ISAPP 2019, Heidelberg, 28 May–4 June 2019

Astrophysical Neutrinos

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Max-Planck-Institut für Physik

(Werner-Heisenberg-Institut)

elusives

neutrinos, dark matter & dark energy physics

SFB 1258

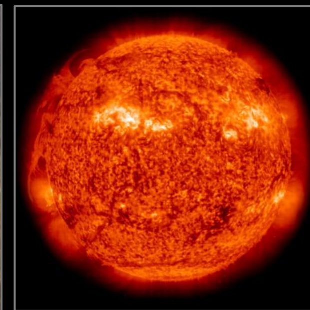
Neutrinos

Dark Matter

Messengers

Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors

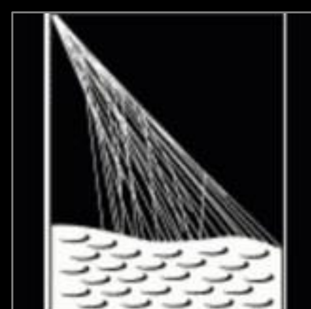


Sun ✓

✓ Particle Accelerators

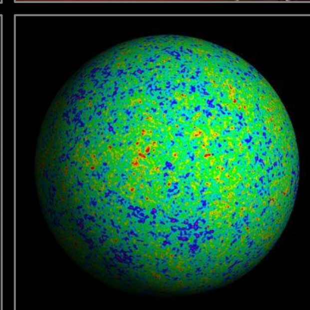
Supernovae
(Stellar Collapse)
SN 1987A ✓

✓ Earth Atmosphere
(From Cosmic Rays)



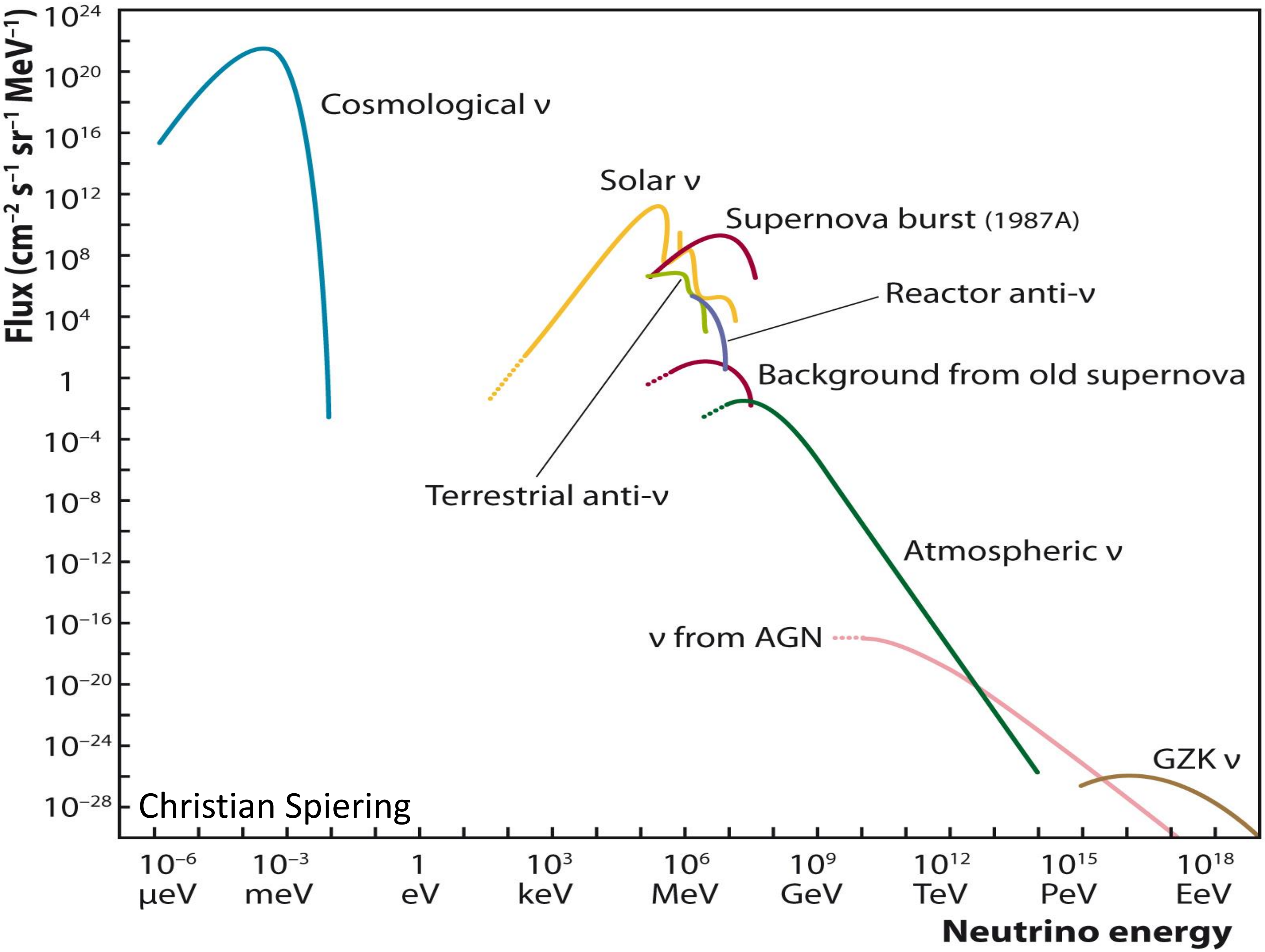
Astrophysical
Accelerators ✓

✓ Earth Crust
(Natural Radioactivity)

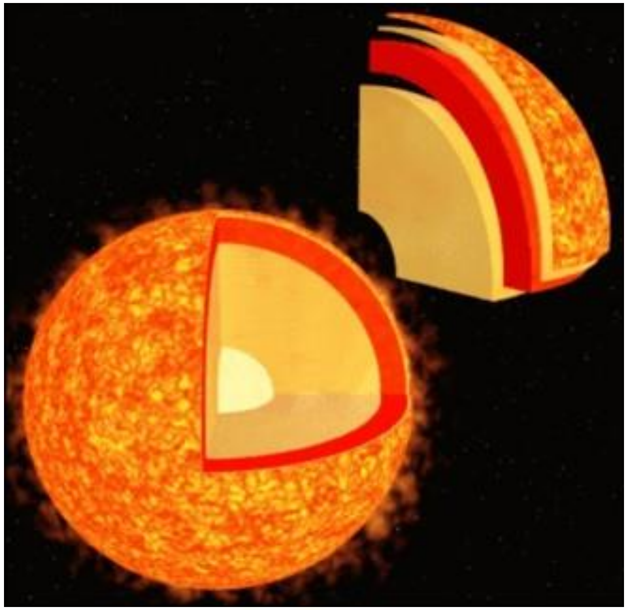


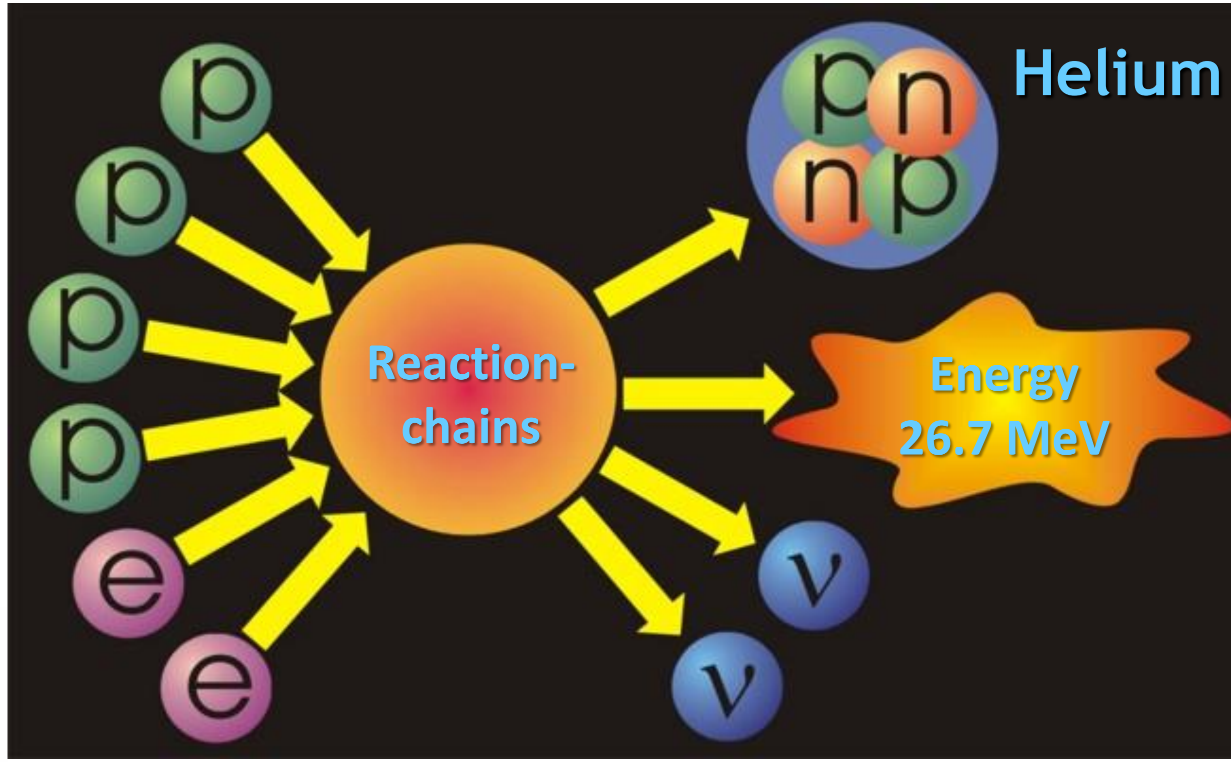
Cosmic Big Bang
(Today 336 ν/cm^3)
Indirect Evidence

Grand Unified Neutrino Spectrum



Neutrinos from the Sun

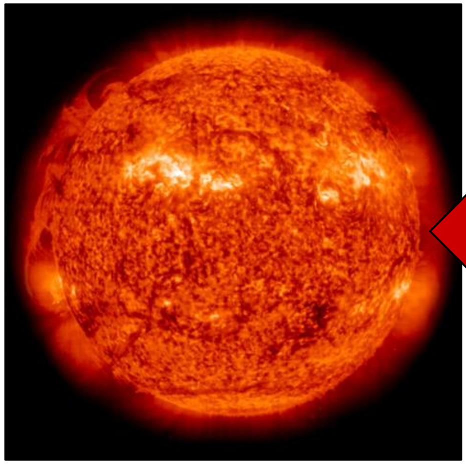




Solar radiation: 98 % light (photons)
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

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

Sun Glasses for Neutrinos?

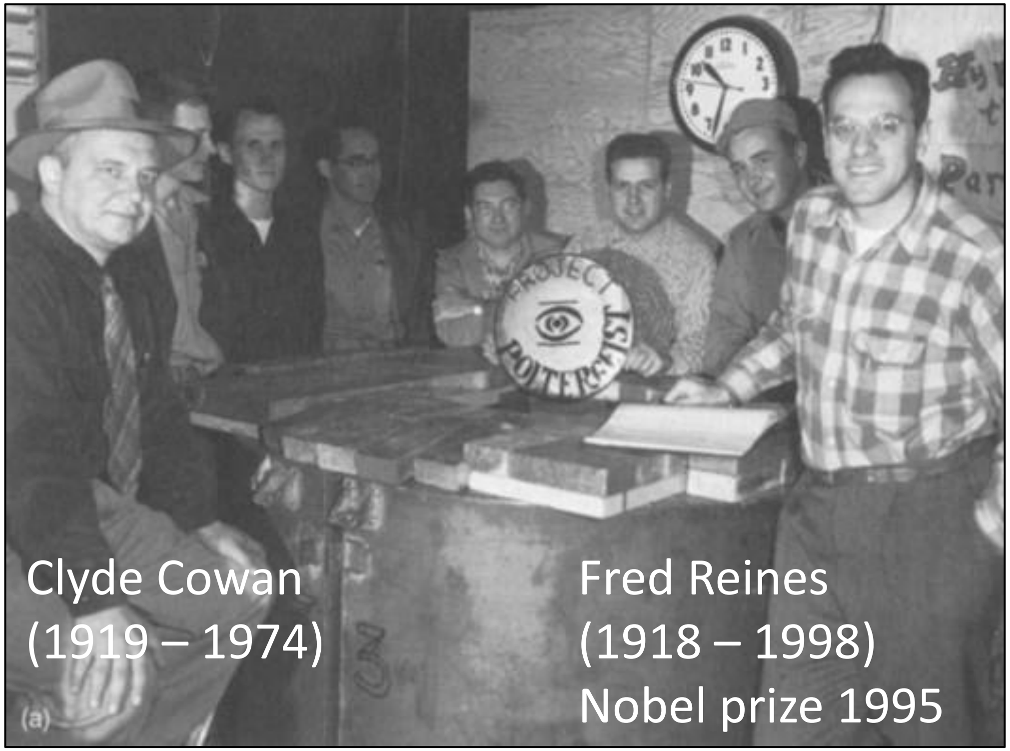


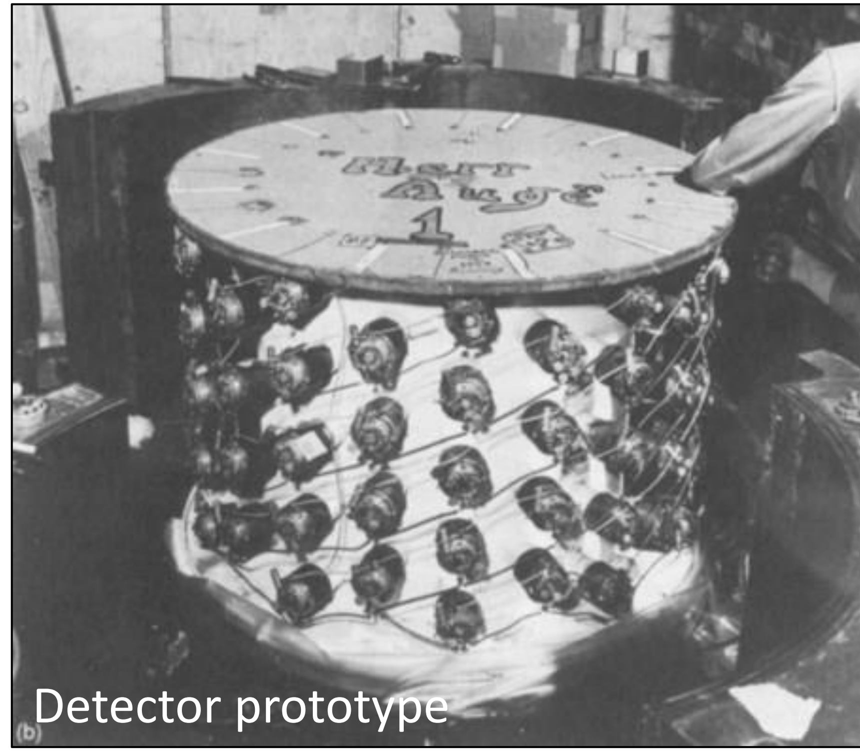
8.3 light minutes

Several light years of lead needed to shield solar neutrinos

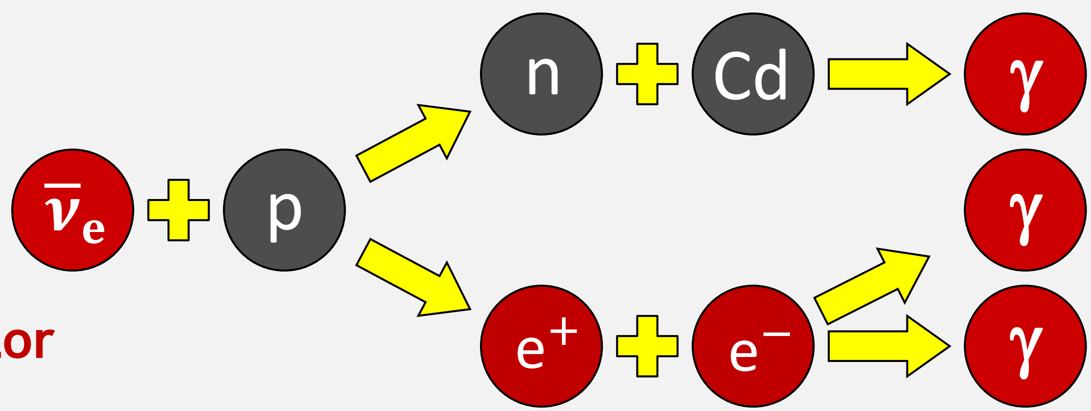
Bethe & Peierls 1934:
… this evidently means that one will never be able to observe a neutrino.

First Detection (1954 – 1956)





Anti-Electron Neutrinos from Hanford Nuclear Reactor



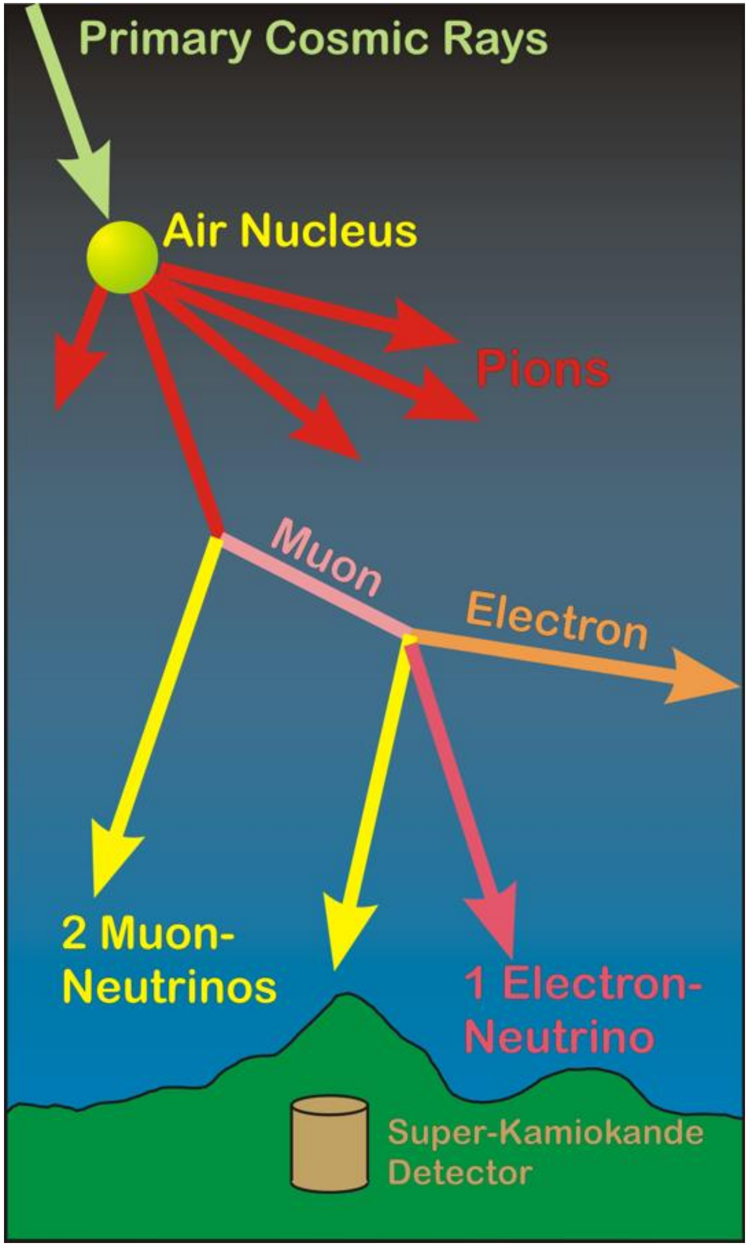
3 Gammas in coincidence

Heisenberg 1936

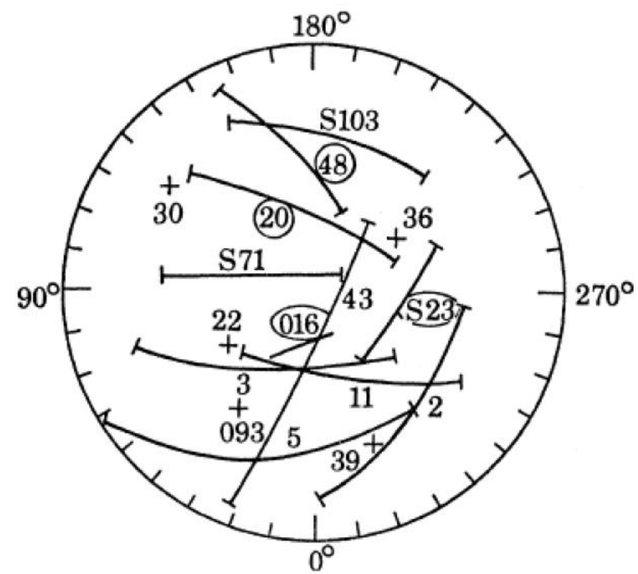
Instead [of protons and neutrons] Pauli's hypothetical 'neutrinos' should contribute substantially to the penetrating radiation. This is because in each shower ... neutrinos should be generated which then would lead to the generation of small secondary showers. The cross section for the generation of 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

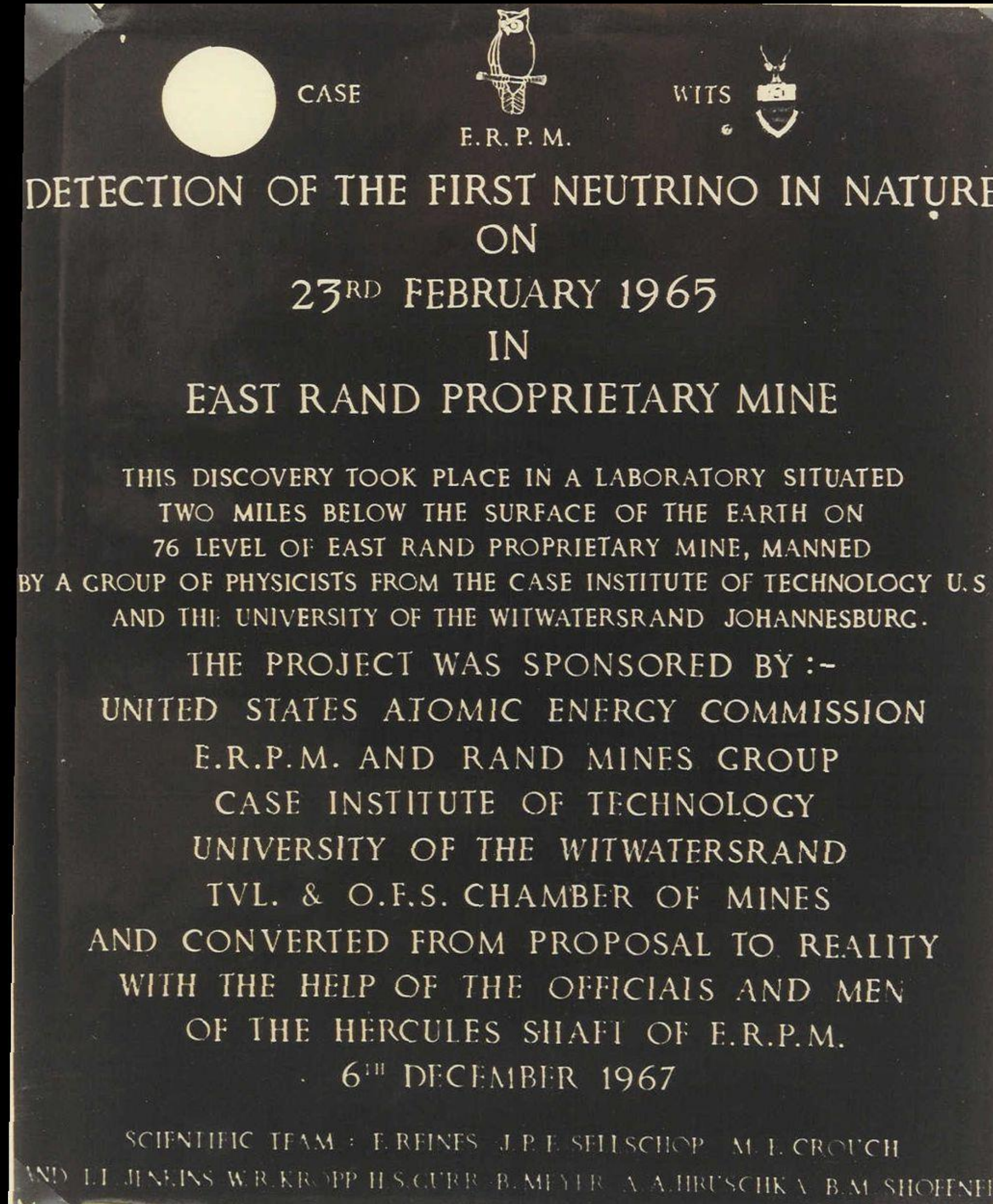
Detection of First Atmospheric Neutrinos 1965



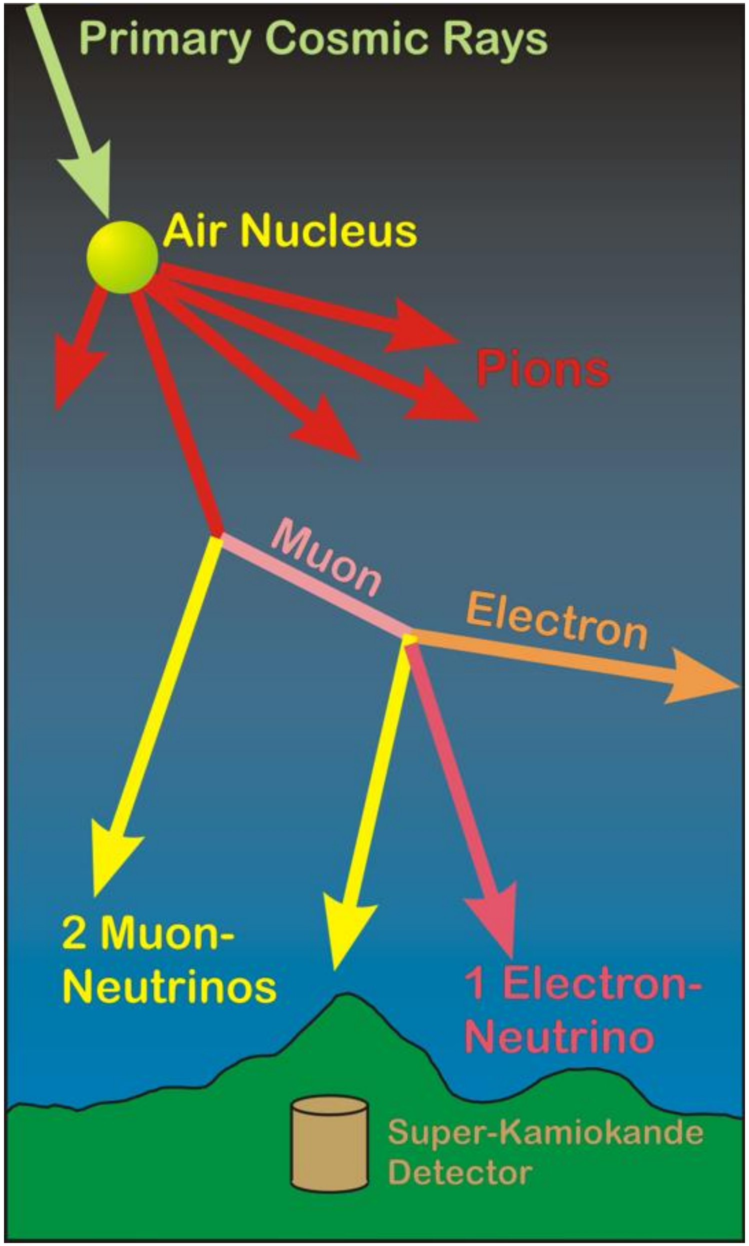
- Kolar Gold Field (KGF) Collaboration
  Japan-India-UK group, 7500 mwe
  Plastic scintillator, Flash tubes
- Chase-Witwatersrand-Irvine (CWI) Coll.
  Mine in South Africa, 8800 mwe
  Liquid scintillator, Horizontal tracks

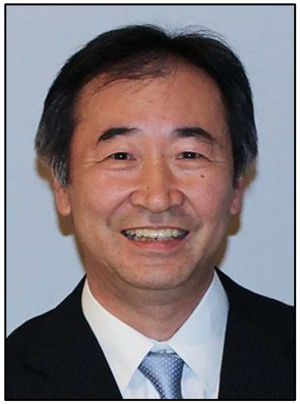


First neutrino sky map with celestial coordinates of 18 Kolar Gold Field neutrino events (Krishnaswamy et al. 1971)


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

Atmospheric Neutrinos

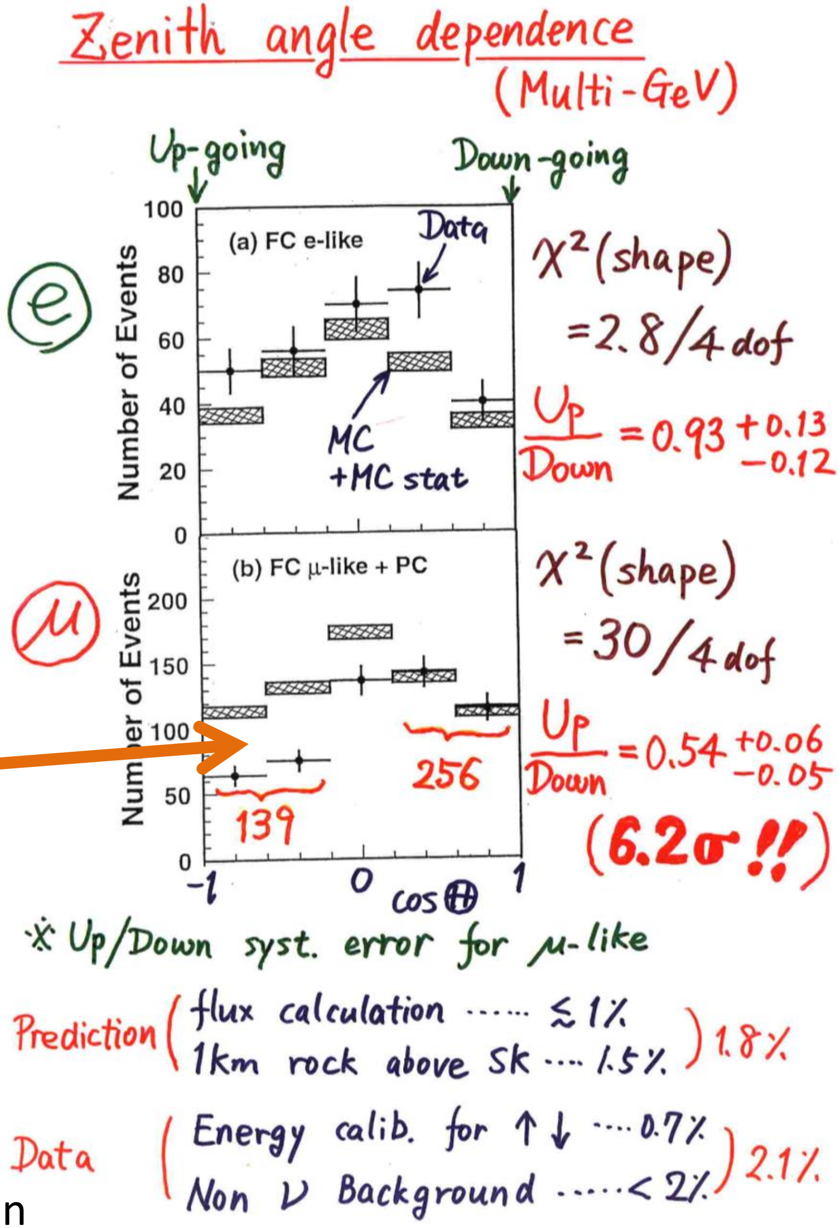




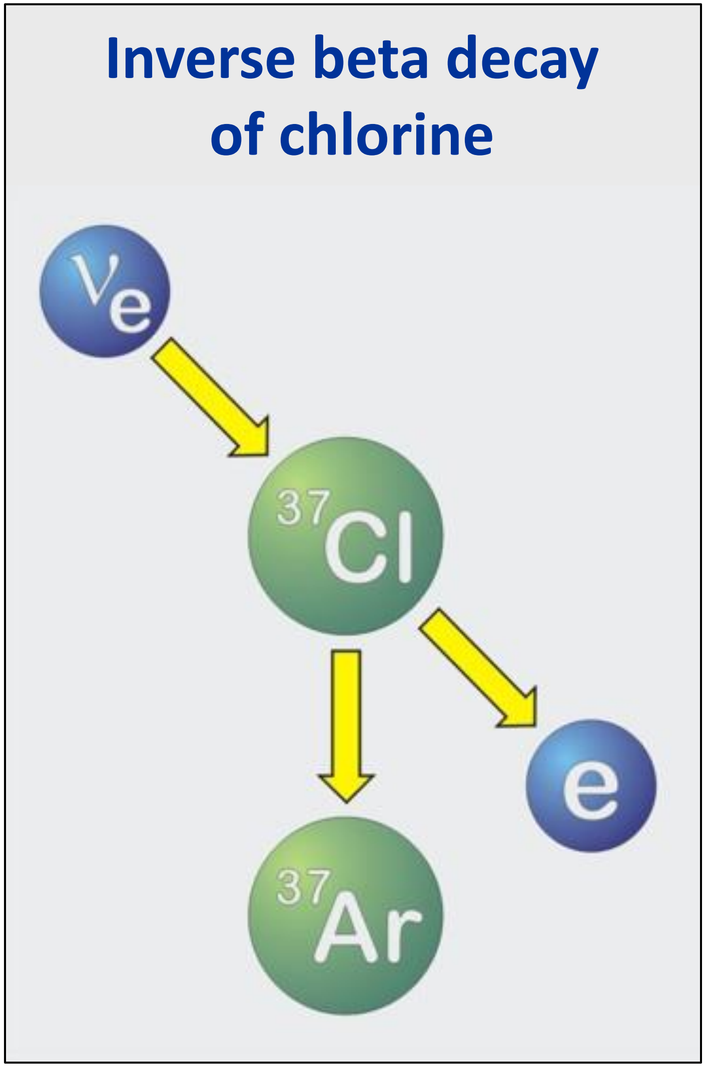
T. Kajita
Univ. Tokyo

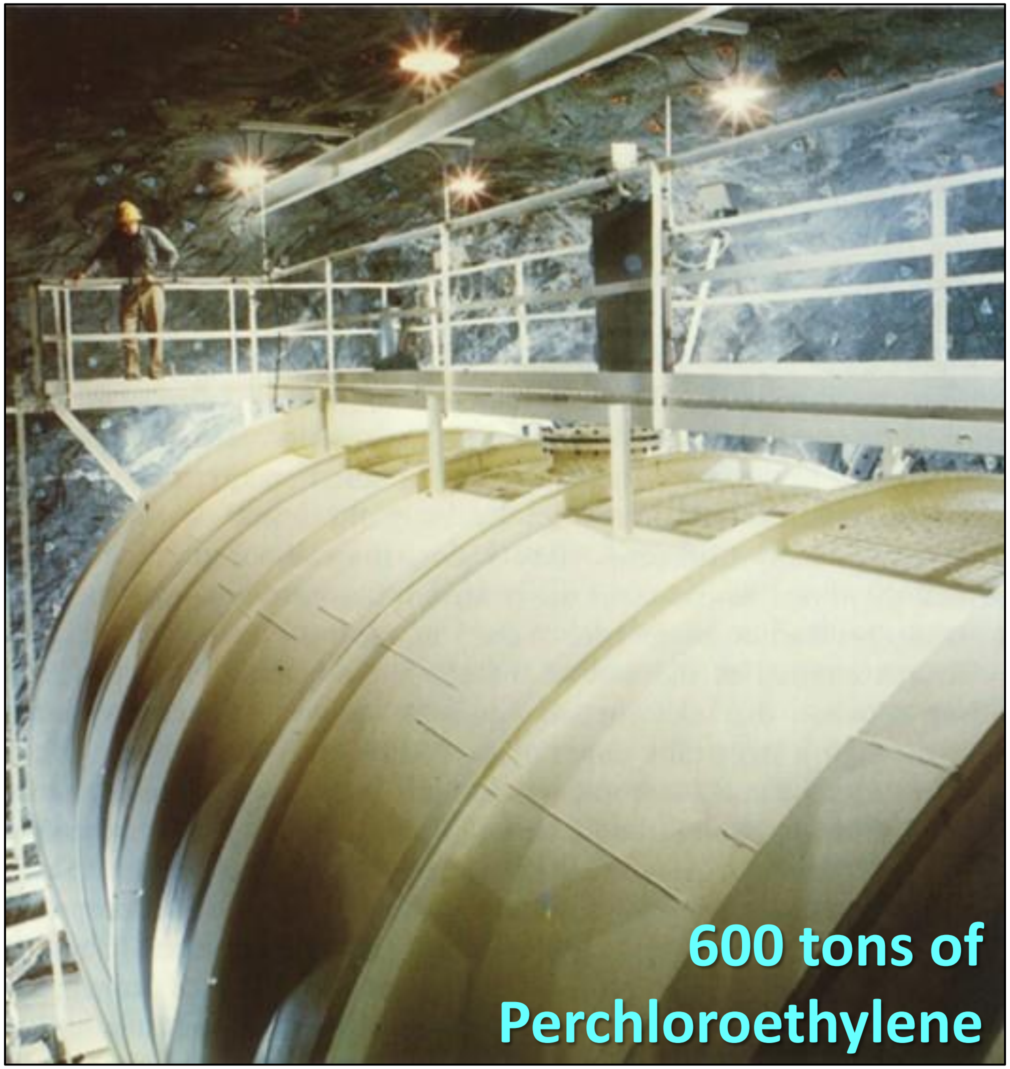
2015

Neutrino 1998
Takayama, Japan



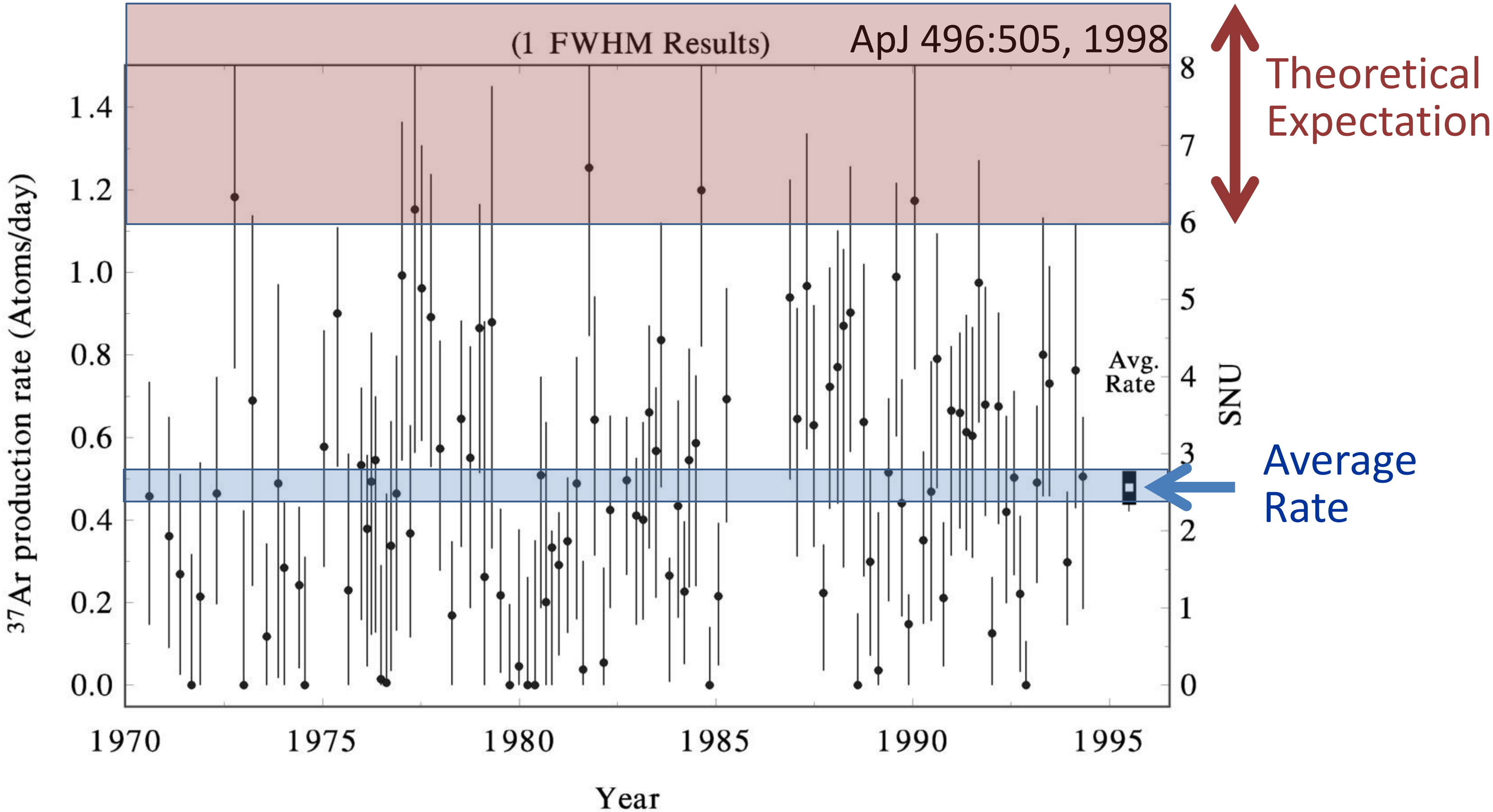
First Measurements of Solar Neutrinos





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

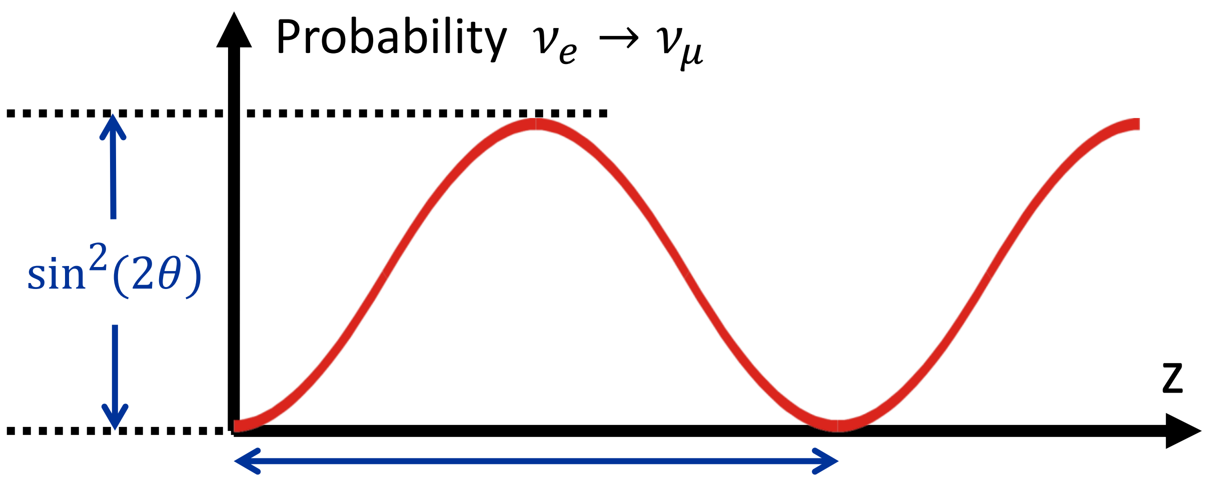
Neutrino Flavor Oscillations

Pontecorvo & Gribov (1968) on “Solar Neutrino Problem“

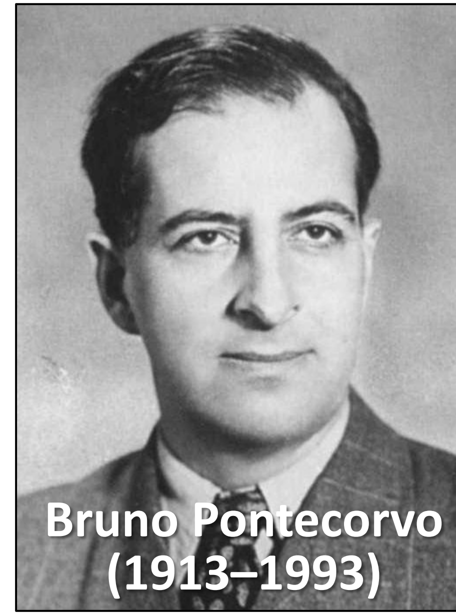
- Neutrinos are superpositions of “mass eigenstates”

$$\nu_e = +\cos\Theta\ \nu_1 + \sin\Theta\ \nu_2$$
$$\nu_\mu = -\sin\Theta\ \nu_1 + \cos\Theta\ \nu_2$$

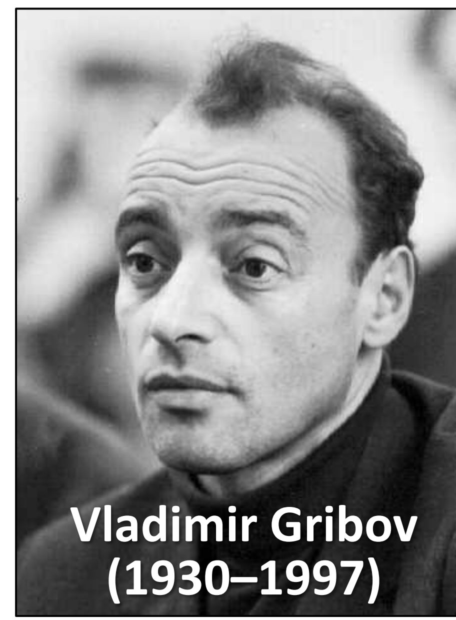
- Different speed of propagation
- Phase difference $\frac{\delta m^2}{2E}L$ causes flavor oscillations
- Similar to “optical activity” of light propagation



Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \frac{E}{\mathrm{MeV}} \left(\frac{\mathrm{eV}}{\delta m}\right)^2$



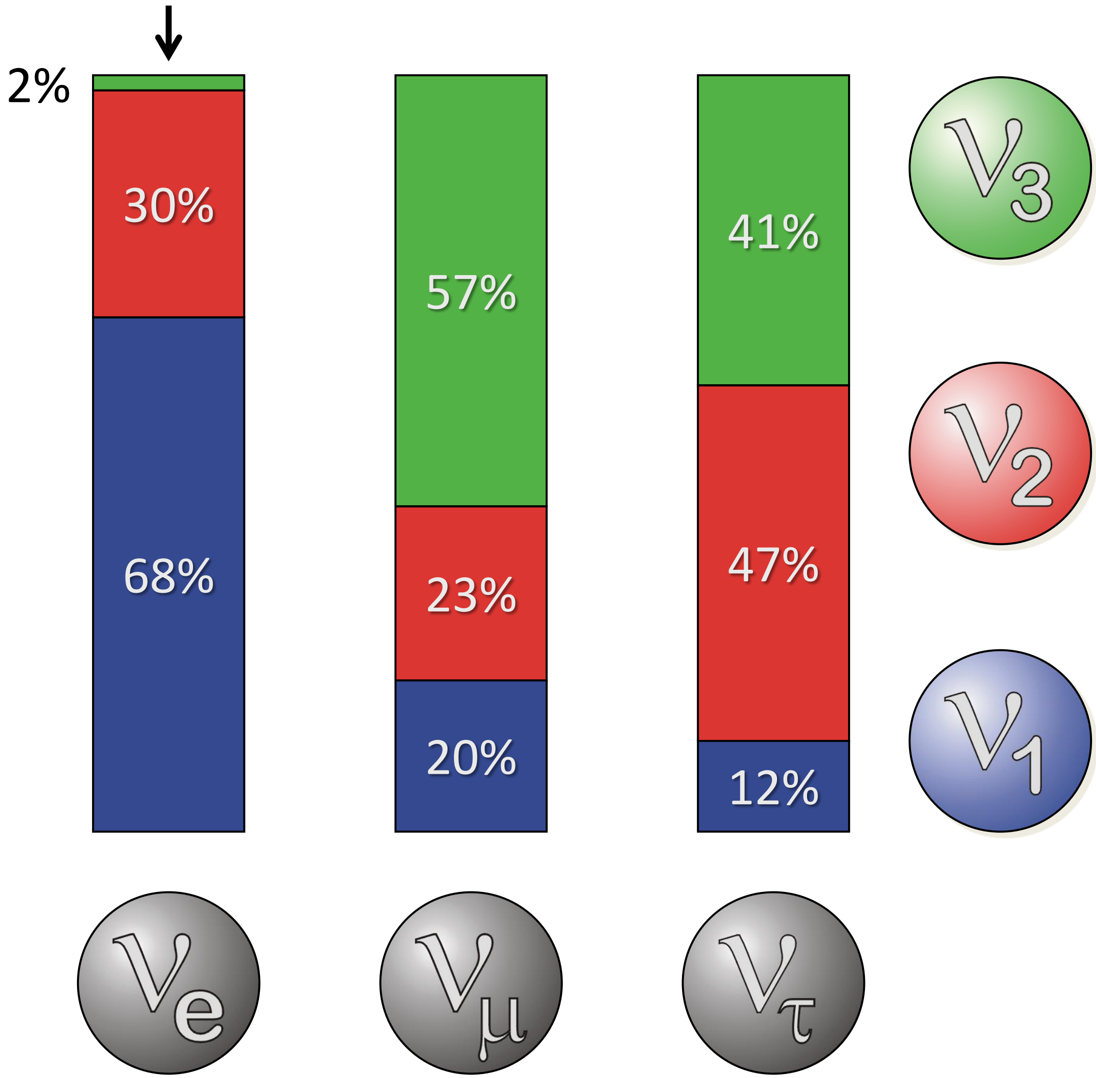
Bruno Pontecorvo (1913–1993)



Vladimir Gribov (1930–1997)

Three Flavor Mixture of Neutrinos

Small “1-3-Mixing” since 2012 measured at reactor-experiments (Double-Chooz, Daya Bay, Reno)

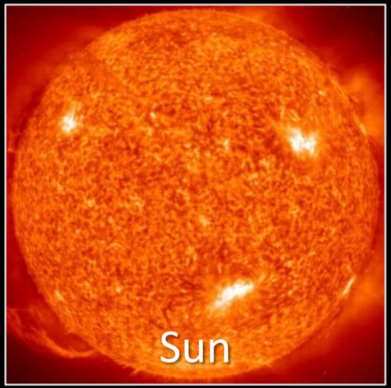


Atmospheric Neutrinos
$m_3^2 - m_2^2 \approx 2400\ \mathrm{meV}^2$

Solar Neutrinos
$m_2^2 - m_1^2 \approx 75\ \mathrm{meV}^2$

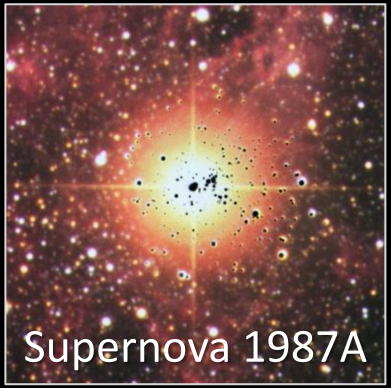
Latest details, e.g., at http://www.nu-fit.org/

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

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

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)

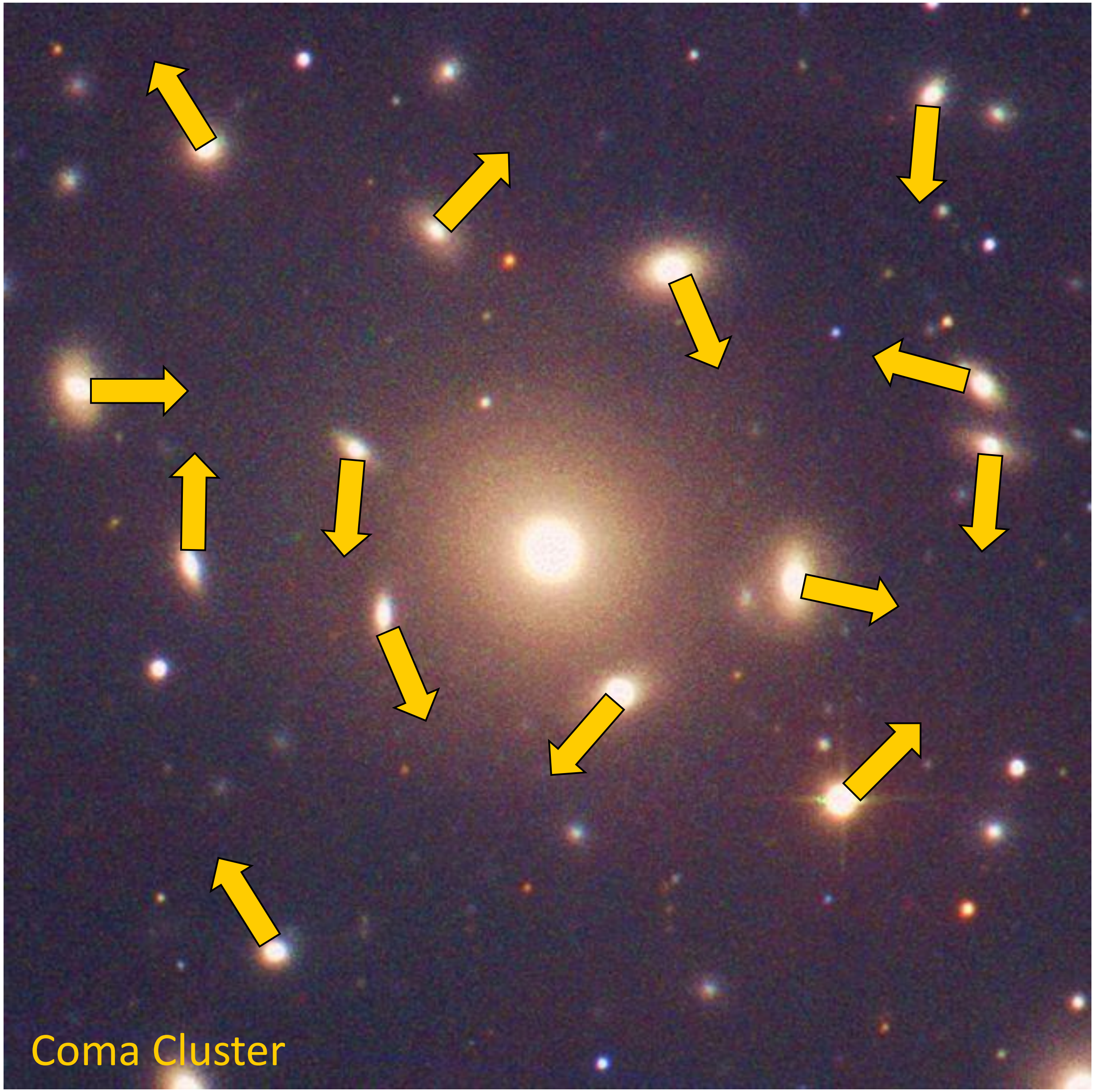
$$U^{\rm tot} = -\frac{1}{2} E_{\rm grav}^{\rm tot}$$

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

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

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

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

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

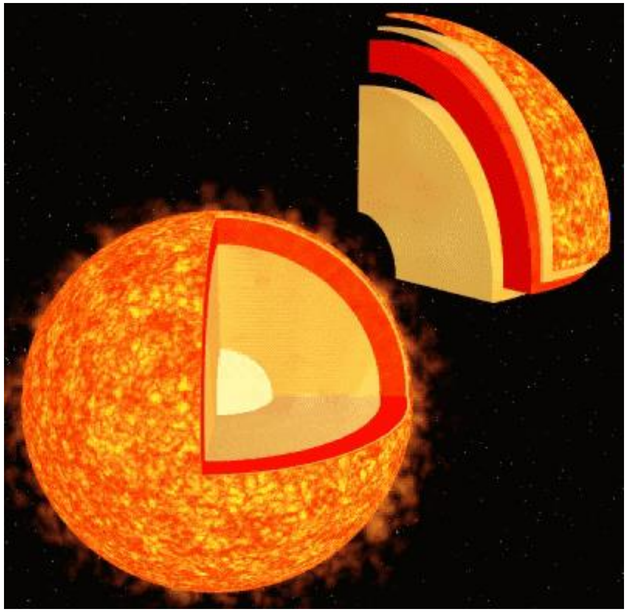
$$\langle E_{\mathrm{grav}}\rangle = -\frac{3}{2}\frac{G_N M_{\mathrm{sun}} m_p}{R_{\mathrm{sun}}} = -3.2\ \mathrm{keV}$$

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

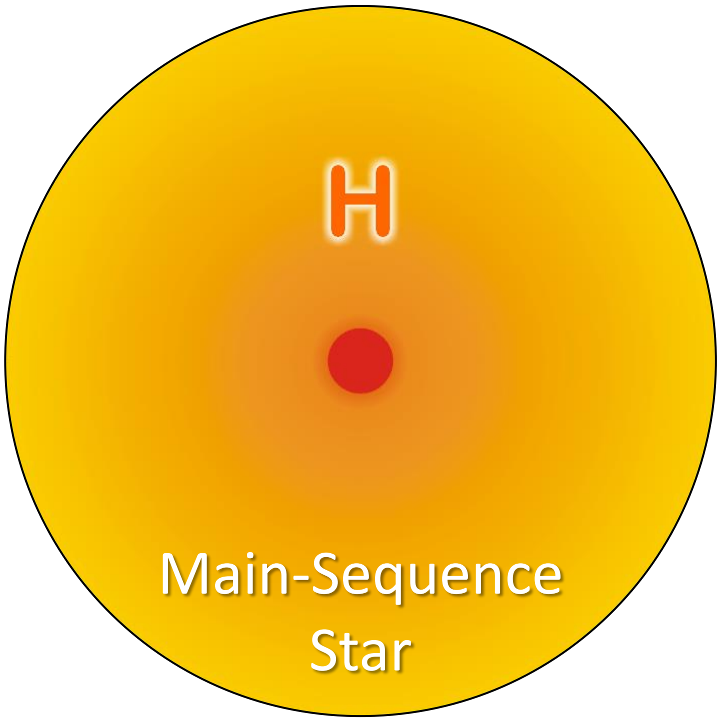
$$T = 1.1\ \mathrm{keV}$$



Central temperature from standard solar models

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

Self-Regulated Nuclear Burning



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

Small Contraction
$\to$ Heating
$\to$ Increased nuclear burning
$\to$ Increased pressure
$\to$ Expansion

Additional energy loss ("cooling")
$\to$ Loss of pressure
$\to$ Contraction
$\to$ Heating
$\to$ Increased nuclear burning

Hydrogen burning at nearly fixed T
$\to$ Gravitational potential nearly fixed:
$G_{\rm N} M/R \sim$ constant
$\to$ $R \propto M$ (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

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

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

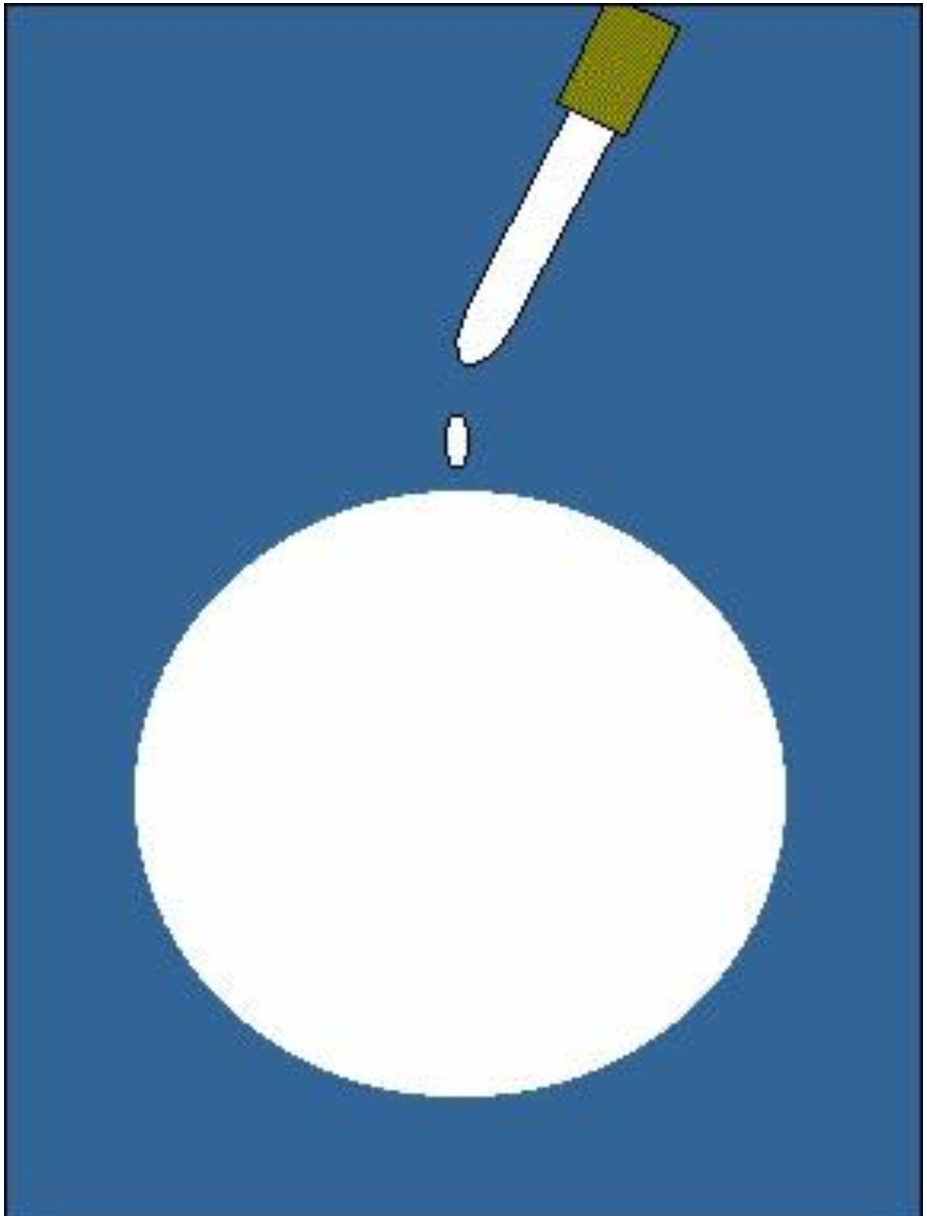
$$P \propto p_\mathrm{F}^4 \propto \rho^{4/3} \propto M^{4/3}R^{-4}$$

No stable configuration

Chandrasekhar mass limit

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

Degenerate Stars ("White Dwarfs")



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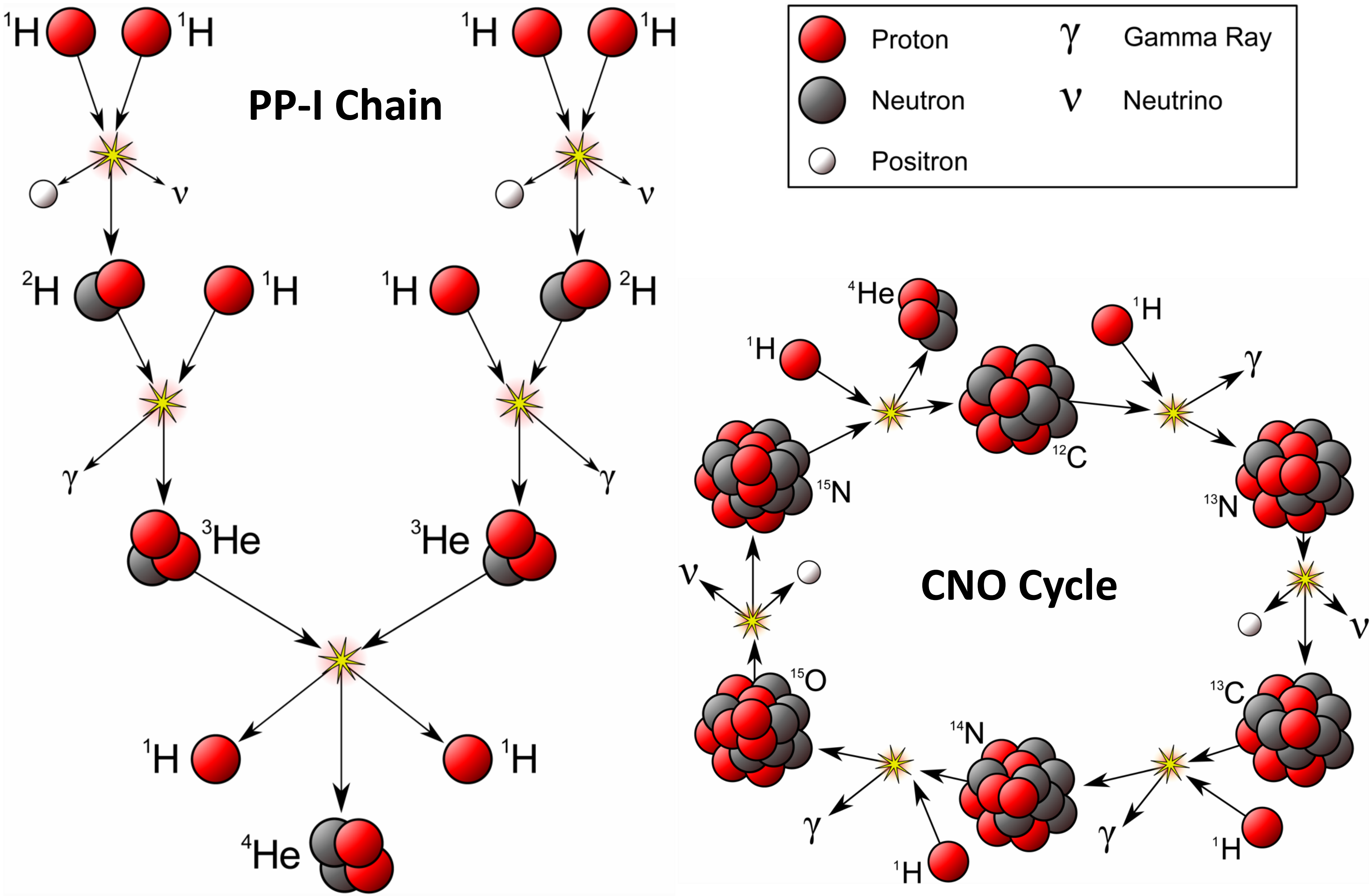
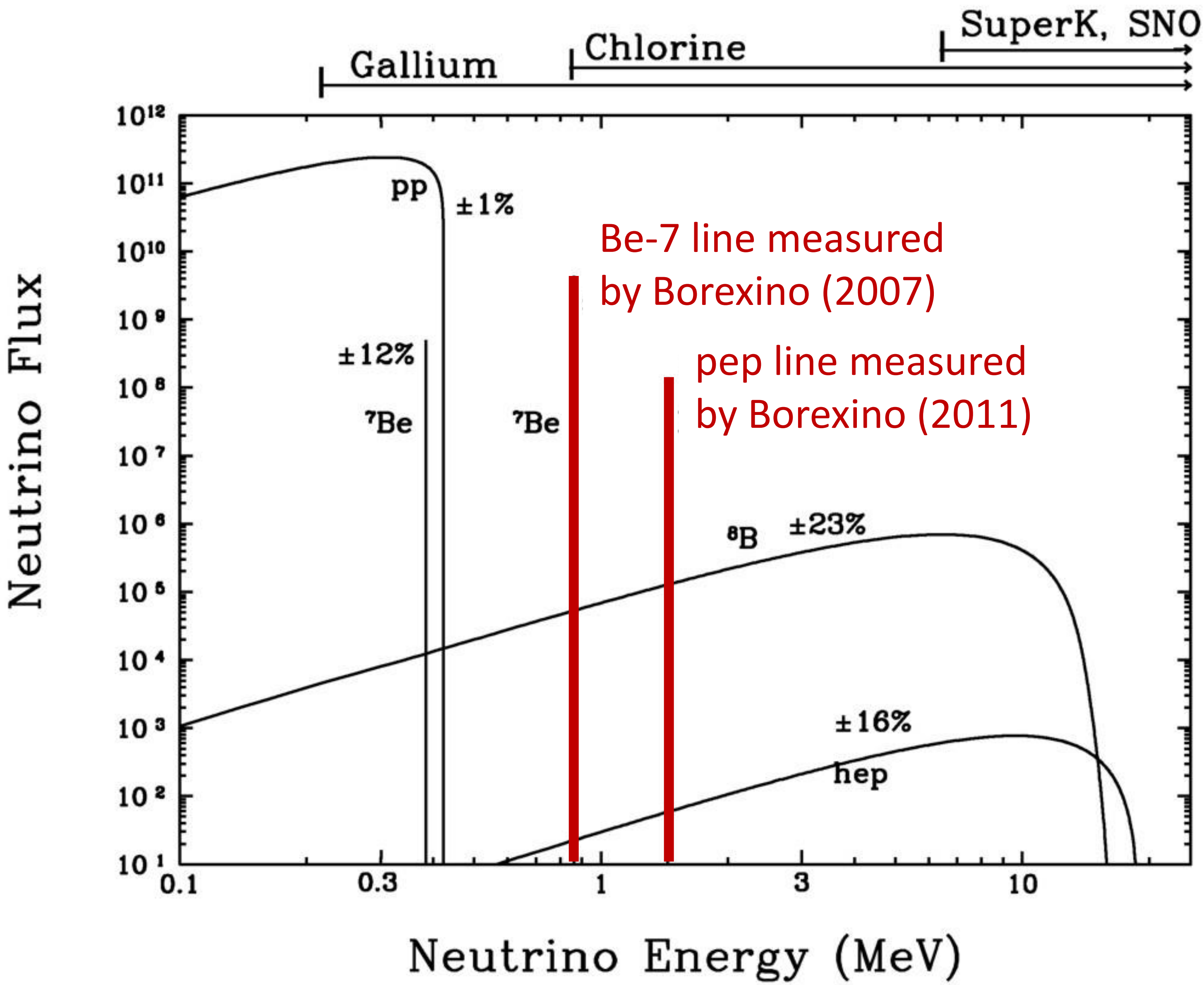
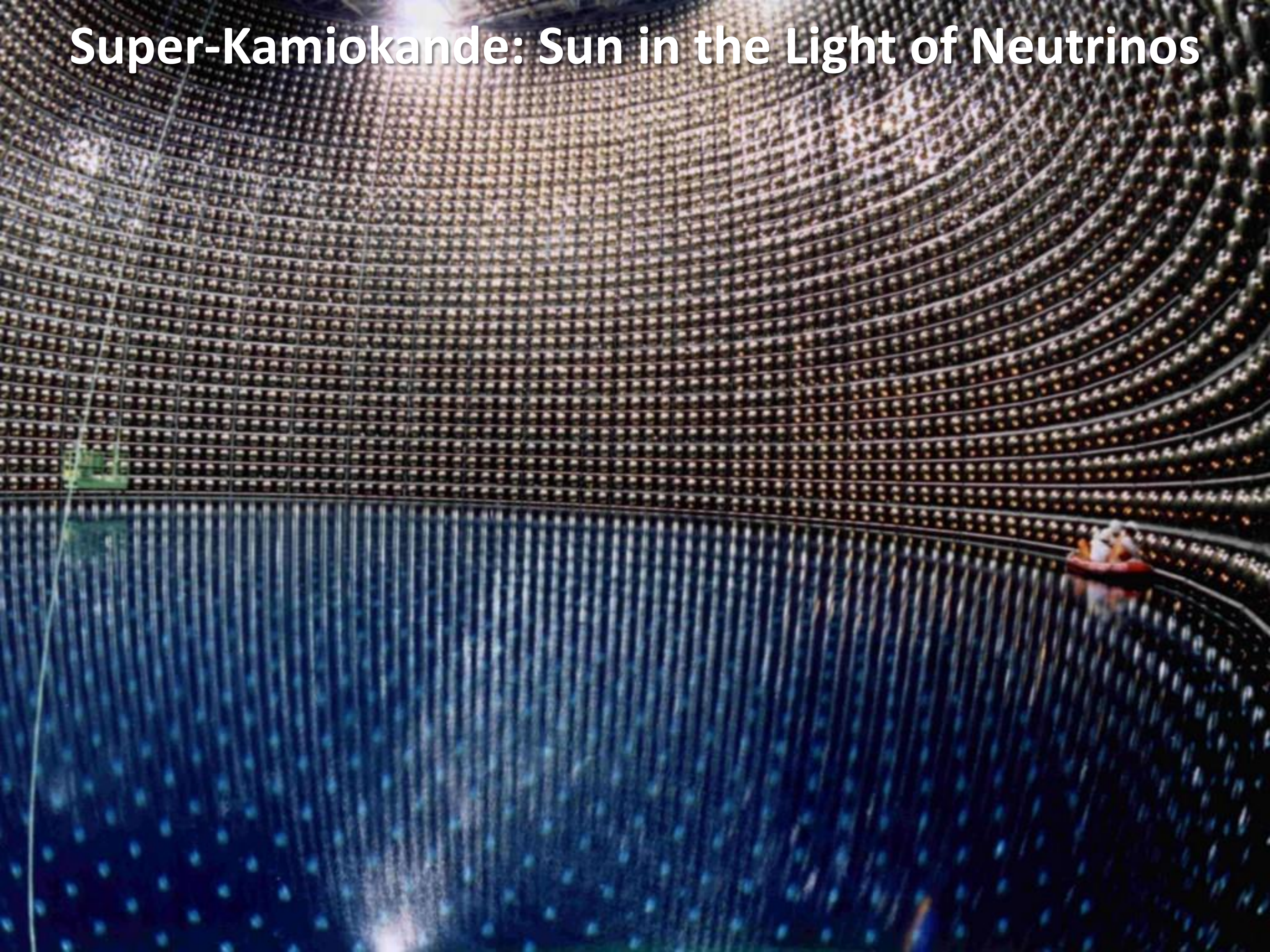
Hydrogen Burning



Solar Neutrino Spectrum



Super-Kamiokande: Sun in the Light of Neutrinos



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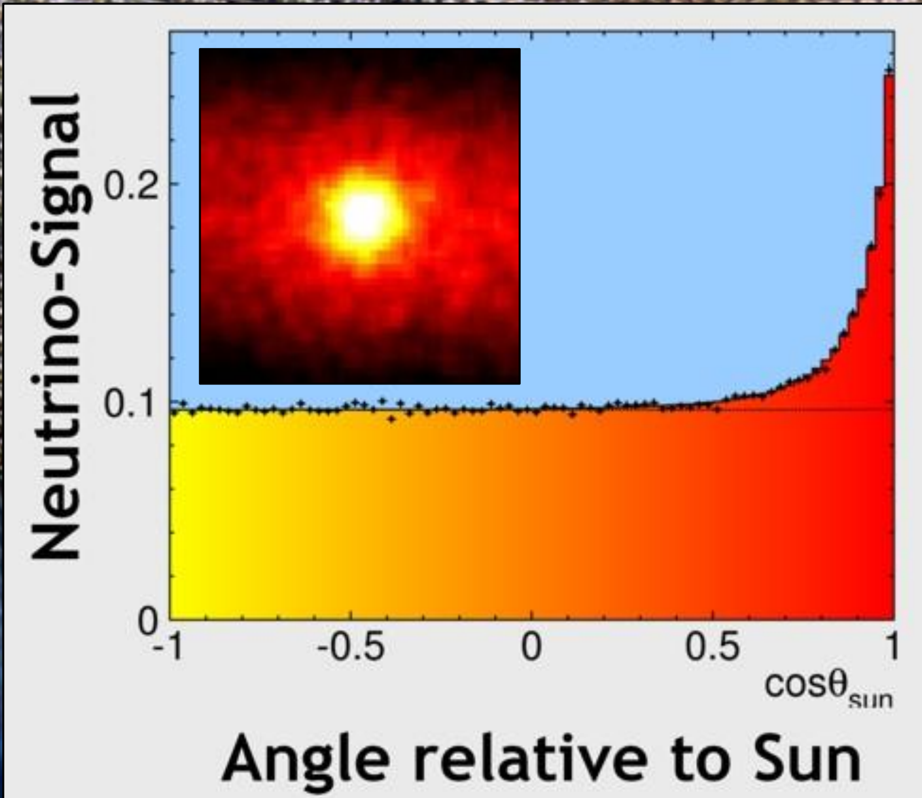
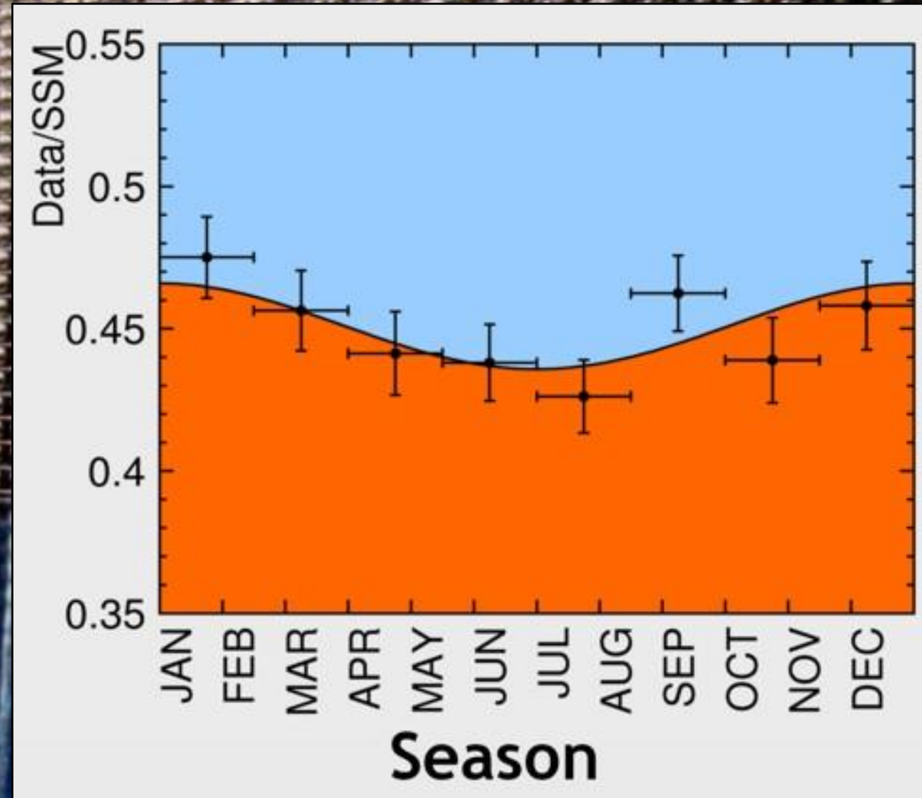
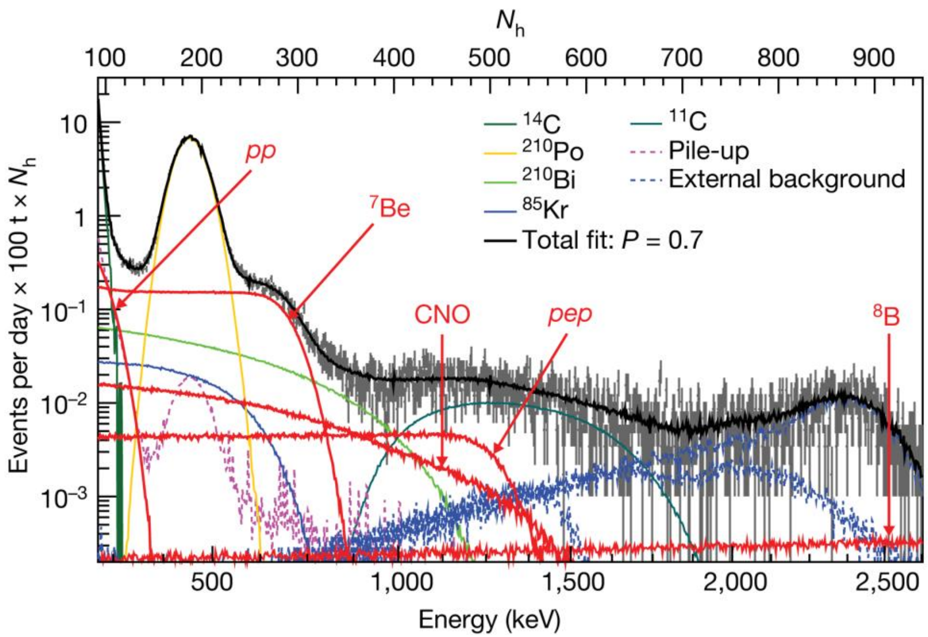
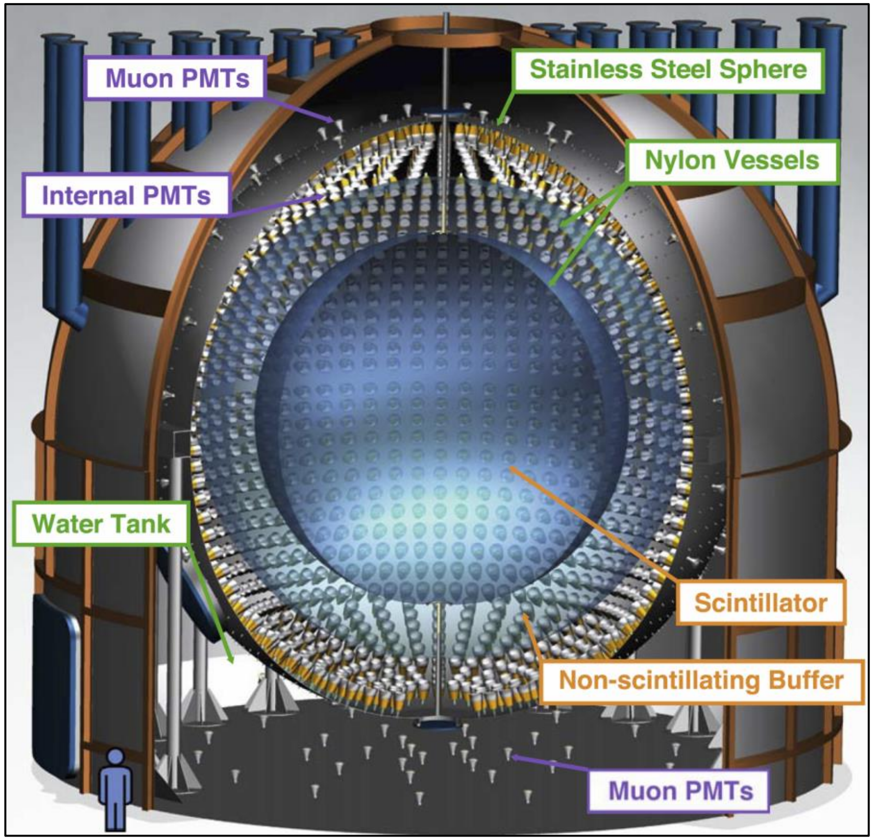


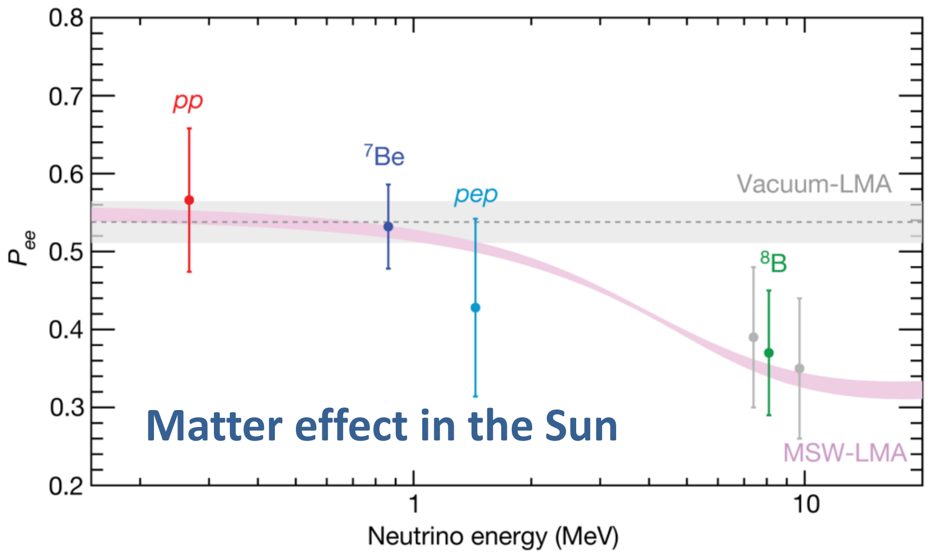


ca. 80,000 solar neutrinos measured in Super-K (1996–2016)

Solar Neutrino Spectroscopy with Borexino

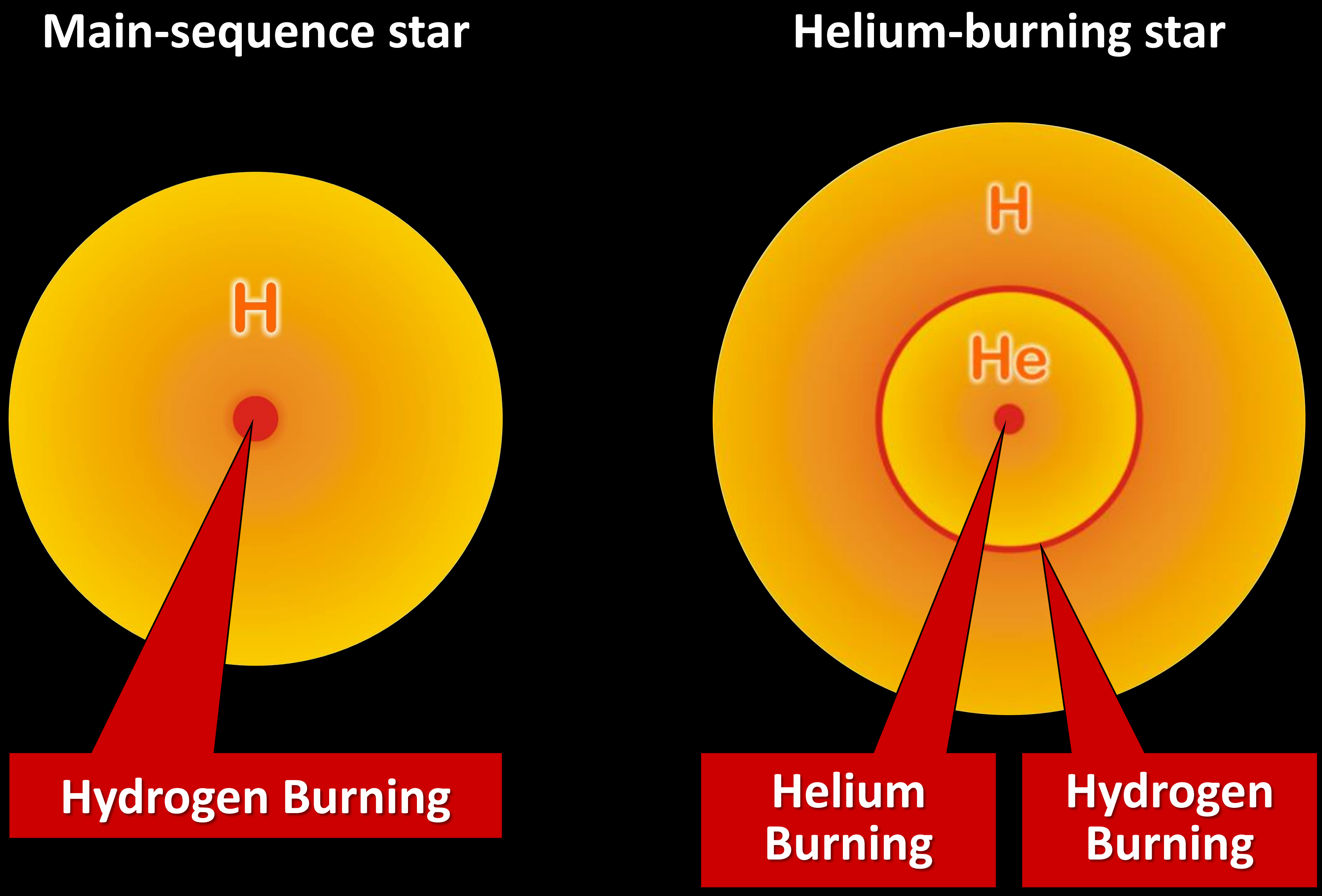




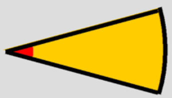
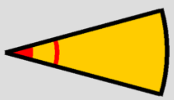
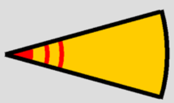
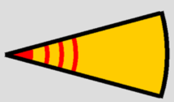
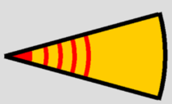
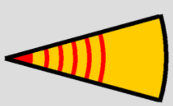


Borexino Collaboration:
Comprehensive measurement of pp-chain solar neutrinos
Nature 562 (2018) 505

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 $\rightarrow$ He	3	5.9	2.1	–	1.2×10^7
	Helium	He $\rightarrow$ C, O	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
	Carbon	C $\rightarrow$ Ne, Mg	53	1.7×10^5	8.6	1.0	6.3×10^3
	Neon	Ne $\rightarrow$ O, Mg	110	1.6×10^7	9.6	1.8×10^3	7.0
	Oxygen	O $\rightarrow$ Si	160	9.7×10^7	9.6	2.1×10^4	1.7
	Silicon	Si $\rightarrow$ Fe, Ni	270	2.3×10^8	9.6	9.2×10^5	6 days

Neutrinos from Thermal Processes

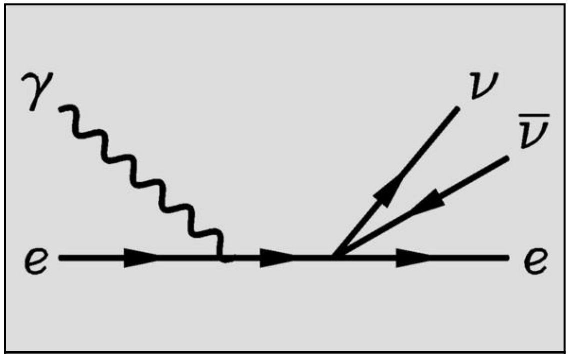
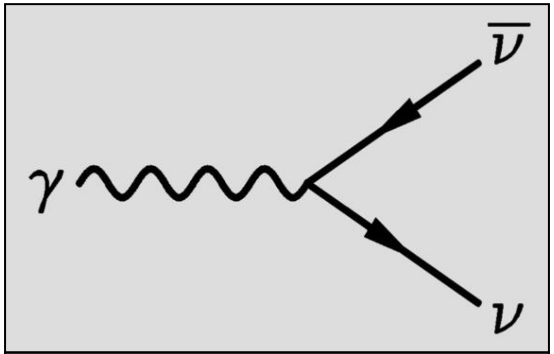
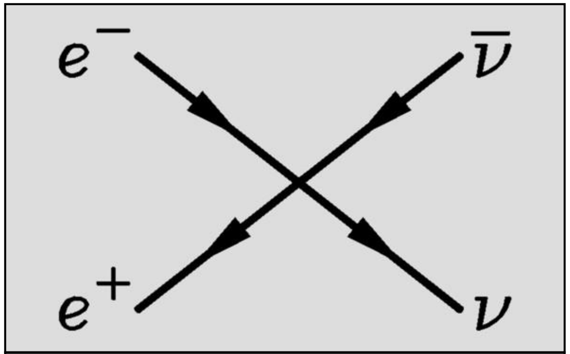


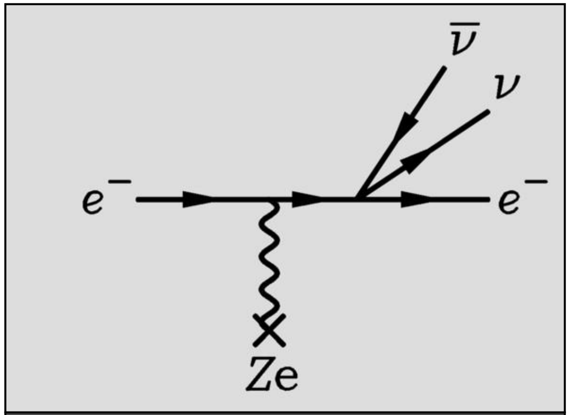
Photo (Compton)



Plasmon decay

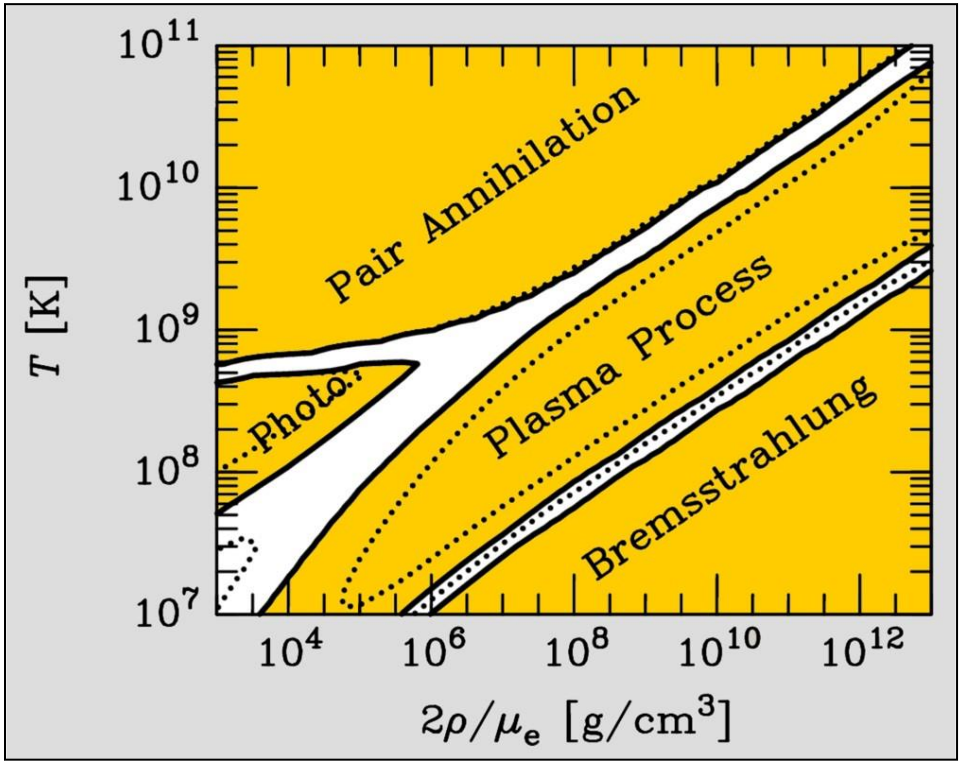


Pair annihilation



Bremsstrahlung

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



Neutrinos from Thermal Processes

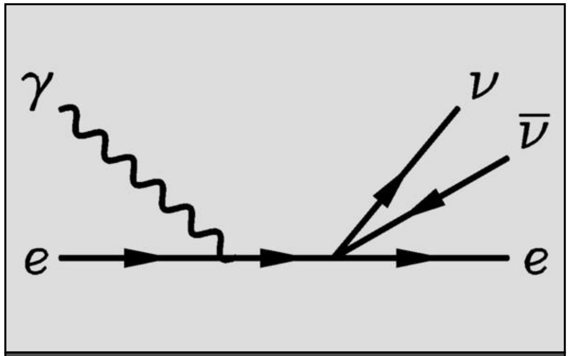
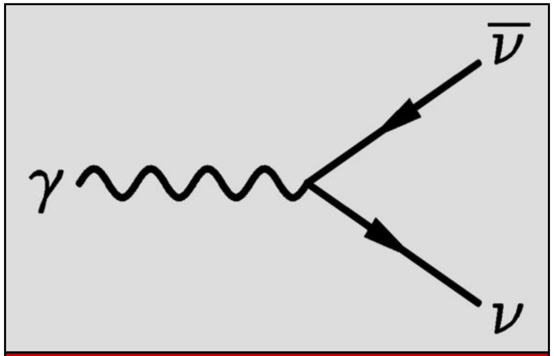
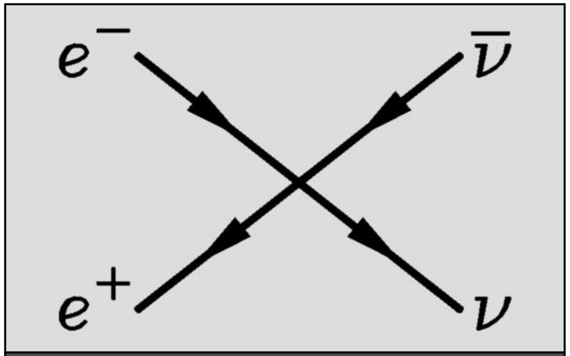


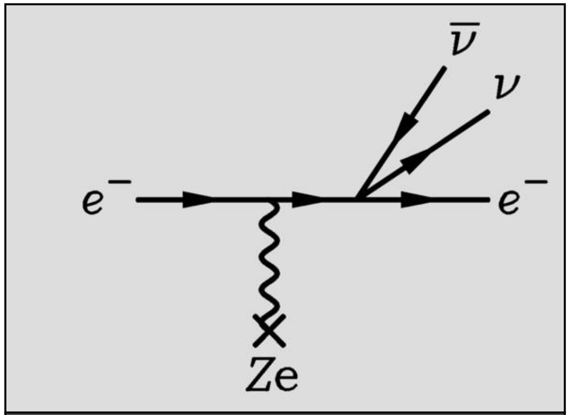
Photo (Compton)



Plasmon decay

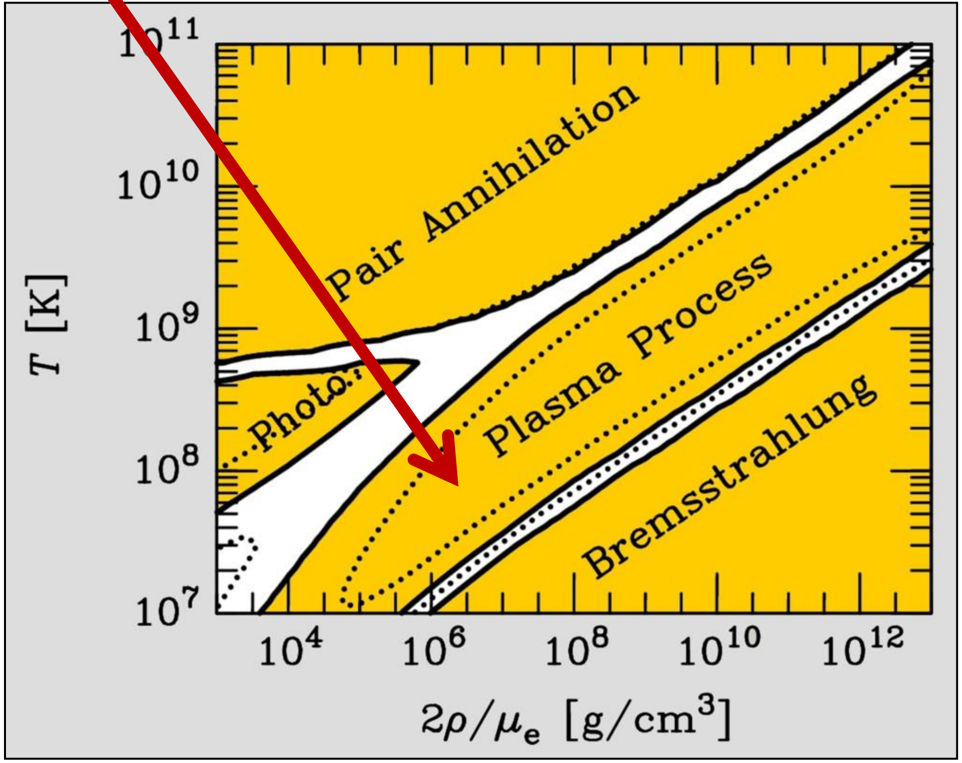


Pair annihilation

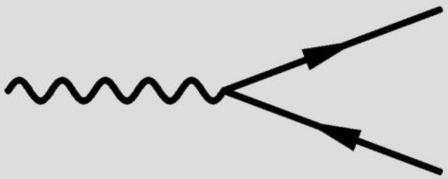
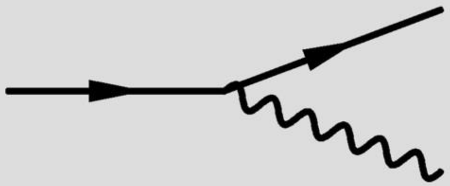


Bremsstrahlung

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

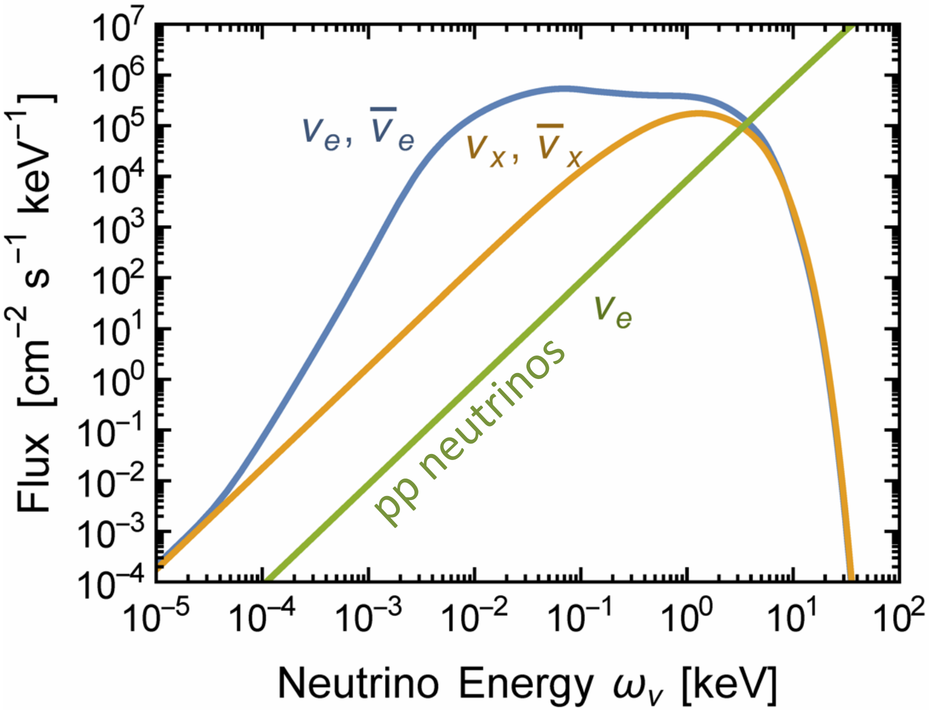


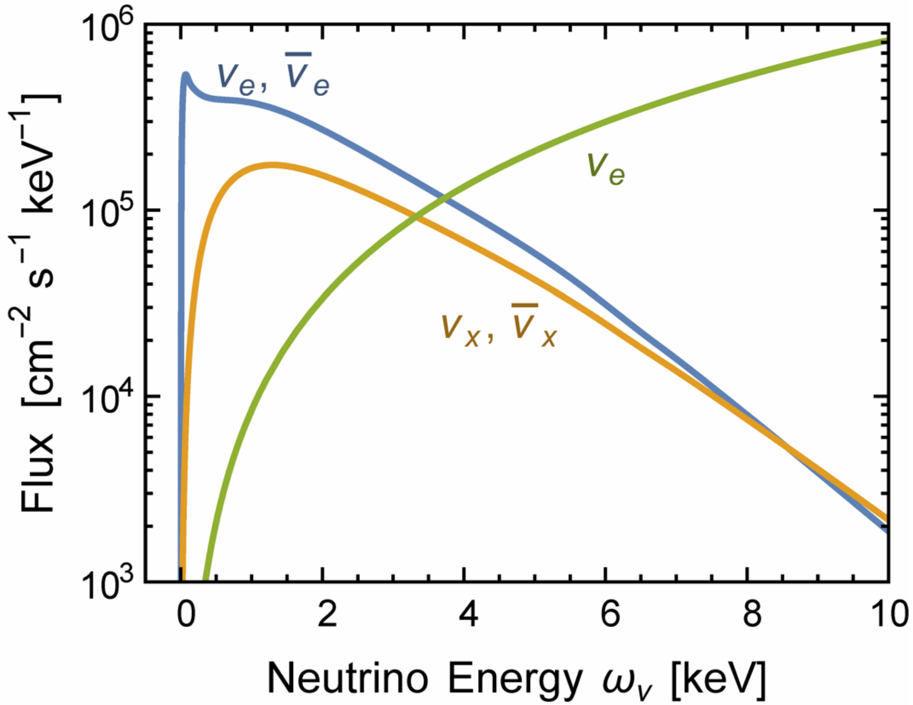
Plasmon Decay vs. Cherenkov Effect

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 $e \to e + \gamma$ 

Solar neutrino flux at keV energies

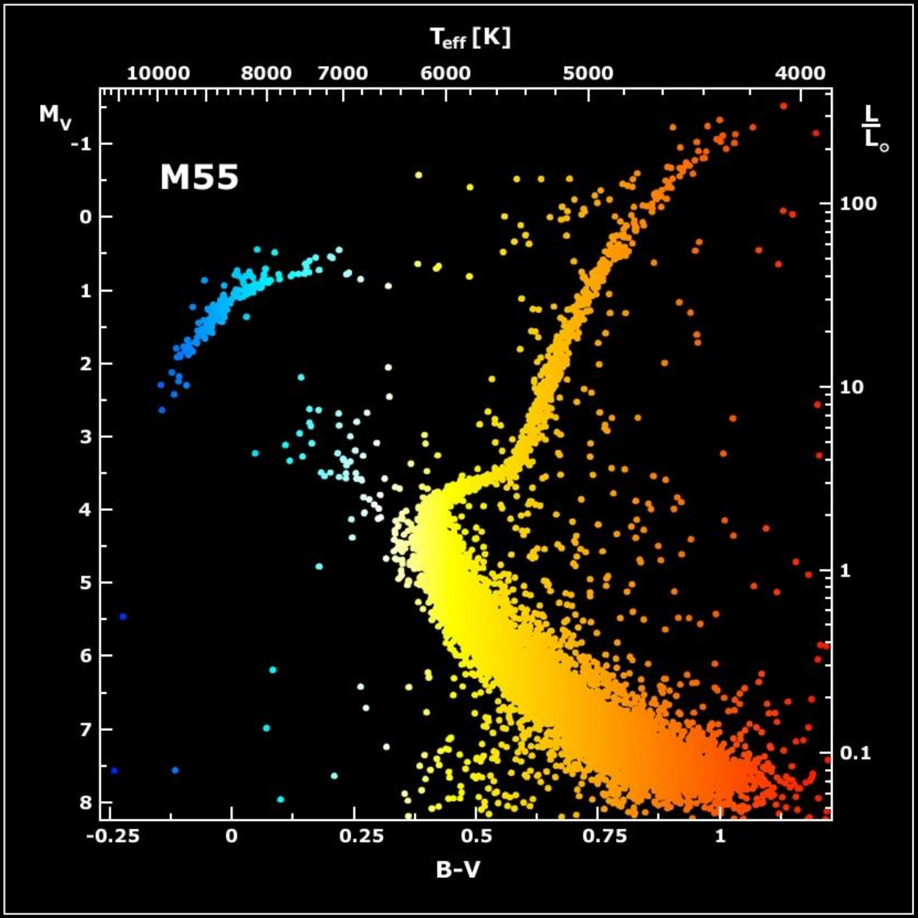
- Thermally produced neutrinos and antineutrinos dominate at keV energies
- Future detection opportunities?



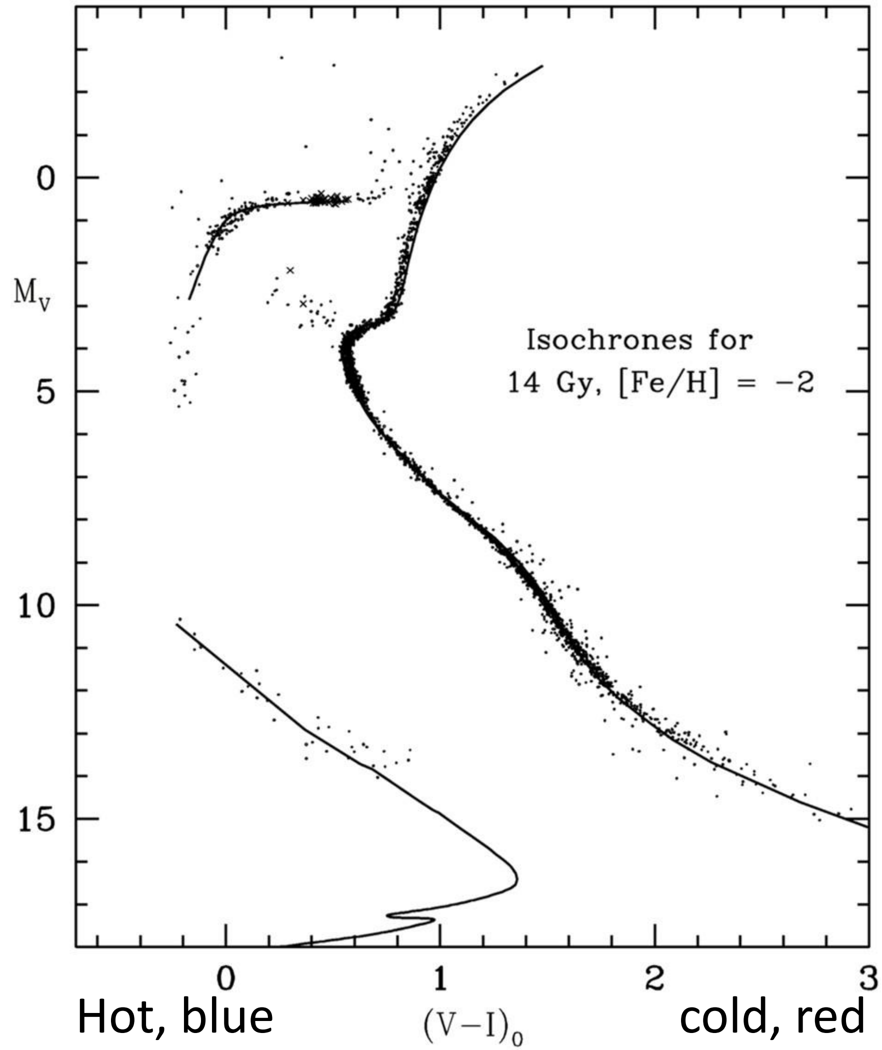


Vitagliano, Raffelt & Redondo, *JCAP 1712 (2017) 010* [arXiv:1708.02248]

Galactic Globular Cluster M55



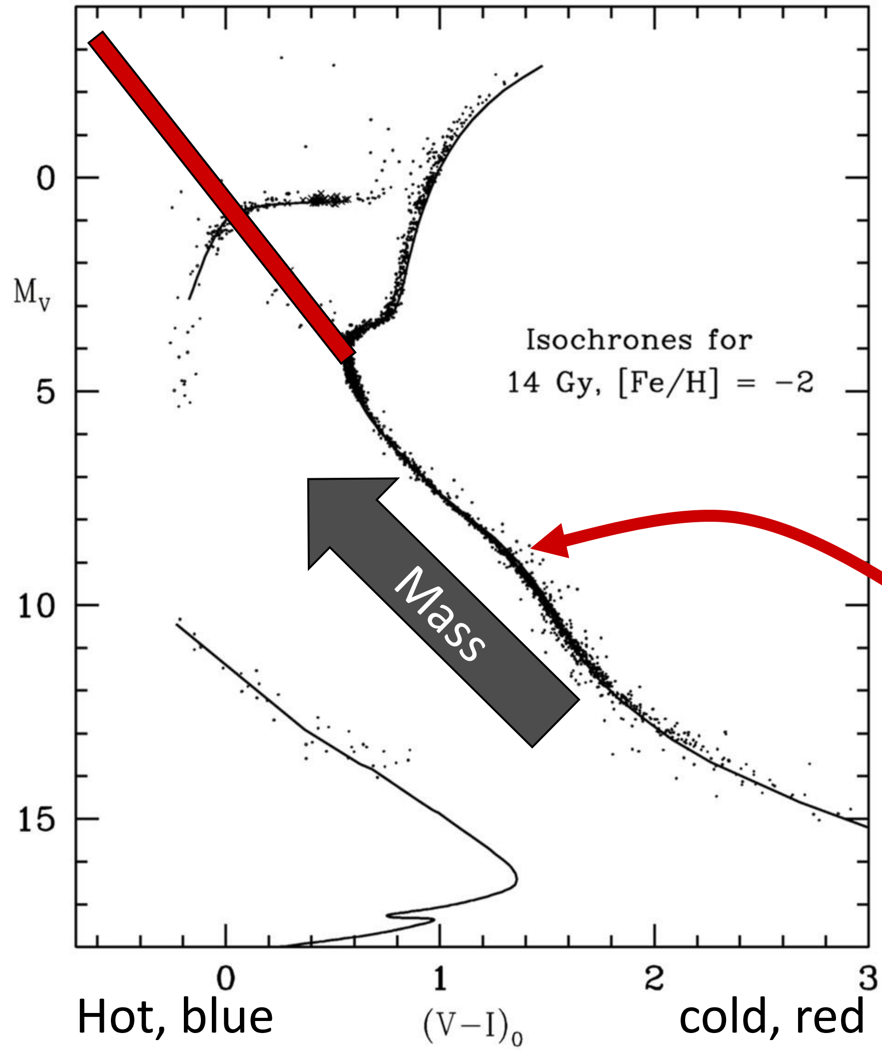
Color-Magnitude Diagram for Globular Clusters

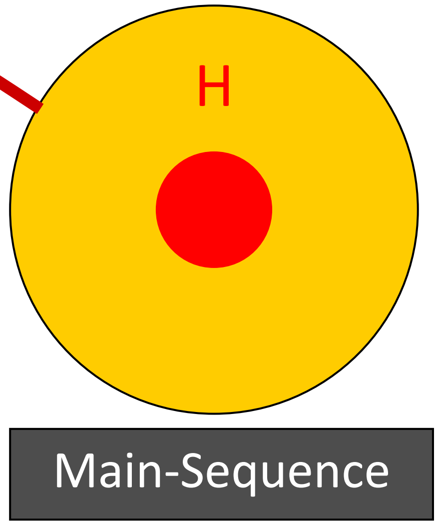


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters

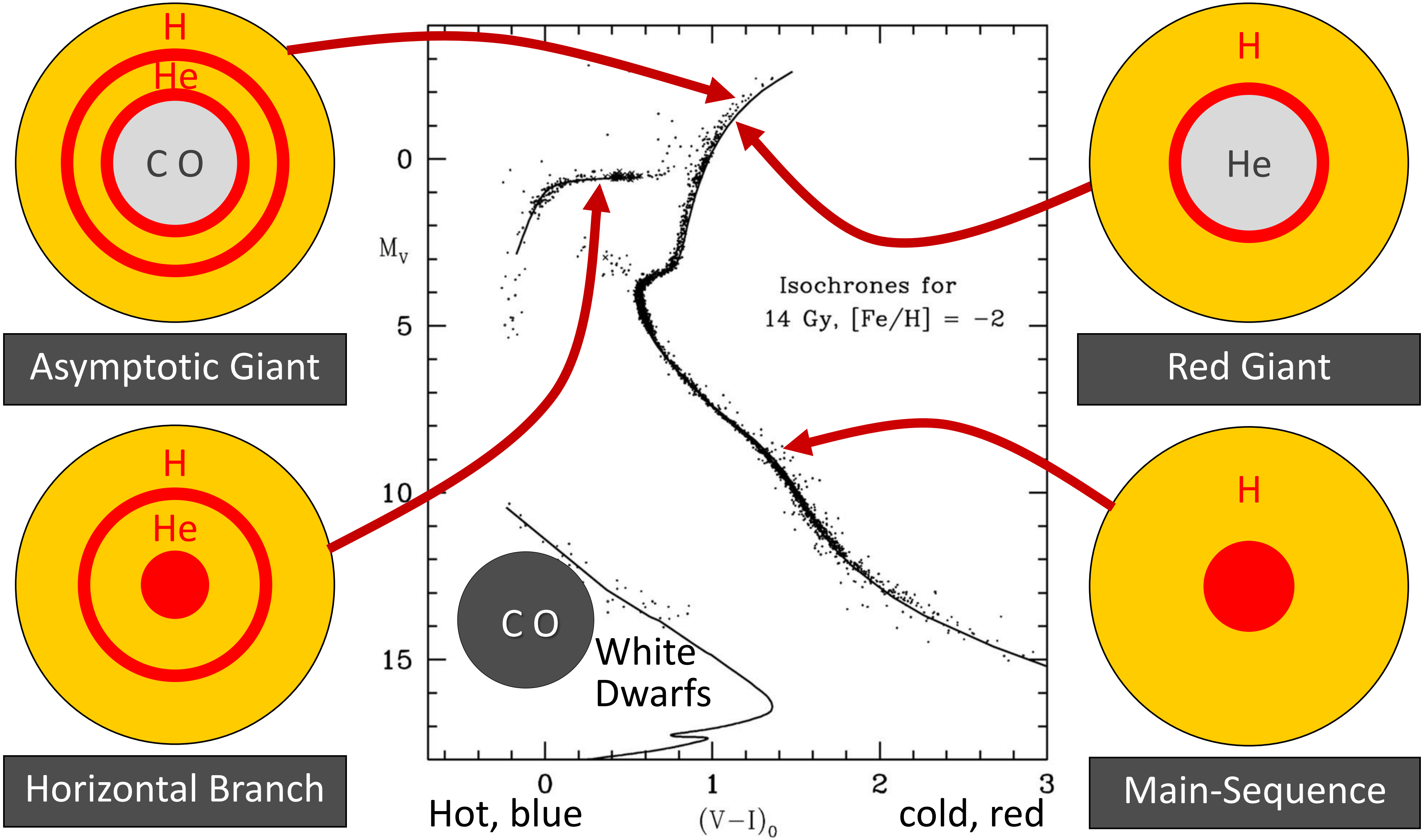
- Stars with M so large that they have burnt out in a Hubble time
- No new star formation in globular clusters





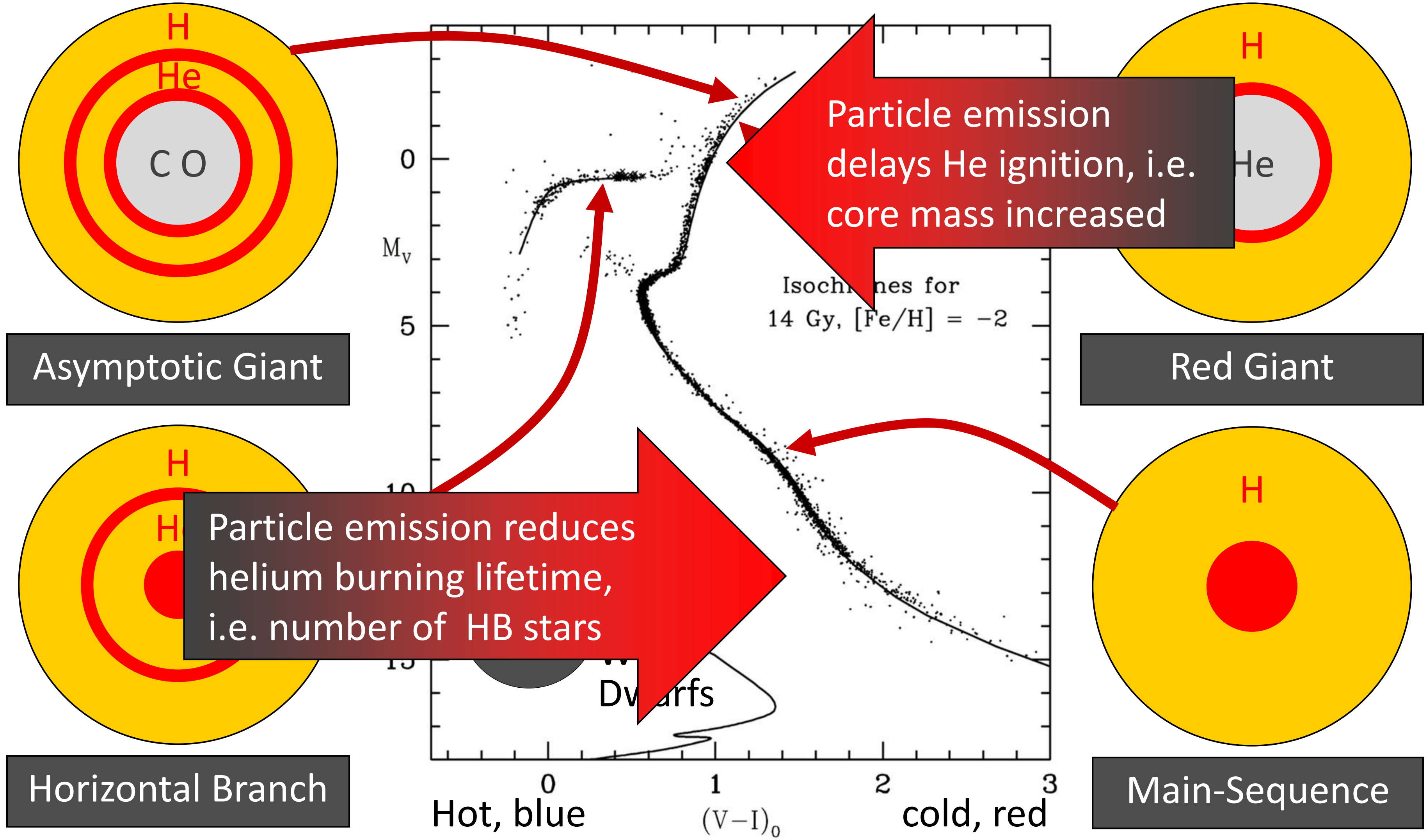
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters



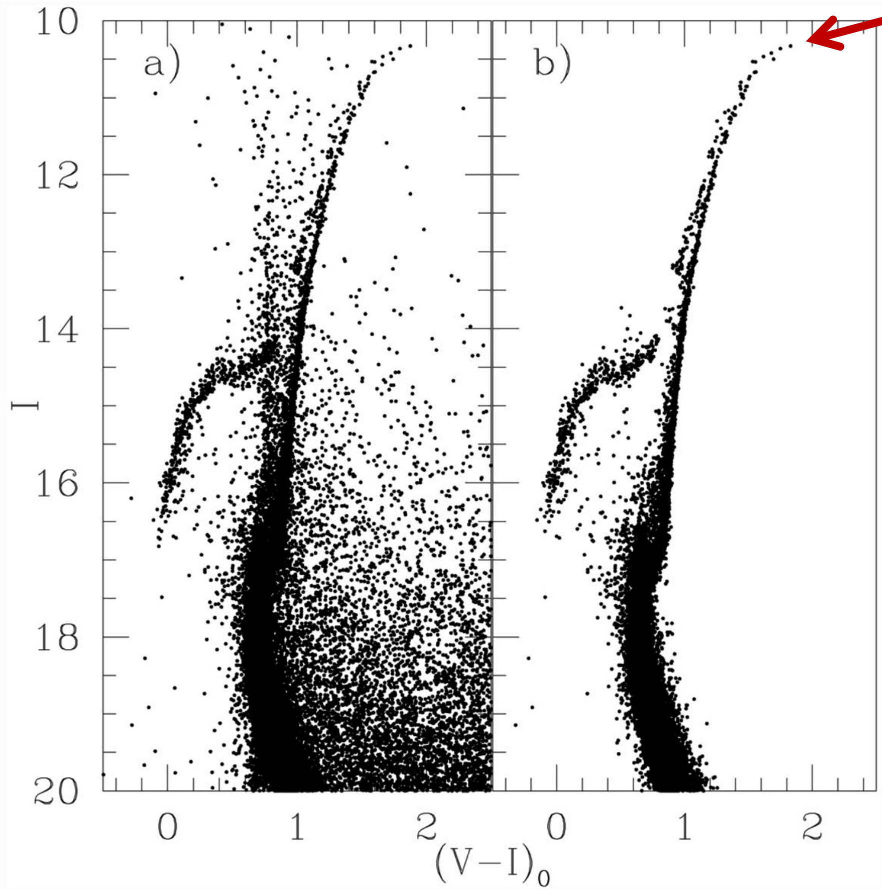
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters

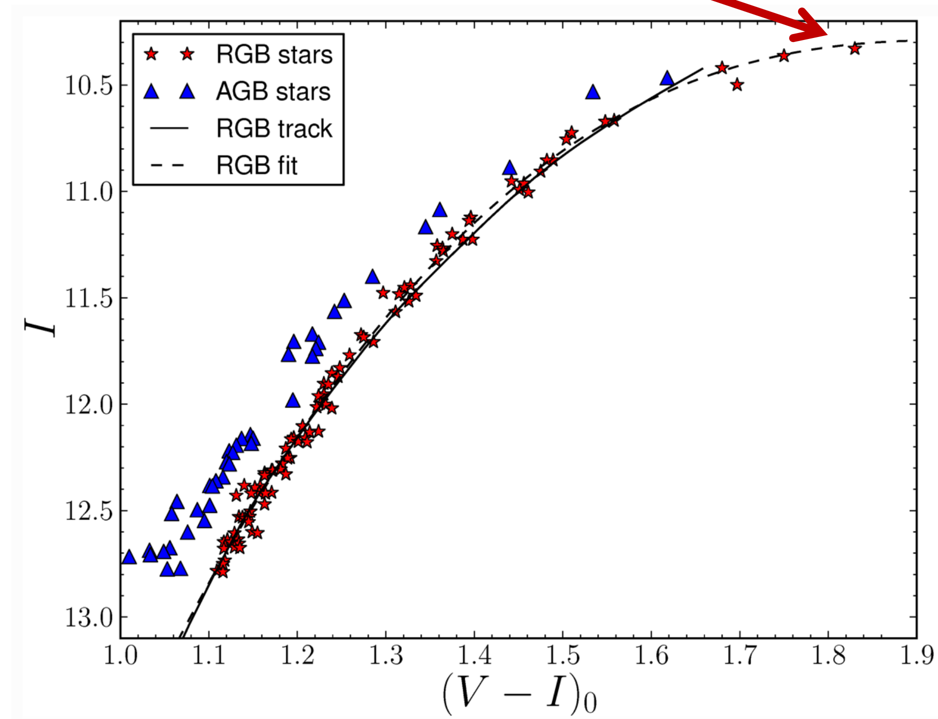


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram of Globular Cluster M5



Brightest red giant measures nonstandard energy loss



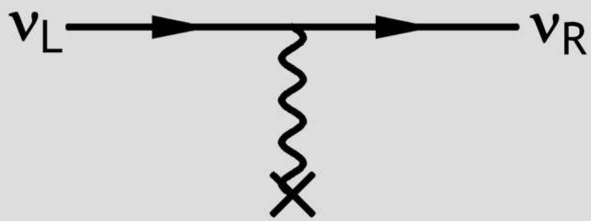
CMD (a) before and (b) after cleaning

CMD of brightest 2.5 mag of RGB

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

Consequences of Neutrino Dipole Moments

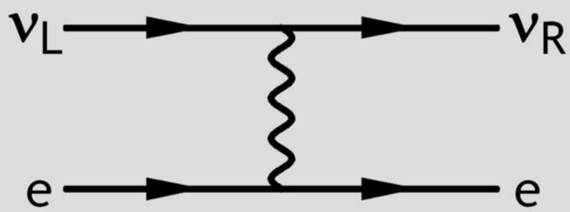
Spin precession in external E or B fields



$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix} = \begin{pmatrix}0 & \mu_\nu B_\perp\\ \mu_\nu B_\perp & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix}$$

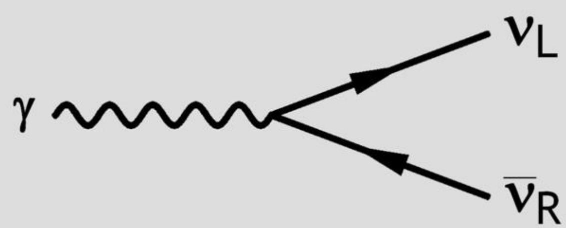
Scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(C_\mathrm{V}+C_\mathrm{A})^2 + (C_\mathrm{V}-C_\mathrm{A})^2\left(1-\frac{T}{E}\right)^2 + (C_\mathrm{V}^2 - C_\mathrm{A}^2)\frac{m_e T}{E^2}\right] + \alpha\mu_\nu^2\left(\frac{1}{T}+\frac{1}{E}\right)$$



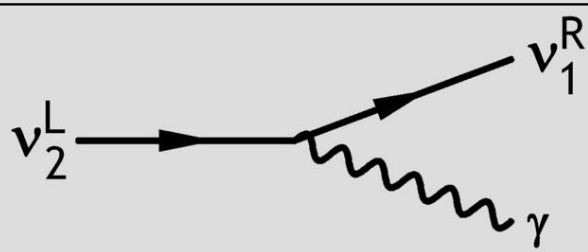
T electron recoil energy

Plasmon decay in stars



$$\Gamma = \frac{\mu_\nu^2}{24\pi}\,\omega_\mathrm{pl}^3$$

Decay or Cherenkov effect

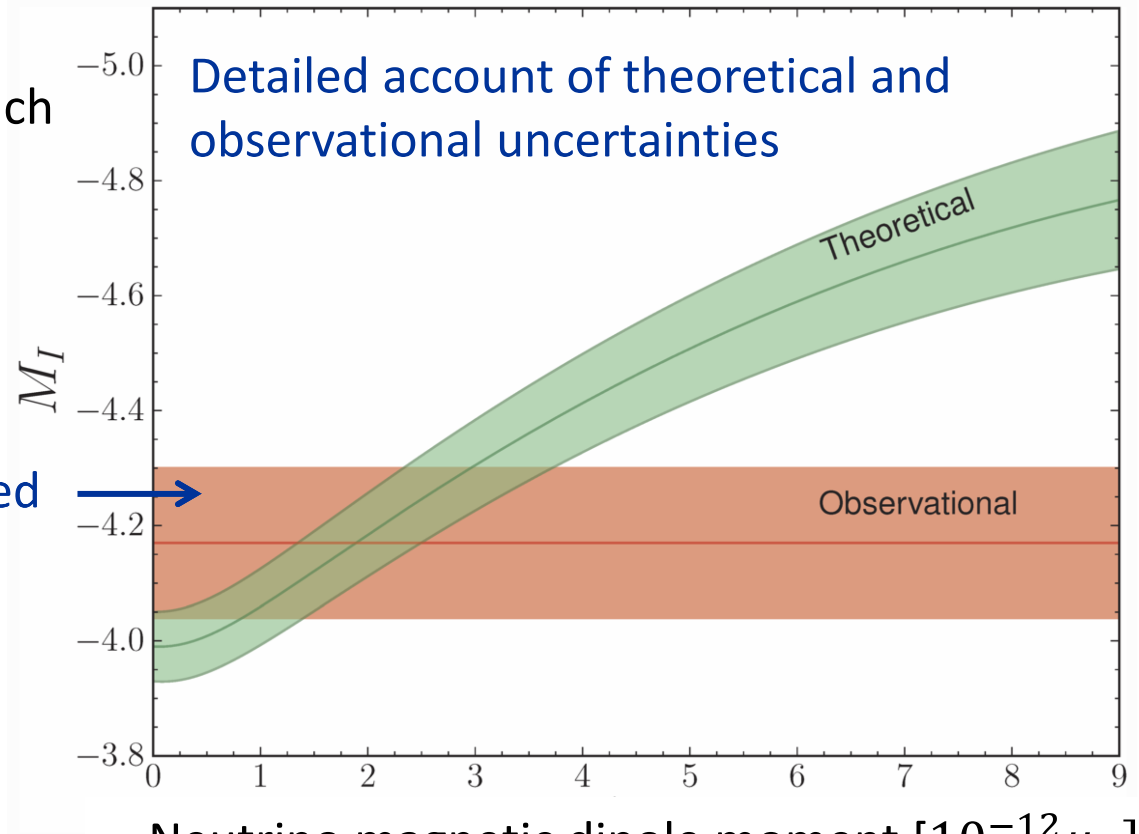


$$\Gamma = \frac{\mu_\nu^2}{8\pi}\left(\frac{m_2^2 - m_1^2}{m_2}\right)^3$$

Neutrino 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

PHYSICAL REVIEW D VOLUME 18, NUMBER 6 15 SEPTEMBER 1978

Astrophysical bounds on the masses of axions and Higgs particles

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(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

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

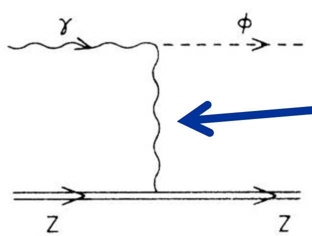
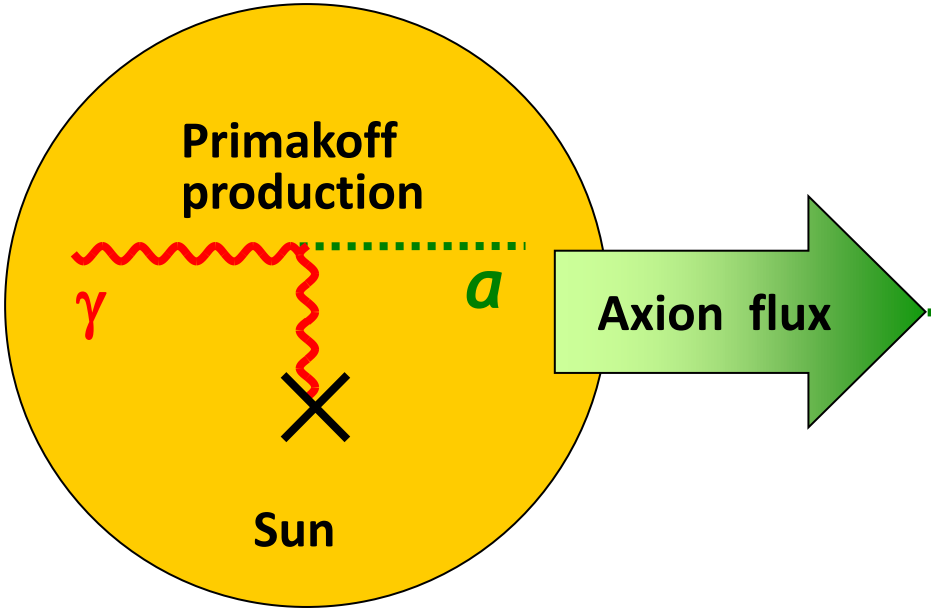


FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

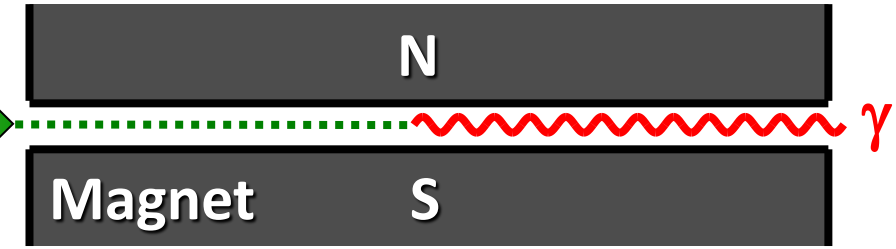
First discussion of Primakoff effect for WW axions ($m_a \gg T$)

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

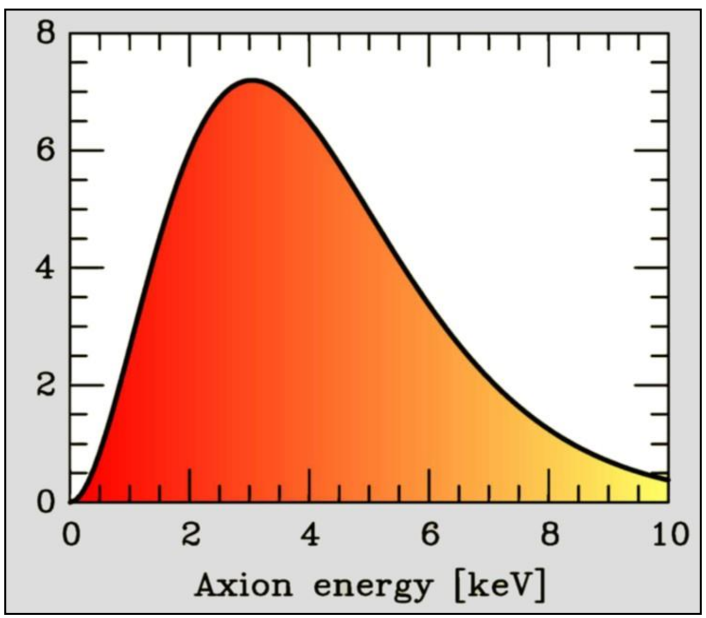
Search for Solar Axions



Axion Helioscope (Sikivie 1983)



Axion-Photon-Oscillation

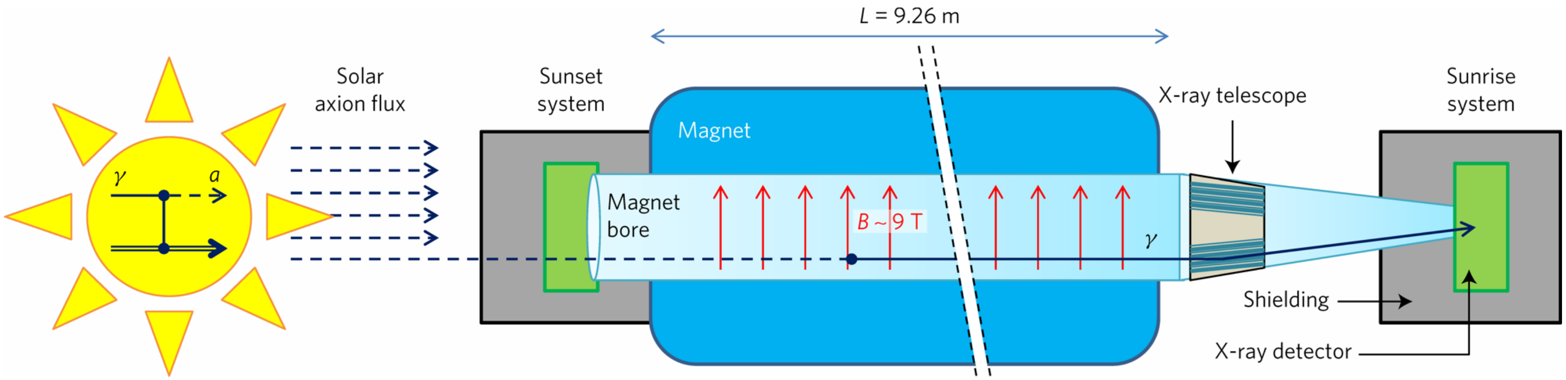


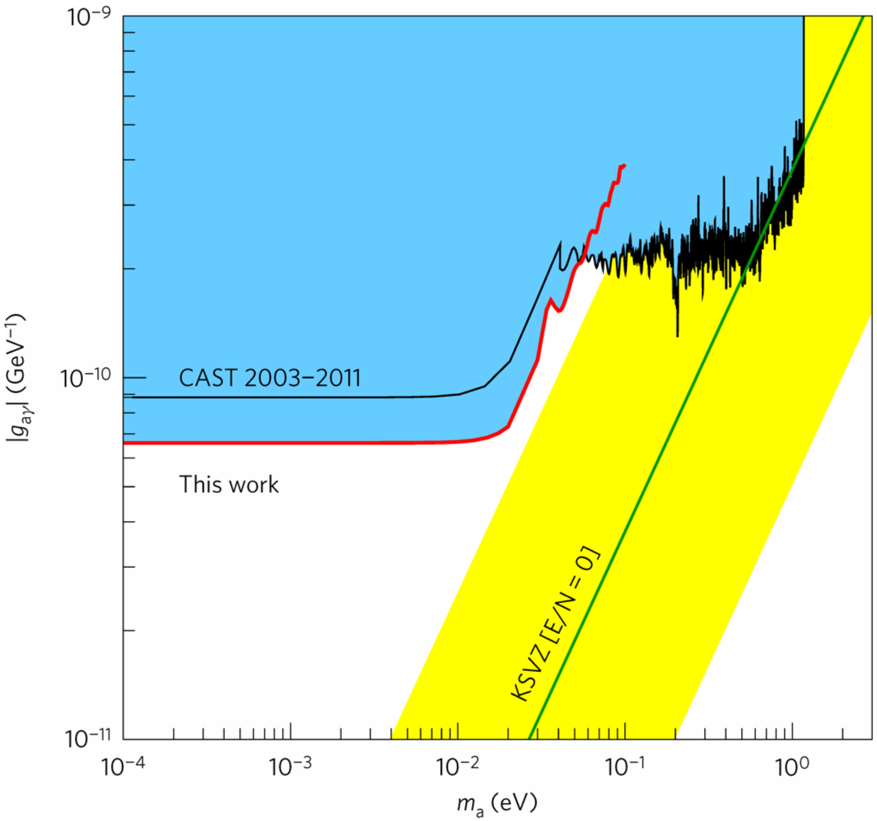
- Tokyo Axion Helioscope ("Sumico") (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

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)

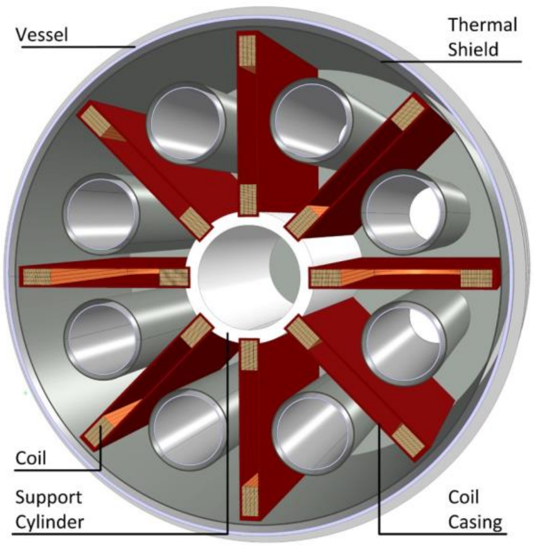
Helioscope Limits

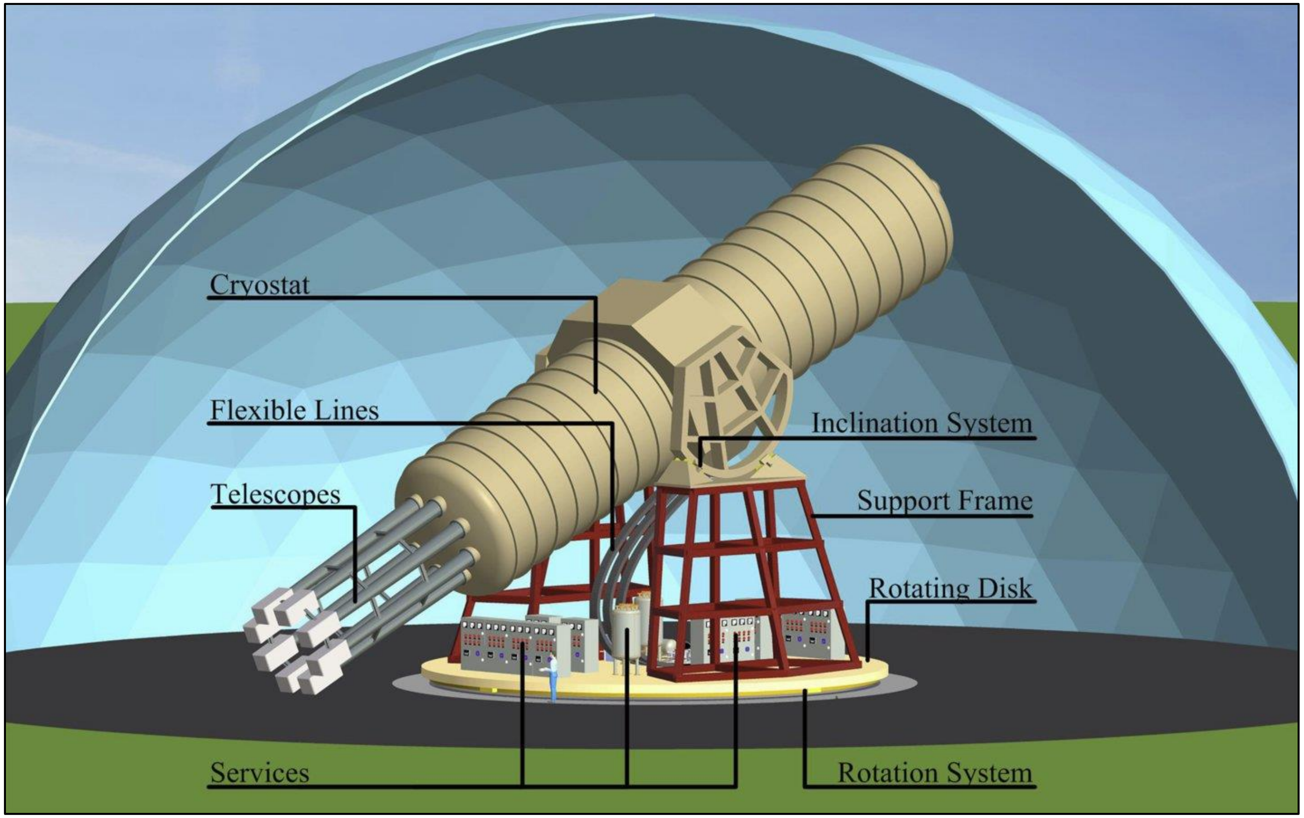




Latest CAST limits on
axion-photon interaction
Nature Physics 13 (2017) 584
arXiv:1705.02290

Next Generation Axion Helioscope (IAXO)



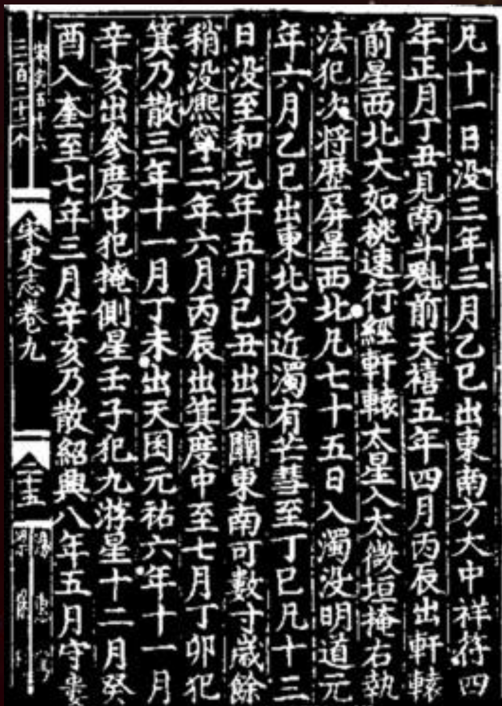


Need new magnet w/
- Much bigger aperture: $\sim 1\ \mathrm{m}^2$ per bore
- Lighter (no iron yoke)
- Bores at T_{room}

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

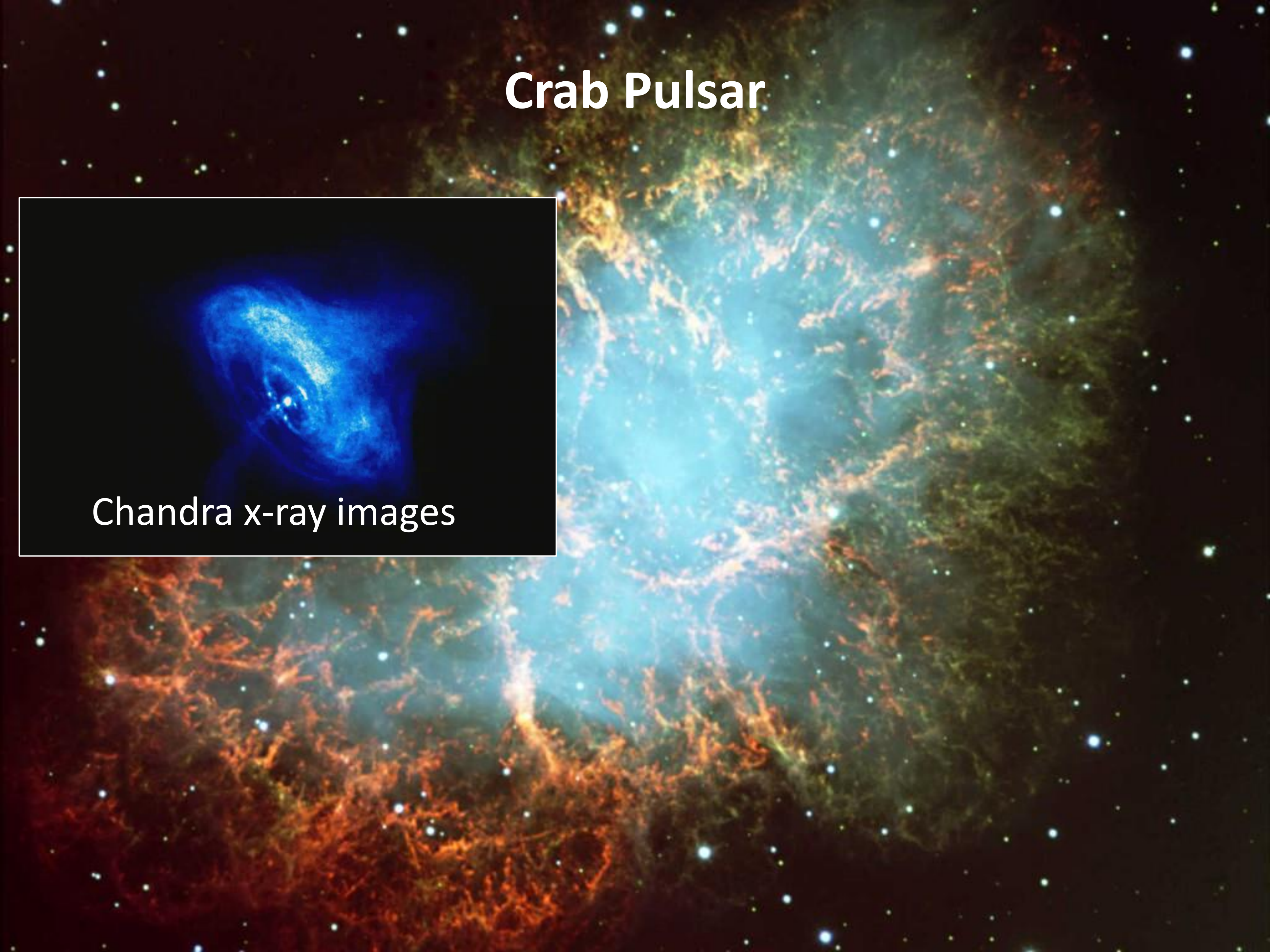
Supernova Neutrinos

Crab Nebula – Remnant of SN 1054

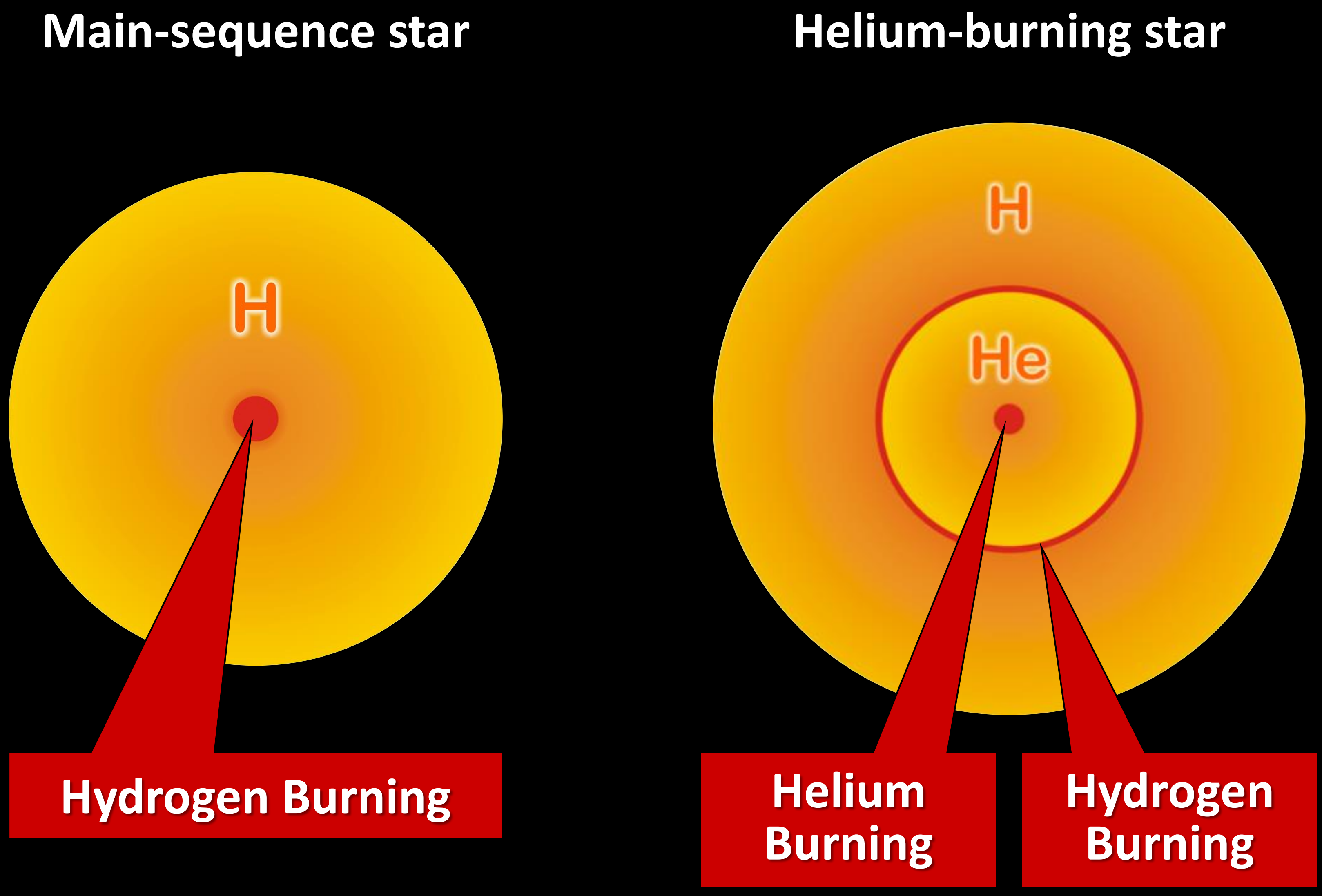


凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

Crab Pulsar

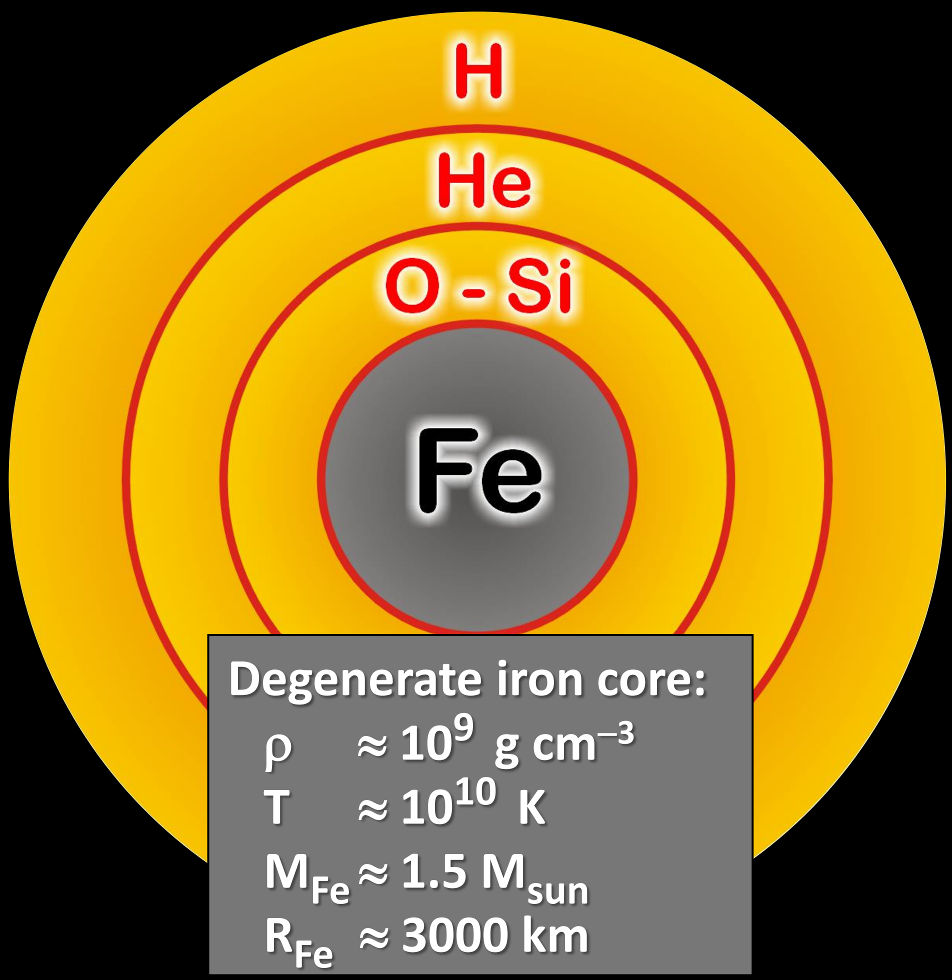


Stellar Collapse and Supernova Explosion

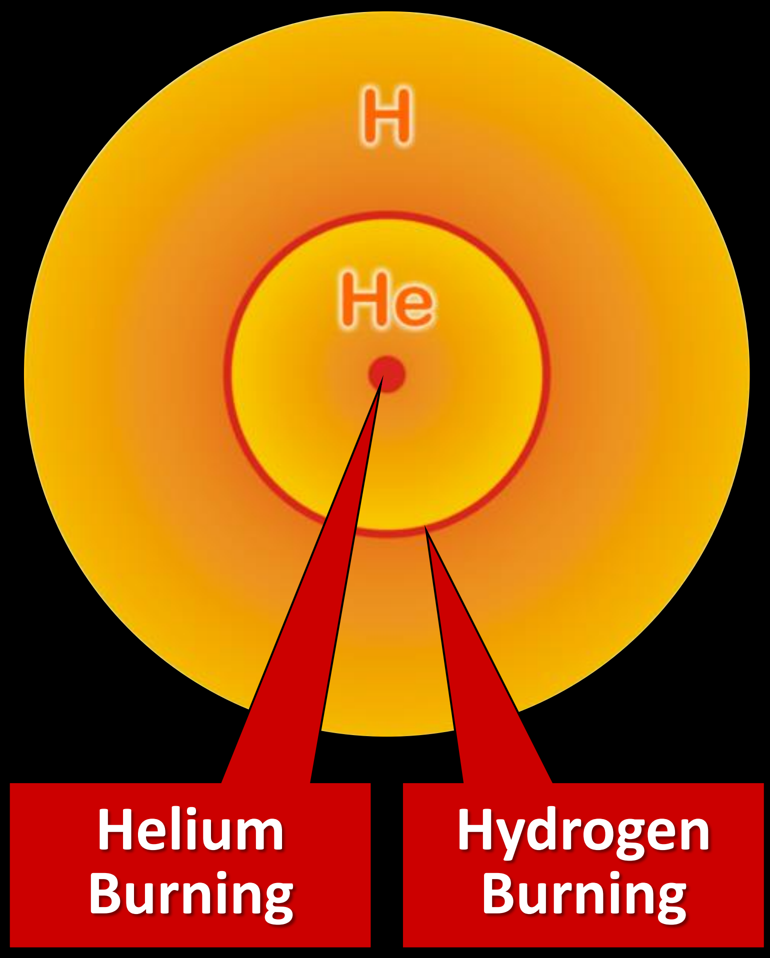


Stellar Collapse and Supernova Explosion

Onion structure

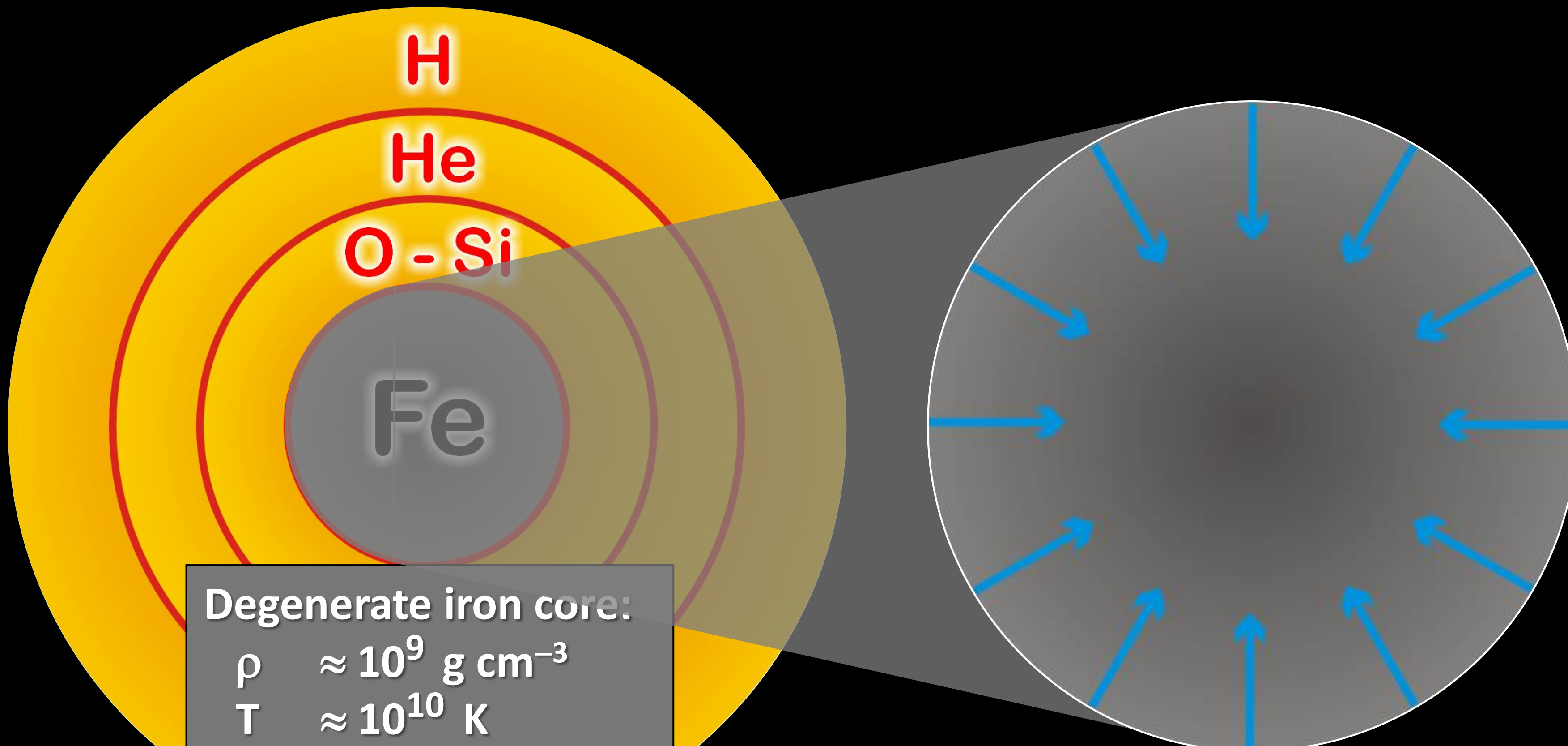


Helium-burning star



Stellar Collapse and Supernova Explosion

Onion structure | **Collapse (implosion)**



Degenerate iron core:

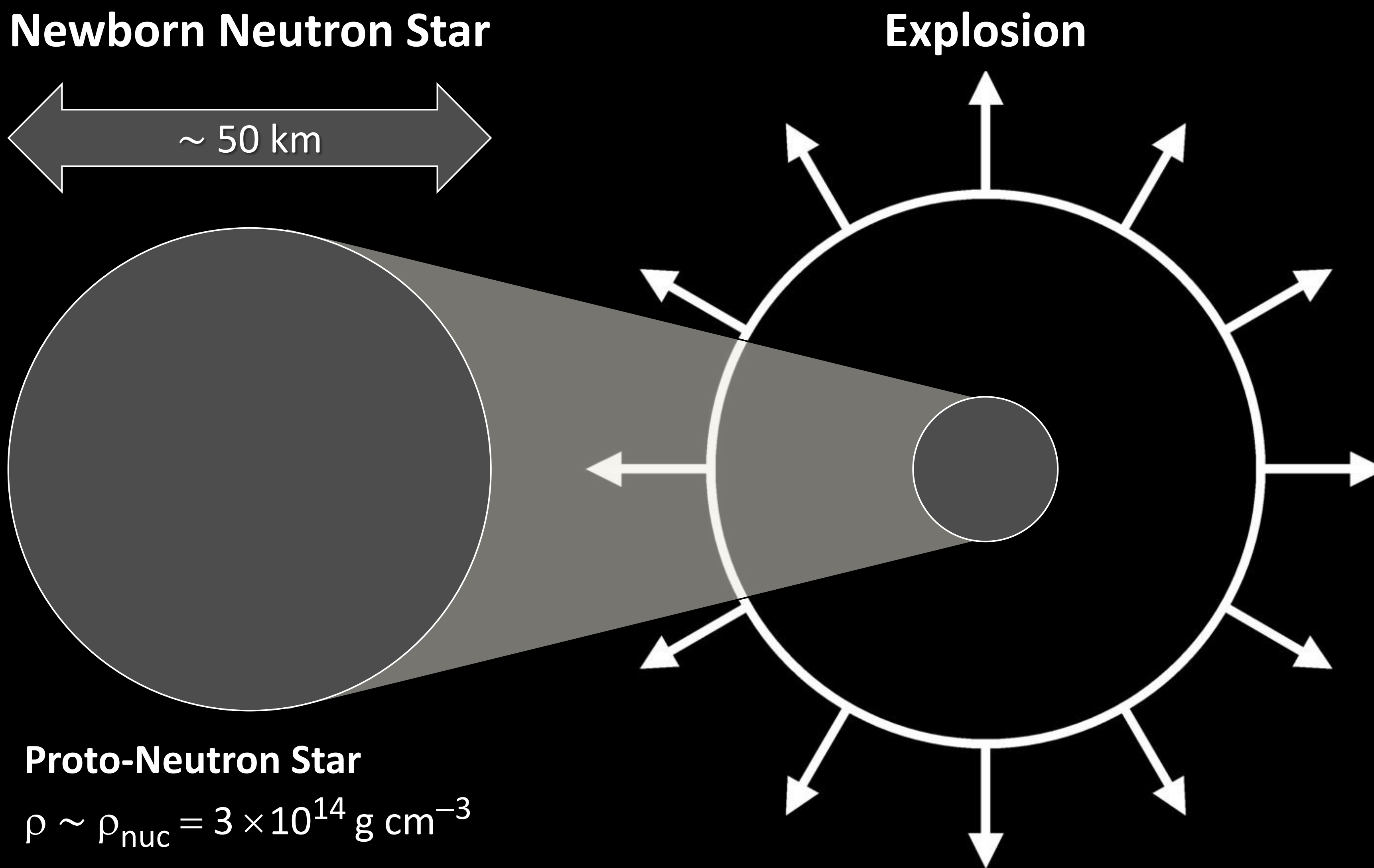
$\rho \approx 10^9\ \mathrm{g\ cm^{-3}}$

$T \approx 10^{10}\ \mathrm{K}$

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 3000\ \mathrm{km}$

Stellar Collapse and Supernova Explosion



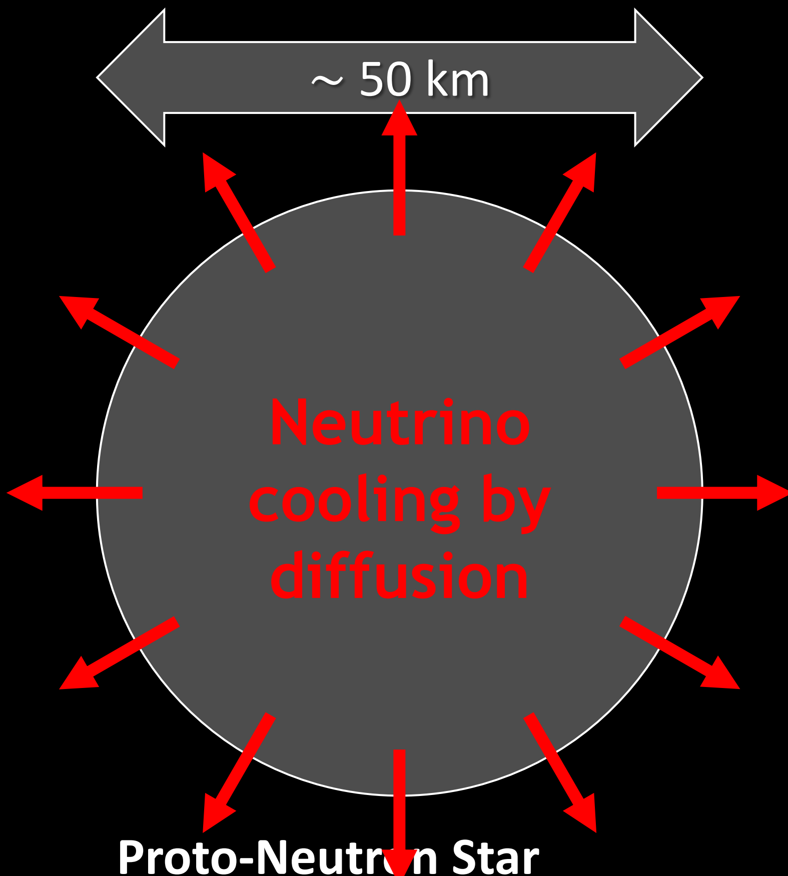
Proto-Neutron Star

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

$T \sim 10\ \mathrm{MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

$T \sim 10$ MeV

Gravitational binding energy

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

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

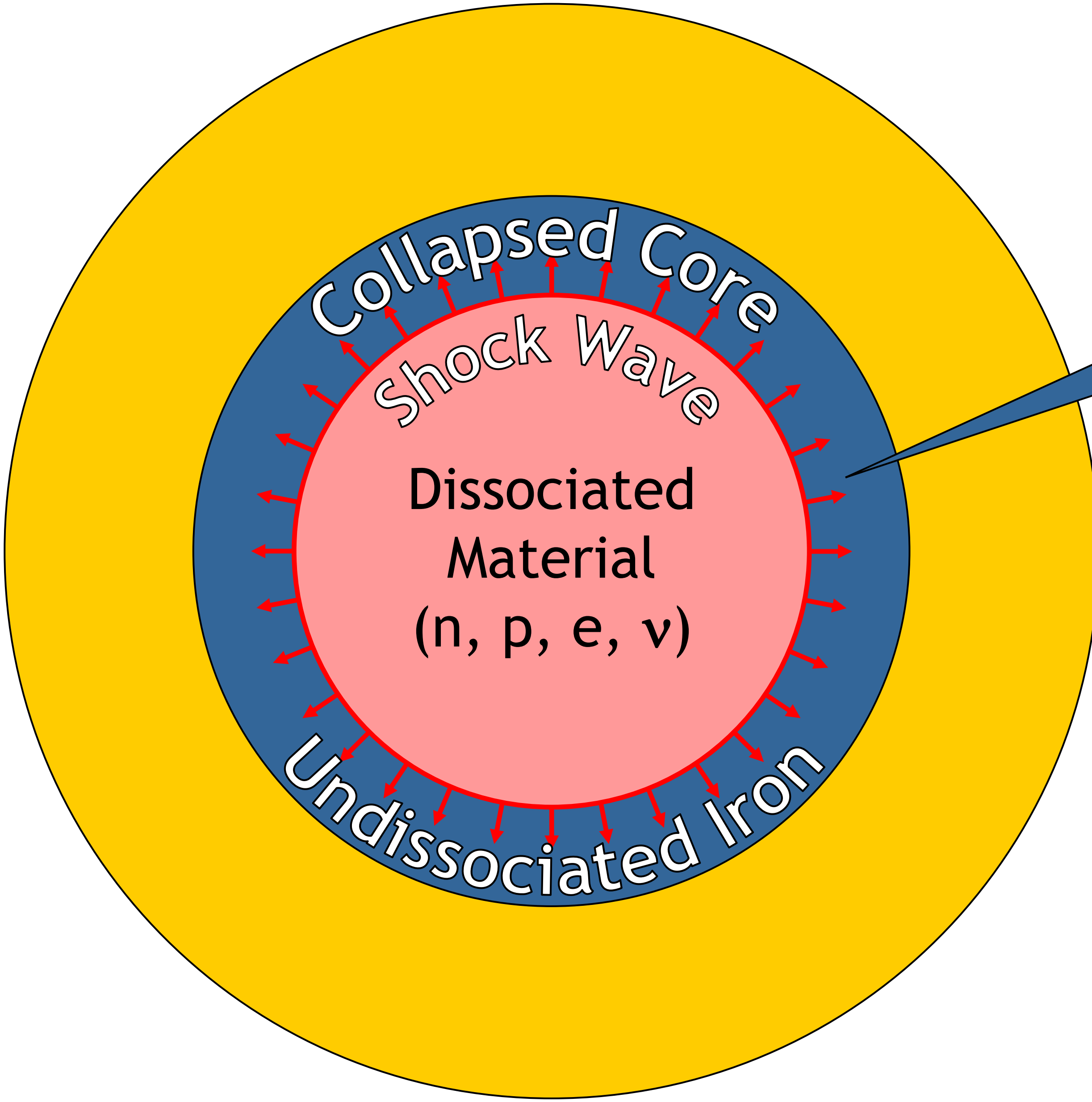
Neutrino luminosity

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

$\sim 3 \times 10^{19}$ L_{SUN}

While it lasts, outshines the entire visible universe

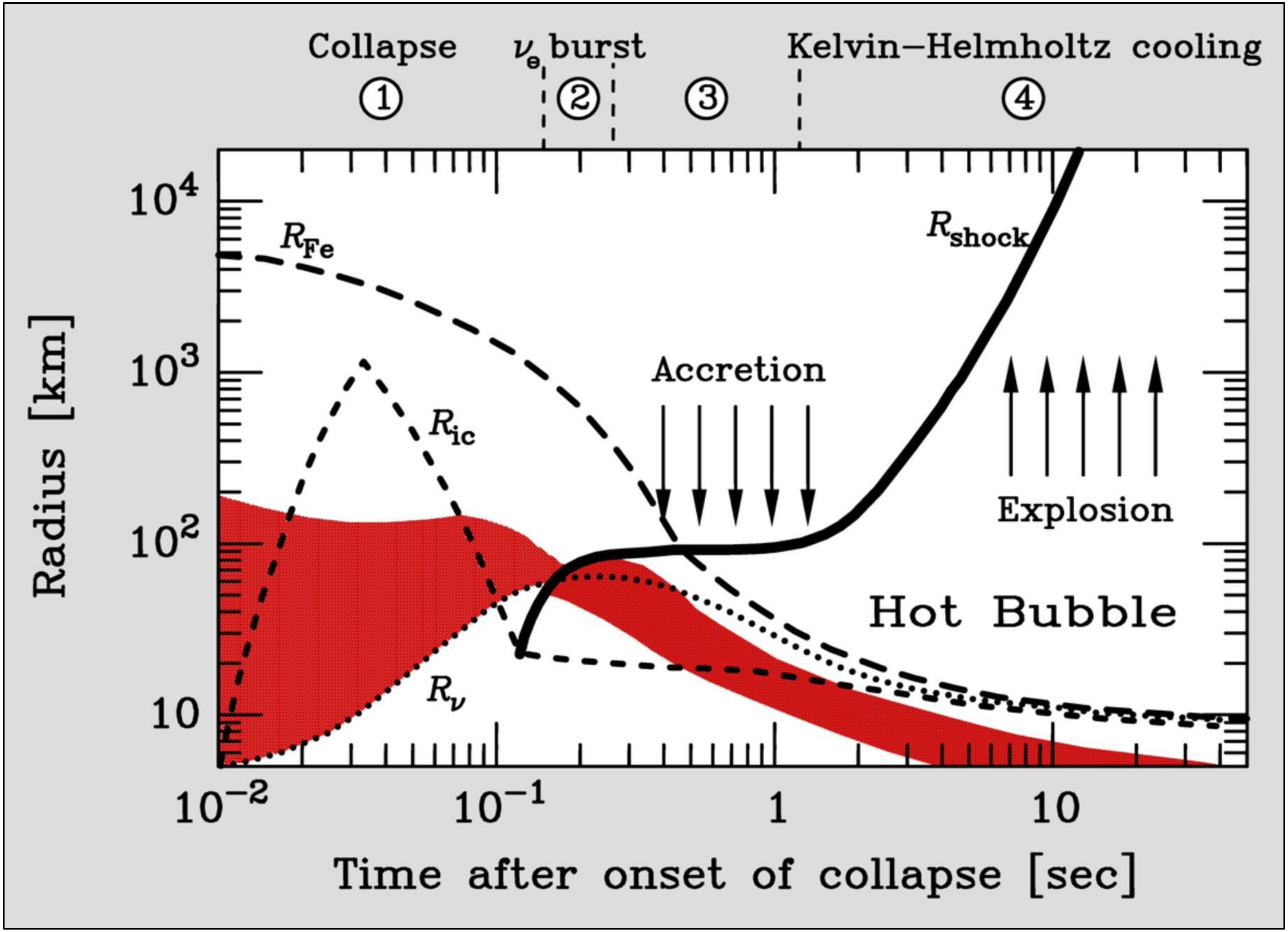
Why No Prompt Explosion?



- $0.1\ M_{sun}$ of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

- **Shock wave forms within the iron core**
- **Dissipates its energy by dissociating the remaining layer of iron**

Supernova Delayed Explosion Scenario

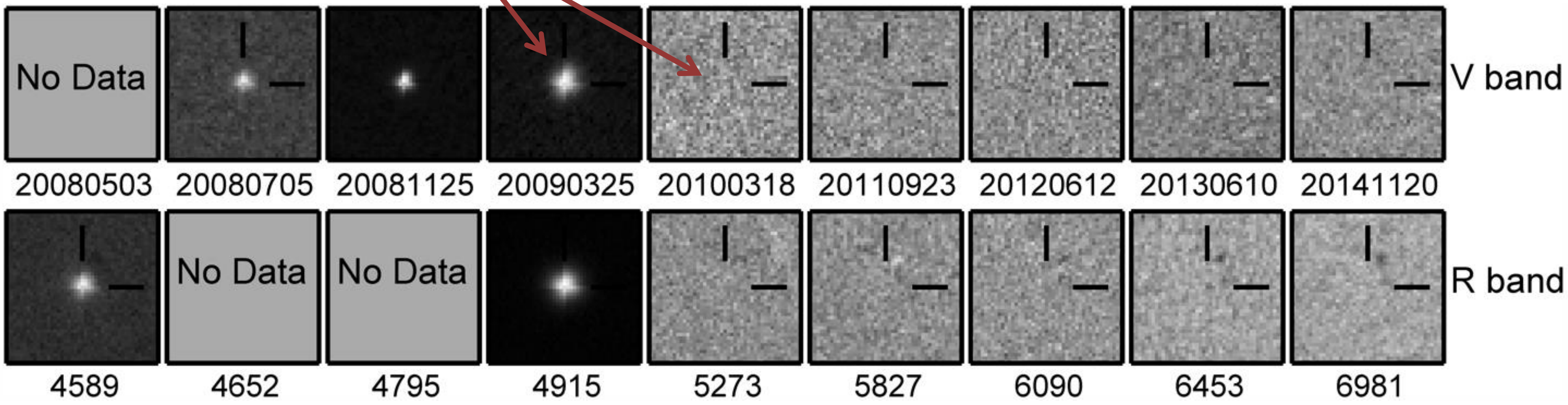


Death Watch for a Million Supergiants

- Monitoring 27 galaxies within 10 Mpc for many years
- Visit typically twice per year
- 10^6 supergiants (lifetime 10^6 years)
- Combined SN rate: about 1 per year

First 7 years of survey:

- 6 successful core-collapse SNe
- 1 candidate failed SN

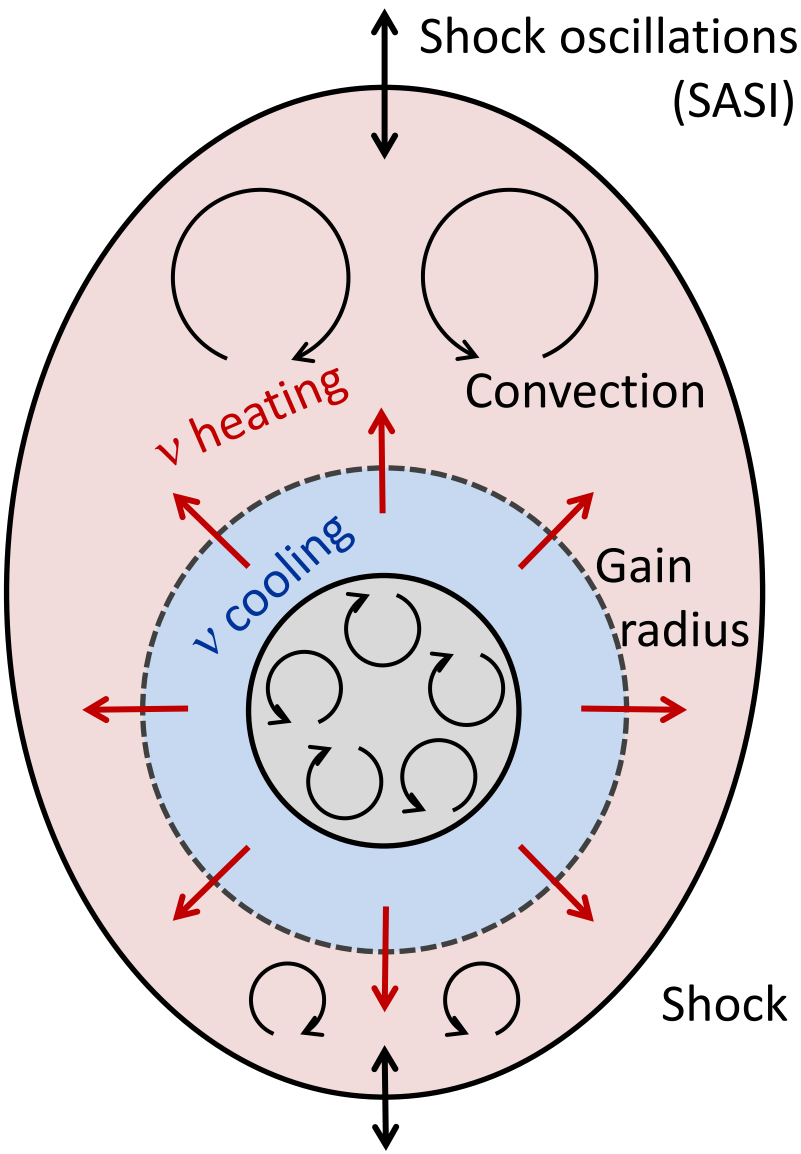


Gerke, Kochanek & Stanek, arXiv:1411.1761

Adams, Kochanek, Gerke, Stanek (& Dai), arXiv:1610.02402 (1609.01283)

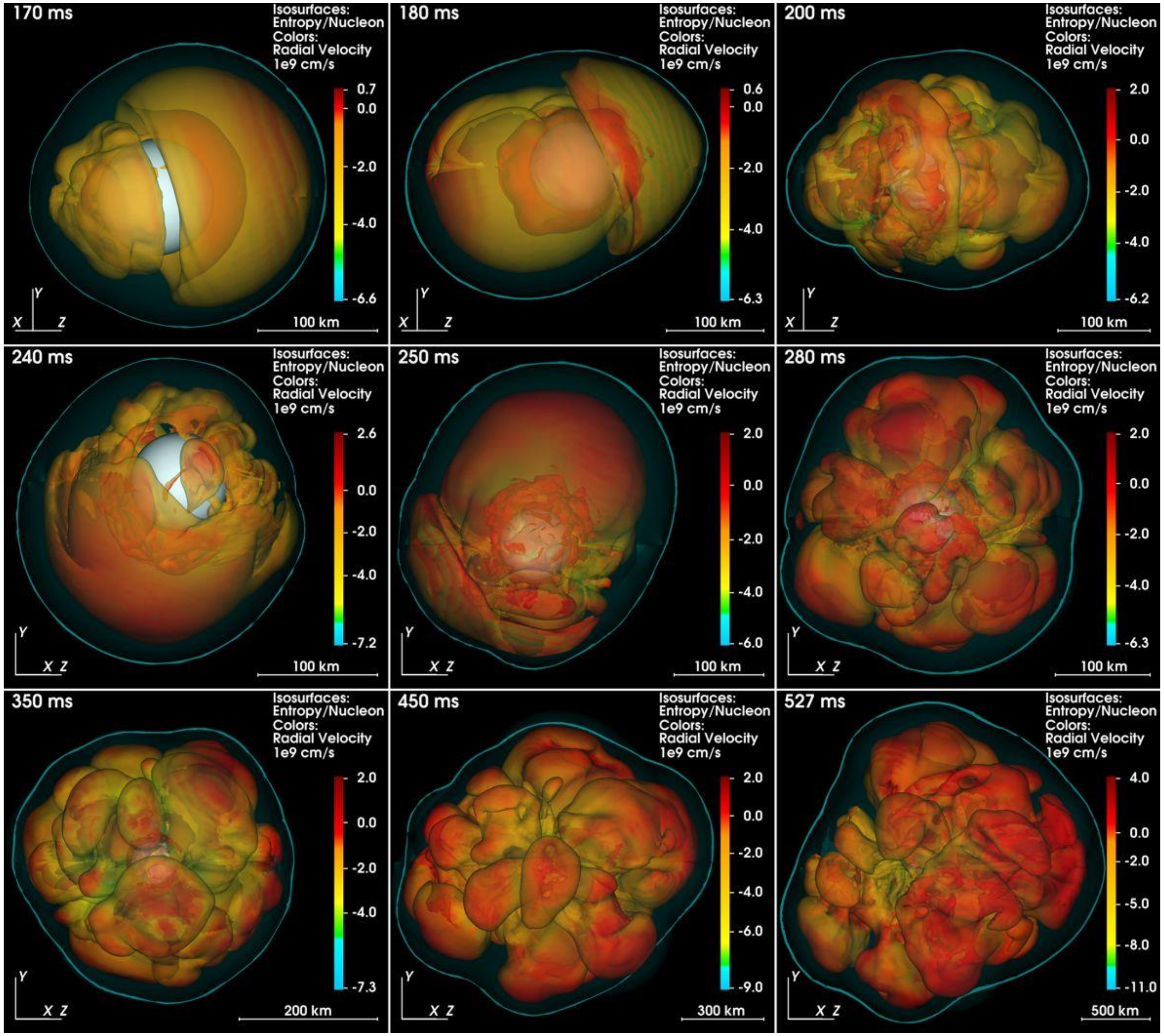
Neutrino-Driven Mechanism – Modern Version

- Stalled accretion shock pushed out to ~150 km as matter piles up on the PNS
- Heating (gain) region develops within some tens of ms after bounce
- Convective overturn & shock oscillations (SASI) enhance efficiency of ν-heating, finally revives shock
- Successful explosions in 1D and 2D for different progenitor masses (e.g. Garching group)
- Details important (treatment of GR, ν interaction rates, etc.)
- First self-consistent 3D studies being performed, sometimes successful explosions



Adapted from B. Müller

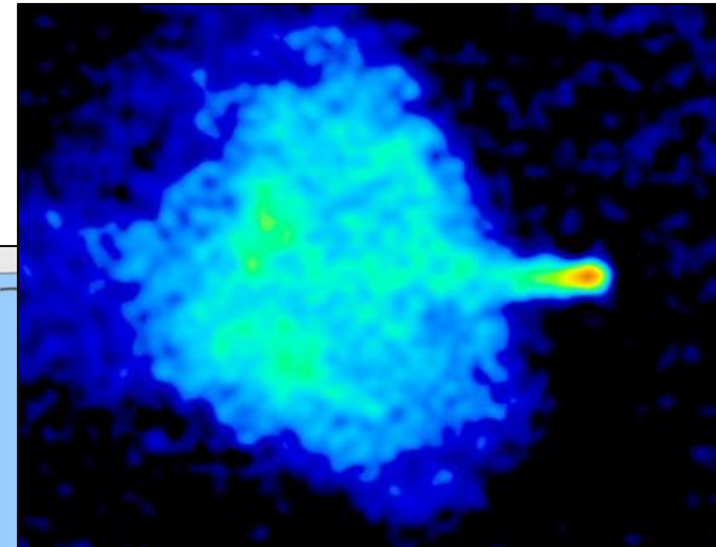
Exploding 3D Garching Model (20 M_{SUN})

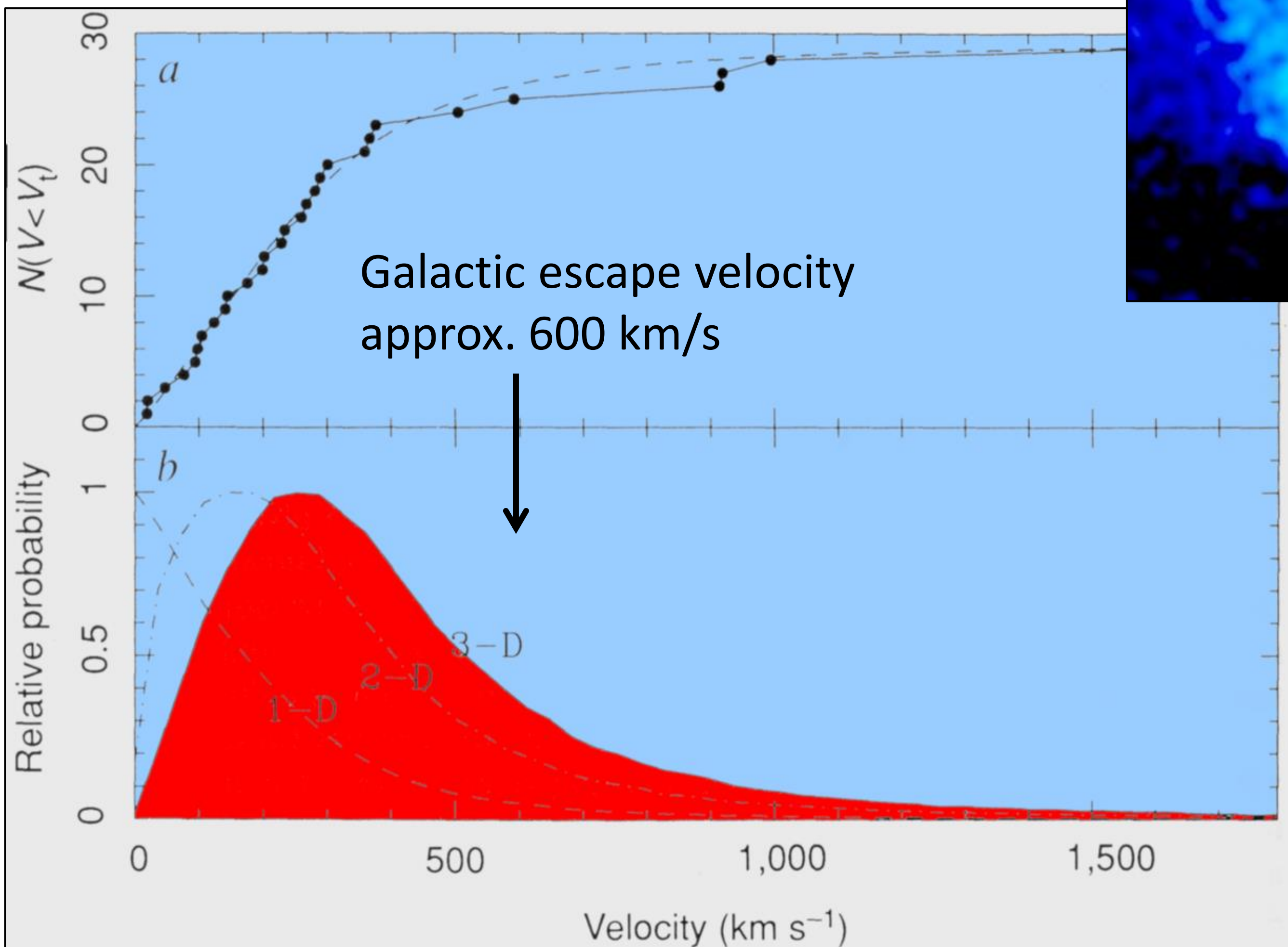


Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

High-Velocity Pulsars

False-color radio image of the SNR G5.4-1.2
and the young radio pulsar PSR 1757-24
(v = 1300–1700 km/s away from the galactic plane)





Pulsar velocity distribution

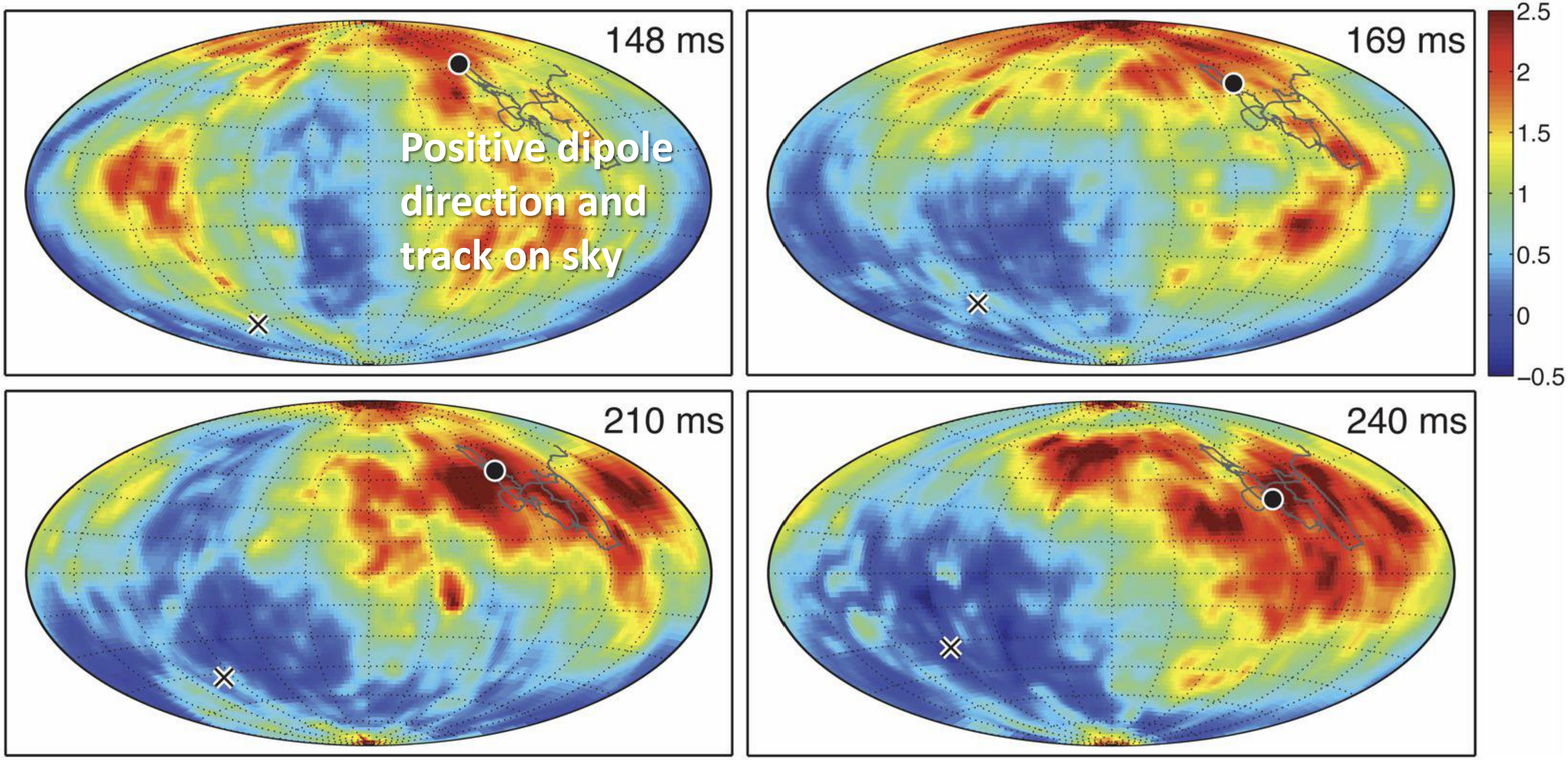
Lyne & Lorimer, Nature 369 (1994) 127

Sky Map of Lepton-Number Flux (11.2 M_{SUN} Model)

Lepton-number flux ($\nu_e - \overline{\nu}_e$) relative to 4π average

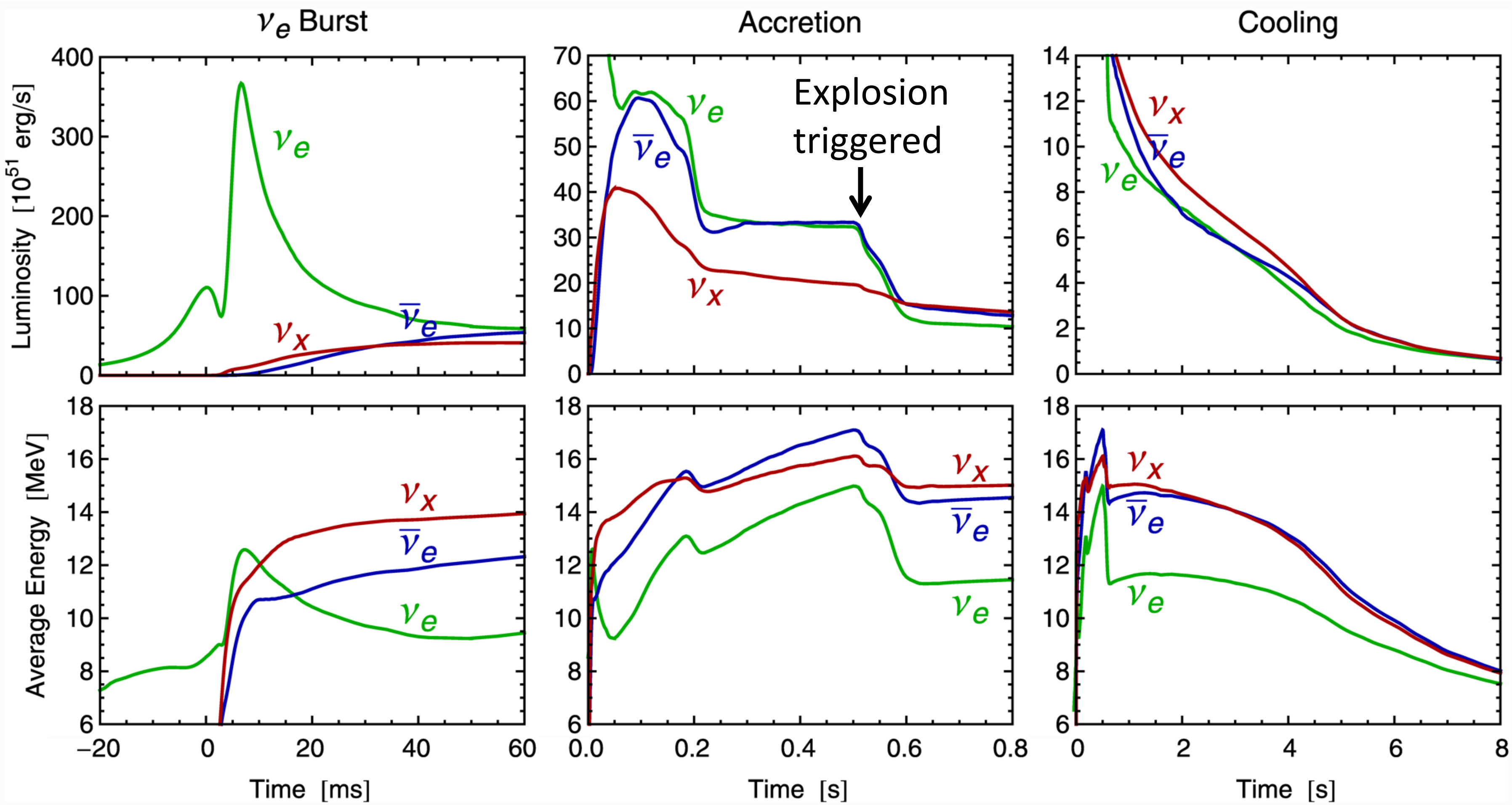
Deleptonization flux into one hemisphere, roughly dipole distribution

(LESA — Lepton Emission Self-Sustained Asymmetry)



Tamborra, Hanke, Janka, Müller, Raffelt & Marek, arXiv:1402.5418

Three Phases of Neutrino Emission



- Shock breakout
- De-leptonization of outer core layers

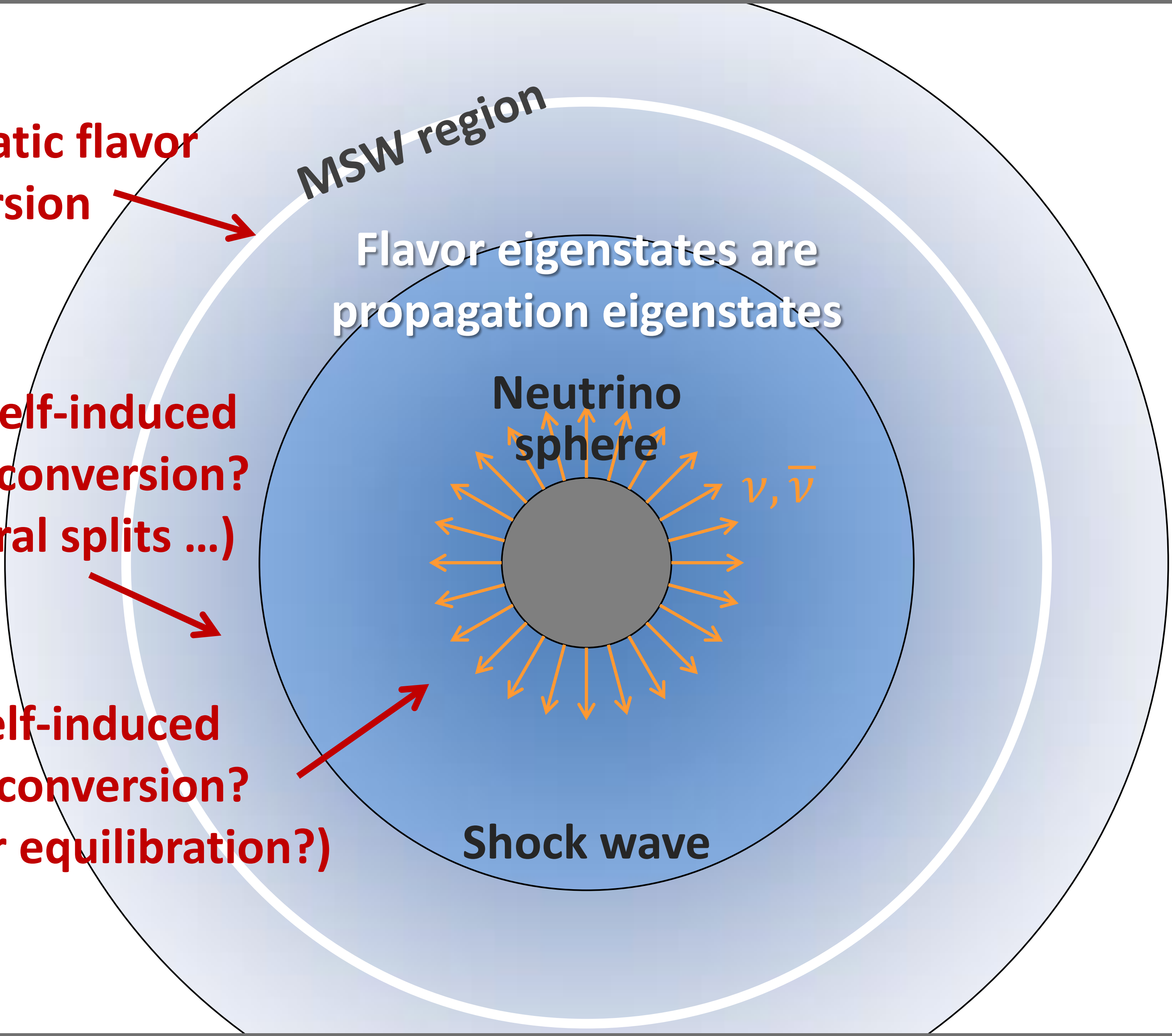
- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Flavor Conversion in Core-Collapse Supernovae

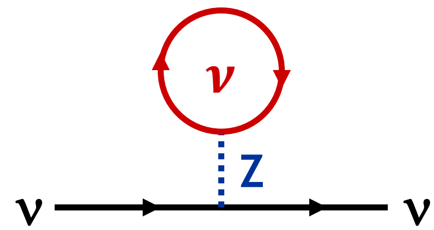
- **Adiabatic flavor conversion**
- **Slow self-induced flavor conversion? (Spectral splits …)**
- **Fast self-induced flavor conversion? (Flavor equilibration?)**



Flavor-Off-Diagonal Refractive Index

2-flavor neutrino evolution as an effective 2-level problem

$$\mathrm{i}\,\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$



Effective mixing Hamiltonian

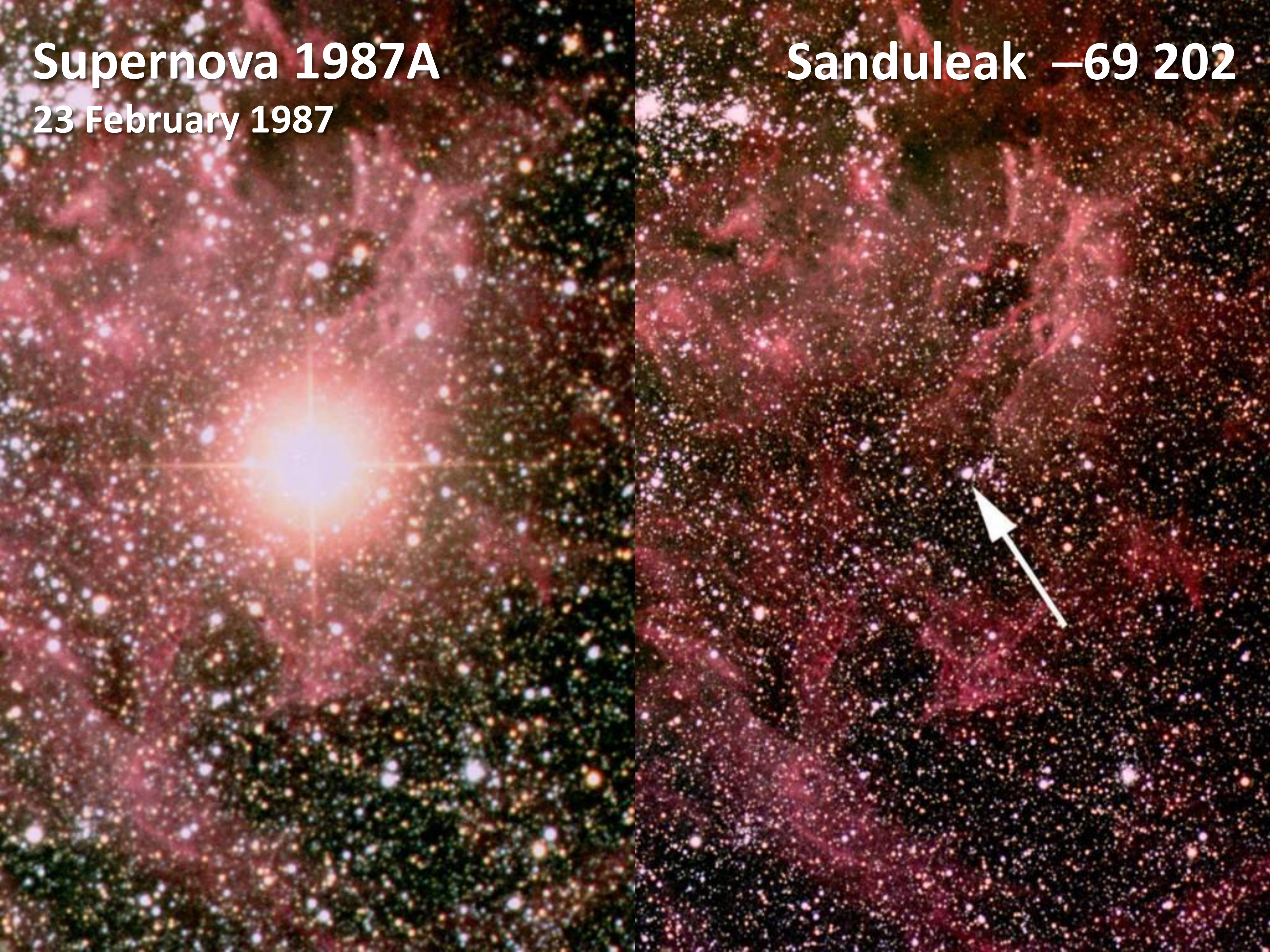
$$H = \frac{M^2}{2E} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_\mathrm{F}\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

Mass term in flavor basis: causes vacuum oscillations

Wolfenstein's weak potential, causes MSW "resonant" conversion together with vacuum term

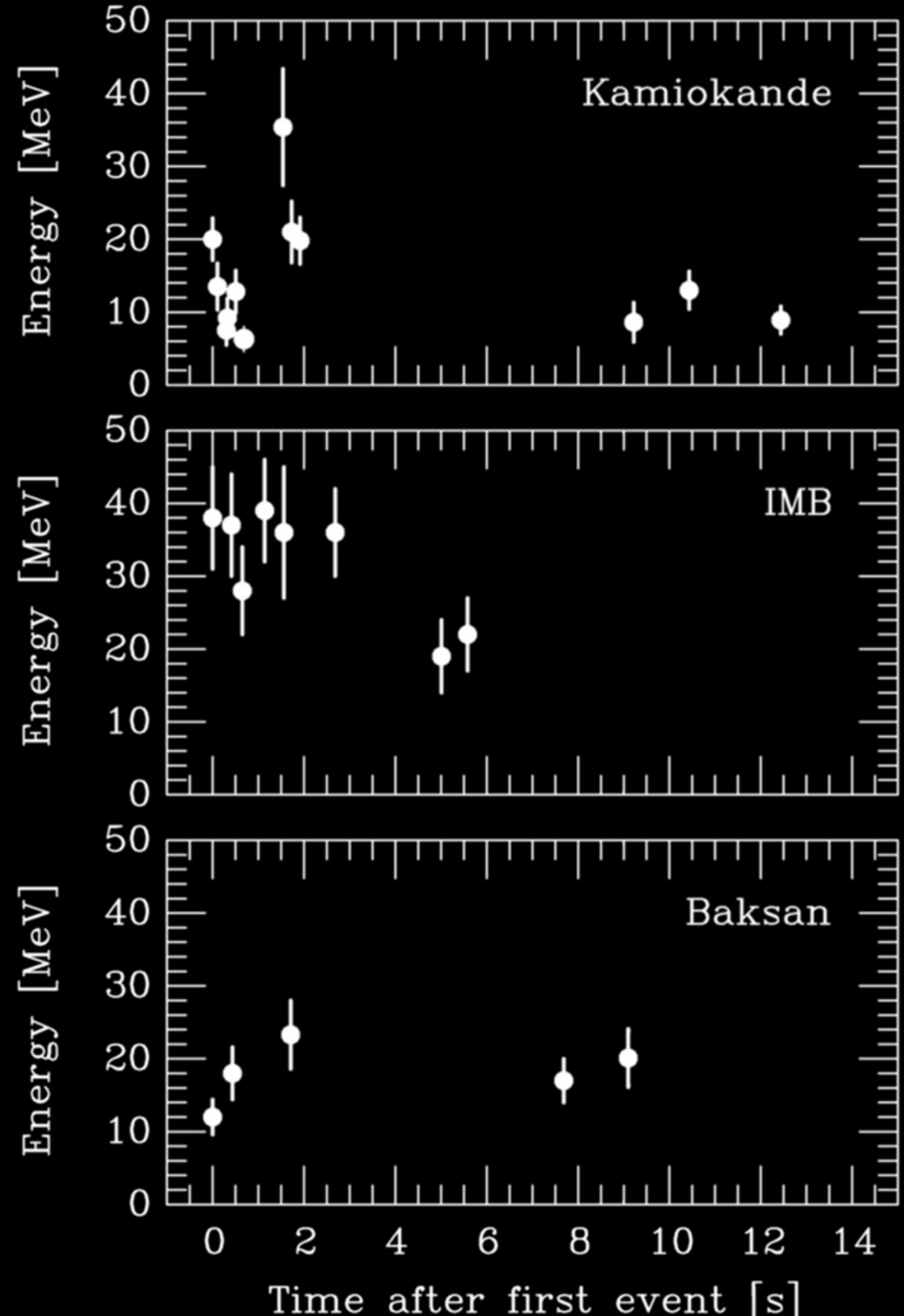
Flavor-off-diagonal potential, caused by flavor oscillations. (J.Pantaleone, PLB 287:128,1992)

Flavor oscillations feed back on the Hamiltonian: Nonlinear effects!

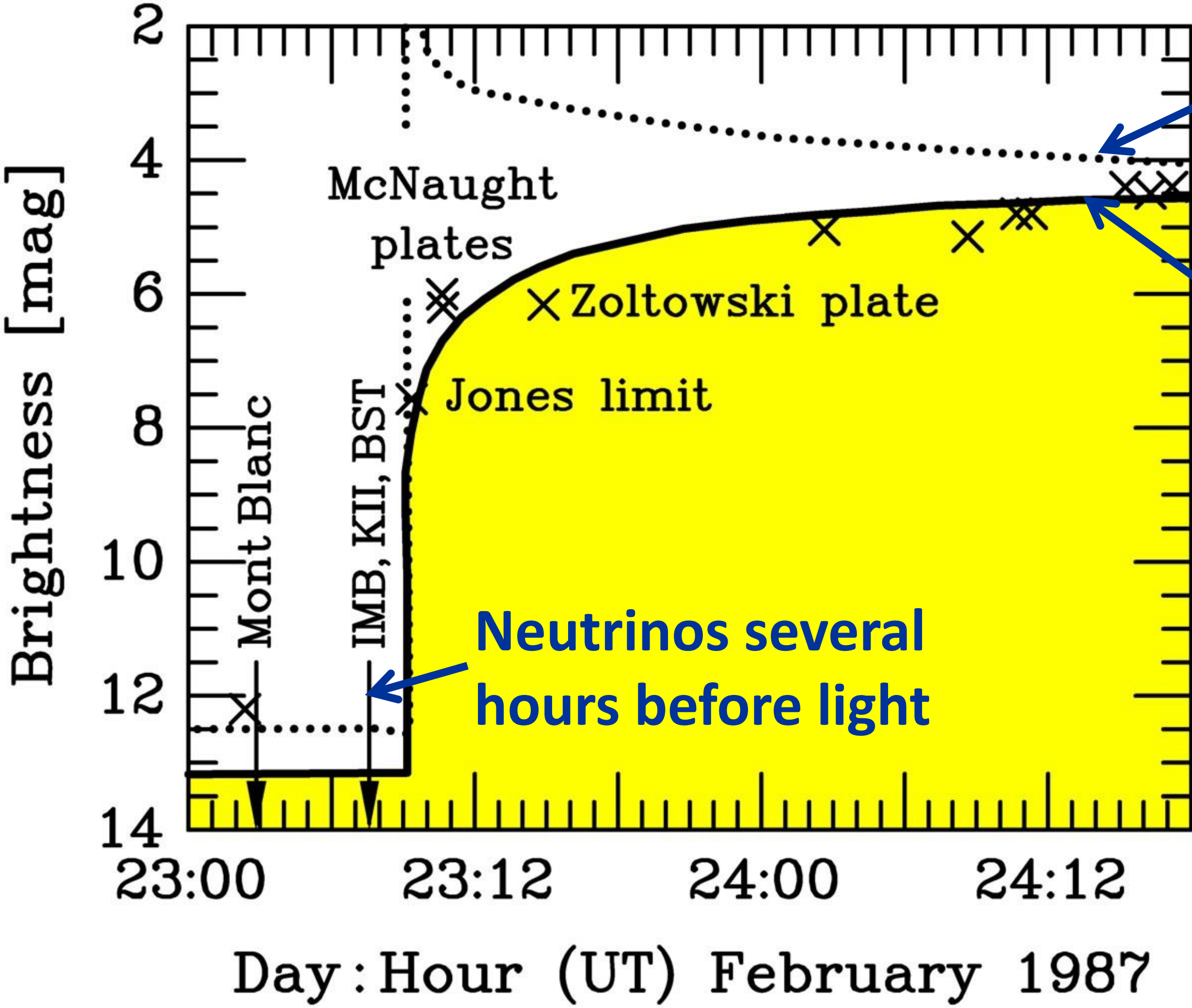

Supernova 1987A
23 February 1987
Sanduleak –69 202

Supernova 1987A

23 February 1987



Early Lightcurve of SN 1987A



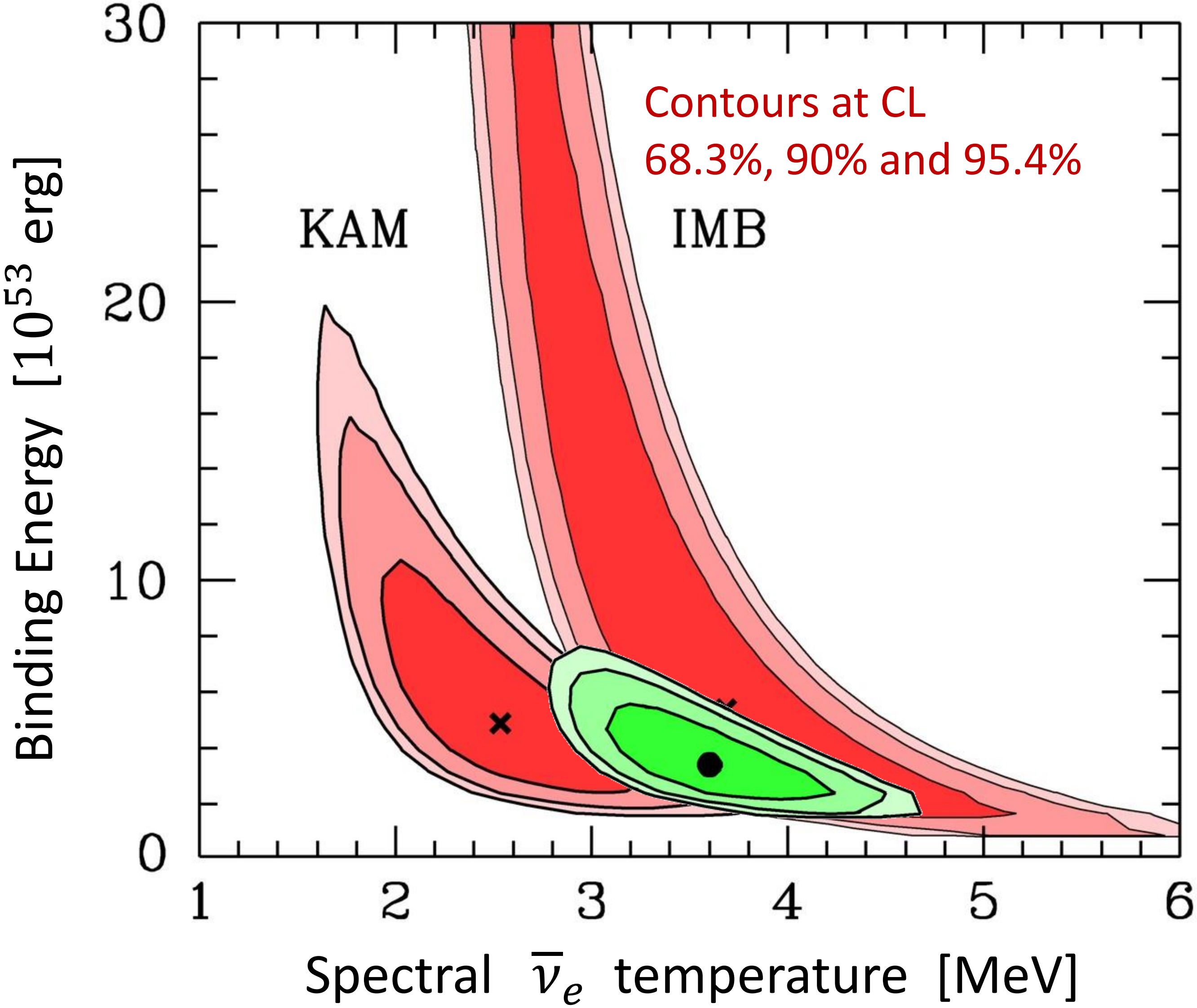
Expected bolometric brightness evolution

Expected visual brightness evolution

Neutrinos several hours before light

Adapted from Arnett et al., ARAA 27 (1989)

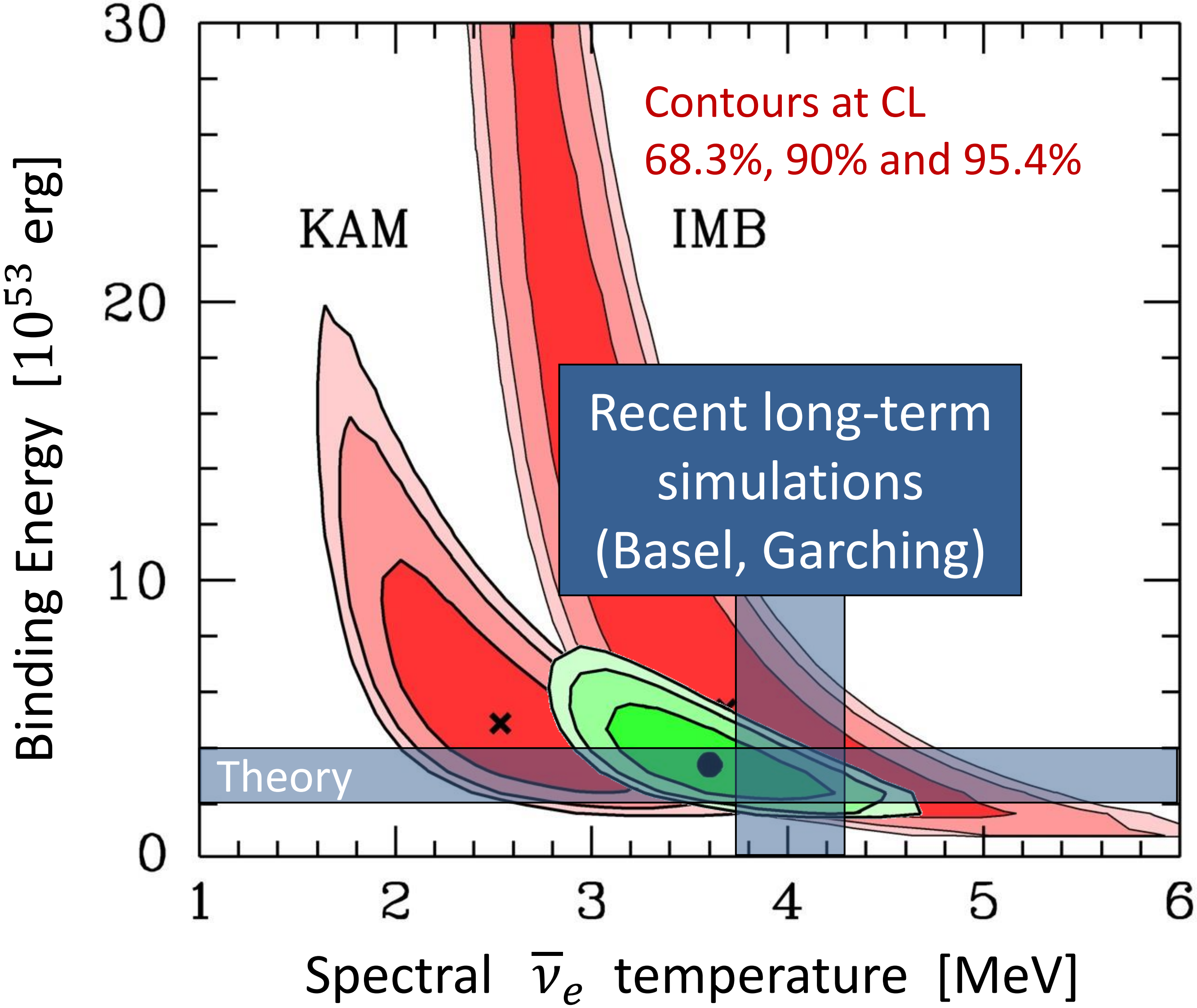
Interpreting SN 1987A Neutrinos



Assume
- Thermal spectra
- Equipartition of energy between $\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau$ and $\overline{\nu}_\tau$

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Interpreting SN 1987A Neutrinos



Assume
- Thermal spectra
- Equipartition of energy between $\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau$ and $\overline{\nu}_\tau$

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Neutrino Limits by Intrinsic Signal Dispersion

Time of flight delay by neutrino mass

G. Zatsepin, JETP Lett. 8:205, 1968

$$\Delta t = 2.57\mathrm{s}\,\frac{D}{50\ \mathrm{kpc}}\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{10\ \mathrm{eV}}\right)^2$$

SN 1987A signal duration implies

$$m_{\nu_e} \lesssim 20\ \mathrm{eV}$$

Loredo & Lamb
Ann N.Y. Acad. Sci. 571 (1989) 601
find 23 eV (95% CL limit) from detailed maximum-likelihood analysis

- At the time of SN 1987A competitive with tritium end-point
- Today $\mathrm{m}_\nu < 2.2\ \mathrm{eV}$ from tritium
- Cosmological limit today $m_\nu \lesssim 0.1\ \mathrm{eV}$

"Milli charged" neutrinos

Path bent by galactic magnetic field, inducing a time delay

$$\frac{\Delta t}{t} = \frac{e_\nu^2 (B_\perp d_B)^2}{6E_\nu^2} < 3\times 10^{-12}$$

SN 1987A signal duration implies

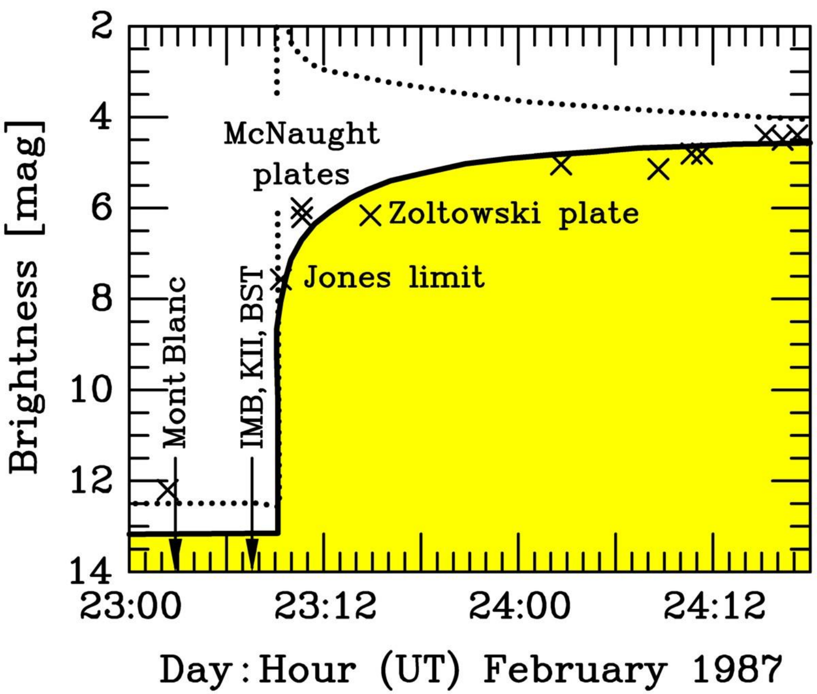
$$\frac{e_\nu}{e} < 3\times 10^{-17}\ \frac{1\mu G}{B_\perp}\ \frac{1\ \mathrm{kpc}}{d_B}$$

- Barbiellini & Cocconi, Nature 329 (1987) 21
- Bahcall, Neutrino Astrophysics (1989)

Assuming charge conservation in neutron decay yields a more restrictive limit of about 3×10^{-21} e

Do Neutrinos Gravitate?

Early light curve of SN 1987A



- Neutrinos arrived several hours before photons as expected
- Transit time for ν and γ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt \, \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

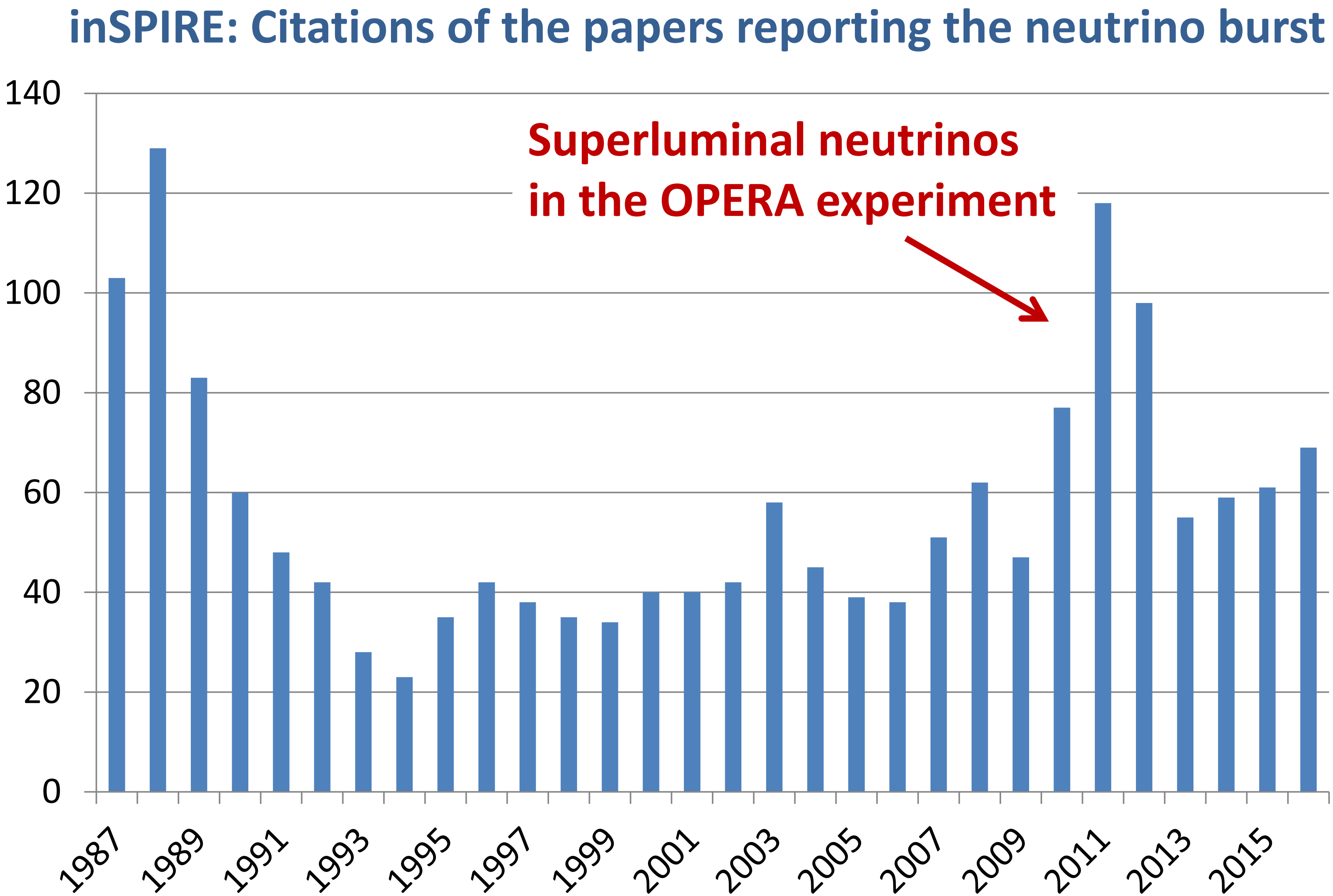
$$\Delta t \approx 1\text{–}5 \text{ months}$$

Neutrinos and photons respond to gravity the same to within

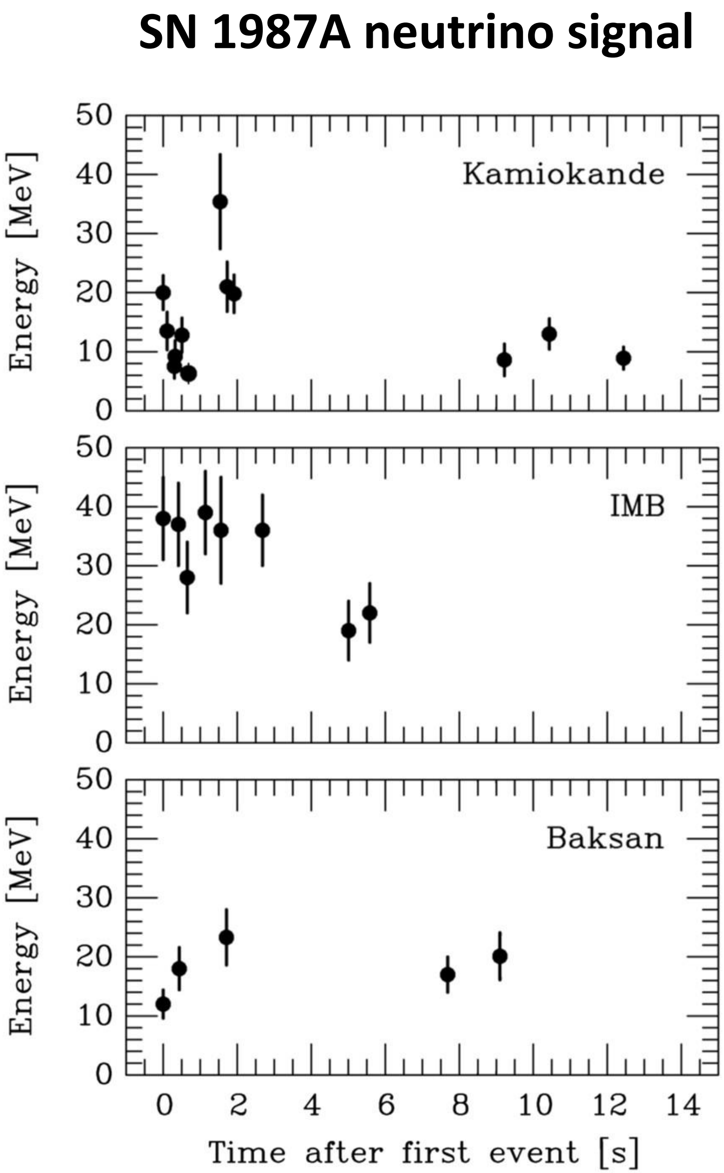
$$1\text{–}4 \times 10^{-3}$$

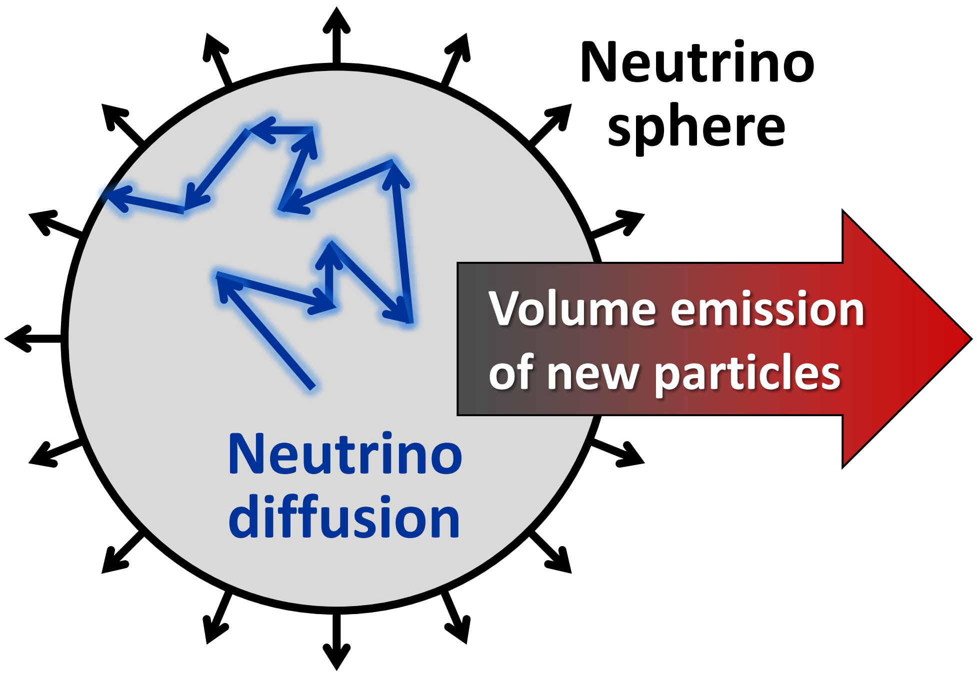
Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

SN 1987A Burst of Neutrino Papers



Supernova 1987A Energy-Loss Argument

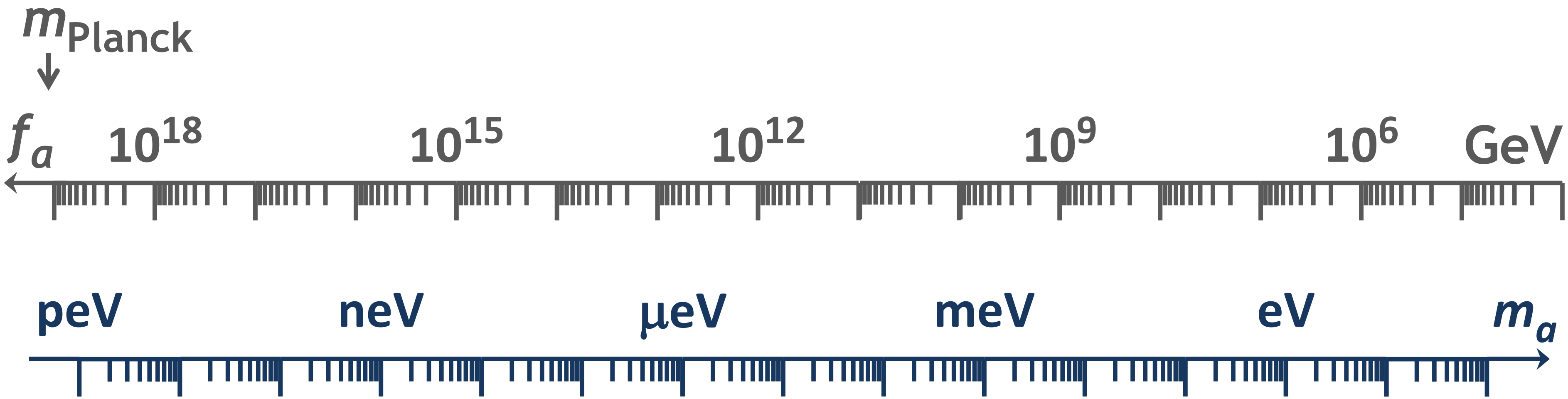




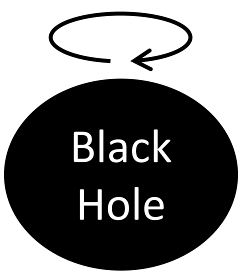
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Bounds



Super Radiance



Opportunities for detection

Astrophysical Bounds (Energy loss of stars)


Neutrinos from Next Nearby SN

Operational Detectors for Supernova Neutrinos

HALO (30)
SNO+ (300)

LVD (400)
Borexino (100)

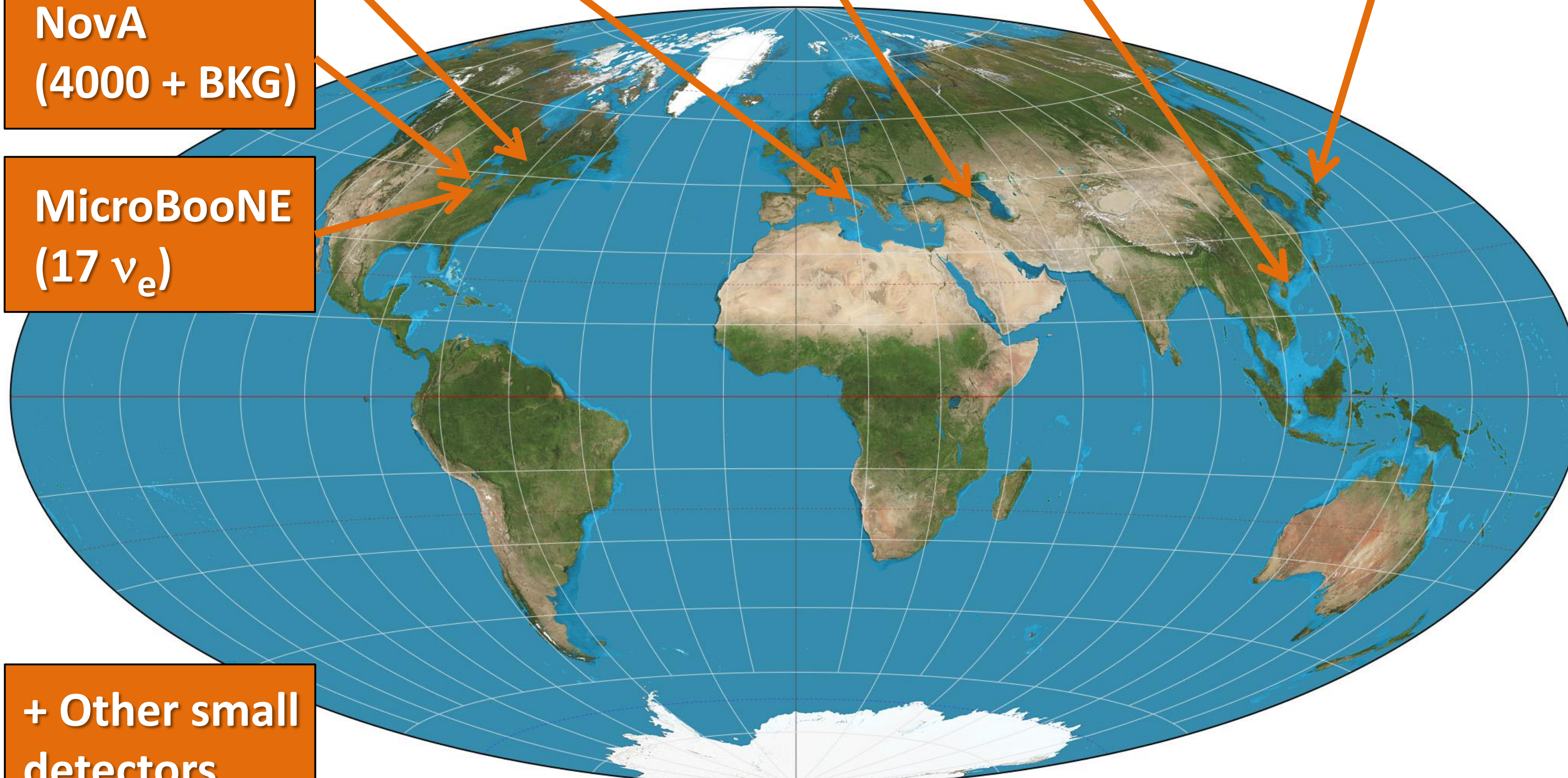
Baksan
(100)

Daya Bay
(100)

Super-K (4000)
KamLAND (400)

NovA
(4000 + BKG)

MicroBooNE
(17 ν_e)



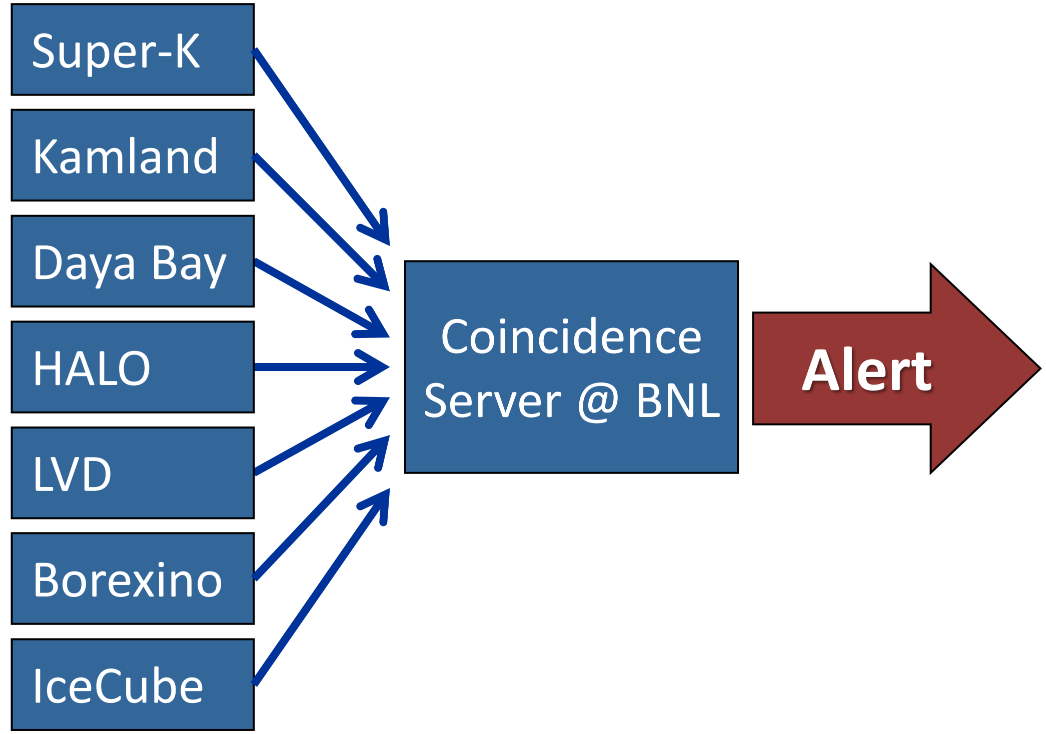
+ Other small detectors with some SN sensitivity

IceCube (10^6)

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

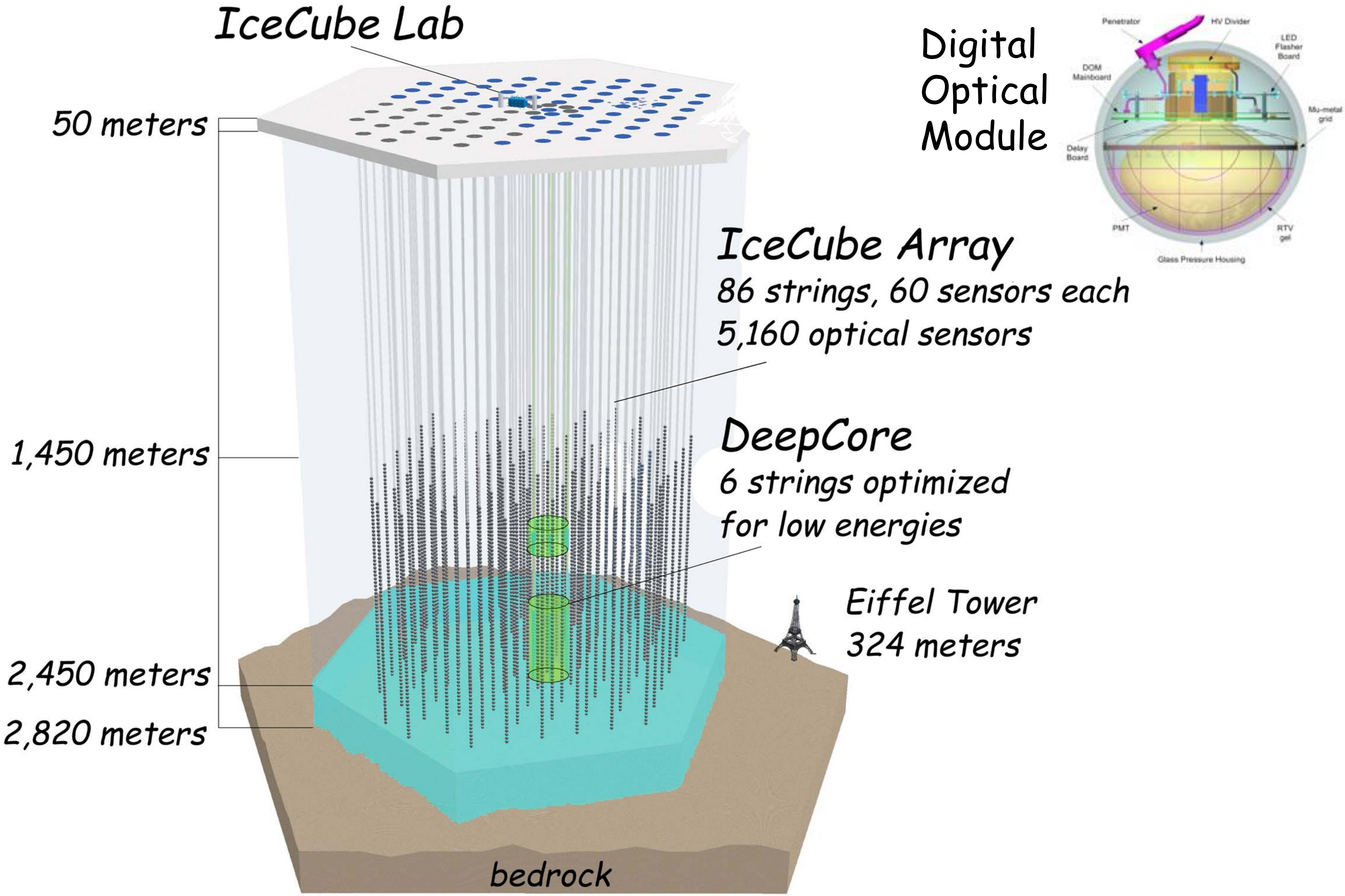
SuperNova Early Warning System (SNEWS)

http://snews.bnl.gov

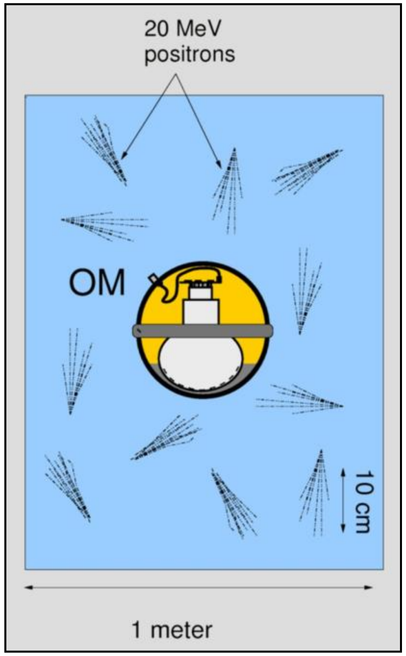


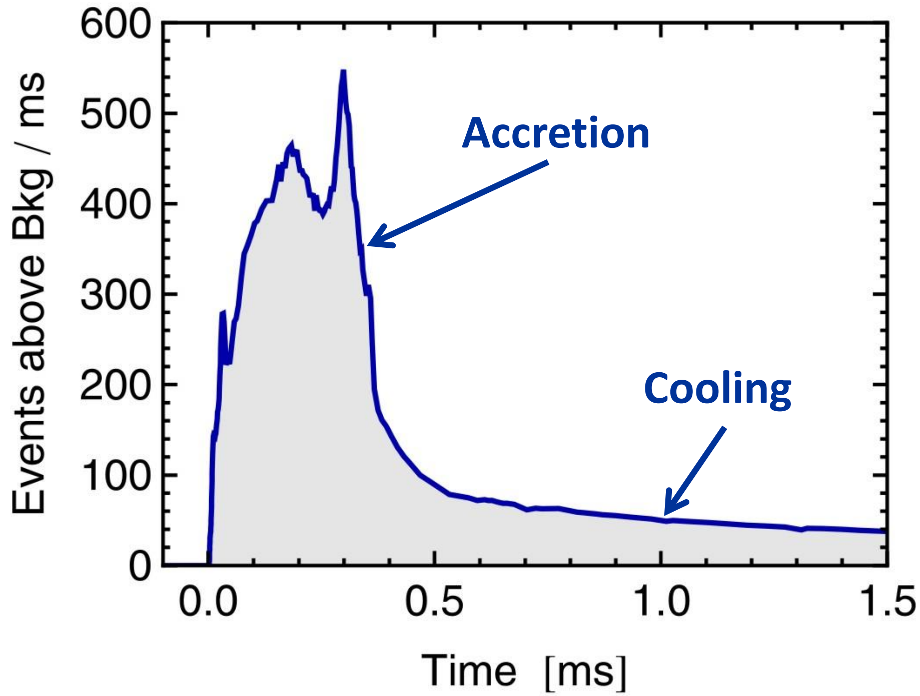
- Neutrinos arrive several hours before optical outburst
- Issue alert to astronomical community
- Trigger to LIGO, NOvA, GCN

IceCube Neutrino Telescope at the South Pole



IceCube as a Supernova Neutrino Detector



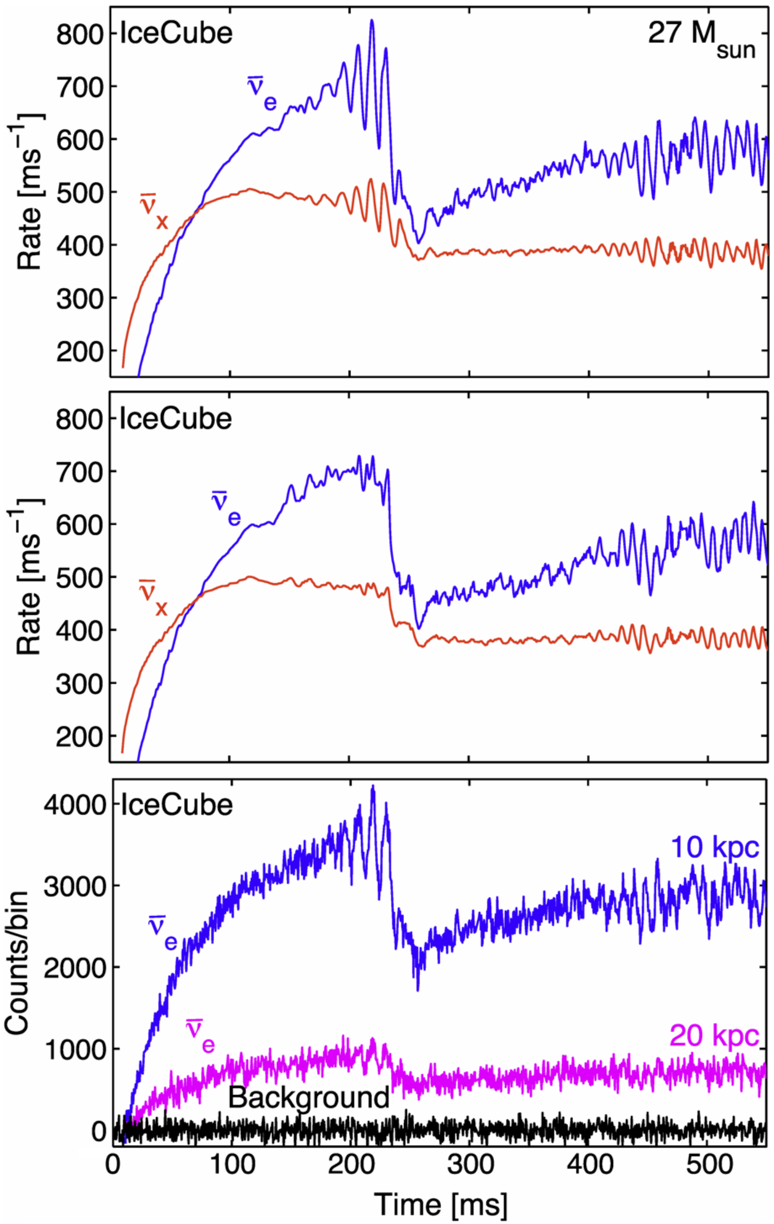


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group [arXiv:0908.1871]

- Each optical module (OM) picks up Cherenkov light from its neighborhood
- ~ 300 Cherenkov photons per OM from SN at 10 kpc, bkgd rate in one OM < 300 Hz
- SN appears as "correlated noise" in ~ 5000 OMs
- Significant energy information from time-correlated hits

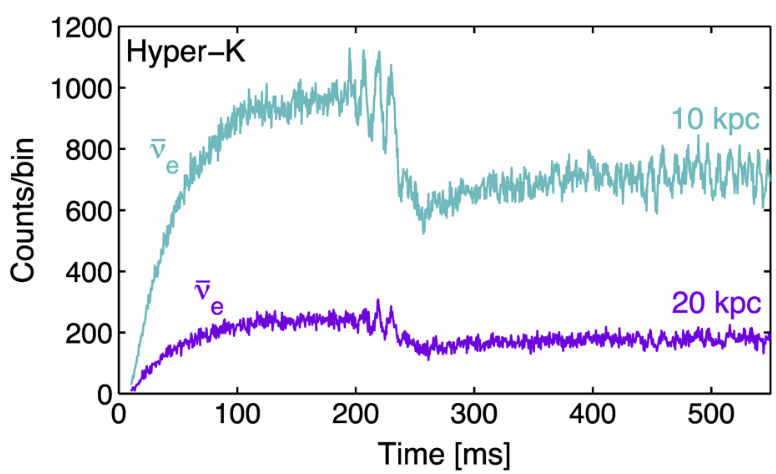
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

SASI Detection Perspectives (27 M_{SUN} Model)



Optimistic Observer Direction (along SASI dipole)

Pessimistic Observer Direction



With shot noise

Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936. See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

Neutrino Mass and Resolving Time Variations

Time-of-flight signal dispersion for next nearby supernova

$$\Delta t = 51\ \mu\text{s}\left(\frac{D}{10\ \text{kpc}}\right)\left(\frac{10\ \text{MeV}}{E_\nu}\right)^2\left(\frac{m_\nu}{100\ \text{meV}}\right)^2$$

- Laboratory: $m_\nu < 2.2$ eV
- Cosmological limit $\sum m_\nu < 0.23$ eV, so that $m_\nu < 0.1$ eV
- KATRIN sensitivity roughly 0.2 eV

To measure fast SN signal variations, cosmological limit and future KATRIN measurement/limit very important!

Time-of-flight measurement of nu mass hopeless with SN nus.

SN Neutrino Detection Channels

Channel	Observable(s)[a]	Interactions[b]
$\nu_x + e^- \to \nu_x + e^-$	C	17/10
$\bar{\nu}_e + p \to e^+ + n$	C, N, A	278/165
$\nu_x + p \to \nu_x + p$	C	682/351
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}^{(*)}$	C, N, G	3/9
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}^{(*)}$	C, N, G, A	6/8
$\nu_x + {}^{12}\mathrm{C} \to \nu_x + {}^{12}\mathrm{C}^*$	G, N	68/25
$\nu_e + {}^{16}\mathrm{O} \to e^- + {}^{16}\mathrm{F}^{(*)}$	C, N, G	1/4
$\bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + {}^{16}\mathrm{N}^{(*)}$	C, N, G	7/5
$\nu_x + {}^{16}\mathrm{O} \to \nu_x + {}^{16}\mathrm{O}^*$	G, N	50/12
$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$	C, G	67/83
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + {}^{40}\mathrm{Cl}^*$	C, A, G	5/4
$\nu_e + {}^{208}\mathrm{Pb} \to e^- + {}^{208}\mathrm{Bi}^*$	N	144/228
$\nu_x + {}^{208}\mathrm{Pb} \to \nu_x + {}^{208}\mathrm{Pb}^*$	N	150/55
$\nu_x + A \to \nu_x + A$	C	9,408/4,974

[a]The observables column lists primary observable products relevant for interactions in current detectors. Abbreviations: C, energy loss of a charged particle; N, produced neutrons; G, deexcitation γs; A, positron annihilation γs. Note there may, in principle, be other signatures for future detector technologies or detector upgrades.

[b]The interactions column gives interactions per kilotonne at 10 kpc for two different neutrino flux models for neutrino energies greater than 5 MeV, computed according to **http://www.phy.duke.edu/~schol/snowglobes**. No detector response is taken into account here, and actual detected events may be significantly fewer. For elastic scattering and inverse β decay, the numbers per kilotonne refer to water; for other detector materials, the numbers need to be scaled by the relative fraction of electrons or protons, respectively. For neutrino-proton elastic scattering, the numbers per kilotonne refer to scintillators.

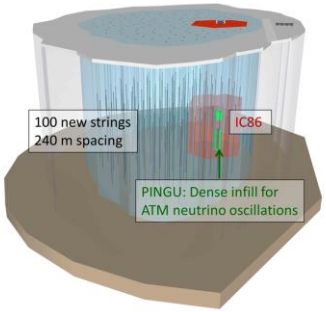
Scholberg, arXiv:1205.6003, see also http://www.phy.duke.edu/~schol/snowglobes

Current and Near-Future SN Neutrino Detectors

Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

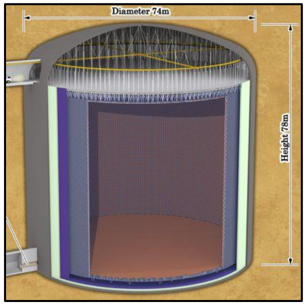
K. Scholberg in arXiv:1508.00785

Next Generation Very-Large-Scale Detectors (2020+)

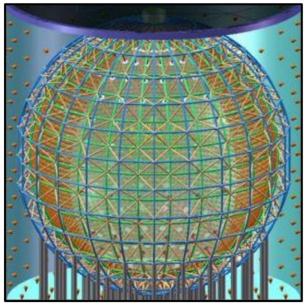


IceCube Gen-2
- Dense infill (PINGU)
- Larger volume (statistics for high-E events)

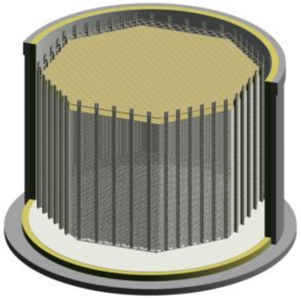
Doubling the number of optical modules



Megaton-class water Cherenkov detector
Notably Hyper-Kamiokande
SN neutrino statistics comparable to IceCube,
but with event-by-event energy information

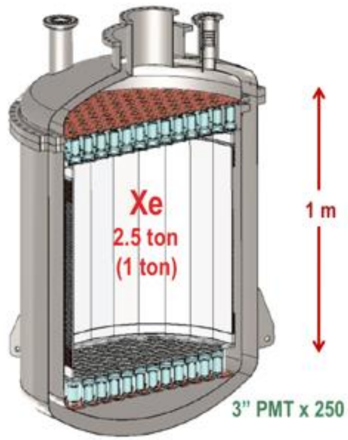


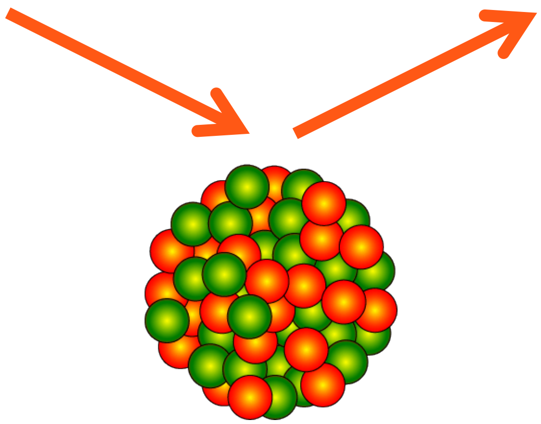
Scintillator detectors (20 kilotons)
- JUNO in China for reactor nus (construction)
- RENO-50 in Korea for reactor nus (plans)
- Baksan Large Volume Scintillator Detector (discussions in Russia)



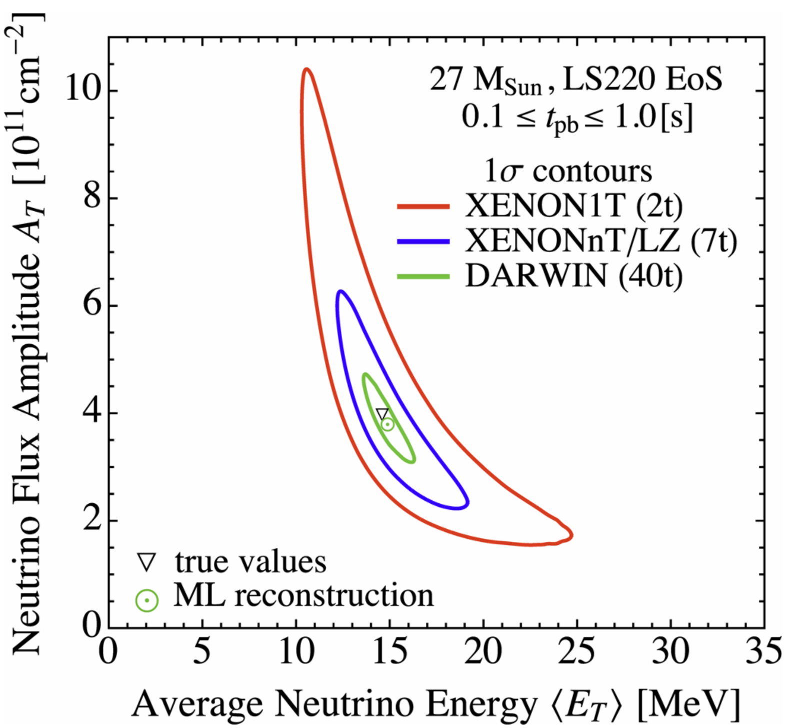
Liquid argon time projection chamber
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC ν_e signal)
- But cross sections poorly known

Xenon Dark Matter Detectors





- Coherent scattering of low-E nus on Xe (77 neutrons)
- All 6 nu species contribute

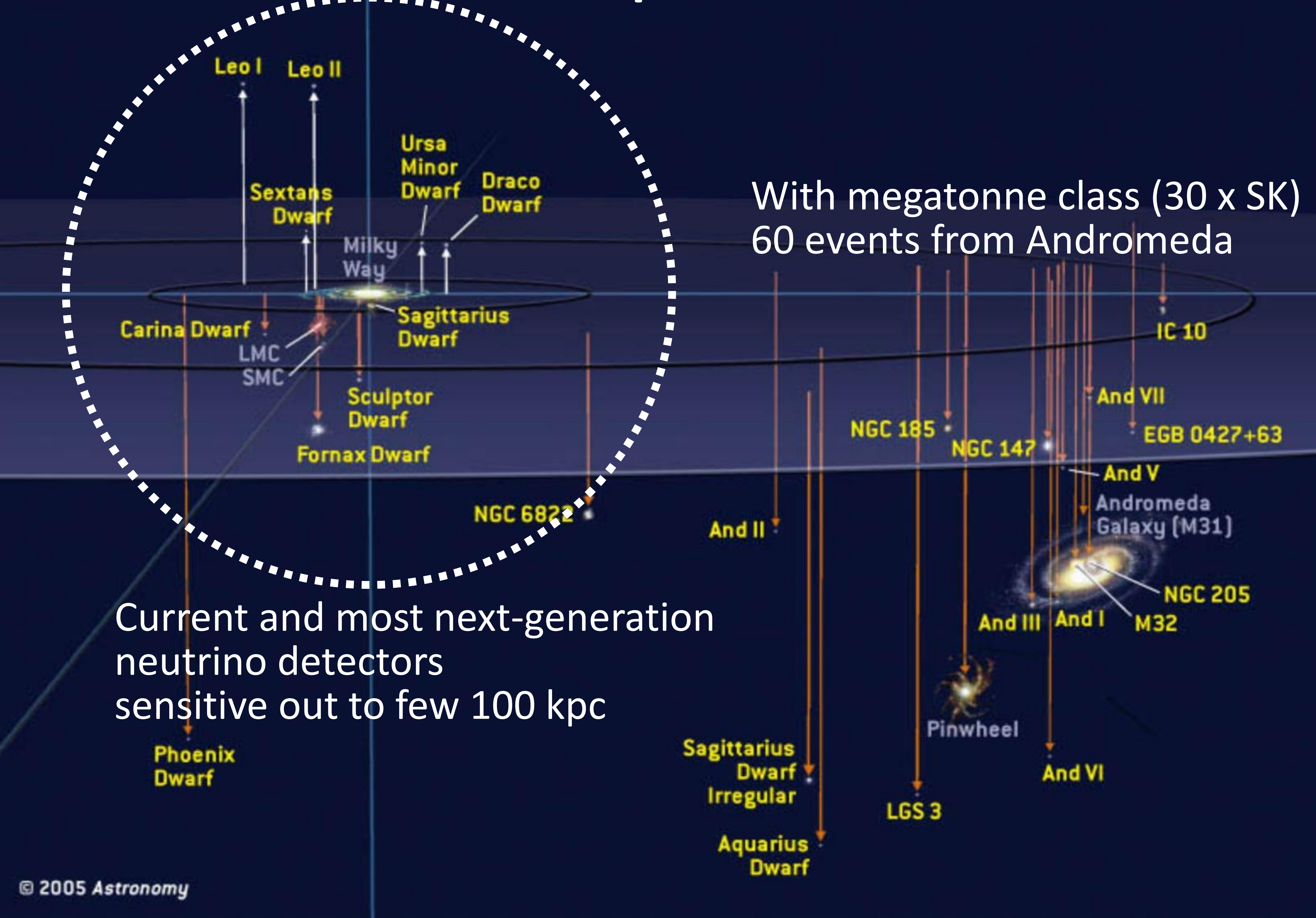


Pinning down SN neutrino flux and average energy

See for example
Horowitz et al. (astro-ph/0302071)
Chakraborty et al. (arXiv:1309.4492)
XMASS Collaboration (arXiv:1604.01218)
Lang et al. (arXiv:1606.09243)

Supernova Rate

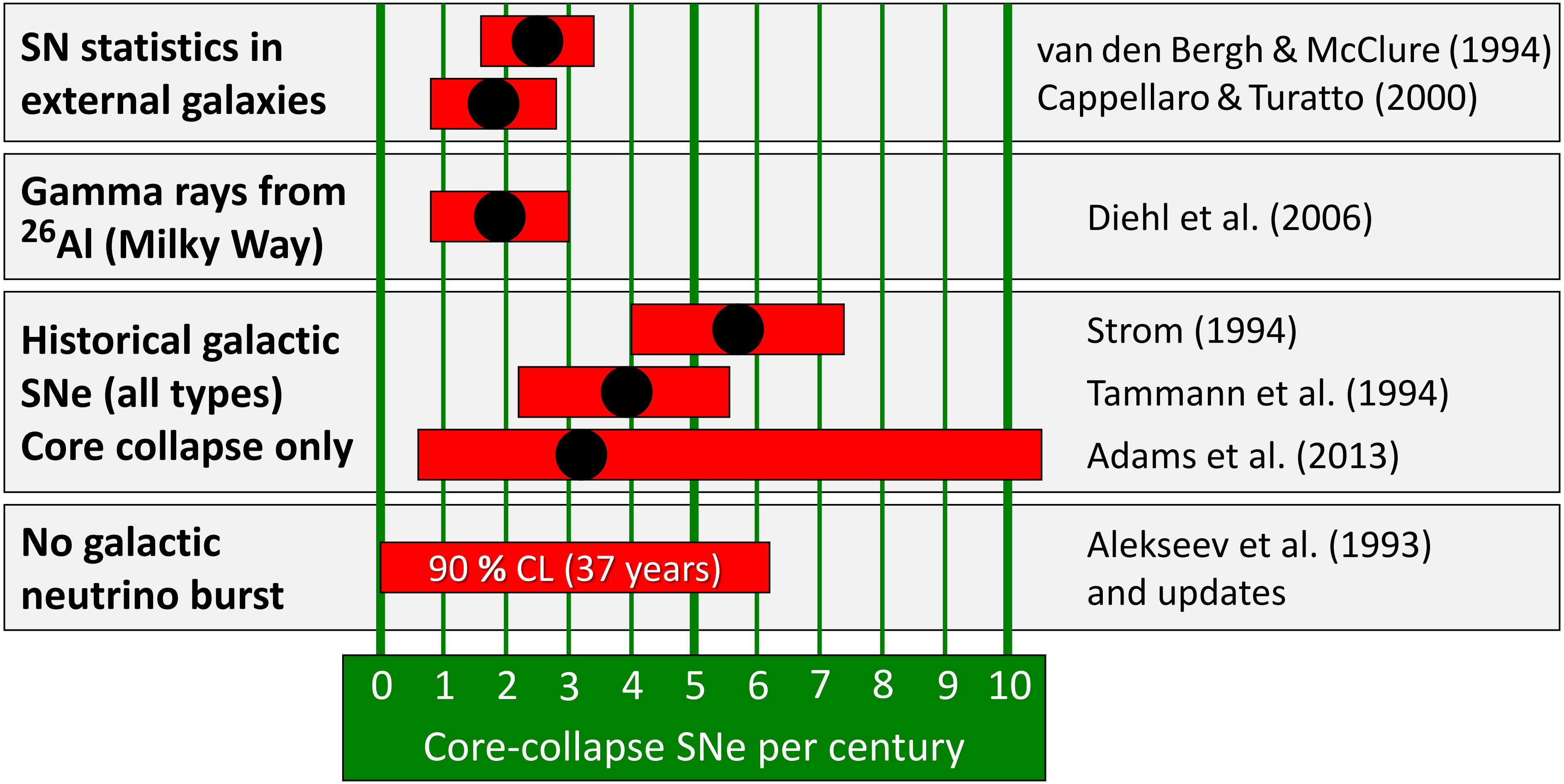
Local Group of Galaxies



With megatonne class (30 x SK)
60 events from Andromeda

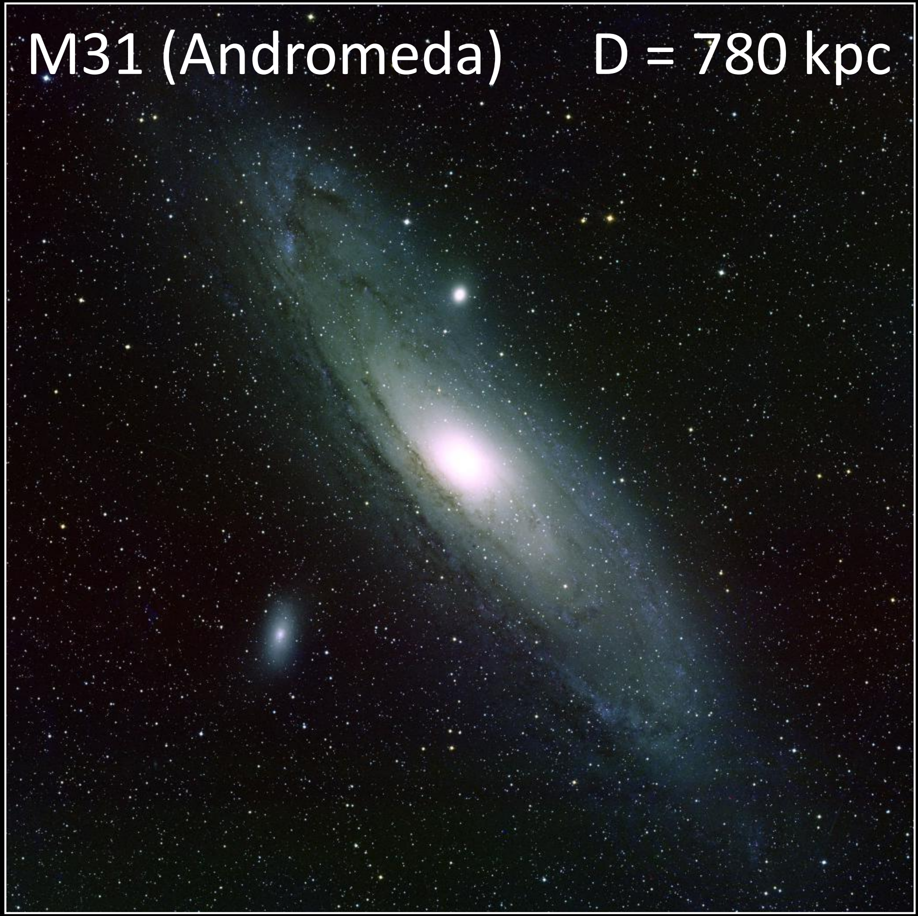
Current and most next-generation
neutrino detectors
sensitive out to few 100 kpc

Core-Collapse SN Rate in the Milky Way

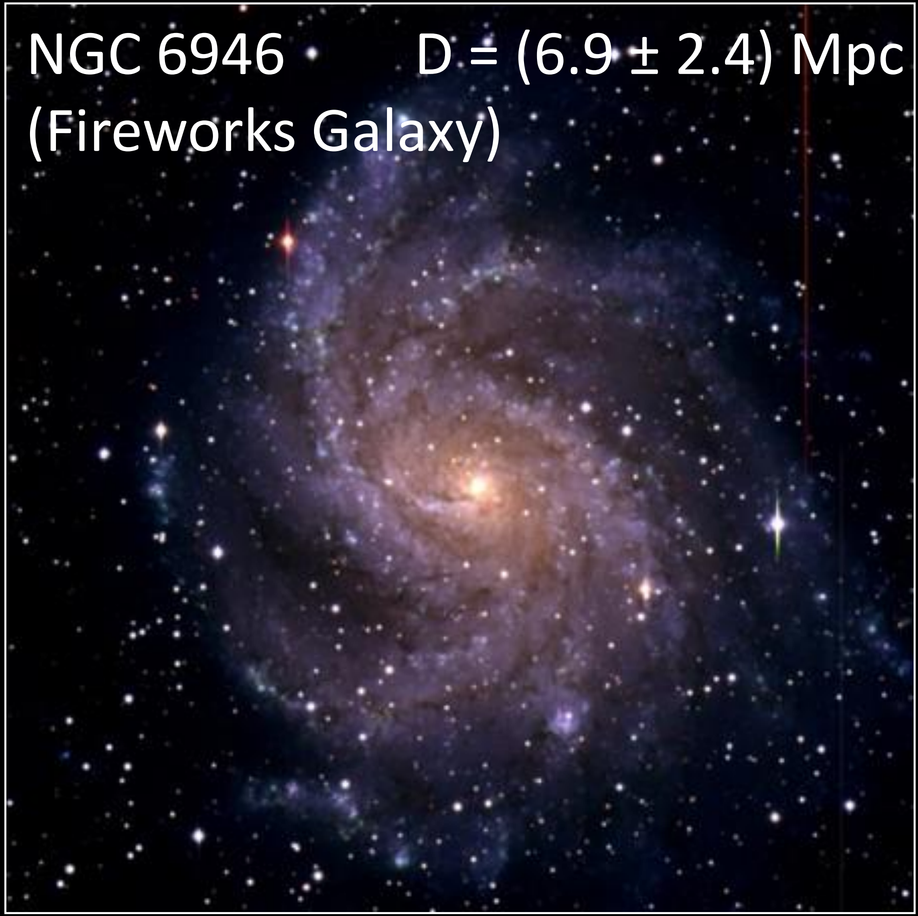


van den Bergh & McClure, ApJ 425 (1994) 205. Cappellaro & Turatto, astro-ph/0012455.
Diehl et al., Nature 439 (2006) 45. Strom, A&A 288 (1994) L1.
Tammann et al., ApJ 92 (1994) 487. Adams et al., ApJ 778 (2013) 164.
Alekseev et al., JETP 77 (1993) 339.

High and Low Supernova Rates in Nearby Galaxies

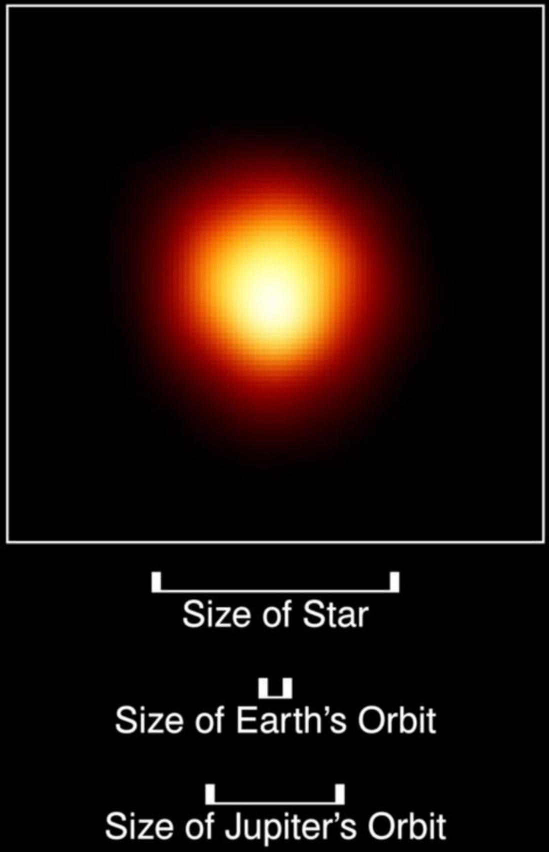


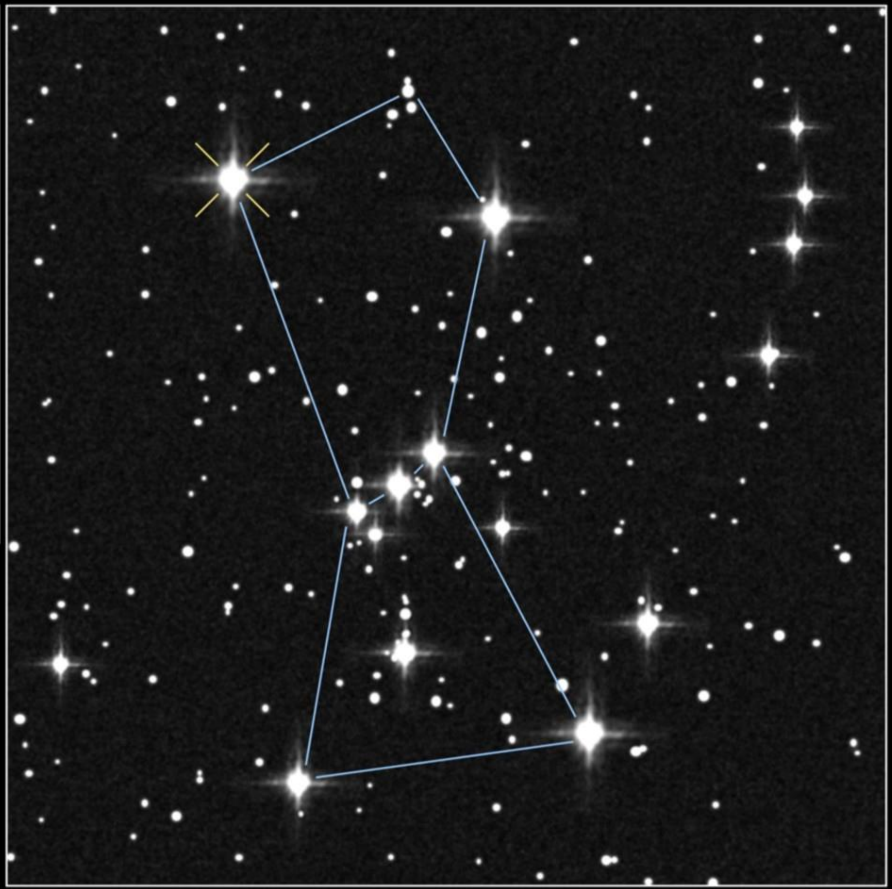
Last Observed Supernova: 1885A



Observed Supernovae:
1917A, 1939C, 1948B, 1968D, 1969P,
1980K, 2002hh, 2004et, 2008S,
N6946-BH1 (failed SN 2009/10)

The Red Supergiant Betelgeuse (Alpha Orionis)





First resolved image of a star other than Sun

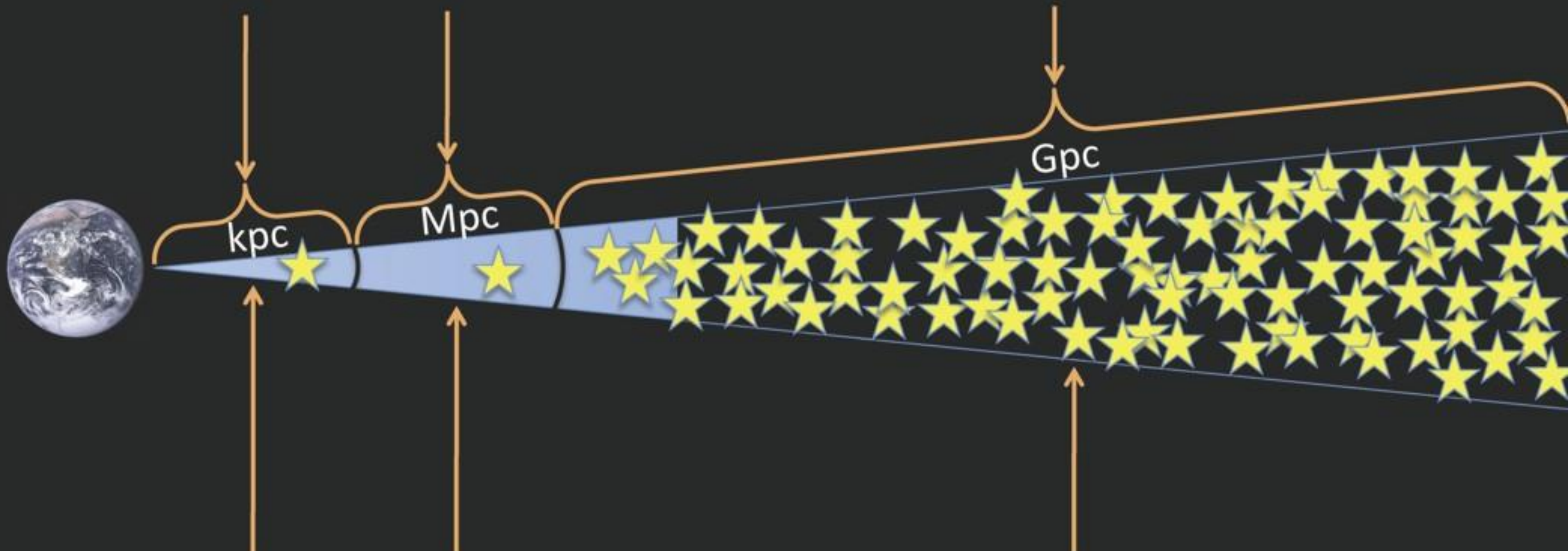
Distance (Hipparcos) 130 pc (425 lyr)

If Betelgeuse goes Supernova:

- 6×10^7 neutrino events in Super-Kamiokande
- 2.4×10^3 neutrons /day from Si burning phase (few days warning!), need neutron tagging [Odrzywolek, Misiaszek & Kutschera, astro-ph/0311012]

Distance Scales and Detection Strategies

N >> 1 : Burst   N ~ 1 : Mini-Burst   N << 1 : DSNB



Rate ~ 0.01/yr   Rate ~ 1/yr   Rate ~ 10^8/yr

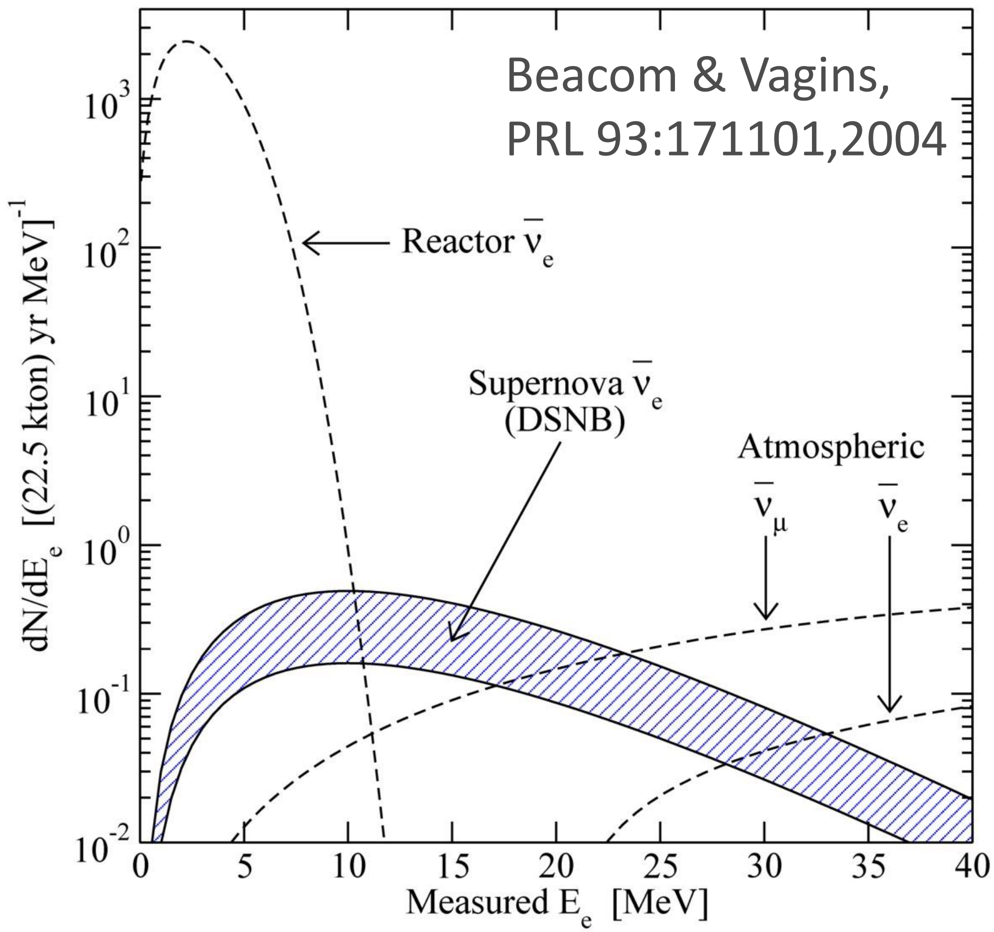
high statistics, all flavors

object identity, burst variety

cosmic rate, average emission

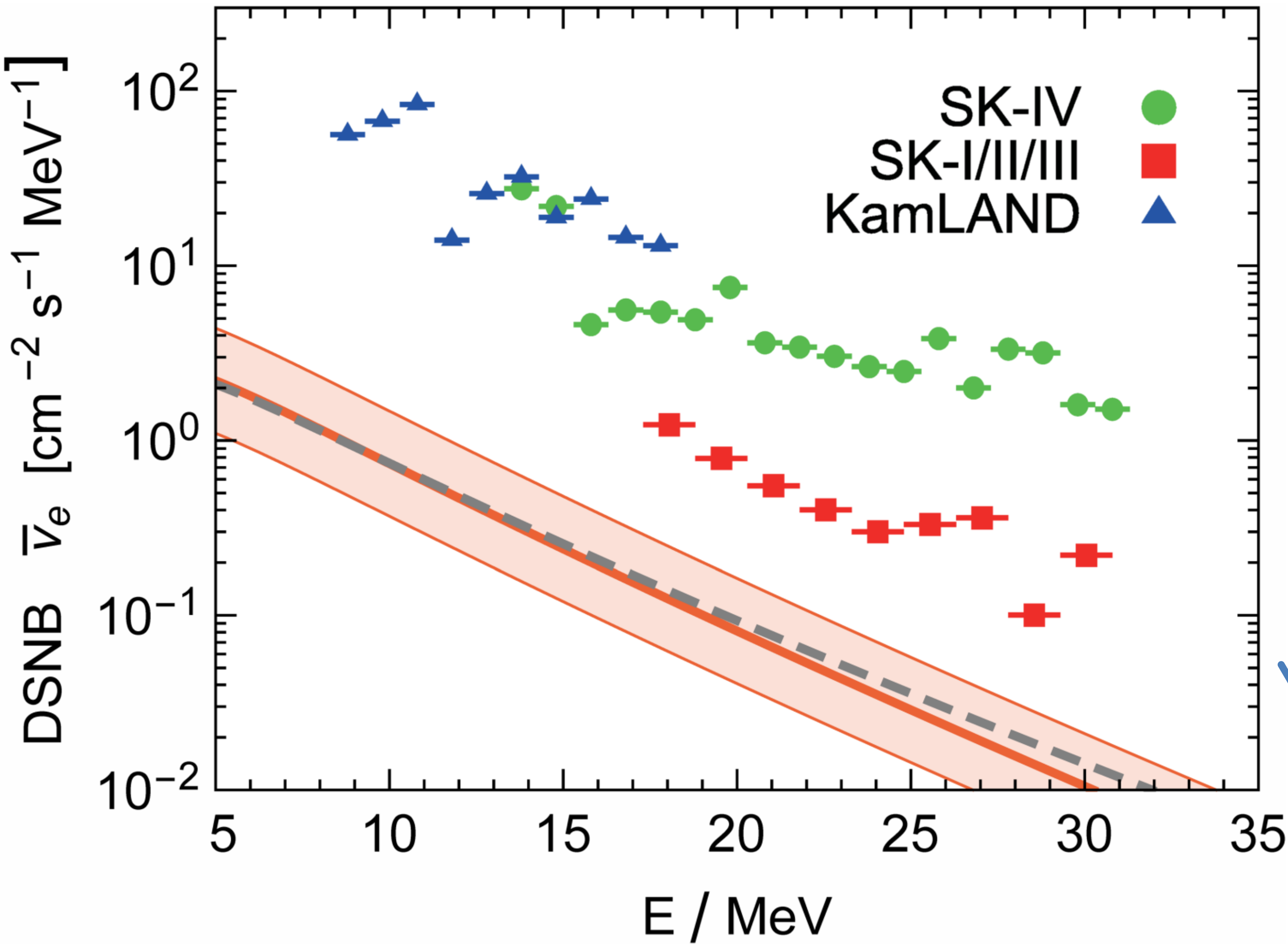
Diffuse Supernova Neutrino Background (DSNB)

- A few core collapses/sec in the visible universe
- Emitted ν energy density
  ~ extra galactic background light
  ~ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  $\sim 10\ \mathrm{cm^{-2}\ s^{-1}}$
  mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!



Window of opportunity between reactor $\overline{\nu}_e$ and atmospheric ν bkg

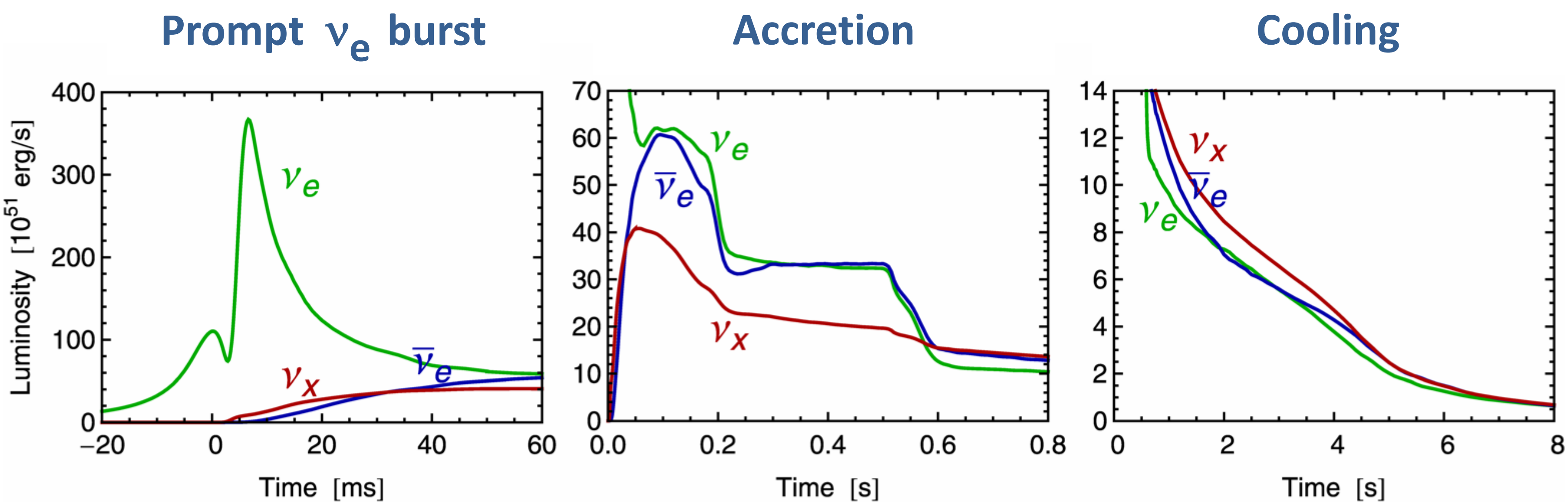
Experimental DSNB Limits



- Super-K with Gadolinium enhancement (neutron tagging)
- JUNO

will probably lead to detection

Three Phases – Three Opportunities



“Standard Candle”

- SN theory
- Distance
- Flavor conversions
- Multi-messenger time of flight

Strong variations (progenitor, 3D effects, black hole formation, …)

- Testing astrophysics of core collapse
- Flavor conversion has strong impact on signal

EoS & mass dependence

- Testing Nuclear Physics
- Nucleosynthesis in neutrino-driven wind
- Particle bounds from cooling speed (axions …)

Many large detectors online for next decades

Every year a 3% chance

I am optimistic to see more SN neutrinos!