INTEGRAL School, Les Diablerets (CH), March/April 2000

"Radionuclides and Gamma-Ray Line Astronomy"

Invited Lectures
by
Roland Diehl
MPE Garching

- Part I: Gamma-Rays and Nucleosynthesis
  - **Nucleosynthesis Processes**
  - **Radioactive Decay**
  - **Cosmic Nucleosynthesis Sites**
- Part II: Observed Cosmic Radioactivities
  - **Supernovae**
  - **Diffuse Radioactivities & Various Connections**

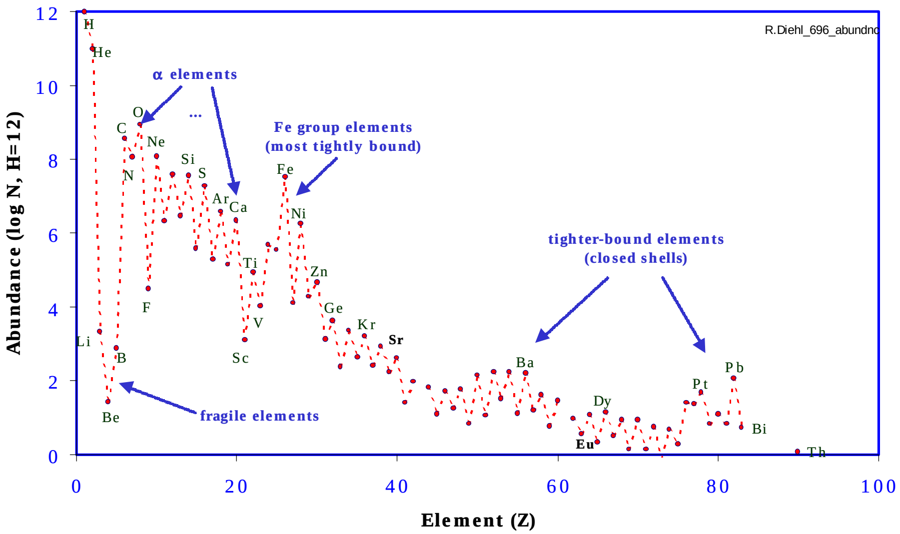
Nucleosynthesis Processes: Reading the Abundances

- **Observed Abundances Show Striking Patterns:**
  - Abundances Vary Much for Light Elements uf to ~ Fe-Group, are ~Similar Order of Magnitude for Elements >65
  - H and He are by far the Most Abundant Elements
  - Li, Be, B Fall in a Deep Minimum (9 Orders of Magnitude)
  - Elements C....Ca Show Exponentially-Declining Abundances
  - There is a Abundance Clear Peak Around Fe
  - Upon Close Look, There are Two Local Peaks Around Ba and Pb
- **Nuclear Processes / Reactions "Connect" Neighbouring Isotopes (Reactions –> n, p, or α capture or stripping)**

=>

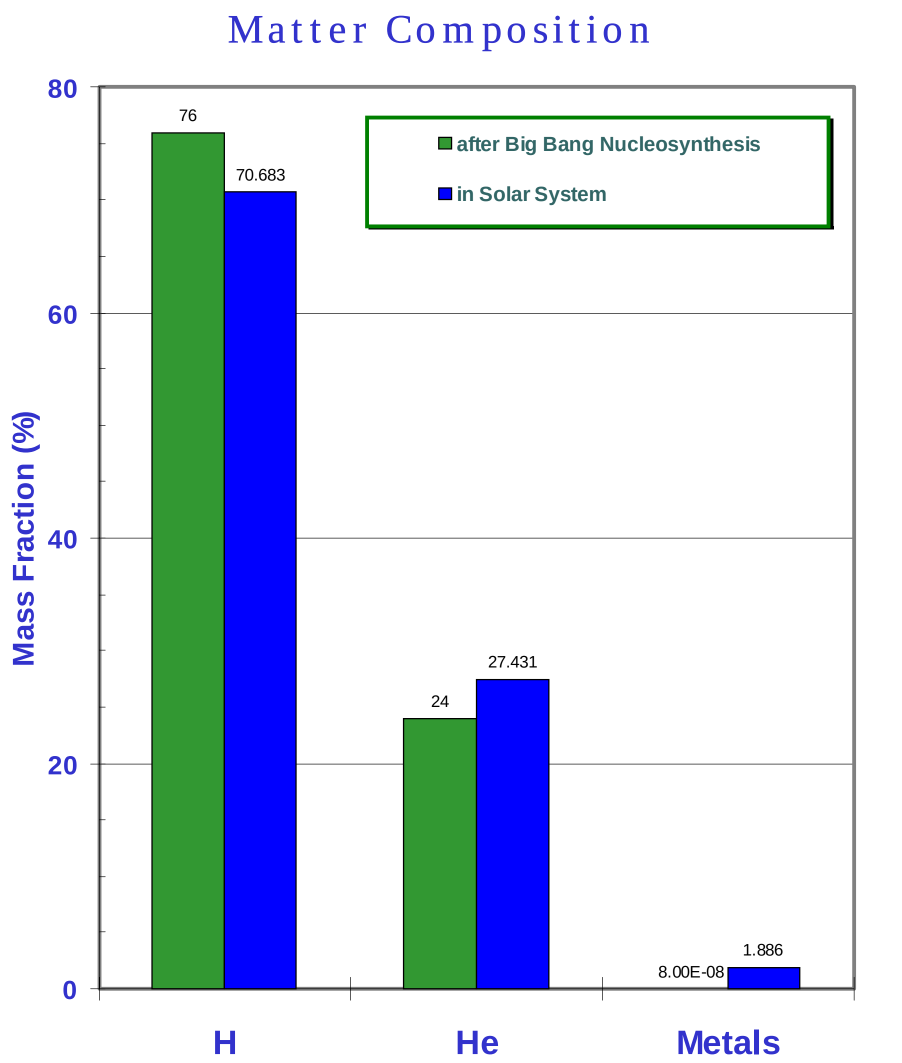
- Big-Bang Nucleosynthesis Formed H and He
- Nuclear Equilibrium Burning Formed Fe Elements
- An "α-Process" Plays a Leading Role for Elements C...Ca
- Elements Heavier Than Fe Formed from Fe Elements

Standard Abundances

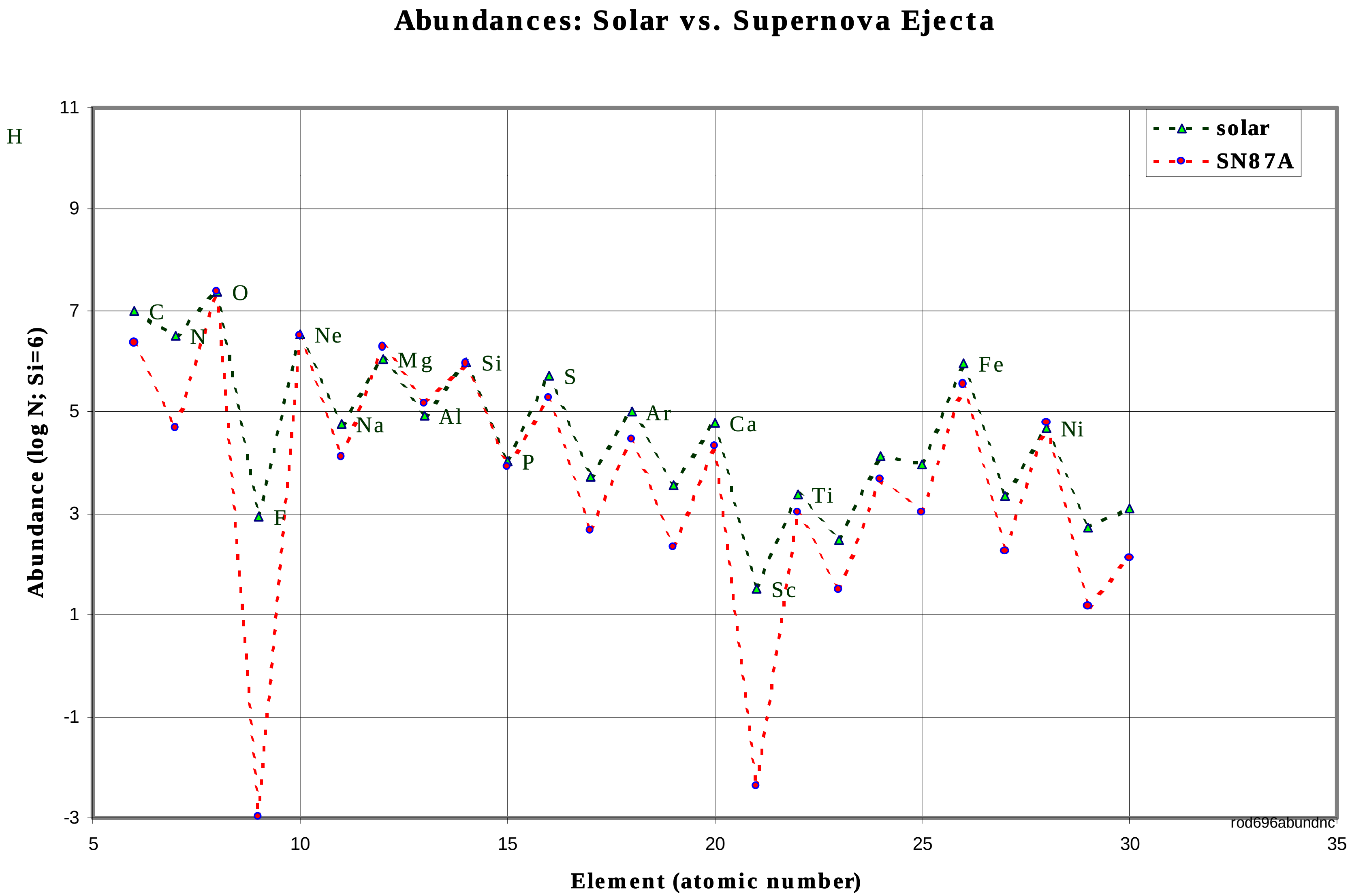


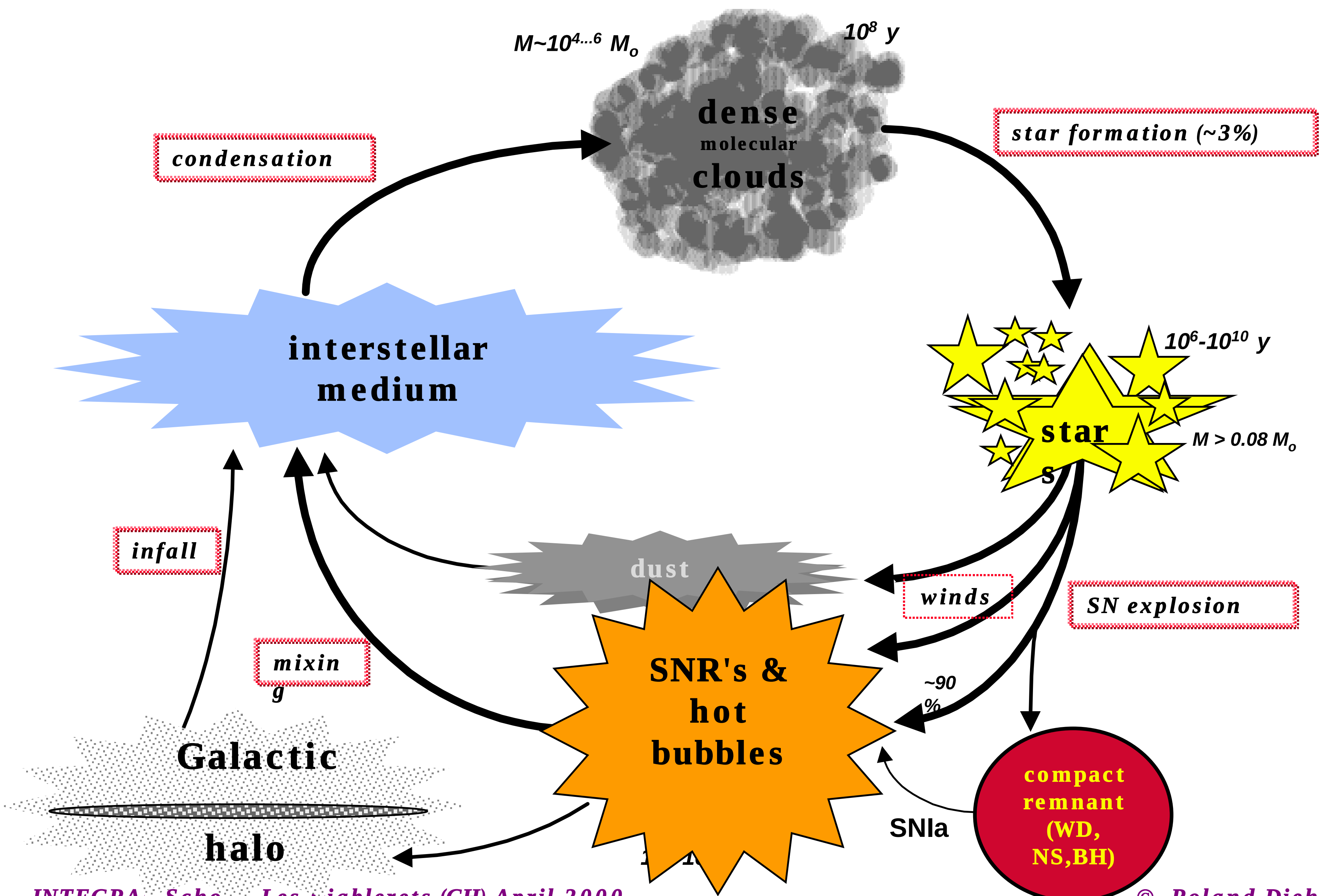
Cosmic Matter Composition

R.Diehl / '96 abundnc



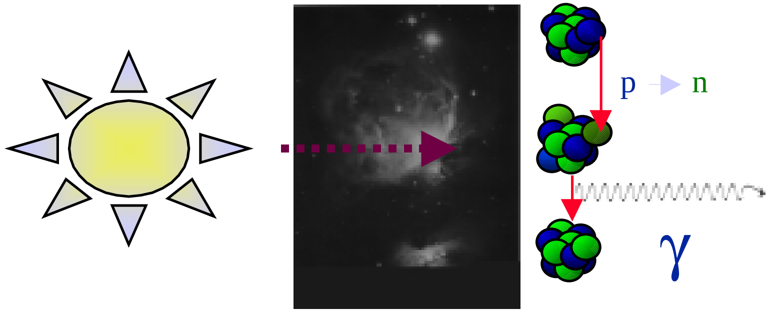
Abundances in Different Parts of the Universe



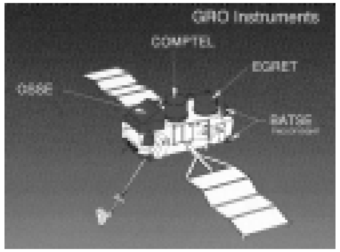

M~10^{4...6} M_o
10^8 y
dense
molecular
clouds
condensation
star formation (~3%)
interstellar
medium
10^6-10^10 y
star
s
M > 0.08 M_o
infall
dust
winds
SN explosion
mixin
g
SNR's &
hot
bubbles
~90
%
Galactic
halo
SNIa
compact
remnant
(WD,
NS,BH)

Radioactivity Traces from Nucleosynthesis

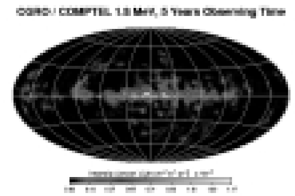
- **Long-Lived Isotopes Decay Outside Nucleosynthesis Site**

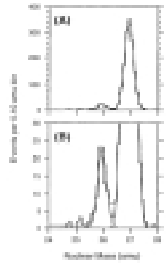


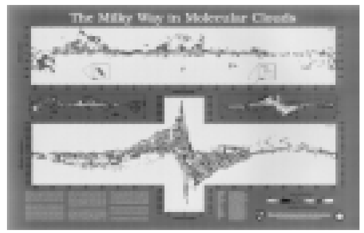
- **Radioactive-Decay Gamma-Rays Can Be Observed Through Gamma-Ray Telescopes**
- **Isotopic Ratios Can Be Observed in Cosmic Rays, Molecular Lines, Stellar Surfaces, ...**
- **Isotopic-Ratio Modifications Can Be Measured in Meteorites (Solar Material, but also Interstellar Grains)**

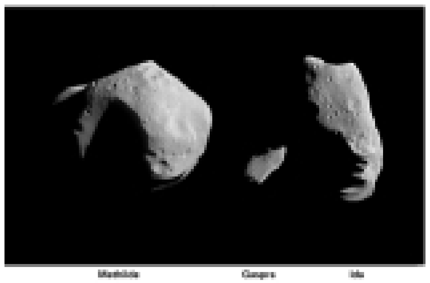


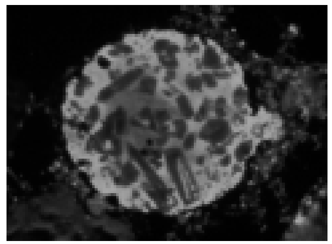
^{26}Al, ^{44}Ti, ^{56}Co, ^{57}Co





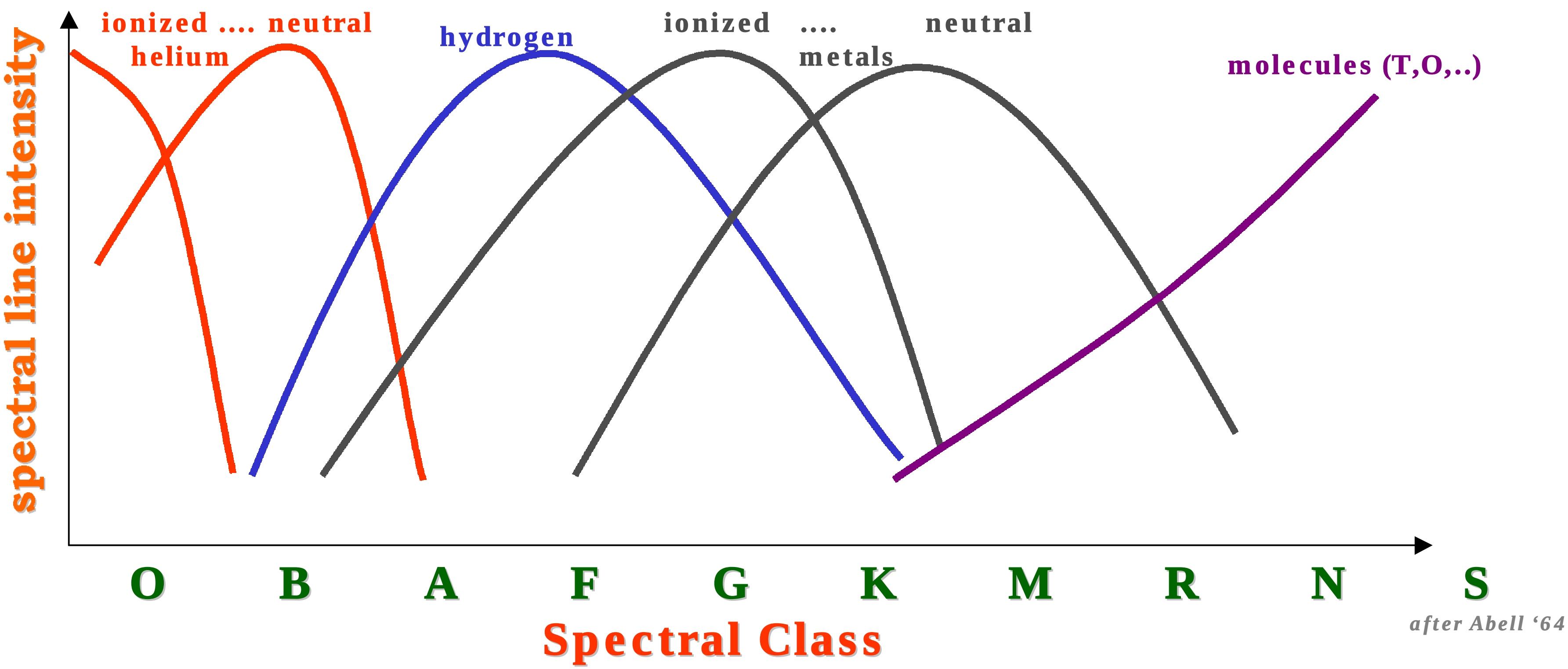




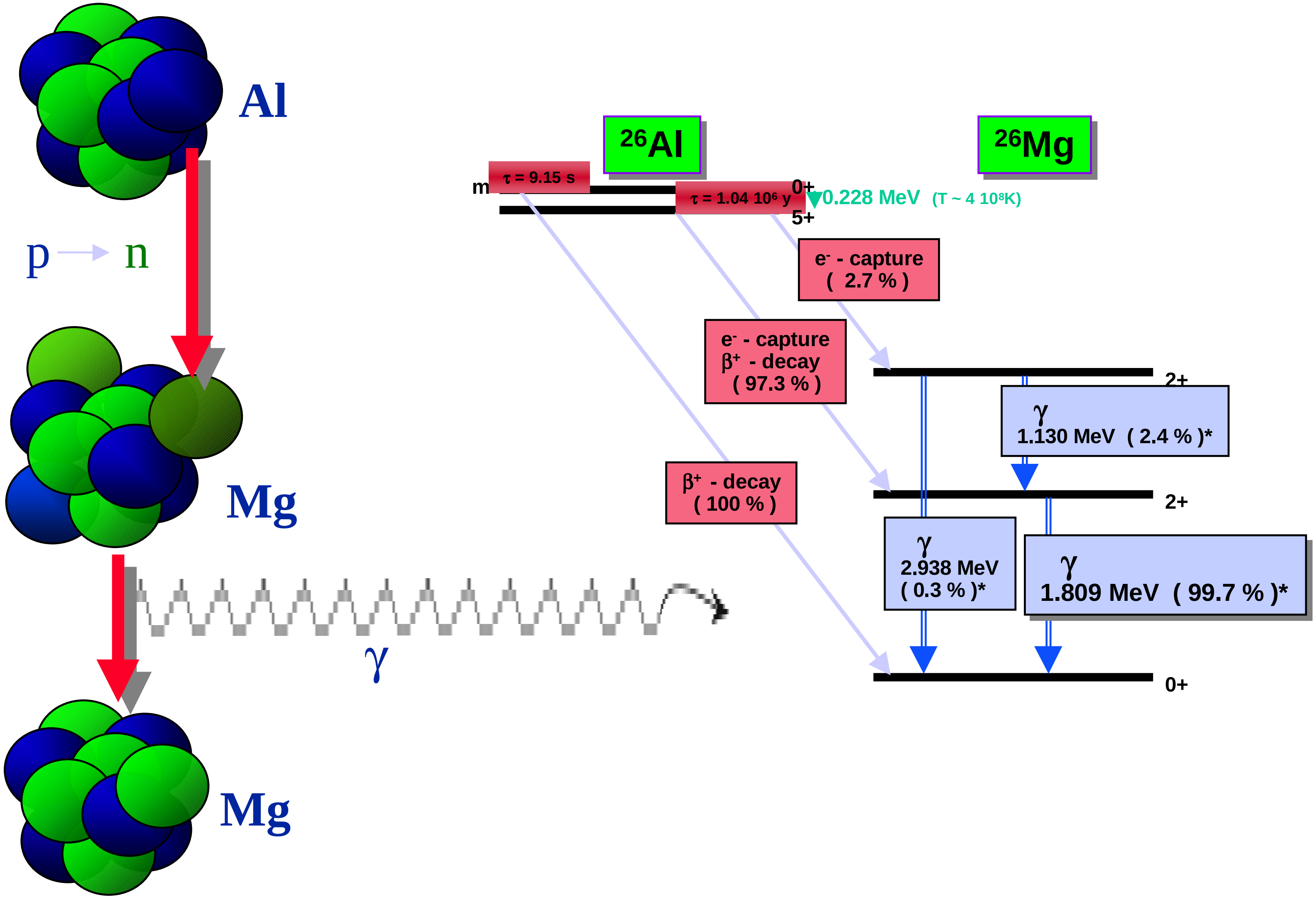


Stellar Classification and Radiation Origin

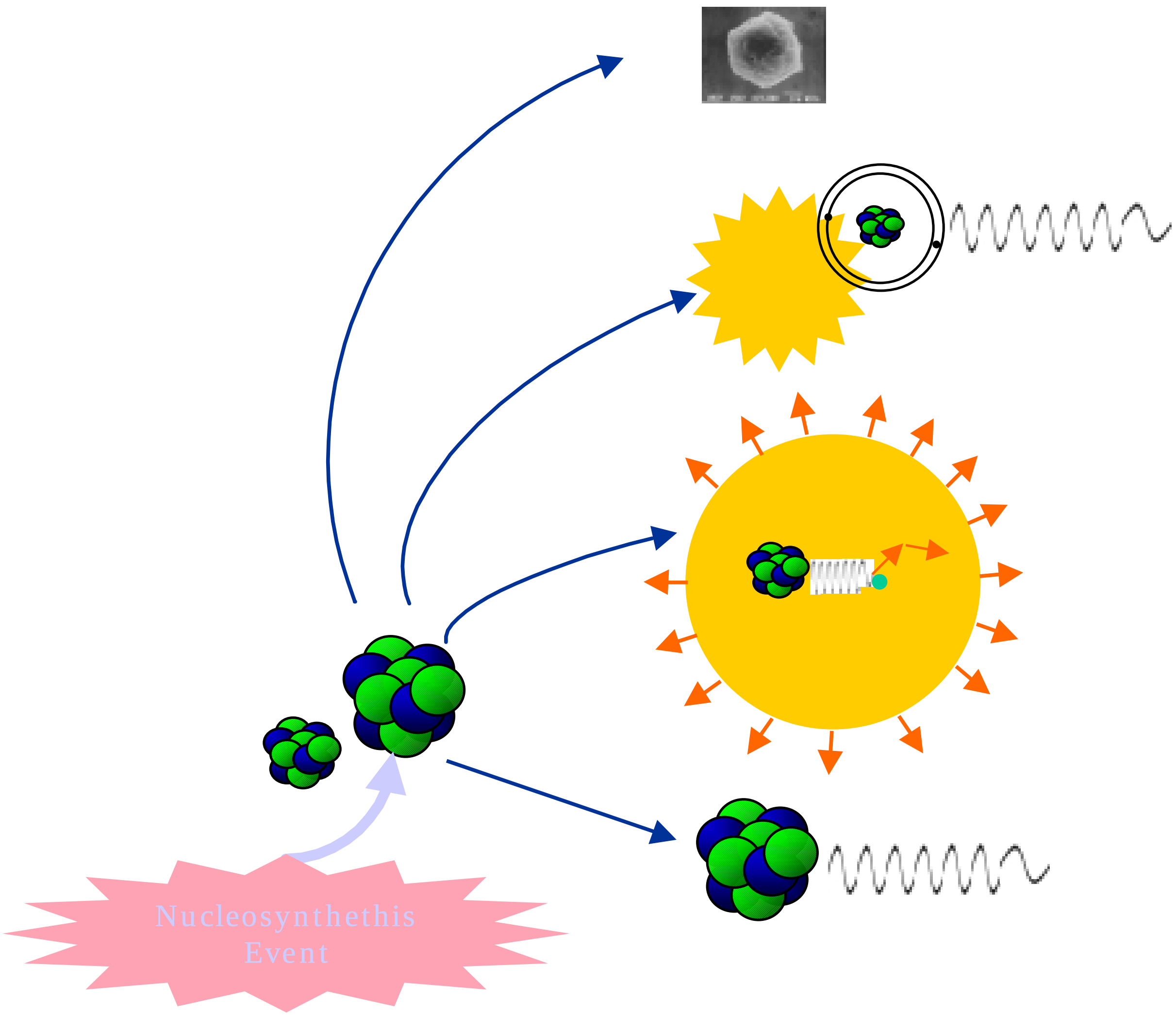
- **Spectral Classification Encodes Temperature**
- **Plasma Radiation Mechanism Depends on Temperature**
  - ☞ Molecules and Dust
  - ☞ Neutral Atoms
  - ☞ Ionized Atoms



Radioactive Decay



Studies of Nucleosynthesis



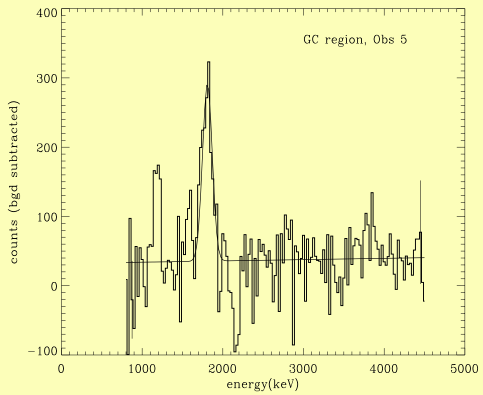
- Meteoritic Studies
- Atomic Lines in Photosphere & Corona (opt,UV, X)
- Bolometric Light in Different Frequency Ranges (Comptonized, Thermalized, Dust)
- Gamma-Ray Lines from Radioactive Isotopes

- **Gamma-Rays from Radioactive Decays Relate Directly to Isotopic Abundance**
- **Different Isotopes Probe Different Parameters of Nucleosynthesis Sites**

Objectives of Radioactivity Gamma-Ray Astronomy: Relevant Isotopes

Isotope	Decaytime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^*+e^+$	847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^*+e^+$	1157, 78, 68
^{26}Al	1.04 10^6y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	2.0 10^6y	$^{60}Fe \rightarrow {}^{60}Co^*$	1173, 1332
e^+	.... 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

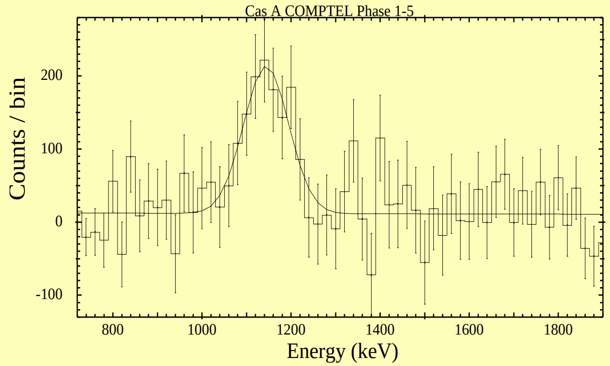
COMPTEL Detections of Radioactivity



Gamma-Ray Line at 1.809 MeV

Attributed to ^{26}Al Decay (Decay Time $\tau \sim$ 1 Mio Years)

Detected and Mapped in the Full Sky



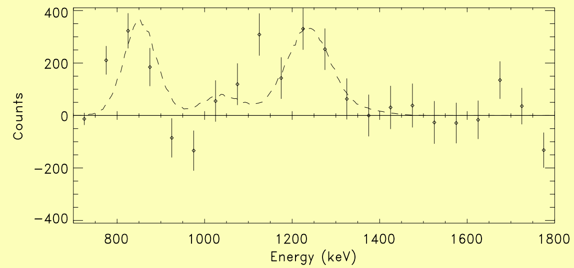
Number of selected events: 21253

Latitude ......: >40.10 deg

Gamma-Ray Line at 1.157 MeV

Attributed to ^{44}Ti Decay (Decay Time $\tau \sim$ 89 Years)

Detected from 317-y-old SN Cas A at 3.4 kpc



Gamma-Ray Lines at 0.847 and 1.238 MeV

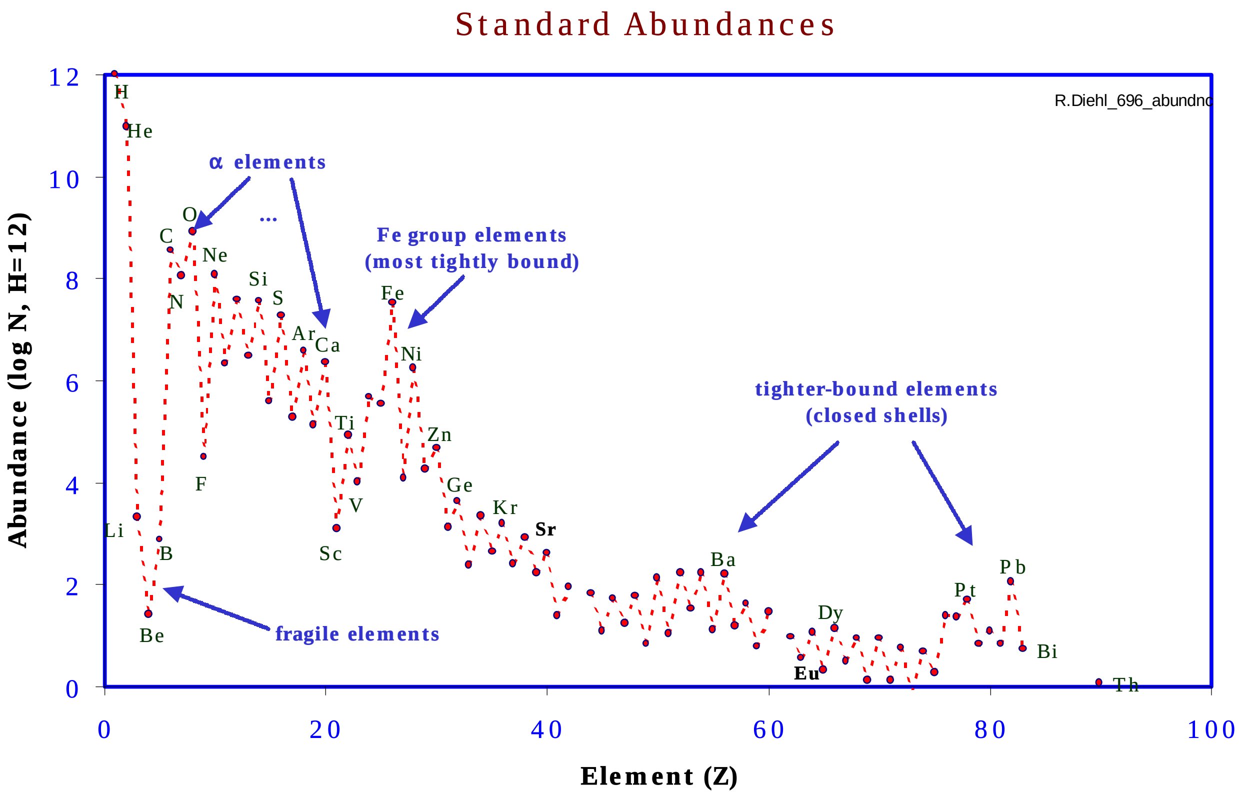
Attributed to ^{56}Co Decay (Decay Time $\tau \sim$ 111 Days)

Detected (marginally) from SN 1991T at ~17Mpc Distance

Gamma-Ray Line Astrophysics - The Goals

- **Utilize / Open a New Astronomical Window**
  - Penetration of Gamma-Rays
  - Unique/Direct Inference of Isotope Abundances
- **Calibrate Engines of Stars / Novae / Supernovae**
  - Nuclear Reactions as Root Energy Source
  - Radio-Isotopes Emit Gamma-Ray Lines
- **Study Parameters of Nucleosynthesis Sites**
  - Identify Operating Nuclear Reaction Chains per Site
  - Constrain Environmental Par's (T,ρ,τ_{conv})
- **Study Energetic-Particle Processes**
  - Acceleration Mechanisms (Solar Flares)
  - Cosmic Ray Source Regions (Nuclear-Excitation Lines)

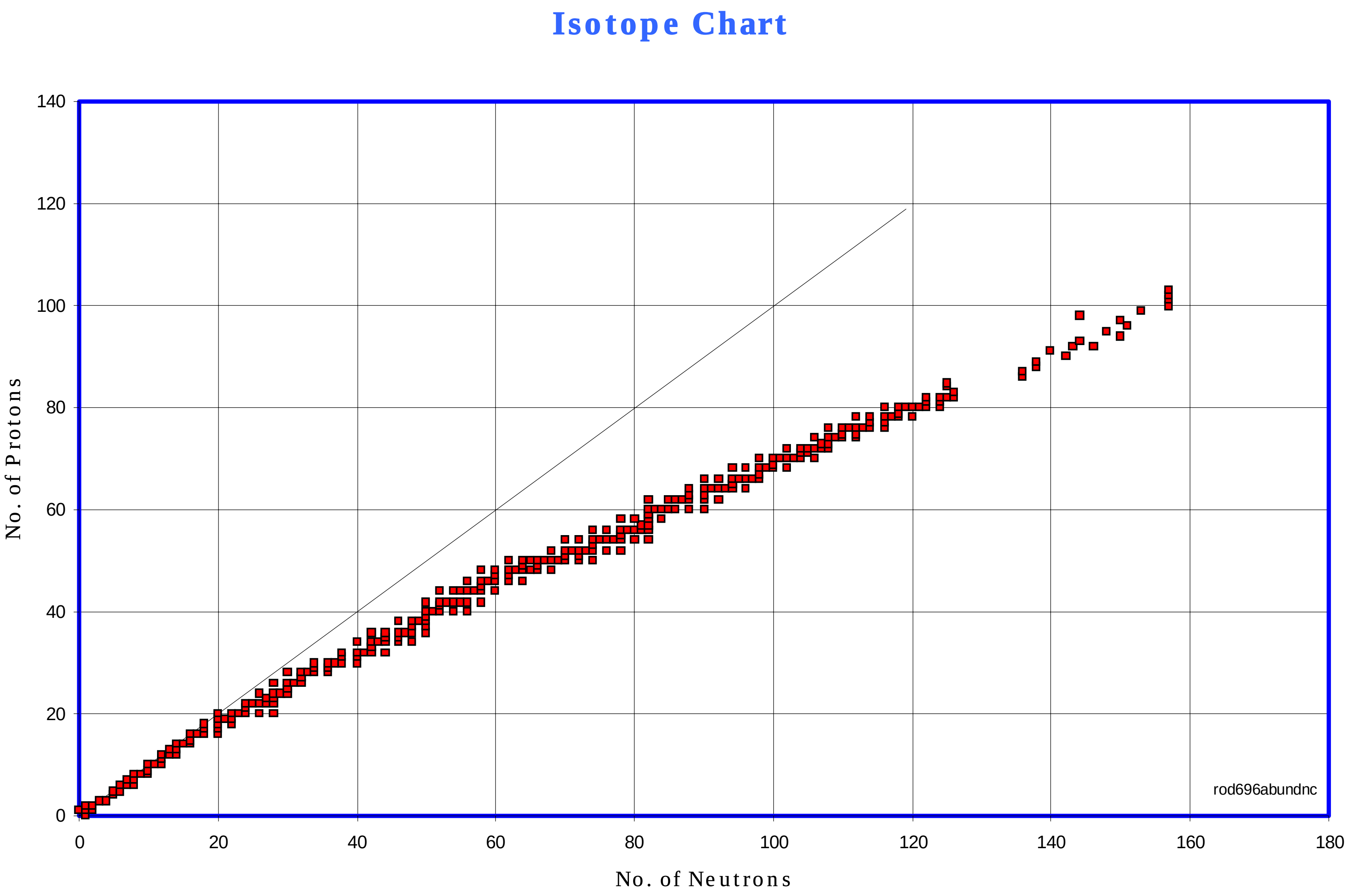
Cosmic Radioactivities



Goals:

- Understand the Physical Processes which Shaped the Pattern of Abundances in (different parts of) the Universe
- Provide Complementary Measurements on Cosmic Sites of Nucleosynthesis

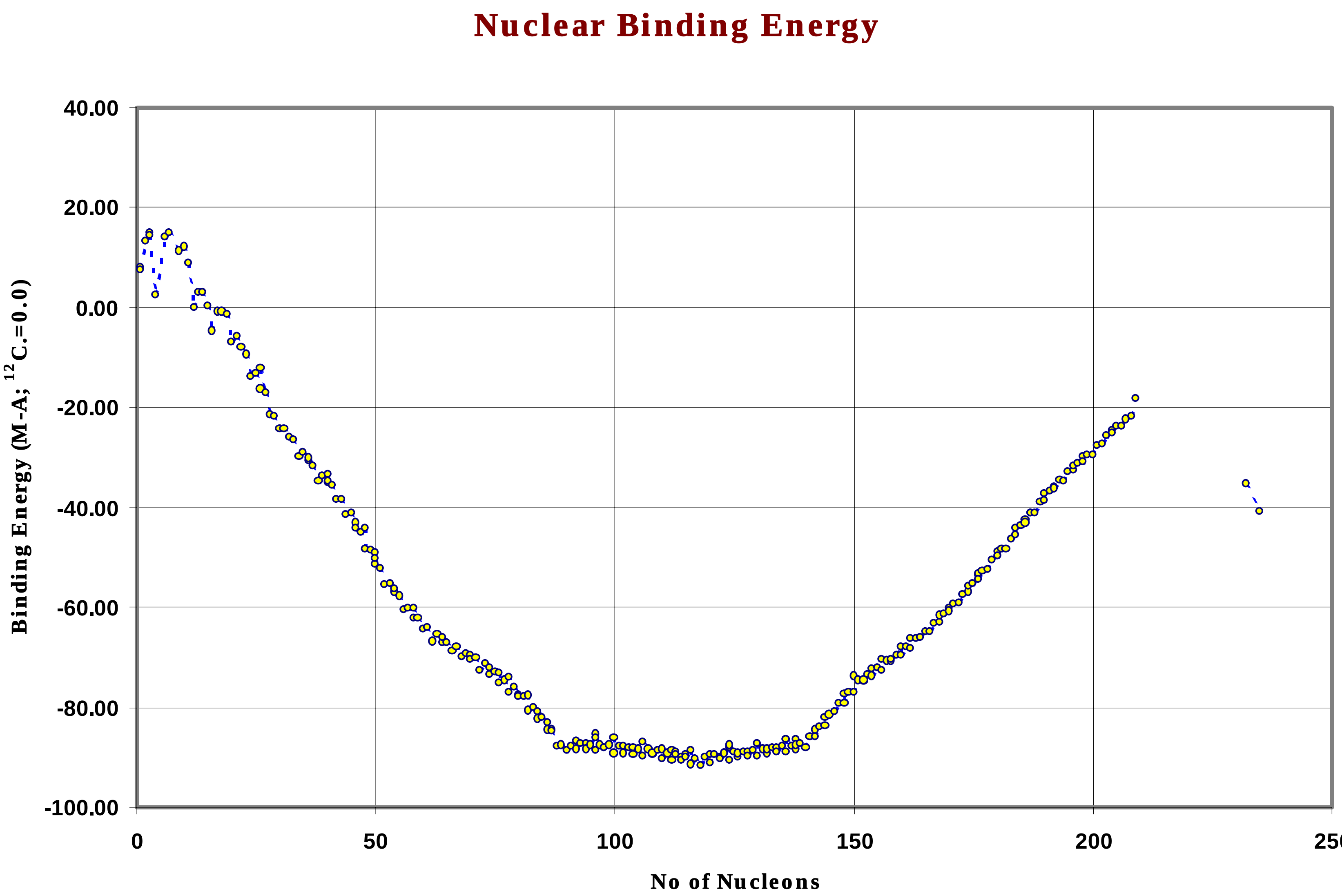
The Stable Isotopes of Matter



Nuclear Reactions in Cosmic Nucleosynthesis

- **Strong Interactions**
    - p Capture
    - n Capture
    - Heavy-Ion Reactions
    - Resonances
  - Nuclear Force Range: ~10^{-15} m = fm
  - Reaction Times 10^{-16}...10^{-22} s
  - Coulomb Repulsion -> Tunneling ('Gamov Peak')
  - Stellar Reaction Cross Sections Interpolated from Measurements at Lab. Energies ('astrophysical S-Factor')
- **Weak Interactions**
    - $n + \nu_e \leftrightarrow p + e^-$ 'β Decays'
  - 'Slow' Compared to Strong Reactions
  - *log (ft)* values with (t >> 10^{-16}s)

The Nuclear Binding Force in Different Nuclei



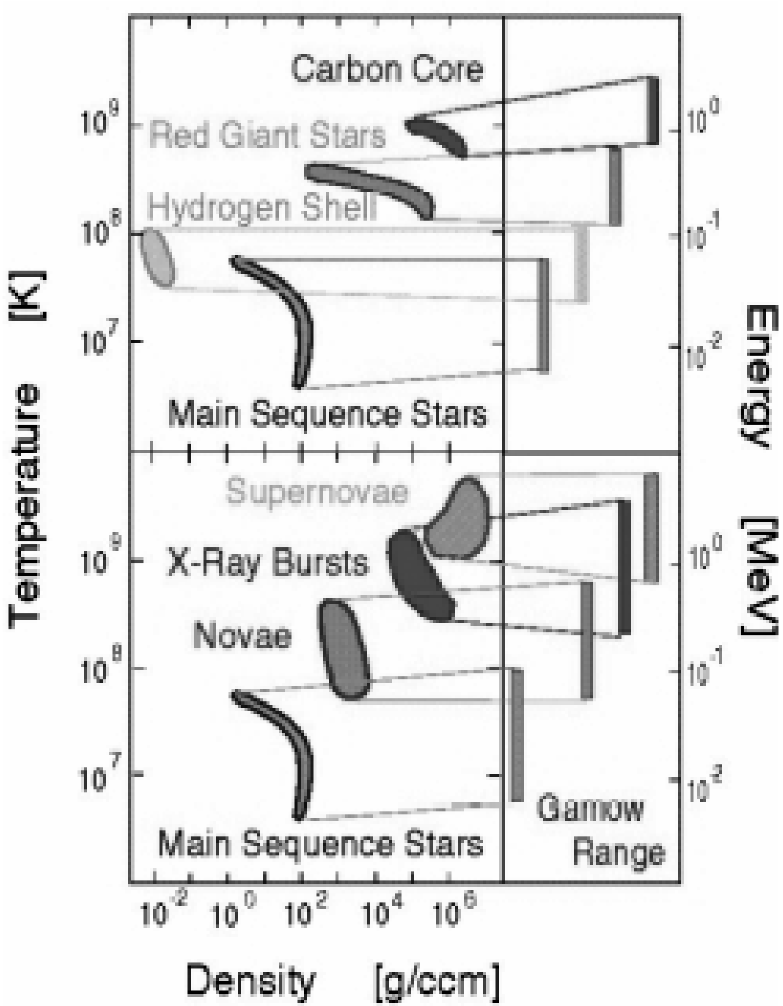
Cosmic Nucleosynthesis Environments

Nuclear Burning Requirements:

- **<σv> * Q ≥ Local Cooling Rate**

=>

- **Dense & Hot Environments**

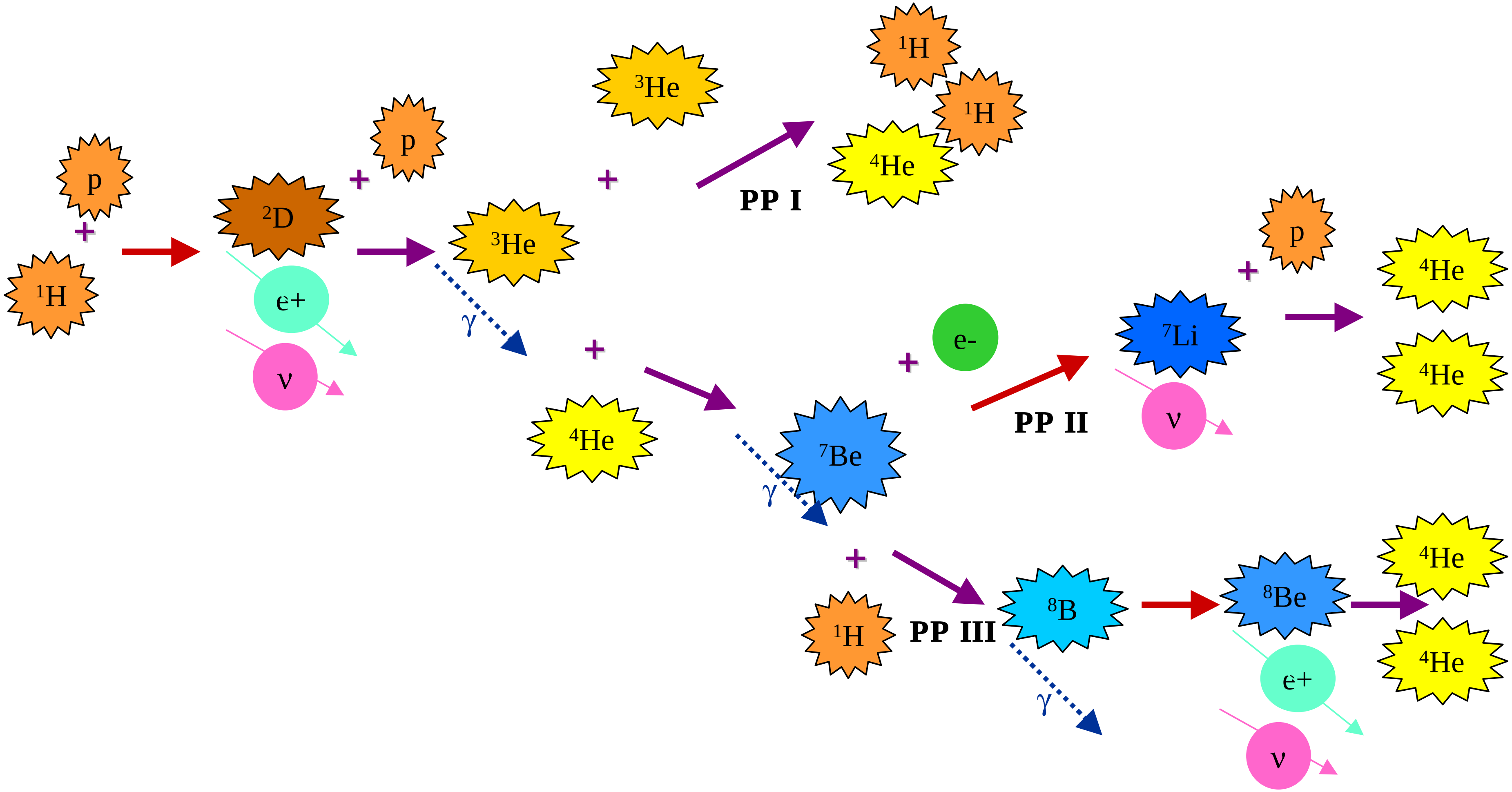


for a Stellar Mass Range of 1-30 M_o:

- Nuclear Burning in Stellar Cores and Shells (top)
- Nuclear Burning in Explosive Sites (bottom)
- Gamov Windows (righthand side)

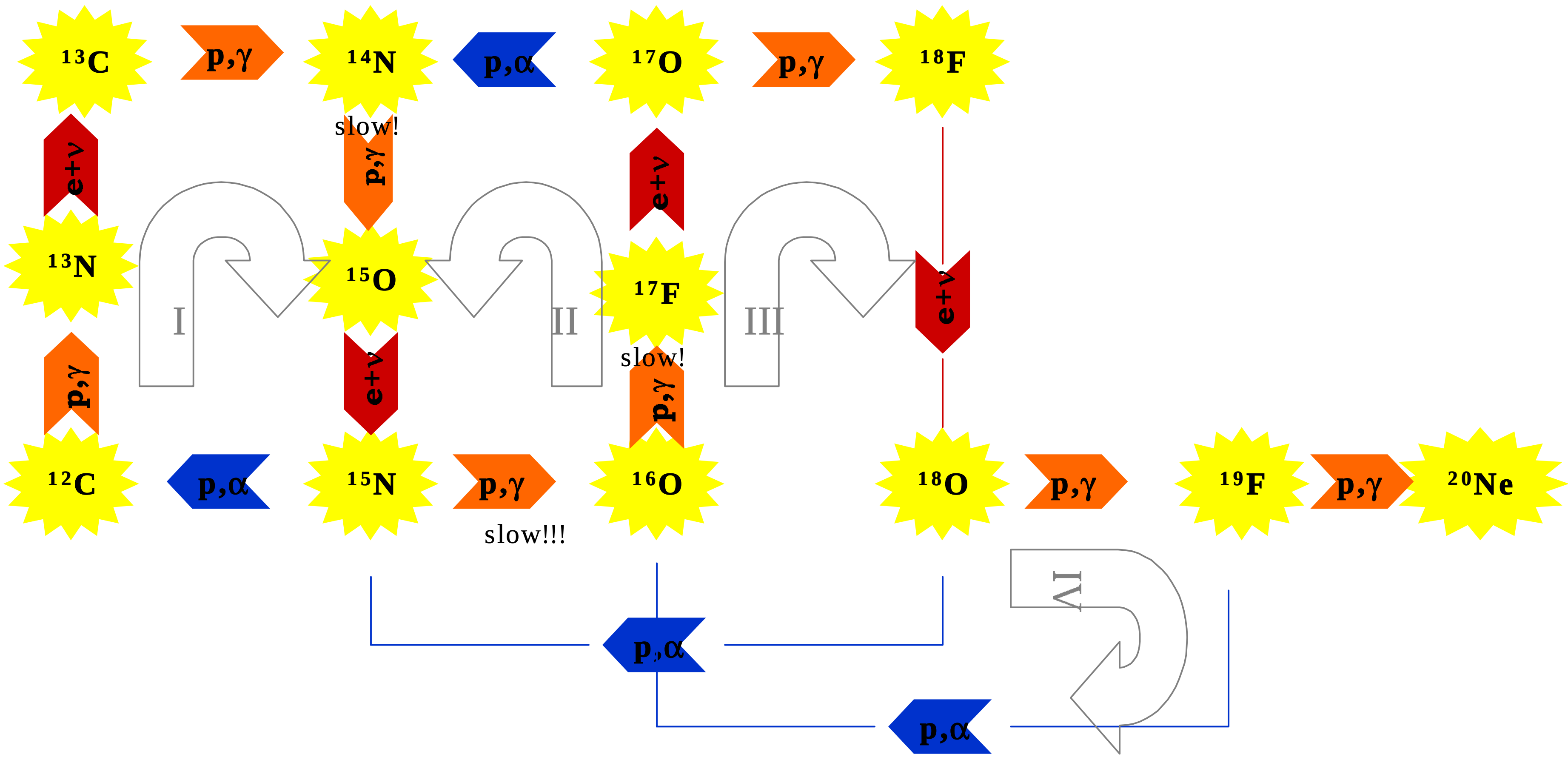
Elementary Nuclear-Reaction Cycles

- **H Burning: p-p Chains**



Elementary Nuclear Burning Cycles

- **H Burning: CNO Cycle**



☞ **Net Burning towards ^{14}N**

☞ **^{12}C / ^{13}C ~4** (SAD:89)

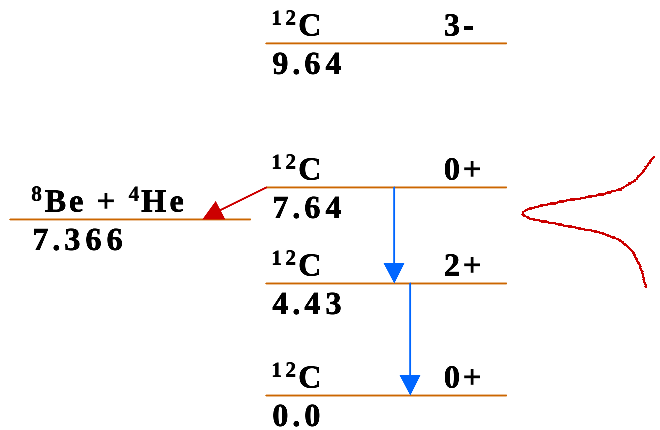
Elementary Nuclear-Burning Cycles

- **He Burning: 3α Cycle**

$$^{4}He + {}^{4}He \rightleftharpoons {}^{8}Be$$

$$^{8}Be + {}^{4}He \rightleftharpoons {}^{12}C^{*} \longrightarrow {}^{12}C^{*} \longrightarrow {}^{12}C$$

☞ Lifetime ^{8}Be ~ 7 10^{-16} s
☞ ^{8}Be(α,γγ)^{12}C through Excited Level at 278 keV+ *(Salpeter, Hoyle)*
☞ $\varepsilon \sim T_8^{40}$ –> He Flash



Elementary Nuclear-Burning Cycles

- **He Burning: 3α Cycle**

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

☞ Lifetime $^{8}Be \sim 7\ 10^{-16}$ s

☞ $^{8}Be(\alpha,\gamma\gamma)^{12}C$ through Excited Level at 278 keV+ *(Salpeter, Hoyle)*

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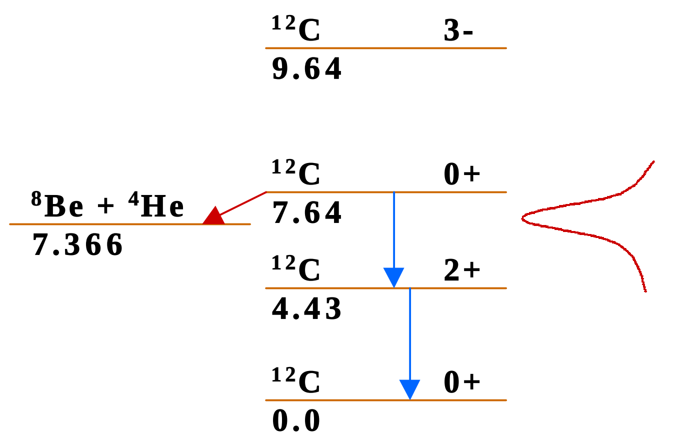
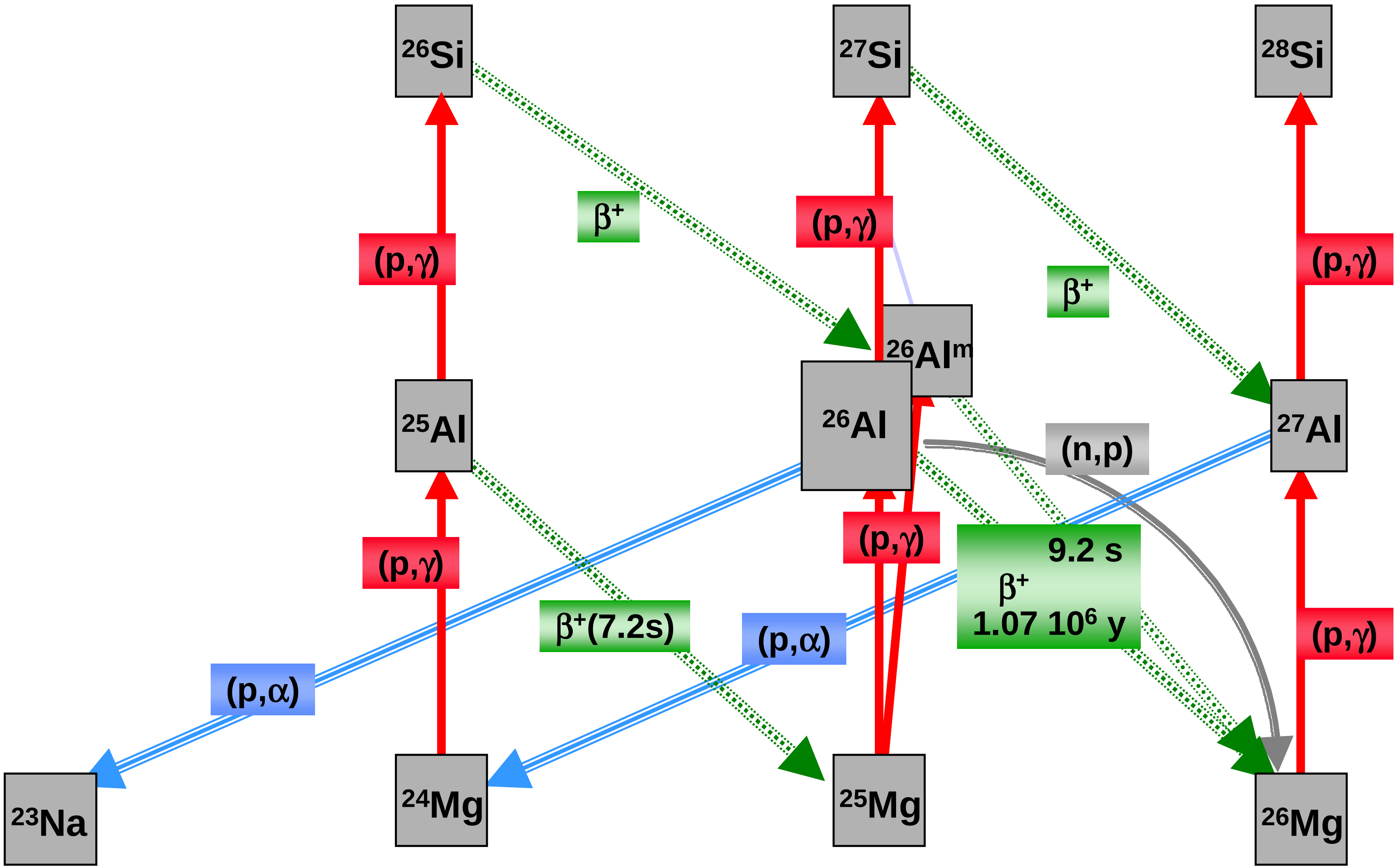
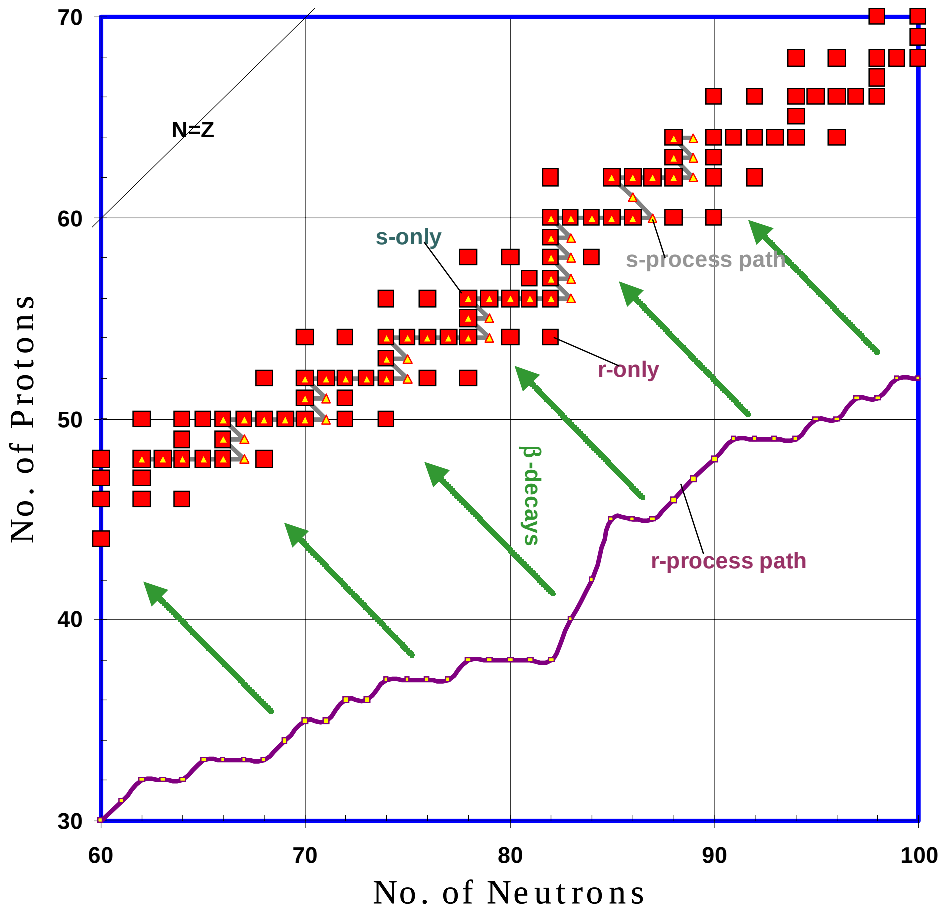


^{26}Al Nucleosynthesis: Example of a Cosmic Reaction Network, Common for Intermediate-Mass Isotopes



Production of Elements Beyond the Fe Peak: r-Process and s-Process



- **Seed Nuclei (~ Fe-Group Elements) Capture Neutrons**
- **β Decays Establish Final Abundances**
  - n capture faster than β-decay –> r-process
  - n capture slower than β-decay –> s-process

Nucleosynthesis: “Processes”,“Categories”

	Process	*Site*	*Key Isotopes*
☆ **H burning**	pp chains, CNO cycle	all stars	^{4}He; ^{13}C ^{14}N
☆ **He burning**	3-α process	most stars	^{12}C ^{16}O ^{20}Ne ^{24}Mg
☆ **α-process**	hot burning with excess α’s	mass. stars, SNae	^{20}Ne ^{24}Mg ^{28}Si ^{32}S ^{36}Ar ^{40}Ca
☆ *Fe-group elements:*			
e-process	thermal equilibrium (NSE)	SNae (thermonucl)	Fe-group elements (~56)
☆ *n-rich heavy elements:*			
s-process	n capt. slower than β-decay	He-burning stars	elements >62 close to valley of stability
r-process	n capt. faster than β-decay	SNae (CC)	elements >62, also further from valley of stability
☆ **spallation**	energetic heavy-ion collision	ISM / cosmic rays	^{6}Li $^{8,9}Be$ $^{10,11}B$
☆ *p-rich isotopes:*			
rp-process	hot H burning	novae	p-rich elements <Fe group
p-process	n depletion (‘γ-process’)	??	p-rich elements >62
☆ ‘normal’ nuclear reactions [(n,γ), (p,γ), (α,γ)...]		stars, SNae	in-between elements
☆ **ν-process**	ν excitation of nuclei	SNae (CC)	various contributions
☆ **x-process**	*unknown; make up for BBN+Spallation definiency*	??	(^{2}H Li Be B)

Objectives of Radioactivity Gamma-Ray Astronomy:
Nucleosynthesis Environments

Stellar Cores & Shells	Nuclear Reaction Networks (T),
	Hydrostatic Burning & Convection
	Products only from SN & Wind
WR and AGB Stars	Convection Enhanced, Wind Feeds
	ISM with Products; HBB
Novae	Hot Hydrogen Burning
Core Collapse Supernovae	Shockfront Burning in Shell-Like Star
Supernovae Type Ia	NSE Processing of Stellar Remnant
Interstellar Medium	~Laboratory-like Nuclear Reactions

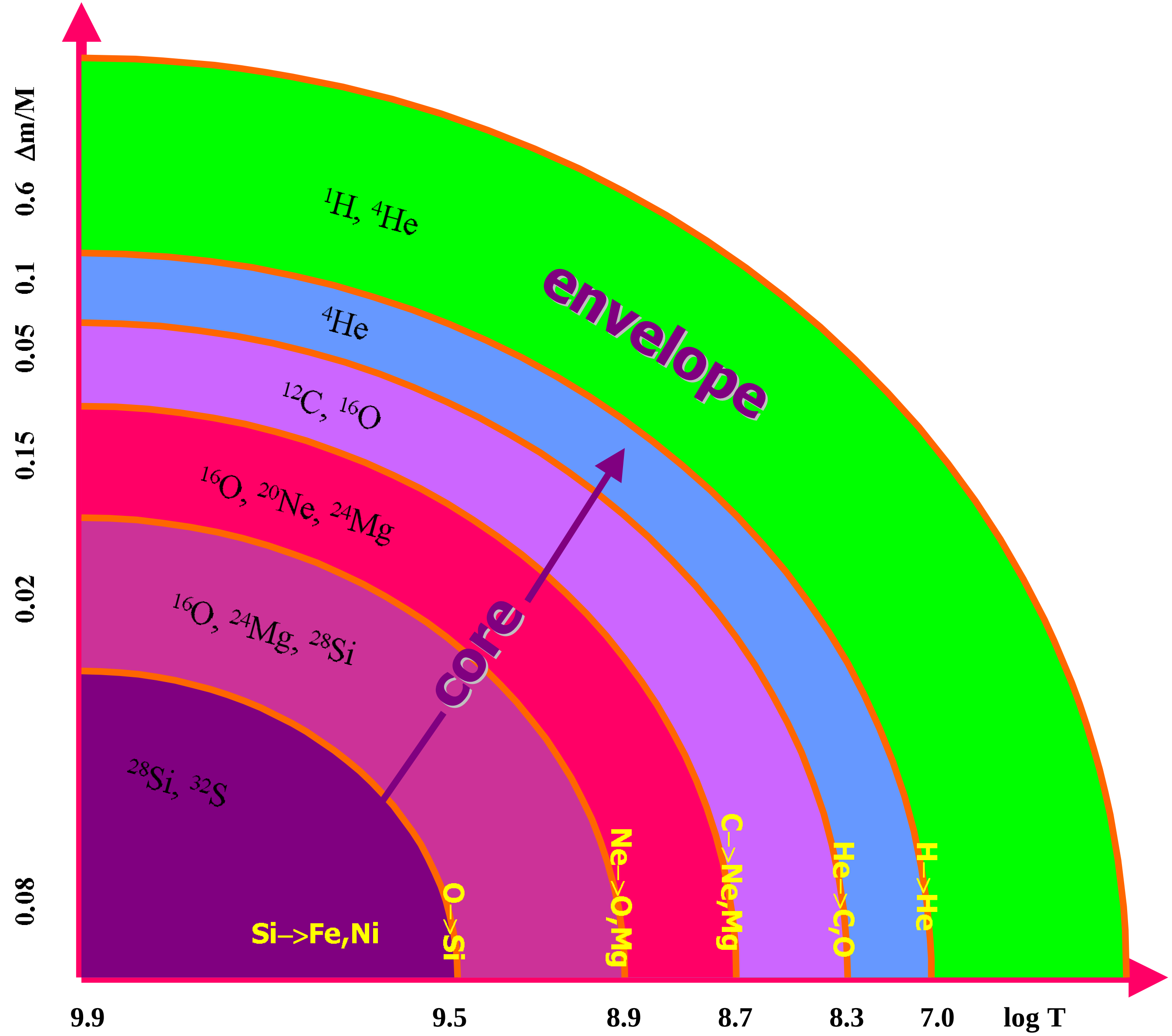
⟹ Variety of Nucleosynthesis Conditions (Temp., Dens.) and Timescales

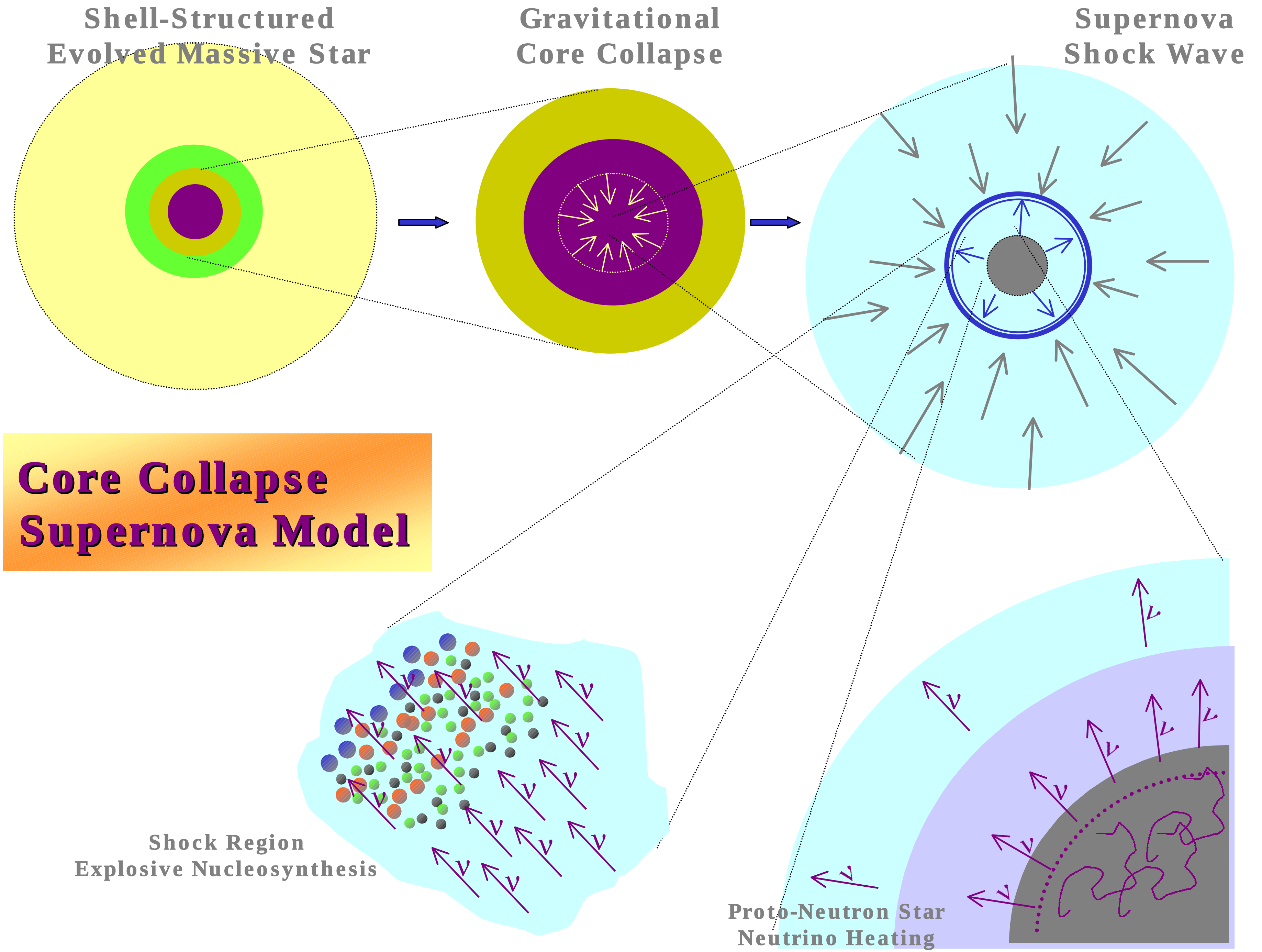
Objectives of Radioactivity Gamma-Ray Astronomy:
Different Objectives per Isotope:

^{7}Be:	Novae	Nova Convection & Nucleosynthesis
^{56}Ni & ^{57}Ni:	SN	SN Nucleosynthesis & Envelope Structure
^{22}Na:	Novae	Binary Evolution, Nucleosynthesis
^{44}Ti:	SN	SN Mass Cut, SN Rate
^{26}Al, ^{60}Fe, (e^{+})	Galaxy	Nucleosynthesis (Location, Rate)

Massive Star Core Structure

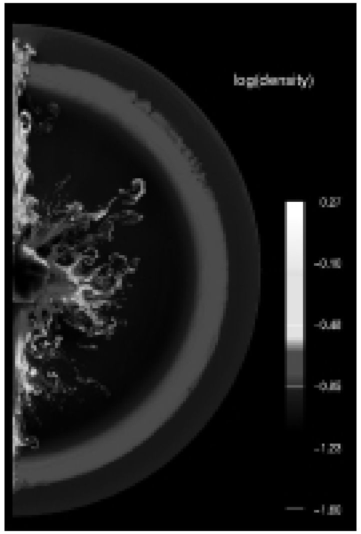
(25 M_o)




Shell-Structured
Evolved Massive Star
Gravitational
Core Collapse
Supernova
Shock Wave
Core Collapse
Supernova Model
Shock Region
Explosive Nucleosynthesis
Proto-Neutron Star
Neutrino Heating
of Shock Region from Inside
ν

Core Collapse Supernova Evolution

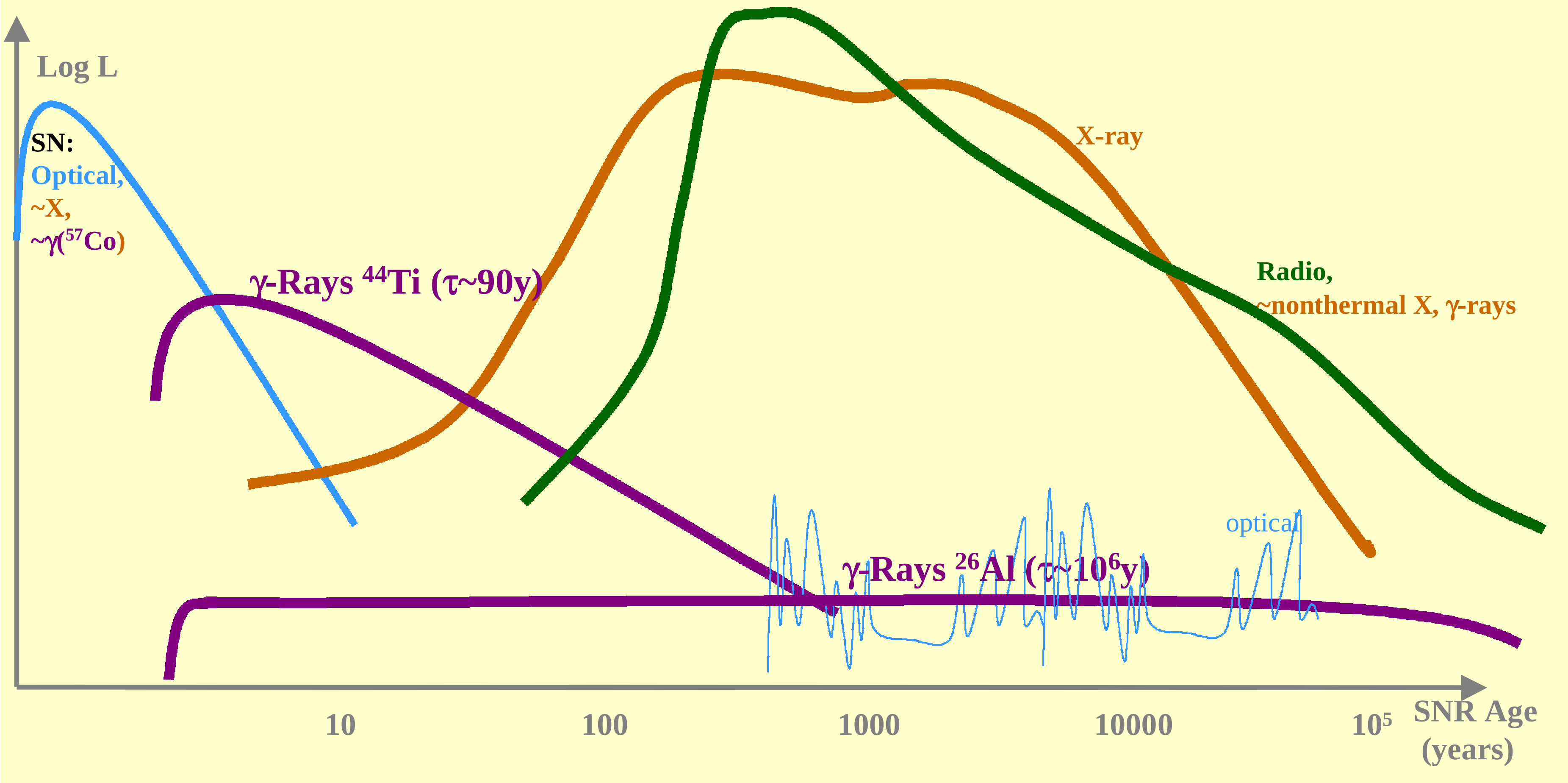
- **Phases and Time Scales**

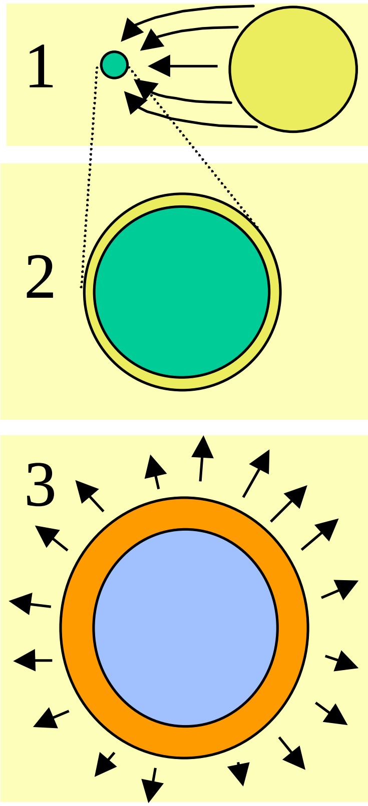


– Core Collapse	
– Convection in Inner Zones	50 ms .....
– Shock at Fe/Si Interface	100 ms
– End of NSE burning	250 ms
– End of Convection	400 ms
– End of Nuclear Burning	500...700 ms
– Explosive-Product Shell/Shock Detachment	
– Shock at C-O/He Interface	1..5 s
– Rayleigh-Taylor Instability Development	1...50 s
– Reverse-Shock Deceleration of Ejecta	50..100 s
– Beginning of Ballistic Clump Motions	100 s

Gamma-Rays from Supernovae and Their Remnants

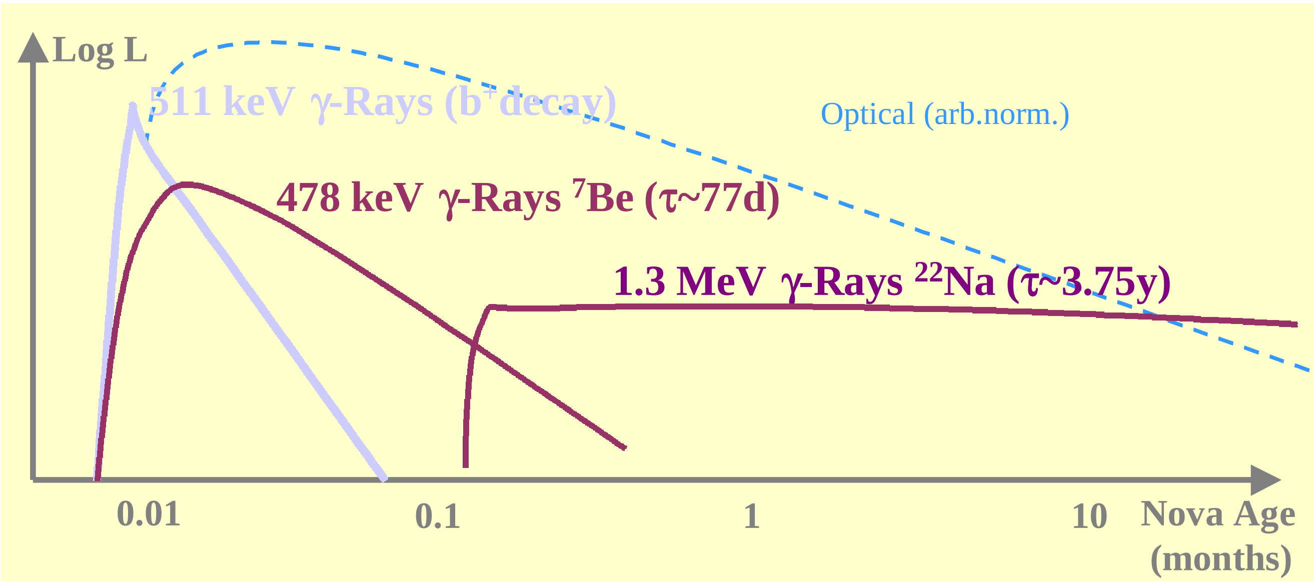
- **SN Nucleosynthesis → Radioactivity Line Emission**
- **SNR Particle Acceleration → Continuum Emission**
- **SN Blast Wave / ISM Impact → other Characteristic Emission**





Gamma-Ray Lines from Novae

- **Nova = Thermonuclear Runaway in White-Dwarf Shell Accumulated from Low-Level Accretion in Binary System**
- $dM/dt \sim 10^{-9} M_o/y$; $M_{accr} \sim 5\ 10^{-5} M_o$; $M_{ejected} \sim 2\ 10^{-4} M_o$
- ~30% Ne-rich Novae, others CO Novae
- **Hot H Burning at $T>10^8$K–> p-Capture on CNO Seeds**
- **Gamma-Ray Sources:**
  - ☆ **β+ Radioactivity** $I_\gamma \sim 1\ 10^{-2}$ **ph cm^{-2} s^{-1} @1kpc**
  - ☆ **^{7}Be (from ^{3}He(α,γ))** $I_\gamma \sim 2\ 10^{-6}$ **ph cm^{-2} s^{-1} @1kpc**
  - ☆ **^{22}Na (from ^{20}Ne(p,γ))** $I_\gamma \sim 4\ 10^{-6}$ **ph cm^{-2} s^{-1} @1kpc**
  - ☆ **^{26}Al (from ^{25}Mg(p,γ))** $I_\gamma \sim 1\ 10^{-10}$ **ph cm^{-2} s^{-1} @1kpc**



Issues:

- ☹ **Dredge-Up from WD**
- ☹ **TNR Rise Time**
- ☹ **M_{WD}, M_{accr}**
- ☹ **M_{ej}**
- ☹ **....**
- ☹ **Need CLOSE Nova**
- ☹ **Need Early Exposure**