ILIAS Axion Training, 30 Nov-2 Dec 2005, CERN, Geneva

Astrophysical Axion Bounds

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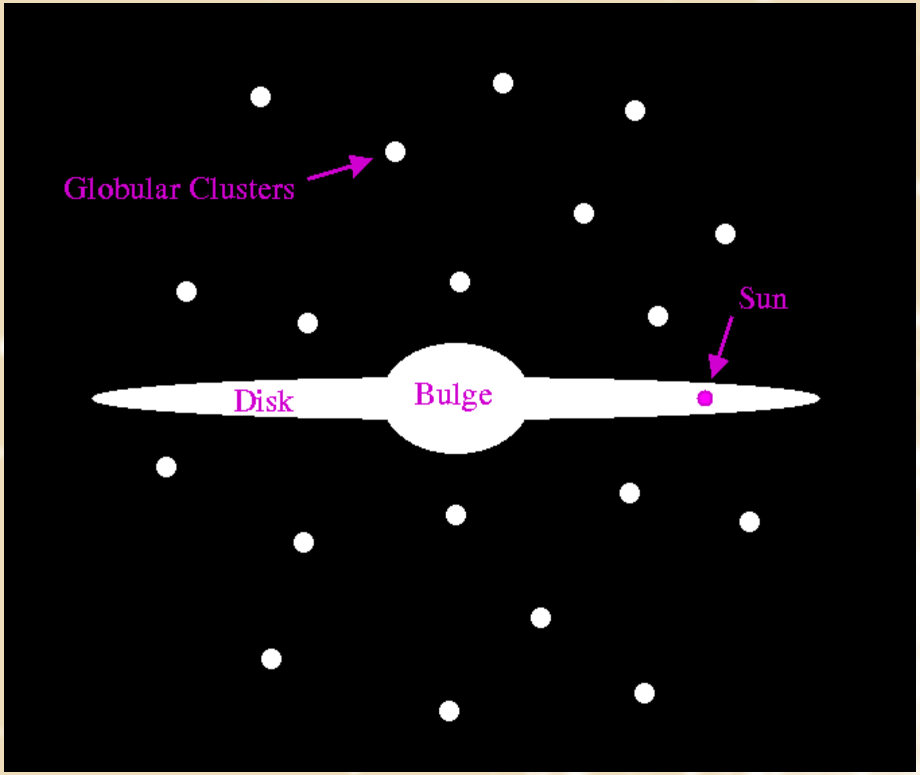
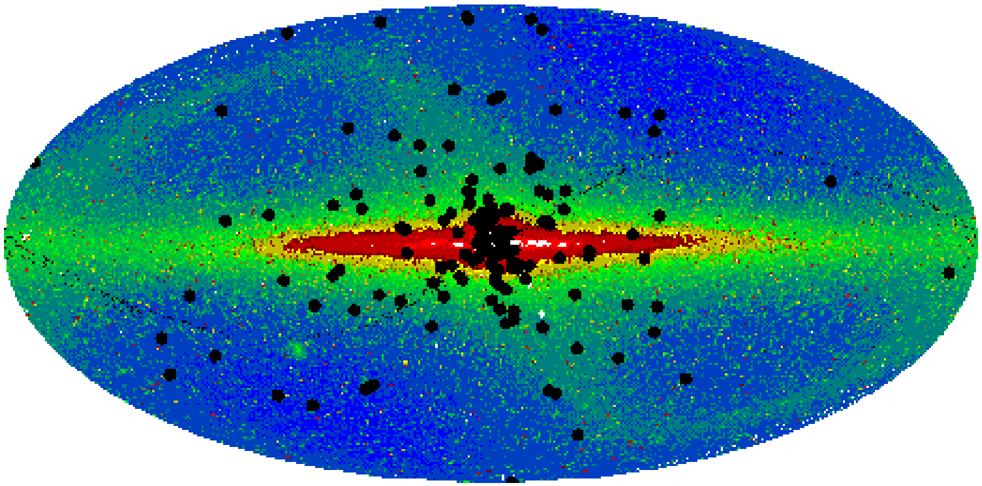
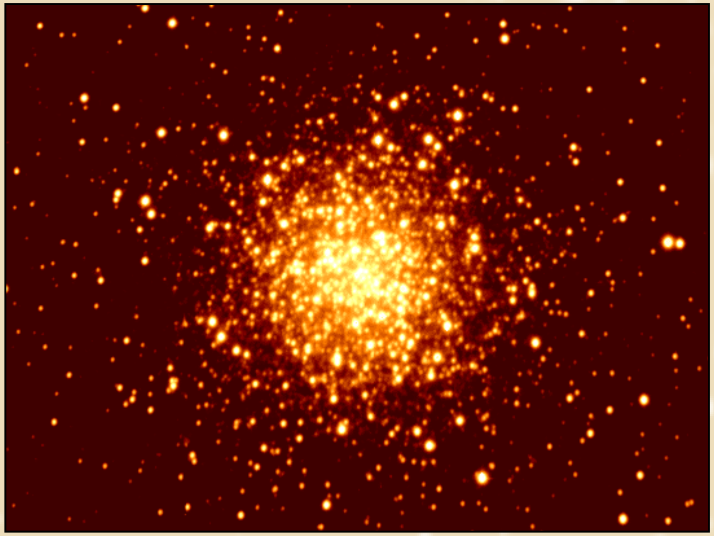
Globular Clusters of the Milky Way





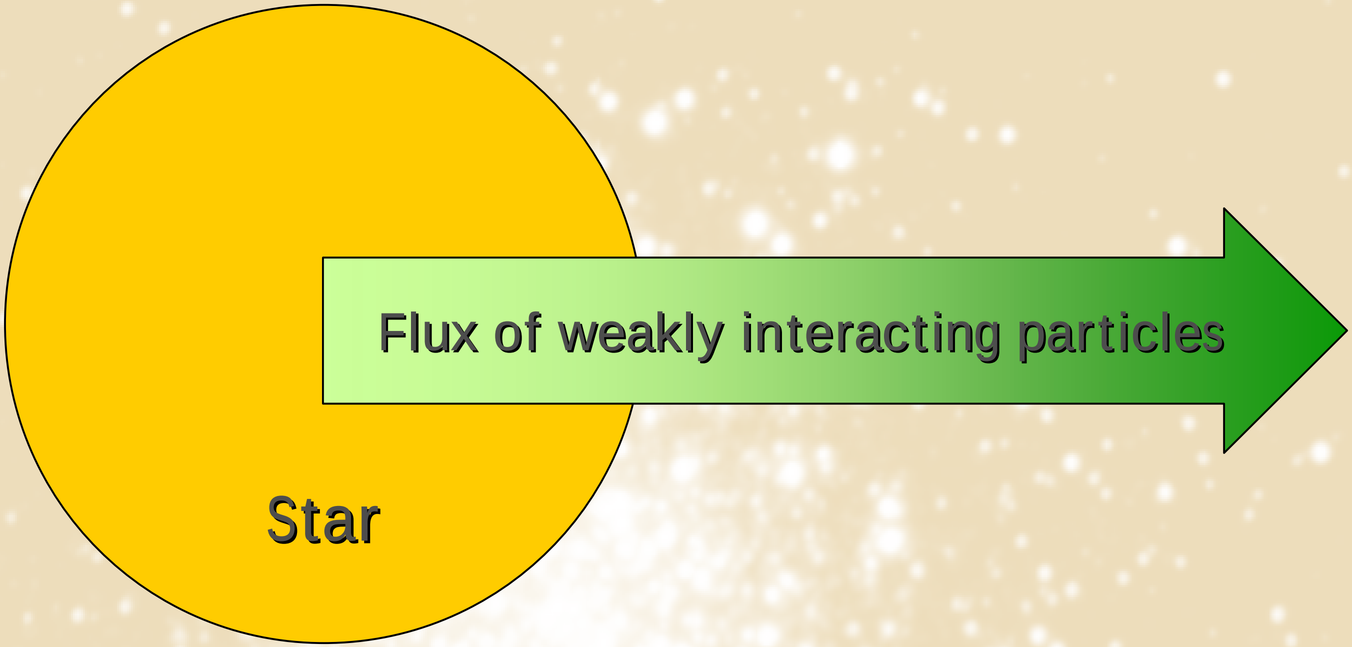
http://www.dartmouth.edu/~chaboyer/mwgc.html

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



The galactic globular cluster M3

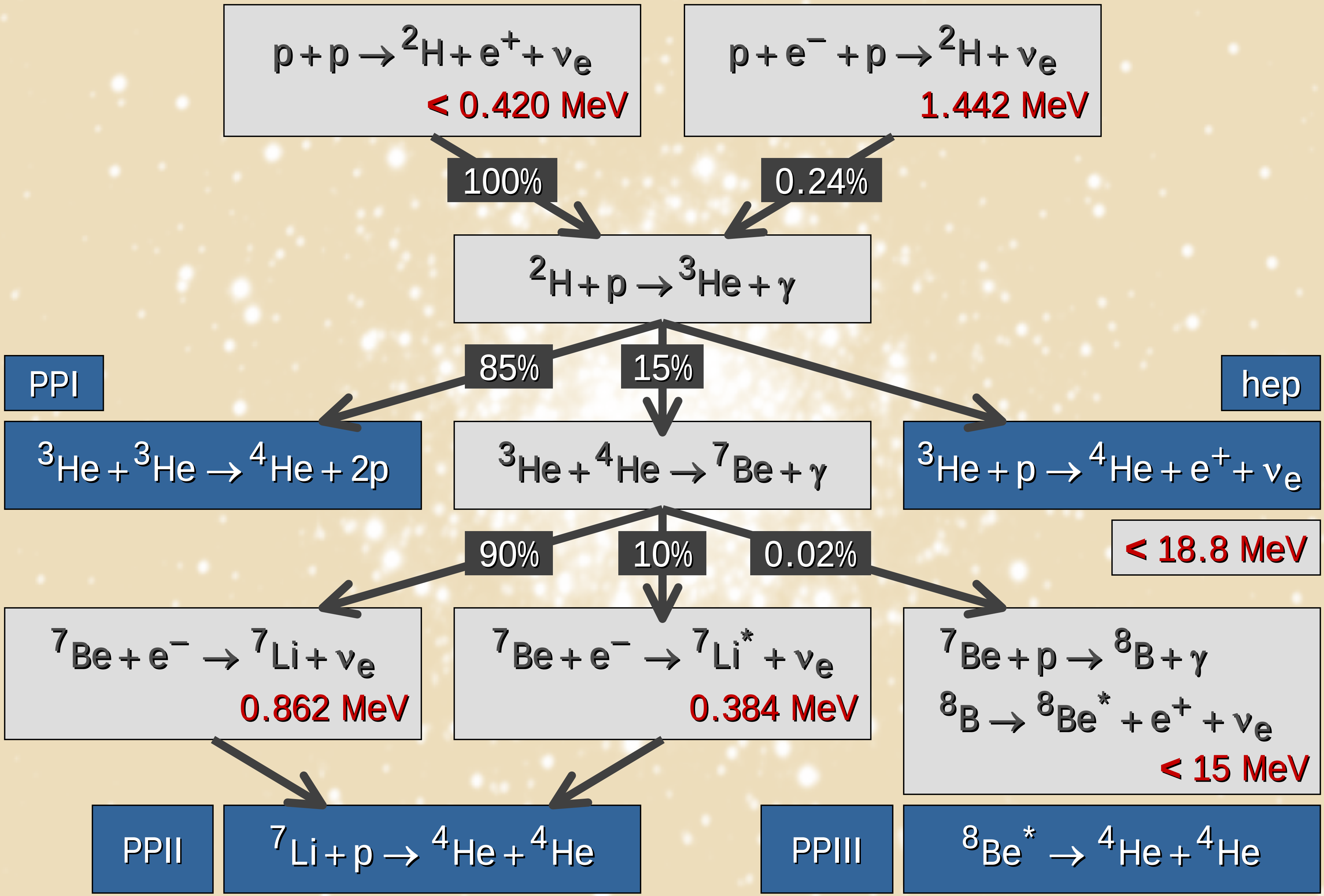
Basic Argument



- Invisible axions have very small mass
- Emission from stellar plasma not suppressed by threshold effects (analogous to neutrinos)
- New energy-loss channel
- Back-reaction on stellar properties and evolution

- What are the emission processes?
- What are the observable consequences?

Hydrogen burning: Proton-Proton Chains



Neutrinos from Thermal Plasma Processes

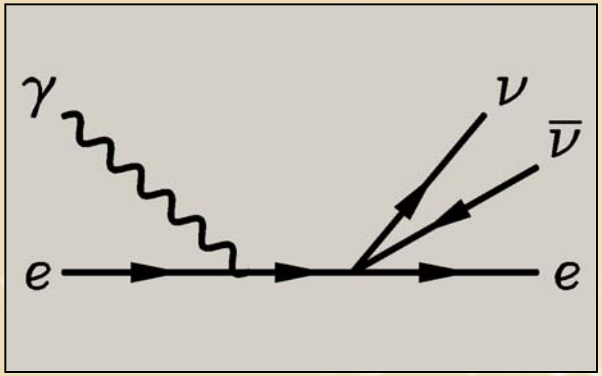
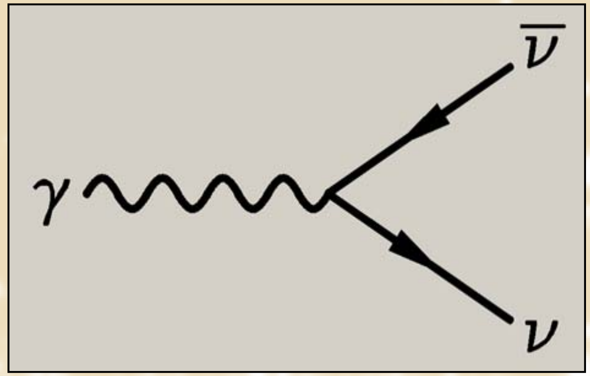
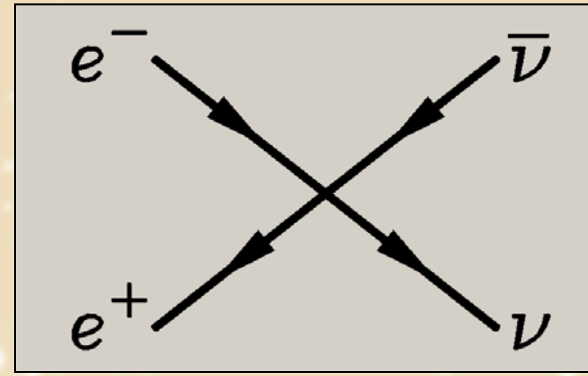


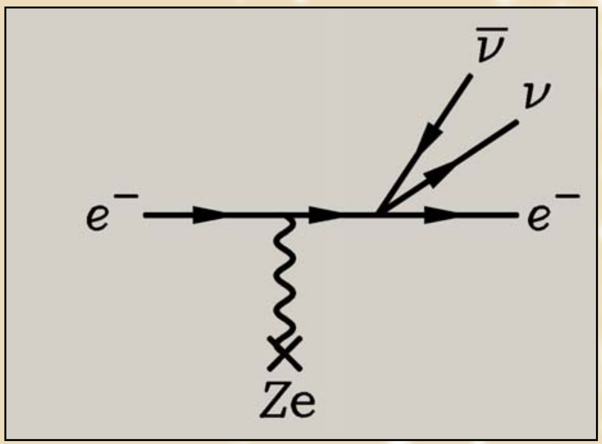
Photo (Compton)



Plasmon decay

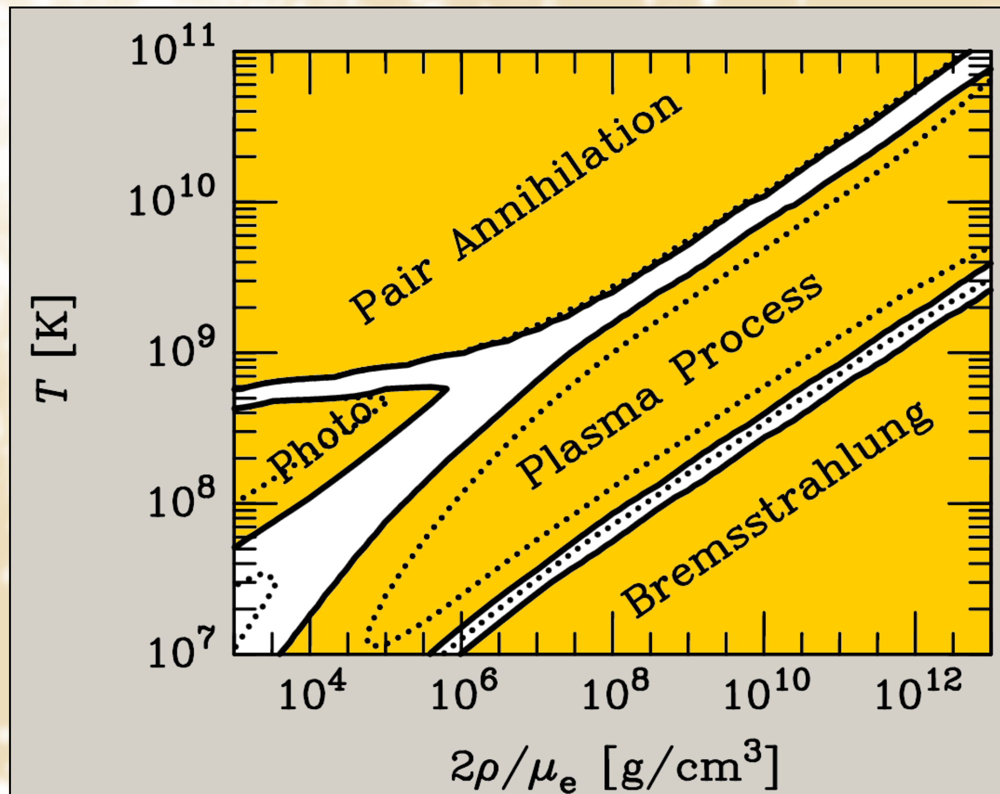


Pair annihilation



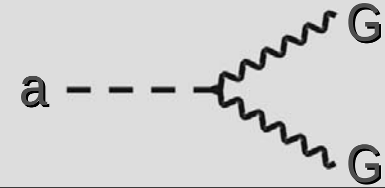
Bremsstrahlung

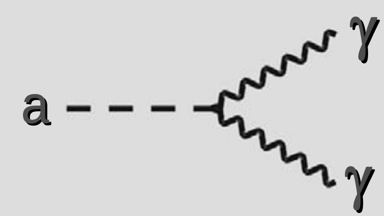
These processes first discussed in 1961-63 after V–A theory

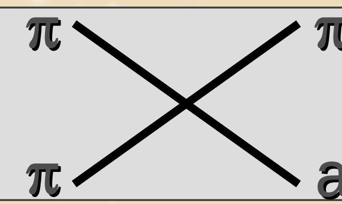


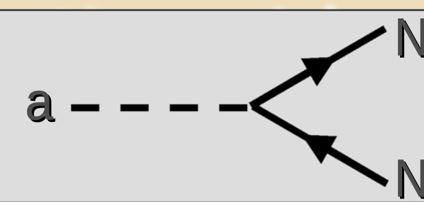
Axion Properties

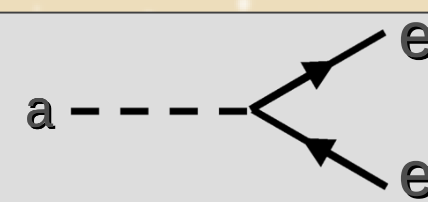
Gluon coupling (Generic property)	$L_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$
Mass	$m_a = \frac{0.6\,\mathrm{eV}}{f_a/10^7\,\mathrm{GeV}} \approx \frac{m_\pi f_\pi}{f_a}$
Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\vec{E}\cdot\vec{B}\,a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$
Pion coupling	$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \ldots)\partial^\mu a$
Nucleon coupling (axial vector)	$L_{aN} = \frac{C_N}{2f_a}\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\partial_\mu a$
Electron coupling (optional)	$L_{ae} = \frac{C_e}{2f_a}\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\,\partial_\mu a$



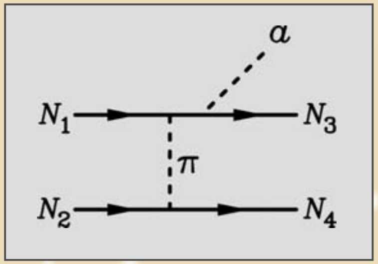
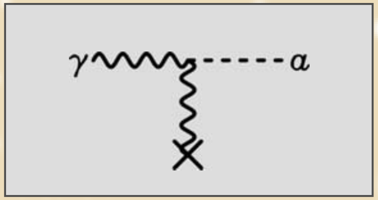
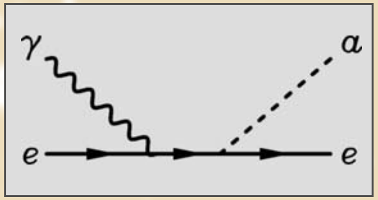
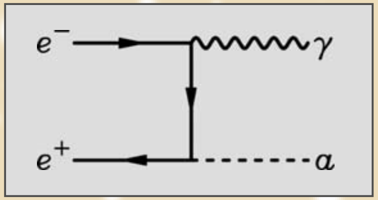
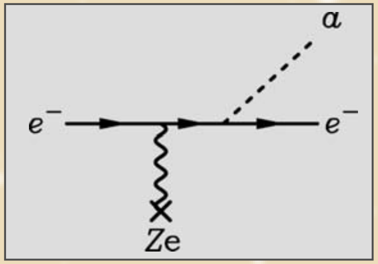




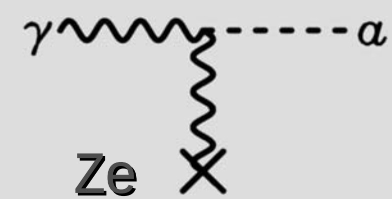




Axion or Graviton Emission Processes in Stars

Nucleons	$\frac{C_N}{2f_a}\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\,\partial^\mu a$	Nucleon Bremsstrahlung	
Photons	$C_\gamma\,\frac{\alpha}{2\pi f_a}\,\vec{E}\cdot\vec{B}\,a$	Primakoff	
Electrons	$\frac{C_e}{2f_a}\overline{\Psi}_e\gamma_\mu\gamma_5\Psi_e\,\partial^\mu a$	Compton	
		Pair Annihilation	
		Electromagnetic Bremsstrahlung	

Primakoff Process in the Sun

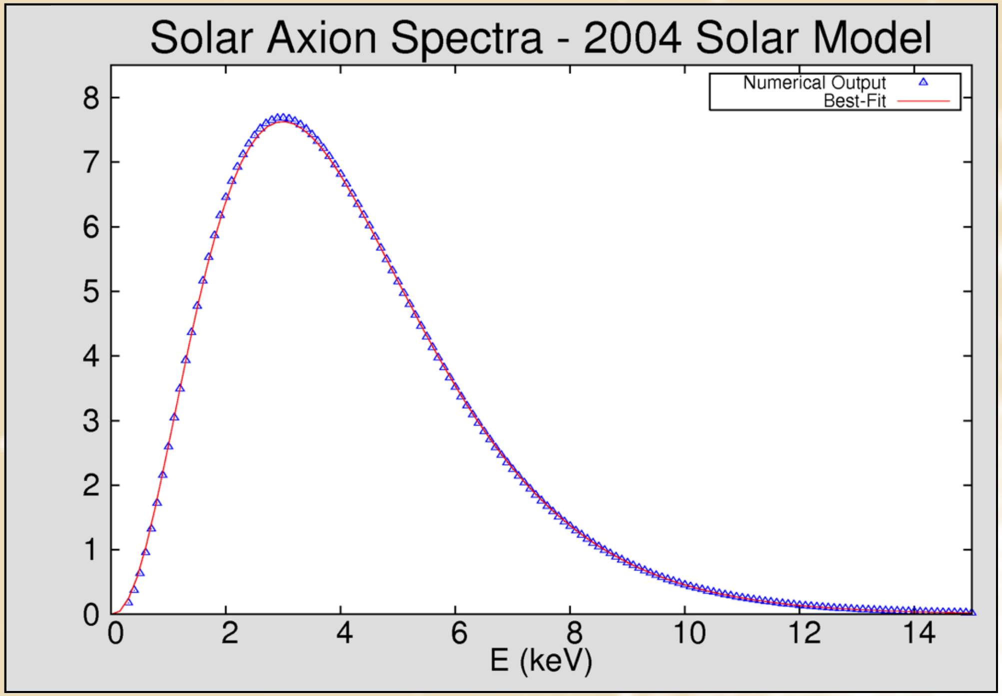
Interaction Lagrangian	$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$
Primakoff cross section	$\frac{d\sigma_{\gamma \to a}}{d\Omega} = \frac{g_{a\gamma}^2 Z^2 \alpha}{8\pi} \frac{\left\vert \vec{k}_a \times \vec{k}_\gamma \right\vert^2}{\left\vert \vec{k}_a - \vec{k}_\gamma \right\vert^4}$ 
Conversion rate (screening effects, no nuclear recoil)	$\Gamma_{\gamma \to a} = \frac{g_{a\gamma}^2 T k_S^2}{32\pi} \left[\left(1 + \frac{k_S^2}{4E^2} \right) \ln \left(1 + \frac{4E^2}{k_S^2} \right) - 1 \right]$
Screening scale (non-relativistic non-degenerate)	$\kappa_S^2 = \frac{k_S^2}{4T^2} = \frac{\pi\alpha}{T^3} n_B \left(Y_e + \sum_j Z_j^2 Y_j \right)$ Sun $\kappa_S^2 \approx 12$ HB Star $\kappa_S^2 \approx 2.5$

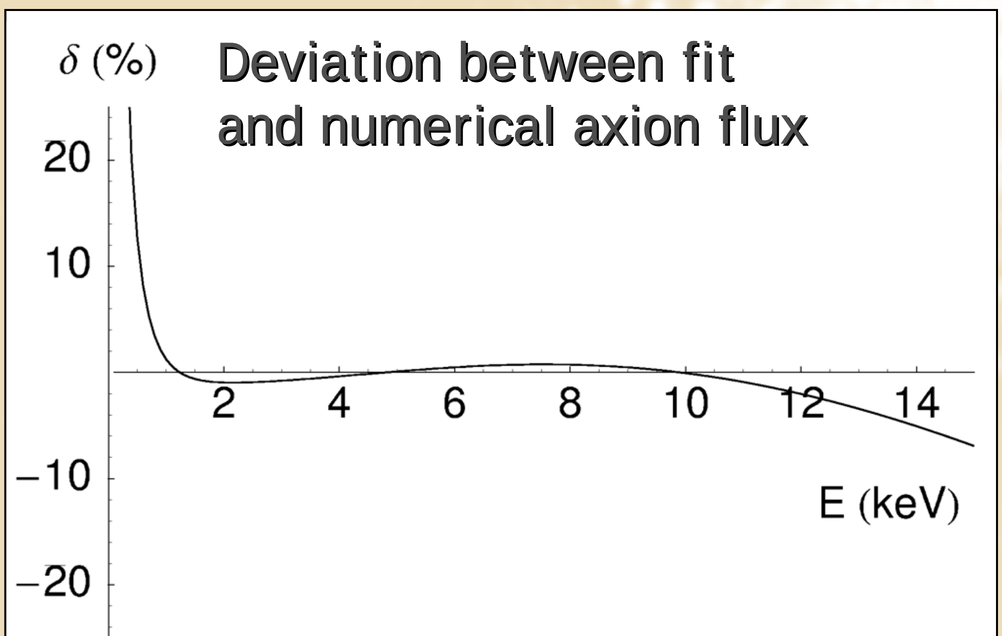
- G. Raffelt, "Astrophysical axion bounds diminished by screening effects", Phys. Rev. D 33 (1986) 897 (Part of GR's Ph.D. Thesis)
- Consistent with results from FTD methods, see Altherr, Petitgirard & del Rio Gaztelurrutia, Astropart. Phys. 2 (1994) 175

Energy-Loss Rate of the Sun

Conversion rate	$\Gamma_{\gamma\to a} = \frac{g_{a\gamma}^2 T k_S^2}{32\pi}\left[\left(1+\frac{k_S^2}{4E^2}\right)\ln\left(1+\frac{4E^2}{k_S^2}\right)-1\right]$ $\approx g_{10}^2\ 10^{-15}\,\mathrm{s}^{-1}$ for few keV-energy photons (Sun) $g_{10} = \frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}$
Energy-Loss Rate	$Q = \int \frac{2d^3\vec{k}_\gamma}{(2\pi)^3}\frac{\Gamma_{a\to\gamma}E}{e^{E/T}-1} = \frac{g_{a\gamma}^2 T^7}{4\pi}F(\kappa_S^2)$ $F(\kappa_S^2) = \frac{\kappa_S^2}{2\pi^2}\int_0^\infty dx\left[(x^2+\kappa_S^2)\ln\left(1+\frac{x^2}{\kappa_S^2}\right)-x^2\right]\frac{x}{e^x-1}$
Solar Axion Luminosity	$L_a = g_{10}^2\ 1.85\times10^{-3}L_{\mathrm{sun}}$

Solar Axion Spectrum





"Power-law" fit

$$\frac{d\Phi_a}{dE} = A\left(\frac{E}{\bar{E}}\right)^{\alpha} e^{-(\alpha+1)\,E/\bar{E}}$$

Average energy

$$\langle E\rangle = \bar{E}$$

For $\alpha = 2$ the fit is identical with a Maxwell-Boltzmann distribution

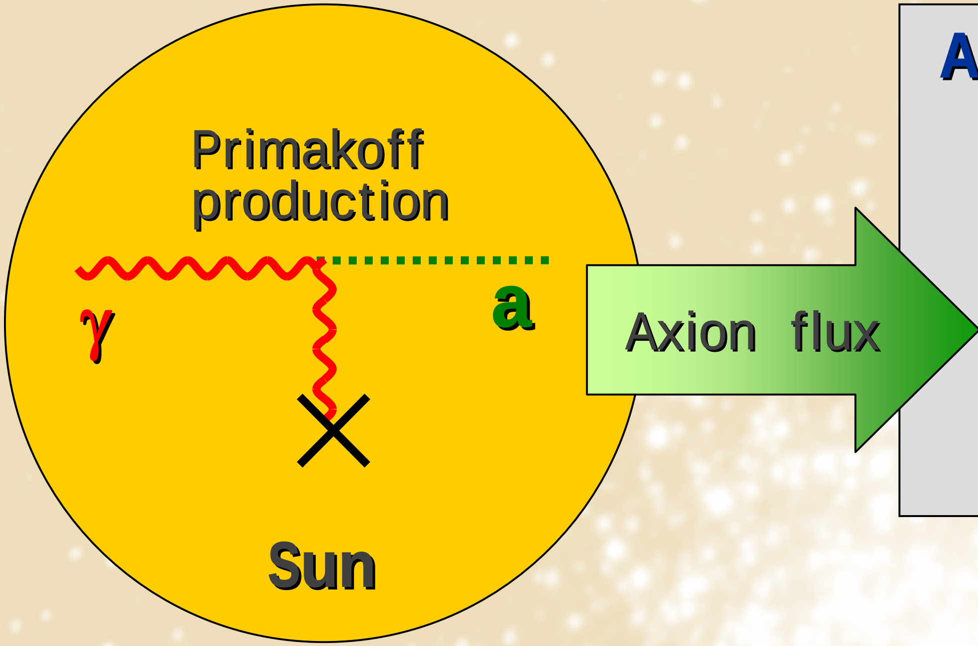
Determine A, α, and $\bar{E}$ such that the total axion flux, $\langle E\rangle$ and $\langle E^2\rangle$ are exactly reproduced

With 2004 solar model

$$\bar{E} = 4.196\ \text{keV}$$

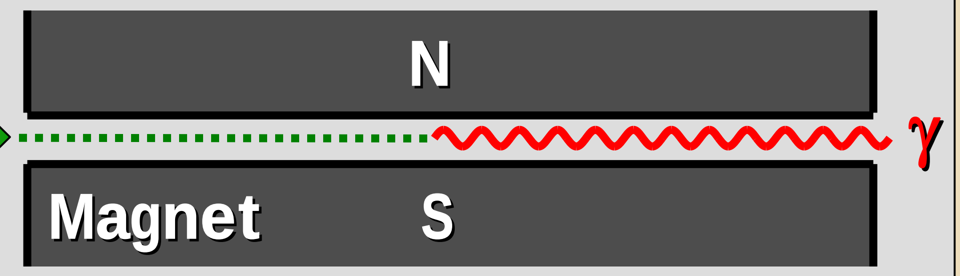
$$\alpha = 2.481$$

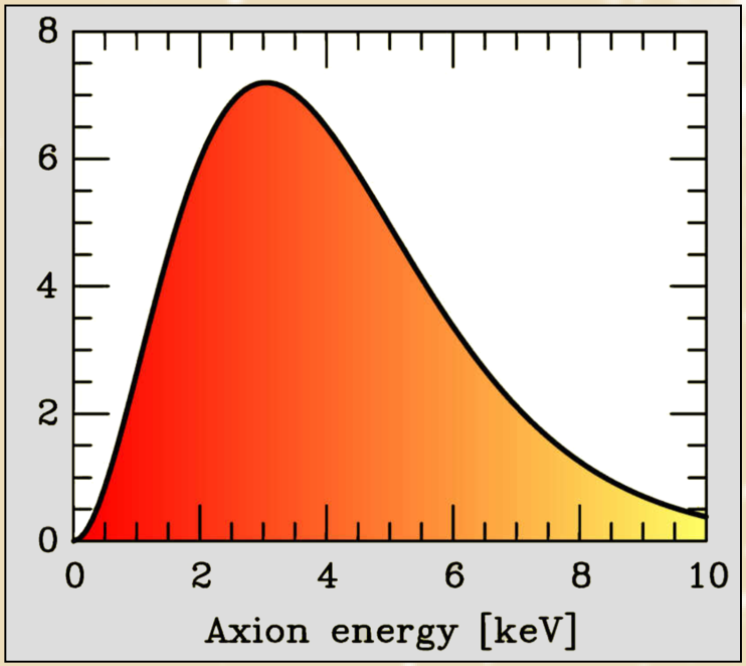
Search for Solar Axions



Axion Helioscope (Sikivie 1983)

Axion-Photon-Oscillation





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

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

Basics of Stellar Evolution

Equations of Stellar Structure

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

Hydrostatic equilibrium	$\frac{dP}{dr} = -\frac{G_N M_r \rho}{r^2}$
Energy conservation	$\frac{dL_r}{dr} = 4\pi r^2 \varepsilon \rho$
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)

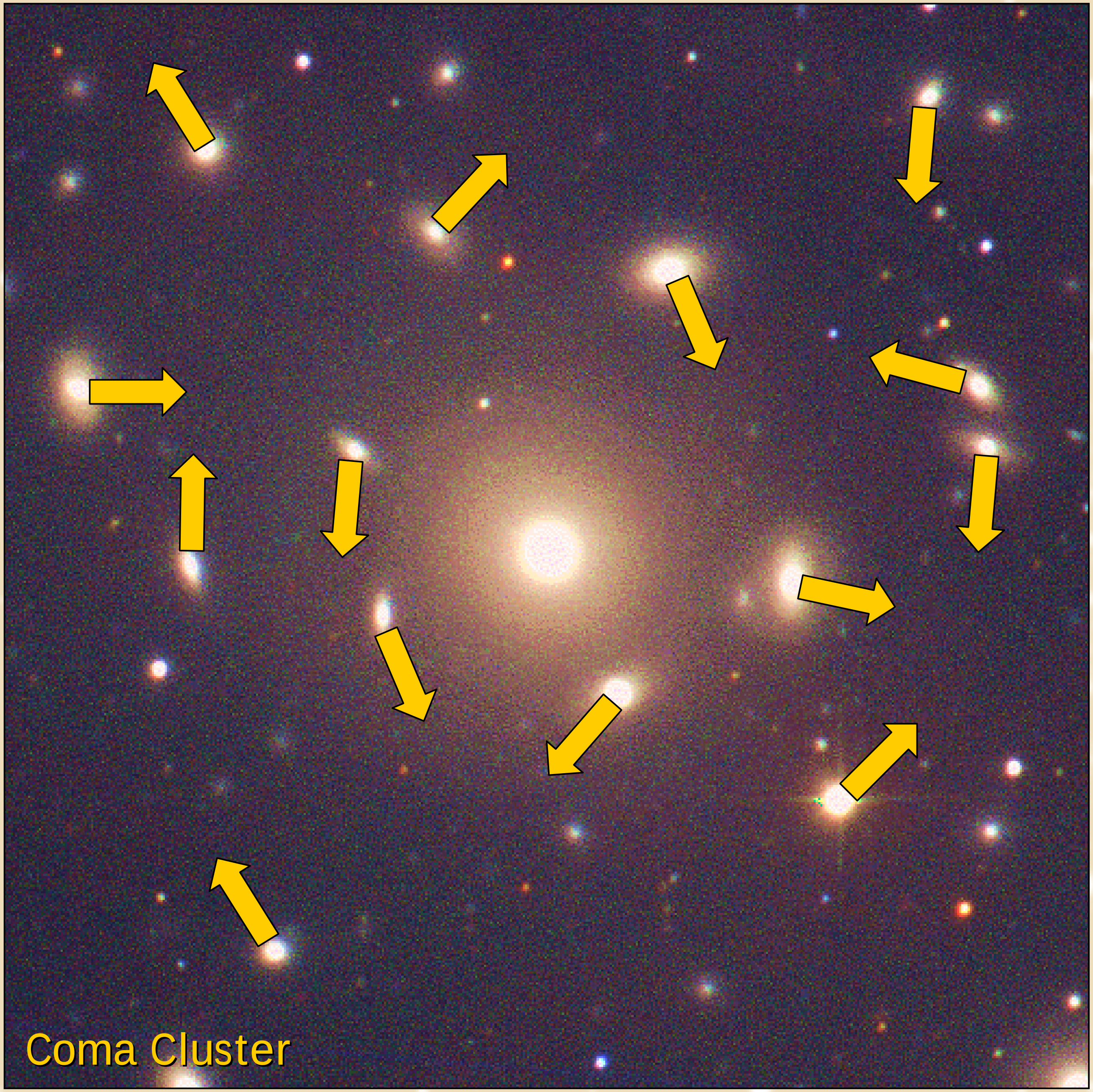
r	Radius from center
P	Pressure
G_N	Newton's constant
ρ	Mass density
M_r	Integrated mass up to r
L_r	Luminosity (energy flux)
ε	Local rate of energy generation [erg/g/s]
	$\varepsilon = \varepsilon_{nuc} + \varepsilon_{grav} - \varepsilon_\nu$
κ	Opacity
	$\kappa^{-1} = \kappa_\gamma^{-1} + \kappa_c^{-1}$
κ_γ	Radiative opacity
	$\kappa_\gamma \rho = \langle \lambda_\gamma \rangle^{-1}_{\text{Rosseland}}$
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	$-3\int_0^R dr\, 4\pi r^2 P = E_{grav}^{tot}$
Classical monatomic gas: $P = \frac{2}{3}U$ (U density of internal energy)	$U^{tot} = -\frac{1}{2}E_{grav}^{tot}$
Average energy of single "atoms" of the gas	$\langle E_{kin}\rangle = -\frac{1}{2}\langle E_{grav}\rangle$ — Virial Theorem

Most important tool to understand self-gravitating systems

Dark Matter in Galaxy Clusters



A gravitationally bound system of many particles obeys the virial theorem

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

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

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

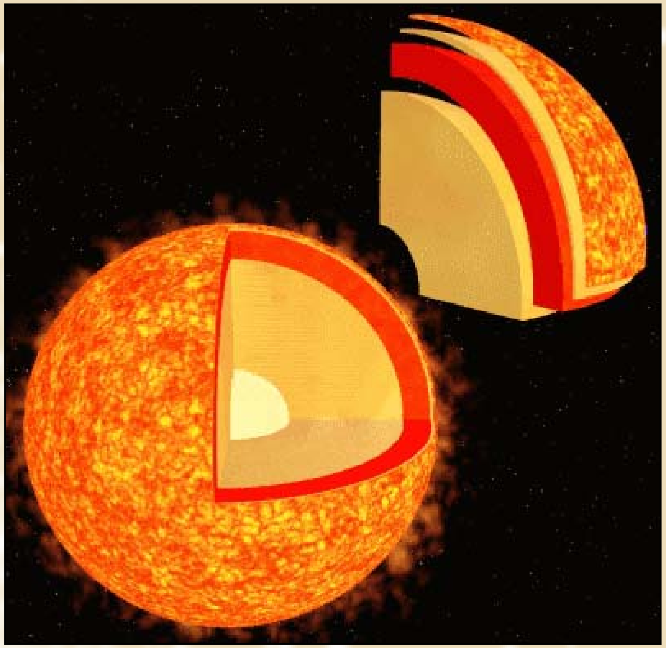
Velocity dispersion from Doppler shifts and geometric size

Total Mass

Virial Theorem Applied to the Sun

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

Virial Theorem



Approximate Sun as a homogeneous sphere with

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

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

Gravitational potential energy of a proton near center of the sphere

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

Thermal velocity distribution

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

Estimated temperature

$T = 1.1\ \mathrm{keV}$

Central temperature from standard solar models

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

Thermonuclear Reactions and Gamow Peak

Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling

Tunneling probability

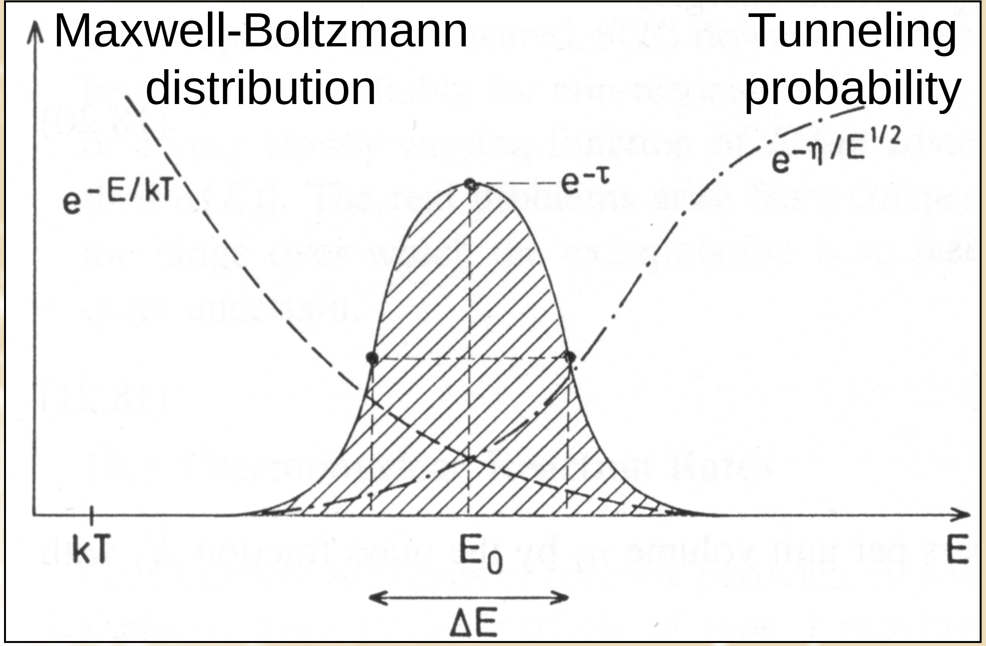
$$p \propto E^{-1/2} e^{-2\pi\eta}$$

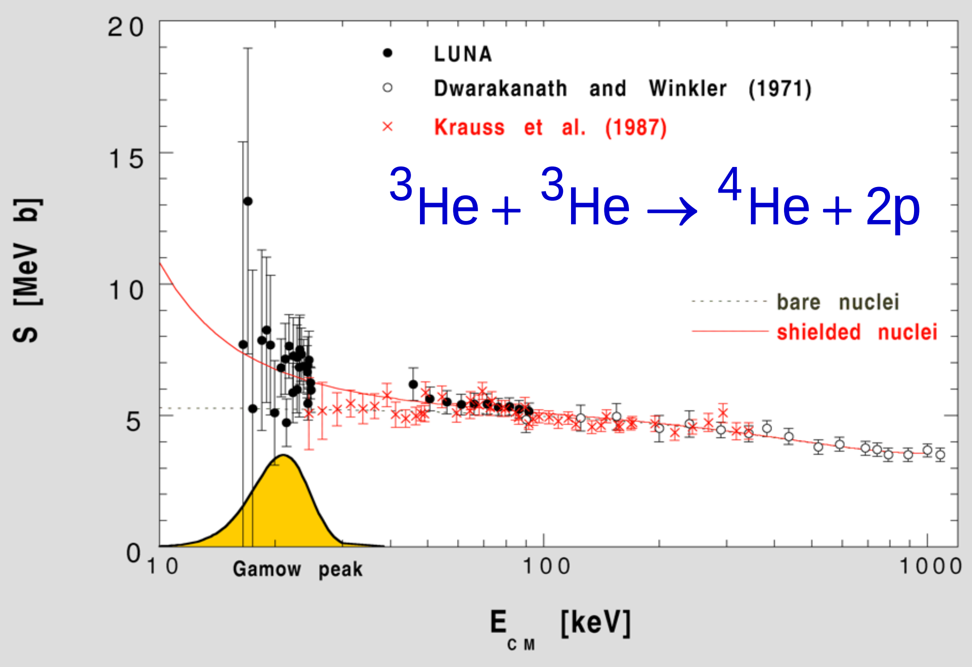
With Sommerfeld parameter

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

Parameterize cross section with astrophysical S-factor

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





LUNA Collaboration, nucl-ex/9902004

Main Nuclear Burnings

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

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

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

Helium burning

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

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

$${}^{12}C + {}^4He \rightarrow {}^{16}O$$

$${}^{16}O + {}^4He \rightarrow {}^{20}Ne$$

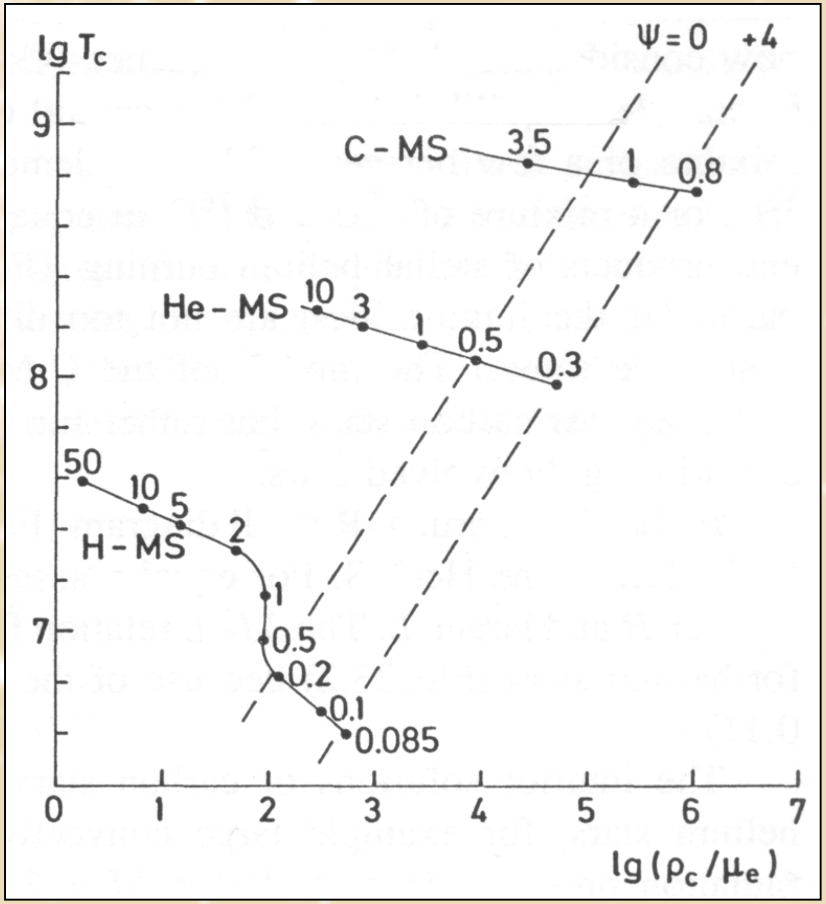
Typical temperatures: 10^8 K (~10 keV)

Carbon burning

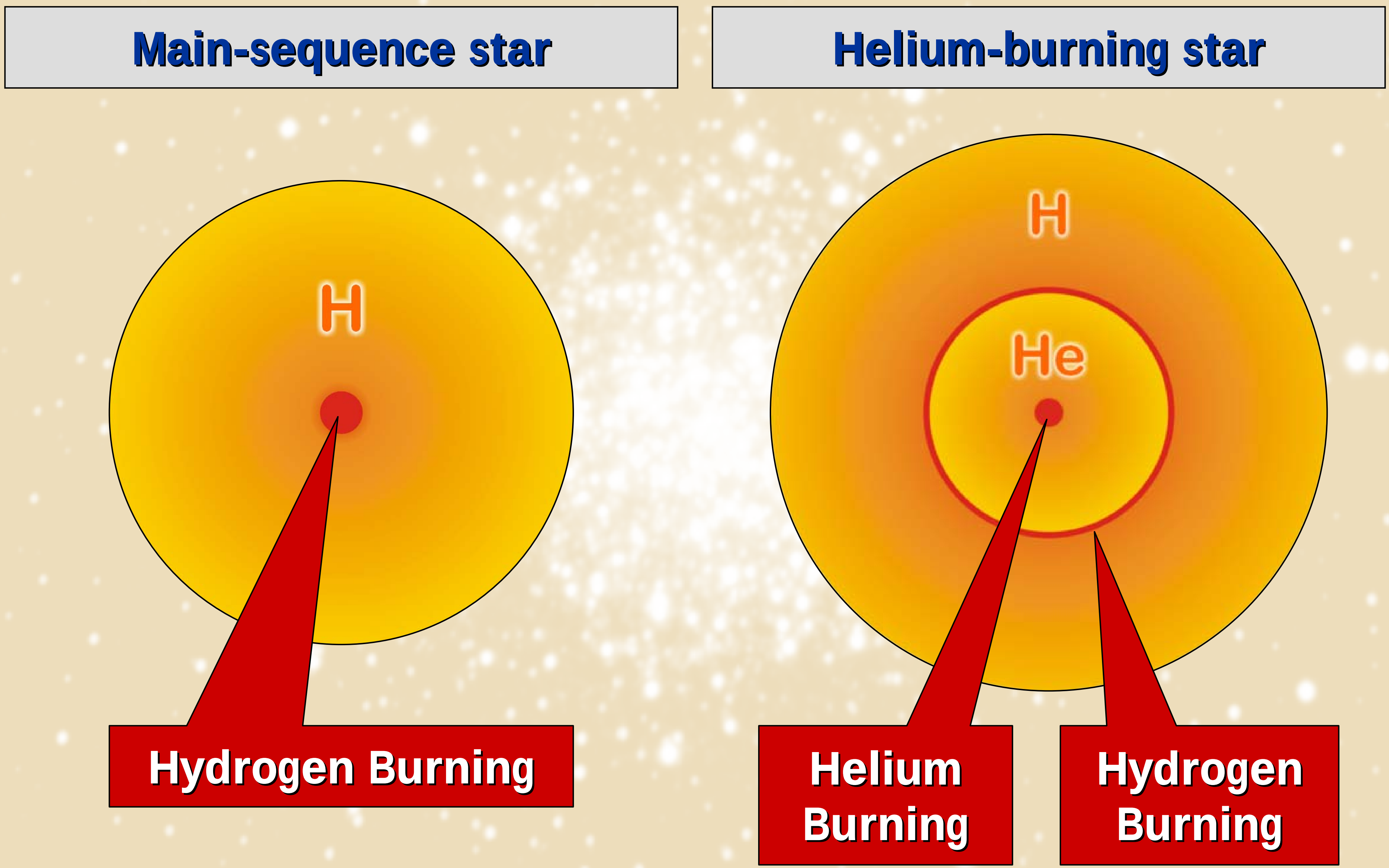
Many reactions, for example

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

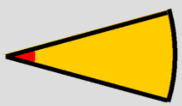
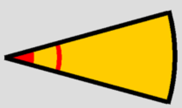
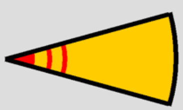
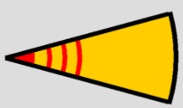
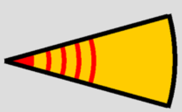
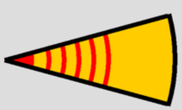
Typical temperatures: 10^9 K (~100 keV)



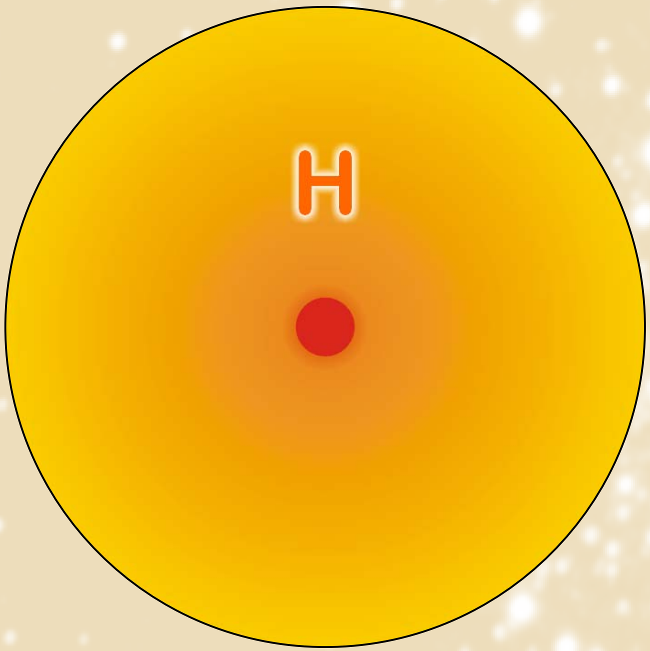
Hydrogen Exhaustion



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}]	L_ν/L_γ	Duration [years]
	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

Self-Regulated Nuclear Burning



Main-Sequence Star

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

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

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

Hydrogen burning at a nearly fixed T
→ Gravitational potential nearly fixed: $G_N M/R \sim$ constant
→ $R \propto M$ (More massive stars bigger)

Modification of Stellar Properties by Axion Emission

Homologous changes of stellar structure

Assume that some small perturbation (e.g. axion emission) leads to "homologous" modification of stellar structure, i.e. every point is mapped to a new position $r' = yr$

Requires power-law relations for constitutive relations

- Nuclear burning rate $\varepsilon \propto \rho^n T^m$
- Mean opacity $\kappa \propto \rho^s T^t$

Implies for other quantities:

- Density $\rho'(r') = y^{-3}\rho(r)$
- Pressure $p'(r') = y^{-4}p(r)$
- Temperature gradient $dT'(r')/dr' = y^{-2}\, dT(r)/dr$

Impact of small exotic energy loss

Modified nuclear burning rate $\varepsilon \propto (1-\delta_x)\varepsilon_{nuc}$

Assume Kramers opacity law $s = 1, \quad t = -3.5$

Hydrogen burning $n = 1, \quad m = 4-6$

$$\frac{\delta R}{R} = \frac{-2\delta_x}{2m+5} \qquad \frac{\delta L_\gamma}{L_\gamma} = \frac{\delta_x}{2m+5} \qquad \frac{\delta T}{T} = \frac{\delta_x}{2m+5}$$

Degenerate Stars ("White Dwarfs")

Assume T very small
→ No thermal pressure
→ Electron degeneracy is pressure source

Pressure ~ Momentum density x Velocity

- Electron density $n_e = p_F^3 / (3\pi^2)$
- Momentum p_F (Fermi momentum)
- Velocity $v \propto p_F / m_e$
- Pressure $P \propto p_F^5 \propto \rho^{5/3} \propto M^{5/3} R^{-5}$
- Density $\rho \propto M R^{-3}$
  (Stellar mass M and radius R)

Hydrostatic equilibrium

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

With dP/dr ~ –P/R we have approximately

$$P \propto G_N M \rho R^{-1} \propto G_N M^2 R^{-4}$$

Inverse mass-radius relationship for degenerate stars: $R \propto M^{-1/3}$

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

(Y_e electrons per nucleon)

For sufficiently large mass, electrons become relativistic

- Velocity = speed of light
- Pressure

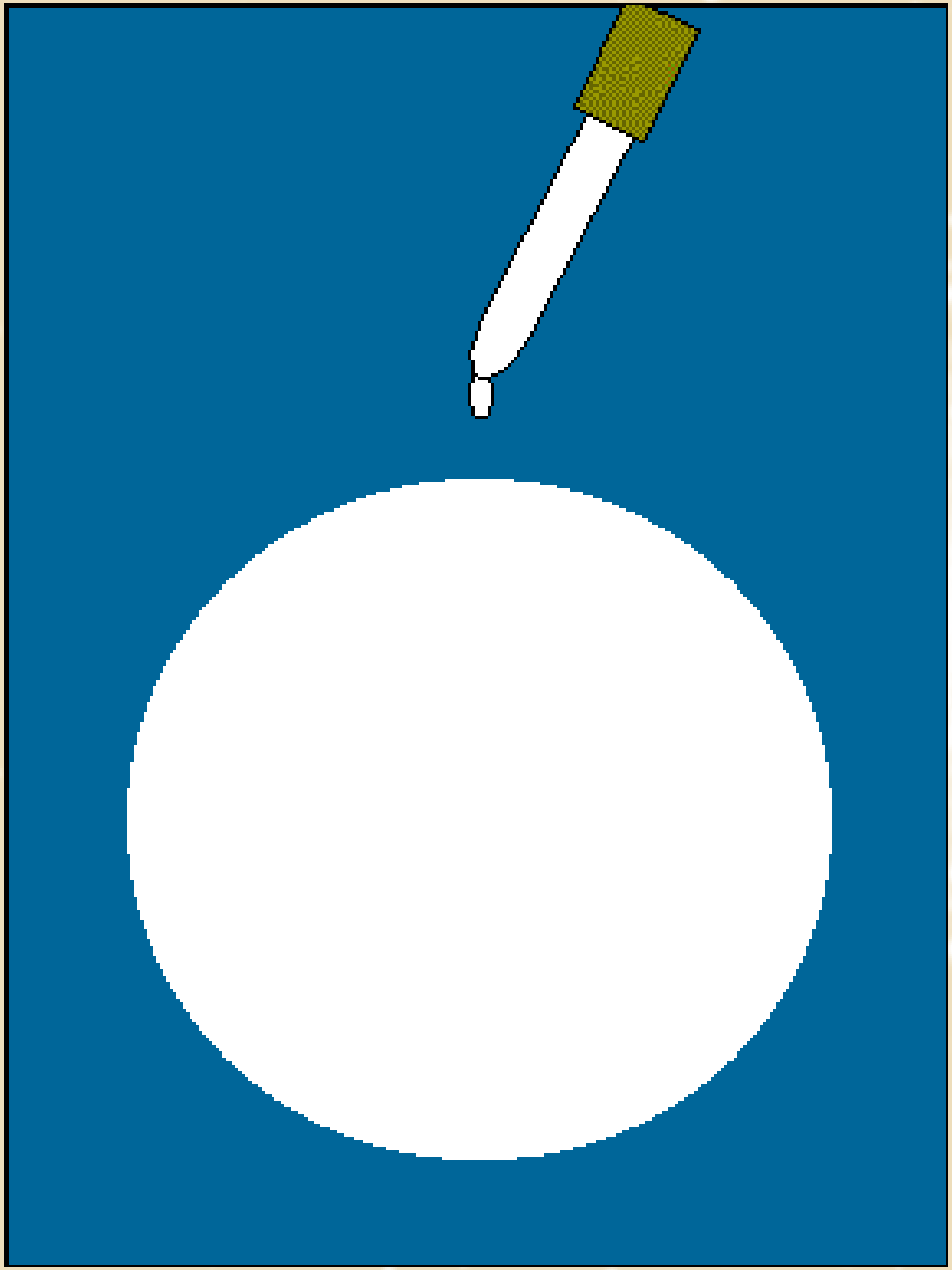
$$P \propto p_F^4 \propto \rho^{4/3} \propto M^{4/3} R^{-4}$$

No stable configuration

Chandrasekhar mass limit

$$M_{Ch} = 1.457\ M_{sun} (2Y_e)^2$$

Degenerate Stars



Inverse mass-radius relationship for degenerate stars: $R \propto M^{-1/3}$

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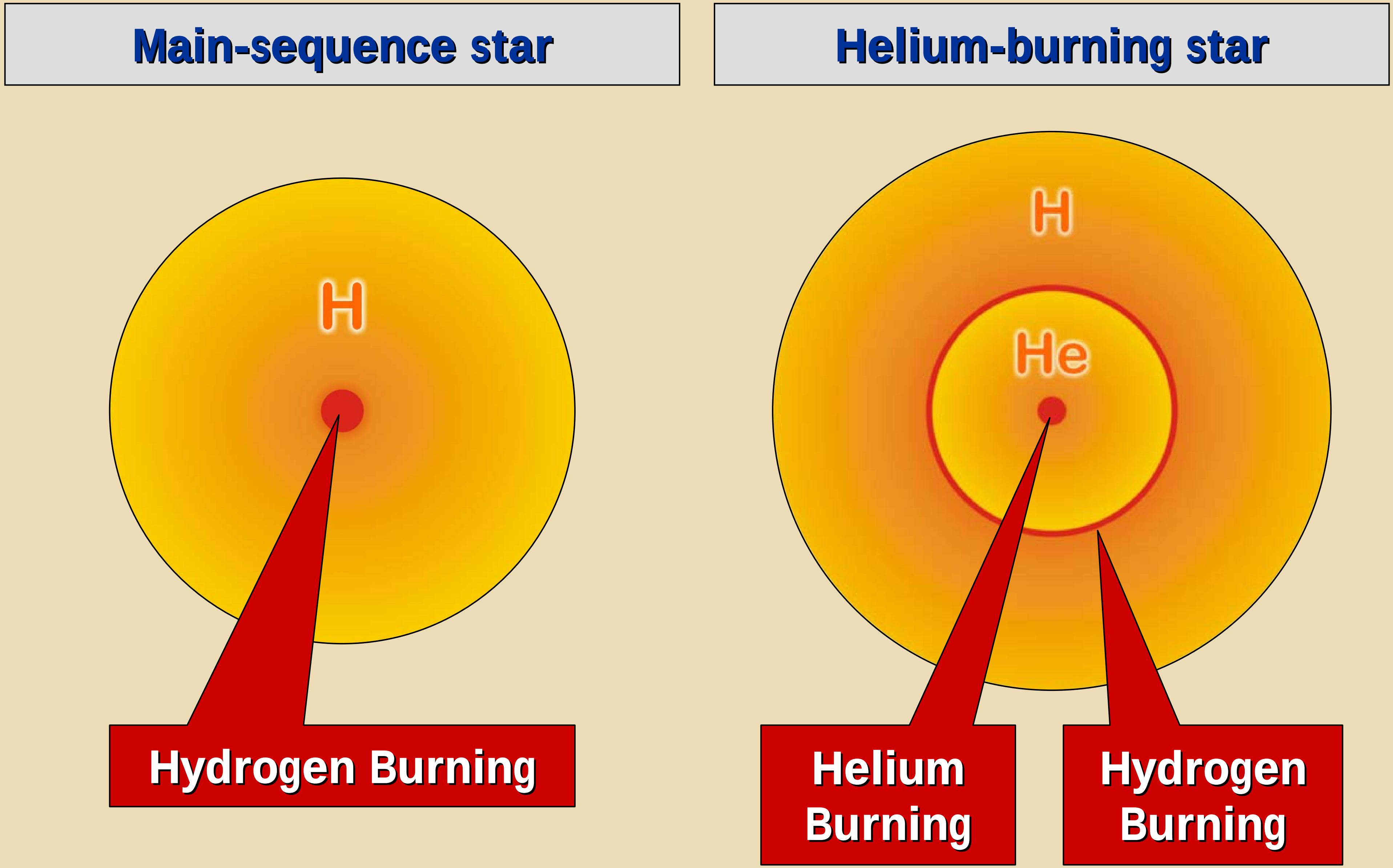
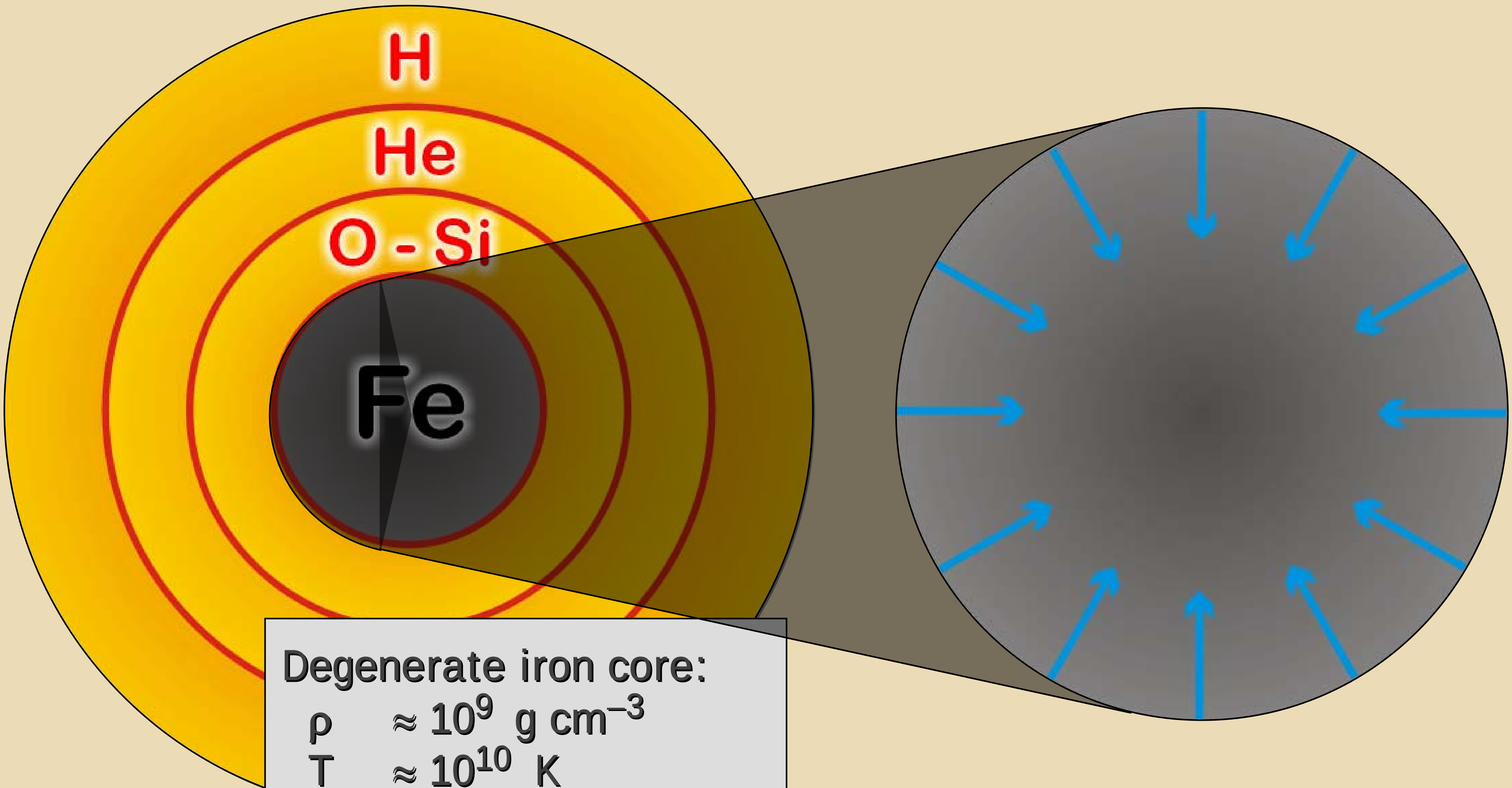
$$M_{Ch} = 1.457\ M_{sun}\,(2Y_e)^2$$

Stellar Collapse



Stellar Collapse

Onion structure | **Collapse (implosion)**



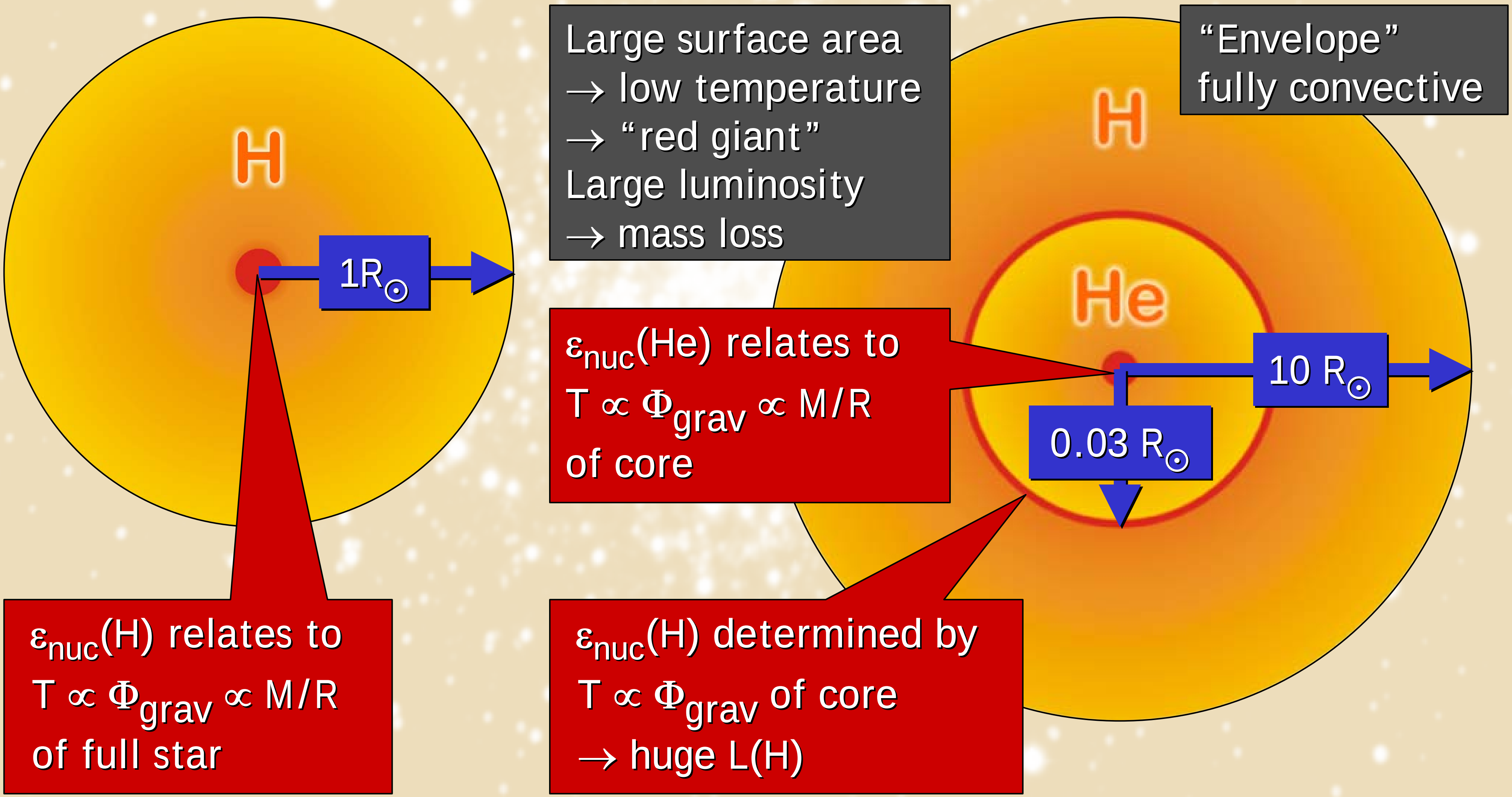
Degenerate iron core:

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

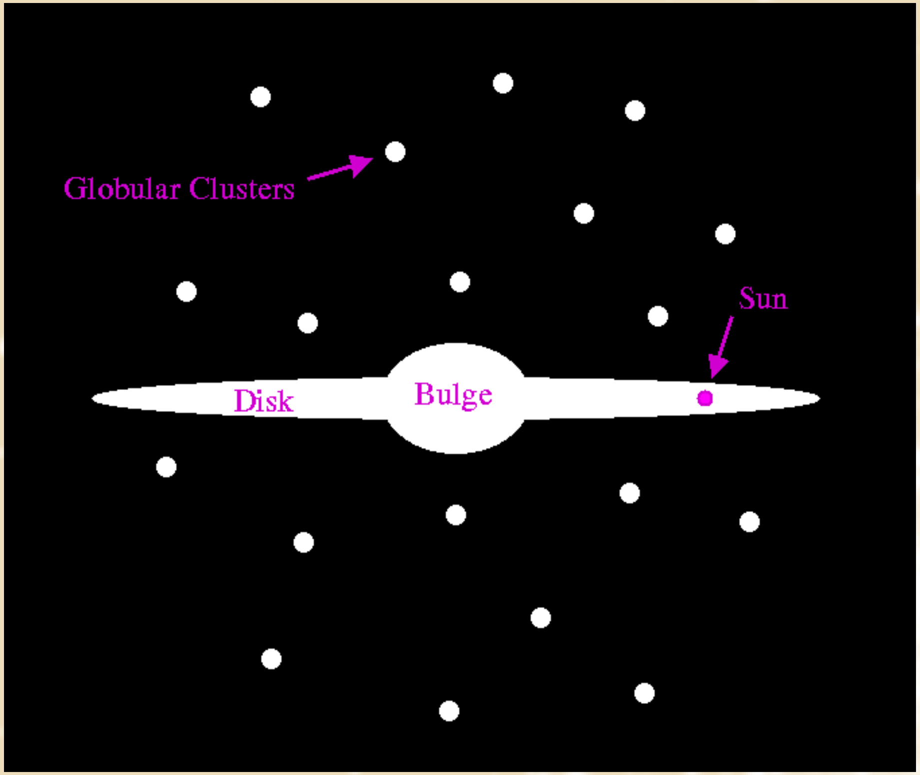
Giant Stars

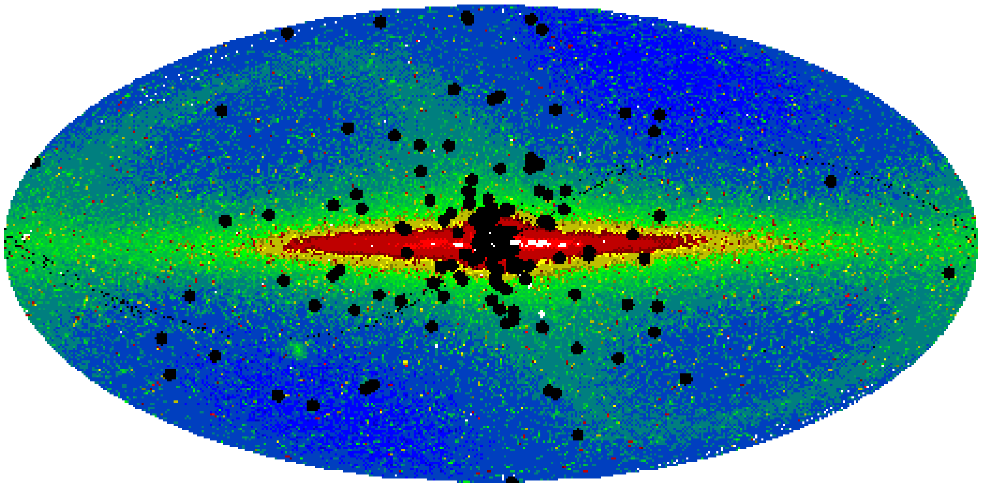
Main-sequence star $1M_\odot$ (Hydrogen burning)

Helium-burning star $1M_\odot$



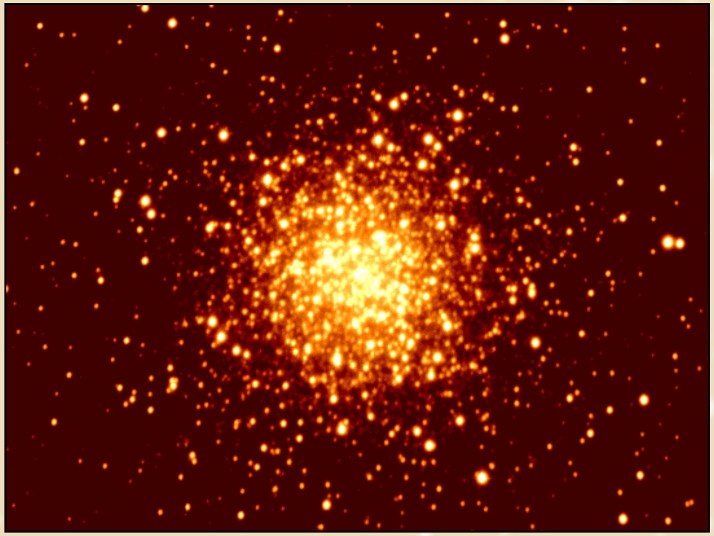
Globular Clusters of the Milky Way





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

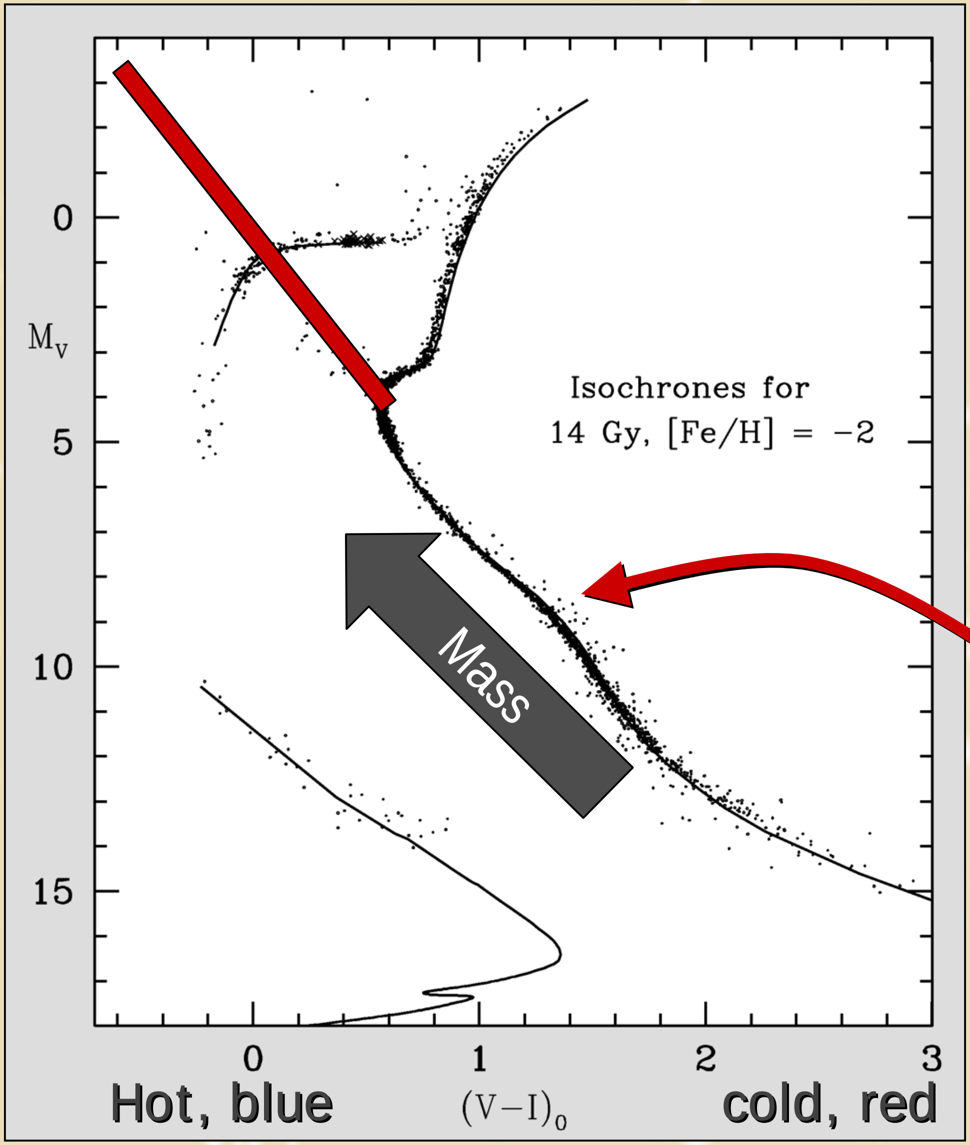
Globular clusters on top of the FIRAS 2.2 micron map of the Galaxy

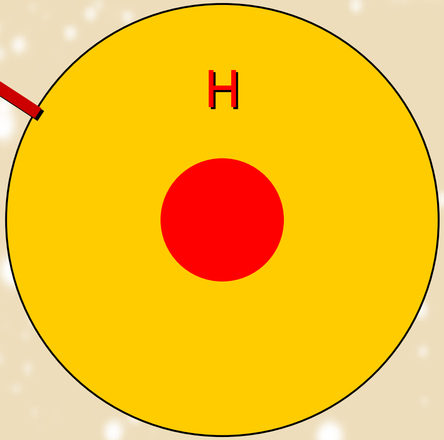


The galactic globular cluster M3

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

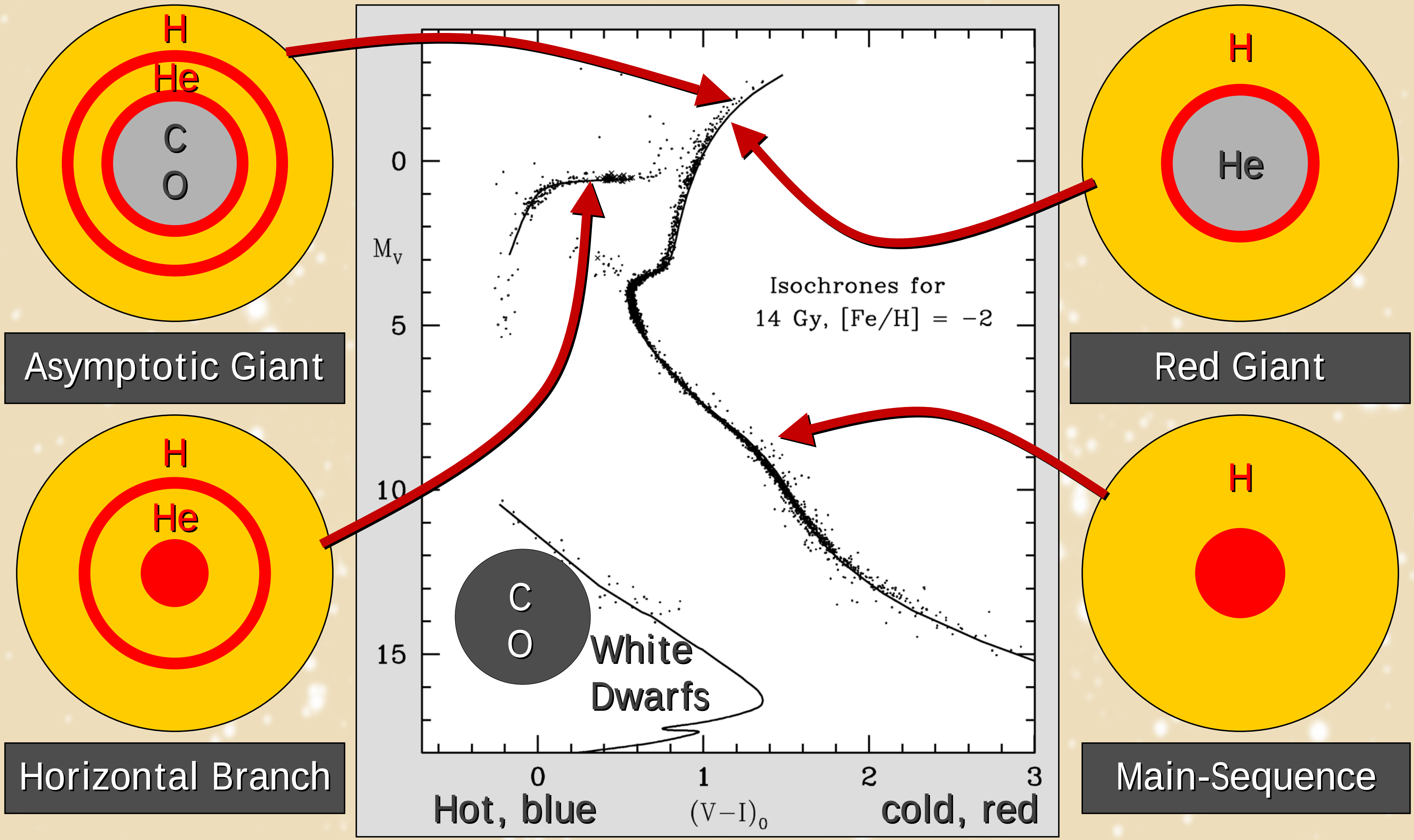




Main-Sequence

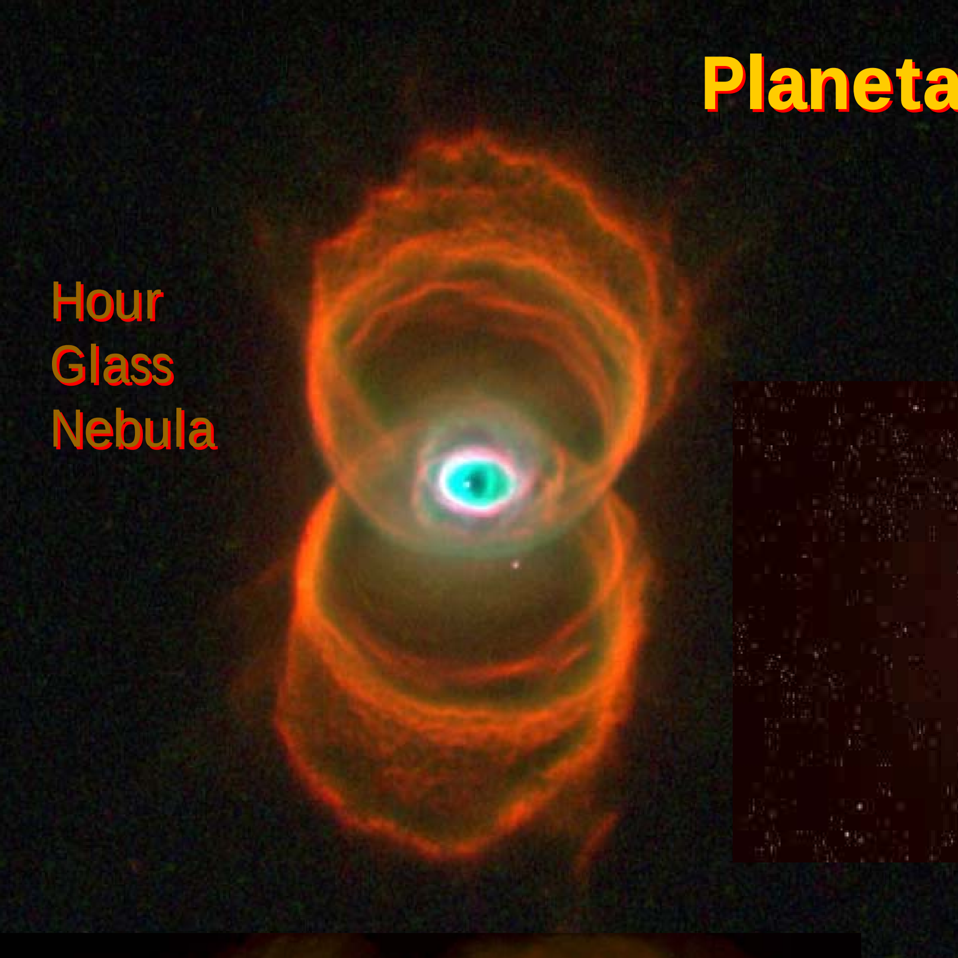
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters

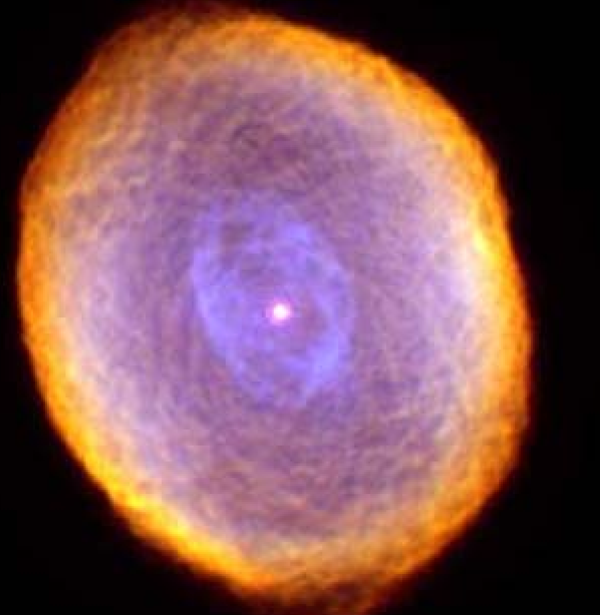


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Planetary Nebulae



Hour Glass Nebula



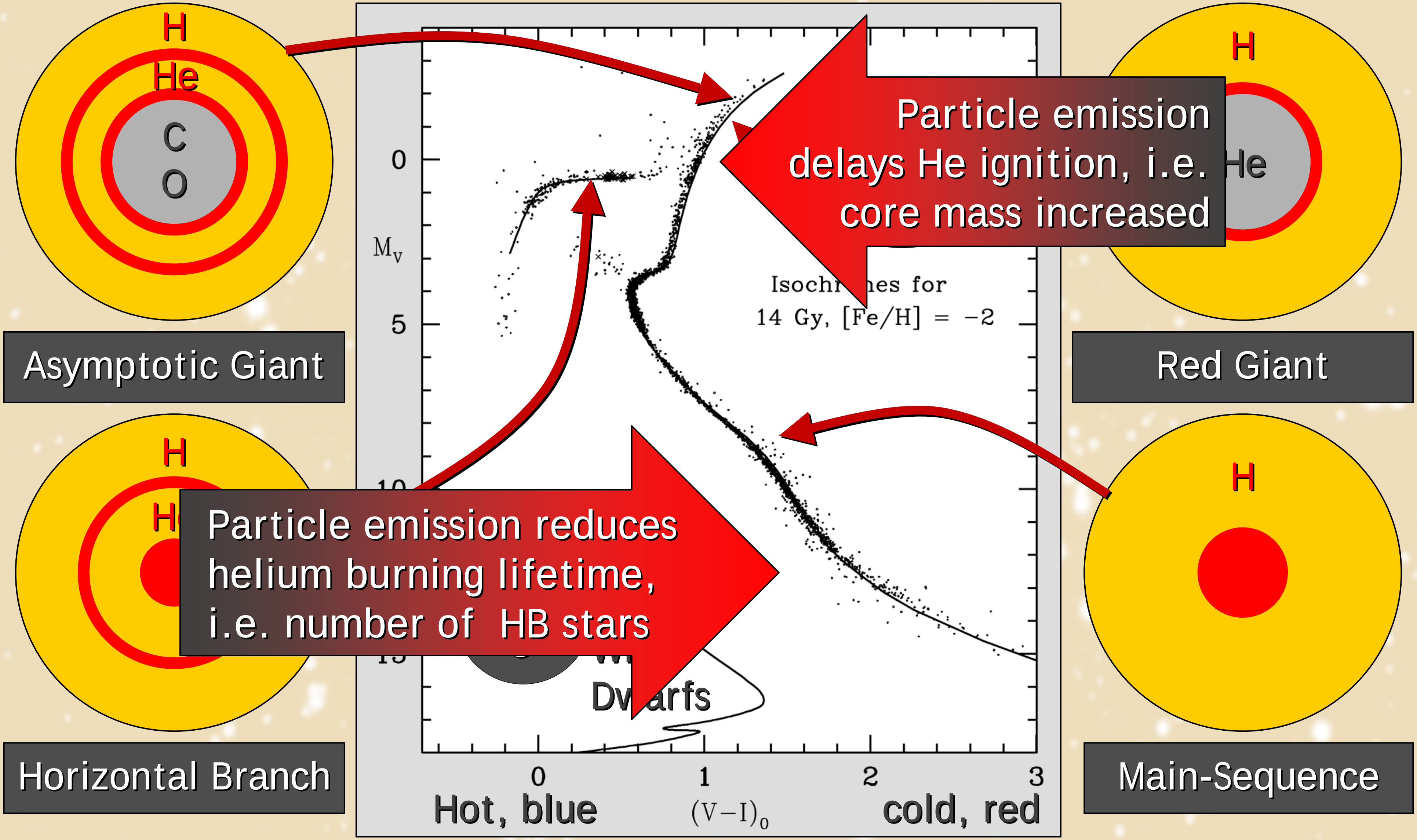
Planetary Nebula IC 418

Planetary Nebula NGC 3132

Eskimo Nebula

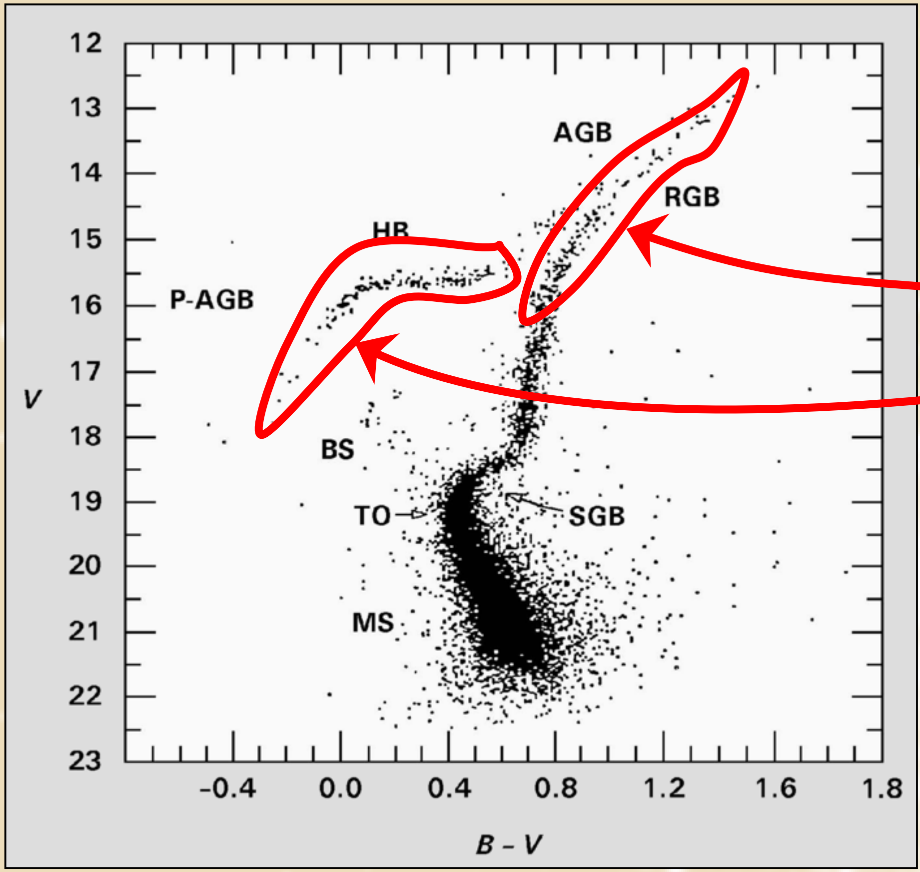
Globular-Cluster Limit on Axion-Photon Coupling

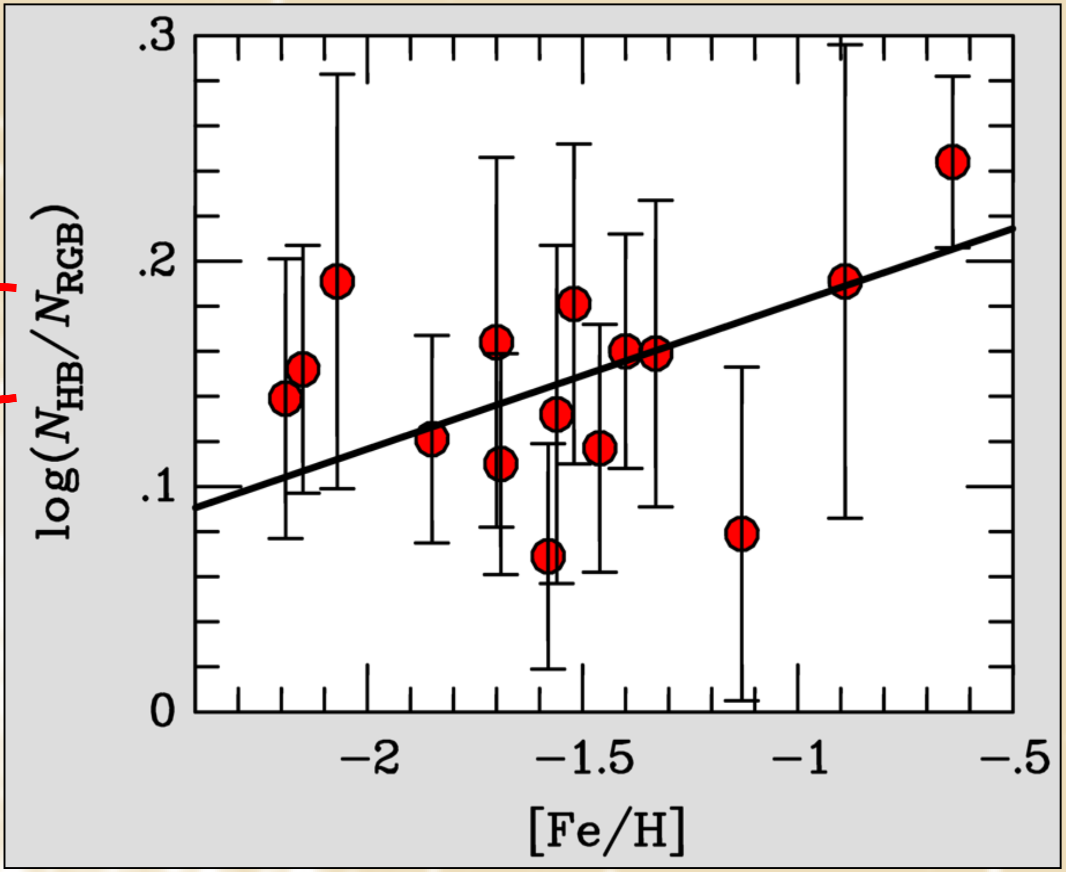
Color-Magnitude Diagram for Globular Clusters



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

Helium-Burning Lifetime of Horizontal-Branch Stars

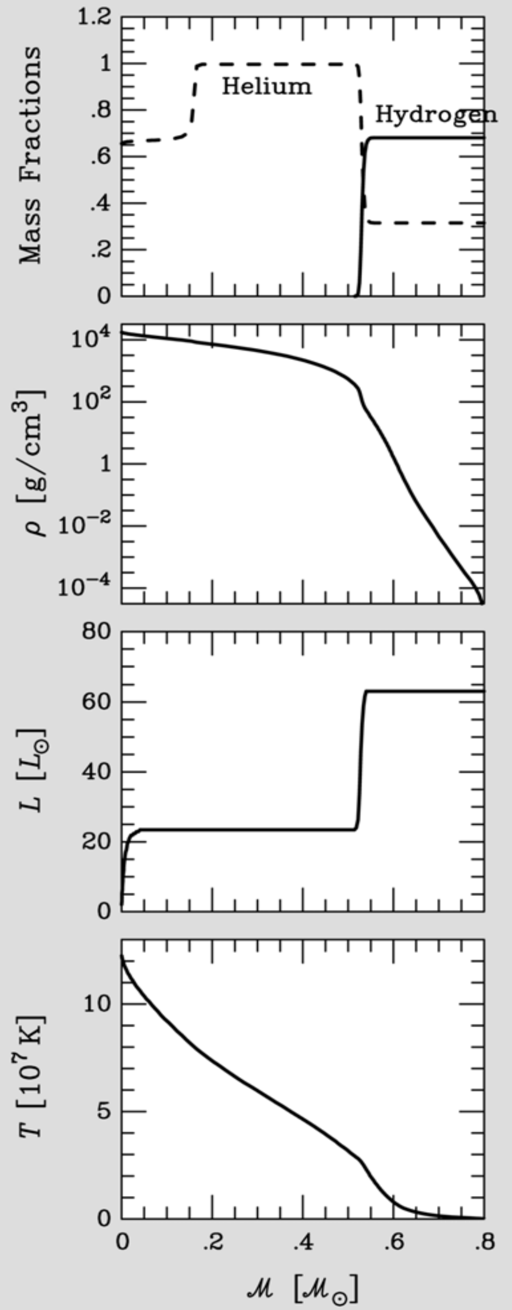




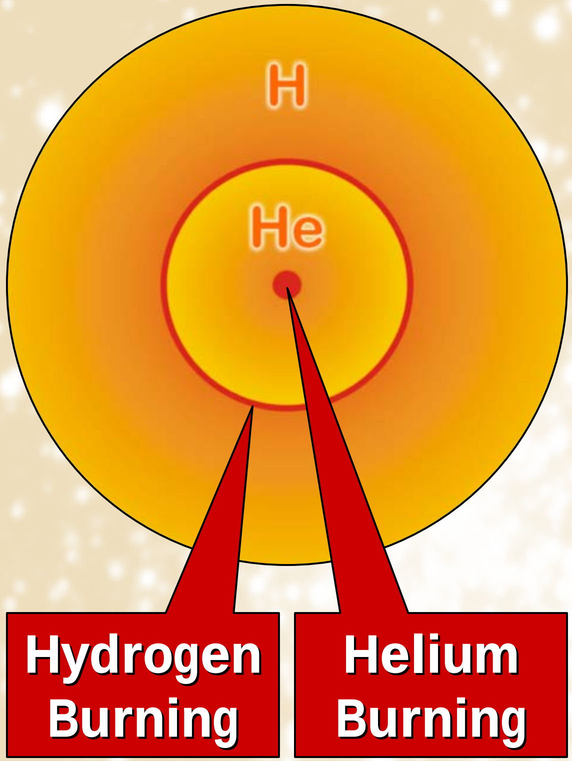
Number ratio of HB-Stars/Red Giants in 15 galactic globular clusters (Buzzoni et al. 1983)

Helium-burning lifetime established within ±10%

Globular-Cluster Limit on Axion-Photon Coupling



Helium-burning star

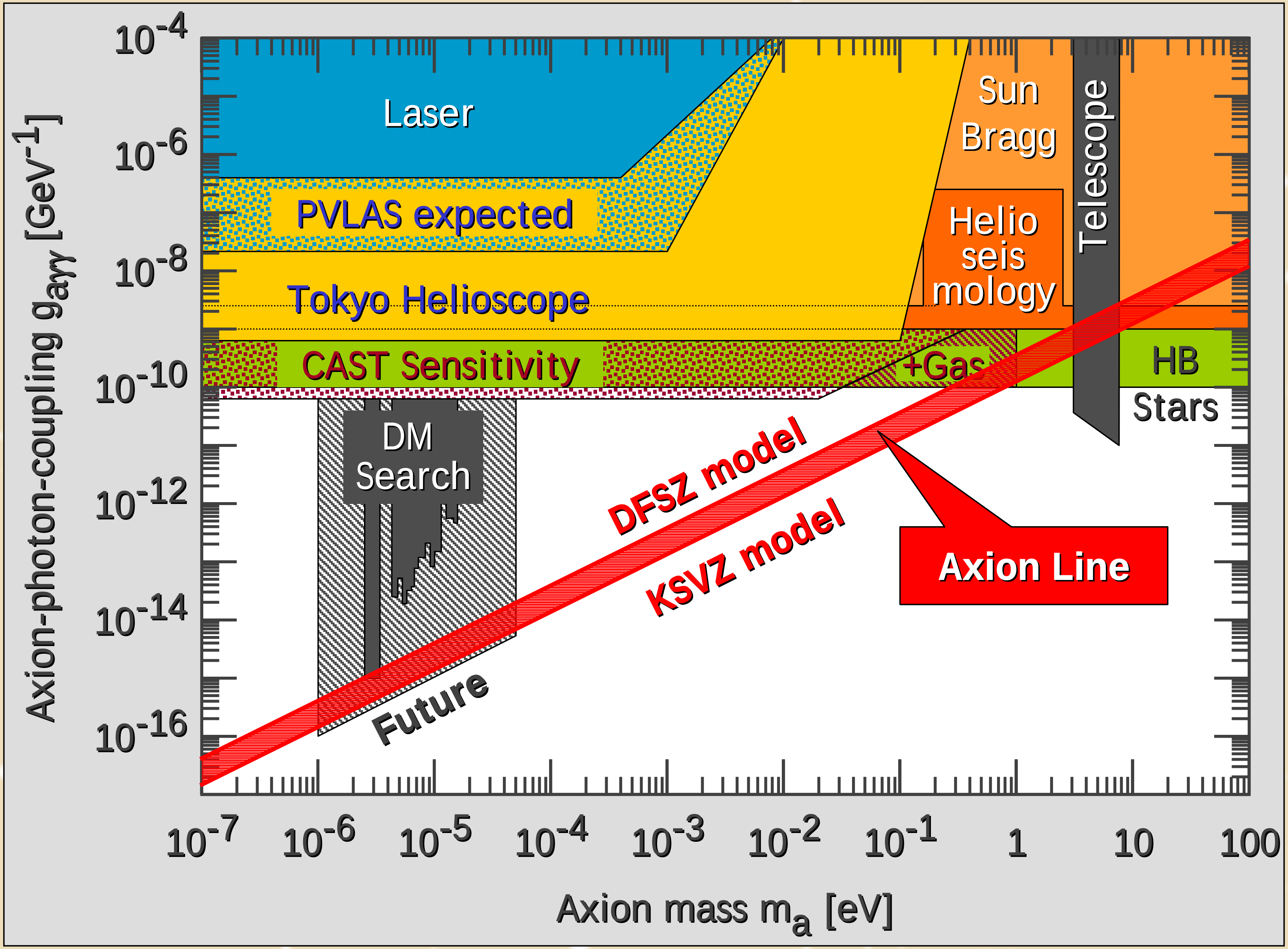


- Helium-burning luminosity
  $L_{3\alpha} \approx 20\ L_\odot$
  $T \approx 10$ keV
  $\rho \approx 10^4$ g cm^{-3}
- Core-average nuclear energy generation rate
  $\varepsilon_{3\alpha} \approx 80$ erg g^{-1} s^{-1}
- Core-average Primakoff emission rate
  $\varepsilon_{\rm Primakoff} \approx g_{10}^2\ 30$ erg g $^{-1}$ s^{-1}
- Reduction of helium-burning lifetime

$$\frac{\tau}{\tau_0} \approx \frac{1}{1+0.4\, g_{10}^2}$$

- Adopt nominal limit $g_{10} < 1$
  (More restrictive limit if using 10% precision for helium burning lifetime)

Limits on Axion-Photon-Coupling



Model-Dependence of Axion-Photon Coupling

Translating limits on the axion-photon coupling into limits on the Peccei-Quinn scale or axion mass depends on model uncertainties

Light quark mass ratio

$$z = \frac{m_u}{m_d} = 0.3 - 0.7$$

$z = 0.56$ "Canonical value"

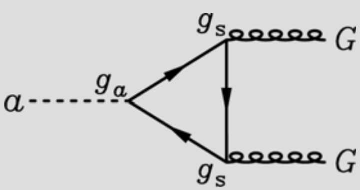
Mass

$$m_a = \frac{f_\pi m_\pi}{f_a} \frac{\sqrt{z}}{1+z} \qquad \frac{\sqrt{z}}{1+z} = 0.42 - 0.49$$

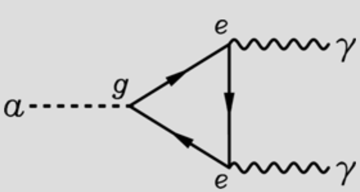
Axion-photon coupling

$$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F} a = g_{a\gamma} \vec{E} \cdot \vec{B}\, a$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \underbrace{\frac{2}{3} \frac{4+z}{1+z}}_{1.8-2.2} \right)$$



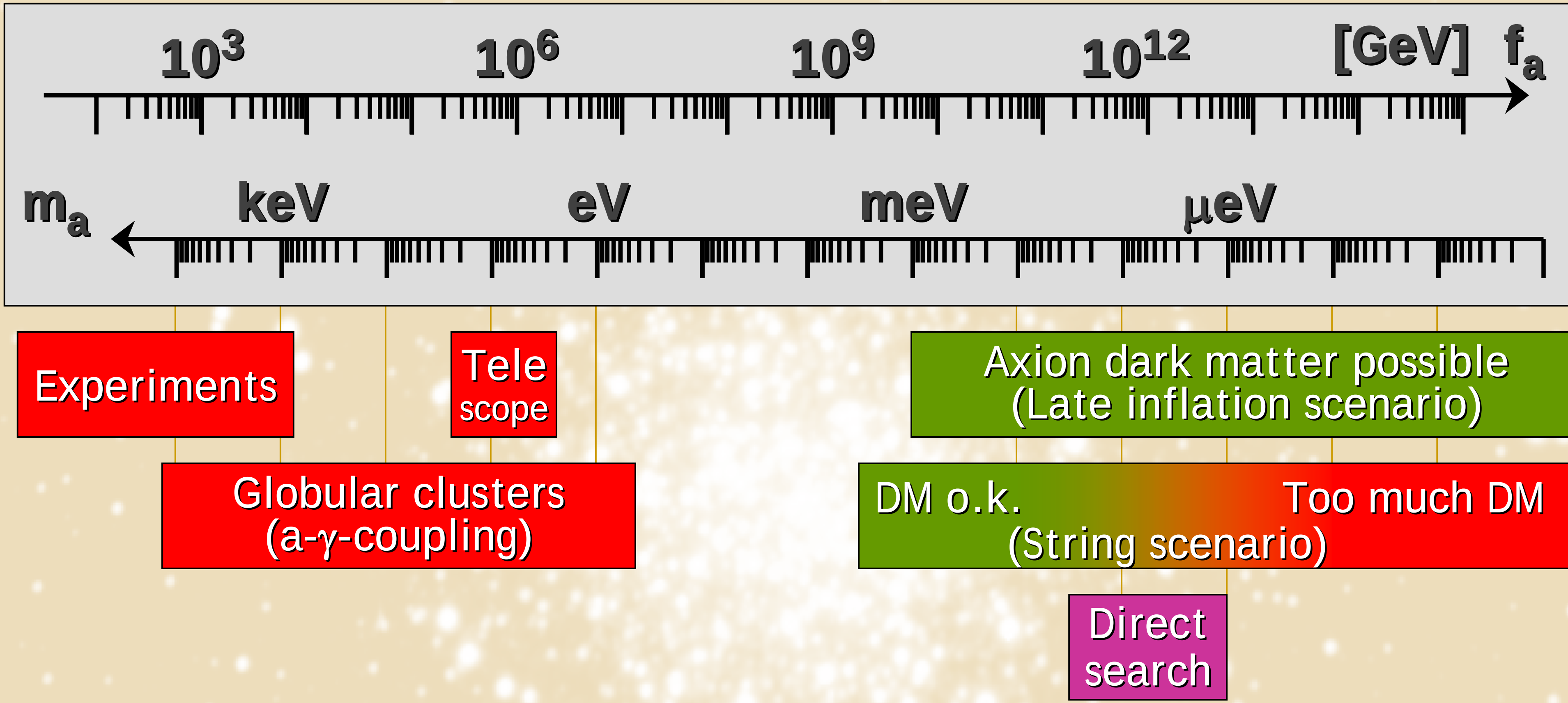
Gluon anomaly coefficient N



Electromagnetic anomaly coefficient E

E/N = 0 (KSVZ), E/N = 8/3 (DFSZ), or many other …
But requires fine-tuning to strongly suppress $g_{a\gamma}$

Astrophysical Axion Bounds



Free Streaming vs Trapping of New Particles

Free Streaming Mean Free Path ≫ Stellar Radius	Trapping Mean Free Path ≪ Stellar Radius

Energy conservation

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

Hydrostatic Equilibrium

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

Energy transfer

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

Free Streaming

Weakly interacting particles constitute a new energy-loss channel in addition to neutrinos and thus violate "energy conservation," reducing the available nuclear energy

$$\varepsilon = \varepsilon_{nuc} - \varepsilon_\nu - \varepsilon_x$$

Strong effect on stellar evolution when

ε_x comparable to ε_{nuc}

Trapping

Weakly interacting particles achieve local thermal equilibrium and thus contribute an energy-transfer channel in addition to photons and conduction

$$\kappa^{-1} = \kappa_c^{-1} + \kappa_\gamma^{-1} + \kappa_x^{-1}$$

Relation to average mean free path

$$(\kappa_\gamma \rho)^{-1} = \langle \lambda_\gamma \rangle_{\text{Rosseland}}$$

Strong effect on stellar structure when

$\lambda_x \gtrsim \lambda_\gamma$

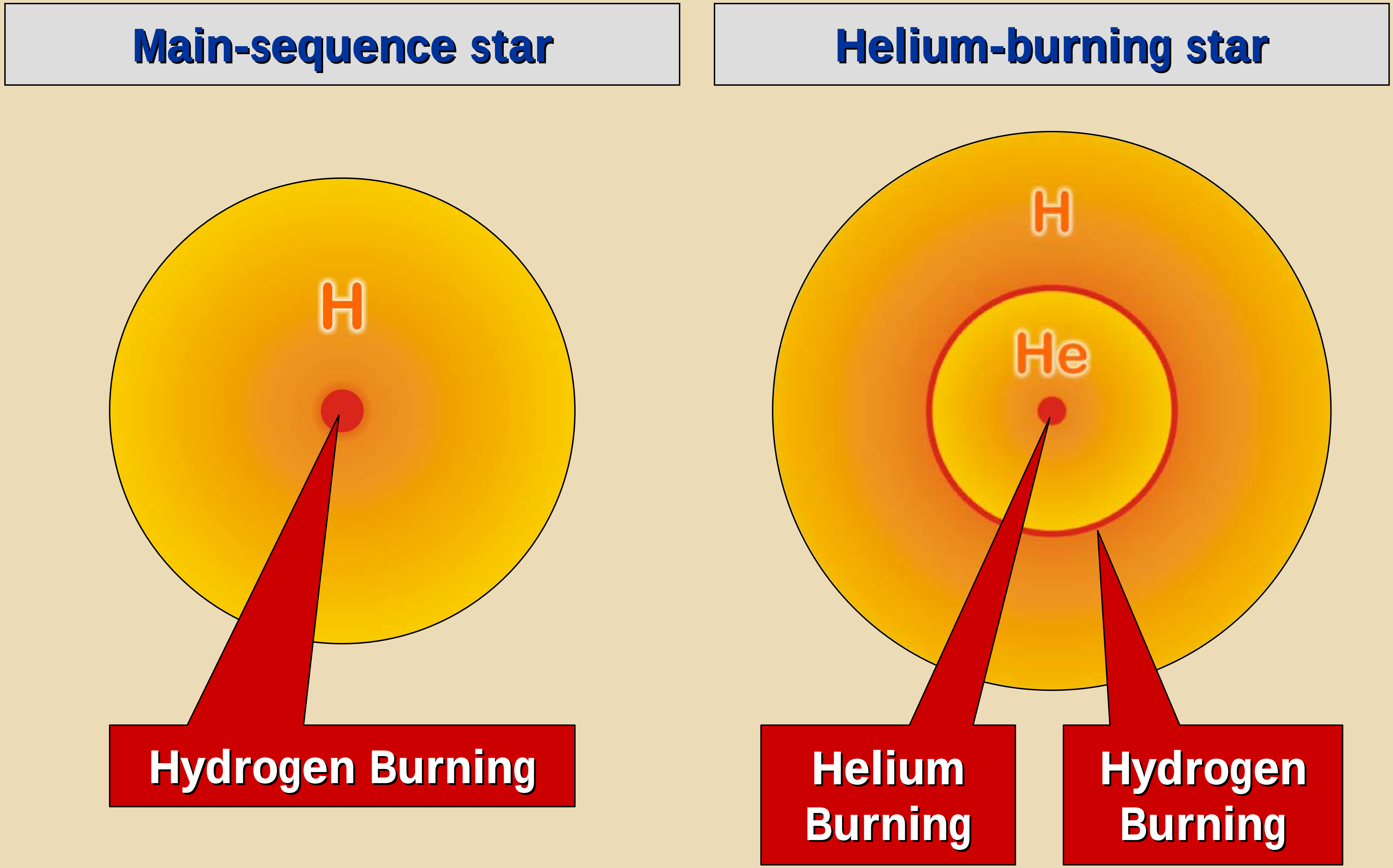
Strongest effect of new particles when mean free path ~ stellar radius

Supernova 1987A Limits on the Axion-Nucleon Coupling


Sanduleak –69 202

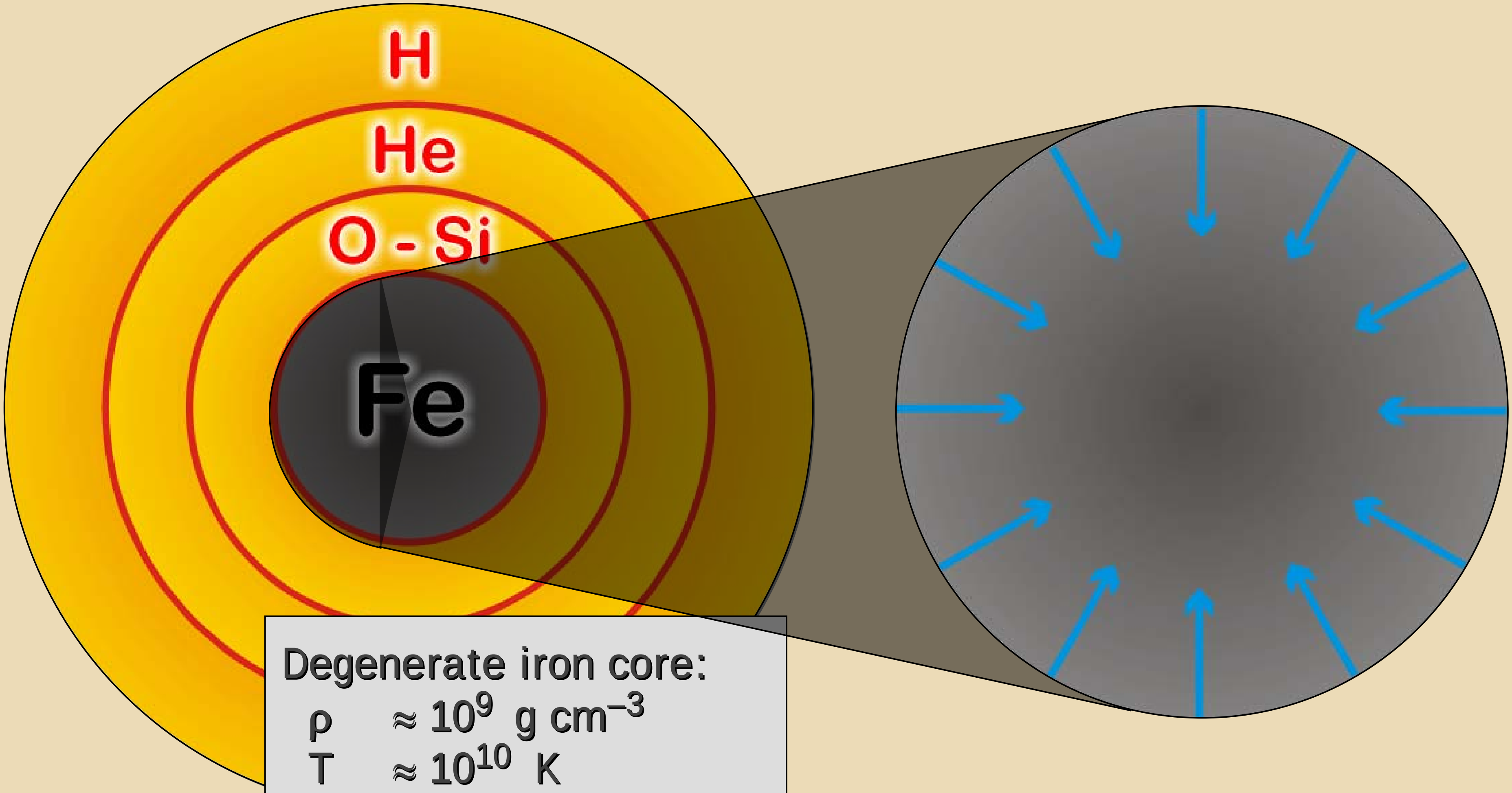
Supernova 1987A
23 February 1987

Stellar Collapse



Stellar Collapse

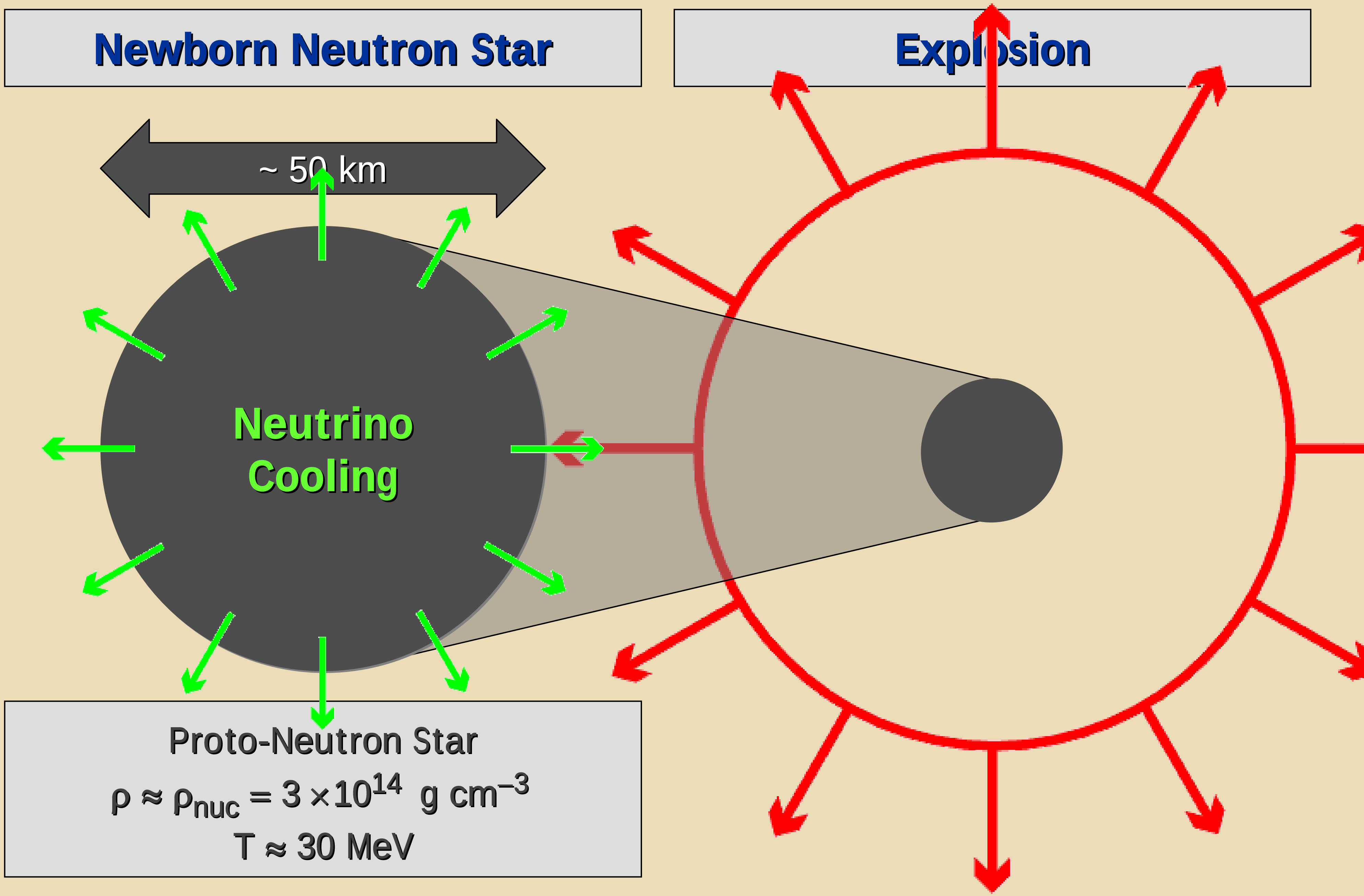
Onion structure | **Collapse (implosion)**



Degenerate iron core:

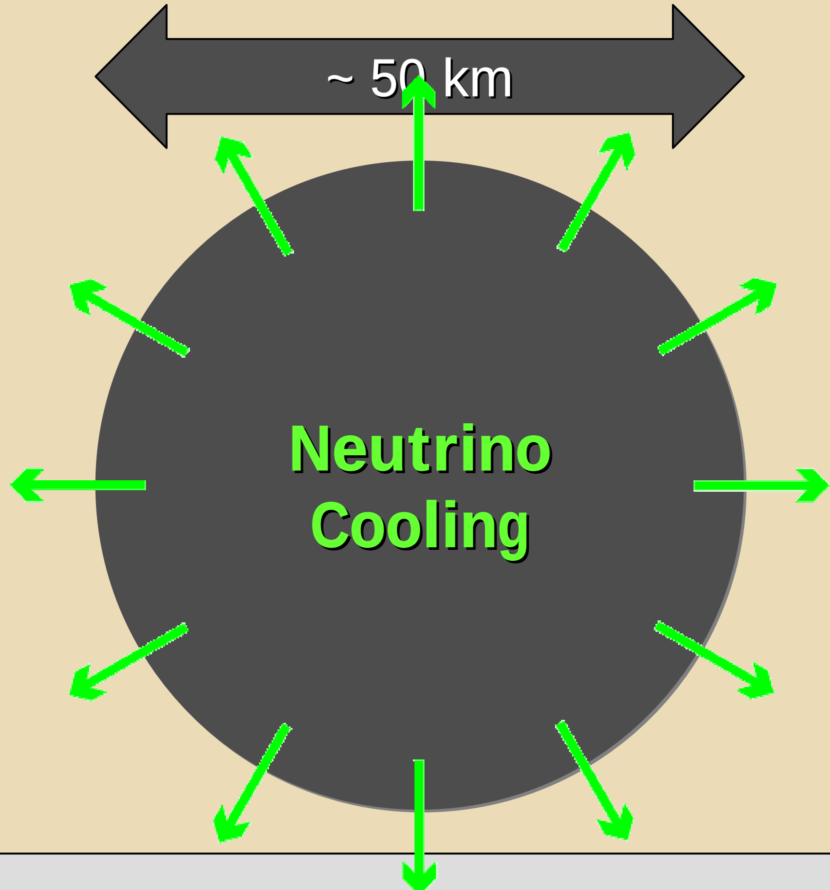
$\rho \approx 10^9$ g cm^{-3}
$T \approx 10^{10}$ K
$M_{Fe} \approx 1.5\ M_{sun}$
$R_{Fe} \approx 8000$ km

Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

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

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

Gravitational binding energy

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

This shows up as

99% Neutrinos

1% Kinetic energy of explosion (1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

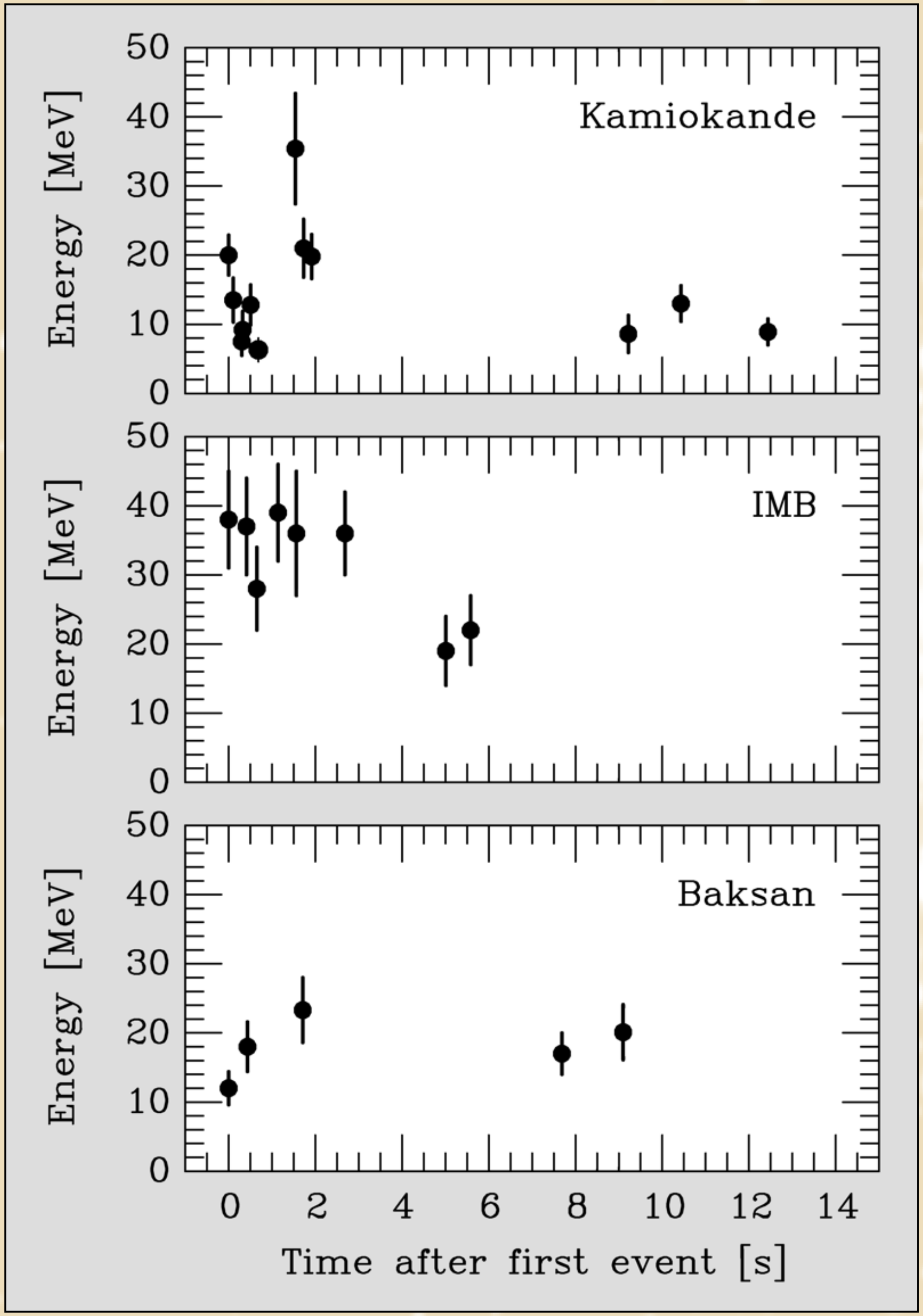
Neutrino luminosity

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

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

While it lasts, outshines the entire visible universe

Neutrino Signal of Supernova 1987A



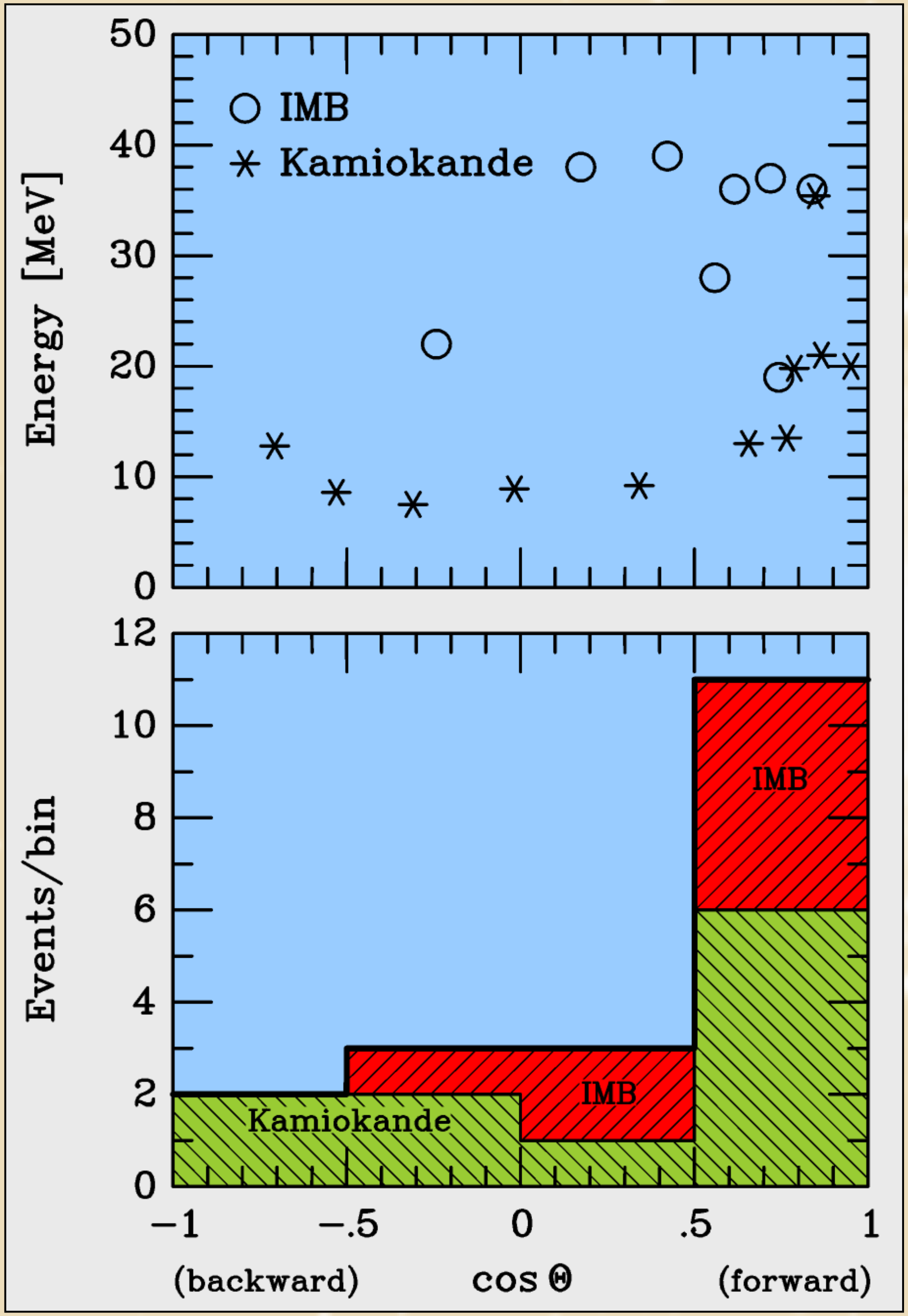
Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

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

Angular Distribution of SN 1987A Neutrinos



Main detection reaction

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

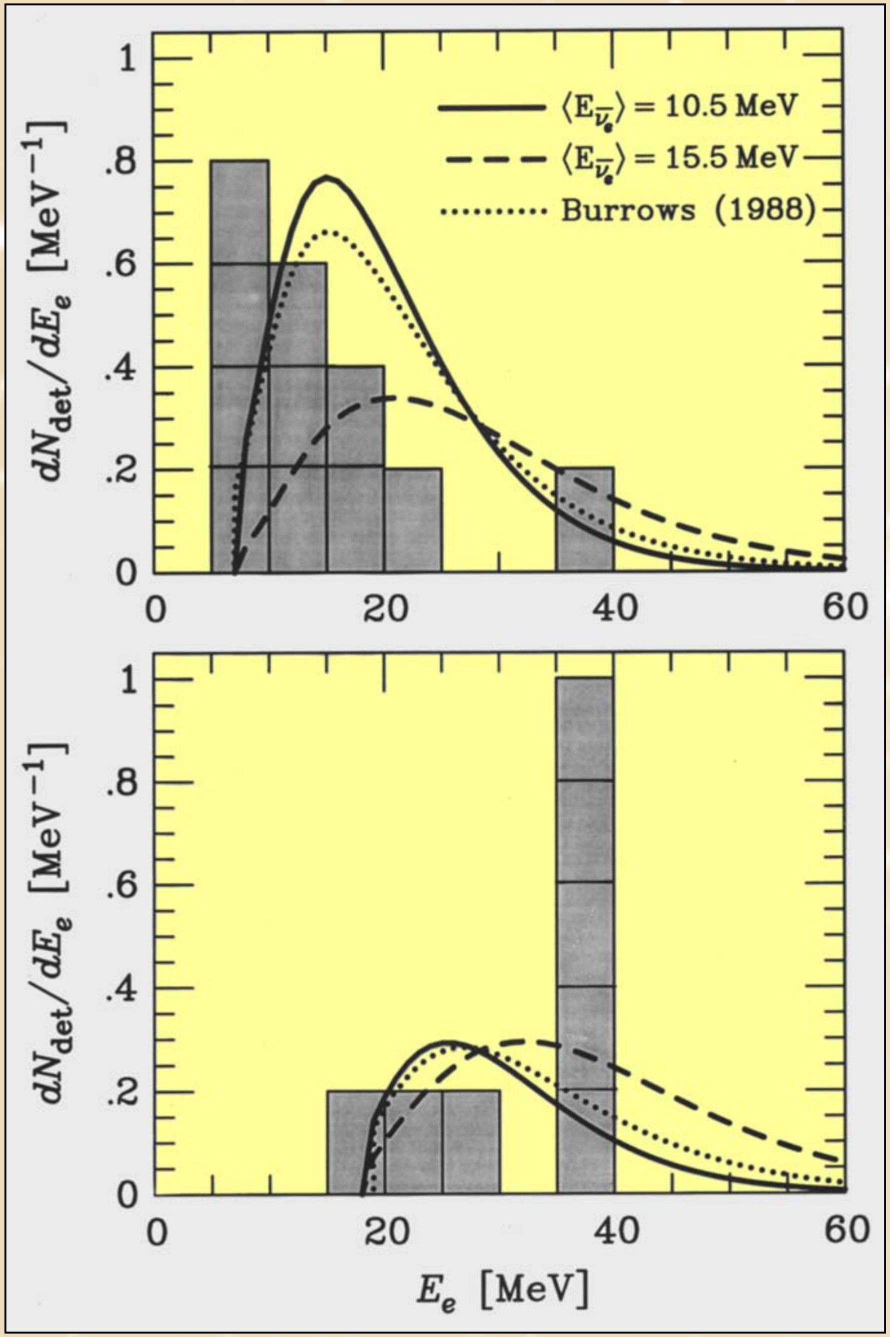
is essentially isotropic for the relevant energies.

Expect only a fraction of an event from forward-peaked reaction

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

Observed signal compatible with isotropy only at approx. 0.1% CL, but no alternative known

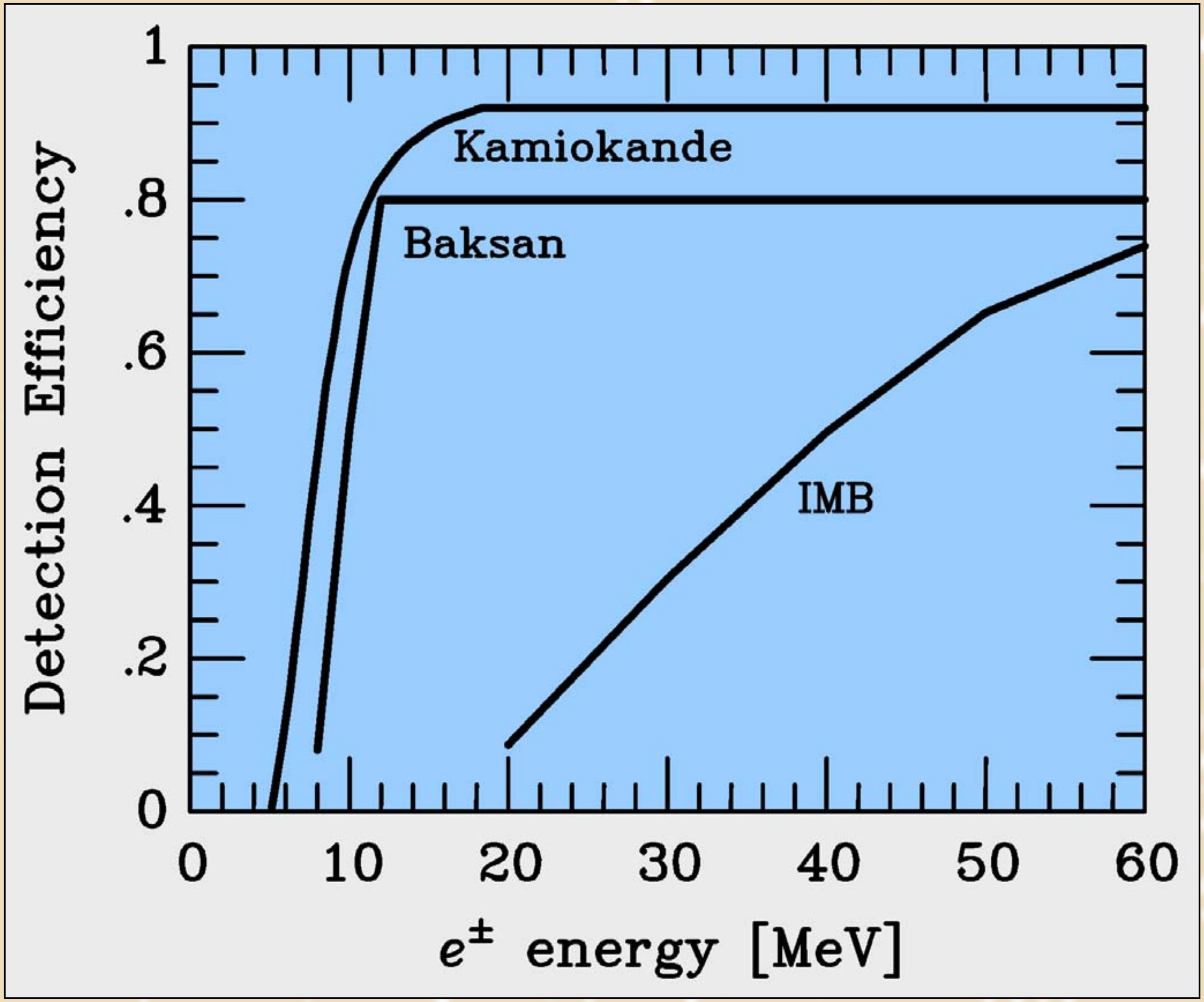
Energy Distribution of SN 1987A Neutrinos



Kamiokande II

IMB

Trigger Efficiencies at the Detectors



Fiducial volumes for SN 1987A detection

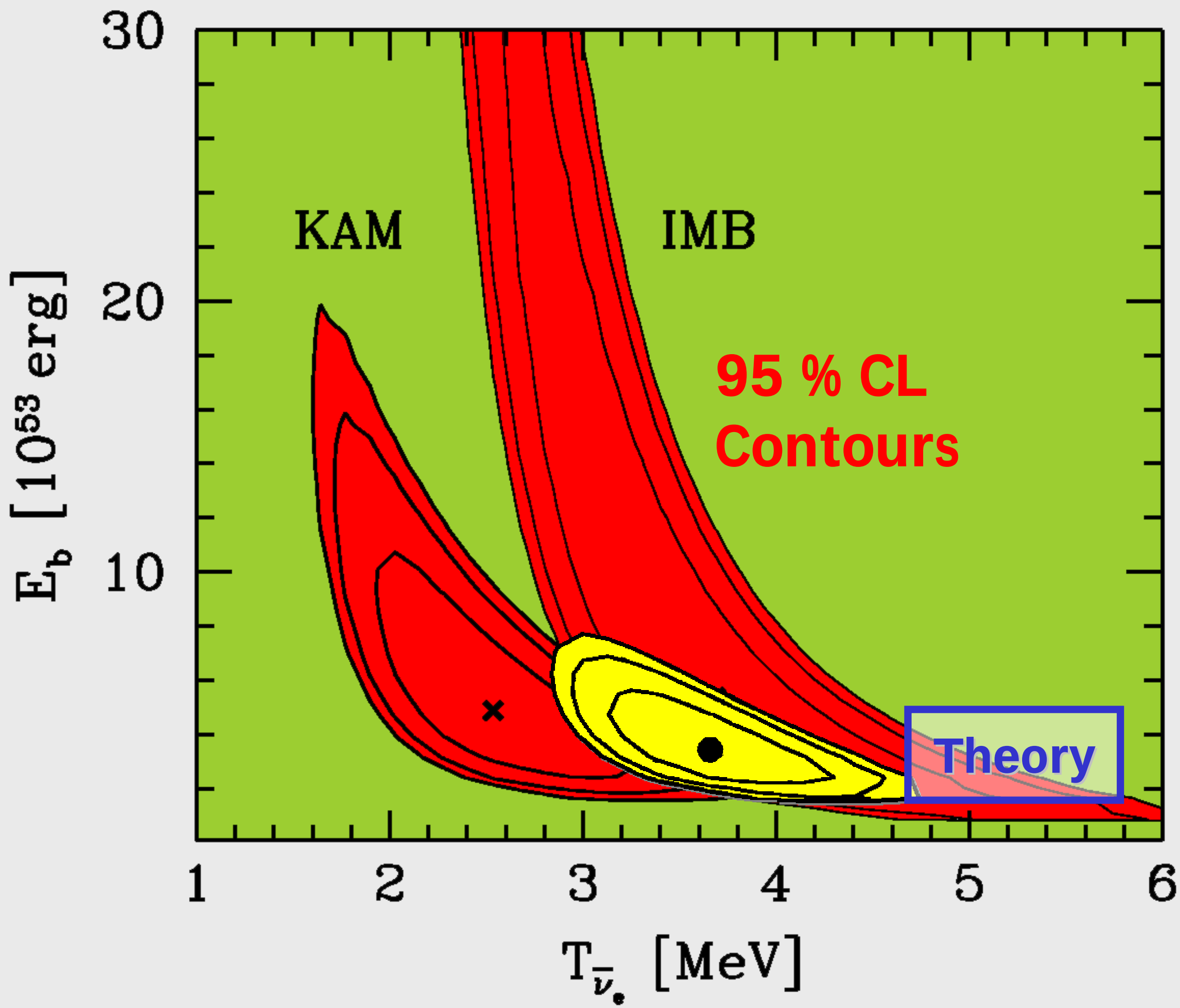
Kamiokande II
- 2140 tons water
- (1.43×10^{32} protons)

IMB
- 6800 tons water
- (4.6×10^{32} protons)

BST
- 200 tons scintillator
- (1.88×10^{31} protons)

Interpreting SN 1987A Neutrinos

Total Binding Energy

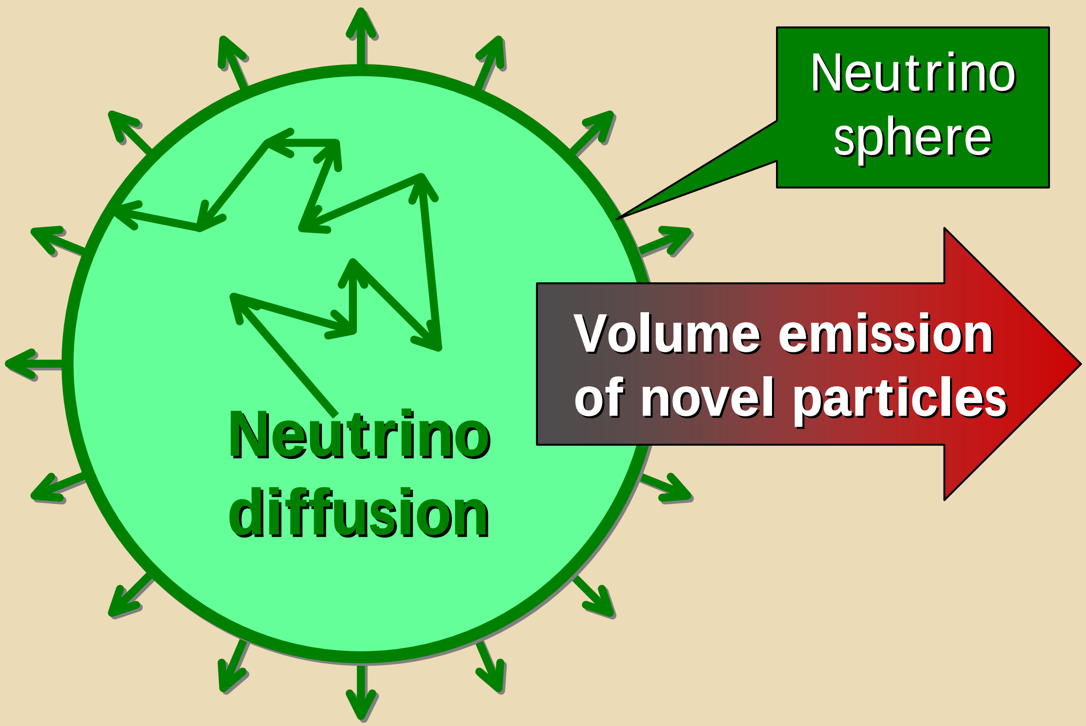


Spectral $\overline{\nu}_e$ Temperature

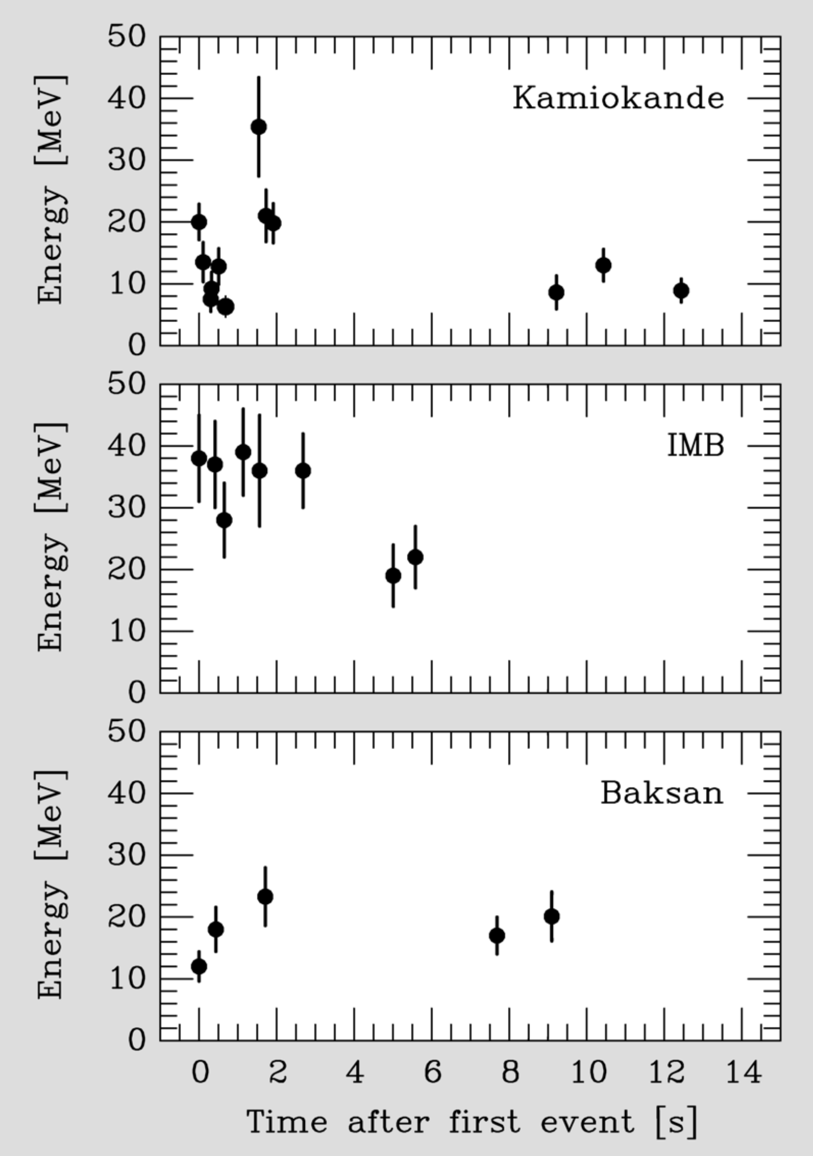
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

The Energy-Loss Argument



SN 1987A neutrino signal

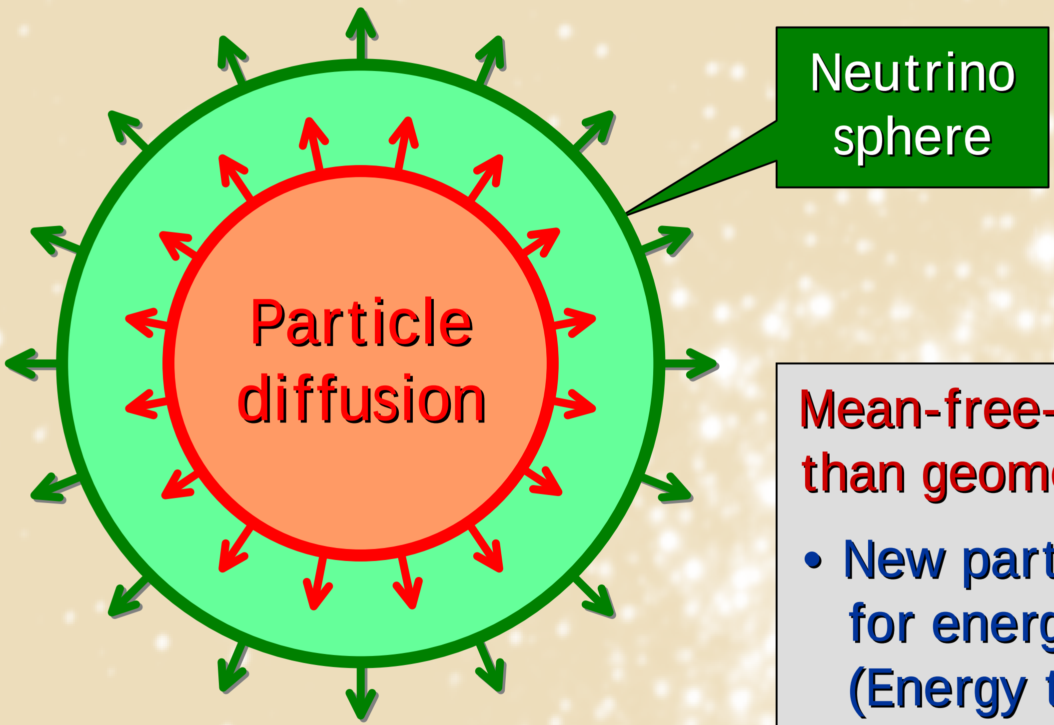


Assuming that the neutrino burst was not shortened by more than ~ ½ leads to an approximate requirement on a novel energy-loss rate of

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

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

The Energy-Loss Argument in the Trapping Limit



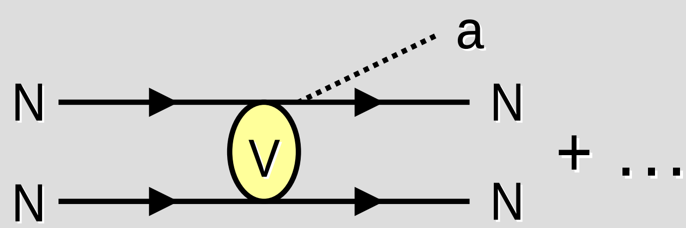
Mean-free-path of new particles less than geometric dimension of star

- New particles are more important for energy transfer than neutrinos (Energy transfer $\propto$ mfp)
- Efficiency of energy transfer must be less than that of neutrinos or else speed up cooling of PNS, again shortening the observed SN 1987A signal

Axion Emission from a Nuclear Medium

Axion-nucleon interaction is of current-current form:

$$\mathcal{L}_{int} = \frac{C_N}{2f_a}\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a} J^A_\mu \partial^\mu a$$



Nucleon-Nucleon Bremsstrahlung

Energy loss rate (erg $\text{cm}^{-3}\,\text{s}^{-1}$)

$$Q = \int d\Gamma_a \int d\Gamma_{\text{Nucleons}} |M|^2 \omega$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

Axion energy

Dynamical structure function

Difficulties include:

- Realistic nucleon-nucleon interaction potential (even in vacuum)
- Many-body effects (effective mass, spin-spin correlations …)
- Axion couplings in the nuclear medium
- Multiple-scattering effects:

  Frequency of NN collisions exceeds typical axion energy

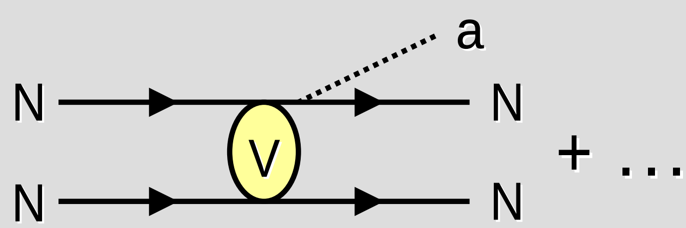
  $\tau_{\text{coll}} < \omega^{-1}$

  Expect LPM-type destructive interference effects

Axion Emission from a Nuclear Medium

Axion-nucleon interaction is of current-current form:

$$L_{int} = \frac{C_N}{2f_a}\,\overline{\Psi}_N \gamma_\mu \gamma_5 \Psi_N \partial^\mu a = \frac{C_N}{2f_a}\, J_\mu^A \partial^\mu a$$



Nucleon-Nucleon Bremsstrahlung

Energy loss rate (erg cm^{-3} s^{-1})

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$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

Axion energy

Dynamical structure function

Diffic

- Rea
- Mar
- Axi
- Mul

Fre

τ_{col}

Exp

- Fundamentally the dynamical structure function is a correlator of the nucleon axial current
- Non-relativistic nucleons: ~ nucleon spin density operator σ

$$S(\omega,k) = \frac{4}{3n_B} \int_{-\infty}^{+\infty} dt\, e^{i\omega t} \langle \vec{\sigma}(t,k) \cdot \vec{\sigma}(0,-k) \rangle$$

- Example for the fluctuation and dissipation theorem of linear-response theory: Axion emission determined by spontaneous nucleon spin fluctuations

Properties of the Dynamical Structure Function

Nucleon spin-density autocorrelation function	$S(\omega,k)=\frac{4}{3n_B}\int_{-\infty}^{+\infty}dt\,e^{i\omega t}\langle\sigma(t,k)\cdot\sigma(0,-k)\rangle$
Normalization, ignoring many-body correlations	$\int_{-\infty}^{+\infty}\frac{d\omega}{2\pi}S(\omega,k)=\frac{1}{n_B}\int\frac{2d^3p}{(2\pi)^3}f_p(1-f_{p+k})$
Detailed balancing	$S(-\omega,k)=e^{-\omega/T}S(\omega,k)$ consequence of non-commuting $\sigma(t)$ at different times
Symmetric form	$\bar{S}(\omega,k)=\frac{S(-\omega,k)+S(\omega,k)}{2}$ → $S(\omega,k)=\frac{2\bar{S}(\omega,k)}{1+e^{-\omega/T}}$
Long-wavelength limit ($k\to 0$)	$\bar{S}(\omega)=\frac{4}{3}\int_{-\infty}^{+\infty}dt\,e^{i\omega t}\left\langle\frac{s(t)\cdot s(0)+s(0)\cdot s(t)}{2}\right\rangle$
Is Fourier transform of single-nucleon spin correlation function	$\bar{R}(t)=\frac{4}{3}\left\langle\frac{s(t)\cdot s(0)+s(0)\cdot s(t)}{2}\right\rangle$

Spin Relaxation Rate

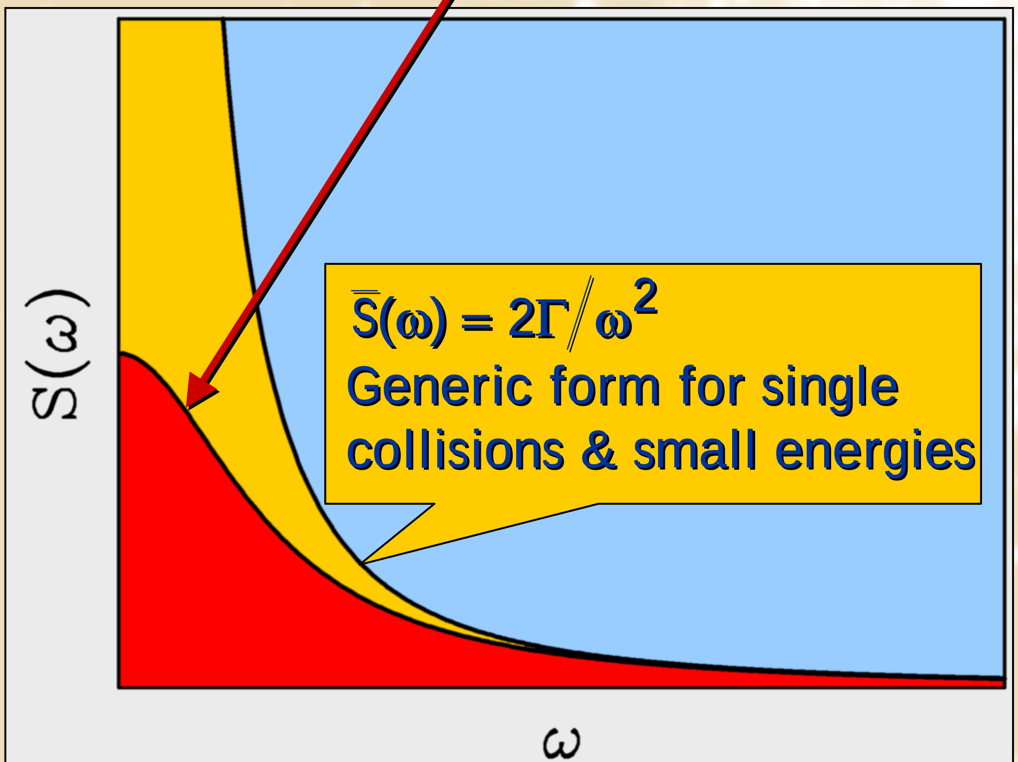
A spin immersed in a bath of scatterers with spin-dependent forces relaxes exponentially for uncorrelated kicks (Markov chain)

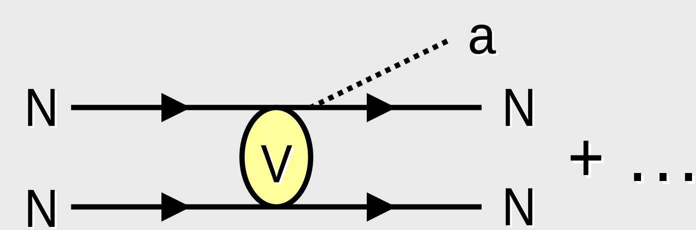
$$\overline{R}(t) = e^{-\Gamma t}$$

with Γ the "spin relaxation rate", leading to the Fourier transform

$$\overline{S}(\omega) = \frac{2\Gamma}{\omega^2 + \Gamma^2}$$

Lorentzian structure function, includes multiple scattering effects





Nucleon-Nucleon Bremsstrahlung

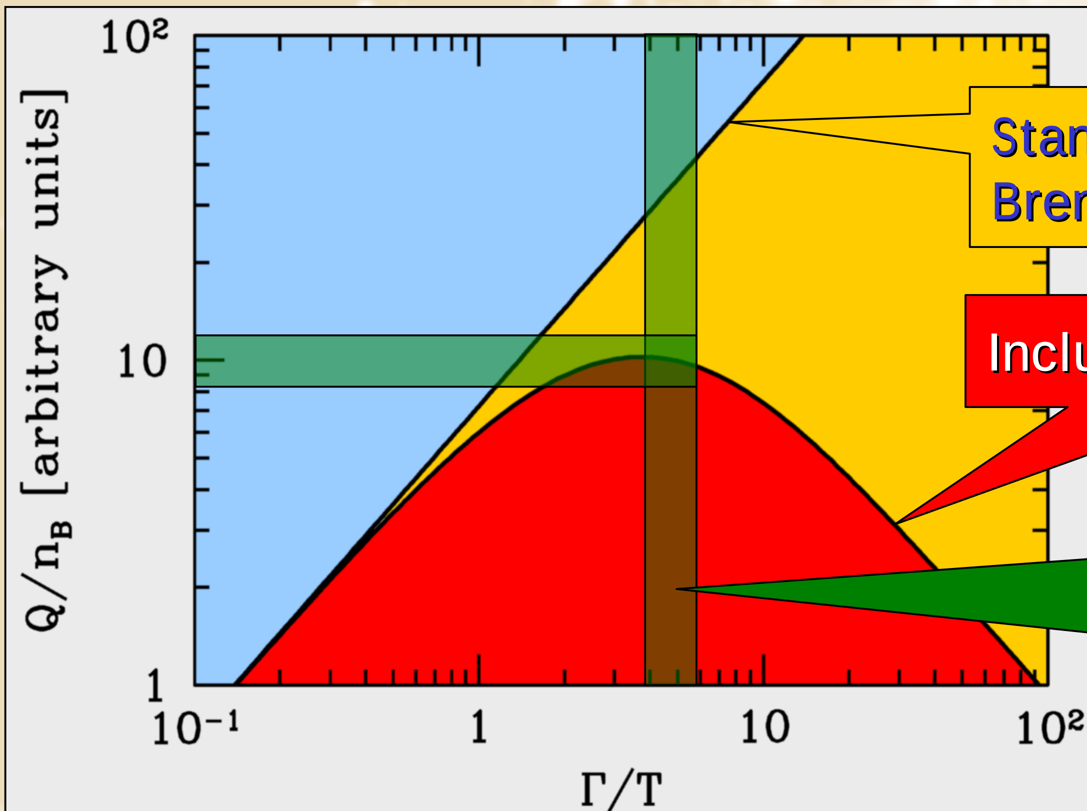
Identify coefficient Γ from bremsstrahlung calculation with spin relaxation rate

Axion Emission Rate

$$Q = \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 \frac{2\Gamma}{\omega^2+\Gamma^2} \frac{2}{1+e^{\omega/T}} \propto \begin{cases} n_B^2 & \text{for small density} \\ n_B^{-1} & \text{for large density} \end{cases}$$

Axionic volume energy loss rate of nuclear medium



Standard behavior: Bremsstrahlung rate $\propto \rho^2$

Including LPM effect

One-pion exchange potential in Born approximation:

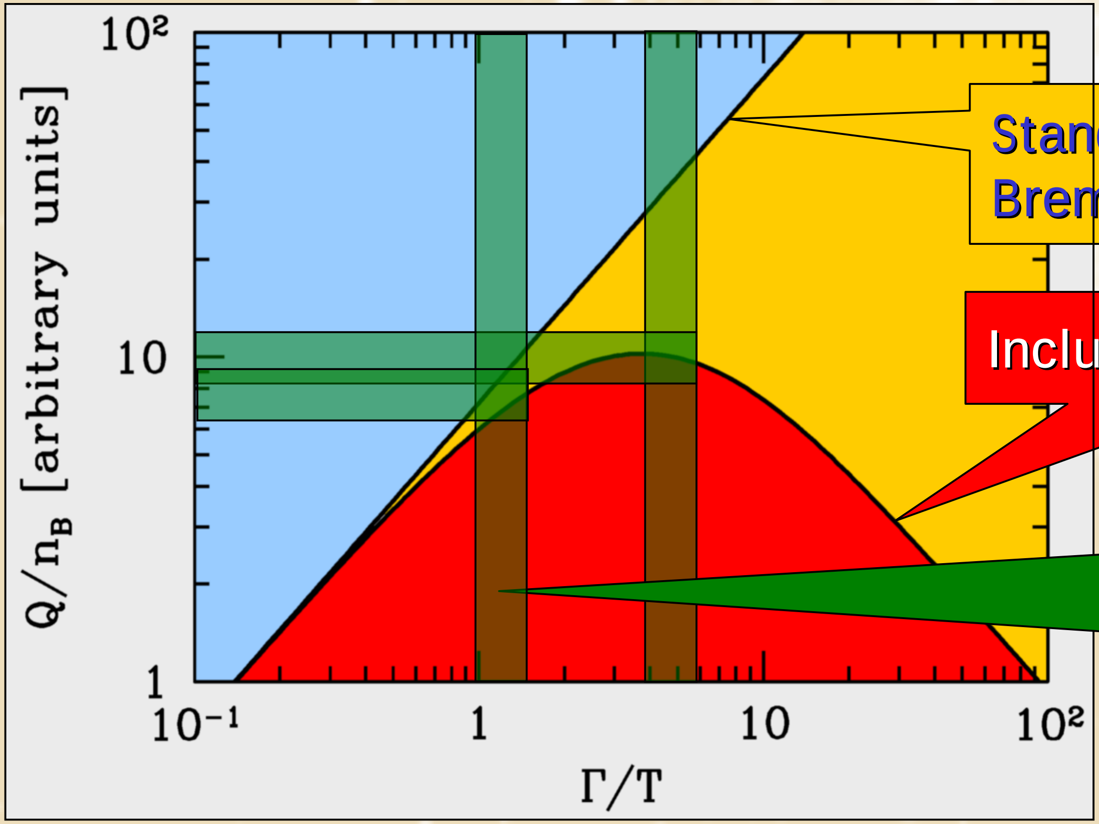
$$\frac{\Gamma}{T} \approx 1.25 \frac{\rho}{10^{14}\,\mathrm{g\,cm^{-3}}} \sqrt{\frac{30\,\mathrm{MeV}}{T}}$$

Axion Emission Rate

$$Q = \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 S(-\omega)$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2} \int_0^\infty d\omega\, \omega^4 \frac{2\Gamma}{\omega^2 + \Gamma^2} \frac{2}{1+e^{\omega/T}} \propto \begin{cases} n_B^2 & \text{for small density} \\ n_B^{-1} & \text{for large density} \end{cases}$$

Axionic volume energy loss rate of nuclear medium

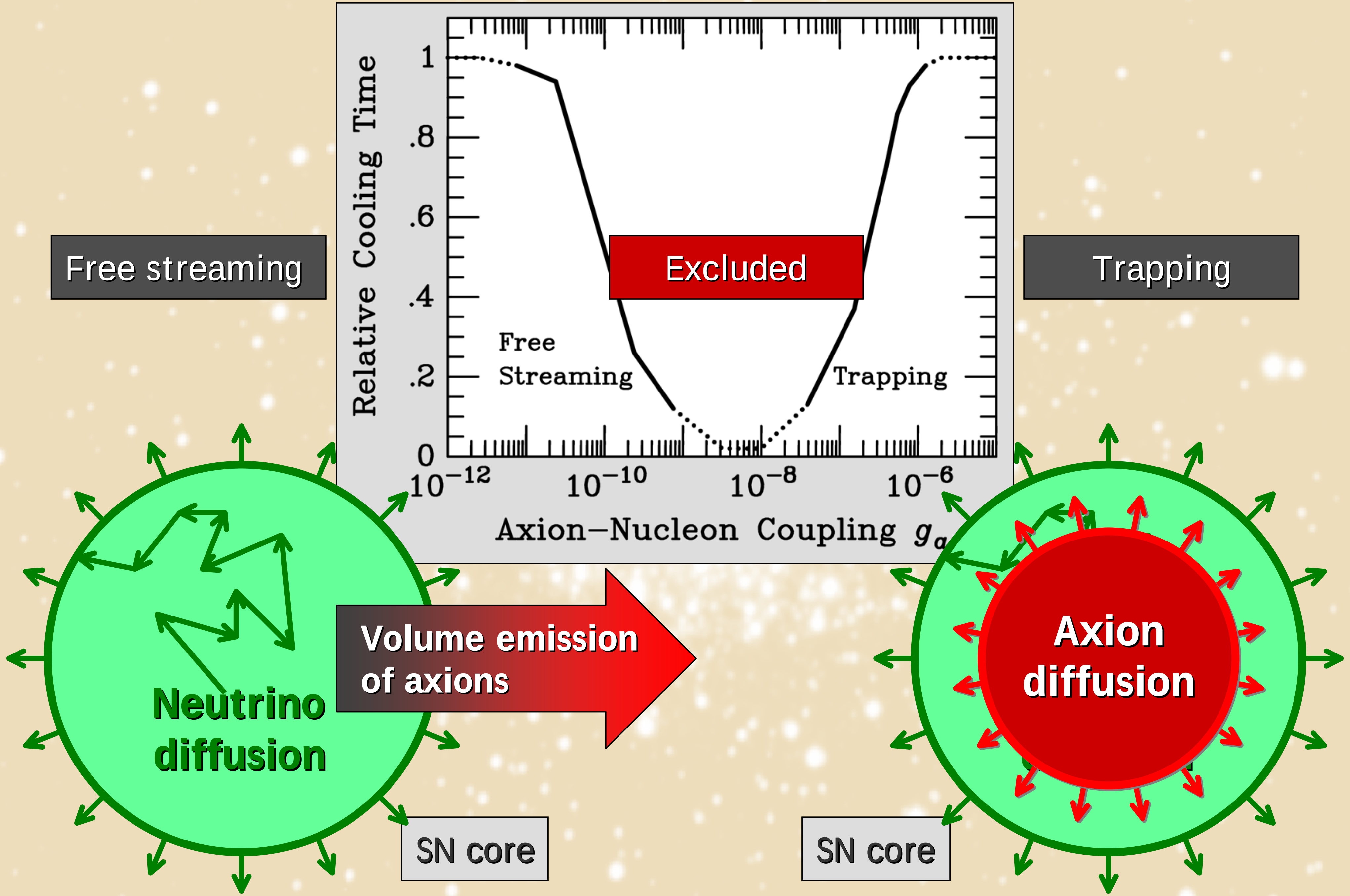


Standard behavior: Bremsstrahlung rate $\propto \rho^2$

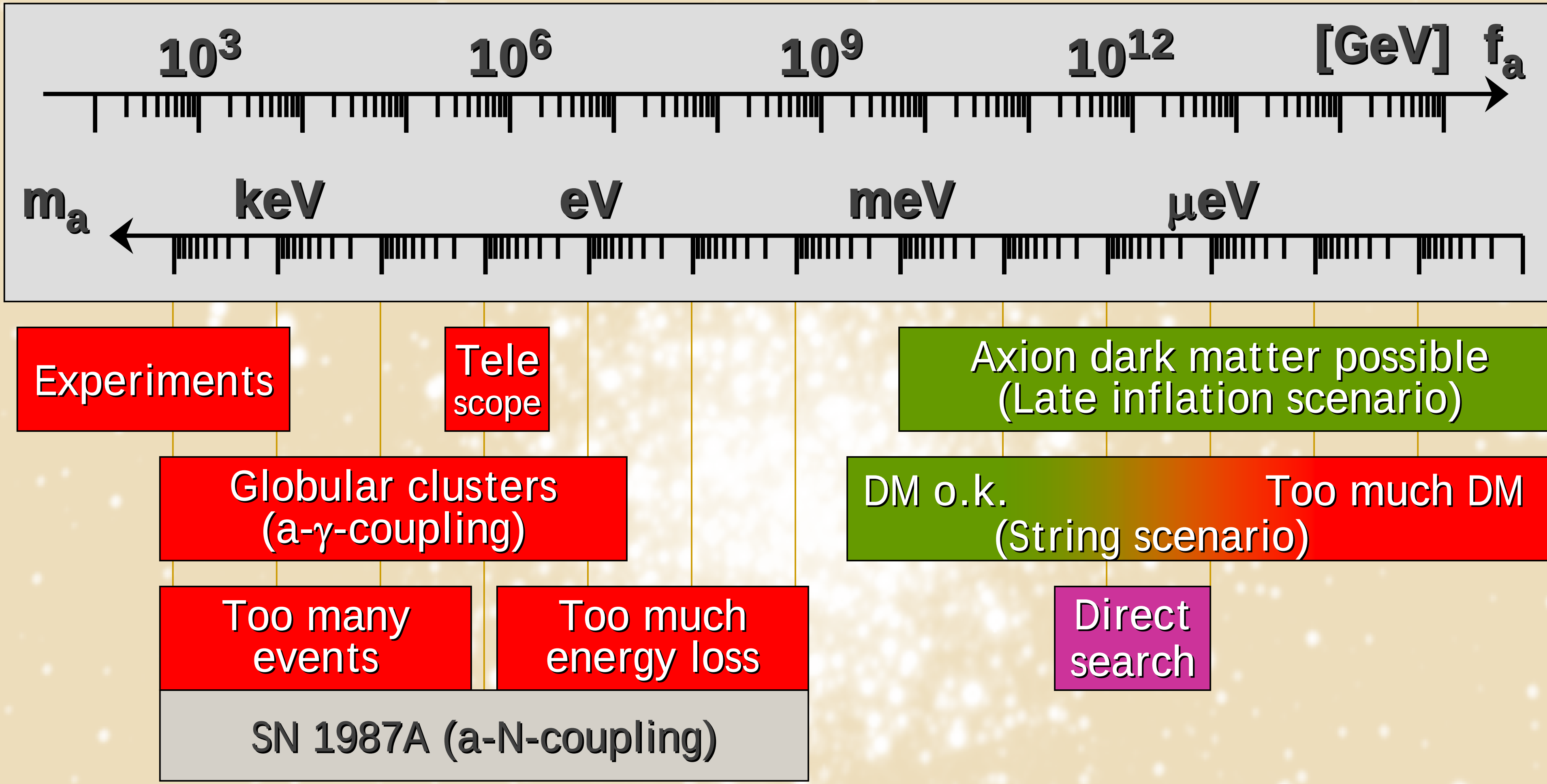
Including LPM effect

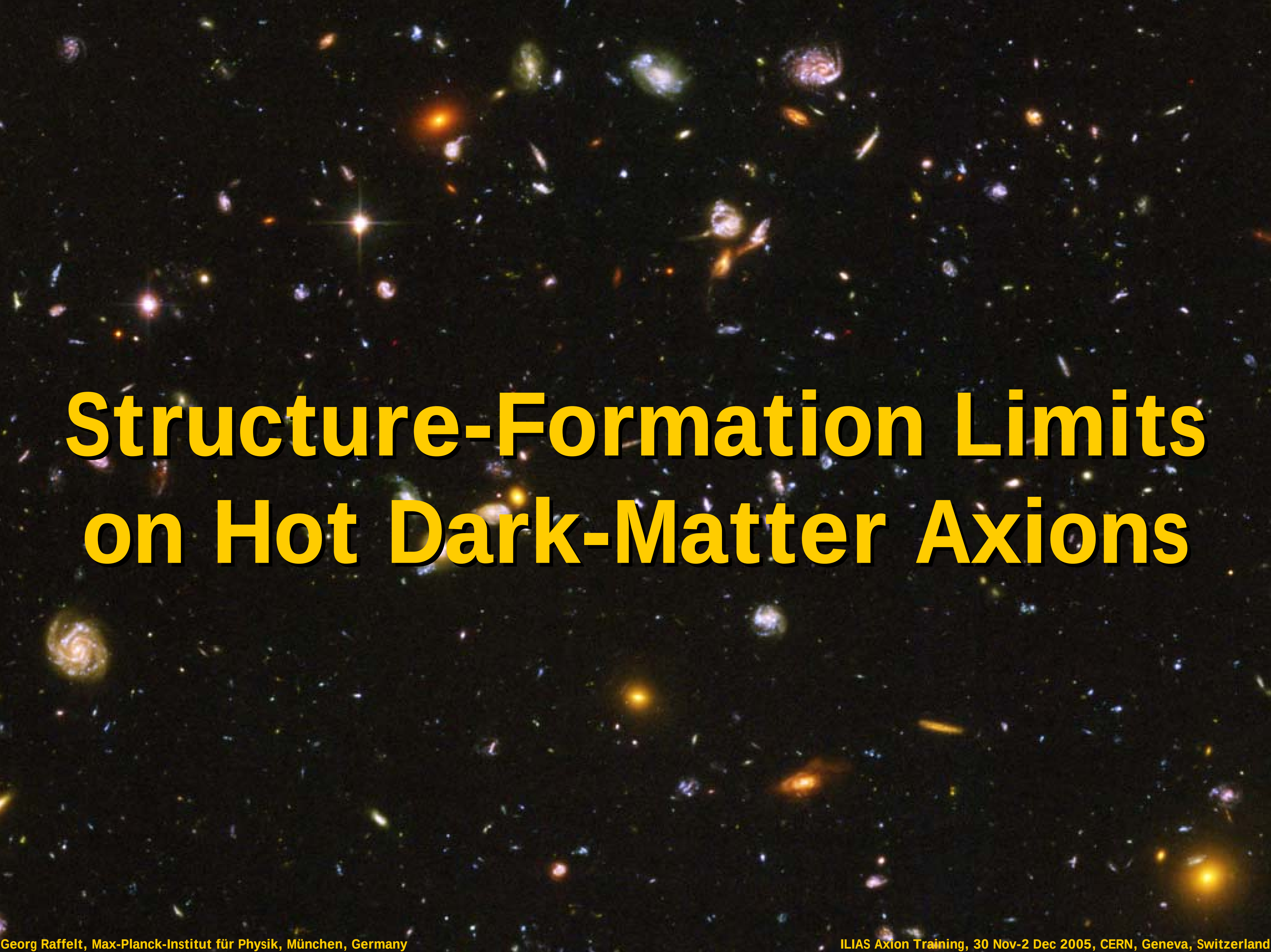
Using phase shifts from nuclear scattering data [Hanhart, Phillips & Reddy, astro-ph/0003445]

SN 1987A Axion Limits



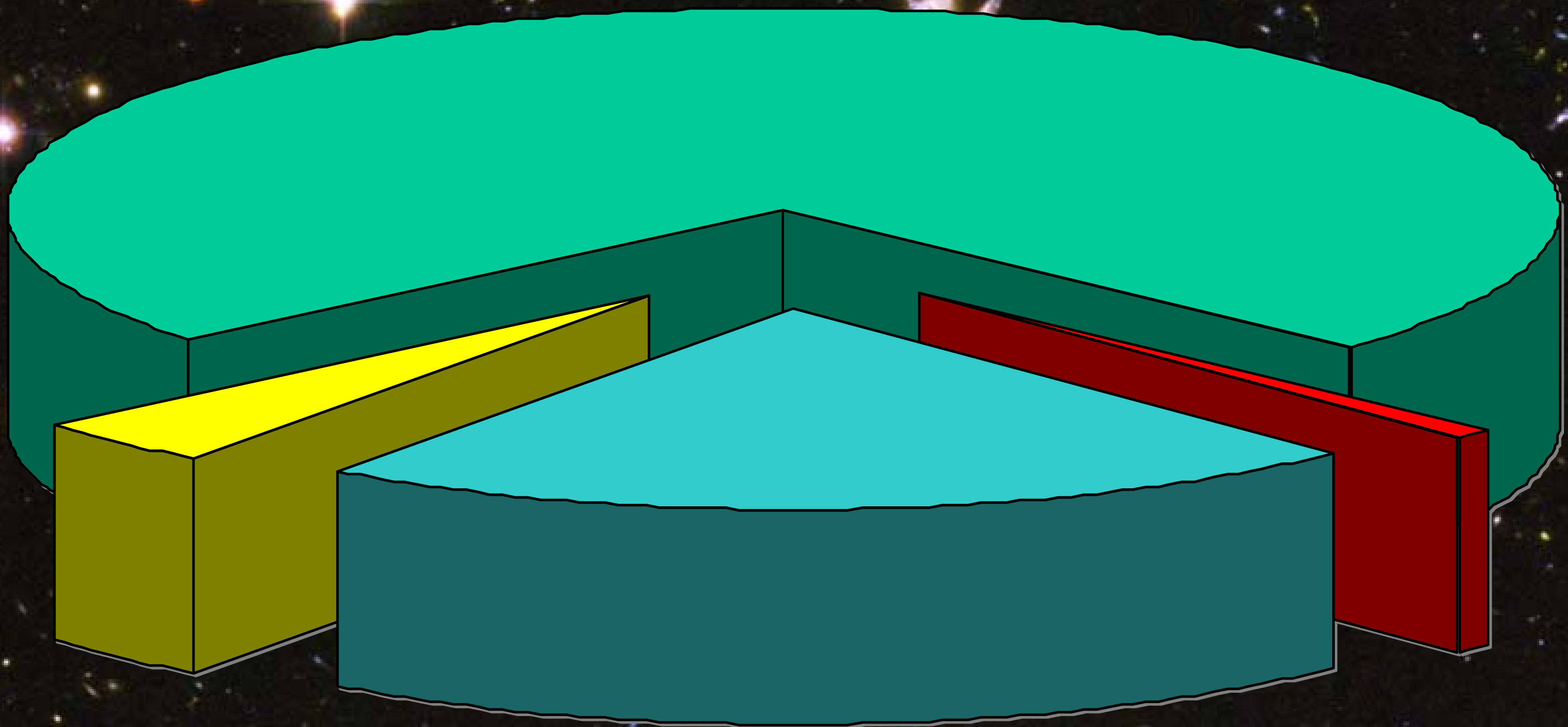
Astrophysical Axion Bounds





Structure-Formation Limits on Hot Dark-Matter Axions

Dark Energy 73%
(Cosmological Constant)



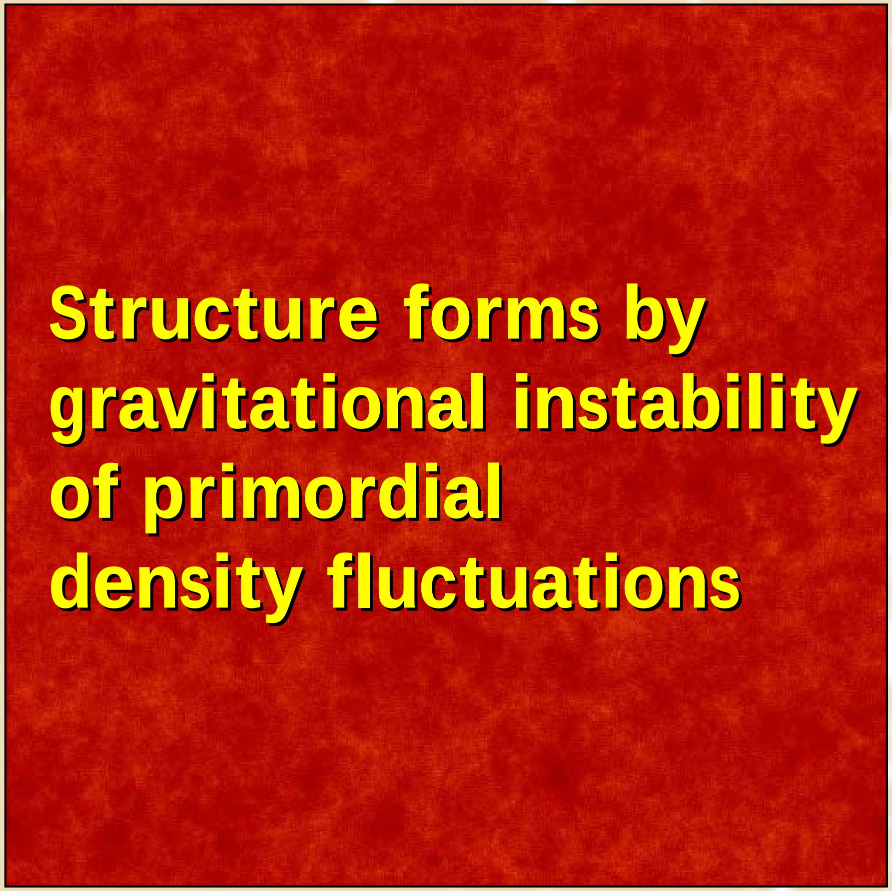
Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

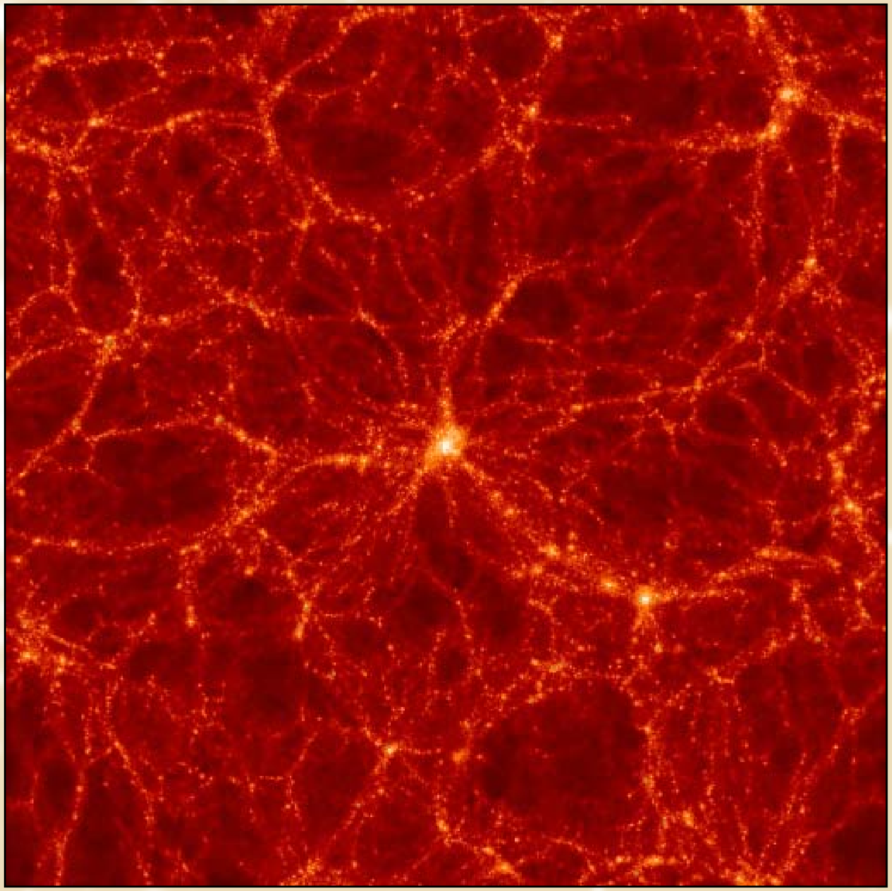
Neutrinos
0.1–2%

Formation of Structure

Smooth	Structured

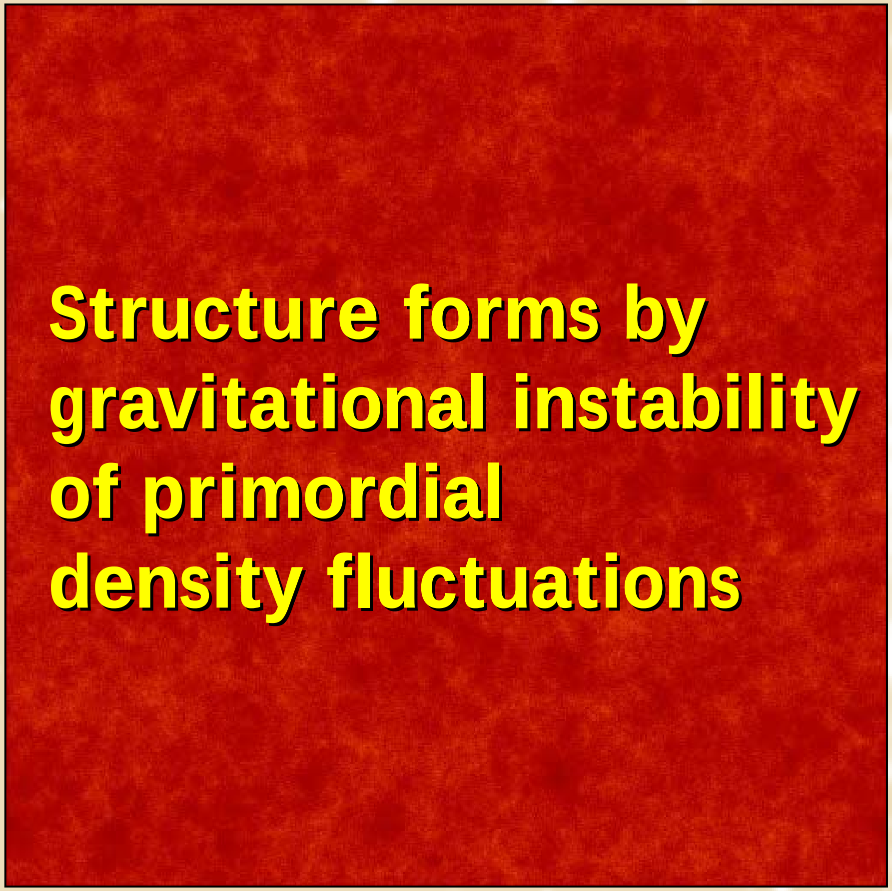


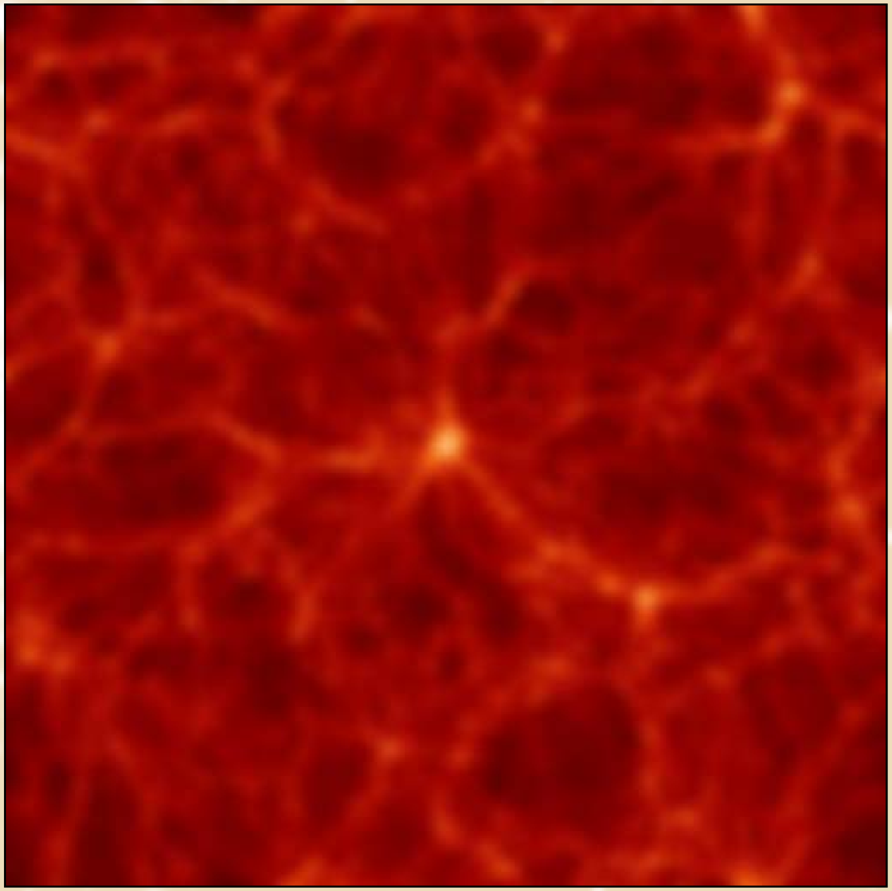
Structure forms by gravitational instability of primordial density fluctuations



Formation of Structure

Smooth → **Structured**

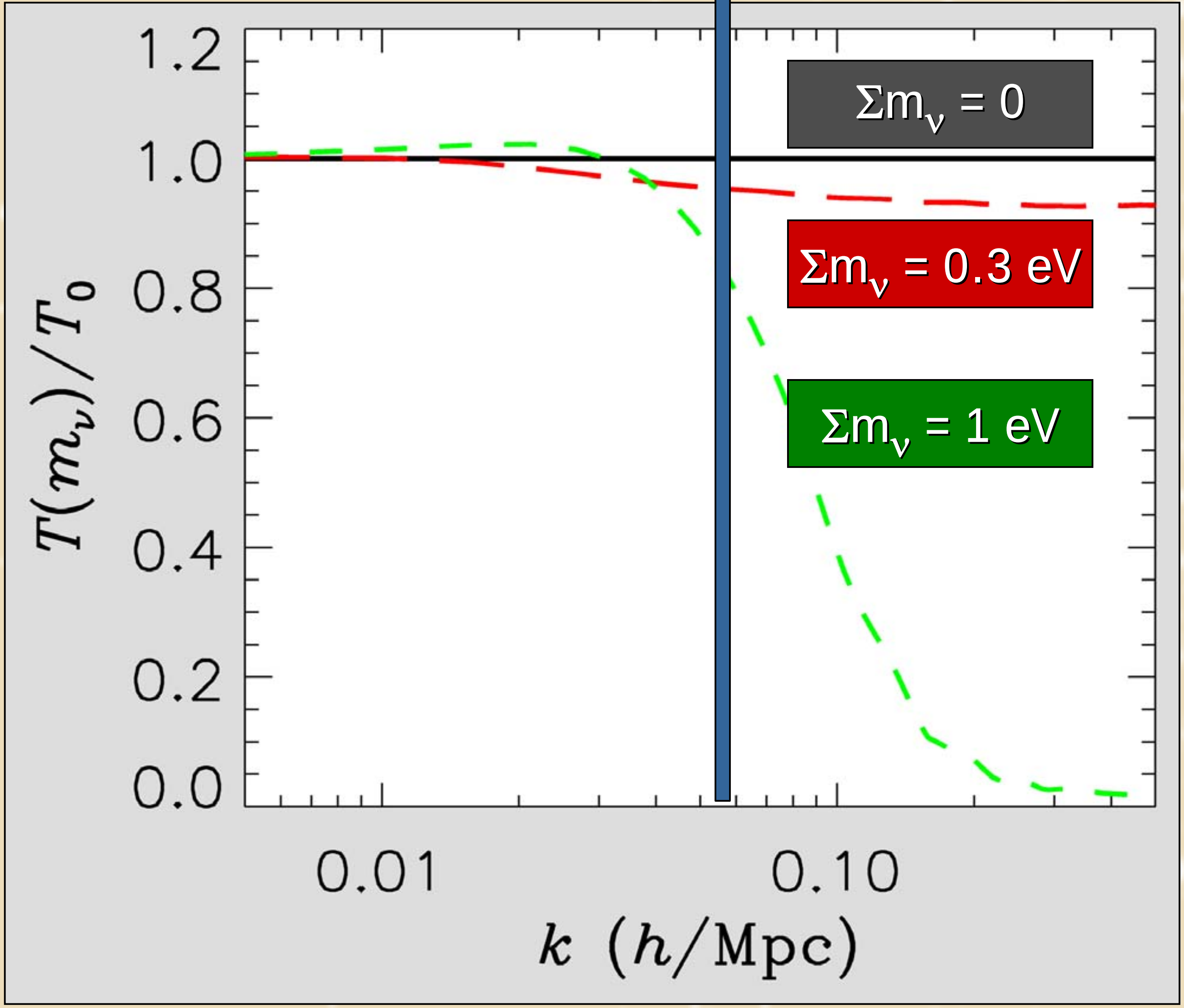




A fraction of hot dark matter suppresses small-scale structure

Neutrino Free Streaming – Transfer Function

Power suppression for $\lambda_{FS} \lesssim 100$ Mpc/h



Hannestad, Neutrinos in Cosmology, hep-ph/0404239

Transfer function

$P(k) = T(k)\, P_0(k)$

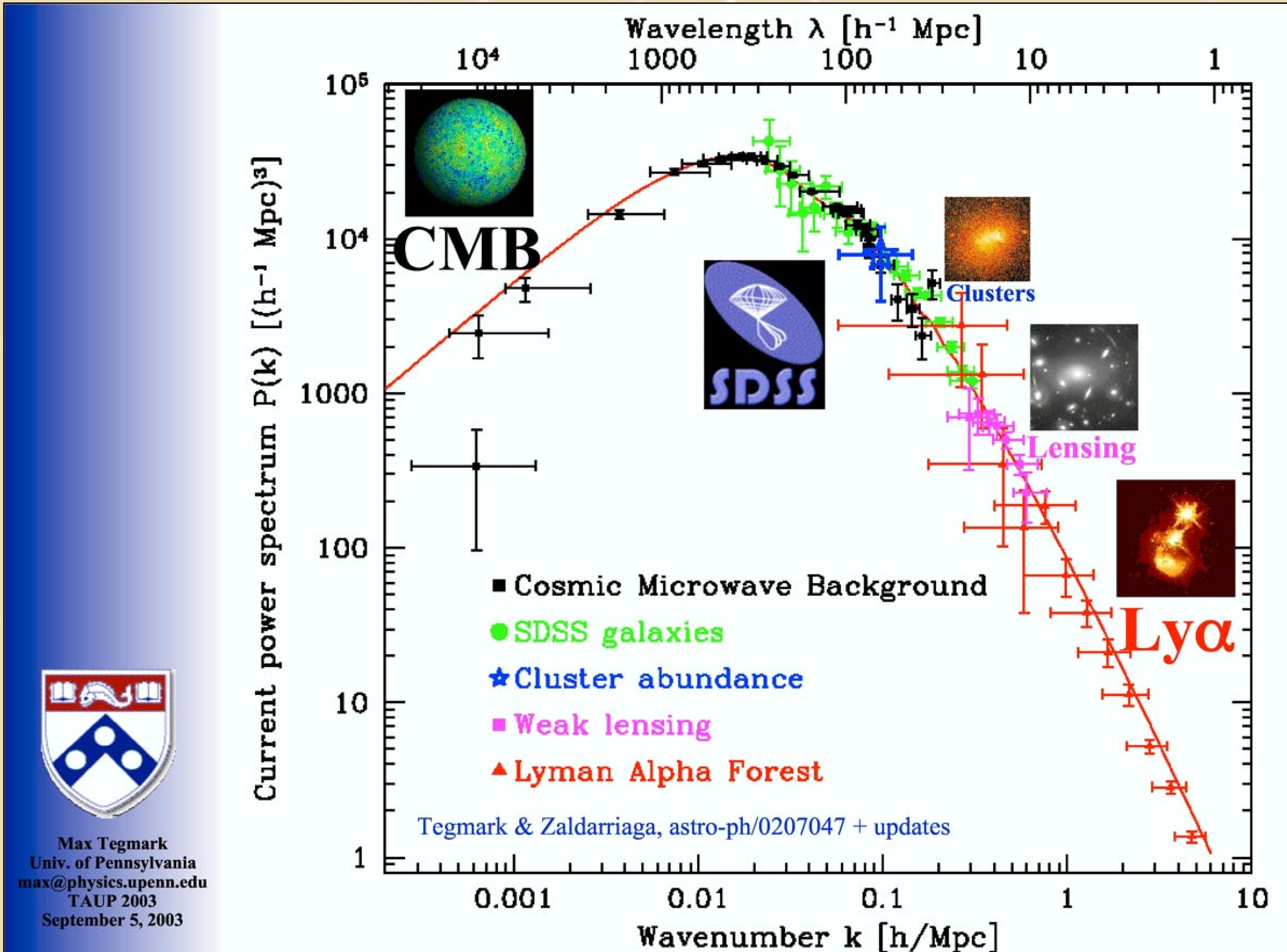
Effect of neutrino free streaming on small scales

$T(k) = 1 - 8\Omega_\nu/\Omega_M$

valid for

$8\Omega_\nu/\Omega_M \ll 1$

Power Spectrum of Cosmic Density Fluctuations



Recent Cosmological Limits on Neutrino Masses

	Σm_ν/eV (limit 95%CL)	Data / Priors
Ichikawa, Fukugita, Kawasaki 2004 [astro-ph/0409768]	2.0	WMAP
Tegmark et al. 2003 [astro-ph/0310723]	1.8	WMAP, SDSS
Hannestad 2003 [astro-ph/0303076]	1.01	WMAP, CMB, 2dF, HST
Spergel et al. (WMAP) 2003 [astro-ph/0302209]	0.69	WMAP, CMB, 2dF, HST, σ_8
Barger et al. 2003 [hep-ph/0312065]	0.75	WMAP, CMB, 2dF, SDSS, HST
Crotty et al. 2004 [hep-ph/0402049]	1.0 0.6	WMAP, CMB, 2dF, SDSS & HST, SN
Hannestad 2004 [hep-ph/0409108]	0.65	WMAP, SDSS, SN Ia gold sample, Ly-α data from Keck sample
Seljak et al. 2004 [astro-ph/0407372]	0.42	WMAP, SDSS, Bias, Ly-α data from SDSS sample

Sensitivity Forecasts for Future LSS Observations

Lesgourgues, Pastor & Perotto, hep-ph/0403296	Planck & SDSS	Σm_ν > 0.21 eV detectable at 2σ
	Ideal CMB & 40 x SDSS	Σm_ν > 0.13 eV detectable at 2σ
Abazajian & Dodelson astro-ph/0212216	Future weak lensing survey 4000 deg^2	$\sigma(m_\nu) \sim 0.1$ eV
Kaplinghat, Knox & Song, astro-ph/0303344	CMB lensing	$\sigma(m_\nu) \sim 0.15$ eV (Planck) $\sigma(m_\nu) \sim 0.044$ eV (CMBpol)
Wang, Haiman, Hu, Khoury & May, astro-ph/0505390	Weak-lensing selected sample of > 10^5 clusters	$\sigma(m_\nu) \sim 0.03$ eV

Extending the Mass Bound to Other Low-Mass Particles

Assume a generic hot dark matter particle that was in thermal equilibrium at some cosmological epoch

- Internal particle degrees of freedom (e.g. spin states) g_X
- Mass m_X
- Effective number of thermal degrees of freedom at freeze-out g_*

Contribution to cosmic mass density

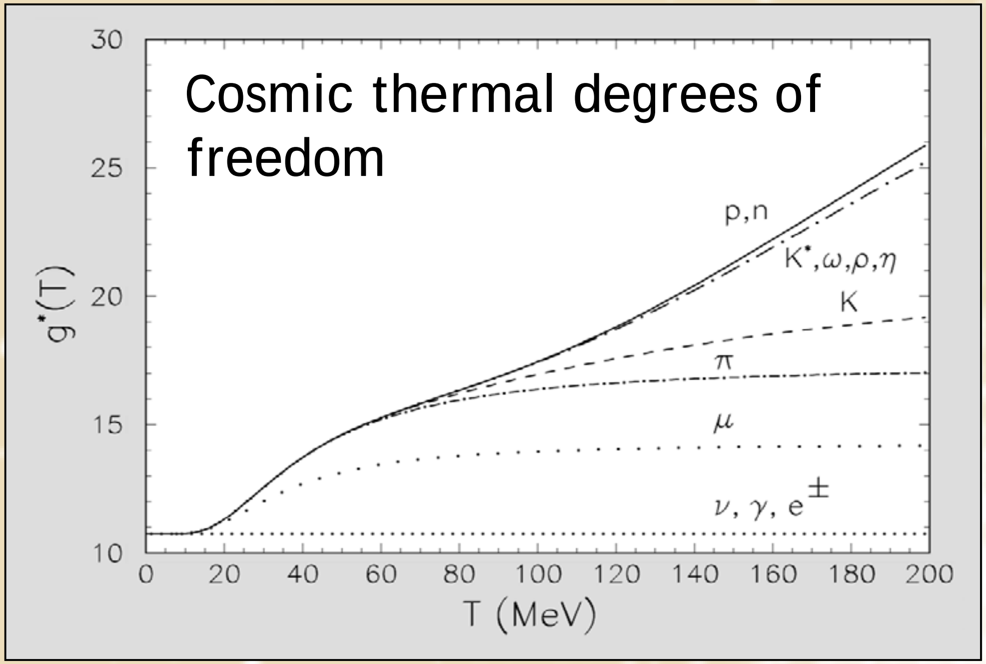
$$\Omega_X h^2 = \frac{m_X g_X}{183\ \mathrm{eV}} \frac{10.75}{g_{*X}} \times \begin{cases} 1 & \text{for fermions} \\ 4/3 & \text{for bosons} \end{cases}$$

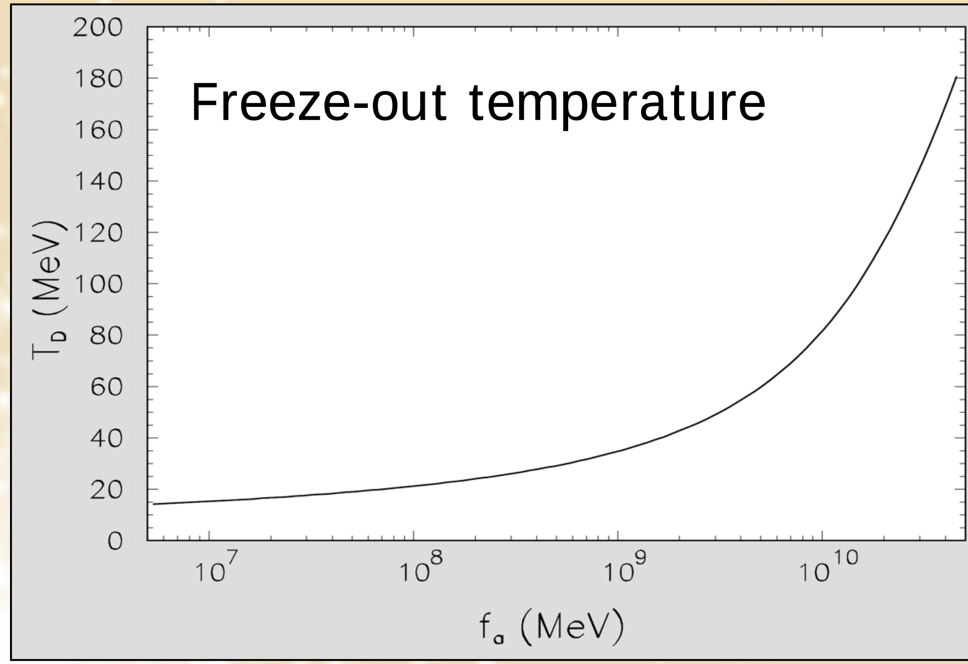
Free-streaming length

$$\lambda_{FS} \approx \frac{20\ \mathrm{Mpc}}{\Omega_X h^2} \left(\frac{T_X}{T_\nu}\right)^4 \left[1 + \log\left(3.9 \frac{\Omega_X}{\Omega_m} \frac{T_\nu^2}{T_X^2}\right)\right]$$

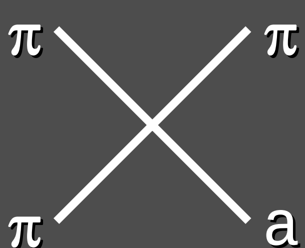
Perform maximum likelihood analysis for different choices of g_X and g_* to derive cosmological limit on m_X

Axion Freeze-Out



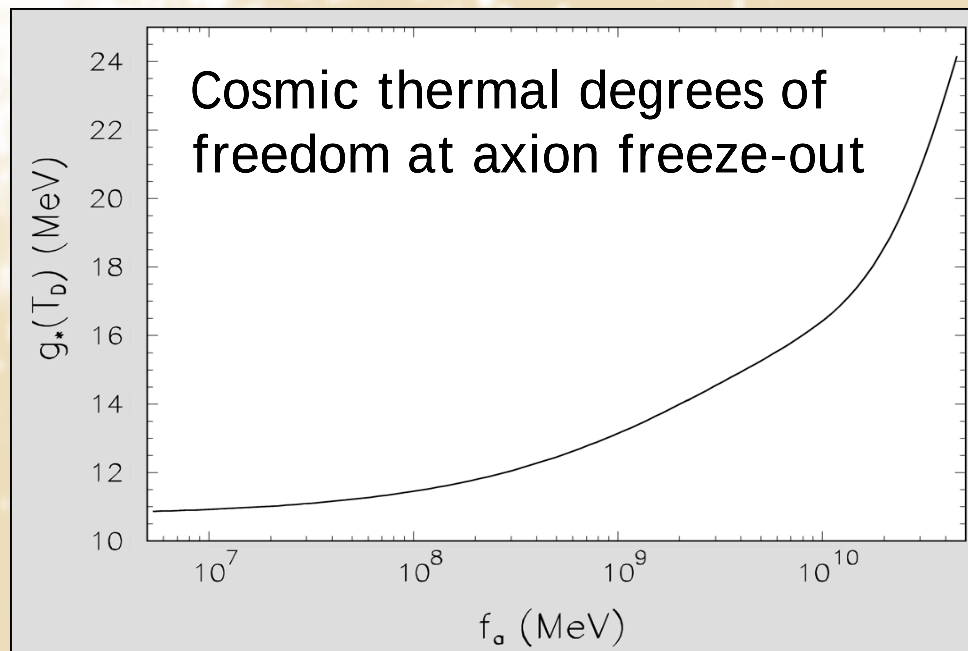


$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0)\partial^\mu a$$

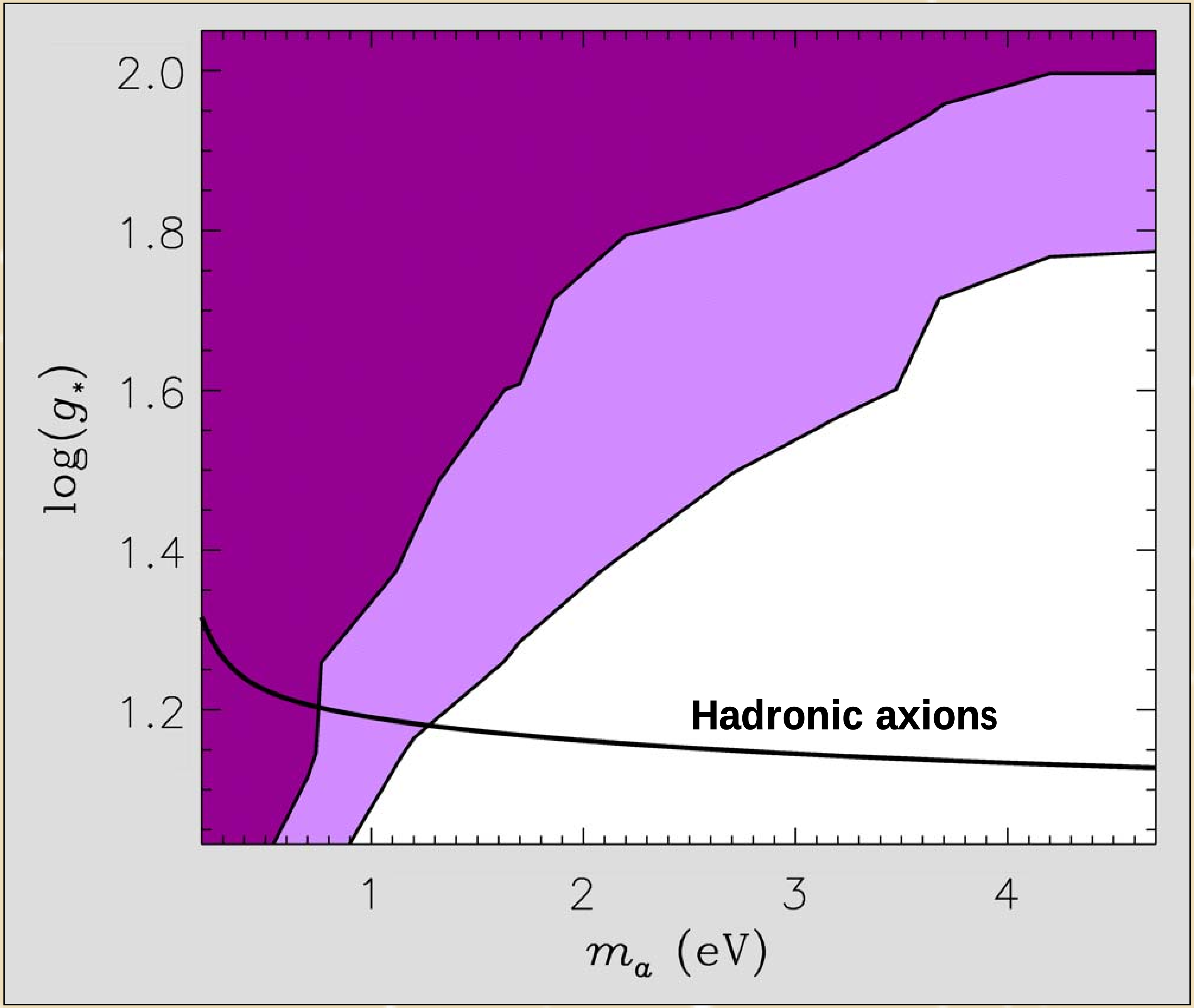


$$C_{a\pi} = \frac{1-z}{3(1+z)} \approx 0.094$$

Chang & Choi, PLB 316 (1993) 51



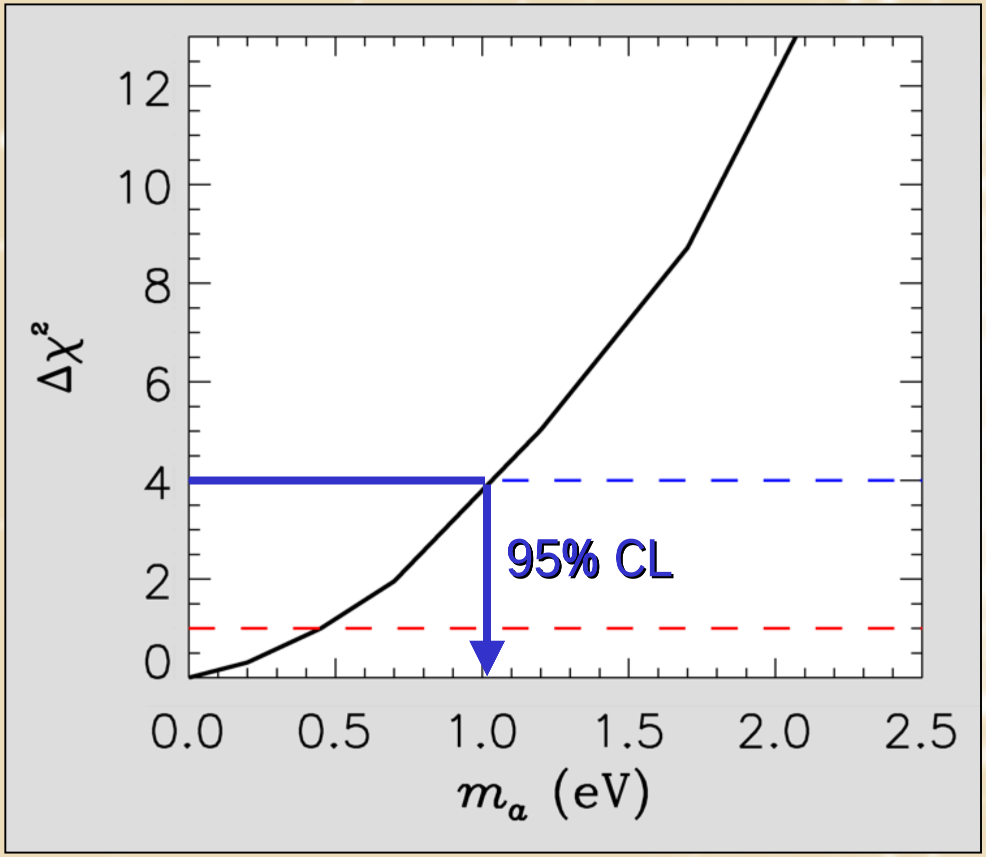
Structure-Formation Exclusion Range for Axions



Hannestad, Mirizzi & Raffelt, hep-ph/0504059

Mass Limits on Hot Dark Matter Axions and Neutrinos

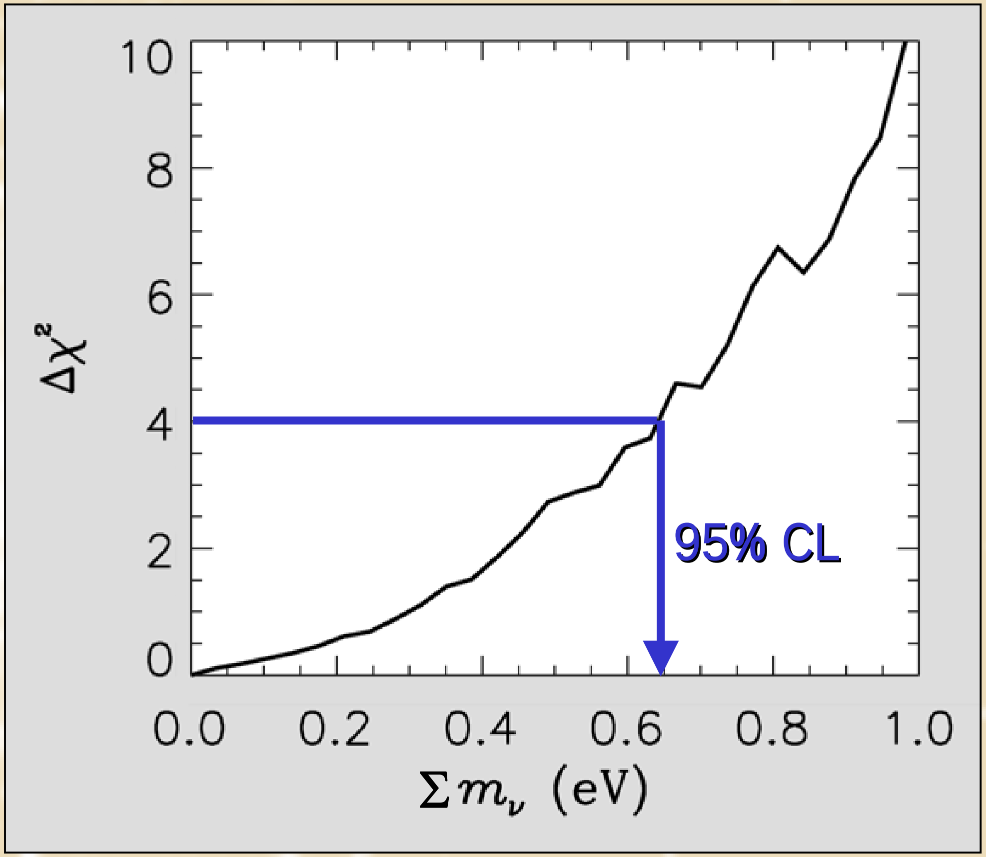
Hannestad, Mirizzi & Raffelt
hep-ph/0504059



Axions

$m_a < 1.05$ eV (95% CL)

Hannestad, astro-ph/0409108
(Seesaw proceedings, Paris, 2004)

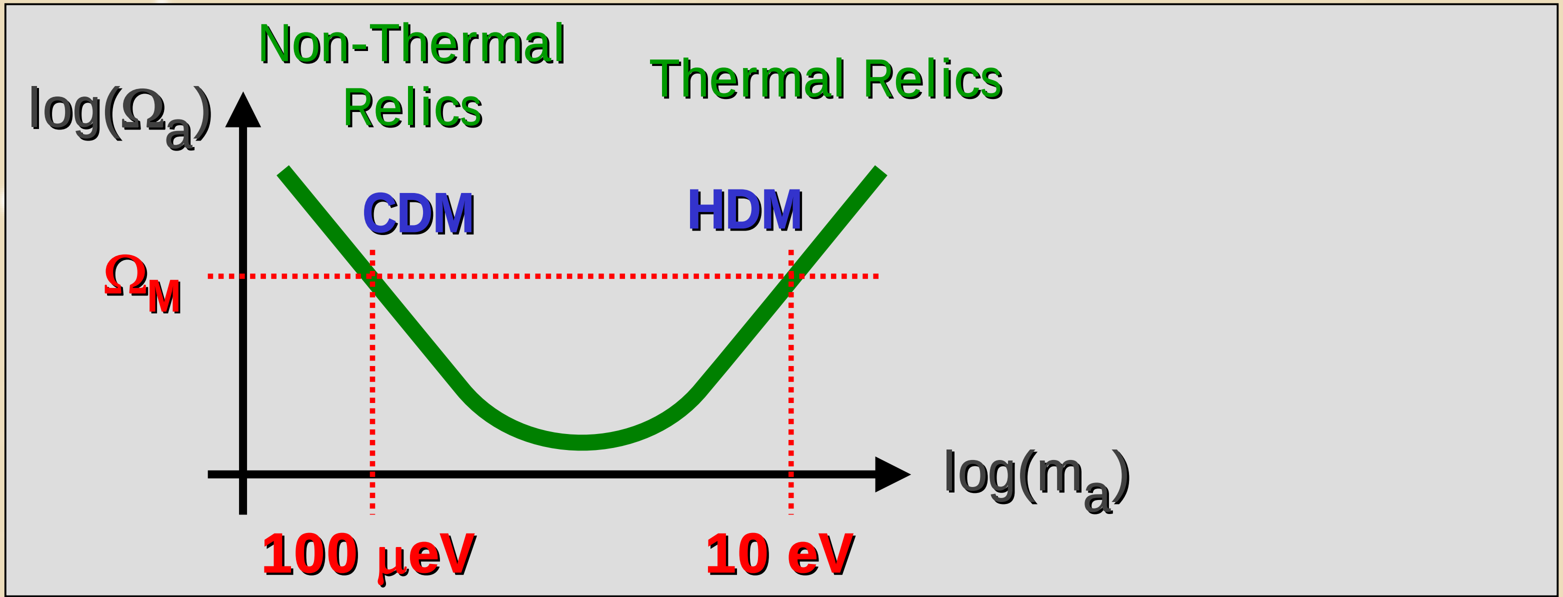


Neutrinos

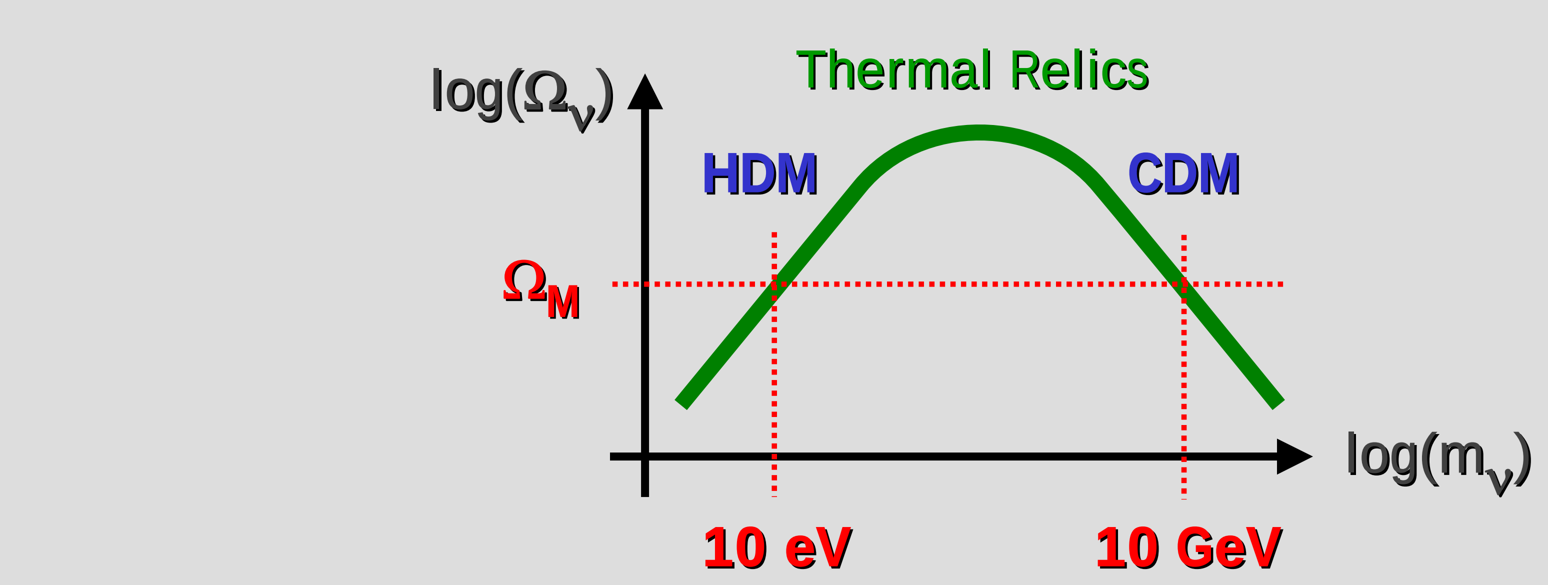
$\Sigma m_\nu < 0.65$ eV (95% CL)

Lee-Weinberg Curve for Neutrinos and Axions

Axions



Neutrinos



Astrophysical Axion Bounds