Nuclear Astrophysics (Stars and Compact Objects and their connection to multi-messenger astronomy)

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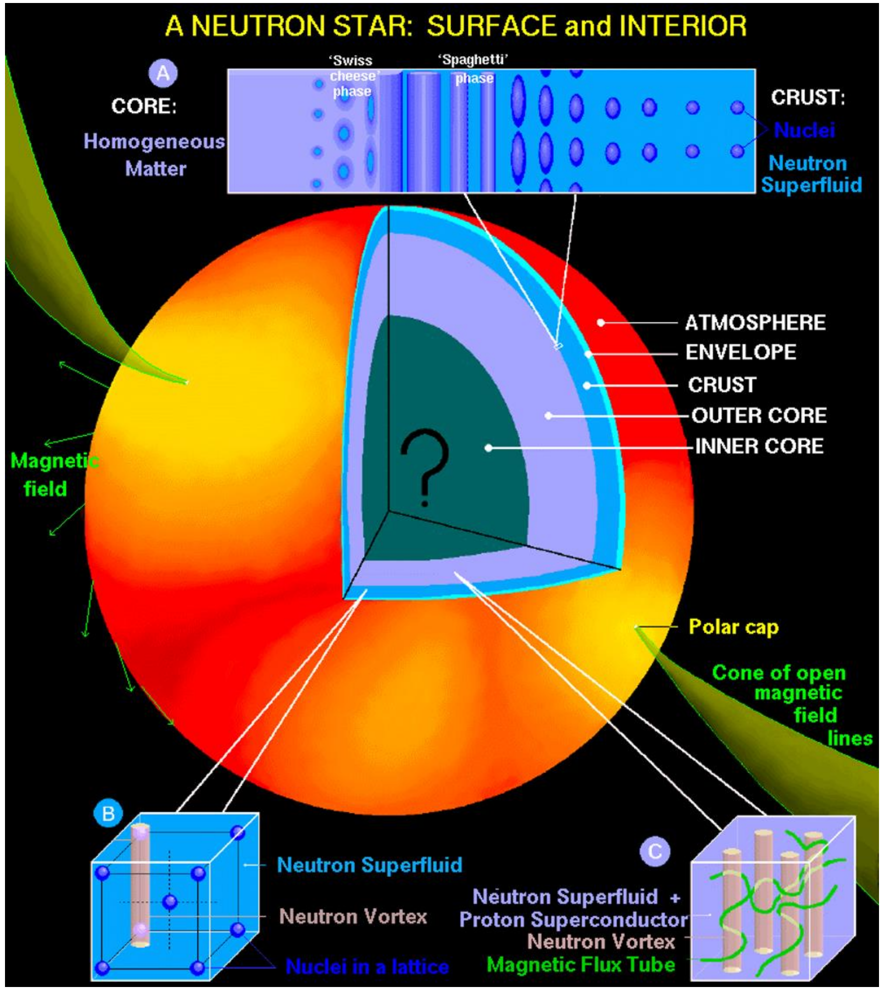
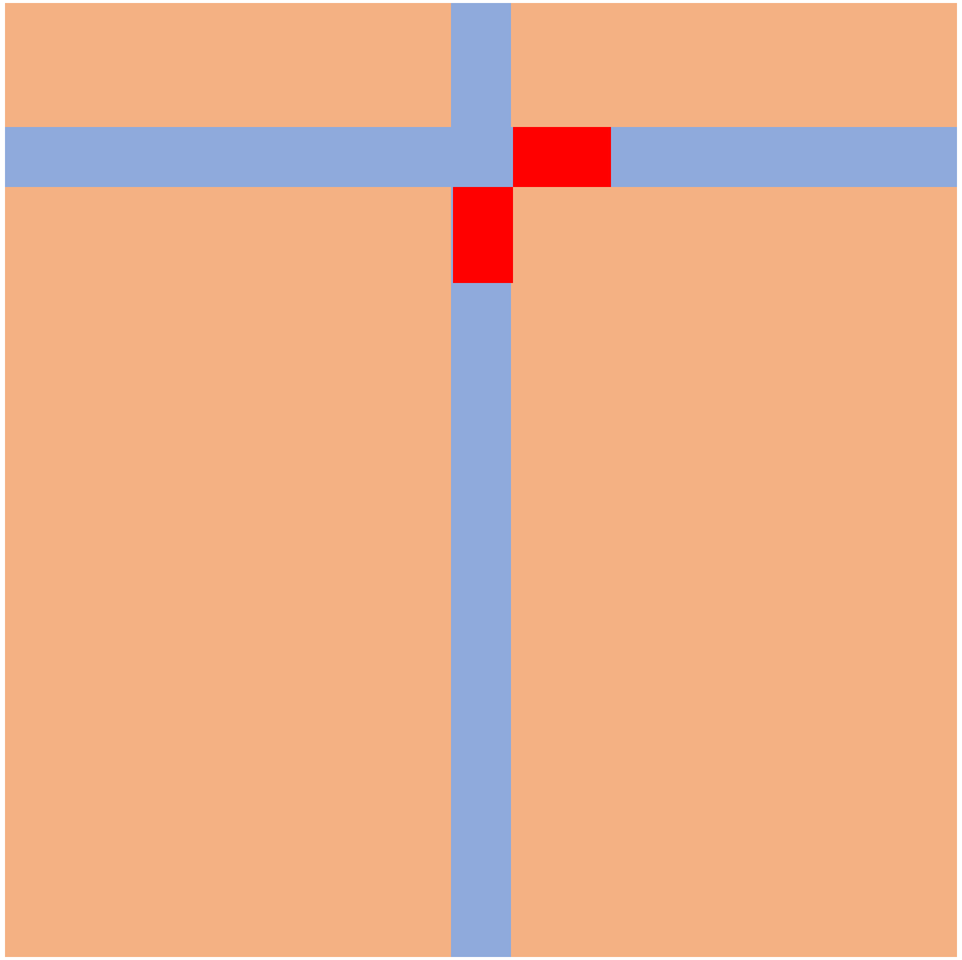
Personal Journey toward Astrophysics

- Was a master student to study nuclear theory, but ended up with leaving the field of nuclear physics for astrophysics
- Did not have any intention to use computers for my research career but ended up with spending the entire PhD years on the code development
- Finally came back to nuclear physics community
- Astrophysics with nuclear physics, computation, and more else
- Do not need to put any constraint on who I am or what I do: my limit is my imagination

Astrophysics that I have understood so far



Lattimer & Prakash (2004, Science, 304, 536)



What I have learned and thought to know so far

- Basic courses in physics
- Quantum field theory: Lagrangian, Feynmann diagram, renormalization, etc.
- Computer codes: Fortran, python, etc.
- Algorithms: PDEs for hydrodynamics, solvers for rate equations, etc.
- And more …
- (Ideas and scientific writing)

Nuclear Astrophysics =
Astronomy (Observation)
\+ Nuclear Physics (Theory)
\+ Nuclear Physics (Experiment)

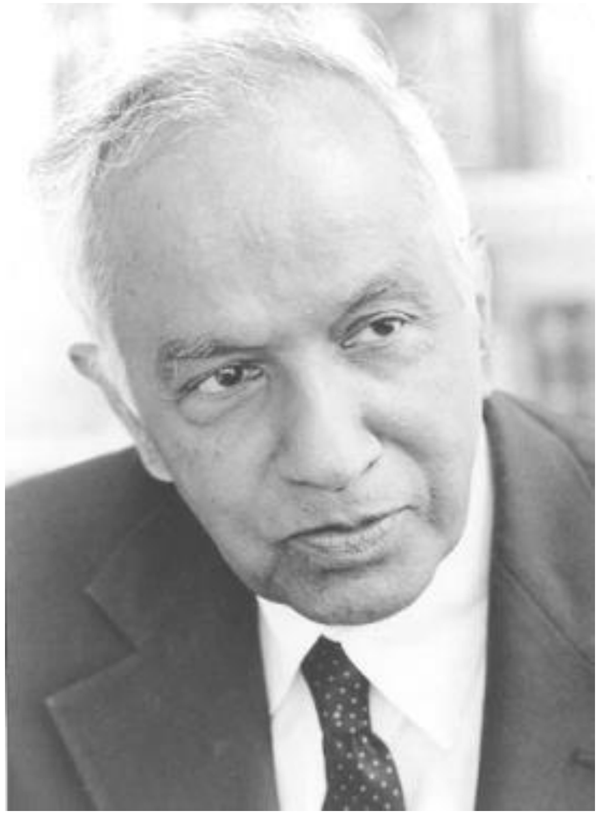
Outline

- History of Nuclear Astrophysics
- Observations and Theory
  - Stellar Evolution
  - X-ray Burst
- Experiments

Nobel Prizes I

Hans Bethe
1967
Stellar Nucleosynthesis (1939)

William Alfred Fowler
1983
Discovery of ^{12}C resonance (1952)



Subrahmanyan Chandrasekhar
1983
Structure and evolution of stars (1939)

Nobel Prizes II

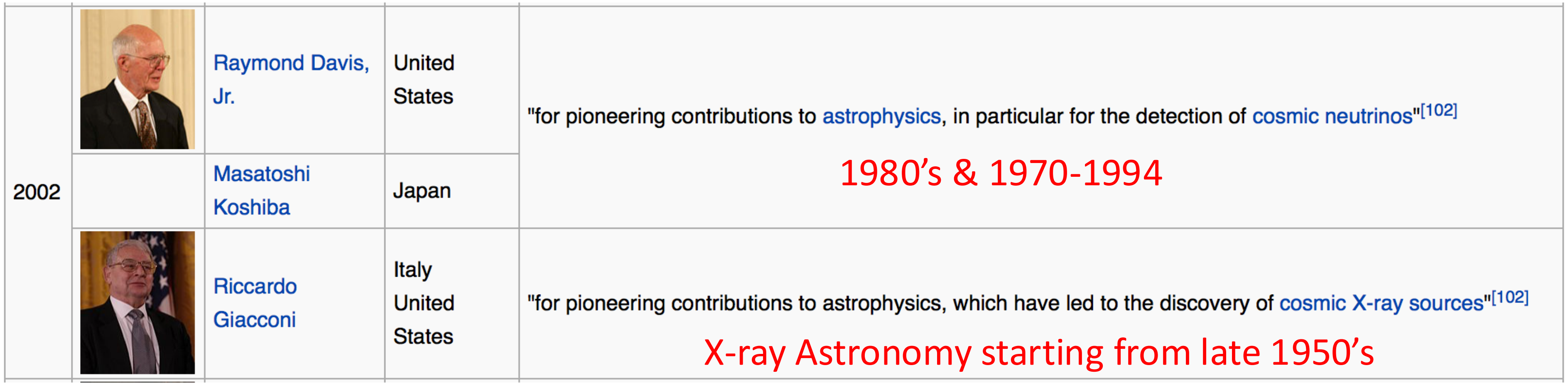
Arthur B. McDonald
2015
Solar neutrino oscillation
(2001)

Takaaki Kajita
2015
Atmospheric neutrino oscillation
(1998)

More Nobel Prizes I

2011		Saul Perlmutter	United States	"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"[111]
		Brian P. Schmidt	Australia United States	
		Adam G. Riess	United States	

1998

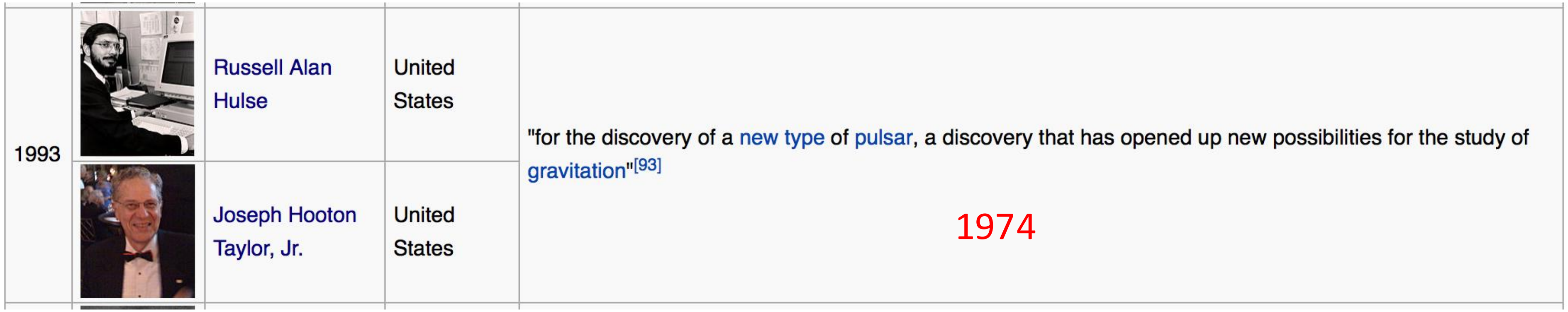


2002		Raymond Davis, Jr.	United States	"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"[102]
		Masatoshi Koshiba	Japan	
		Riccardo Giacconi	Italy United States	"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"[102]

1980's & 1970-1994

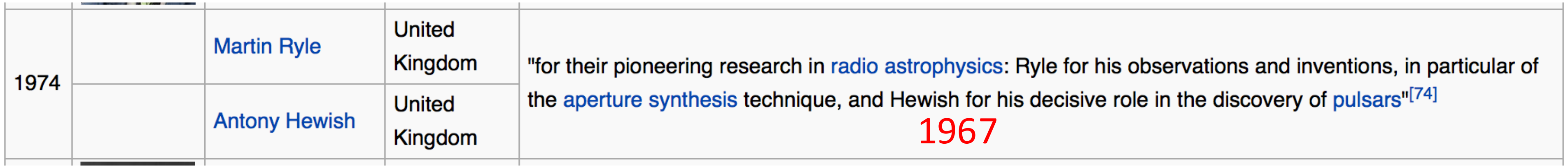
X-ray Astronomy starting from late 1950's

More Nobel Prizes II



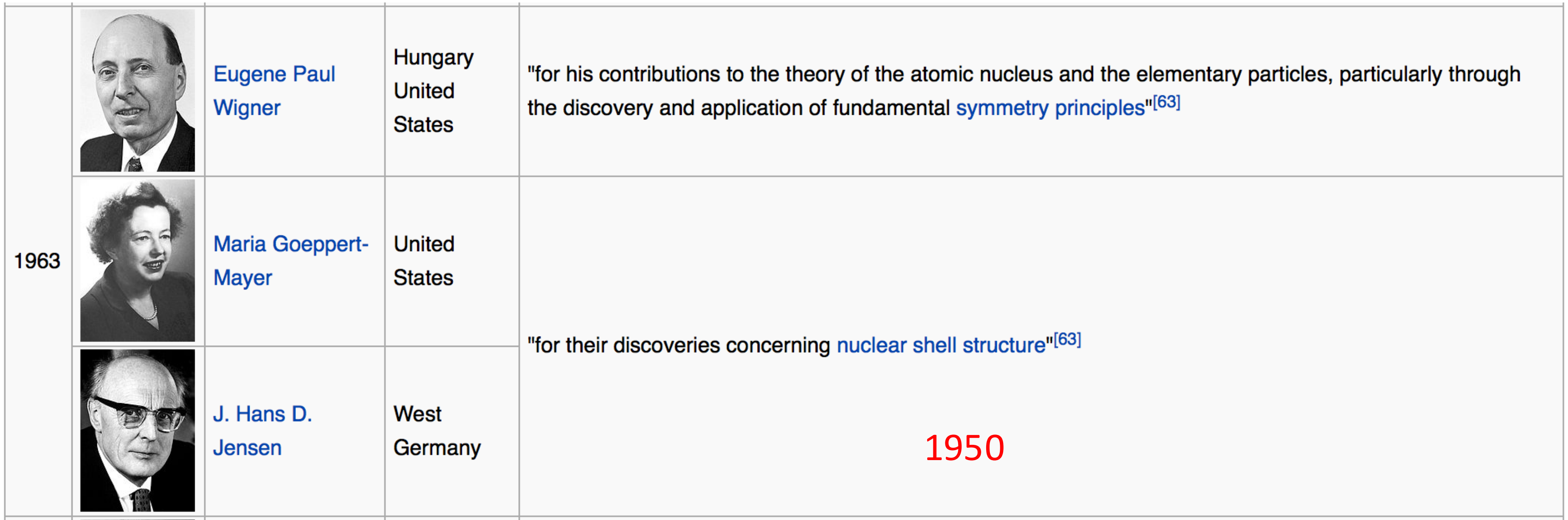
1993		Russell Alan Hulse	United States	"for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"[93]
		Joseph Hooton Taylor, Jr.	United States	

1974



1974		Martin Ryle	United Kingdom	"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"[74]
		Antony Hewish	United Kingdom	

1967

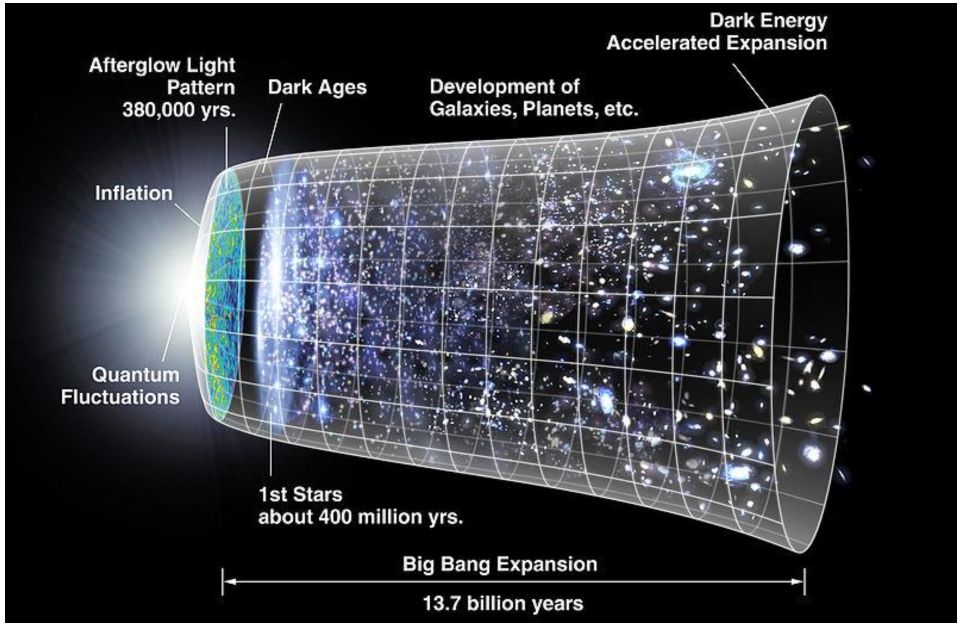


1963		Eugene Paul Wigner	Hungary United States	"for his contributions to the theory of the atomic nucleus and the elementary particles, particularly through the discovery and application of fundamental symmetry principles"[63]
		Maria Goeppert-Mayer	United States	"for their discoveries concerning nuclear shell structure"[63]
		J. Hans D. Jensen	West Germany	

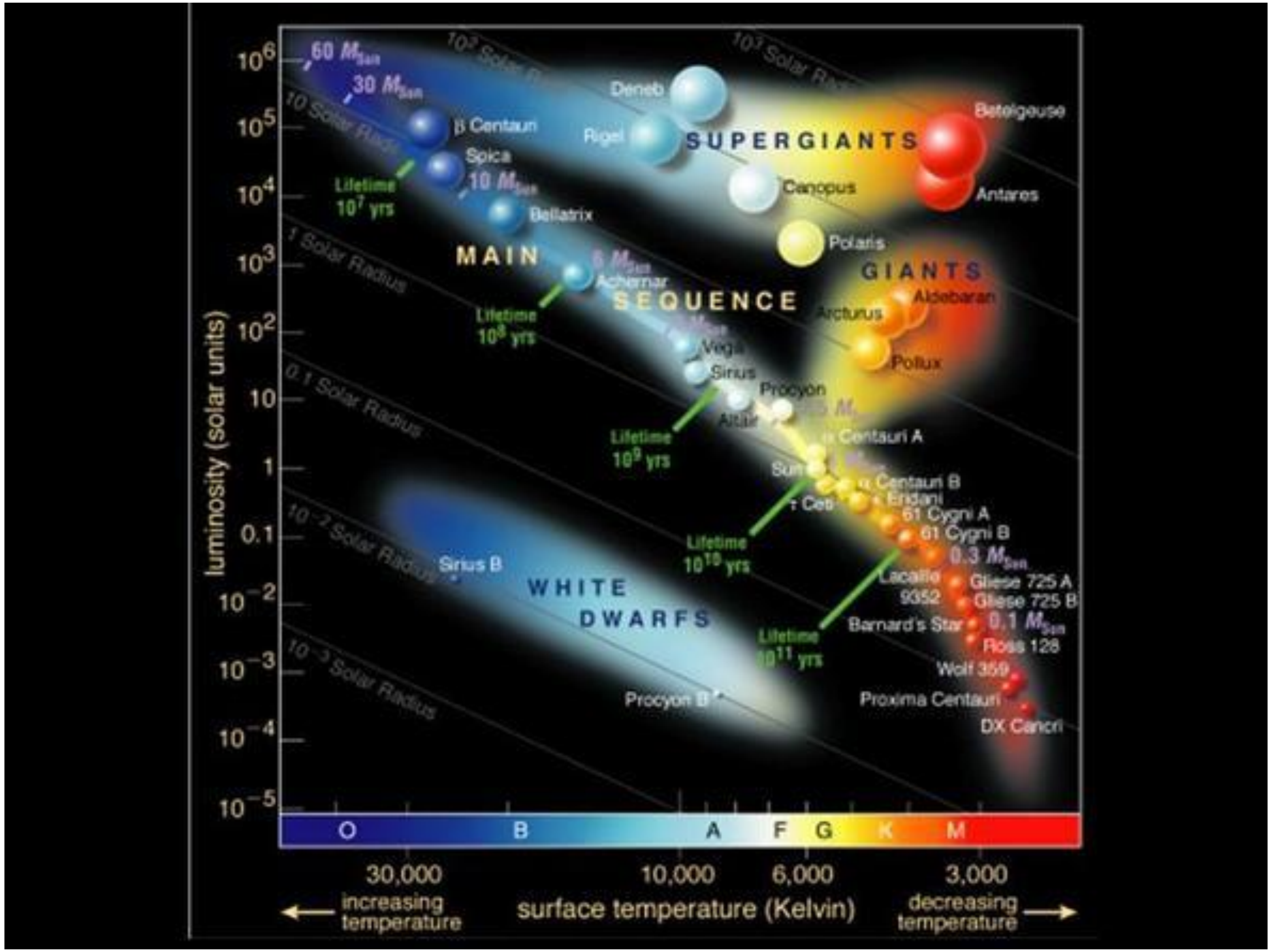
1950

Stellar Evolution

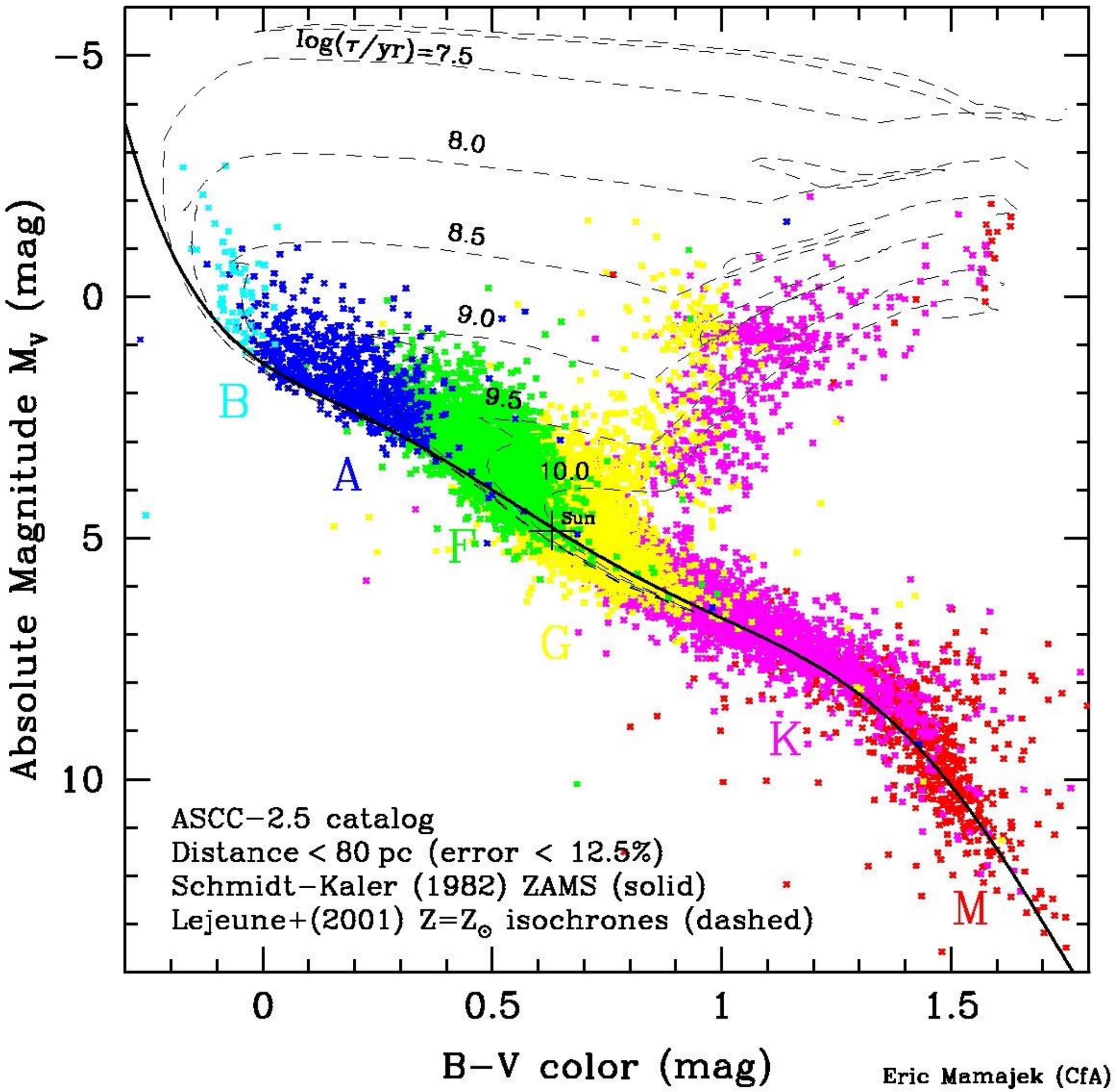
- Stars are building blocks of the universe.



Hertzsprung–Russell Diagram



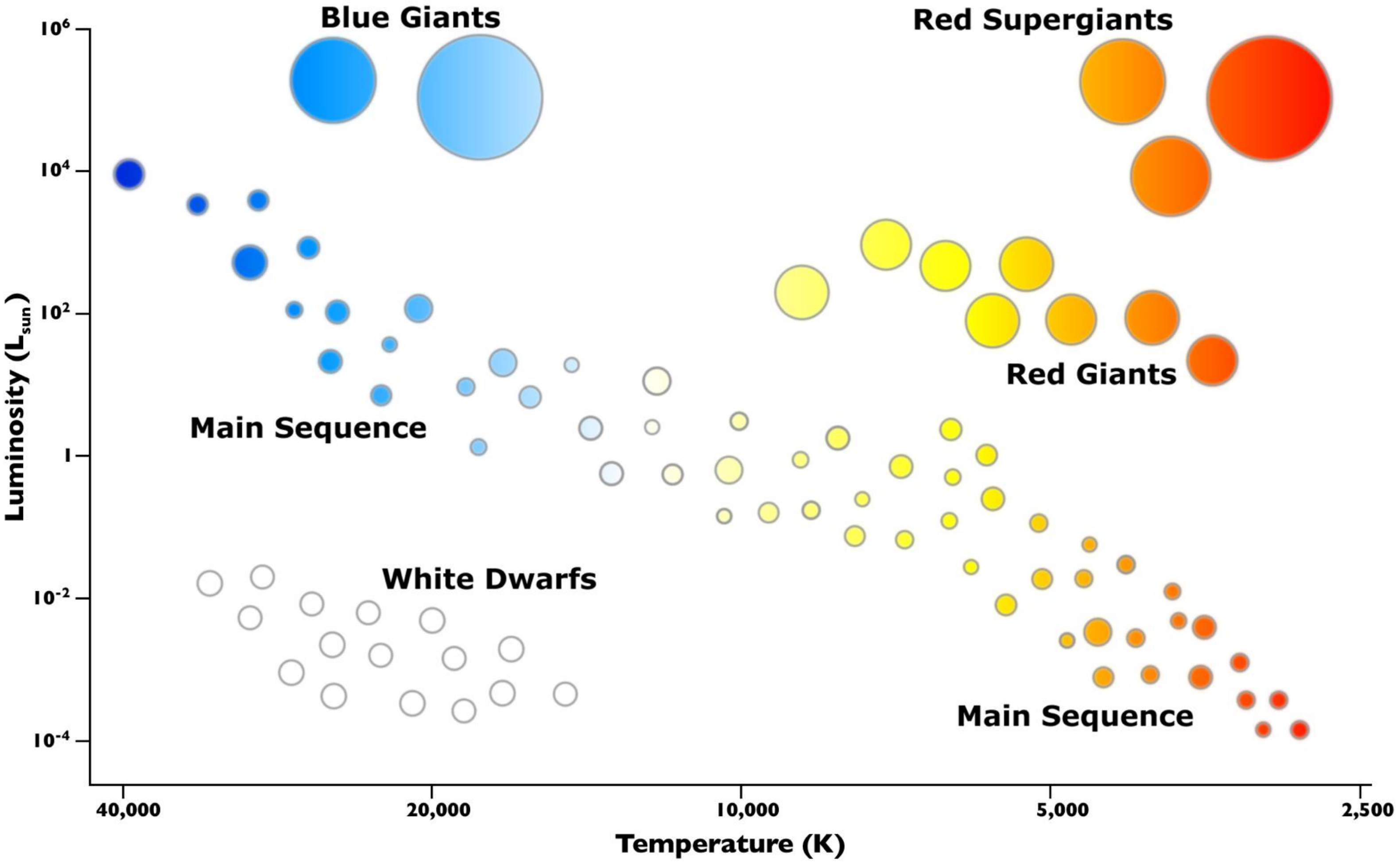
별의 진화: 관측



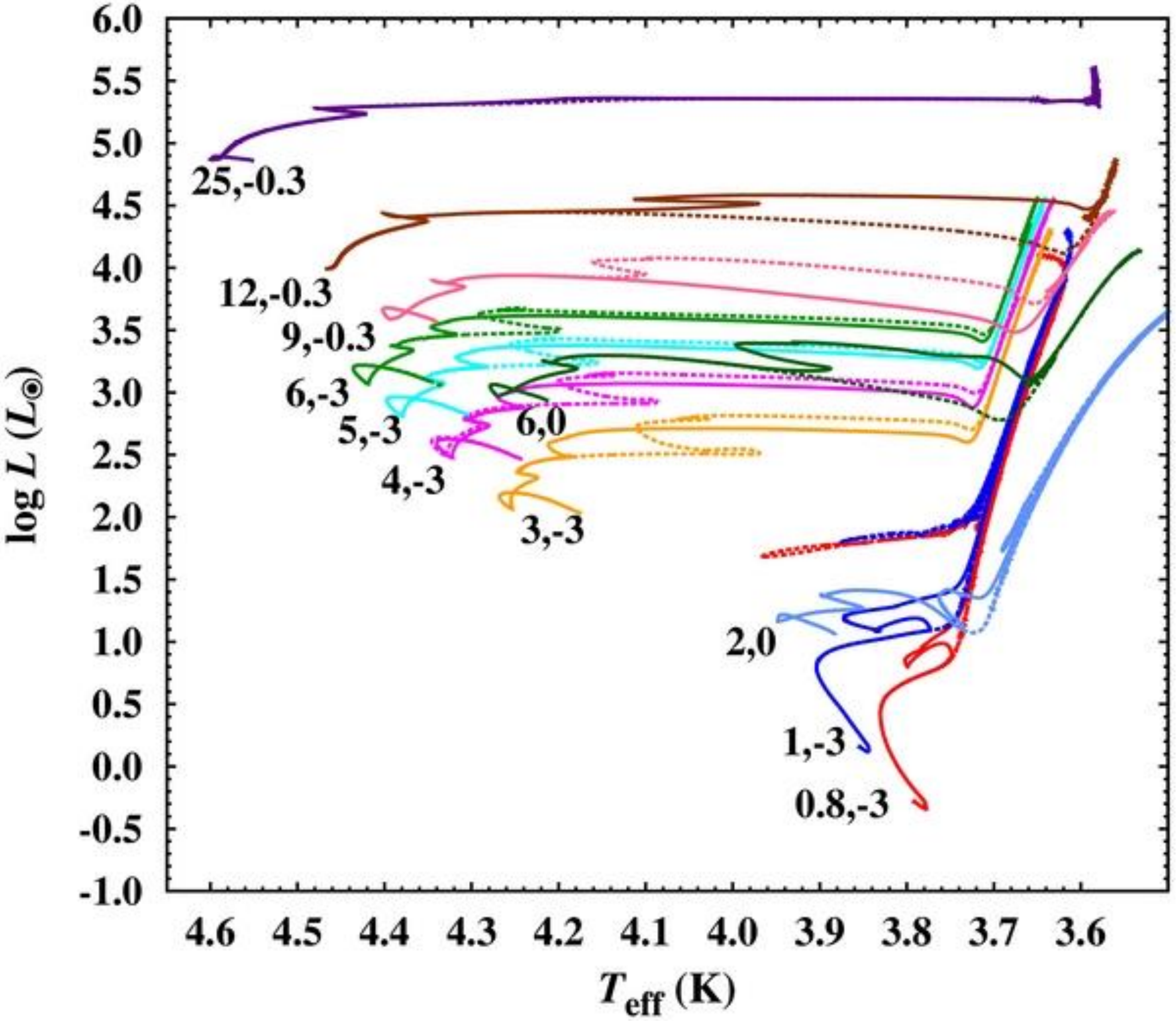
우리 주위
80 pc 이내에
있는 별들

별의 진화: 이론

Hertzprung-Russell diagram



별의 진화: 시뮬레이션



1. 별은 둥글다.
2. 별은 빛난다.
3. 별 내부의 중력을 견디는 힘
4. 별 내부의 핵 융합 반응
5. 에너지 전달: 빛 또는 대류

1. 별의 초기 질량
2. 별에 포함된 원소의 구성비

별의 진화를 결정

Theory of Stellar Evolution

Basic equations to calculate stellar structure(Using Lagrangian coordinates)

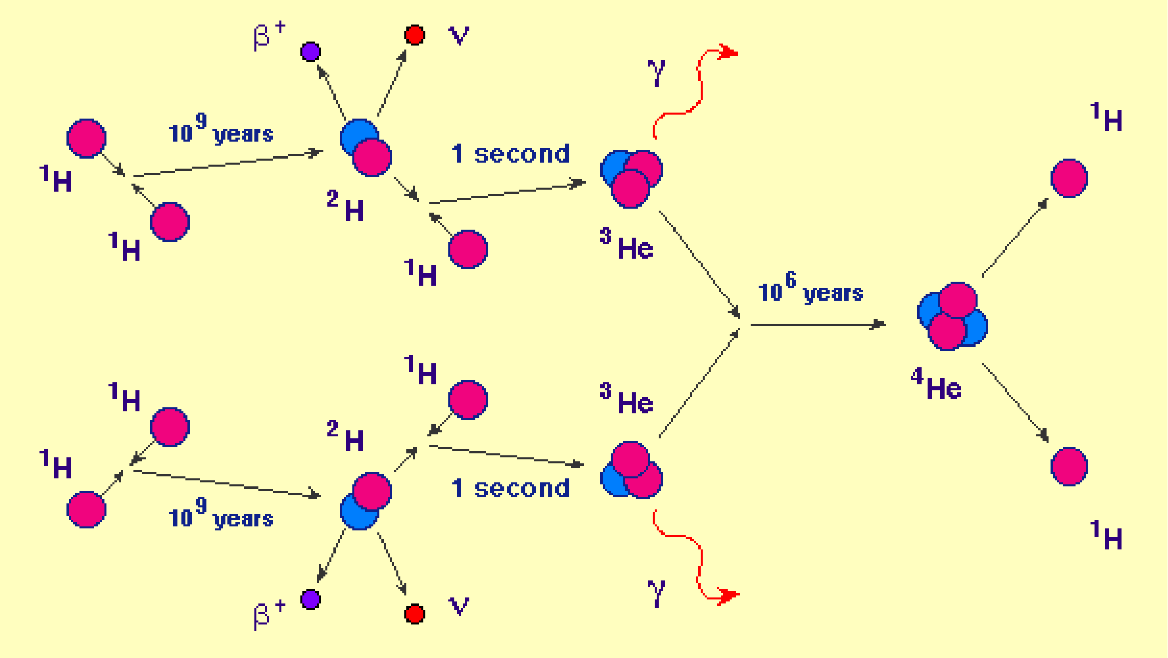
1. $\frac{dP(M)}{dM} = -\frac{GM}{4\pi r^4(M)}$ Hydrostatic equilibrium equation
2. $\frac{dL(M)}{dM} = \varepsilon - T\frac{dS}{dt}$ Thermal energy conservation equation
3. $\frac{dT}{dM} = -\frac{3kL}{4acT^3 16\pi^2 r^4}$ Energy transfer equation for radiative equilibrium condition
4. $\frac{dT}{dM} = \frac{\Gamma_2 - 1}{\Gamma_2}\frac{T}{P}\frac{dP}{dM}$ Energy transfer equation for convective condition

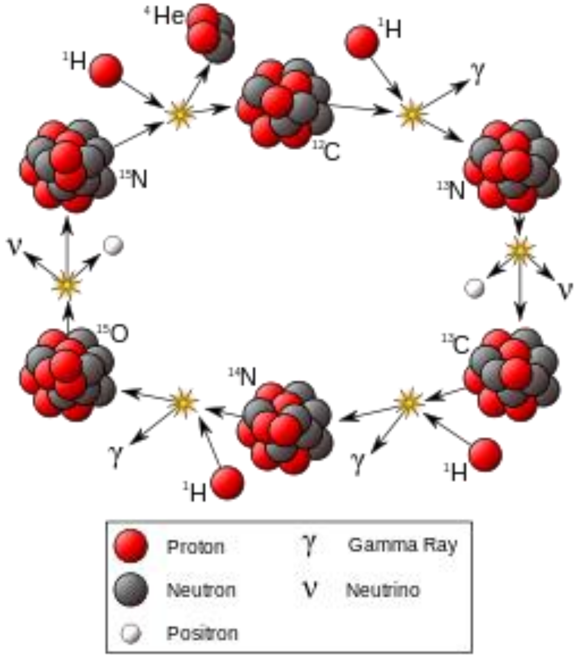
To calculate the composition of a star, we need to solve general composition change equation

5 . $\left[\frac{\partial N(A,Z)}{\partial t}\right]_{nuclear\ reaction} = r_{generation}(A,Z) - r_{annihilation}(A,Z)$

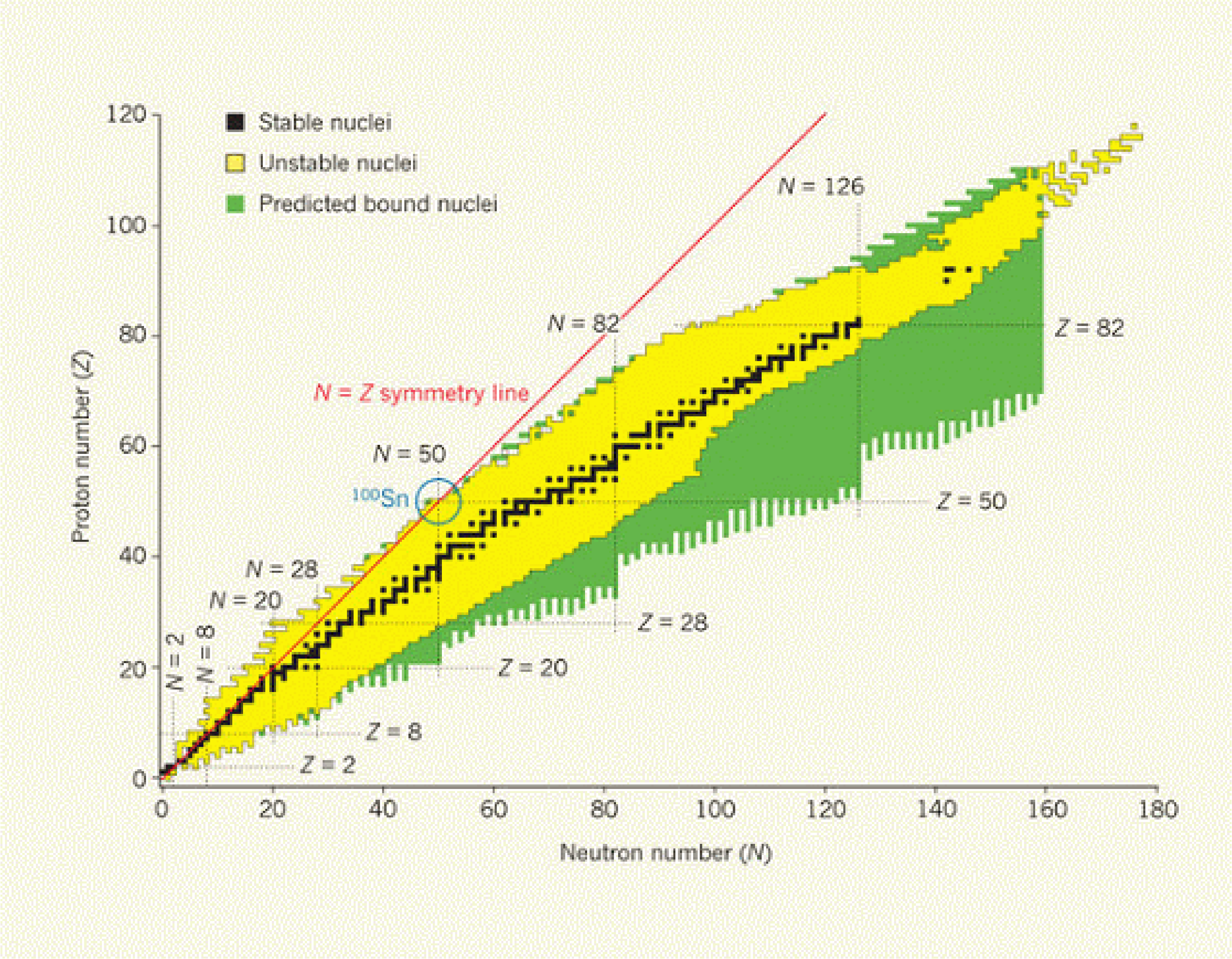
This equation should include all related isotopes. So it is generally represented by a matrix form.

Nuclear Reactions Inside a Star

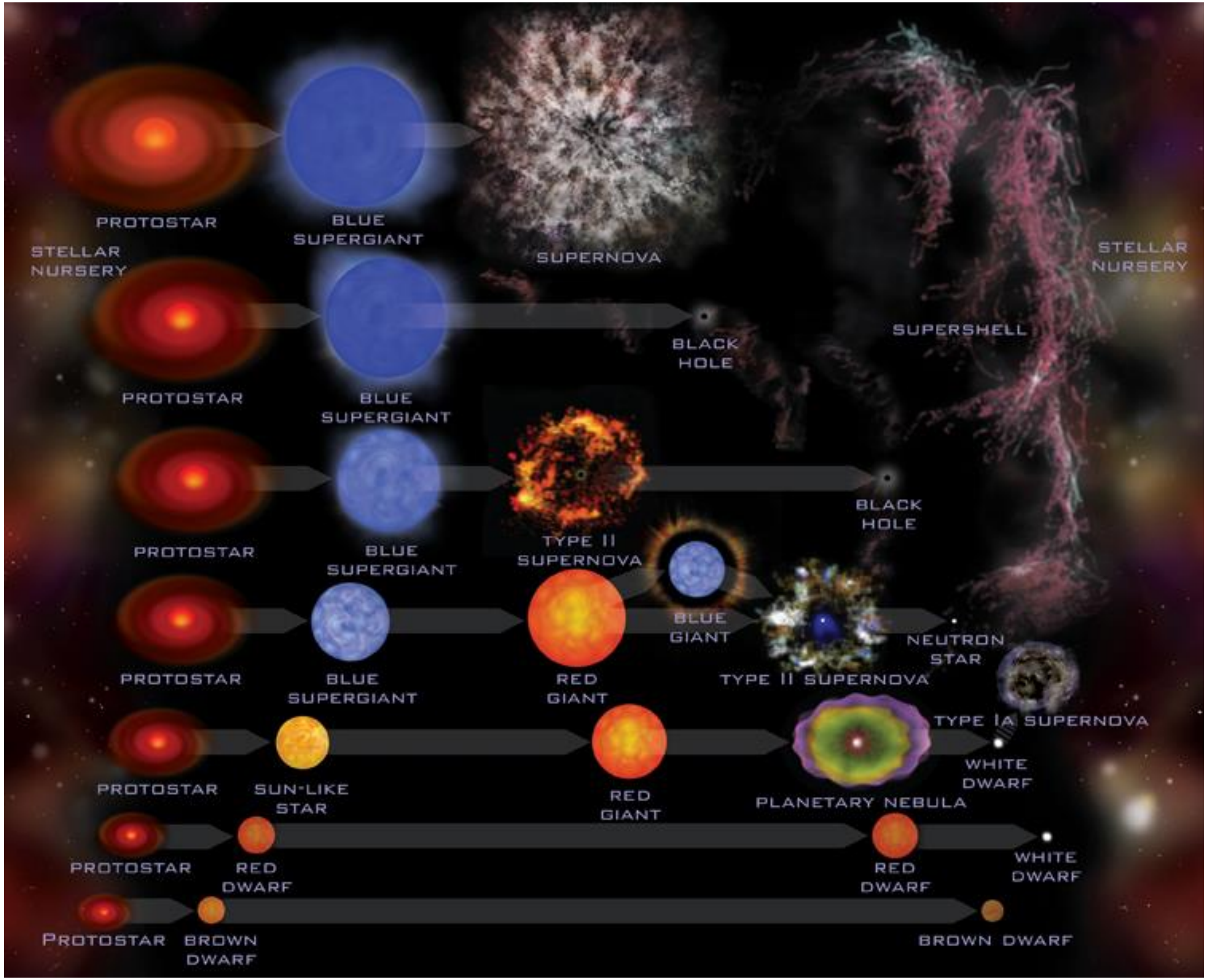




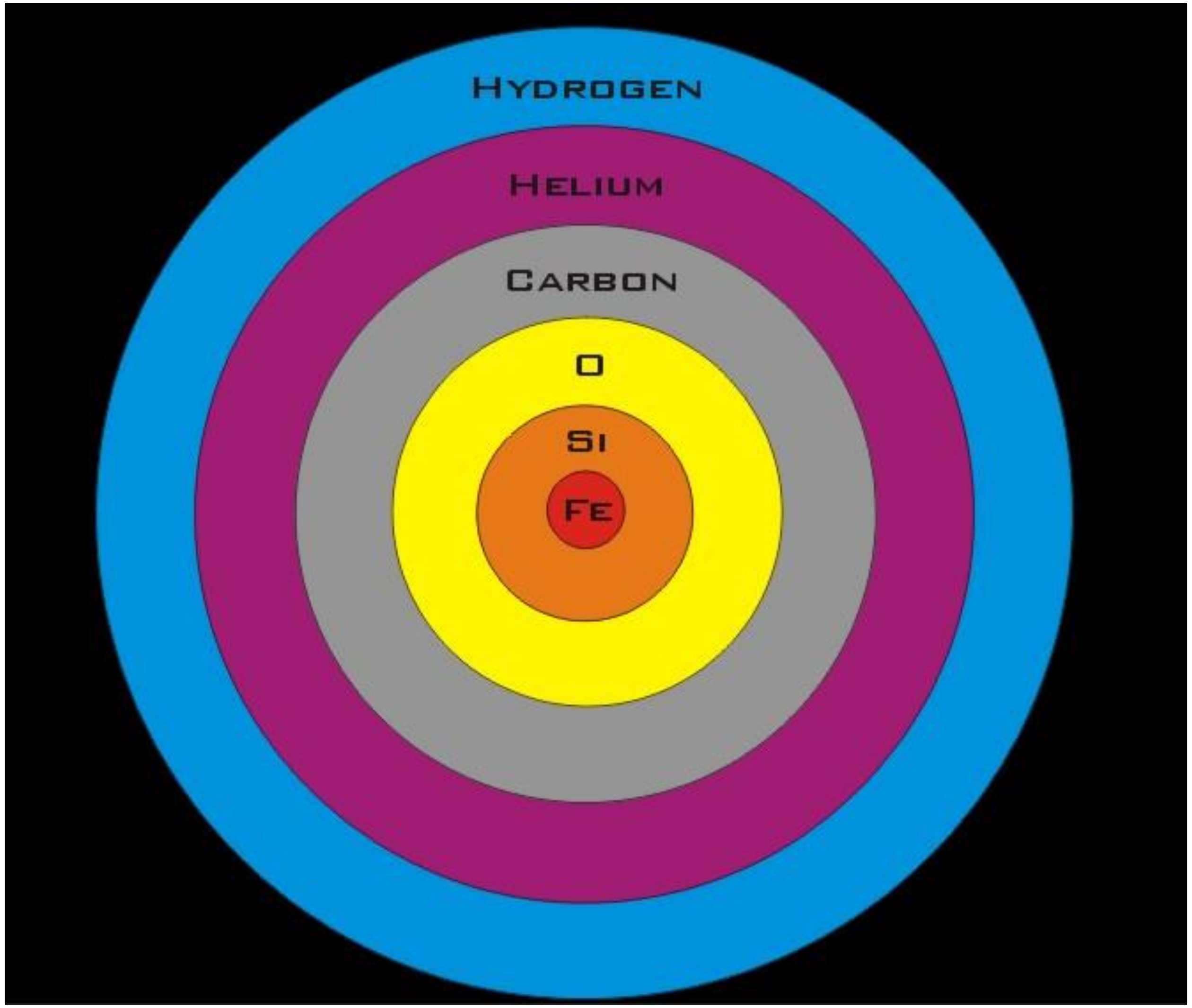
Nuclear Chart



Star’s Life

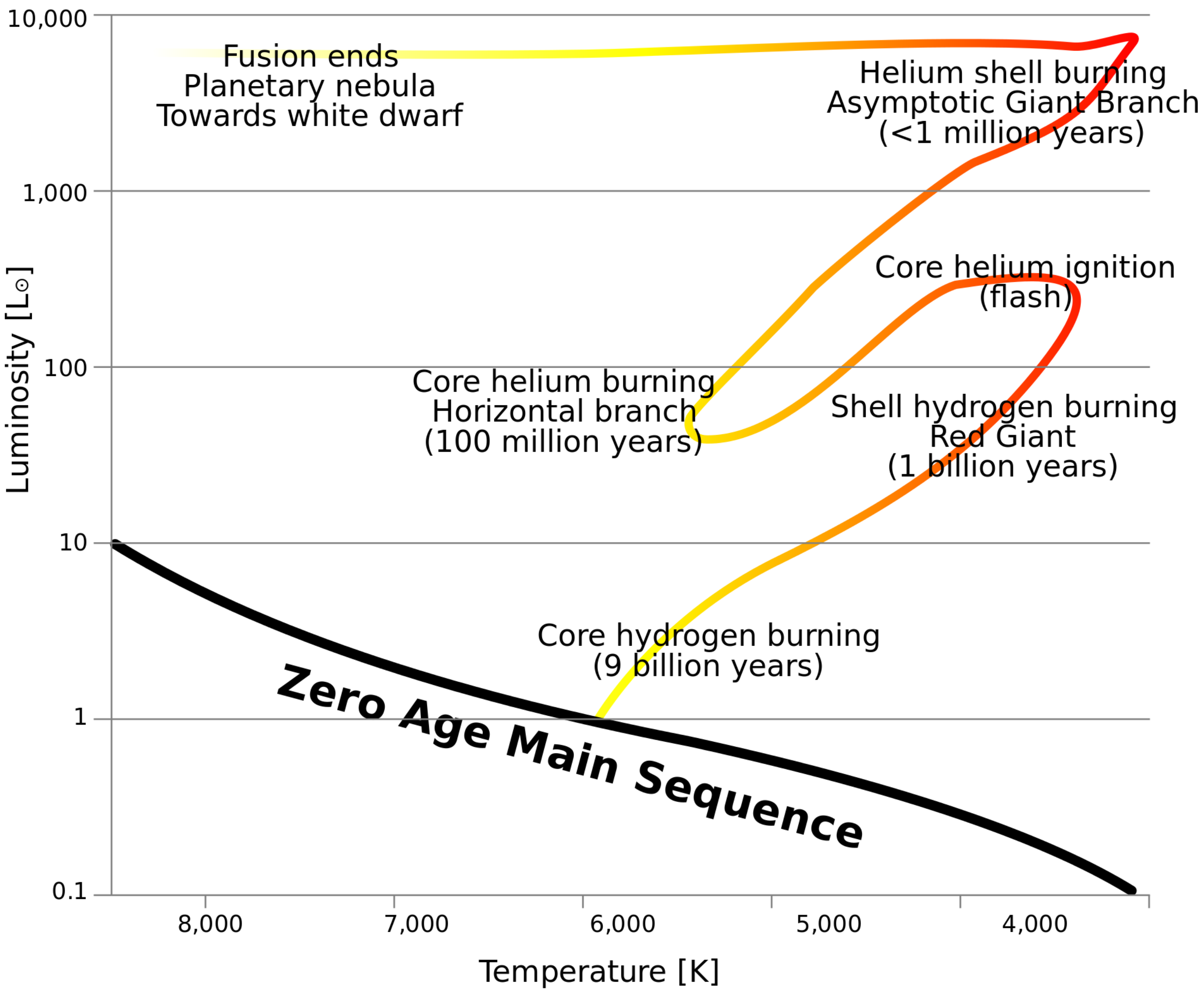

PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

Inside of Old Massive Star: Onion-like Structure

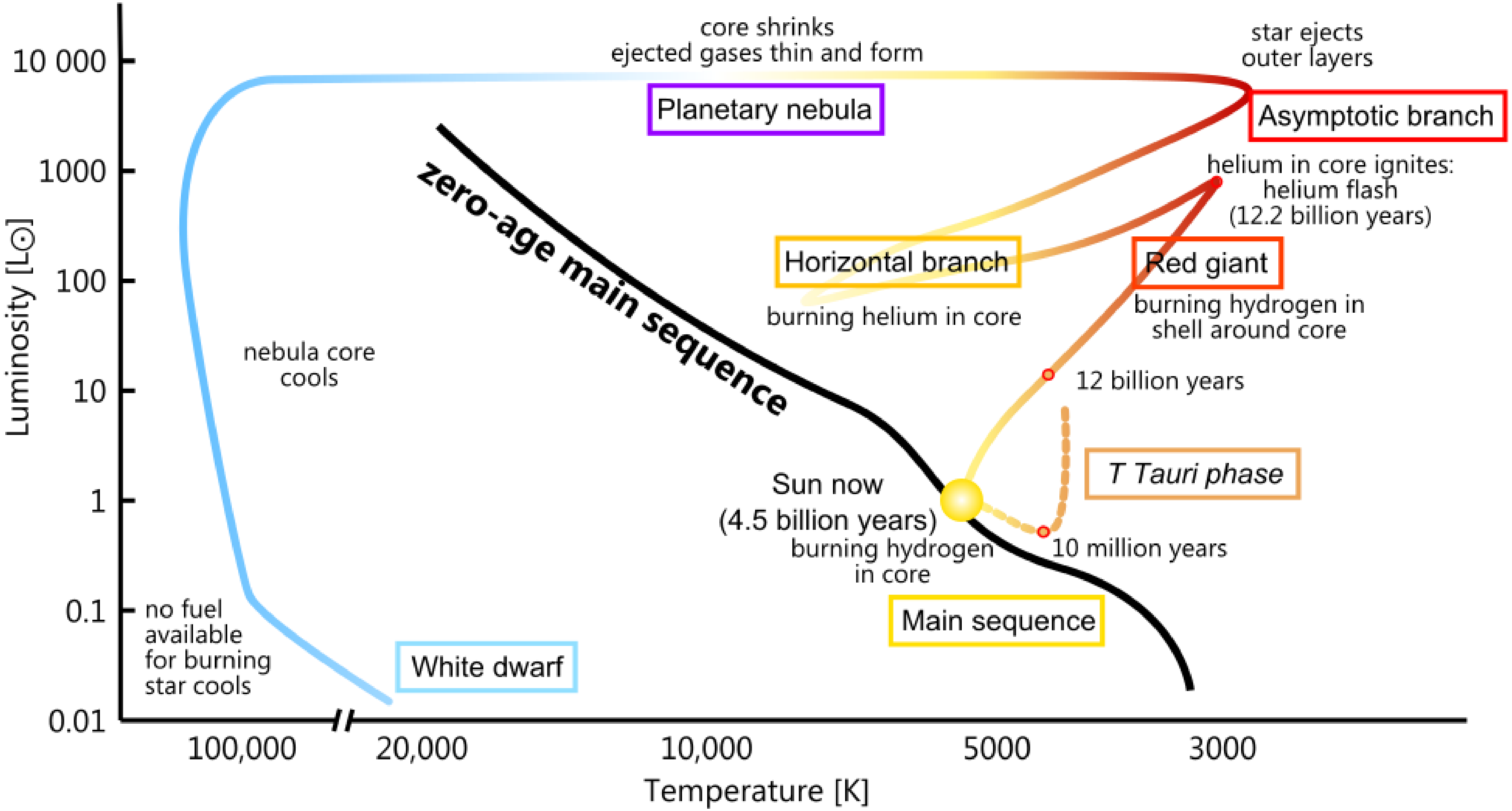


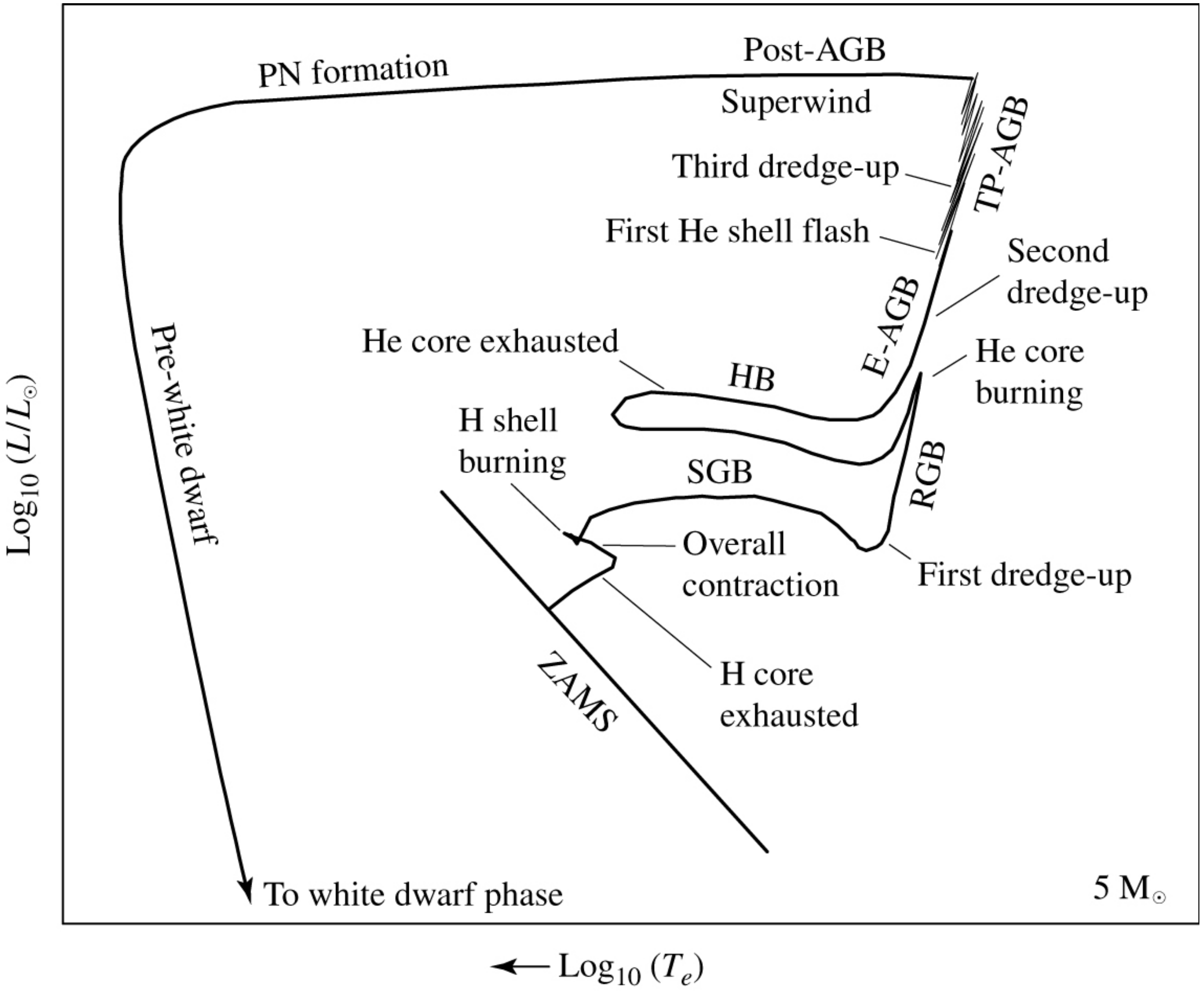
Evolution of the Sun

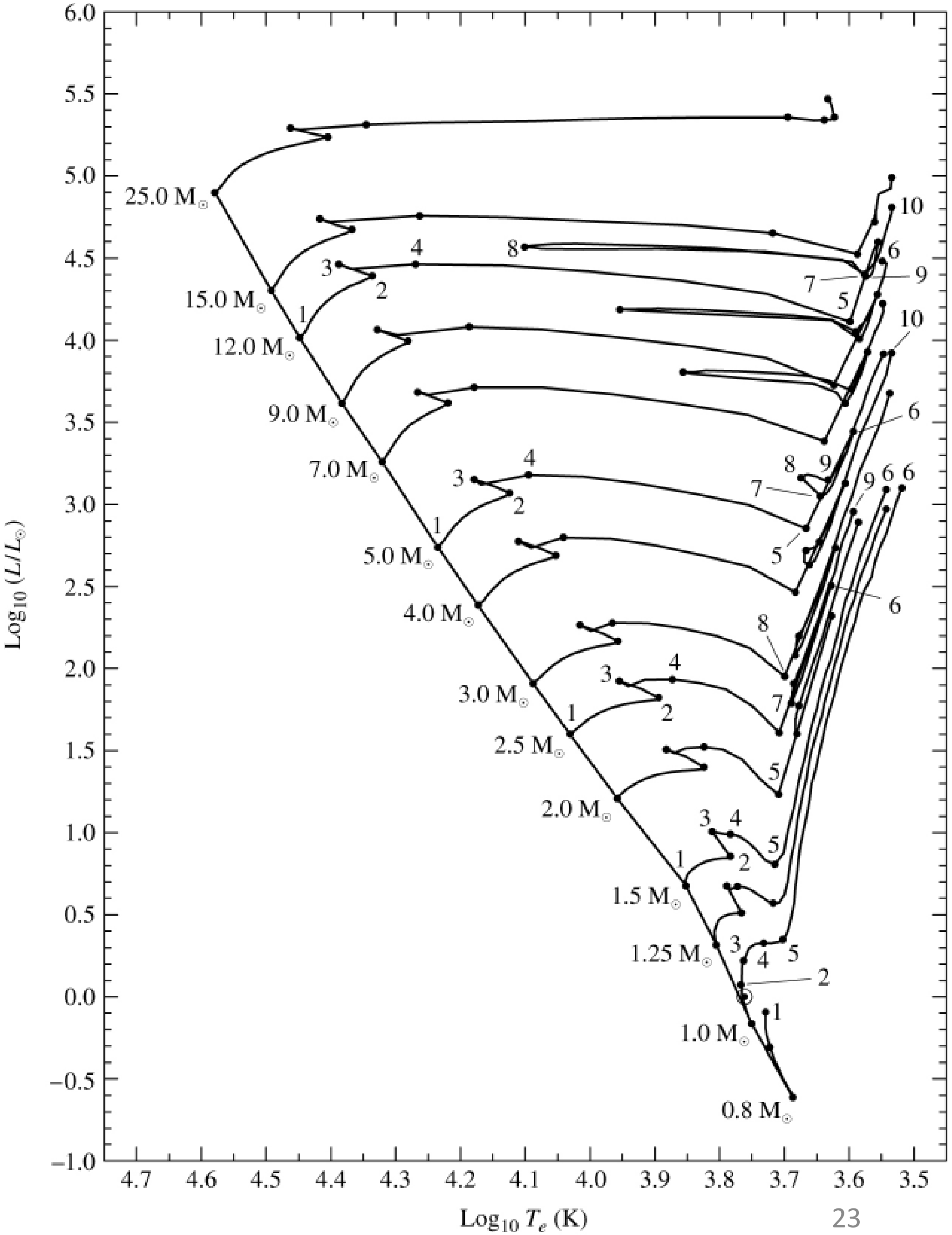
from main sequence to end of fusion

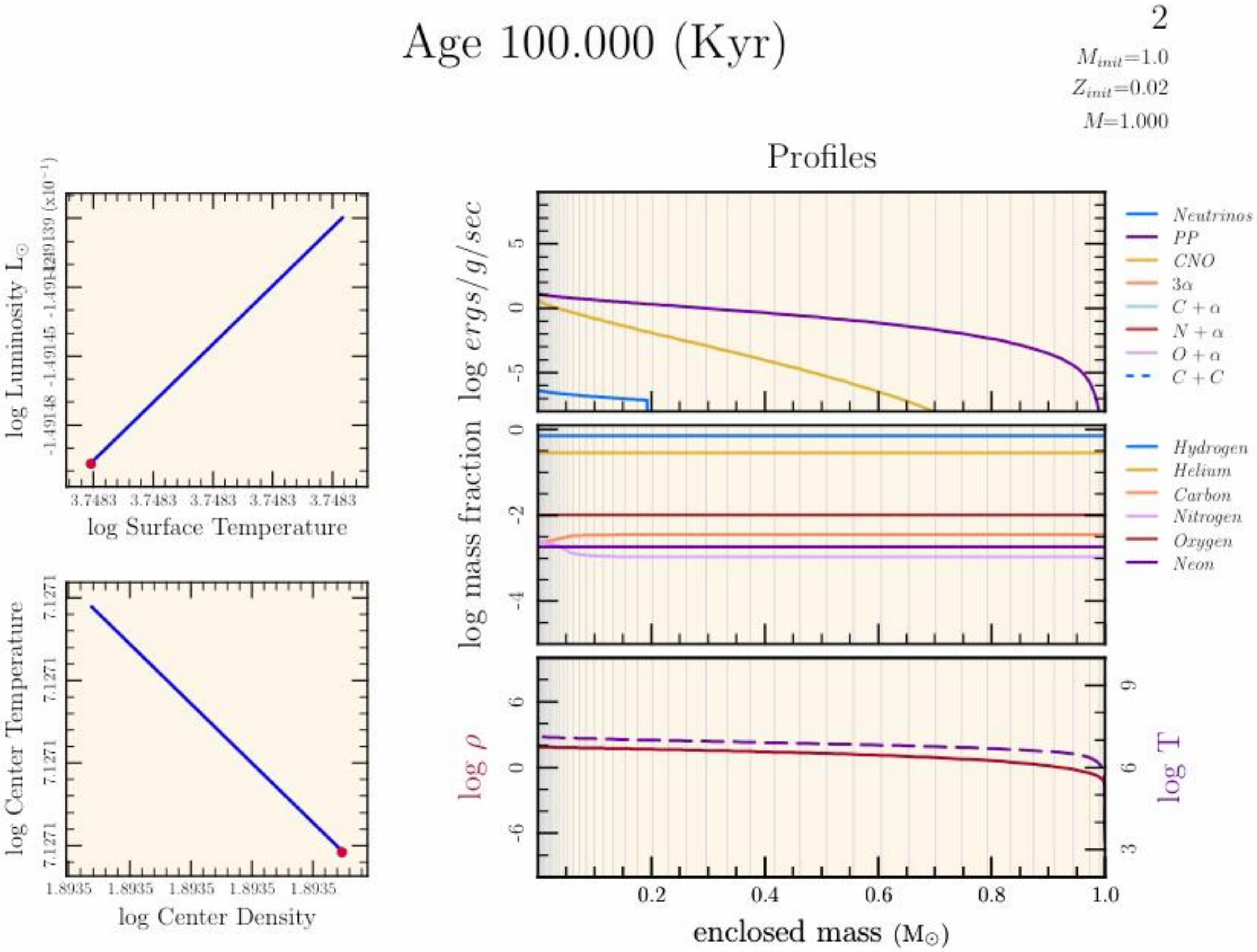


	~9 Ga		~1 Ga		~100 Ma		~10 000 a		
Stage:	Main sequence	>	Red giant	>	Horizontal branch	>	Planetary nebula	>	White dwarf
Sun's age:	4.5 Ga (now)		12.2 Ga		12.3 Ga		12.3305 Ga		12.3306 Ga




PN formation
Post-AGB
Superwind
Third dredge-up
TP-AGB
First He shell flash
Second dredge-up
E-AGB
He core exhausted
HB
He core burning
H shell burning
SGB
RGB
Overall contraction
First dredge-up
H core exhausted
ZAMS
Pre-white dwarf
To white dwarf phase
5 M$_\odot$
Log$_{10}$ ($L/L_\odot$)
← Log$_{10}$ (T_e)


25.0 M$_\odot$
15.0 M$_\odot$
12.0 M$_\odot$
9.0 M$_\odot$
7.0 M$_\odot$
5.0 M$_\odot$
4.0 M$_\odot$
3.0 M$_\odot$
2.5 M$_\odot$
2.0 M$_\odot$
1.5 M$_\odot$
1.25 M$_\odot$
1.0 M$_\odot$
0.8 M$_\odot$
1
2
3
4
5
6
7
8
9
10
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
4.7
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
Log$_{10}$ ($L/L_\odot$)
Log$_{10}$ T_e (K)


Age 100.000 (Kyr)
2
M_{init}=1.0
Z_{init}=0.02
M=1.000
log Luminosity L⊙
-1.49148
-1.49145
-1.49142
-1.49139
(x10⁻¹)
3.7483
3.7483
3.7483
3.7483
3.7483
log Surface Temperature
log Center Temperature
7.1271
7.1271
7.1271
7.1271
1.8935
1.8935
1.8935
1.8935
1.8935
log Center Density
Profiles
log ergs/g/sec
5
0
-5
Neutrinos
PP
CNO
3α
C + α
N + α
O + α
C + C
log mass fraction
0
-2
-4
Hydrogen
Helium
Carbon
Nitrogen
Oxygen
Neon
log ρ
6
0
-6
log T
9
6
3
0.2
0.4
0.6
0.8
1.0
enclosed mass (M⊙)

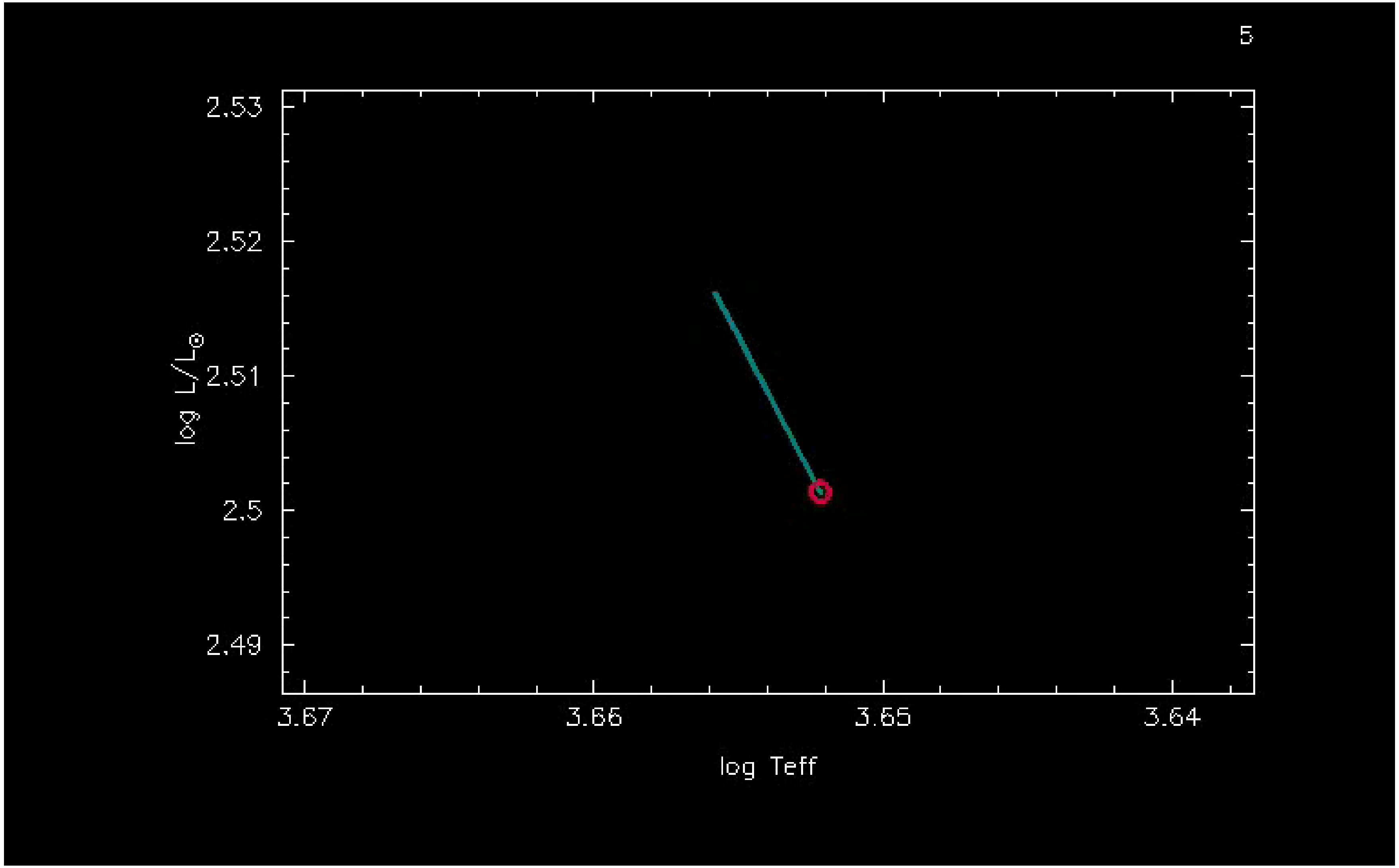
Simulation Tool: MESA

Paxton et al. 2011, ApJS (MESA I)

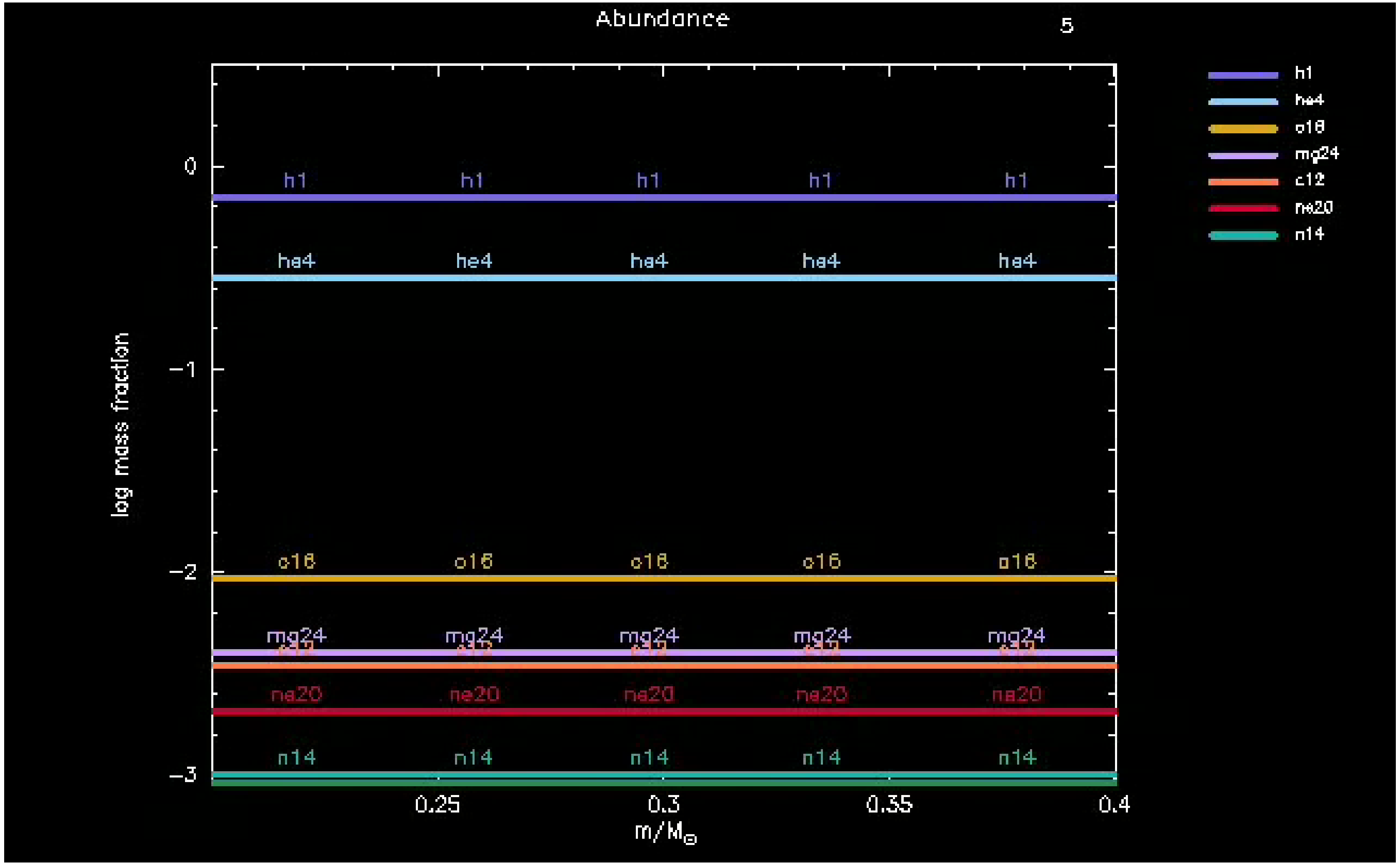
Modules for Experiments in Stellar Astrophysics

- 1D stellar evolution code
- **Openness**: anyone can download sources from the website.
- **Modularity**: independent modules for physics and for numerical algorithms; the parts can be used stand-alone.
- **Wide Applicability**: capable of calculating the evolution of stars in a wide range of environments.
- **Comprehensive Microphysics**: up-to-date, wide-ranging, flexible, and independently useable microphysics modules.
- **Modern Techniques**: advanced AMR, fully coupled solution for composition and abundances, mass loss and gain, etc.

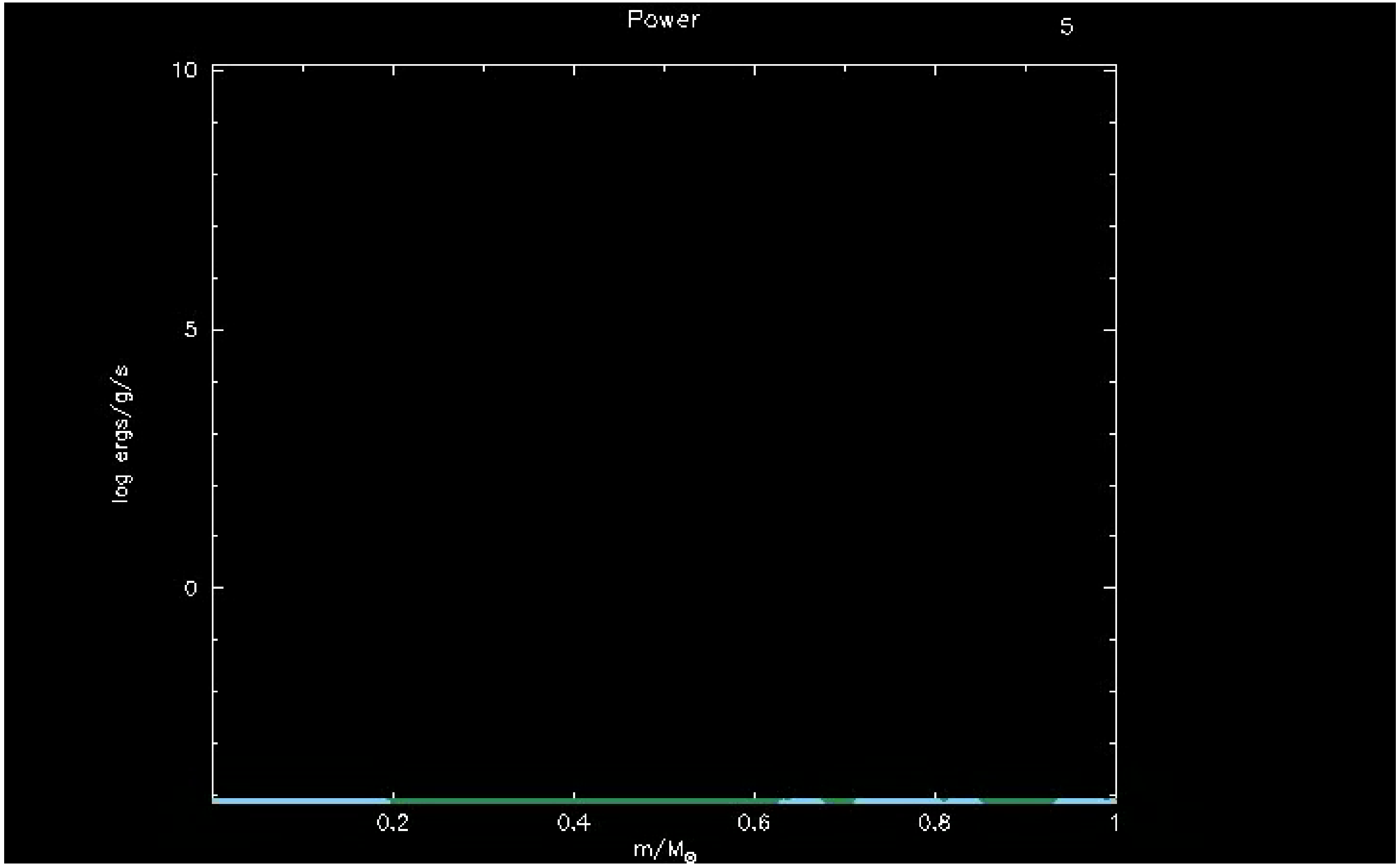
Evolution of the Sun Traced by MESA



Nuclear Reactions inside the Sun

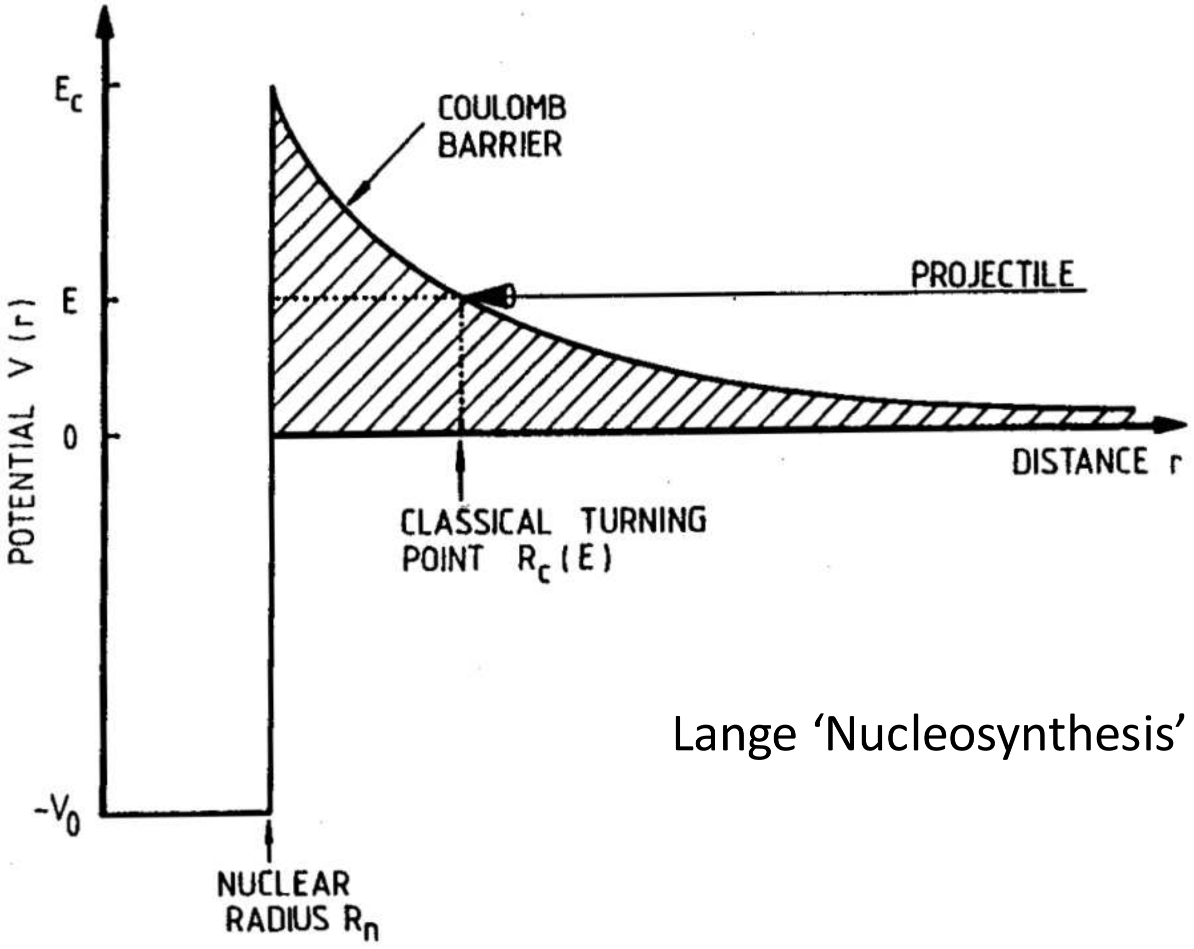


Energy Generation



Thermonuclear Reactions

(for a dummy like me)



Lange ‘Nucleosynthesis’ SS 2012

C. Nuclear reaction rate

Definition: nuclear reaction rate $\boxed{r_{xy} := N_x \cdot N_y \cdot v \cdot \sigma(v)}$

with: N_x, N_y number density of particles x, y (i.e., particles per cm^3)
v relative velocity between x and y
$\sigma(v)$ cross section
$[r]$ = reactions per cm^3 per s = $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$

- in stellar gas: Maxwell-Boltzmann distribution of velocities $\Phi(v)$

$\Rightarrow$ $r_{xy} = N_x N_y \langle\sigma v\rangle$

$$\text{with } \langle\sigma v\rangle := \int_0^\infty \Phi(v) v \sigma(v) dv$$

$$\Phi(v) = 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right) = f(T)$$

$$\text{with } m = \frac{m_x m_y}{m_x + m_y} = \text{“reduced mass”}$$

$$E = \tfrac{1}{2} m v^2$$

$$\Rightarrow \boxed{\langle\sigma v\rangle = \left(\frac{8}{\pi m}\right)^{\frac{1}{2}} \frac{1}{(kT)^{\frac{3}{2}}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE}$$

E. Astrophysical S-factor

Cross section (B) $\Rightarrow \sigma(E) \sim \pi\lambda^2 \sim 1/E$

Tunnel effect (D) $\Rightarrow \sigma(E) \sim \exp(-2\pi\eta),\ \eta \sim 1/\sqrt{E}$

$\Rightarrow$ define S(E) such that

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\cdot S(E)$$

$$\Rightarrow \langle\sigma v\rangle = \left(\frac{8}{\pi m}\right)^{1/2}\frac{1}{(kT)^{3/2}}\int_0^\infty S(E)\exp\left[-\frac{E}{kT}-\frac{b}{\sqrt{E}}\right]dE$$

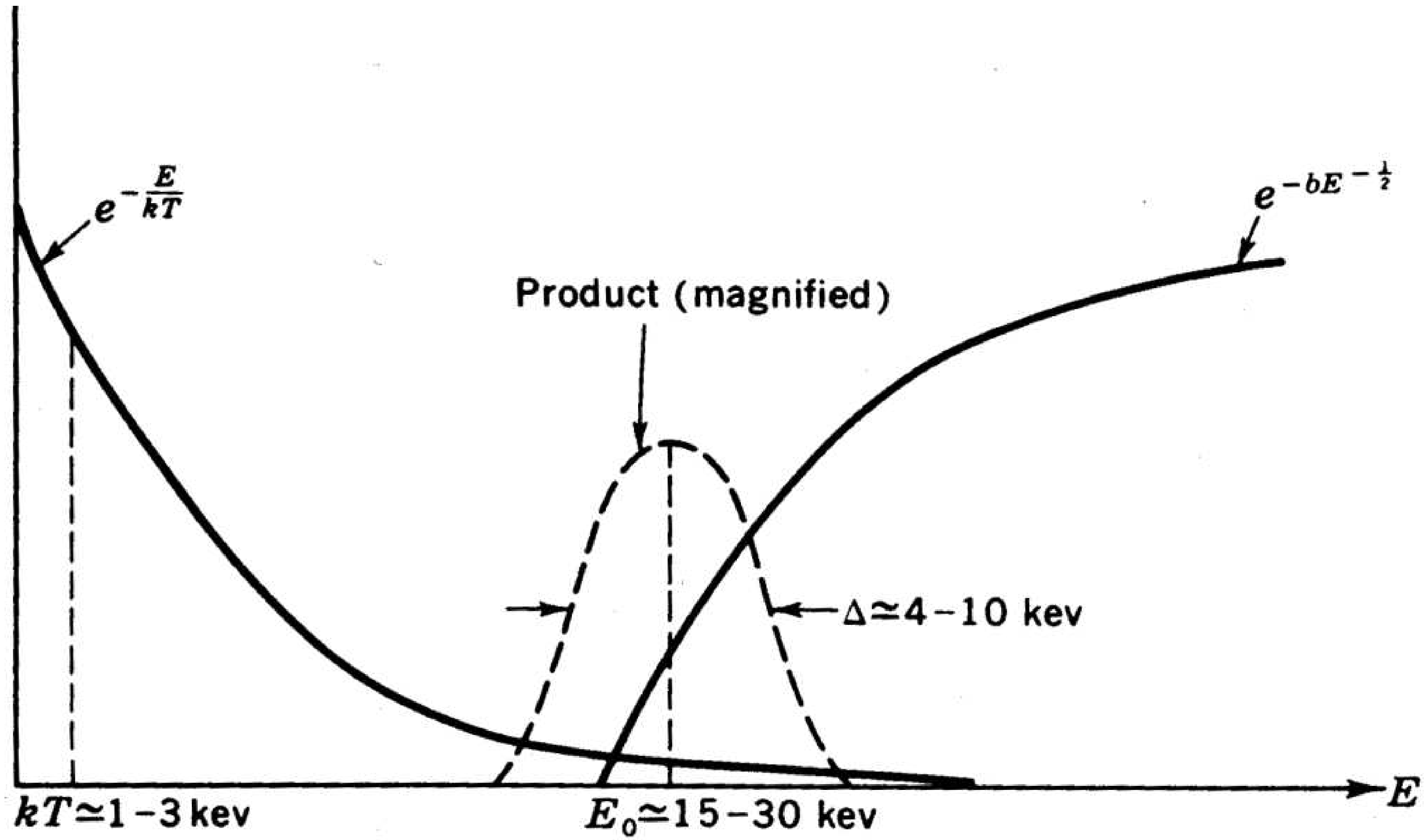
with $b := (2m)^{1/2}\pi e^2 Z_x Z_y/\hbar$

$= 0.989 Z_x Z_y A^{1/2}\quad[(\mathrm{MeV})^{1/2}]$

(b^2 = “Gamow energy”)

- often: S(E) varies slowly with E
  - → Gamow-peak at energy $E_0 > kT$
  - → for narrow T-range: $S(E) \simeq S(E_0) =$ const.

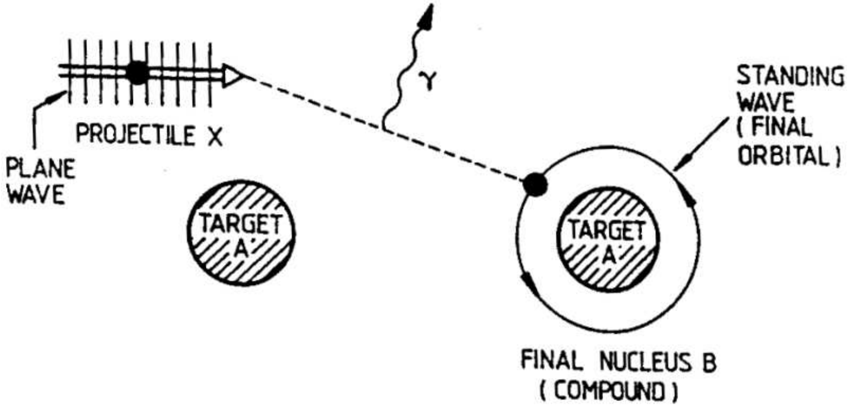
$$\Rightarrow \langle\sigma v\rangle = \left(\frac{8}{\pi m}\right)^{1/2}\frac{1}{(kT)^{3/2}}S(E_0)\int_0^\infty \exp\left(-\frac{E}{kT}-\frac{b}{\sqrt{E}}\right)dE$$

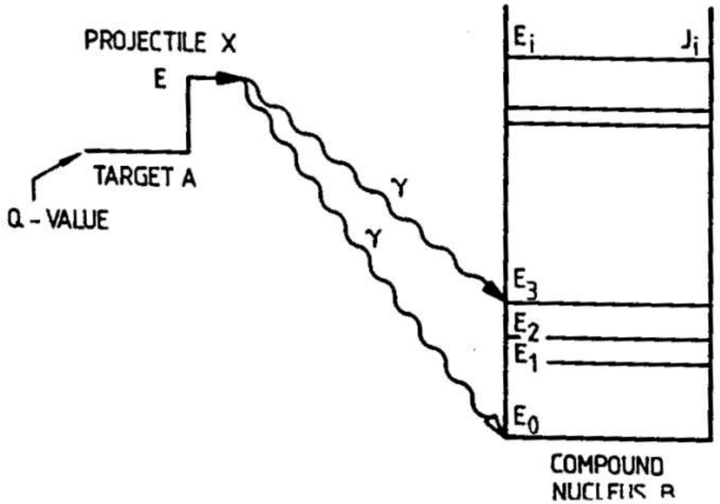

$e^{-\frac{E}{kT}}$
$e^{-bE^{-\frac{1}{2}}}$
Product (magnified)
$\Delta \simeq 4-10$ kev
$kT \simeq 1-3$ kev
$E_0 \simeq 15-30$ kev
E

direct capture reaction : A(X , γ)B

nucleus A captures projectile X directly to the low-energy state of nucleus B (see Fig. 2.7)

→ σ varies smoothly with energy
→ all projectile energies above Q-value are possible
→ non-resonant reaction



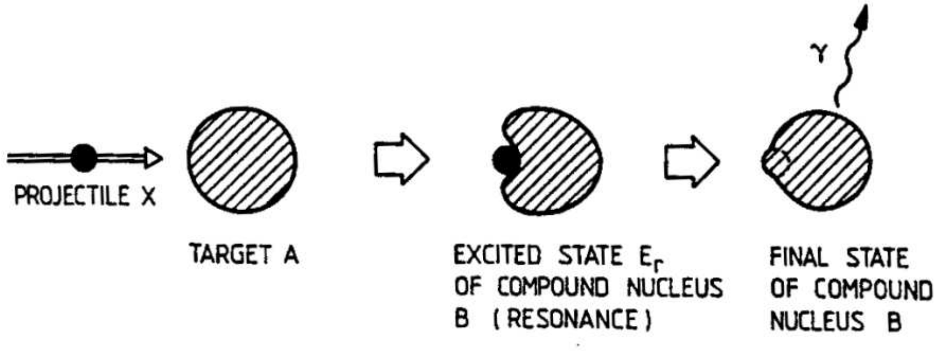


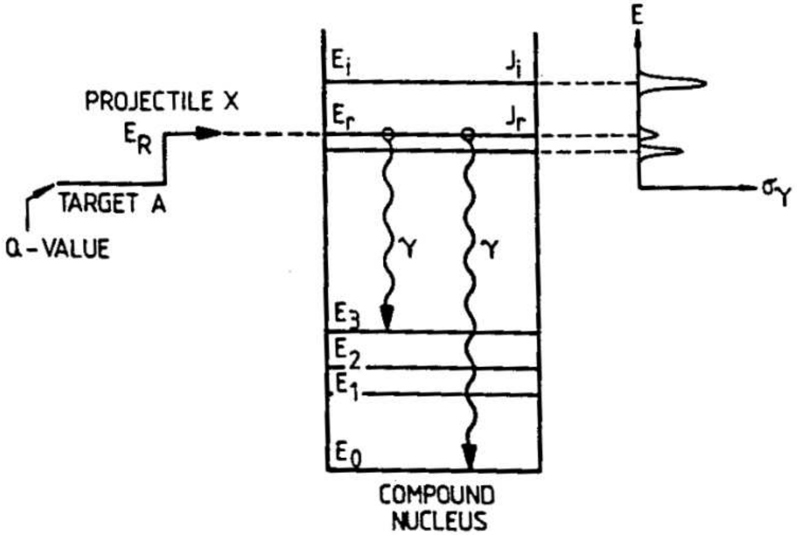
resonant capture reaction : $A(X,\gamma)B$

$A + X$ form excited compound nucleus B^*, which later decays to low-energy state
$B^* \to B + \gamma$ (see Fig. 2.8)

→ 2 step process
→ possible only if projectile energy matches the energy level of the excited state B^*!
→ $\sigma(E)$ may have large local maxima
→ resonant reaction

⇝ energy levels of nuclei often not accurately known





Complications

- Metallicity
- Convection
- Mass Loss
- Rotation
- Magnetic Field
- And More

Convection: Mixing Length Theory

$$V_{\rm conv}=\frac{1}{2}\left(\frac{GM}{\rho r^2}\Delta\nabla\rho\right)^{1/2} l,$$

$$D_{\rm conv}=\frac{1}{3}V_{\rm conv}l.$$

$$\left(\frac{\partial Y_i}{\partial t}\right)_{\rm conv}=\frac{\partial}{\partial M(r)}\left[(4\pi r^2\rho)^2 D\,\frac{\partial Y_i}{\partial M(r)}\right],$$

Mass Loss

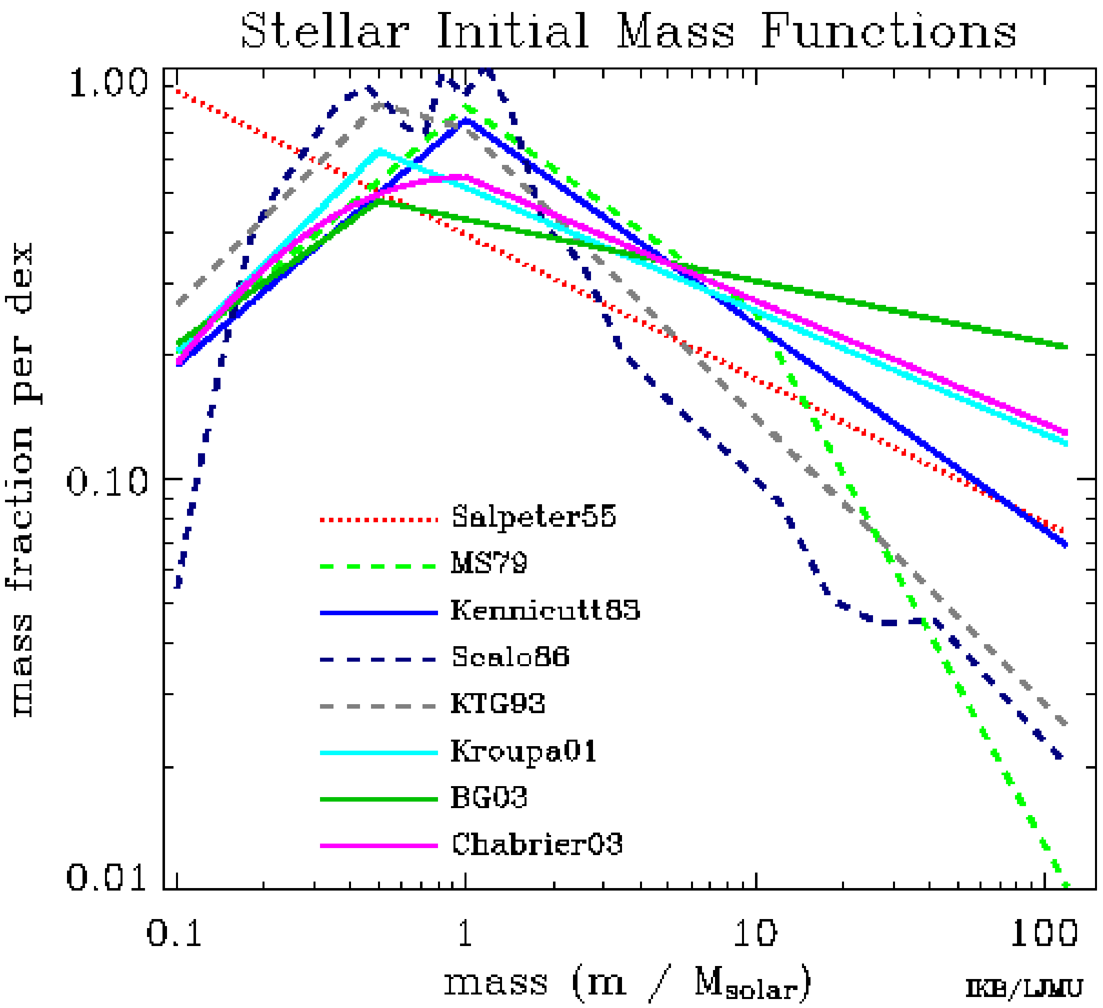
$$\log\left(\frac{\dot{M}}{M_\odot\ \mathrm{yr}^{-1}}\right)=\begin{cases}-12.43+1.5\log(L/L_\odot)-2.85X_\mathrm{s} & \text{if}\quad \log(L/L_\odot)\geqslant 4.45\\ -36.28+6.8\log(L/L_\odot) & \text{if}\quad \log(L/L_\odot)<4.45,\end{cases}$$

MESA: Dutch Wind Scheme
A Combination of
Glebbeek et al. 2009
Vink et al. 2001
Nugis & Lamers 2000
Nieuwenhuijzen & de Jager 1990

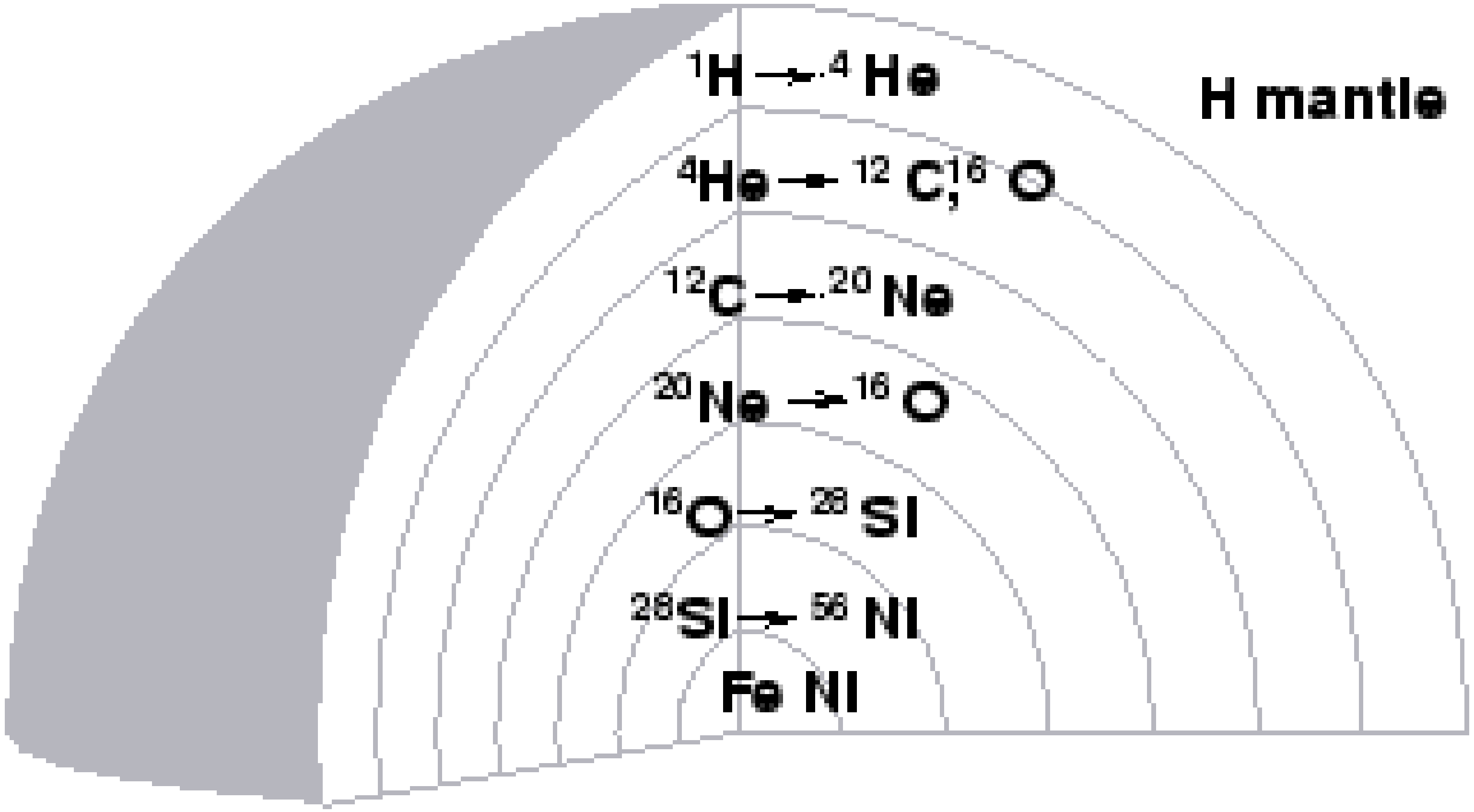
MESA: Updates

- Paxton et al. 2013, ApJS (MESA II)
- Rotation
    - Affects mixing, angular momentum transport, and mass loss
    - Effect of internal magnetic field through dynamo: mixing and angular momentum transport
- New Treatment of Convection
    - Reduces computing times in radiation-dominated convective regions
    - Allows for the calculation down to core-collapse

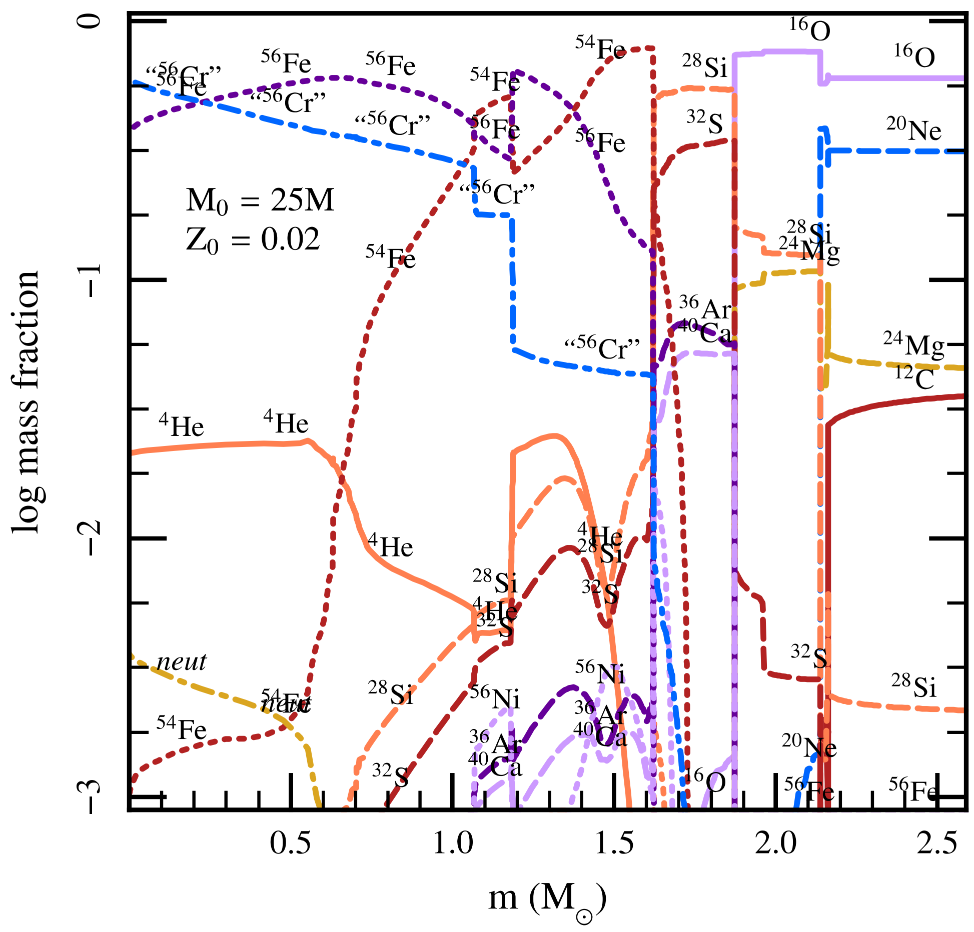
Initial Mass Function



Pre-supernova near the end of a massive star’s life

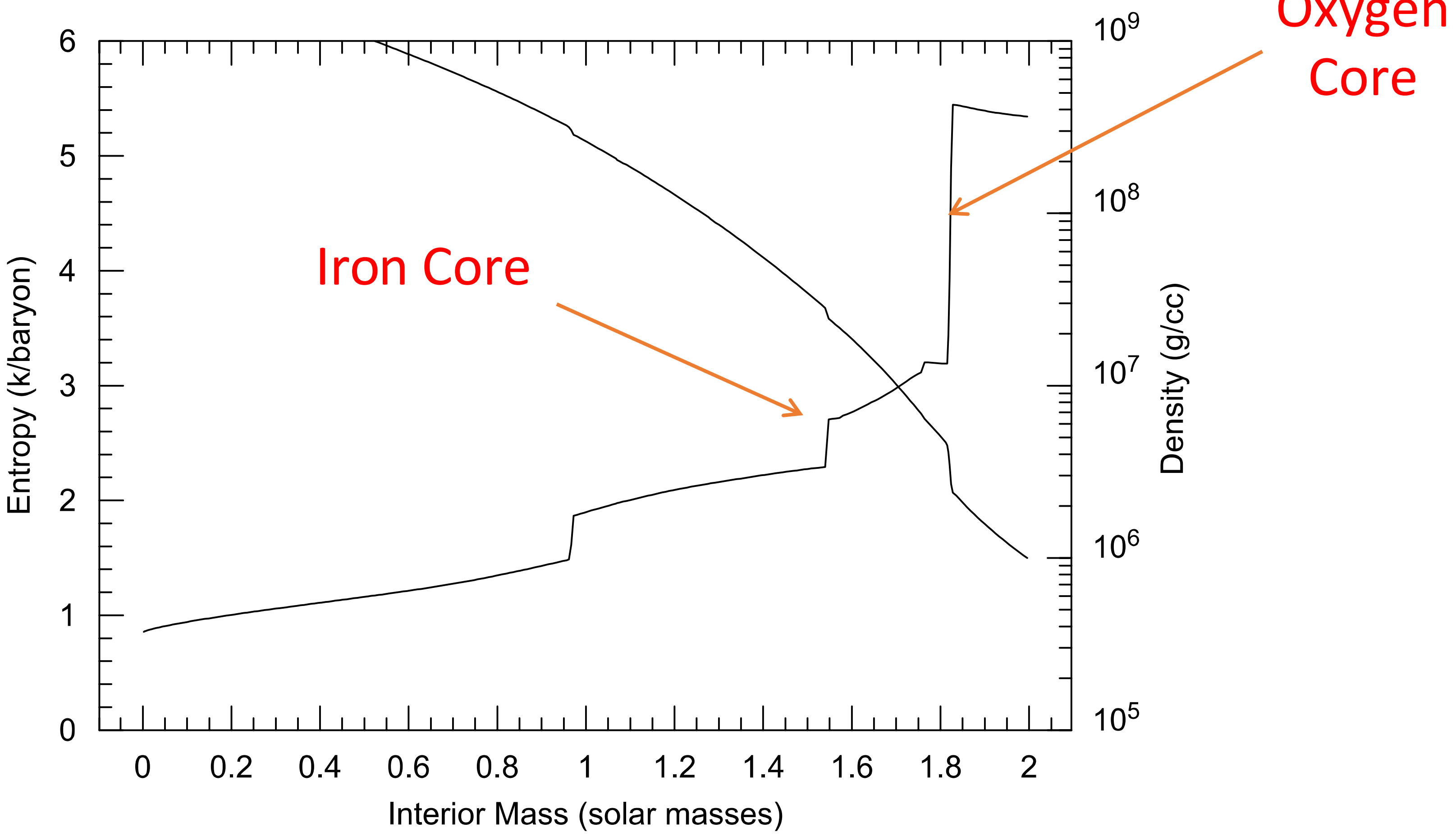


Onion-like Structure of Pre-Supernova



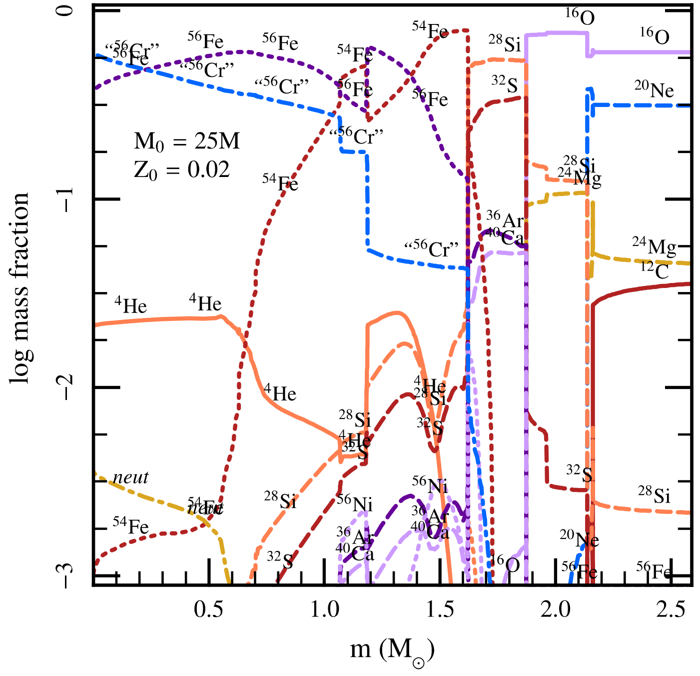
Paxton et al. 2011, ApJS (MESA I)

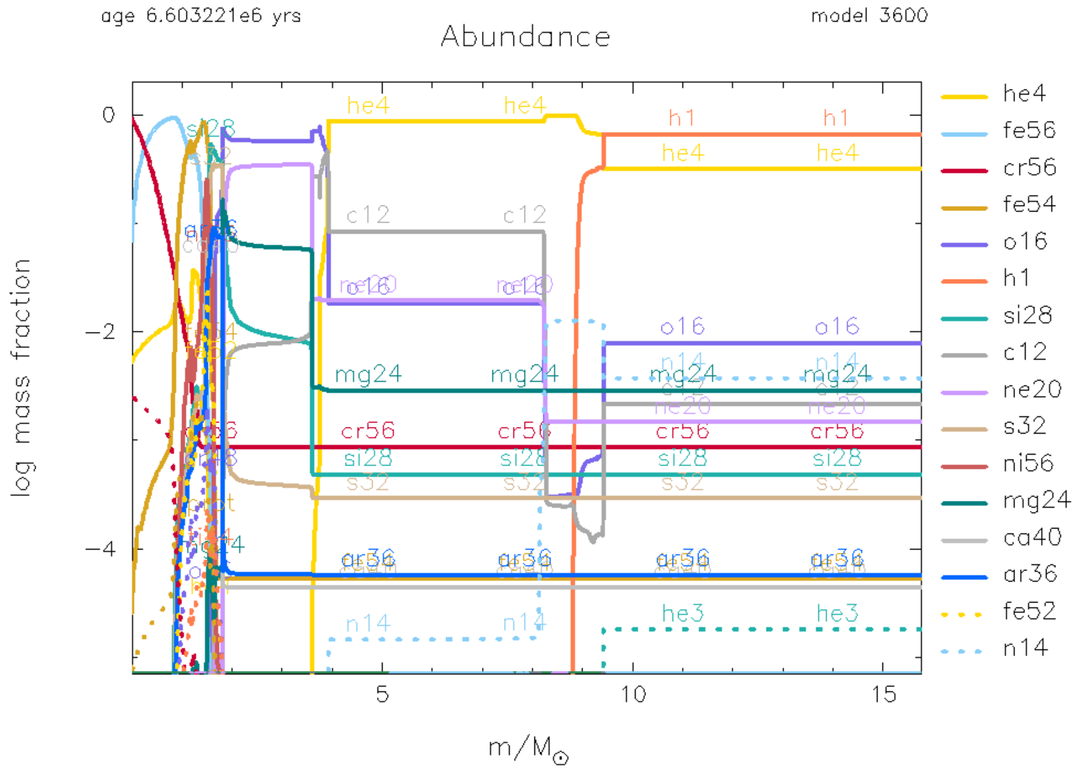
Where does the bounce begin?

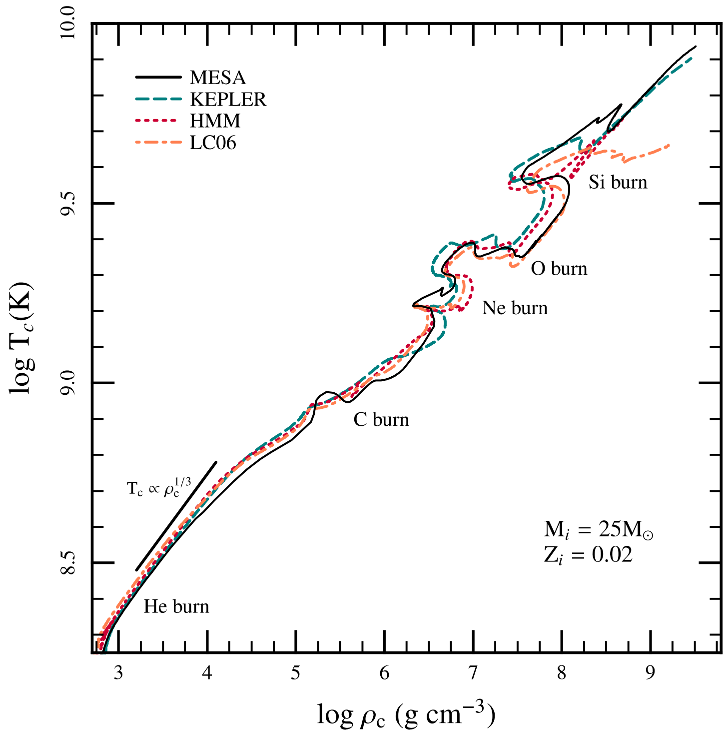


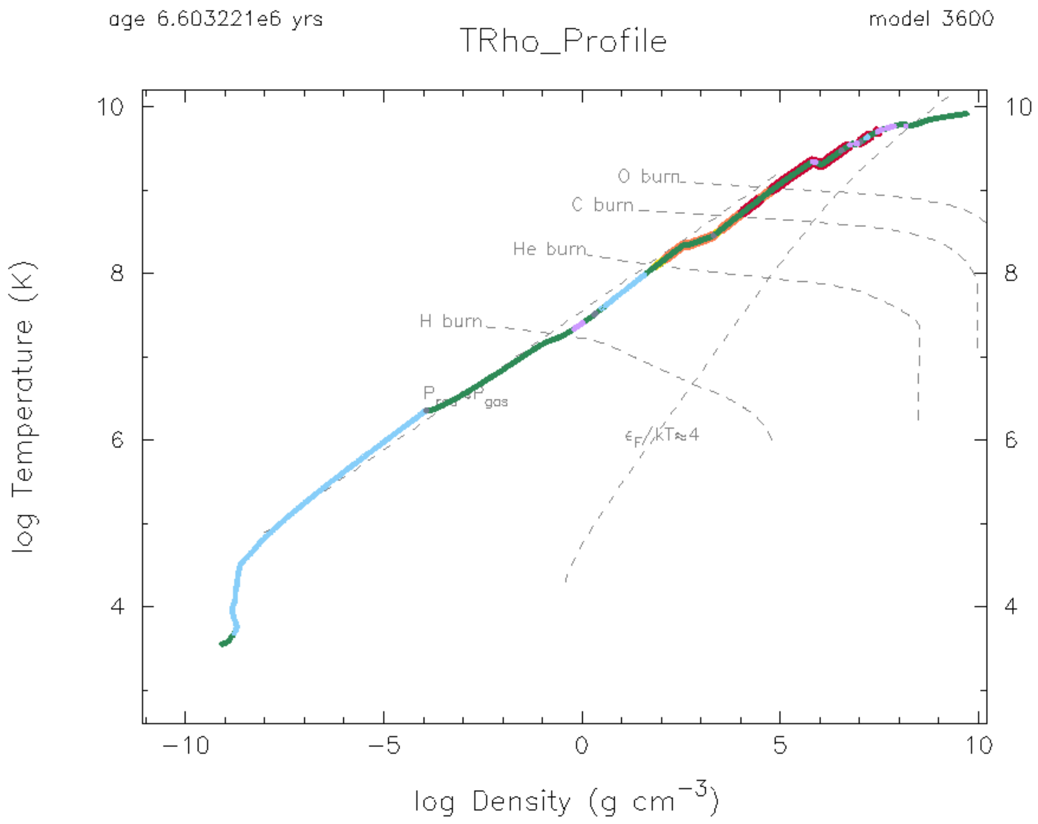
Woosley & Heger, 2007 (from 20 M_sun)

25 M⊙ with Solar Metallicity






MESA
KEPLER
HMM
LC06
Si burn
O burn
Ne burn
C burn
He burn
$T_c \propto \rho_c^{1/3}$
$M_i = 25M_\odot$
$Z_i = 0.02$
log T_c(K)
10.0
9.5
9.0
8.5
3
4
5
6
7
8
9
log ρ_c (g cm^{-3})


age 6.603221e6 yrs
TRho_Profile
model 3600
O burn
C burn
He burn
H burn
$P_{rad} = P_{gas}$
$\epsilon_F / kT \approx 4$
log Temperature (K)
10
8
6
4
−10
−5
0
5
10
log Density (g cm^{-3})

H Burning (p-p chain)

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

p-p-I: 85%	p-p-II: 15%	p-p-III: 0.01%
${}^{3}He + {}^{3}He \rightarrow \alpha + p + p$	${}^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$	${}^{3}He + \alpha \rightarrow {}^{7}Be + \gamma$
	${}^{7}Be + e^{-} + {}^{7}Li + \nu_e$	${}^{7}Be + p \rightarrow {}^{8}B + \gamma$
	${}^{7}Li + p \rightarrow \alpha + \alpha$	${}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu_e$
		${}^{8}Be \rightarrow \alpha + \alpha$

Nuclear Reactions during MS

- Hydrogen Burning through CNO cycle

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(e^{+}\nu)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(e^{+}\nu)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$$

- Helium Burning

$$3\alpha \rightarrow {}^{12}\mathrm{C}$$

$$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$$

$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^{+}\nu)^{18}\mathrm{O}$$

Nuclear Synthesis during H Burning

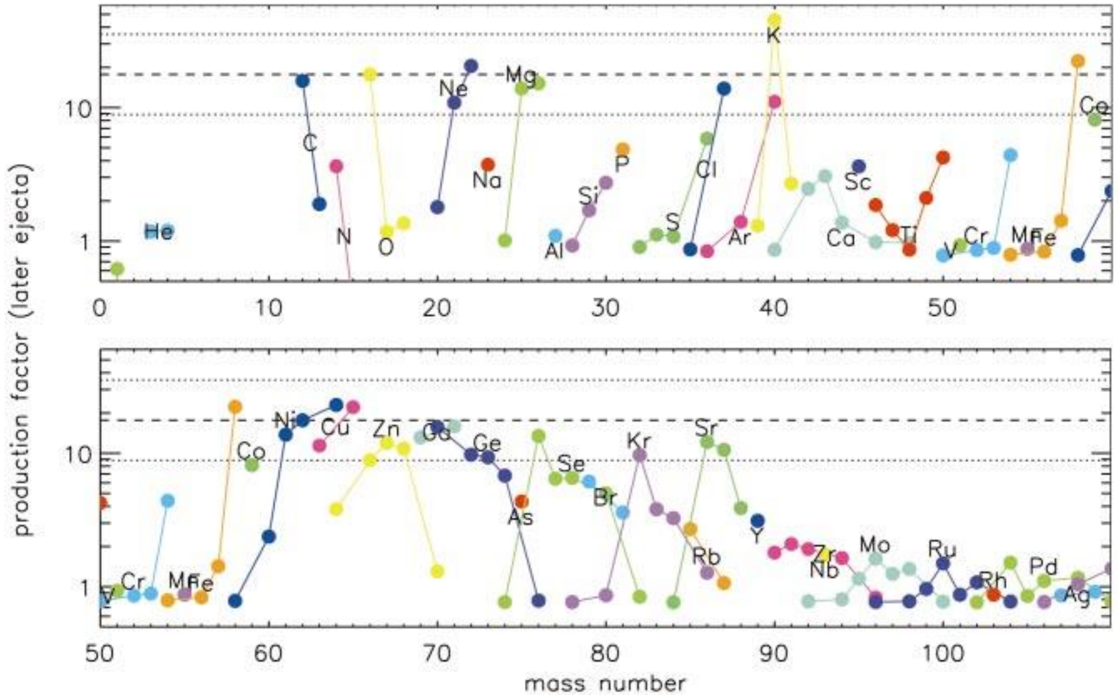
- $^{14}N(p,\gamma)^{15}N$
- $^{12}C(p,\gamma)^{13}C$
- $^{25}Mg(p,\gamma)^{26}Al$
- $^{16}O(p,\gamma)^{17}O$
- $^{17}O(p,\gamma)^{18}F$
- $^{17}O(p,\alpha)^{14}N$

Nuclear Synthesis during He Burning

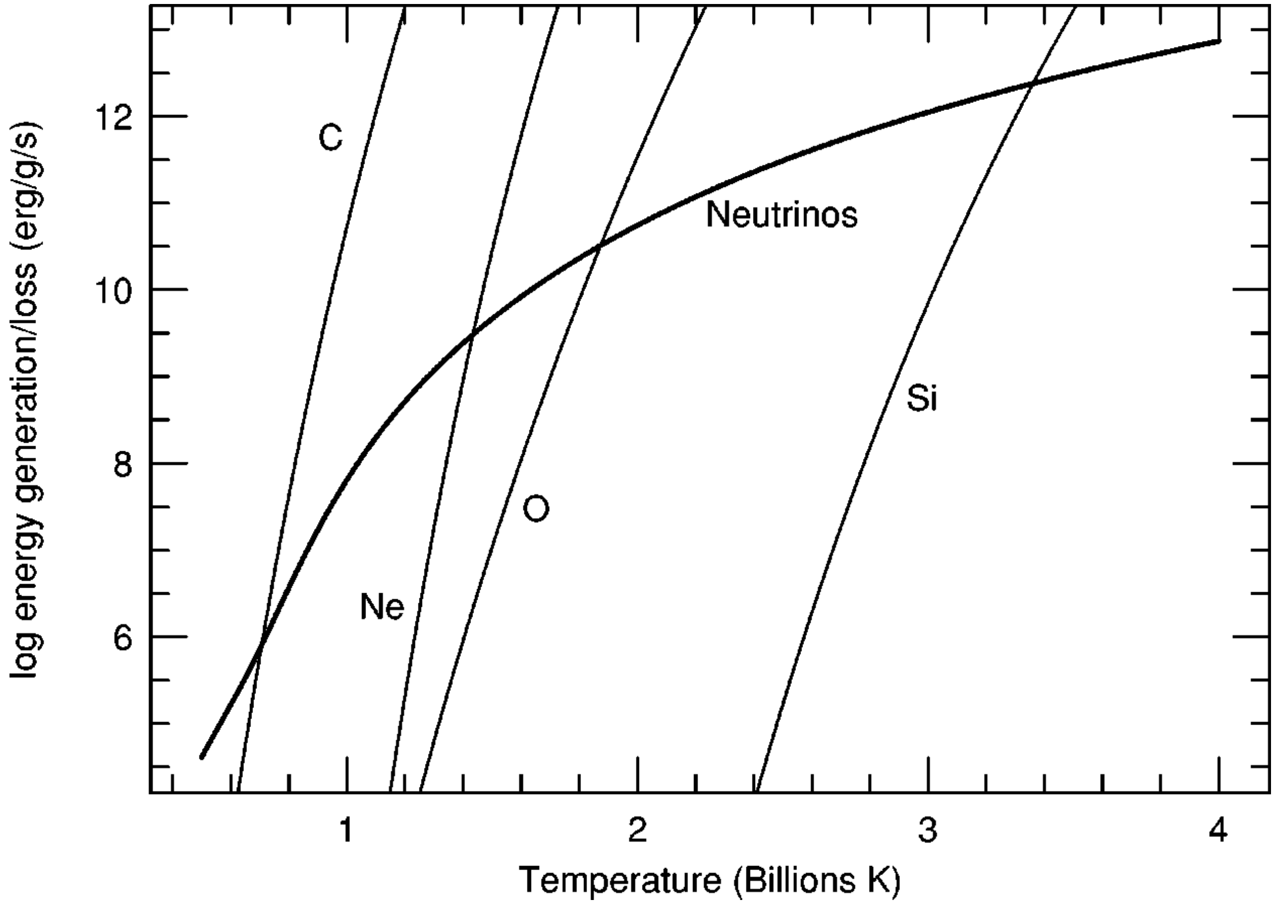
- $^{14}N(\alpha,\gamma)^{18}F(e^+,\nu)^{18}O$
- $^{18}O(\alpha,\gamma)^{22}Ne$
- $^{15}N(\alpha,\gamma)^{19}F$
- $^{18}O(p,\alpha)^{15}N$
- $^{14}N(n,p)^{14}C$

S-process

- Mainly during He burning
    - ^{22}Ne(α,n)^{25}Mg provides neutrons.
    - ^{22}Ne(α,γ)^{26}Mg is also possible.



Advanced Nuclear Burning Stages



C Burning

$$\begin{aligned} {}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* &\rightarrow {}^{23}\mathrm{Mg} + n - 2.62\ \mathrm{MeV} \\ &\rightarrow {}^{20}\mathrm{Ne} + \alpha + 4.62\ \mathrm{MeV} \\ &\rightarrow {}^{23}\mathrm{Na} + p + 2.24\ \mathrm{MeV}. \end{aligned}$$

${}^{20}\mathrm{Ne}(p,\gamma){}^{21}\mathrm{Na}(e^{+}\ \nu){}^{21}\mathrm{Ne}$
${}^{21}\mathrm{Ne}(p,\gamma){}^{22}\mathrm{Na}(e^{+}\ \nu){}^{22}\mathrm{Ne}$

Ne Burning

$$2\ {}^{20}\mathrm{Ne} \rightarrow {}^{16}\mathrm{O} + {}^{24}\mathrm{Mg} + 4.59\ \mathrm{MeV}.$$

${}^{20}\mathrm{Ne}(\gamma,\alpha){}^{16}\mathrm{O}$
${}^{20}\mathrm{Ne}(\alpha,\gamma){}^{24}\mathrm{Mg}$

${}^{24}\mathrm{Mg}(\alpha,\gamma){}^{28}\mathrm{Si}$
${}^{25}\mathrm{Mg}(\alpha,n){}^{28}\mathrm{Si}$
${}^{26}\mathrm{Mg}(\alpha,n){}^{29}\mathrm{Si}$
${}^{26}\mathrm{Mg}(p,n){}^{26}\mathrm{Al}$
……

O Burning

$$
\begin{aligned}
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{32}\mathrm{S}^* &\rightarrow {}^{31}\mathrm{S} + n + 1.45\ \mathrm{MeV} \\
&\rightarrow {}^{31}\mathrm{P} + p + 7.68\ \mathrm{MeV} \\
&\rightarrow {}^{30}\mathrm{P} + d - 2.41\ \mathrm{MeV} \\
&\rightarrow {}^{28}\mathrm{Si} + \alpha + 9.59\ \mathrm{MeV.}
\end{aligned}
$$

Weak Interactions

${}^{30}P(e^+\ \nu){}^{30}S$

${}^{33}S(e^-\ \nu){}^{33}P$

…..

Quasiequilibrium Clusters

${}^{28}Si(n,\gamma){}^{29}Si$

${}^{29}Si(\gamma,n){}^{28}Si$

Si Burning

- Not direct $^{28}\mathrm{Si} + {}^{28}\mathrm{Si} \rightarrow {}^{56}\mathrm{Ni}.$
- Under the quasiequilibrium clusters

$$^{28}\mathrm{Si}(\alpha,\gamma)^{32}\mathrm{S}(\gamma,p)^{31}\mathrm{P}(\gamma,p)^{30}\mathrm{Si}(\gamma,n)^{29}\mathrm{Si}(\gamma,n)^{28}\mathrm{Si},$$

- With the decay of Silicon

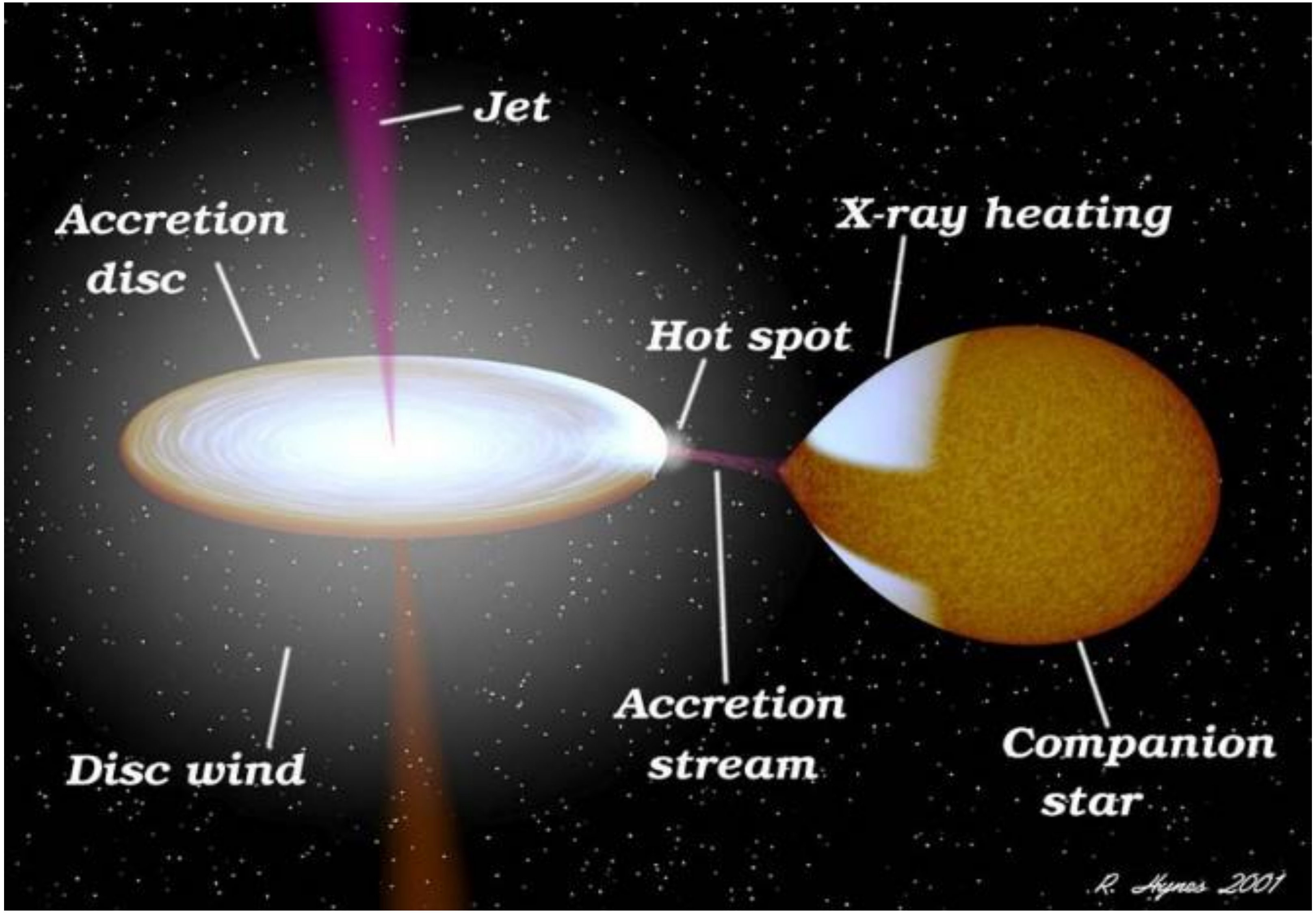
$$^{28}\mathrm{Si}(\gamma,\alpha)^{24}\mathrm{Mg}(\gamma,\alpha)^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}(\gamma,2\alpha)\alpha$$

X-ray Bursts (XRBs)

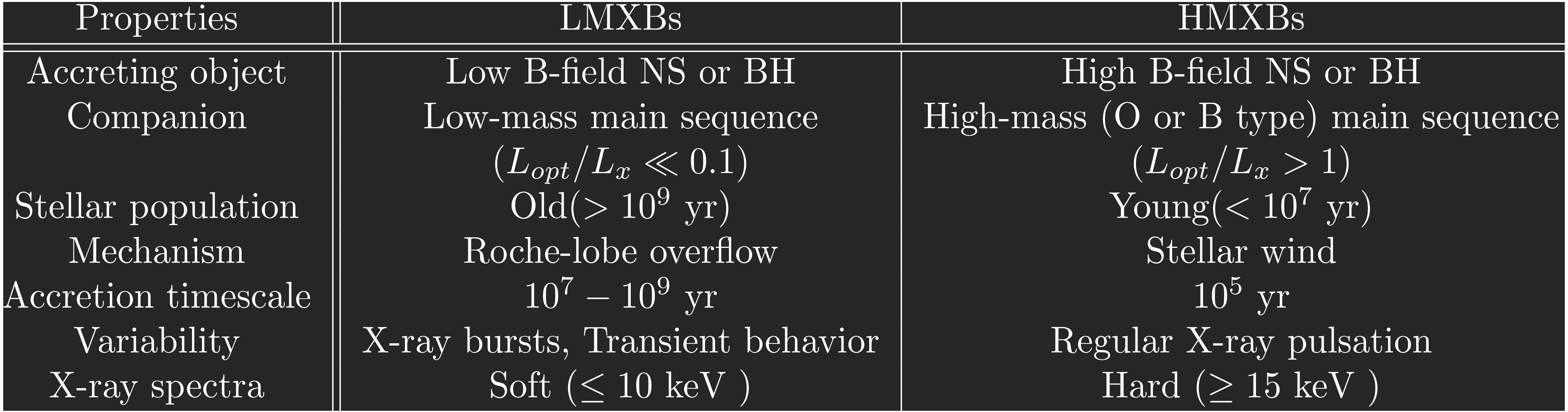
X-ray Binary

- X-ray binary - Wikipedia
- X-ray source first detected in the sky.
- Named as such because it is bright in X-ray and in a binary.
- Depending on the companion star (one of the binary)
  - Low mass X-ray binary (LMXB): a low-mass (dim) companion
  - High mass X-ray binary (HMXB): a high-mass (bright) companion
- Accretion disk around NS or BH is hot enough to emit thermal X-ray. <- This ideas was first proposed to explain the bright X-ray observed and then confirmed by following observations. <- observation of new phenomena followed by theoretical (or modeling) efforts.

Schematic view of X-ray binary



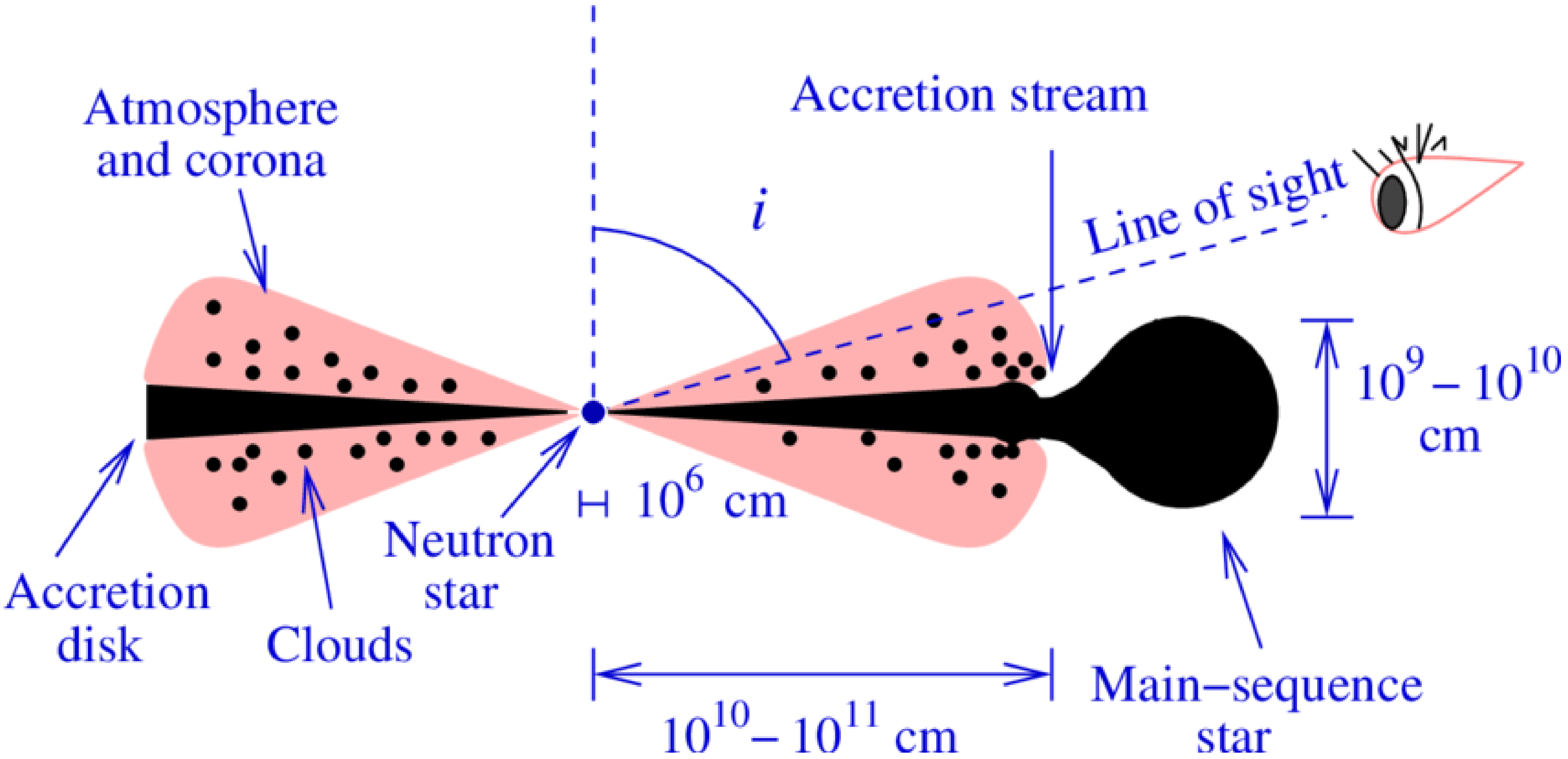
LMXB vs. HMXB



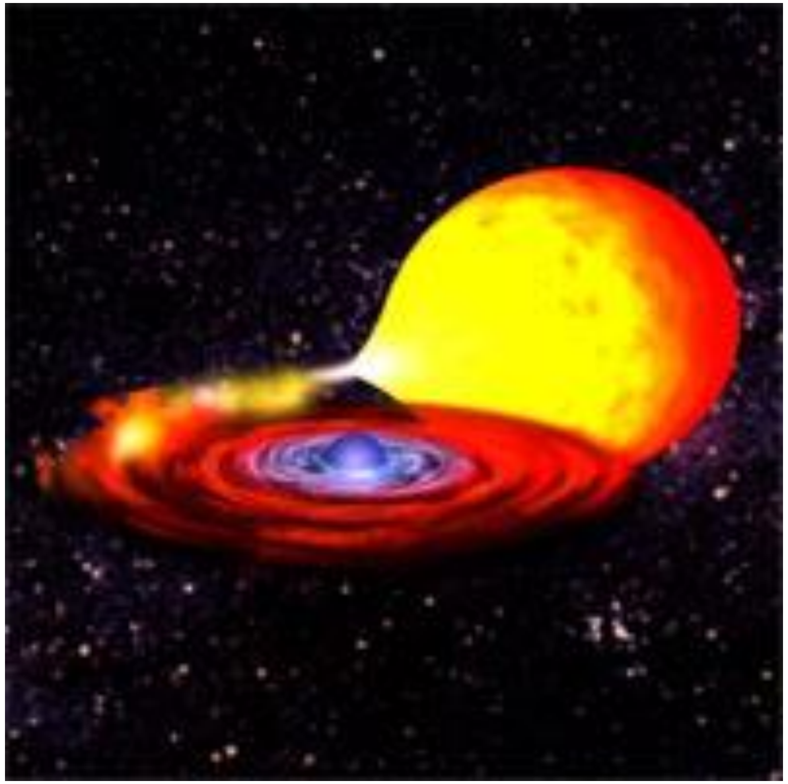
Properties	LMXBs	HMXBs
Accreting object	Low B-field NS or BH	High B-field NS or BH
Companion	Low-mass main sequence ($L_{opt}/L_x \ll 0.1$)	High-mass (O or B type) main sequence ($L_{opt}/L_x > 1$)
Stellar population	Old($> 10^9$ yr)	Young($< 10^7$ yr)
Mechanism	Roche-lobe overflow	Stellar wind
Accretion timescale	$10^7 - 10^9$ yr	10^5 yr
Variability	X-ray bursts, Transient behavior	Regular X-ray pulsation
X-ray spectra	Soft (≤ 10 keV)	Hard (≥ 15 keV)

Table 1: Summary of LMXBs and HMXBs (Rosswog et al. 2011)

Theoretical view of LMXB



X-ray Bursts (XRBs)



Rossi X-Ray Timing Explorer (RXTE)
1995 - 2012

X-ray Burst (XRB)

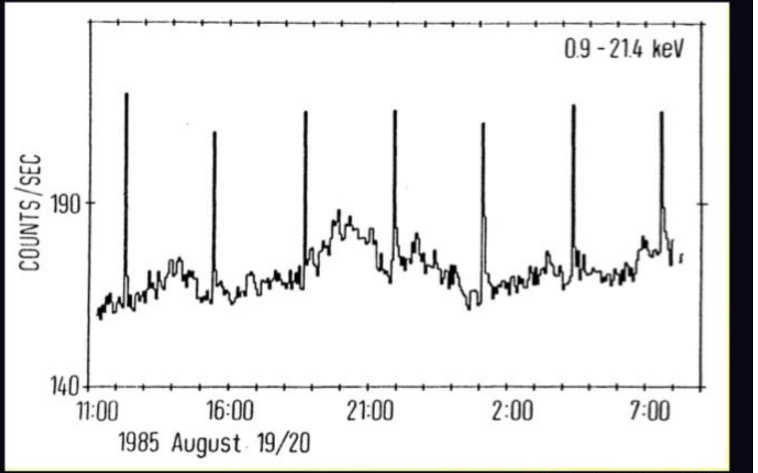
- X-ray burster - Wikipedia
- XRBs are found only in LMXBs but much brighter than LMXBs.
- Named as bursts because LMXBs are already bright in X-ray
- After XRBs were discovered, an immediate question followed. What caused XRBs? An answer is due to the runaway nuclear reaction often called rapid-proton capture process (rp-process).
- Photospheric radius expansion (PRE) occurs when the energy of XRB is large enough to be close to Eddington luminosity.

* Eddington luminosity

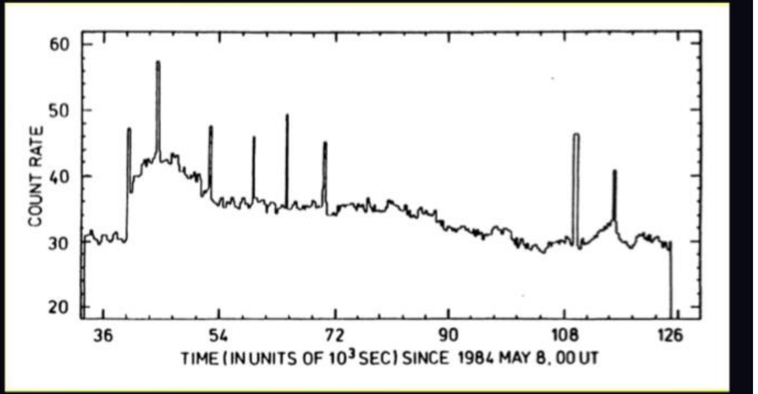
  - Force due to radiation = Gravitational Force

What are the characteristic of Type I X-ray bursts?

- Occurs on the neutron star surface in LMXBs by nuclear ignition (unstable H or He)
- Energy range ~ 10keV (soft X-ray)
- Maximum luminosity ~ 10^{38} erg/s (Eddington limit)
- recurrence time ~ hours to days
- X-ray softening during decay
- regular or irregular bursts recurrence



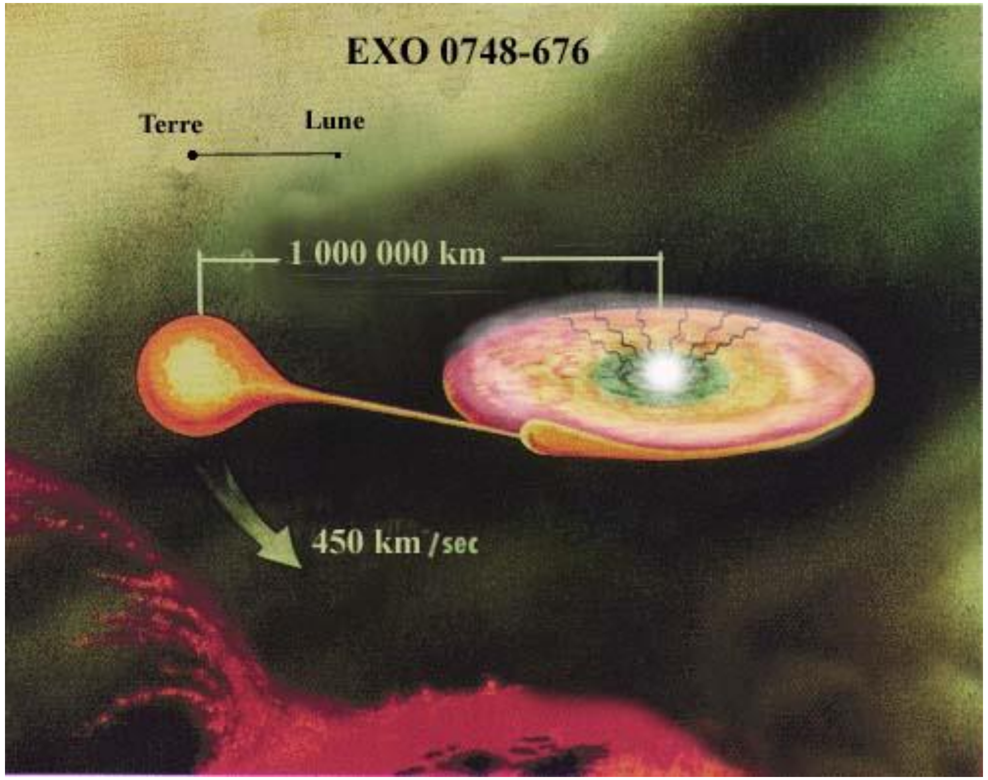
4U 1820-30

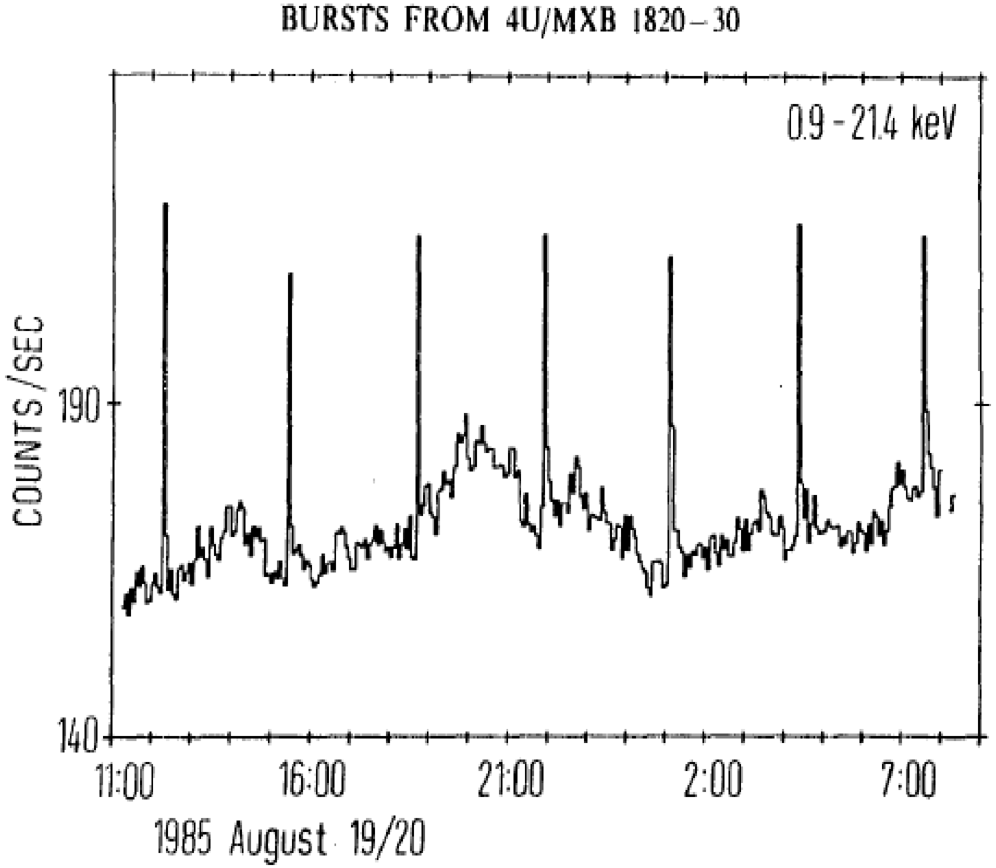


1636-536

number of Type I X-ray bursters ~ 84(2007)
(of ~160 LMXBs), 2/3 located in the Galactic Bulge

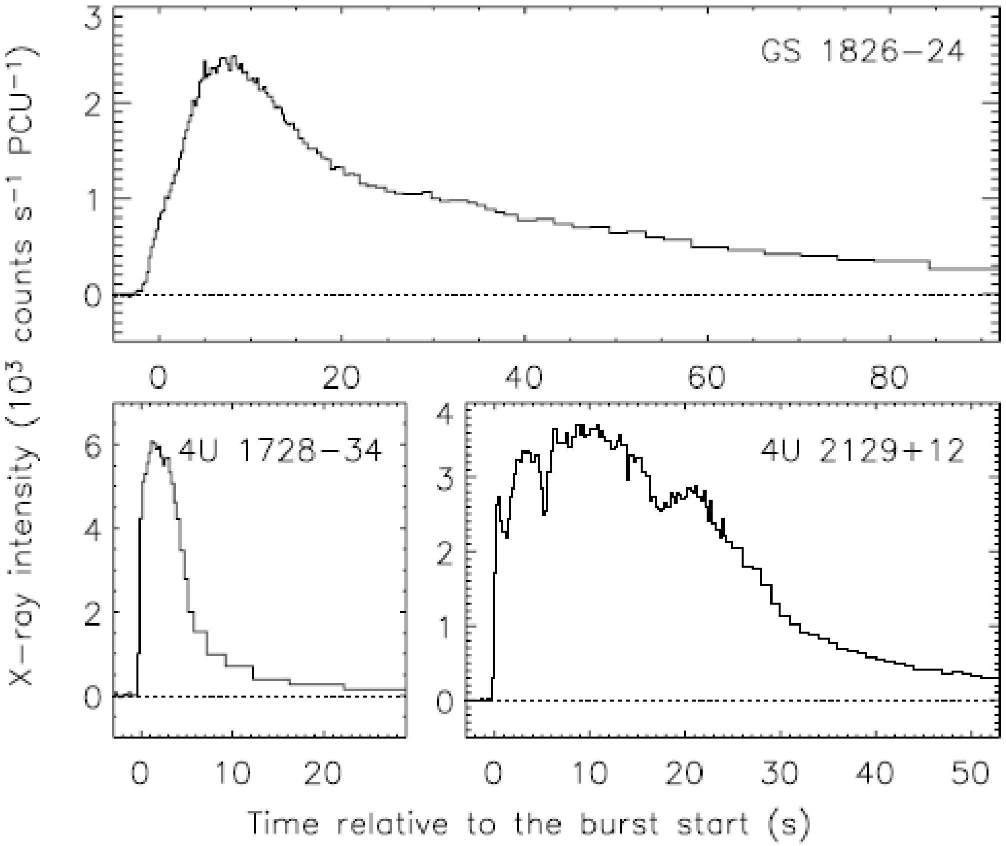
X-ray Bursts (XRBs) in Low Mass X-ray Binary (LMXB)





Light Curves of XRBs

- Burst duration: tens to hundreds of seconds



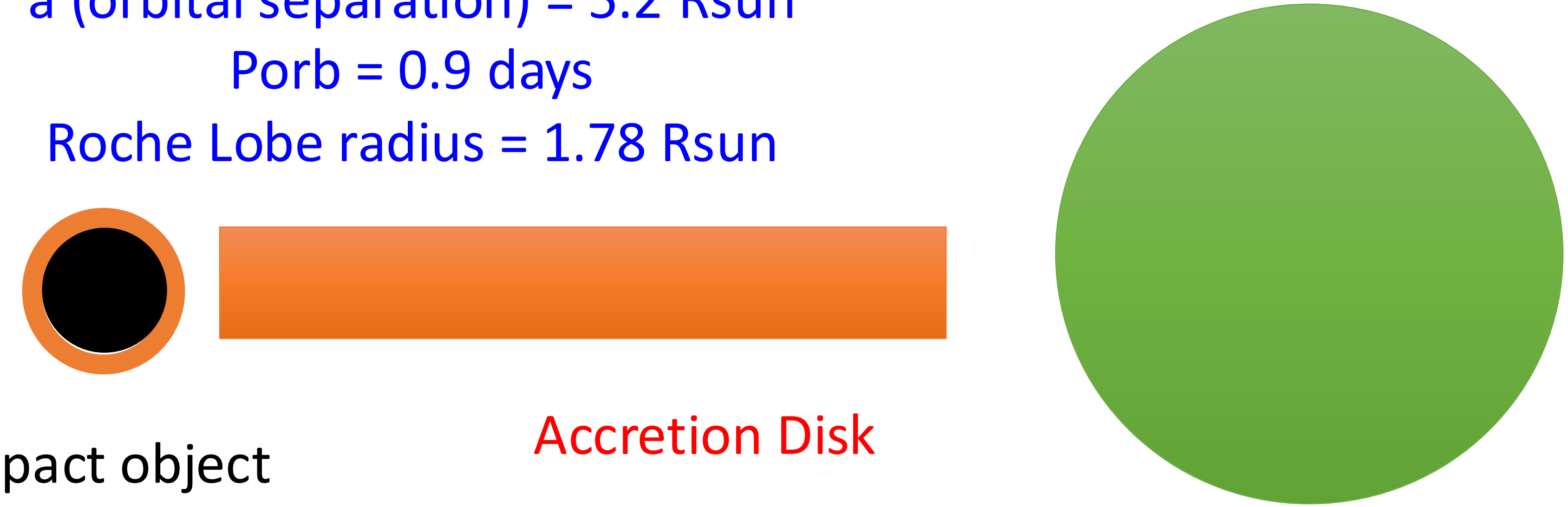
Galloway et al. 2008, ApJS

Modeling XRBs: in the context of X-ray Binary

Candidate Configuration (Ferraro+ 2015)

a (orbital separation) = 5.2 Rsun
Porb = 0.9 days
Roche Lobe radius = 1.78 Rsun

Rsun = 7×10^5 km
KeV = 1.2×10^7 K



Compact object
(NS or BH)

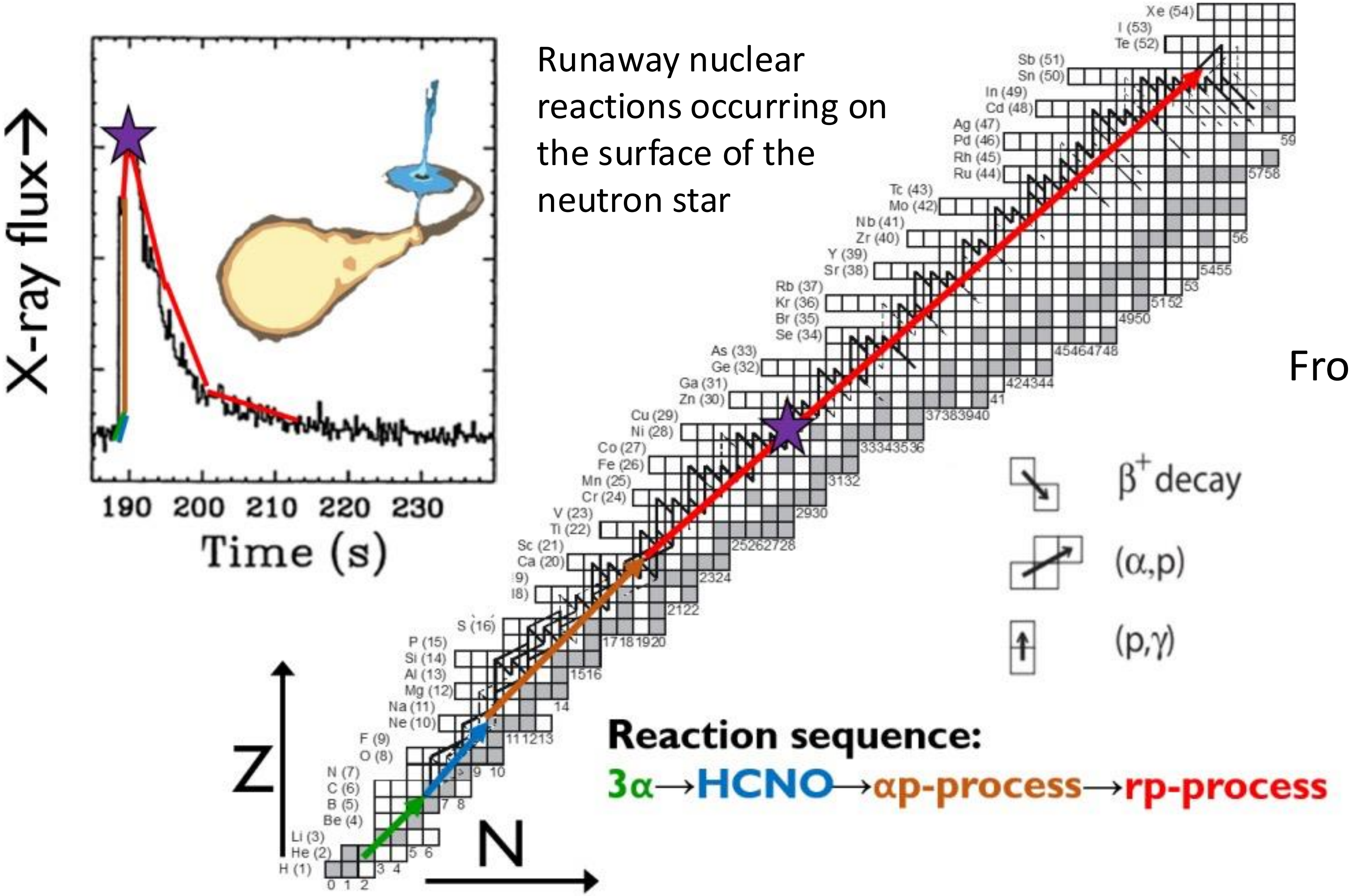
Mns = 1.4 Msun
Rns = 10 km

Accretion Disk

Energy budget:
fraction of
(G Mns m_p)/Rns
= 200 MeV

Companion

Mcomp = 0.9 Msun
Rcomp = 1.7 Rsun
Teff = 5440 K



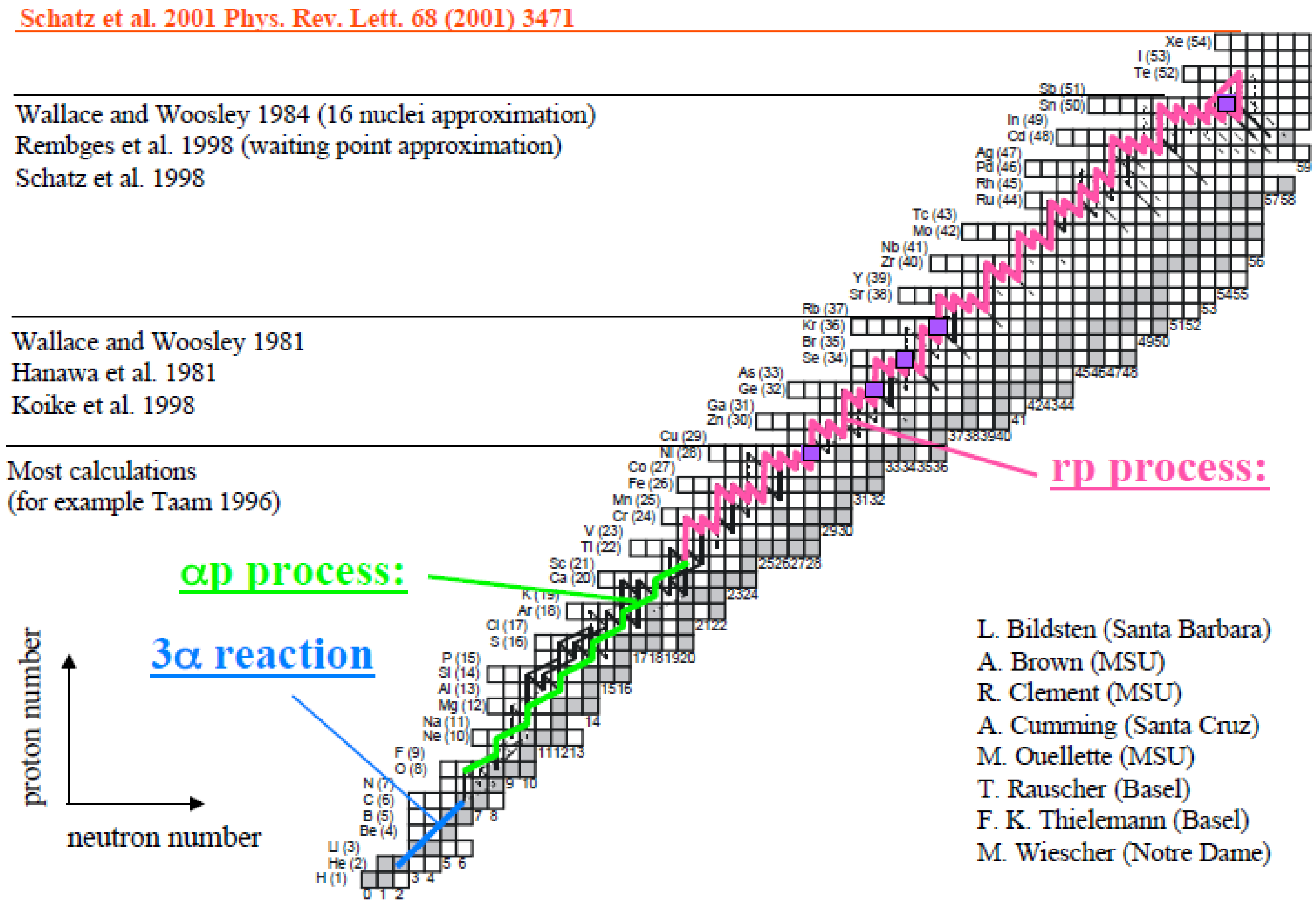
Runaway nuclear reactions occurring on the surface of the neutron star

Reaction sequence:
3α→HCNO→αp-process→rp-process

From Meisel et al. 2018

Figure 6. Nuclear reaction sequence powering Type I X-ray bursts [101] with colored lines indicating rates driving particular parts of the X-ray burst light-curve [76].

Thermonuclear burning during X-ray burst – STEP 1: one zone model



Schatz et al. 2001 Phys. Rev. Lett. 68 (2001) 3471

Wallace and Woosley 1984 (16 nuclei approximation)
Rembges et al. 1998 (waiting point approximation)
Schatz et al. 1998

Wallace and Woosley 1981
Hanawa et al. 1981
Koike et al. 1998

Most calculations
(for example Taam 1996)

L. Bildsten (Santa Barbara)
A. Brown (MSU)
R. Clement (MSU)
A. Cumming (Santa Cruz)
M. Ouellette (MSU)
T. Rauscher (Basel)
F. K. Thielemann (Basel)
M. Wiescher (Notre Dame)

From Schatz's Presentation

Waiting Points Nuclei

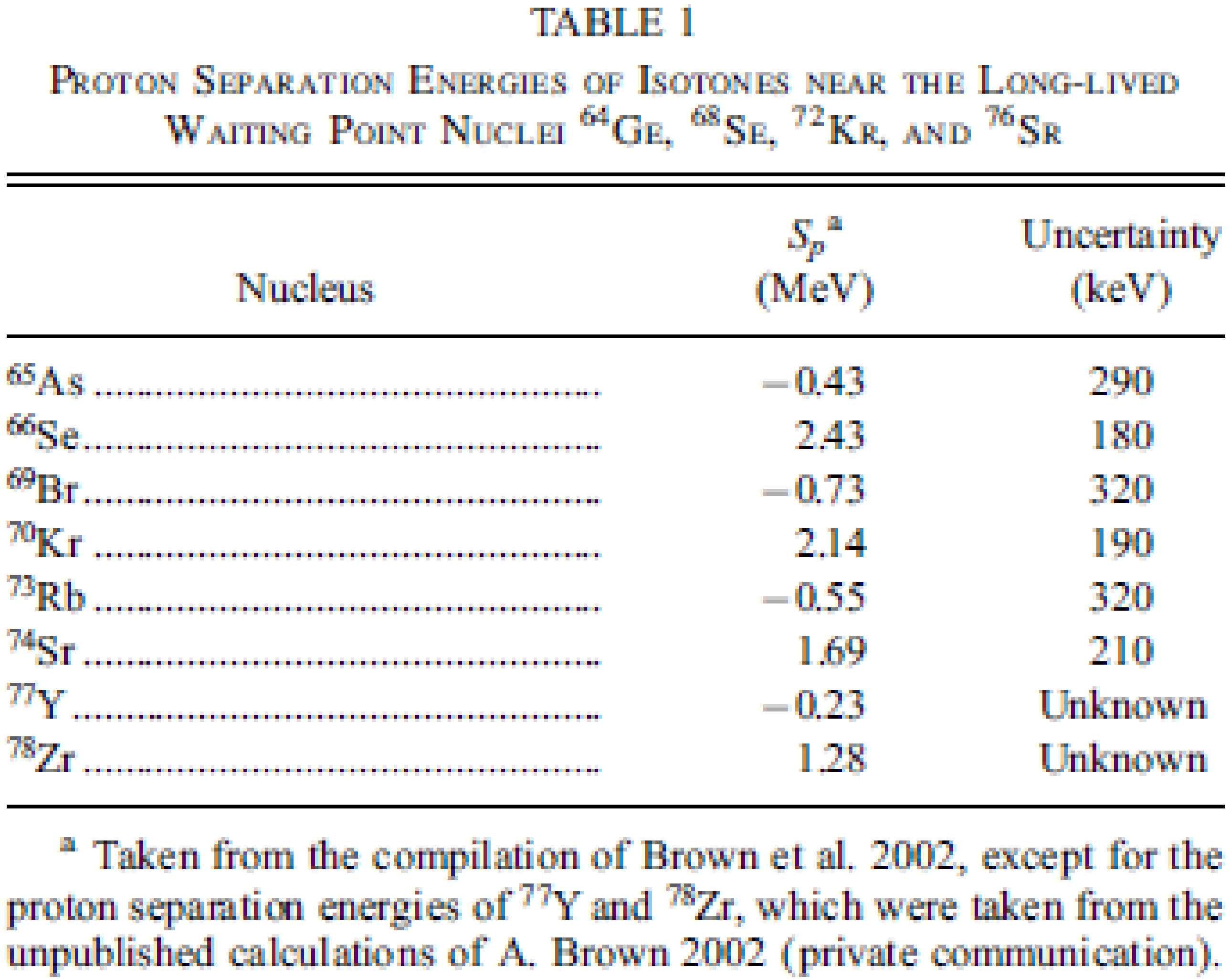


TABLE 1

PROTON SEPARATION ENERGIES OF ISOTONES NEAR THE LONG-LIVED WAITING POINT NUCLEI ^{64}GE, ^{68}SE, ^{72}KR, AND ^{76}SR

Nucleus	S_p[a] (MeV)	Uncertainty (keV)
^{65}As	−0.43	290
^{66}Se	2.43	180
^{69}Br	−0.73	320
^{70}Kr	2.14	190
^{73}Rb	−0.55	320
^{74}Sr	1.69	210
^{77}Y	−0.23	Unknown
^{78}Zr	1.28	Unknown

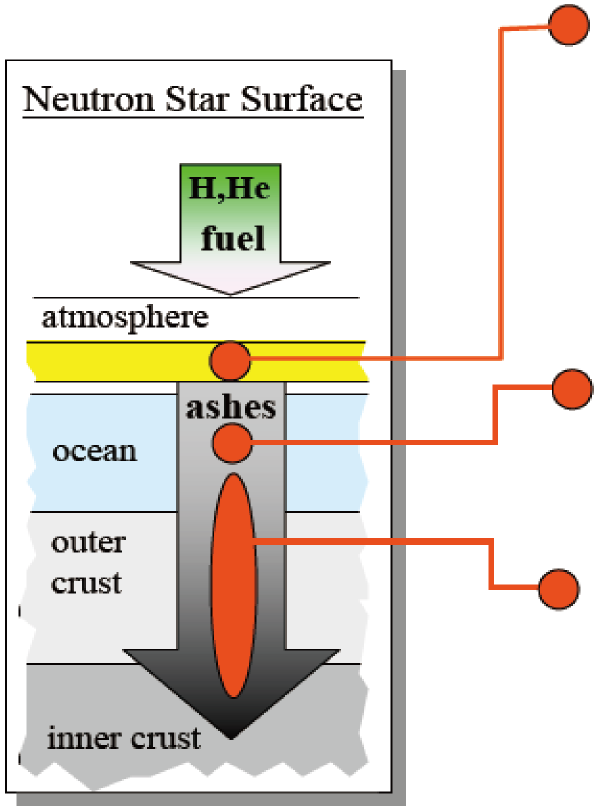
[a] Taken from the compilation of Brown et al. 2002, except for the proton separation energies of ^{77}Y and ^{78}Zr, which were taken from the unpublished calculations of A. Brown 2002 (private communication).

Woosley et al., 2004, ApJS

Models for XRBs

Accretion onto the surface of neutron star

Nuclear reactions on accreting neutron stars



H and He burning (rp-process)

- X-ray bursts lightcurves (10s – min's)
- Radius expansion
- Nucleosynthesis (p-nuclei ?)
- Start composition for deeper processes

Deep burning: H-EC/ C-fusion
Photodisintegration of heavy ashes

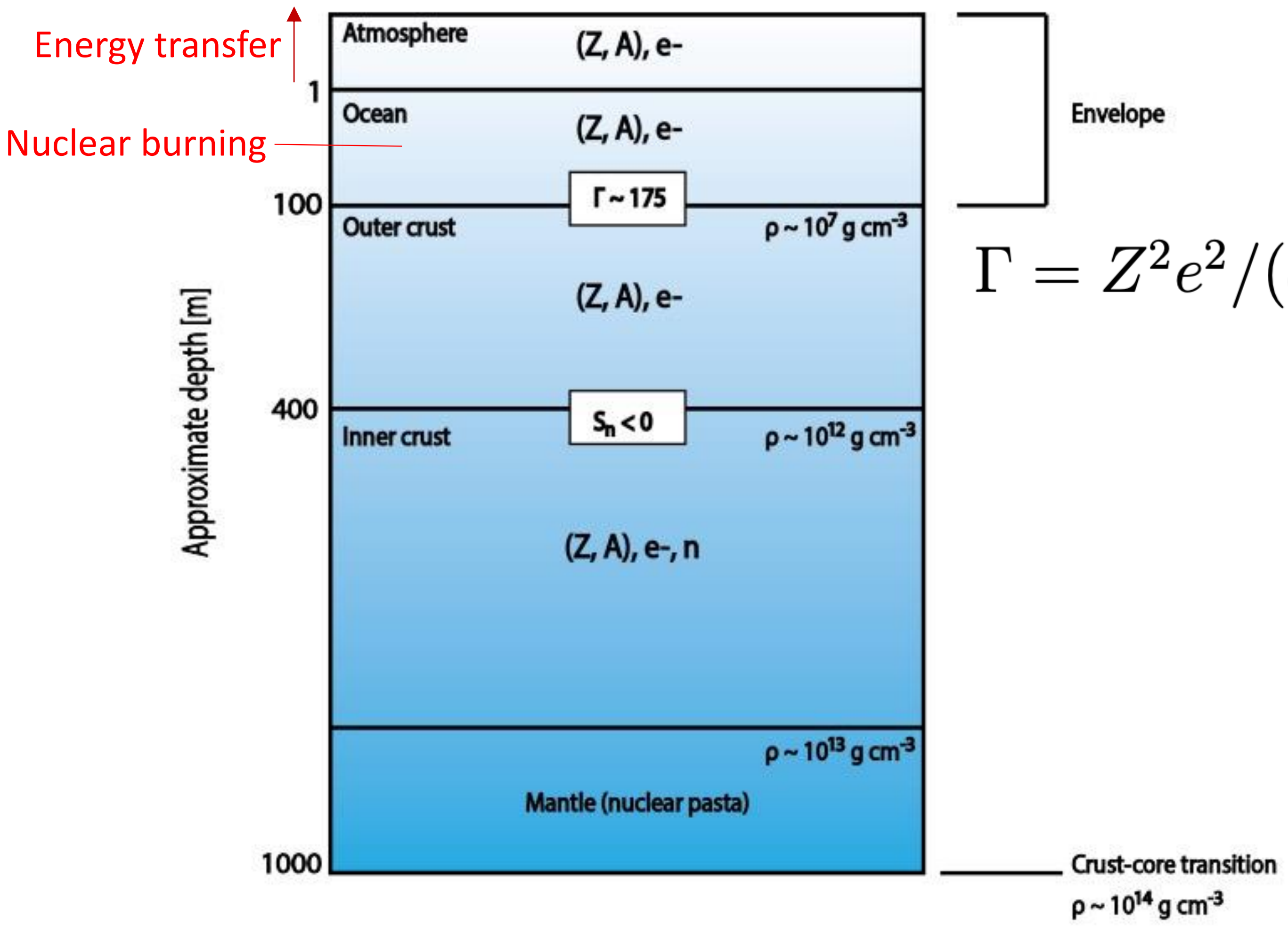
- Superbursts

Electron captures
Pycnonuclear fusion reactions

- Cooling / off state observations
- Heat feeds back on burst properties
- Gravitational wave emission
- Magnetic fields

From Schatz's Presentation

Modeling XRBs: In the perspective of the structure of the neutron star



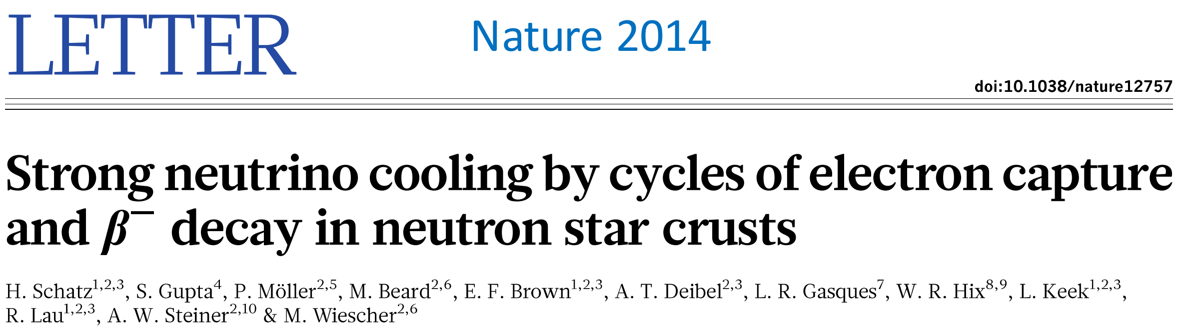
Energy transfer

Nuclear burning

$$\Gamma = Z^2 e^2/(a k_{\rm B} T), \text{ where } a = [3/(4\pi n_i)]^{1/3}$$

Figure 1. Schematic of the outer layers of a neutron star.

- From Meisel et al. 2018



Nature 2014

LETTER

doi:10.1038/nature12757

Strong neutrino cooling by cycles of electron capture and β^- decay in neutron star crusts

H. Schatz[1,2,3], S. Gupta[4], P. Möller[2,5], M. Beard[2,6], E. F. Brown[1,2,3], A. T. Deibel[2,3], L. R. Gasques[7], W. R. Hix[8,9], L. Keek[1,2,3], R. Lau[1,2,3], A. W. Steiner[2,10] & M. Wiescher[2,6]

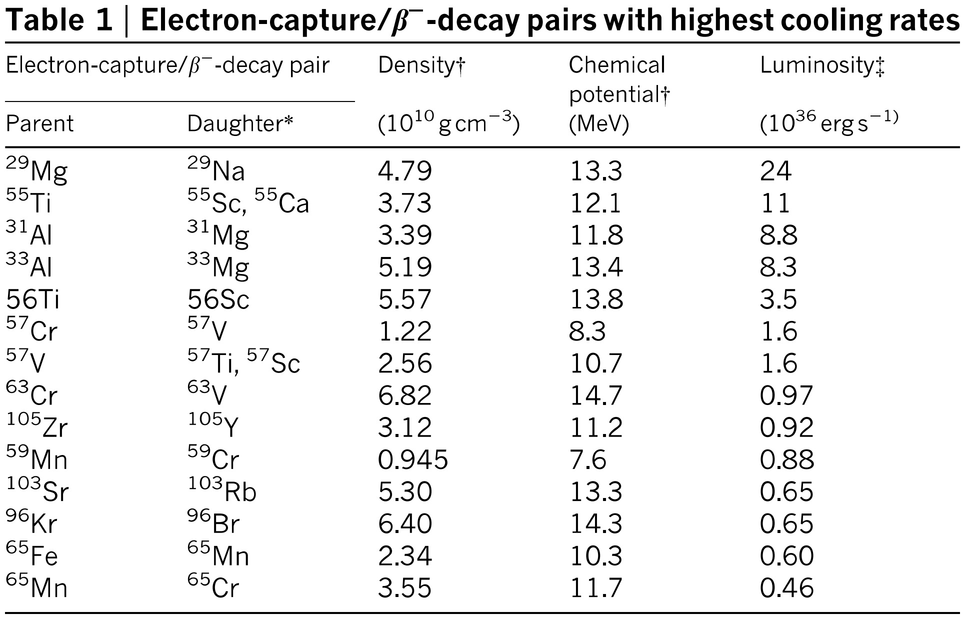
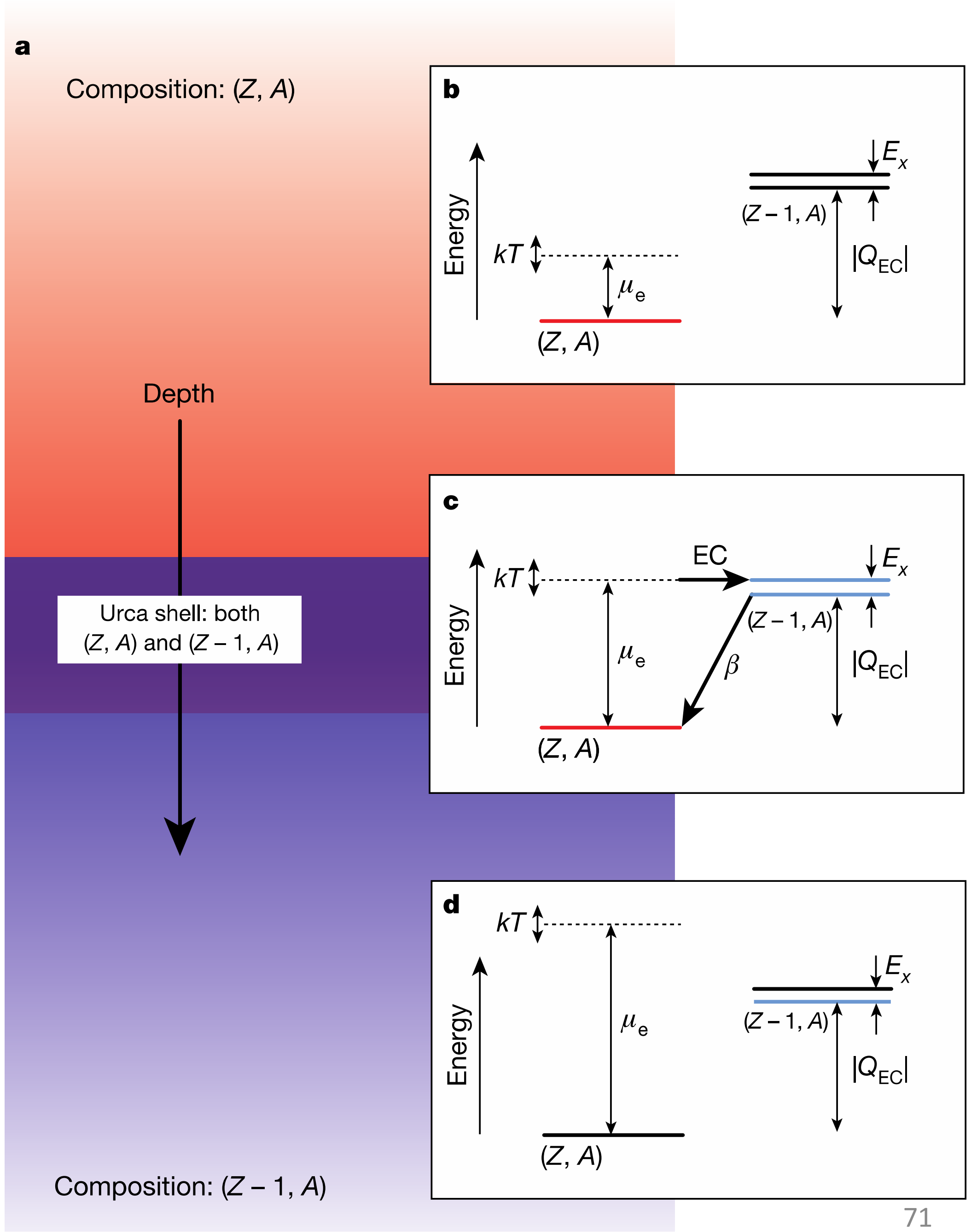


Table 1 | Electron-capture/β^--decay pairs with highest cooling rates

Electron-capture/β^--decay pair		Density†	Chemical potential†	Luminosity‡
Parent	Daughter*	(10^{10} g cm^{-3})	(MeV)	(10^{36} erg s^{-1})
^{29}Mg	^{29}Na	4.79	13.3	24
^{55}Ti	^{55}Sc, ^{55}Ca	3.73	12.1	11
^{31}Al	^{31}Mg	3.39	11.8	8.8
^{33}Al	^{33}Mg	5.19	13.4	8.3
56Ti	56Sc	5.57	13.8	3.5
^{57}Cr	^{57}V	1.22	8.3	1.6
^{57}V	^{57}Ti, ^{57}Sc	2.56	10.7	1.6
^{63}Cr	^{63}V	6.82	14.7	0.97
^{105}Zr	^{105}Y	3.12	11.2	0.92
^{59}Mn	^{59}Cr	0.945	7.6	0.88
^{103}Sr	^{103}Rb	5.30	13.3	0.65
^{96}Kr	^{96}Br	6.40	14.3	0.65
^{65}Fe	^{65}Mn	2.34	10.3	0.60
^{65}Mn	^{65}Cr	3.55	11.7	0.46



Nuclear Reactions for Type I X-ray Bursts

- Hydrogen burning by CNO-cycle
- 3-alpha reaction
- alpha-p reaction
- p-gamma reaction
- weak interactions

$$e^- + {}^A Z \rightarrow {}^A(Z-1) + \nu_e,$$

$$ {}^A Z \rightarrow {}^A(Z-1) + e^+ + \nu_e,$$

$$3\alpha \rightarrow {}^{12}\mathrm{C}\ (p,\gamma)\ {}^{13}\mathrm{N}\ (p,\gamma)\ {}^{14}\mathrm{O}\ (\alpha,p)\ {}^{17}\mathrm{F}(p,\gamma)\ {}^{18}\mathrm{Ne}\ (\alpha,p)\ {}^{21}\mathrm{Na}\ (p,\gamma)\ {}^{22}\mathrm{Mg}\ (\alpha,p)\ {}^{25}\mathrm{Al}\ldots.$$

1D Multi-Zone Model

- Woosley et al., 2004, ApJS
    - Nuclear reaction networks of ~1300 isotopes

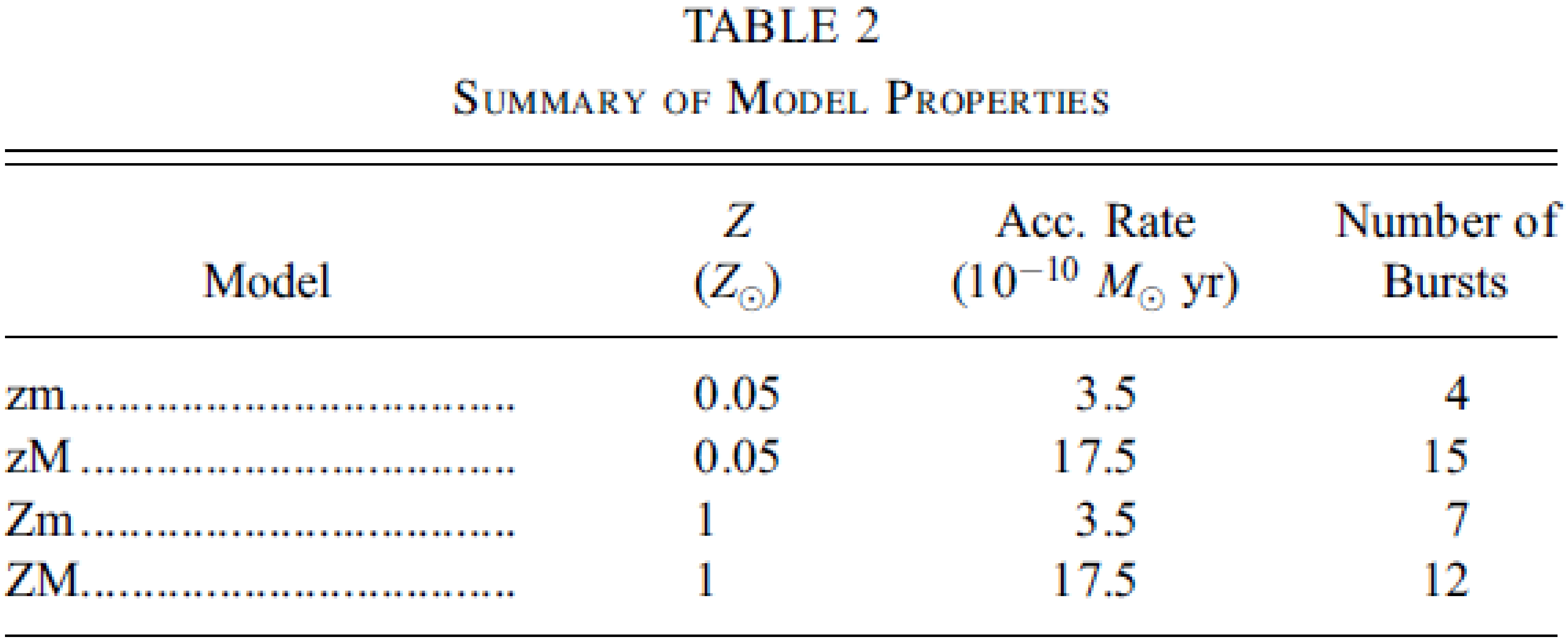
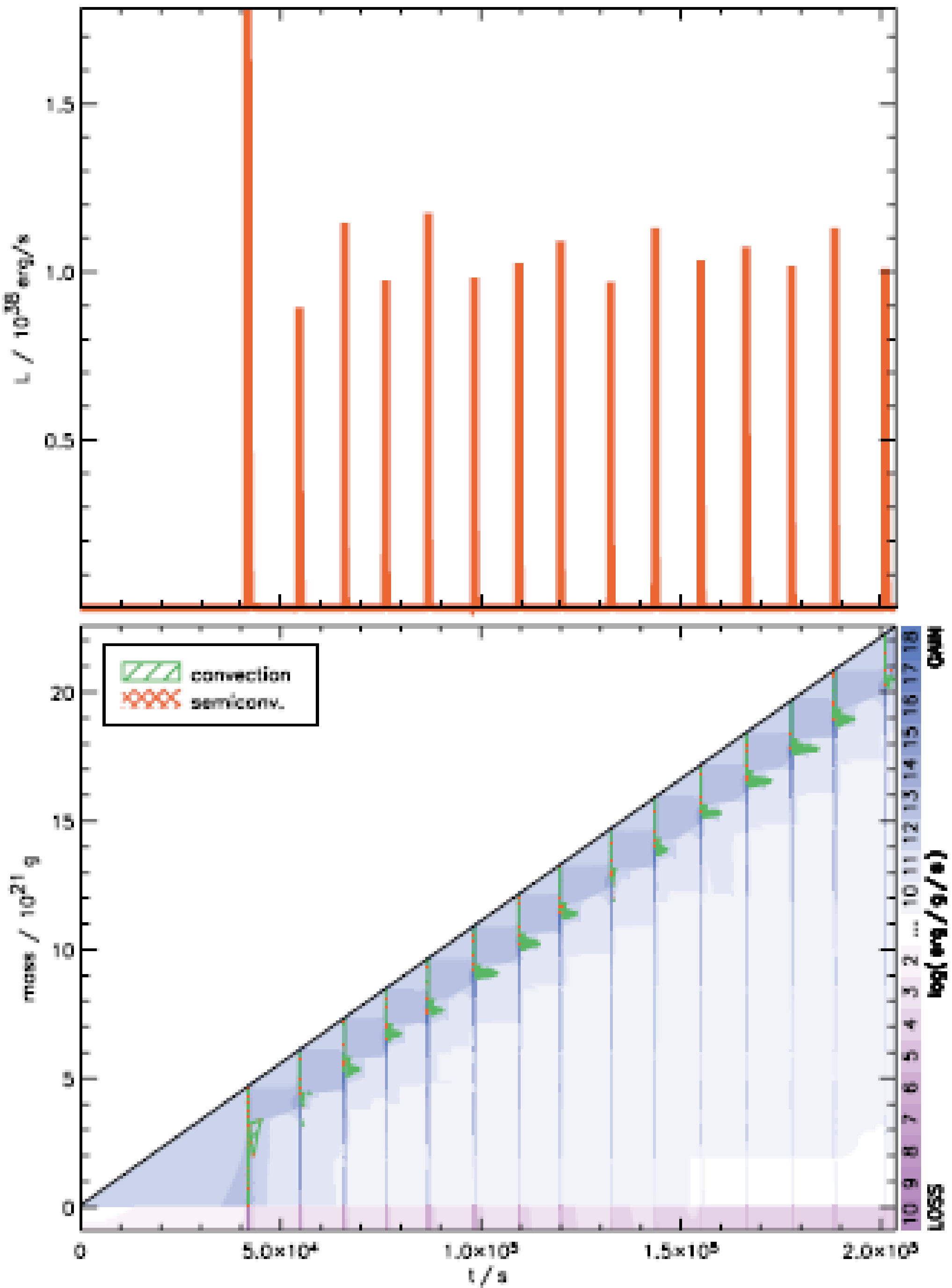


TABLE 2

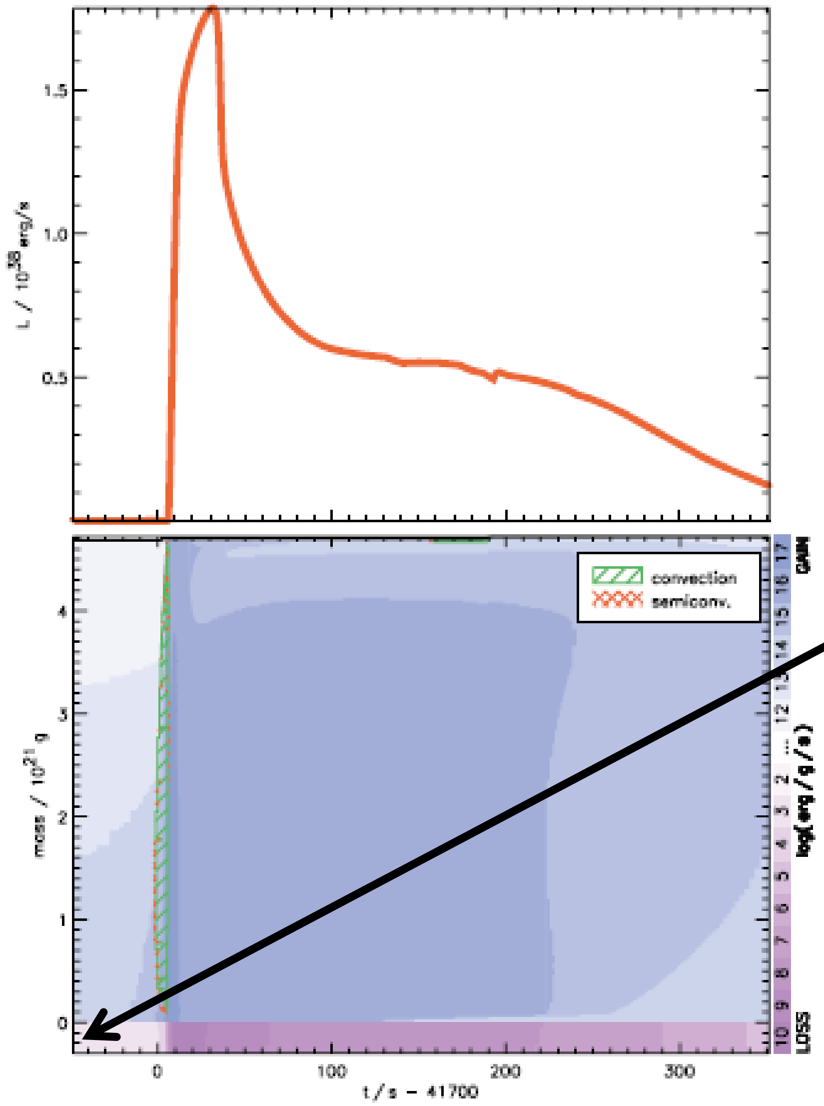
Summary of Model Properties

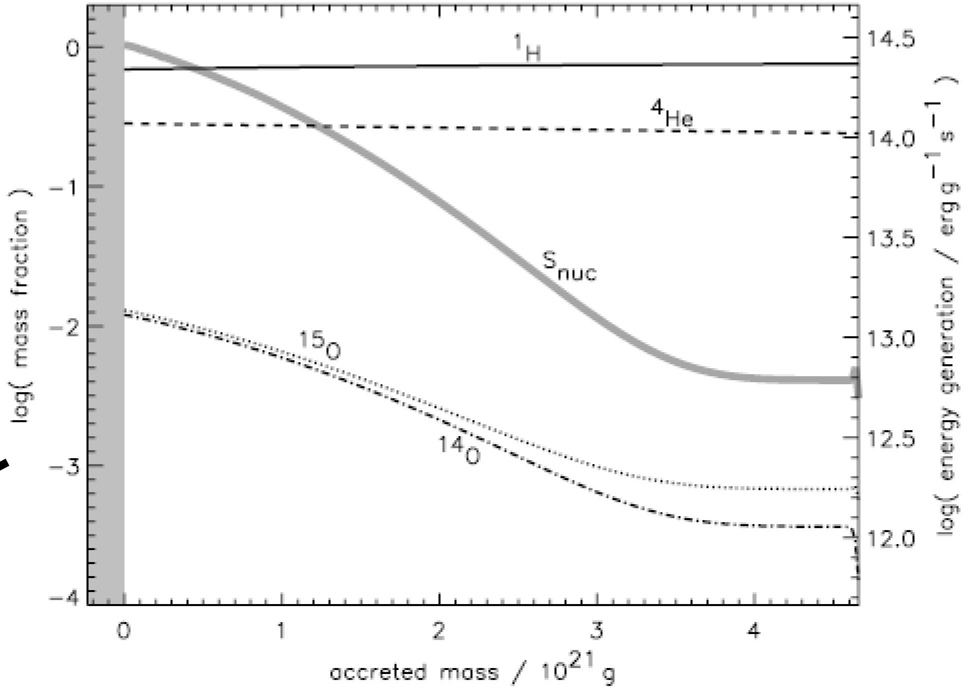
Model	Z ($Z_\odot$)	Acc. Rate ($10^{-10}\ M_\odot$ yr)	Number of Bursts
zm	0.05	3.5	4
zM	0.05	17.5	15
Zm	1	3.5	7
ZM	1	17.5	12

Evolution of the zM-Model



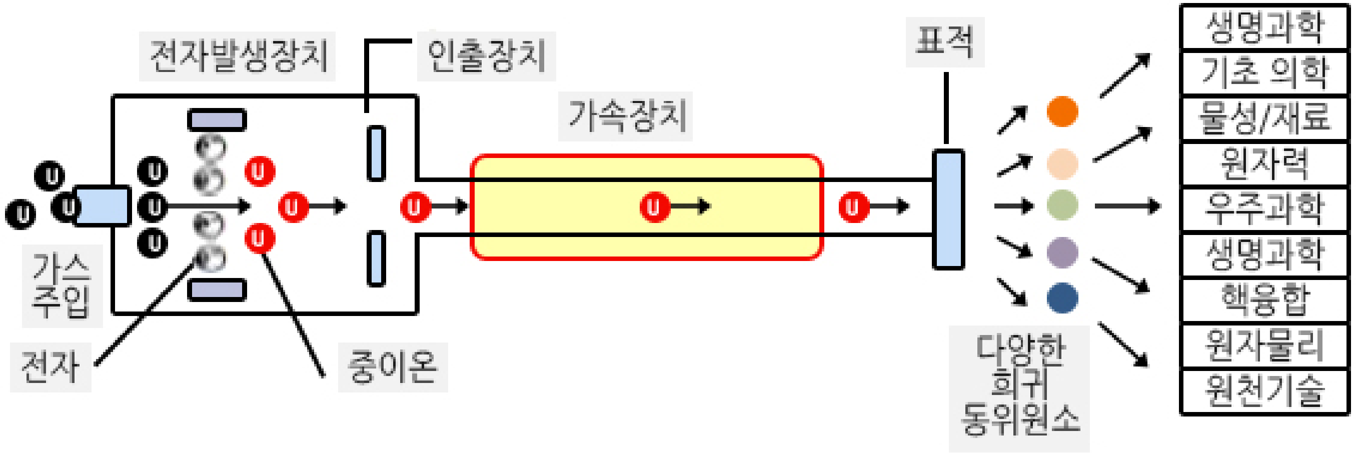
Composition of the 1st Burst of the zM-Model



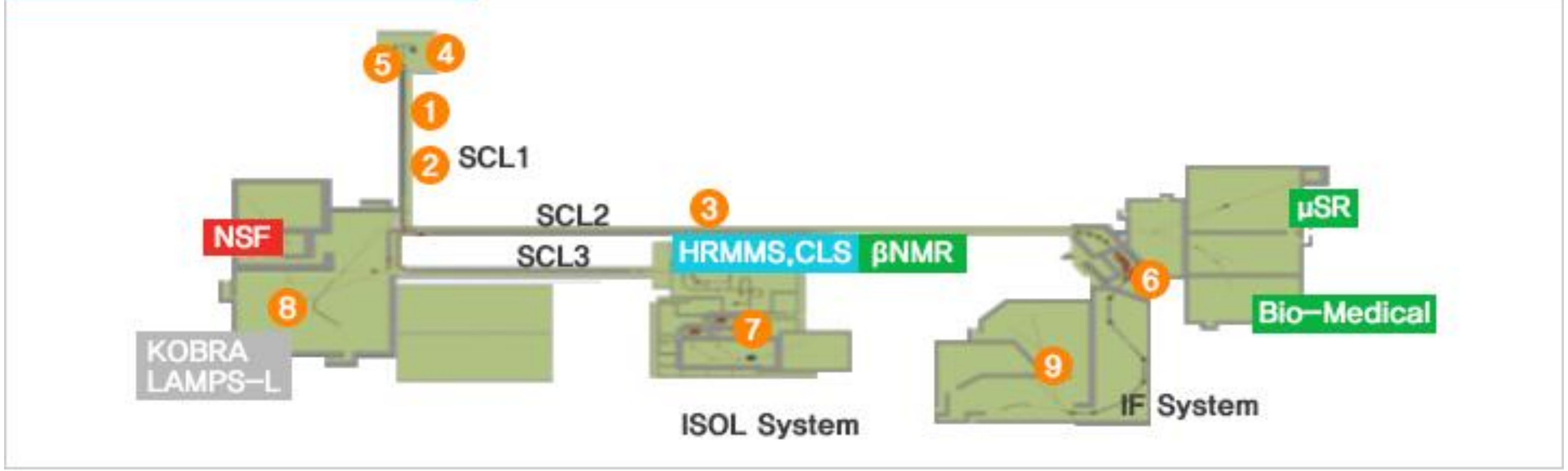


RAON (Korean Rare Isotope Accelerator)

Experiments of Nuclear Astrophysics @RAON



중이온가속기 주요 장치 구축 현황



Summary

- Nuclear physics provides key information to understand various astrophysical phenomena such as stars and X-ray bursts.
- Nuclear reactions in astrophysical environments are still uncertain requiring better theoretical modeling and more accurate experimental measurements.
- RAON will be able to contribute to resolving some uncertain issues in nuclear astrophysics.

Searching for Undiscovered but Detectable Astrophysical Phenomena for the Multi-Messenger Astronomy

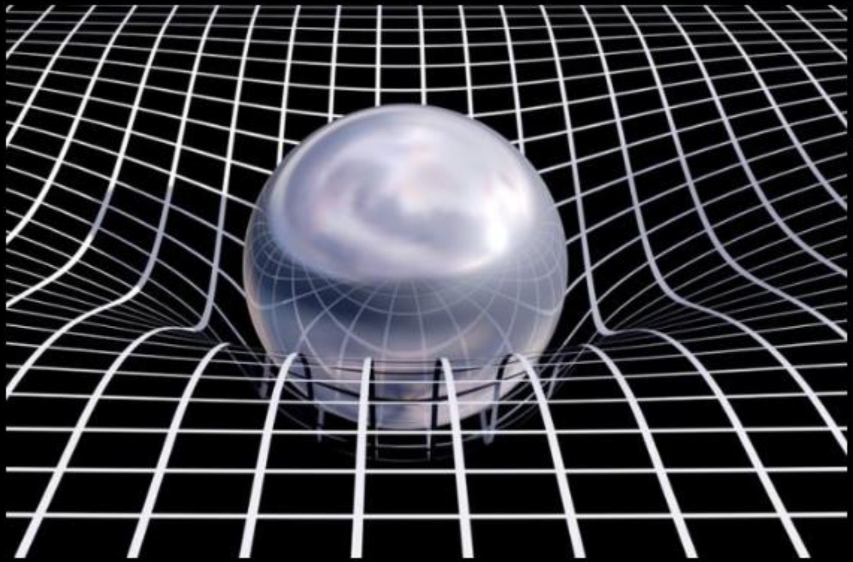
Contents

- Multi-Messenger Astronomy
  - Gravitational Wave (GW)
  - Neutrino Astronomy
  - (Cosmic-ray)
- Hunting for New Phenomena
  - Nearby massive evolved stars
  - Compact binaries: X-ray bursts (XRBs)
  - Order estimation (Back-of-Envelope Calculation)
  - Binary neutron stars in highly eccentric closed (elliptical) orbits
- Remaining issues (Devils are in details)

GRAVITATIONAL WAVE

- According to Einstein's general theory of relativity

Mass → Curvature of Space-time → Gravity



GRAVITATIONAL WAVE

- Therefore,

If an object (mass) undergoes accelerated motion

↓

The space-time fluctuates

↓

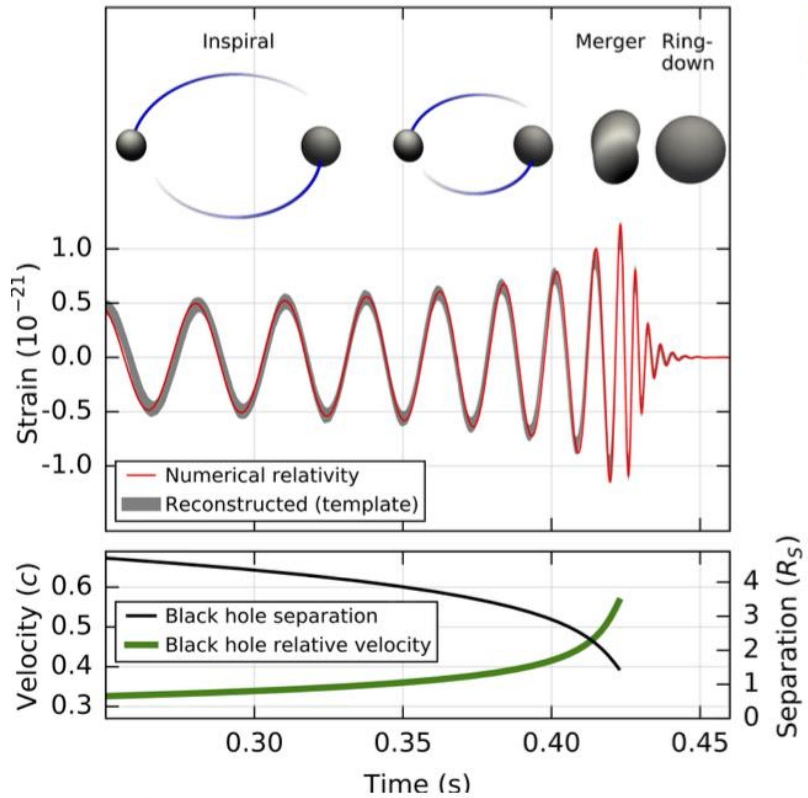
Changes of space-time spread out → **Gravitational Wave**

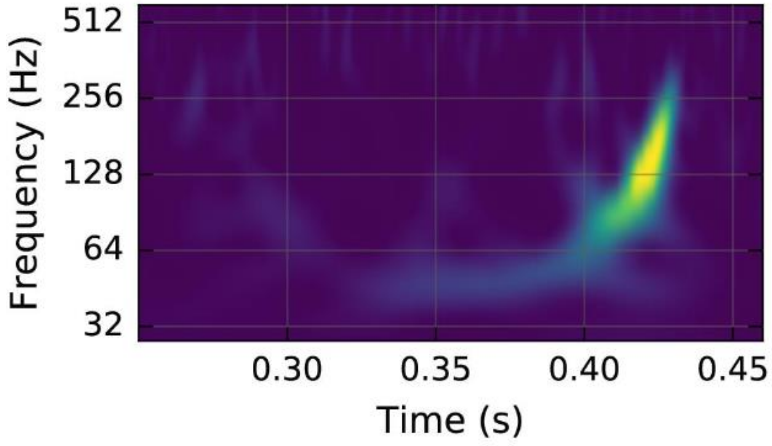
GRAVITATIONAL WAVE

- Observation Difficulty
  - The weakest force of the 4 forces that make up fundamental interactions.
    - Gravity ($6*10^{-39}$) < Weak interaction (10^{-6}) < Electromagnetism (1/137) < Strong interaction (1)
  - Too tiny of changes
    - Maximum amplitude of GW150914 (1st detected): $4*10^{-21}$ km (< Proton radius = $8.4*10^{-19}$ km)

1 ly = 9.461e+12 km

A change equivalent to the thickness of one hair





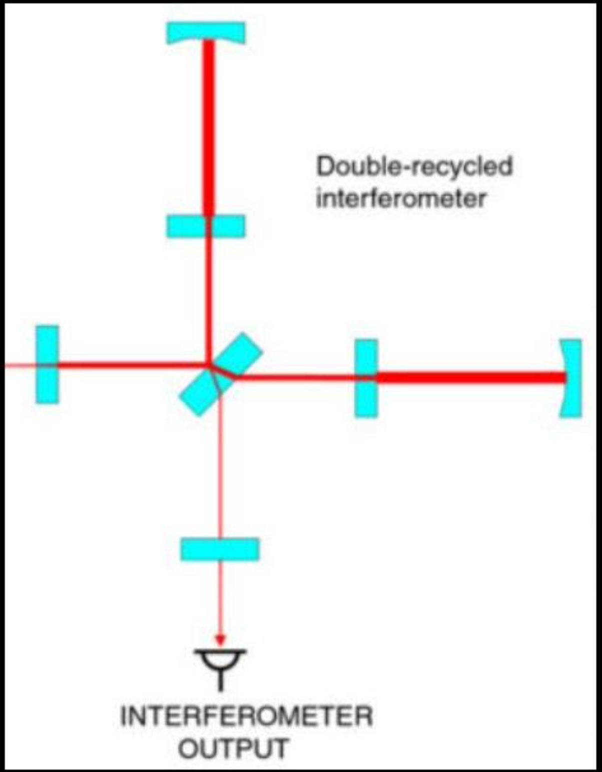
7

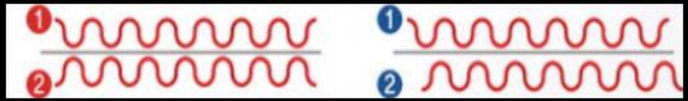
BINARY BLACK HOLE (BBH) MERGER

- The first case in which humans detected gravitational waves
- GW150914
  - First detected
  - 36 M_s + 29 M_s -> 62 M_s + GW (3M_s)
  - Relativity velocity increased from 0.3c to 0.6c
  - About 1.3 * 10^{10} ly
  - 0.2 sec
  - GW's spectrogram is called "chirp"

GW DETECTOR: GROUND BASE

- Basic Principle: Michelson Interferometer
  - Laser light is sent into detector
  - A “splitter” splits the light and sends out two identical beams along the arms
    - Arm Length: LIGO – 4km, VIRGO, KAGRA – 3km
  - The light waves bounce and return
    - A hundreds of times
  - GW affects the interferometer’s arms differently
  - Normally, the light returns unchanged to the splitter from both arms
    - The light waves cancel each other out.
  - If the arms are disturbed by a GW
    - The light waves will have travelled different distances.
    - Light then escapes through the splitter and hits the detector





Normal

GW detects

2.5 GENERATION DETECTOR: KAGRA

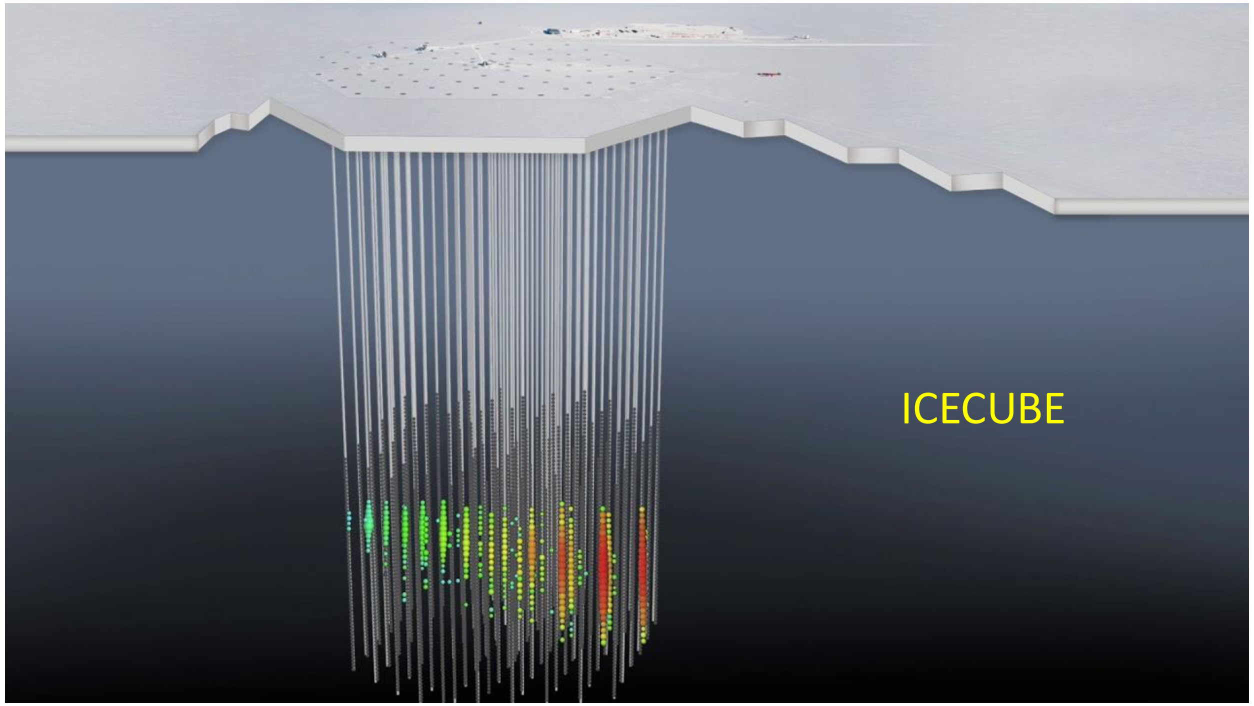
- KAmioka GRAvitational wave detector (KAGRA)
- Gifu Prefecture, Japan
- Michelson Interferometer
    - 3 km arm
- Asia's first gravitational wave observatory
- Underground
- Cryogenic (About -250 °C)

Neutrino Astronomy and Astrophysics

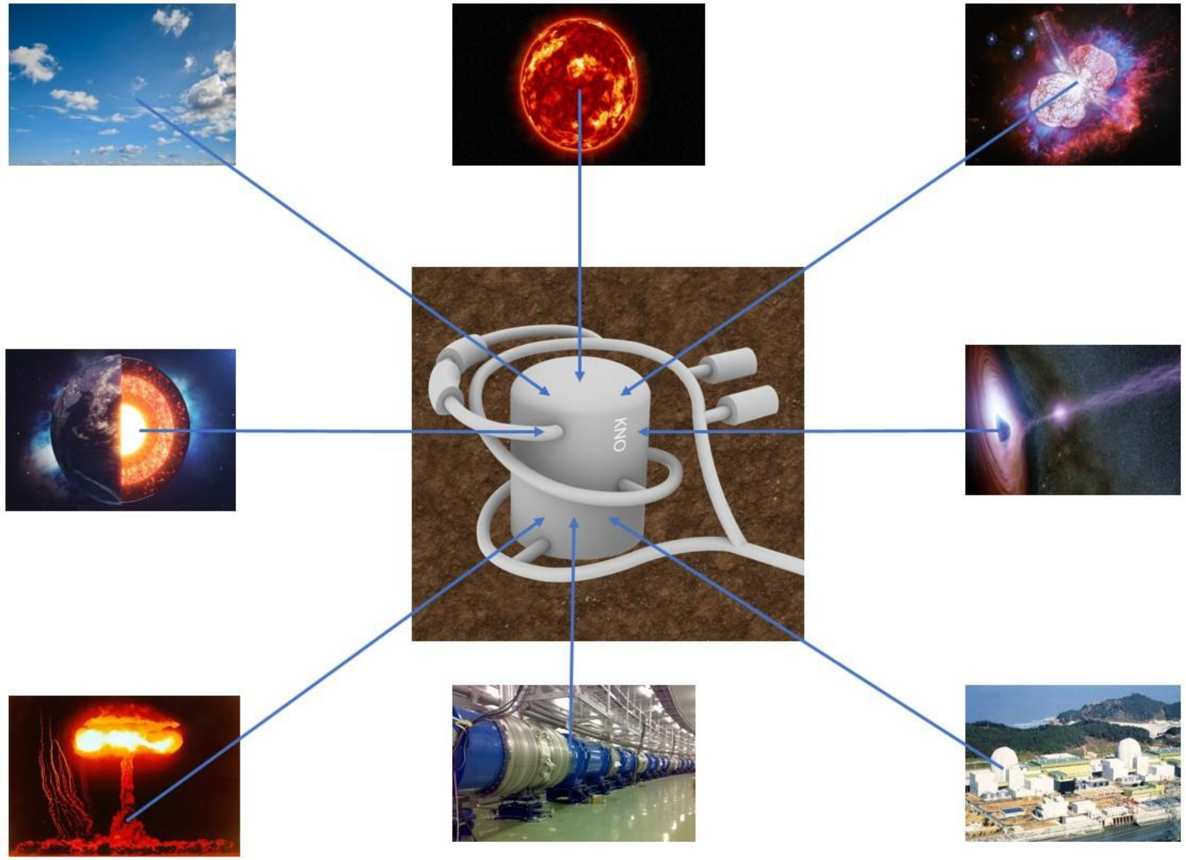
- Neutrino astronomy
  - Emerging as an important part of multi-messenger astronomy together with gravitational wave (GW)
  - Many neutrino detectors/observatories are operating, under construction, and planned: ICECUBE, KM3NET, DUNE, Hyper-Kamiokande, JUNO
  - (Tentative) Korean Neutrino Observatory (KNO) is being pursued
- Neutrino astrophysics is not new at all!
  - Various astrophysical sites and production mechanisms for neutrino emission have been studied for a long time
  - But predicting detectability on operating/planned detectors is NEW!!

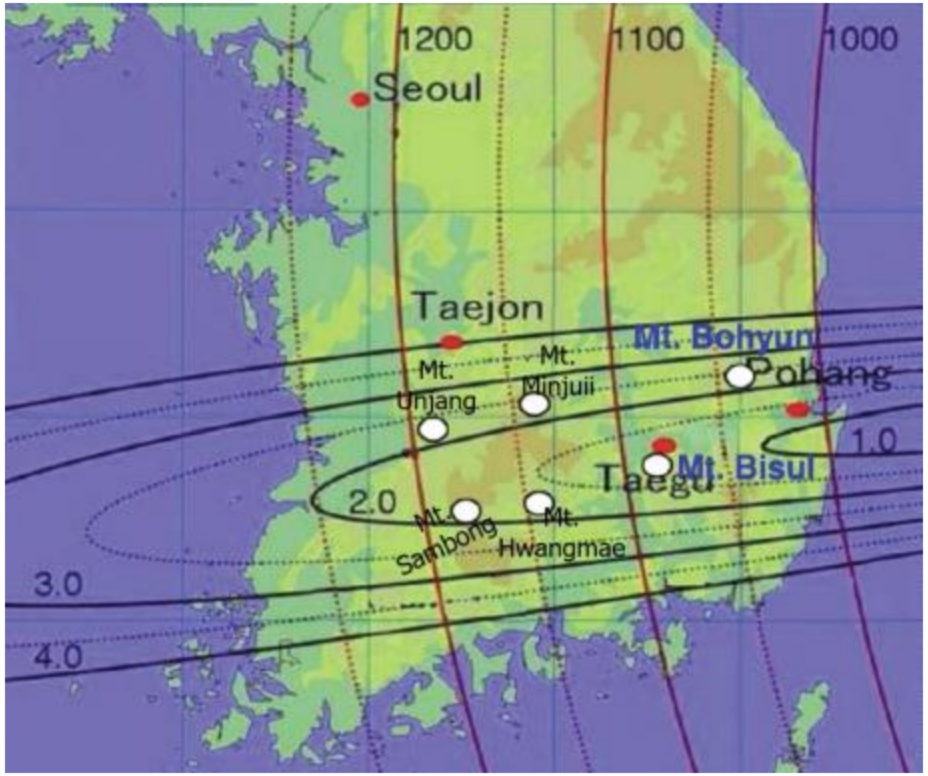
Neutrino Astronomy/Detector

- Detected
  - Solar and atmospheric neutrinos: lead to neutrino oscillation
  - Supernova explosion: 1987A
  - Distant galaxy: blazar TXS 0506+056



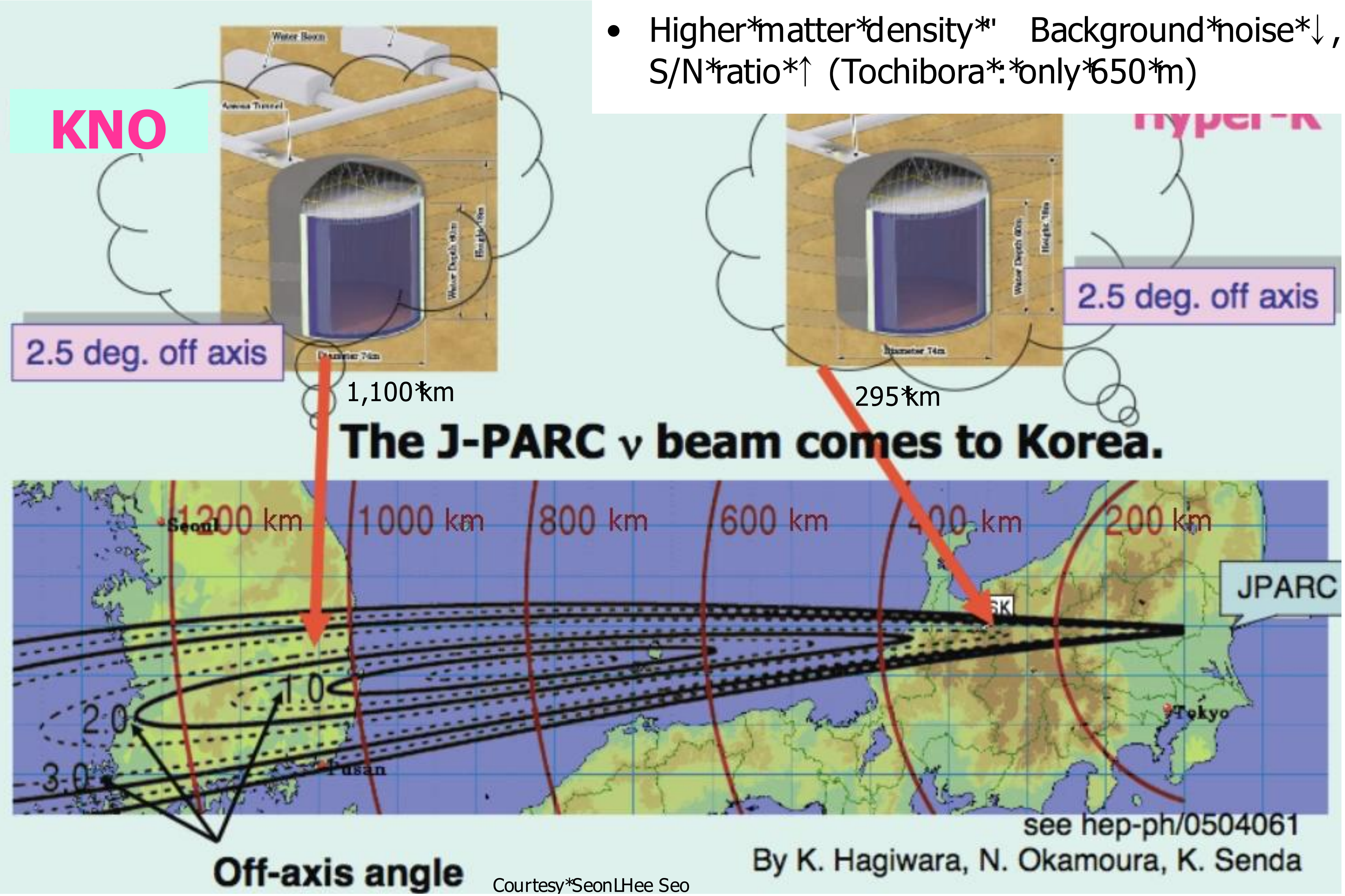
Korean Neutrino Observatory





Korean*Neutrino*Observatory*(KNO)*and*HyperLKamiokande (HK)

- KNO’s*longer*baseline*" oscillation*efficiency*increases*(But,*not*too*long*distance…)
- Higher*matter*density*" Background*noise*↓, S/N*ratio*↑ (Tochibora*:*only*650*m)



1,100*km

295*km

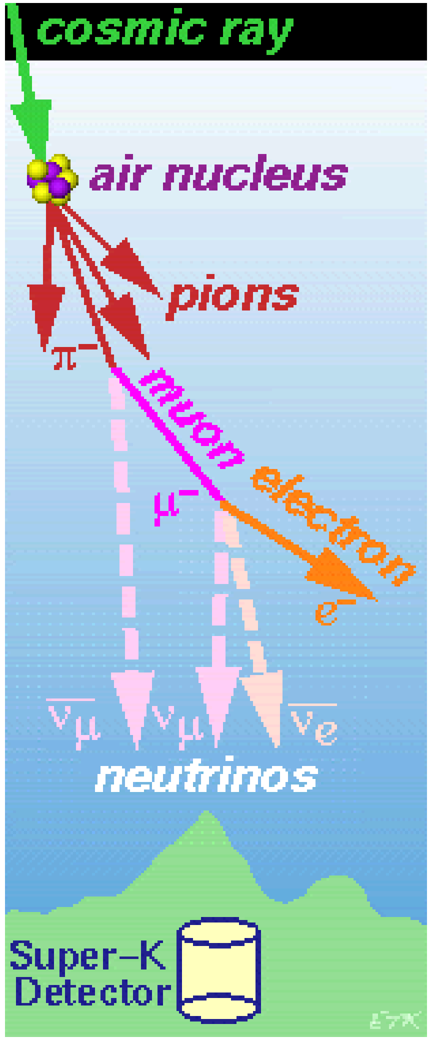
see hep-ph/0504061

By K. Hagiwara, N. Okamoura, K. Senda

Courtesy*SeonLHee Seo

Astrophysical Sites for Neutrino Emission I

- Cosmic-ray: high energy neutrinos (> GeV, typically > TeV or even PeV)
  - Anywhere high energy particles (protons) exist
  - Strong acceleration processes such as shock waves, magnetic fields, and jets are required -> correlation among high energy electromagnetic radiation like X-ray and gamma-ray, ultra-high cosmic-ray, and neutrino emission
  - Atmospheric neutrino: detected
  - Active galaxies (with active galactic nuclei: AGN/blazar): detected
  - Clusters of galaxies & nearby star-burst galaxies: predicted to have negligible detectability (recent work by Prof. Ryu and his students at UNST/CHEA)
  - Other sites?



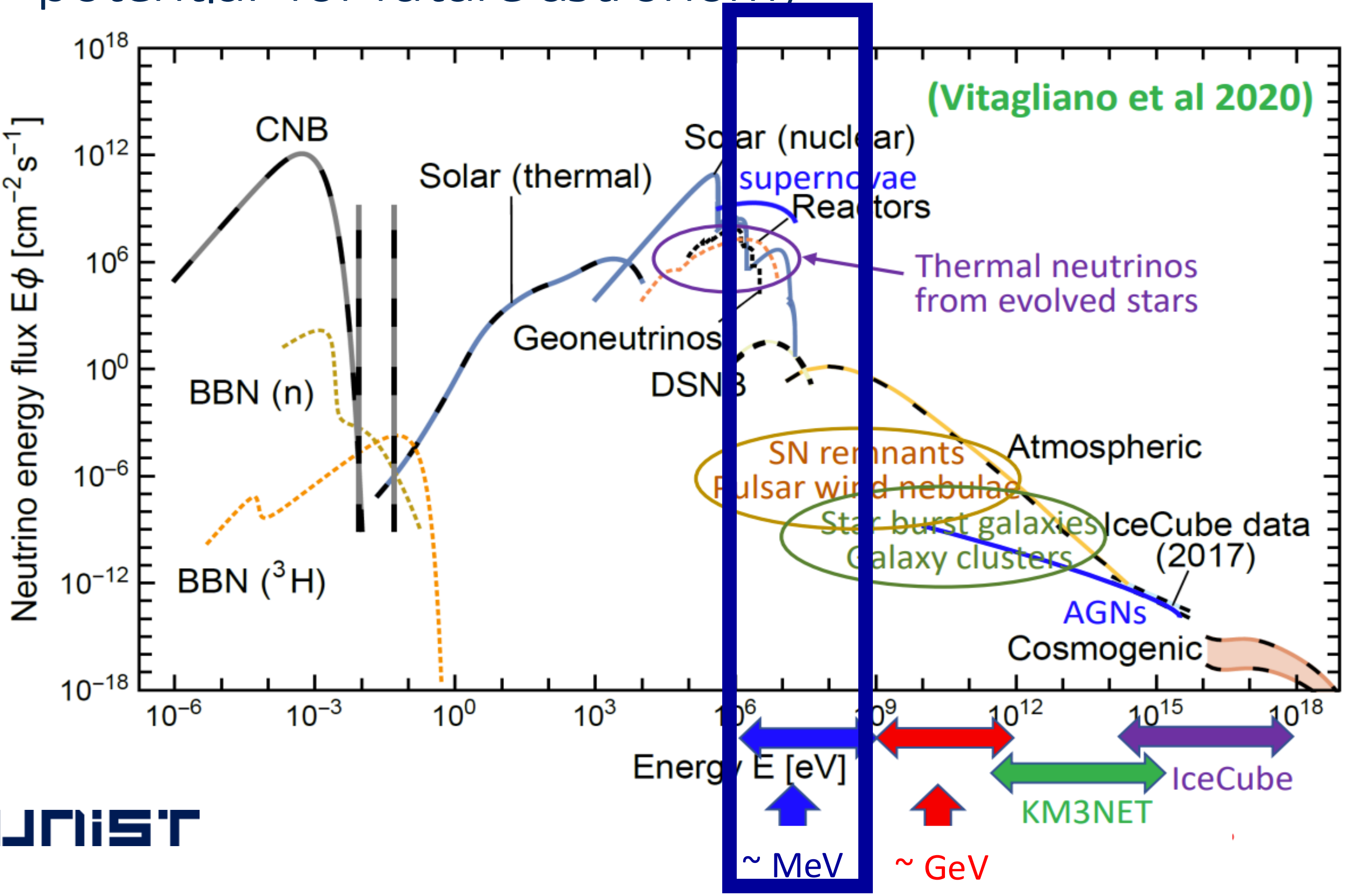
Astrophysical Sites for Neutrino Emission II

- Anywhere in the universe where weak interaction occurs!
- Nuclear reactions: low energy neutrinos (< GeV, typically a few tens of MeV)
  - Inside stars -> Solar neutrinos (detected)
  - Supernovae -> SN 1987A (detected)
  - Compact binary mergers (NS-NS or NS-BH): only GW detected -> many predictions (# of models >> # of observed events: very common in astronomy/astrophysics)
  - X-ray bursts: from rp-process. Did not get much attention thus/but worth investigating their potential contribution to detectability
  - Other sites? Carbon-burning massive stars (Red SuperGiants)

Detecting MeV neutrinos from evolved stars

Motivation

Neutrino astronomy, as a part of multi-messenger astronomy, has a great potential for future astronomy



Neutrinos interact weakly with baryonic matters

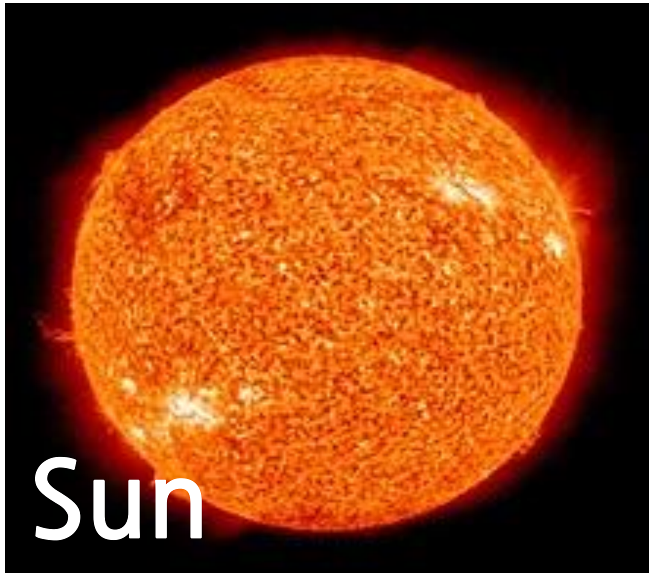
Cross sections of neutrinos with baryonic matter

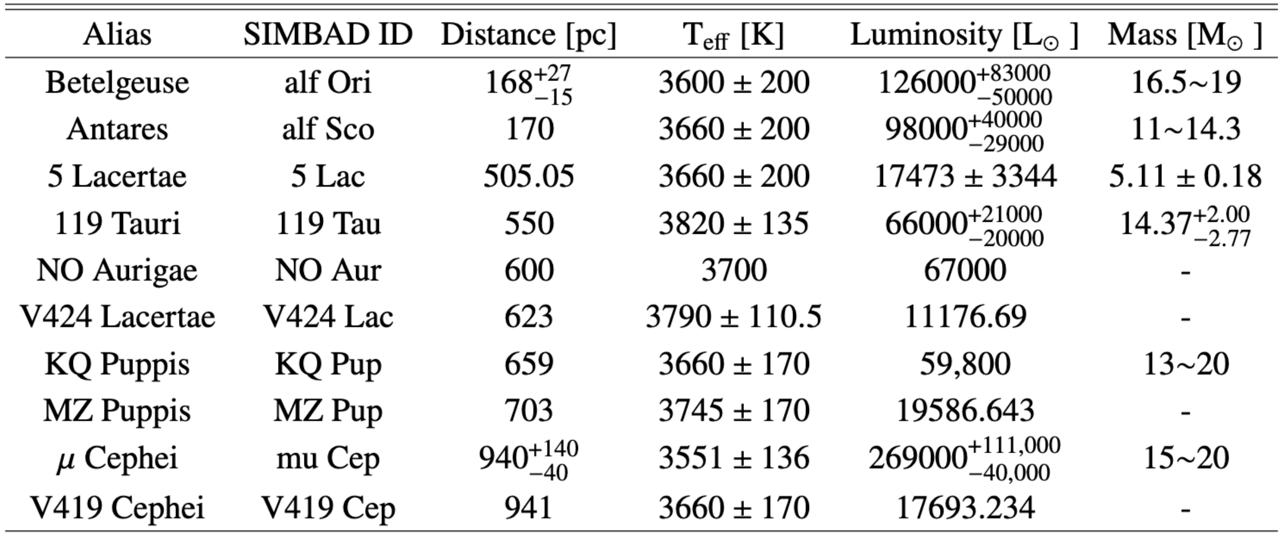
$$\simeq 10^{-44}\ \text{cm}^2$$

Cross sections of Photons with baryonic matter

$$\simeq 10^{-24}\ \text{cm}^2$$

MeV Neutrino sources





Alias	SIMBAD ID	Distance [pc]	$T_{\rm eff}$ [K]	Luminosity [$L_\odot$]	Mass [$M_\odot$]
Betelgeuse	alf Ori	168^{+27}_{-15}	3600 ± 200	126000^{+83000}_{-50000}	16.5~19
Antares	alf Sco	170	3660 ± 200	98000^{+40000}_{-29000}	11~14.3
5 Lacertae	5 Lac	505.05	3660 ± 200	17473 ± 3344	5.11 ± 0.18
119 Tauri	119 Tau	550	3820 ± 135	66000^{+21000}_{-20000}	$14.37^{+2.00}_{-2.77}$
NO Aurigae	NO Aur	600	3700	67000	-
V424 Lacertae	V424 Lac	623	3790 ± 110.5	11176.69	-
KQ Puppis	KQ Pup	659	3660 ± 170	59,800	13~20
MZ Puppis	MZ Pup	703	3745 ± 170	19586.643	-
μ Cephei	mu Cep	940^{+140}_{-40}	3551 ± 136	$269000^{+111,000}_{-40,000}$	15~20
V419 Cephei	V419 Cep	941	3660 ± 170	17693.234	-

Table 1. Red Supergiant Catalog in 1kpc

Motivation

From what other sources can MeV neutrinos be detected? → Red supergiant?

Detection MeV neutrinos: Only Sun, and SN1987A

How can MeV neutrinos be detected?

Number of targets (Detector size)

$$\text{Event rate} = \underline{f} \times \underline{N} \times \sigma(E) \times \underline{\phi(F)}$$

Trigger rate

Cross-section

Neutrino flux + energy

→ 2) Detector simulation

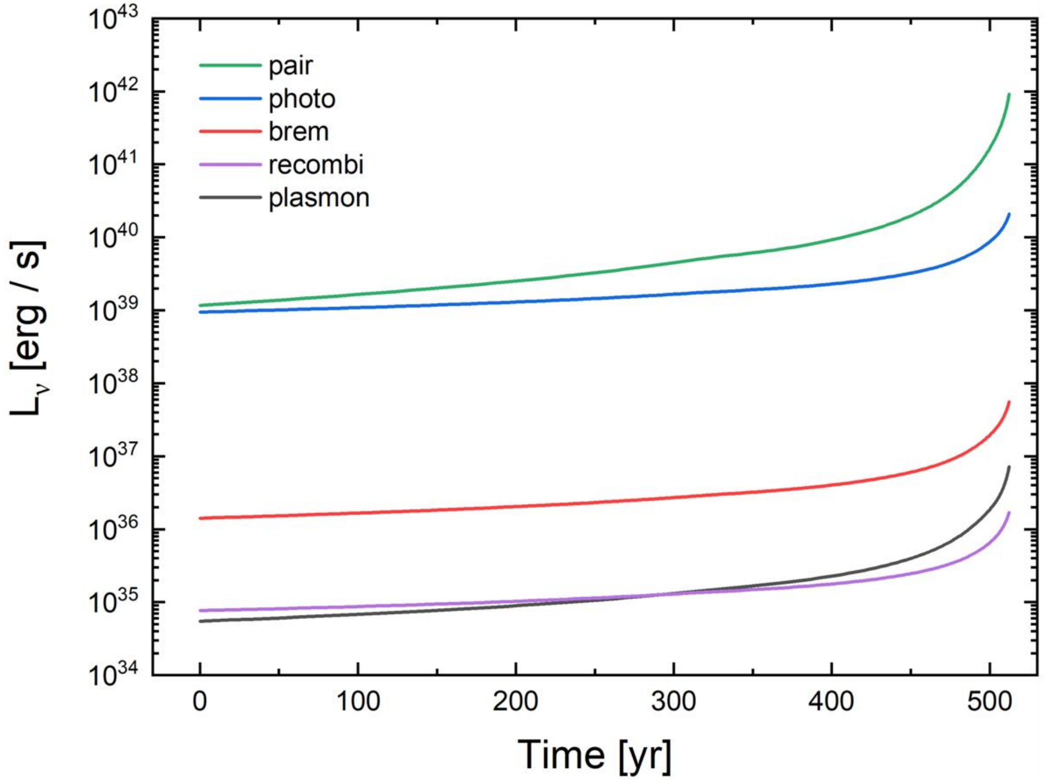
→ 1) Stellar evolution + Neu. spectrum

Neutrino from stars

01 Nuclear reactions (electron and positron capture, and nuclear decays)

02 Thermal processes

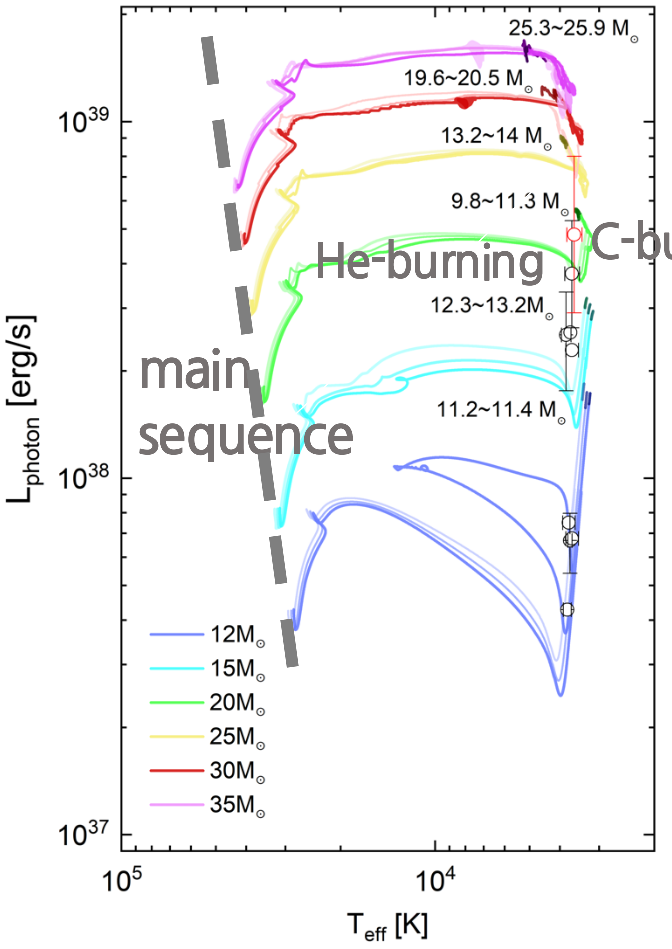
- Plasmon decay $(\gamma_{\text{plasmon}} \rightarrow \nu_e + \bar{\nu}_e)$
- Photoneutrino production $(e^- + \gamma \rightarrow e^- + \nu_e + \bar{\nu}_e)$
- Pair annihilation $(e^- + e^+ \rightarrow \nu_e + \bar{\nu}_e)$
- Bremsstrahlung $(e^- + {}^A\mathrm{Z} \rightarrow e^- + {}^A\mathrm{Z} + \nu_e + \bar{\nu}_e)$
- Recombination $(e^-_{\text{continuum}} \rightarrow e^-_{\text{bound}} + \nu_e + \bar{\nu}_e)$

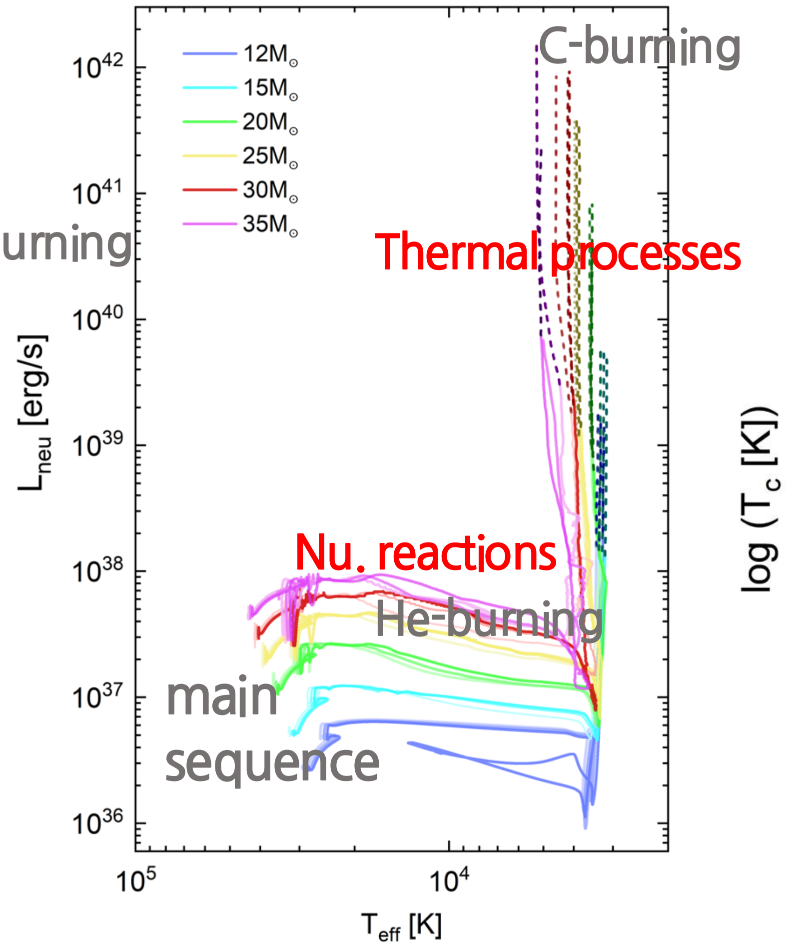


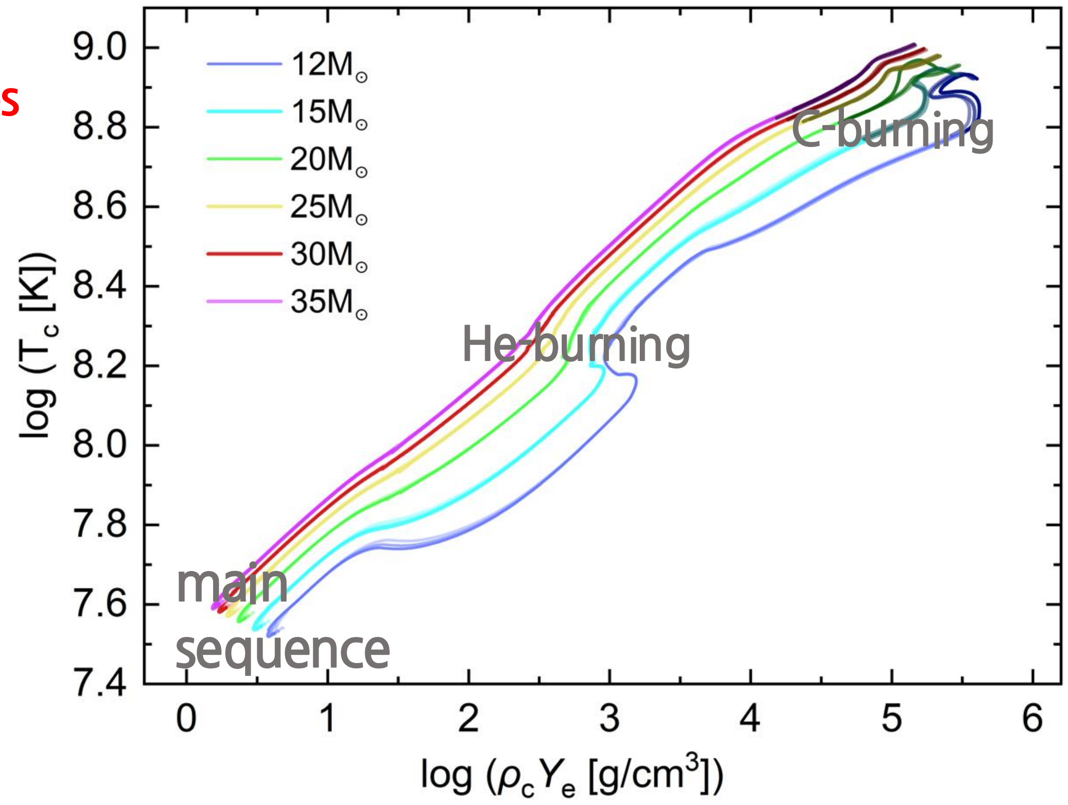
Single star models

Cf) Sun : $L_{\nu,\odot} = 0.02398 \cdot L_{\gamma,\odot}$ ~10^{31}erg/s

~$10^{40\sim42}$ erg/s



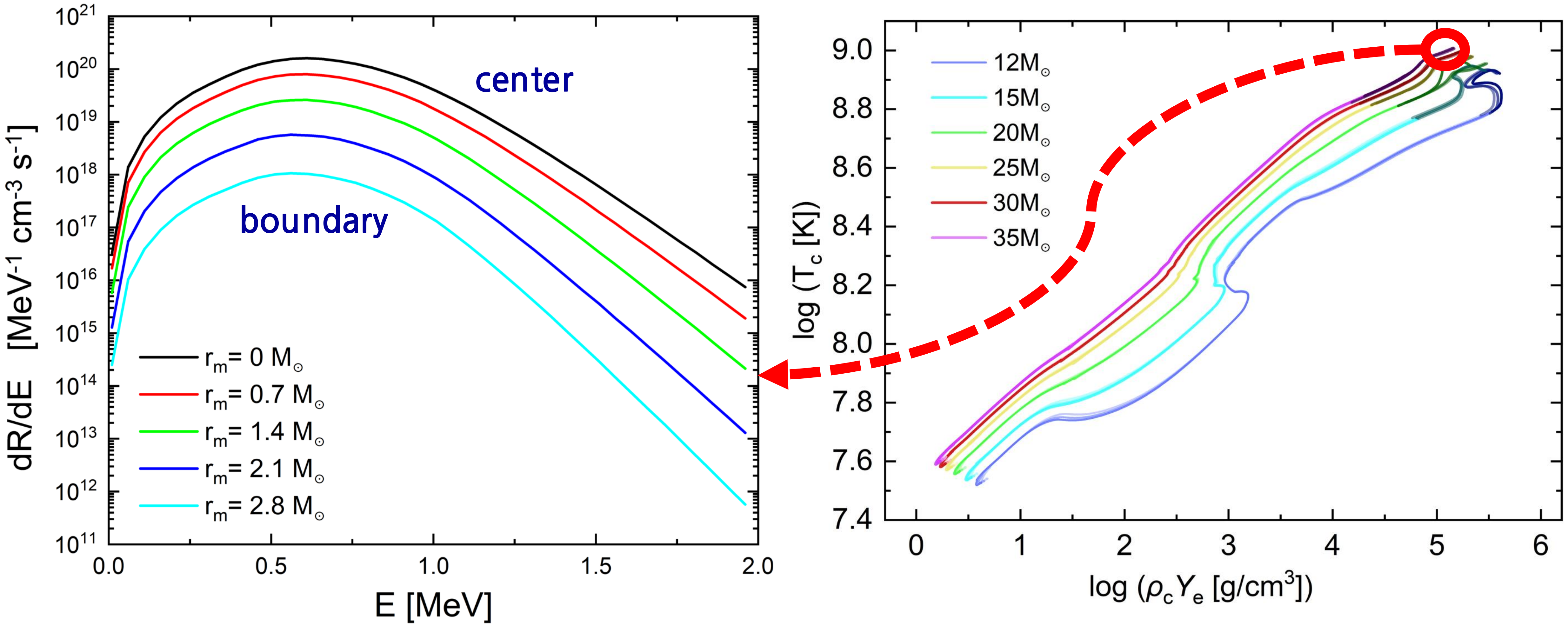




Performed by MESA(Modules for Experiments in Stellar Astrophysics)

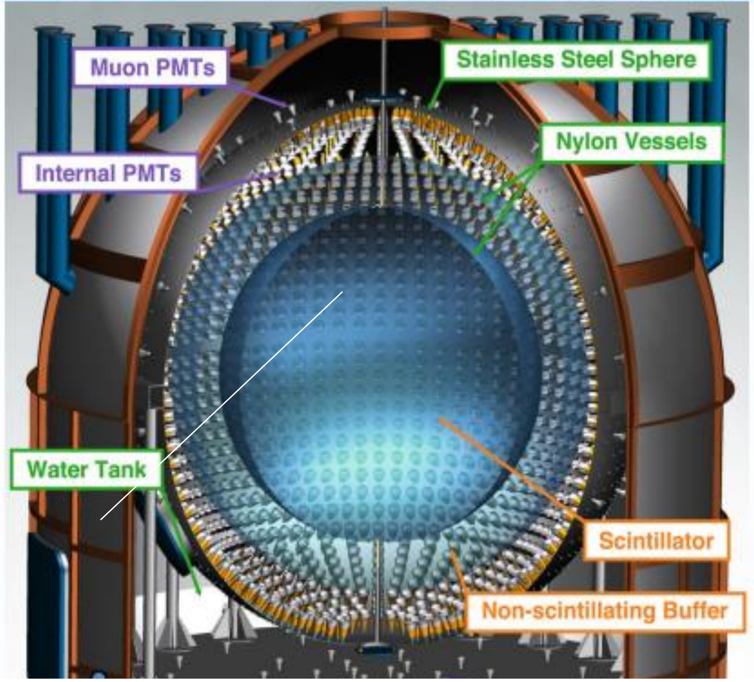
Z = 0.01, 0.015, and 0.02

RSG neutrino spectrum (pair-annihilation) – function of T, ρ_e

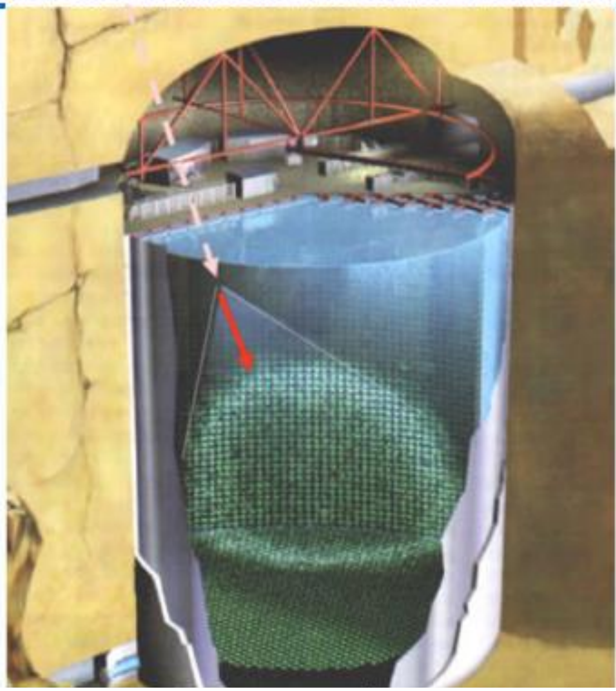


Neutrino Detectors for ~ MeV neutrinos

Motivation



Borexino



Super Kamiokande

Liquid scintillator

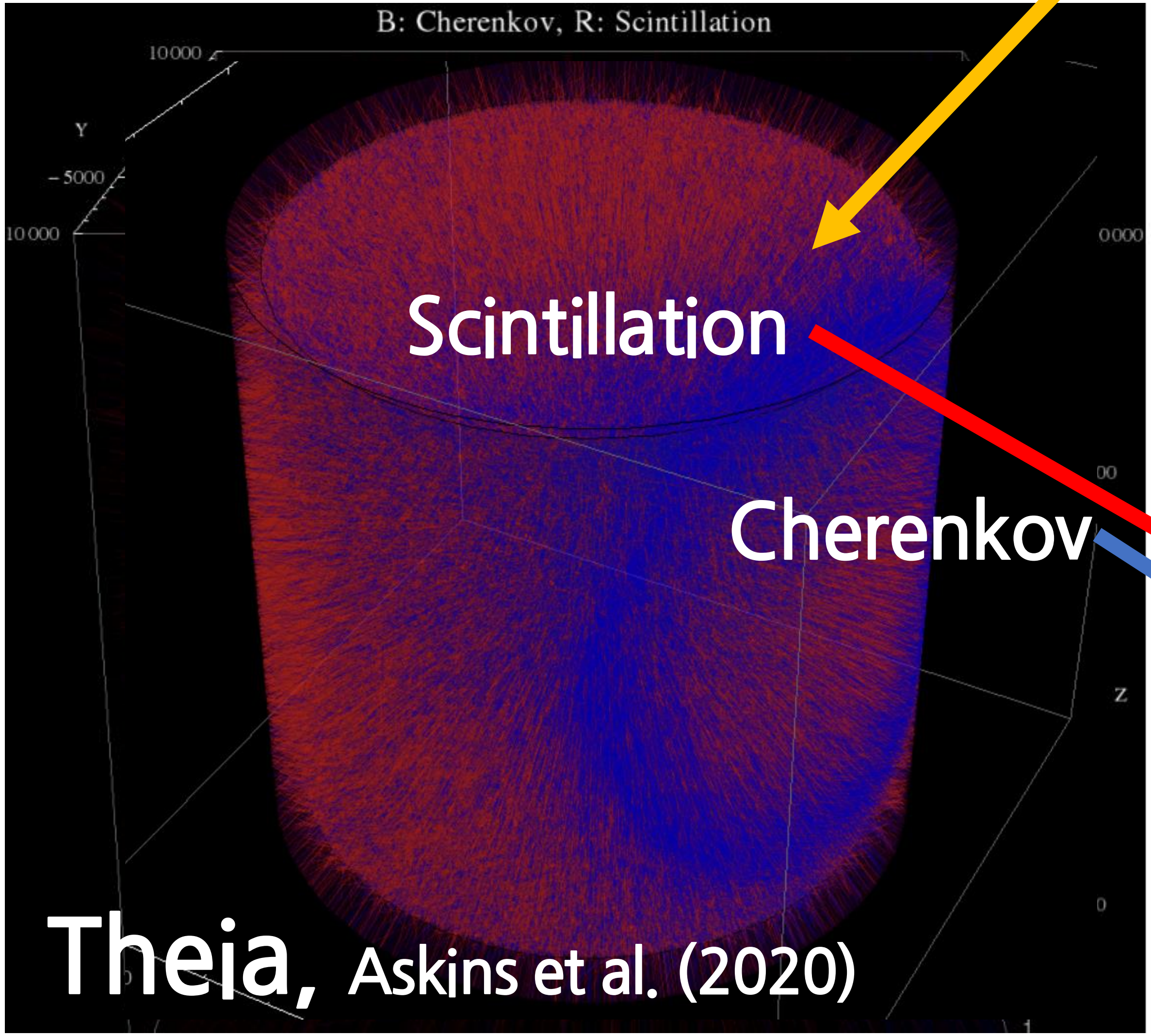
High Energy Resolution/ NO Source Direction

＋

Cherenkov detector

Source Direction / Energy Range 3.5MeV~

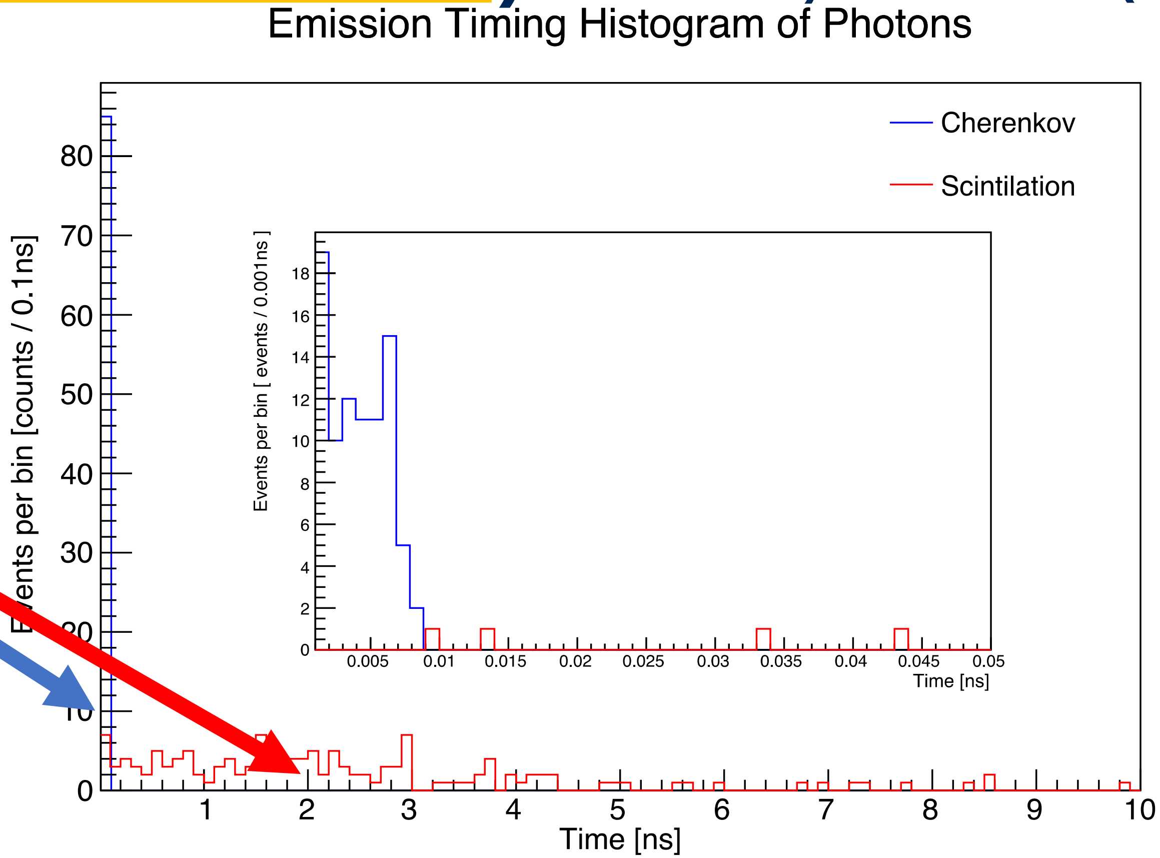
Hybrid detector (Water based liquid scintillator) – Theia, Askin et al. (2020)



Scintillation

Cherenkov

Theia, Askins et al. (2020)

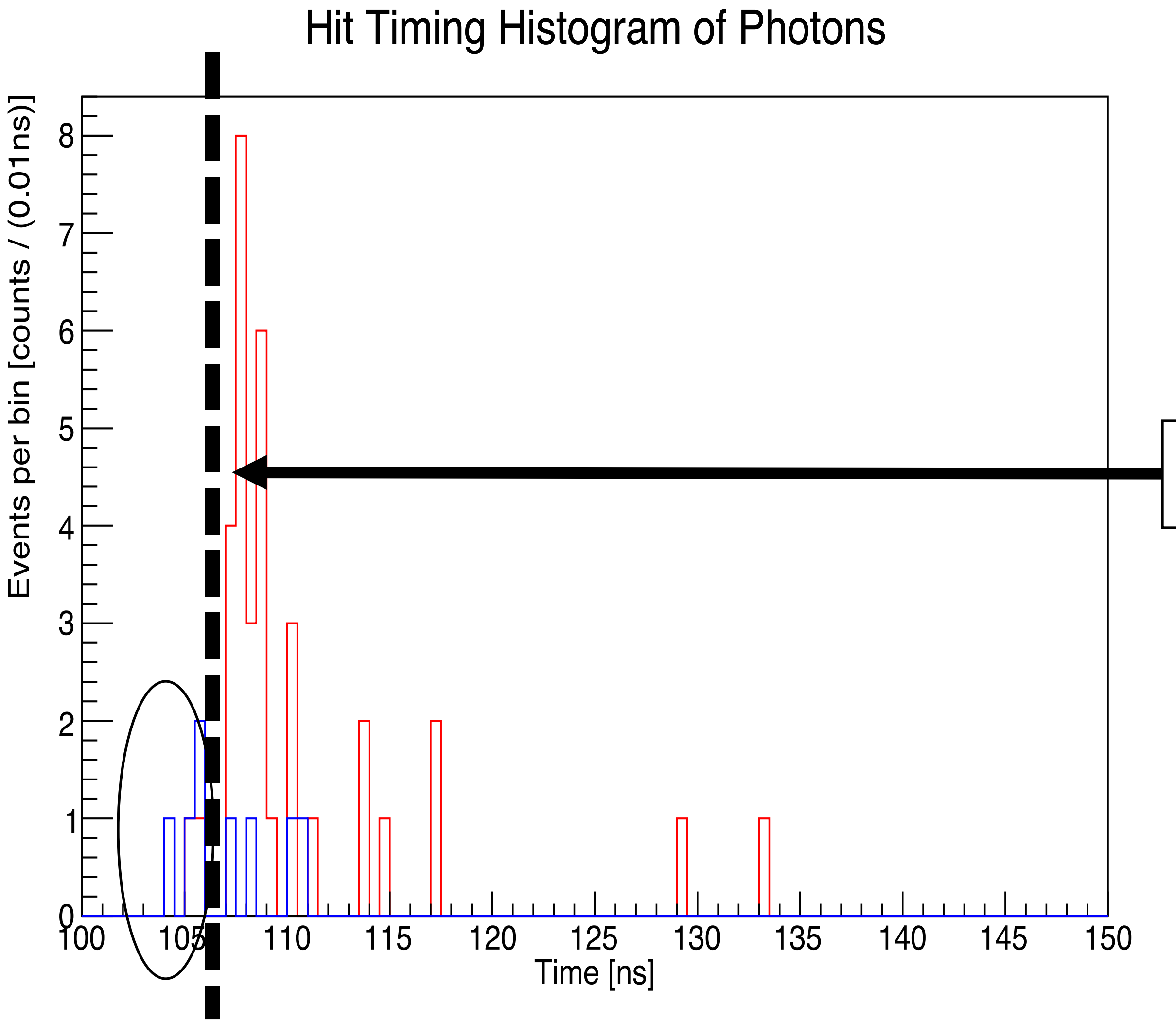


PMT → LAPPD

(Large Area Picosecond Photo-Detectors)

→ Time resolution ~ 100ps

Detector simulations (NuWro + Geant4)

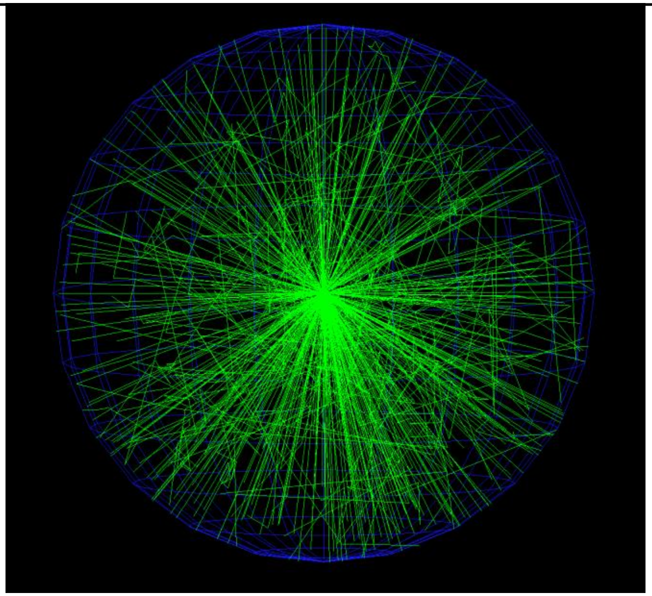


- **50kT $(r = 23\ [m])$, Sphere**
- **100% LAPPD coverage**

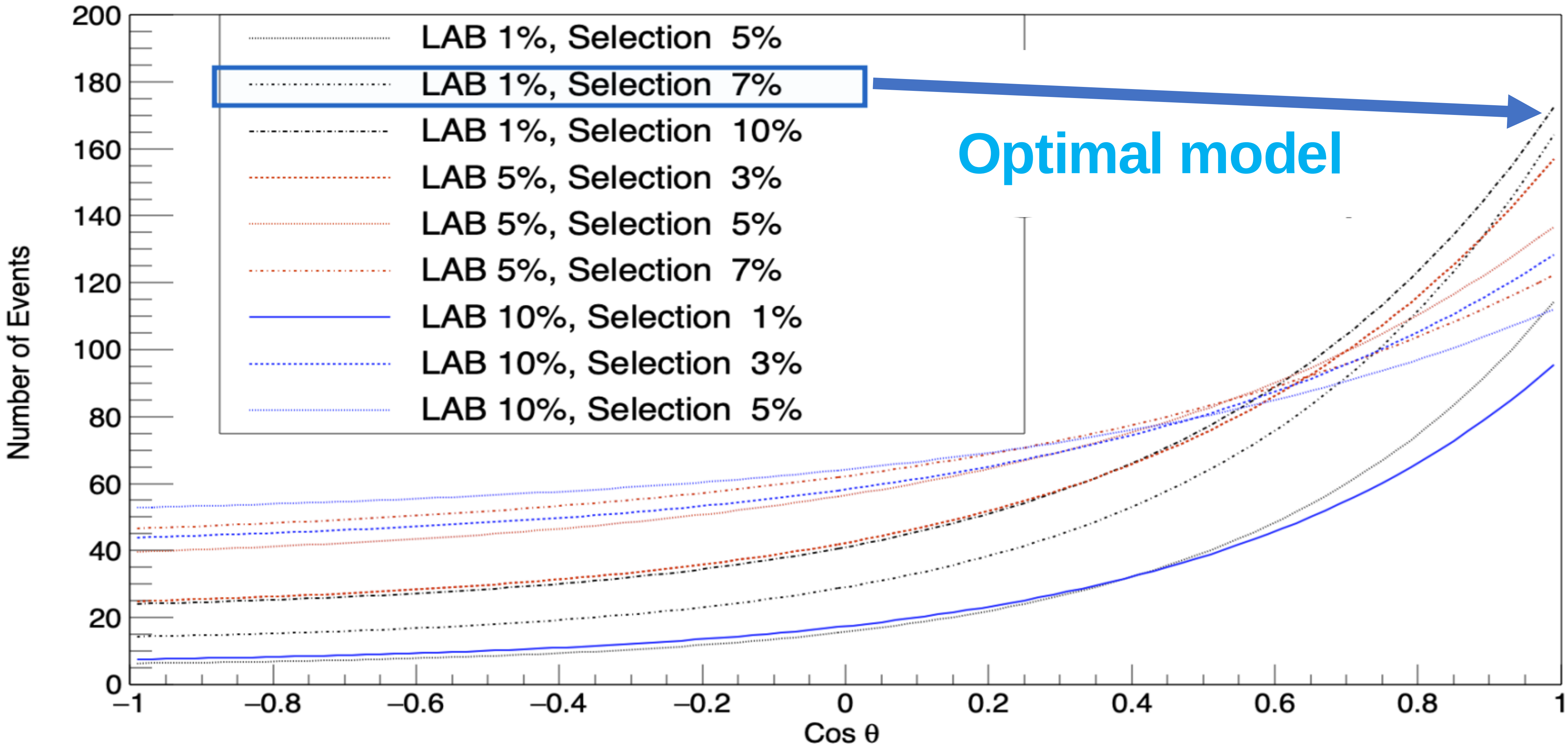
1. **Water + LAB (Liquid Argon Benzene)**

   1 - 10%

2. **Selection-cut 1 - 10%, 7%**



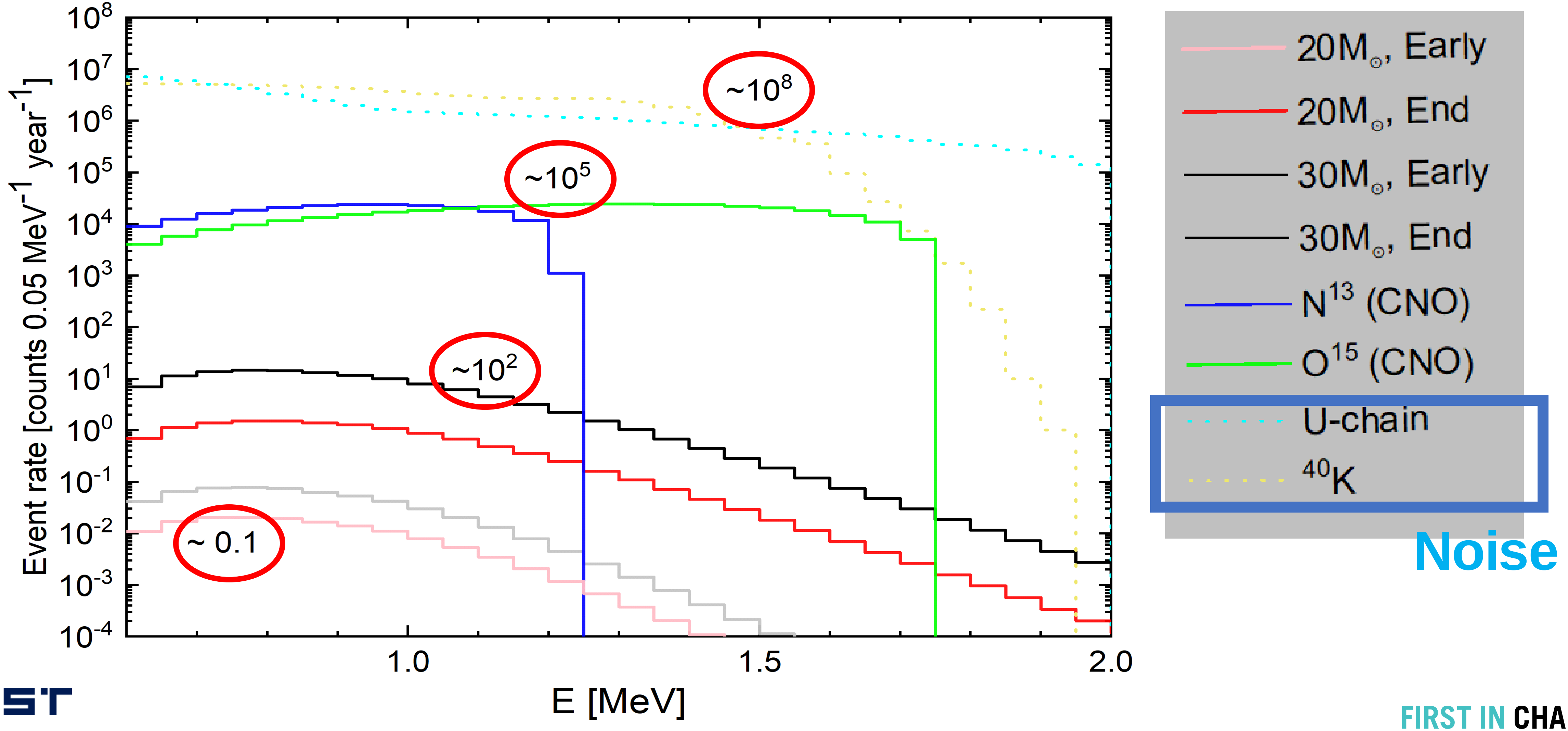
Detector performance



Optimal model

RSG's neutrinos (C-burn) with HD

RSG at 200 pc



Summary

1. Neutrino luminosity of RSGs, especially carbon burning stars, is about **$\sim10^{46\sim48}$ MeV/s,** and each neutrino has energy of **~ 0.7 MeV**
2. It is currently implausible to observe these neutrinos however, if future detectors based on new technologies such as LAPPD and WbLs were designed to target these low-energy neutrinos, detecting these would be possible in the future.
3. The most challenging task remaining will be to define and reduce noise signals.