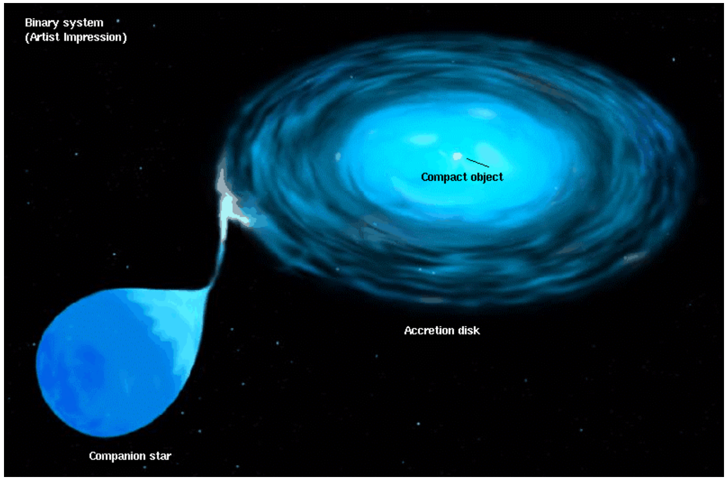
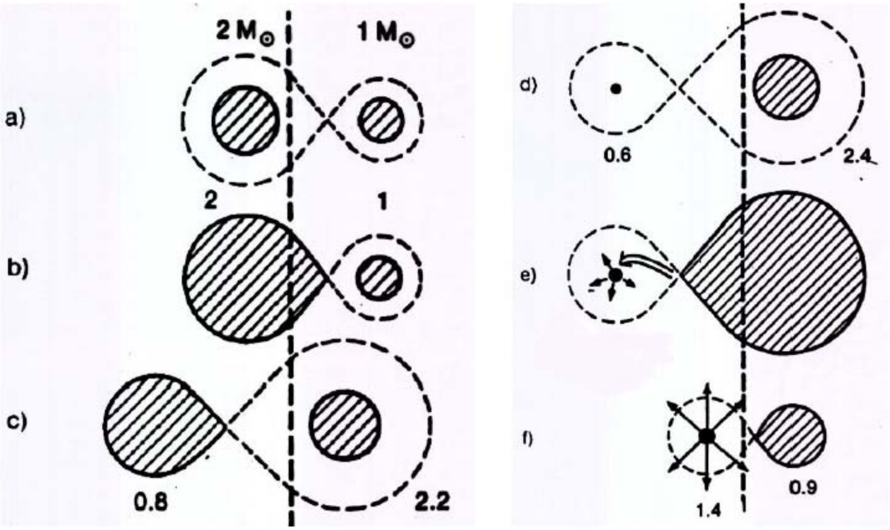
Binary System Evolution

- Characteristics
  - ☆ Mass of Components
    - ☞ High-Mass Binaries
    - ☞ Low-Mass Binaries
  - ☆ Orbits and Mass Transfer
    - ☞ Interacting / Quiet Phases for Elliptical Binaries (e.g. WR140)
      - Wind Interactions, CR & Dust Formation
    - ☞ Accreting Binaries
      - Accretion Rate / Disk Instabilities: Cataclysmic Variables , QPO's
      - Transient Events from Accreted Layer: Novae, Type I X-ray Bursts, Thermonuclear Supernovae
    - ☞ Metal-Enriched Envelope
      - Unusual Radiation Characteristics and Wind Phases
      - Evolution Unlike Single Star





How much Energy

- 4 (^{1}H) --> ^{4}He + 2 e$^+$ + 2 neutrinos + energy

- Energy released = 25 MeV
- = 4 x 10 $^{-12}$ Joules
- = 1 x 10 $^{-15}$ Calories

- But the sun does this 10^{38} times a second !
  - Sun has 10^{56} H atoms to burn !

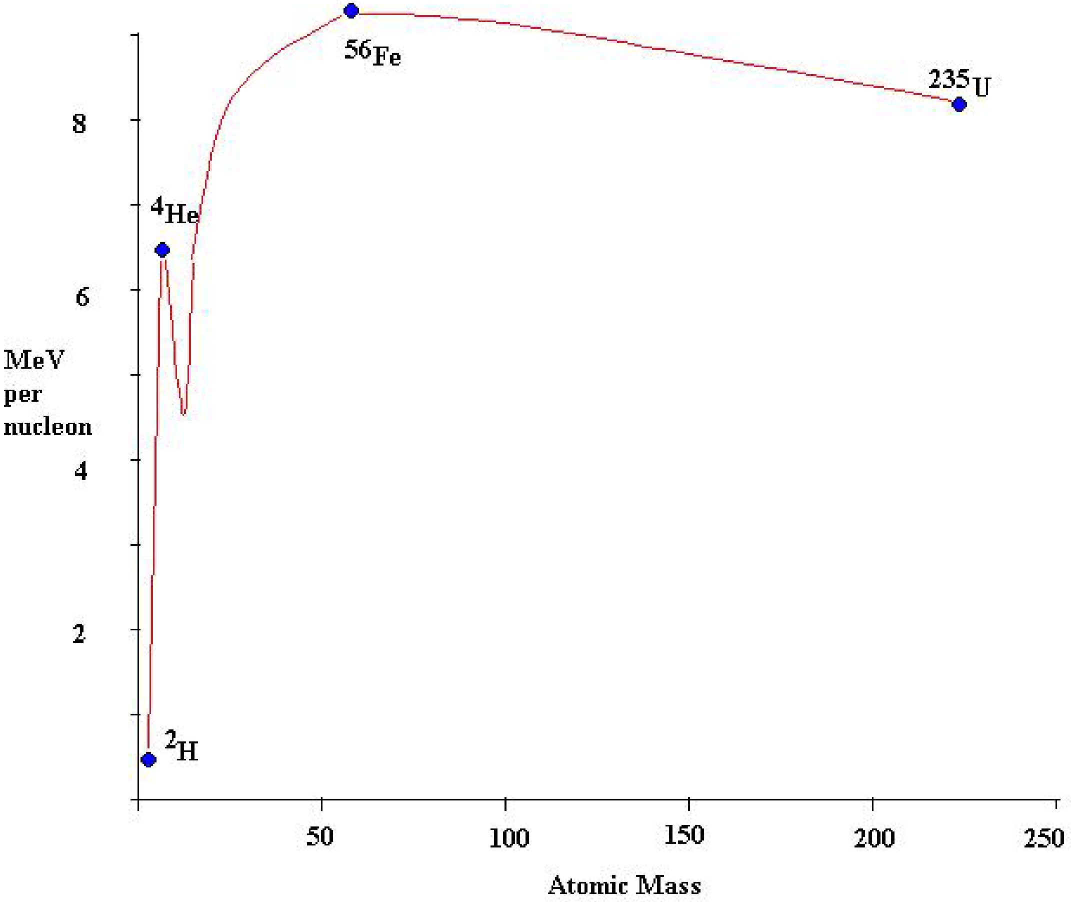
More Fusion !

- At 100 million degrees Celsius, Helium fuses:

- 3 (^{4}He) --> ^{12}C + energy
- (Be produced at an intermediate step)
- (Only 7.3 MeV produced)

- Energy sustains the expanded outer layers
- of the Red Giant

Nuclear Binding Energy

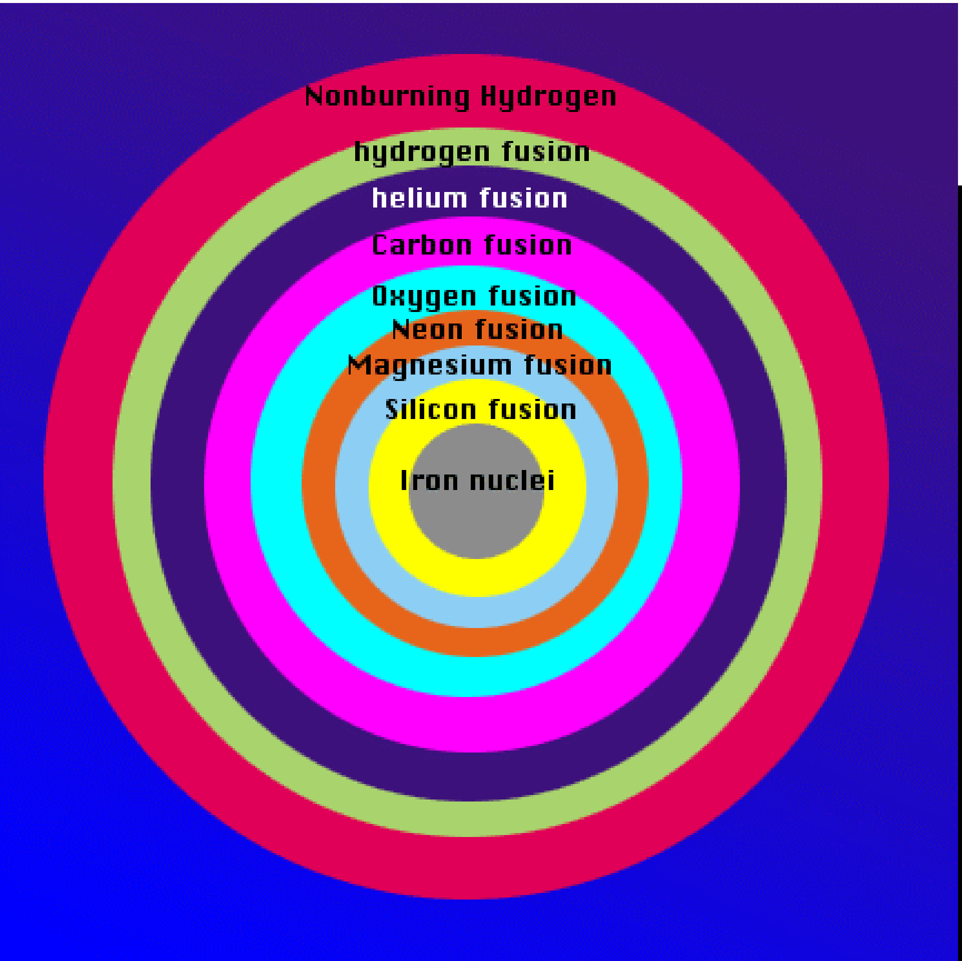


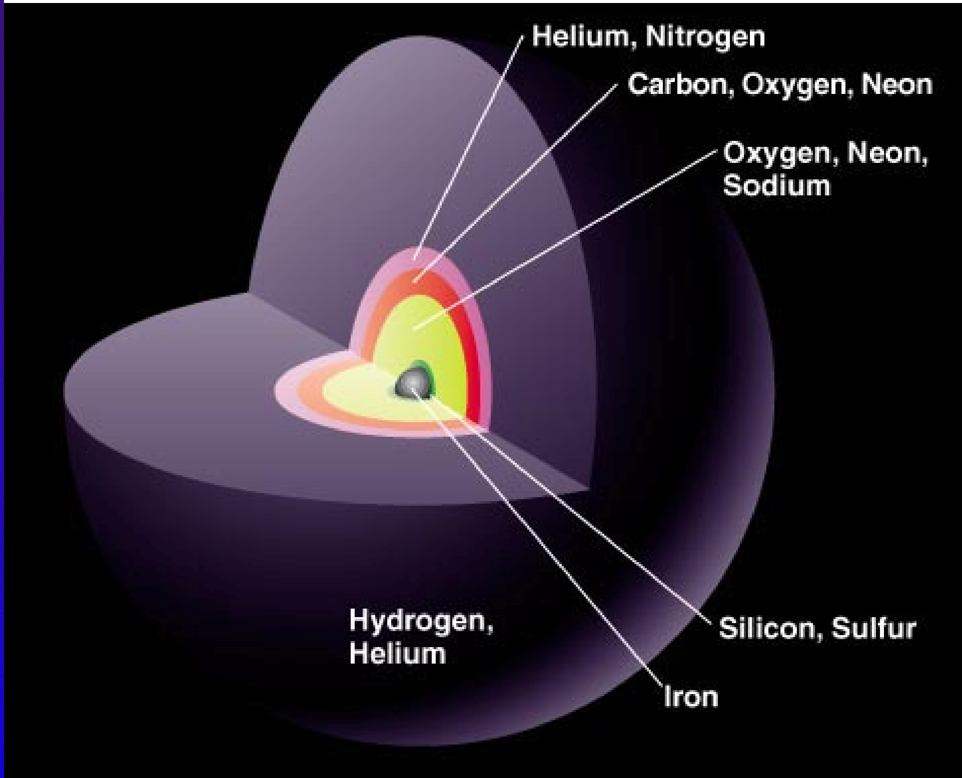
The binding energy is a measure of the force holding the nucleus of an atom together.

- ☆ The higher the binding energy, the more tightly bound is the nucleus.
- ☆ The most tightly bound nucleus of all is iron-56.
- ☆ Elements with atomic masses less than 56 can undergo fusion to form elements that are more stable.
- ☆ Elements with atomic masses greater than 56 can undergo fission.

The End of the Line for Massive Stars

Massive stars burn a succession of elements.





Nuclear Burning in Binaries

X-ray bursts	transient He burning on NS
Nova	transient H burning on WD
Supersoft sources	stable H burning on WD
Supernova Ia	explosive C burning in WD

X-ray Bursts

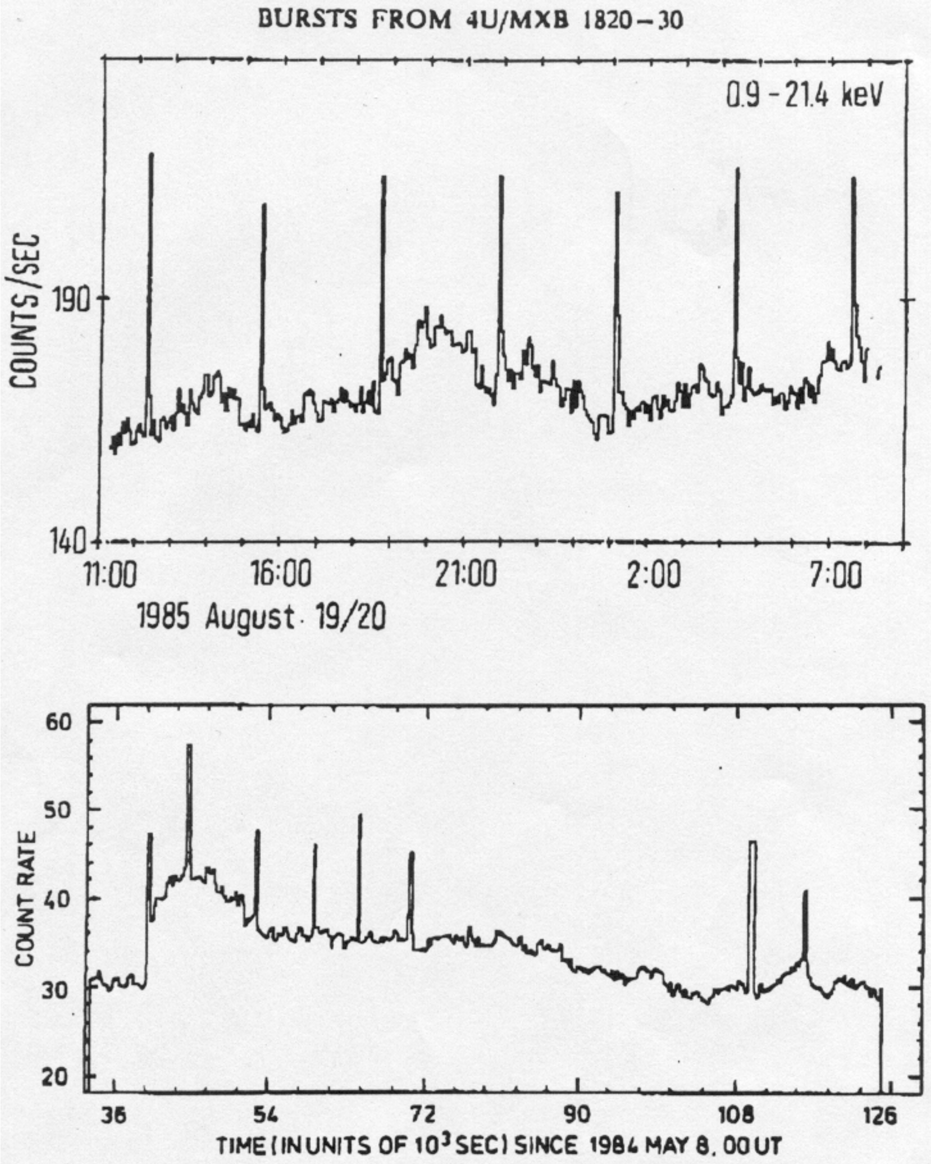
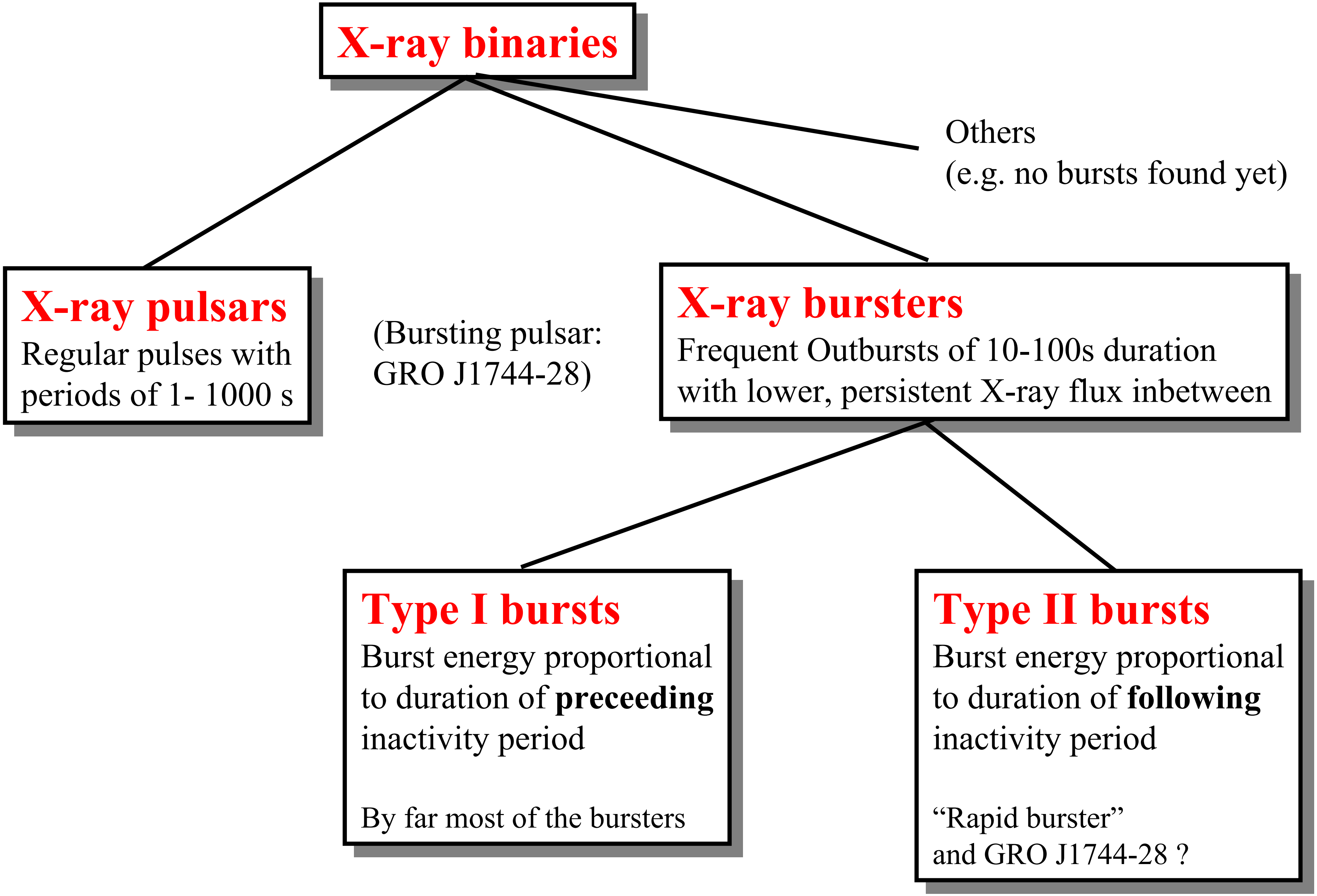


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

- 10^{36}-10^{38} erg/s
- duration 10 s – 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon !

(stars 10^{33}-10^{35} erg/s)



X-ray binaries

X-ray pulsars

Regular pulses with periods of 1- 1000 s

(Bursting pulsar: GRO J1744-28)

X-ray bursters

Frequent Outbursts of 10-100s duration with lower, persistent X-ray flux inbetween

Others
(e.g. no bursts found yet)

Type I bursts

Burst energy proportional to duration of **preceeding** inactivity period

By far most of the bursters

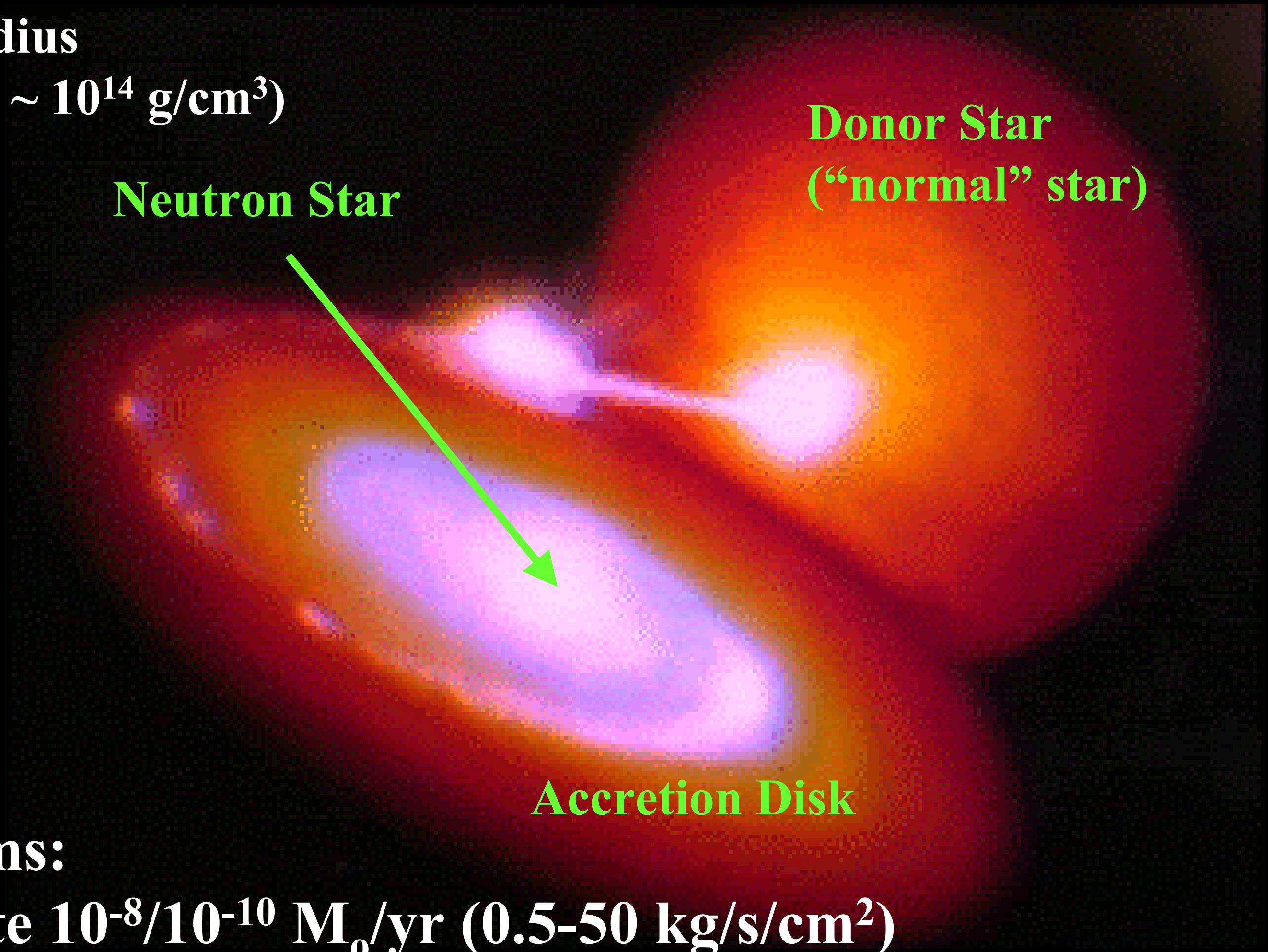
Type II bursts

Burst energy proportional to duration of **following** inactivity period

“Rapid burster”
and GRO J1744-28 ?

The Model

Neutron stars:
1.4 M_o, 10 km radius
(average density: ~ 10^{14} g/cm^3)



Typical systems:

- accretion rate $10^{-8}/10^{-10}$ M_o/yr (0.5-50 kg/s/cm^2)
- orbital periods 0.01-100 days
- orbital separations 0.001-1 AU's

Energy generation: thermonuclear energy

$4\mathrm{H} \longrightarrow {}^{4}\mathrm{He}$ 6.7 MeV/u

$3\,{}^{4}\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$ 0.6 MeV/u (“triple alpha”)

$5\,{}^{4}\mathrm{He} + 84\,\mathrm{H} \longrightarrow {}^{104}\mathrm{Pd}$ 6.9 MeV/u (rp process)

Energy generation: gravitational energy

$$E = \frac{G\,M\,m_u}{R} = 200\ \mathrm{MeV/u}$$

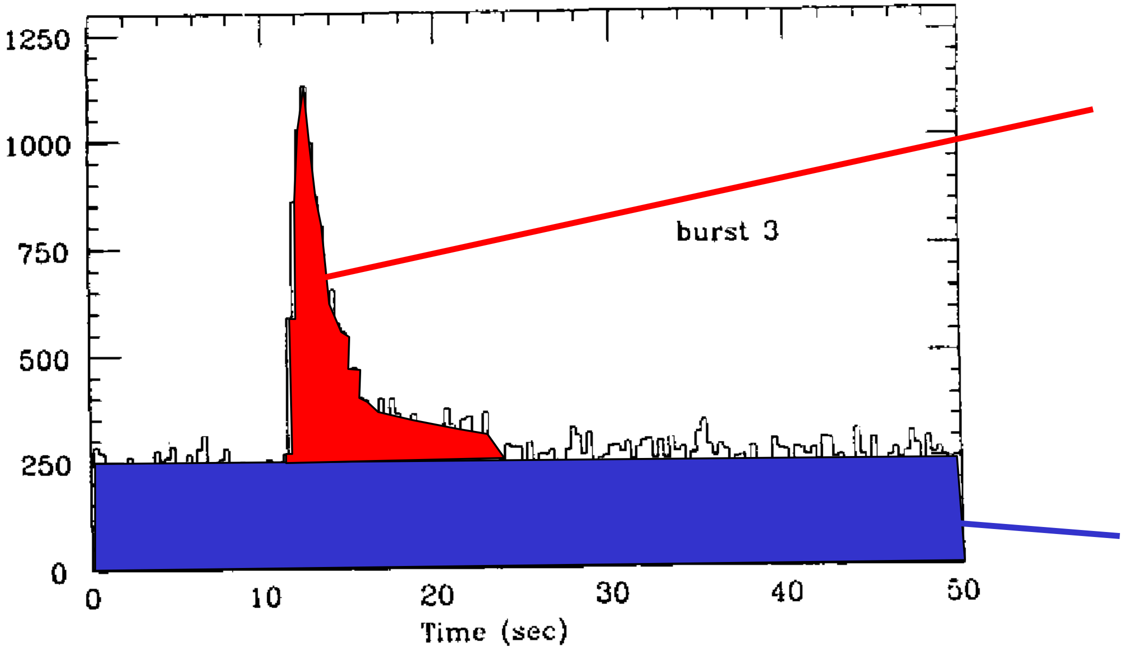
Ratio gravitation/thermonuclear ~ 30 - 40

Ignition: triple alpha

Main energy production: rp (capture of ≥2 neutrons + β-decays)

Observation of thermonuclear energy

Unstable, explosive burning in bursts (release over short time)



Burst energy thermonuclear

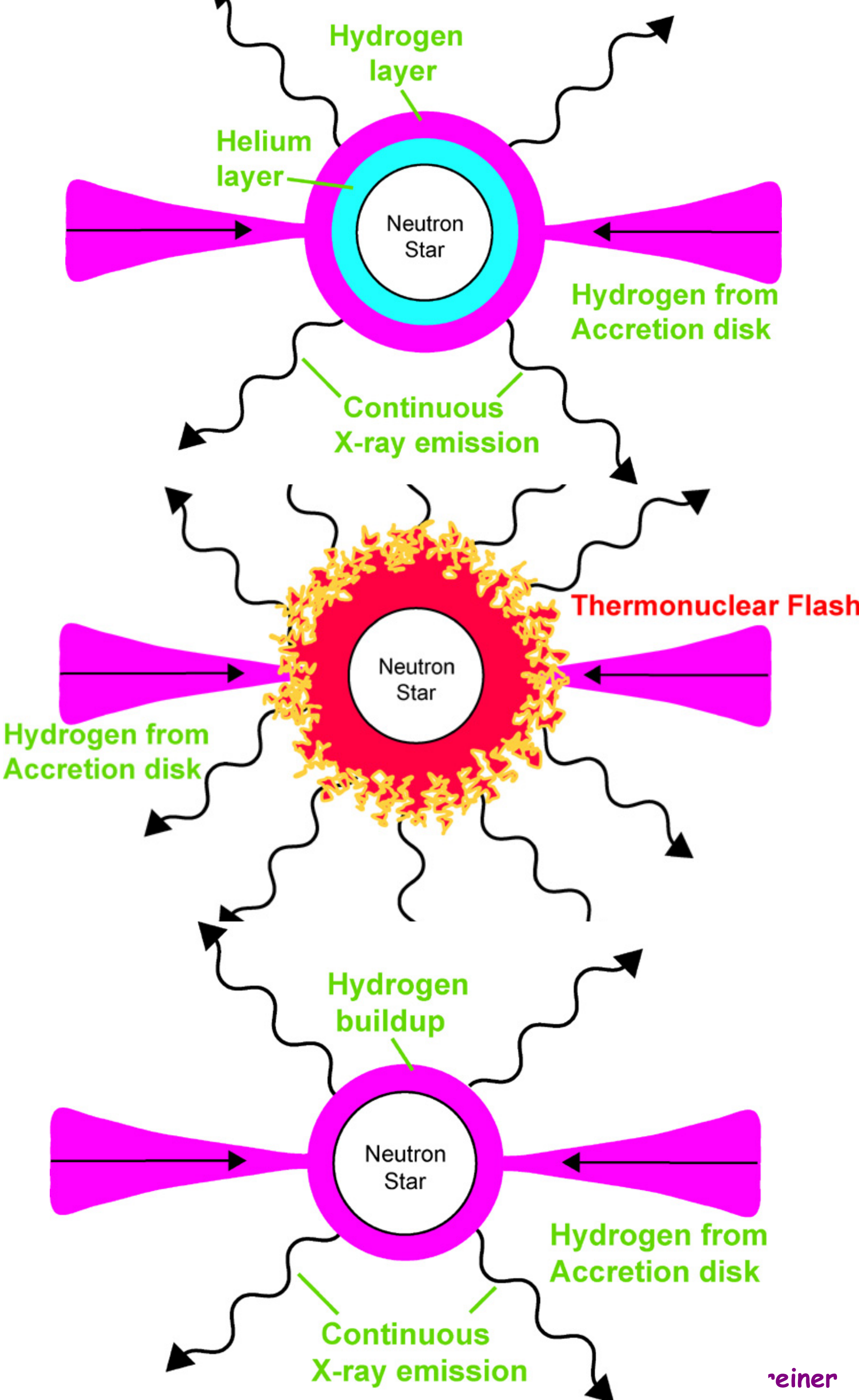
Persistent flux gravitational energy

$L_{persistent} \sim (25\text{-}100) \times L_{burst}$

≈ ratio of gravitational/thermonuclear energy

X-Ray Bursters

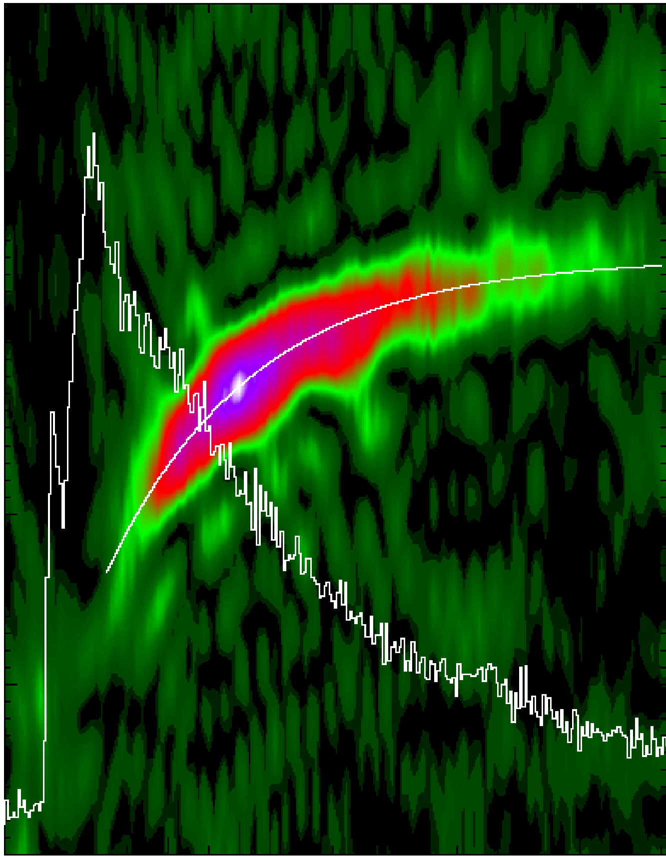
- Analogous to hydrogen flashes on white dwarfs (novae), on a neutron star, the hydrogen slowly fuses into helium and then a helium flash can occur
  - ☆ rather than peaking in the optical range, helium flashes are hotter and in the x-ray range
    - ☞ X-ray burster



Properties and Explanation

Burst profiles vary greatly, but characteristic features include

- a sudden, rapid (1-10 sec) increase in X-ray flux, reaching 5 to 20 times quiescent values
- a more extended period of decay (10 sec to several minutes), during which X-ray intensity decays



Explained burst properties:

- the energies (~10^{38} to 10^{39} erg)
- their rise time (seconds)
- duration (~10 to 100 seconds)
- spectral softening
- recurrence intervals (several hours)
- Oscillations during burst

Arguments for thermonuclear origin of type I bursts:

- ratio burst energy/persistent X-ray flux ~ 1/30 – 1/40
  (ratio of thermonuclear energy to gravitational energy)
- type I behavior: the longer the preceeding fuel accumulation
  the more intense the burst
- spectral softening during burst decline (cooling of hot layer)

Arguments for neutron star as burning site

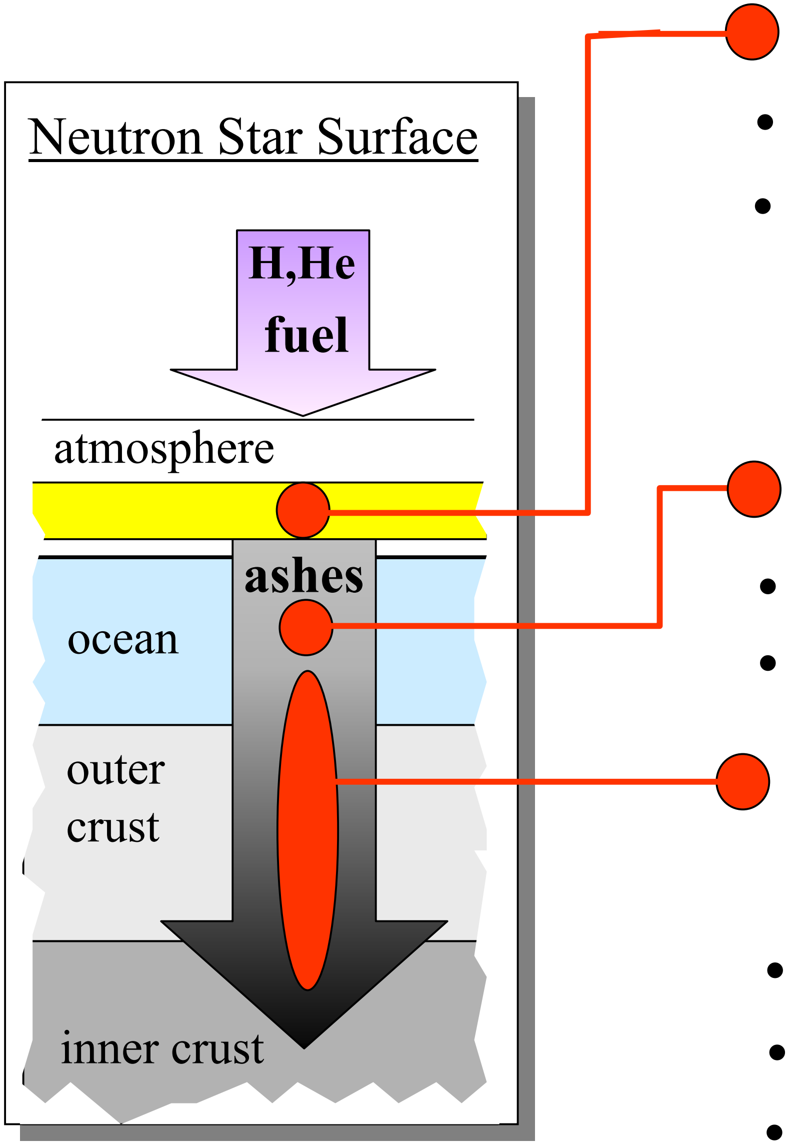
- consistent with optical observations (only one star, binary)
- Stefan-Boltzmann $L = \sigma A\, T^4_{\mathrm{eff}}$ gives typical neutron star radii
- Maximum luminosities consistent with Eddington luminosity
  for a neutron star (radiation pressure balances gravity)

$$L_{\mathrm{edd}} = 4\pi c G M/\kappa = 2.5 \times 10^{38} (M/M_{\odot})(1+X)^{-1} \text{ erg/s}$$

(this is non relativistic – relativistic corrections need to be applied)

κ=opacity, X=hydrogen mass fraction

Nuclear reactions on accreting neutron stars



Thermonuclear burning (rp process)

- Why do burst durations vary ? (10s – min)
- What nuclei are made in the explosion ?
  - Galactic nucleosynthesis contribution ?
  - Start composition for deeper processes ?

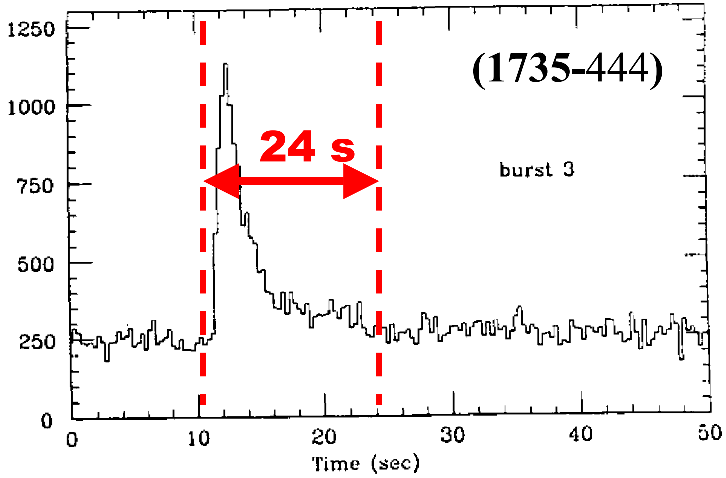
Deep H, C, … burning

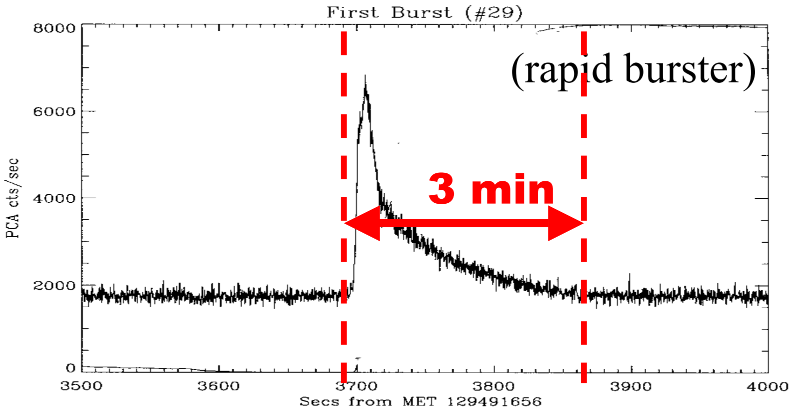
- Origin of Flares ?
- Origin of Superbursts ?

Electron captures
Pycnonuclear reactions

- Gravitational wave emission ?
- Crust heating ?
- Dissipation of magnetic fields ?

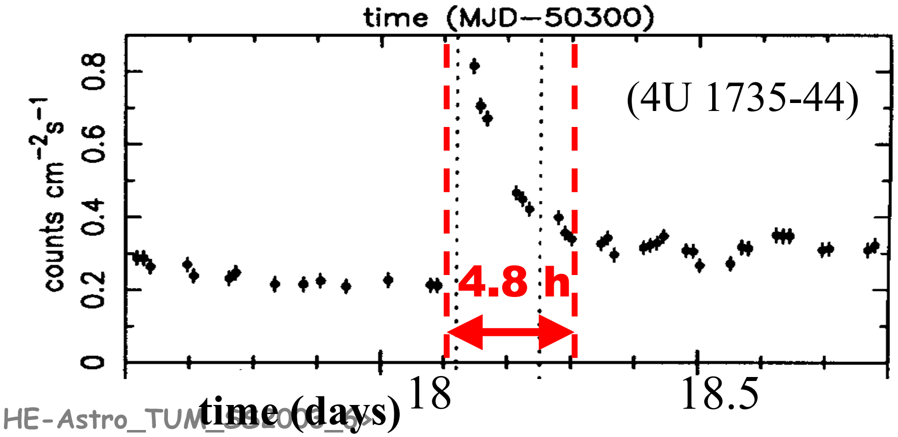
Need nuclear physics to answer and to understand observations





Normal type I bursts:

- duration 10-100 s
- ~10^{39} erg

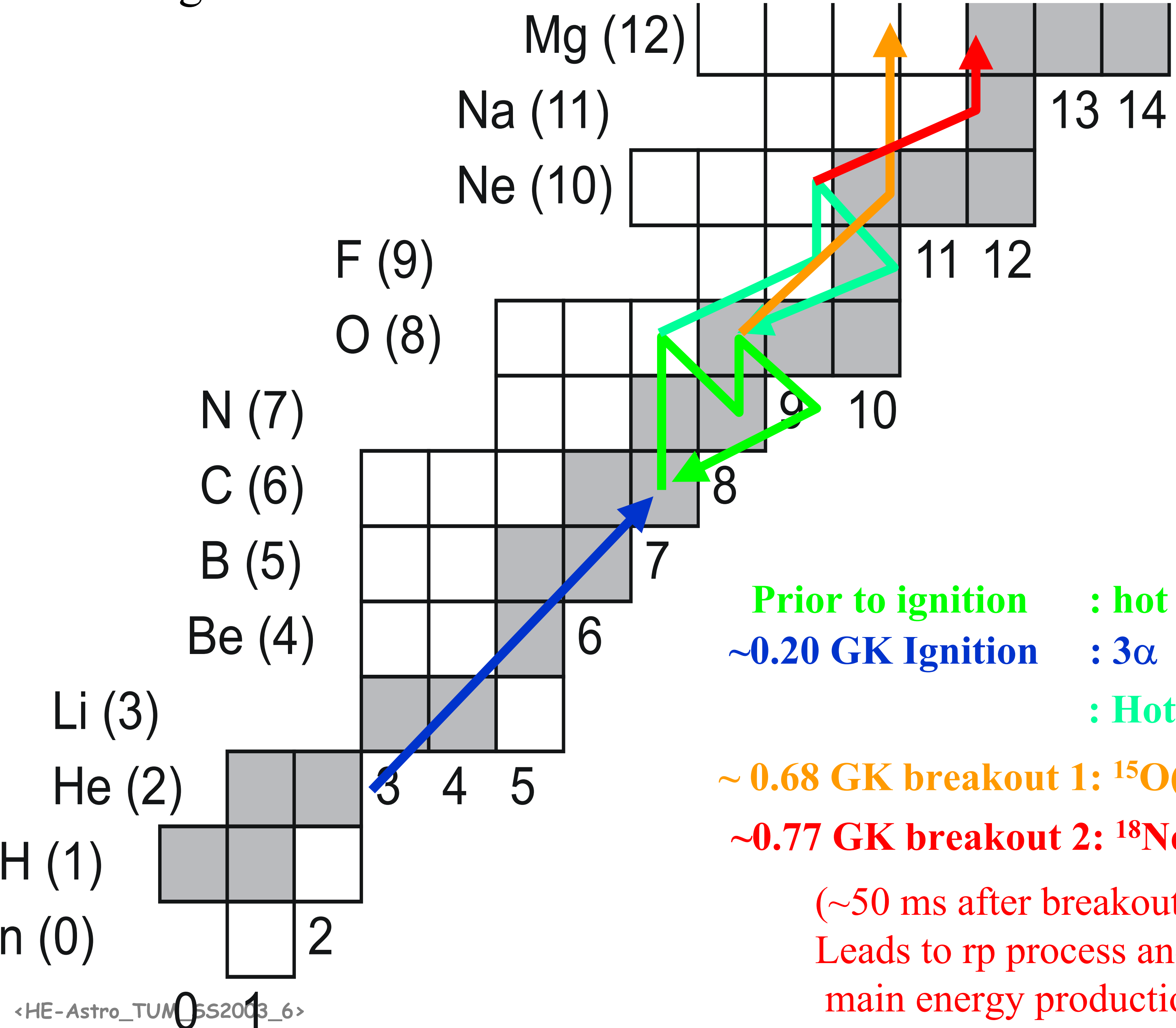


Superbursts:

(discovered 2001, so far 7 seen in 6 sources)

- duration …
- ~10^{43} erg
- rare (every 3.5 yr ?)

Burst Ignition:



Prior to ignition : hot CNO cycle

~0.20 GK Ignition : 3α

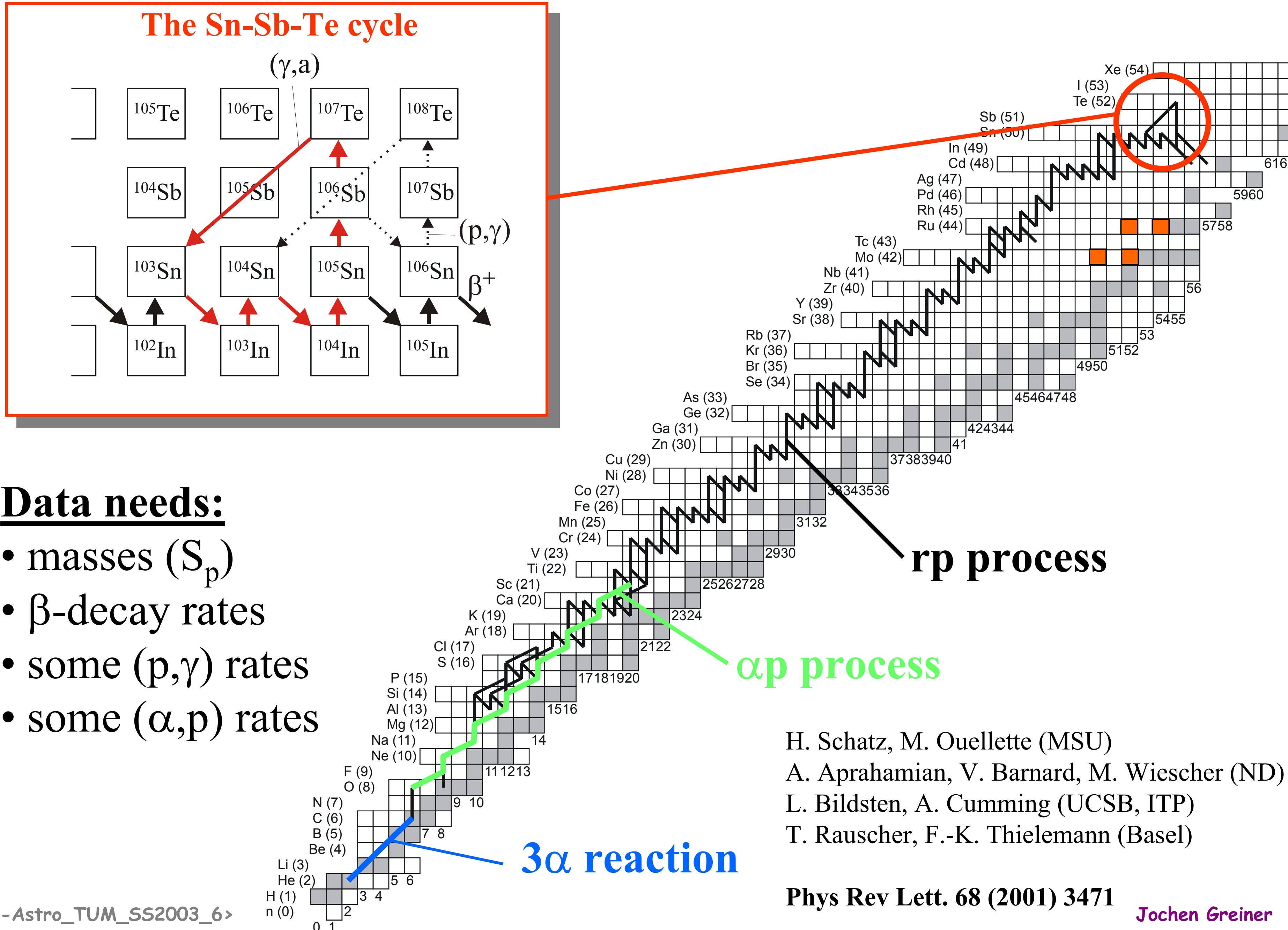
: Hot CNO cycle II

~ 0.68 GK breakout 1: ^{15}O(α,γ)

~0.77 GK breakout 2: ^{18}Ne(α,p)

(~50 ms after breakout 1)
Leads to rp process and
main energy production

Thermonuclear burning during X-ray burst



Data needs:

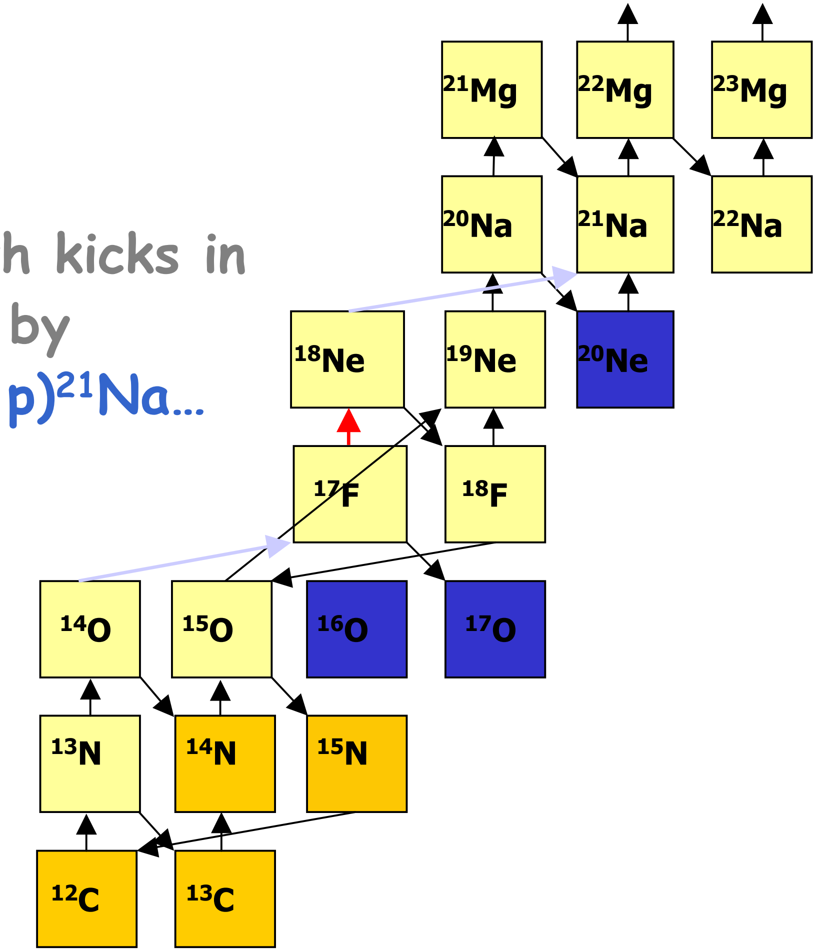
- masses (S_p)
- β-decay rates
- some (p,γ) rates
- some (α,p) rates

H. Schatz, M. Ouellette (MSU)
A. Aprahamian, V. Barnard, M. Wiescher (ND)
L. Bildsten, A. Cumming (UCSB, ITP)
T. Rauscher, F.-K. Thielemann (Basel)

Phys Rev Lett. 68 (2001) 3471

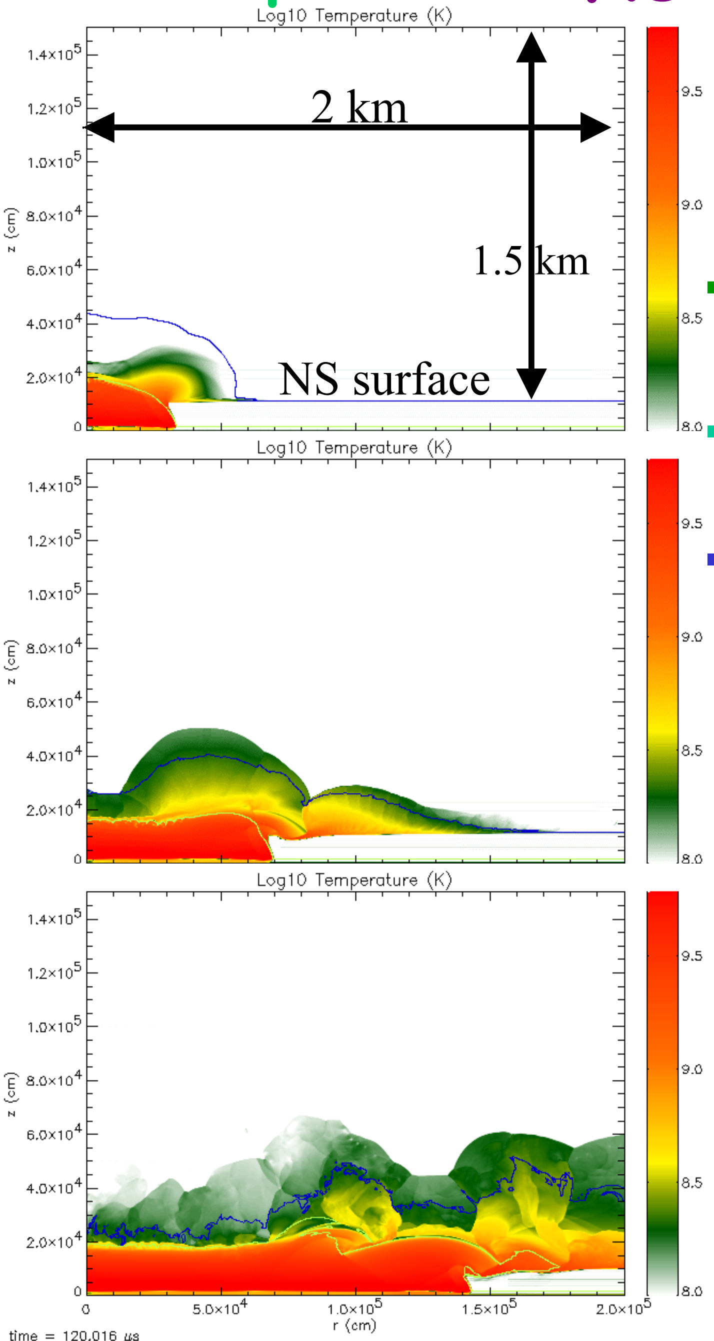
Reaction path in X-ray burster

- T_9>0.8
  - ☆ Alternative breakout path kicks in
  - ☆ Reaction flow dominated by $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$…



He Detonation on NS

Temperature



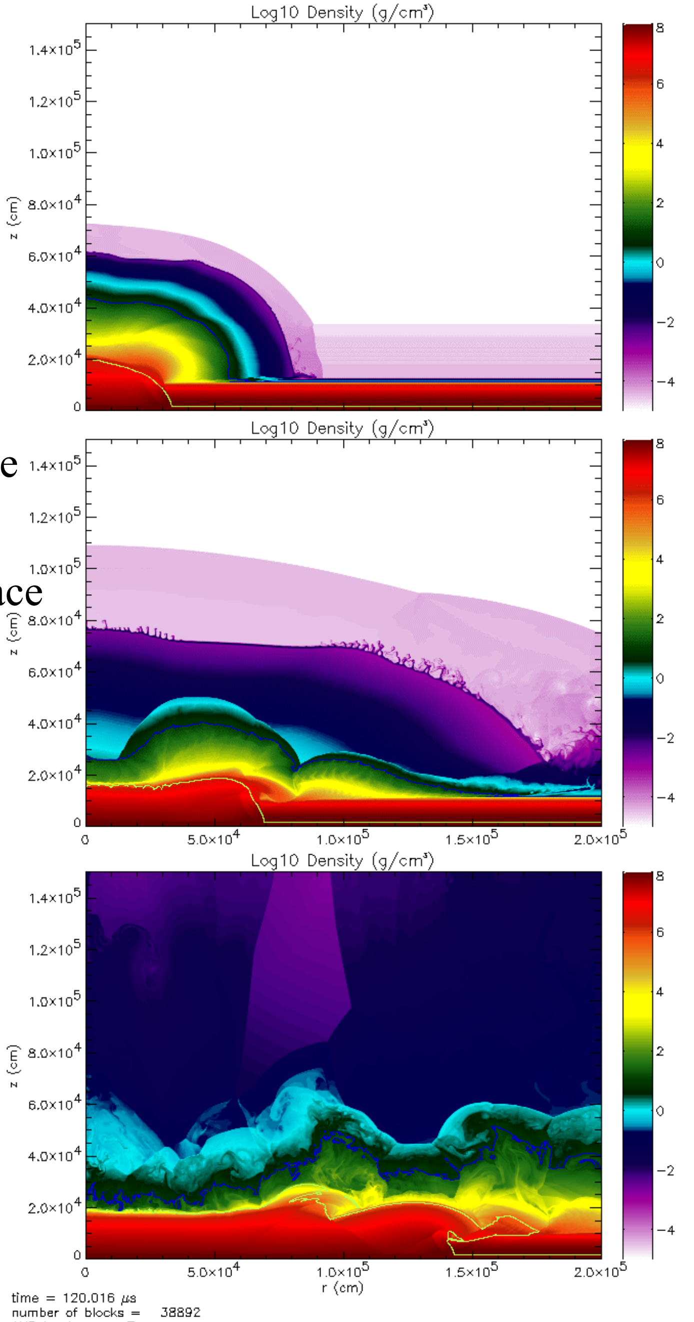
🟩 0.95 He mass fraction =fuel/ash separation

🟦 0.95 Ni mass fraction =NS/acc-layer interface

🟦 10 g/cm^3 density = original envelope surface

Detonation travels with 13000 km/s = 3ms from pole to pole

Density



Photospheric NS Radius Expansion

Peak fluxes sometimes show flat-topped profile

➡ luminosity becomes so high that atmosphere of NS temporarily expands due to radiation pressure

➡ can be used to determine NS radii:

$L = L_{Edd}$; T measured from X-ray spectrum

$$L_\infty = 4\pi R_\infty^2 \; \sigma T_\infty^4 = 4\pi d^2 F_\infty$$

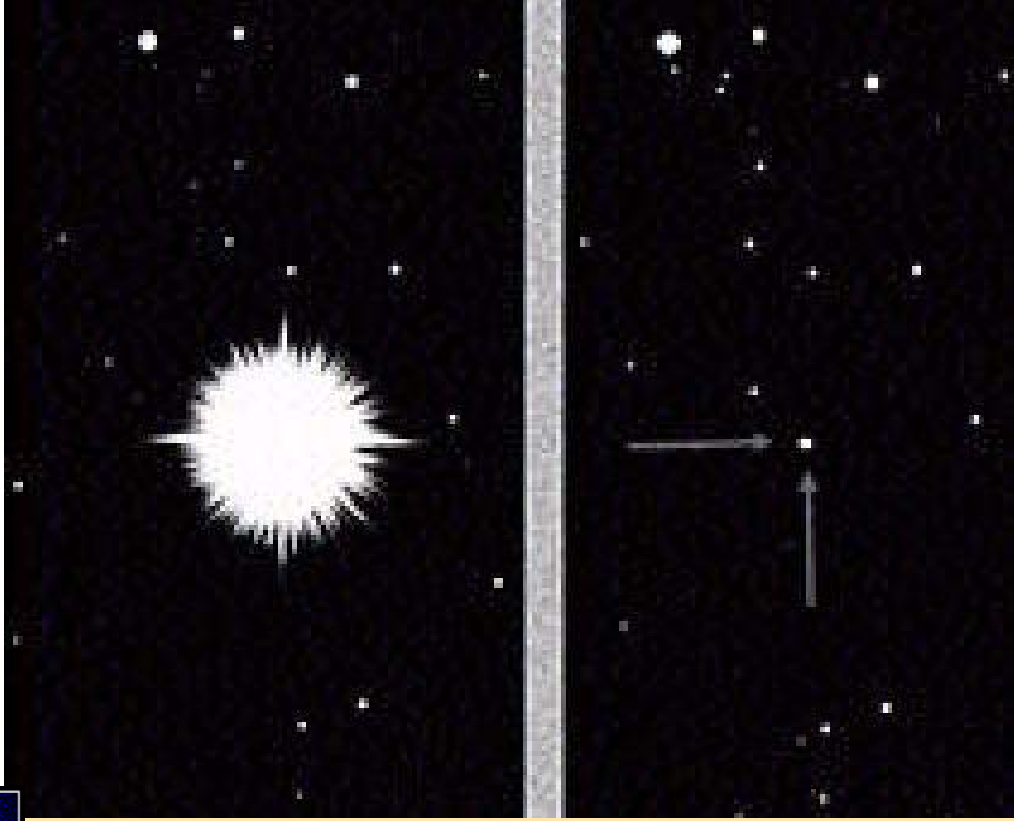
correction for gravitational redshift:

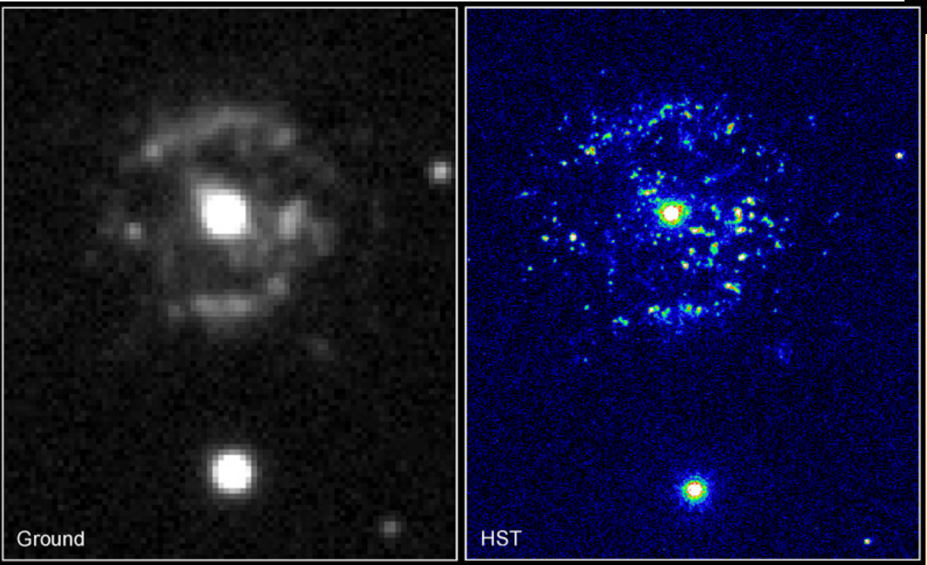
$$1+z = [1-2GM/(Rc^2)]^{-1/2} \quad (1+z \text{ varies with expansion})$$

➡ constraints on M,R of NS: thus constraints on EOS

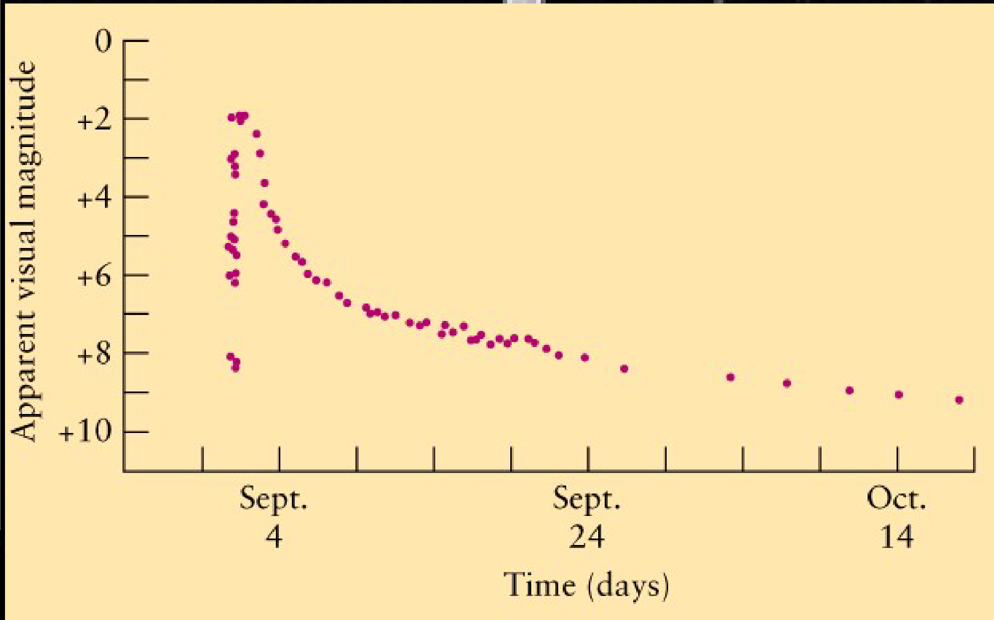
Novae

- Once accreted hydrogen layer on white dwarf becomes dense enough, H surface burning ignites:
  - ☞Hydrogen flash of fusion--a **Nova** occurs



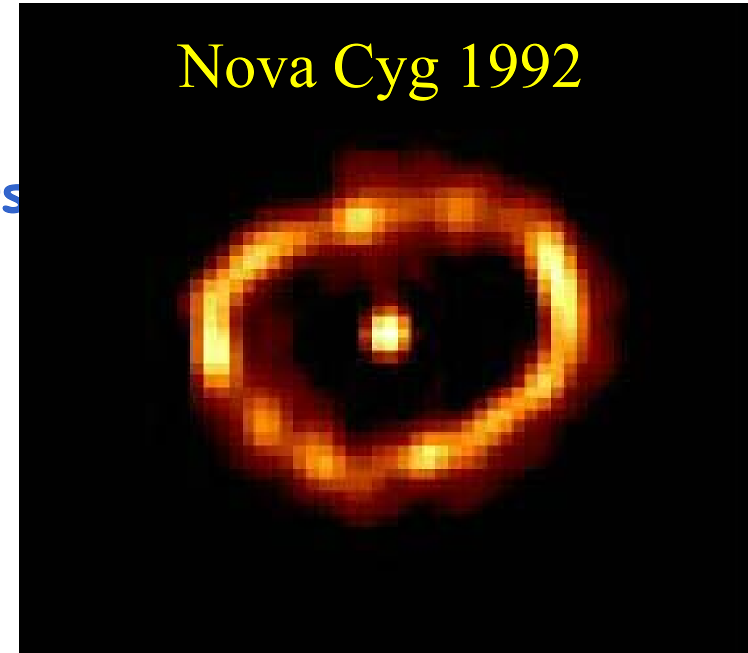


Recurring Nova T Pyxidis HST • WFPC2
PRC97-29 • ST ScI OPO • September 18, 1997
M. Shara and R. Williams (ST ScI), R. Gilmozzi (ESO) and NASA

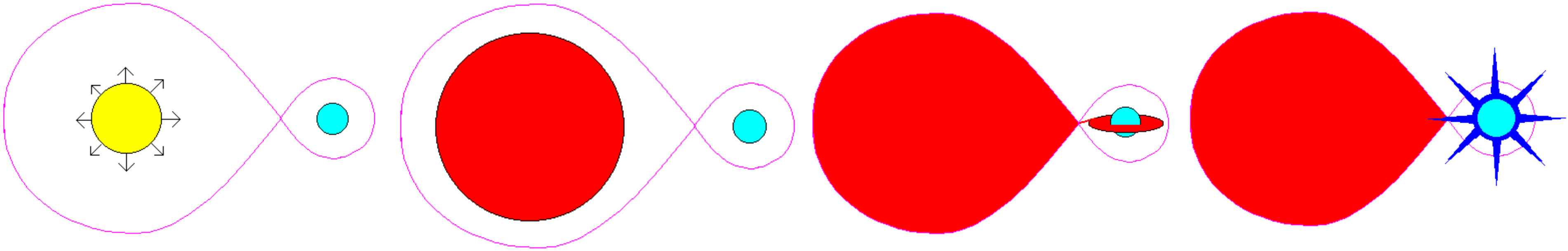


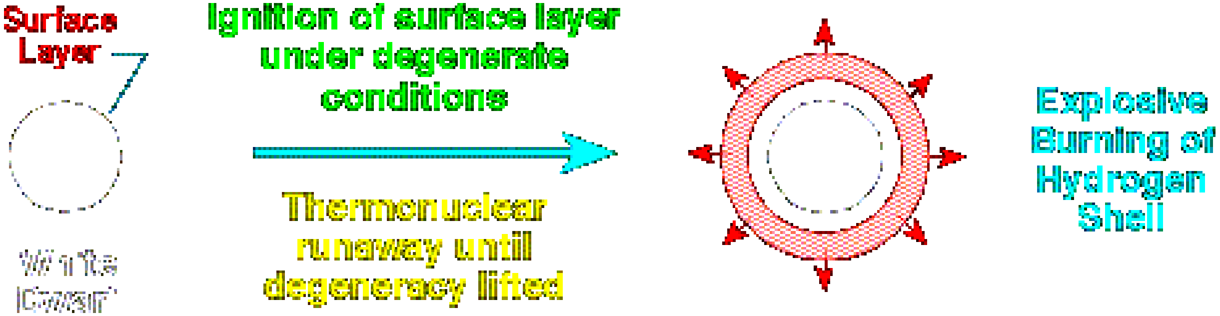
Nova properties

- 10 mag or more brightness increase over 1-2 days (factor 10^5)
- Drop typically 3 mag in 1-2 months
- Back to original brightness after a few years or decades
- Explosion blows off part of envelope (nebula)
- Nebula expands with 100-5000 km/s
- White dwarf – low mass main sequence binary
- Began as wider binary, then common envelope evolution tightens the binary
- Repetition: 10^5 years
- Recurrent novae: repeat every 20-100 yrs


Nova Cyg 1992

Novae





Surface Layer

White Dwarf

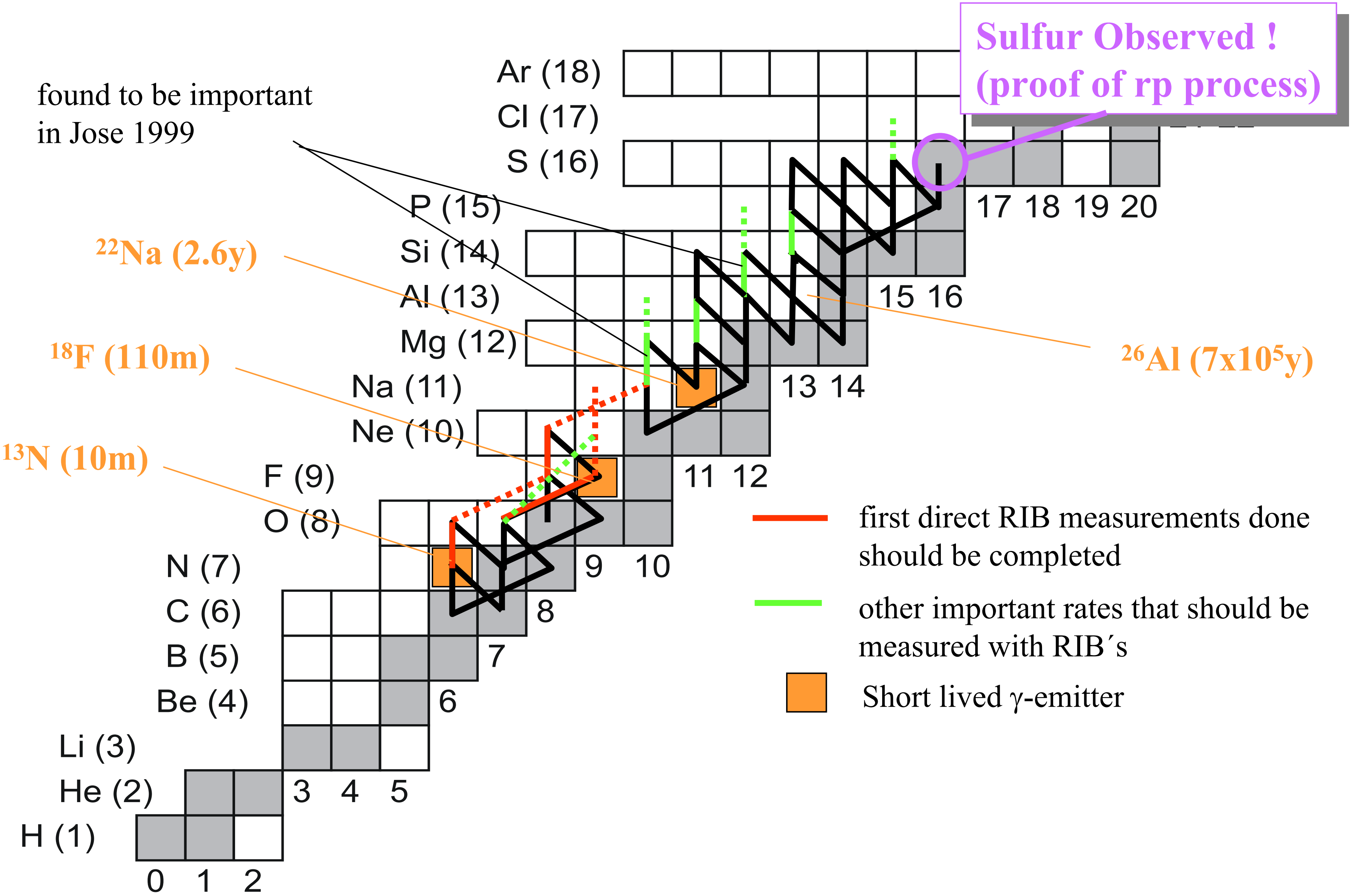
Ignition of surface layer under degenerate conditions

Thermonuclear runaway until degeneracy lifted

Explosive Burning of Hydrogen Shell

Reaction sequence in novae

Example: ONeMg Nova, 1.35 M_sol white dwarf (Starrfield 1996) τ~3min, T_{max}=0.36GK



Sulfur Observed !
(proof of rp process)

found to be important
in Jose 1999

^{22}Na (2.6y)

^{18}F (110m)

^{13}N (10m)

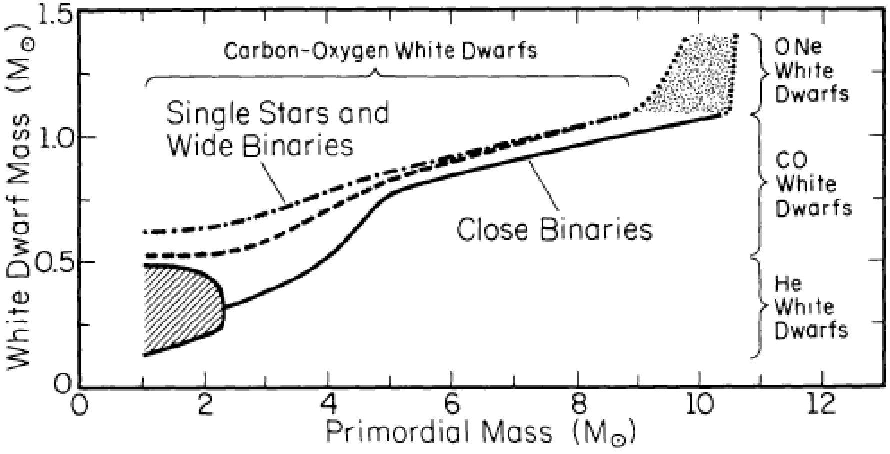
^{26}Al (7x10^{5}y)

🟥 first direct RIB measurements done should be completed

🟩 other important rates that should be measured with RIB´s

🟧 Short lived γ-emitter

Formation of Compact Objects



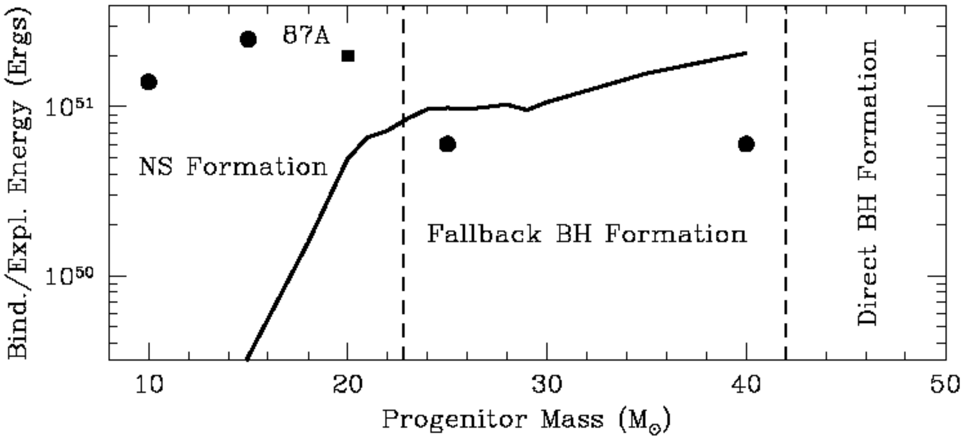
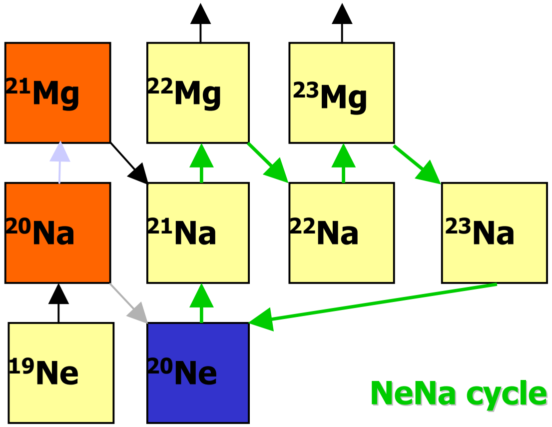


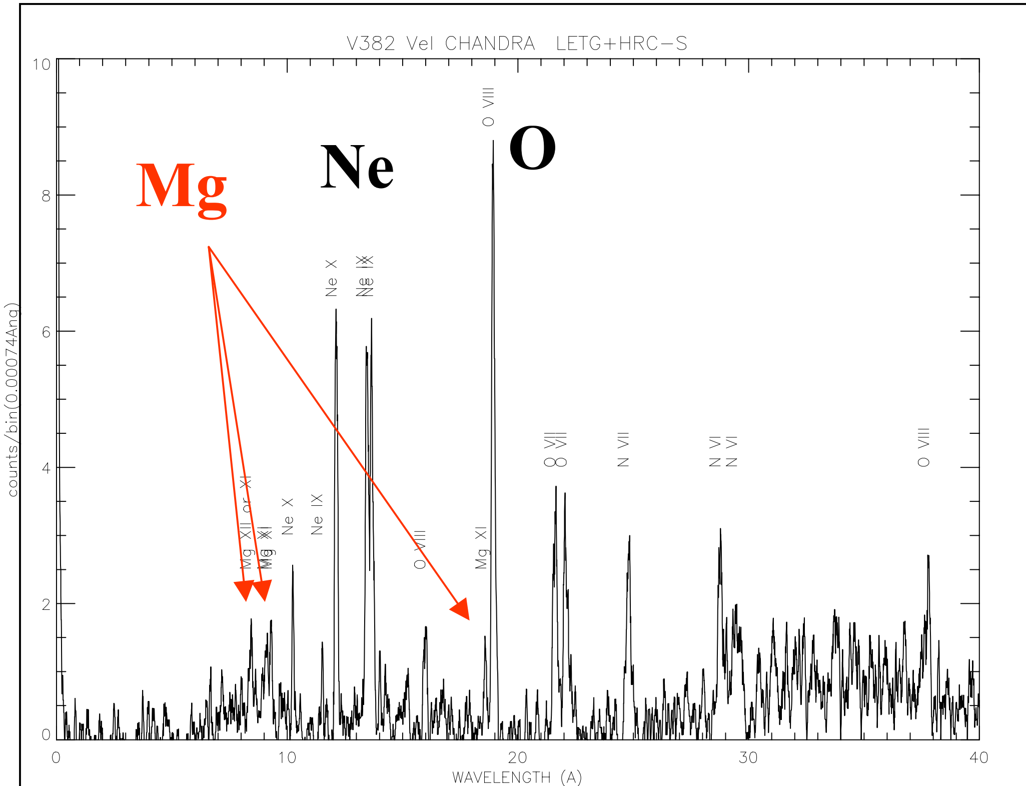
Figure 3. Binding energy/explosion energy *vs.* progenitor mass assuming no mass loss. The solid line is the binding energy of all but the inner 3 $M_\odot$ of the stellar core. If the explosion energy is not at least this powerful, the star will collapse to a black hole. The four circular dots denote the explosion energies from core-collapse simulations and the square is the predicted explosion energy observed from SN 1987A.

- **Type Depends on Mass of Companion star**
  - ☞ 1-8 $M_\odot$ → White Dwarf <1.4 $M_\odot$
  - ☞ 8-22 $M_\odot$ → Neutron Star 1.4-3 $M_\odot$
  - ☞ >22 $M_\odot$ → Black Hole >3 $M_\odot$
- **WD Mass Spectrum**
  - ☞ Peak at ~0.5-0.6 $M_\odot$

Astrophysical significance: ONeMg Novae

- Temperatures achieved are too low for breakout
  - ☆ NeNa and MgAl cycles thought to provide necessary energy production.
- NeNa cycle:
  - ☆ First stage is $^{20}Ne(p,\gamma)^{21}Na$.
    - ☞ Where does the ^{20}Ne come from?
  - ☆ β-decay of ^{20}Na feeds ^{20}Ne.
  - ☆ Rate of $^{20}Na(p,\gamma)$ compared to the β^+ decay of ^{20}Na (448ms) determines abundance of ^{20}Ne



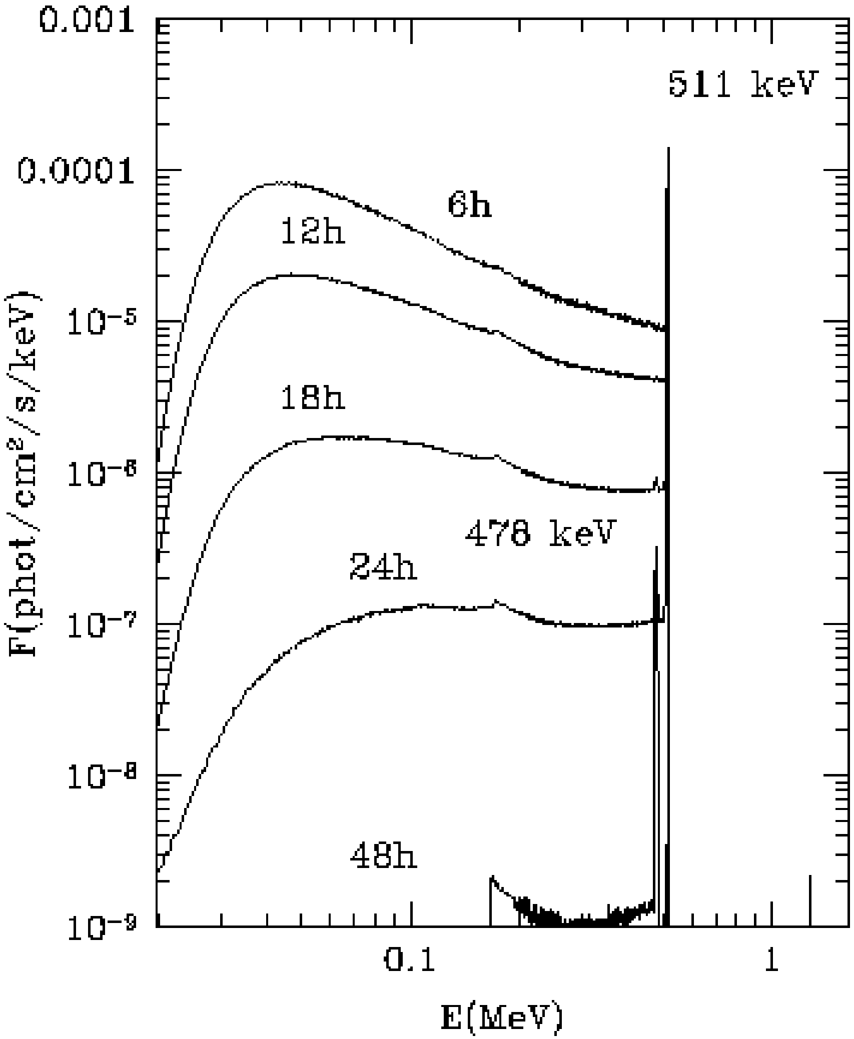


Gamma-Ray Lines in Novae

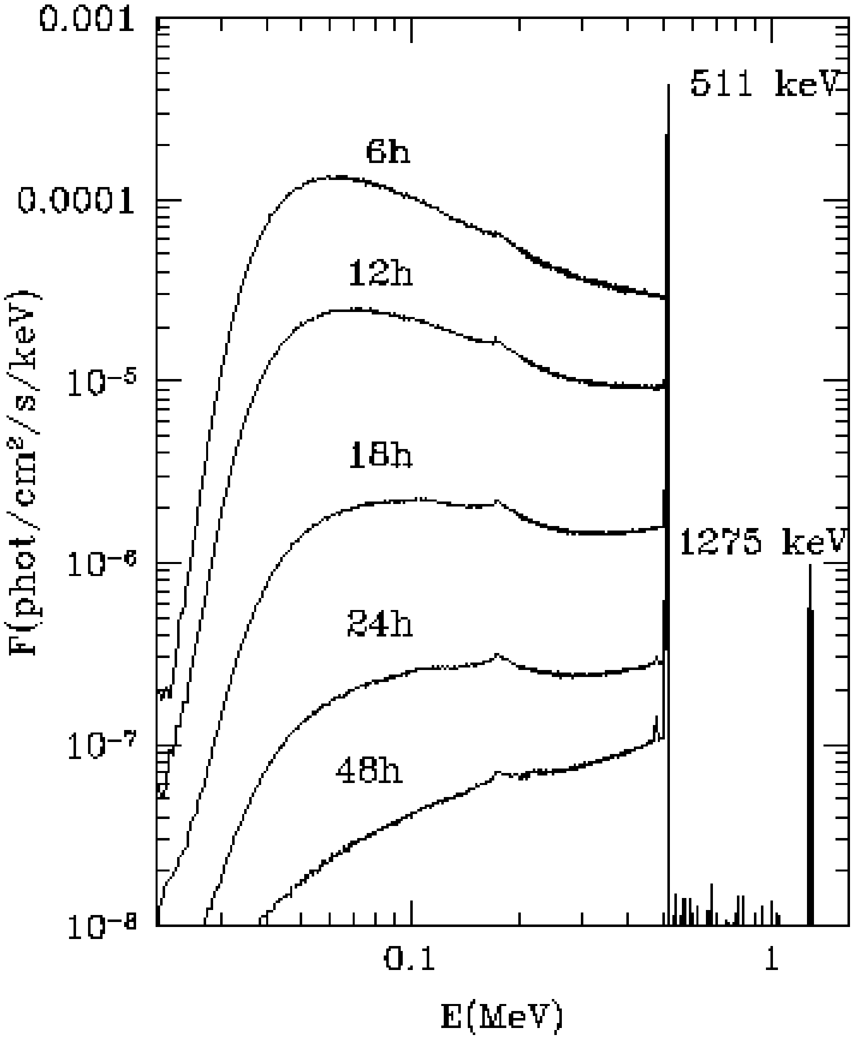
	Energy	Timescale
^{22}Na observation in novae - ^{21}Na(p,γ)^{22}Mg(β+)^{22}Na* ☆ e.g., **INTEGRAL (launched Oct '02)**	1.275 MeV	3.7 y
Synthesis of ^{22}Na in ONe novae - **^{20}Ne(p,γ)^{21}Na(p,γ)^{22}Mg(β+)^{22}Na** **or** **^{20}Ne(p,γ)^{21}Na(β+)^{21}Ne(p,γ)^{22}Na**		
^{7}Be(EC)^{7}Li	478 keV	53 d
Beta-decays of ^{13}N (862s), ^{14}O (102s), ^{15}O (176s), ^{18}F(158m)	511 keV	1 d

Predicted Flux for nova within 1 kpc

CO nova 1.15 M_O

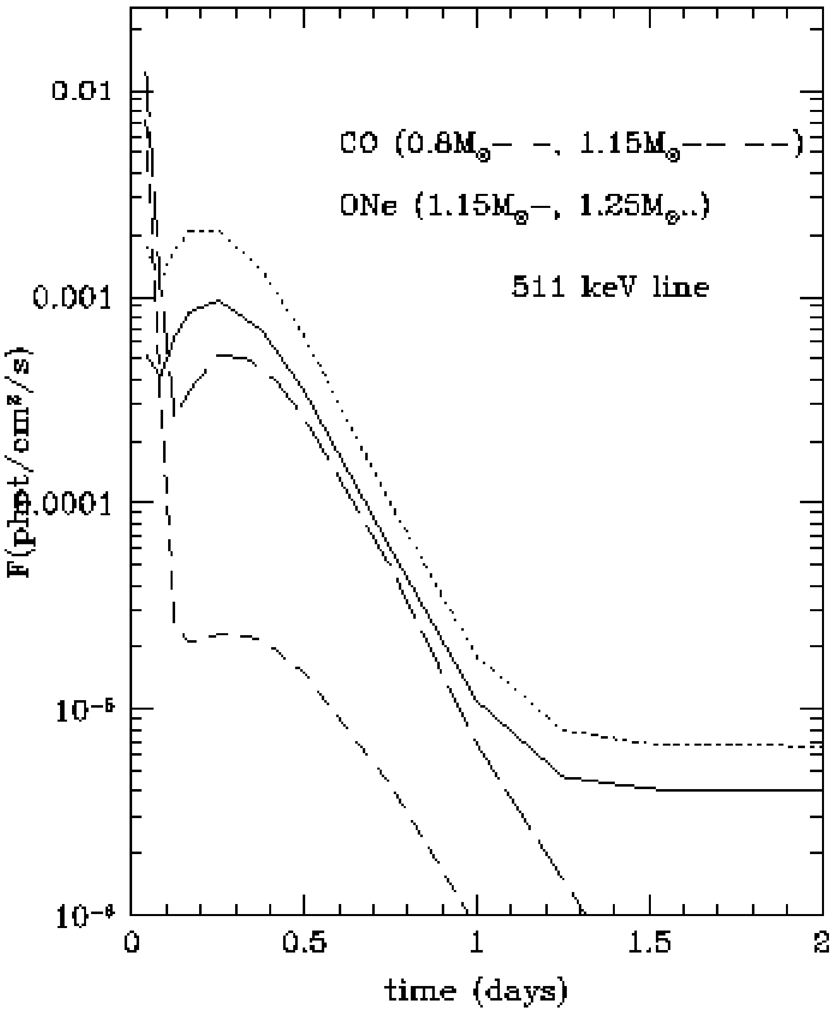


ONe nova 1.25 M_O

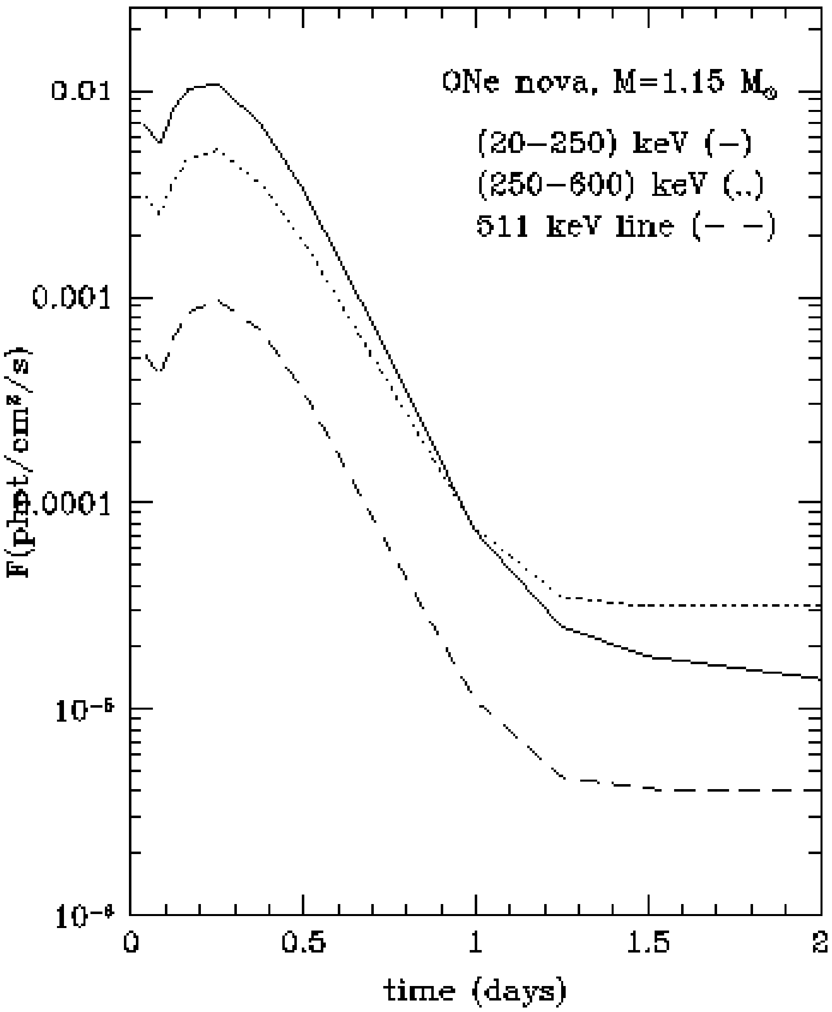


Predicted Flux for nova within 1 kpc

511 keV line

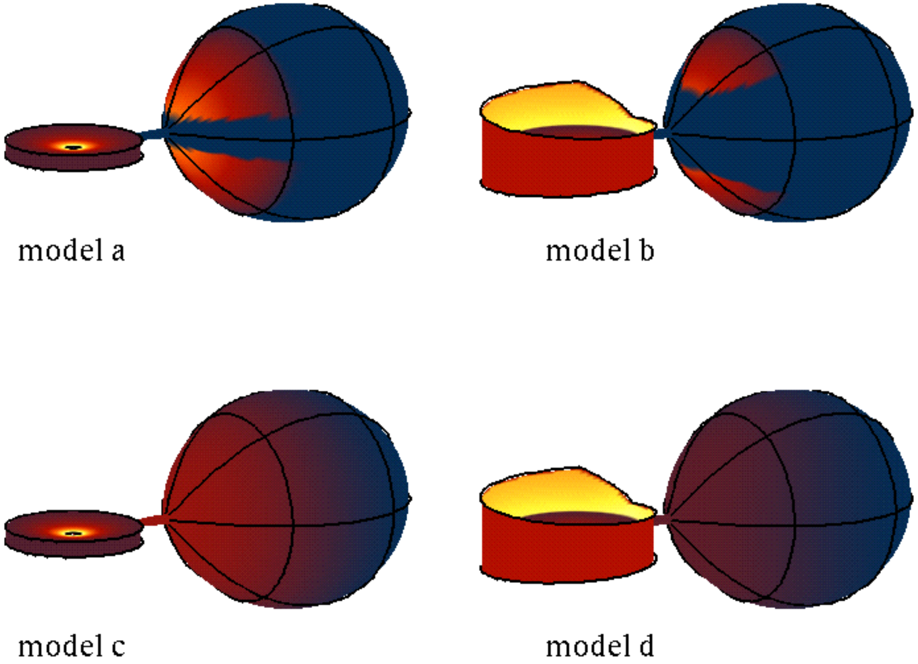


Continuum

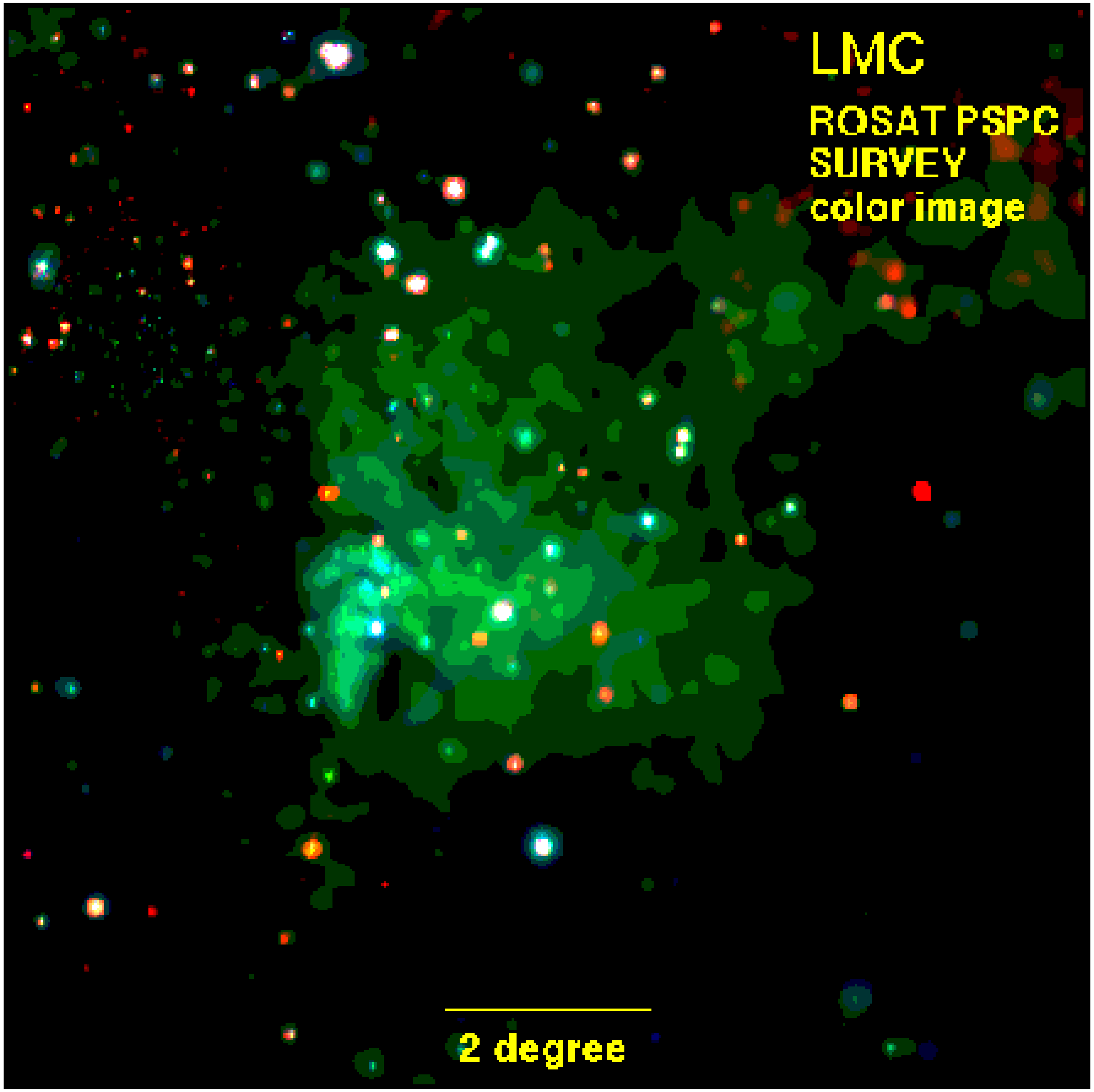


Supersoft X-ray Sources

- 90% of intrinsic source photons <0.5 keV
- High X-ray luminosity (10^{37} - 10^{38} erg/s)
- Binary systems, orbital periods 0.5-2.5 days
- Discovered in Magellanic Clouds, most known in nearby galaxies
- ~30 objects known
- Optical: accretion disk spectrum
- Wide eclipses: flared disk



Supersoft X-ray Sources



Binary Components

Primary

X-ray spectrum → radius

Radial velocity curve → f(M)

white dwarf

Secondary

orbital periods,

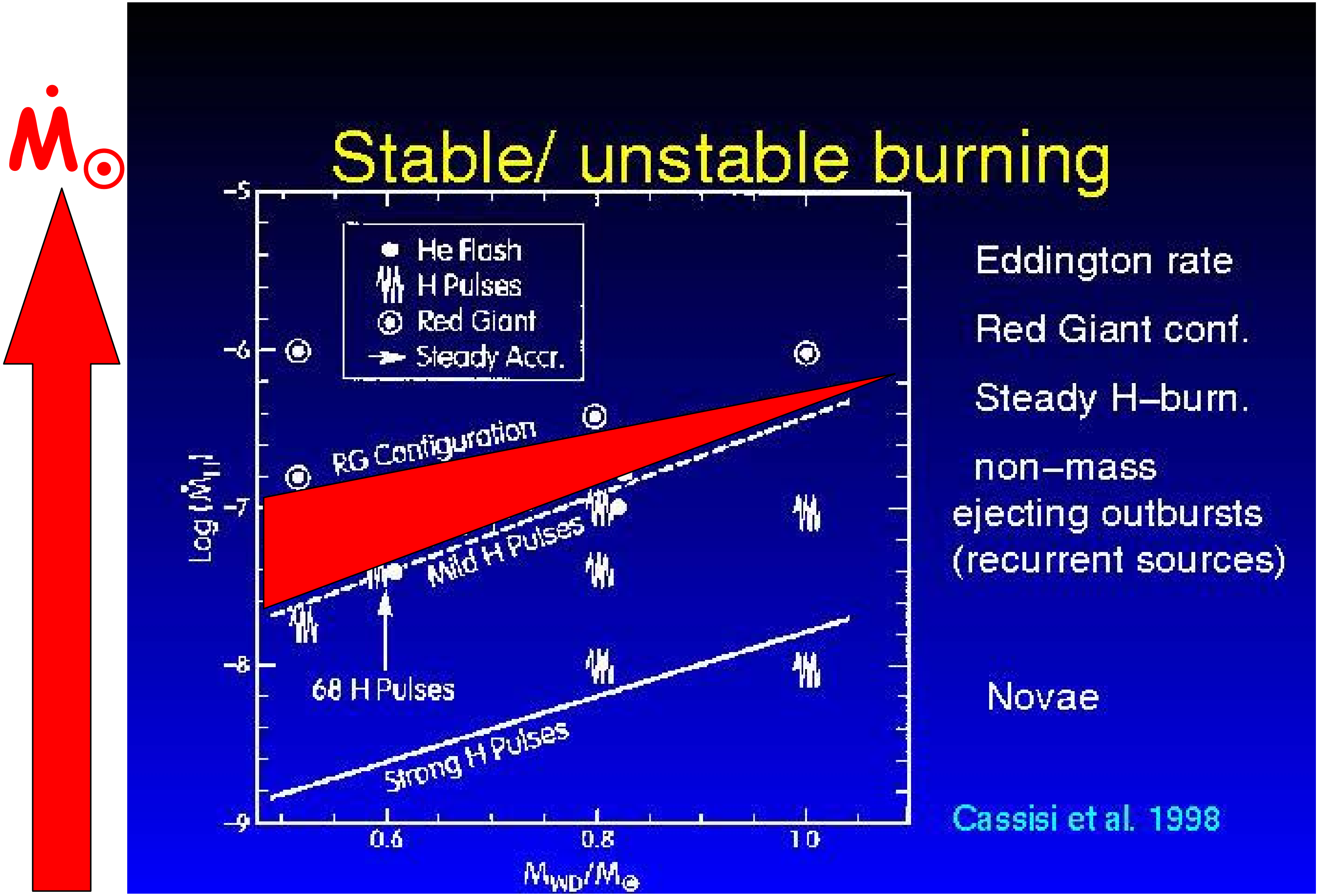
Roche Lobe filling

1-2 $M_\odot$ main-sequence

→ accretion cannot produce 10^{38} erg/s on WD

→ nuclear burning (but remains to be proven!)

Supersoft X-ray Sources



Stable/ unstable burning

Eddington rate

Red Giant conf.

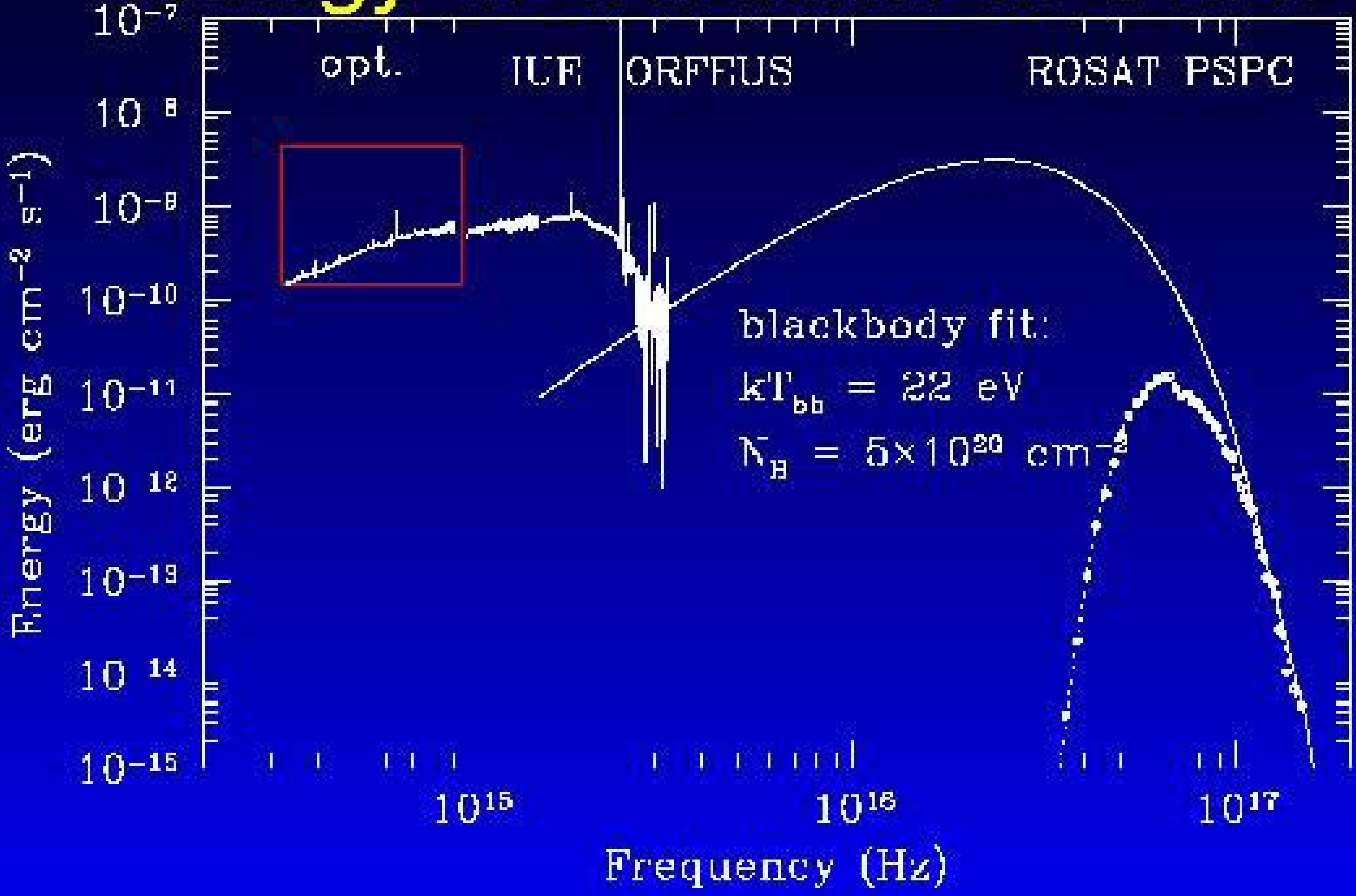
Steady H–burn.

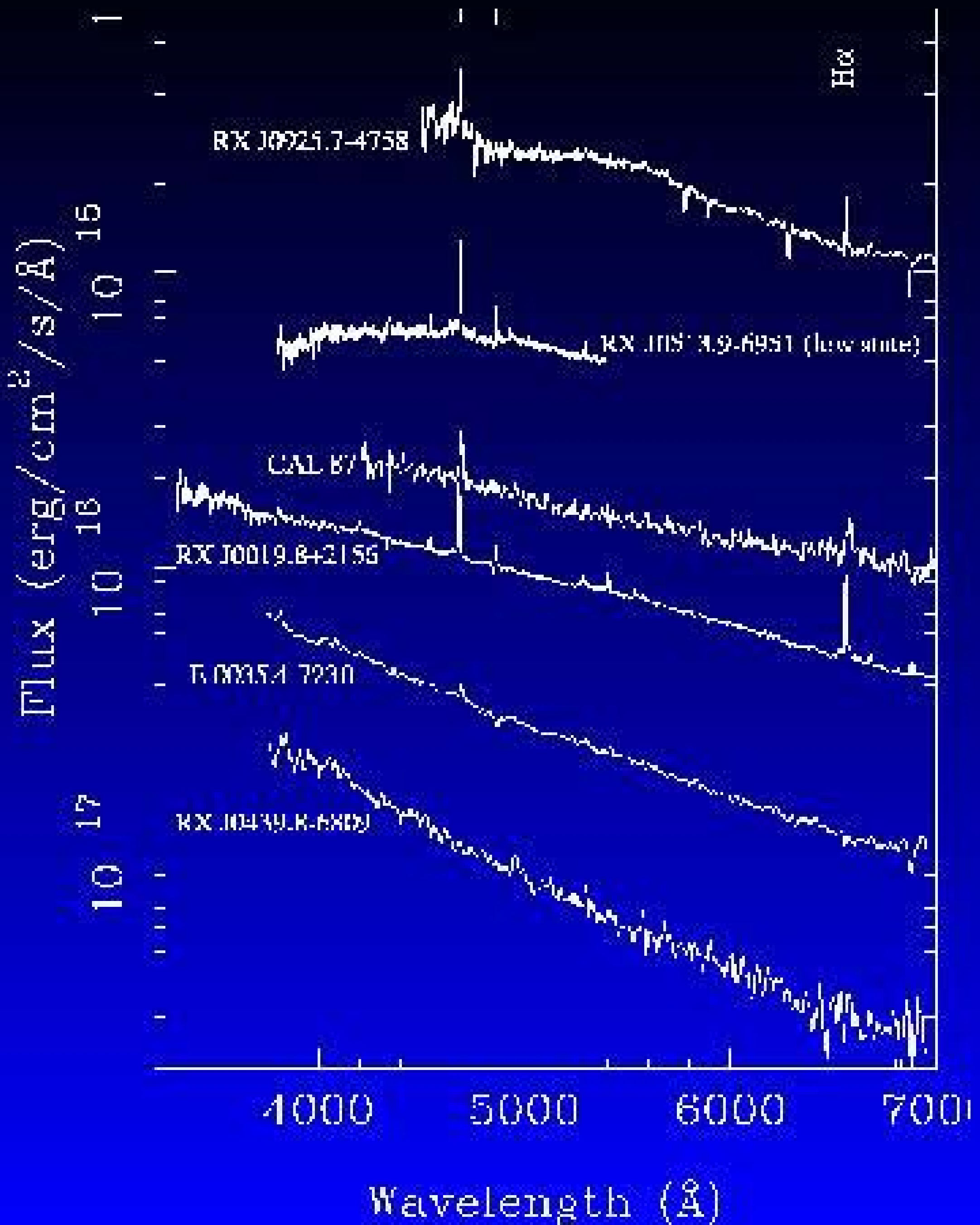
non–mass
ejecting outbursts
(recurrent sources)

Novae

Cassisi et al. 1998

Energy distribution of SSXBs





Optical spectra of SSXBs I.

blue continuum

H, He I, He II emission

no donor–star features

van Teeseling 1998

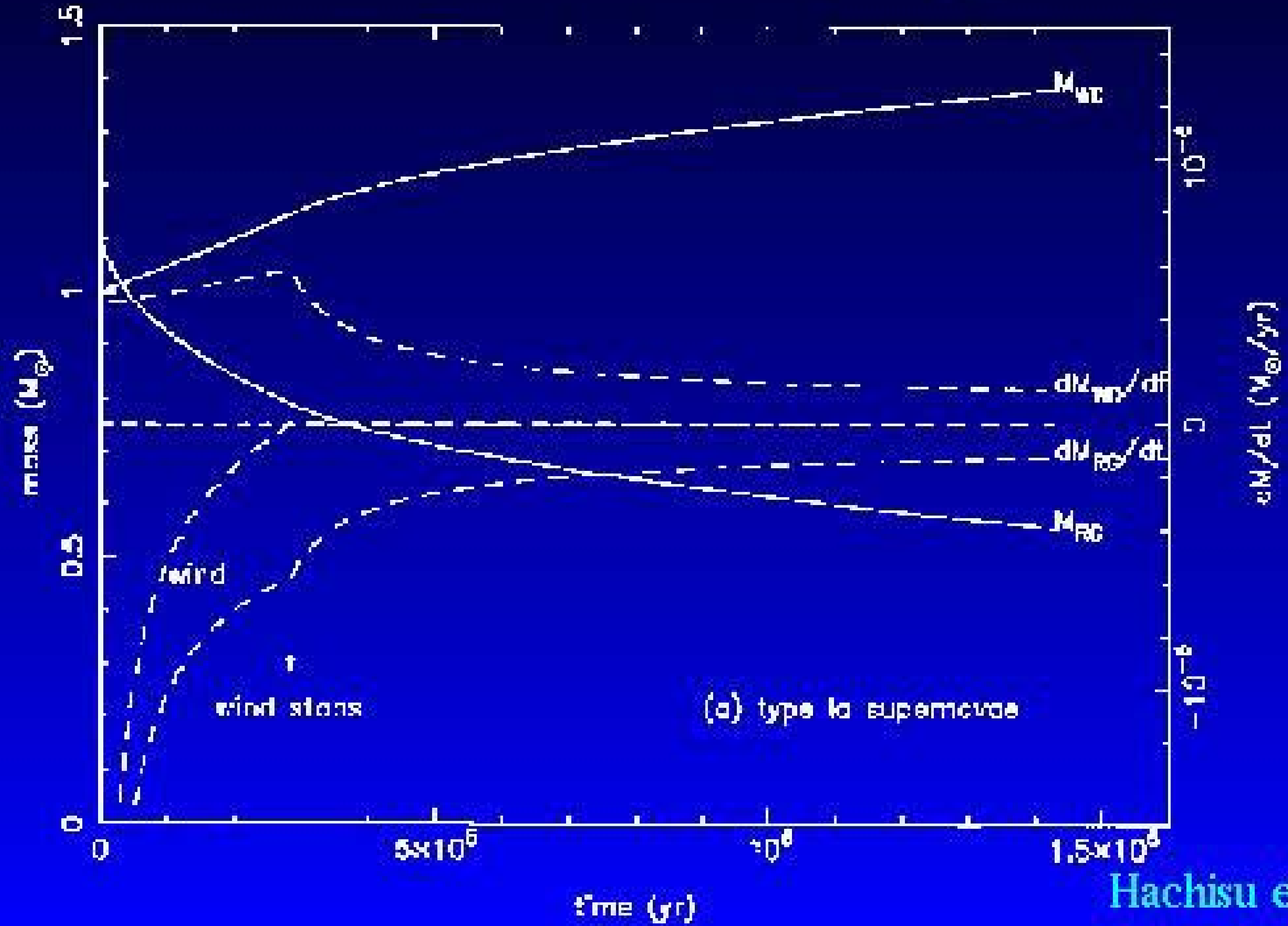
Relevance for astrophysics

I. population density

	Population Synthesis	Inferred from Observations	RASS detected (SSXBS)
M31	400 – 6000	800 – 5000	34
Milky Way	100 –1500	400 – 3000	10 (2)
LMC	20 – 300	15 – 60	8 (6)
SMC	5 – 60	10 – 40	4 (1)

Rappaport & Distefano 1996

Relevance for astrophysics
II. SSXBs as SN Ia progenitors

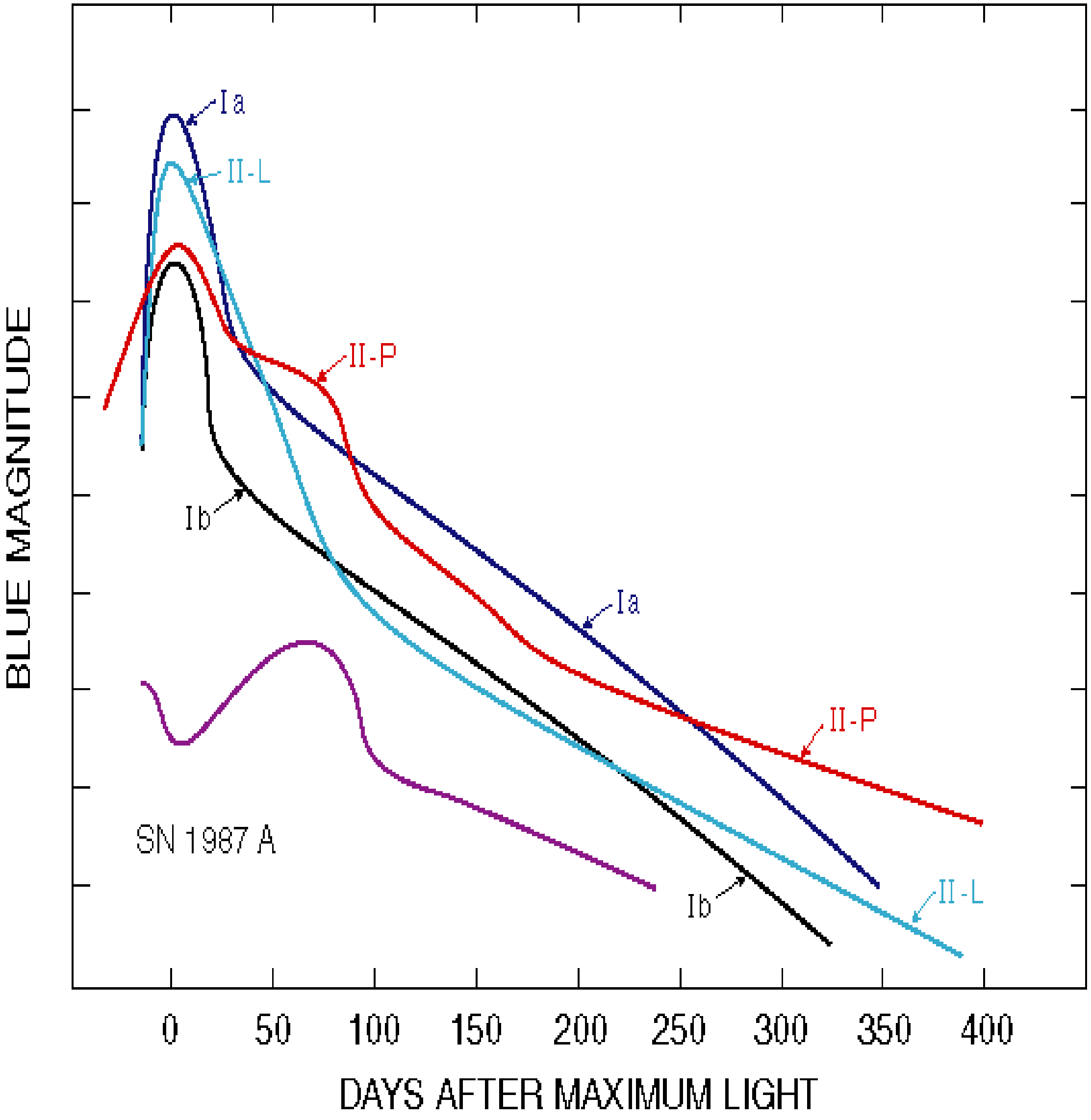


Hachisu et al. 1996

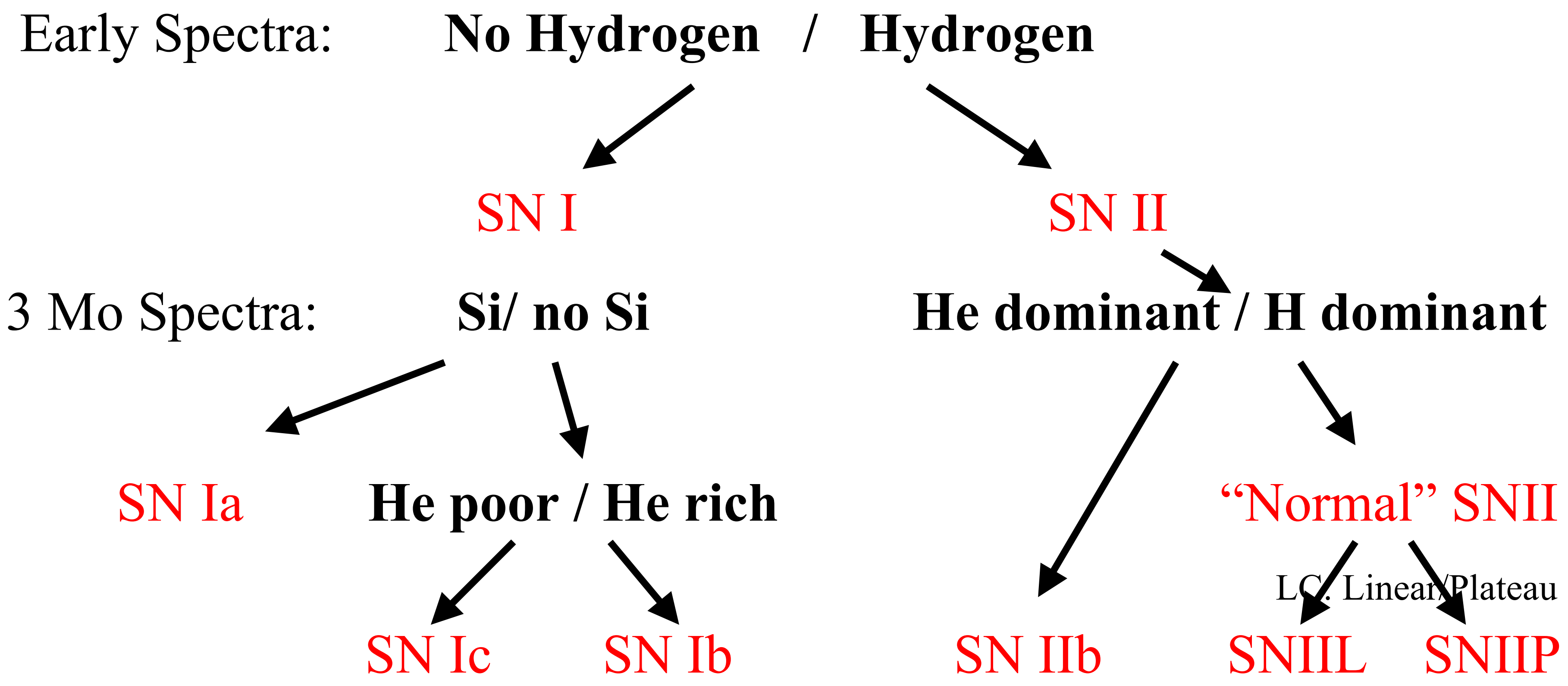
Supernovae

- Explosion of a Star
- Nuclear Energy Release
  - ☆ Radioactive By-Products of Explosive Nucleosynthesis
  - ☆ Progressive Transparency of Exploding Star

  - ☆ Thermonuclear Supernovae (Type Ia)
  - ☆ Gravitational Collapse Supernovae (Types II, Ib/c)



Supernova Classification



Early Spectra: **No Hydrogen / Hydrogen**

SN I

SN II

3 Mo Spectra: **Si/ no Si**

He dominant / H dominant

SN Ia

He poor / He rich

"Normal" SNII

LC: Linear/Plateau

SN Ic

SN Ib

SN IIb

SNIIL

SNIIP

Detonation of

Accreting WD

Core Collapse, outer layers stripped.

H&He removed

H mantle removed

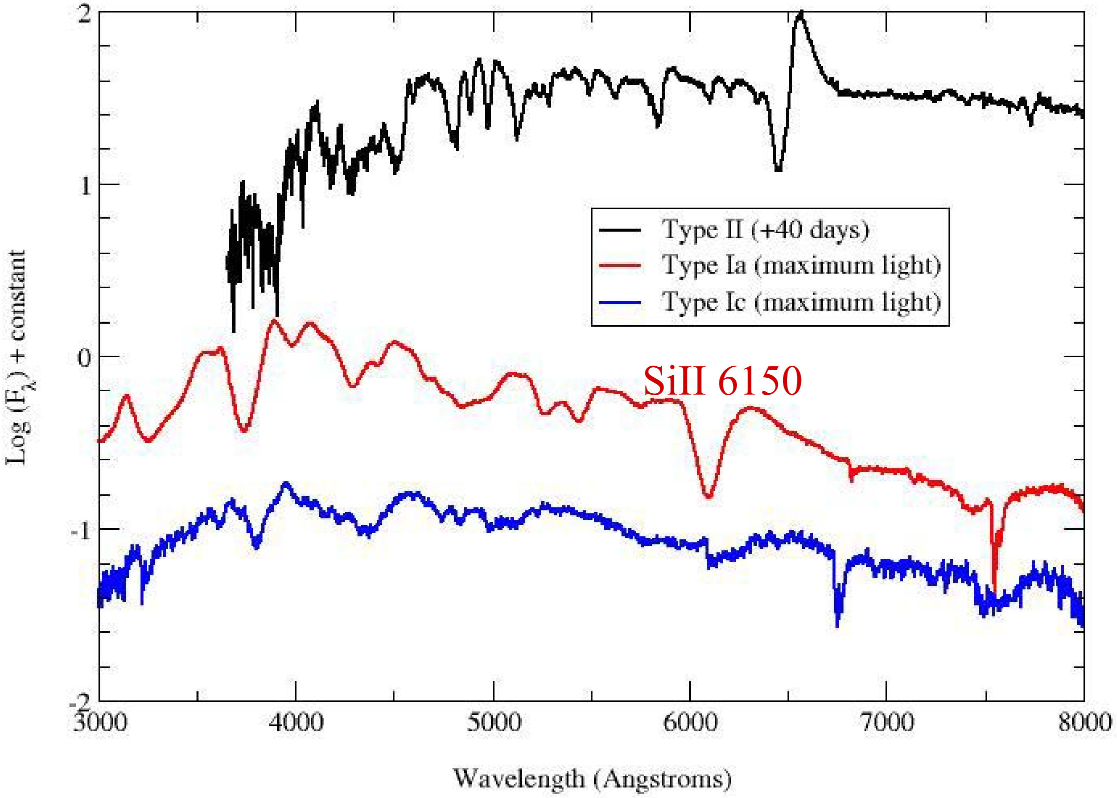
Core collapse

Most H removed

Core collapse of

massive progenitor.

Classification and Definition of a SN Ia



Only supernova subtype to occur in elliptical galaxies. Progenitor is therefore in a binary system and undergoes a thermonuclear runaway as it approaches Chandrasekhar limit.

Basic Understanding of SNe Ia

What we know…:

- WD in binary system accretes hydrogen
- when Chandrasekhar mass is reached, WD collapses, explosively ignites Carbon, and is destroyed completely
- SNe Ia are very good *standard* candles: same maximum luminosity
- Powered by the decay of $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$

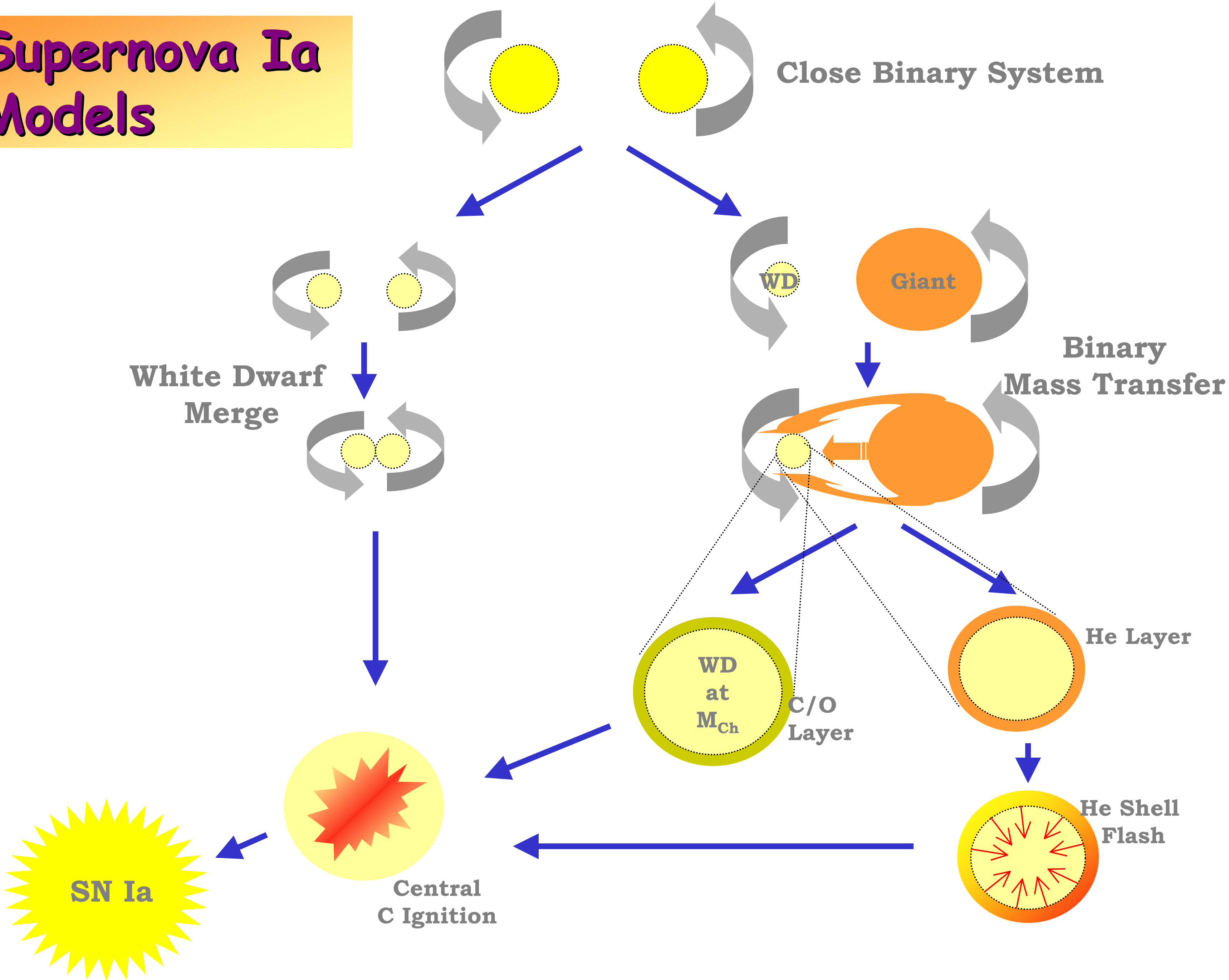
  $\sim 0.6\ M_{sun} = 10^{43}$ erg/s at peak

  this explains the light curves (temporal evolution of photometry)
- produces velocities ~ 0.1c
- Lack H/He, show strong intermediate mass and iron peak elements
- They occur in all types of galaxies

…and what we don't:

- Evolution with redshift
- Asphericities

Supernova Ia Models

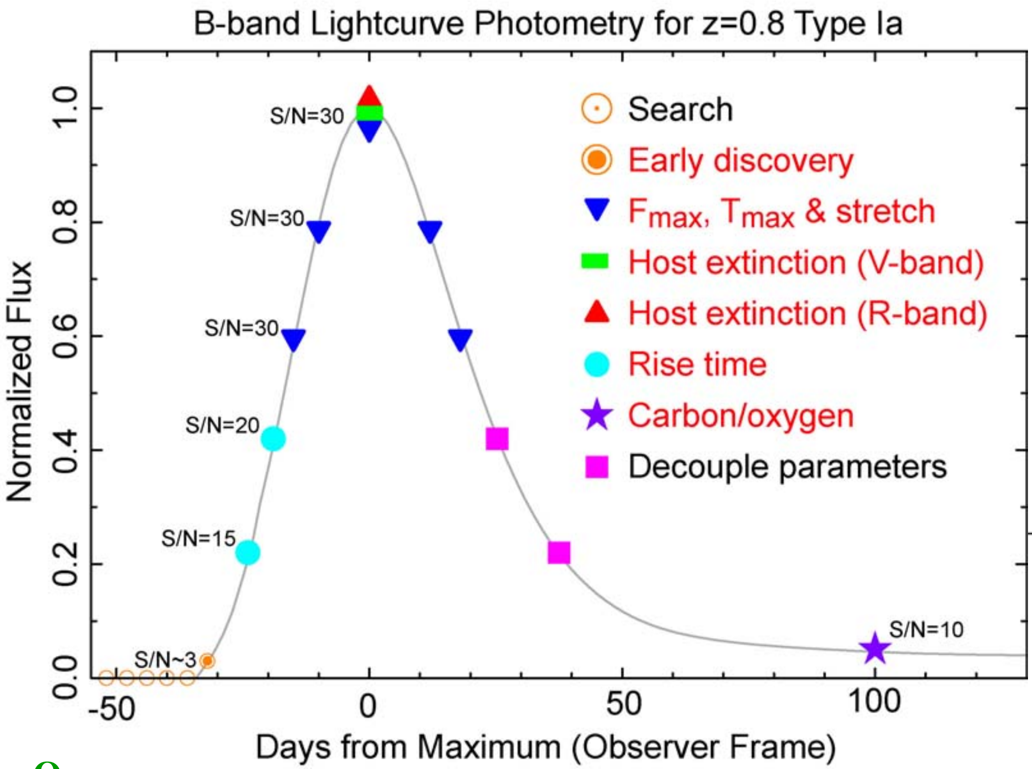


Close Binary System

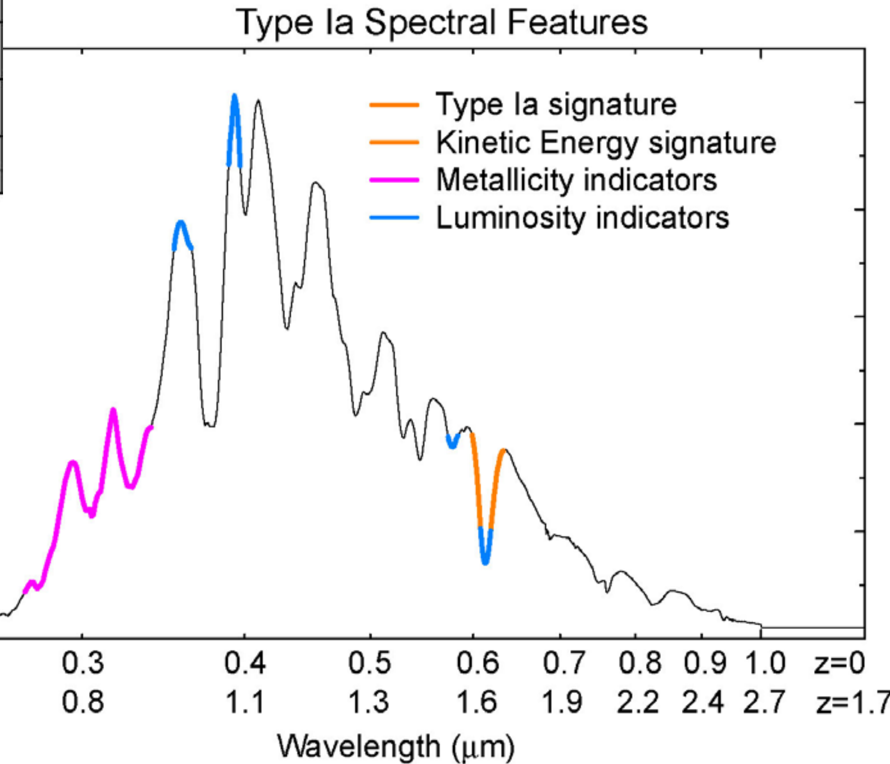
White Dwarf Merge

Binary Mass Transfer

SN Ia Characteristics



What we want to measure both spectroscopically and photometrically.



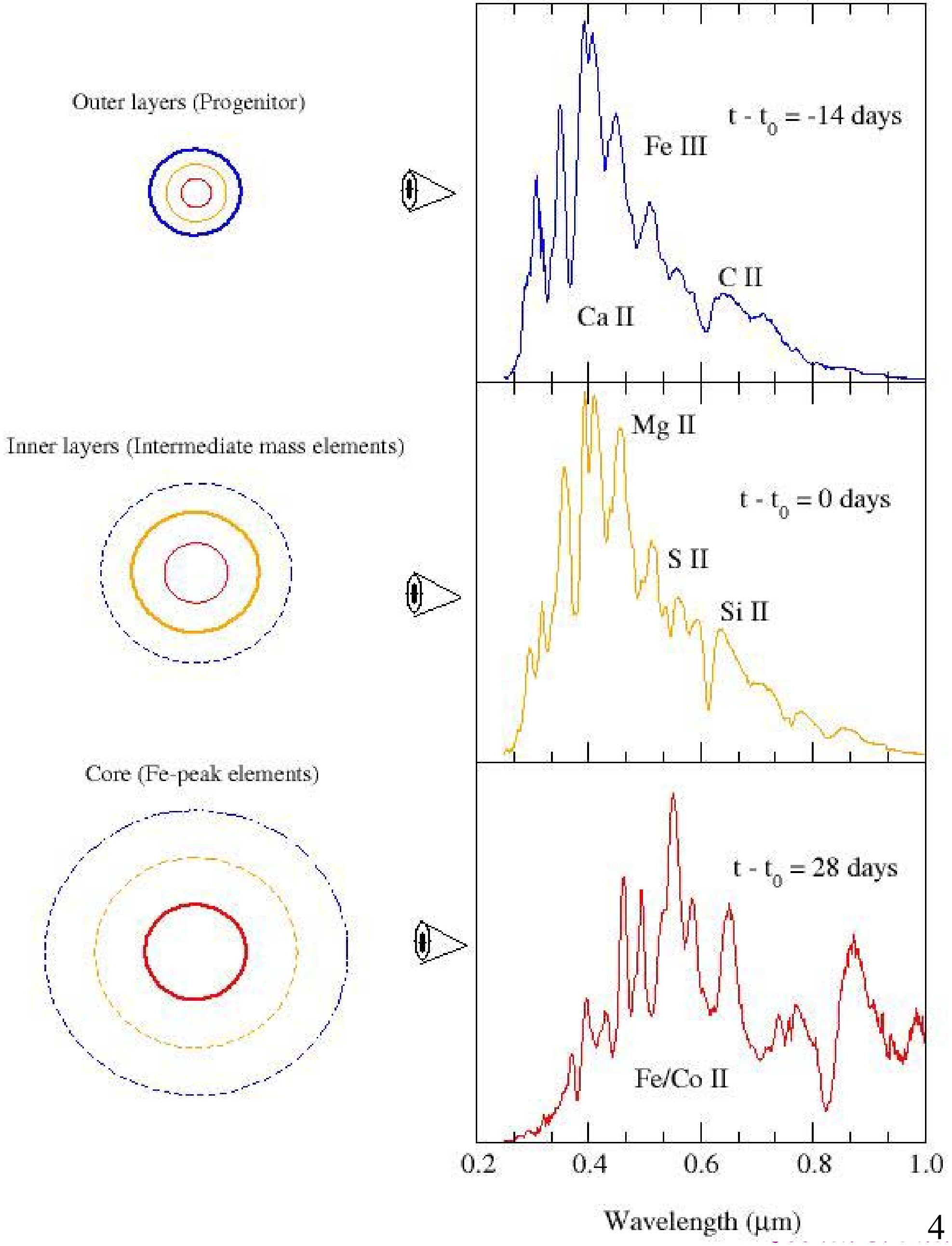
OBSERVABLES

- Stretch – Light Curve Shape
- Spectral Correlations
- Metallicity
- Rise Times
- Kinetic Energy
- C-to-O ratio
- Asymmetries

SN Ia Cat Scan

Unlike many astrophysical objects a SN Ia bares all.

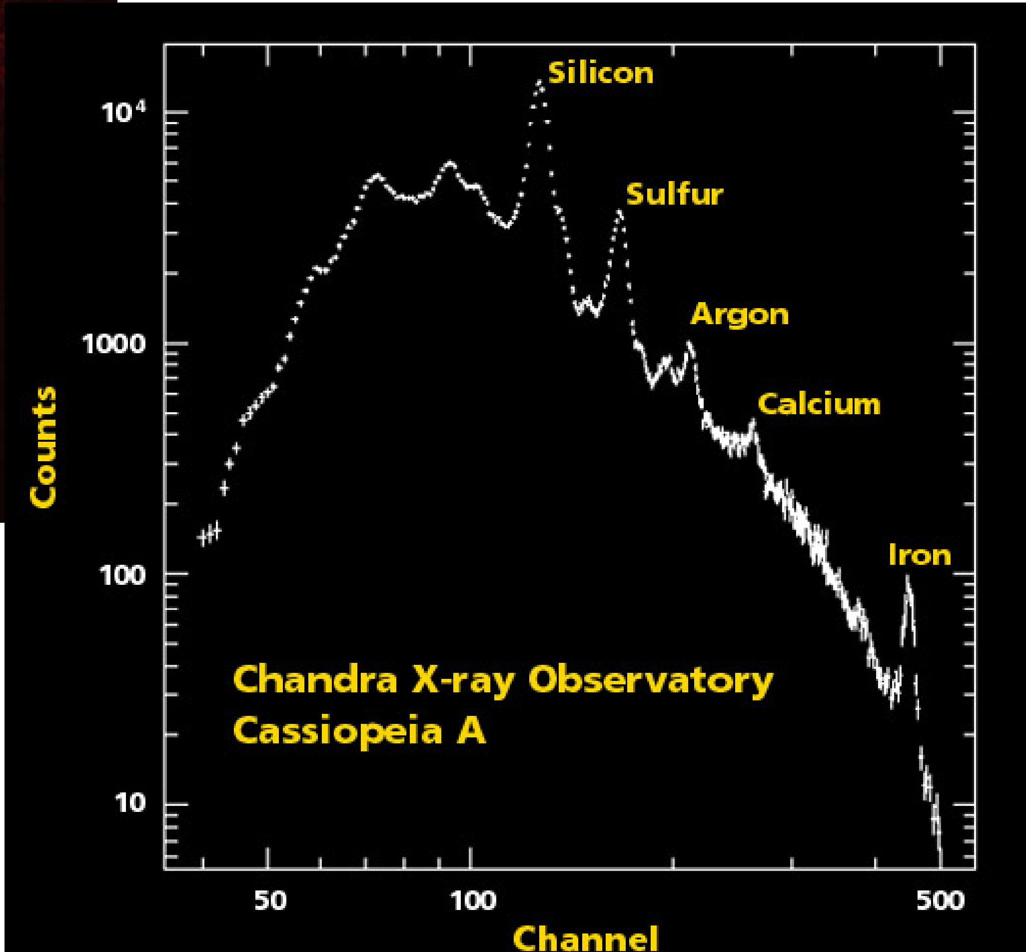
As the supernova expands, and the atmosphere dilutes itself, one is able to peer deeper and deeper into the explosion event. This enables you to study the supernova inside out as a function of time and gain an understanding of the progenitor, nucleosynthesis products, explosion mechanism and kinetic energy.



Cas-A supernova remnant

X-ray spectroscopy:

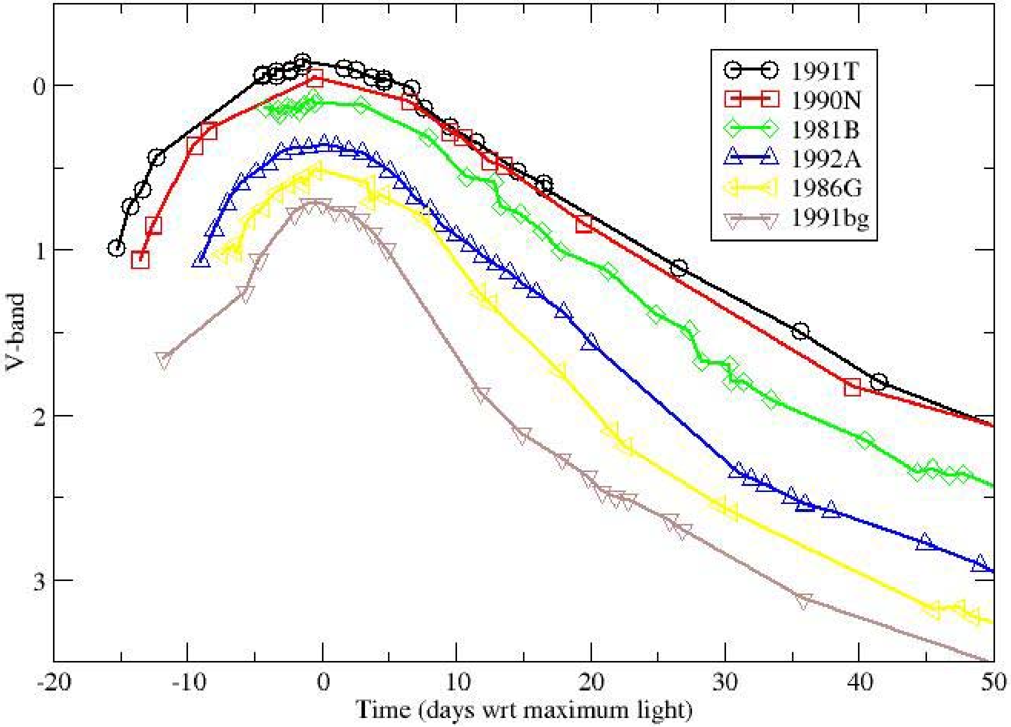
element abundances



SN Ia Differences

Light Curve Shape
Relationships

SN Ia are not all the same. Variations occur in their light curves and spectra. Use width around maximum as the “stretch” parameter to correct for these differences.



Modeling the SNe Ia

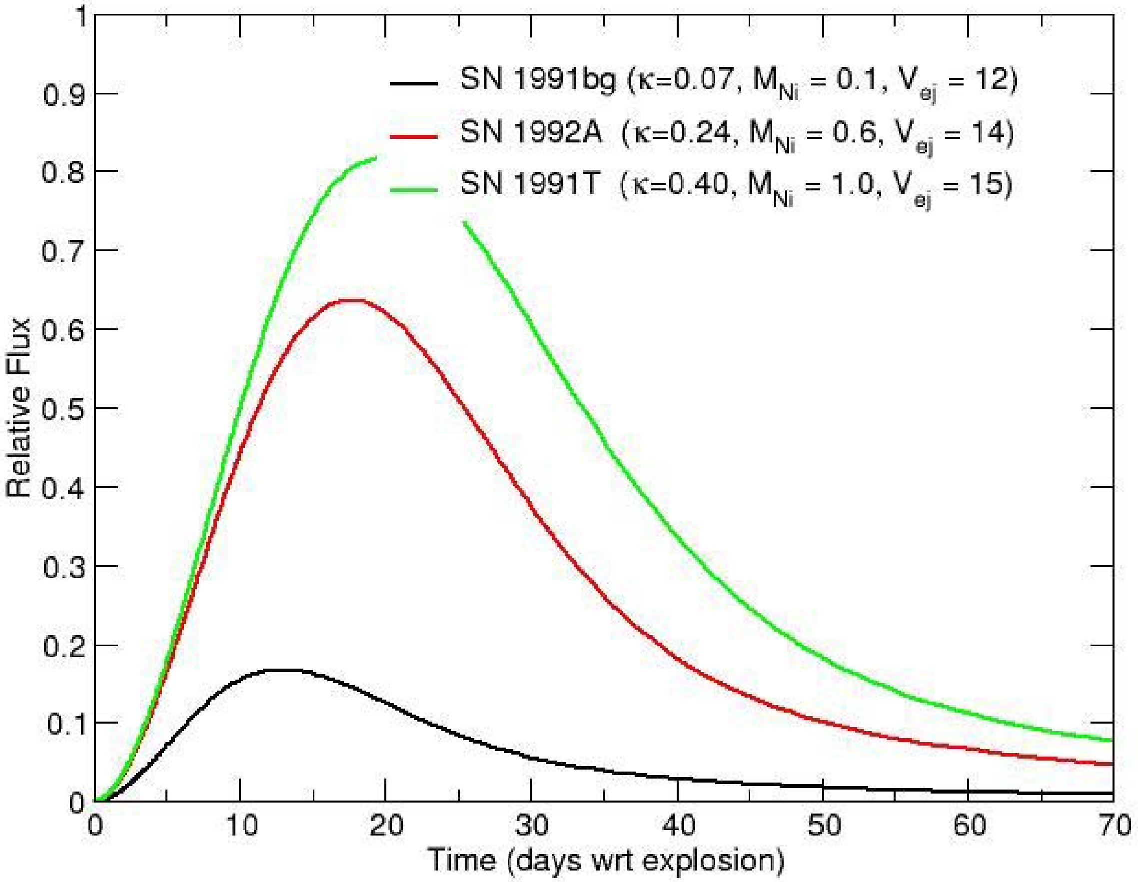
Simple relationship: More ^{56}Ni → Higher Temperatures → Higher Opacities

= Brighter/Broader SNe Ia

The higher opacities allow to trap the radiation more effectively and release it later making for broader light curves.

Parameters for modelling SN Ia light curve:

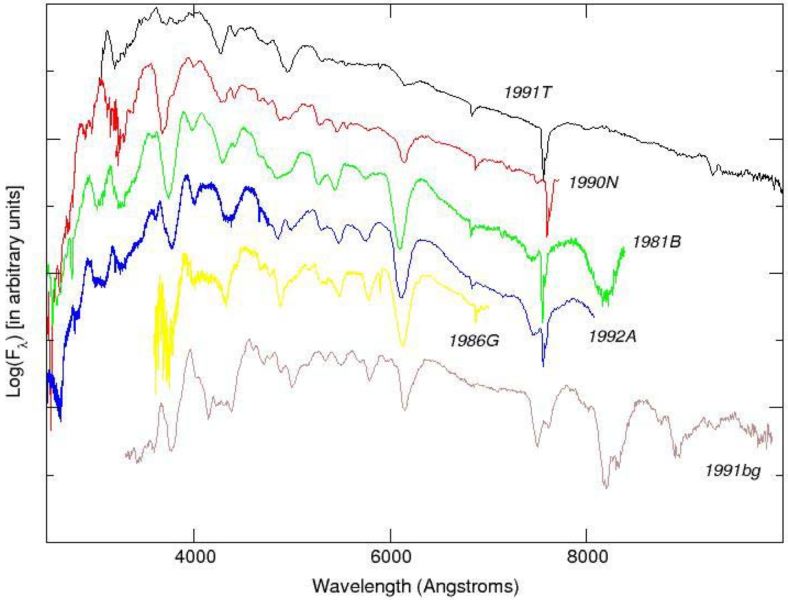
- ^{56}Ni mass
- Opacity
- Kinetic Energy



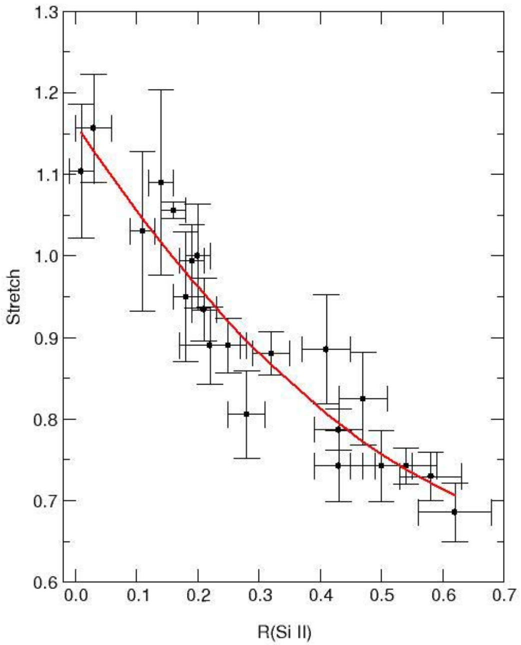
SN Ia Spectral Correlations

Spectral Relationships

The spectra also follow a sequence (here at maximum light) from the dim to the bright.



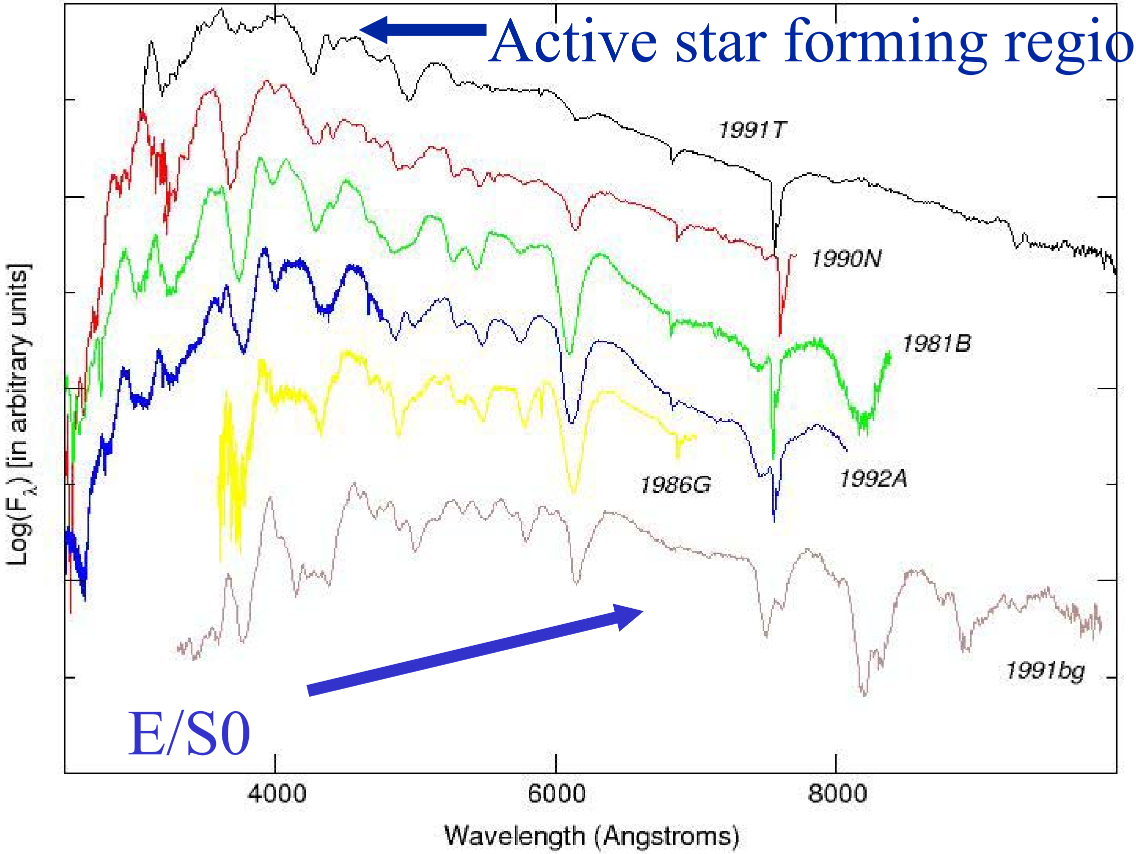
Ratio of Si II Features vs. Stretch



Observationally this is characterized by the presence of lower to higher excitation and /or ionization of the ionic species in the spectra.

SN Ia Environments

In general, the normal SN Ia occur in all types of galaxies whereas the bright (1991T-like) SN occur only in star forming regions and the faint (1991bg-like) SN occur in old elliptical galaxies.



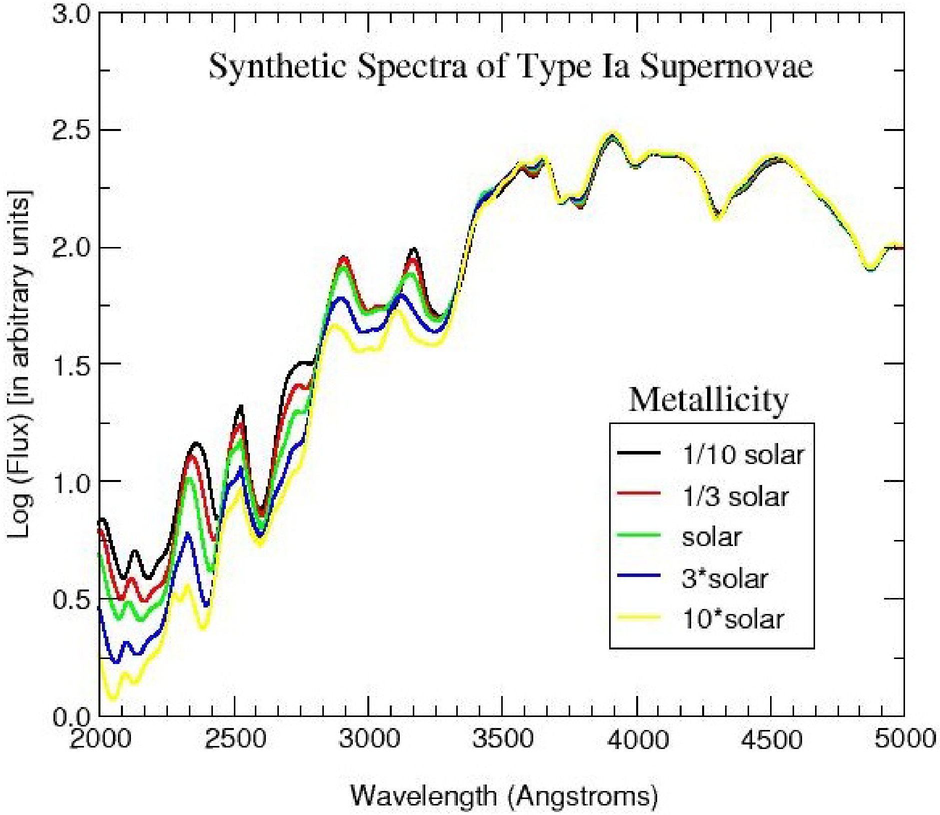
Active star forming regions

E/S0

SN Ia Metallicity - Models

Metallicity Differences in the Progenitor.

The basic effect is to change the level of flux below 400nm where the Fe peak ionic species dominate the opacity. The higher the abundance of metals, the more suppressed the flux (everything else being equal).



Cosmological Relevance: Distance Indicator

Assumption:
always the same process during SN Ia explosion

→ **same absolute brightness**
→ **define standard candle**

Determine Distance from $1/R^2$ dependence