Physics & Astrophysics of Neutrinos

Yong-Zhong Qian（钱永忠）
School of Physics & Astronomy, University of Minnesota
Center for Nuclear Astrophysics, Shanghai Jiao Tong University

CCEPP Summer School 2017 on Neutrino Physics
July 6-8, 2017

Outline

Scientific Marxism
科学马克思主义

Primary status of matter
物质第一性

Spiral ascent in learning
认识的螺旋形上升

Interconnection among everything
万事万物的普遍联系

Ultimate test by experiments
实践是检验真理的唯一标准

Neutrinos in the Cosmos: A Nobel Perspective

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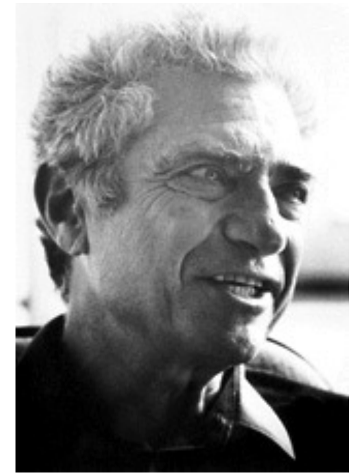
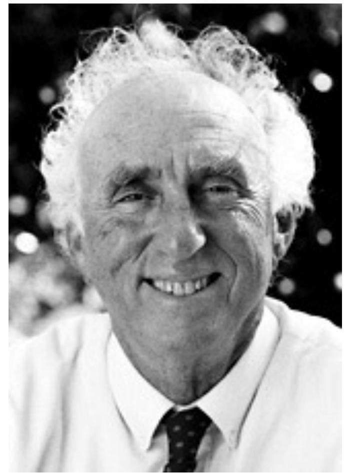
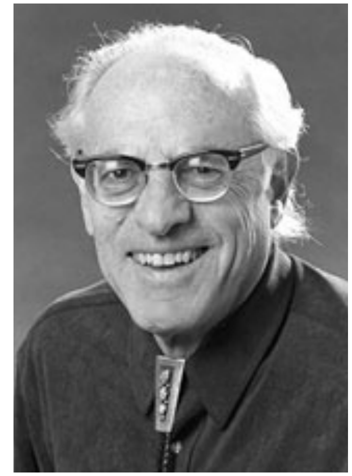
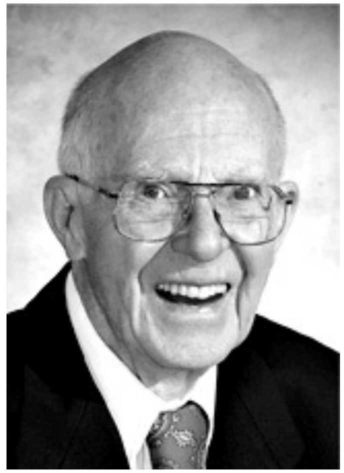


The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino.



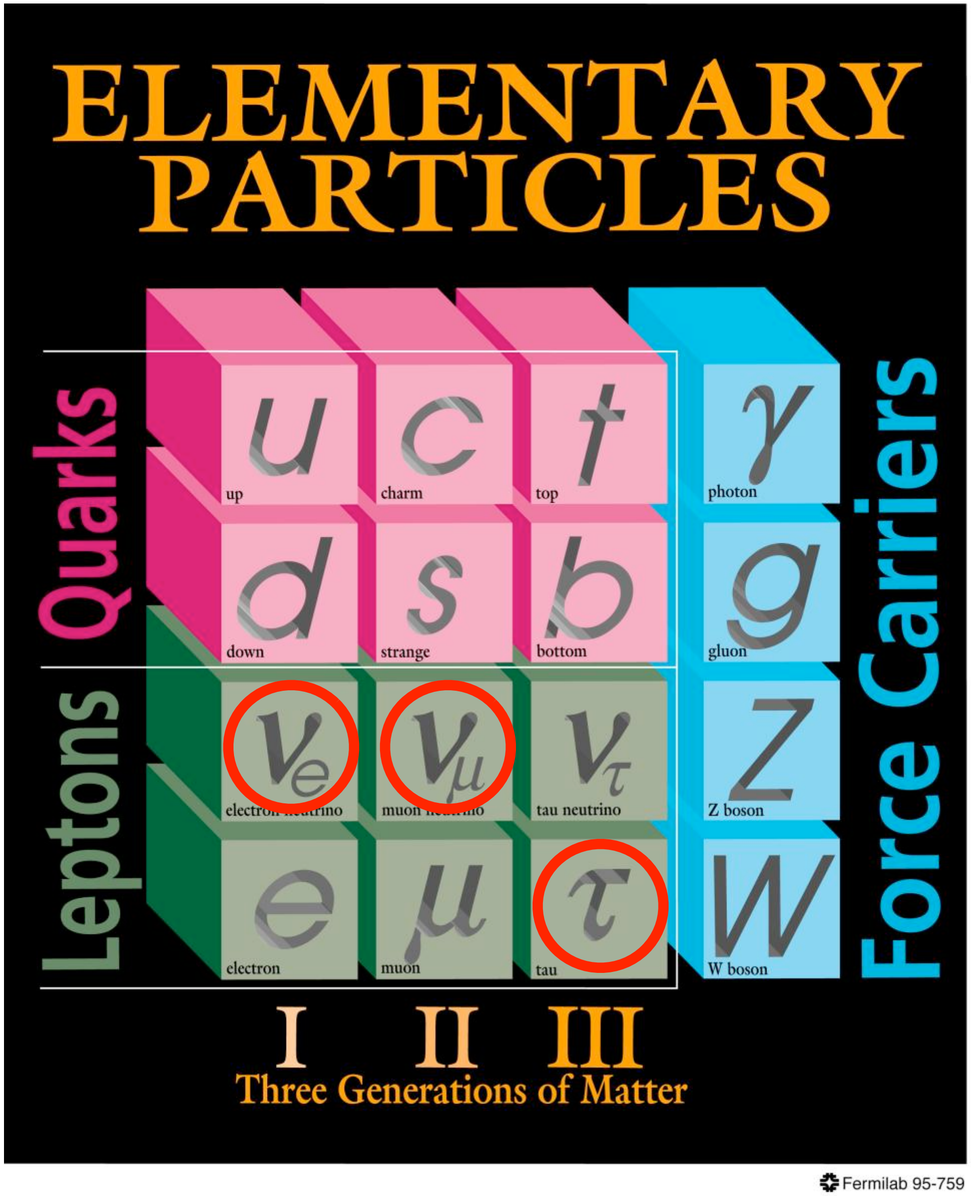


The Nobel Prize in Physics 1995 was awarded for pioneering experimental contributions to lepton physics jointly with one half to Martin L. Perl for the discovery of the tau lepton and with one half to Frederick Reines for the detection of the neutrino.

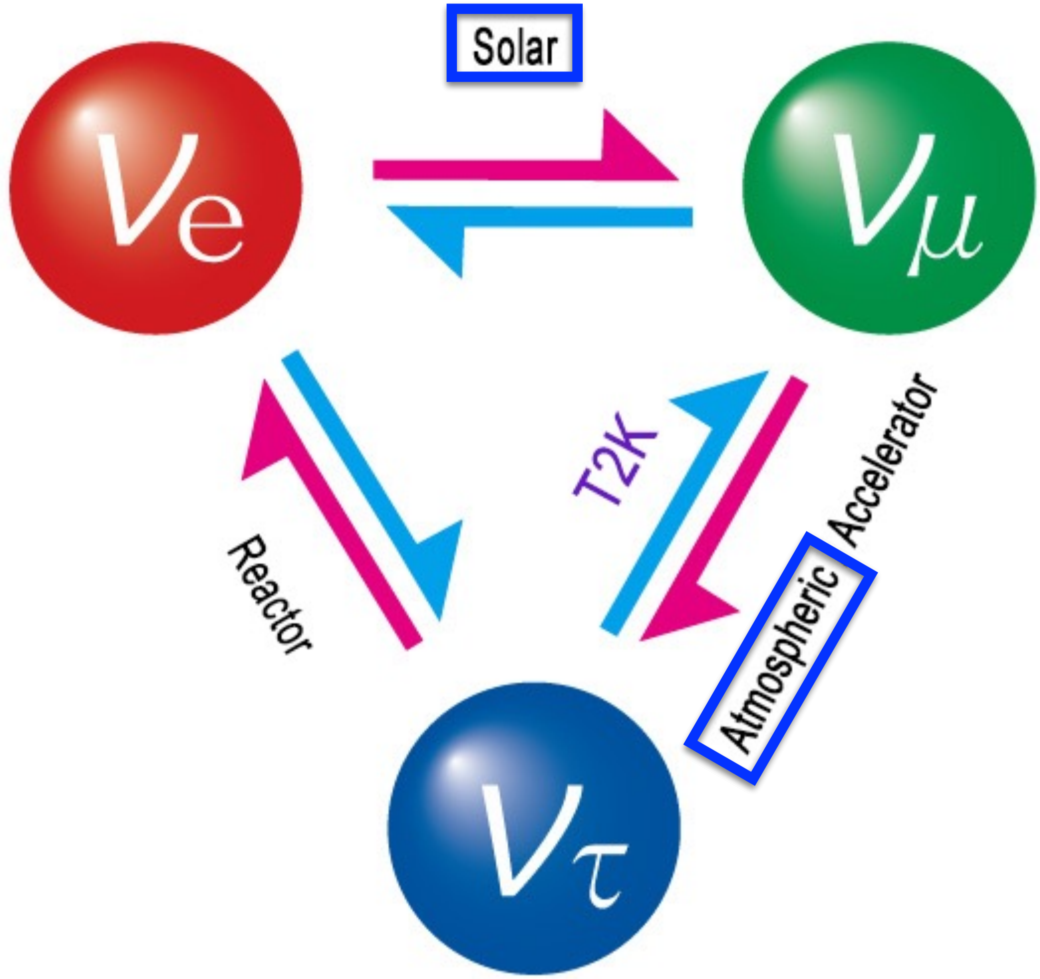


The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos and the other half to Riccardo Giacconi for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources.

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations, which shows that neutrinos have mass.

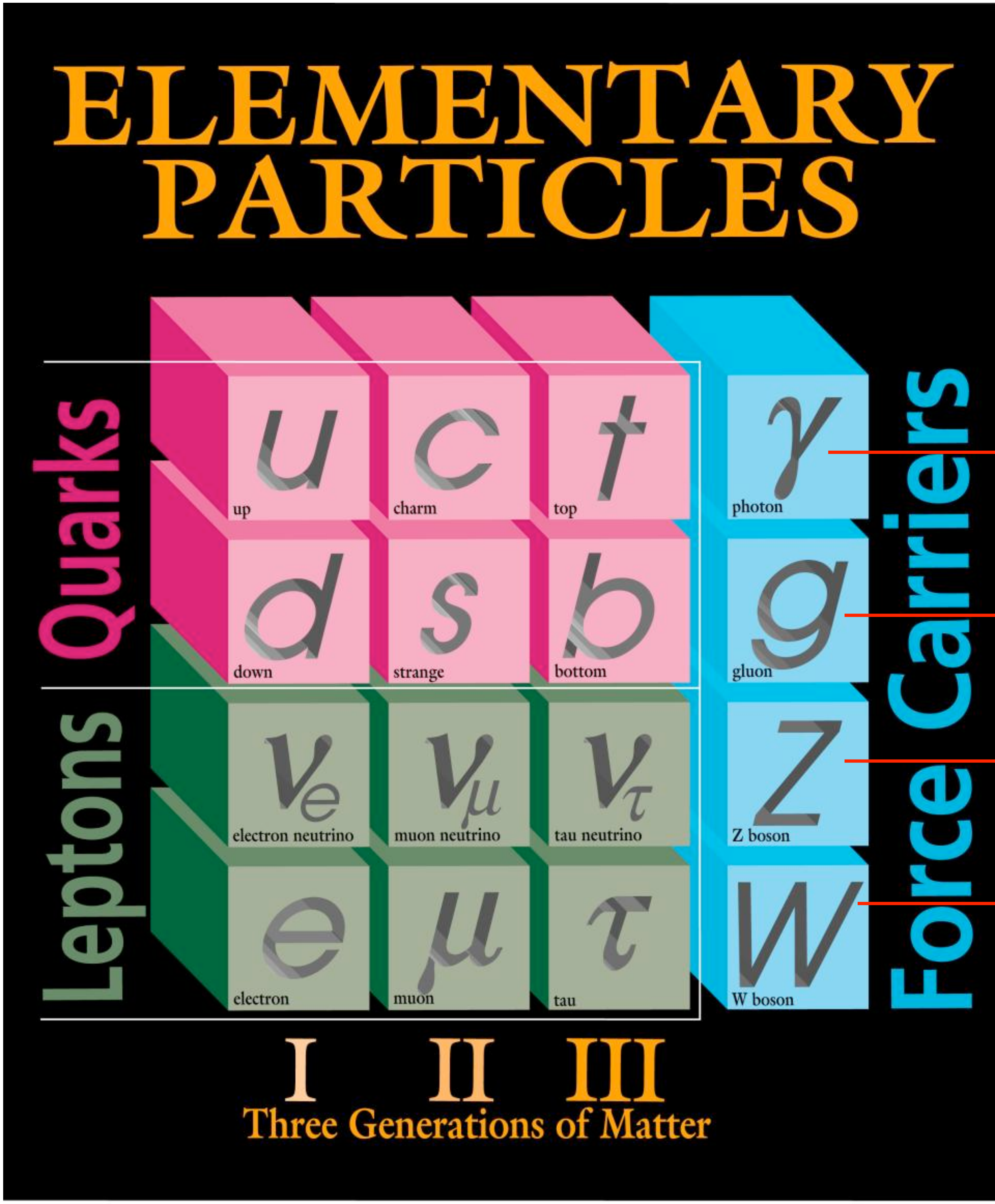


Standard Model



Neutrino oscillation between three generations

Beyond Standard Model



Fermilab 95-759

Fundamental Interactions

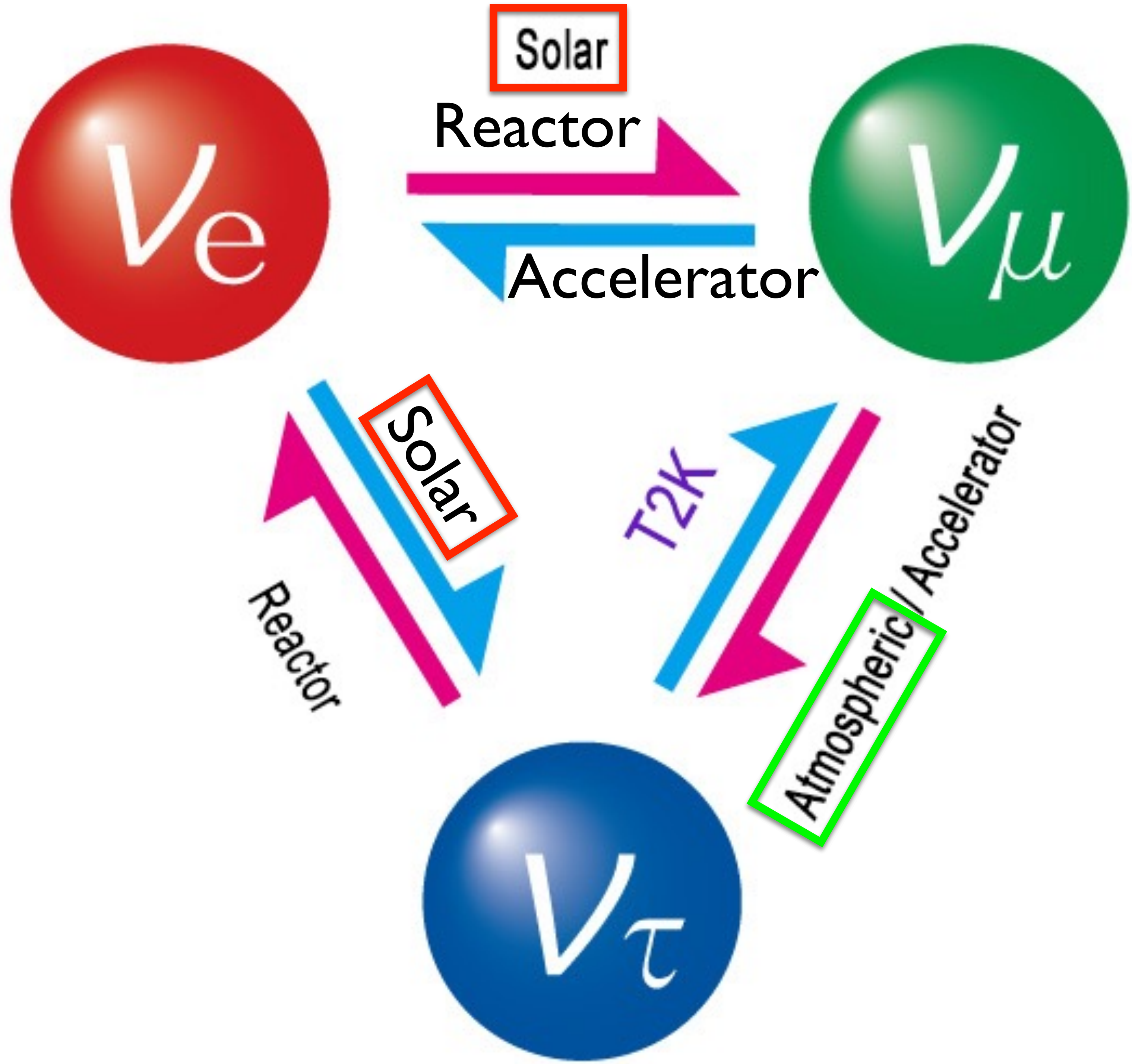
Electromagnetic

Strong

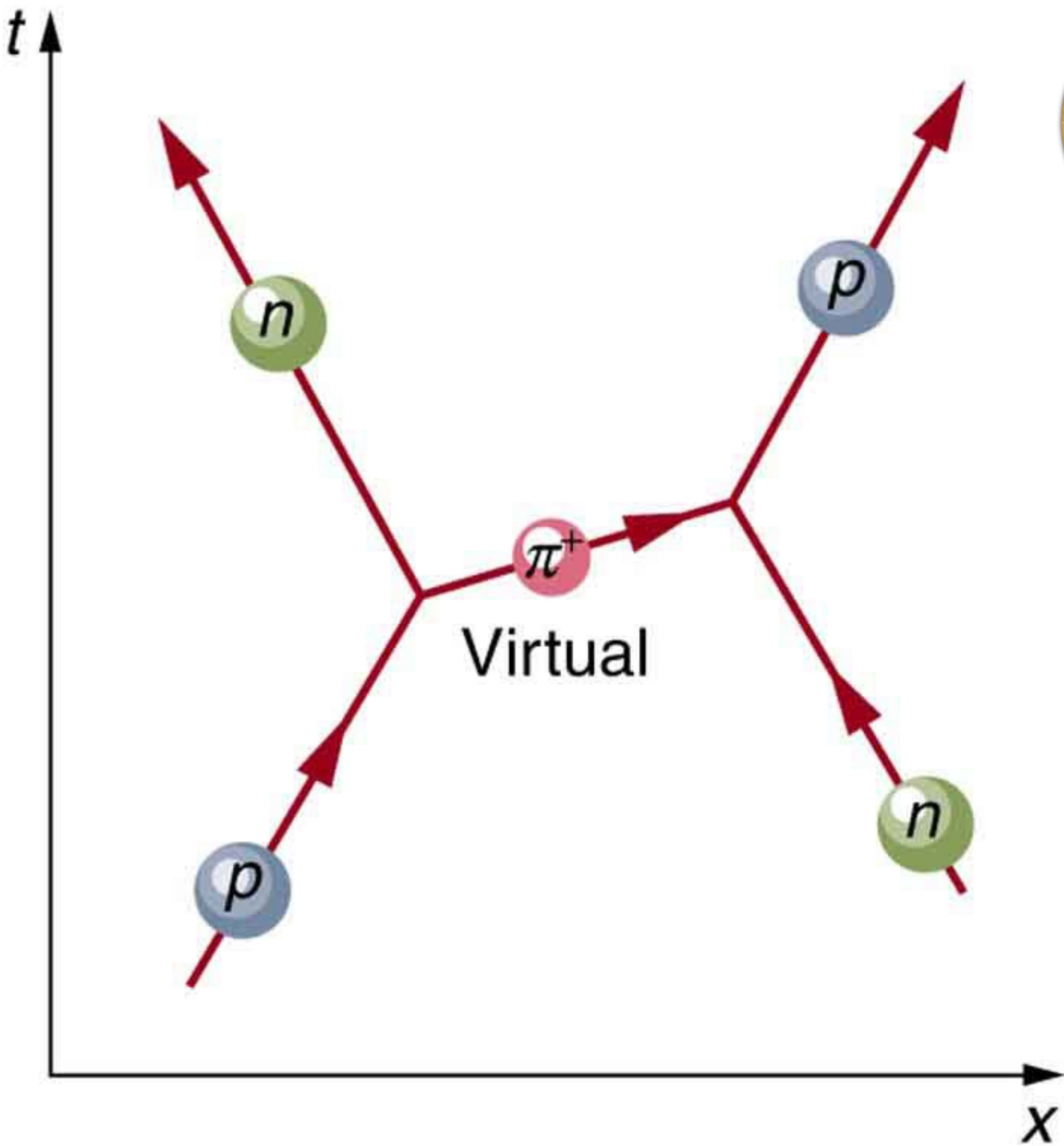
Weak (NC)

Weak (CC)

Gravitational



Solar
Reactor
Accelerator
Solar
Reactor
T2K
Atmospheric / Accelerator



Yukawa
(1949)

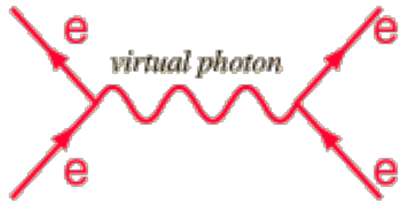
$$\delta E \cdot \delta t \sim \hbar$$

$$m_\pi c^2 \left(\frac{\delta r}{c}\right) \sim \hbar$$

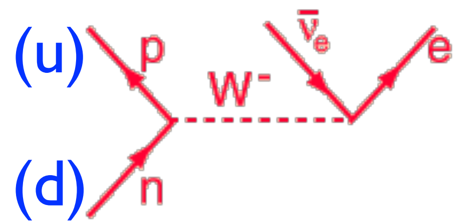
$$m_\pi c^2 \sim \frac{\hbar c}{\delta r}$$

$$\delta r \sim 2 \text{ fm} \Rightarrow$$

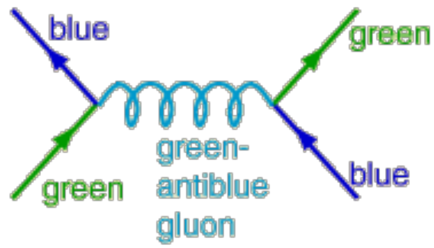
$$m_\pi c^2 \sim 100 \text{ MeV}$$



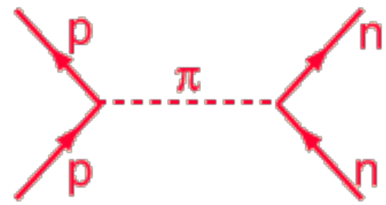
Electromagnetic



Weak
(charged-current)

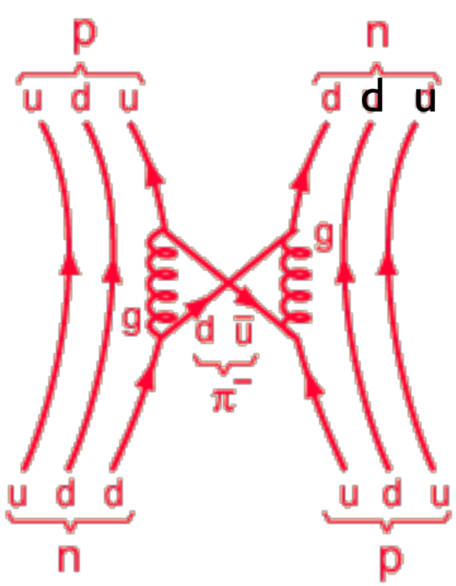


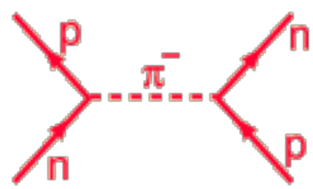
between quarks



between nucleons

Strong Interaction





strong interactions

$$p + A(Z,N) \to \pi^0 + \cdots$$

$$p + A(Z,N) \to \pi^+ + \cdots$$

$$p + A(Z,N) \to \pi^- + \cdots$$

electromagnetic interaction

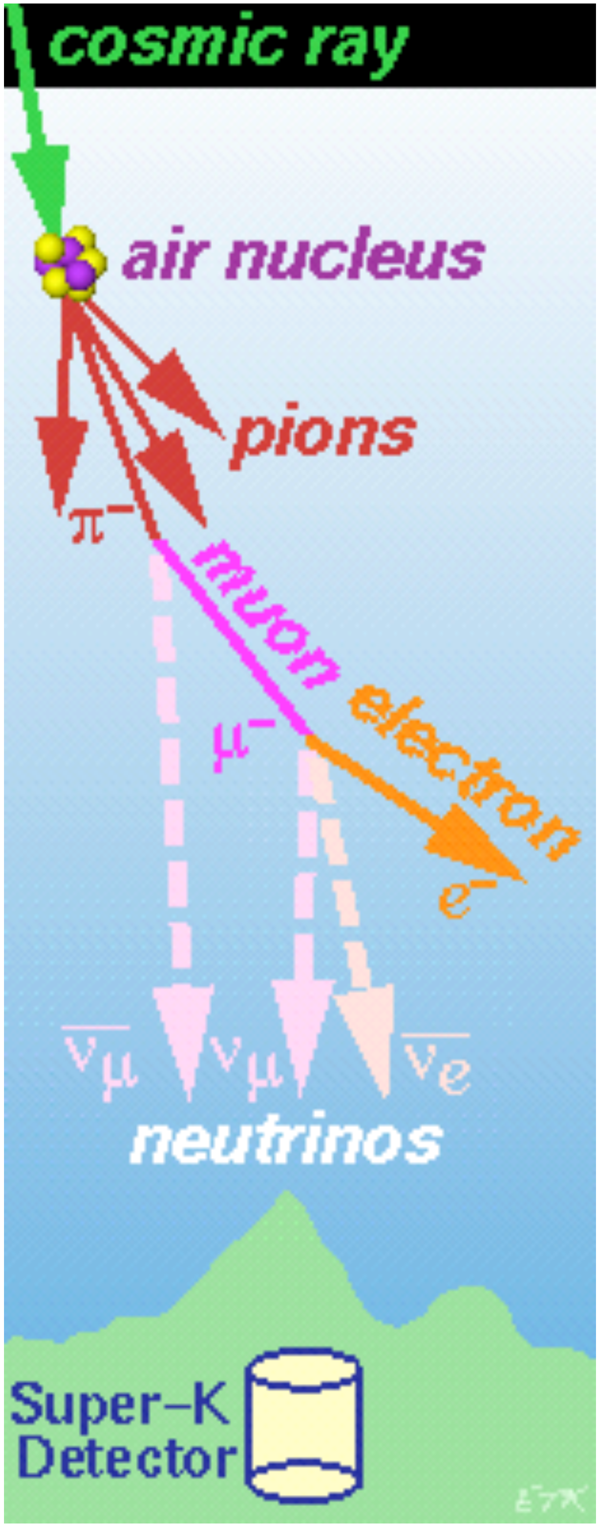
$$\pi^0 \to 2\gamma \ (\tau = 8.4 \times 10^{-17} \text{ s})$$

charged-current weak interactions

$$\pi^+ \to \mu^+ + \nu_\mu \ (\tau = 2.6 \times 10^{-8} \text{ s})$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \ (\tau = 2.2 \times 10^{-6} \text{ s})$$

$$\nu_\mu + A(Z,N) \to \mu^- + \cdots$$

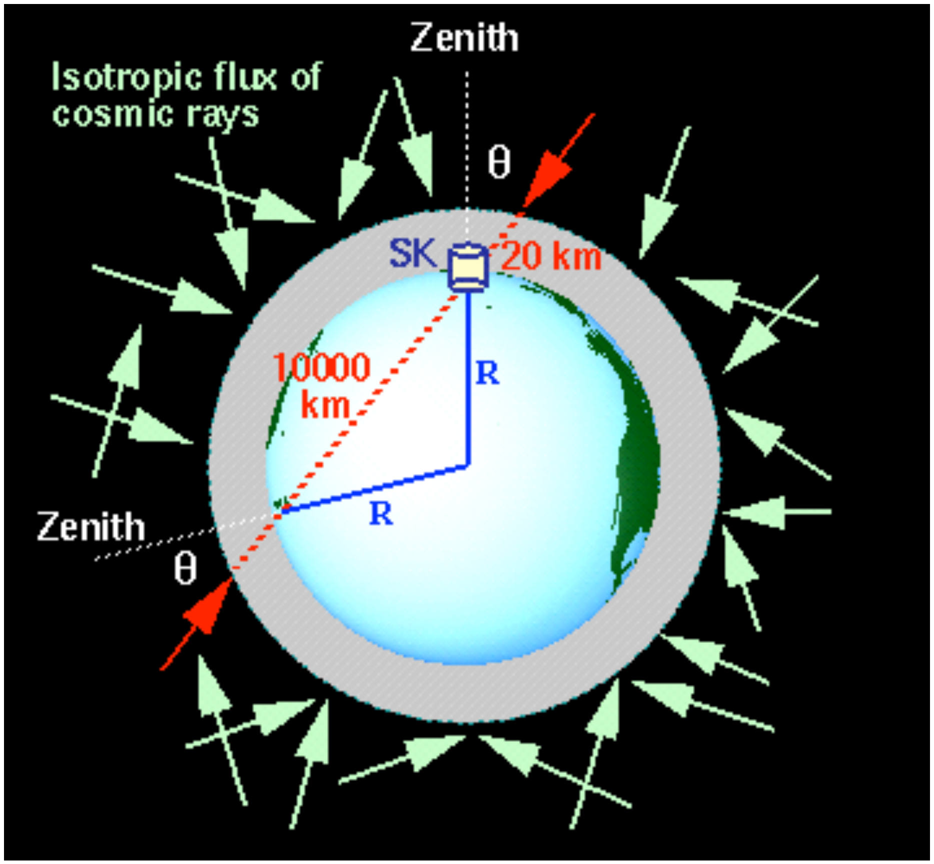


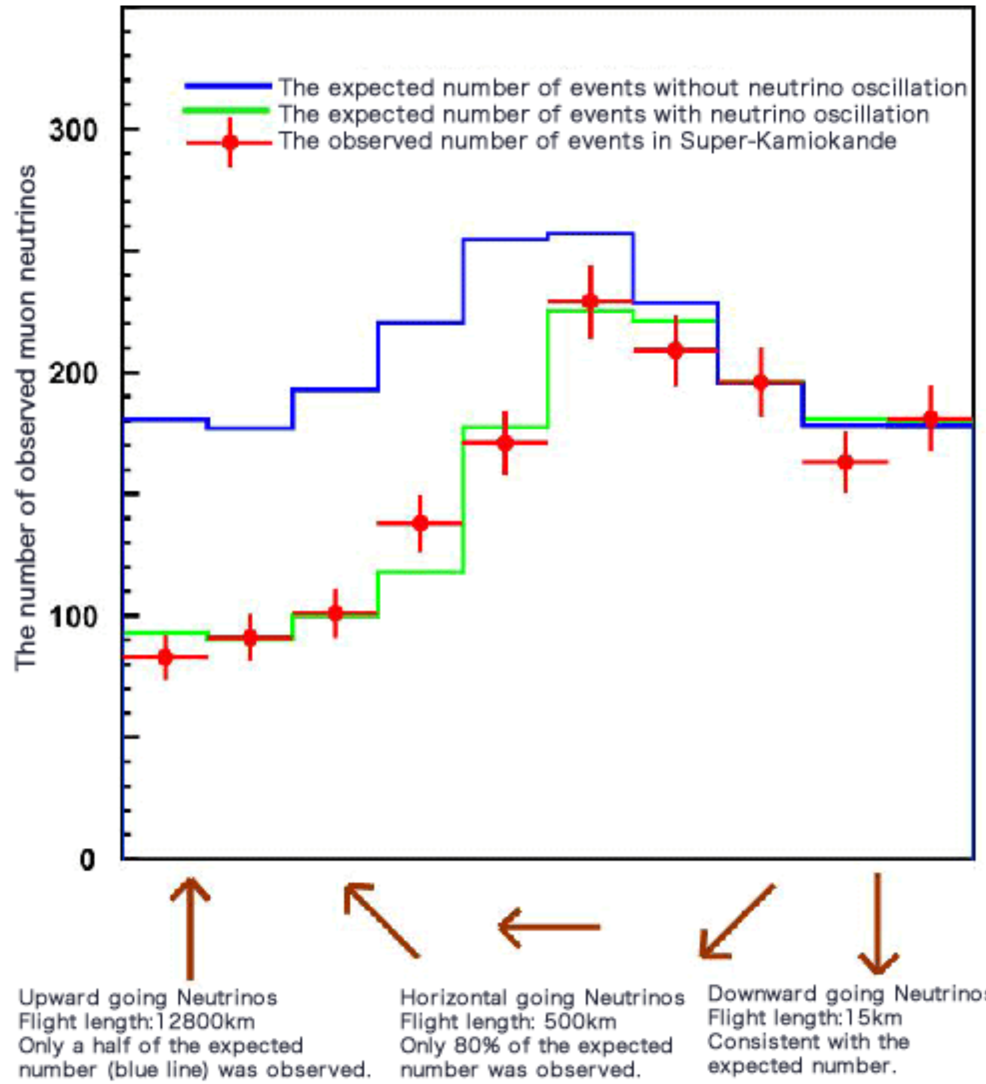
The Nobel Prize in Physics 1936
was divided equally between
Victor Franz Hess for
his discovery of cosmic radiation
and Carl David Anderson for
his discovery of the positron.

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Atmospheric Neutrino Oscillations



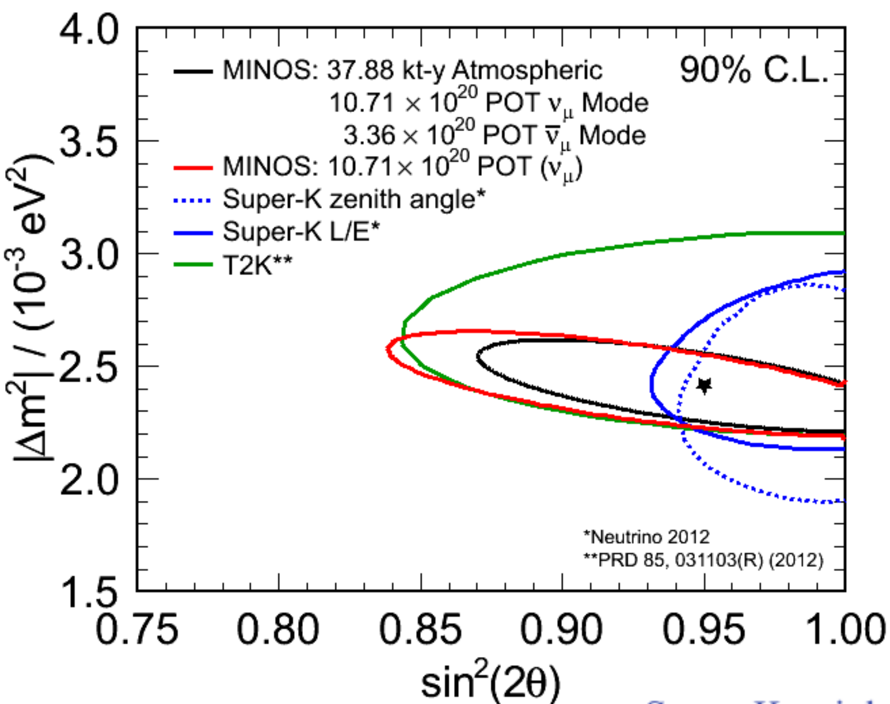


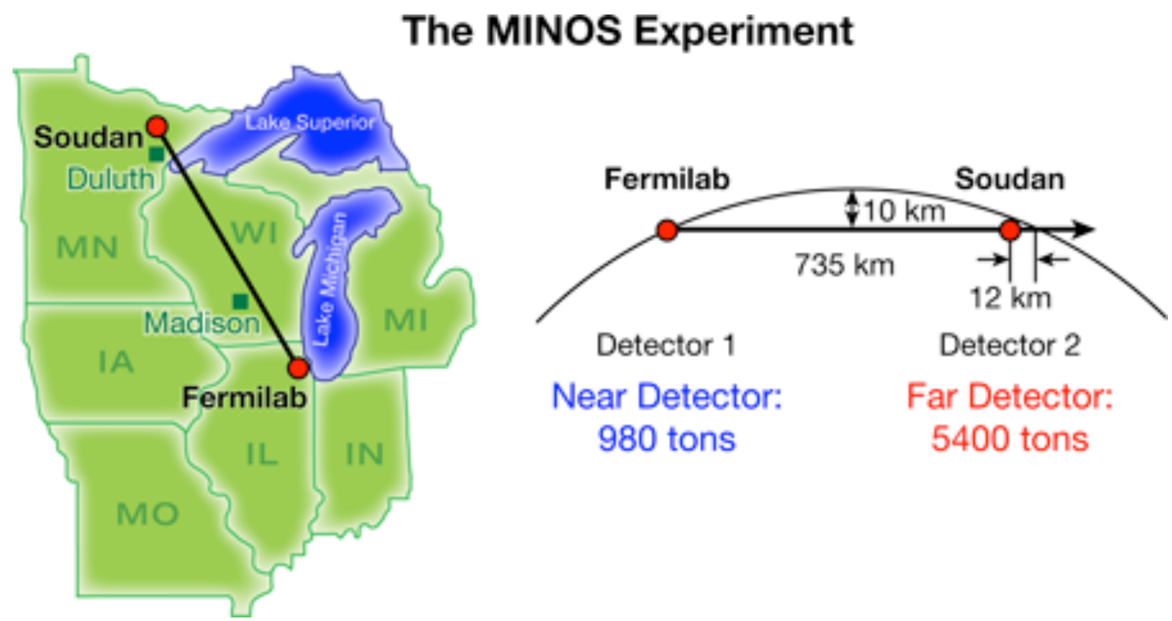
$$\nu_\mu \rightleftharpoons \nu_\tau \ \& \ \bar{\nu}_\mu \rightleftharpoons \bar{\nu}_\tau$$

vacuum oscillations

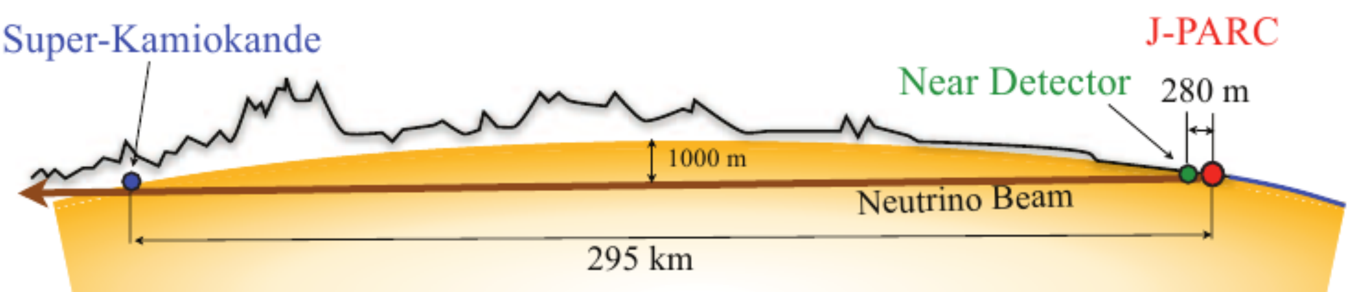
$$P_{\nu_\mu}(t) = 1 - \sin^2 2\theta_{\rm v} \sin^2\left(\frac{\delta m^2}{4p}t\right) \to 1 - \frac{1}{2}\sin^2 2\theta_{\rm v}$$

$$\frac{\delta m^2}{4p}t \approx \frac{\delta m^2}{4E_\nu}x = 1.27\left(\frac{\delta m^2}{10^{-3}\ \mathrm{eV}^2}\right)\left(\frac{\mathrm{GeV}}{E_\nu}\right)\left(\frac{x}{10^3\ \mathrm{km}}\right)$$

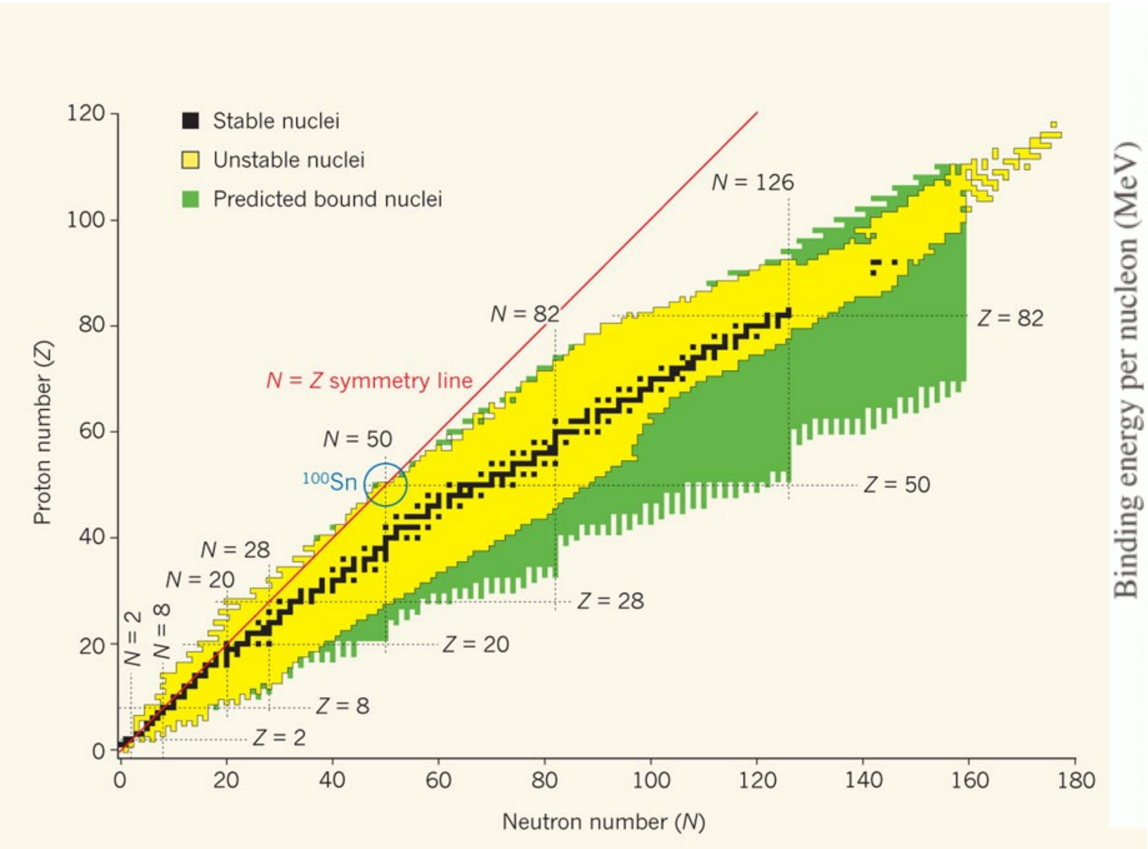


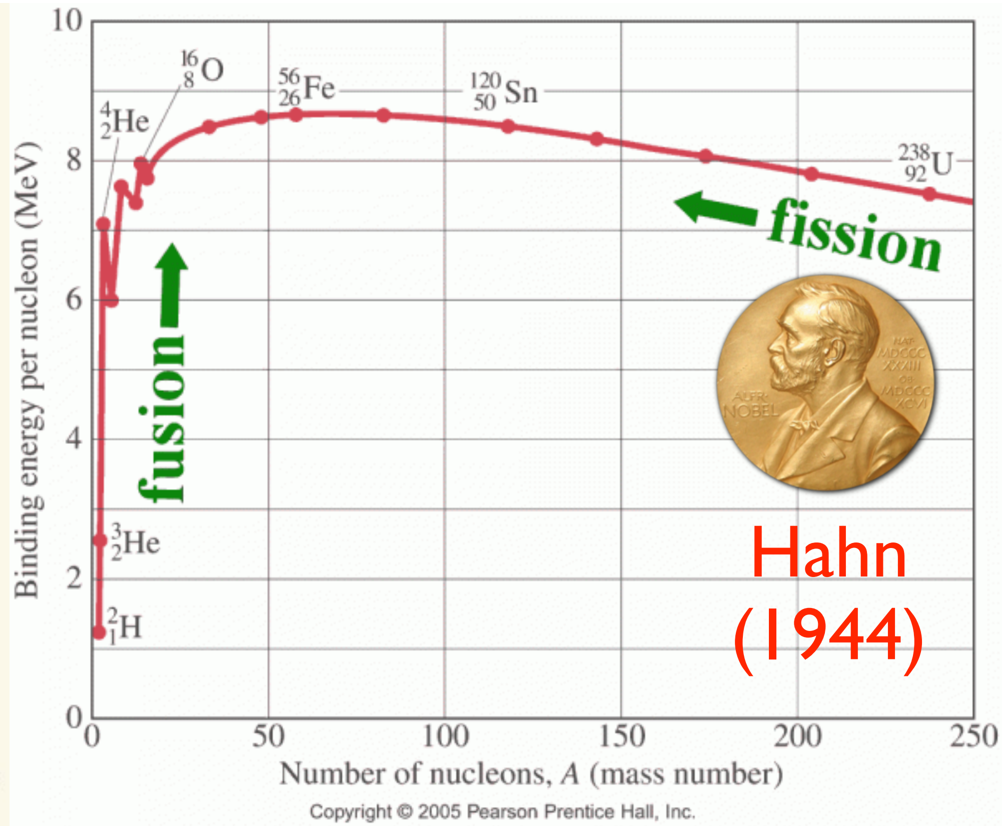


T2K



Other Sources of Neutrinos





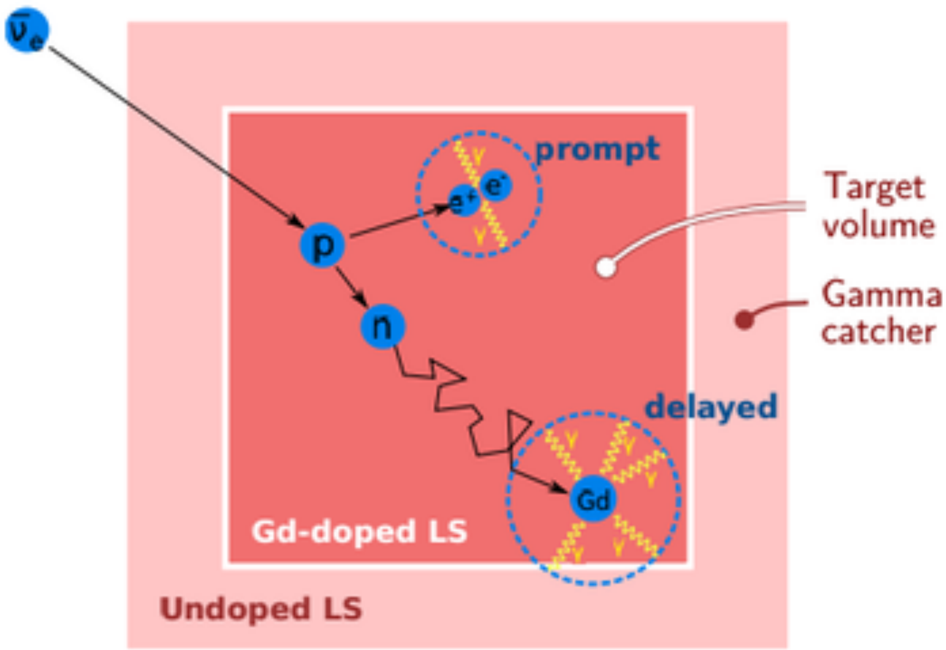
fission fragments: $A(Z,N) \to A(Z+1, N-1) + e^- + \bar{\nu}_e$

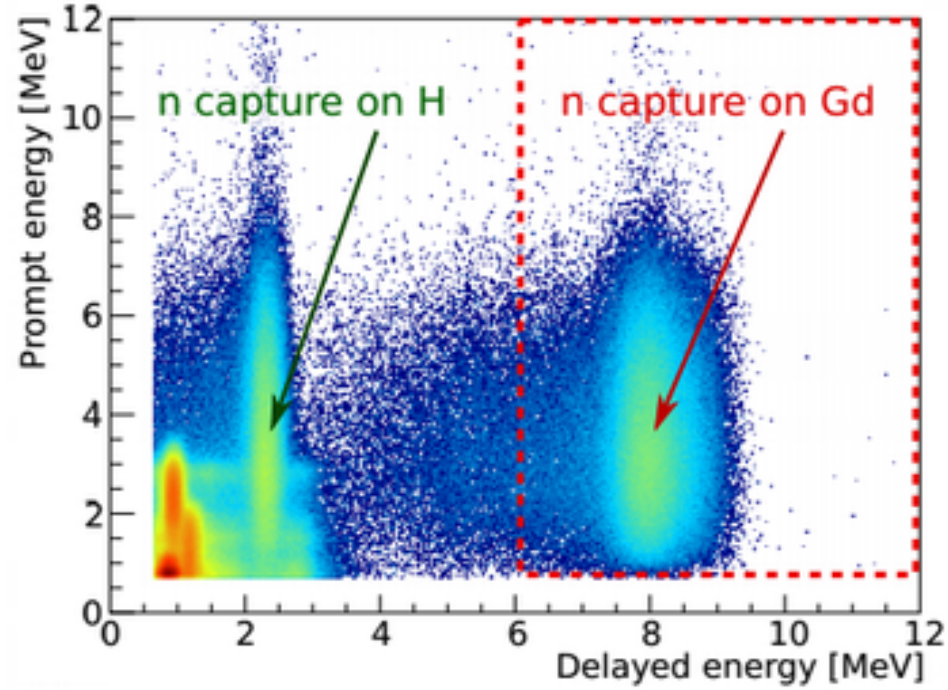
$$\text{“}n\text{”} \to \text{“}p\text{”} + e^- + \bar{\nu}_e$$

detection of reactor neutrinos: $\bar{\nu}_e + p \to n + e^+$

solar fusion neutrinos: $4p \to {}^4_2\text{He} + 2e^+ + 2\nu_e$

Modern Version of the Discovery Experiment





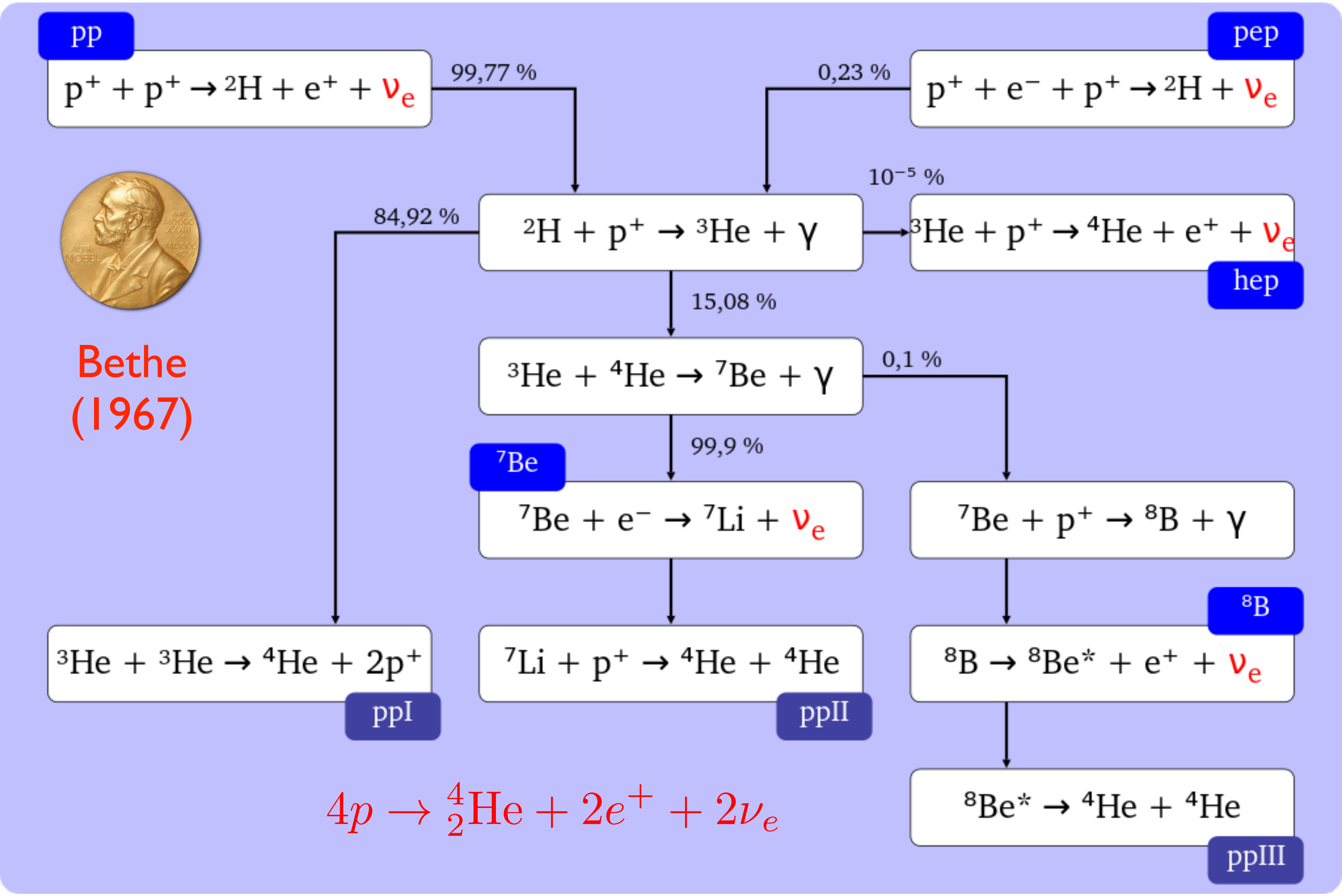
Prompt+delayed coincidence provides distinctive signature

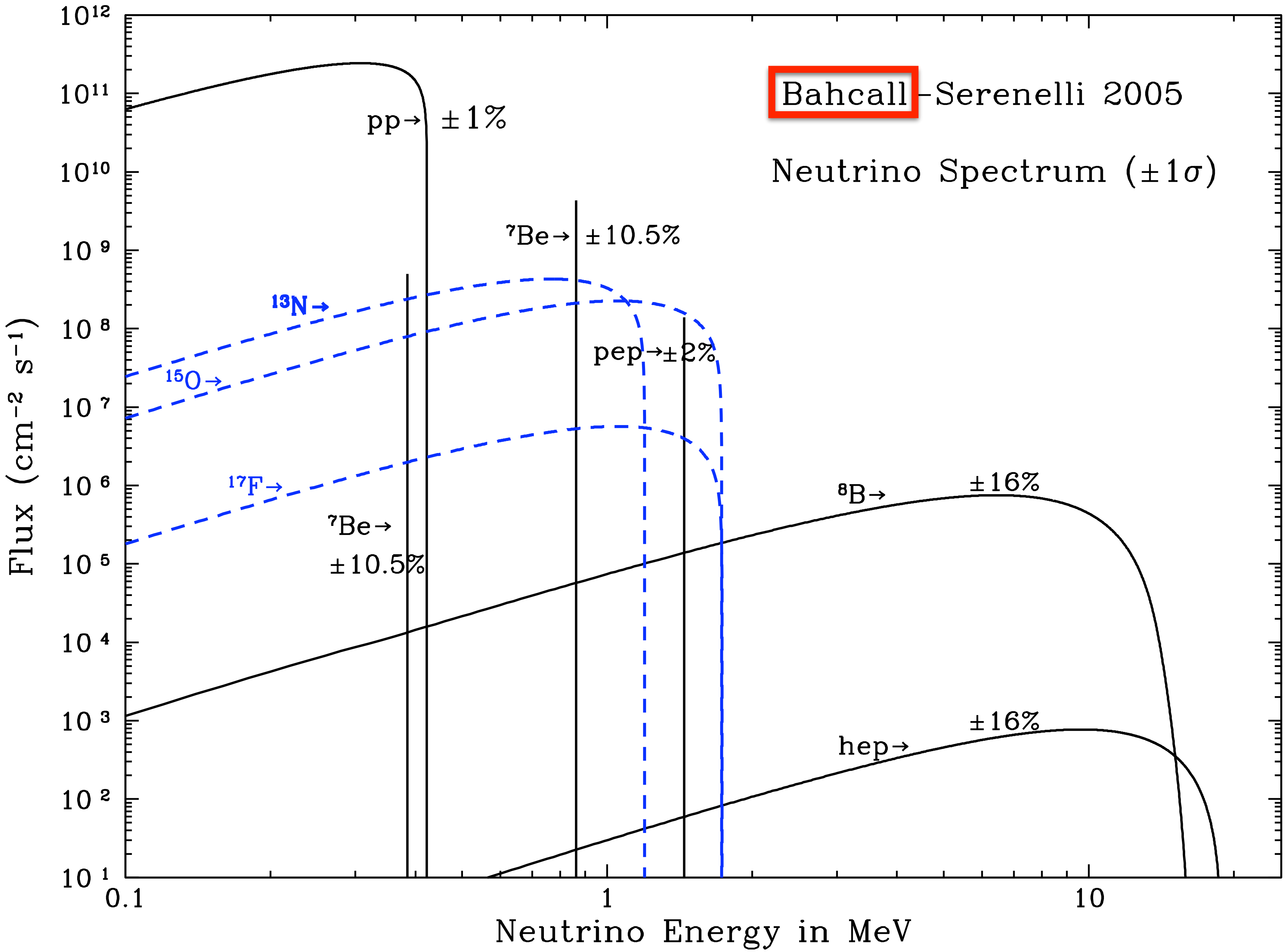
$\bar{\nu}_e + p \rightarrow e^+ + n$ *prompt*

$\rightarrow + p \xrightarrow{\tau \approx 200\,\mu s} D + \gamma$ (2.2 MeV)

$\rightarrow + Gd \xrightarrow{\tau \approx 28\,\mu s} Gd^* \rightarrow Gd + n\gamma$ (8 MeV) *delayed*

Solar Neutrinos





Bahcall-Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
pep→±2%
⁷Be→
±10.5%
⁸B→
±16%
hep→
±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
0.1
1
10

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

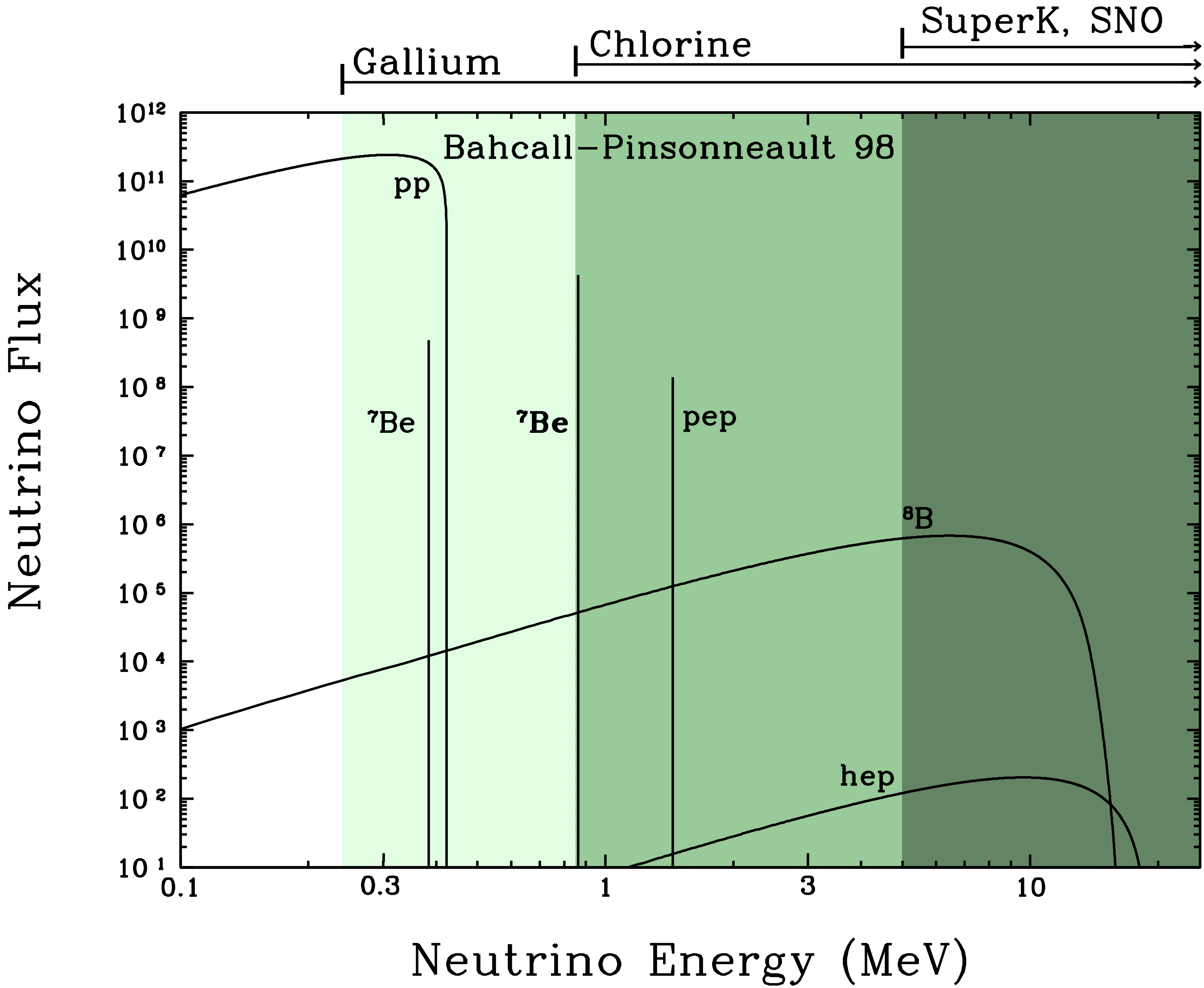
PRESENT STATUS OF THE THEORETICAL PREDICTIONS FOR THE ^{36}Cl SOLAR-NEUTRINO EXPERIMENT*

John N. Bahcall† and Neta A. Bahcall‡
California Institute of Technology, Pasadena, California

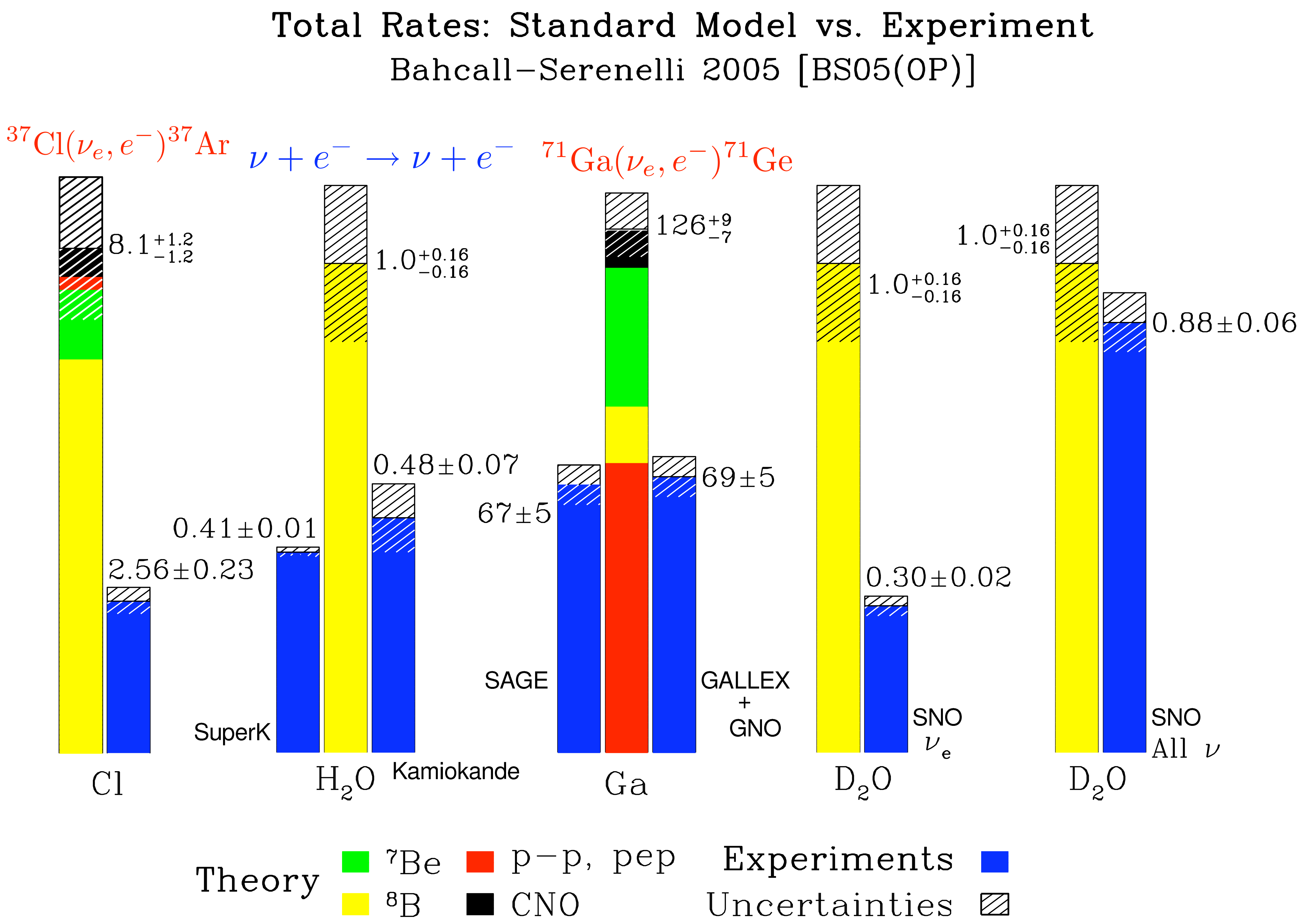
and

Giora Shaviv§
Cornell University, Ithaca, New York
(Received 8 April 1968)

The theoretical predictions for the ^{37}Cl solar-neutrino experiment are summarized and compared with the experimental results of Davis, Harmer, and Hoffman. Three important conclusions about the sun are shown to follow.



SuperK, SNO
Chlorine
Gallium
Bahcall−Pinsonneault 98
pp
7Be
7Be
pep
8B
hep
Neutrino Flux
Neutrino Energy (MeV)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10



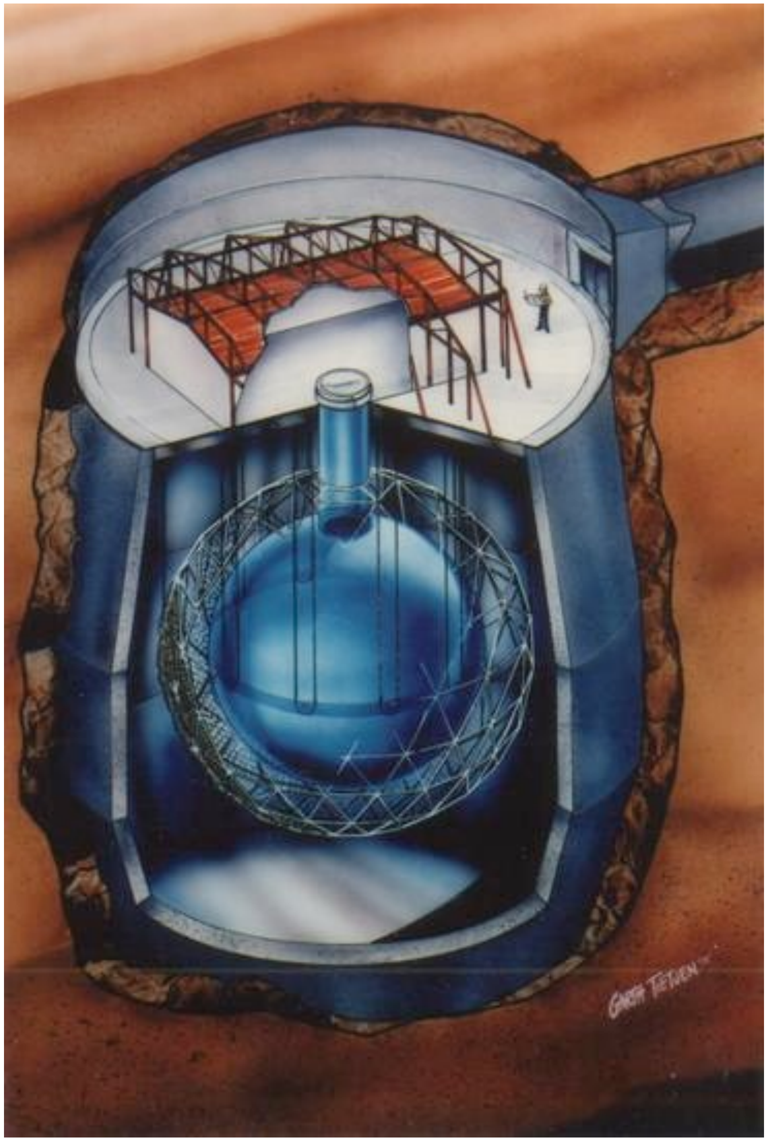
Total Rates: Standard Model vs. Experiment
Bahcall−Serenelli 2005 [BS05(OP)]
$^{37}Cl(\nu_e, e^-)^{37}Ar$
$\nu + e^- \rightarrow \nu + e^-$
$^{71}Ga(\nu_e, e^-)^{71}Ge$
$8.1^{+1.2}_{-1.2}$
2.56±0.23
0.41±0.01
$1.0^{+0.16}_{-0.16}$
0.48±0.07
126^{+9}_{-7}
67±5
69±5
$1.0^{+0.16}_{-0.16}$
0.30±0.02
$1.0^{+0.16}_{-0.16}$
0.88±0.06
SuperK
Kamiokande
SAGE
GALLEX + GNO
SNO ν_e
SNO All ν
Cl
H_2O
Ga
D_2O
D_2O
Theory
^7Be
^8B
p−p, pep
CNO
Experiments
Uncertainties

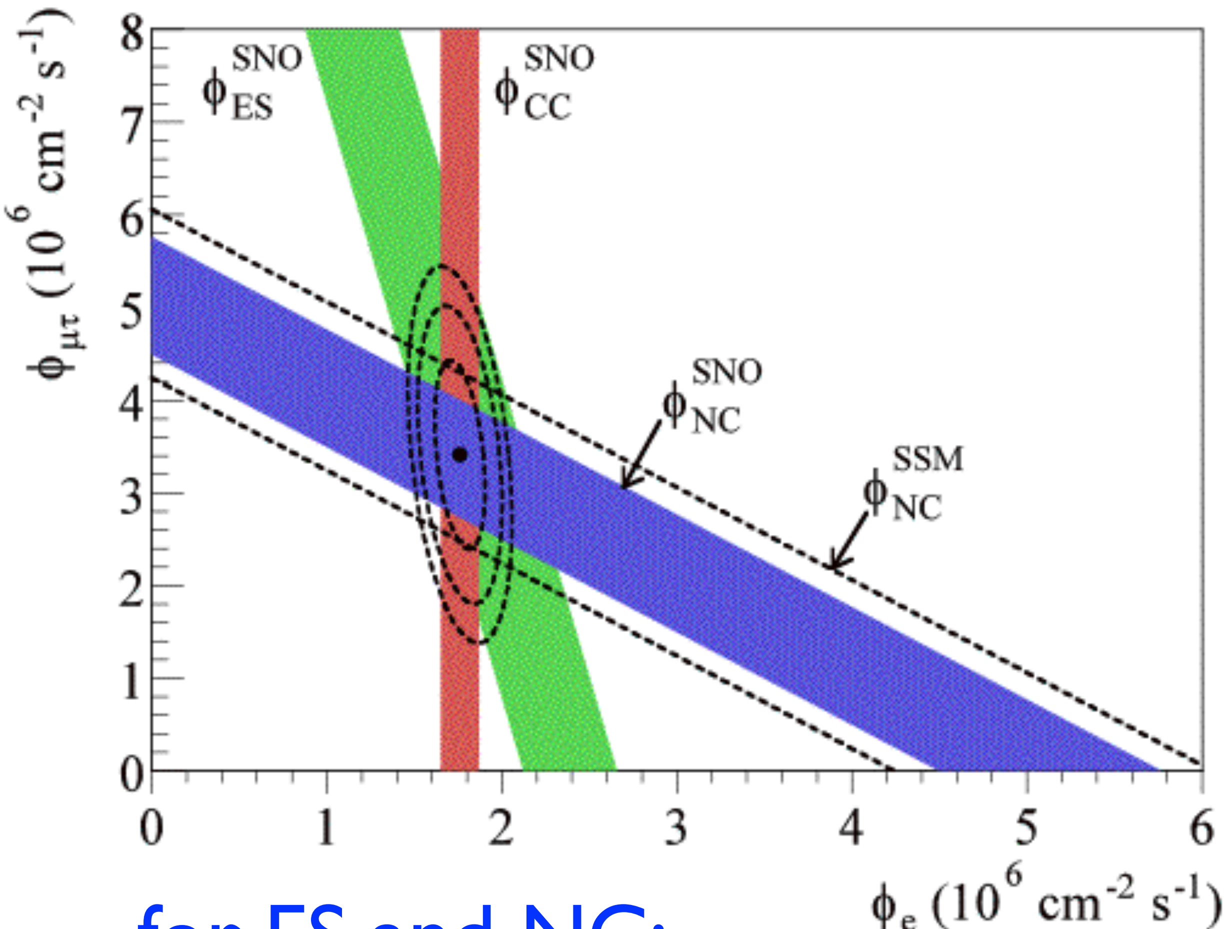
Sudbury Neutrino Observatory (SNO)

$\nu + e^- \rightarrow \nu + e^-$ (ES)

$\nu_e + d \rightarrow p + p + e^-$ (CC)

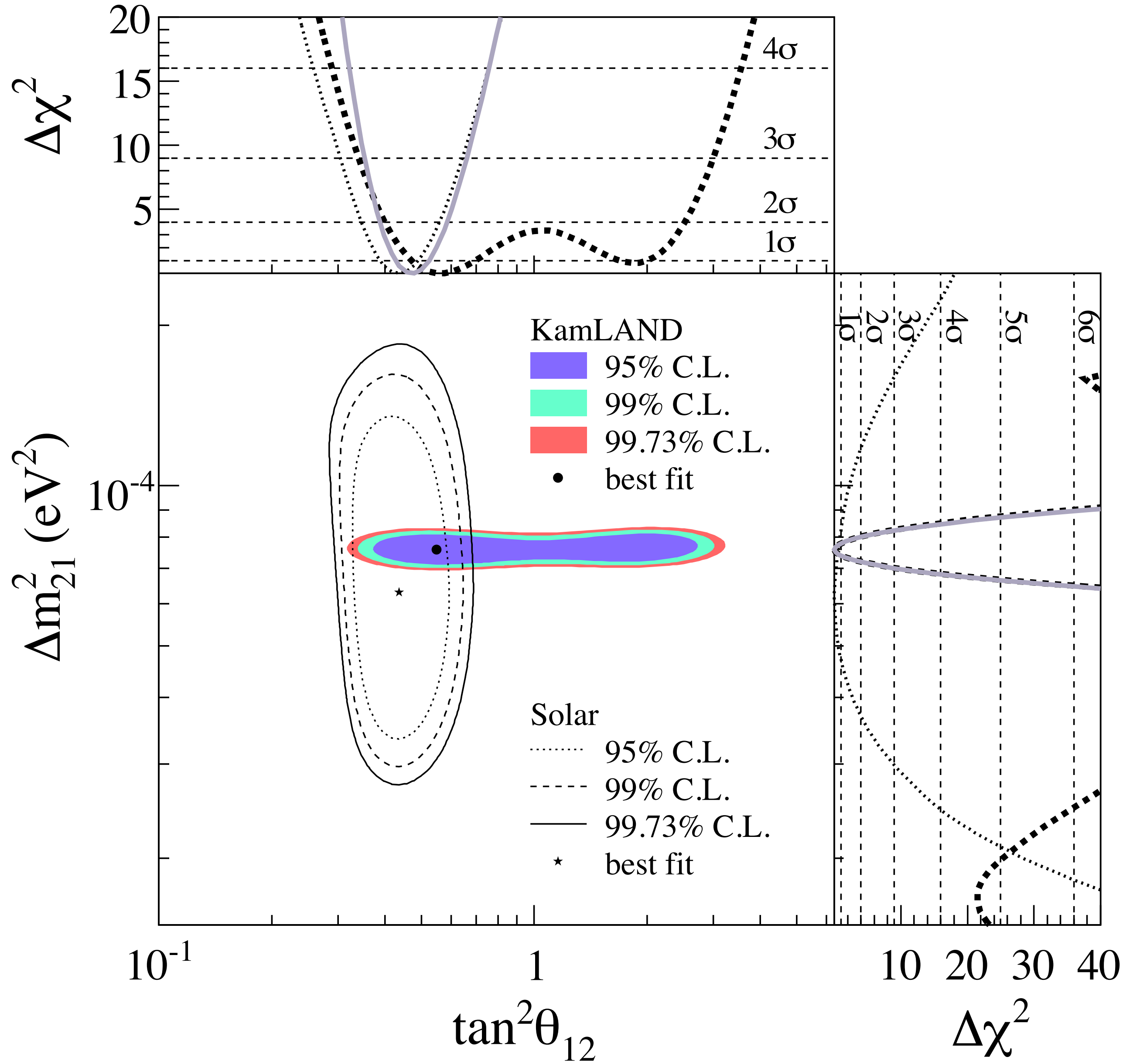
$\nu + d \rightarrow p + n + \nu$ (NC)





for ES and NC:

$$\phi_{\mu\tau}\langle\sigma\rangle_{\mu\tau} + \phi_e\langle\sigma\rangle_e = R_{\rm det}$$

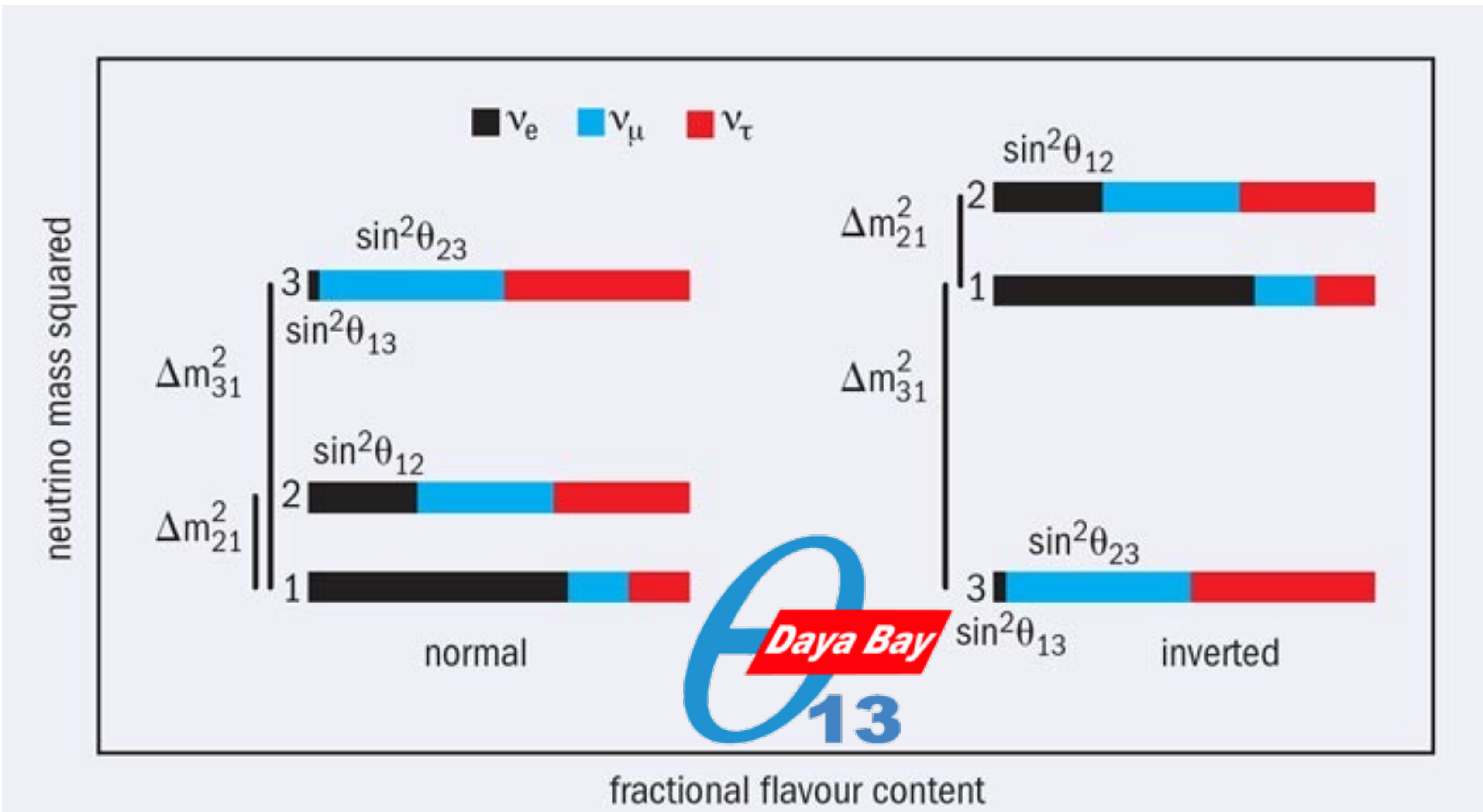


$$\frac{\delta m_\odot^2}{4E_\nu}x = 1.27\left(\frac{\delta m_\odot^2}{10^{-4}\ \mathrm{eV}^2}\right)\left(\frac{\mathrm{MeV}}{E_\nu}\right)\left(\frac{x}{10\ \mathrm{km}}\right)$$

Three Neutrino Mixing

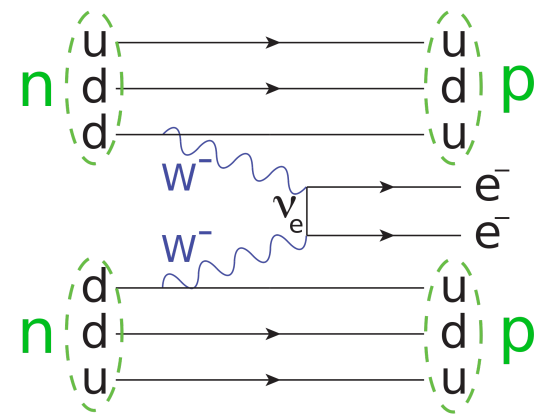
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle, \quad |\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$



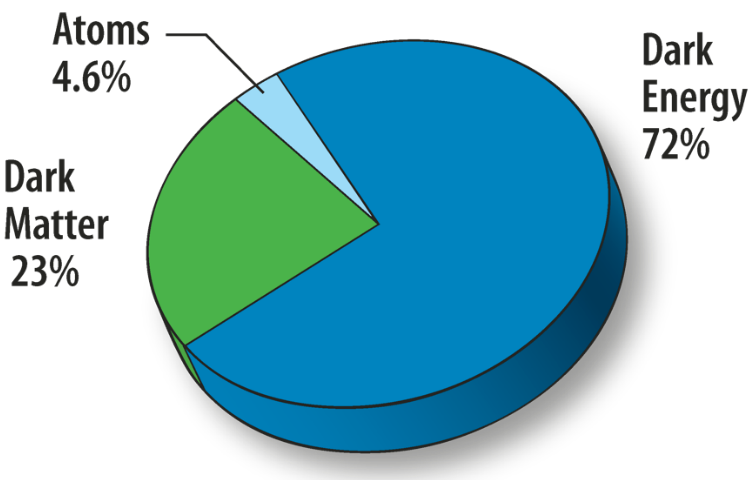
Unknown Properties of Neutrinos

- What is their mass ordering ?
- Do they violate CP ?
- What are their absolute masses ?
- Are they their own antiparticles ?
- Are there sterile neutrinos ?

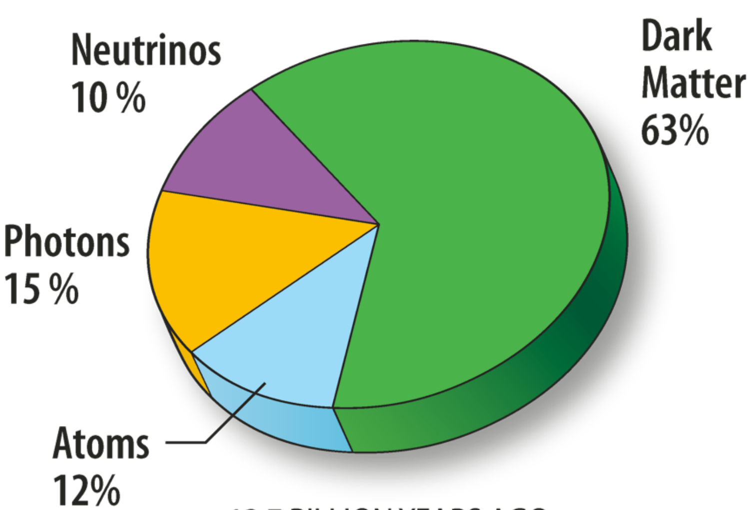


$0\nu\beta\beta$

How do neutrinos affect the evolution of the universe ?



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

$$\nu_e + n \rightleftharpoons p + e^-$$

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

$$n/p < 1 \Rightarrow p\,(75\%) + {}^4\mathrm{He}\,(25\%)$$

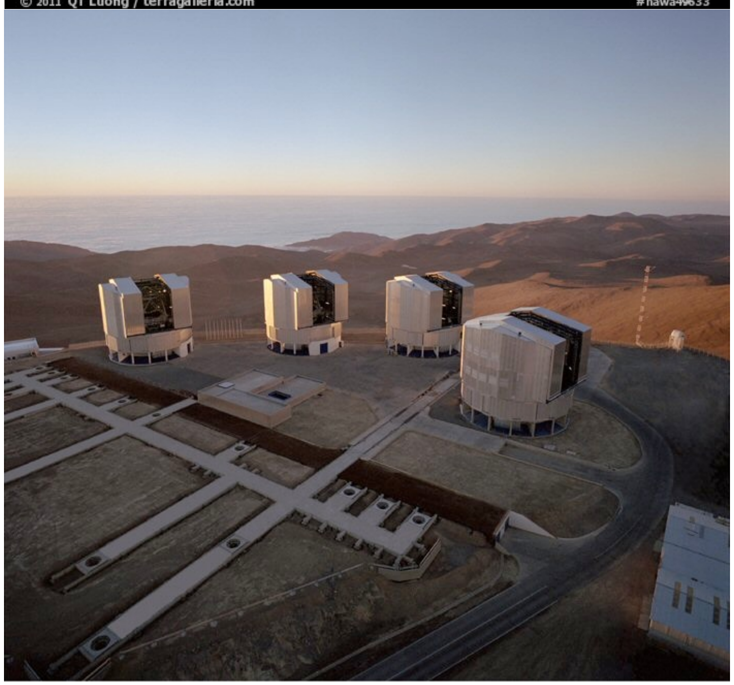
- Neutrinos & baryogensis
- Sterile neutrinos & big bang nucleosynthesis
- Sterile neutrinos & galaxy formation
- Neutrinos & supernova explosion/nucleosynthesis

FACILITY FOR RARE ISOTOPE BEAMS

FAIR

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

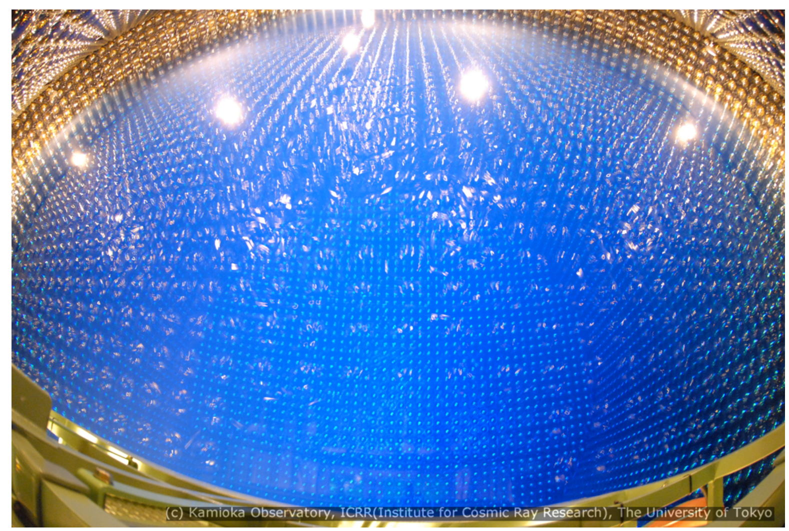
RIKEN NISHINA CENTER
RIKEN Nishina Center for Accelerator-Based Science



NOvA

T2K

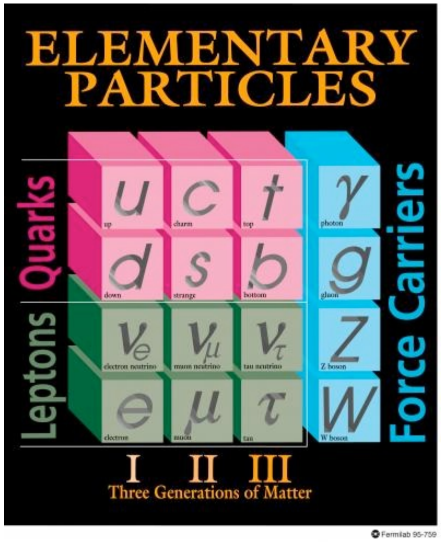
JUNO



Neutrinos & the Origin of the Elements

Yong-Zhong Qian
School of Physics & Astronomy, University of Minnesota
Center for Nuclear Astrophysics, Shanghai Jiao Tong University

CCEPP Summer School 2017 on Neutrino Physics
July 7, 2017

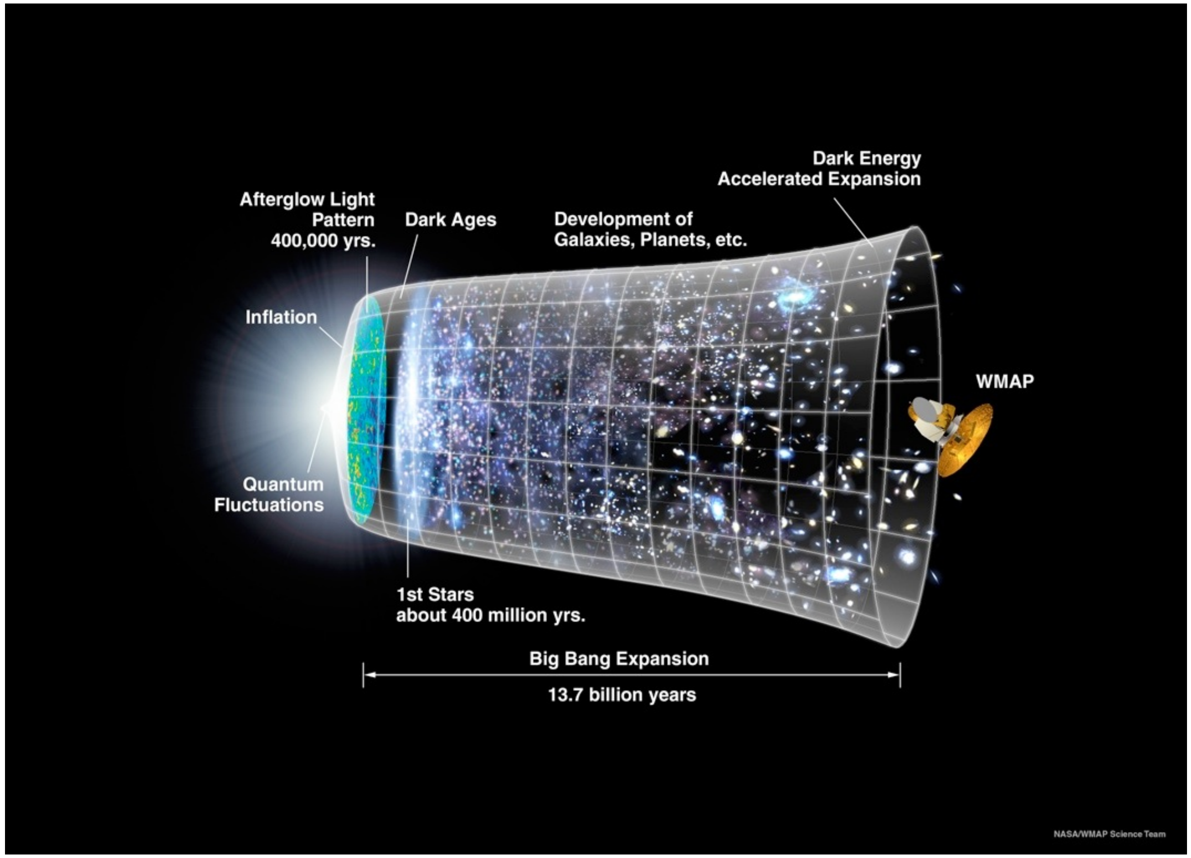


Some of the Biggest Questions Connecting Quarks and the Cosmos

Board on Physics and Astronomy
US National Academy of Sciences

- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?

- How were the elements from iron to uranium made?



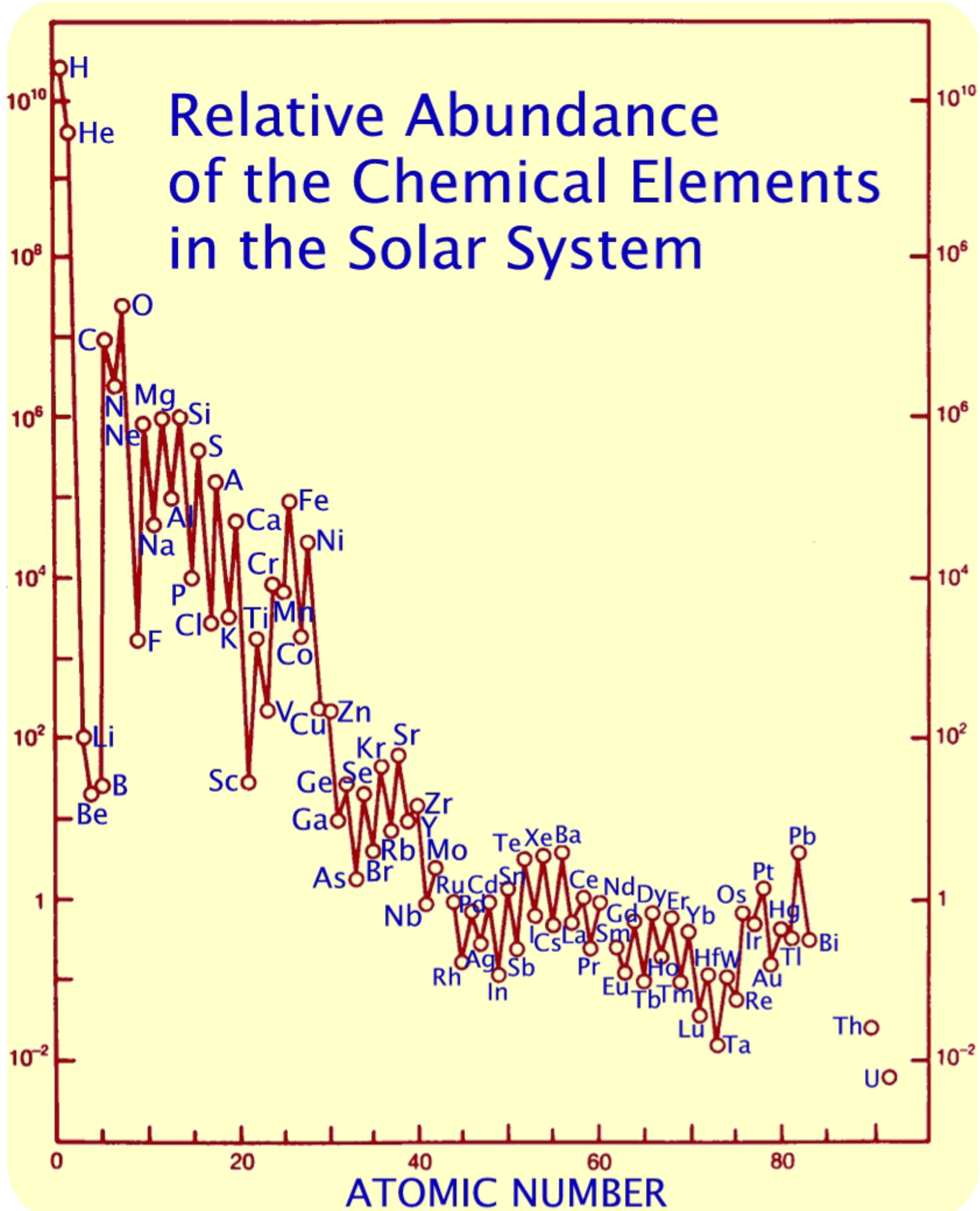
Big Bang:

75% H + 25% He
(by mass)

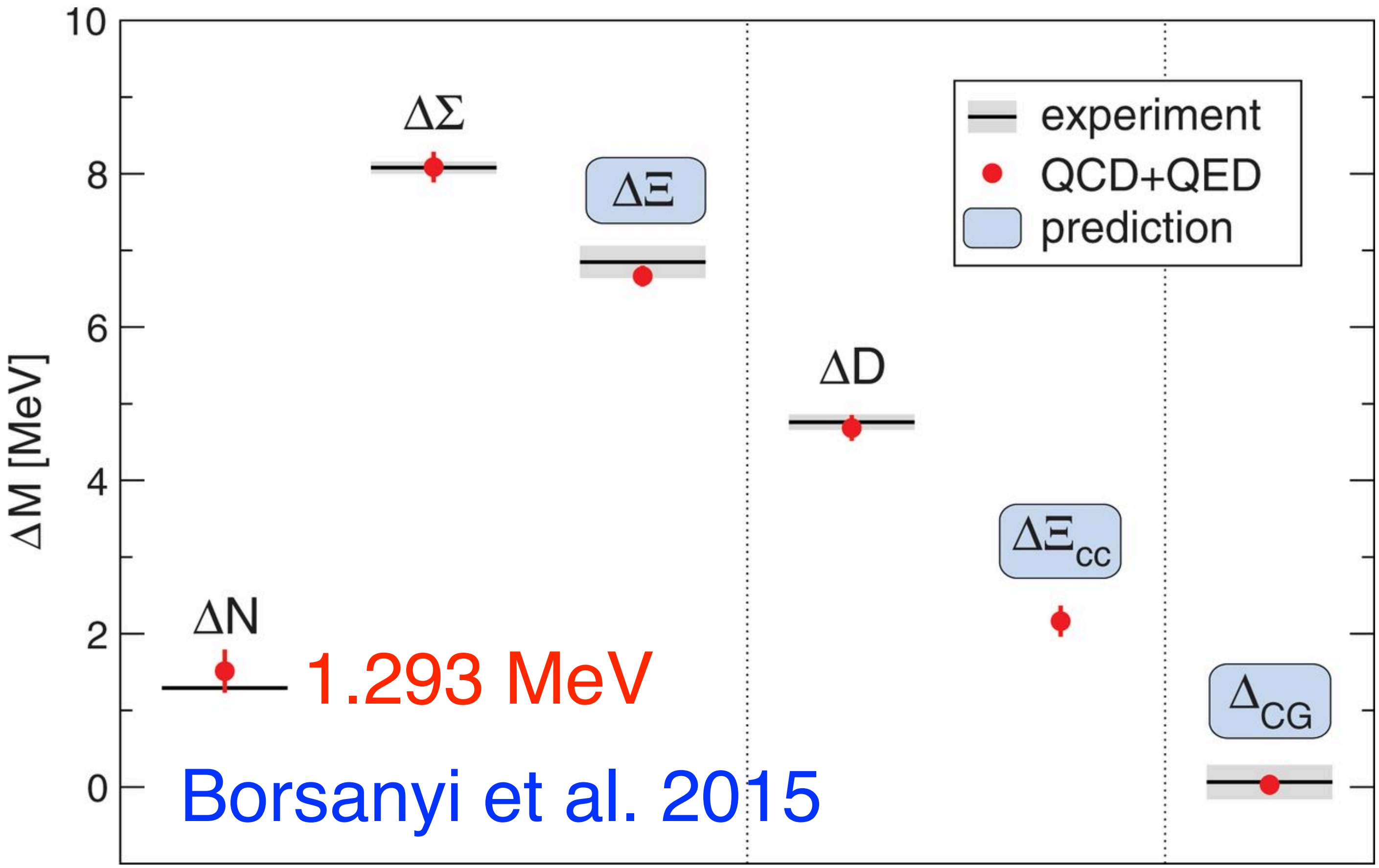
Sun:

71.5% H + 27.0% He
+1.4% "Metals"

$$\text{“}p\text{”} \rightarrow \text{“}n\text{”} + e^+ + \nu_e$$



Standard Model of Particle Physics & Life of a Baryon: Big Bang Nucleosynthesis



$$\frac{n}{p} = \exp\left(-\frac{M_n - M_p}{T}\right) < 1$$

Basics of Big Bang Nucleosynthesis

initial state ($T > 1$ MeV): $n,\ p$

$$X_n + X_p = 1 \Rightarrow \text{need } n/p$$

rate of change in abundance:

$$\frac{dY_i}{dt} = P(t) - D(t)Y_i\,,\ Y_i = \frac{X_i}{A_i},\ n_i = \rho_b N_A Y_i$$

$$\left.\begin{array}{l} P(t): \ \text{production rate} \\ D(t): \ \text{destruction rate} \end{array}\right\} \text{both depend on } T(t) \text{ and } \rho_b(t)$$

$T(t)$ specified by dynamics of expansion

$\rho_b(t)$ specified by conservation of entropy per baryon

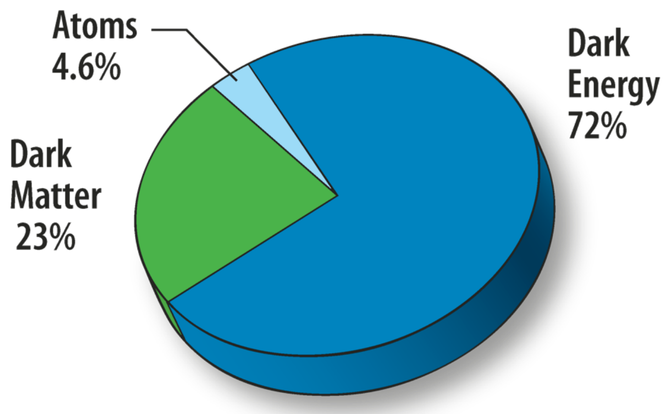
$$s \propto g^*_{\text{eff}}(t)\frac{T^3}{\rho_b} \propto g^*_{\text{eff}}(t)\frac{n_\gamma}{n_b} = \text{const.}$$

$$\text{baryon-to-photon ratio: } \eta = \frac{n_{b,0}}{n_{\gamma,0}} \Rightarrow s \approx \frac{3.6}{\eta}$$

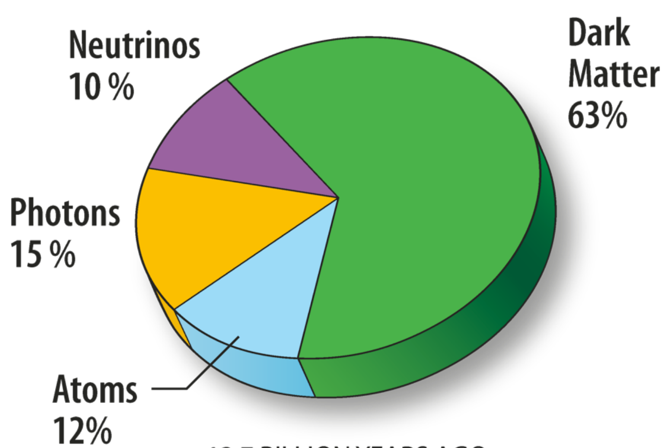
expansion of the early universe

mass conservation $\Rightarrow \rho_b(t) + \rho_{\rm dm}(t) = \rho_m(t) = \rho_{m,0}\left[\frac{R_0}{R(t)}\right]^3$

photon number conservation: $n_\gamma(t)R(t)^3 = n_{\gamma,0}R_0^3$



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

$$n_\gamma \propto T_\gamma^3 \Rightarrow T_\gamma(t) = T_{\gamma,0}\frac{R_0}{R(t)}$$

$$\rho_\gamma \propto T_\gamma^4 \Rightarrow \rho_\gamma = \rho_{\gamma,0}\left[\frac{R_0}{R(t)}\right]^4$$

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G\rho + \frac{\Lambda}{3} - \frac{Kc^2}{R^2}$$

$$\Rightarrow \left(\frac{\dot{R}}{R}\right)^2 \approx \frac{8\pi}{3}G\rho_{\rm rel}$$

entropy conservation $\Rightarrow$ evolution of $\rho_{\rm rel}$ at $100 > T > 1$ MeV

$$TS = E + PV - \mu N \Rightarrow S = \frac{E + PV - \mu N}{T}$$

fully relativistic: $S_{\rm rel} = \dfrac{\rho_{\rm rel} V + (\rho_{\rm rel}/3)V}{T} \propto g_{\rm eff} T(t)^3 R(t)^3$

$$g_{\rm eff} = \text{const.} \Rightarrow T(t) \propto R(t)^{-1},\ \dot{T}/T = -\dot{R}/R$$

$$\left(\frac{\dot{R}}{R}\right)^2 = \left(\frac{\dot{T}}{T}\right)^2 = \frac{8\pi}{3} G \rho_{\rm rel} = \left(\frac{8\pi}{3} G\right) g_{\rm eff} \frac{\pi^2}{15} T^4$$

$$T \to \infty \text{ as } t \to 0 \Rightarrow \frac{\dot{T}}{T} = -\sqrt{\frac{8\pi^3}{45} g_{\rm eff} G T^4}$$

$$t \approx \frac{1}{2}\sqrt{\frac{45}{8\pi^3}} \frac{1}{\sqrt{g_{\rm eff} G}} \frac{1}{T^2} = \frac{1.71}{\sqrt{g_{\rm eff}}} \left(\frac{\text{MeV}}{T}\right)^2 \text{ s}$$

$$N_\nu = 3 \Rightarrow g_{\rm eff} = \frac{43}{8},\ t \approx 0.74 \left(\frac{\text{MeV}}{T}\right)^2 \text{ s}$$

BBN and Neutrinos

freeze-out of n/p: $\nu_e + n \rightleftharpoons p + e^-$, $\bar{\nu}_e + p \rightleftharpoons n + e^+$

$$\sigma_{\nu_e n} \approx \frac{G_F^2}{\pi} \cos^2\theta_C (f^2 + 3g^2)(E_{\nu_e} + \Delta)^2$$

$$\sigma_{\bar{\nu}_e p} \approx \frac{G_F^2}{\pi} \cos^2\theta_C (f^2 + 3g^2)(E_{\bar{\nu}_e} - \Delta)^2$$

$$\cos^2\theta_C = 0.95,\ f = 1,\ g = 1.26,\ \Delta = M_n - M_p = 1.293\ \mathrm{MeV}$$

rate per nucleon: $\lambda_{\nu N} \approx \frac{4\pi}{(2\pi)^3} \int_0^\infty \frac{\sigma_{\nu N} E_\nu^2}{\exp(E_\nu/T) + 1} dE_\nu$

$$\approx 0.4 \left(\frac{T}{\mathrm{MeV}}\right)^5 \mathrm{s}^{-1}$$

$$\int_{t_{\mathrm{FO}}}^\infty \lambda_{\nu N} dt \sim \int_0^{T_{\mathrm{FO}}} 0.4 \left(\frac{T}{\mathrm{MeV}}\right)^5 \times 2 \times 0.74 \left(\frac{\mathrm{MeV}}{T}\right)^3 dT$$

$$\sim 0.2 \left(\frac{T_{\mathrm{FO}}}{\mathrm{MeV}}\right)^3 \sim 1 \Rightarrow T_{\mathrm{FO}} \sim 1.7\ \mathrm{MeV}$$

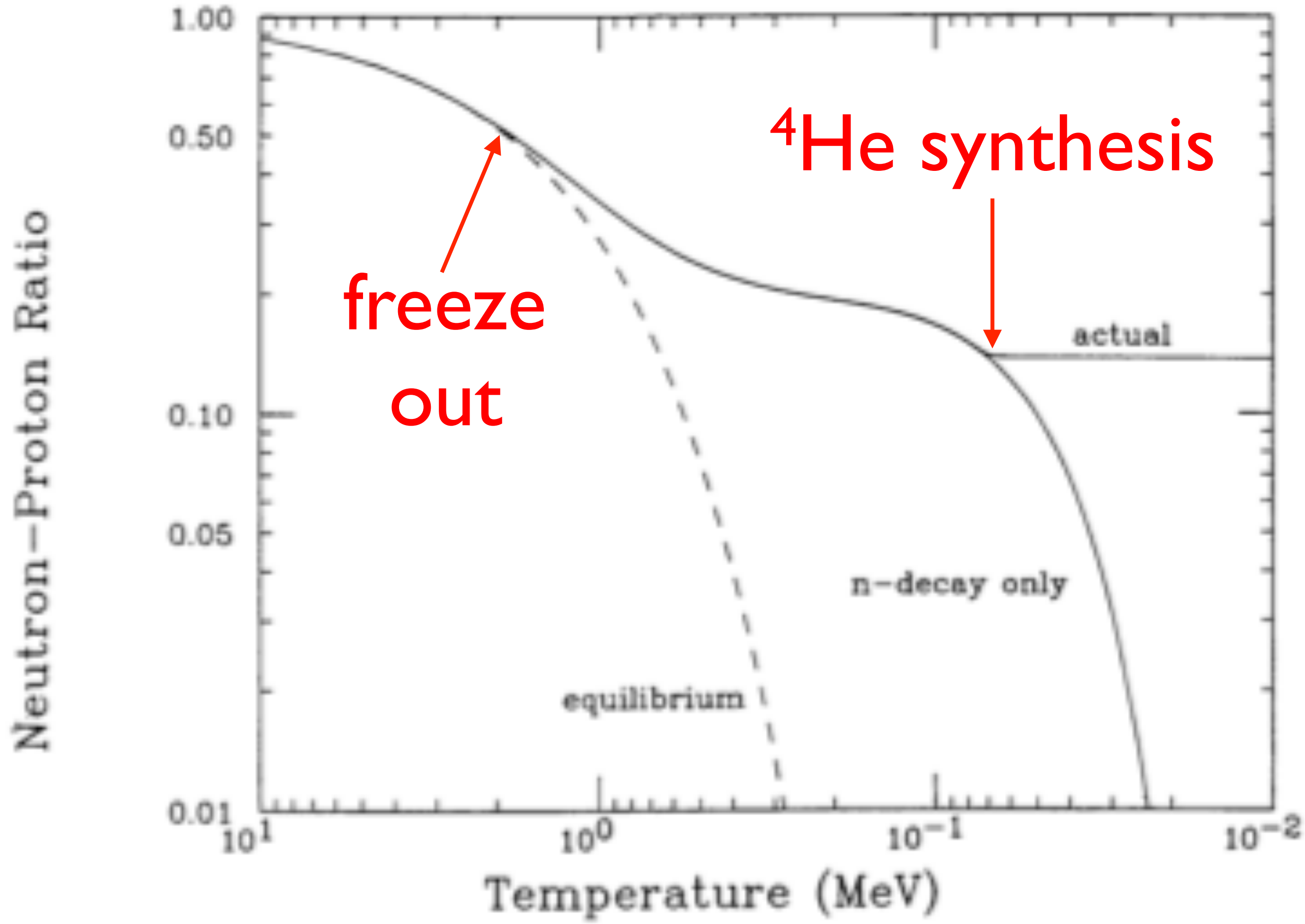


FIG. 1.—Evolution of the neutron-proton ratio with temperature. The NSE ratio is given by the dashed curve. If neutron decay is the only reaction (all other reactions are shut off), the n/p ratio follows the solid curve. The actual final value of the ratio is shown by the straight horizontal line.

$$\frac{n}{p} = \left(\frac{n}{p}\right)_{\rm FO} \exp\left(-\frac{t - t_{\rm FO}}{\tau_n}\right) \sim \exp\left(-\frac{\Delta}{T_{\rm FO}} - \frac{t - t_{\rm FO}}{\tau_n}\right)$$

$$\frac{n}{p} = \left(\frac{n}{p}\right)_{\rm FO} \exp\left(-\frac{t-t_{\rm FO}}{\tau_n}\right) \sim \exp\left(-\frac{\Delta}{T_{\rm FO}} - \frac{t-t_{\rm FO}}{\tau_n}\right)$$

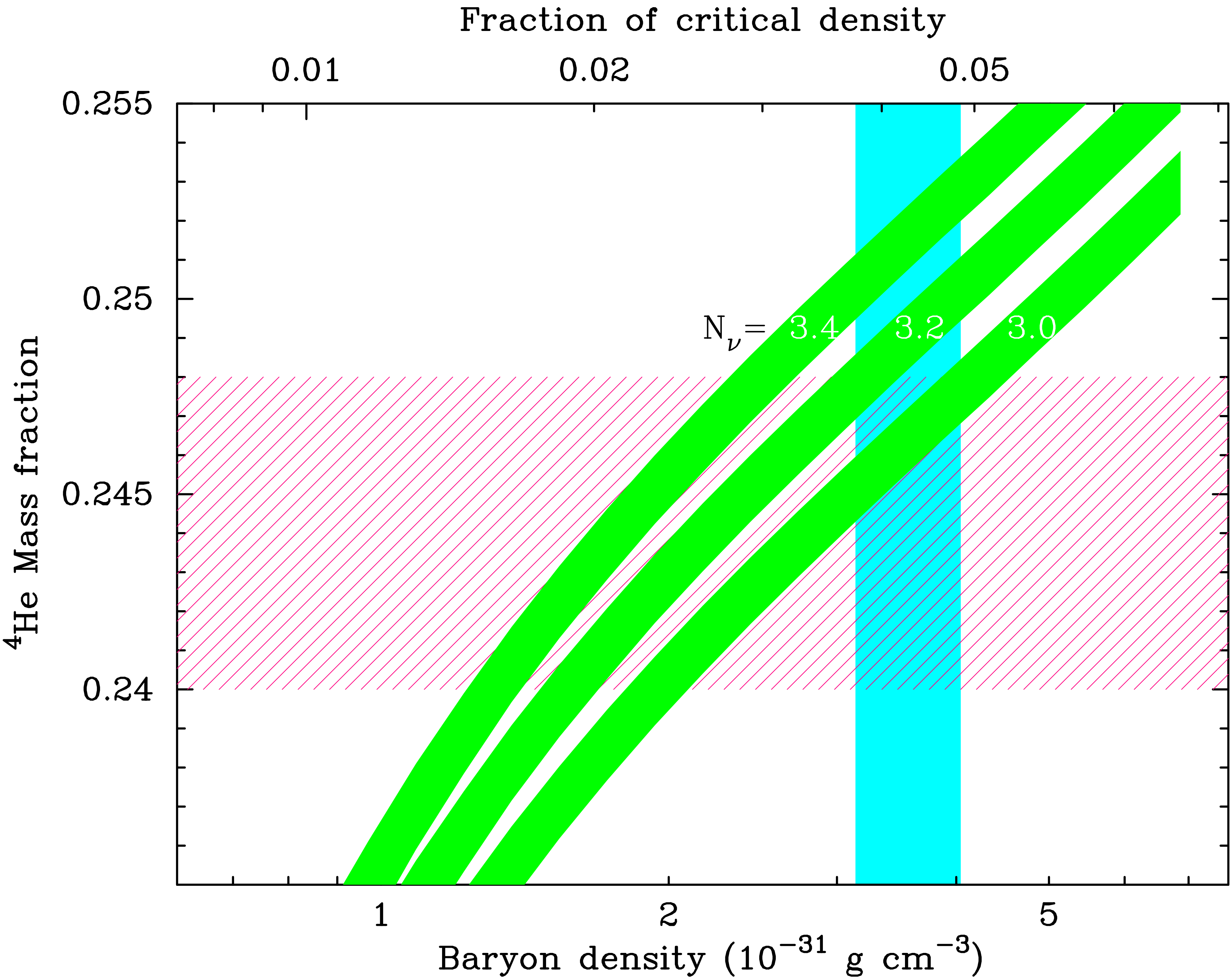
$$^4\text{He production: } X(^4\text{He}) \sim \frac{2n}{n+p} = \frac{2(n/p)}{(n/p)+1}$$

$$t \sim \frac{1}{\sqrt{a+bN_\nu}}\frac{1}{T^2}, \ \lambda_{\nu N} \propto T^5, \ \int_{t_{\rm FO}}^{\infty} \lambda_{\nu N} dt \propto \frac{T_{\rm FO}^3}{\sqrt{a+bN_\nu}} \sim \text{const.}$$

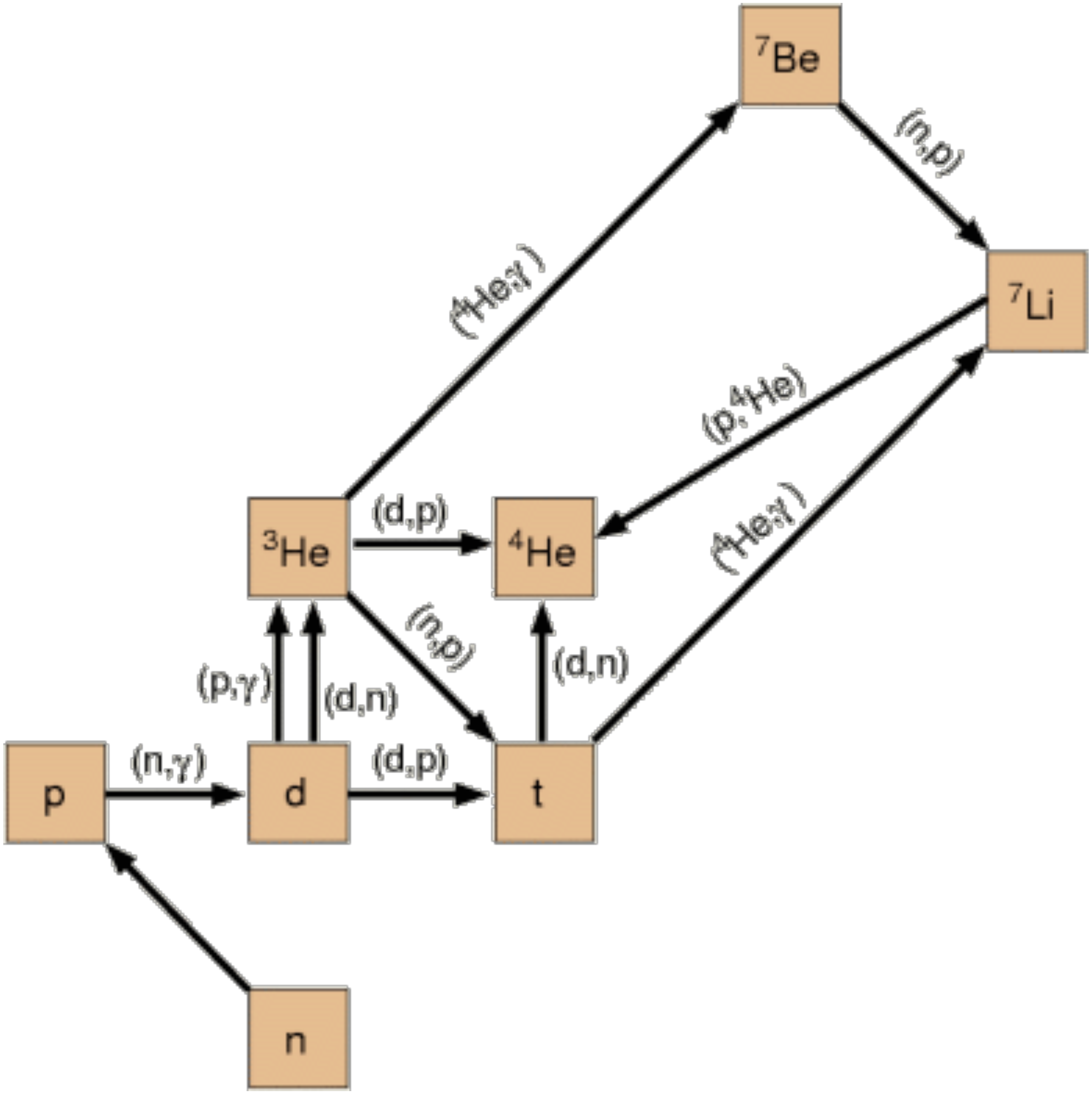
$$N_\nu \uparrow \Rightarrow T_{\rm FO} \uparrow \Rightarrow \left(\frac{n}{p}\right)_{\rm FO} \sim \exp\left(-\frac{\Delta}{T_{\rm FO}}\right) \uparrow$$

$$N_\nu \uparrow \Rightarrow t \downarrow \Rightarrow \frac{n}{p} = \left(\frac{n}{p}\right)_{\rm FO} \exp\left(-\frac{t-t_{\rm FO}}{\tau_n}\right) \uparrow$$

$$N_\nu \uparrow \Rightarrow \frac{n}{p} \uparrow \Rightarrow X(^4\text{He}) \uparrow$$

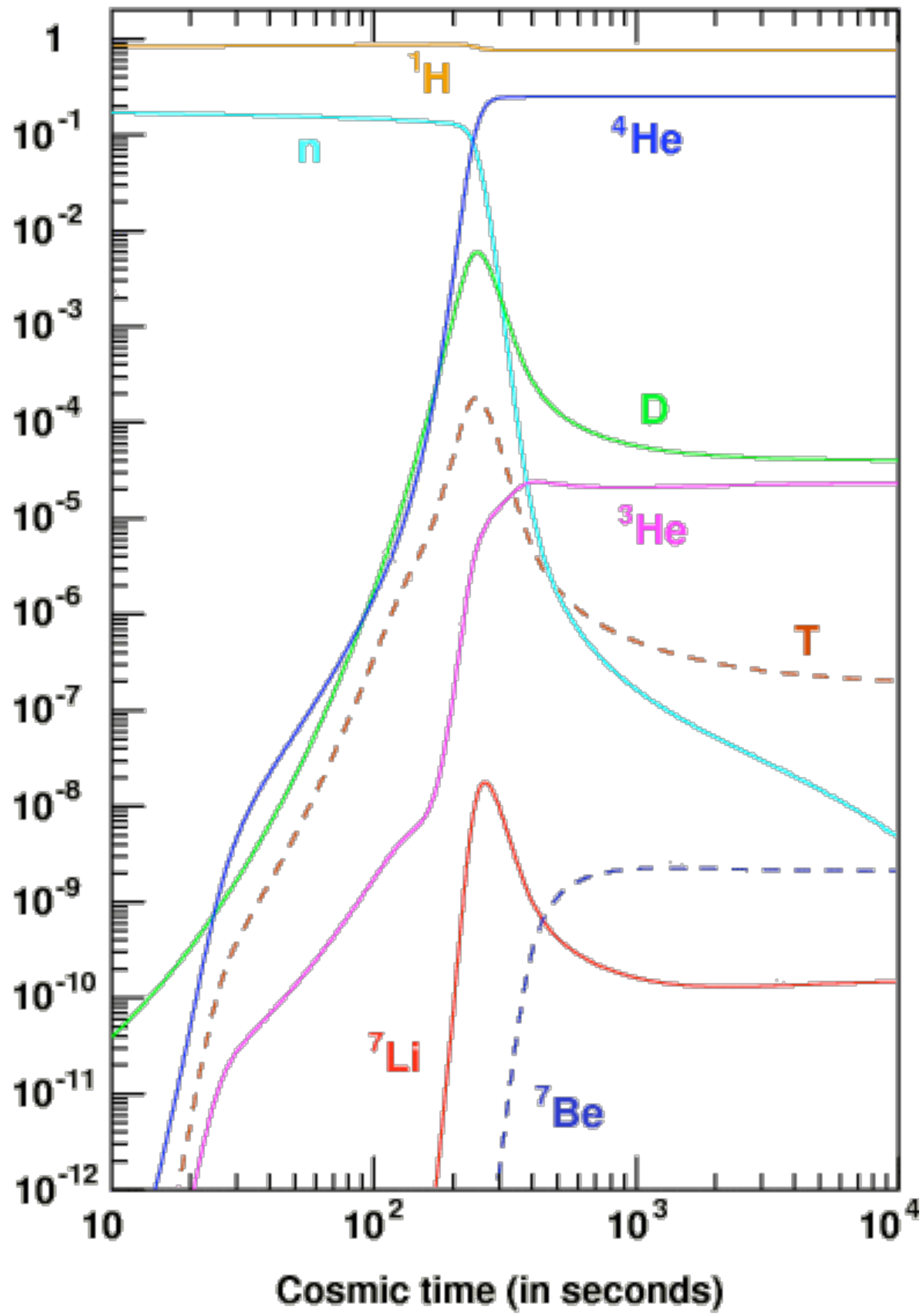


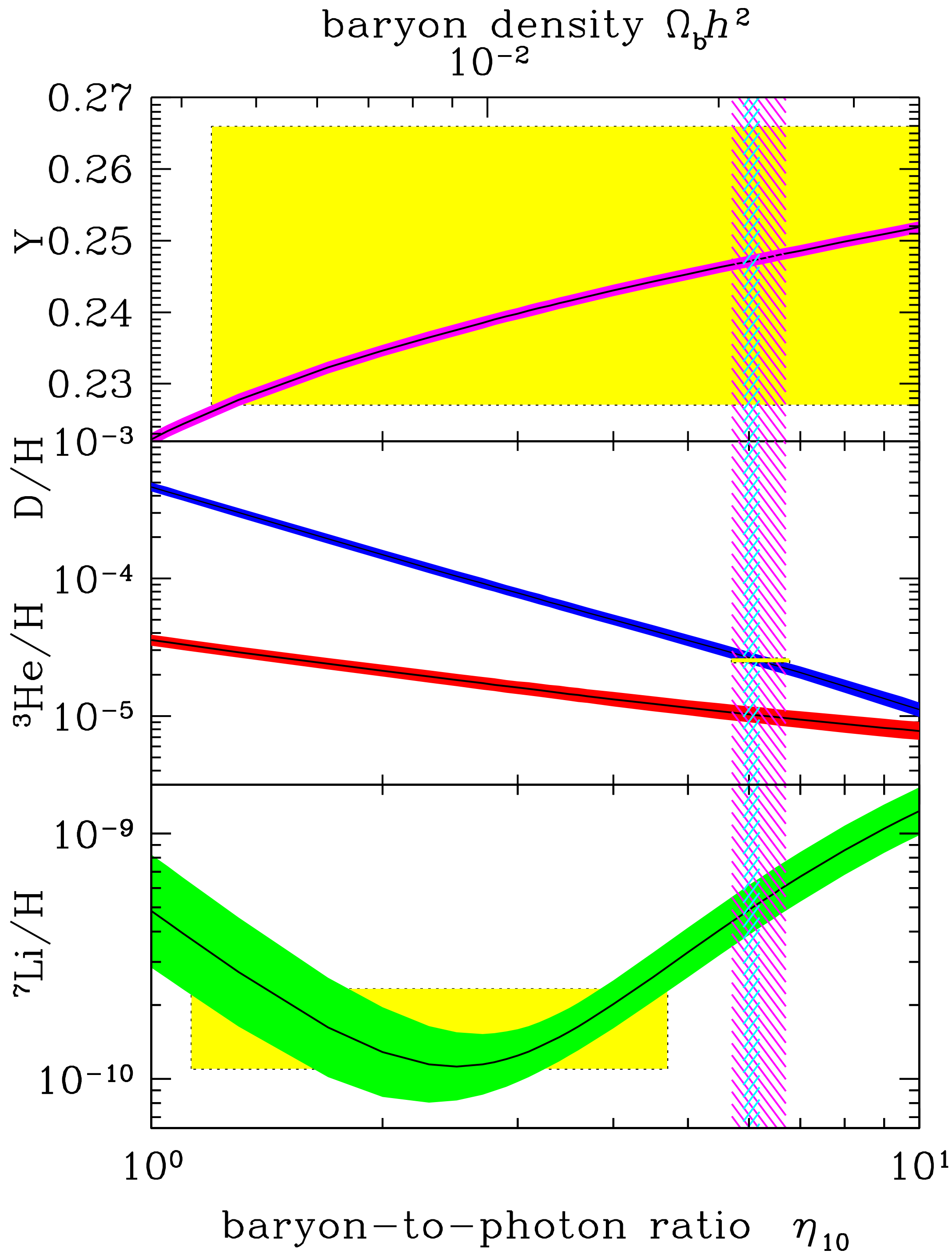
Fraction of critical density
0.01
0.02
0.05
0.255
0.25
0.245
0.24
^{4}He Mass fraction
N_ν = 3.4
3.2
3.0
1
2
5
Baryon density (10^{-31} g cm^{-3})



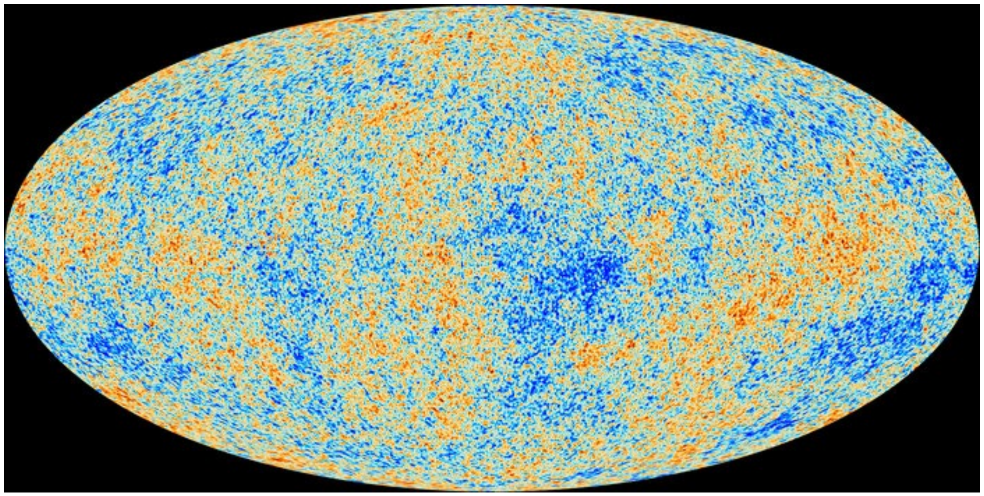
^7Be
(n,p)
^7Li
(^4He,γ)
(p,^4He)
^3He
(d,p)
^4He
(^4He,γ)
(n,p)
(p,γ)
(d,n)
(d,n)
p
(n,γ)
d
(d,p)
t
n

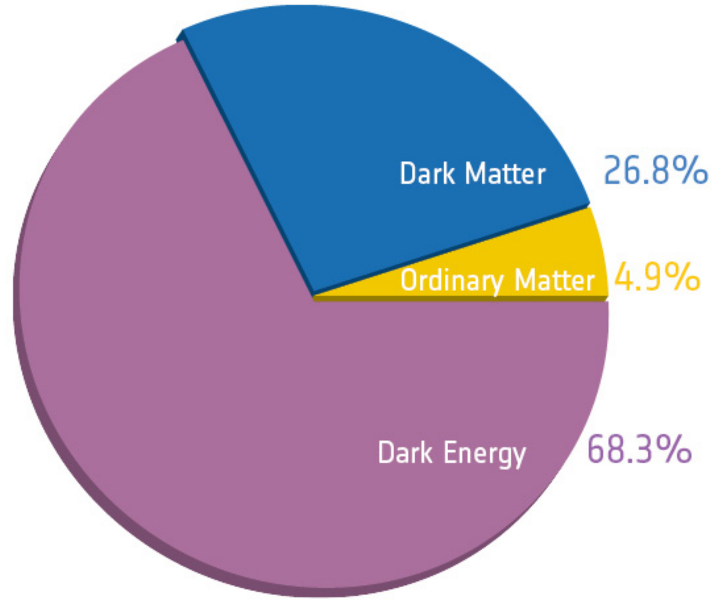
Big Bang Nucleosynthesis

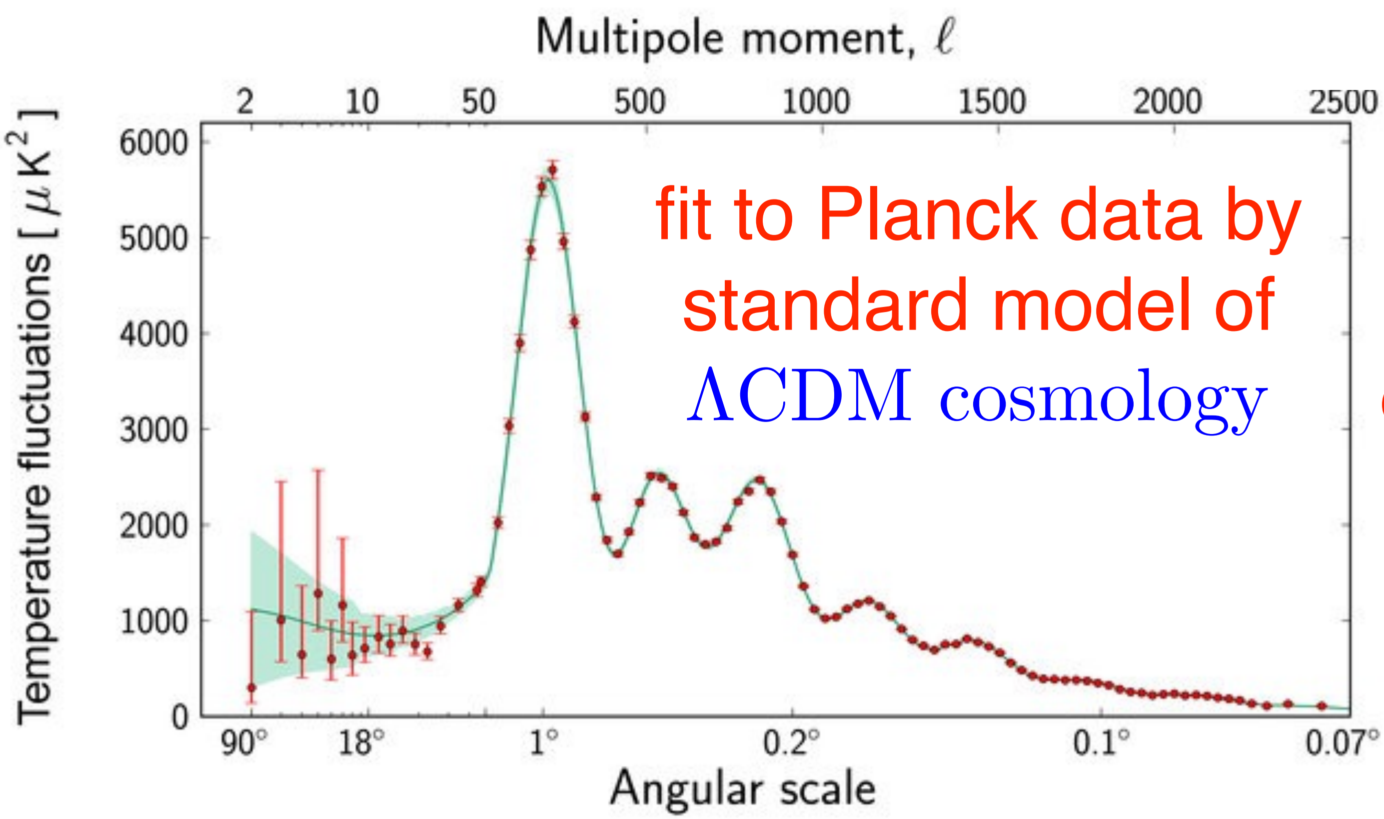




Cosmic Microwave Background Experiments







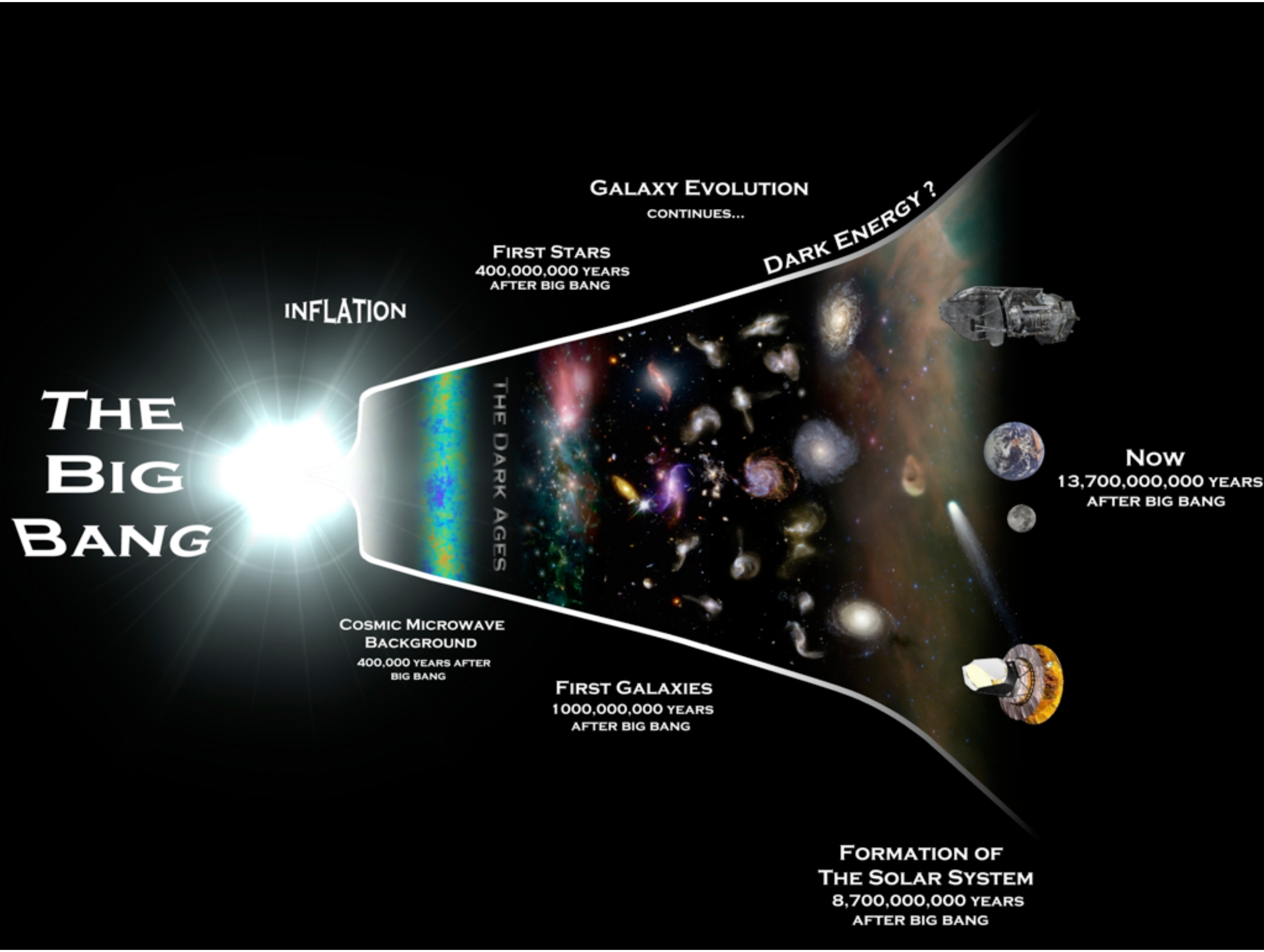
fit to Planck data by standard model of ΛCDM cosmology

6 basic parameters

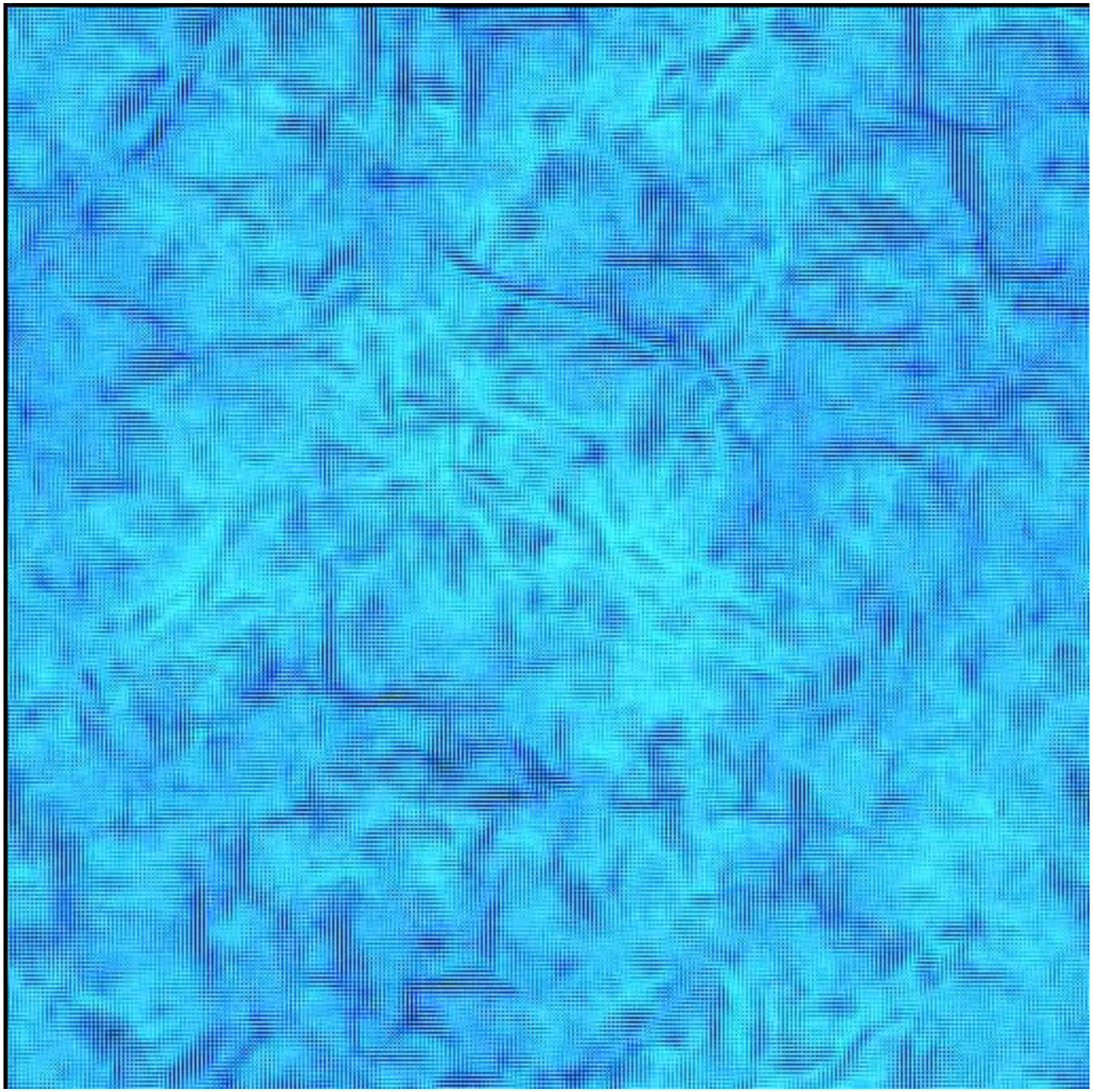
energy densities,

density fluctuations,

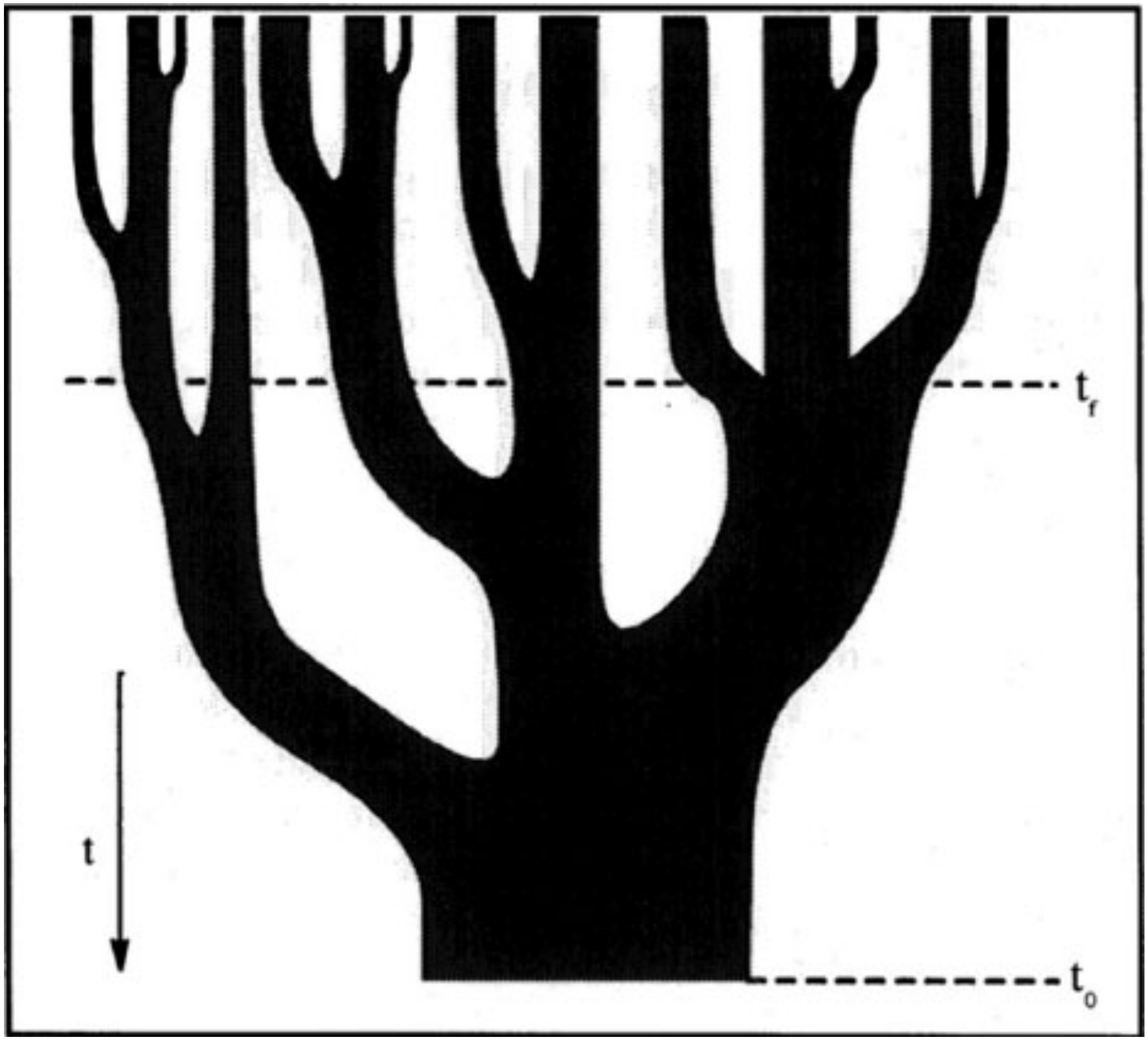
& probability of scattering by electrons

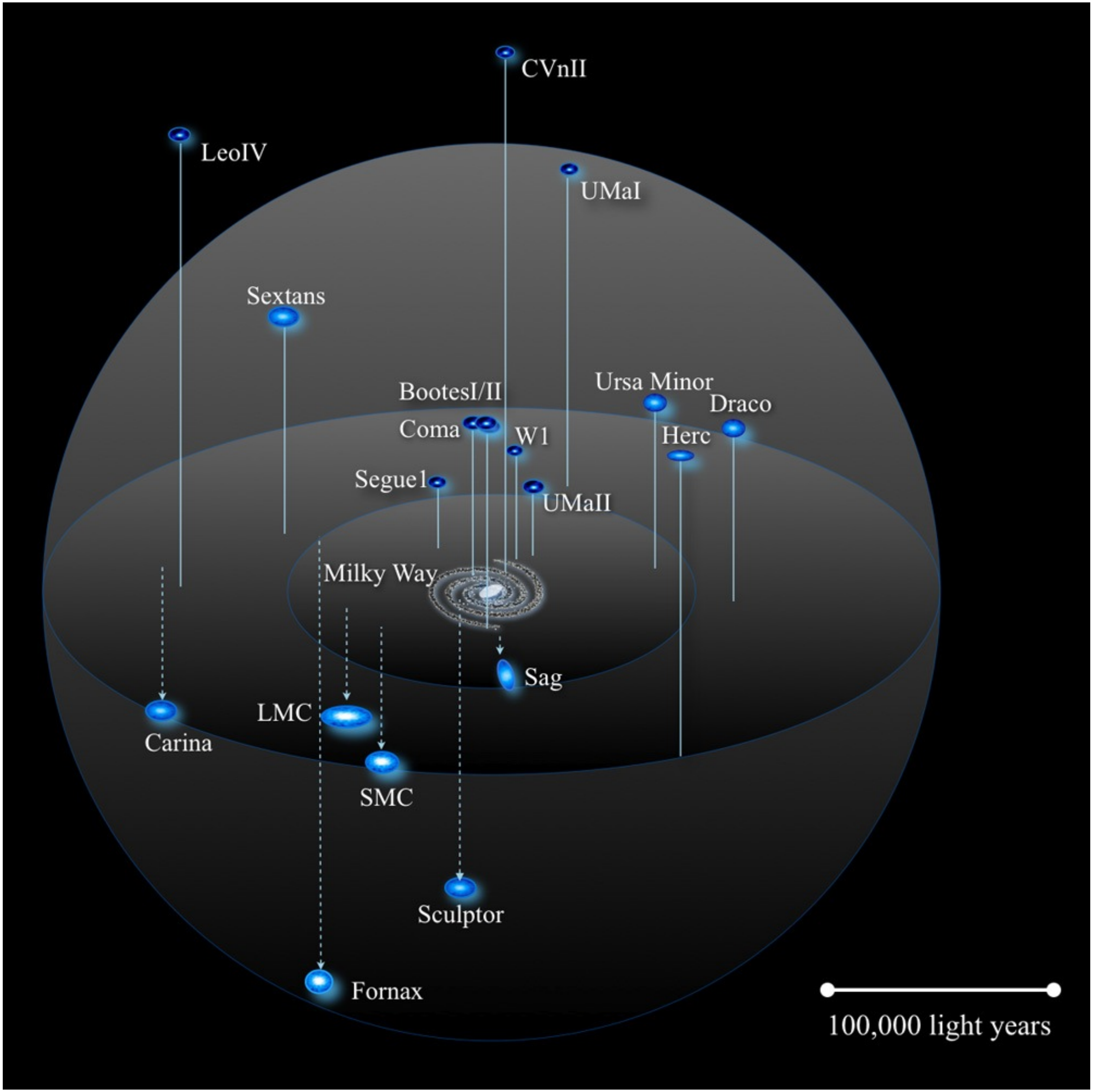

The Big Bang
Inflation
First Stars
400,000,000 years after Big Bang
Galaxy Evolution continues...
Dark Energy ?
The Dark Ages
Cosmic Microwave Background
400,000 years after Big Bang
First Galaxies
1000,000,000 years after Big Bang
Now
13,700,000,000 years after Big Bang
Formation of The Solar System
8,700,000,000 years after Big Bang

Hierarchical Structure Formation

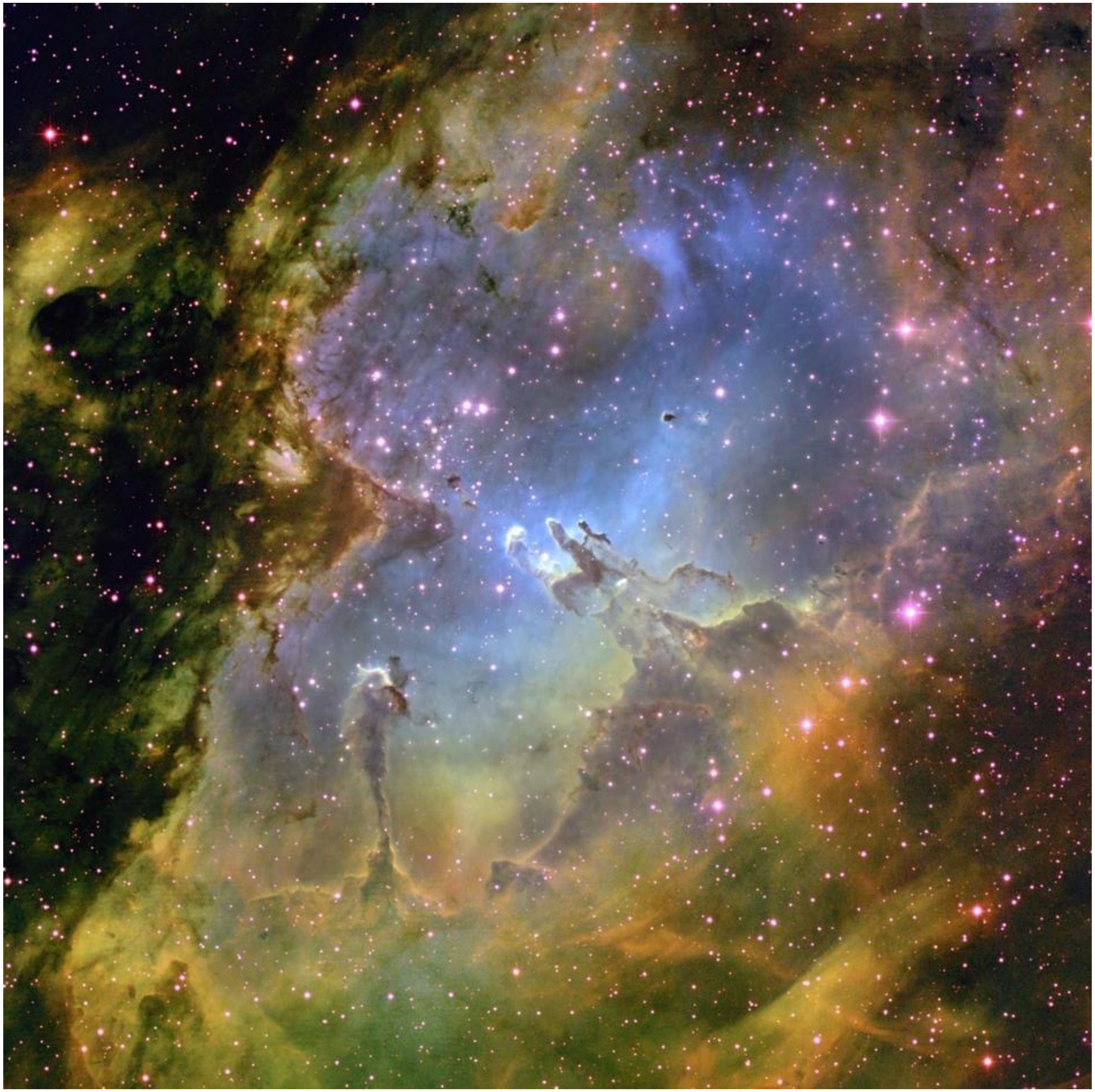


Merger Tree

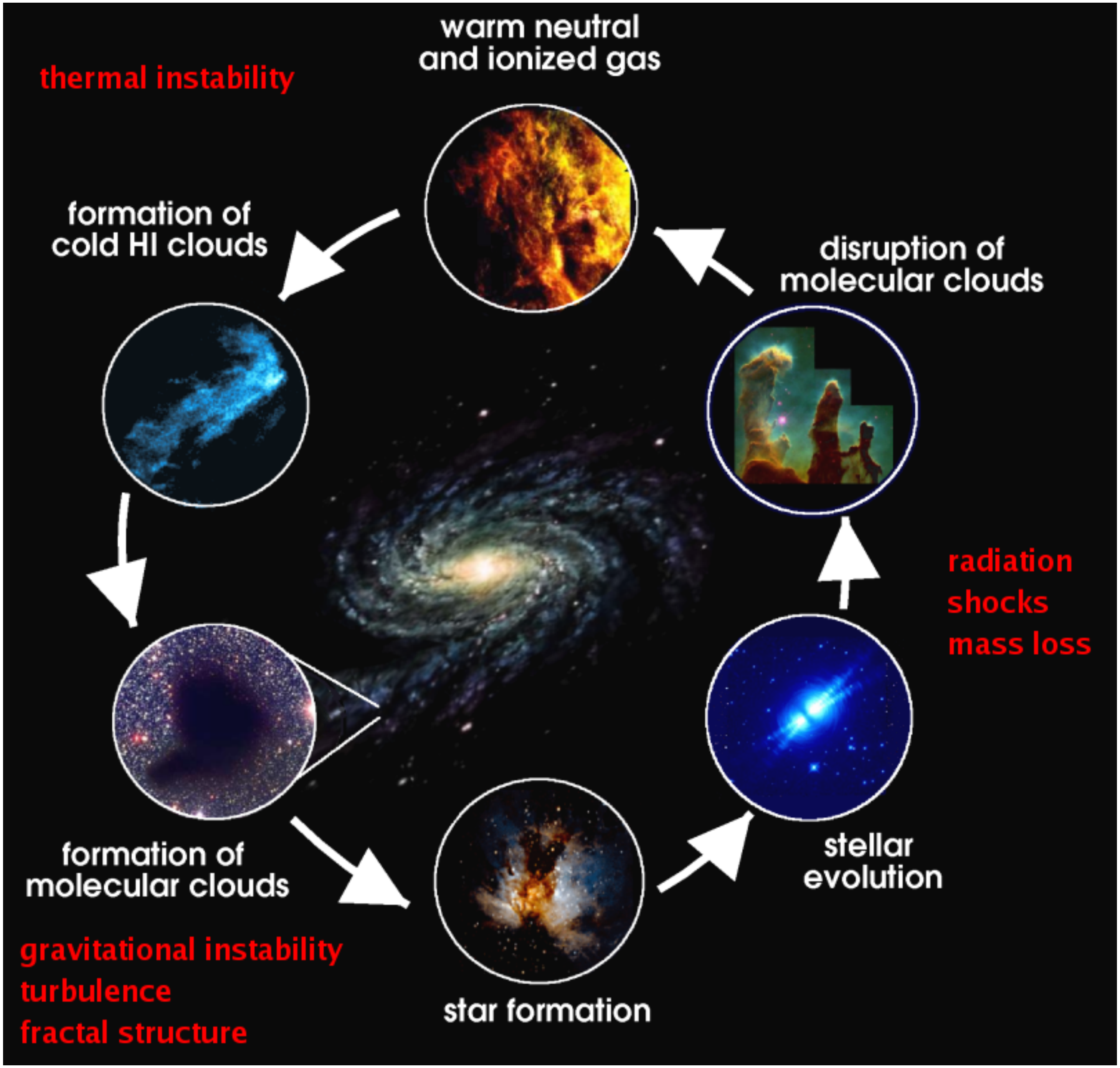



CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years

Giant Molecular Cloud (GMC): Stellar Nursery



Life Cycle of Interstellar Medium



How to Become a Star

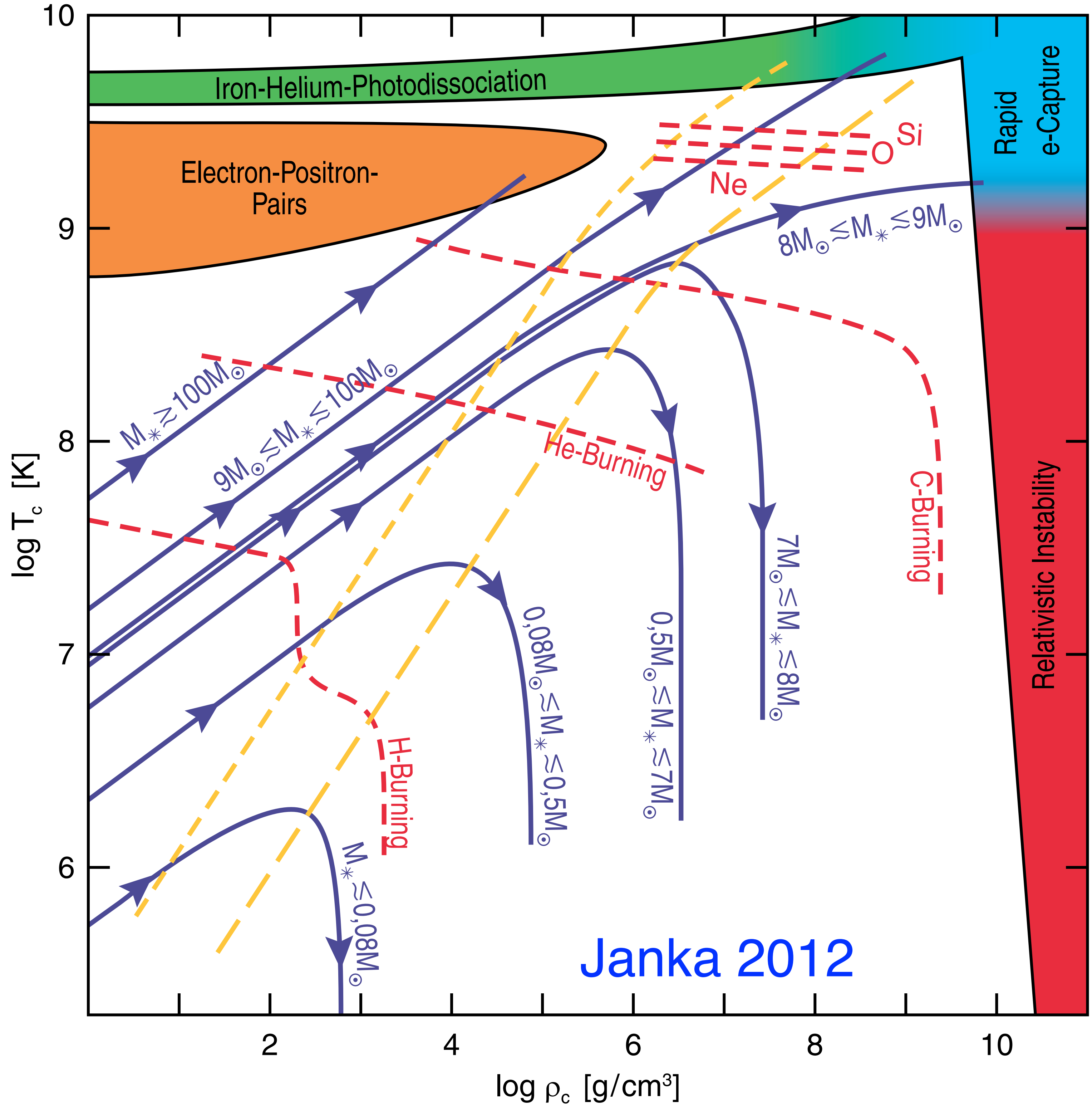
Virial theorem for a contracting gas cloud

$$T_c + \frac{\hbar^2}{2m_e d^2} \sim \frac{GMm_p}{R}$$

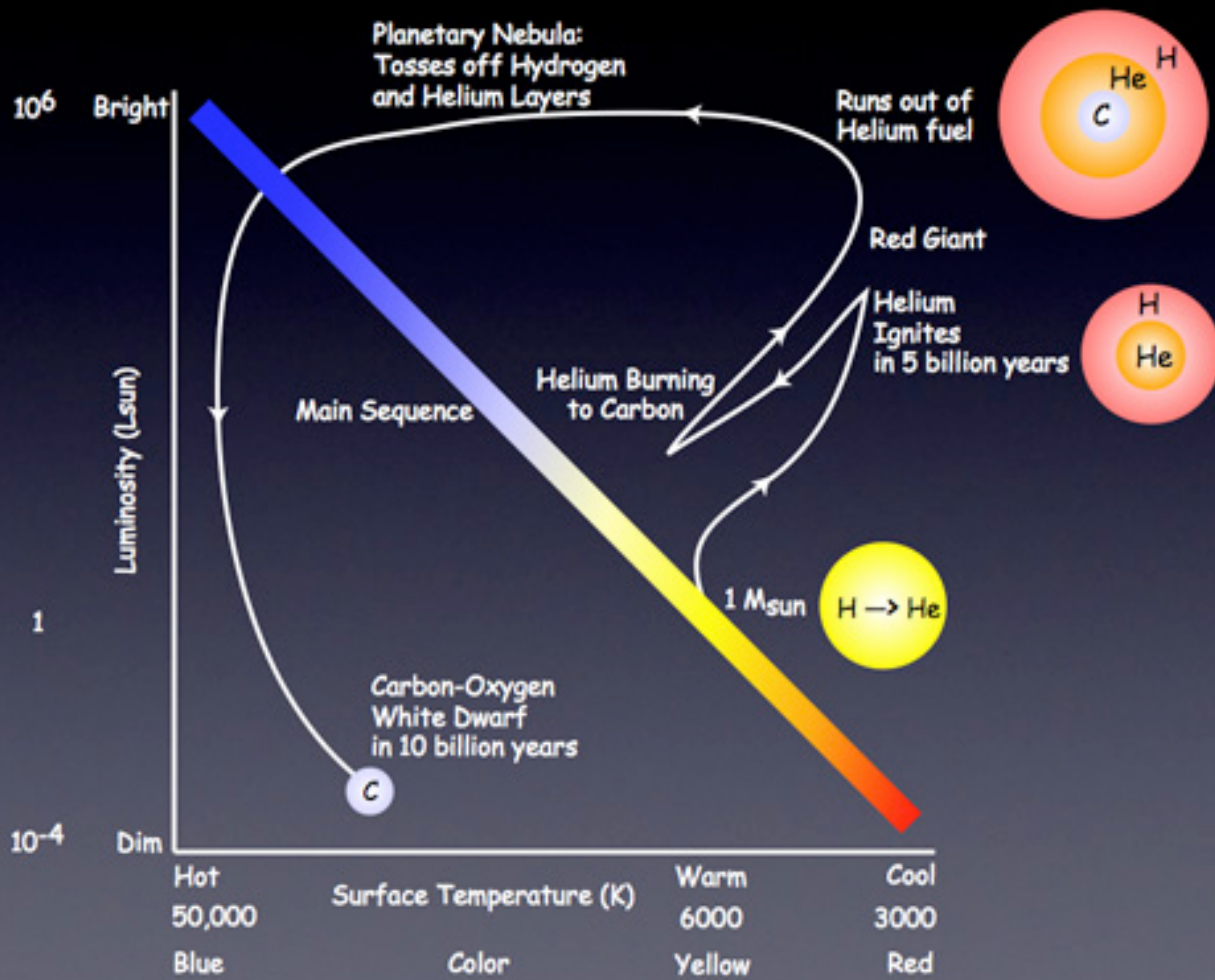
$$\left(\frac{M}{m_p}\right) d^3 \sim R^3 \Rightarrow$$

$$T_c \sim \frac{GMm_p}{R} - \frac{\hbar^2}{2m_e}\left(\frac{M}{m_p}\right)^{2/3}\frac{1}{R^2}$$

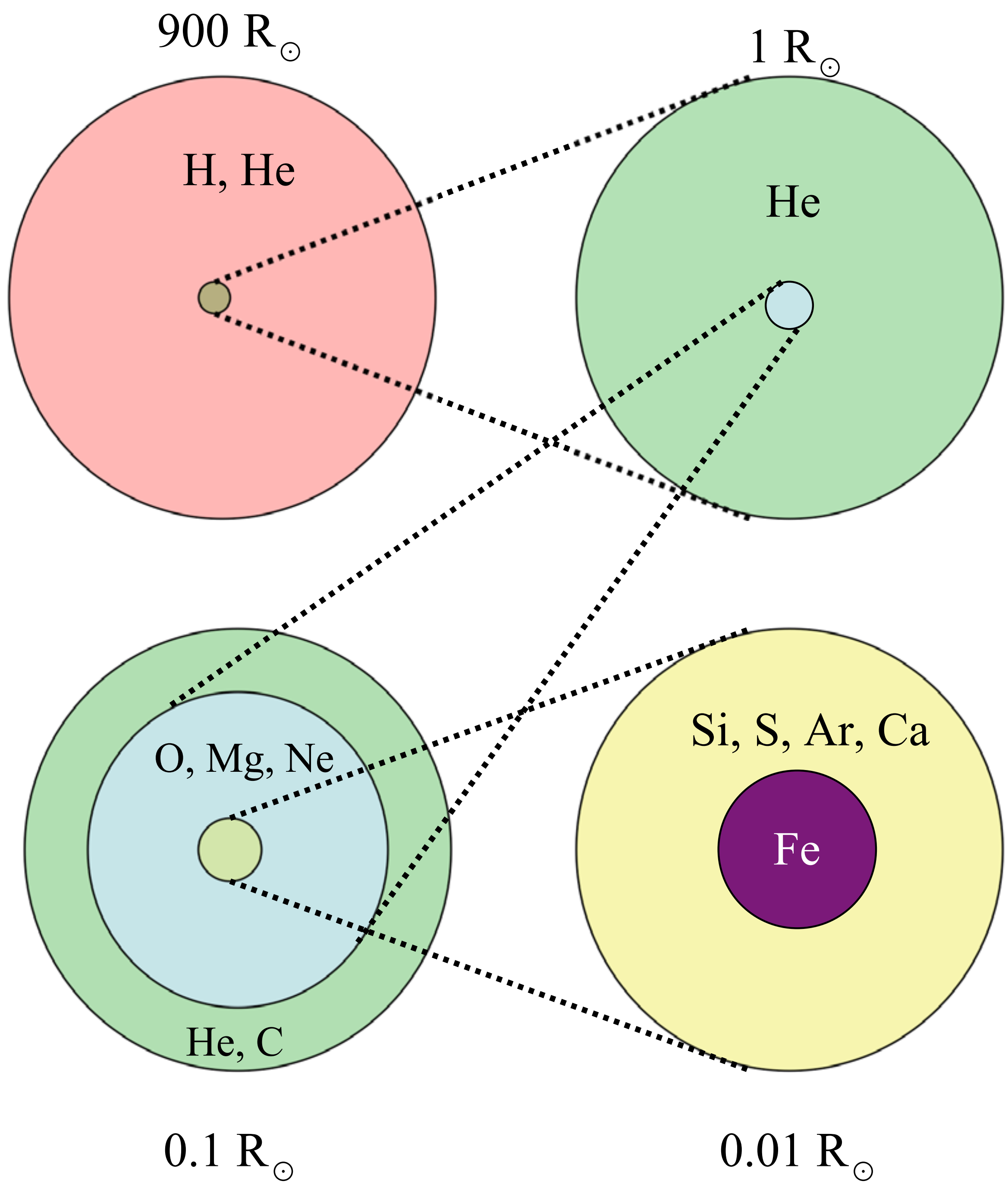
$$\Rightarrow T_{c,\mathrm{max}} \propto M^{4/3}$$

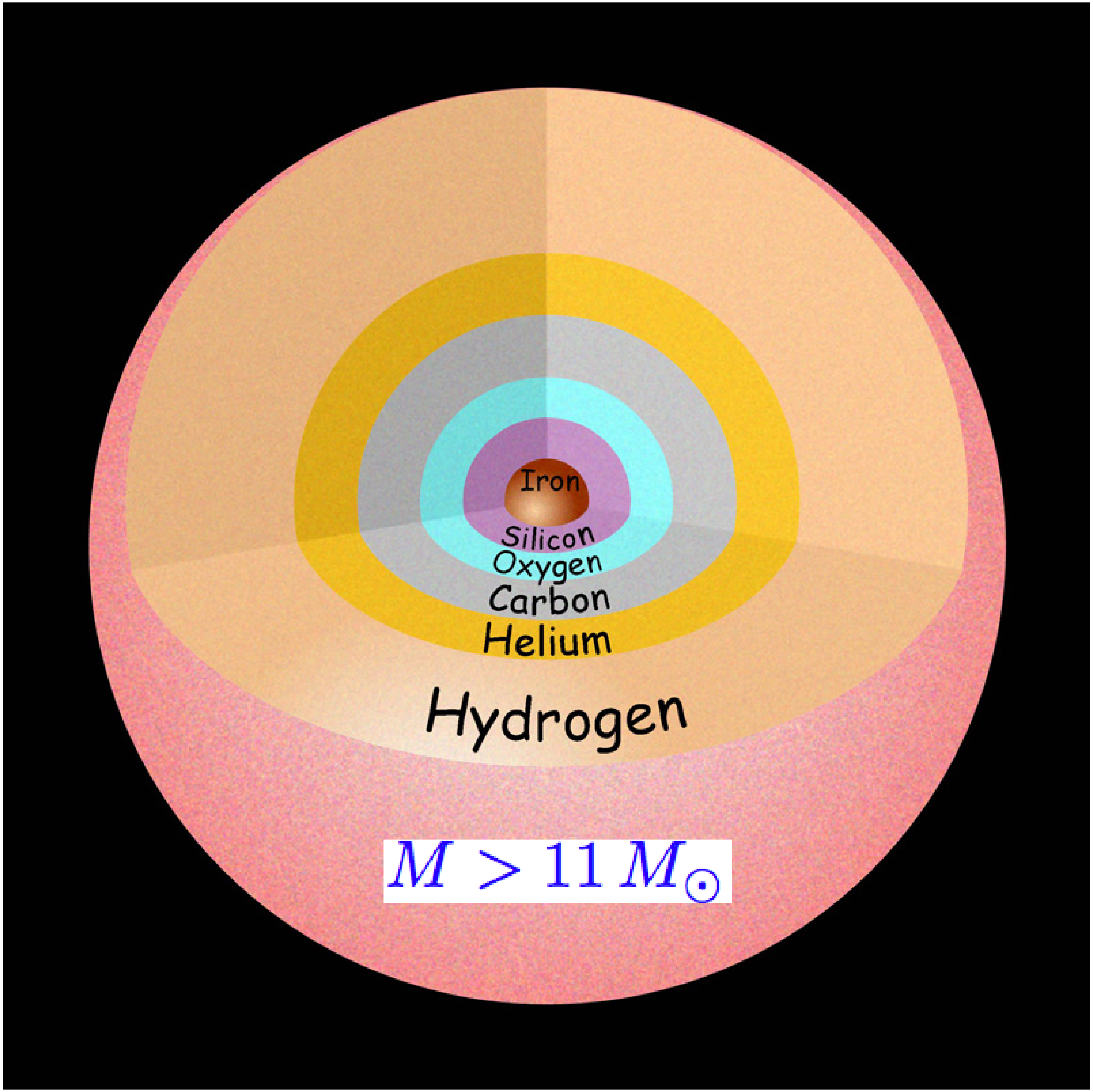

Iron-Helium-Photodissociation
Electron-Positron-Pairs
Rapid e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
M* ≳ 100M⊙
9M⊙ ≲ M* ≲ 100M⊙
8M⊙ ≲ M* ≲ 9M⊙
7M⊙ ≤ M* ≤ 8M⊙
0,5M⊙ ≤ M* ≤ 7M⊙
0,08M⊙ ≤ M* ≤ 0,5M⊙
M* ≤ 0,08M⊙
log Tc [K]
log ρc [g/cm³]
Janka 2012

The final fate of stars like the Sun are carbon-oxygen white dwarfs.



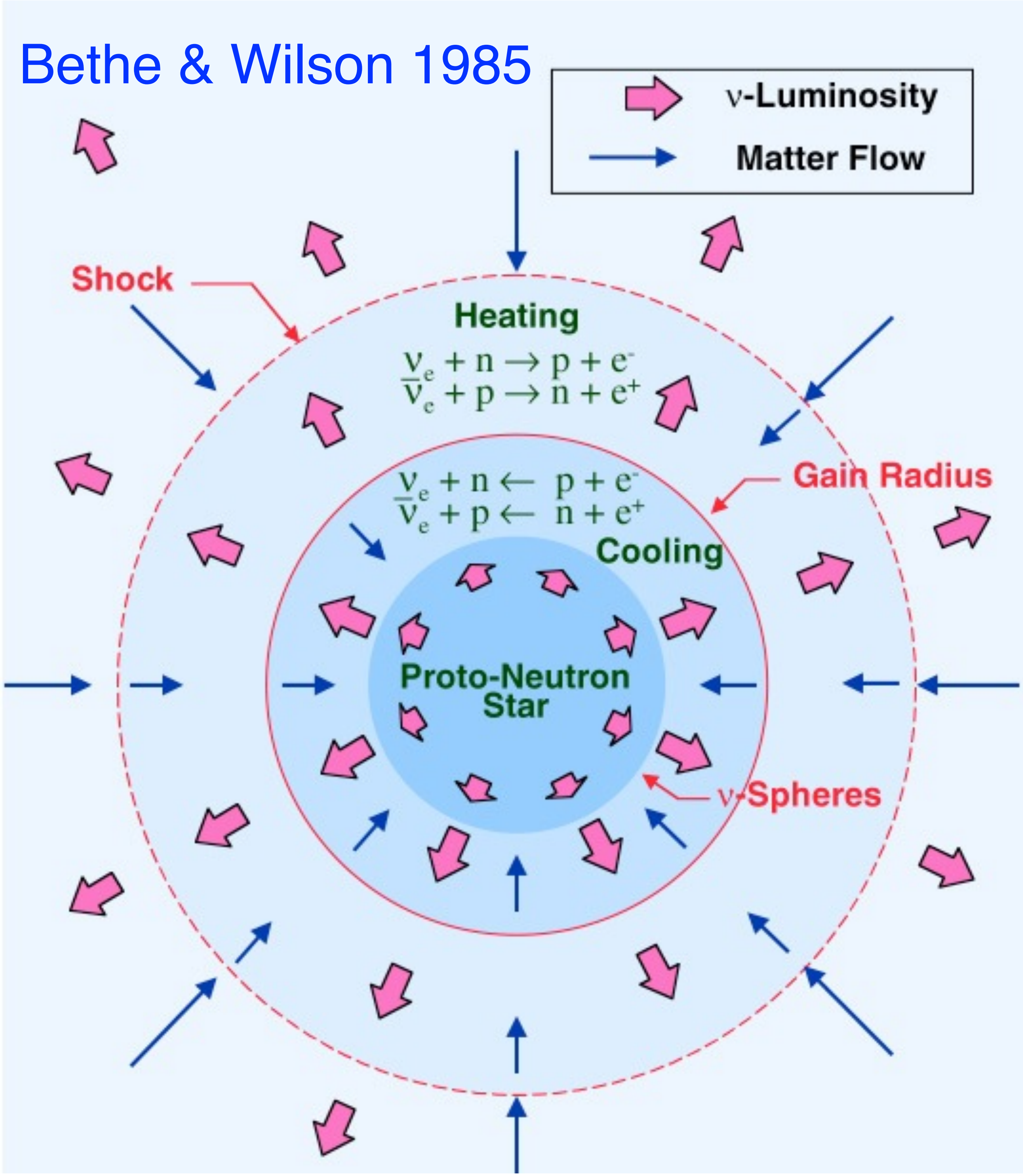
25 $M_\odot$ Presupernova Star



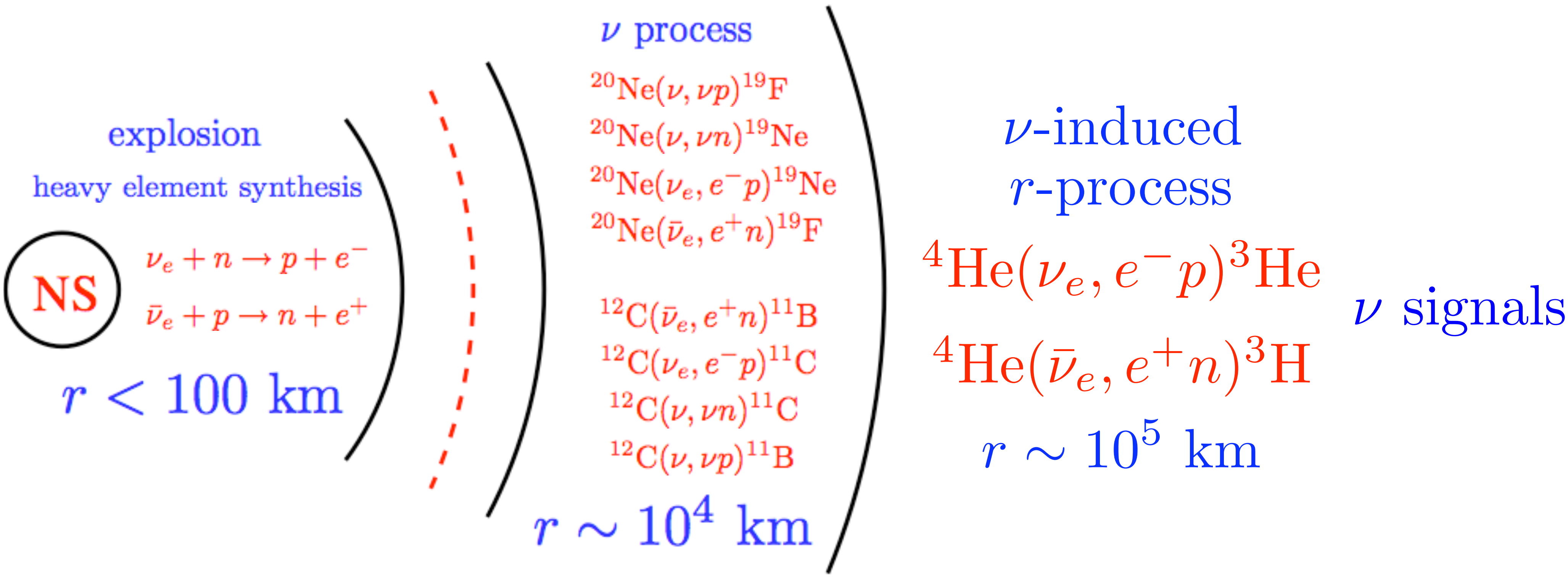


Iron
Silicon
Oxygen
Carbon
Helium
Hydrogen
$M > 11\,M_\odot$

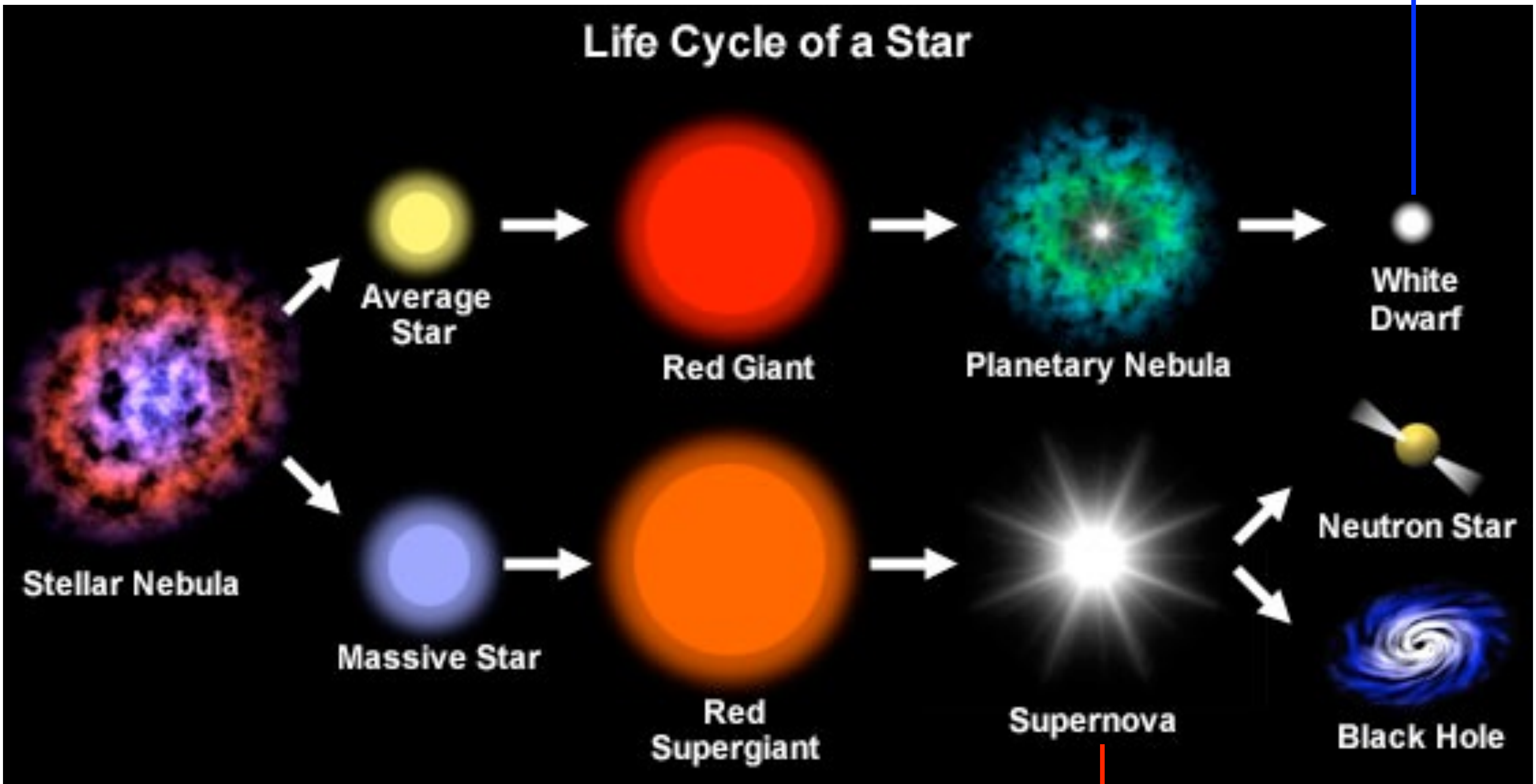
Bethe & Wilson 1985



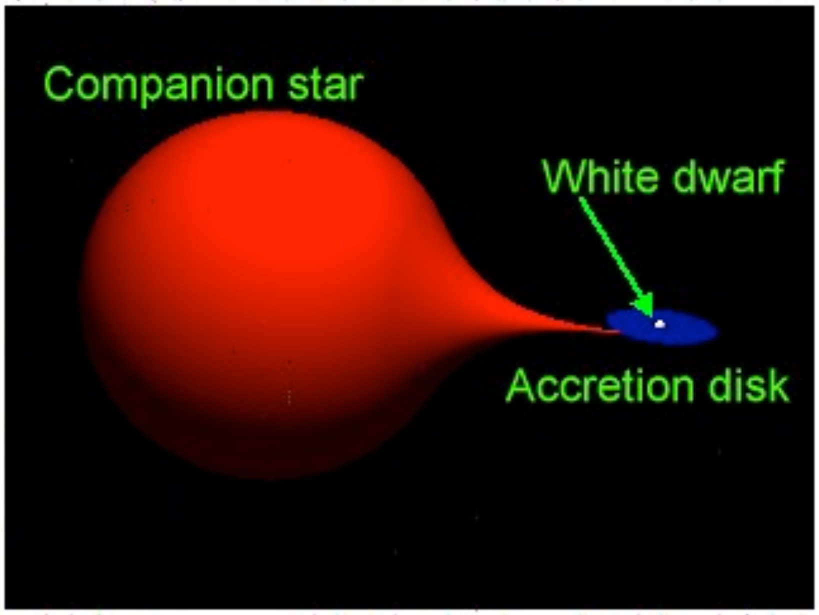
Interplay between Supernova and Neutrino Physics

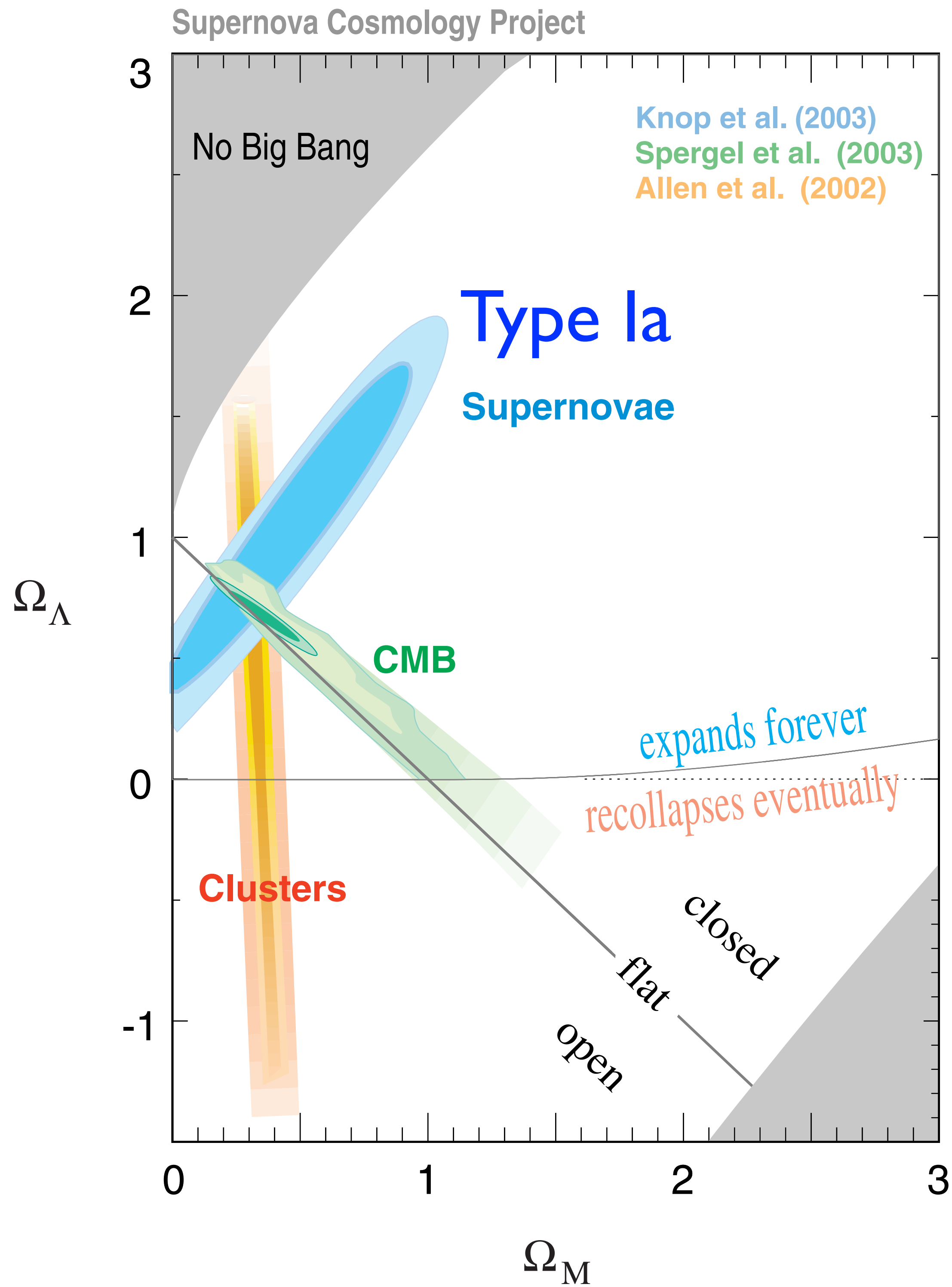


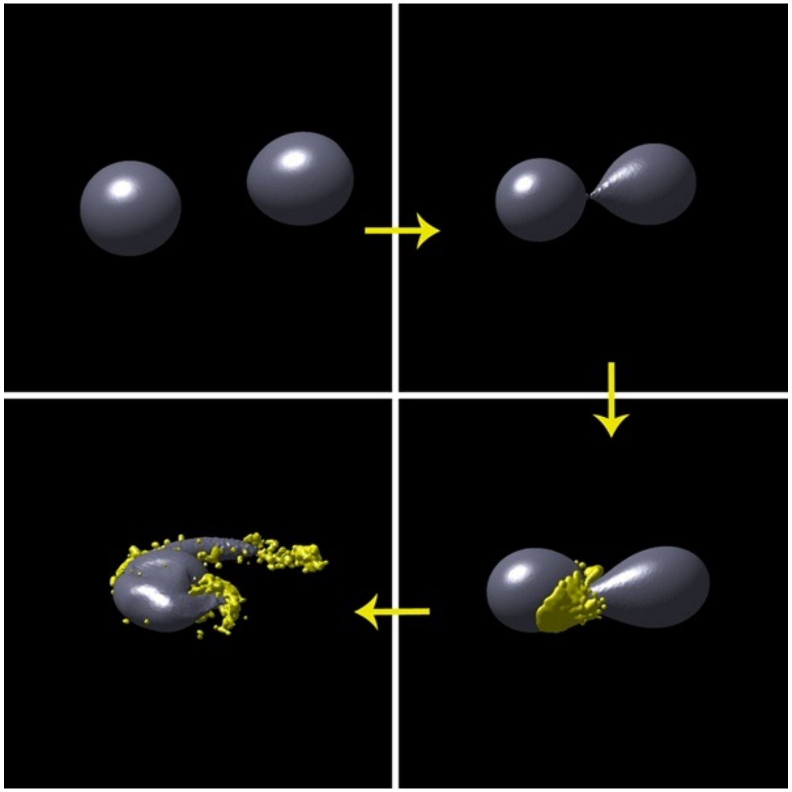
Type Ia SNe

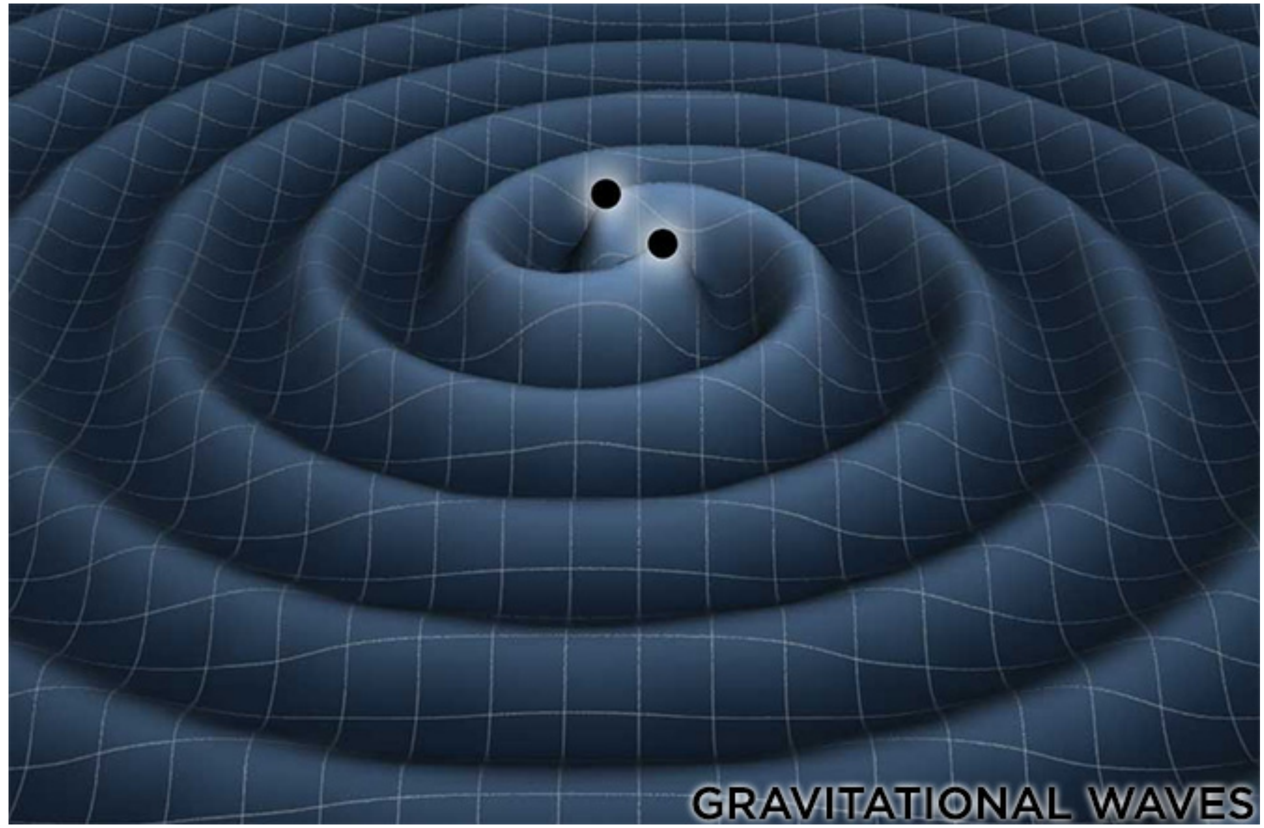


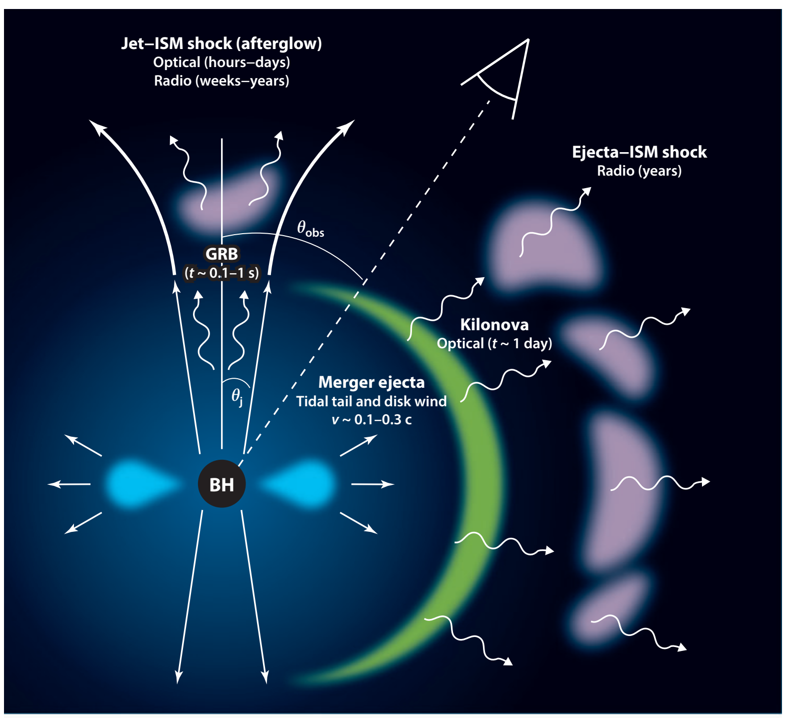
core-collapse SNe (mostly Type II)

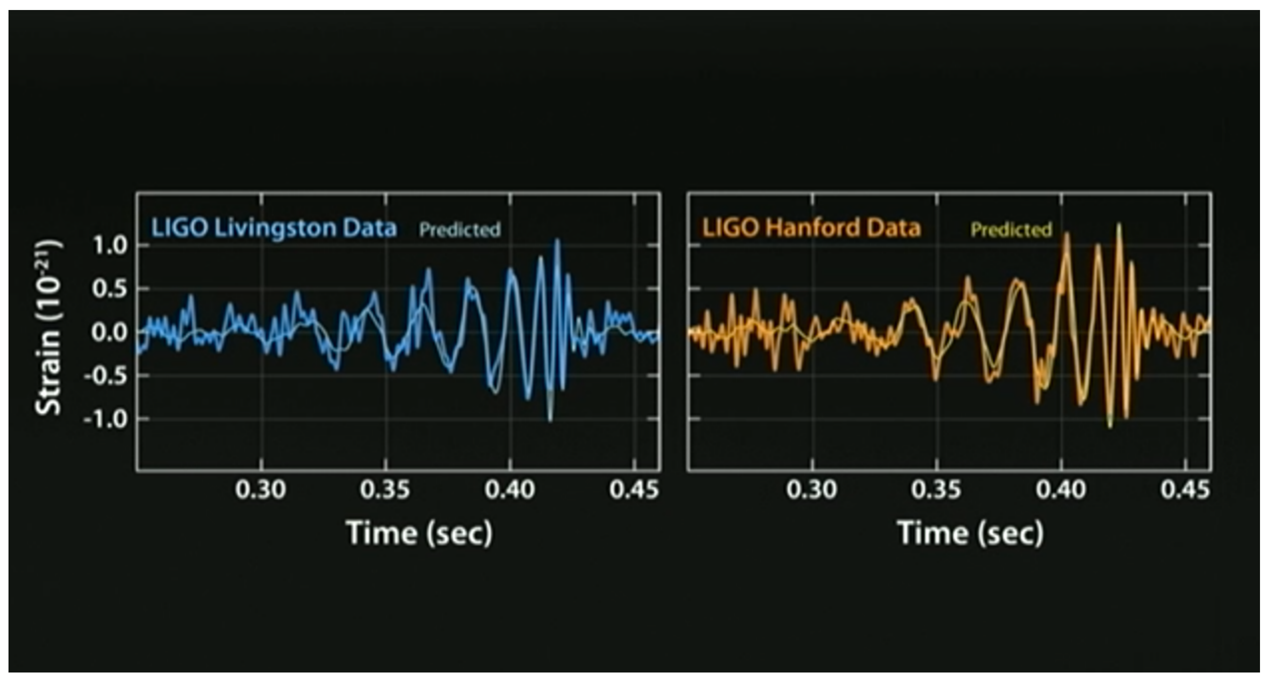

Companion star
White dwarf
Accretion disk


Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Type Ia
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M

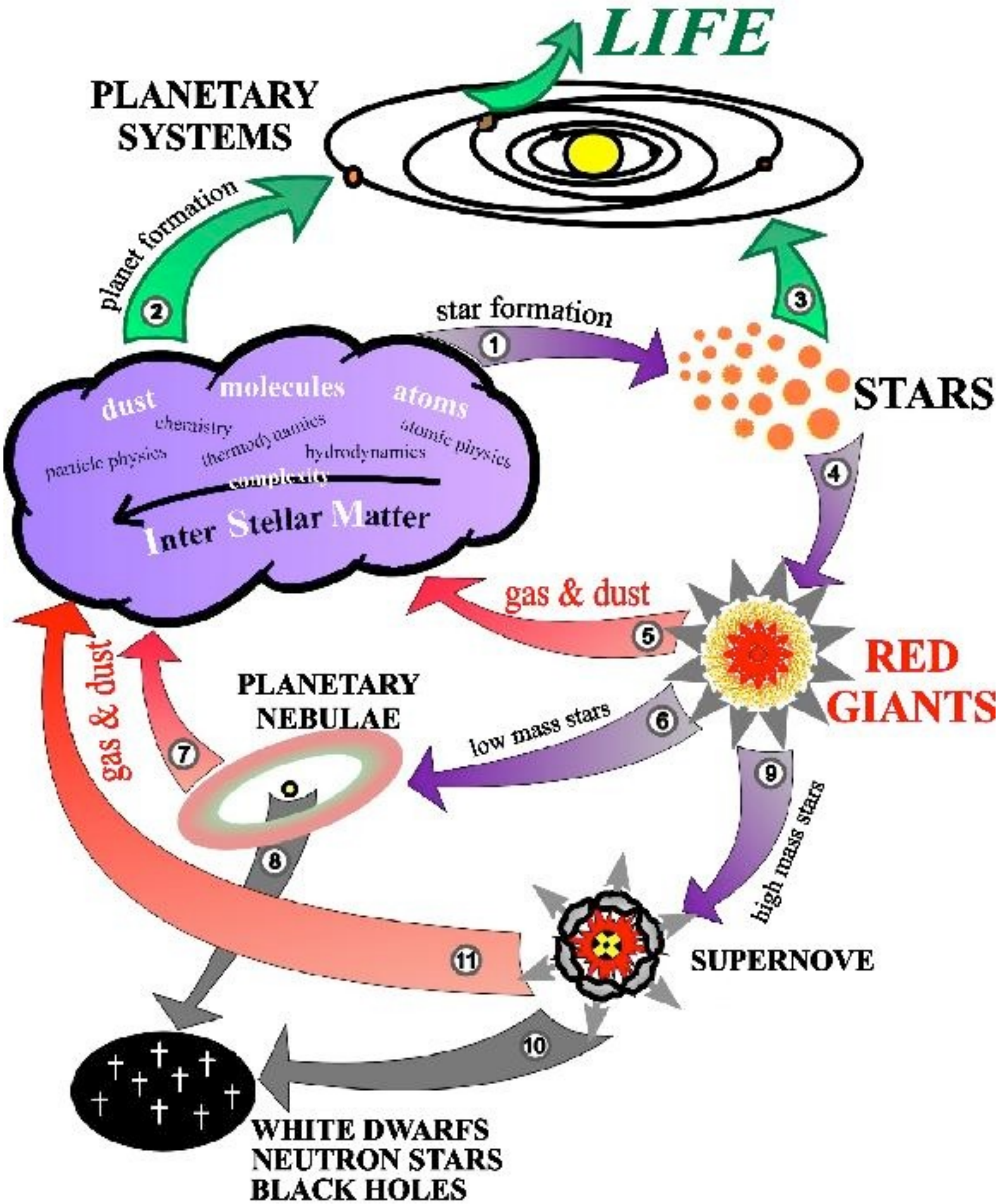


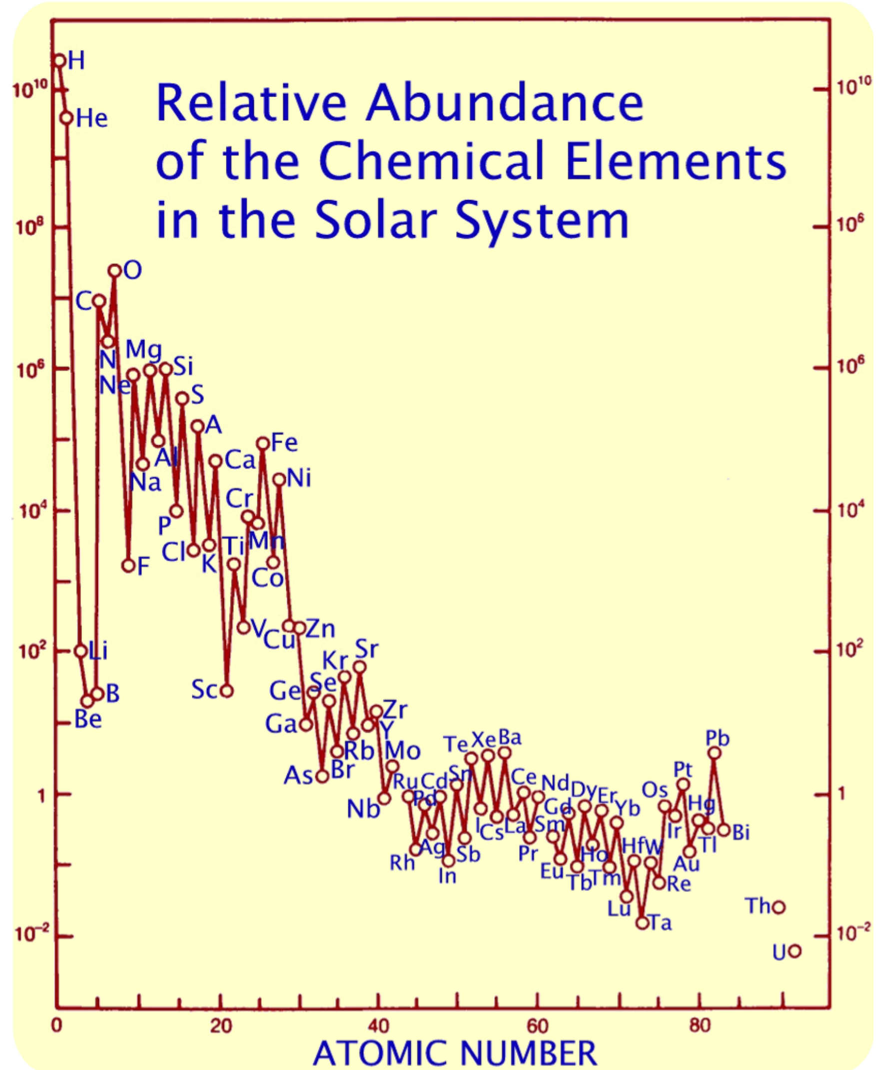

GRAVITATIONAL WAVES


Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)
Ejecta–ISM shock
Radio (years)
θ_{obs}
GRB
(t ~ 0.1–1 s)
Kilonova
Optical (t ~ 1 day)
θ_j
Merger ejecta
Tidal tail and disk wind
v ~ 0.1–0.3 c
BH


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
0.30
0.35
0.40
0.45
Time (sec)

Arise from the Ashes





Quantum Mechanics of Neutrino Oscillations

Yong-Zhong Qian
School of Physics & Astronomy, University of Minnesota
Center for Nuclear Astrophysics, Shanghai Jiao Tong University

CCEPP Summer School 2017 on Neutrino Physics
July 7, 2017

Postulates of Quantum Mechanics

$$|\psi(t)\rangle$$

The state of a system is presented by its wave function.

$$\omega(x,p) \to \Omega(X,P),\ \ [X,P] = i\hbar$$

Observables are represented by Hermitian operators.

$$\Omega|\omega_n\rangle = \omega_n|\omega_n\rangle,\ \ \mathrm{Pr}(\omega_n,t) = |\langle\omega_n|\psi(t)\rangle|^2$$

Eigenvalues and eigenstates of operators describe results of measurement.

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = H|\psi(t)\rangle$$

Evolution of state is governed by the Schrodinger Equation.

Vacuum Neutrino Oscillations

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{v} & \sin\theta_\mathrm{v} \\ -\sin\theta_\mathrm{v} & \cos\theta_\mathrm{v} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = \cos\theta_\mathrm{v}|\nu_2\rangle + \sin\theta_\mathrm{v}|\nu_3\rangle$$

$$|\nu(t)\rangle = \cos\theta_\mathrm{v}|\nu_2\rangle e^{i(px-E_2 t)} + \sin\theta_\mathrm{v}|\nu_3\rangle e^{i(px-E_3 t)}$$

$$E_i = \sqrt{p^2+m_i^2} \approx p + \frac{m_i^2}{2p},\ i=2,3,\ \delta m^2 \equiv m_3^2 - m_2^2$$

$$P_{\nu_\mu}(t) = |\langle\nu_\mu|\nu(t)\rangle|^2 = 1 - \sin^2 2\theta_\mathrm{v} \sin^2\left(\frac{\delta m^2}{4p} t\right)$$

Vacuum Oscillations as Neutrino Flavor Isospin Precession

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{\rm v} & \sin\theta_{\rm v} \\ -\sin\theta_{\rm v} & \cos\theta_{\rm v} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\mathcal{H}_{\rm vac} = \frac{\delta m^2}{4E_\nu} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$ in mass basis

$$\mathcal{H}_{\rm vac} = \frac{\delta m^2}{4E_\nu} \begin{pmatrix} -\cos 2\theta_{\rm v} & \sin 2\theta_{\rm v} \\ \sin 2\theta_{\rm v} & \cos 2\theta_{\rm v} \end{pmatrix} = -\frac{\vec{\sigma}}{2} \cdot \vec{\rm H}$$ in flavor basis

$$\vec{\rm H} = \omega \vec{\rm H}_{\rm v}, \ \ \omega \equiv \frac{\delta m^2}{2E_\nu}, \ \ \vec{\rm H}_{\rm v} \equiv -\hat{\rm e}_x^{\rm f} \sin 2\theta_{\rm v} + \hat{\rm e}_z^{\rm f} \cos 2\theta_{\rm v}$$

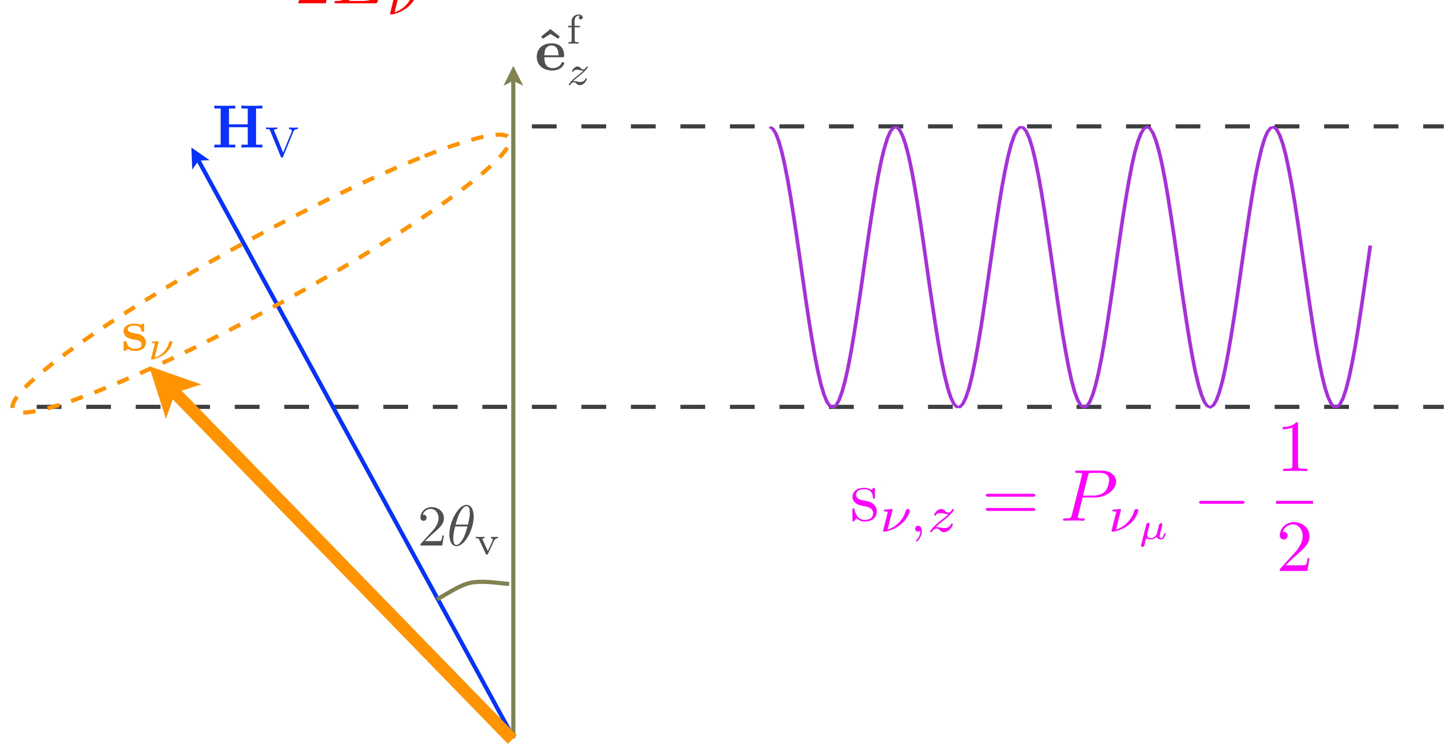
$$\frac{\sigma_z}{2} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{\sigma_z}{2} |\nu_\mu\rangle = \frac{1}{2} |\nu_\mu\rangle, \ \ \frac{\sigma_z}{2} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{\sigma_z}{2} |\nu_\tau\rangle = -\frac{1}{2} |\nu_\tau\rangle$$

$$\psi_\nu = \begin{pmatrix} a_{\nu_\mu} \\ a_{\nu_\tau} \end{pmatrix} \Rightarrow i\frac{d}{dt}\psi_\nu = \mathcal{H}_{\rm vac}\psi_\nu$$

$$\vec{\rm s}_\nu \equiv \psi_\nu^\dagger \frac{\vec{\sigma}}{2}\psi_\nu \Rightarrow {\rm s}_{\nu,z} = \frac{|a_{\nu_\mu}|^2 - |a_{\nu_\tau}|^2}{2} = \begin{cases} 1/2 \uparrow & \text{for } \nu_\mu \\ -1/2 \downarrow & \text{for } \nu_\tau \end{cases}$$

$$\mathcal{H}_{\rm vac} = -\frac{\vec{\sigma}}{2}\cdot\vec{\rm H} \Rightarrow \frac{d}{dt}\vec{\rm s}_\nu = \vec{\rm s}_\nu \times \vec{\rm H}$$

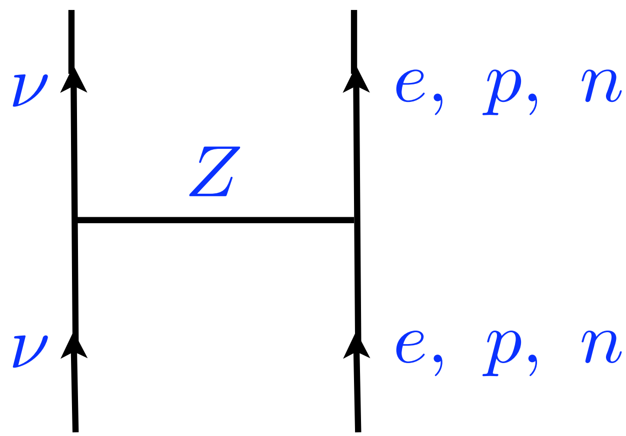
$$\vec{\rm H} = \omega\vec{\rm H}_{\rm v},\ \ \omega \equiv \frac{\delta m^2}{2E_\nu},\ \ \vec{\rm H}_{\rm v} \equiv -\hat{\rm e}_x^{\rm f}\sin 2\theta_{\rm v} + \hat{\rm e}_z^{\rm f}\cos 2\theta_{\rm v}$$

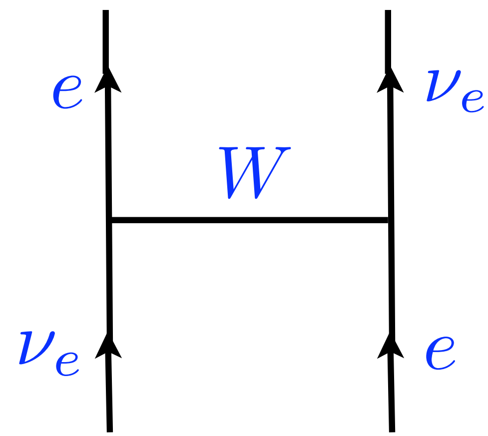


Solar Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot \\ -\sin\theta_\odot & \cos\theta_\odot \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

forward scattering on matter particles





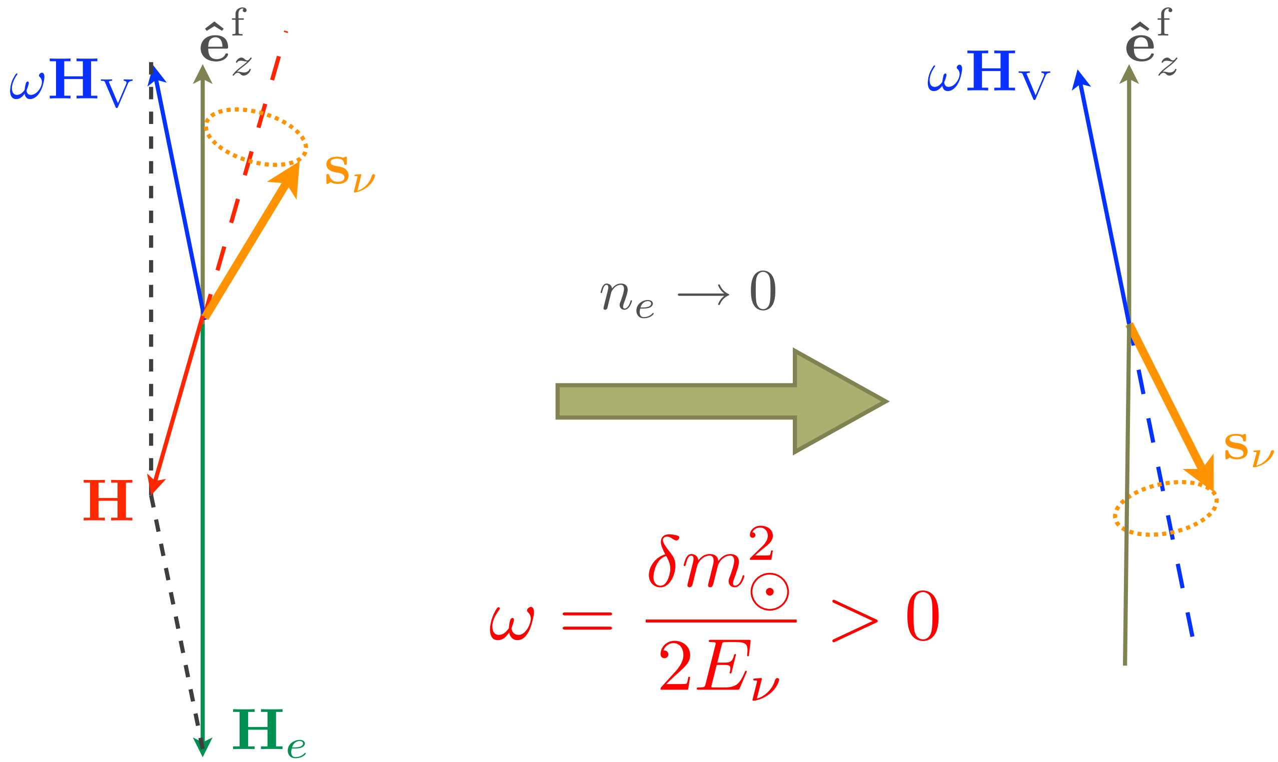
$$\frac{d}{dt}\vec{\mathrm{s}}_\nu = \vec{\mathrm{s}}_\nu \times \vec{\mathrm{H}},\;\; \vec{\mathrm{H}} = \omega\vec{\mathrm{H}}_\mathrm{v} + \vec{\mathrm{H}}_e$$

$$\omega \equiv \frac{\delta m^2_\odot}{2E_\nu},\;\; \vec{\mathrm{H}}_\mathrm{v} \equiv -\hat{\mathrm{e}}^\mathrm{f}_x \sin 2\theta_\odot + \hat{\mathrm{e}}^\mathrm{f}_z \cos 2\theta_\odot$$

$$\vec{\mathrm{H}}_e \equiv -\hat{\mathrm{e}}^\mathrm{f}_z \sqrt{2} G_F n_e$$

Mikheyev-Smirnov-Wolfenstein (MSW) Mechanism

$$\vec{\mathrm{H}} = \omega \vec{\mathrm{H}}_{\mathrm{v}} + \vec{\mathrm{H}}_e, \;\; \vec{\mathrm{H}}_e \equiv -\hat{\mathrm{e}}_z^{\mathrm{f}} \sqrt{2} G_F n_e$$

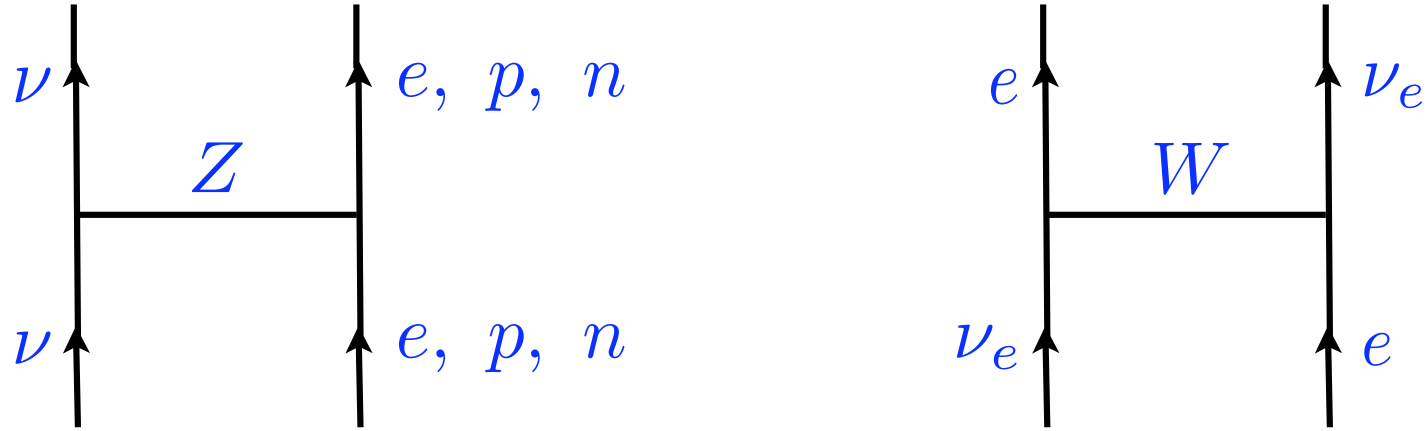


$$\omega = \frac{\delta m_\odot^2}{2E_\nu} > 0$$

resonance: $\omega \cos 2\theta_\odot = \sqrt{2} G_F n_e$

$$P_{\nu_e} = \frac{1}{2} + \mathrm{s}_{\nu,z} \to \frac{1 - \cos 2\theta_\odot}{2} = \sin^2 \theta_\odot$$

Mikheyev-Smirnov-Wolfenstein (MSW) Mechanism



effective interaction Hamiltonian (flavor diagonal):

$$\langle \nu_{\mu,\tau} | H_{\rm int} | \nu_{\mu,\tau} \rangle = 0, \ \langle \nu_e | H_{\rm int} | \nu_e \rangle = \sqrt{2} G_F n_e$$

$$\langle \bar{\nu} | H_{\rm int} | \bar{\nu} \rangle = -\langle \nu | H_{\rm int} | \nu \rangle$$

$\Delta \equiv \frac{\delta m^2}{2E_\nu} \Rightarrow$ **in flavor basis:**

$$H = H_{\rm v} + H_{\rm int} = \text{coefficent} \times \text{identity matrix}$$
$$+ \frac{1}{2} \begin{pmatrix} \sqrt{2} G_F n_e - \Delta \cos 2\theta & \Delta \sin 2\theta \\ \Delta \sin 2\theta & \Delta \cos 2\theta - \sqrt{2} G_F n_e \end{pmatrix}$$

instantaneous mass eigenstates:

$$|\nu_{1m}\rangle = \cos\theta_m|\nu_e\rangle - \sin\theta_m|\nu_\mu\rangle, \ \ |\nu_{2m}\rangle = \sin\theta_m|\nu_e\rangle + \cos\theta_m|\nu_\mu\rangle$$

$$\omega_{1m} = -\frac{1}{2}\sqrt{(\Delta\cos 2\theta - \sqrt{2}G_F n_e)^2 + \Delta^2\sin^2 2\theta}, \ \ \omega_{2m} = -\omega_{1m}$$

$$\cos 2\theta_m = \frac{\Delta\cos 2\theta - \sqrt{2}G_F n_e}{\sqrt{(\Delta\cos 2\theta - \sqrt{2}G_F n_e)^2 + \Delta^2\sin^2 2\theta}}$$

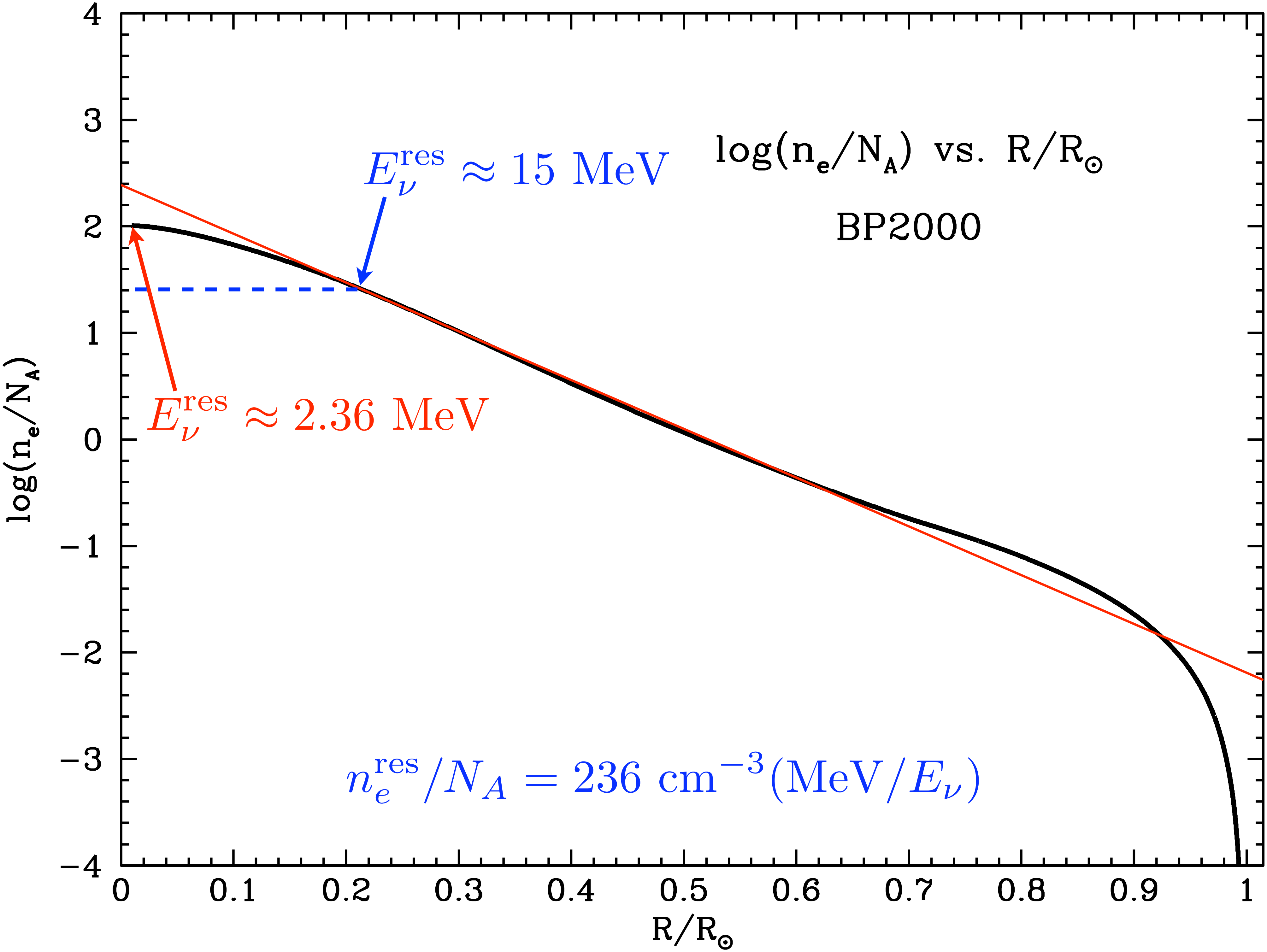
$$\sin 2\theta_m = \frac{\Delta\sin 2\theta}{\sqrt{(\Delta\cos 2\theta - \sqrt{2}G_F n_e)^2 + \Delta^2\sin^2 2\theta}}$$

resonance: $\Delta\cos 2\theta = \sqrt{2}G_F n_e^{\mathrm{res}} = \sqrt{2}G_F N_A Y_e \rho_{\mathrm{res}}$

$$\frac{n_e^{\mathrm{res}}}{N_A} = 6.55\times 10^6\ \mathrm{cm}^{-3}\left(\frac{\delta m^2}{\mathrm{eV}^2}\right)\left(\frac{\mathrm{MeV}}{E_\nu}\right)\cos 2\theta$$

$$\delta m^2 = 8\times 10^{-5}\ \mathrm{eV}^2, \ \ \sin^2 2\theta = 0.8\ (\cos 2\theta \approx 0.45) \Rightarrow$$

$$n_e^{\mathrm{res}}/N_A = 236\ \mathrm{cm}^{-3}(\mathrm{MeV}/E_\nu)$$



log(n_e/N_A) vs. R/R_⊙
BP2000
$E_\nu^{\rm res} \approx 15$ MeV
$E_\nu^{\rm res} \approx 2.36$ MeV
$n_e^{\rm res}/N_A = 236\ {\rm cm}^{-3}({\rm MeV}/E_\nu)$
log(n_e/N_A)
R/R_⊙

$$|\nu_{1m}\rangle = \cos\theta_m|\nu_e\rangle - \sin\theta_m|\nu_\mu\rangle,\ \ |\nu_{2m}\rangle = \sin\theta_m|\nu_e\rangle + \cos\theta_m|\nu_\mu\rangle$$

$$n_e \gg n_e^{\rm res} \Rightarrow \theta_m \sim \pi/2,\ \ \nu_{1m} \sim -\nu_\mu,\ \ \nu_{2m} \sim \nu_e$$

$$n_e = n_e^{\rm res} \Rightarrow \theta_m = \pi/4,\ \ n_e = 0 \Rightarrow \theta_m = \theta$$

adiabatic flavor evolution $\Rightarrow |\nu_e\rangle \rightarrow \sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle$

$$\sin^2 2\theta \sim 0.8 \Rightarrow P_{\nu_e\rightarrow\nu_e} = \sin^2\theta \sim 0.3$$

resonance region:

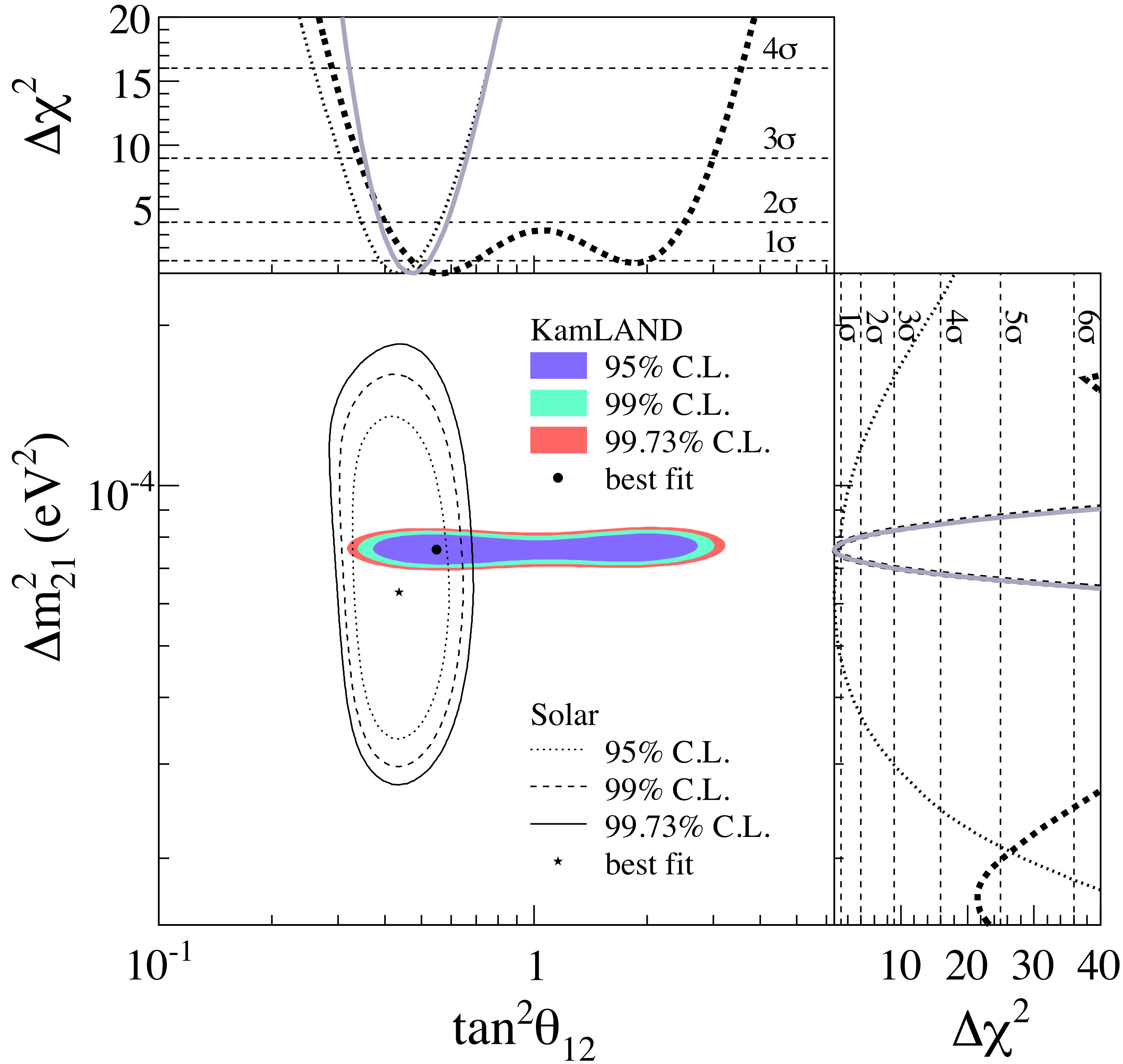
$$\sin^2 2\theta_m = \frac{\Delta^2 \sin^2 2\theta}{(\Delta\cos 2\theta - \sqrt{2}G_F n_e)^2 + \Delta^2\sin^2 2\theta} \geq \frac{1}{2}$$

$$\Rightarrow |\Delta\cos 2\theta - \sqrt{2}G_F n_e| \leq \Delta\sin 2\theta,\ \ |n_e - n_e^{\rm res}| \leq n_e^{\rm res}\tan 2\theta$$

$$\left|\frac{dn_e}{dr}\right|_{\rm res} \delta r = n_e^{\rm res}\tan 2\theta \Rightarrow \delta r = \frac{n_e^{\rm res}\tan 2\theta}{|dn_e/dr|_{\rm res}}$$

adiabatic criterion: $\delta E \sim \dfrac{1}{\delta r} \ll (\omega_{2m} - \omega_{1m})_{\rm min} = \Delta\sin 2\theta$

$$\gamma_{\rm ad} = (\Delta\sin 2\theta)\delta r = \frac{\delta m^2}{2E_\nu}\frac{\sin^2 2\theta}{\cos 2\theta}\left|\frac{d\ln n_e}{dr}\right|_{\rm res}^{-1} \gg 1$$

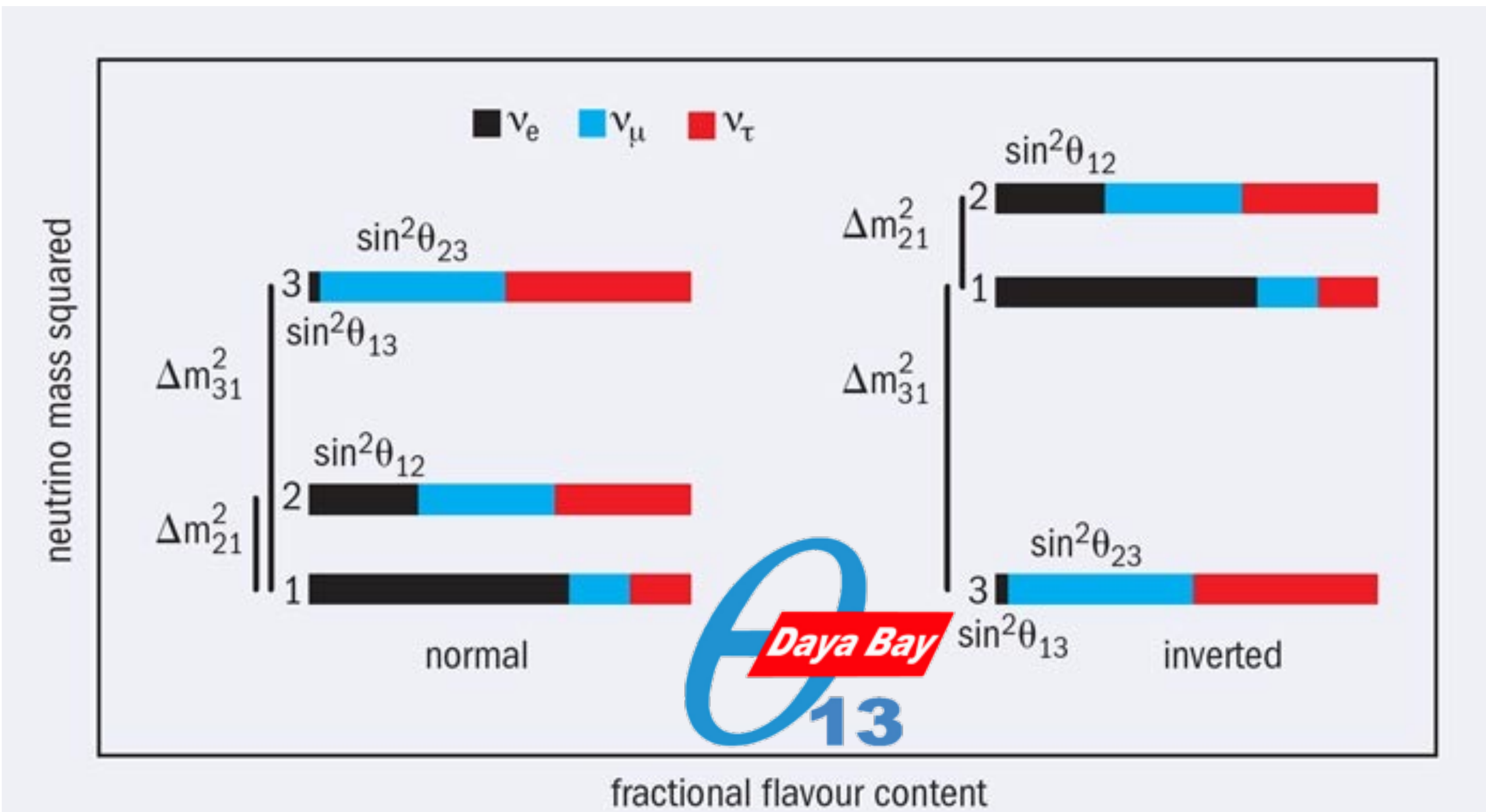


$$\frac{\delta m^2_\odot}{4E_\nu}x = 1.27\left(\frac{\delta m^2_\odot}{10^{-4}\ \mathrm{eV}^2}\right)\left(\frac{\mathrm{MeV}}{E_\nu}\right)\left(\frac{x}{10\ \mathrm{km}}\right)$$

Three Neutrino Mixing

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle, \quad |\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$$

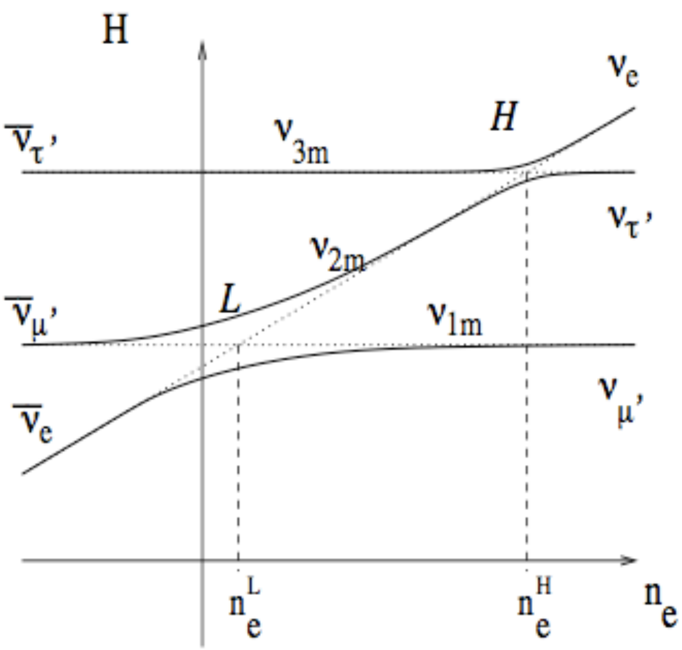
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$



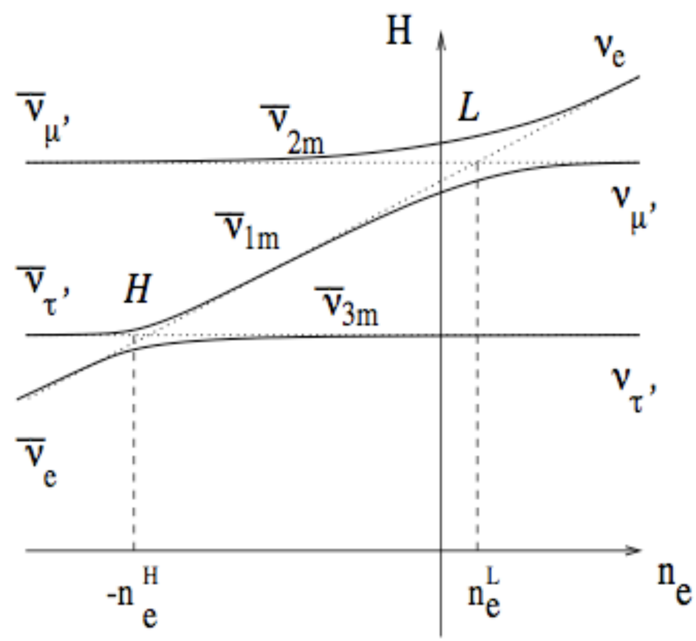
Neutrino Mixing in Vacuum

$$U_{\alpha i} = \langle \nu_\alpha | \nu_i \rangle, \ \bar{U}_{\alpha i} = \langle \bar{\nu}_\alpha | \bar{\nu}_i \rangle$$

Neutrino Flavor Evolution in Matter (MSW only)

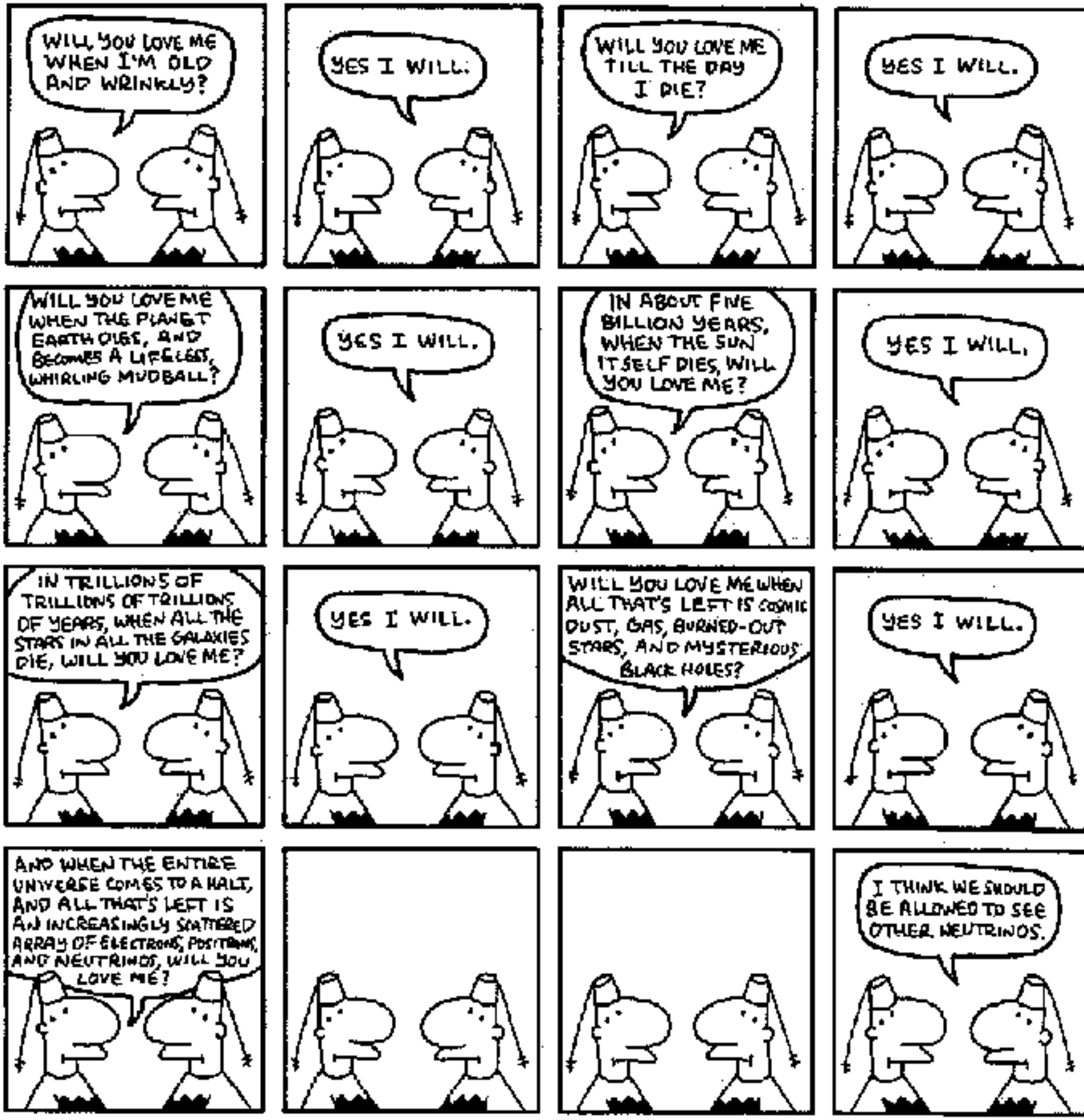


normal mass hierarchy

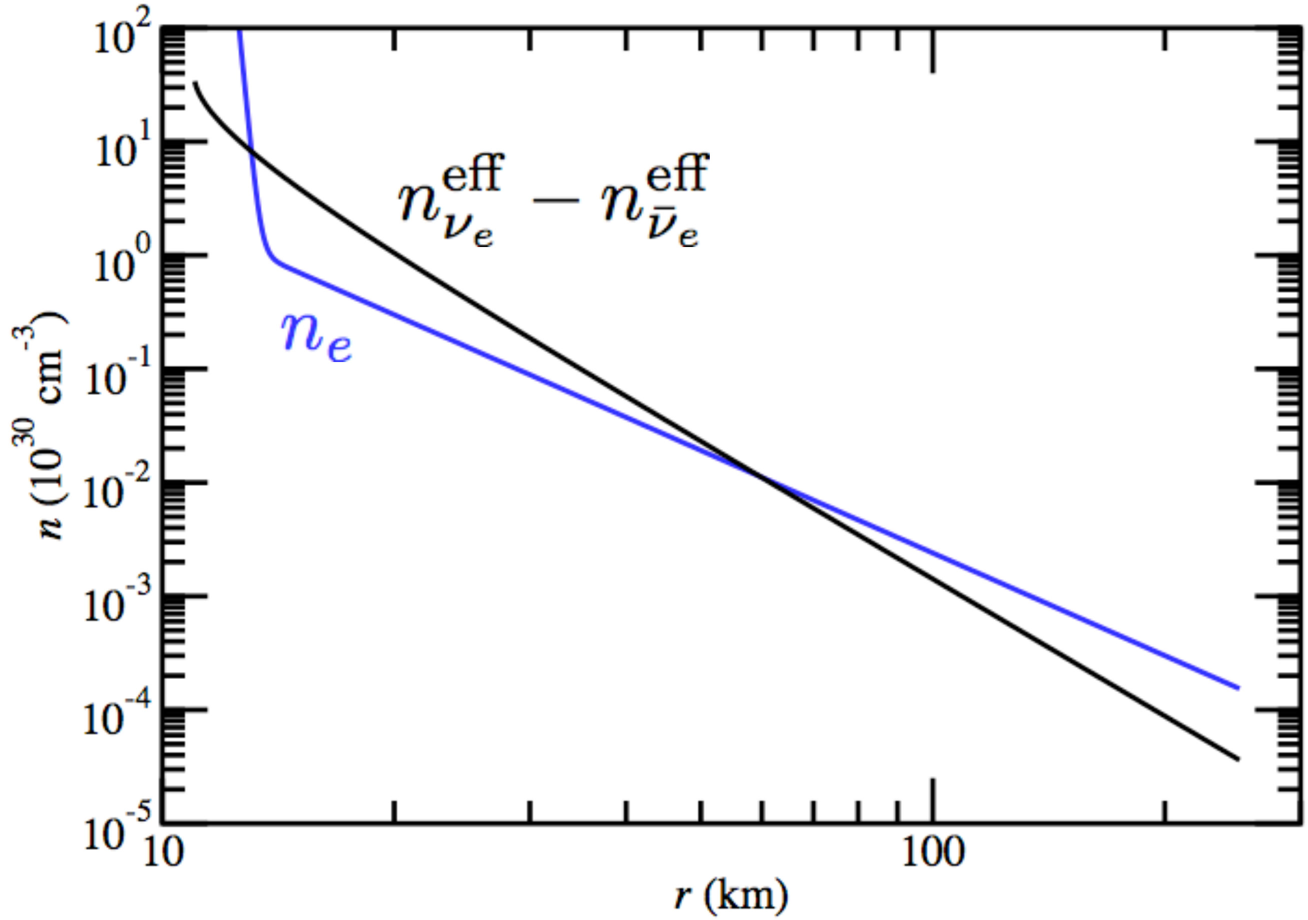


inverted mass hierarchy

LIFE IN HELL/ *Matt Groening*



Dense Neutrino Gas in Supernovae



$$\frac{d\mathbf{s}_i}{dt} = \mathbf{s}_i \times \left(\omega_i \mathbf{H}_{\rm v} + \mathbf{H}_e + \sum_j \mu_{ij} n_{\nu,j} \mathbf{s}_j\right)$$

$$\mu_{ij} \equiv -2\sqrt{2} G_F (1 - \cos\vartheta_{ij})$$

$$\frac{d\mathbf{s}_i}{dt} = \mathbf{s}_i \times \left(\omega_i \mathbf{H}_{\rm v} + \mathbf{H}_e + \sum_j \mu_{ij} n_{\nu,j} \mathbf{s}_j\right)$$

$$s_z^{\rm f} = \begin{cases} 1/2 & \text{for } \nu_e, \bar{\nu}_x \\ -1/2 & \text{for } \nu_x, \bar{\nu}_e \end{cases}, \quad \omega = \begin{cases} \delta m^2/2E & \text{for } \nu_e, \nu_x \\ -\delta m^2/2E & \text{for } \bar{\nu}_e, \bar{\nu}_x \end{cases}$$

simple model: IH, low n_e, mean neutrino trajectory

$$\sum_j \mu_{ij} n_{\nu,j} \mathbf{s}_j \to -\mu(t)\mathbf{S} \Rightarrow \frac{d\mathbf{s}_i}{dt} = \mathbf{s}_i \times [\omega_i \mathbf{H}_{\rm v} - \mu(t)\mathbf{S}]$$

cf. MSW mechanism: $\frac{d\mathbf{s}_i}{dt} = \mathbf{s}_i \times (\omega_i \mathbf{H}_{\rm v} + \mathbf{H}_e)$

how to obtain an approximate mean field S ?

$$\frac{d\mathbf{S}}{dt} \approx \mathbf{S} \times (\omega_{\rm p}\mathbf{H}_{\rm v}), \;\; \frac{d\mathbf{s}_i}{dt} = \mathbf{s}_i \times [\omega_i \mathbf{H}_{\rm v} - \mu(t)\mathbf{S}]$$

in the frame precessing with S

$$\frac{d\tilde{\mathbf{s}}_i}{dt} = \tilde{\mathbf{s}}_i \times [(\omega_i - \omega_{\rm p})\mathbf{H}_{\rm v} - \mu(t)\mathbf{S}]$$

$$t = 0 \Rightarrow -\mu(0)\mathbf{S} \text{ is in the direction of } \mathbf{H}_{\rm v}$$

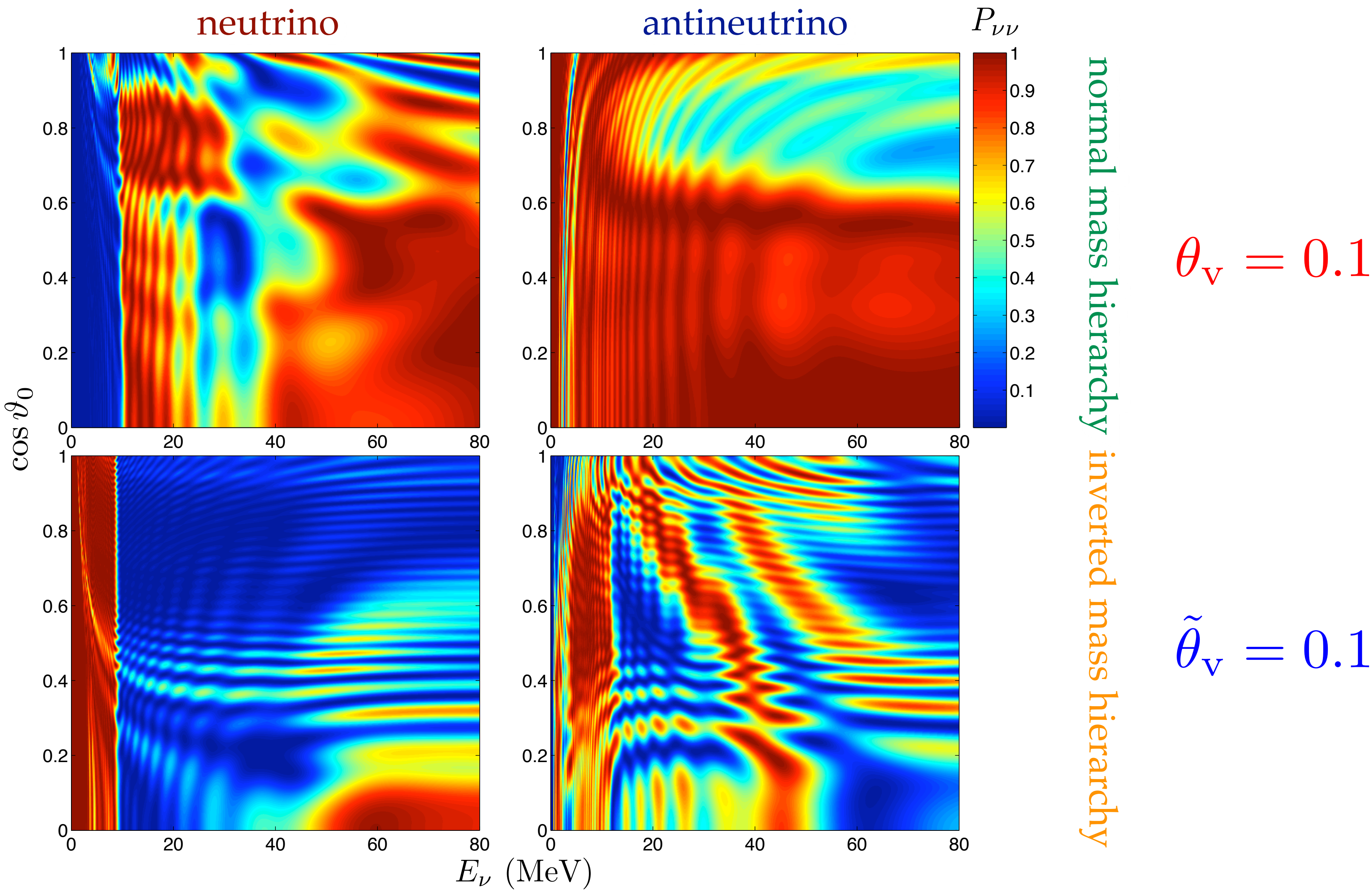
$$\omega_i < 0 \Rightarrow \bar{\nu}_e \rightarrow \bar{\nu}_x$$

$$E_i < E_c \Rightarrow \omega_i > \omega_{\rm p}(t_f), \;\; \nu_e \rightarrow \nu_e$$

$$E_i > E_c \Rightarrow \omega_i < \omega_{\rm p}(t_f), \;\; \nu_e \rightarrow \nu_x$$

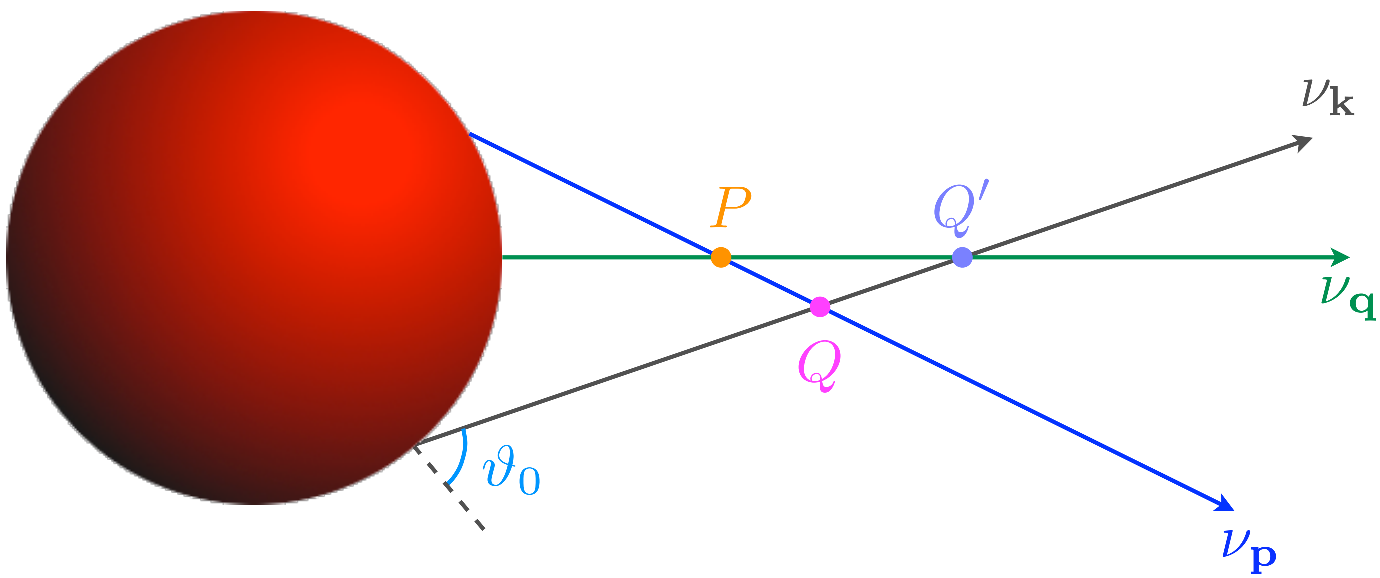
$$\mathbf{S} \cdot \mathbf{H}_{\rm v} \propto \frac{\sum_i n_{\nu,i} \mathbf{s}_i \cdot \mathbf{H}_{\rm v}}{\sum_i n_{\nu,i}} = \text{const.} \Rightarrow \omega_{\rm p}(t_f) \equiv \frac{\delta m^2}{2E_c}$$

Survival Probability at $r = 225$ km



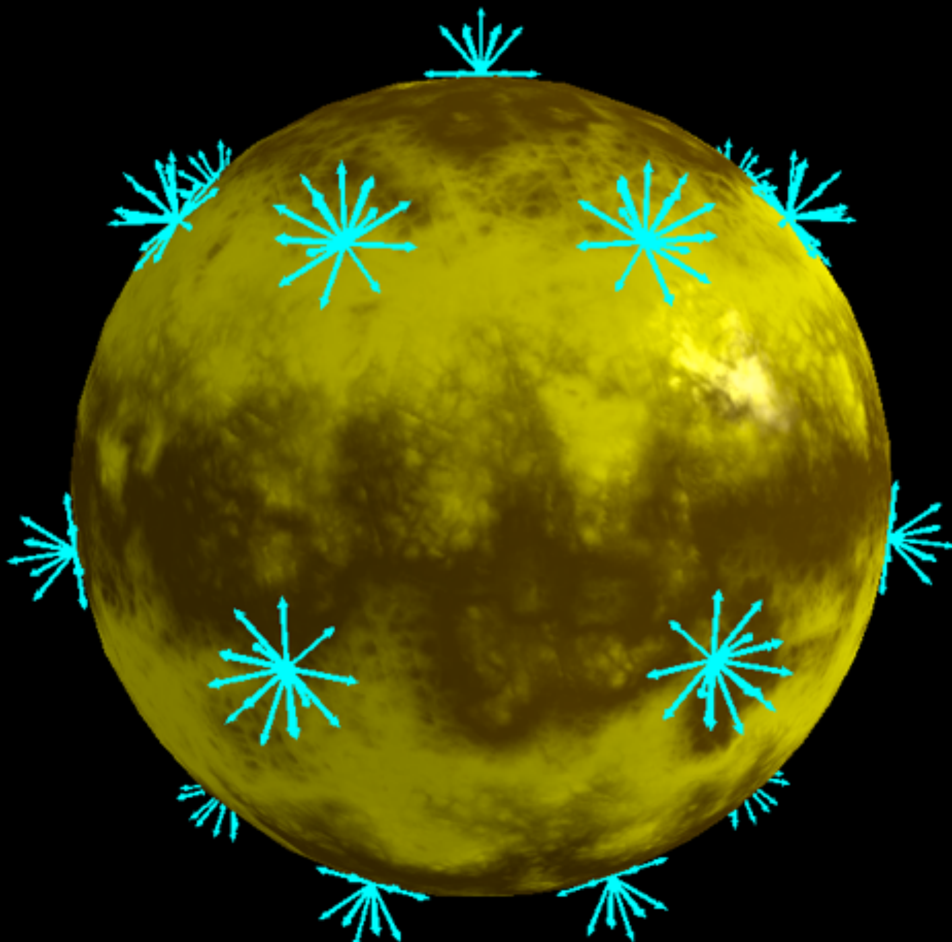
Duan, Fuller, Carlson, & Qian 2006

Geometric Complications of Neutrino Flavor Evolution



$$\mathbf{s}_i \rightarrow \mathbf{s}(E_\nu, \vartheta_0, r)$$

(3+3)D



emission direction

$$\psi(r, E, \vartheta, \varphi, \Theta, \Phi)$$

energy

emission points

Coherent forward scattering only outside neutrino sphere.

Solar Neutrinos

Yong-Zhong Qian
School of Physics & Astronomy, University of Minnesota
Center for Nuclear Astrophysics, Shanghai Jiao Tong University

CCEPP Summer School 2017 on Neutrino Physics
July 8, 2017

What is a Star?

Big glowing ball of gas; Symbol of everlasting light & stability

big & stable: gravity balanced by pressure gradient

pressure proportional to temperature & decreasing outward

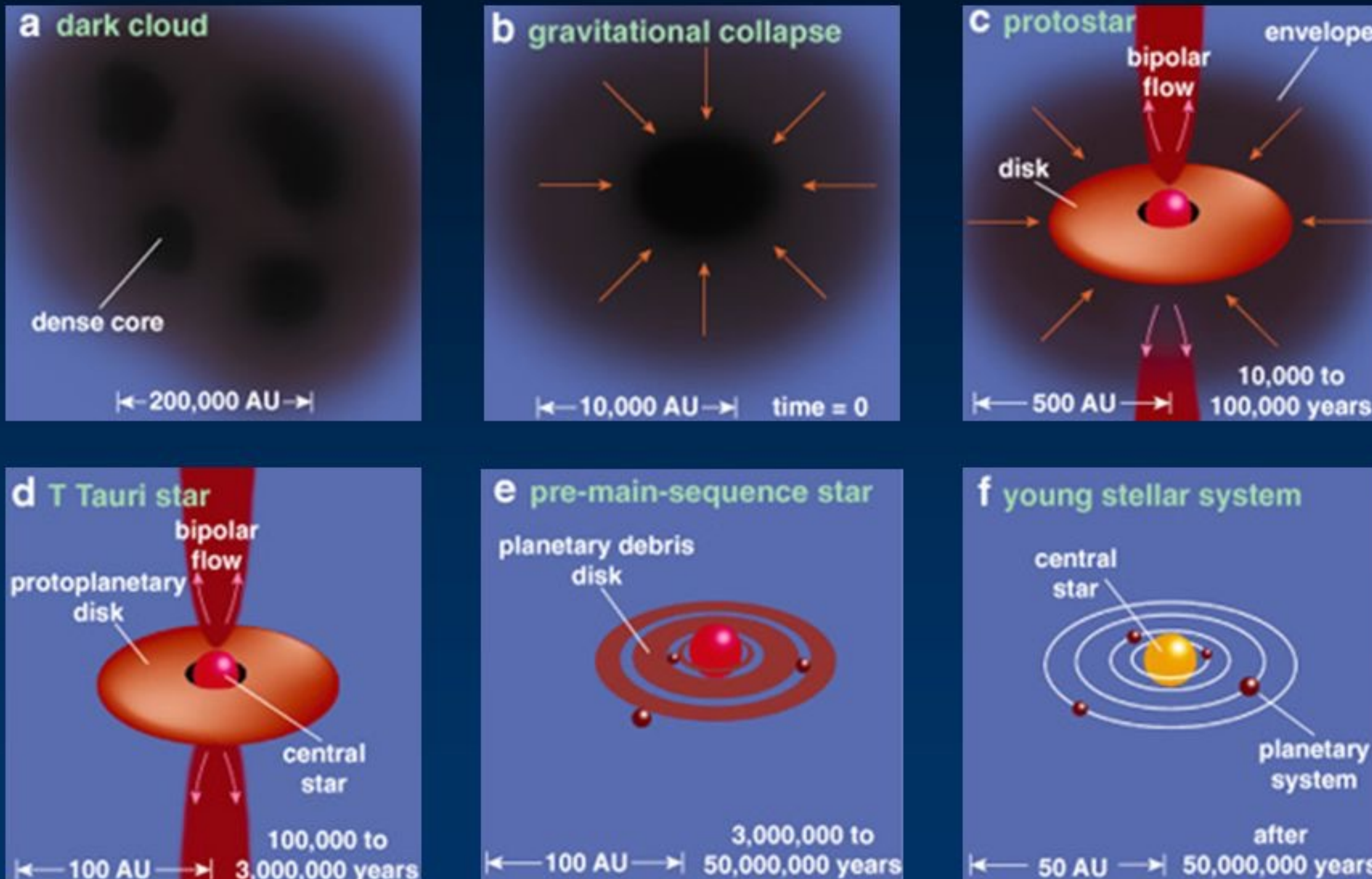
heat flows from hot to cold: energy loss from surface

long-term energy supply at center: nuclear fusion

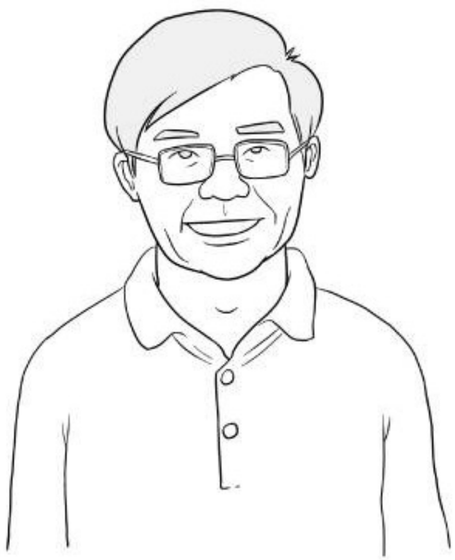
minimum temperature to ignite H: minimum mass ($M_{sun}/12$)

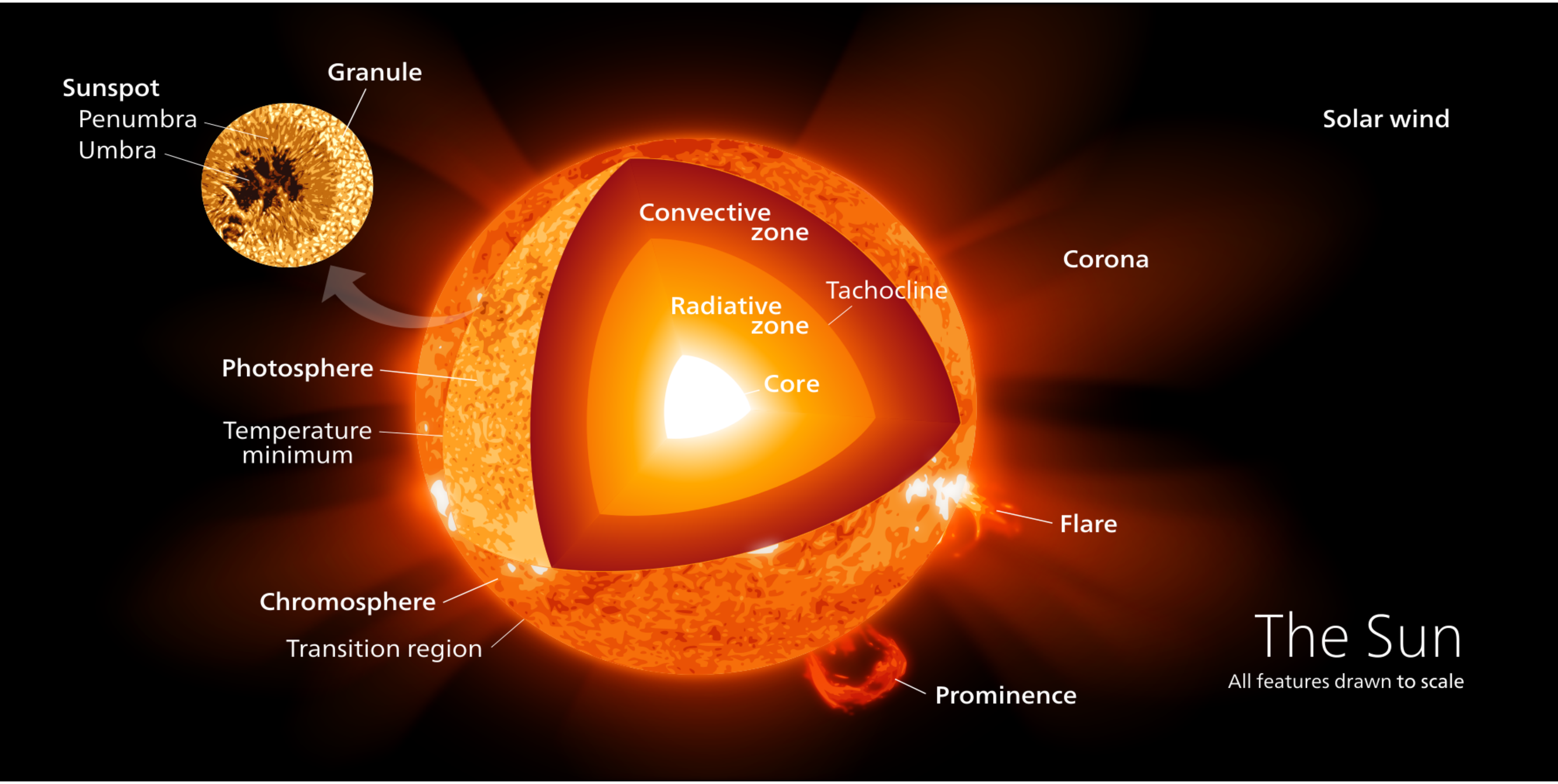
To be a star, the gas ball must be BIG!

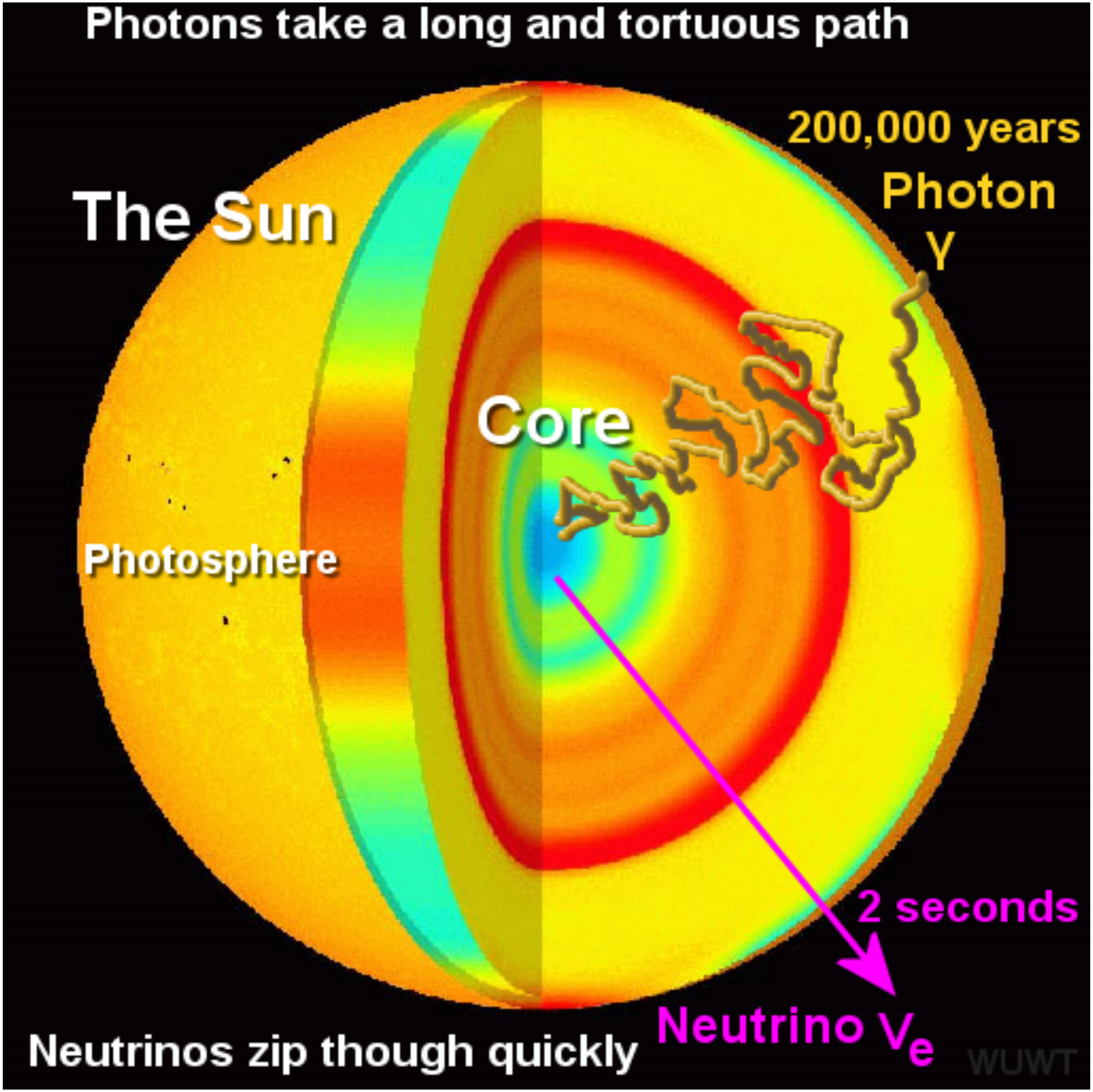
Obligatory star & planet formation slide

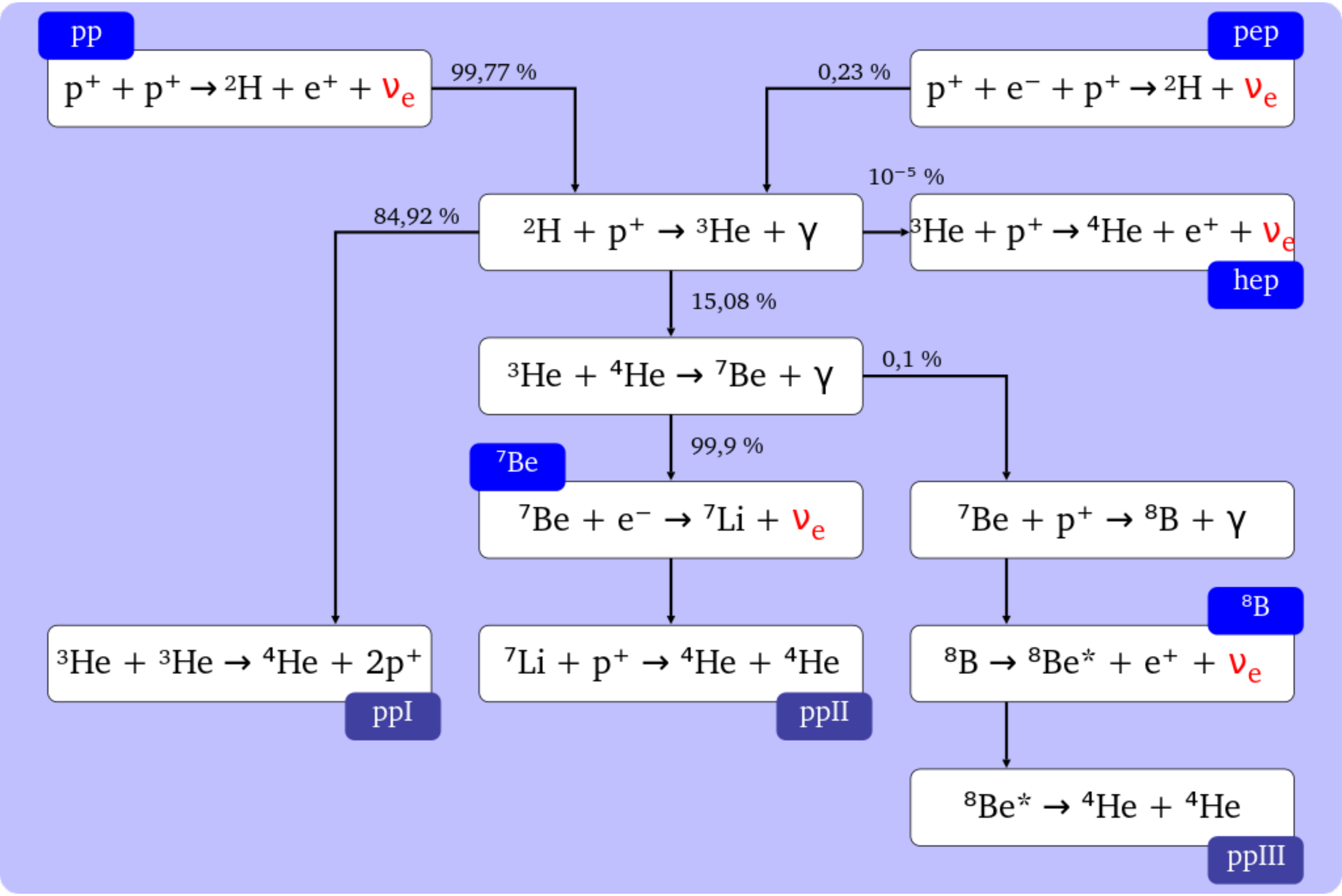


You arose from the death of stars (01/10/2017)

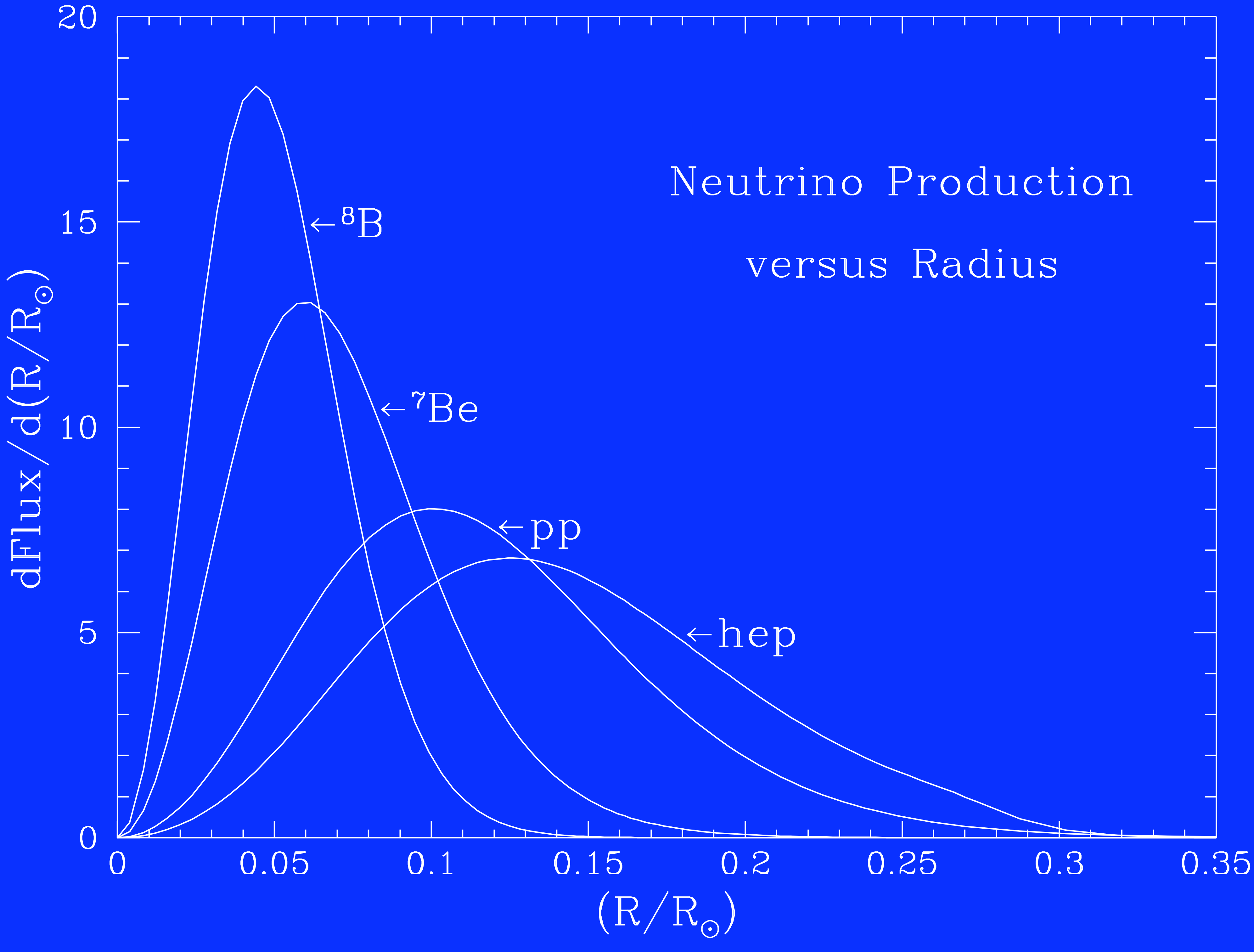



Sunspot
Penumbra
Umbra
Granule
Solar wind
Convective zone
Corona
Tachocline
Radiative zone
Core
Photosphere
Temperature minimum
Flare
Chromosphere
Transition region
Prominence
The Sun
All features drawn to scale

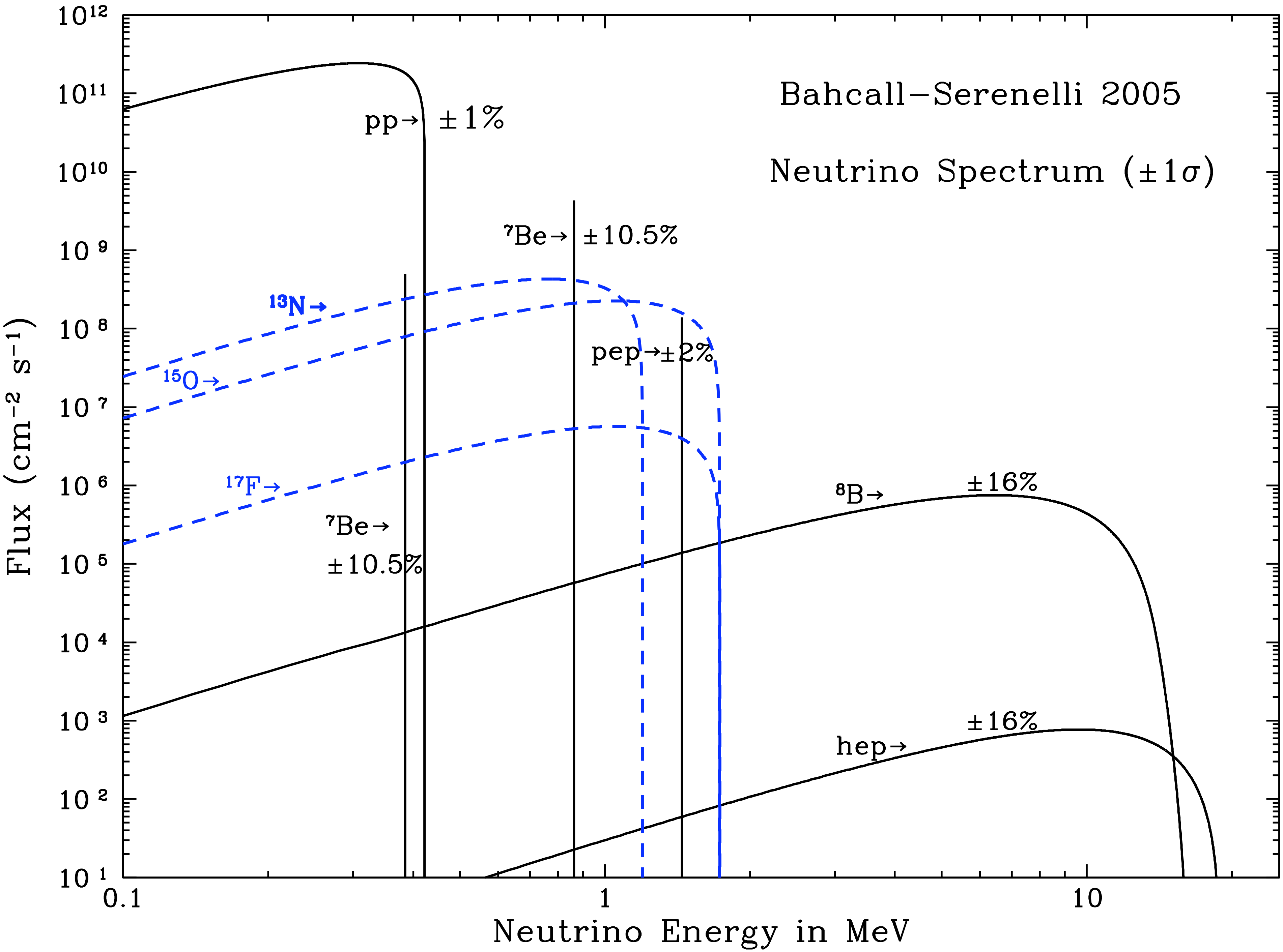

Photons take a long and tortuous path
200,000 years
Photon
γ
The Sun
Core
Photosphere
2 seconds
Neutrino ν_e
Neutrinos zip though quickly
WUWT



pp
$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$
99,77 %
pep
$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$
0,23 %
$^2H + p^+ \rightarrow {}^3He + \gamma$
84,92 %
10⁻⁵ %
$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$
hep
15,08 %
$^3He + {}^4He \rightarrow {}^7Be + \gamma$
0,1 %
99,9 %
7Be
$^7Be + e^- \rightarrow {}^7Li + \nu_e$
$^7Be + p^+ \rightarrow {}^8B + \gamma$
8B
$^3He + {}^3He \rightarrow {}^4He + 2p^+$
ppI
$^7Li + p^+ \rightarrow {}^4He + {}^4He$
ppII
$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$
$^8Be^* \rightarrow {}^4He + {}^4He$
ppIII

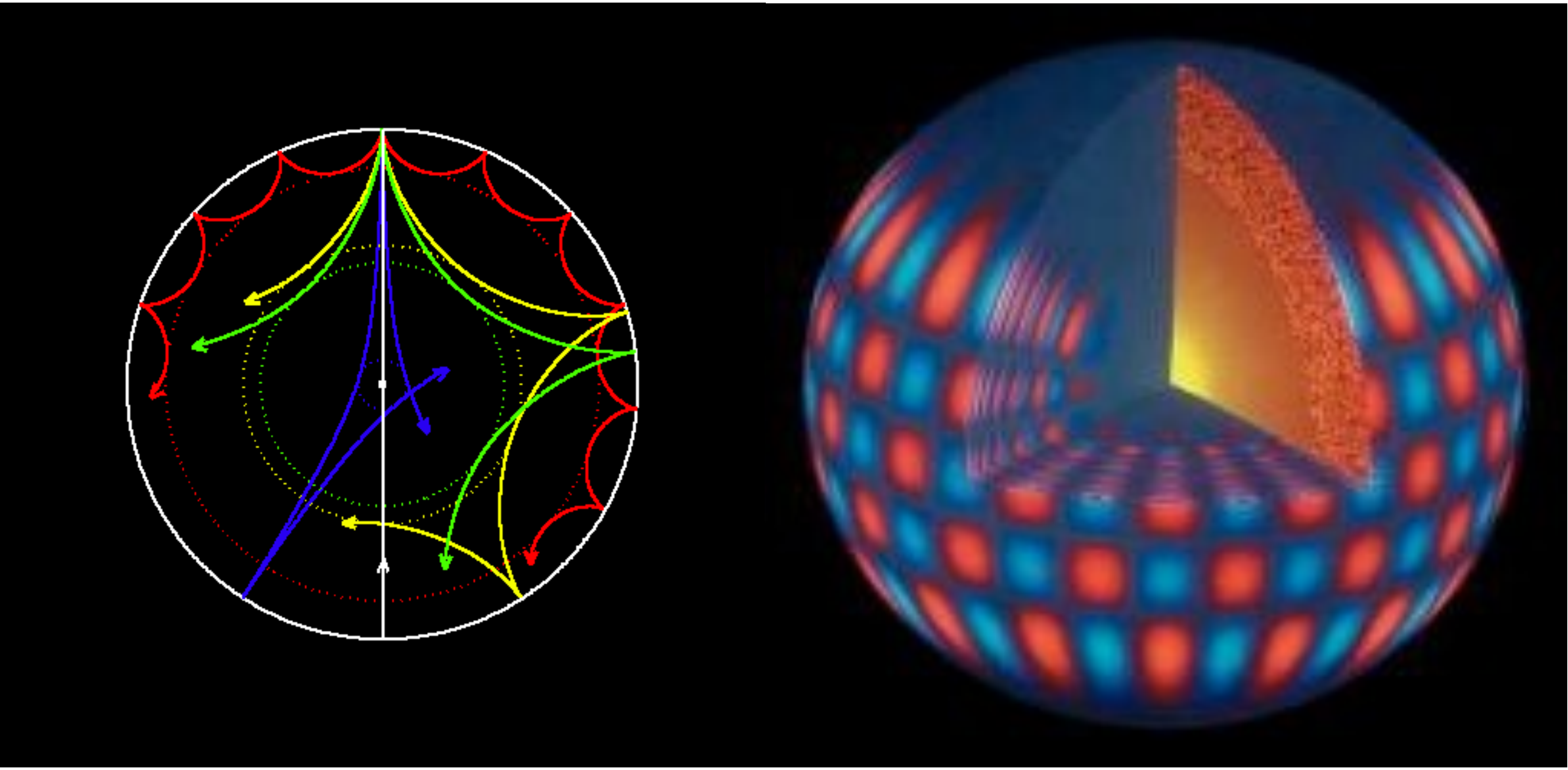


Neutrino Production
versus Radius
←8B
←7Be
←pp
←hep
dFlux/d(R/R☉)
(R/R☉)
0
5
10
15
20
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35

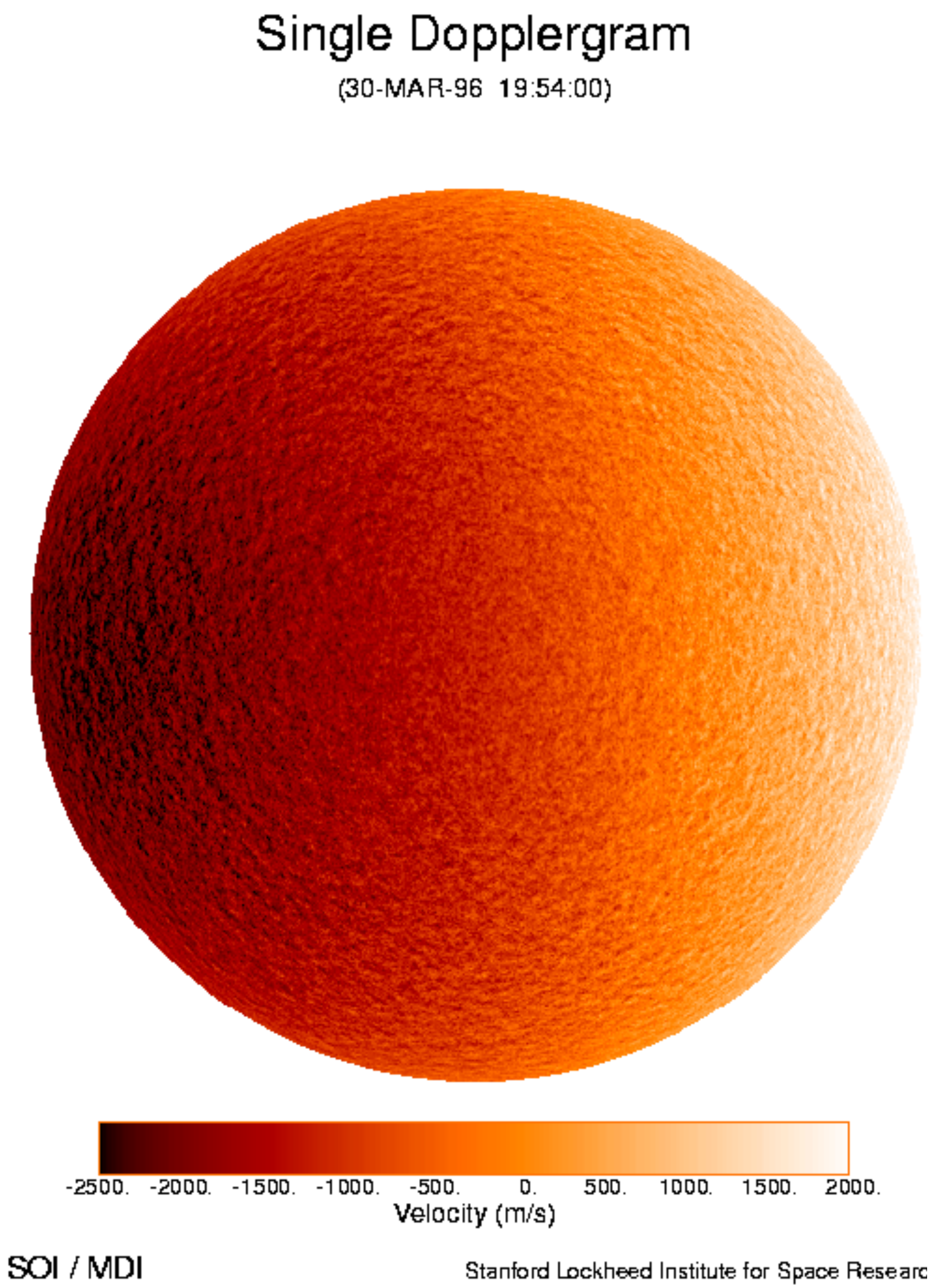


Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
⁷Be→
±10.5%
pep→±2%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
10¹² 10¹¹ 10¹⁰ 10⁹ 10⁸ 10⁷ 10⁶ 10⁵ 10⁴ 10³ 10² 10¹
0.1 1 10

Helioseismology（日震学）

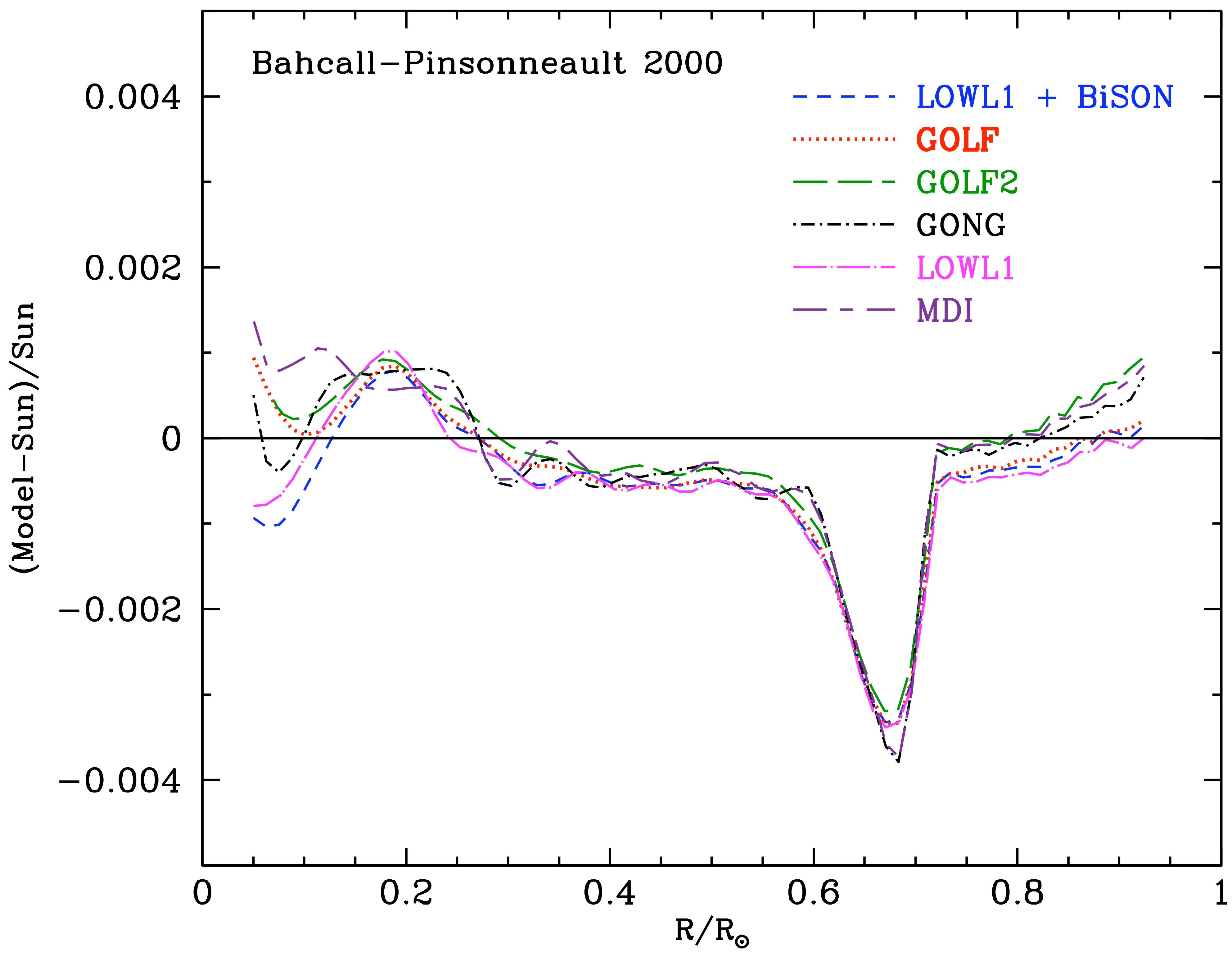


lower l modes penetrate deeper

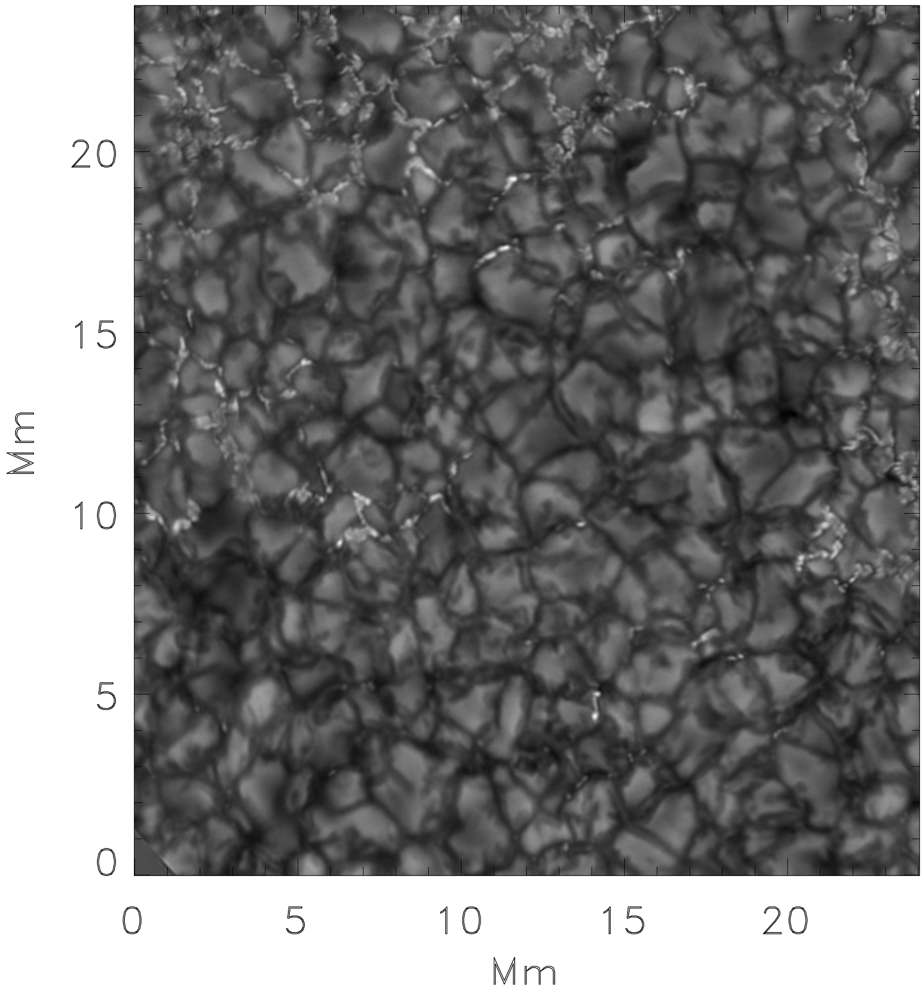


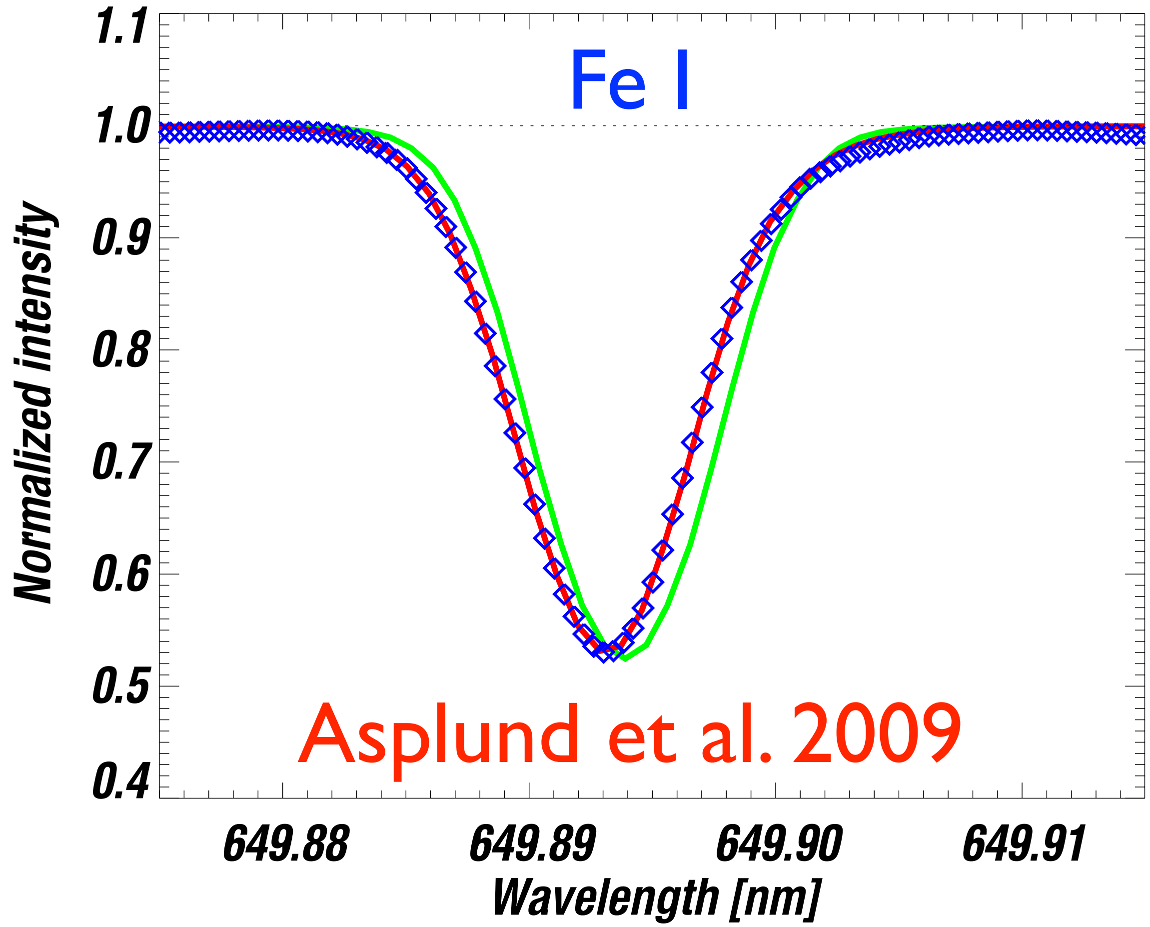
with rotation

rotation subtracted


Bahcall–Pinsonneault 2000
LOWL1 + BiSON
GOLF
GOLF2
GONG
LOWL1
MDI
(Model−Sun)/Sun
R/R⊙
0.004
0.002
0
−0.002
−0.004
0
0.2
0.4
0.6
0.8
1

3D time-dependent modeling of solar atmosphere

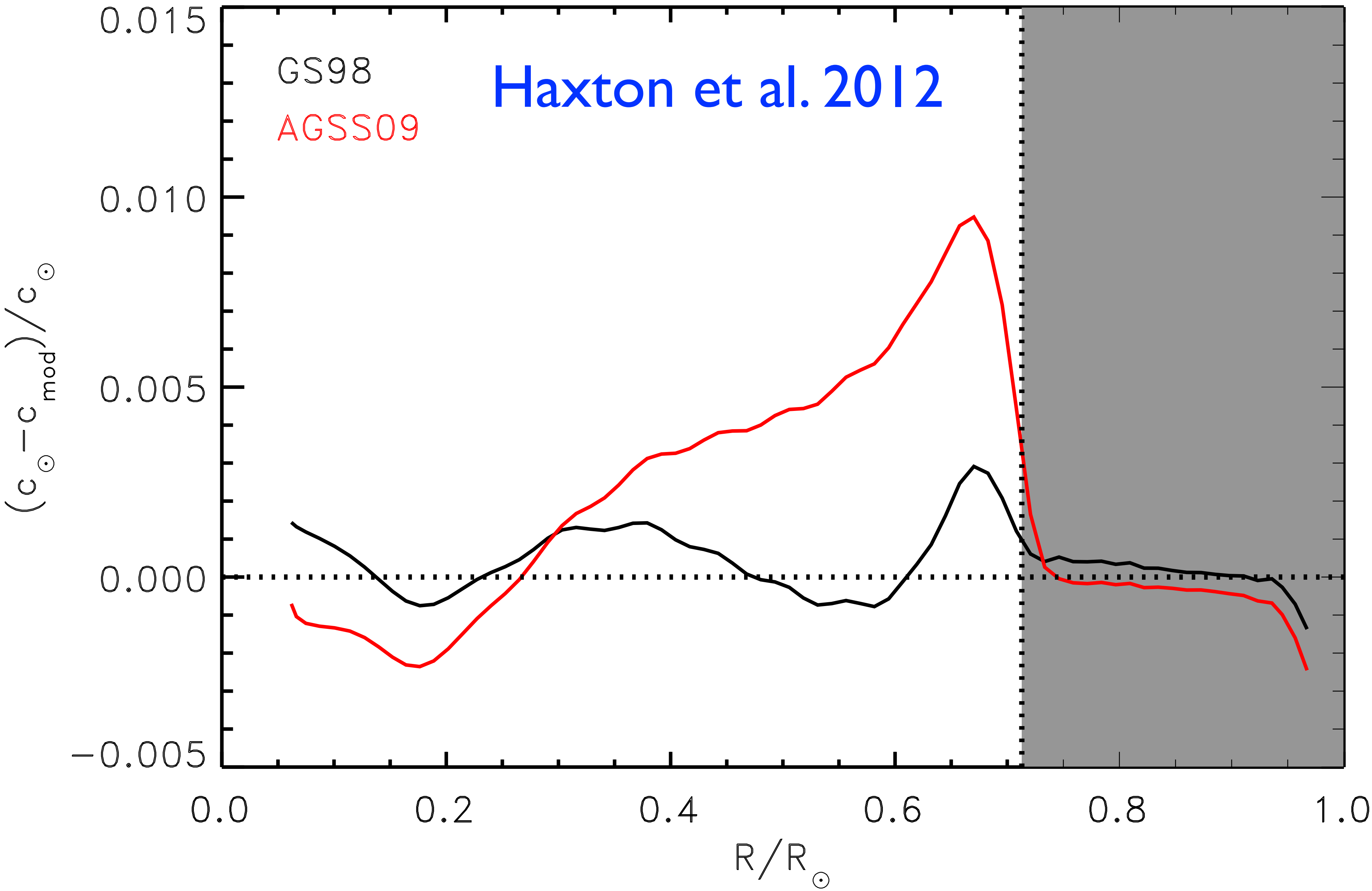




lower abundances of C, N, O, & Ne

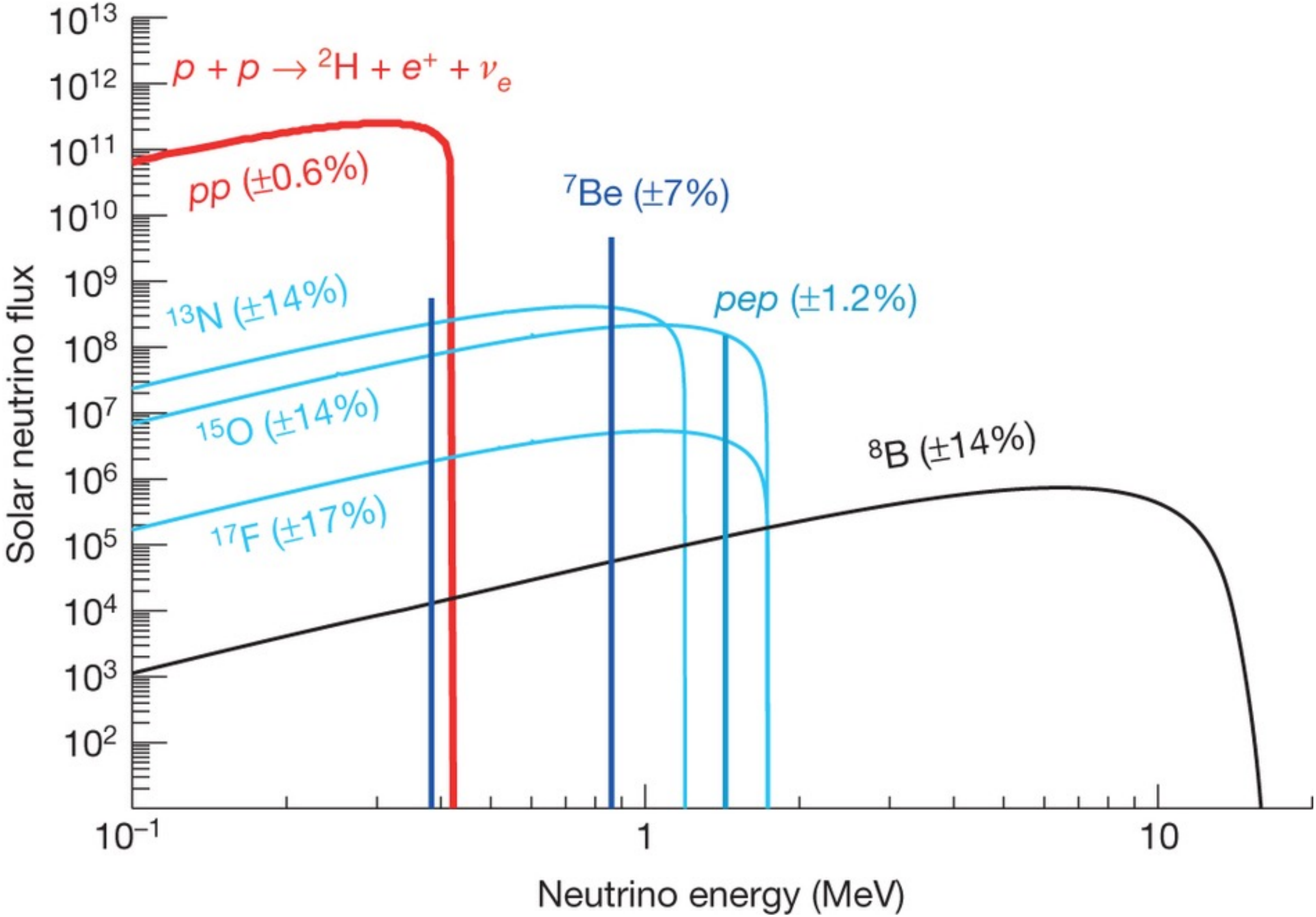
mass fraction of metals

2% → 1.4%

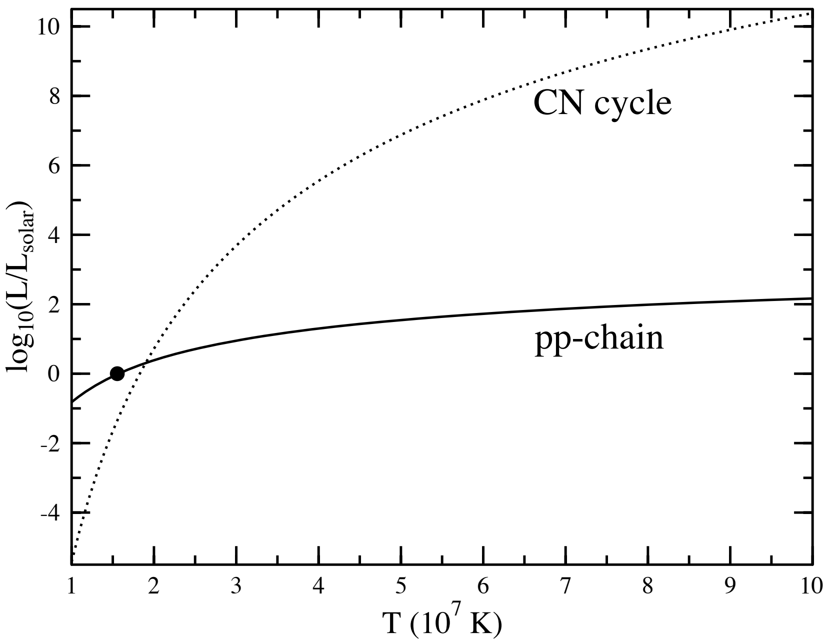


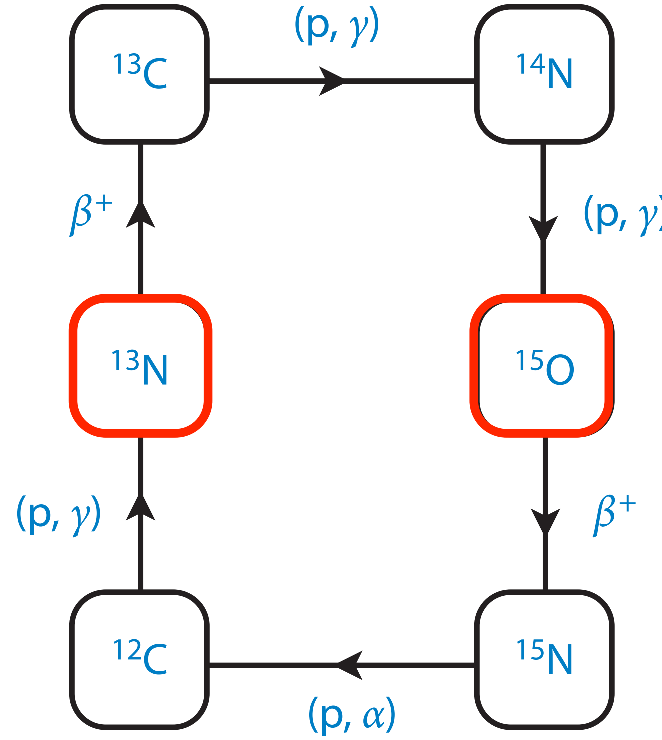
Haxton et al. 2012
GS98
AGSS09
0.015
0.010
0.005
0.000
−0.005
0.0
0.2
0.4
0.6
0.8
1.0
$(c_\odot - c_{mod})/c_\odot$
$R/R_\odot$

		high-Z SSM	low-Z SSM	luminosity constrained fit to data	
ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^++\nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^++\nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^6/cm^2s$
${}^3He+p \to {}^4He+e^++\nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^3/cm^2s$
${}^{13}N \to {}^{13}C+e^++\nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^8/cm^2s$
${}^{15}O \to {}^{15}N+e^++\nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^8/cm^2s$
${}^{17}F \to {}^{17}0+e^++\nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		



$p + p \rightarrow {}^2H + e^+ + \nu_e$
pp (±0.6%)
^{7}Be (±7%)
pep (±1.2%)
^{13}N (±14%)
^{15}O (±14%)
^{17}F (±17%)
^{8}B (±14%)
Solar neutrino flux
Neutrino energy (MeV)
10^{13}
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^{-1}
1
10





- these fluxes depend on the core temperature T (metal-dependent) but also have an additional linear dependence on the total core C+N

- absolute fluxes are uncertain, sensitive to small changes in many solar model uncertainties other than total metallicity

- but an appropriate ratio of the CN and ^{8}B ν flux is independent of these other uncertainties: the measured ^{8}B ν flux can be exploited as a solar thermometer

Nuclear Astrophysics of Solar CN Neutrinos

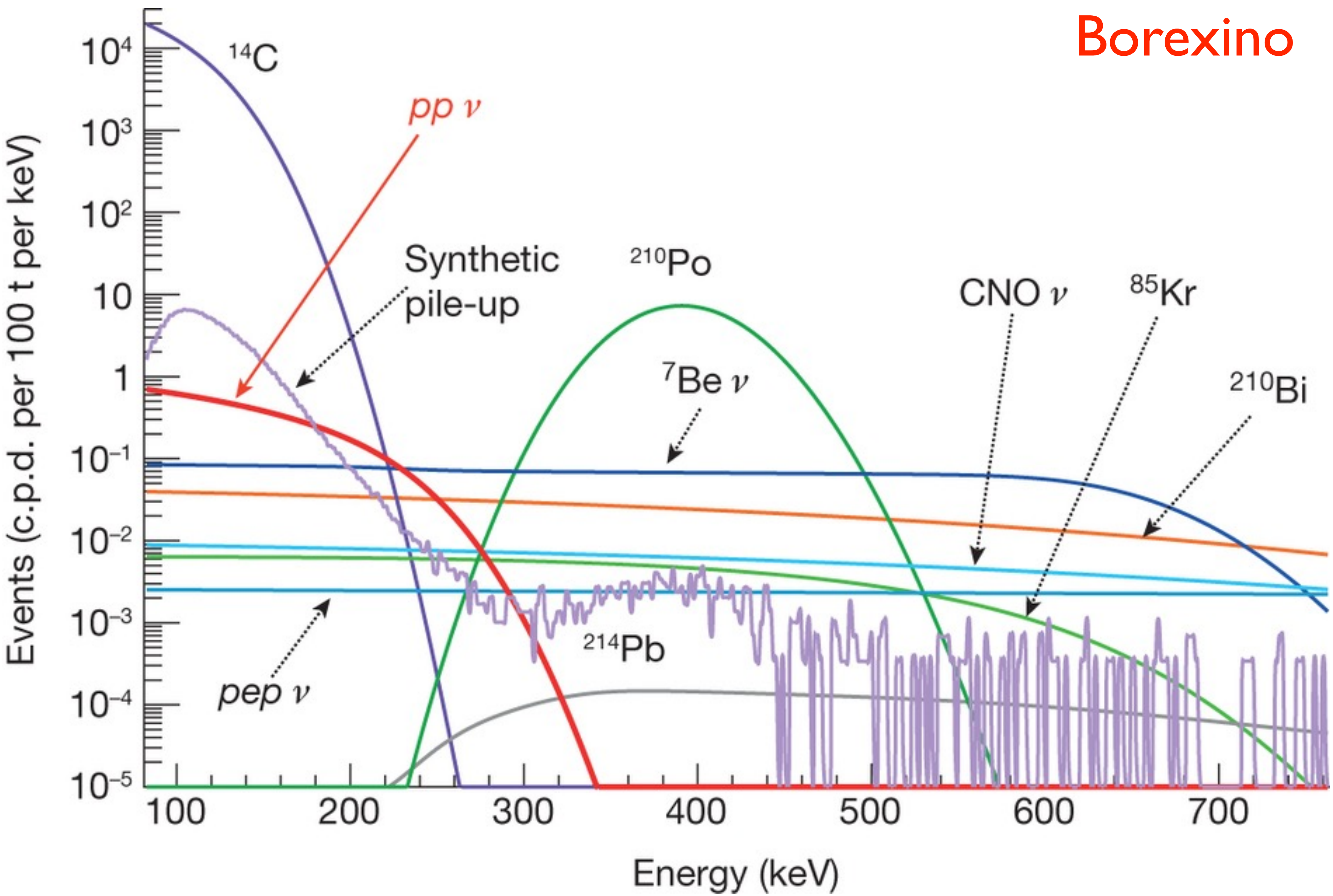
$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

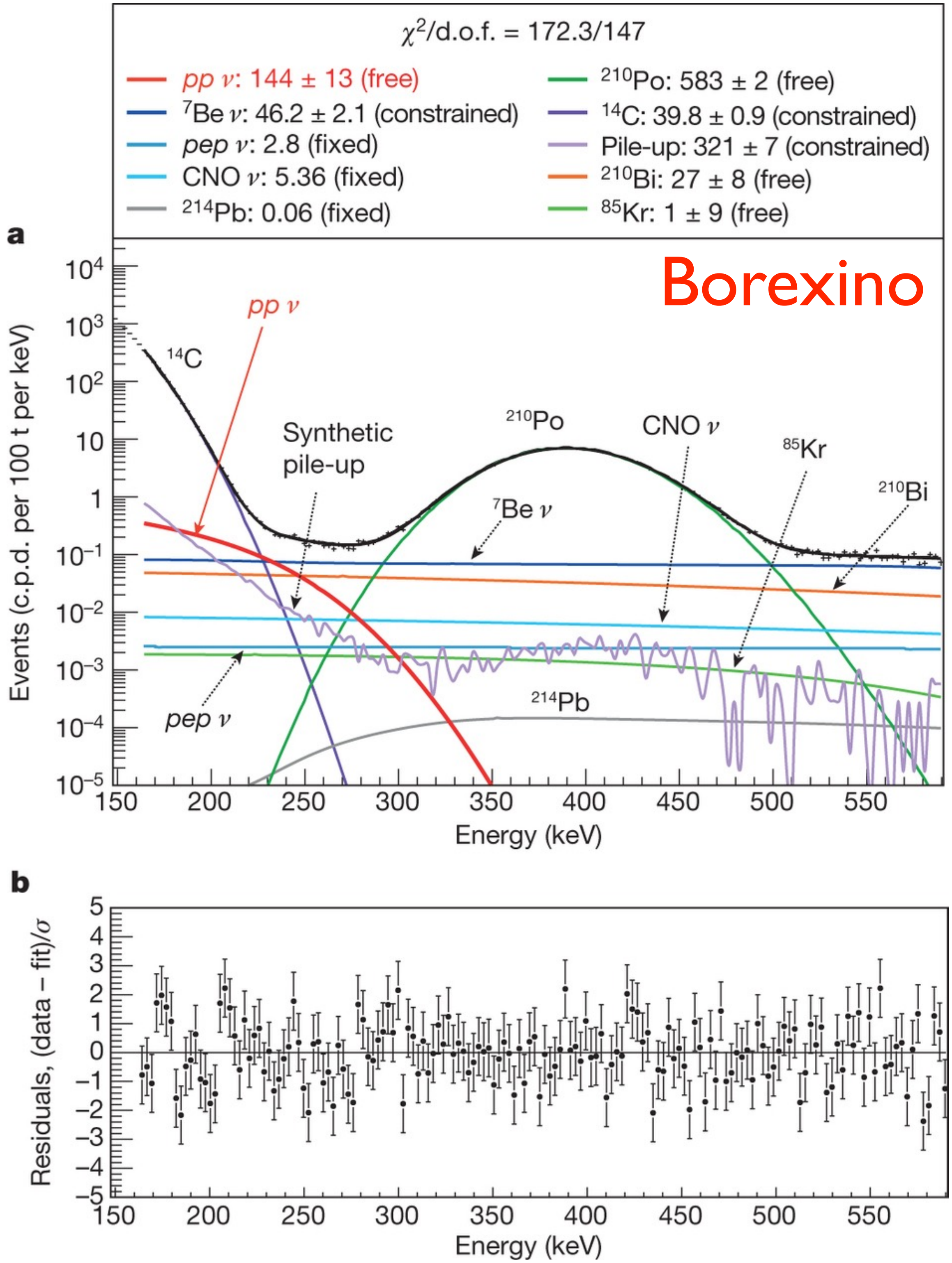
$$\times\ [1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

the entire solar model dependence: luminosity, metalicity, solar age, etc., eliminated -- except for small residual differential effects of heavy element diffusion (necessary to relate today's neutrino measurements to core abundance 4.7 b.y. ago)

$^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ ~7% theoretical uncertainty

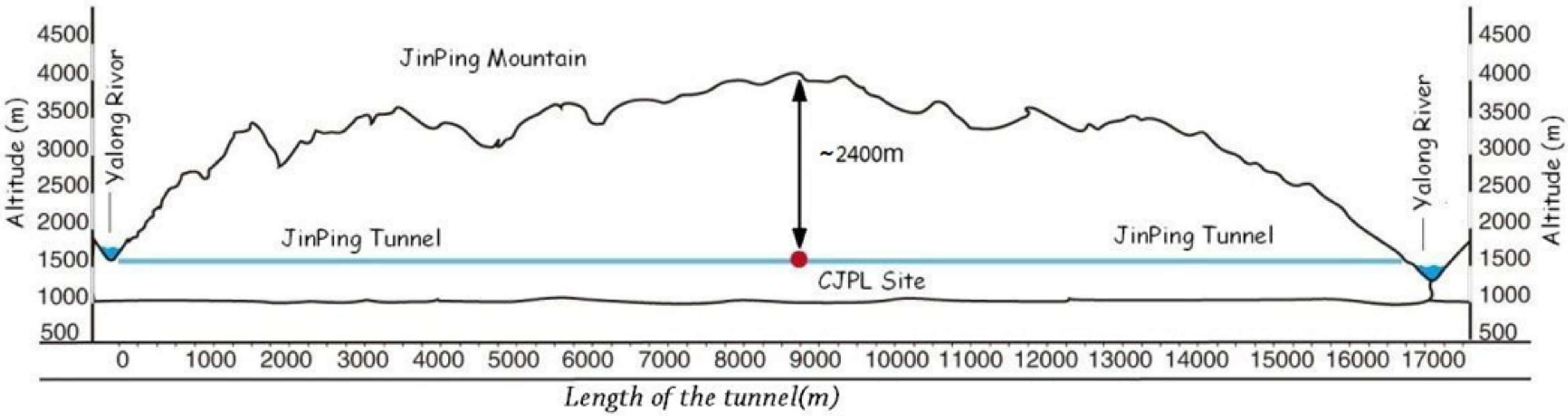
$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ ~7% experimental uncertainty


Borexino
^{14}C
pp ν
Synthetic pile-up
^{210}Po
CNO ν
^{85}Kr
^{7}Be ν
^{210}Bi
^{214}Pb
pep ν
Events (c.p.d. per 100 t per keV)
Energy (keV)
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
600
700



χ²/d.o.f. = 172.3/147
pp ν: 144 ± 13 (free)
⁷Be ν: 46.2 ± 2.1 (constrained)
pep ν: 2.8 (fixed)
CNO ν: 5.36 (fixed)
²¹⁴Pb: 0.06 (fixed)
²¹⁰Po: 583 ± 2 (free)
¹⁴C: 39.8 ± 0.9 (constrained)
Pile-up: 321 ± 7 (constrained)
²¹⁰Bi: 27 ± 8 (free)
⁸⁵Kr: 1 ± 9 (free)
a
Borexino
pp ν
¹⁴C
Synthetic pile-up
²¹⁰Po
CNO ν
⁸⁵Kr
²¹⁰Bi
⁷Be ν
pep ν
²¹⁴Pb
Events (c.p.d. per 100 t per keV)
Energy (keV)
b
Residuals, (data – fit)/σ
Energy (keV)

CJPL



JUNA → $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$

Solar Neutrino Experiment → CN $\nu_\odot$

solar neutrinos are also the ultimate background for detecting dark matter !

summary

1960s

test the solar model: precise determination of core temperature

→

1990s

new neutrino physics: precise weak interaction parameters

→

2020

CN νs, primordial metallicity, solar system formation

Now that we have eliminated the weak interaction uncertainties that held us back for many years, we can finally use solar neutrinos as a precise probe of solar physics

唯有实验才可以裁决

Only Experiments Can Judge

真正的实证方法是这样的：先点亮蜡烛，让烛光指引方向；
从适当整理编类过的而不是杂乱无章的经历出发，抽取原理，
再在已经验证过的原理的基础上进行新的实验

...... the true method of experience first lights the candle, and then by means of the candle shows the way; commencing as it does with experience duly ordered and digested, not bungling or erratic, and from it educing axioms, and from established axioms again new experiments ......

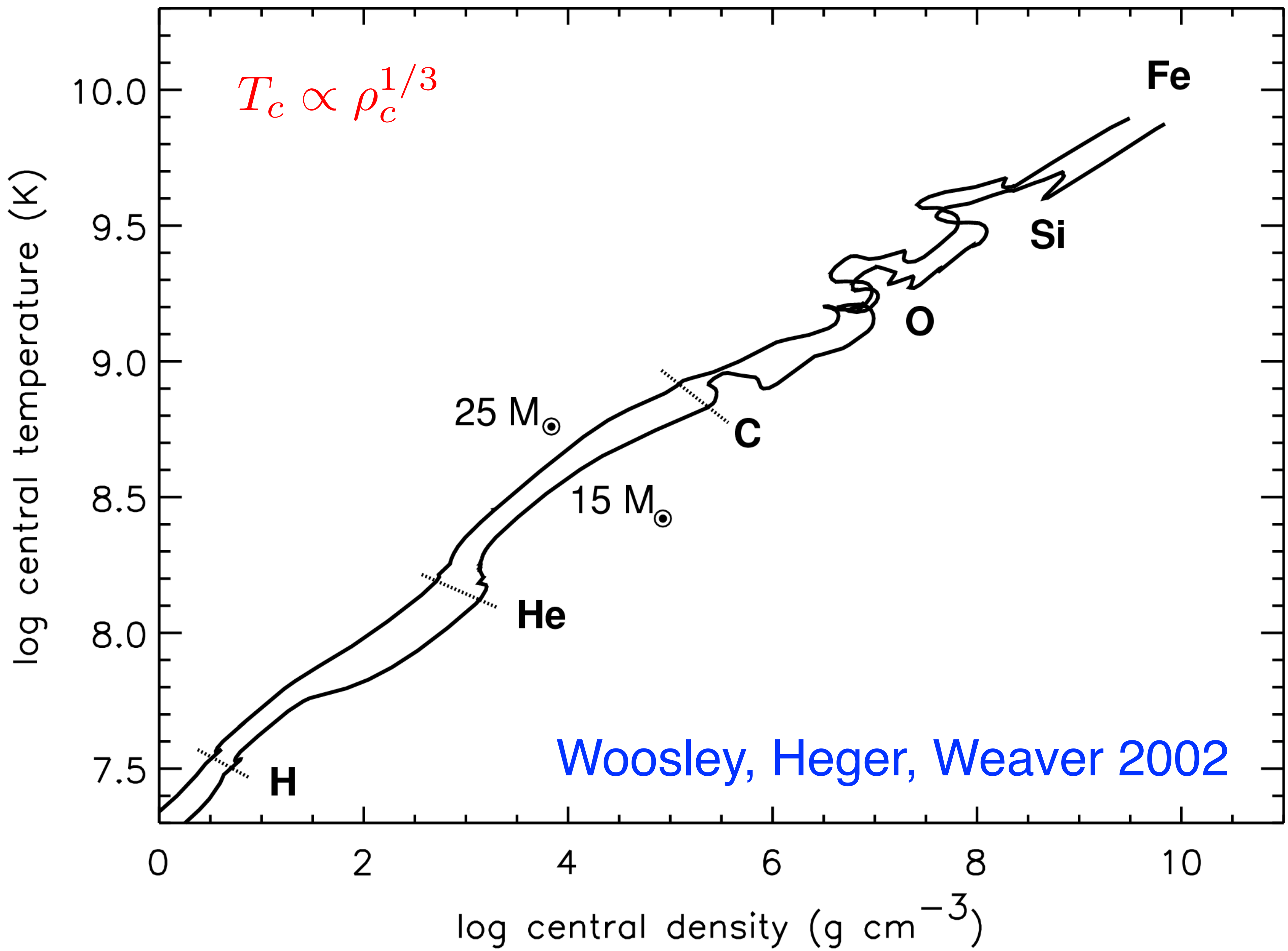
Novum Organum **(1620)**

Francis Bacon

Pre-Supernova & Supernova Neutrinos

Yong-Zhong Qian
School of Physics & Astronomy, University of Minnesota
Center for Nuclear Astrophysics, Shanghai Jiao Tong University

CCEPP Summer School 2017 on Neutrino Physics
July 8, 2017



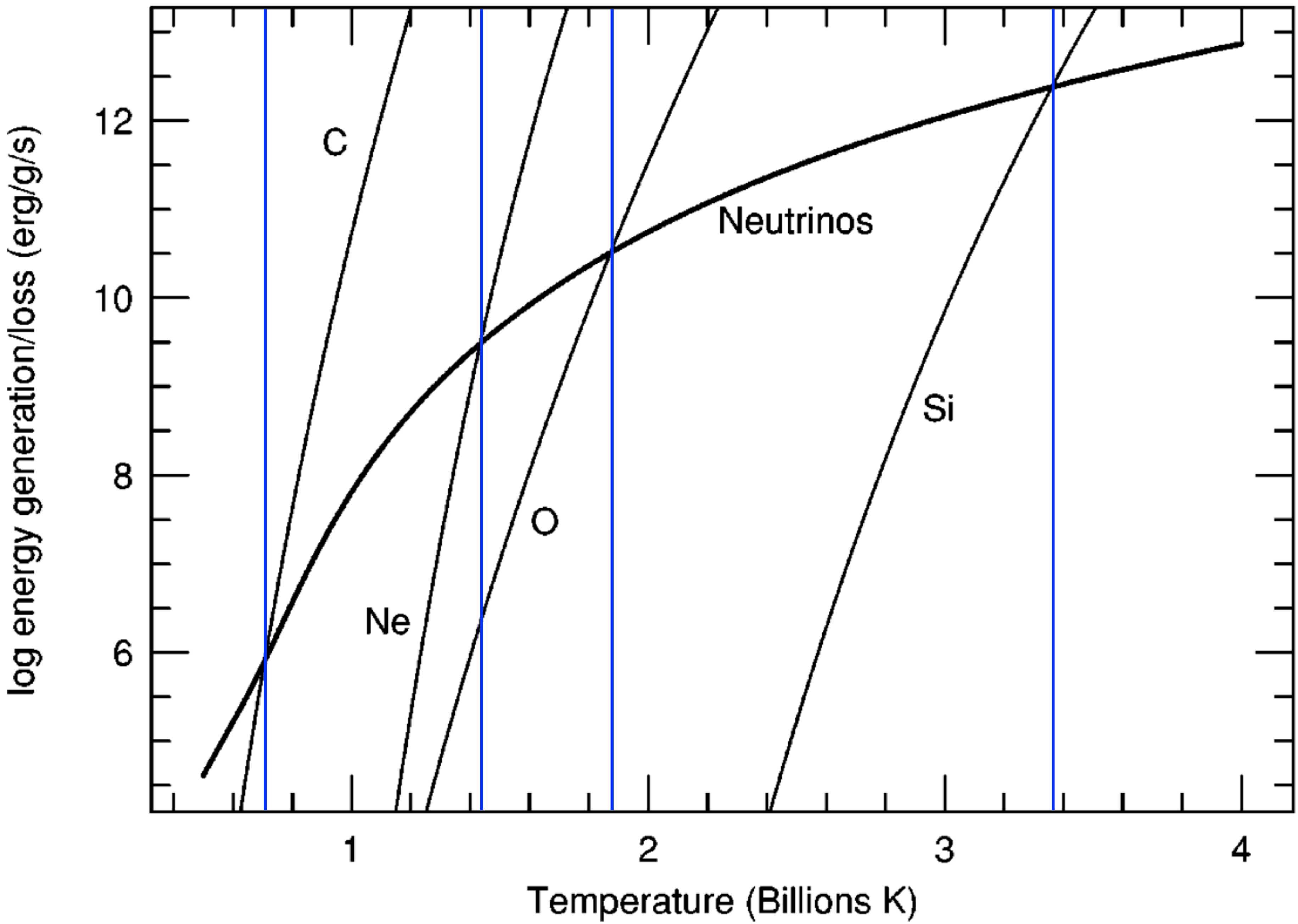
$T_c \propto \rho_c^{1/3}$
Fe
Si
O
C
He
H
25 M$_\odot$
15 M$_\odot$
Woosley, Heger, Weaver 2002
log central temperature (K)
log central density (g cm^{-3})
10.0
9.5
9.0
8.5
8.0
7.5
0
2
4
6
8
10

Nuclear burning stages

(20 $M_{\odot}$ stars)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\ H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\ He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

Energy Generation vs. Loss



Processes of Thermal Neutrino Emission

Pair annihilation

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

Plasmon decay

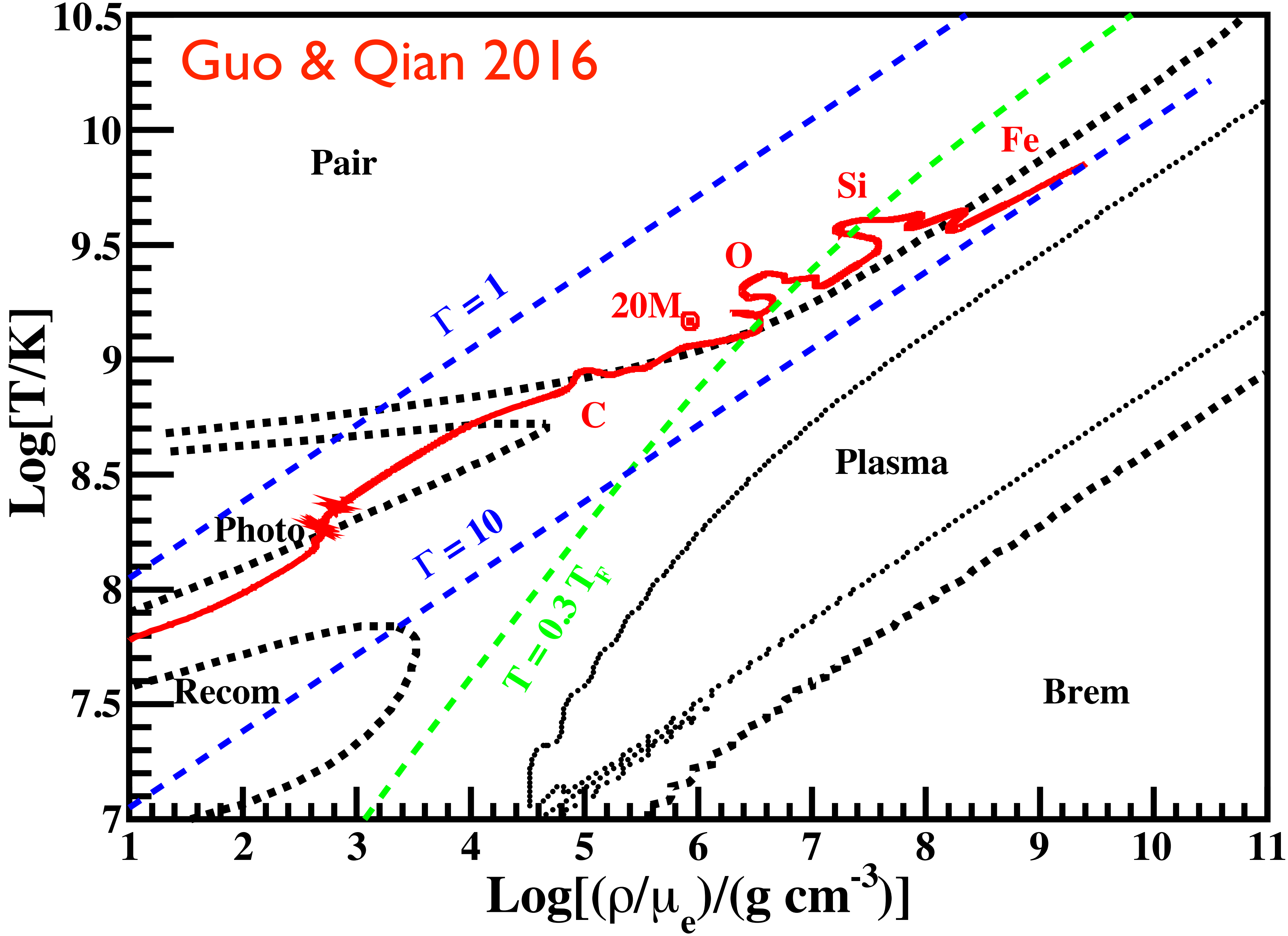
$$\gamma_{\mathrm{pl}} \rightarrow \nu + \bar{\nu}$$

Photo-neutrino emission

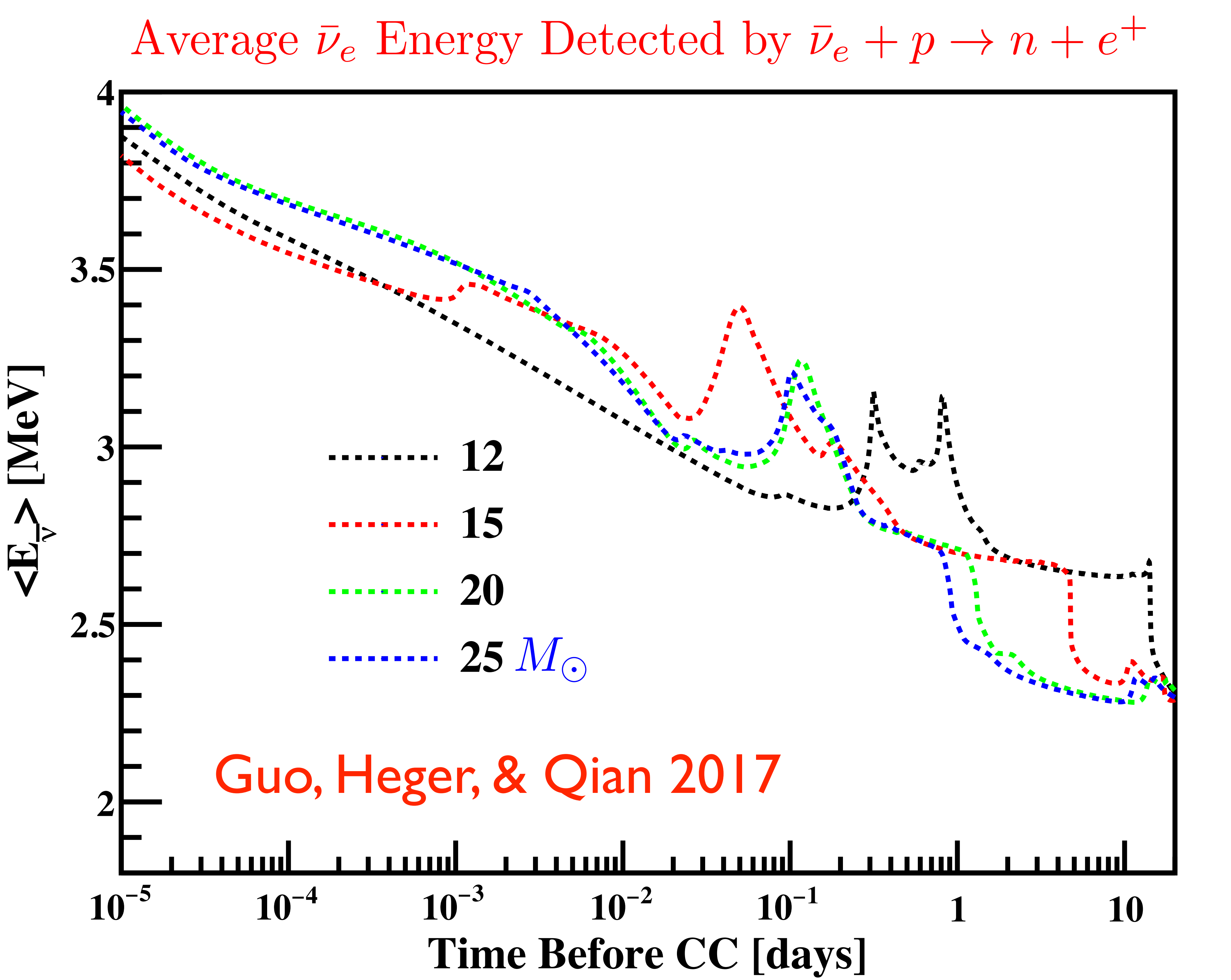
$$\gamma + e^- \rightarrow e^- + \nu + \bar{\nu}$$

Bremsstrahlung

$$(Z, A) + e^- \rightarrow (Z, A) + e^- + \nu + \bar{\nu}$$

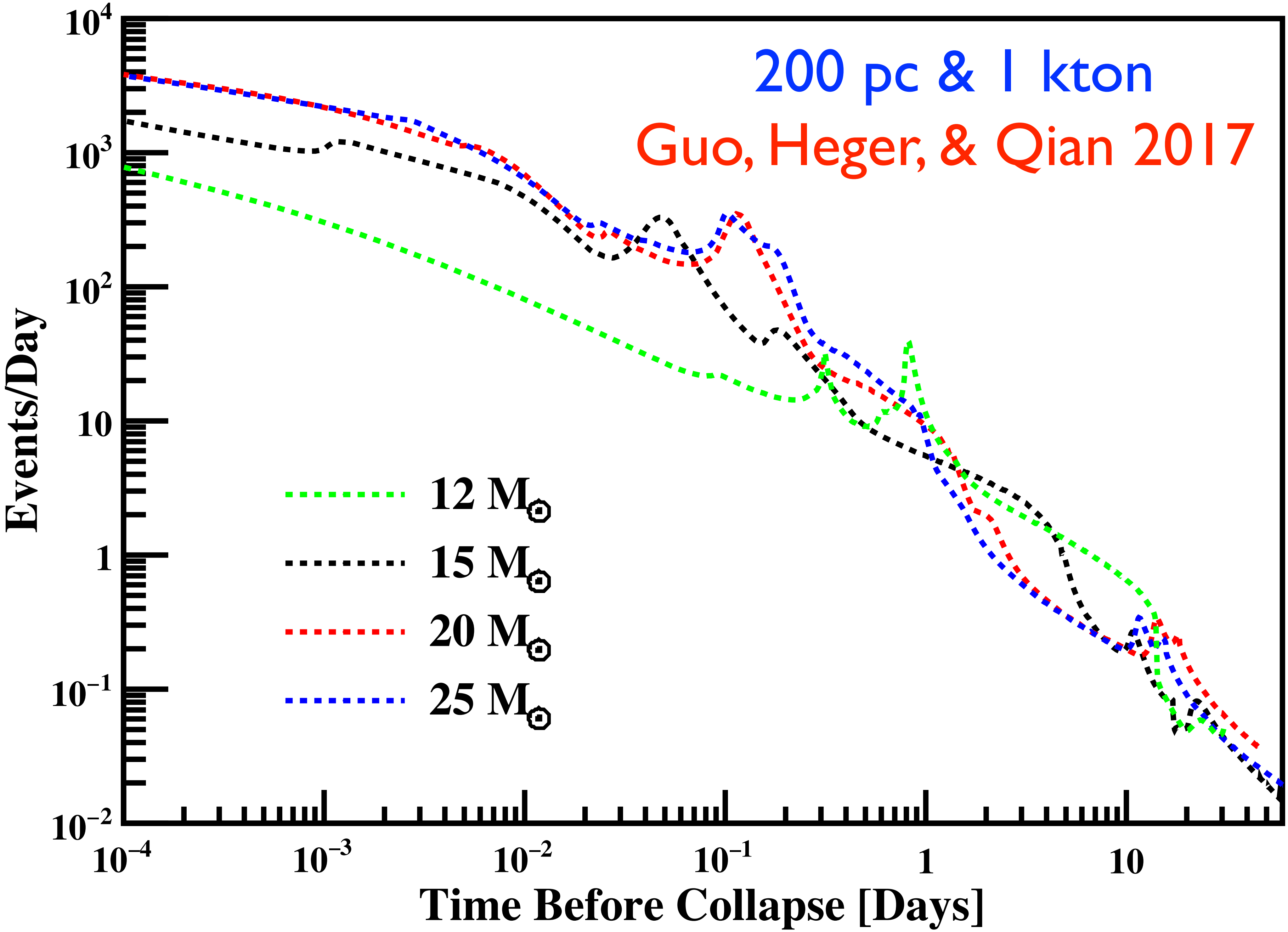


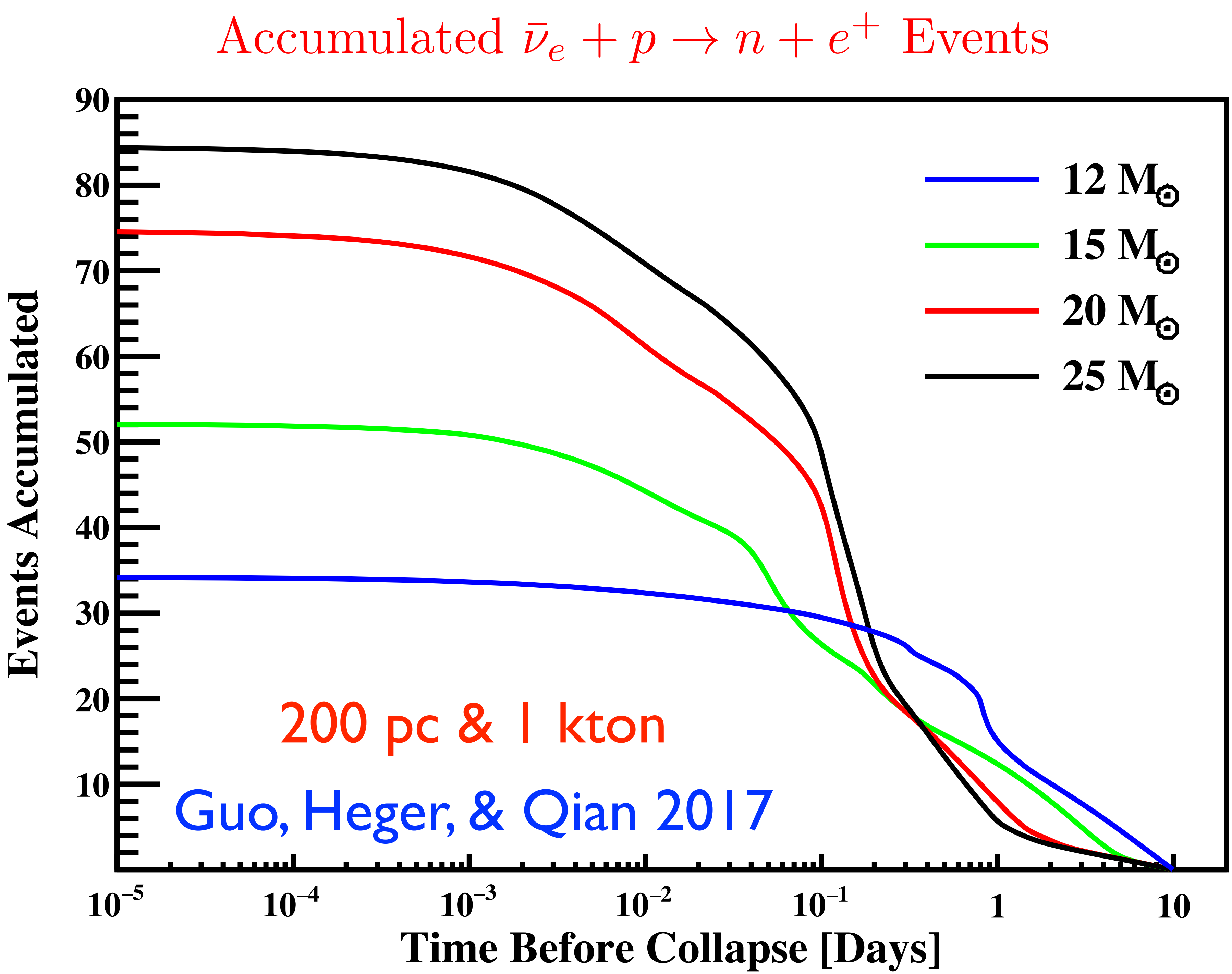
Guo & Qian 2016
Pair
Photo
Recom
Plasma
Brem
Γ = 1
Γ = 10
T = 0.3 T_F
20M_⊙
C
O
Si
Fe
Log[T/K]
Log[(ρ/μ_e)/(g cm^-3)]
10.5
10
9.5
9
8.5
8
7.5
7
1
2
3
4
5
6
7
8
9
10
11



Average $\bar{\nu}_e$ Energy Detected by $\bar{\nu}_e + p \to n + e^+$
4
3.5
3
2.5
2
$<E_{\bar{\nu}}>$ [MeV]
12
15
20
25 $M_\odot$
Guo, Heger, & Qian 2017
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
Time Before CC [days]

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



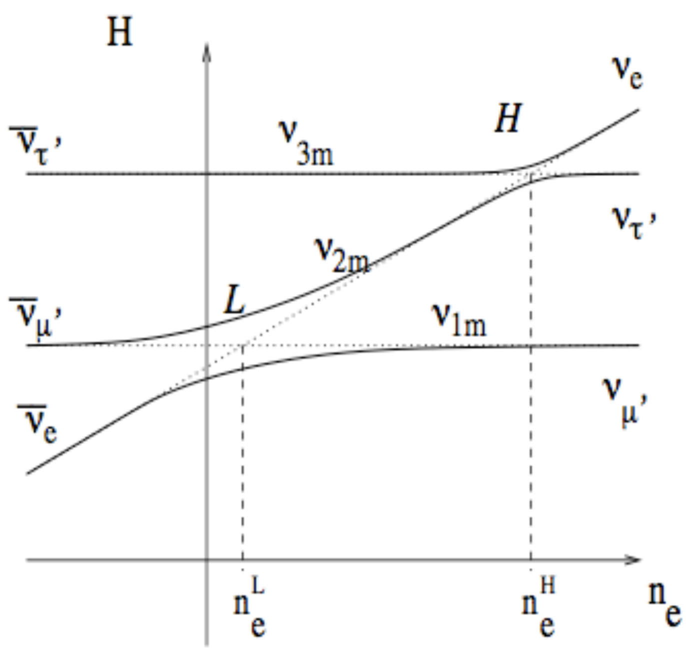


Accumulated $\bar{\nu}_e + p \rightarrow n + e^+$ Events
Events Accumulated
Time Before Collapse [Days]
12 $M_\odot$
15 $M_\odot$
20 $M_\odot$
25 $M_\odot$
200 pc & 1 kton
Guo, Heger, & Qian 2017
90
80
70
60
50
40
30
20
10
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

Neutrino Mixing in Vacuum

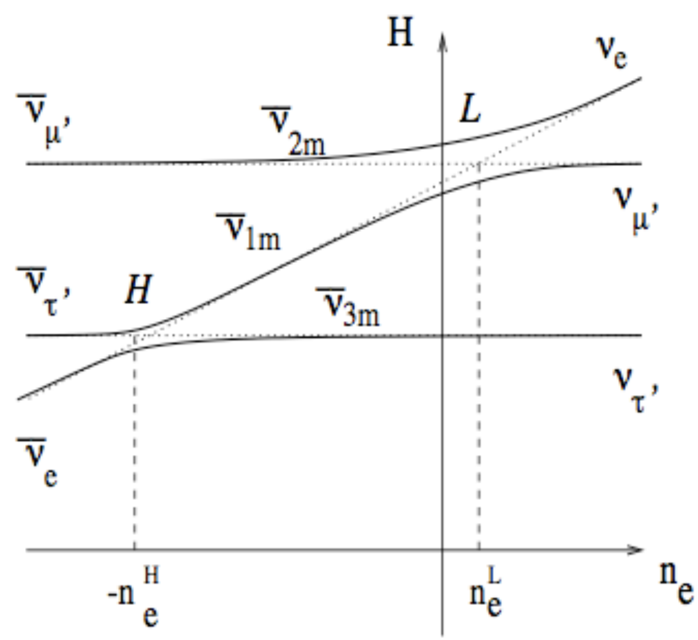
$$U_{\alpha i} = \langle \nu_\alpha | \nu_i \rangle, \ \bar{U}_{\alpha i} = \langle \bar{\nu}_\alpha | \bar{\nu}_i \rangle$$

Neutrino Flavor Evolution in Matter (MSW only)



normal mass hierarchy

$N_{\bar{\nu}_e}/N^0_{\bar{\nu}_e} \approx 0.76$



inverted mass hierarchy

$N_{\bar{\nu}_e}/N^0_{\bar{\nu}_e} \approx 0.21$

What Can Pre-Supernova Neutrinos Tell Us ?

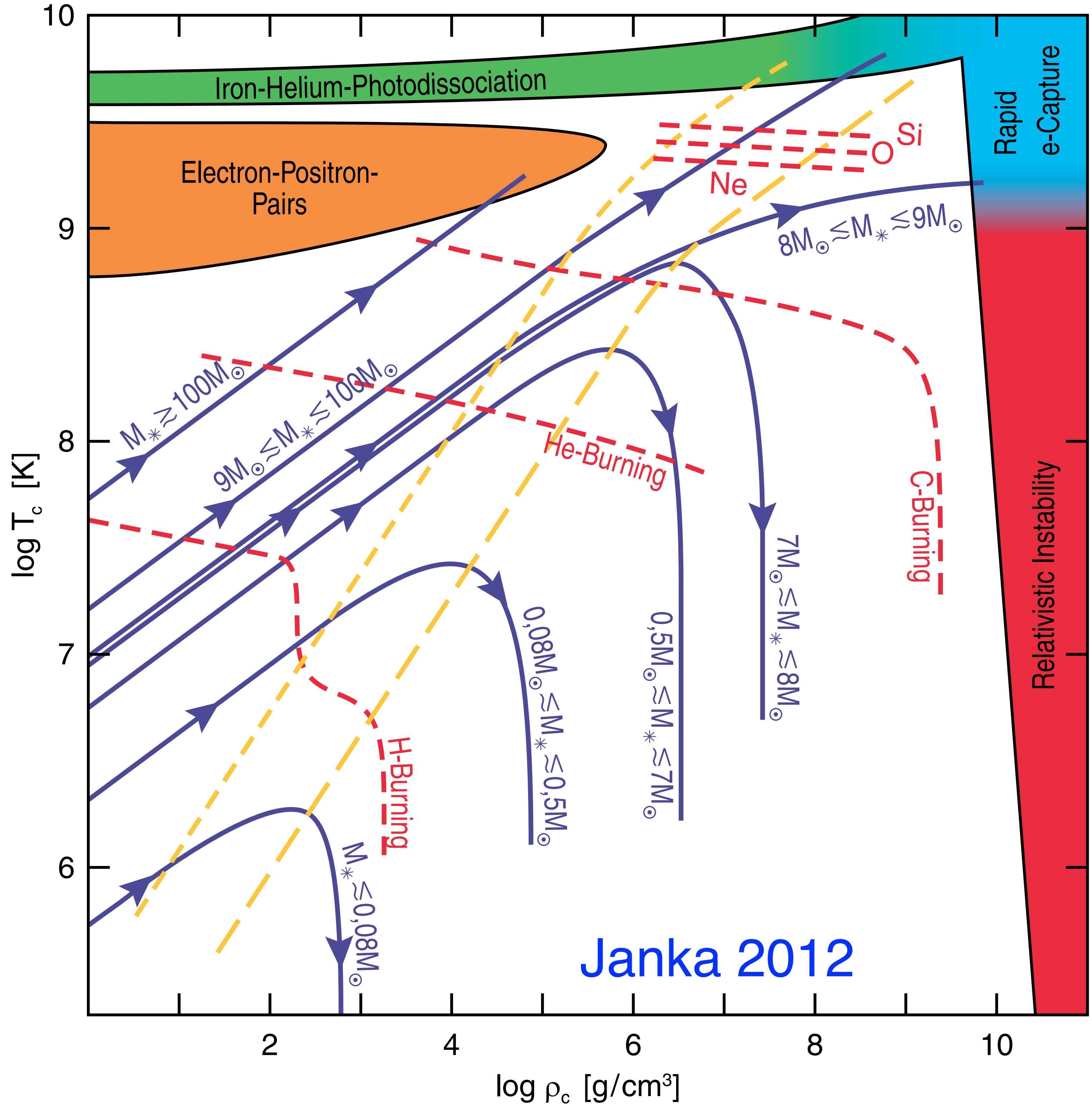
Advance warning of supernovae

Events for 200 pc & 1 kton

Model	$10^{-3} - 10^{-2}$	$10^{-2} - 10^{-1}$	$10^{-1} - 1$	$1 - 10$ Day
$12 M_\odot$	1.28	2.90	14.39	15.09
$15 M_\odot$	6.55	17.89	14.00	12.36
$20 M_\odot$	10.44	18.75	34.52	7.95
$25 M_\odot$	10.79	22.04	43.04	5.70

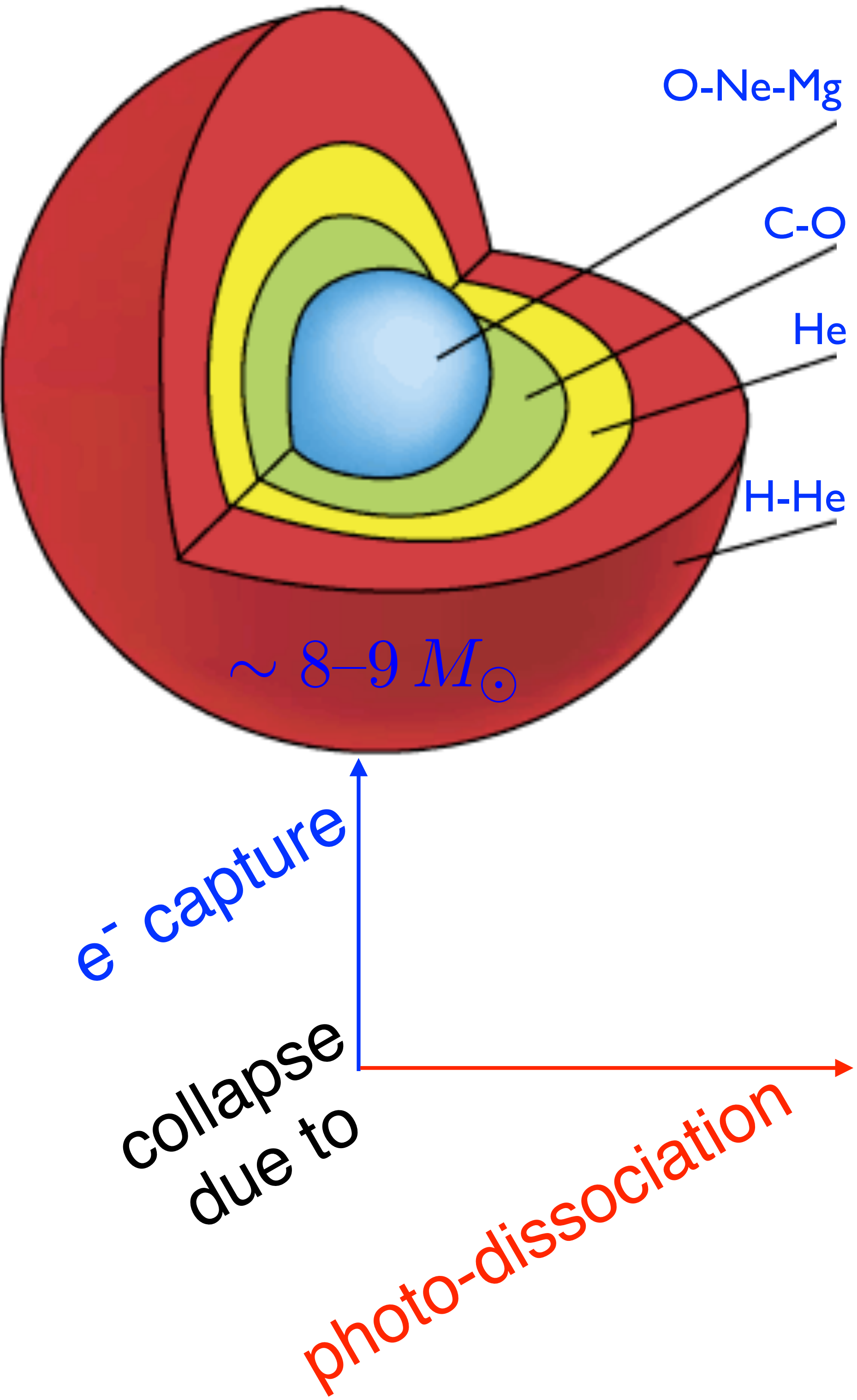
Probe of neutrino mass ordering: NH/IH ~ 3.6

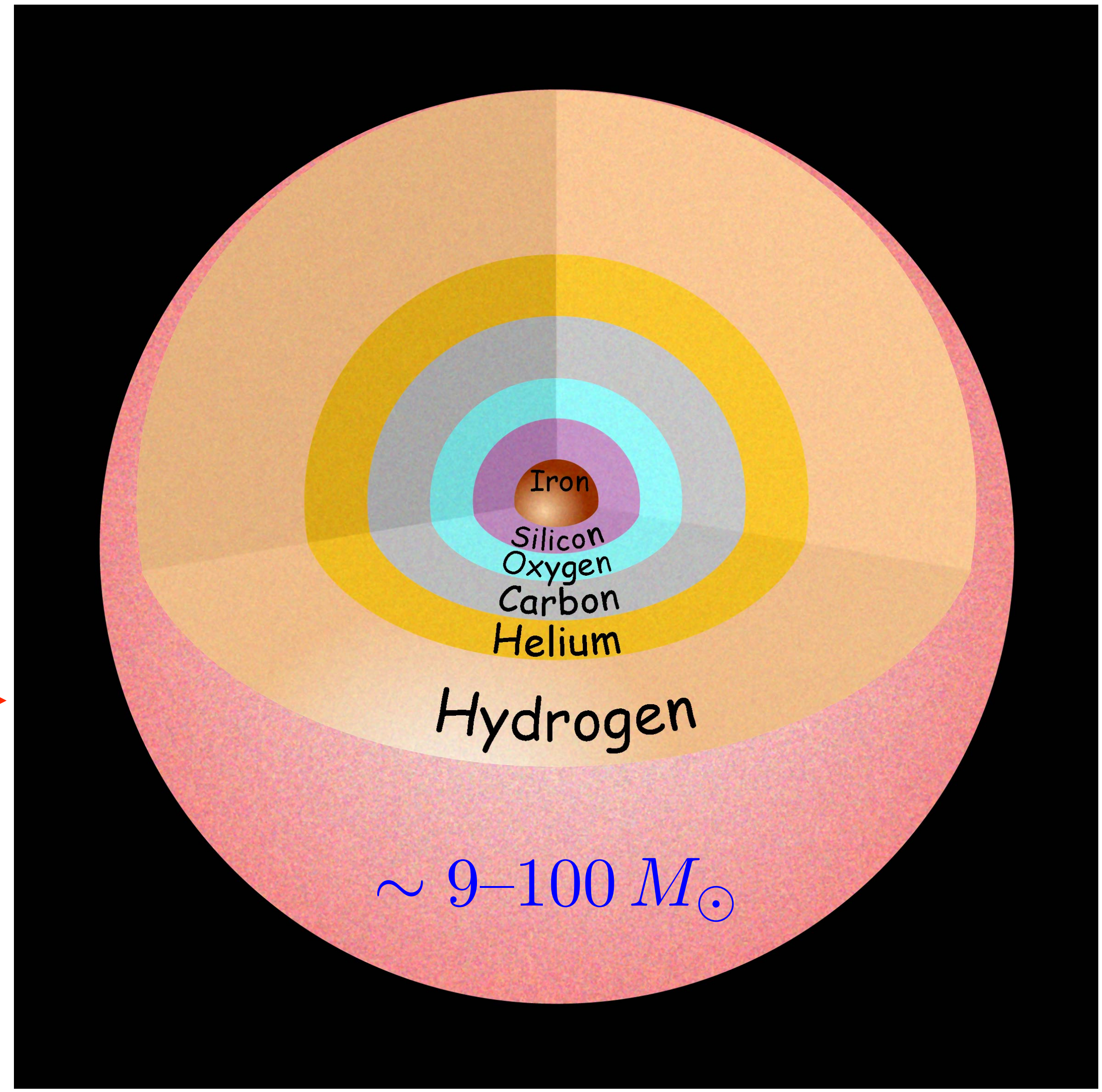
Test of stellar models: progenitor mass



Iron-Helium-Photodissociation
Electron-Positron-
Pairs
Rapid
e-Capture
Relativistic Instability
Si
O
Ne
He-Burning
C-Burning
H-Burning
M⁎≳100M⊙
9M⊙≲M⁎≲100M⊙
8M⊙≲M⁎≲9M⊙
7M⊙≤M⁎≤8M⊙
0,5M⊙≤M⁎≤7M⊙
0,08M⊙≤M⁎≤0,5M⊙
M⁎≤0,08M⊙
Janka 2012
log T_c [K]
log ρ_c [g/cm³]
10
9
8
7
6
2
4
6
8
10

“Onion-Skin” Structure of Pre-SN Stars





Light Curve of SN 1987a

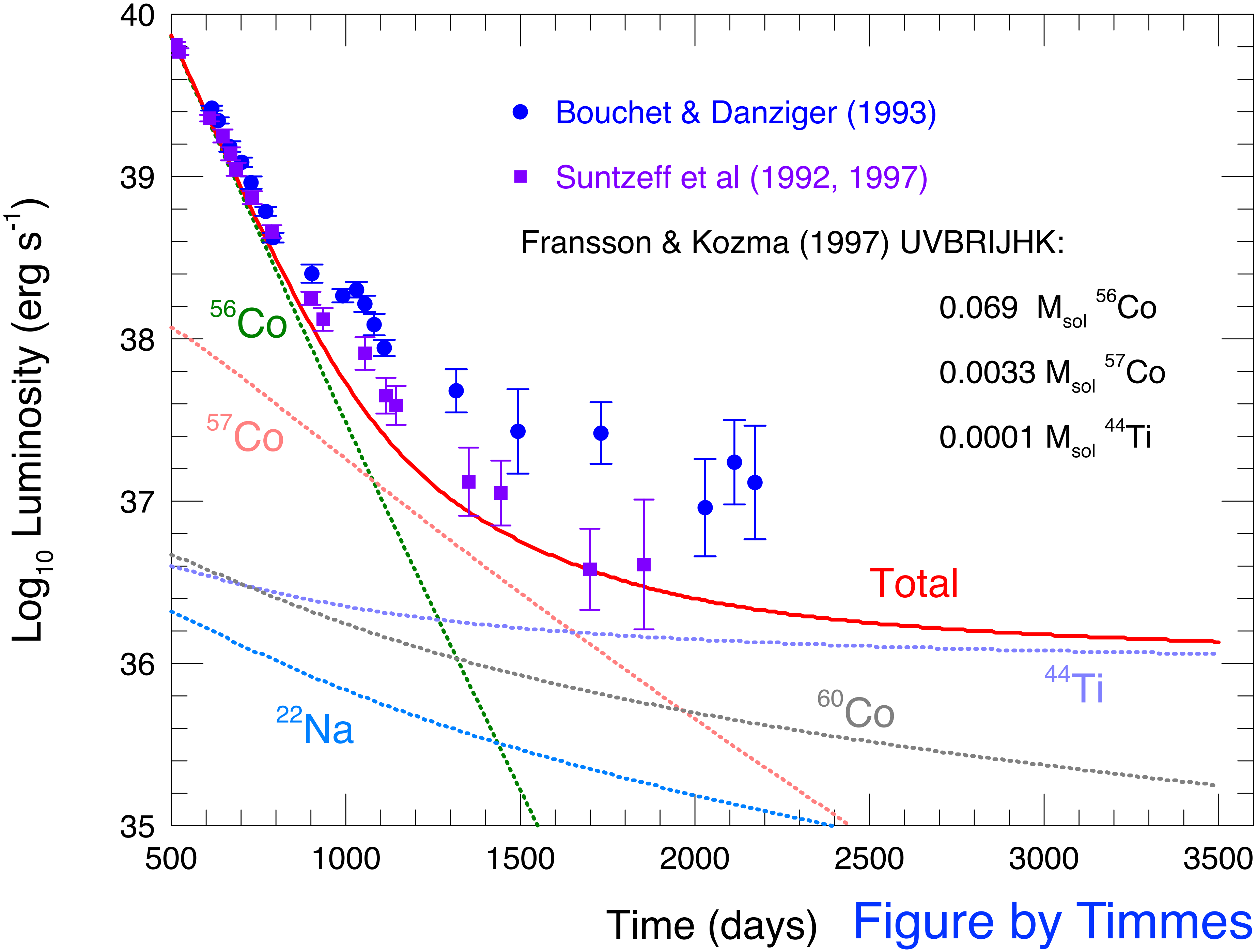
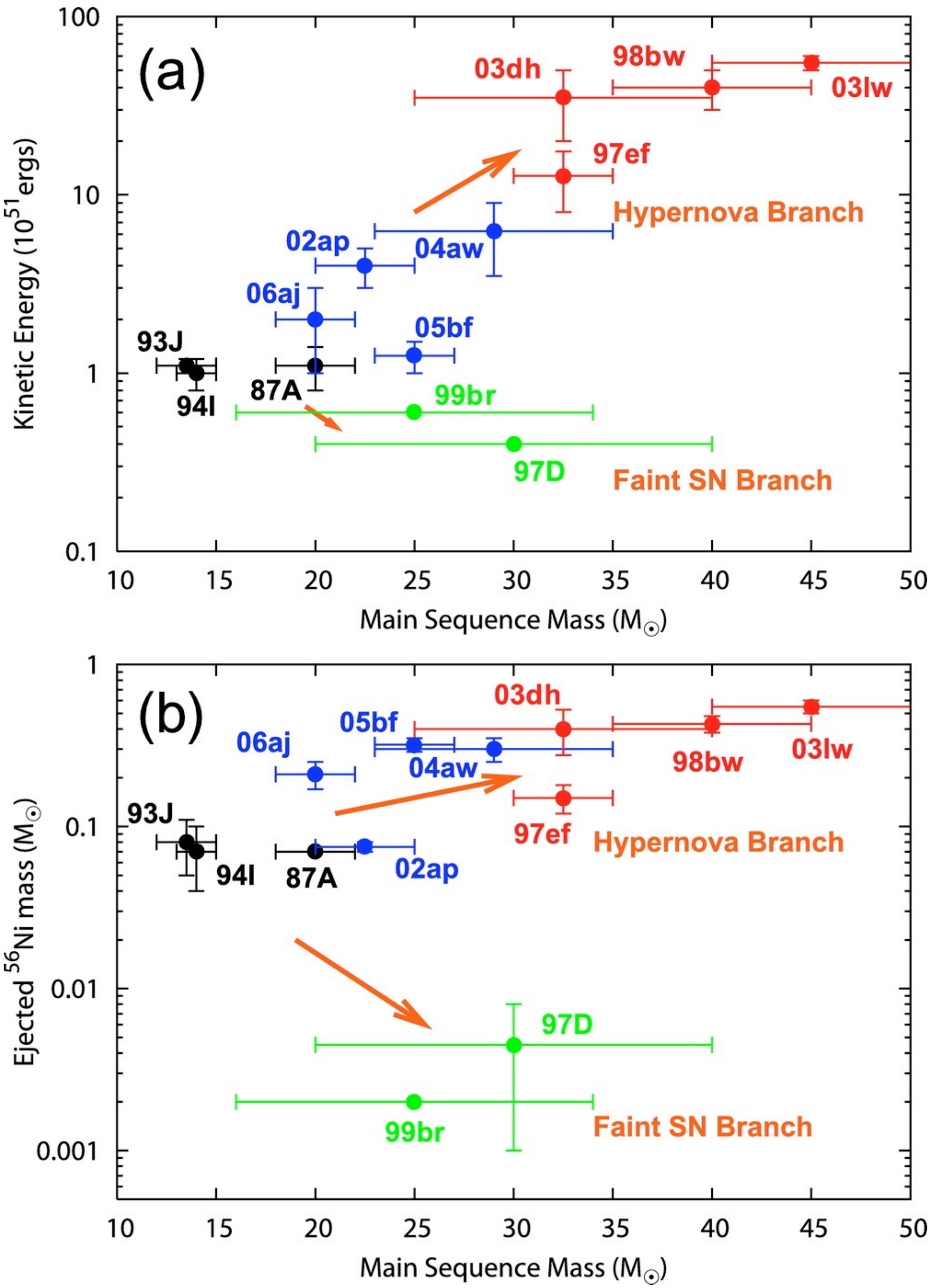


Figure by Timmes



Tominaga et al. (2007)

normal SNe

$M \sim 12\text{–}25\, M_\odot$

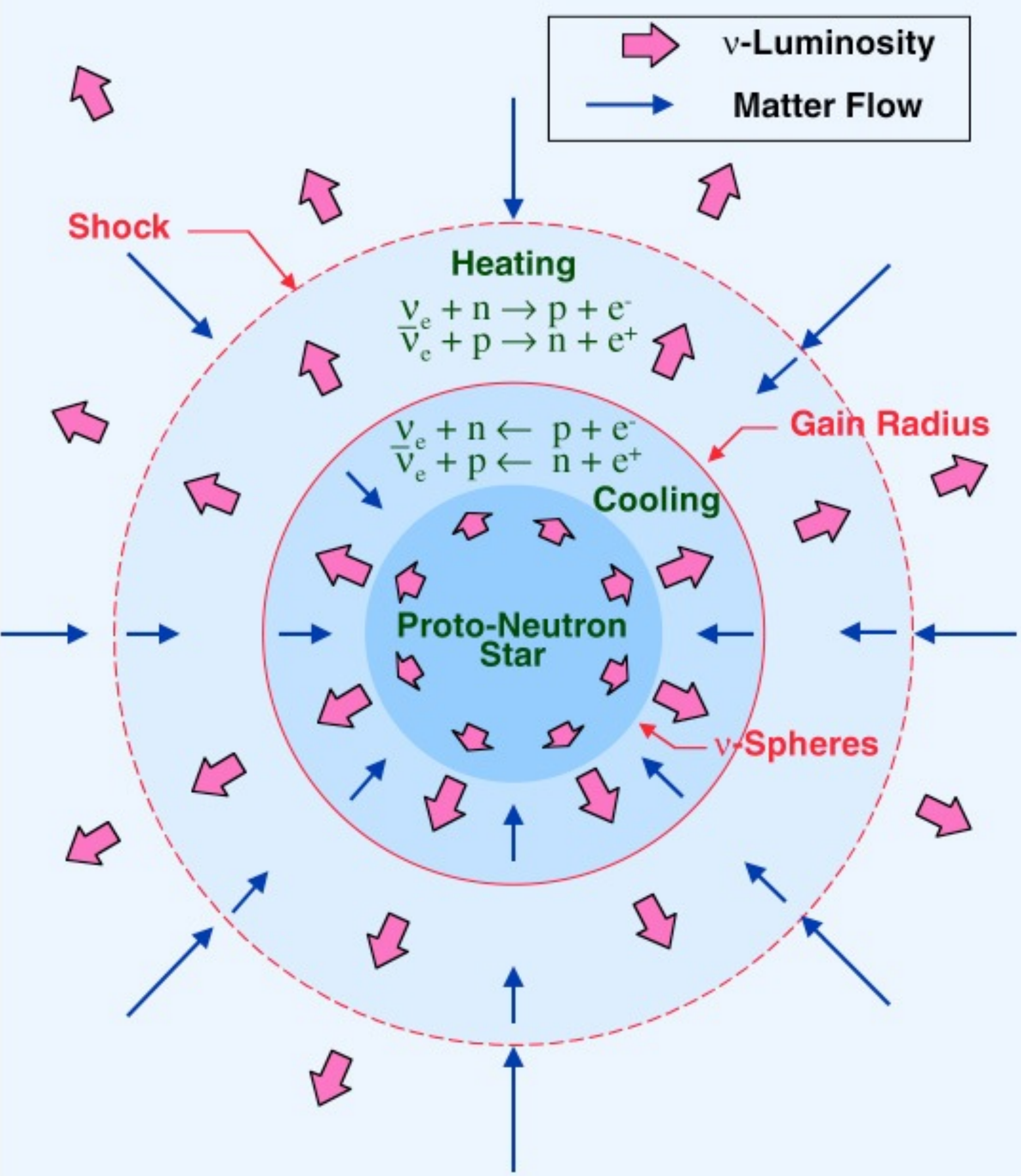
HNe

$M \sim 25\text{–}50\, M_\odot$

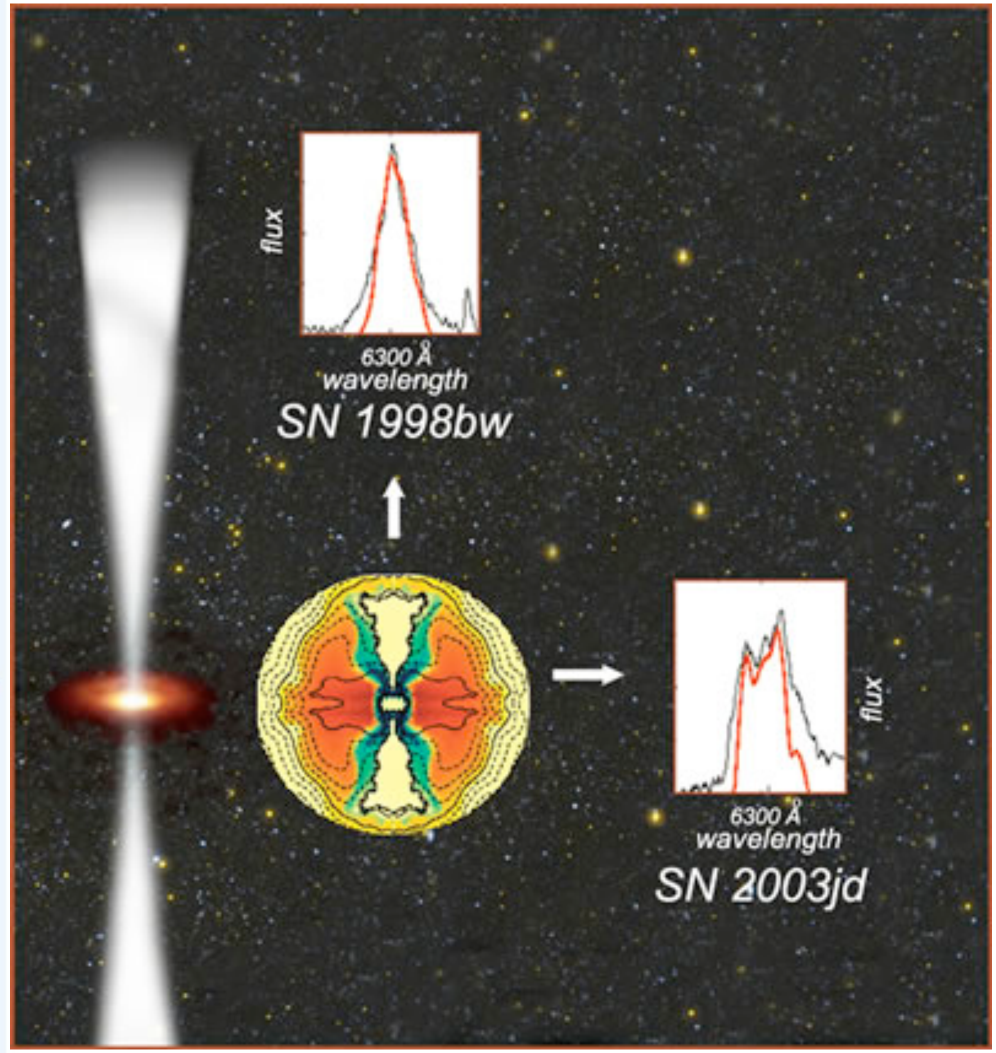
faint SNe

$M \sim 25\text{–}50\, M_\odot$

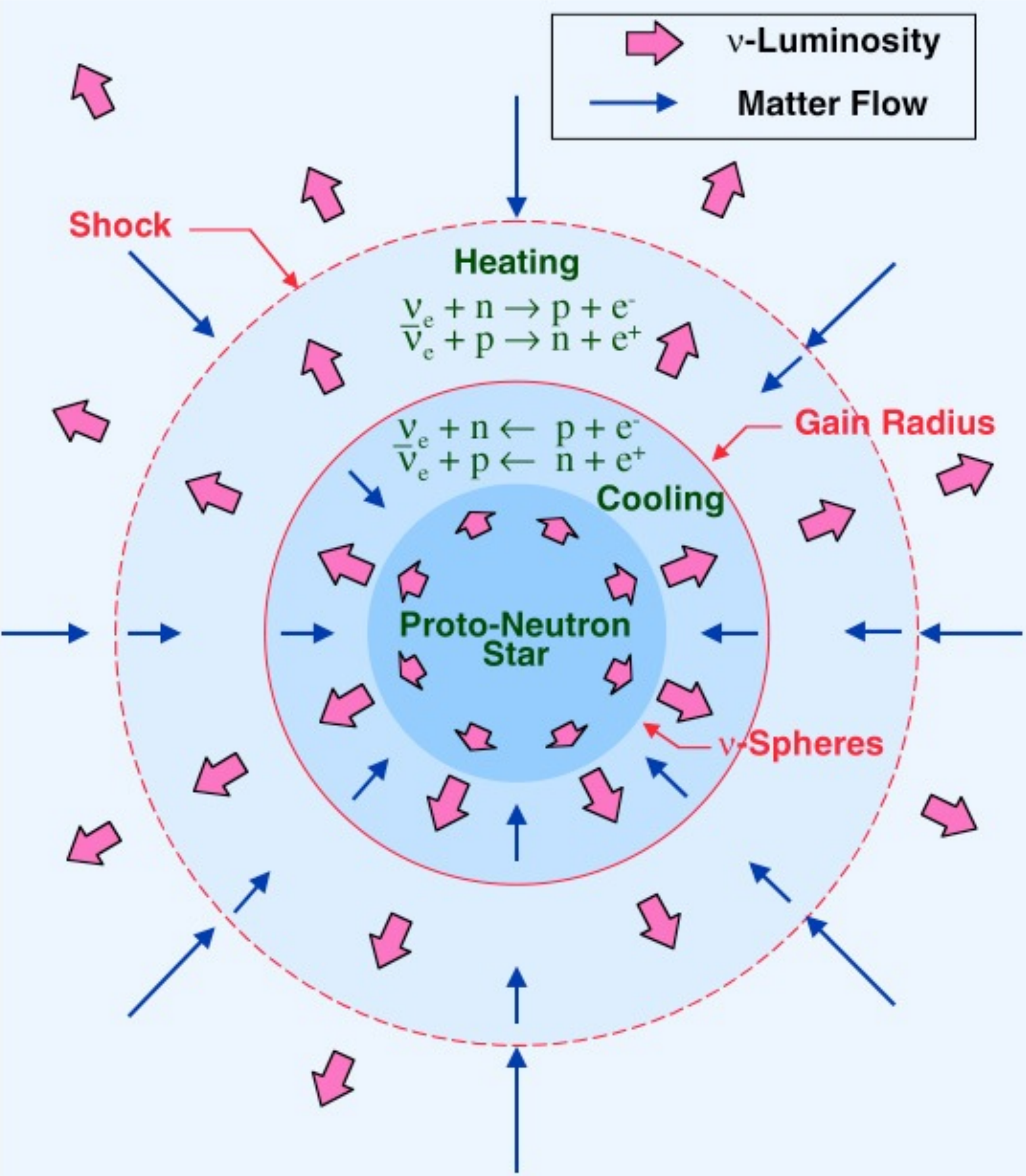
low-mass & normal SNe: neutrino-driven



HNe: strong jets



faint SNe: weak jets



$$\dot{q}_{\nu N} \propto \frac{L_\nu}{\langle E_\nu \rangle} \frac{\langle E_\nu \sigma_{\nu N} \rangle}{r^2}$$

$$\dot{q}_{eN} \propto n_e \langle E_e \sigma_{eN} \rangle$$

$$\propto T^6$$

gain radius r_g

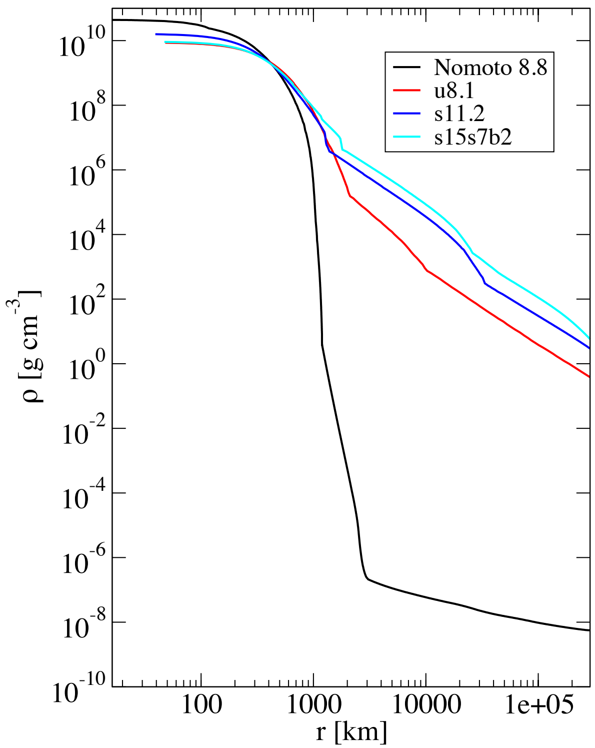
$$\dot{q}_{\nu N}(r_g) = \dot{q}_{eN}(r_g)$$

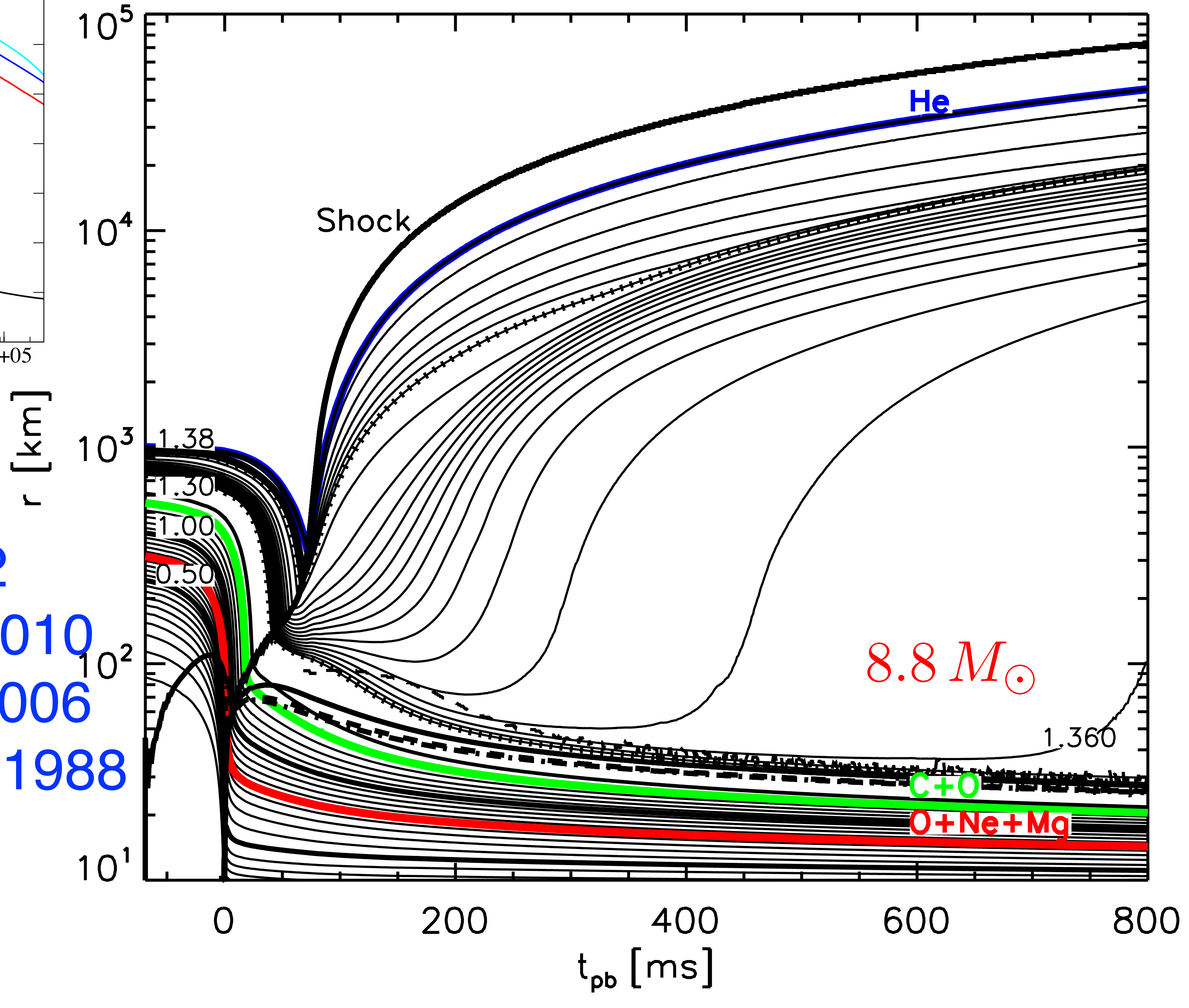
outside gain radius

$$\dot{q}_{\nu N}(r) > \dot{q}_{eN}(r)$$

Bethe & Wilson 1985

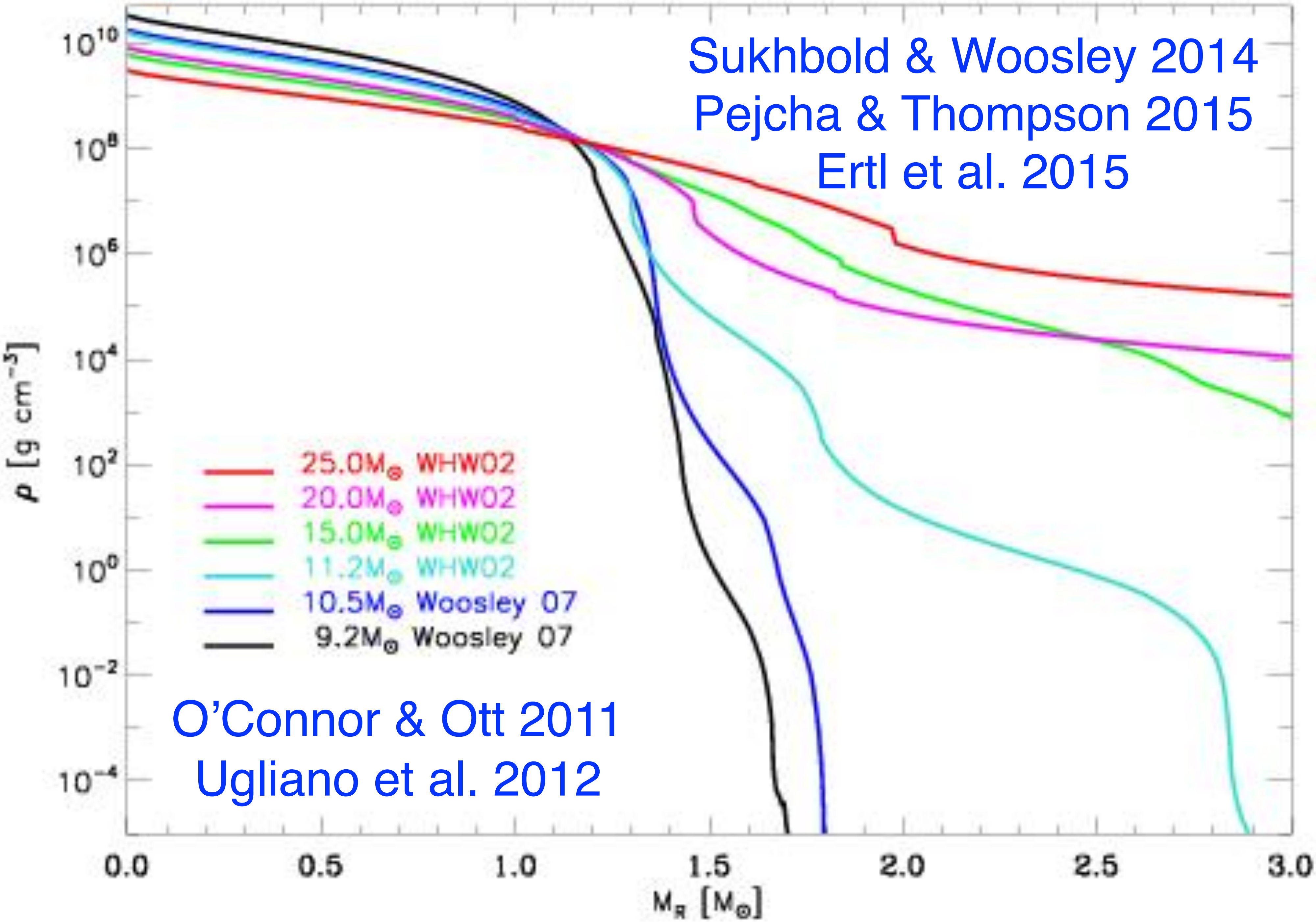
Neutrino-Driven Explosion of a Low-Mass SN

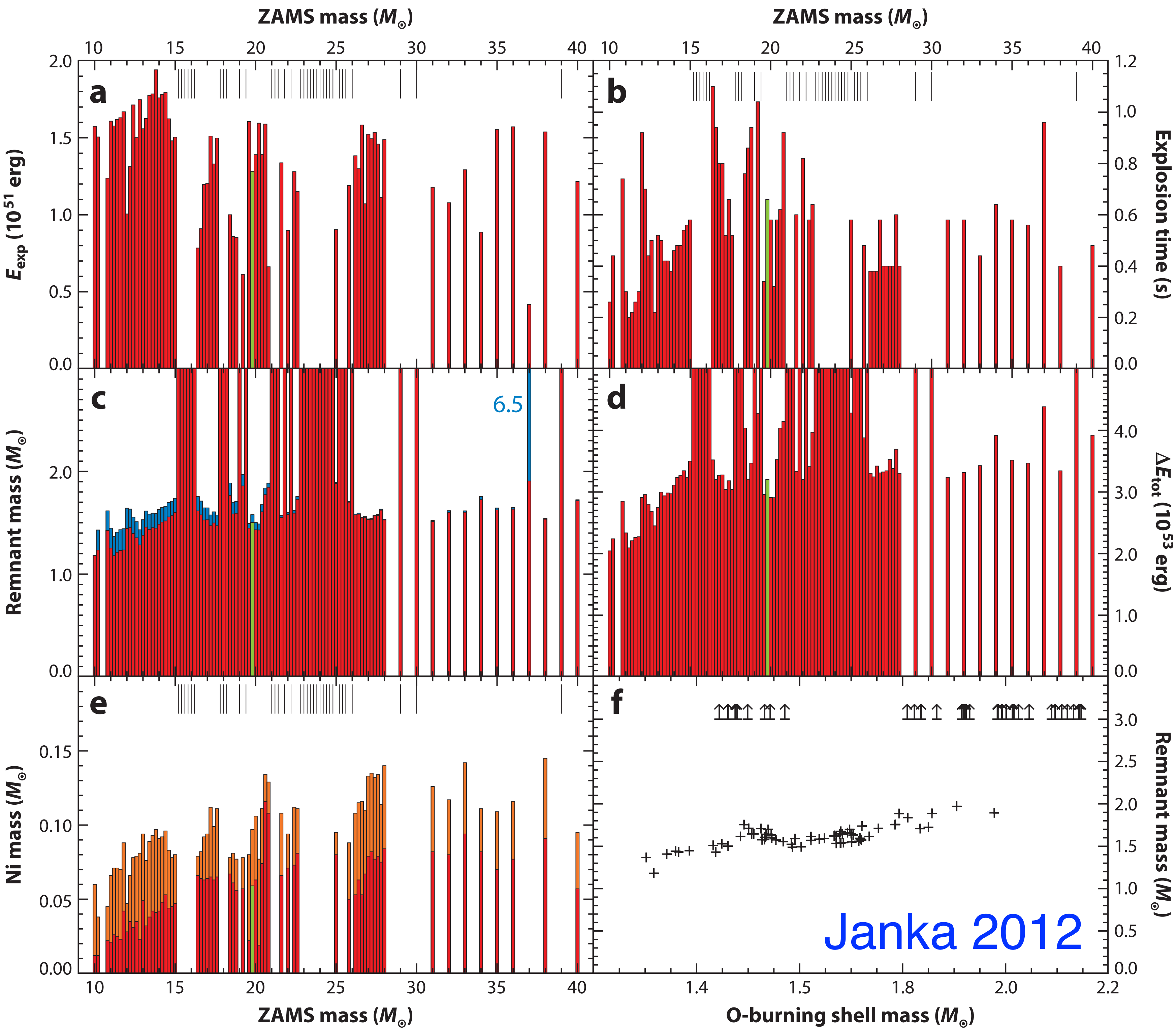




Janka 2012
Fischer et al. 2010
Kitaura et al. 2006
Mayle & Wilson 1988

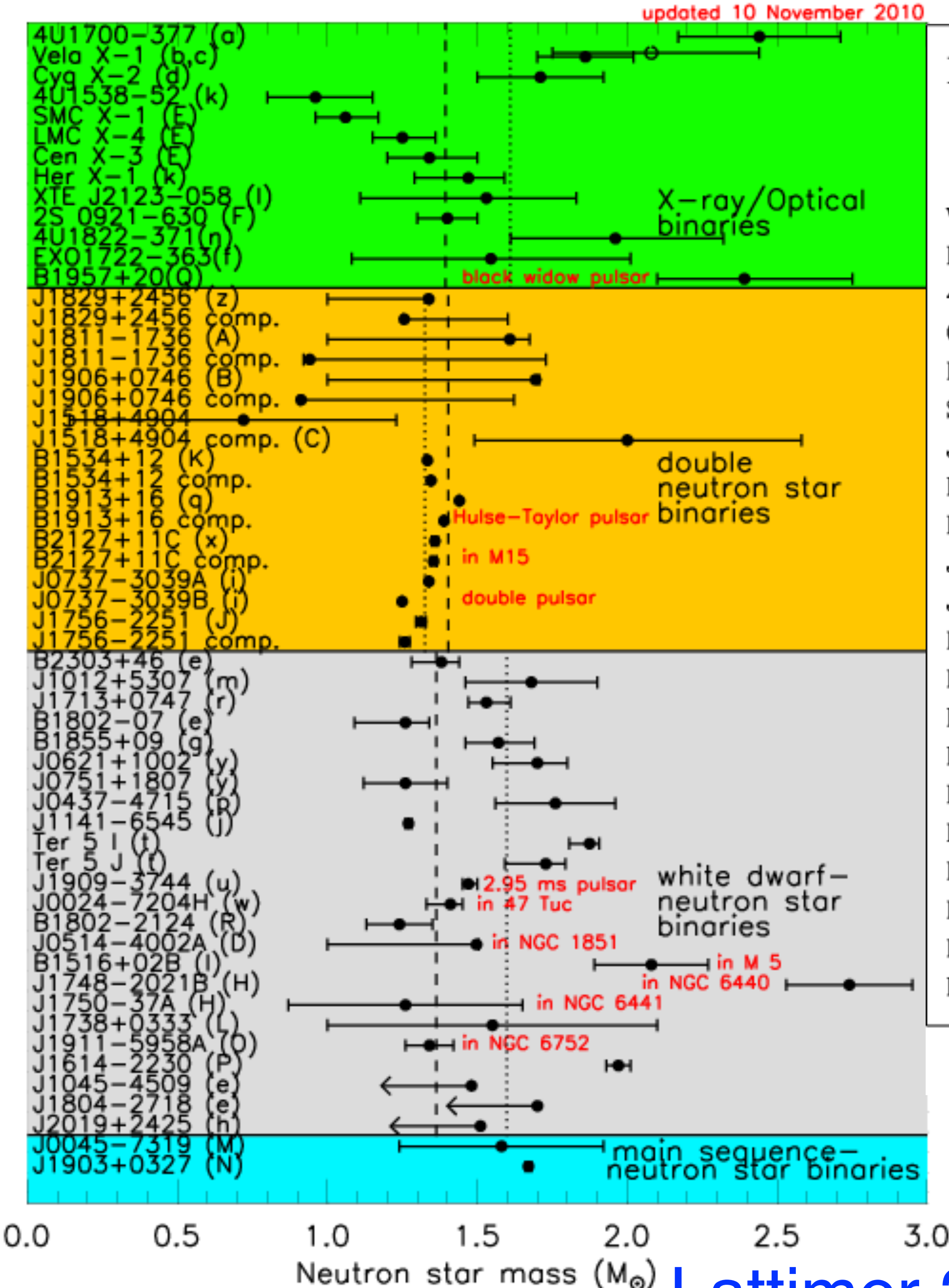
Compactness & Explodability

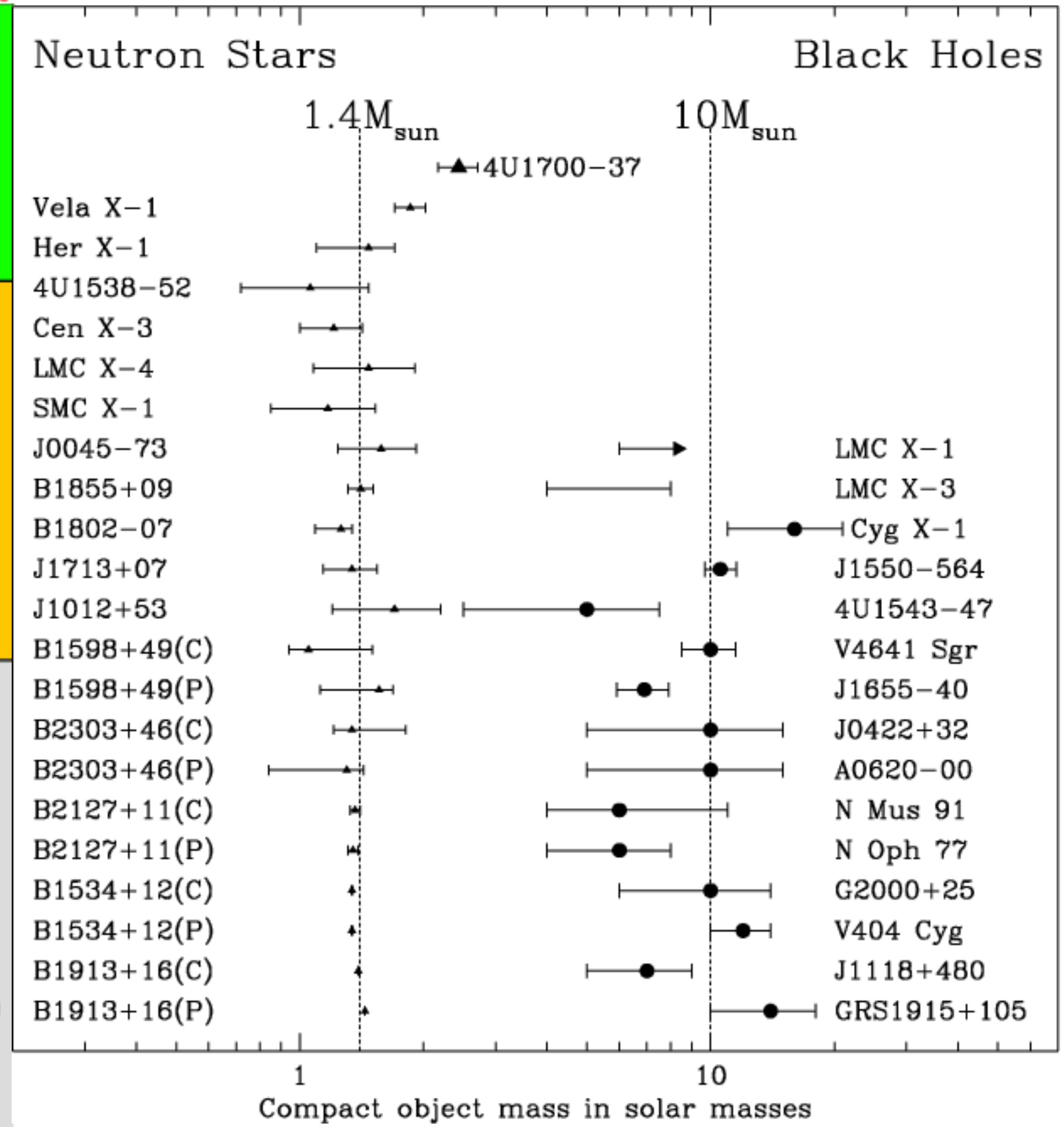




ZAMS mass ($M_\odot$)
O-burning shell mass ($M_\odot$)
E_{exp} (10^{51} erg)
Explosion time (s)
Remnant mass ($M_\odot$)
ΔE_{tot} (10^{53} erg)
Ni mass ($M_\odot$)
6.5
a
b
c
d
e
f
Janka 2012

Neutron Star & Black Hole Masses



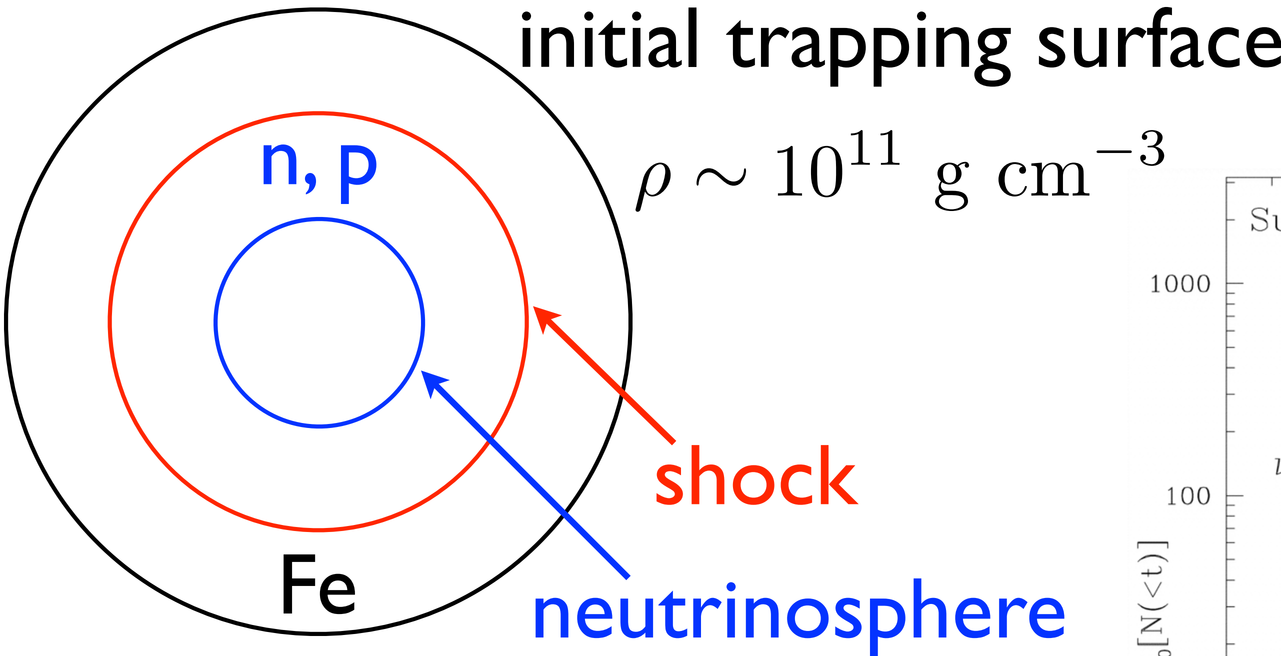


Clark et al. 2002

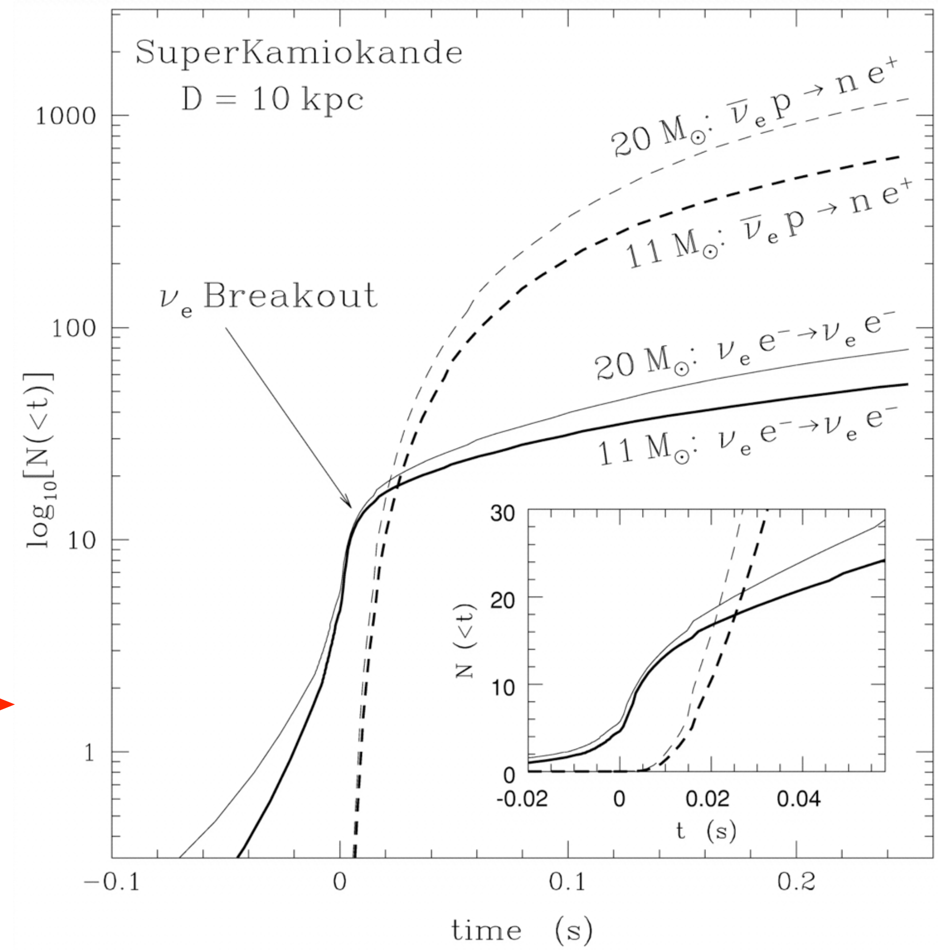
Lattimer 2010

"neutronization" pulse at shock breakout

$$e^- + p \rightarrow n + \nu_e \Rightarrow \text{predominantly } \nu_e$$

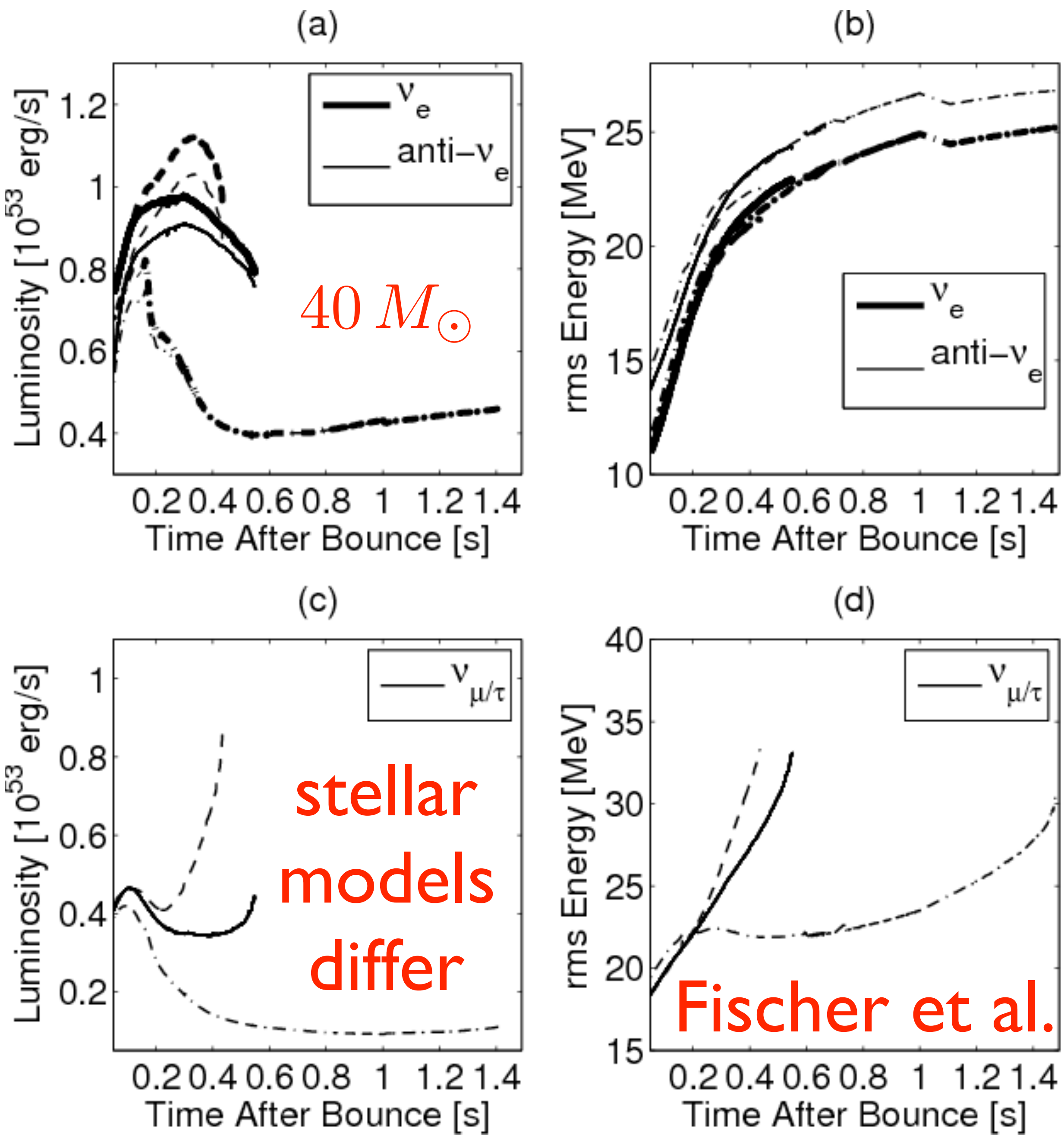


without oscillations



(Thompson et al. 2003)

signature of BH formation: interruption of ν signals



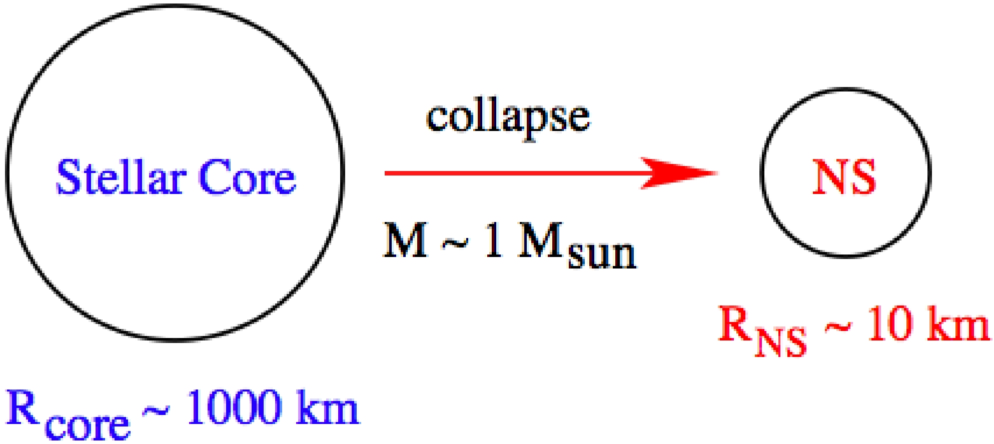
$40\ M_\odot$

stellar models differ

Fischer et al. 2009

followed by neutrino emission from accretion disk around BH?

"Thermal" Neutrino Emission from Proto-NS Cooling



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

$$N + N \to N + N + \nu + \bar{\nu}$$

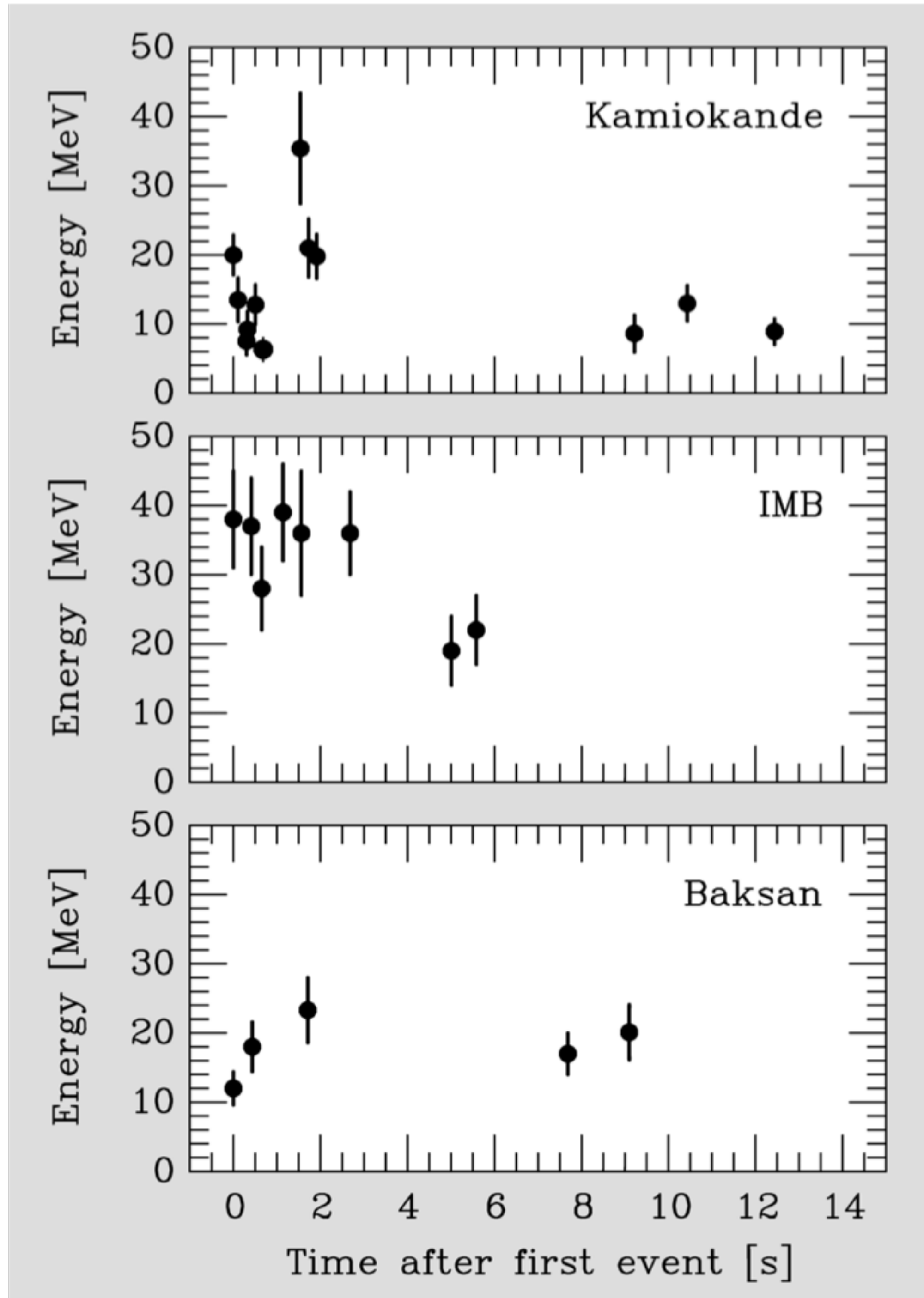
$$\frac{GM^2}{R_{\rm NS}} \sim 3 \times 10^{53}\ {\rm erg}$$

$$\Rightarrow \nu_e,\ \bar{\nu}_e,\ \nu_\mu,\ \bar{\nu}_\mu,\ \nu_\tau,\ \bar{\nu}_\tau$$

for a Galactic SN at ~10 kpc

~10^4 events in SuperK due to

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



Processes Governing SN Neutrino Diffusion

momentum exchange

$$\nu + N \to \nu + N \Rightarrow t_{\rm diff} \sim \text{several seconds}$$

$$L_{\nu_e} \sim L_{\bar{\nu}_e} \sim L_{\nu_{\mu/\tau}} \approx L_{\bar{\nu}_{\mu/\tau}}$$

energy exchange

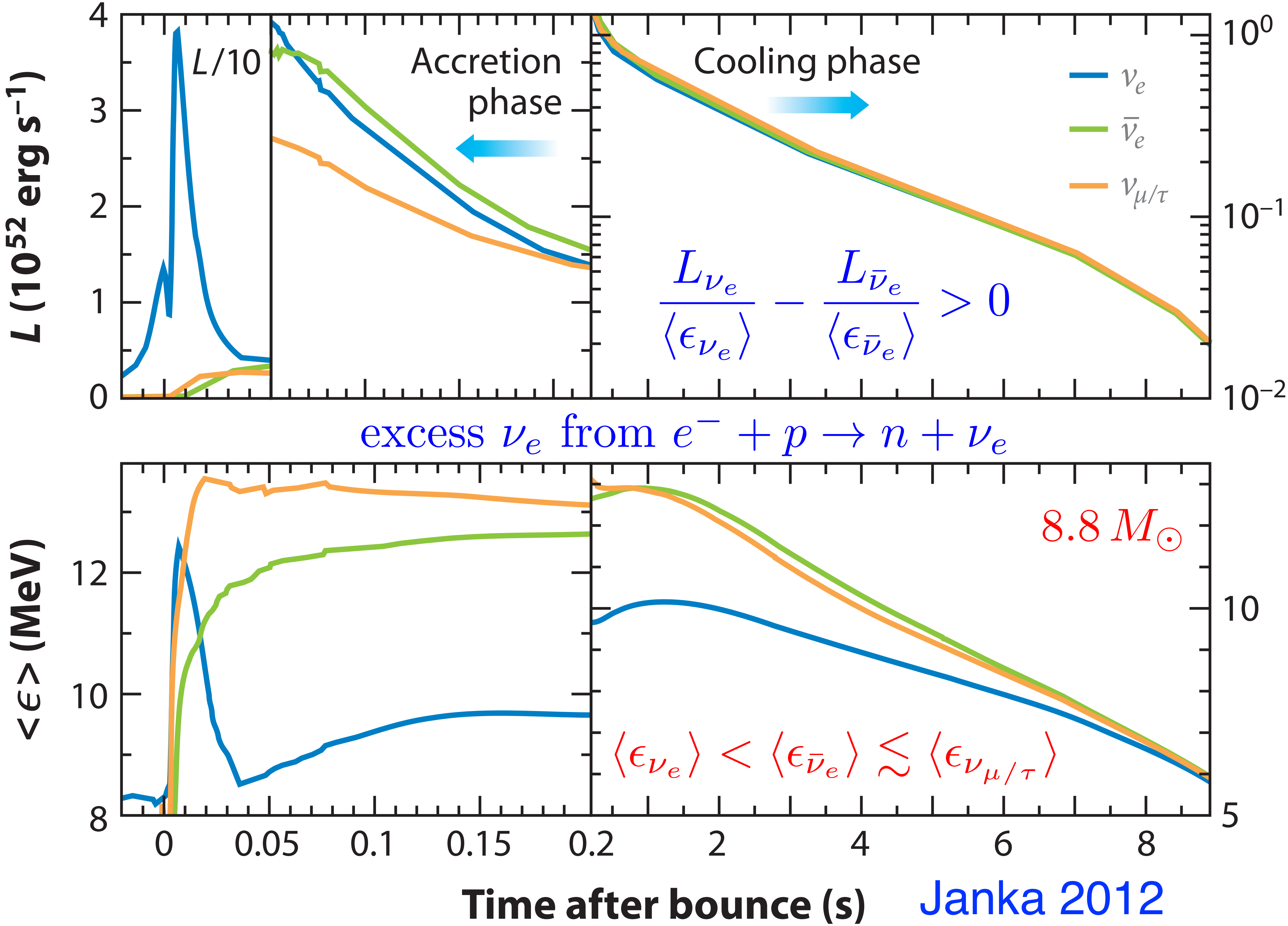
$$\nu + e^- \to \nu + e^-$$

$$\nu_e + n \rightleftharpoons p + e^-$$

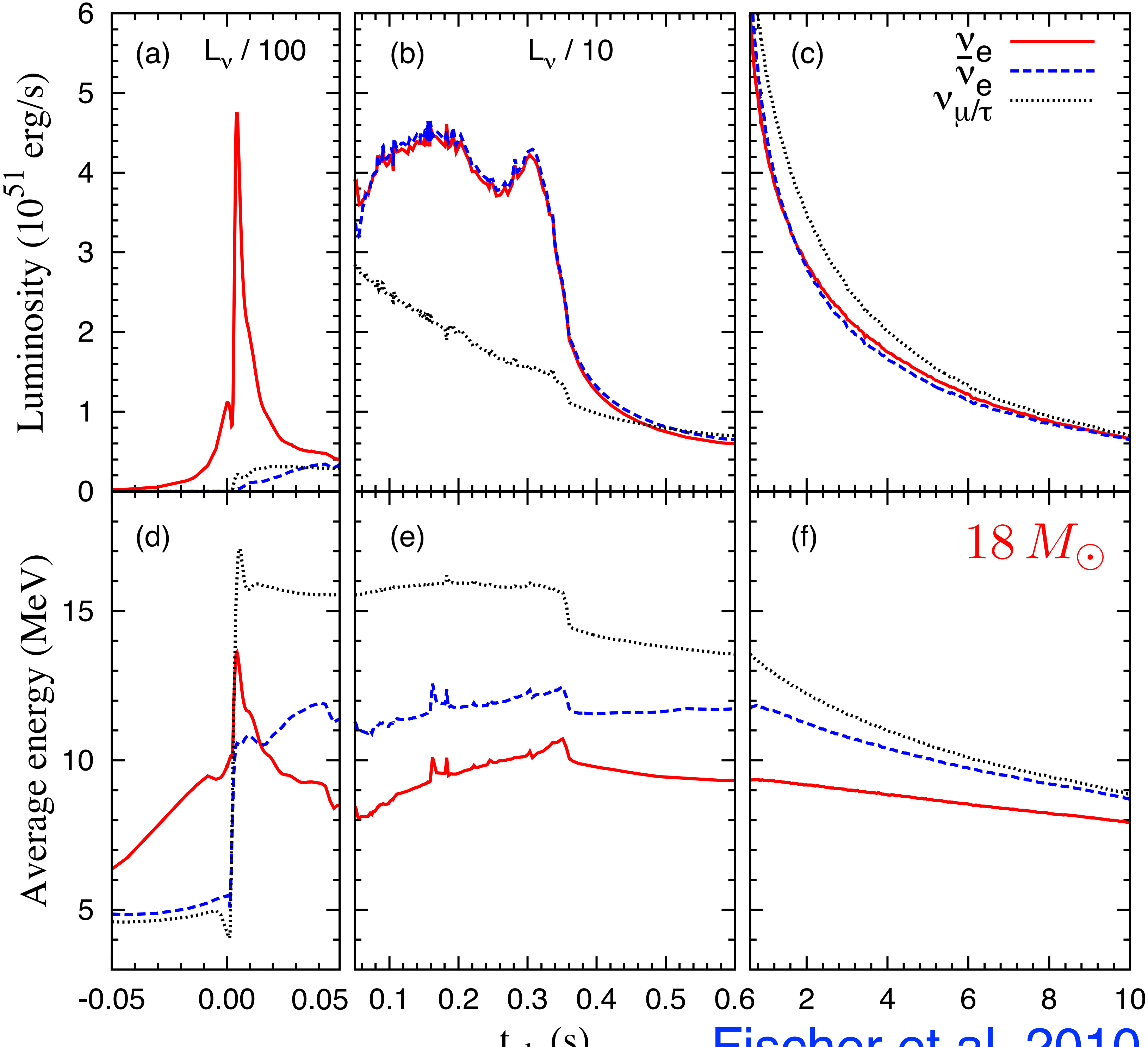
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \lesssim \langle E_{\nu_{\mu/\tau}} \rangle \approx \langle E_{\bar{\nu}_{\mu/\tau}} \rangle$$

Neutrino Emission from a Low-Mass SN



Janka 2012



Fischer et al. 2010

Summary: supernovae and their neutrino signals

- interruption of neutrino signals reveals BH formation

  → progenitor density structure (accretion rate)

  nuclear equation of state (phase transition)

- rich interplay among progenitor structure, shock propagation, neutrino emission & flavor evolution

  "neutronization" pulse at shock breakout relatively simple to study as a probe of neutrino properties

  bulk emission of "thermal" neutrinos gives potential probes of supernova physics & neutrino properties (systematic study of collective & shock effects needed)

- templates of neutrino signals important for study of relic/diffuse supernova neutrino background