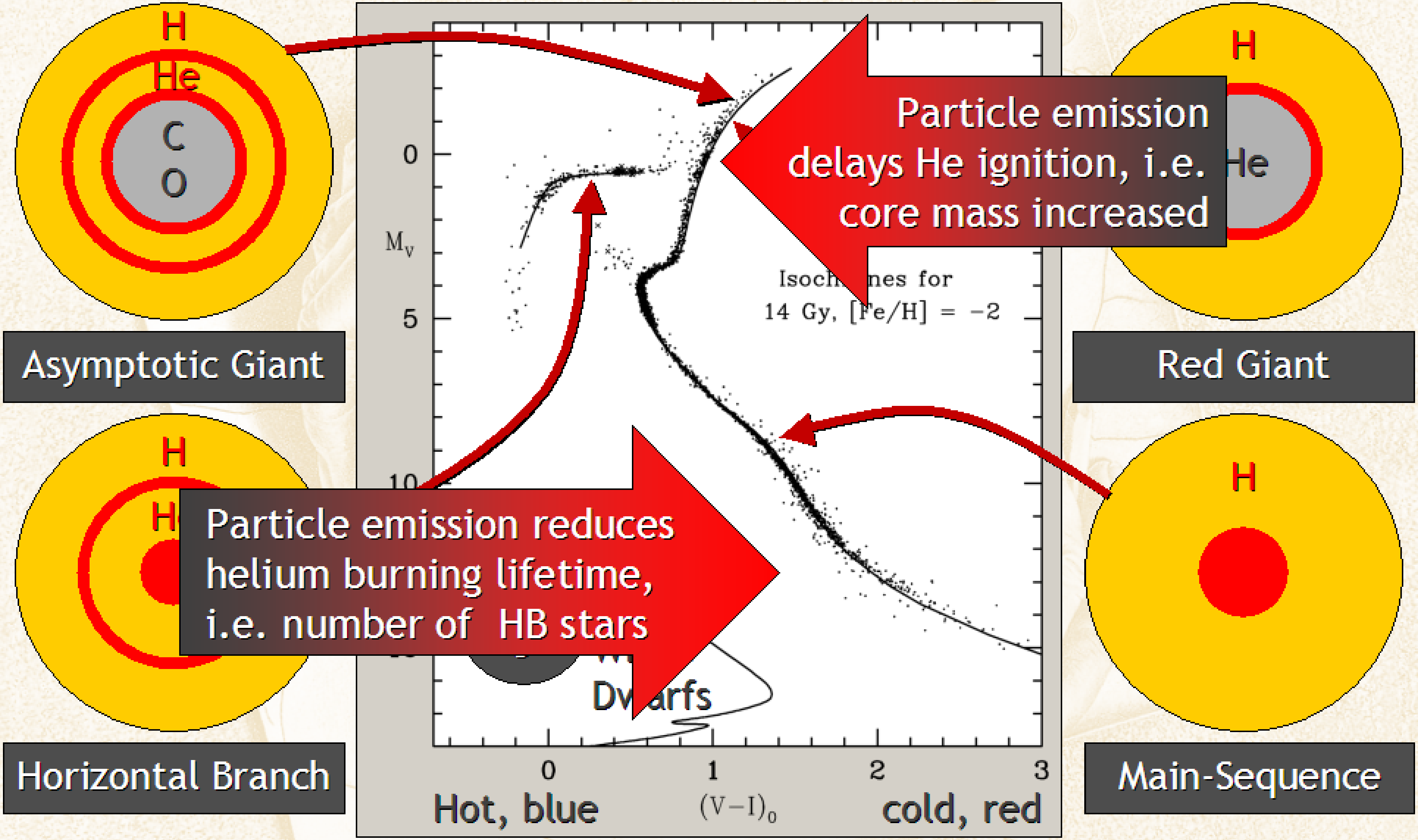
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris)

Color-Magnitude Diagram for Globular Clusters



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

Color-Magnitude Diagram for Globular Clusters



Particle emission delays He ignition, i.e. core mass increased

Particle emission reduces helium burning lifetime, i.e. number of HB stars

Asymptotic Giant

Red Giant

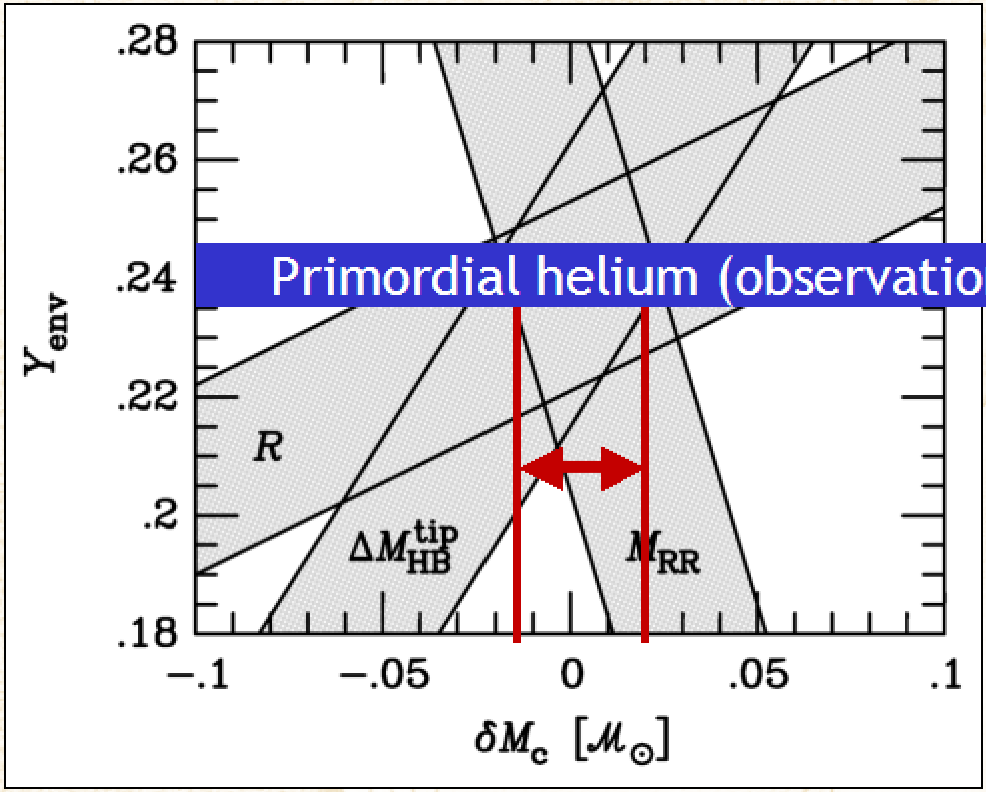
Horizontal Branch

Main-Sequence

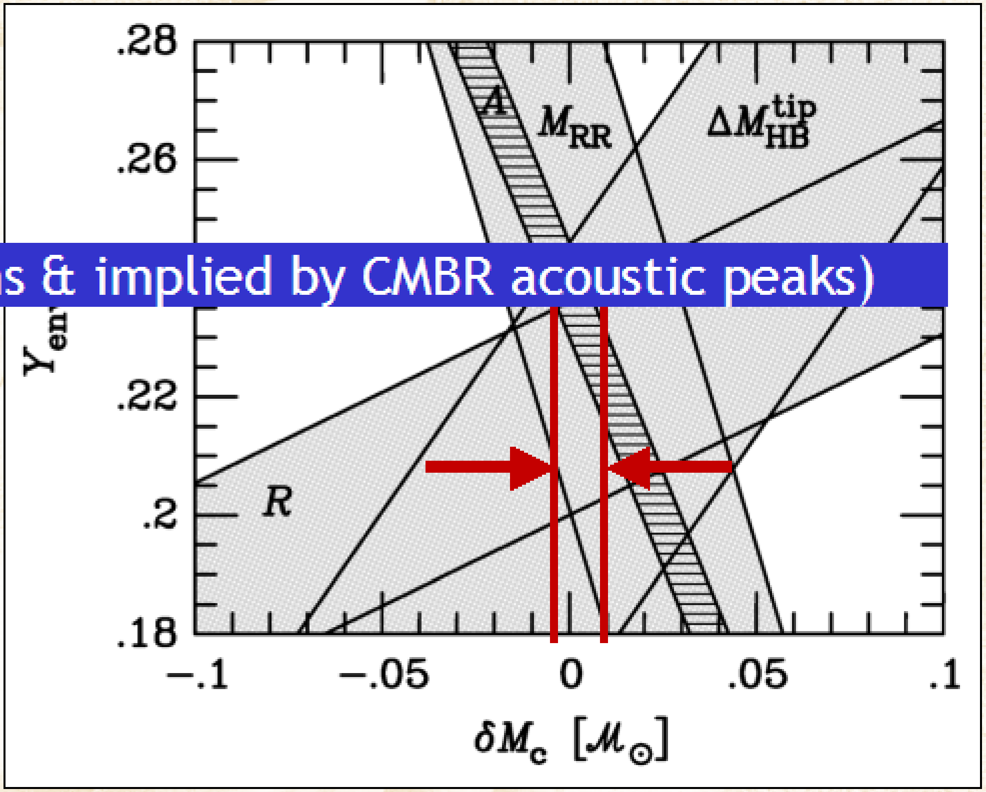
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris)

Core-Mass at Helium Ignition

Primordial helium (observations & implied by CMBR acoustic peaks)



G.Raffelt, Stars as Laboratories for Fundamental Physics (1996)



Catalan et al., astro-ph/9509062

Core mass at helium ignition established to ± 0.02 M_{sun} or ± 4%

Globular Cluster Limits on Neutrino Dipole Moments

Compare magnetic-dipole plasma emission with standard case

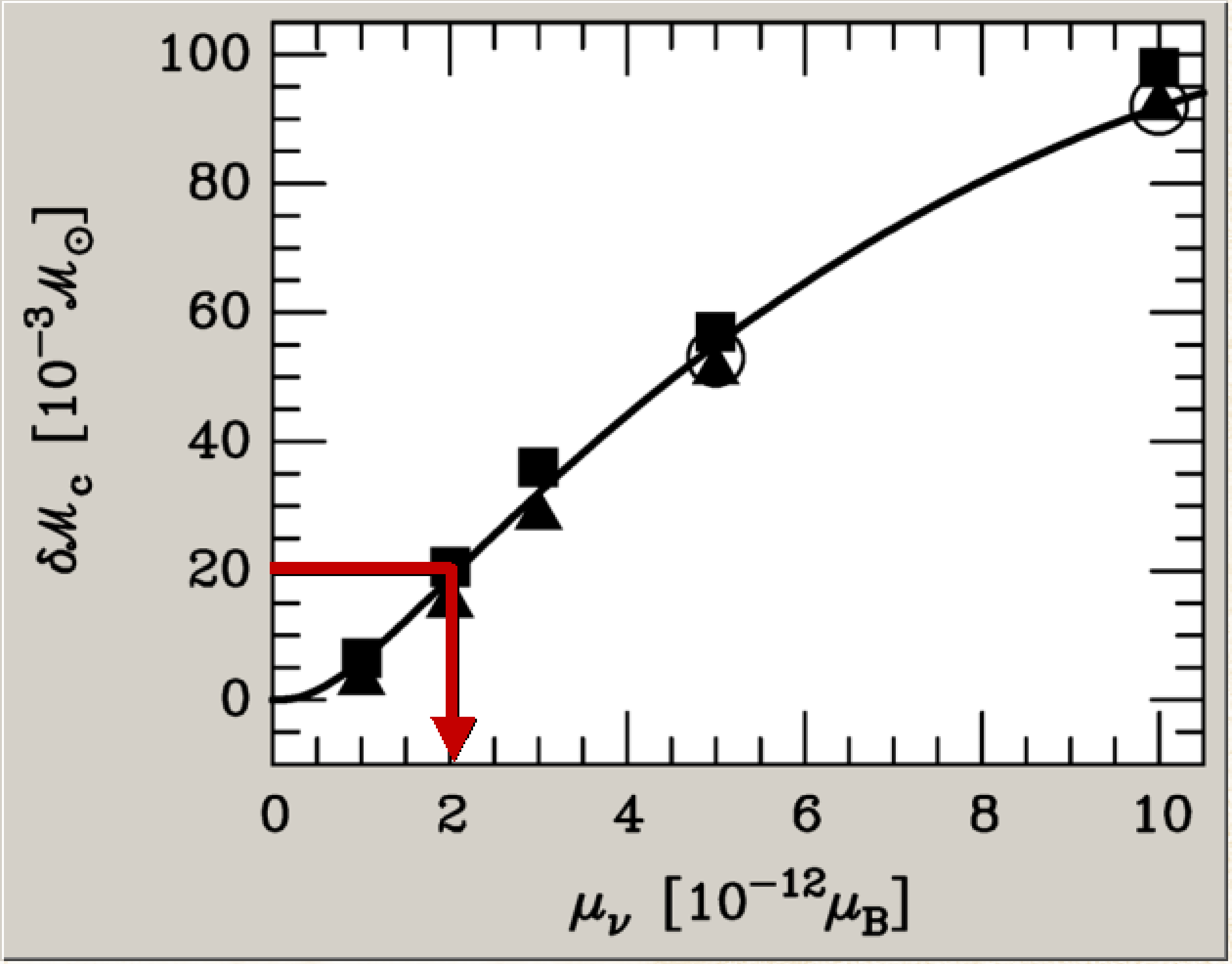
$$\frac{Q_\mu}{Q_{SM}} = \frac{2\pi\alpha\mu_\nu^2}{C_V^2 G_F^2 \omega_{pl}^2}$$

For red-giant core before helium ignition $\omega_{pl} = 18\ \mathrm{keV}$

$$\frac{Q_\mu}{Q_{SM}} = 9\times10^{22}\left(\frac{\mu_\nu}{\mu_B}\right)^2$$

Require this to be < 1

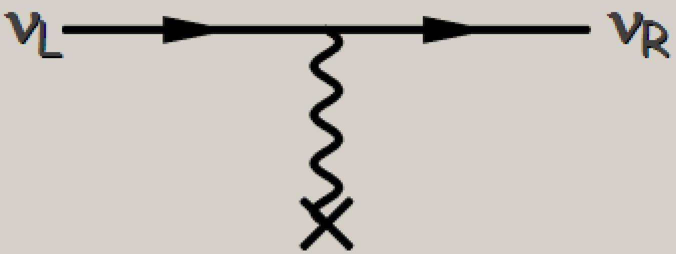
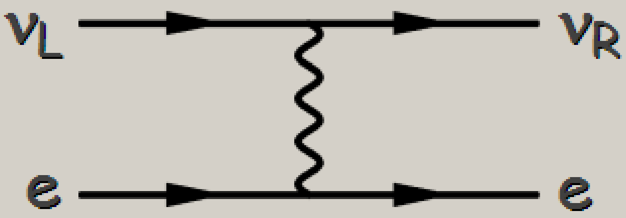
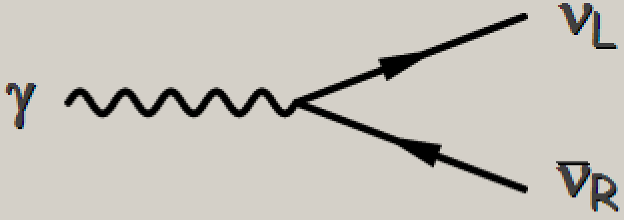
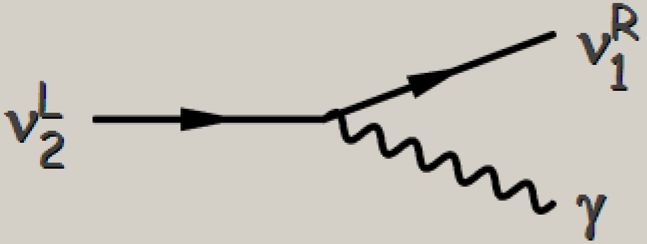
$$\mu_\nu < 3\times10^{-12}\mu_B$$



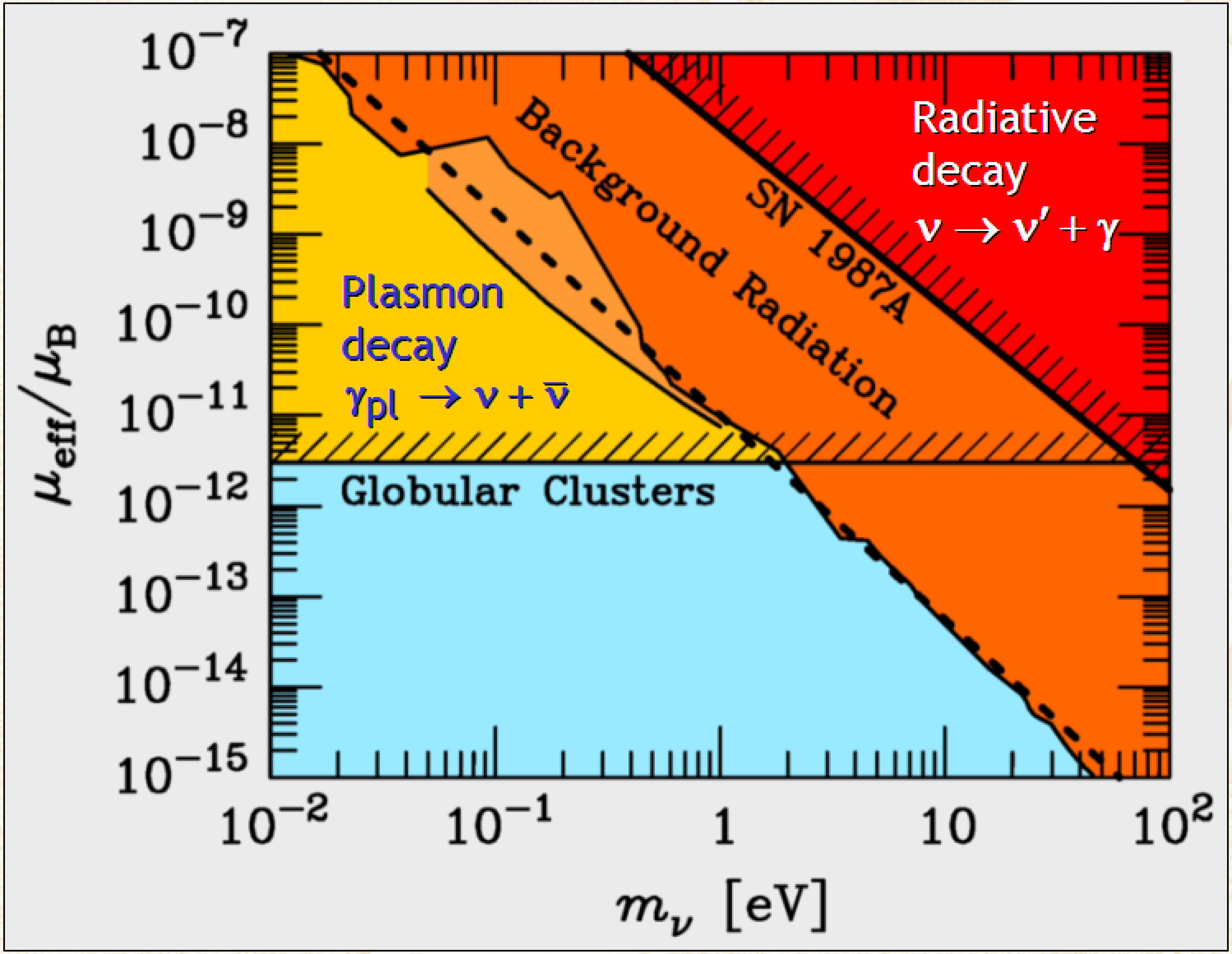
Globular-cluster limit on neutrino dipole moment

$$\mu_\nu < 2\times10^{-12}\mu_B$$

Consequences of Neutrino Dipole Moments

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

Neutrino Radiative Lifetime Limits



$$\Gamma_{\nu\to\nu'\gamma} = \frac{\mu_{\rm eff}^2}{8\pi} m_\nu^3$$

$$\Gamma_{\gamma\to\nu\bar\nu} = \frac{\mu_{\rm eff}^2}{24\pi} \omega_{\rm pl}^3$$

For low-mass neutrinos, plasmon decay in globular cluster stars yields most restrictive limits

Supernova Neutrinos

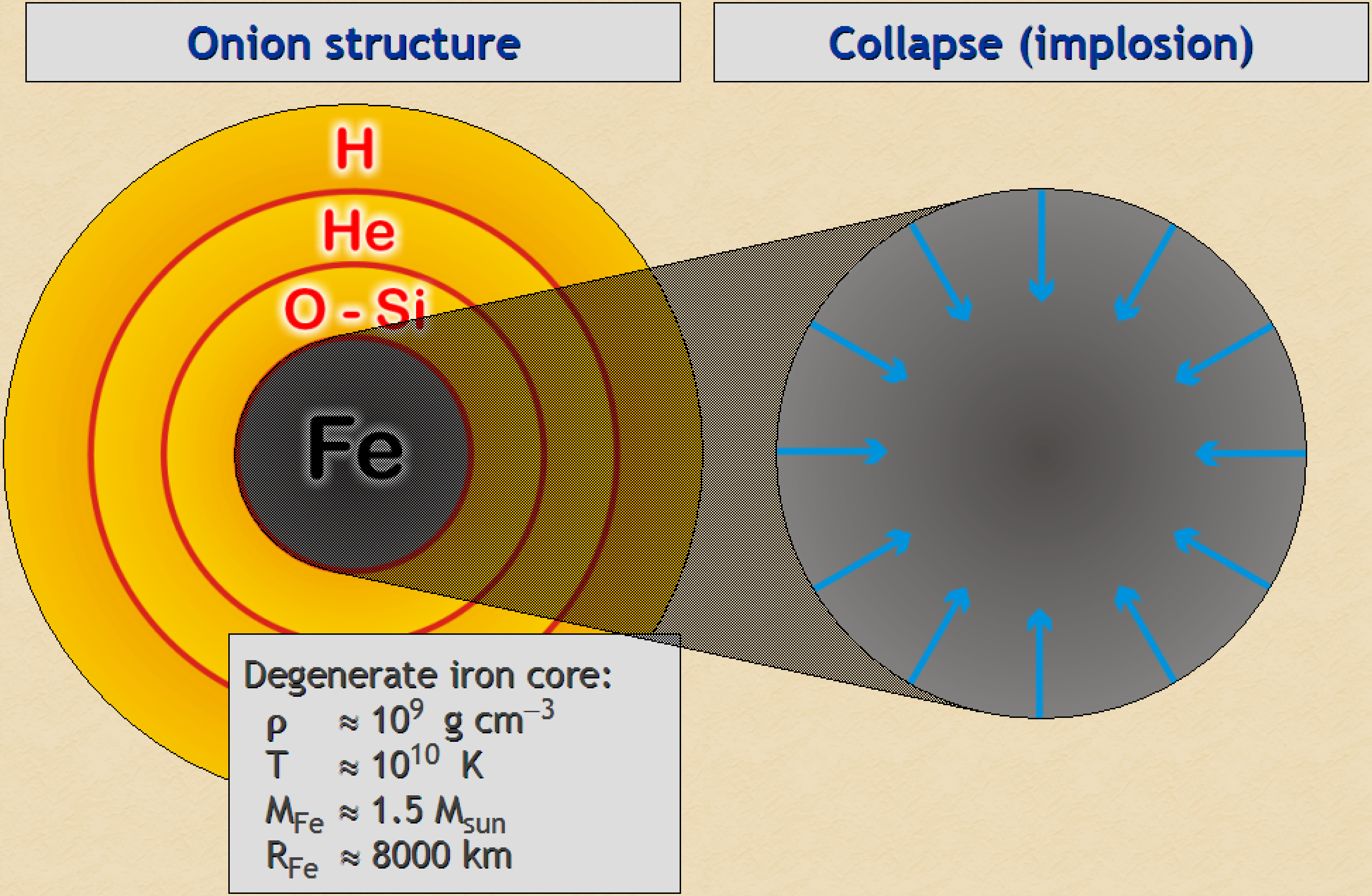
Sanduleak −69 202

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

Supernova 1987A

23 February 1987

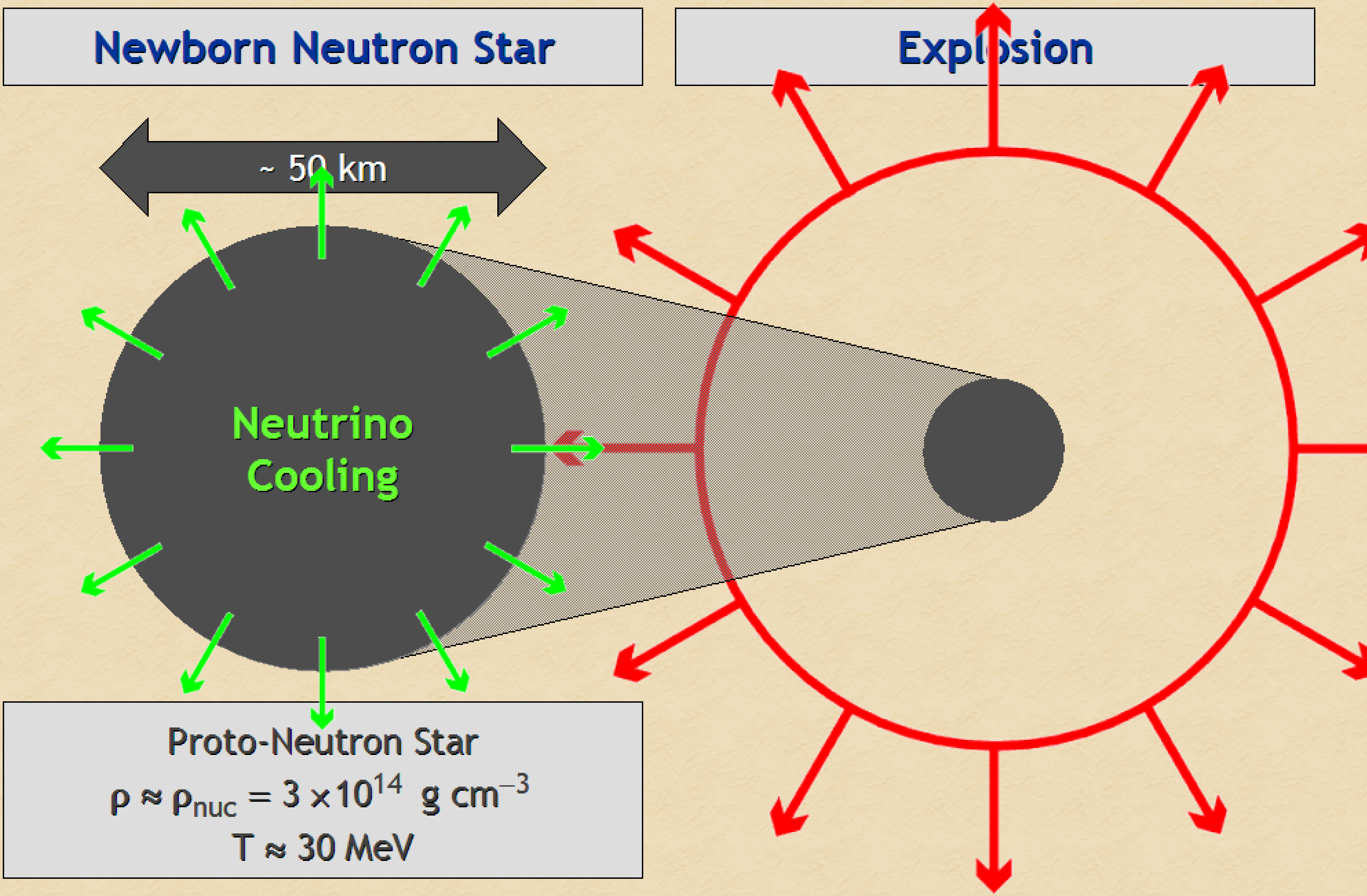
Stellar Collapse and Supernova Explosion



Degenerate iron core:

$\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$
$T \approx 10^{10}\ \mathrm{K}$
$M_{\mathrm{Fe}} \approx 1.5\ M_{\mathrm{sun}}$
$R_{\mathrm{Fe}} \approx 8000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion



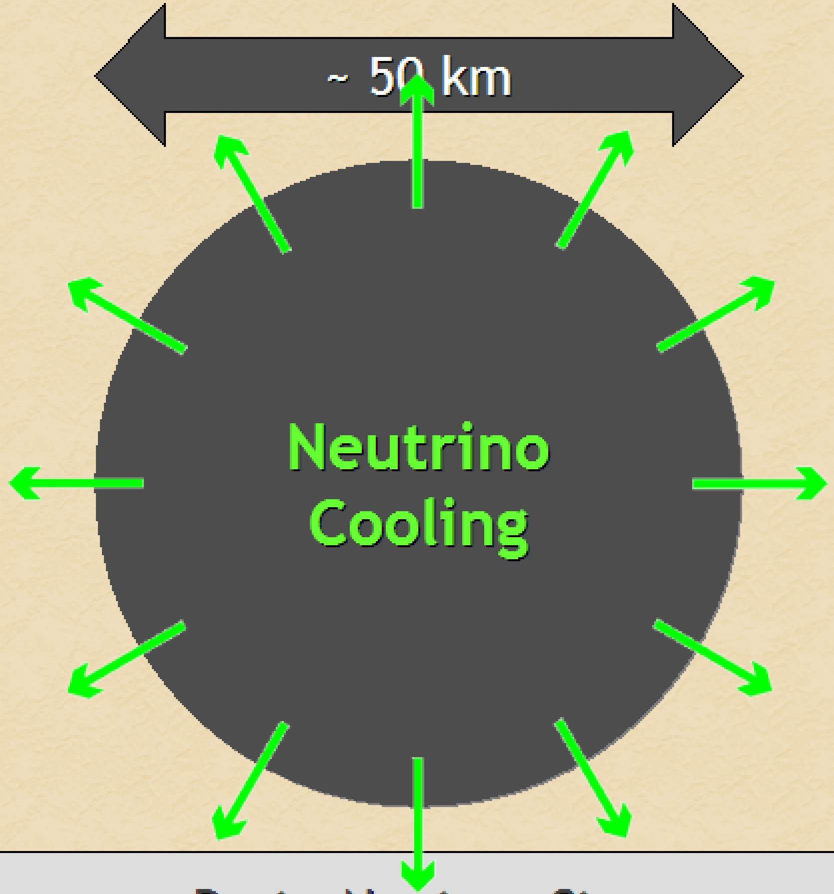
Proto-Neutron Star

$\rho \approx \rho_{\mathrm{nuc}} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14}\ \text{g cm}^{-3}$

$T \approx 30$ MeV

Gravitational binding energy

$E_b \approx 3 \times 10^{53}$ erg $\approx$ 17% $M_{\text{SUN}}\, c^2$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons, outshine host galaxy

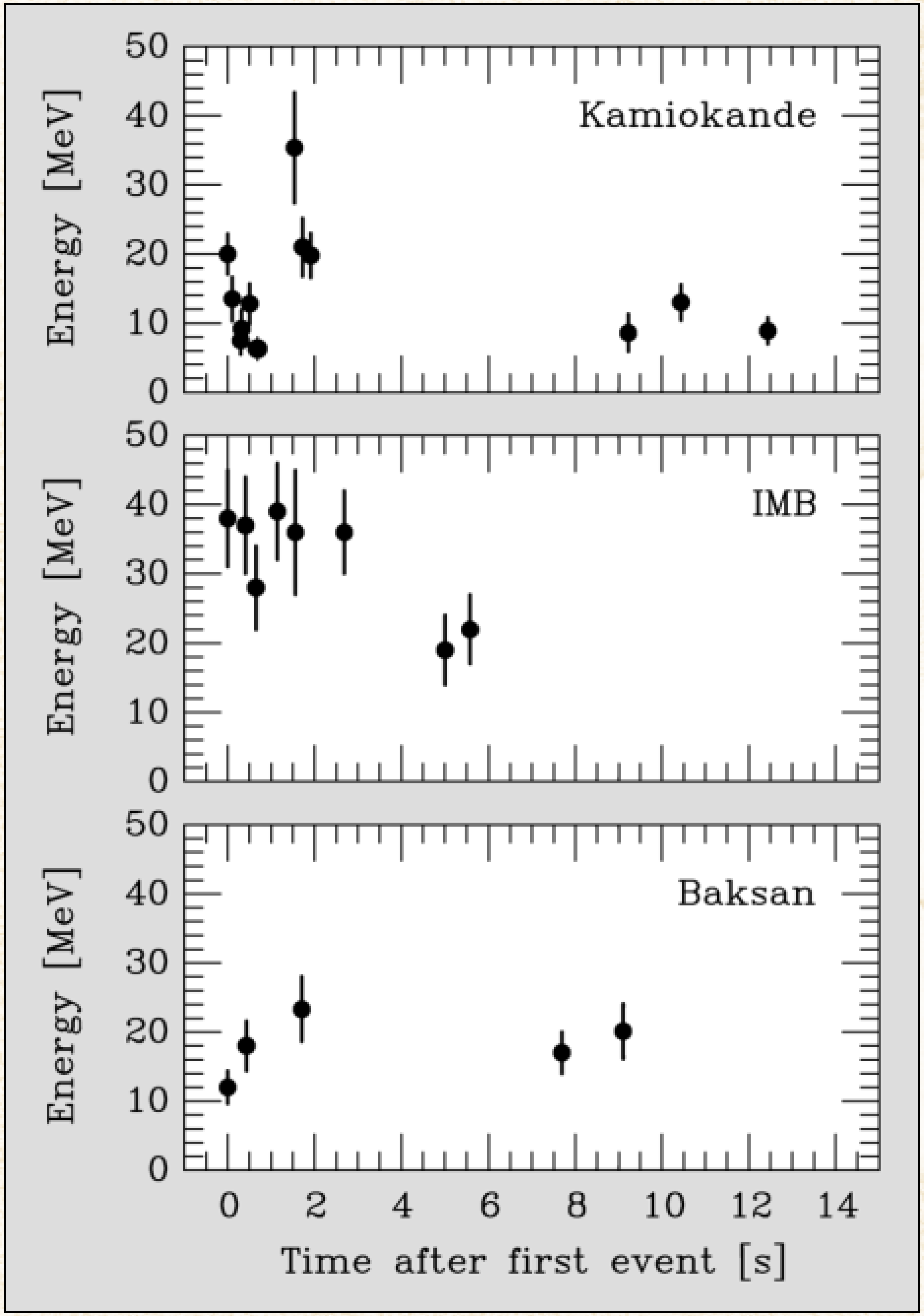
Neutrino luminosity

$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

$\approx 3 \times 10^{19}\ L_{\text{SUN}}$

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

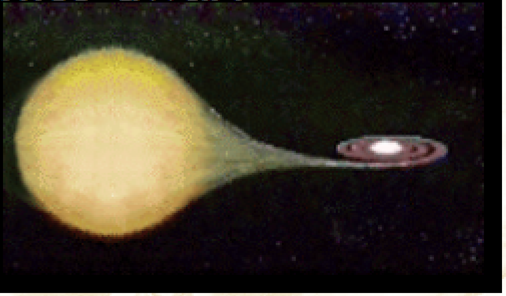
Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Type Ia vs. Core-Collapse Supernovae

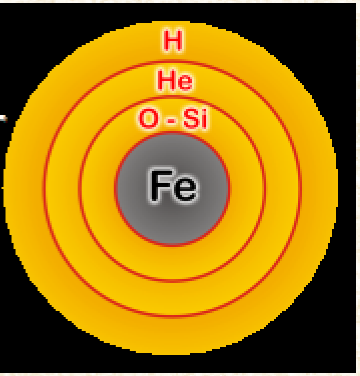
Type Ia

- Carbon-oxygen white dwarf (remnant of low-mass star)
- Accretes matter from companion



Core collapse (Type II, Ib/c)

- Degenerate iron core of evolved massive star
- Accretes matter by nuclear burning at its surface



Chandrasekhar limit is reached – $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

Type Ia	Core collapse
Nuclear burning of C and O ignites → Nuclear deflagration (“Fusion bomb” triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion → Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy ~ 1 MeV per nucleon	Gain of gravitational binding energy ~ 100 MeV per nucleon 99% into neutrinos

Comparable “visible” energy release of ~ 3 × 10^{51} erg

Supernovae the Power Supply for Cosmic Rays?

Required power supply $L_{CR} = V_D\,\rho_{CR}/\tau_{res}$

$\approx 5 \times 10^{40}$ erg/s $\approx 10^7\,L_{Sun}$

Disk volume $V_D = \pi R^2 d \approx \pi\,(15\ \text{kpc})^2\,200\ \text{pc}$

$\approx 4 \times 10^{66}\ \text{cm}^3$

Energy density in CRs $\rho_{CR} \approx 1\ \text{eV} / \text{cm}^3$

Residence time in galaxy $\tau_{res} \approx 6 \times 10^6$ yrs

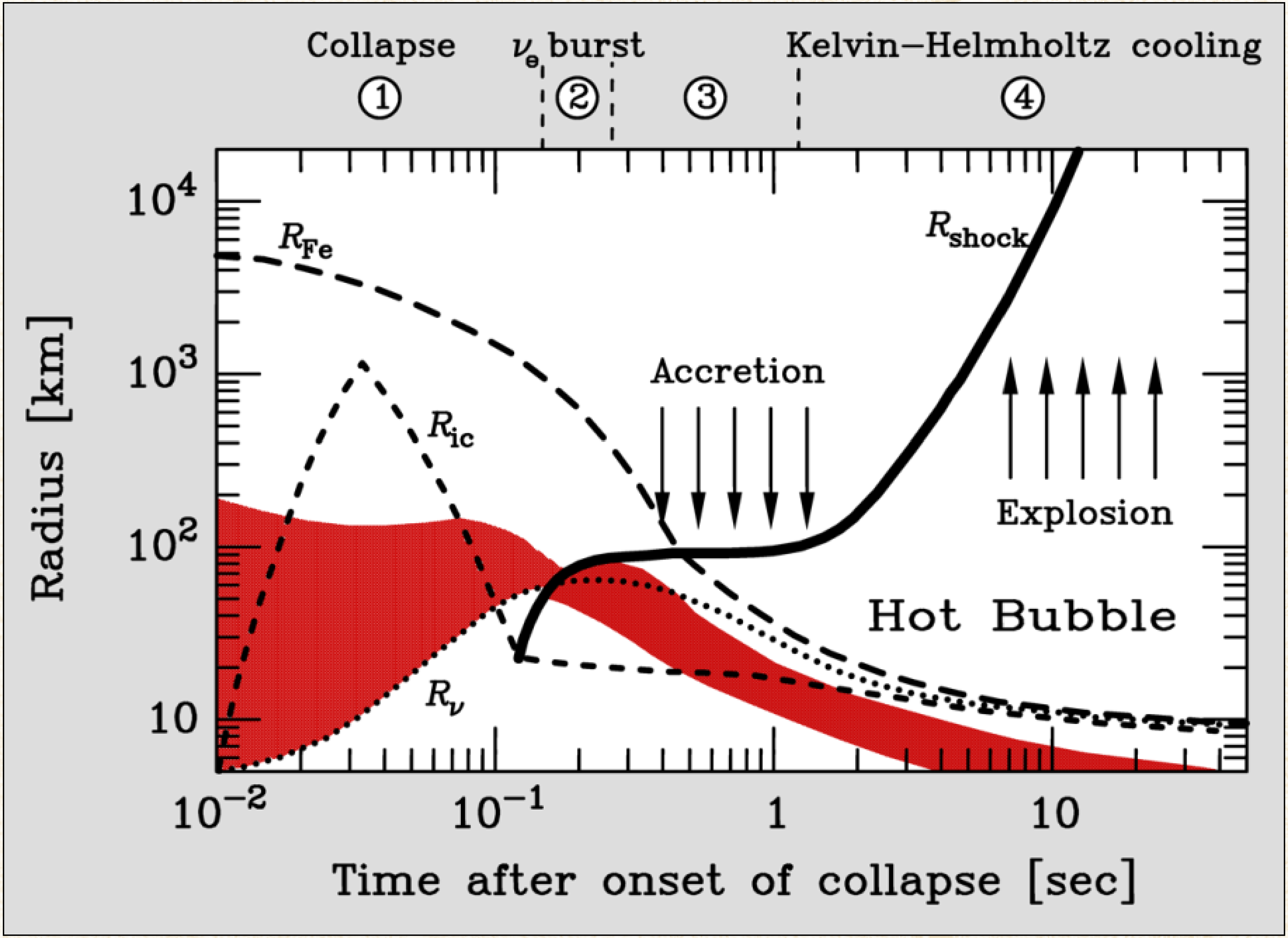
Suggestive of supernovae:

- One SN explosion deposits ~ 3×10^{51} erg in kinetic energy of ejecta into the interstellar medium (ISM)
- Rate approx. 1 SN / 30 years / galaxy

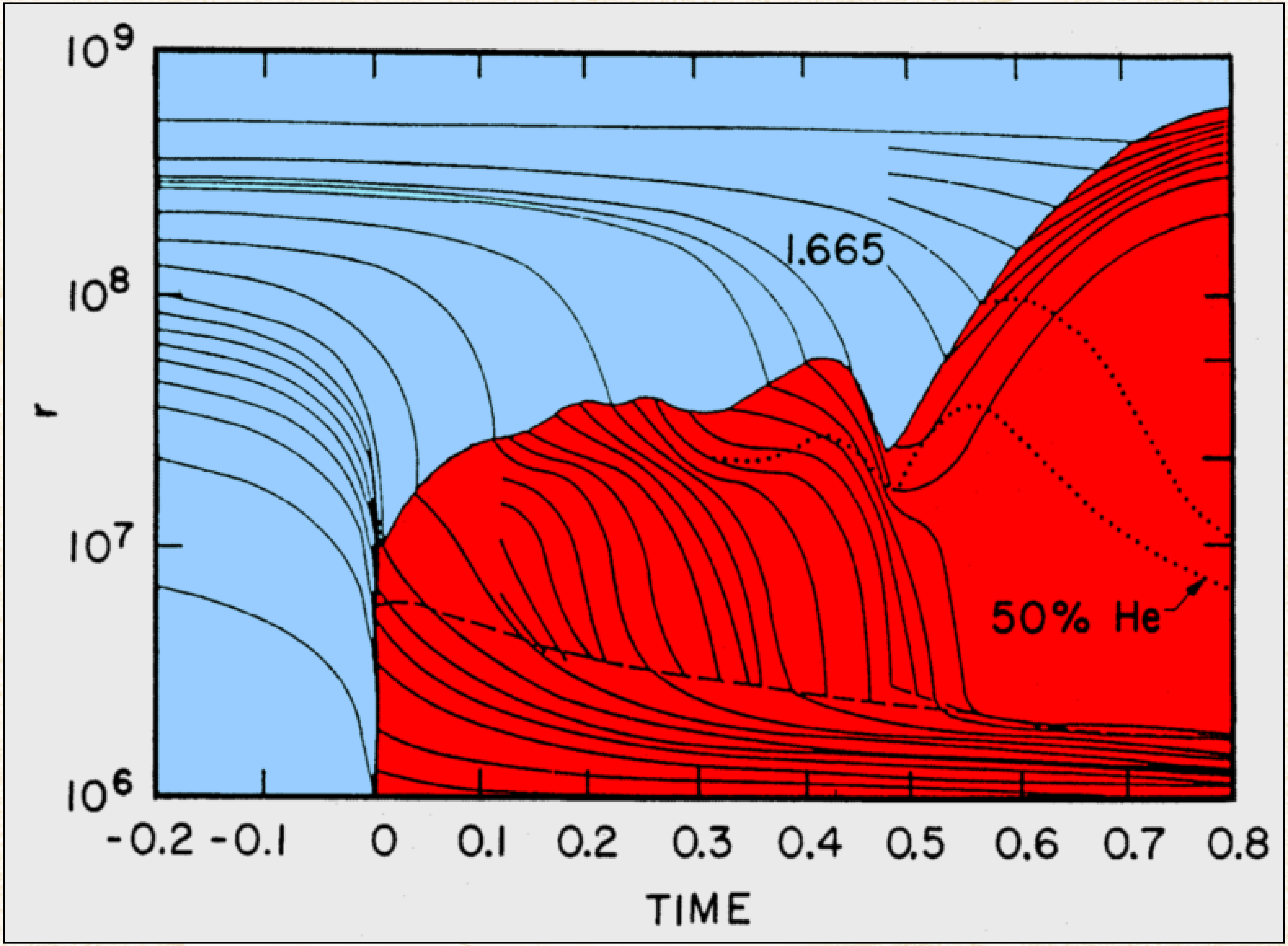
Total average energy deposition: $L_{SN} \approx 3 \times 10^{42}$ erg/s $\approx 50\,L_{CR}$

Efficiency of a few percent required

Supernova Delayed Explosion Scenario



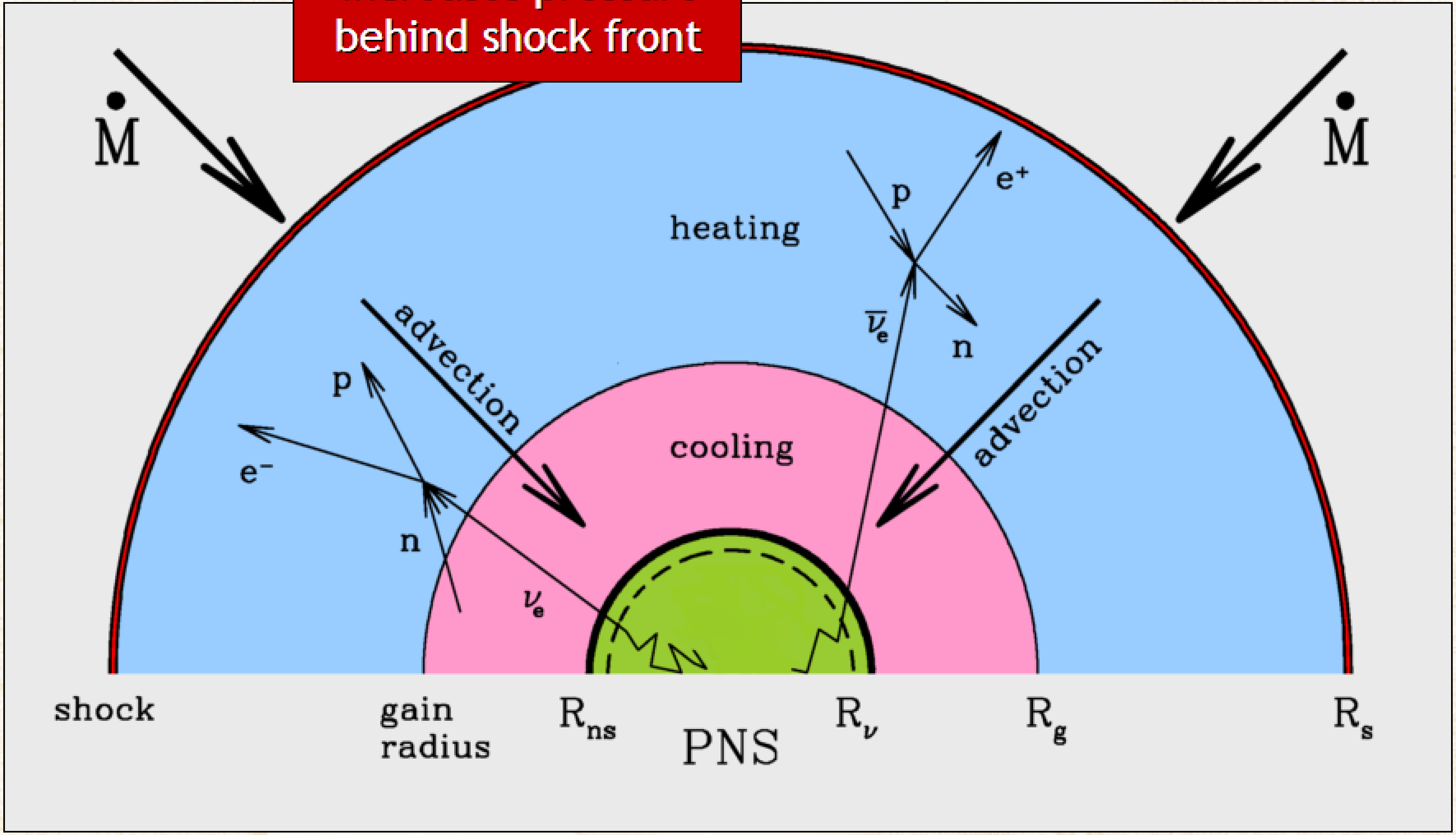
Delayed Explosion



Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys.(1982)
Bethe & Wilson, ApJ 295 (1985) 14

Neutrinos to the Rescue

Neutrino heating increases pressure behind shock front

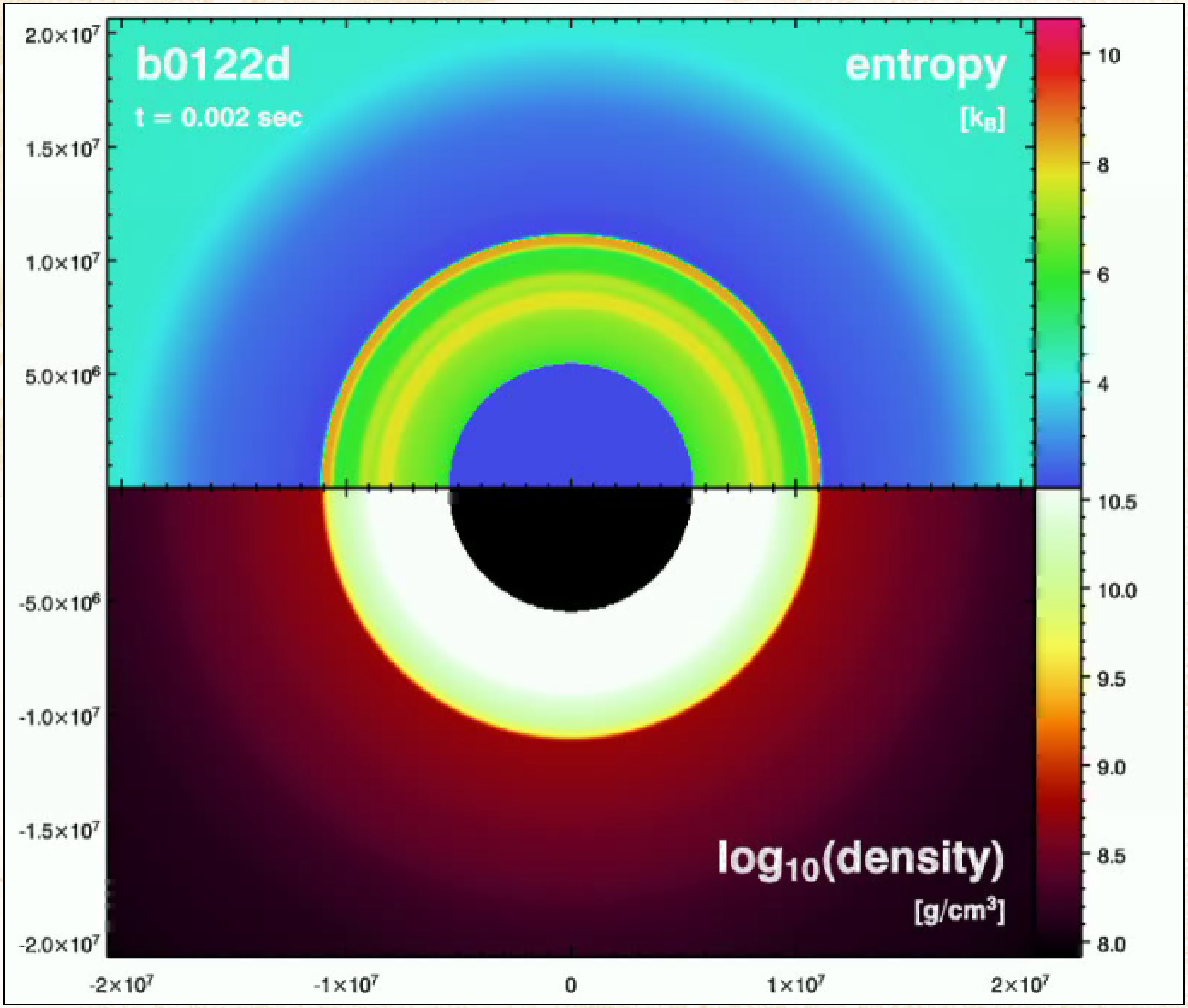


Picture adapted from Janka, astro-ph/0008432

Parametric 2D Studies (180°) by Garching Group

- If explosion develops slowly, convective structures have time to merge to low (l = 1 or 2) mode flow
- Very asymmetric shock expansion and mass ejection although boundary neutrino flux is isotropic

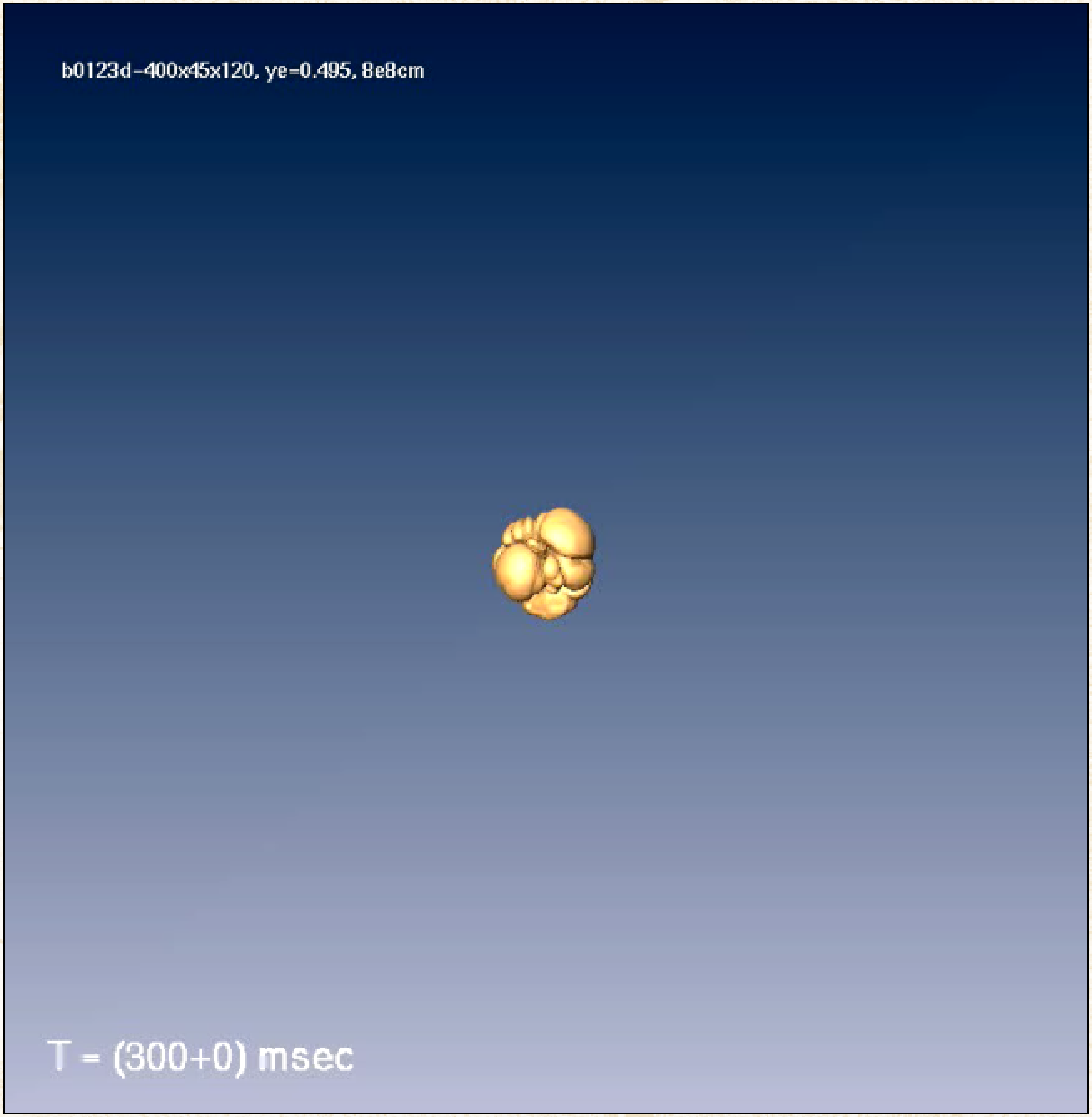
(Scheck et al., PRL 2004 and PhD Thesis)



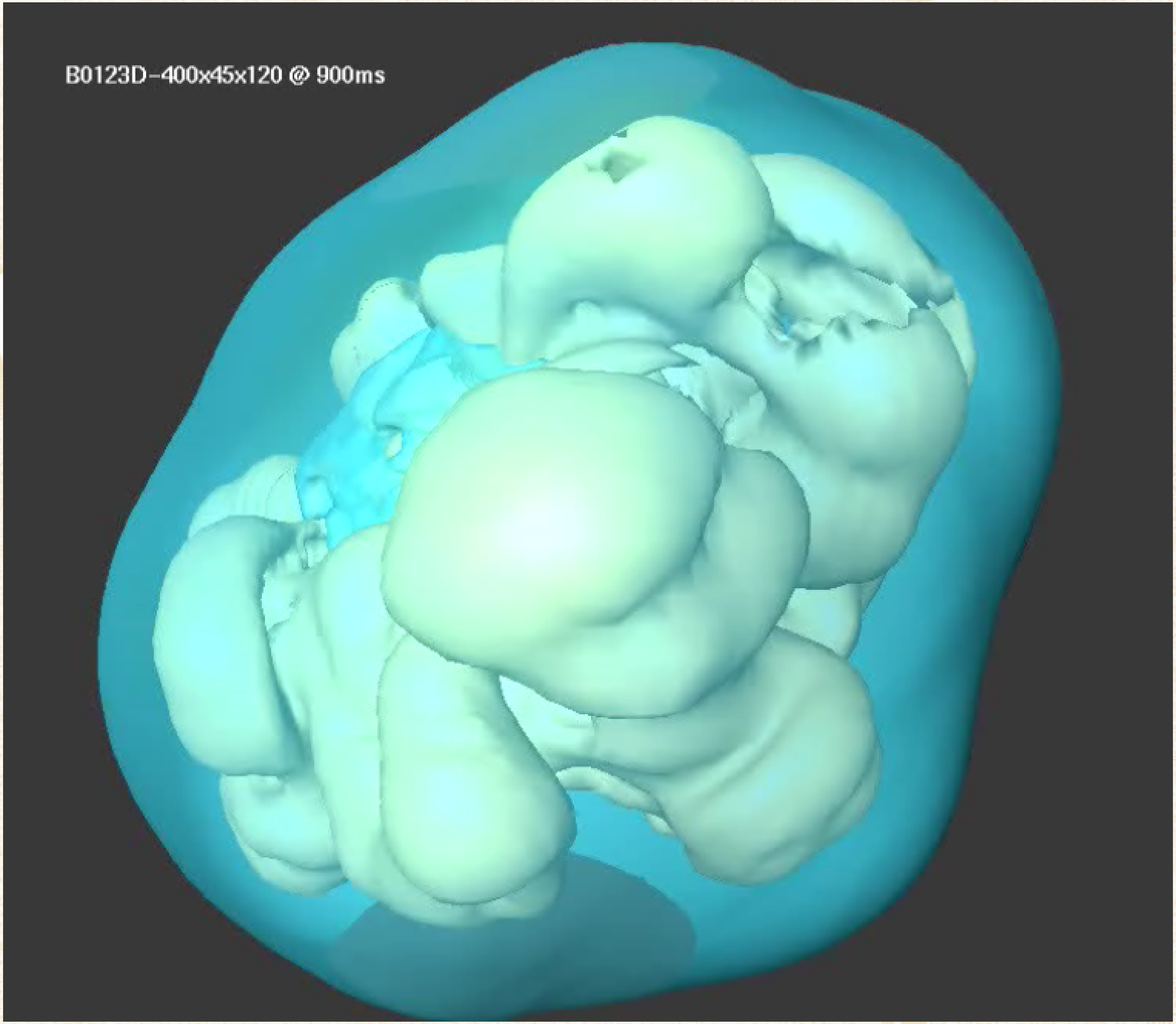
Parametric 3D Studies by Garching Group

- First explosions in 3D show also very large asymmetry
- Convection grows faster than in 2D
- Explosion energy somewhat higher

(L. Scheck
PhD Thesis 2004)



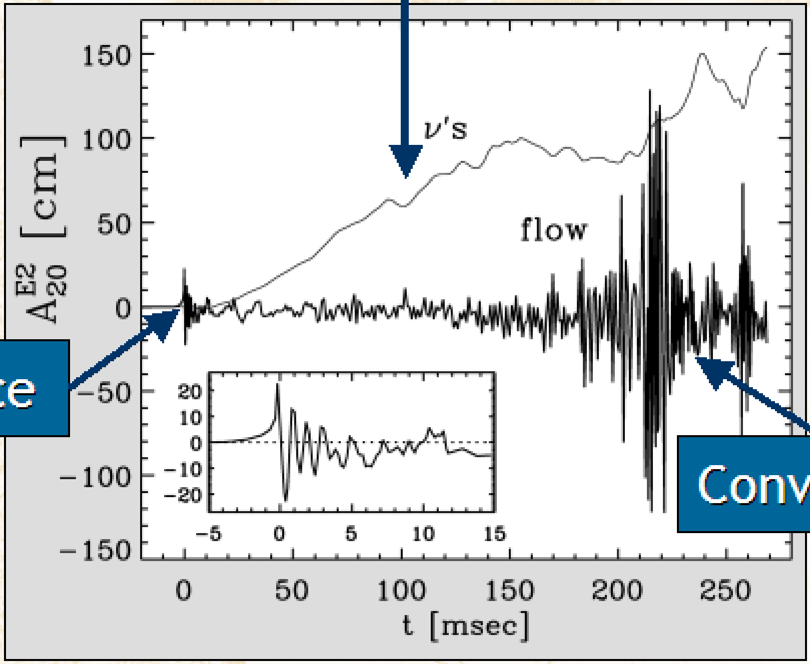
Parametric 3D Studies by Garching Group



Gravitational Waves from Core-Collapse Supernovae

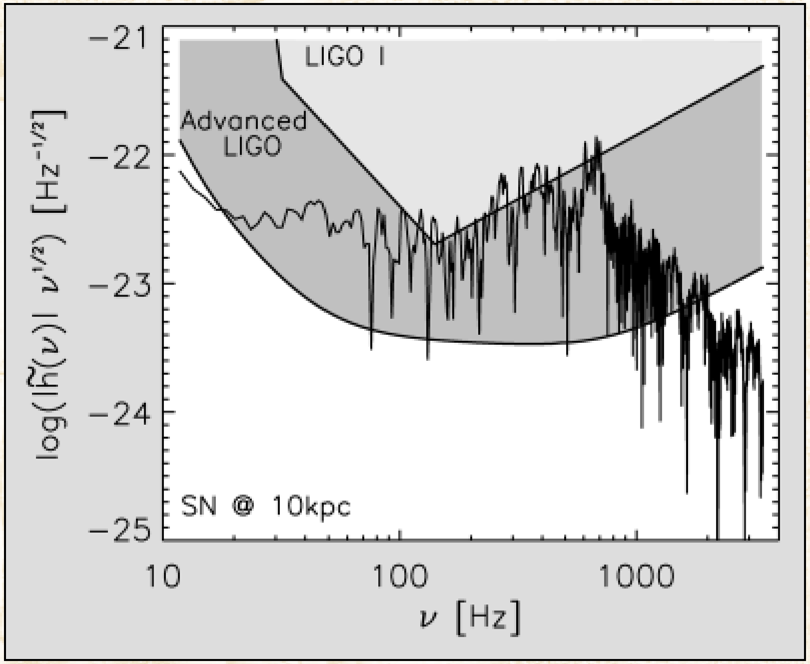
Müller, Rampp, Buras, Janka, & Shoemaker, “Towards gravitational wave signals from realistic core collapse supernova models,” astro-ph/0309833

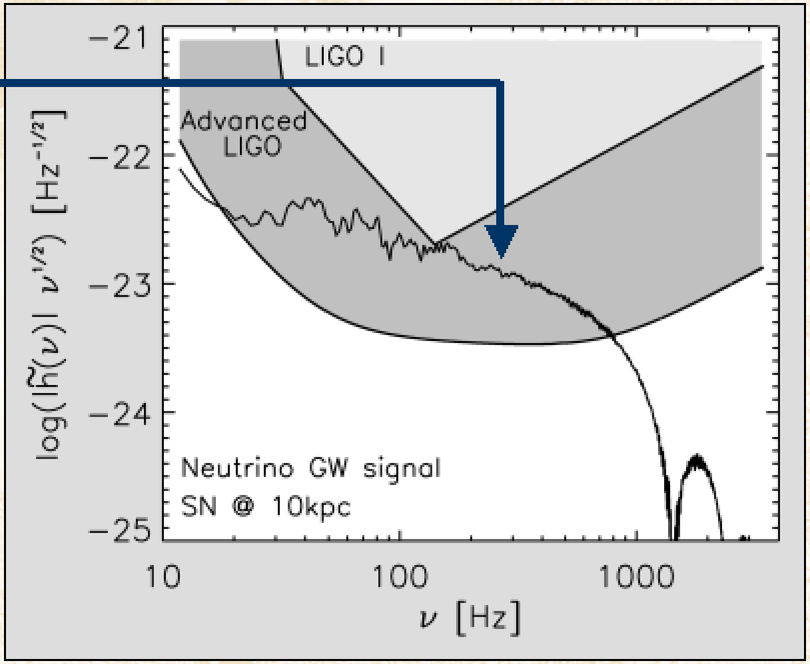
Asymmetric neutrino emission



Bounce

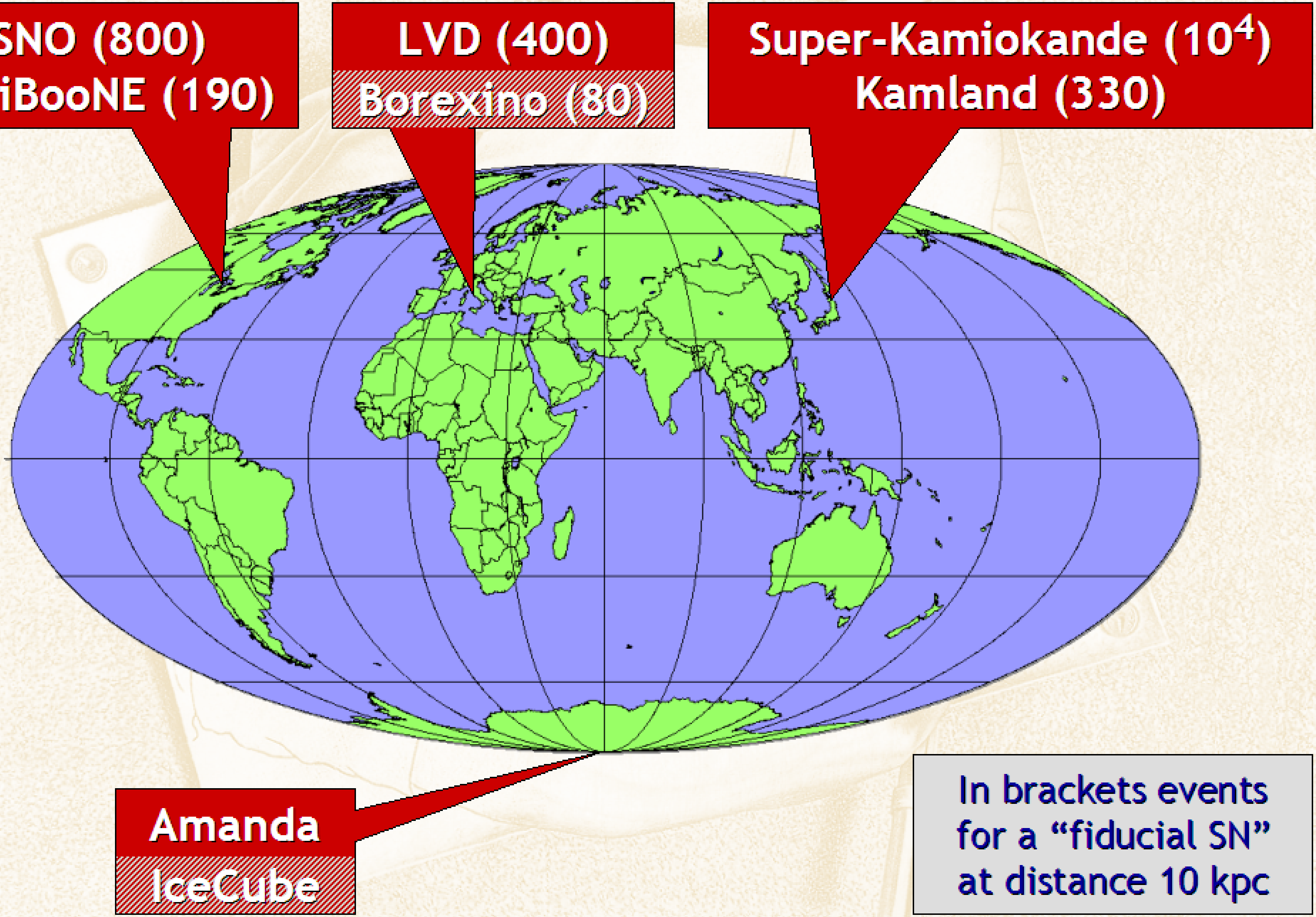
Convection





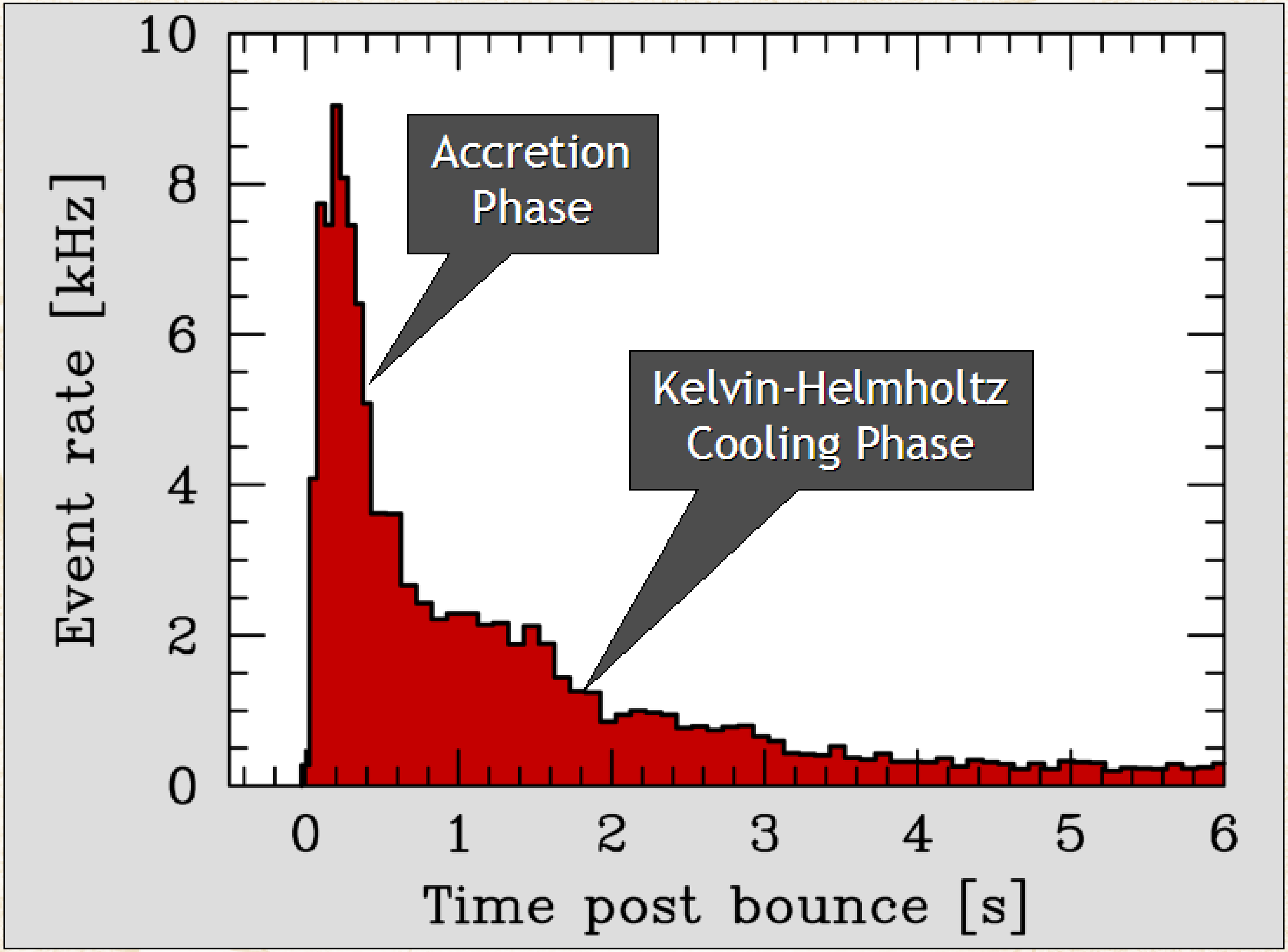
The gravitational-wave signal from convection is a generic and dominating feature

Large Detectors for Supernova Neutrinos



In brackets events for a "fiducial SN" at distance 10 kpc

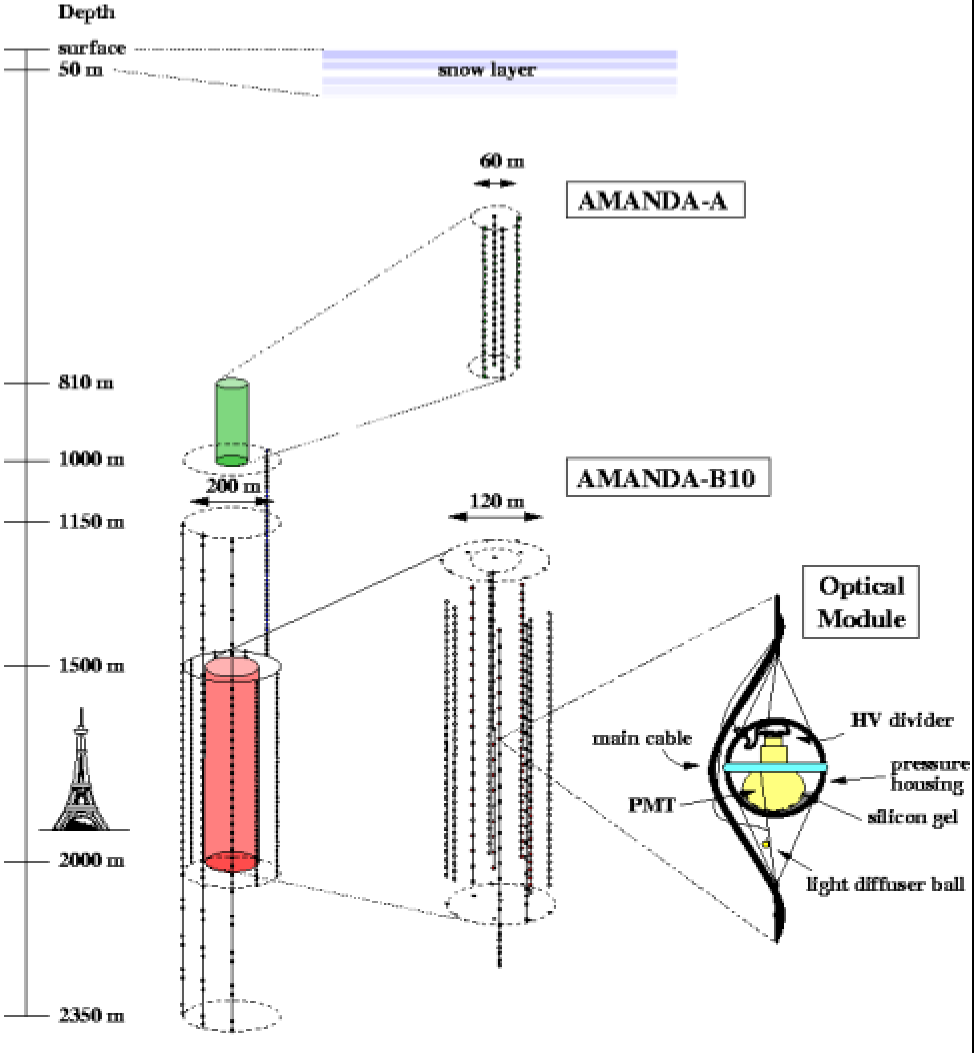
Simulated Supernova Signal at Super-Kamiokande



Simulation for Super-Kamiokande SN signal at 10 kpc, based on a numerical Livermore model
[Totani, Sato, Dalhed & Wilson, ApJ 496 (1998) 216]

Southpole Ice-Cherenkov Neutrino Detectors

AMANDA II (0.1 km^3, 800 PMTs)

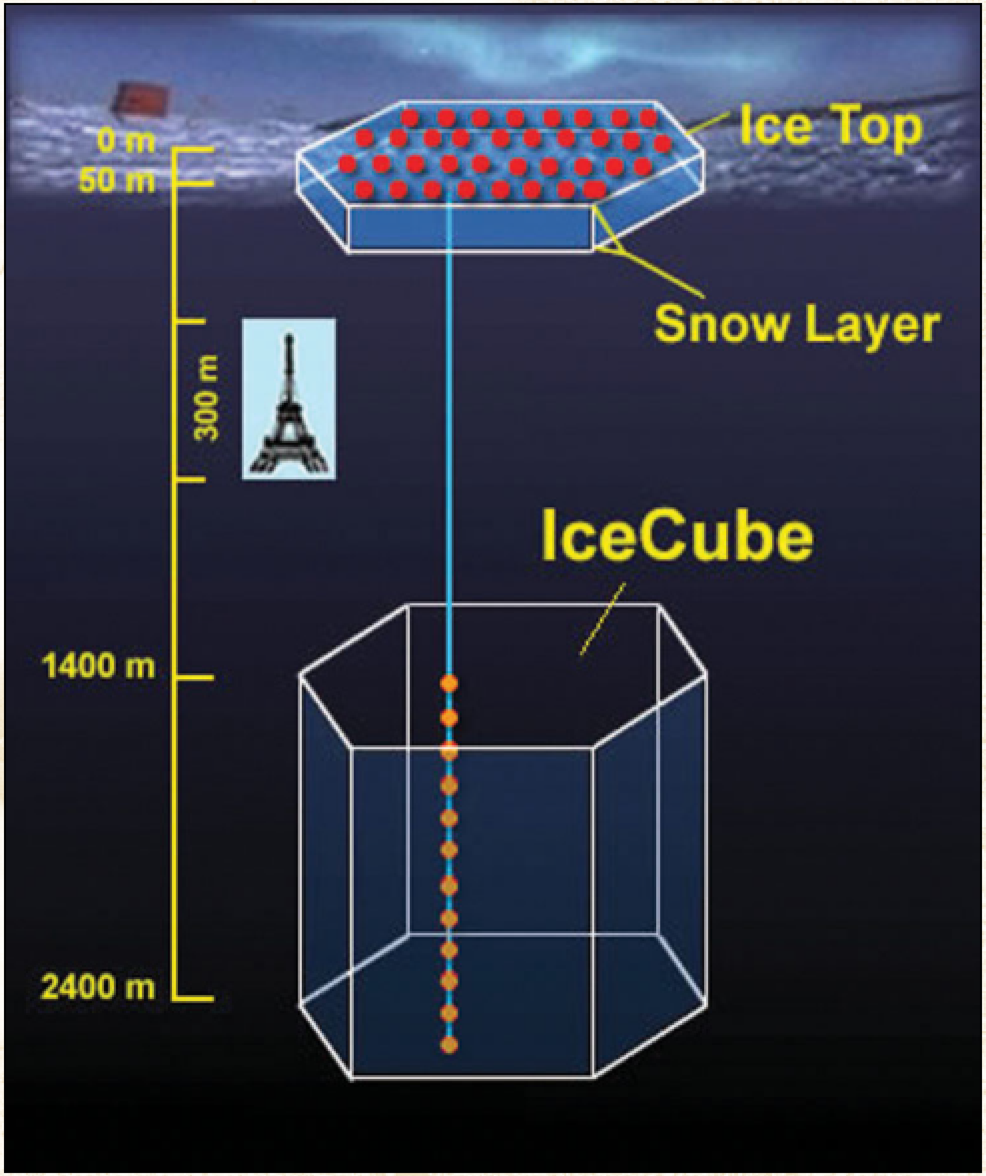


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Future IceCube (1 km^3, 4800 PMTs)

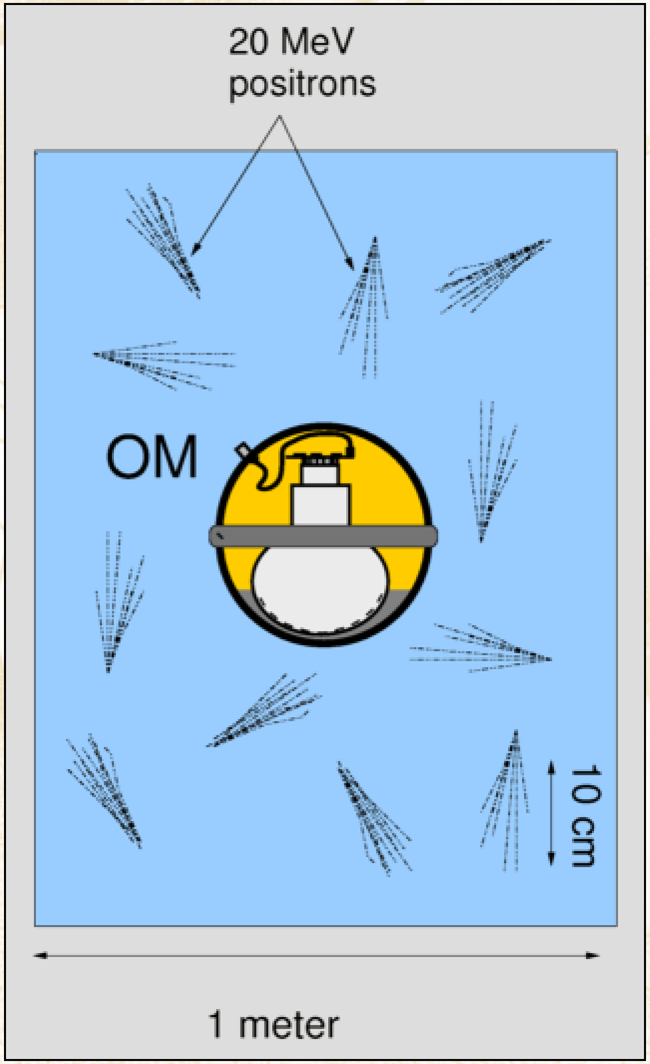


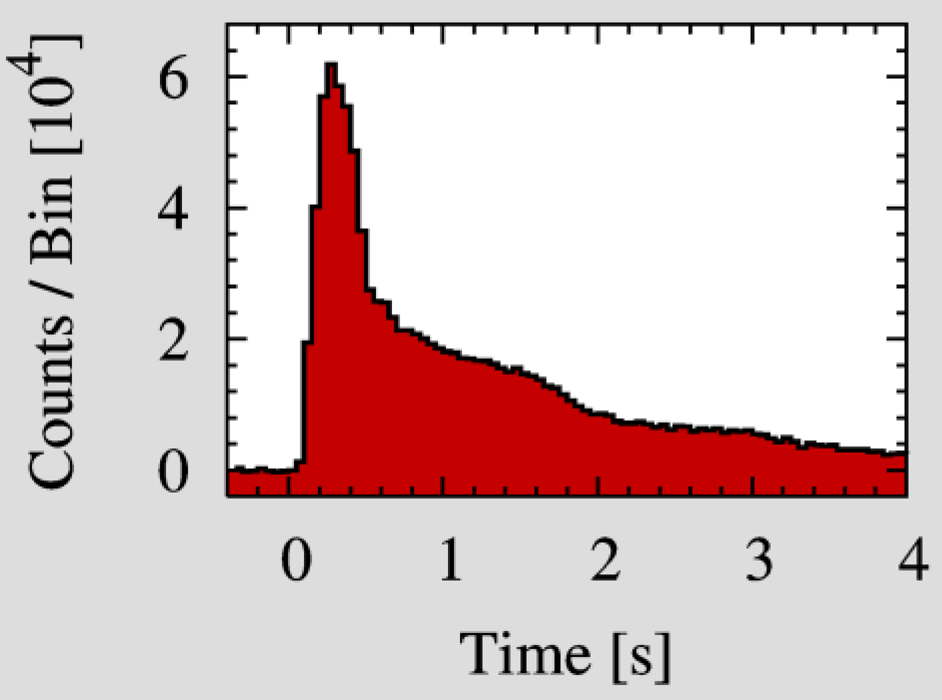
IceCube as a Supernova Neutrino Detector

Each optical module (OM) picks up Cherenkov light from its neighborhood. SN appears as “correlated noise”.

~ 300 Cherenkov photons per OM from a SN at 10 kpc

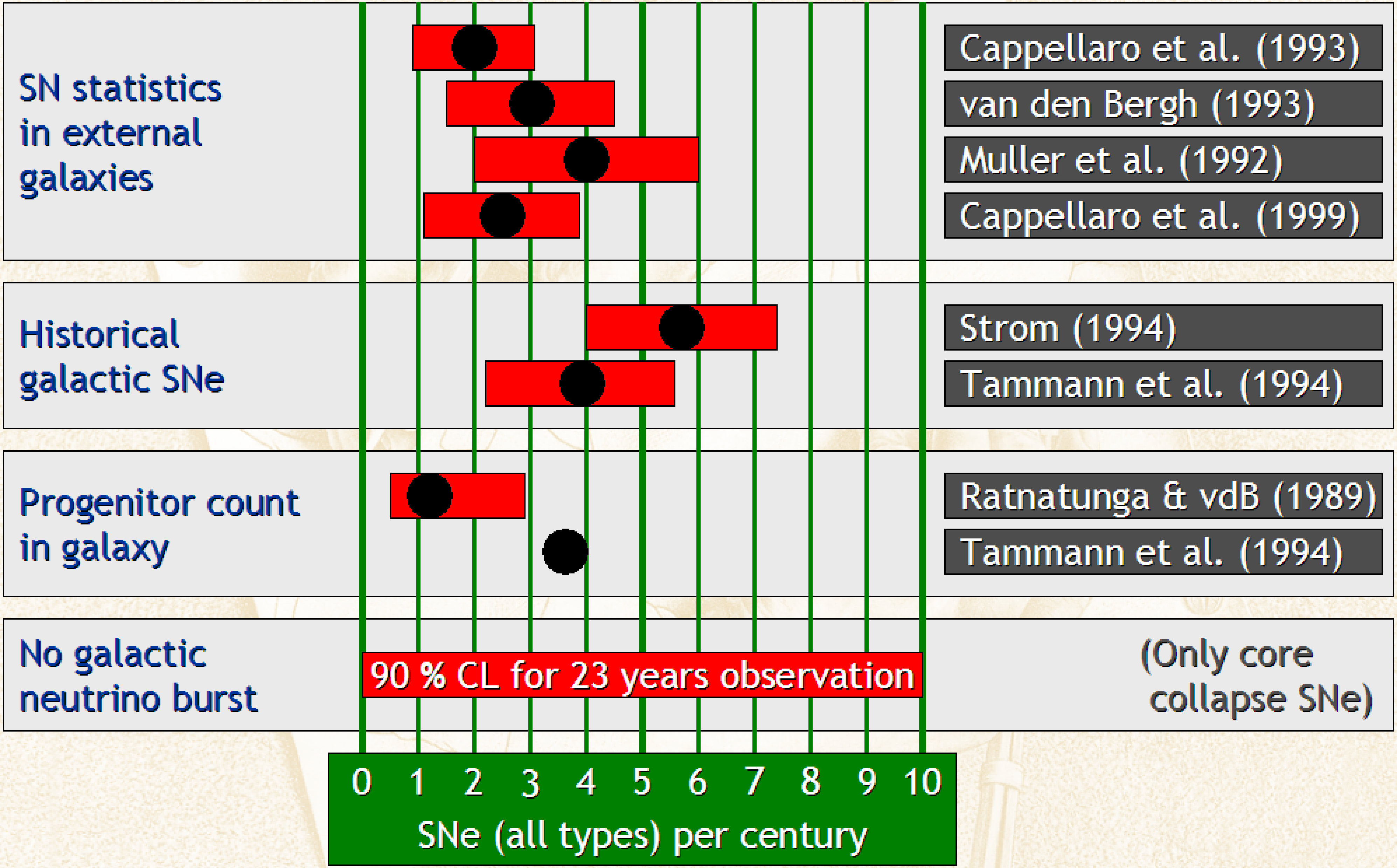
Noise per OM < 500 Hz



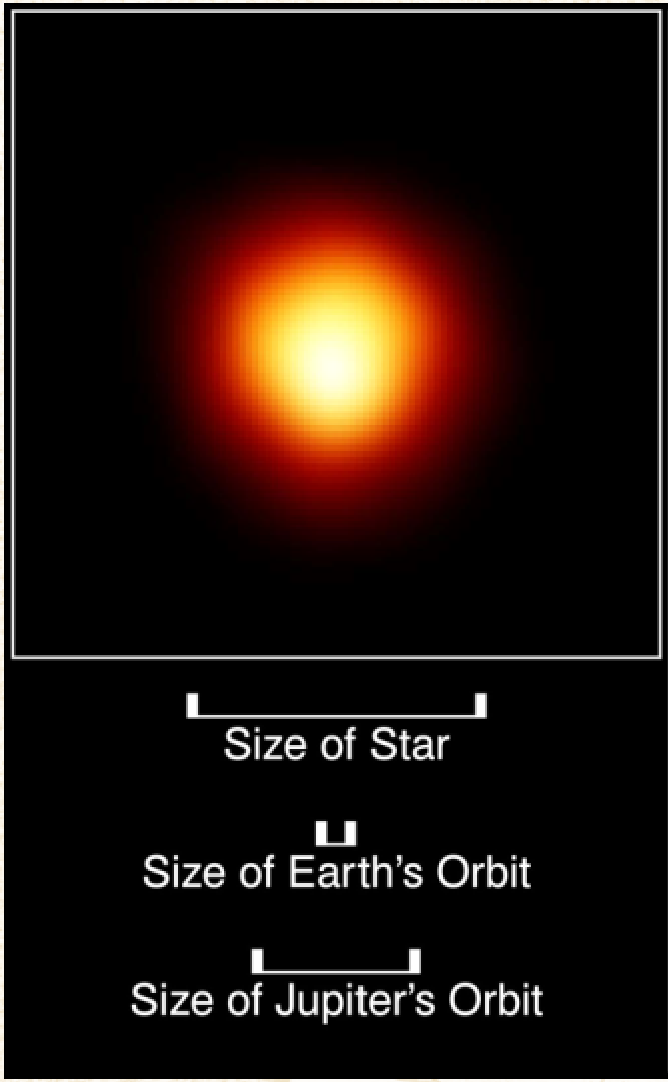


IceCube SN signal at 10 kpc, based on a numerical Livermore model [Dighe, Keil & Raffelt, hep-ph/0303210]

Estimates of the Galactic Supernova Rate



The Red Supergiant Betelgeuse (Alpha Orionis)

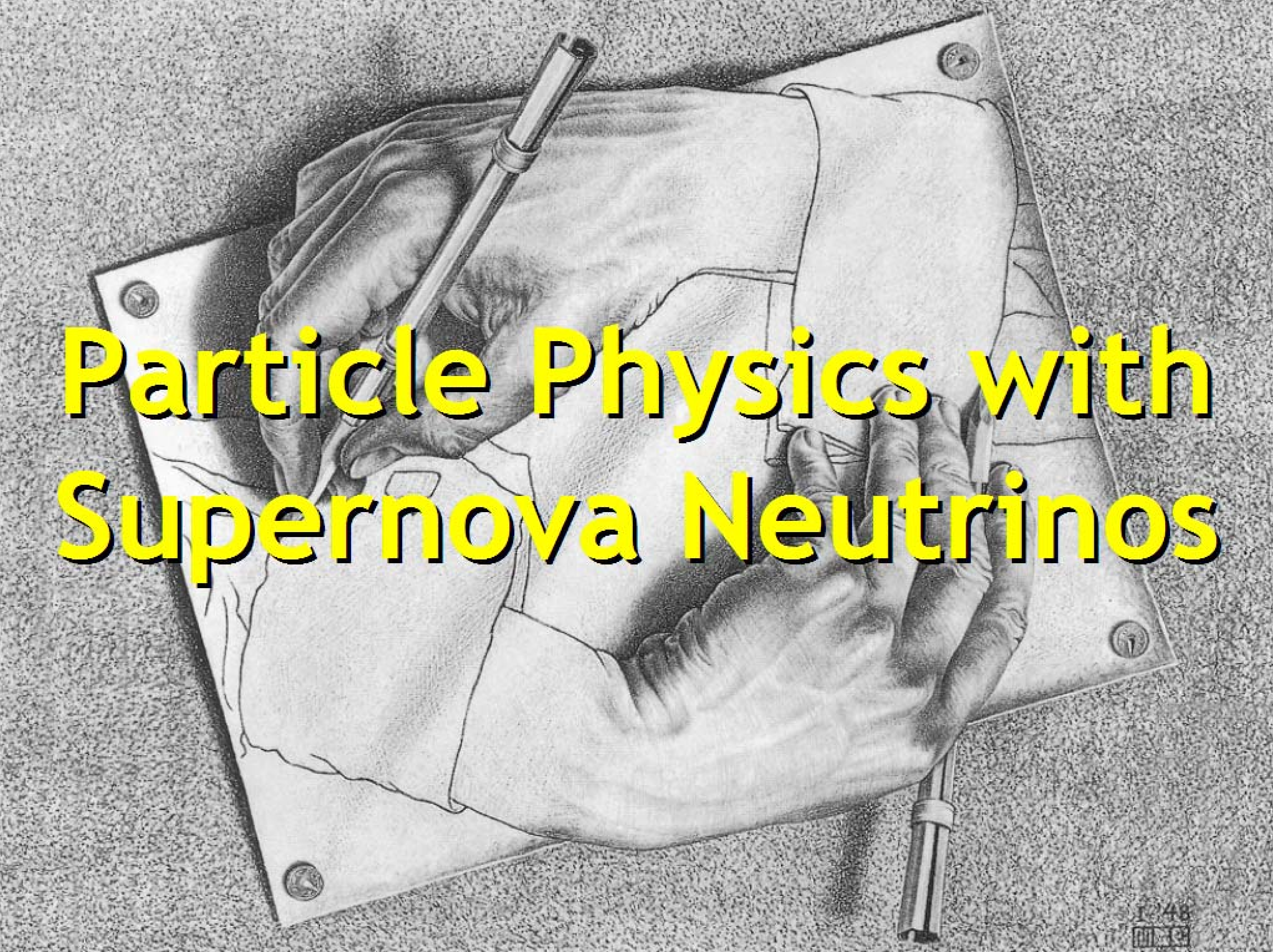


First resolved image of a star other than Sun

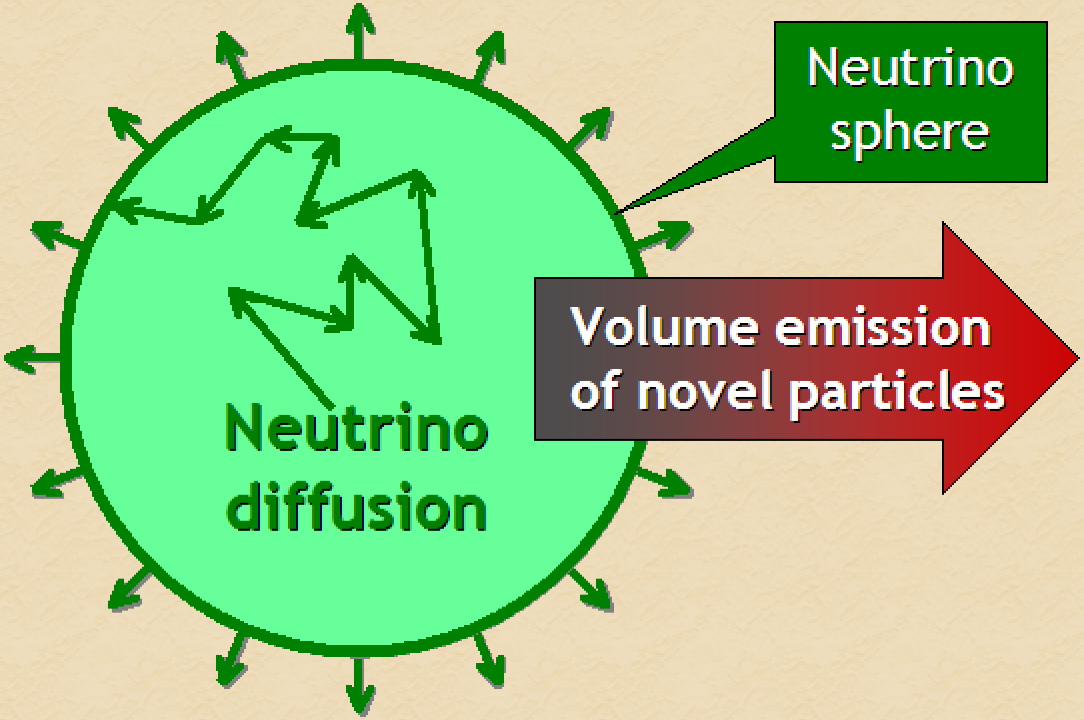
Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova
6×10^7 neutrino events
in Super-Kamiokande

Particle Physics with Supernova Neutrinos



The Energy-Loss Argument



Neutrino sphere

Volume emission of novel particles

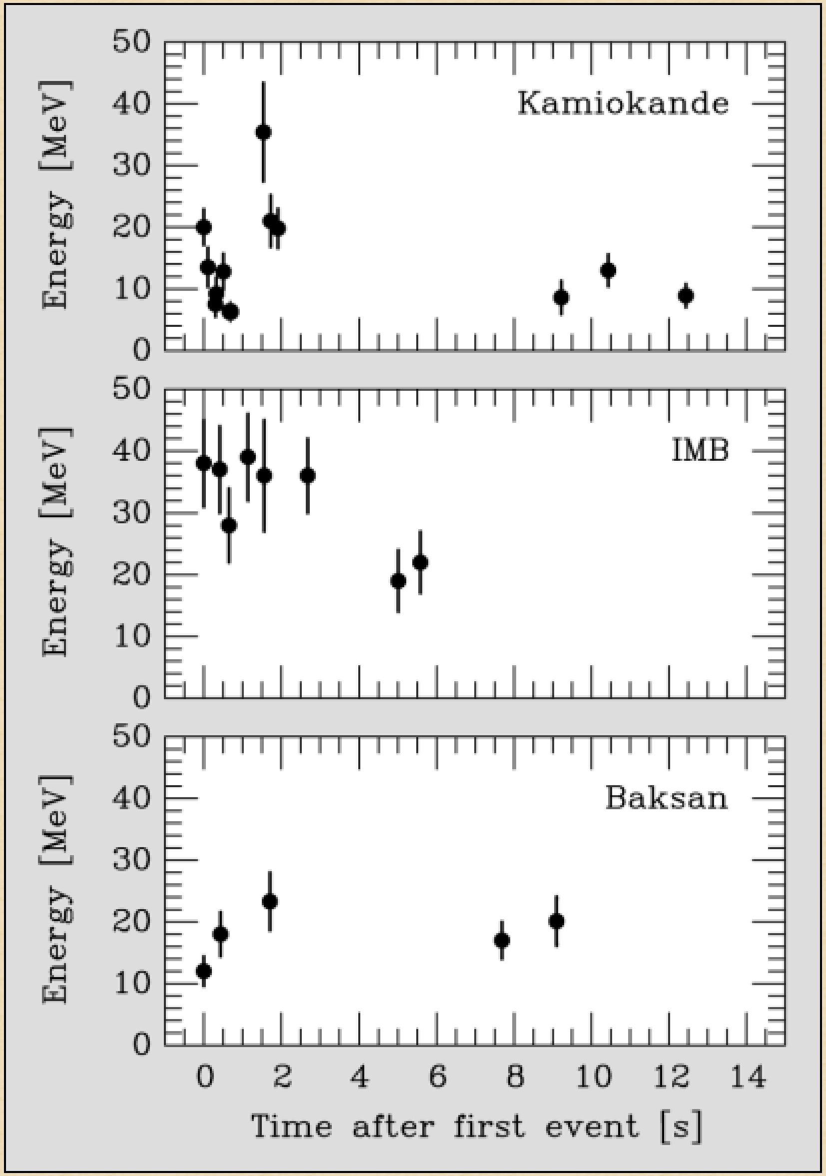
Neutrino diffusion

Assuming that the neutrino burst was not shortened by more than ~ ½ leads to an approximate requirement on a novel energy-loss rate of

$$\varepsilon_X < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

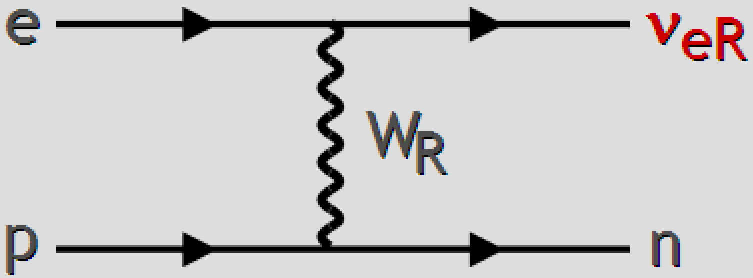
for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30$ MeV

SN 1987A neutrino signal



Right-Handed Neutrinos (Dirac Neutrinos)

Right-handed currents



Average scattering rate in SN core involving ordinary left-handed neutrinos

$$\Gamma_L \approx 10^{10}\,\mathrm{s}^{-1}$$

For right-handed neutrinos

$$\Gamma_R \approx \frac{G_R^2}{G_F^2}\,\Gamma_L$$

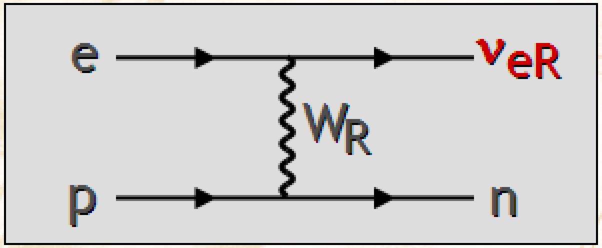
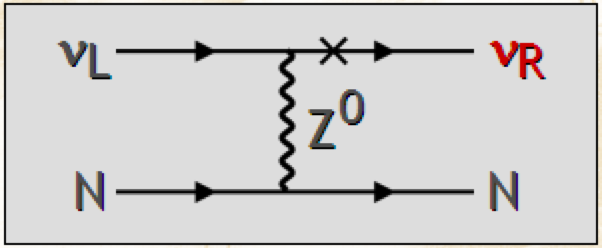
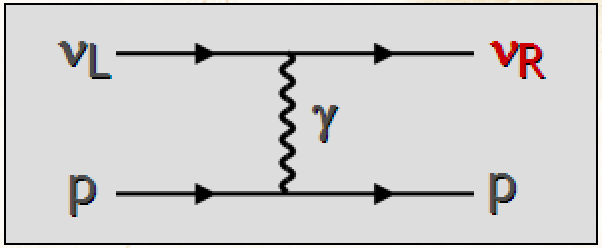
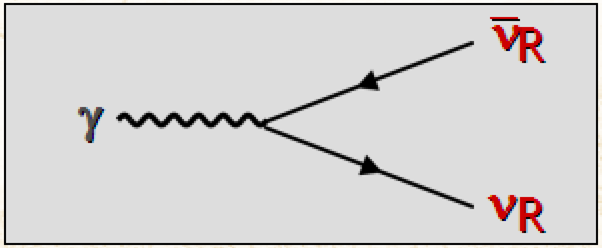
To avoid complete energy loss in ~ 1 s

$$\frac{G_R^2}{G_F^2}\,10^{10}\,\mathrm{s}^{-1} < 1\,\mathrm{s}^{-1}$$

$$G_R < 10^{-5}\,G_F$$

Dirac Neutrinos

- If neutrinos are Dirac particles, right-handed states exist that do not interact by ordinary weak interactions
- Couplings are constrained by SN 1987A energy-loss argument

Right-handed currents		$G_R \lesssim 10^{-5}\ G_F$
Dirac mass		$m_D \lesssim 30$ keV
Dipole moments		$\mu_\nu \lesssim 10^{-12}\ \mu_B$
Milli charge		$e_\nu \lesssim 10^{-9}\ e$

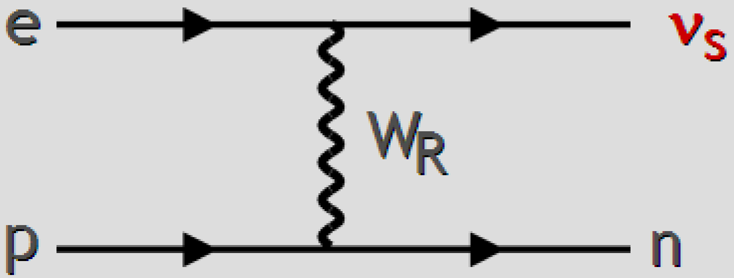
Right-Handed Neutrinos in the Early Universe

- If neutrinos are Dirac particles, will the right-handed components achieve thermal equilibrium in the early universe before big-bang nucleosythesis?
- This would modify the light-element abundances in significant ways, notably increase the helium abundance

	Required strength	SN 1987A limit
Right-handed charged current	$G_R \sim 10^{-3}\, G_F$	$G_R \lesssim 10^{-5}\, G_F$
Dirac mass	few 100 keV	30 keV
Dipole moment	$\sim 0.5 \times 10^{-10}\ \mu_B$	$10^{-12}\ \mu_B$

Sterile Neutrinos

Active-sterile mixing



Electron neutrino appears as sterile neutrino in ½ $\sin^2(2\Theta_{es})$ of all cases

$$\Gamma_s \approx \frac{1}{2}\sin^2(2\Theta_{es})\,\Gamma_L$$

Average scattering rate in SN core involving ordinary left-handed neutrinos

$$\Gamma_L \approx 10^{10}\,\mathrm{s}^{-1}$$

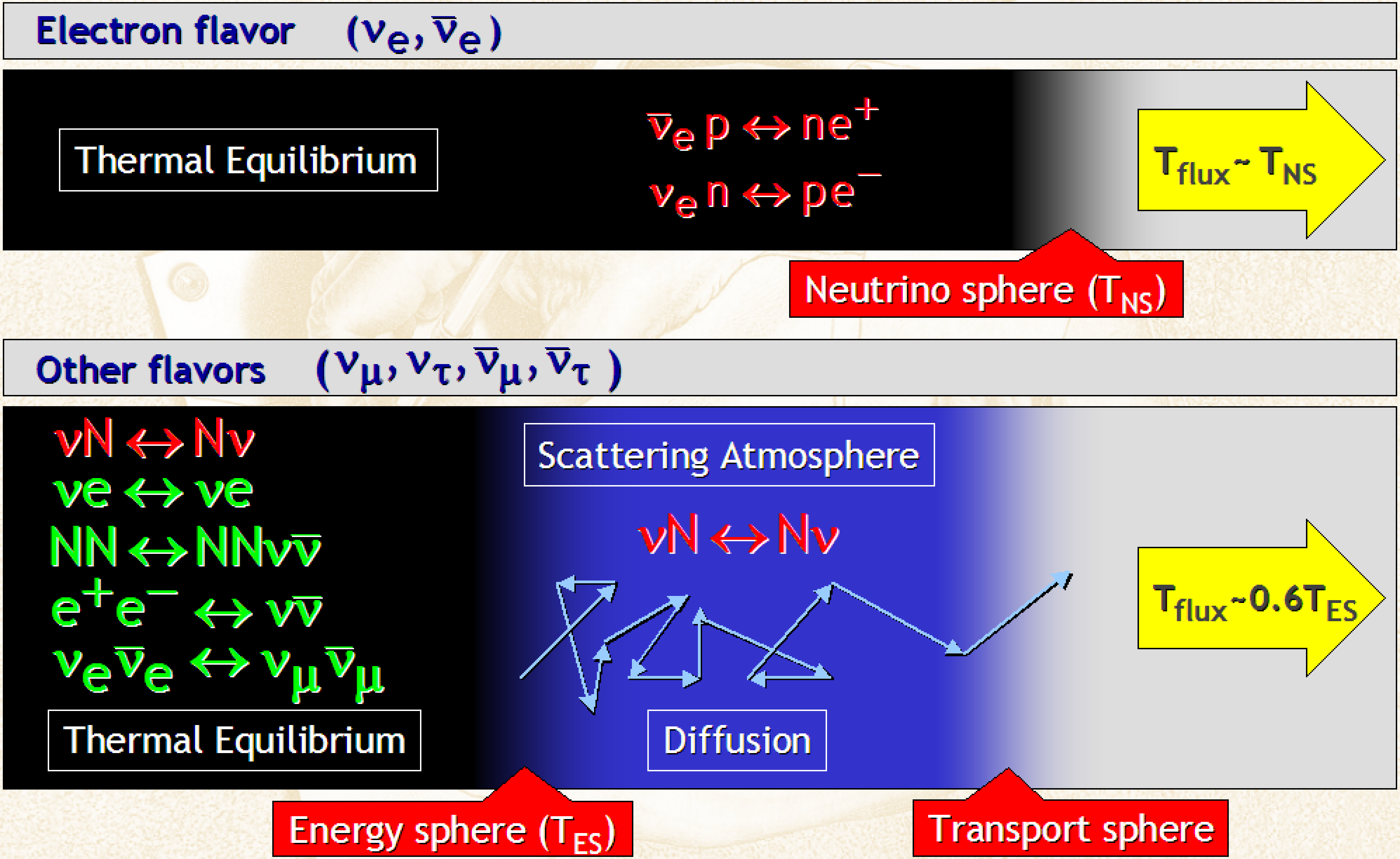
To avoid complete energy loss in ~ 1 s

$$\frac{1}{2}\sin^2(2\Theta_{es})\,10^{10}\,\mathrm{s}^{-1} < 1\,\mathrm{s}^{-1}$$

$$\sin^2(2\Theta_{es}) \lesssim 3\times 10^{-10}$$

Flavor Oscillations of Supernova Neutrinos

Supernova Neutrino Spectra Formation



Electron flavor $(\nu_e, \bar{\nu}_e)$

Thermal Equilibrium

$\bar{\nu}_e\, p \leftrightarrow n e^+$

$\nu_e\, n \leftrightarrow p e^-$

$T_{\rm flux} \sim T_{\rm NS}$

Neutrino sphere ($T_{\rm NS}$)

Other flavors $(\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau)$

$\nu N \leftrightarrow N \nu$

$\nu e \leftrightarrow \nu e$

$NN \leftrightarrow NN\nu\bar{\nu}$

$e^+e^- \leftrightarrow \nu\bar{\nu}$

$\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$

Thermal Equilibrium

Scattering Atmosphere

$\nu N \leftrightarrow N \nu$

Diffusion

$T_{\rm flux} \sim 0.6\, T_{\rm ES}$

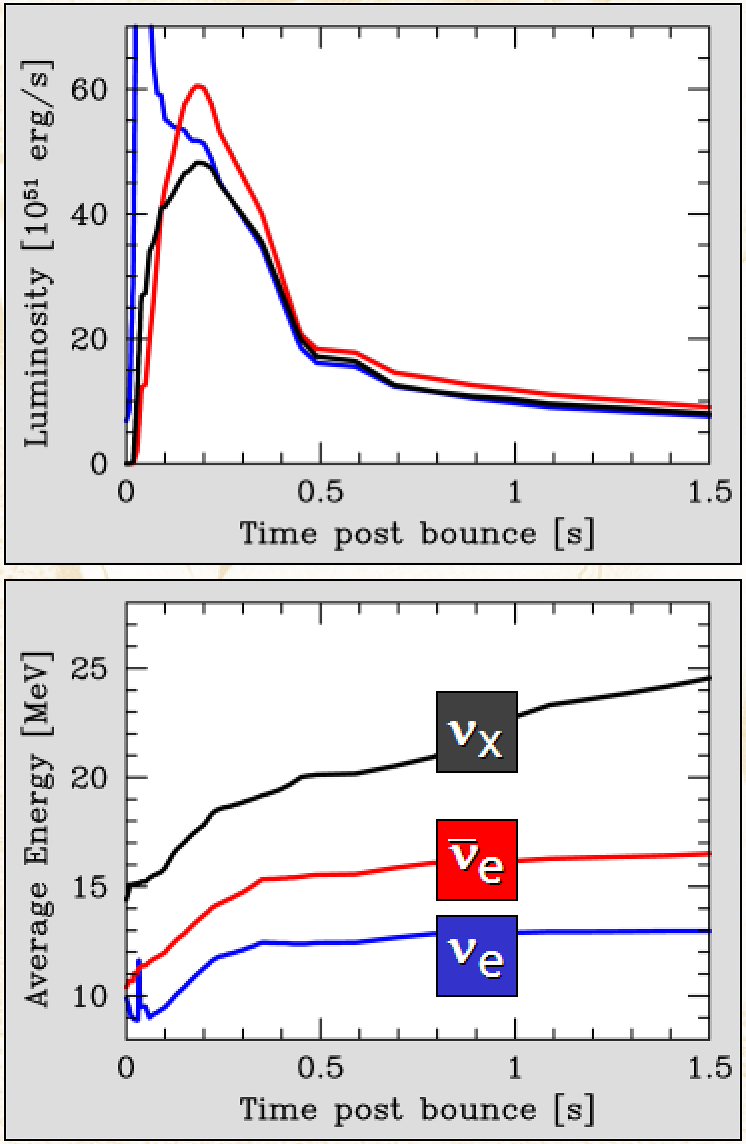
Energy sphere ($T_{\rm ES}$)

Transport sphere

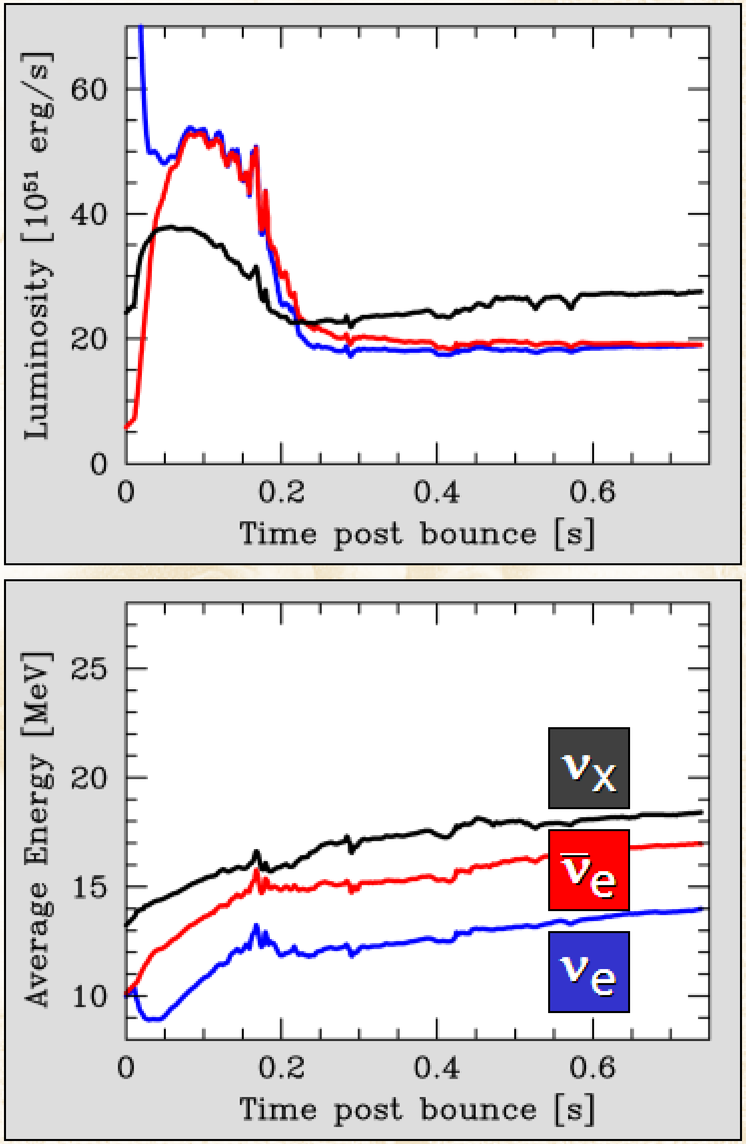
Raffelt (astro-ph/0105250), Keil, Raffelt & Janka (astro-ph/0208035)

Fluxes and Spectra from Numerical Simulations

Livermore (traditional)
[ApJ 496 (1998) 216]

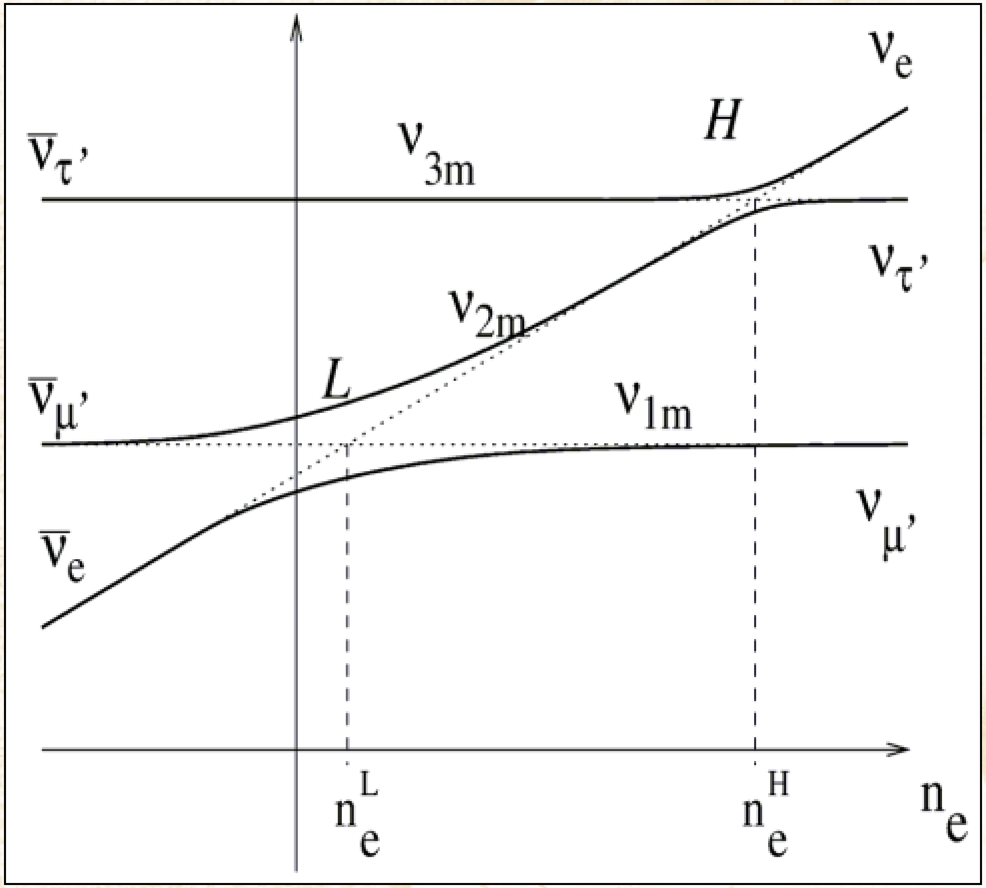


Garching (new microphyiscs)
[astro-ph/0303226]

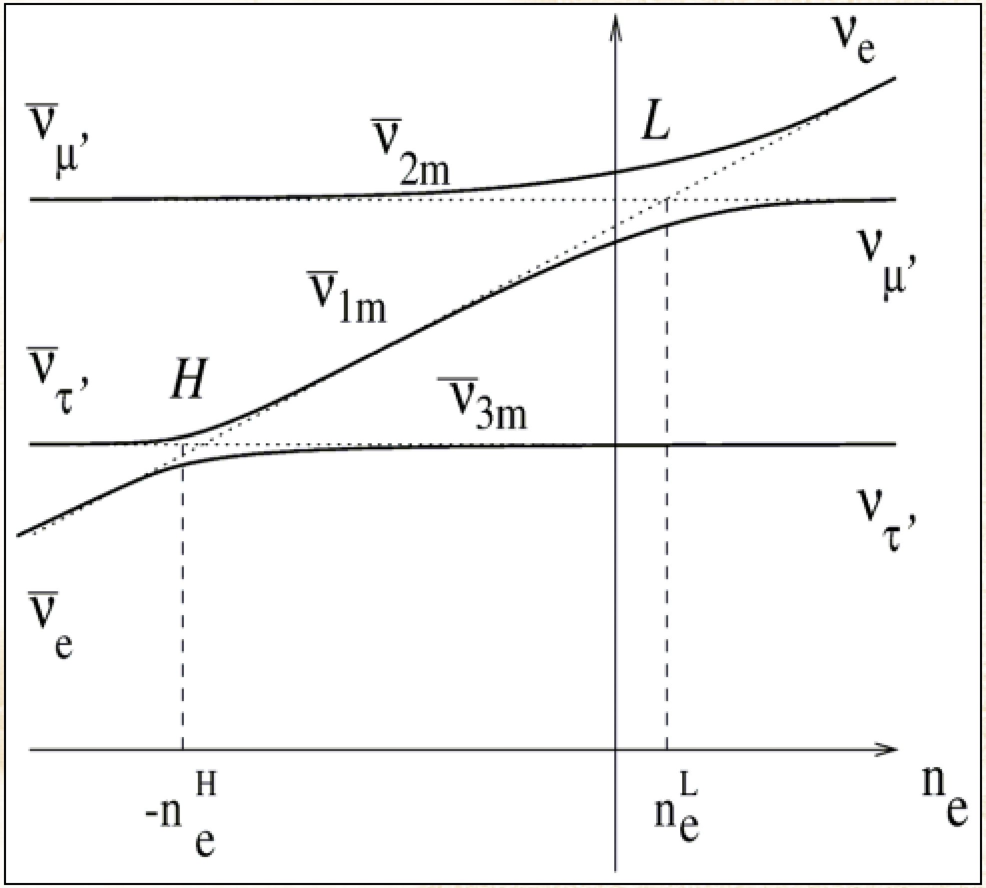


Level-Crossing Diagram in a SN Envelope

Normal mass hierarchy



Inverted mass hierarchy



Dighe & Smirnov, Identifying the neutrino mass spectrum from a supernova neutrino burst, astro-ph/9907423

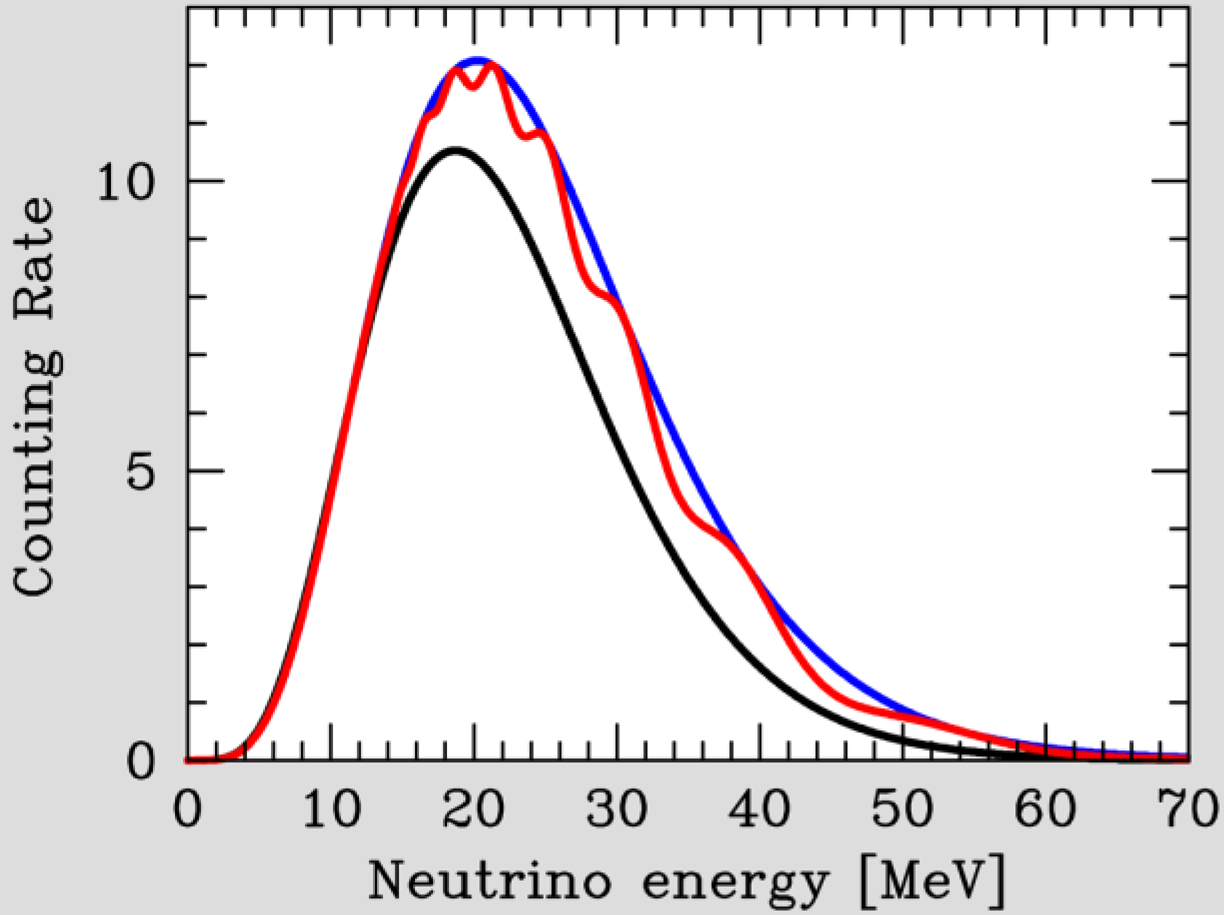
Spectra Emerging from Supernovae

Primary fluxes	F_e^0 for ν_e $F_{\bar e}^0$ for $\bar\nu_e$ F_x^0 for $\nu_\mu, \bar\nu_\mu, \nu_\tau, \bar\nu_\tau$
After leaving the supernova envelope, the fluxes are partially swapped	$F_e^0 = pF_e^0 + (1-p)F_x^0$ $F_{\bar e}^0 = \bar p F_{\bar e}^0 + (1-\bar p)F_x^0$ $\frac{1}{4}\sum F_x = \frac{2+p+\bar p}{4}F_x^0 + \frac{1-p}{4}F_e^0 + \frac{1-\bar p}{4}F_{\bar e}^0$

Case	Mass ordering	$\sin^2(2\Theta_{13})$	Survival probability	
			p (for ν_e)	$\bar p$ (for $\bar\nu_e$)
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12})$
B	Inverted		$\sin^2(\Theta_{12})$	0
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$

Oscillation of Supernova Anti-Neutrinos

Measured $\bar{\nu}_e$ spectrum at a detector like Super-Kamiokande



Assumed flux parameters

Flux ratio $\bar{\nu}_e : \bar{\nu}_\mu = 0.8 : 1$

$\langle E(\bar{\nu}_e) \rangle = 15\,\mathrm{MeV}$

$\langle E(\bar{\nu}_x) \rangle = 18\,\mathrm{MeV}$

Mixing parameters

$\Delta m^2_{\mathrm{sun}} = 60\,\mathrm{meV}^2$

$\sin^2(2\theta) = 0.9$

No oscillations

Oscillations in SN envelope

Earth effects included

Π(Dighe, Kachelriess, Keil, Raffelt, Semikoz, Tomàs),
hep-ph/0303210, hep-ph/0304150, hep-ph/0307050, hep-ph/0311172

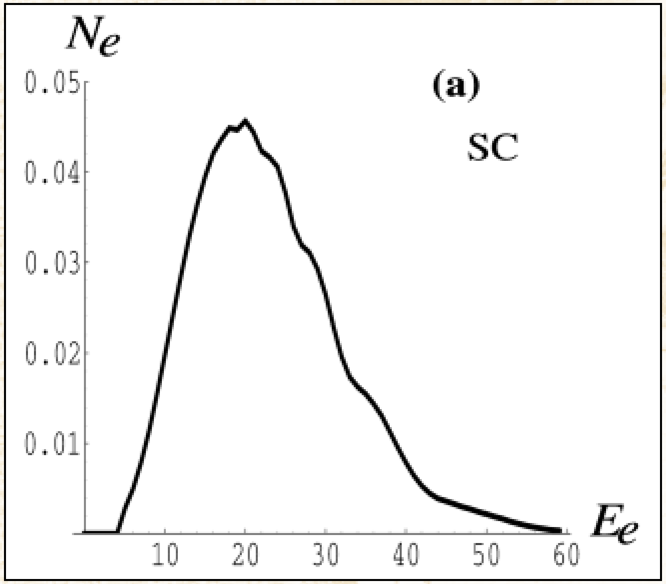
Robust Strategies for Observing Earth Effects

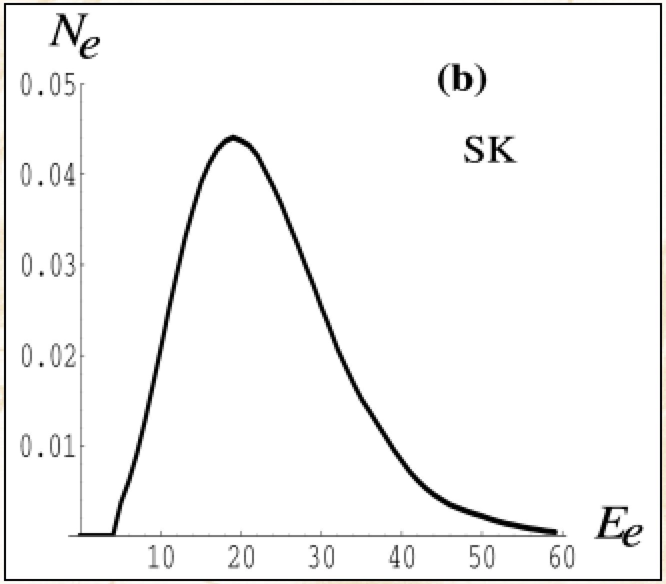
One detector observes SN shadowed by Earth

Case 1: Identify "wiggles" in signal of single detector
Problem: Smearing by limited energy resolution

Case 2:

- Another detector observes SN directly
- Identify Earth effects by comparing signals





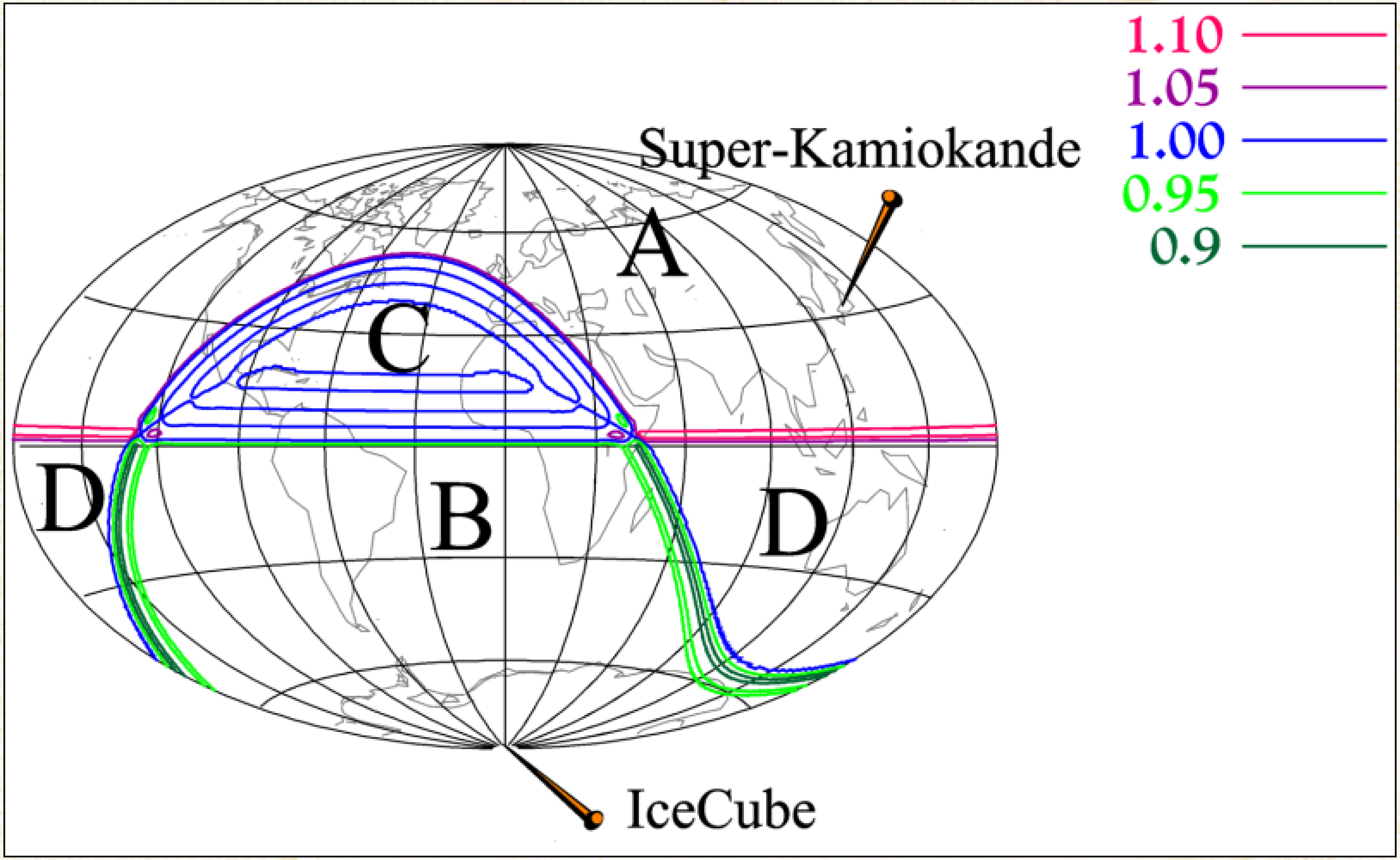
Scintillation detector
~ 2000 events
may be enough

Water Cherenkov
Need megatonne
with ~ 10^5 events

Dighe, Keil & Raffelt, "Identifying Earth matter effects on supernova neutrinos at a single detector" [hep-ph/0304150]

Positively observing Earth effects implies normal mass ordering if $\sin^2(\Theta_{13}) \gtrsim 10^{-3}$ (e.g. established by reactor experiment)

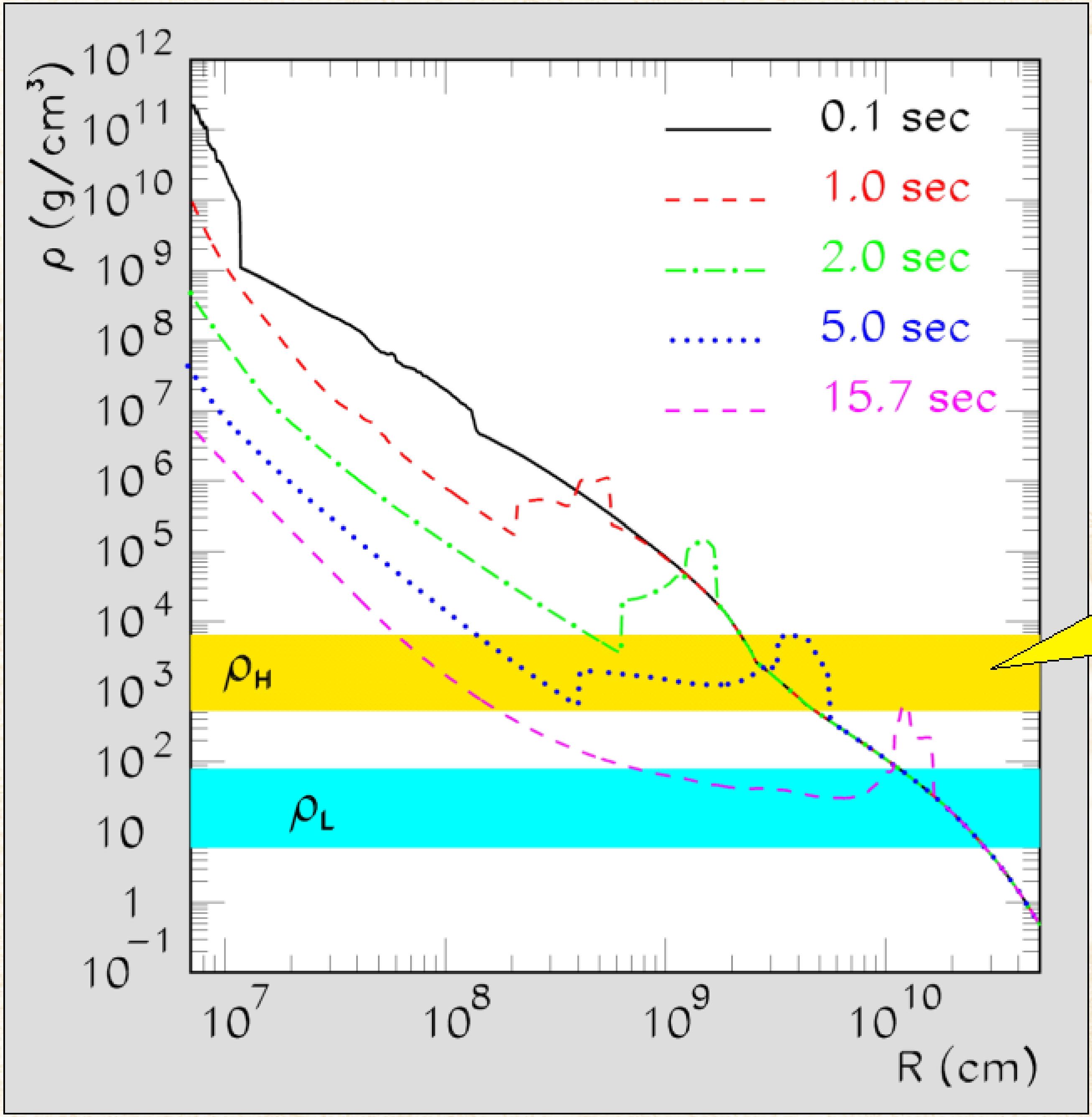
Two-Detector Sky Coverage with Super-K & IceCube



Dighe, Keil, Raffelt hep-ph/0303210

Earth effects appear in		IceCube	A	35%	Suitable for two-detector method
	Super-K		B	35%	
	Super-K	IceCube	C	15%	Approx. same signal in both detectors
			D	15%	

Supernova Shock Propagation and Neutrino Oscillations

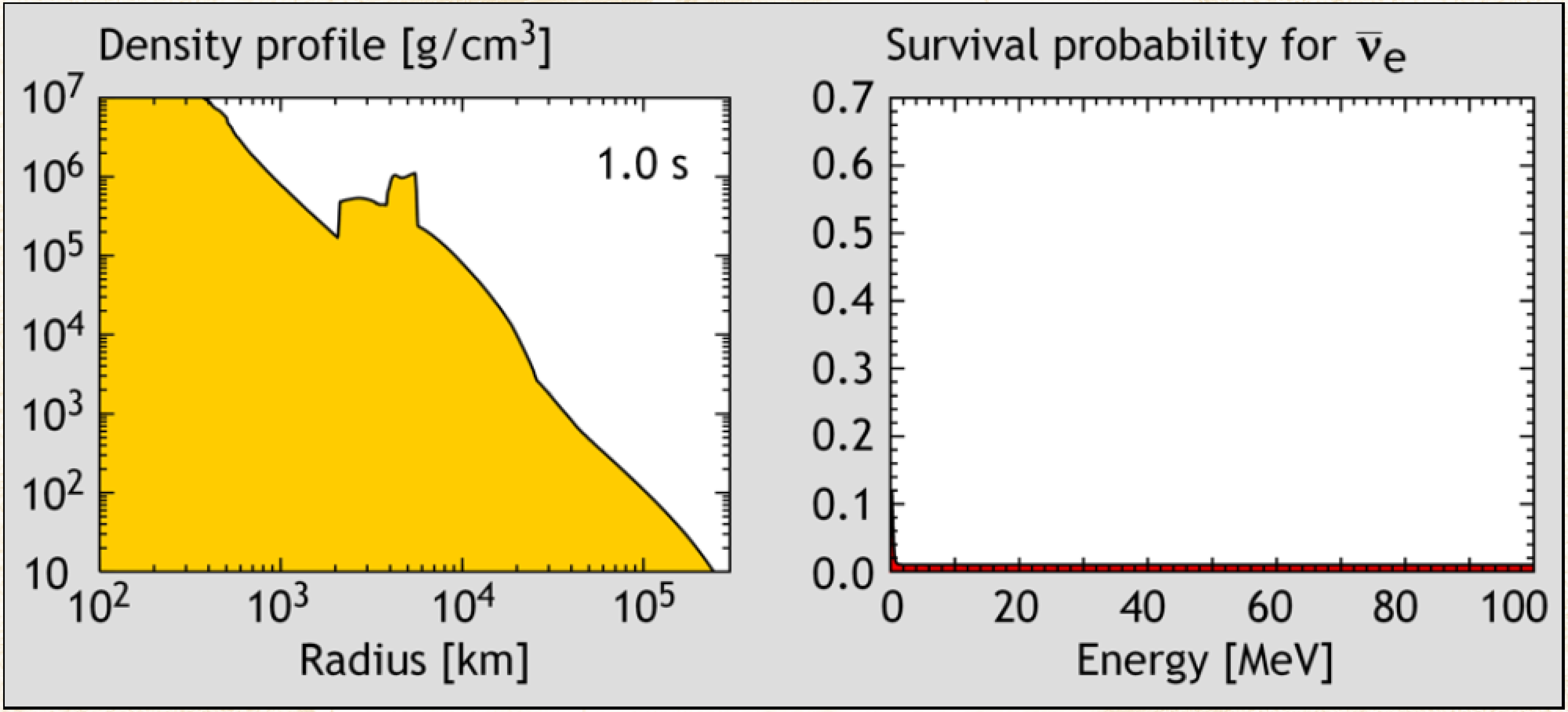


Schirato & Fuller:
Connection between supernova shocks, flavor transformation, and the neutrino signal
[astro-ph/0205390]

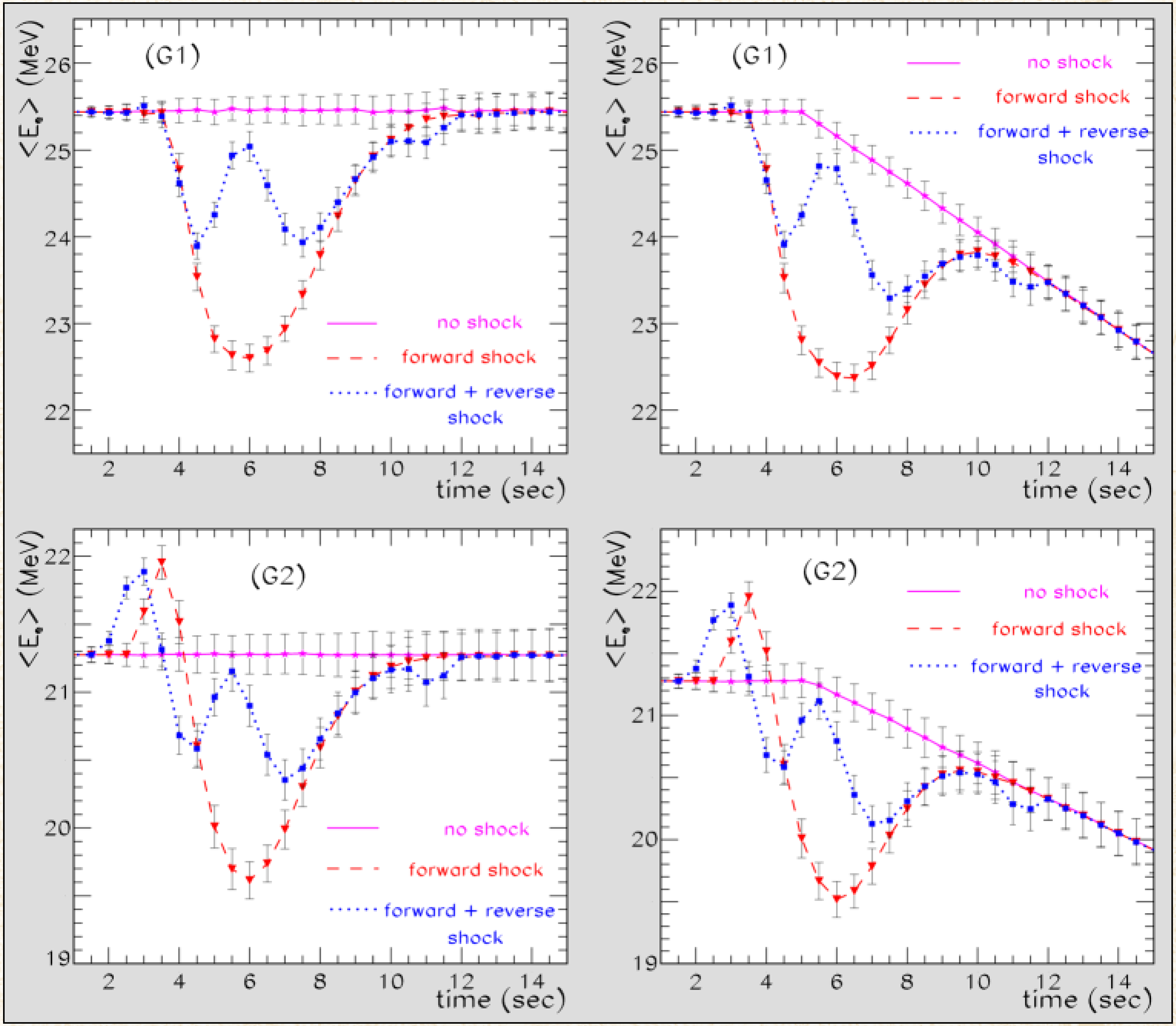
Resonance density for Δm^2_{atm}

R. Tomàs, M. Kachelriess, G. Raffelt, A. Dighe, H.-T. Janka & L. Scheck:
Neutrino signatures of supernova forward and reverse shock propagation
[astro-ph/0407132]

Shock-Wave Propagation and Survival Probability



Signature in a Megatonne Cherenkov Detector



$$\frac{\mathrm{Flux}(\bar{\nu}_e)}{\mathrm{Flux}(\bar{\nu}_x)} = 0.8$$

$$E_0(\bar{\nu}_e) = 15\,\mathrm{MeV}$$
$$E_0(\bar{\nu}_x) = 18\,\mathrm{MeV}$$

$$\frac{\mathrm{Flux}(\bar{\nu}_e)}{\mathrm{Flux}(\bar{\nu}_x)} = 0.5$$

$$E_0(\bar{\nu}_e) = 15\,\mathrm{MeV}$$
$$E_0(\bar{\nu}_x) = 15\,\mathrm{MeV}$$

Observable Features in a Water Cherenkov Detector

Case	Mass ordering	$\sin^2(2\Theta_{13})$	p	$\bar{p}$	Observable effects in $\bar{\nu}_e$ channel
A	Normal	$\gtrsim 10^{-3}$	0	$\cos^2(\Theta_{12})$	Earth effects
B	Inverted		$\sin^2(\Theta_{12})$	0	Shock-wave propagation
C	Any	$\lesssim 10^{-5}$	$\sin^2(\Theta_{12})$	$\cos^2(\Theta_{12})$	Earth effects

Neutrinos in Astrophysics and Cosmology

Neutrinos responsible for ordinary astrophysical and cosmological phenomena	• Dominant radiation component in the early universe • Crucial role in big-bang nucleosynthesis • Dark-matter component (but subdominant) • May be responsible for baryonic matter in the universe (leptogenesis) • Important (sometimes dominant) cooling agent of stars • May trigger supernova explosions • May be crucial for r-process nucleosynthesis
Heavenly laboratories for new particle physics phenomena	• Cosmological limit (future detection?) of nu mass scale • Flavor oscillations of solar and atmospheric neutrinos • Neutrino oscillations from a future galactic supernova • Limits on “exotic” neutrino properties (dipole moments, right-handed interactions, decays, flavor-violating neutral currents, sterile nus, …)
Neutrinos as astrophysical messengers	• Look into the solar interior (“measure” temperature) • Watch stellar collapse directly • Neutrinos from all cosmological supernovae • Astrophysical accelerators for cosmic rays • Annihilation signature for neutralino dark matter