Thermonuclear supernovae

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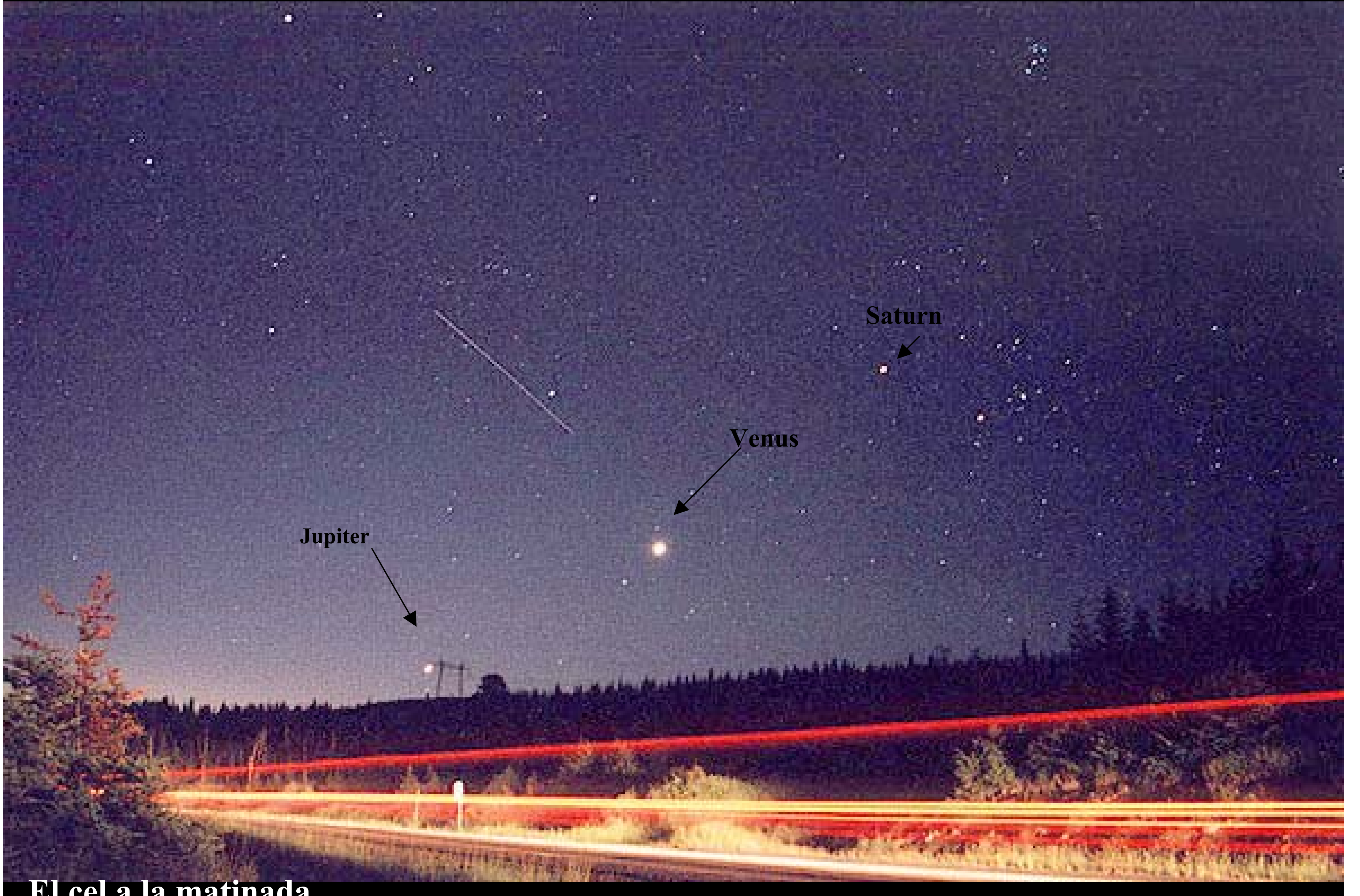
És el cel inmutable?



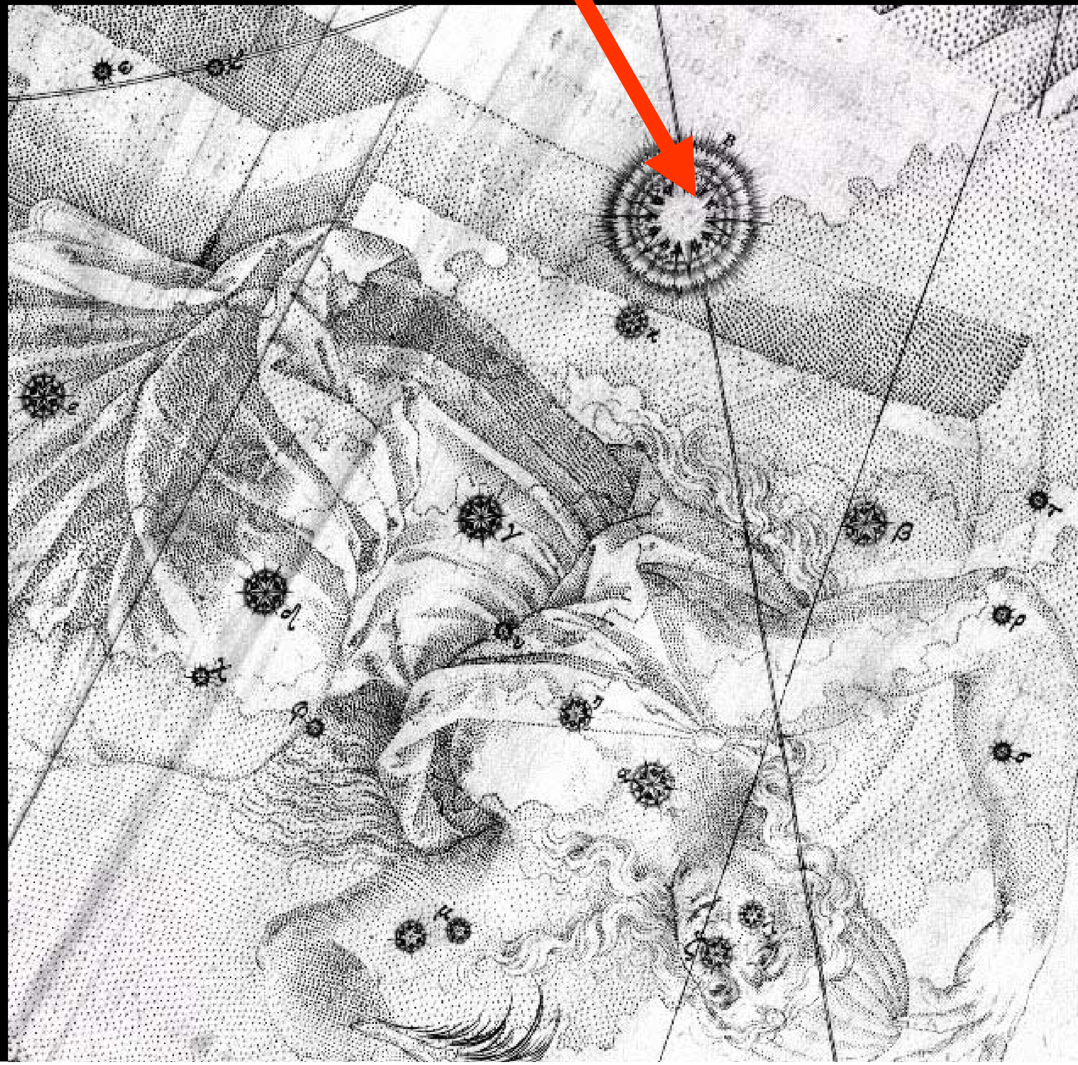
El cel a la matinada

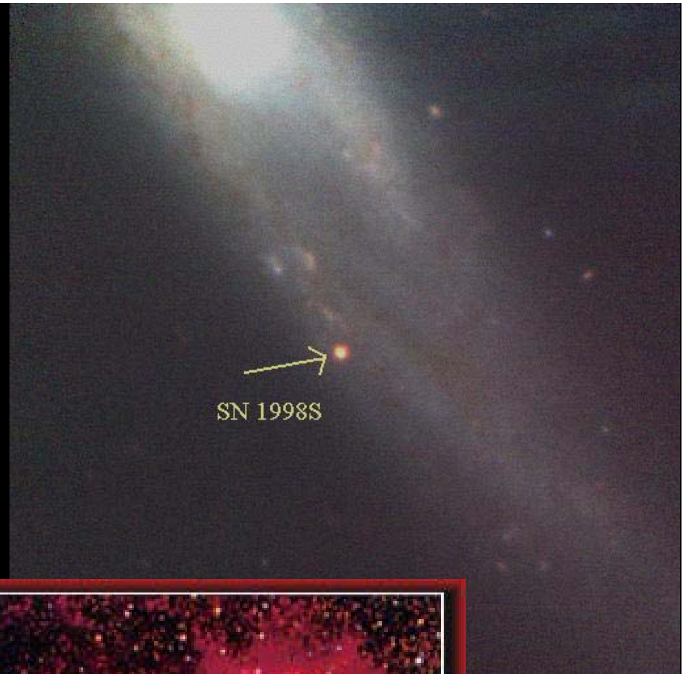
Figure 1: Artist concept of SN1006. Credit and Copyright:Tunç Tezel.

Tycho Brahe

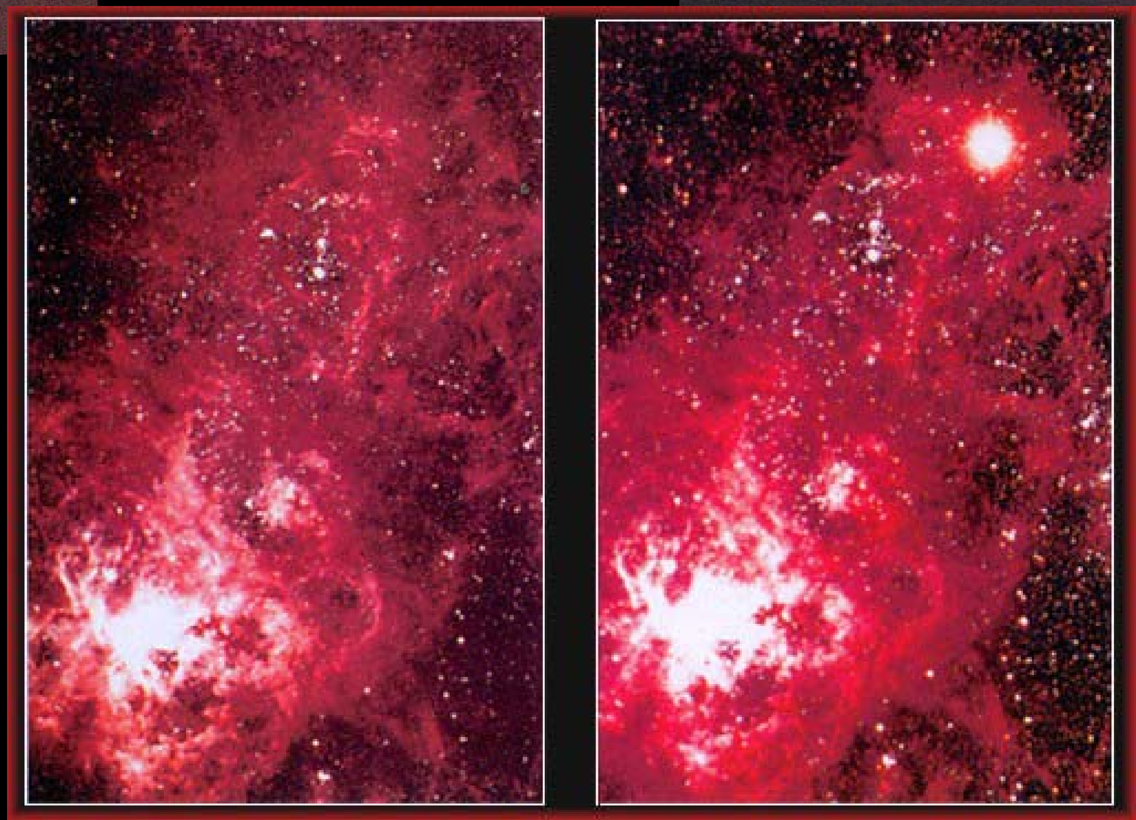
Uraniborg

SN1572
Cassiopeia





SN1987A



Supernoves

Evidències de la mort de les estrelles

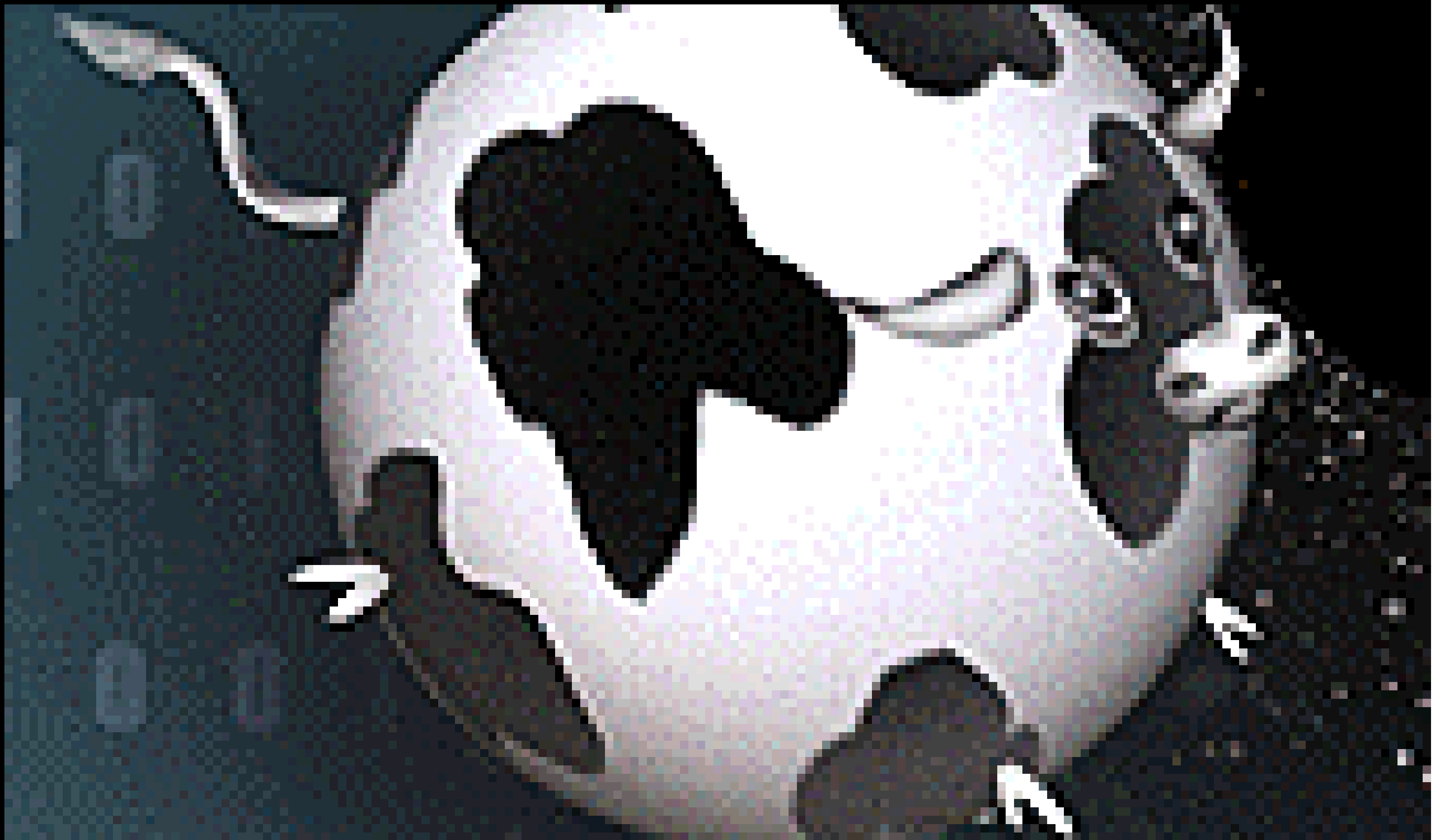
10^{51} erg d’energia cinètica!

Tota l’estrella està implicada a l’explosió

Exploding stars

- They play a fundamental role in shaping the galaxy
  - They inject 10^{51} ergs/explosion in the form of kinetic energy per event
    - They trigger the formation of new stars
    - They accelerate cosmic rays
    - They power intense galactic winds that can even remove the galactic gas and kill the process of star formation
  - They inject several M_o of freshly synthesized chemical elements, both stable and radioactive.
  - They play a key role on the origin and evolution of life
    - They synthesize the elements necessary to build rocky planets
    - They synthesize the biogenic elements
    - They can sterilize large regions of the Galaxy

Usually, spherical symmetry is assumed: only radial gradients are allowed. But ...



Hydrostatic Equilibrium

Characteristic times

Hydrodynamic time: $\tau_{HD} \approx 440\ \rho^{-1/2}$

Thermal time: 10^7 yr

Nuclear time: 10^9 yr

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

$$\rho \approx \frac{M}{R^3}$$

$$\frac{dp}{dr} \approx \frac{P}{R}$$

$$P \approx M^2 R^{-4}$$

Electron degeneracy

At high densities e⁻ are dominant

$$P \cong P_{e,0}(\rho) + P_{e,1}(\rho,T) + P_{i,1}(\rho,T)$$

If $T \rightarrow 0$

$$P_{e,1}(\rho,T) \rightarrow 0$$

$$P_{i,1}(\rho,T) \rightarrow 0$$

$$P_{e,0} = K_{NR}\rho^{5/3}$$

Even at T=0 electrons (and other fermions) are able to exert pressure!

$$P_{e,0} = K_{ER}\rho^{4/3}$$

Zero temperature structures can exist

The virial theorem

$$E_G = -3\int_* P\,dV$$

Non Relativistic Particles

$P = 2/3\ e$

$E_i = -1/2\ E_G$

During a gravitational transition from an equilibrium configuration to another one, half of the energy is radiated away and half is invested in internal energy.

Extremely Relativistic Particles

$P = 1/3\ e$

$E_i = -E_G$

Relativistic stars are not bounded

$M_{Ch} = 1.44 <2Y_e>^2\ M_o$

Non relativistic electrons

If electrons are non relativistic

$$P \approx (MR^{-3})^{5/3} = M^{5/3} R^{-5}$$

Hydrostatic equilibrium:

$$P \approx M^2 R^{-4}$$

It is always possible to find an equilibrium structure
The star only needs to contract

R decreases when M increases

Nuclear reactions

Virial theorem $\Rightarrow E_i \cong E_G$

$E_i \sim MT$

$E_G \sim M^2 R^{-1}$

$T \sim M/R$

$\rho \sim M R^{-3}$

$\rho \sim T^3 M^{-2}$

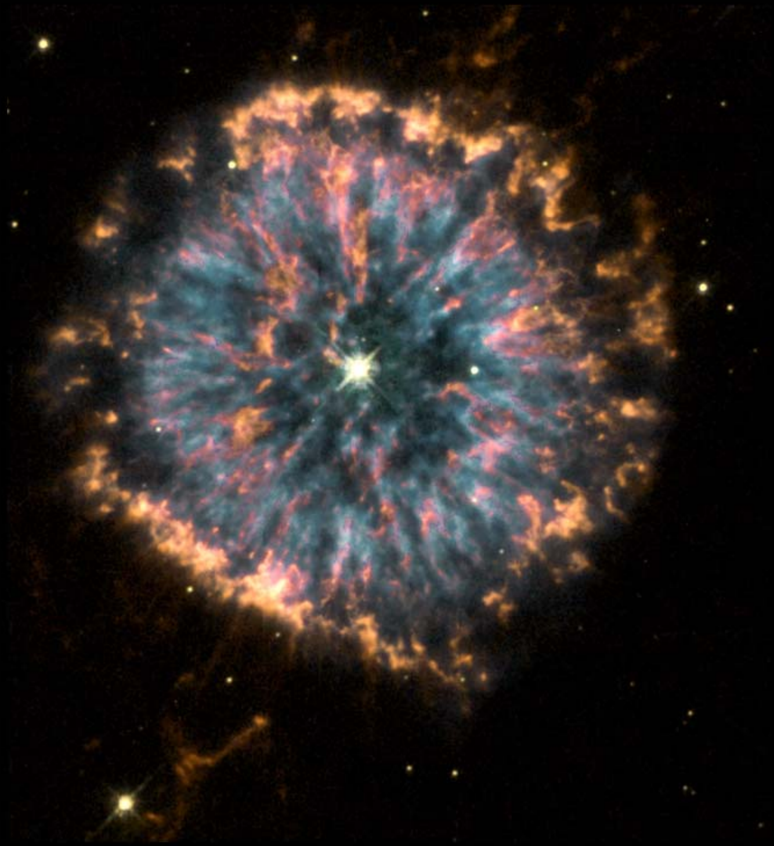
Each burning phase occurs at a fixed temperature

$\rho \sim M^{-2}$

Light stars ignite nuclear reactions at high densities

Electron degeneracy can stop the nuclear burning process

M<0.08 Mo, H is never ignited
M<0.5 Mo, He is never ignited
M<8-9 Mo, C is never ignited
M<10-12 Mo, Ne is never ignited
M>10-12 Mo, Fe cores are formed



M<0.5 Mo, form He cores
M<8-9 Mo, form C/O cores
M<10-12 Mo, form O/Ne

These limits change in binary systems.
If close enough, stars
with 2.5 Mo can give He wd of ~ 0.4 Mo

If M↑ R↓ $\Rightarrow E_F\uparrow$
When $E_F >> m_e c^2$ electrons become relativistic

Relativistic electrons

If electrons are relativistic

$$P \approx (MR^{-3})^{4/3} = M^{4/3} R^{-4}$$

Hydrostatic equilibrium:

$$P \approx M^2 R^{-4}$$

It is not possible to find an equilibrium structure

There is not a length scale

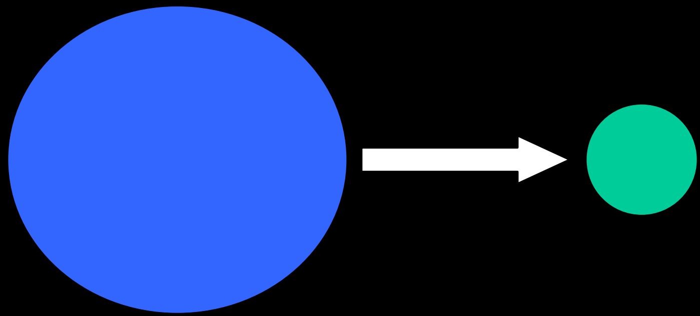
If $\delta E < 0$ $\delta R < 0$ The star contracts

If $\delta E > 0$ $\delta R > 0$ The star expands

The ideal scenario for catastrophic events !

Explosive sources of energy

Gravitational collapse



Electron degenerate core

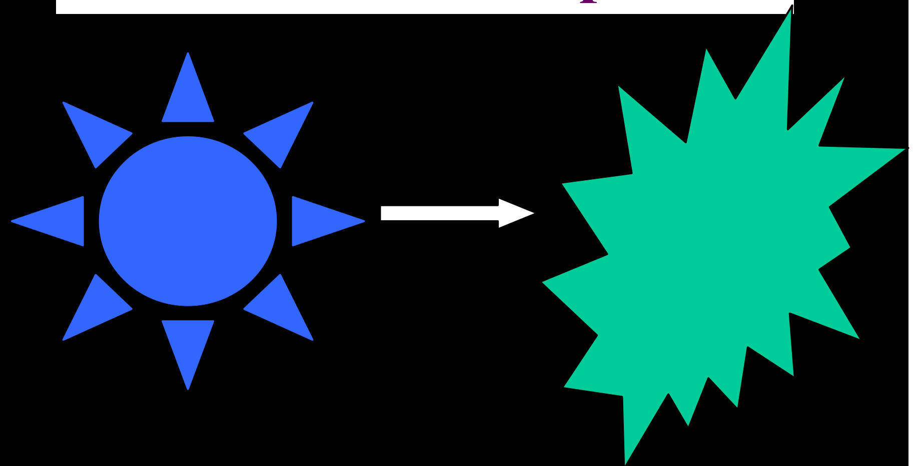
M ~ 1.4 Mo
R ~ 10^8-10^9 cm

Neutron star

M ~ 1.4 Mo
R ~ 10^6 cm

$\Delta E_G \sim 10^{53}$ erg
K ~ 10^{51} erg
$E_{em} \sim 10^{49}$ erg

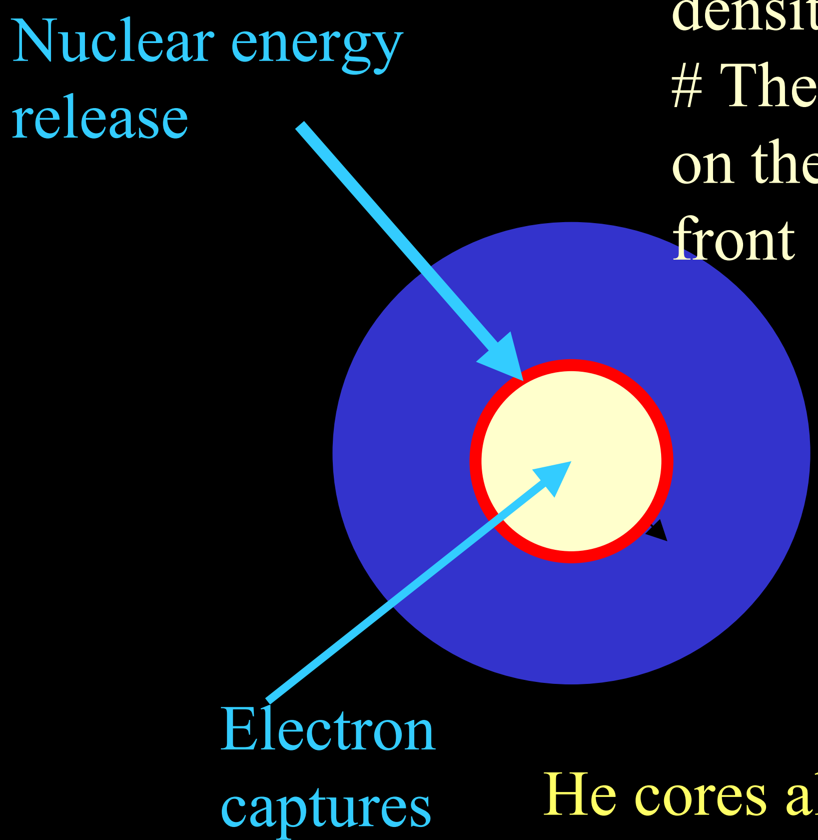
Thermonuclear explosion



$\{^{12}C, ^{16}O\} \rightarrow \{^{56}Ni\}$
q ~ 7×10^{17} erg/g
1 Mo x q ~ 10^{51} erg
K ~ 10^{51} erg
$E_{em} \sim 10^{49}$ erg
$L_{max} \sim 10^{43}$ erg/s

The energy losses by electron captures depend on the ignition density

The injected energy depends on the velocity of the burning front



He cores always explode

CO cores can explode or collapse

ONe cores always collapse

Fe cores always collapse

$M<0.8\ M_\odot$ → $\tau>1/H_O$

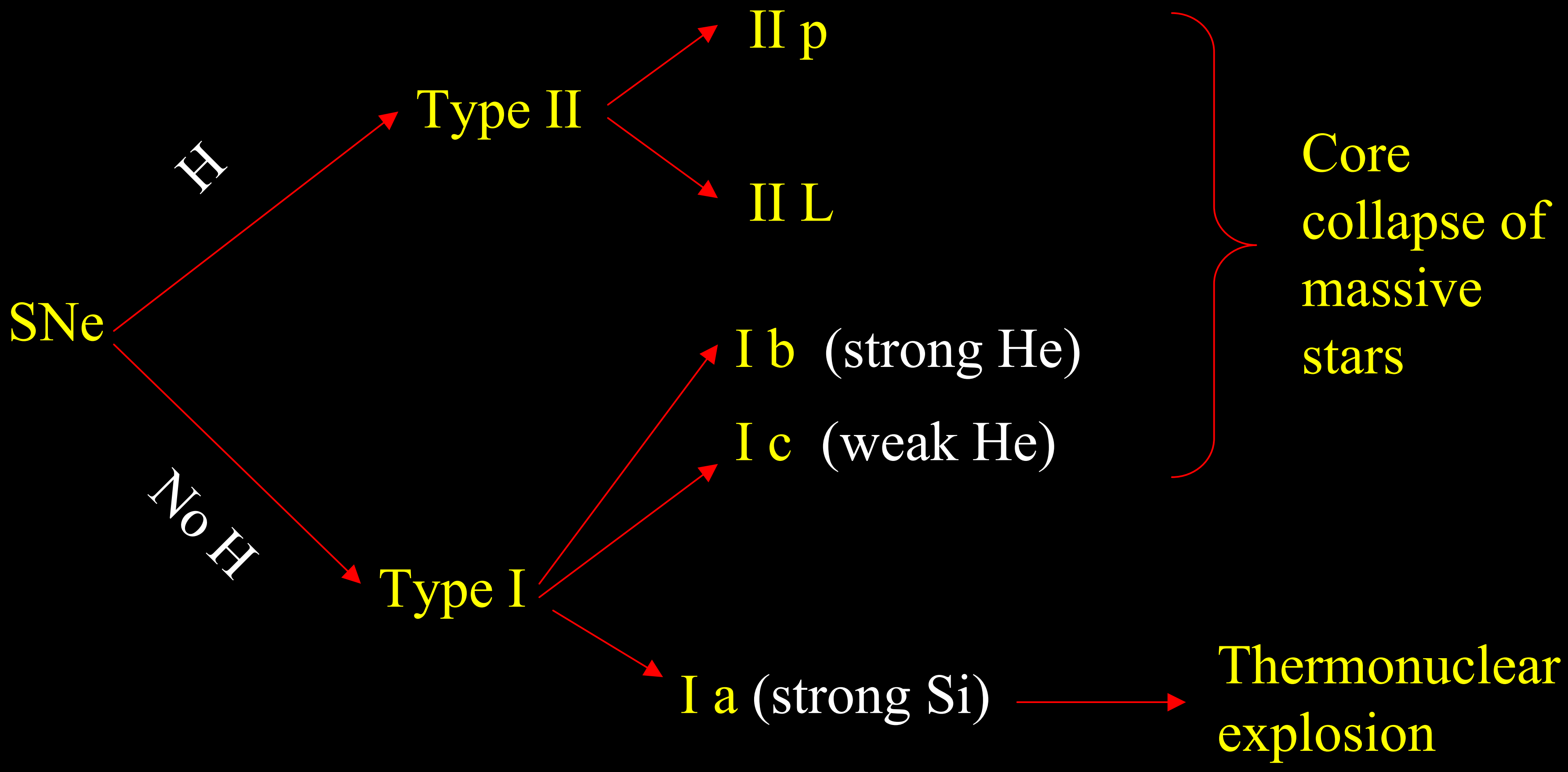
$0.8<M/M_\odot<8$ →
- **30 Myr<τ< 15 Gyr**
- $0.5<M_f/M_\odot<1.1$ **CO WD**

$8<M/M_\odot<11$ →
- τ~10–30 Myr
- $M_f=1.2\text{-}1.3\ M_\odot$ **ONe WD**

$11<M/M_\odot<100$ →
- **τ~ 1-10 Myr**
- $M_f=1.2\text{-}2.5\ M_\odot$
- **Fe collapse NS/BH**

$M>100\ M_\odot$ →
- **τ~ 1 Myr**
- **may or may not explode**

SNe Classification



based on spectra and light curve morphology

SNe Statistics

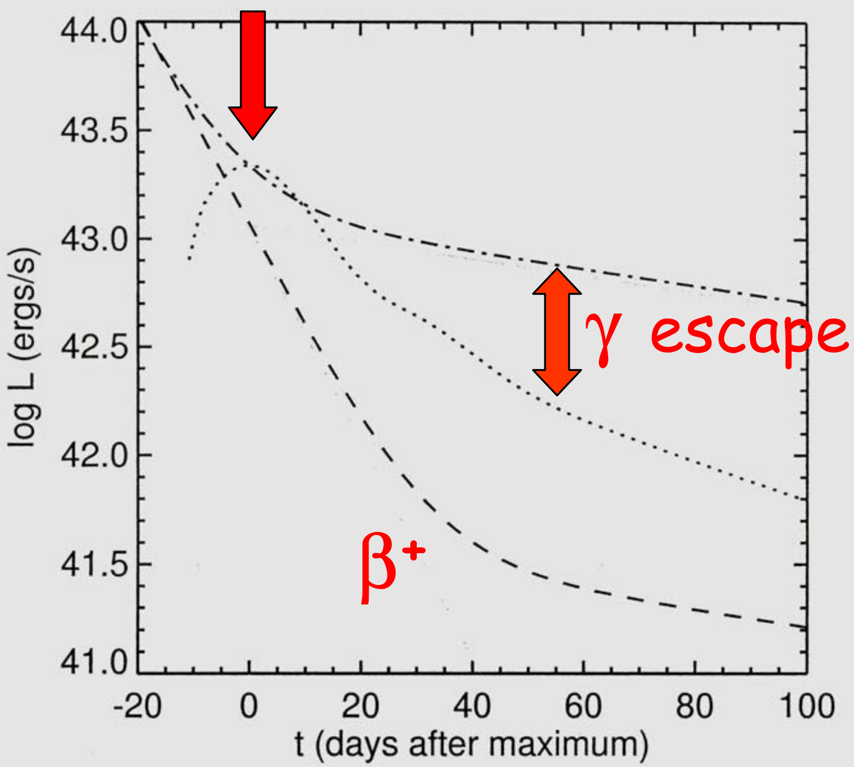
SN rate per unit Mass (10^{-11} M_o 10^{-2} yr $(H_o/75)^2$

Galaxy	Ia	Ib/c	II	All
E-S0	0.16±0.03	< 0.01	< 0.01	0.16±0.03
S0a-Sb	0.29±0.07	0.16±0.07	0.69±0.17	1.14±0.20
S0c-Sd	0.46±0.10	0.30±0.11	1.89±0.34	2.65±0.37
All	0.27±0.03	0.11±0.03	0.53±0.07	0.91±0.08

Cappellaro, Barbon, Turatto 2003

II. Light Curves

Bolometric LCs ↔ Radioactive energy



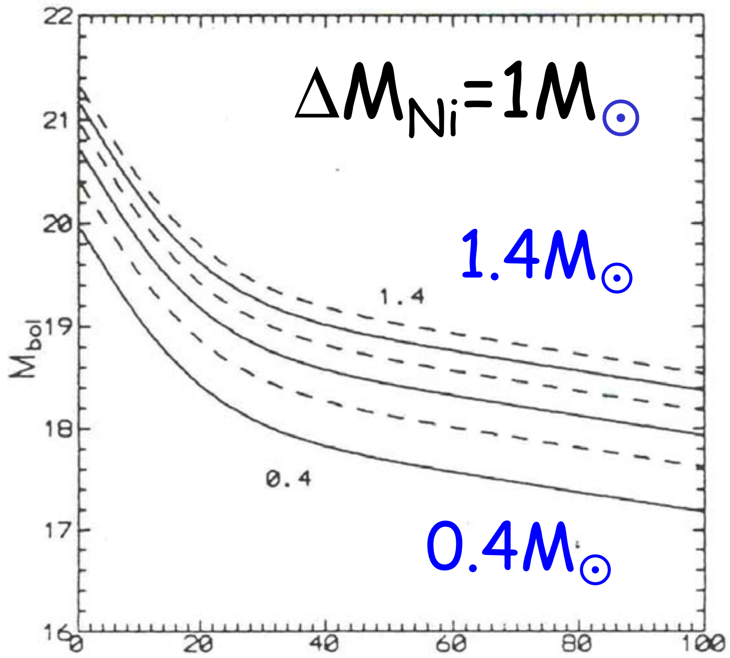
Leibundgut 2003

$^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

$\tau_{1/2}$: 6.1 d 77.7 d

γ γ **(81%)**

β+ **(19%)**



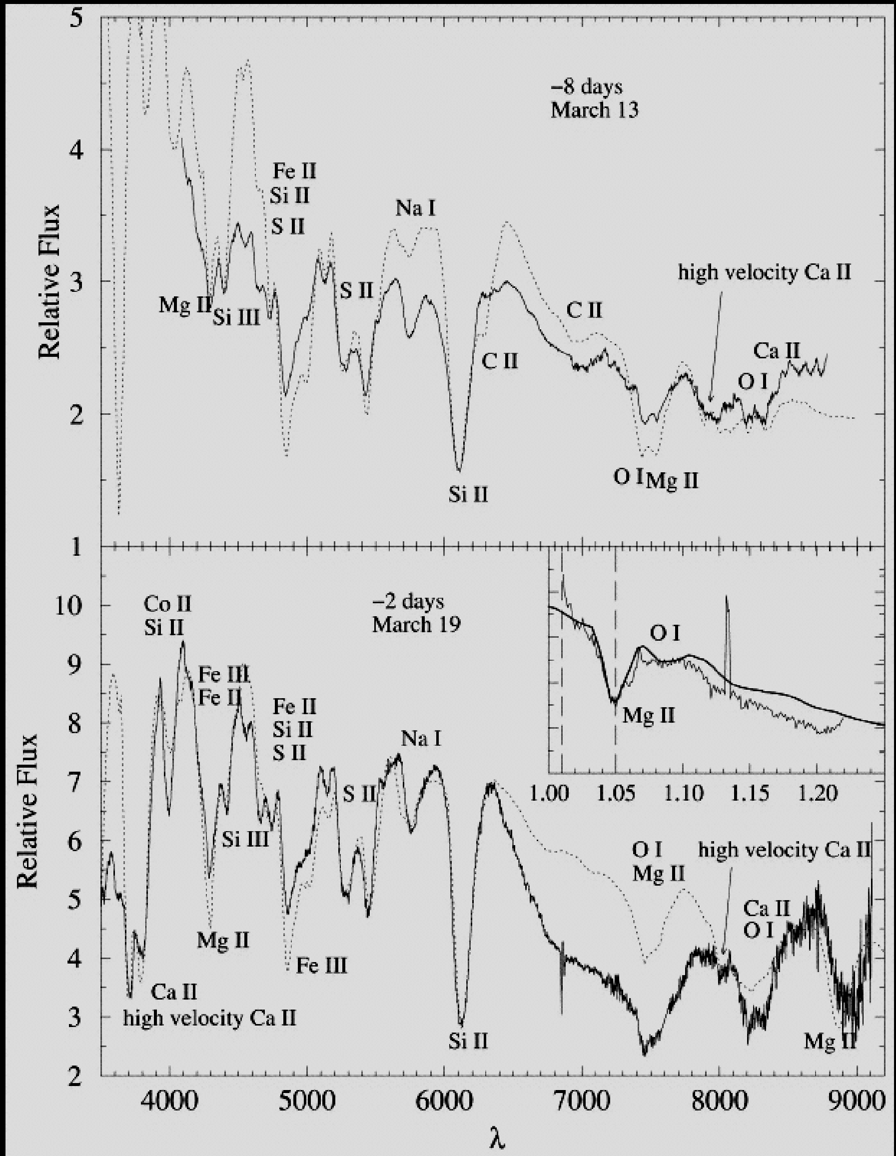
Observational constraints. I

- H must be absent at the moment of the explosion
  - There are some evidences (weak) of H-lines before maximum or at late epochs
- Progenitors should be long lived to account for their presence in all galaxies, including ellipticals
- The explosion should produce at least ~ 0.3 M_0 of ^{56}Ni to account for the light curve and late time spectra

SNIa are caused by the explosion of a C/O white dwarf in a binary system

(He white dwarfs detonate and are converted in Fe and ONe collapse to a neutron star)

Spectra: abundances & velocities



Hatano et al. 1999

- Peak: absorption

CII OI SiII
SI CaII MgII

Incomplete burning

10000 → 15000 km/s

Near-IR:
SiII CaII MgII
Fe peak

"small" polarization

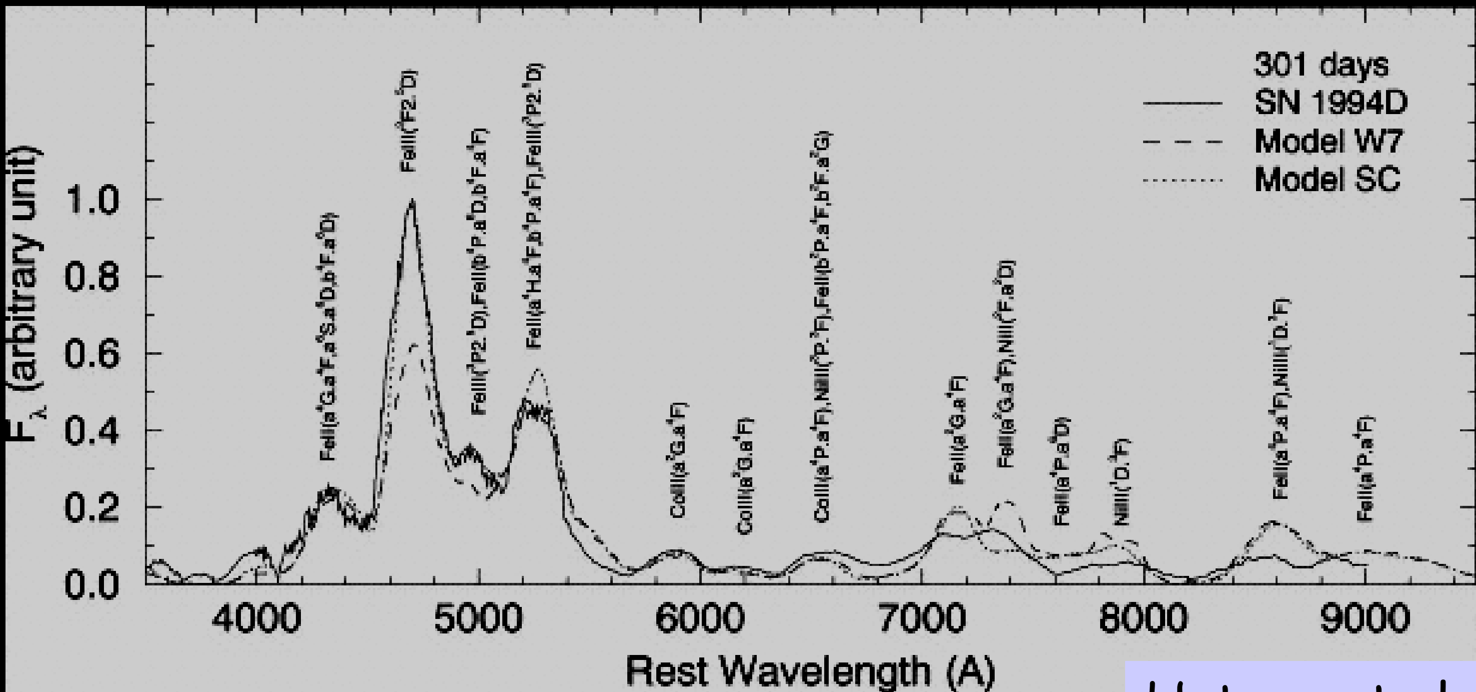
Nebular spectra

- Late time: emission

Fe Co

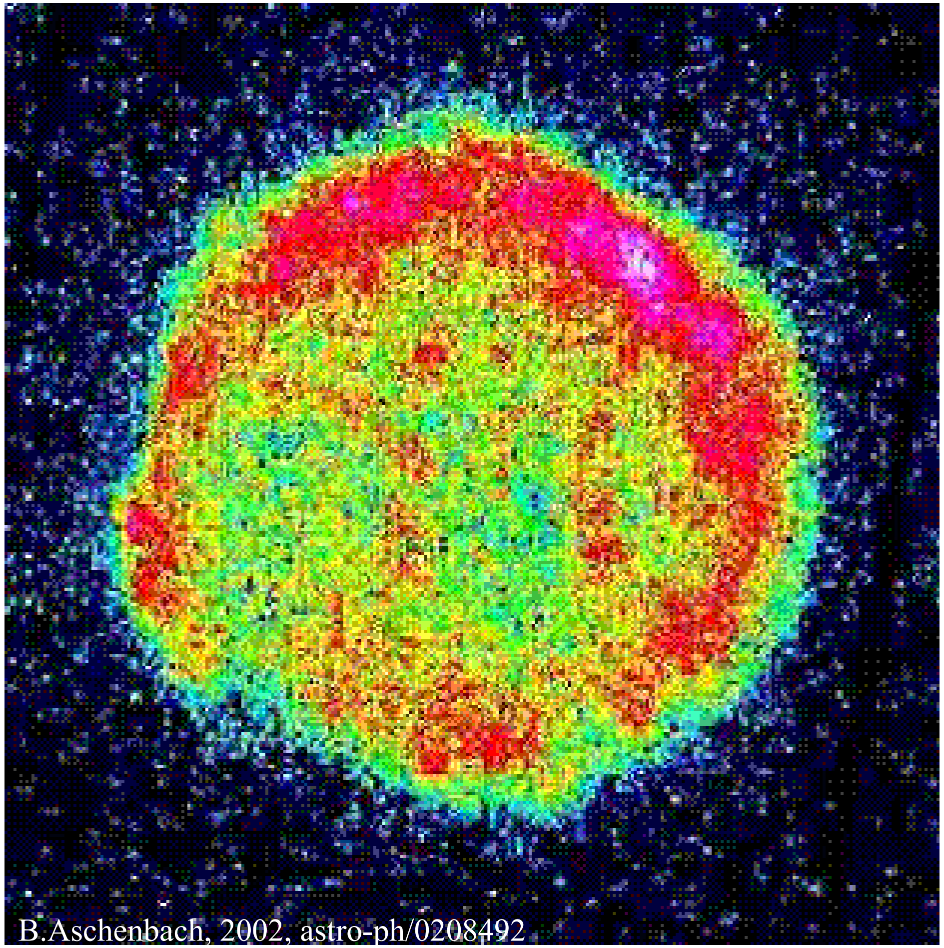
Complete burning

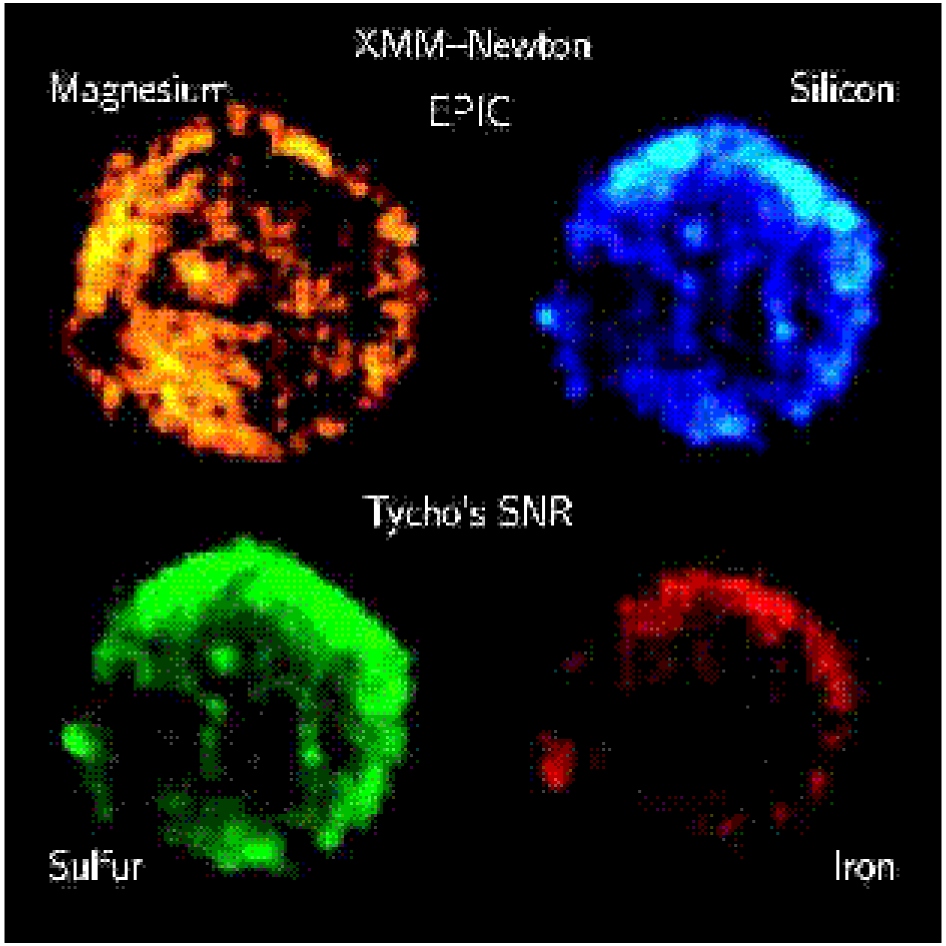
< 10000 km/s



Hatano et al. 1999

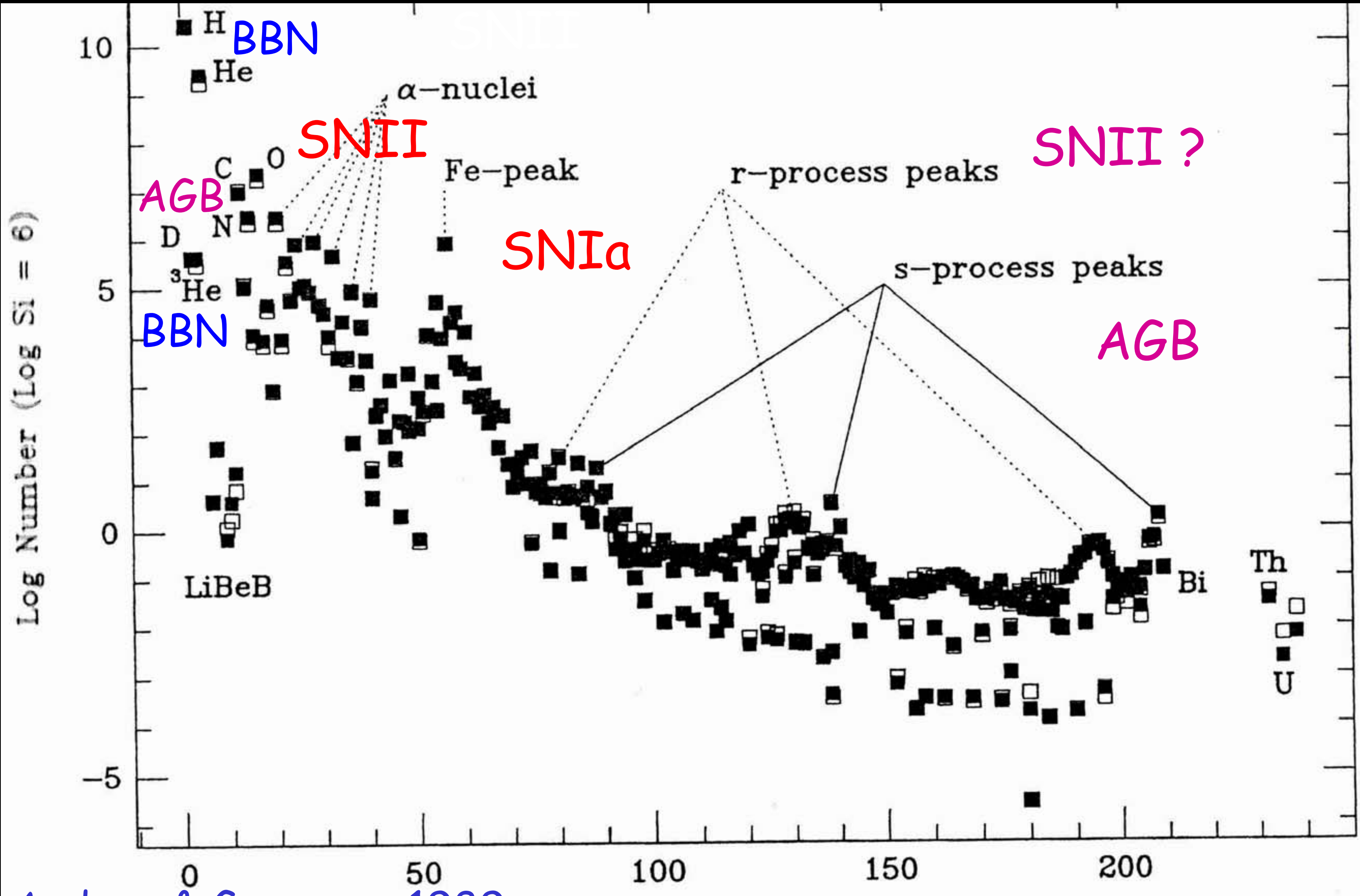
Tycho Remnant (SN 1572)





XMM-Newton

Solar system abundances



Anders & Grevesse 1989
Cameron 1982 (Arnett 1996)

Observational constraints. II

- Intermediate elements must be present in the outer layers to account for the spectrum at maximum light

The burning must be subsonic. It can be supersonic only if $\rho < 10^7$ g/cm^3

The abundances of the iron peak elements (^{54}Fe, ^{58}Ni, ^{54}Cr) must be compatible with the Solar System abundances after mixing with gravitational supernova products

Neutron excesses have to be avoided:

- Post-burning e^- -captures
- Neutrons stored as ^{22}Ne

- Decrease ignition density
- Decrease ^{22}Ne content
- Reduce the SNIa galactic contribution

Thermonuclear runaways

The necessary condition is that the energy must be released in a time shorter than the dynamical time

Nuclear heating time:

$$\tau_n = \frac{c_V T}{\dot{\varepsilon}_n}$$

$$c_V = \frac{3}{2}\frac{\Re}{\mu}$$

$$\dot{\varepsilon}_n \propto T^{\alpha} e^{-(T_0/T)^{\beta}}$$

The hydrodynamical time:

$$\tau_{HD} = \frac{l}{c_s}$$

In hydrostatic equilibrium

$$\tau_{HD} = \tau_{ff}$$

$$\tau_{ff} = \left(24\pi G\bar{\rho}\right)^{-1/2} = \frac{444}{\sqrt{\bar{\rho}}}$$

The instability condition is: $\tau_n < \tau_{HD}$

$$\frac{3\left(24\pi G\right)^{1/2}\Re}{3\mu Q_0 R_0}\rho^{1/2}T^{1-\alpha}e^{(T_0/T)^{\beta}} \leq 1$$

Deflagration temperature

$$\tau_n(T_D) = \tau_{HD}(T_D)$$

Why typical stars are stable?: They stabilize the fuel by means of adiabatic expansions

The efficiency of the adiabatic cooling is defined as the expansion, $\delta\rho$, experienced to restore pressure equilibrium

$$\frac{\delta\rho}{\rho_0} = \frac{1}{\Gamma_1 \rho_0}\left(\frac{\partial P}{\partial T}\right)_\rho \frac{QN_A}{AC_V}\Delta X$$

Where ΔX is the amount of burned fuel

In the gas ideal case:

$$\frac{\delta\rho}{\rho_0} = \frac{2}{5}\Delta X \frac{\mu}{A}\frac{Q}{kT}$$

Since Q ~ 1 MeV and kT ~ 1-100 keV adiabatic cooling is very efficient and stars are stable

If the electronic degenerate component is dominant:

$$\left(\frac{\partial P_e}{\partial T}\right)_\rho << \left(\frac{\partial P_i}{\partial T}\right)_\rho$$

$$\frac{\delta\rho}{\rho_0} = \left(\frac{\Delta X}{2}\frac{\mu}{A}\frac{Q}{kT}\right)\frac{P_i}{P_i + P_e} \approx \frac{P_i}{P_e} << 1$$

Cooling is only efficient if $P_i > P_e$

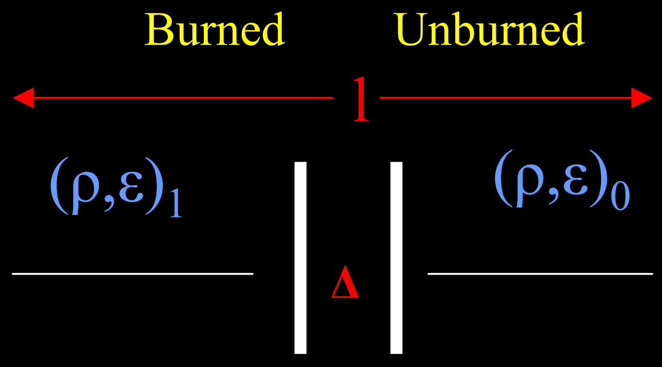
Thermonuclear runaways occur if: $T_{def} < T_F$

H is not a good explosive because it needs weak interactions to convert p in n (novae)

He and C are good explosives (supernovae)

$\Delta << 1$

The burning front



Mass, momentum and energy conservation

$$\rho_1 u_1 = \rho_0 u_0$$

$$P_1 + \rho_1 u_1^2 = P_0 + \rho_0 u_0^2$$

$$\varepsilon_1 + \frac{P_1}{\rho_1} + \frac{u_1^2}{2} = \varepsilon_0 + \frac{P_0}{\rho_0} + \frac{u_0^2}{2}$$

Two types of solutions

$P_1 > P_0$, $V_1 < V_0$ → Detonation: v_{front} supersonic versus the unburned material; sonic or subsonic versus the burned material

$P_1 < P_0$, $V_1 > V_0$ → Deflagration: v_{front} always subsonic versus the unburned & burned material

Deflagrations

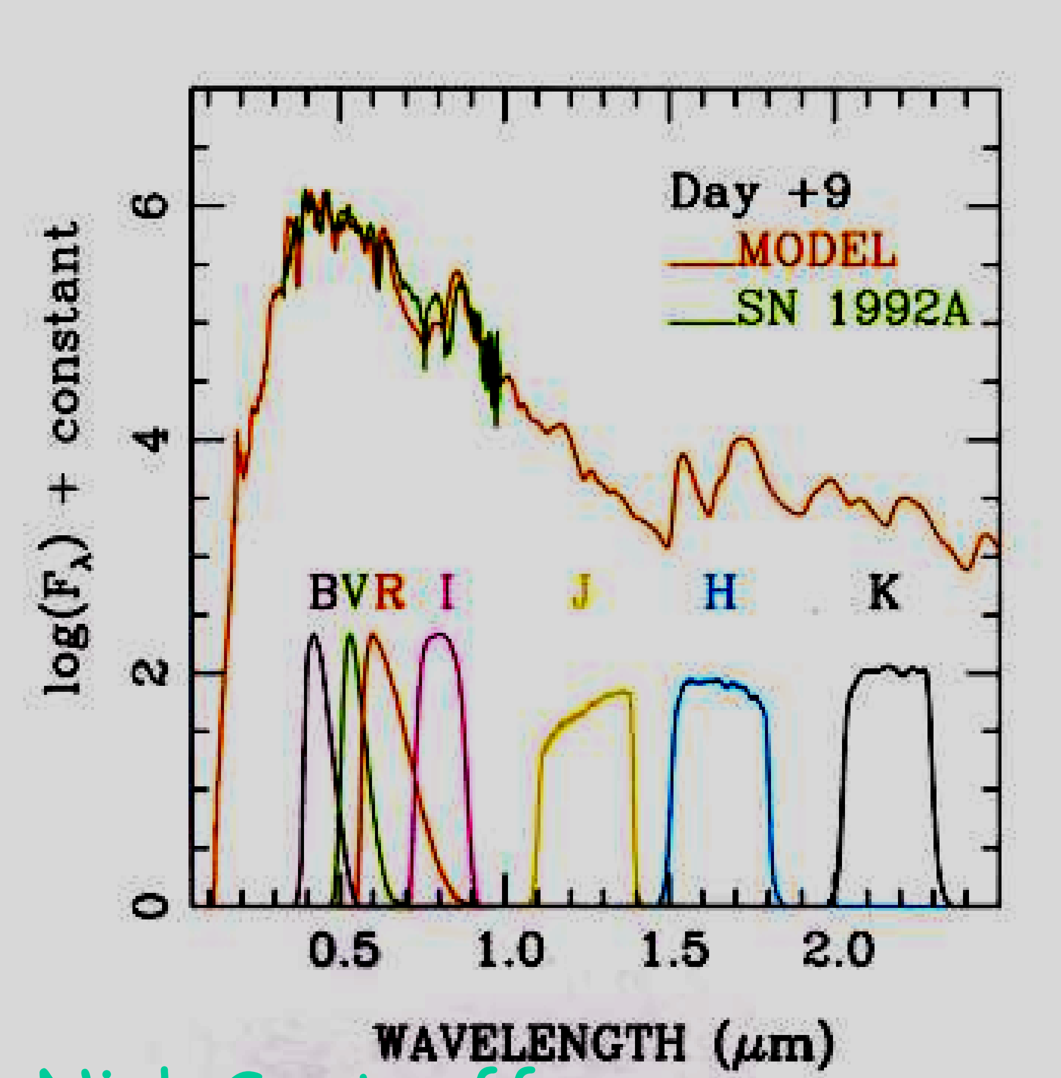
In spherical symmetry burned material is at rest at the center, $v_1 = 0$

Assume unburned material at rest, $v_0 = 0$
Mass and momentum conservation demands:
$V_0 (P_1 - P_0) = u_0 (u_0 - u_1)$
or
$V_0 (P_1 - P_0) = u_1 D$
in the frame at rest

But if
$P_1 - P_0 < 0$ & $D > 0$
then
$v_1 < 0$
in contradiction with the hypothesis

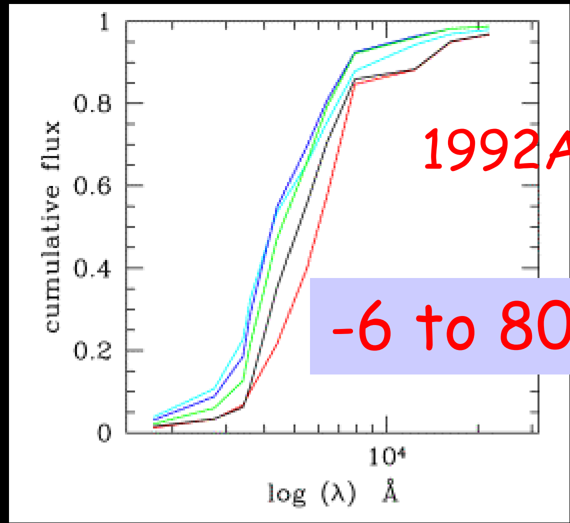
A deflagration can only exist if it generates a precursor shock that burst matter outwards!

Flux & Filters



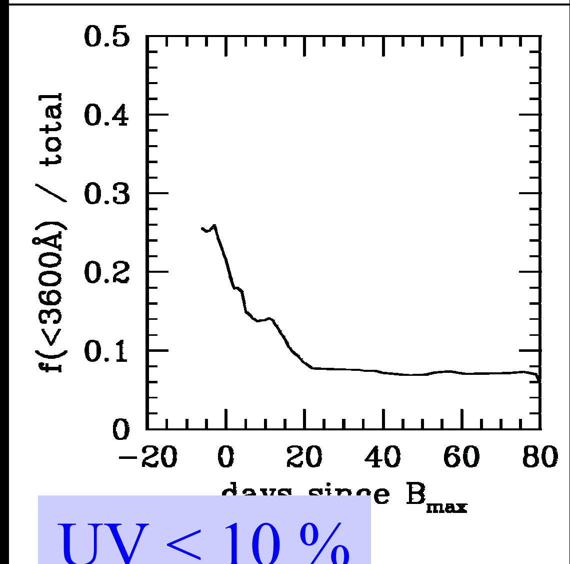
Nick Suntzeff

>80% flux in the optical



1992A

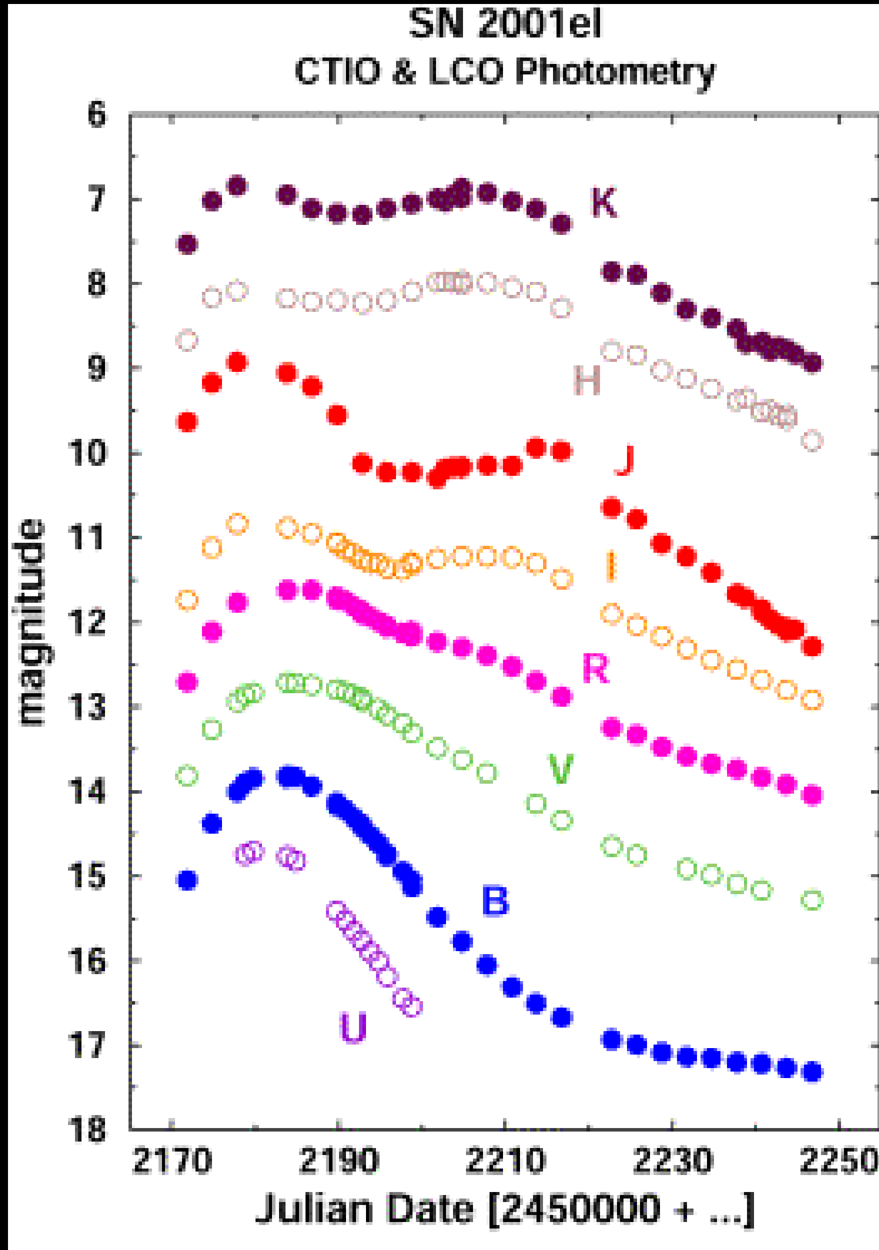
-6 to 80 d



UV < 10 %

I. Observations

UBVRIJHK



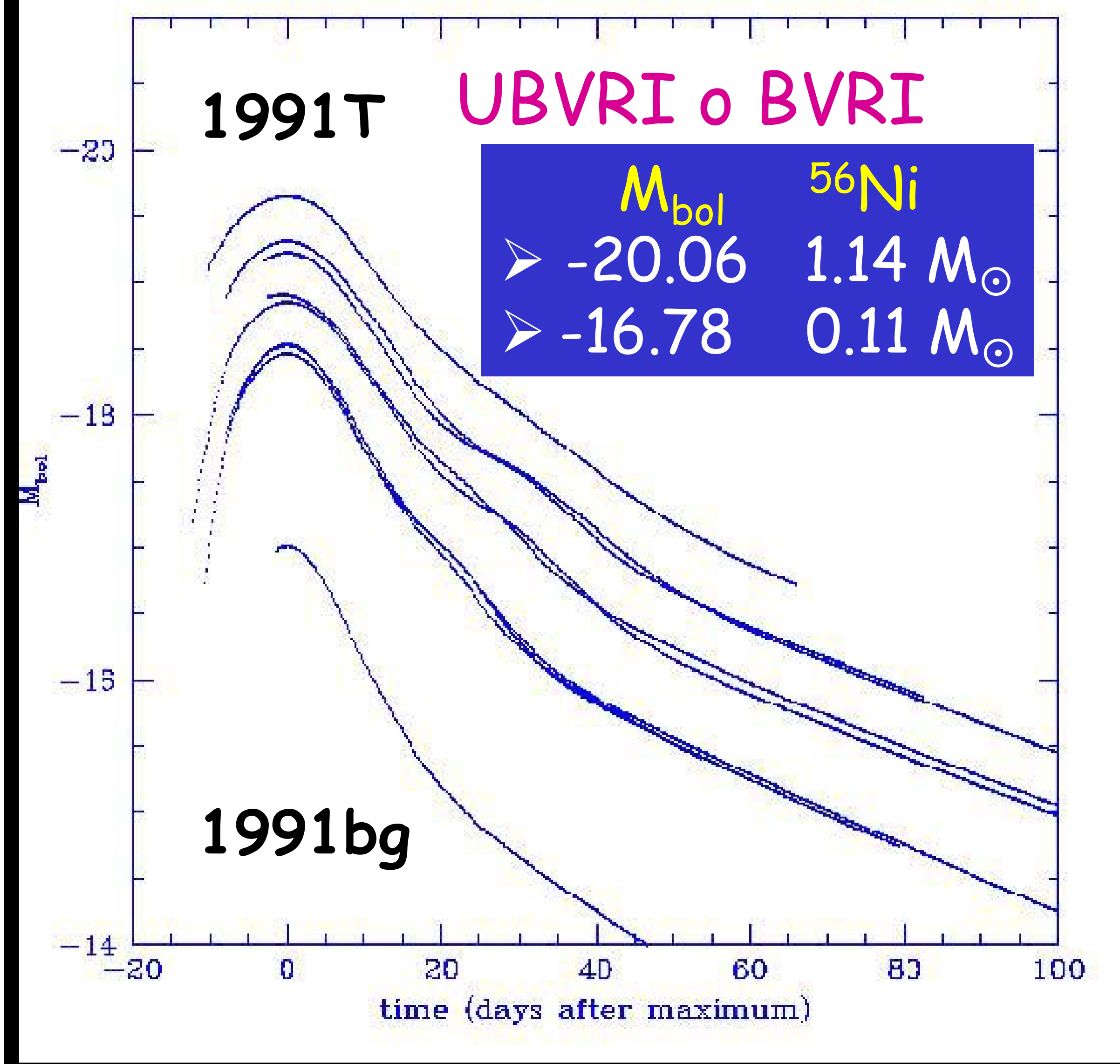
Most of the emission in the Optical and NIR

2nd peak IJHK

Elias 1981 Meikle 2000

Ni mass from observed M_{MAX}

Contardo, Leibundgut, Vacca, 2001



Time of maximum assumed:

$\Delta t_{expl} = 17$ d

16 to 20 d ➜ 10% Ni

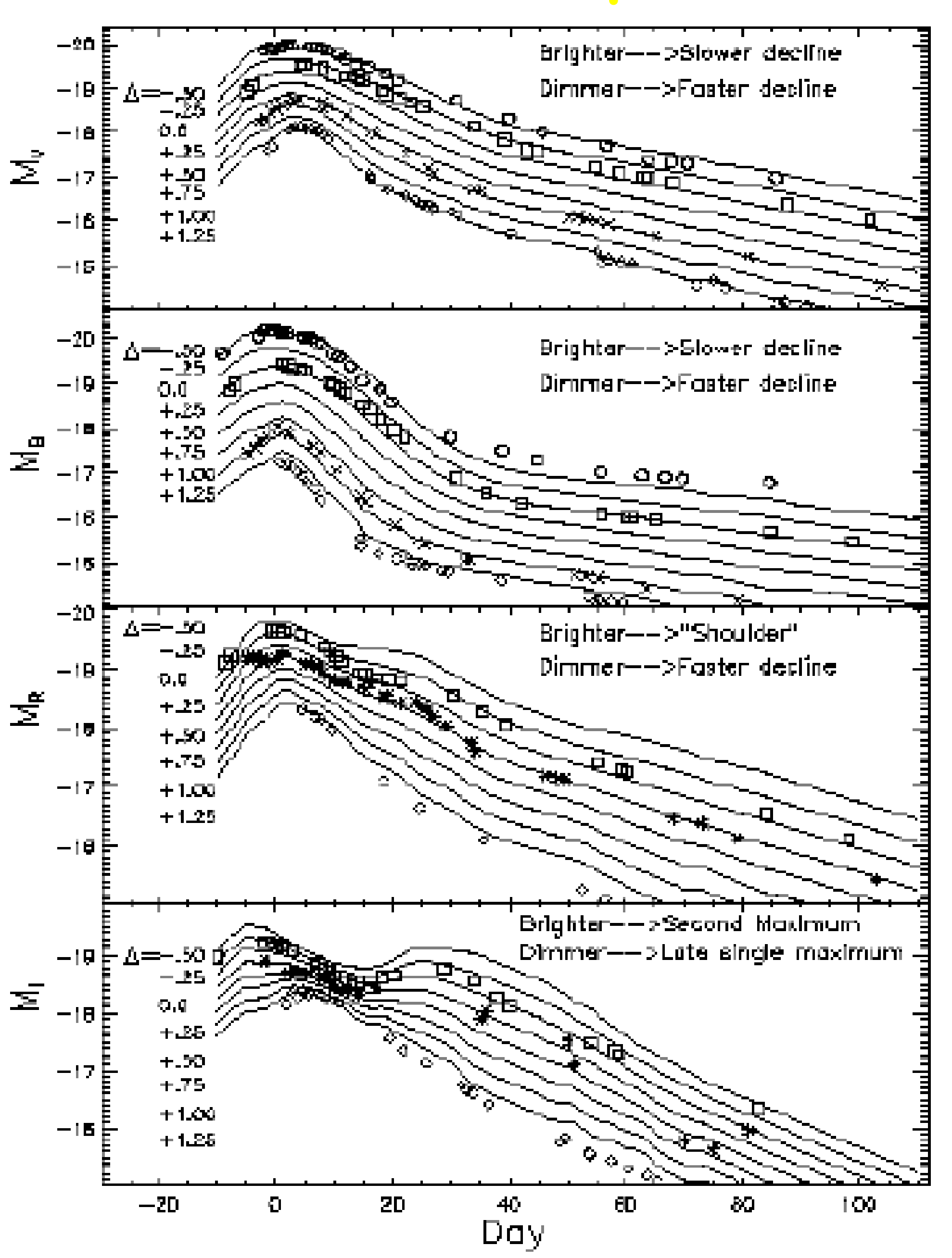
+ Problems:

- Distance
- Reddening

Other methods:

- LCs up to 800 d
  Cappellaro et al 1997
- Late IR spectra (Fe)
  Spyromilo et al 1992

MAX-LC Shape Relations



Correlation

$M_{MAX} \leftrightarrow$ Decline rate

Brighter

Slower Decline

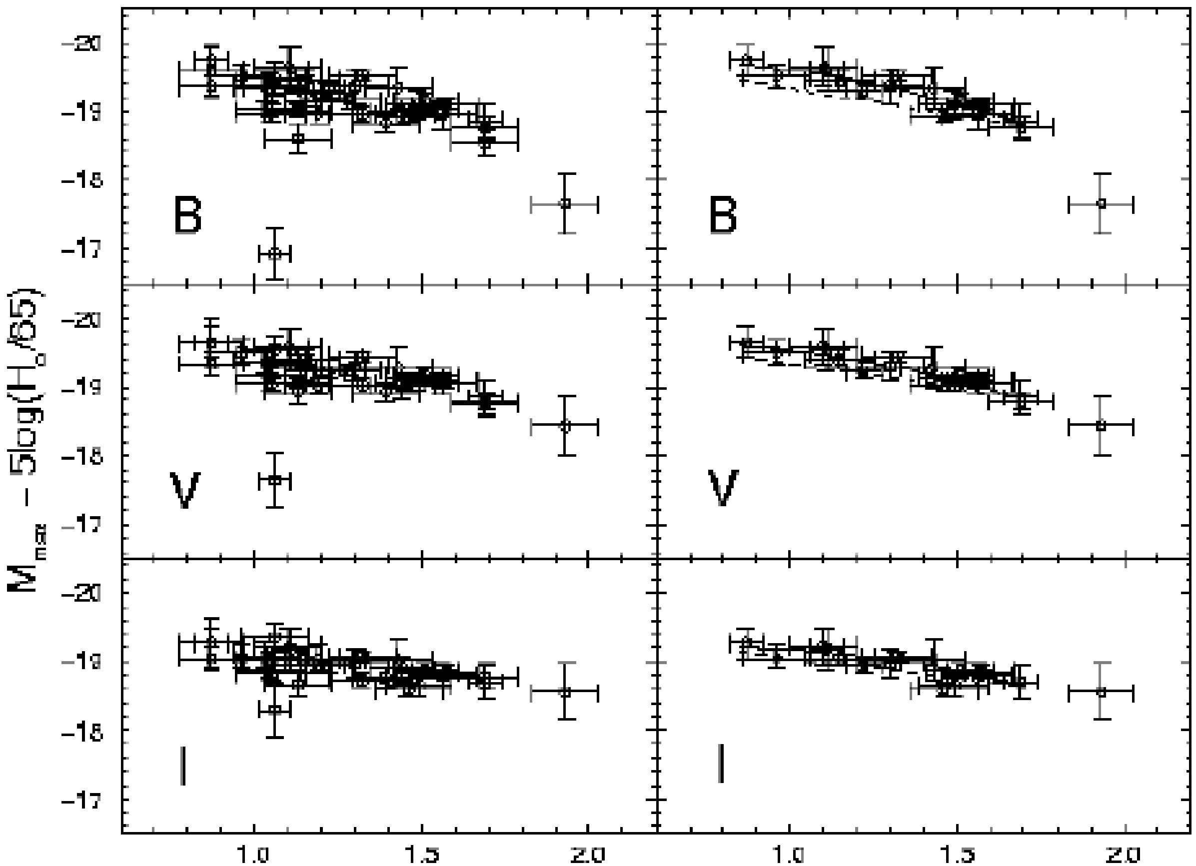
Dimmer

Faster Decline

Riess et al. , 1997

Maximum Brightness - Decline Relation

Phillips et al. 1996, 1999



Δm_{15}

M_{max}-Δm_{15}

$\langle\sigma\rangle = 0.17$ mag

Caution: local calibrations

Cosmology & SN Ia

- Bright
- Homogeneous
- No evolutionary effects

➡ 

Standard Model of Cosmology (SNe Ia + CMB)

$\Omega_m \sim 0.3$ $\Omega_\lambda \sim 0.7$

60 km/s/Mpc < H_o < 70 km/s/Mpc

Age of the Universe ~ 14000 Myr

Observational constraints. III

- Homogeneity?
  - Differences in brightness: Overluminous (SN 1991T), underluminous (SN1991bg)
  - Differences in the expansion velocity (v_{exp} ~ 10,000-15,000 km/s)
- Two points of view:
  - There is a bulk of homogeneous supernovae plus some peculiars
  - SNIa display a continuous range of values

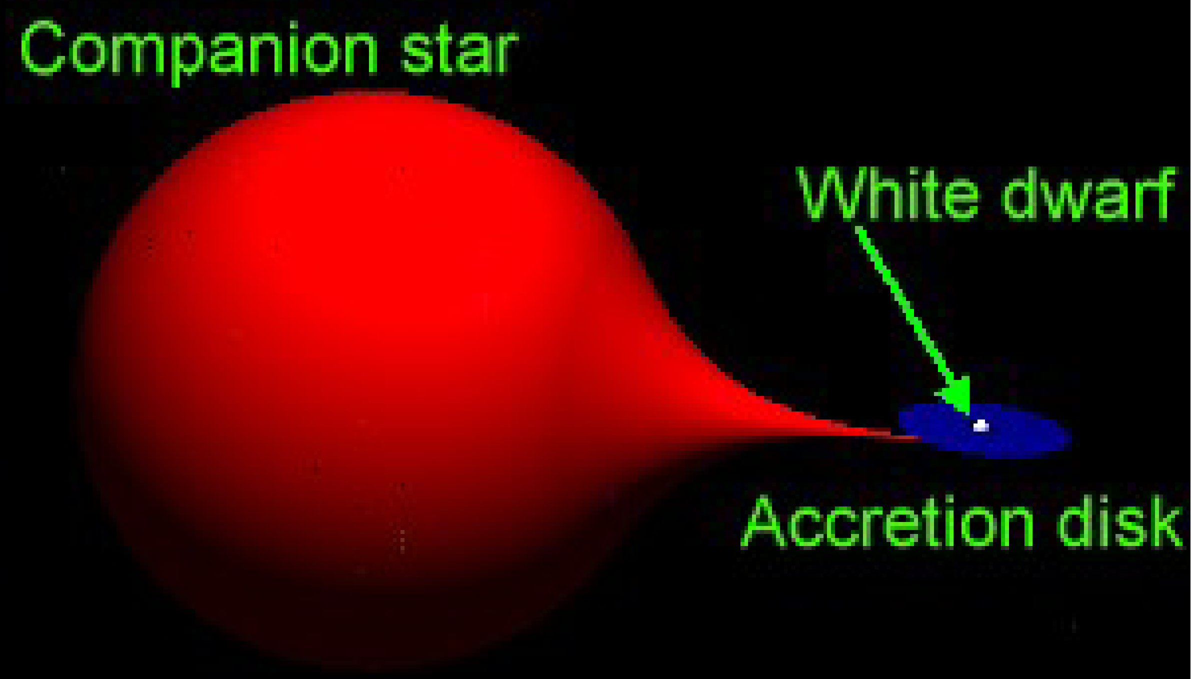
- Is there a unique scenario & unique mechanism able to accommodate the normal behavior plus that of dissidents?
- Is there a mechanism able to produce a continuous range of situations?
- Can both mechanisms coexist?

Anything able to explode eventually do it !!!

The outcome depends on:

Accretion rate

Chemical composition of accreted matter



CO accreting WD

Merging of two CO WD.
The outcome depends on the rate. AIC?

He accreting WD

$10^{-9} < M_t < 5x10^{-8} M_o yr^{-1}$
off center detonation
CO+He star, normal or degenerte

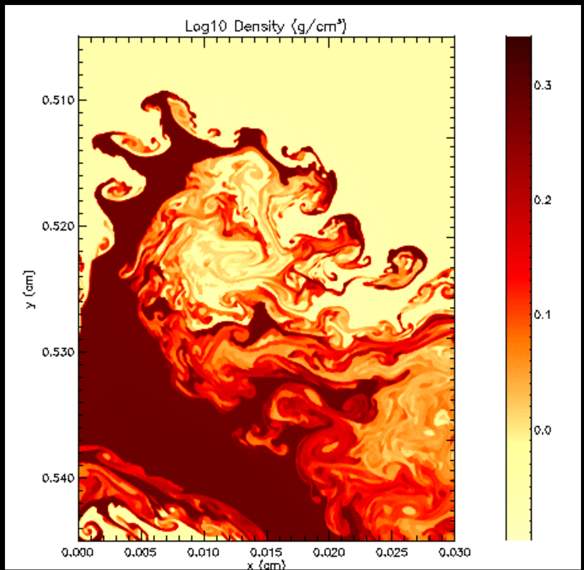
H accreting WD

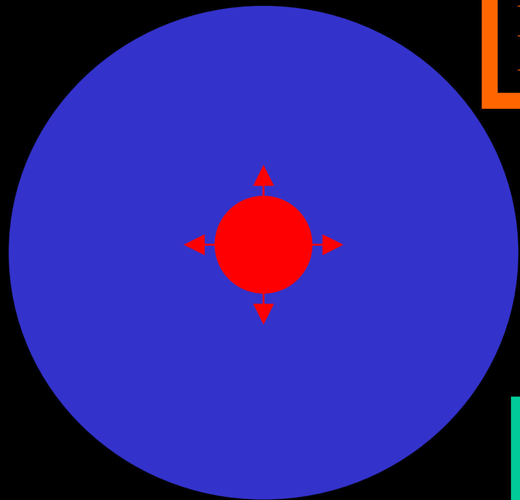
$M_t < 10^{-9}$ Mo yr^{-1} Nova
1o^{-9} $< M_t < 10^{-6} M_o yr^{-1}$ Steady burning or weak flashes. He detonation in some cases
$10^{-6} < M_t < M_t$(Eddington) Red giant and common envelope

Exploding mechanisms

Detonation: supersonic flame
If $\rho > 10^7$ g/cc $\Rightarrow$ C,O $\rightarrow$ Ni
If $\rho \leq 10^7$ g/cc $\Rightarrow$ C,O $\rightarrow$ Si,Ca, S, ...

Other possibilities:
Deflagration + detonation
Pulsating delayed detonation



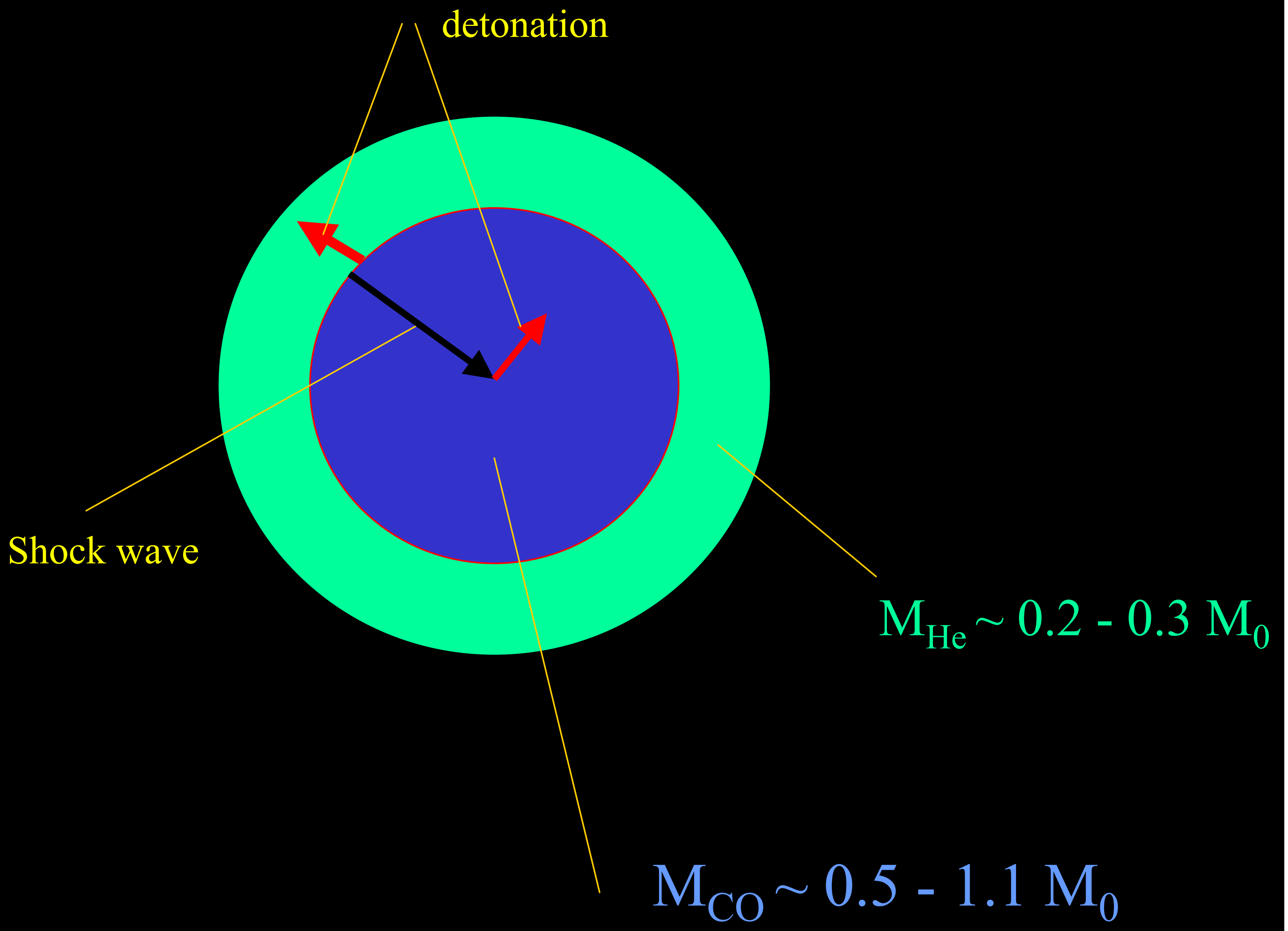


The laminar flame becomes turbulent:
* Rayleigh-Taylor instability
* Kelvin- Helmholtz

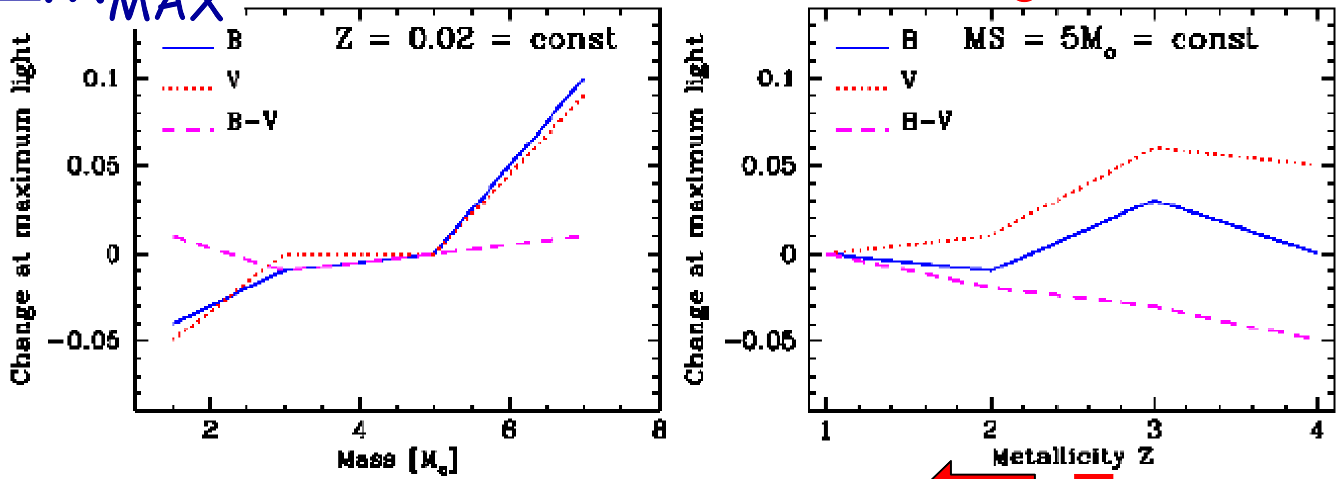
Deflagration: subsonic velocity
laminar flame: $v \sim 0.01\ c_s$
Turbulent flame: $v \sim 0.1 - 0.3\ c_s$

Flame surface increases
effective velocity increases

Exploding mechanisms: Off center ignition



ΔM_{MAX} **Reference: 5 $M_\odot$ Z=0.02**



M_{MS} →

Z ←

Z: 0.02 10^{-3} 10^{-4} 10^{-10}

Back in time

Z ↓

t_{evol} ↓ M_{MS} ↑

M_{MS} ↑ C/O ≤ 22% ↓

L ↓ ≤ 0.15 mag

V_{ph} ↓ 2000 km/s

t_{Rise} ↑ 1.7 days

Z ↓ C/O ≤ 9 %

L ~ ≤ 0.05 mag

but Umeda et al. 1999

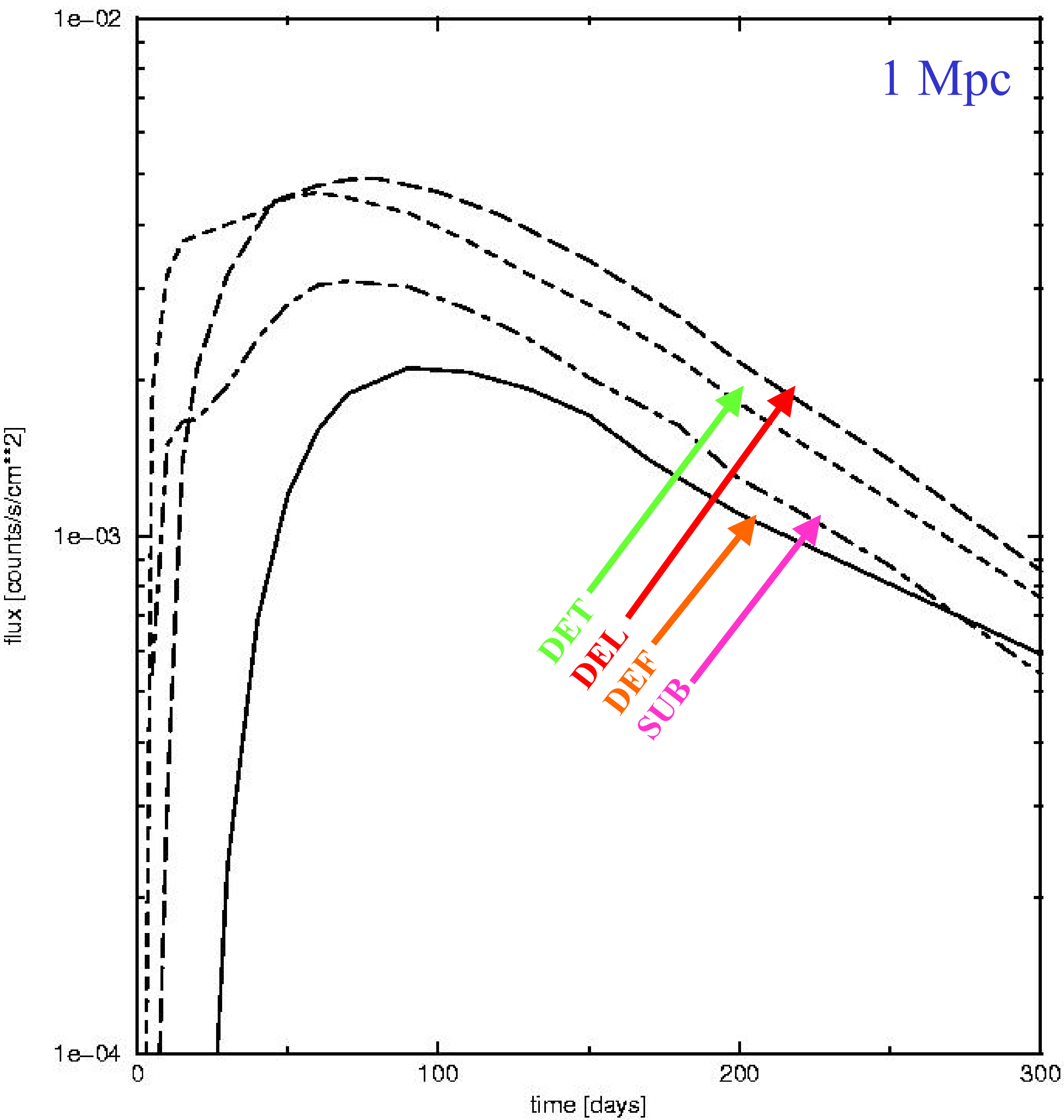
B,U,UV → B-V ↓

Dark Energy ?? ~ 0.1 - 0.05 mag

Light curves

847 keV

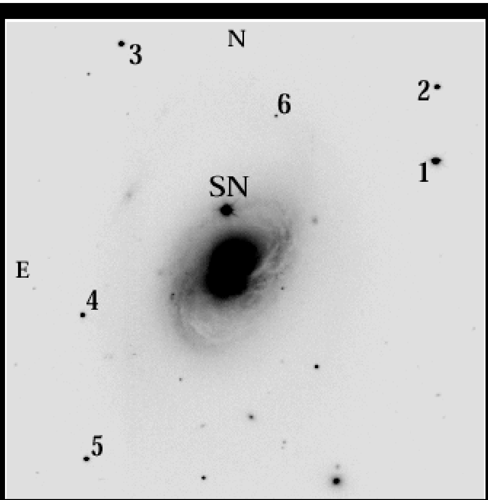
^{56}Co

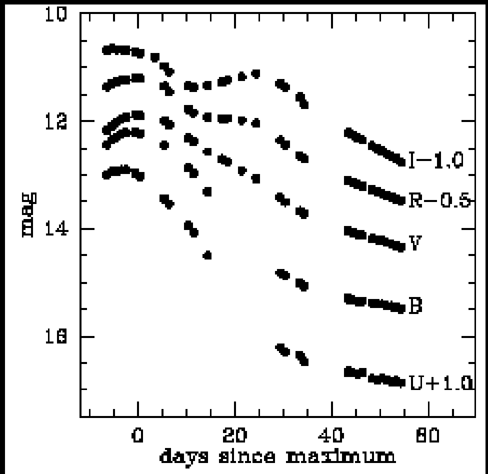


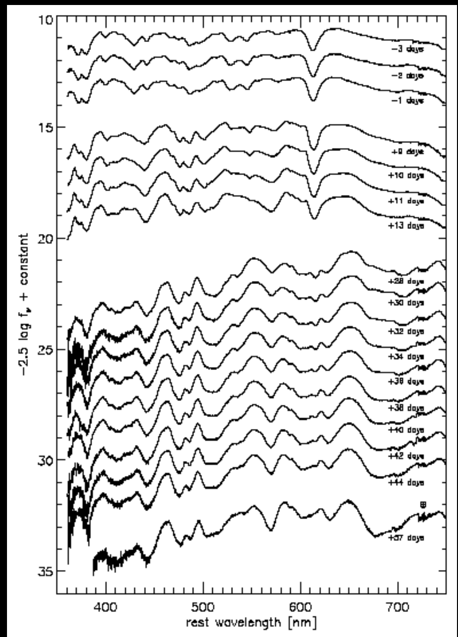
SN 1998bu

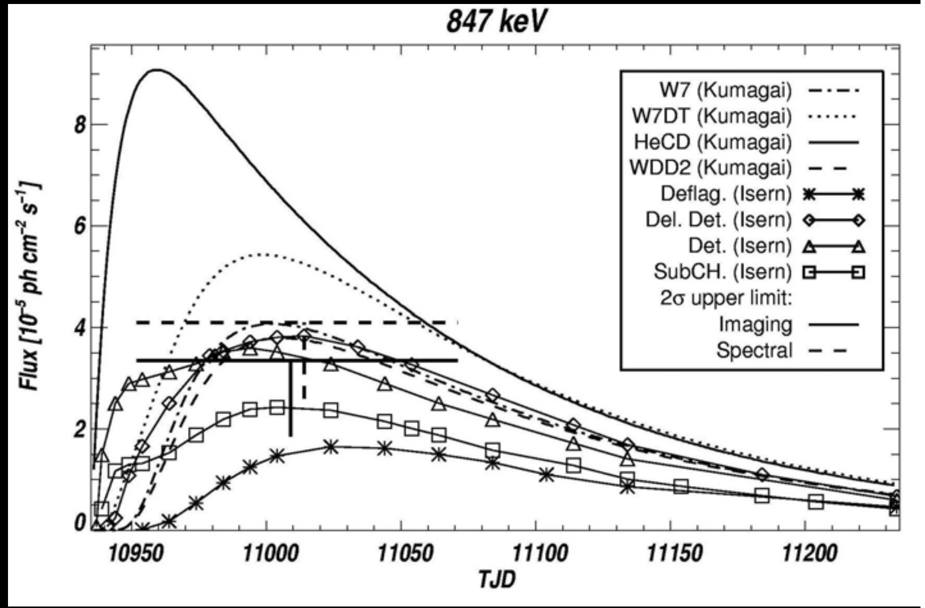
M96
d = 8- 12 Mpc

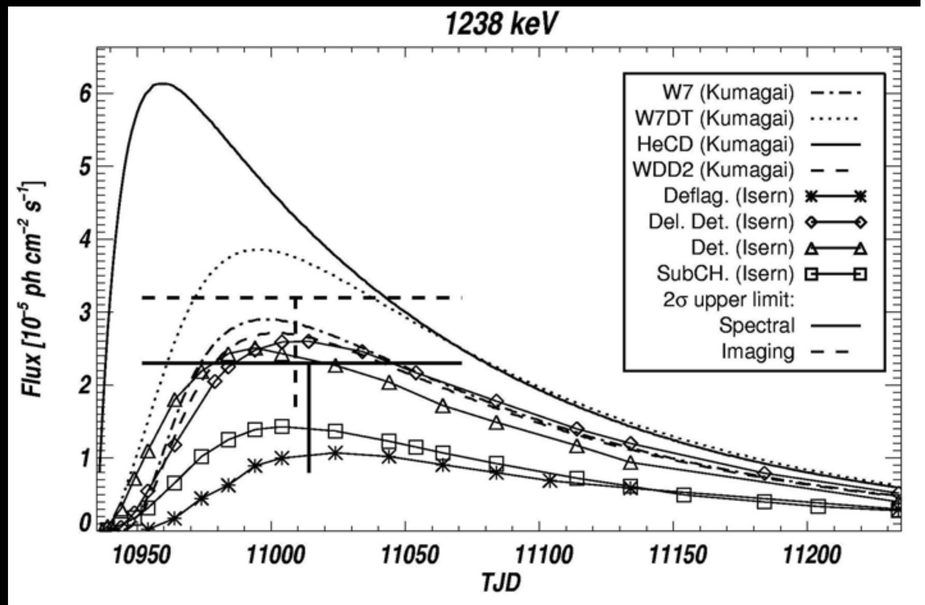
(From Diehl'02)







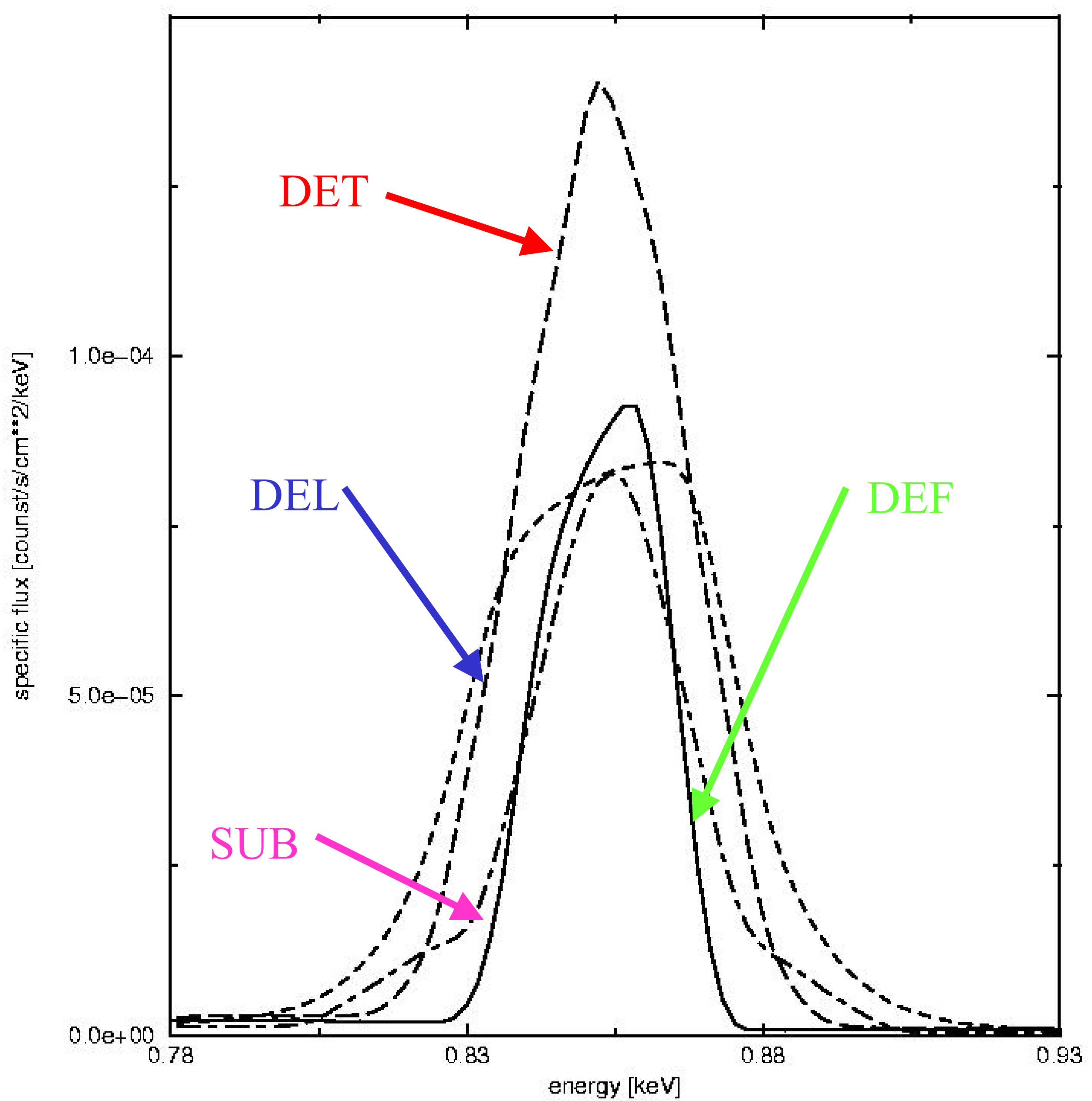




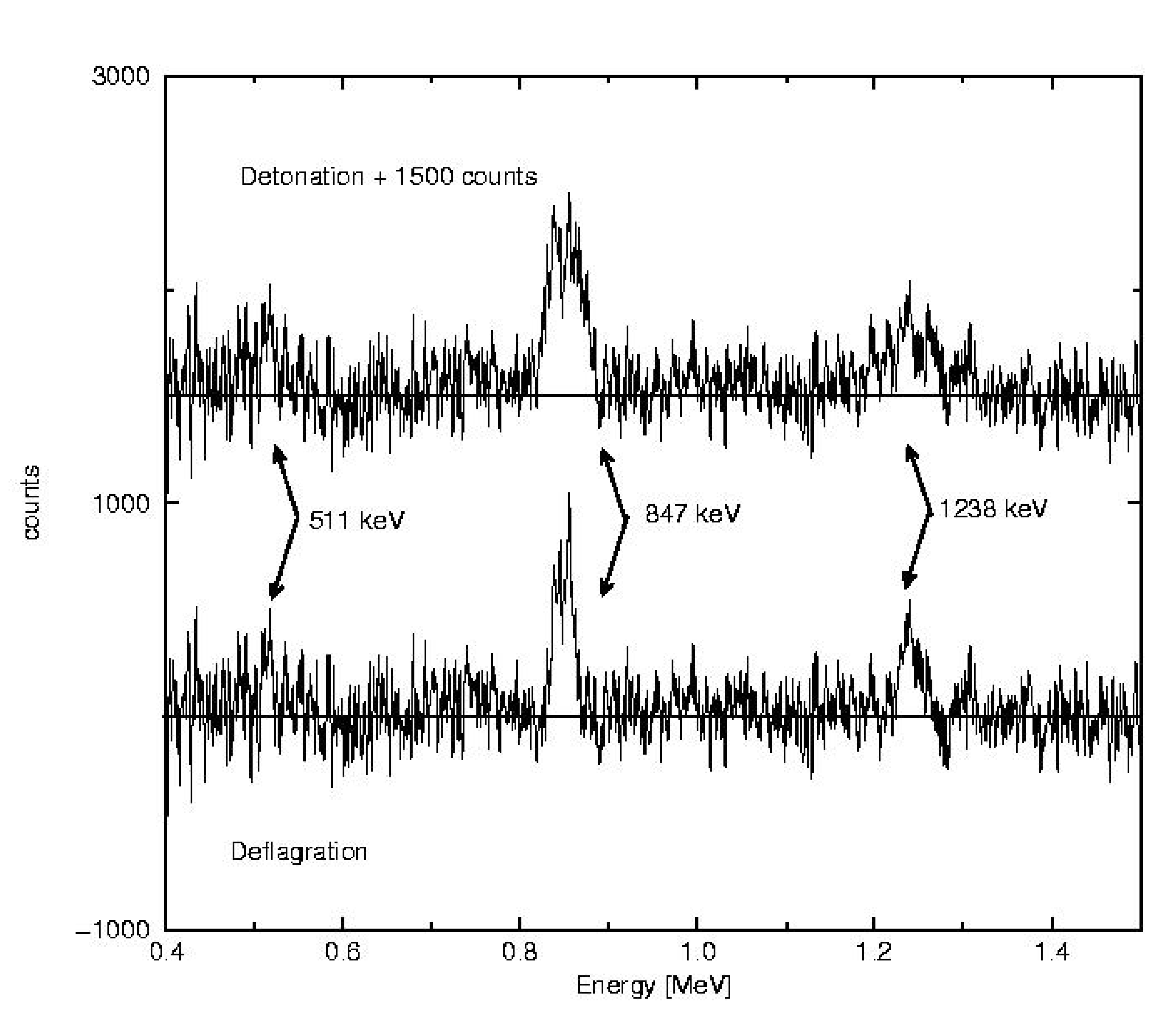
	Flux (phot/cm^2/s)
847 keV	<3.1-4.1 x 10^{-5}
1238 keV	<2.3 – 3.1 x 10^{-5}

Line profiles for the 847 keV line

D = 1 Mpc
t = 120 d



Simulated observational spectra



D = 5 Mpc
$t_{int} = 10^6$ s

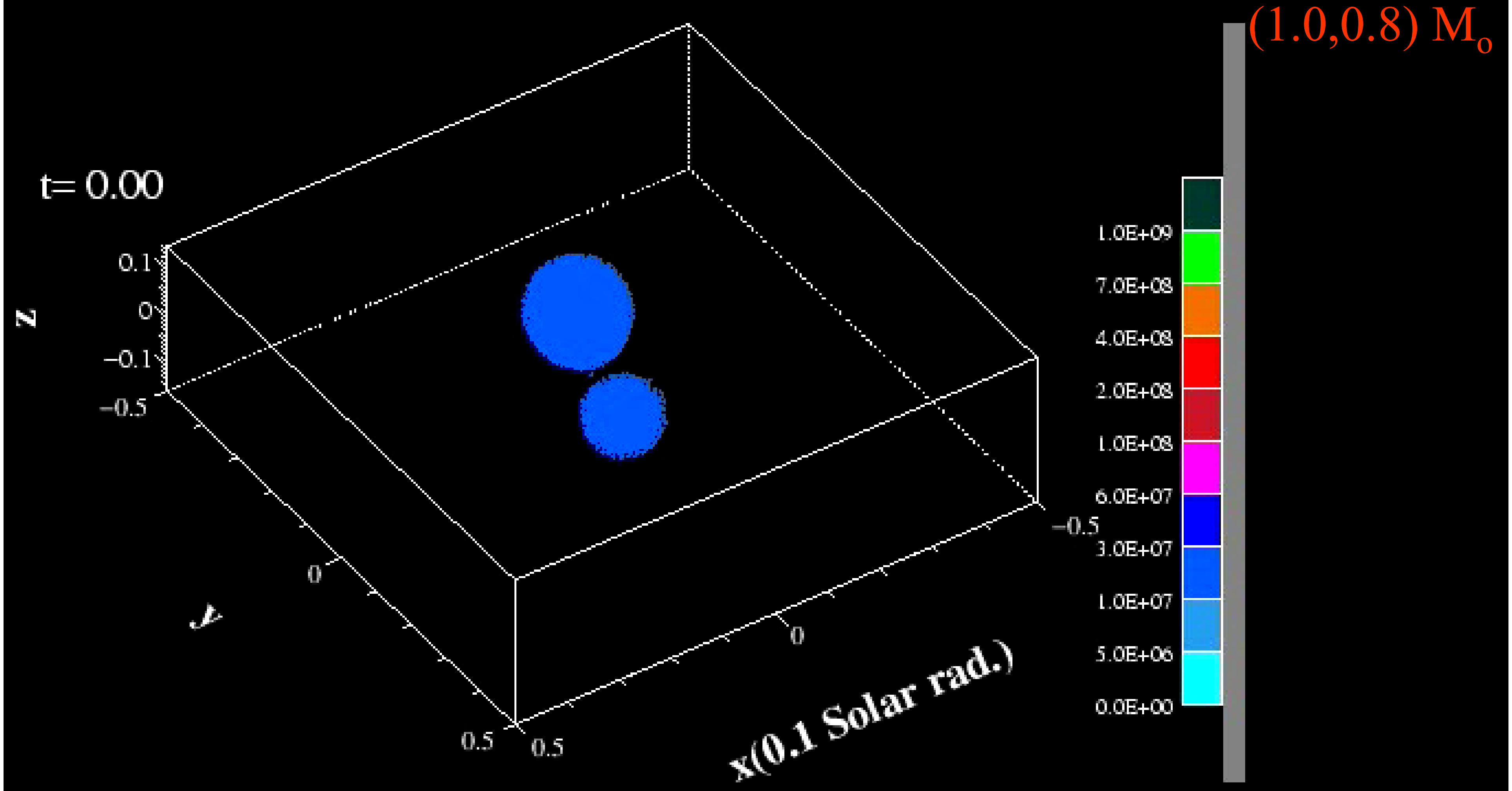
SPI/INTEGRAL

- INTEGRAL can provide useful information for
- SNIa, provided they occur close enough, on the
- basis of:
  - –Line light curves
  - –Properties of the continuum
  - –Line profiles
- Because of the poor understanding of the flame
- properties we have to use parametrized values.
- In this case there are ambiguities in the
- information provided by the gamma-rays alone.
- Independent information is necessary

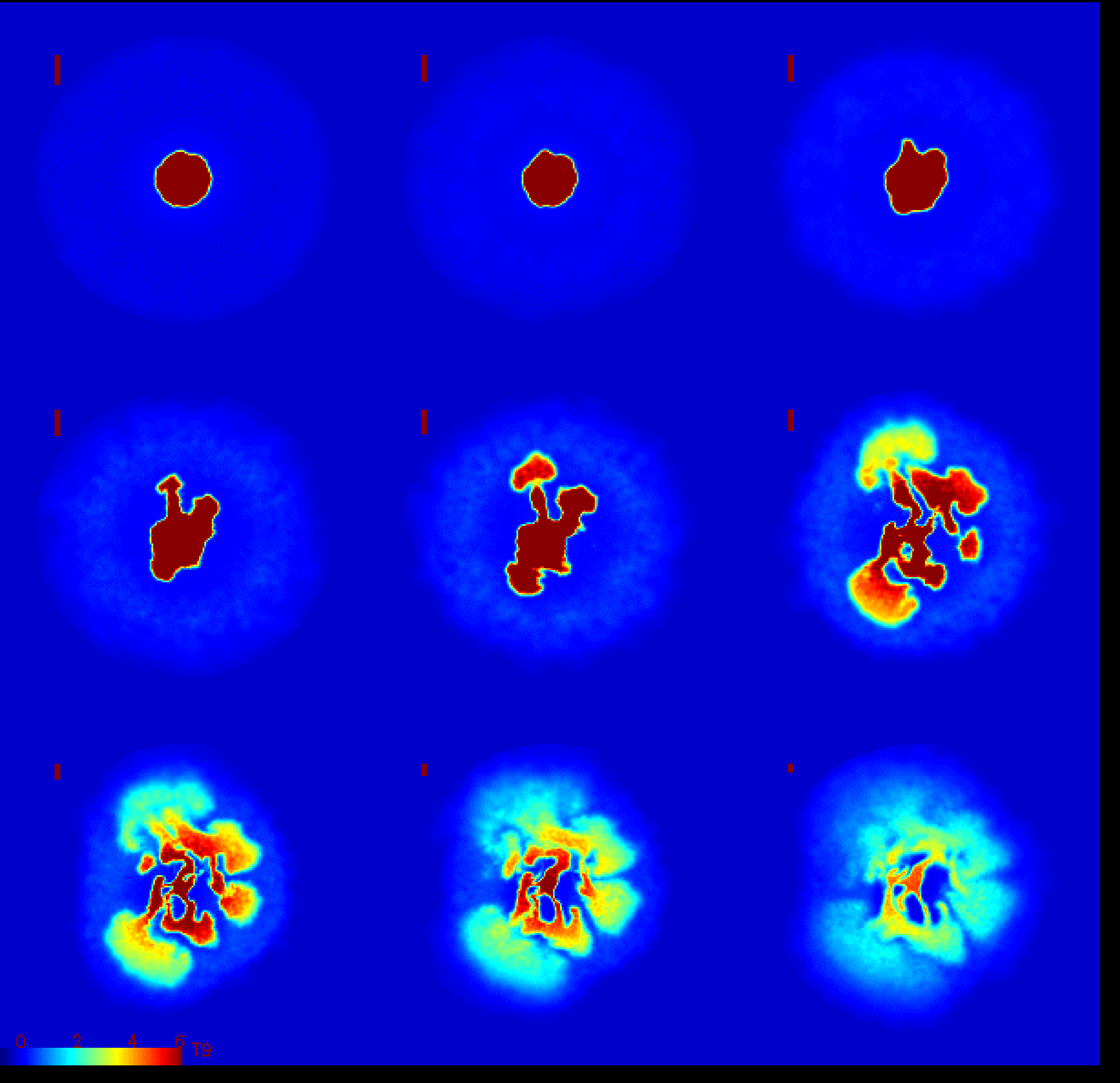
Departures from spherical symmetry?

- The physics of the flames indicates they are unstable and departures from spherical symmetry easily appear
- The scenarios in which the explosion occurs are not symmetric
- Nevertheless, observations suggest that these departures are small:
  - The homogeneity of the light curve s & spectra indicates photospheric perturbations < 10%
  - Standard SNIa show small polarizations (Wang et al 2001)
  - But subluminous display polarizations ~ 0.7% (Howell et al 2001)

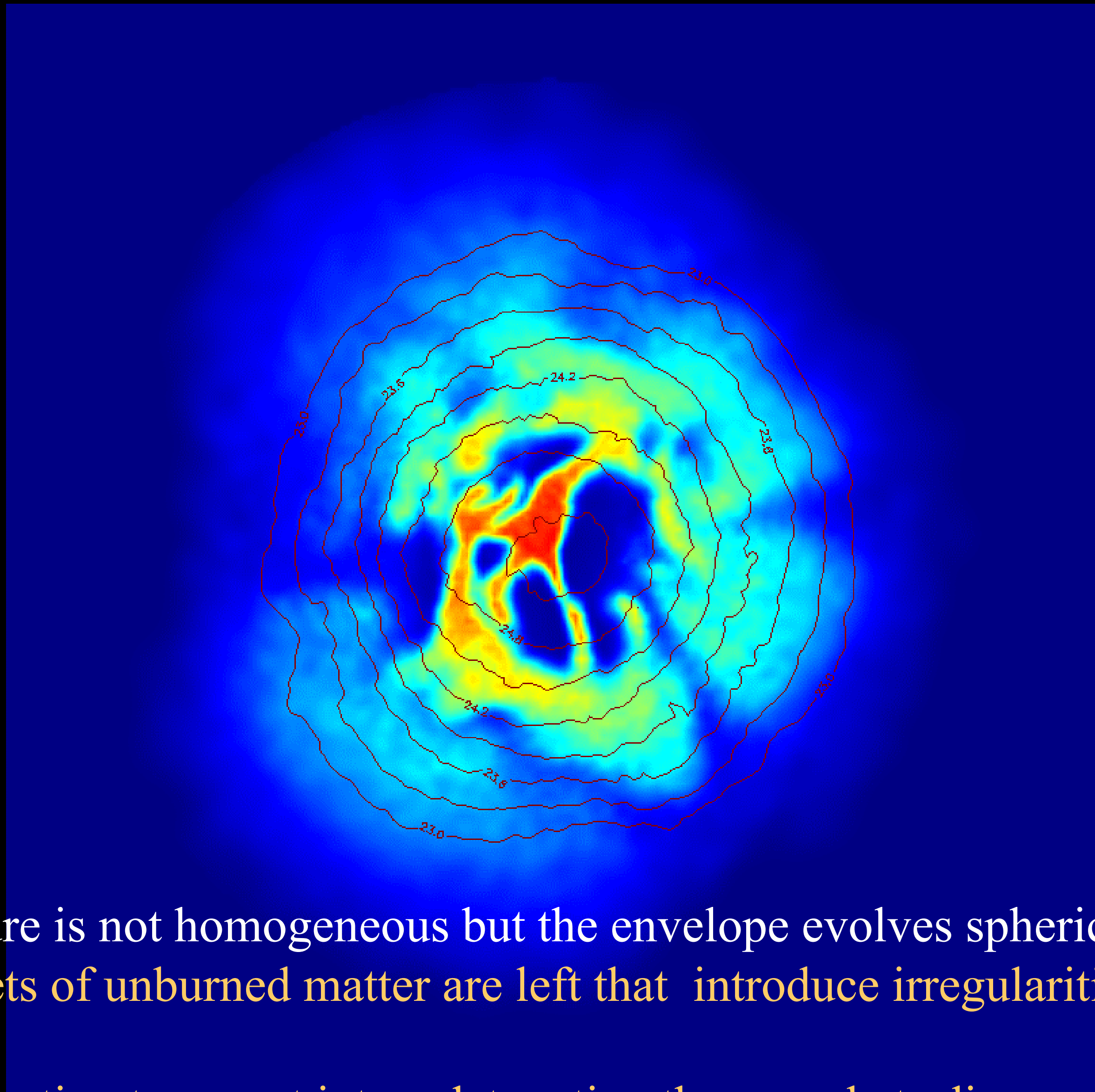
- Since SNIa occur in binary systems, large scale departures from sphericity can occur
- Double degenerate systems



Central deflagration: T; time = 0 – 1.55 s; (Bravo, Garcia-Senz, Serichol)
= 400 km



T & P at the end of the deflagration phase (t=1.55 s)

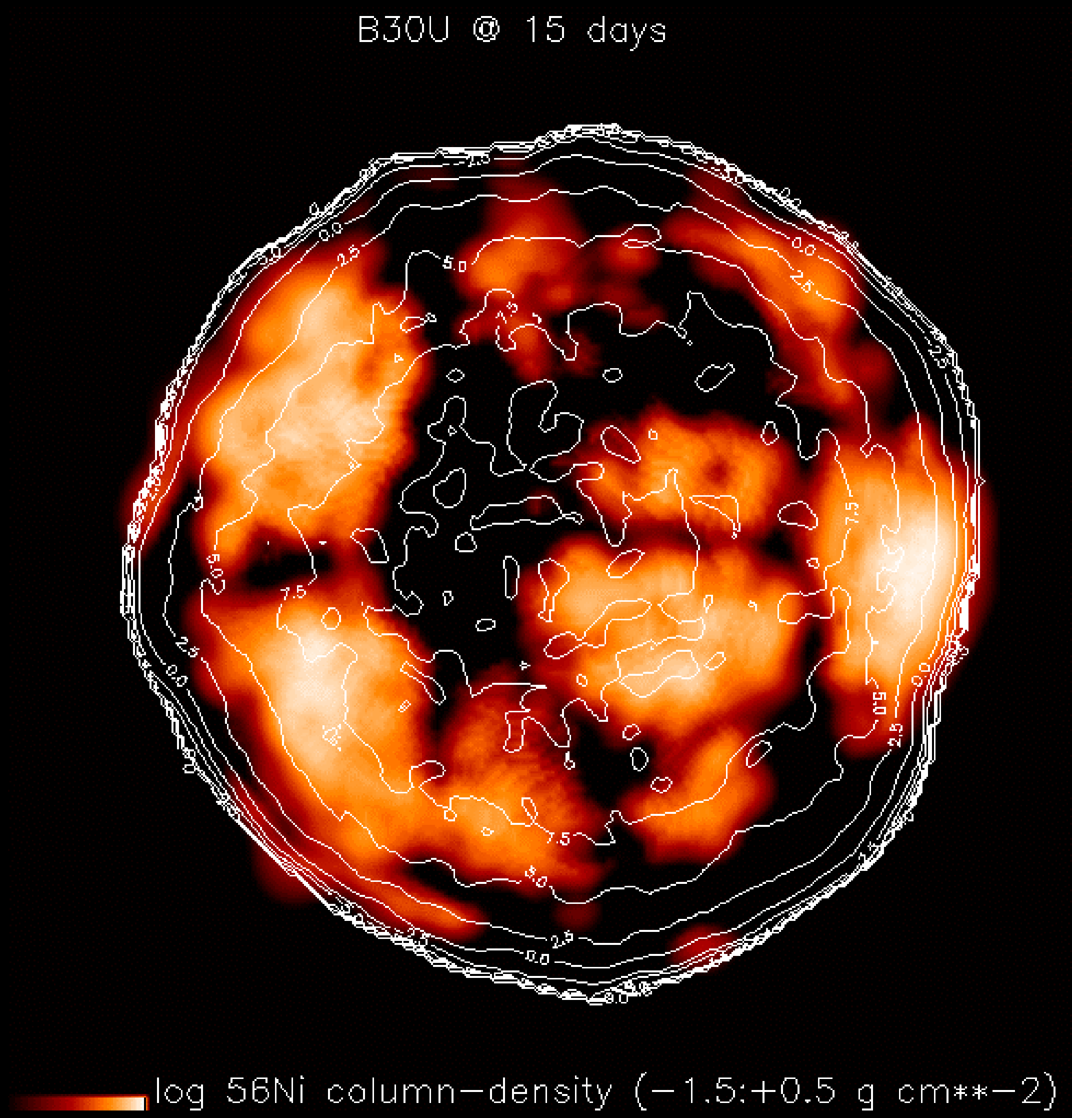


The front structure is not homogeneous but the envelope evolves spherically.

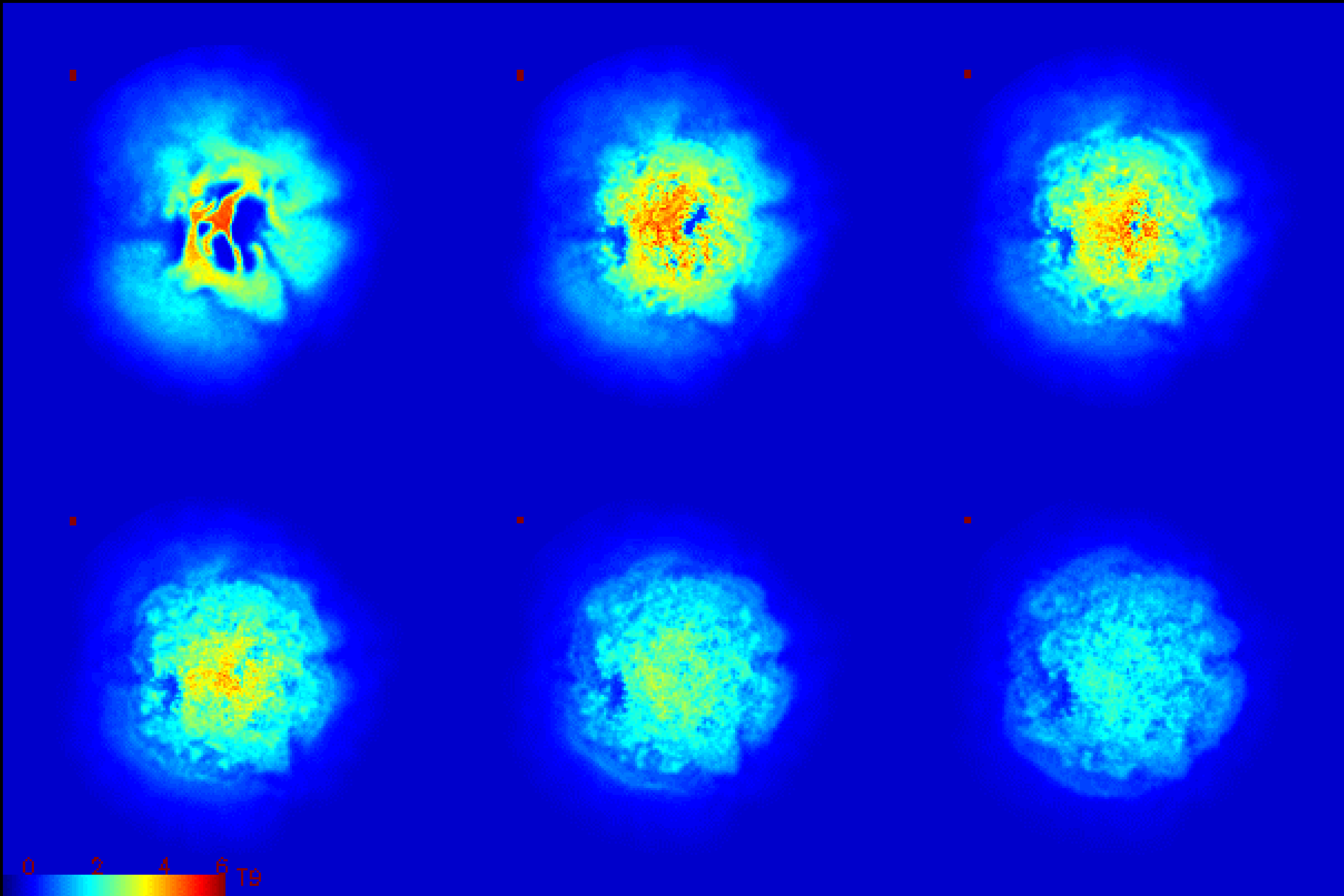
Large pockets of unburned matter are left that introduce irregularities in the line profiles

If the deflagration turns out into a detonation these pockets disappear

•The problem of the 56Ni clumps (García-Senz & Bravo 2004):

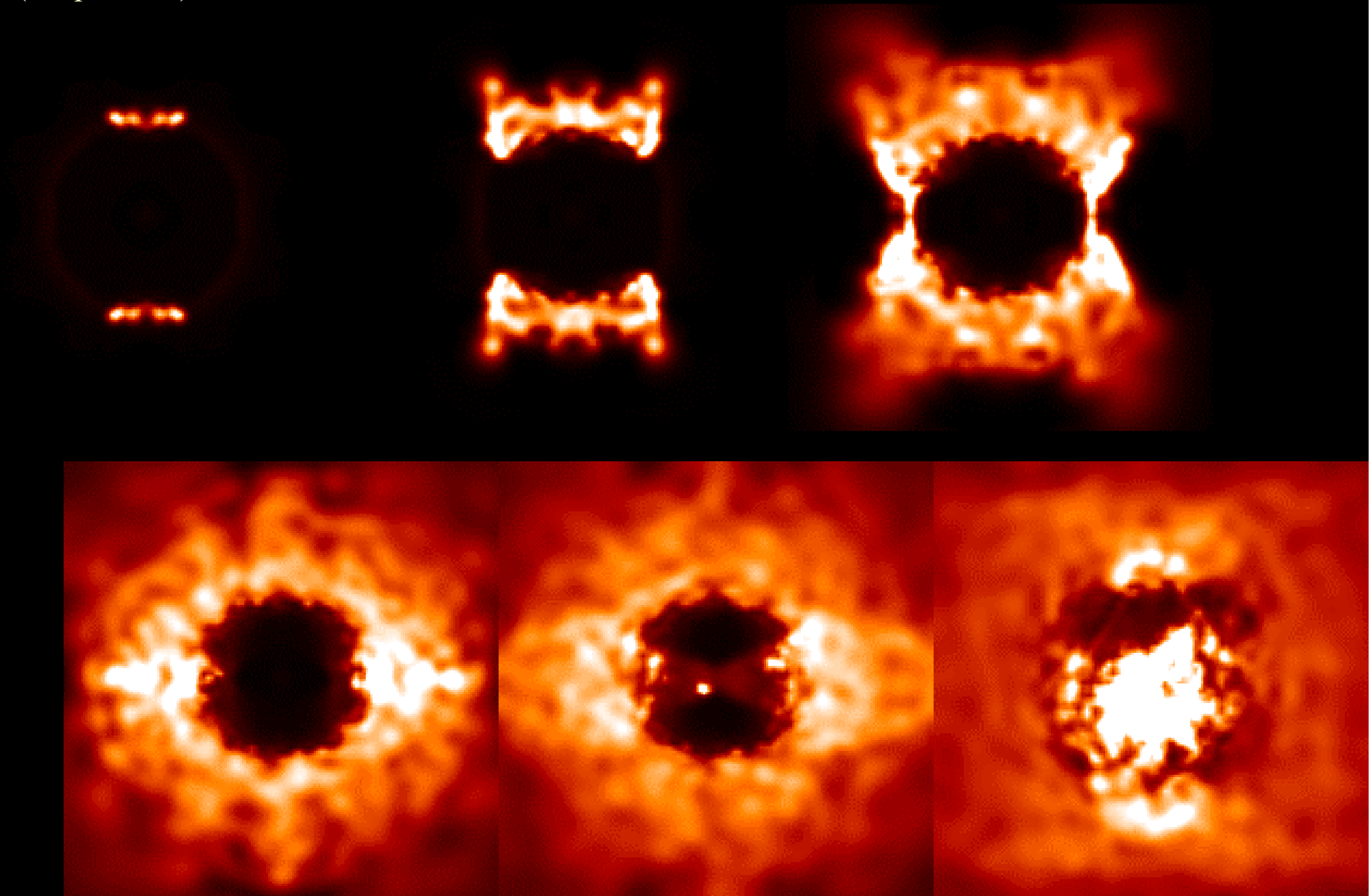


The detonation starts: t = 1.55 -2.06 s

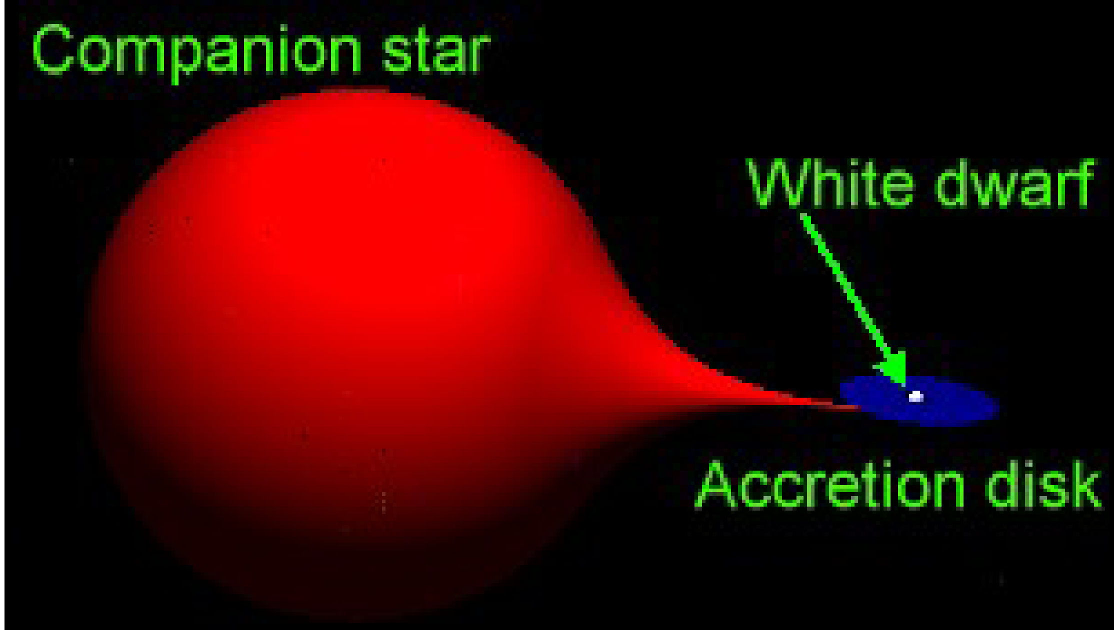


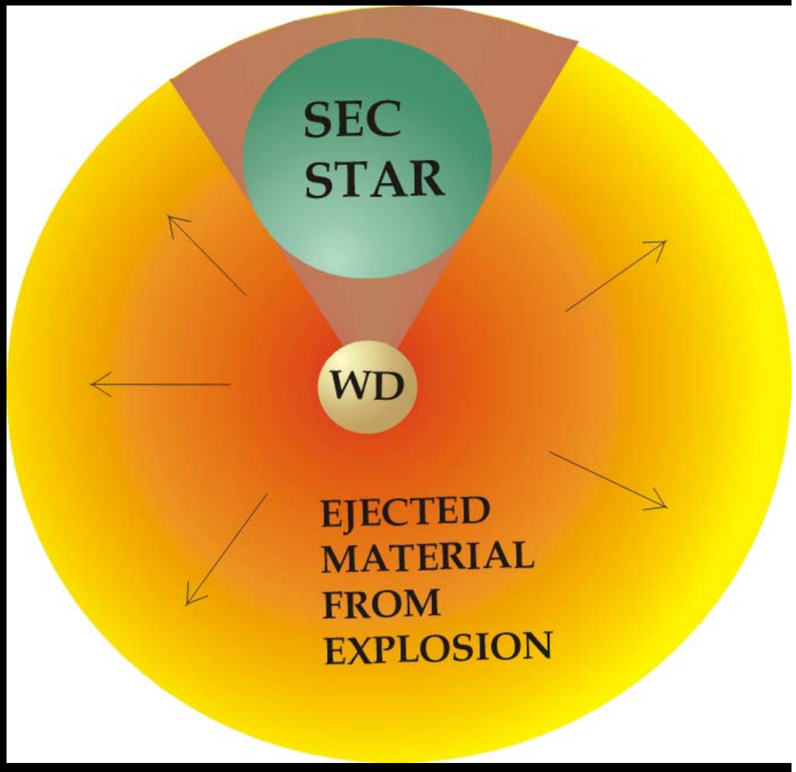
Off center detonations (E. Bravo et al IEEC/UPC)

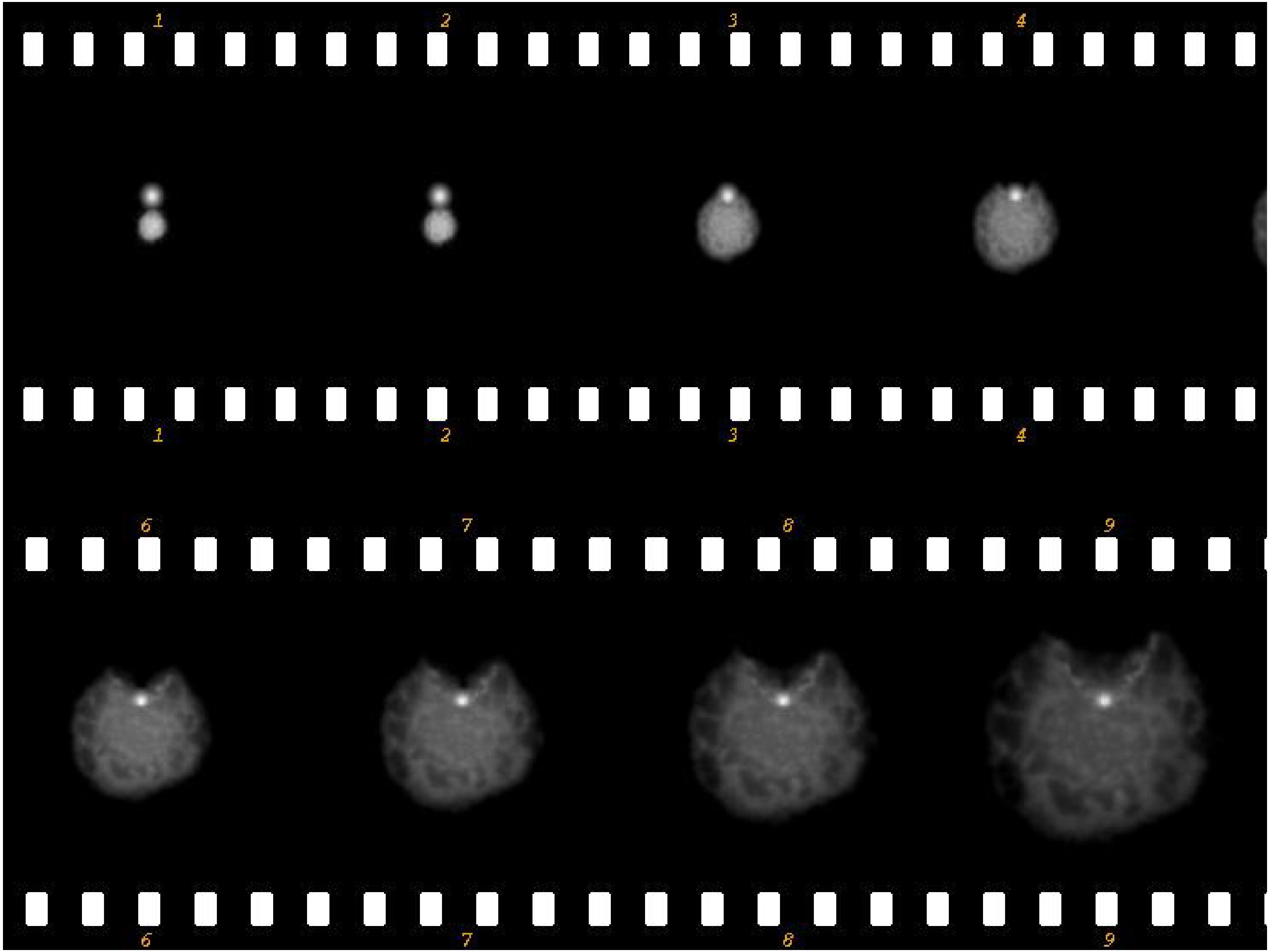
(temperature)

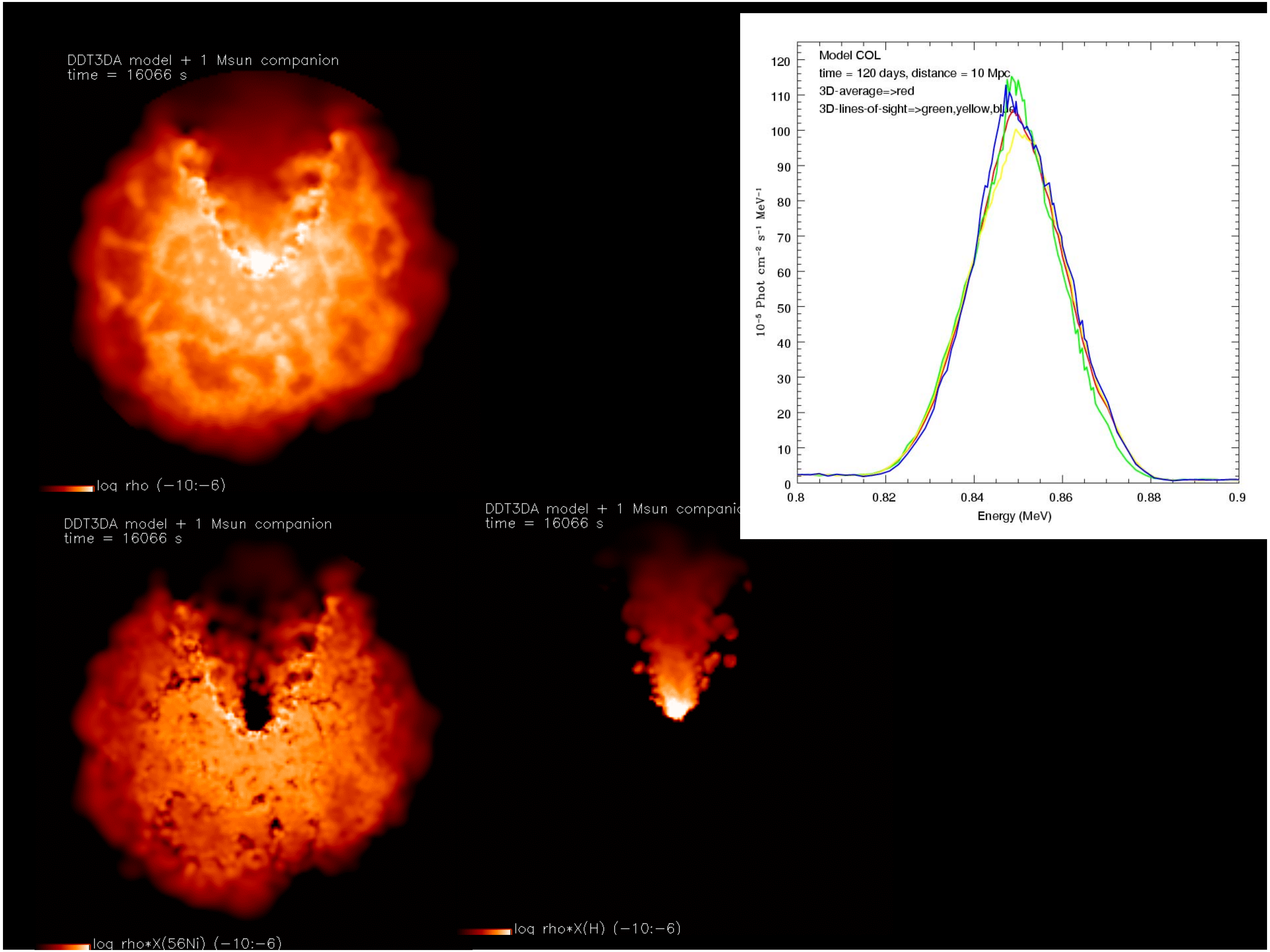


Single degenerate scenario

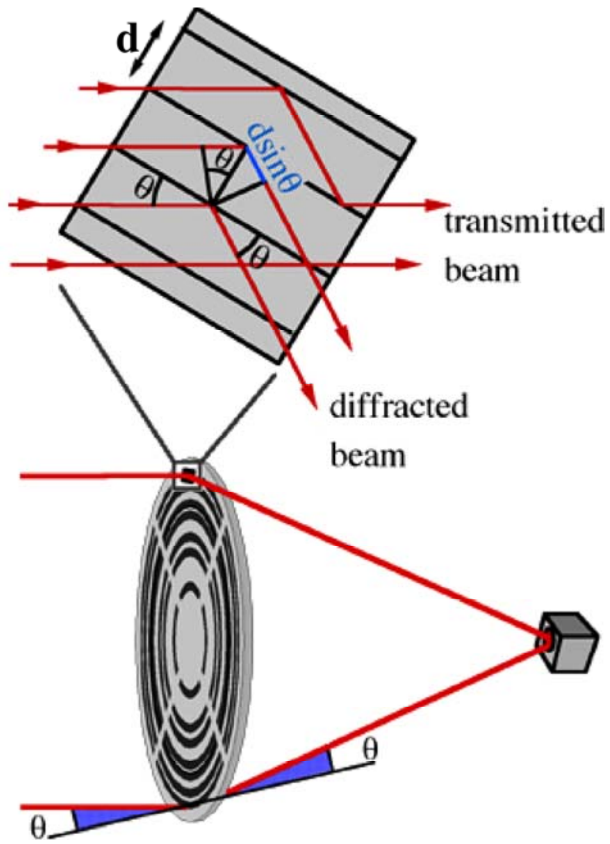





1
2
3
4
1
2
3
4
6
7
8
9
6
7
8
9


DDT3DA model + 1 Msun companion
time = 16066 s
log rho (−10:−6)
DDT3DA model + 1 Msun companion
time = 16066 s
log rho*X(56Ni) (−10:−6)
DDT3DA model + 1 Msun companion
time = 16066 s
log rho*X(H) (−10:−6)
Model COL
time = 120 days, distance = 10 Mpc
3D-average=>red
3D-lines-of-sight=>green,yellow,blue
10⁻⁵ Phot cm⁻² s⁻¹ MeV⁻¹
Energy (MeV)

Focusing Gamma-Rays - how ?

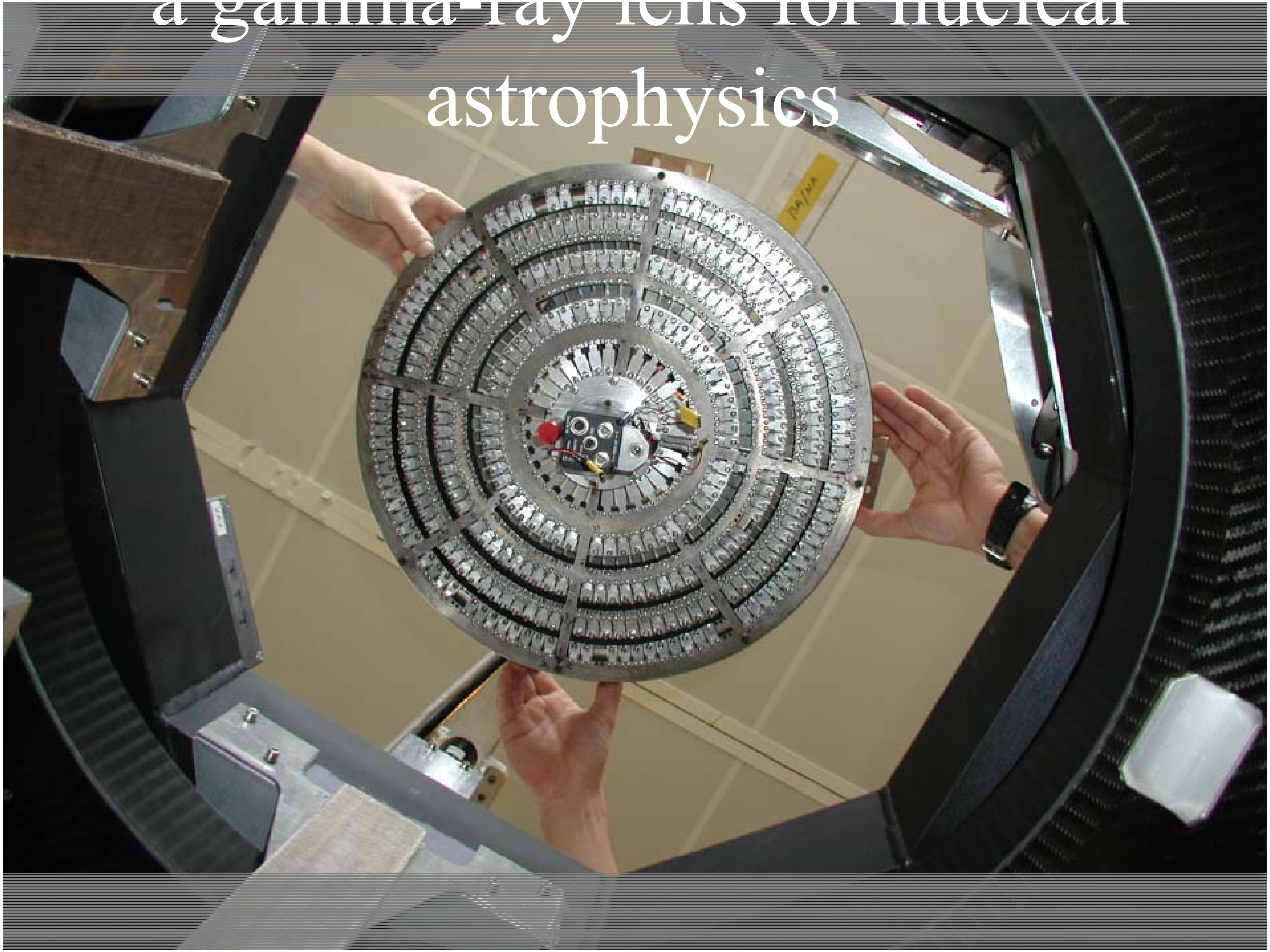


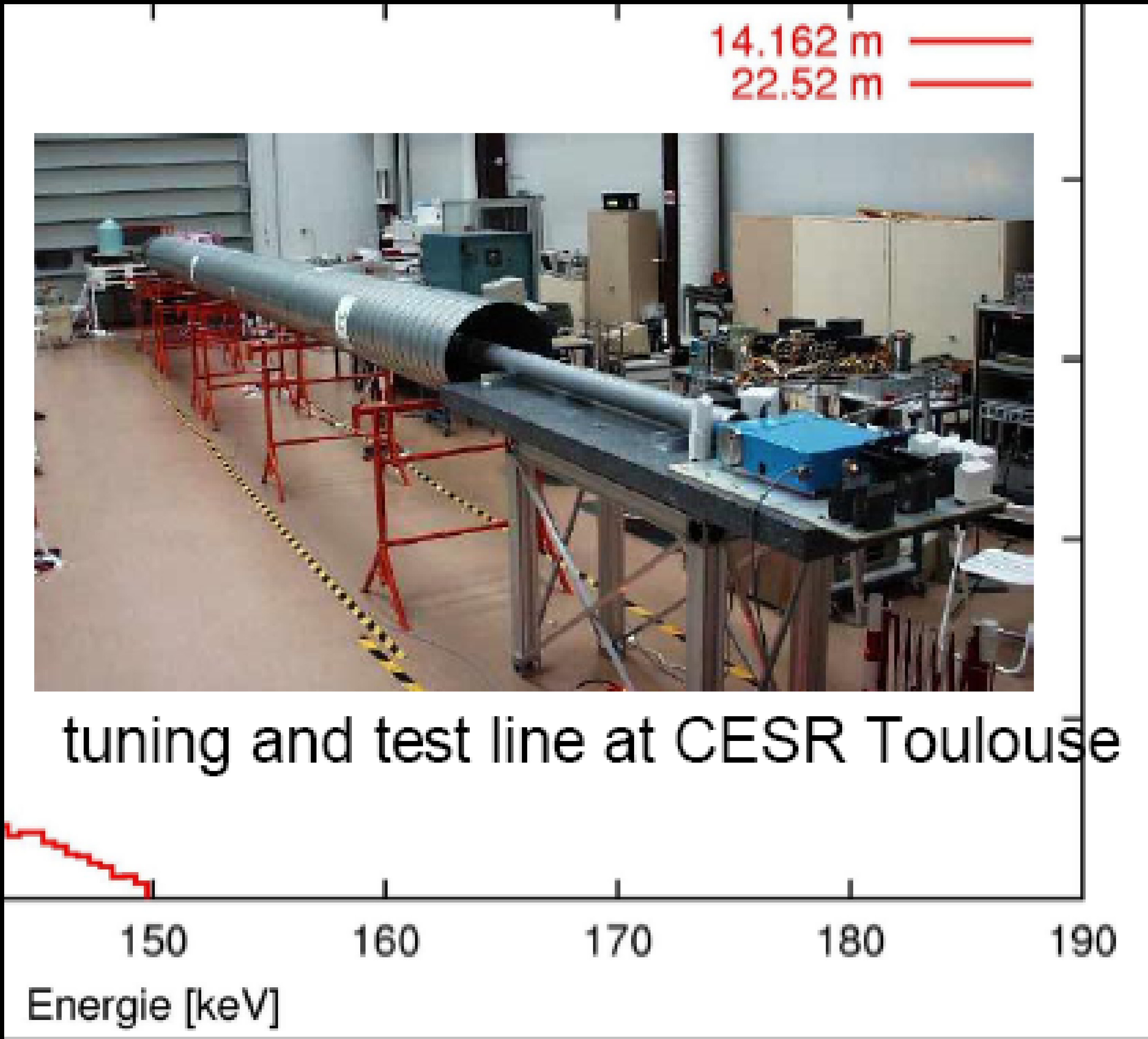
λ(511 keV)	=	$2.42632 \cdot 10^{-2}$ Å
Bragg condition		
2dsinθ	=	nλ
d[220]	=	2.0004Å
arcsin(λ/2d)	=	0.347°
Laue-type Gamma-ray lens		
2θ	=	0.695°
ex. radius [220]	=	10.1 cm
=> focal lenght	=	8.2 m

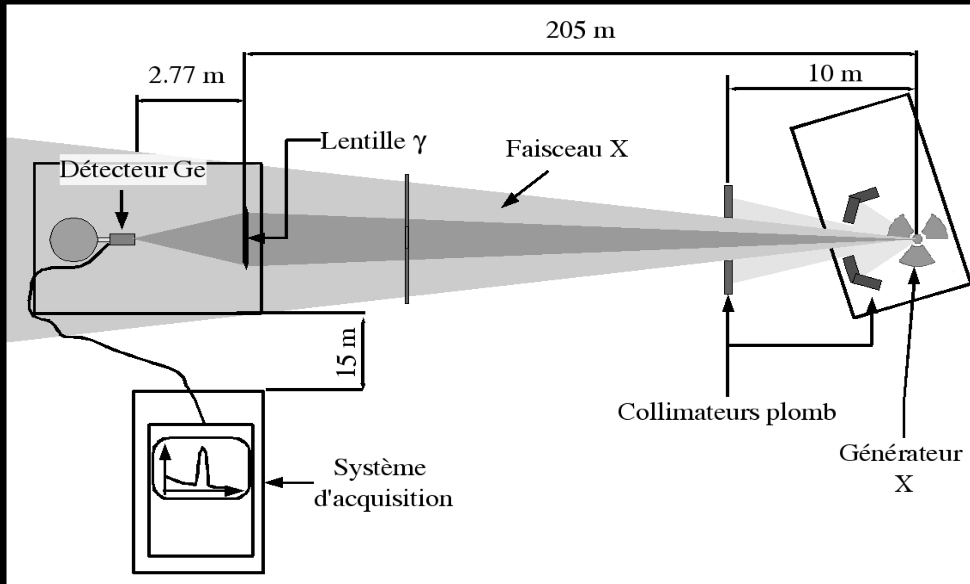
narrow band Laue lens : higher orders at larger radia (CLAIRE)

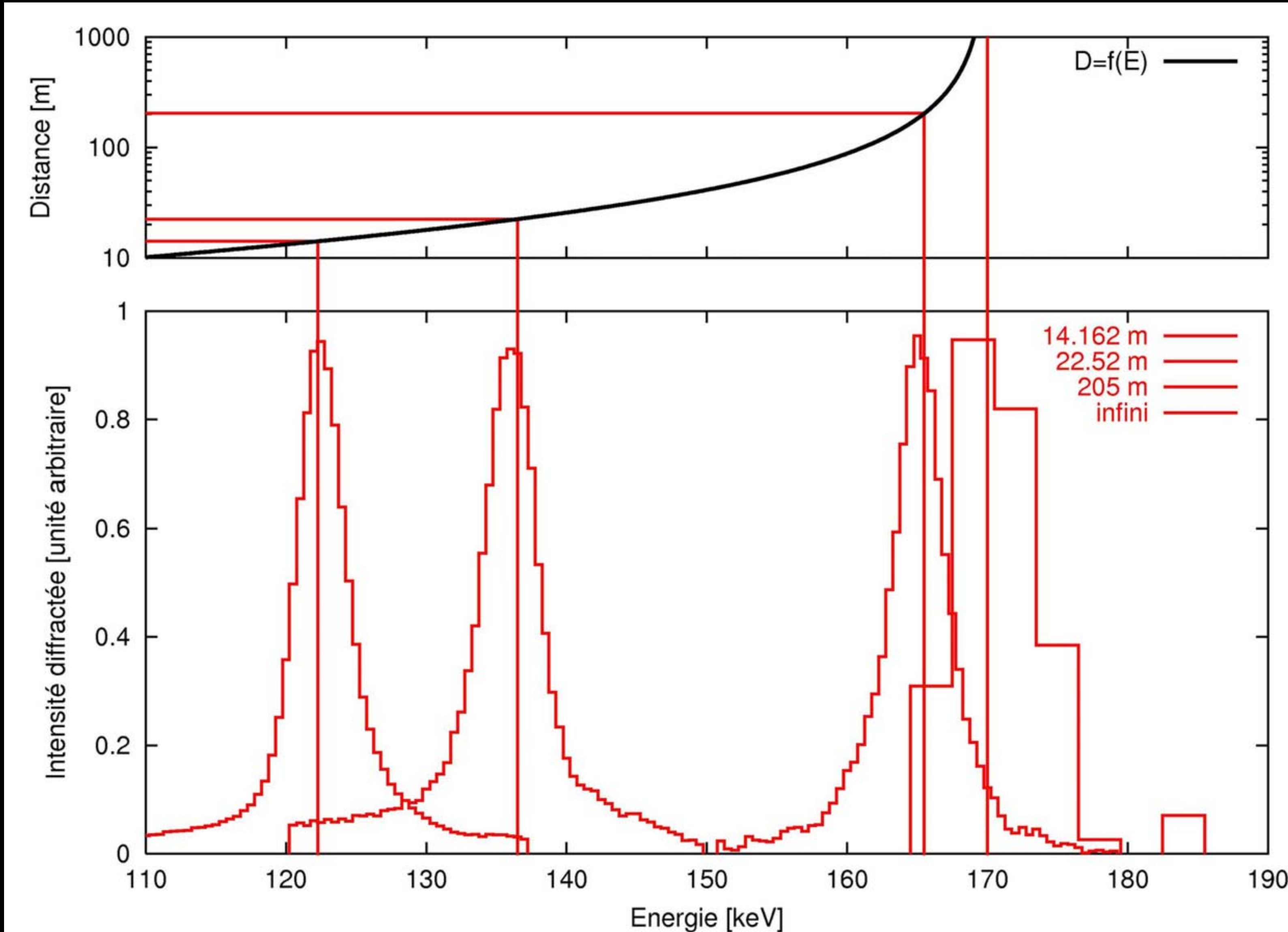
broad band Laue lens : most efficient order at all radia (MAX)

a gamma-ray lens for nuclear astrophysics

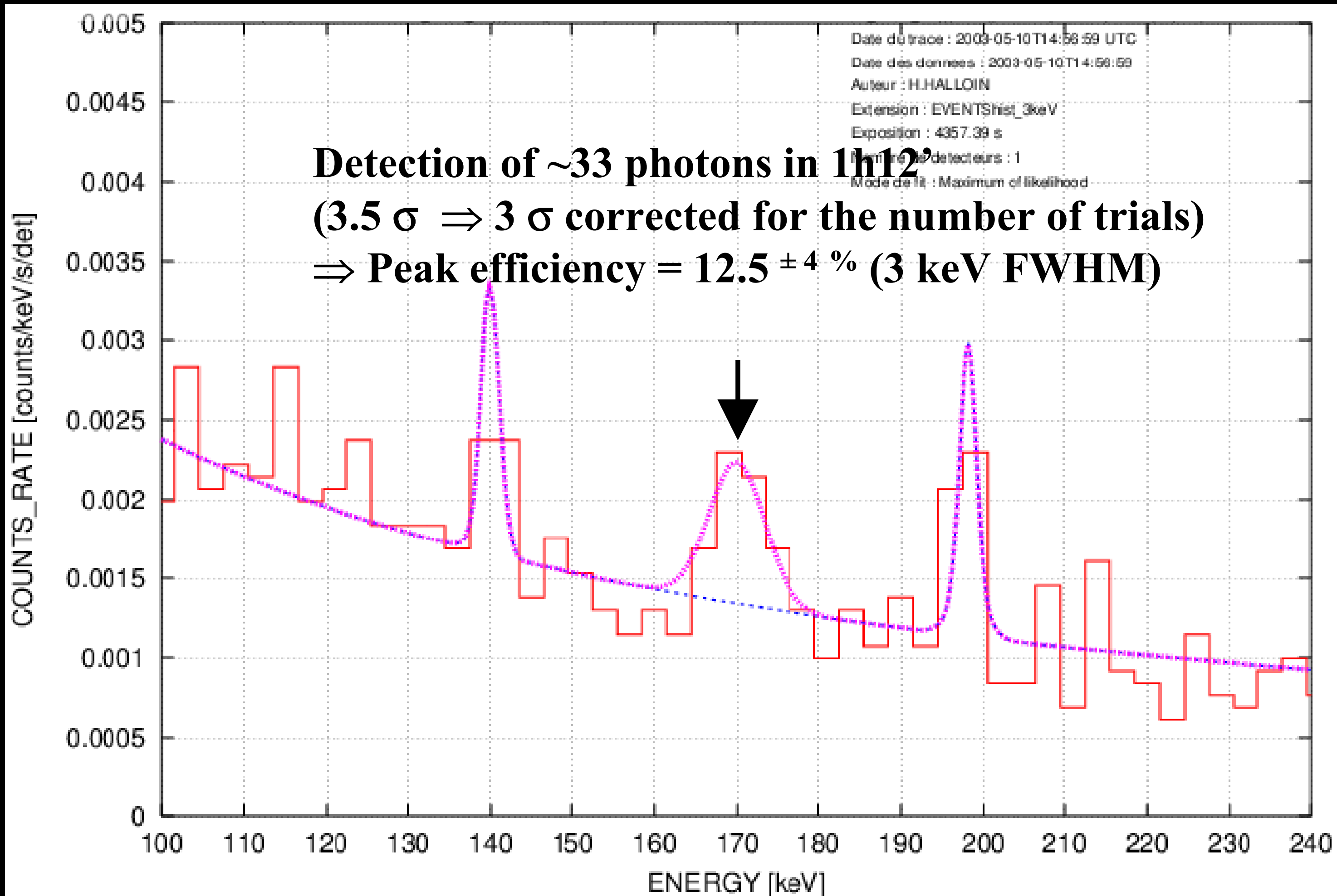



14.162 m
22.52 m
tuning and test line at CESR Toulouse
150
160
170
180
190
Energie [keV]


205 m
2.77 m
10 m
Lentille γ
Faisceau X
Détecteur Ge
15 m
Collimateurs plomb
Générateur X
Système d'acquisition


D=f(E)
Distance [m]
1000
100
10
14.162 m
22.52 m
205 m
infini
Intensité diffractée [unité arbitraire]
1
0.8
0.6
0.4
0.2
0
110
120
130
140
150
160
170
180
190
Energie [keV]





Date du trace : 2003-05-10T14:56:59 UTC
Date des donnees : 2003-05-10T14:56:59
Auteur : H.HALLOIN
Extension : EVENTShist_3keV
Exposition : 4357.39 s
detecteurs : 1
Mode de fit : Maximum of likelihood
Detection of ~33 photons in 1h12'
(3.5 σ ⇒ 3 σ corrected for the number of trials)
⇒ Peak efficiency = 12.5 ± 4 % (3 keV FWHM)
COUNTS_RATE [counts/keV/s/det]
ENERGY [keV]
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240

MAX/

10^{-7} /phot/cm2/s

Ge ring 511 keV

Cu ring 850 keV