# Endpoints of stellar evolution

The end of stellar evolution is an inert core of spent fuel that cannot maintain gas pressure to balance gravity

Such a core can be balanced against gravitational collapse by electron degeneracy pressure IF the total mass is less than the Chandrasekhar mass limit:

## Chandrasekhar Mass:

Only if the mass of a inert core is less than Chandrasekhar Mass $M_{ch}$

$$\boxed{M_{Ch} \approx 5.85\, Y_e^2 M_\Theta}$$

Electron degeneracy pressure can prevent gravitational collapse

**In more massive cores electrons become relativistic and gravitational collapse occurs (then $p \sim n^{4/3}$ instead of $p \sim n^{5/3}$).**

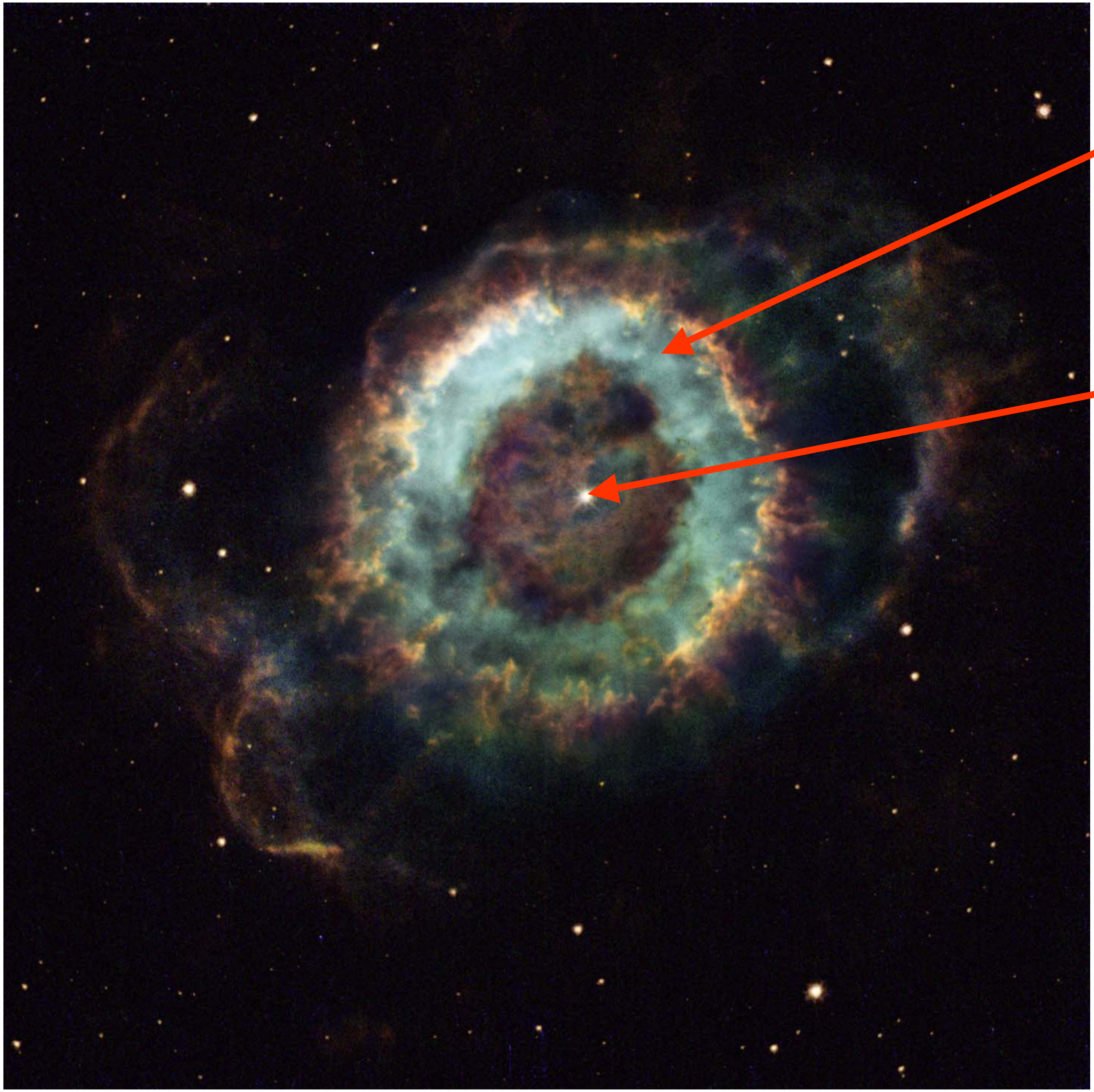
For N=Z $M_{Ch}$=1.46 $M_0$

Mass and composition of the core depends on the ZAMS mass and the previous burning stages:

| $M_{ZAMS}$ | Last stage | Core | Mass | Result |
| --- | --- | --- | --- | --- |
| $< 0.3\ M_0$ | H burning | He | $M<M_{Ch}$ | **core survives** |
| $0.3\text{-}\ 8\ M_0$ | He burning | C,O | | |
| $8\text{-}12\ M_0$ | C burning | O,Ne,Mg | | |
| $> 8\text{-}12\ M_0$ | Si burning | Fe | $M>M_{Ch}$ | **collapse** |

How can $8\text{-}12 M_0$ mass star get below Chandrasekhar limit ?

# Death of a low mass star: a “Planetary Nebula”



Envelope of star blown into space

And here’s the core !
a “white dwarf”

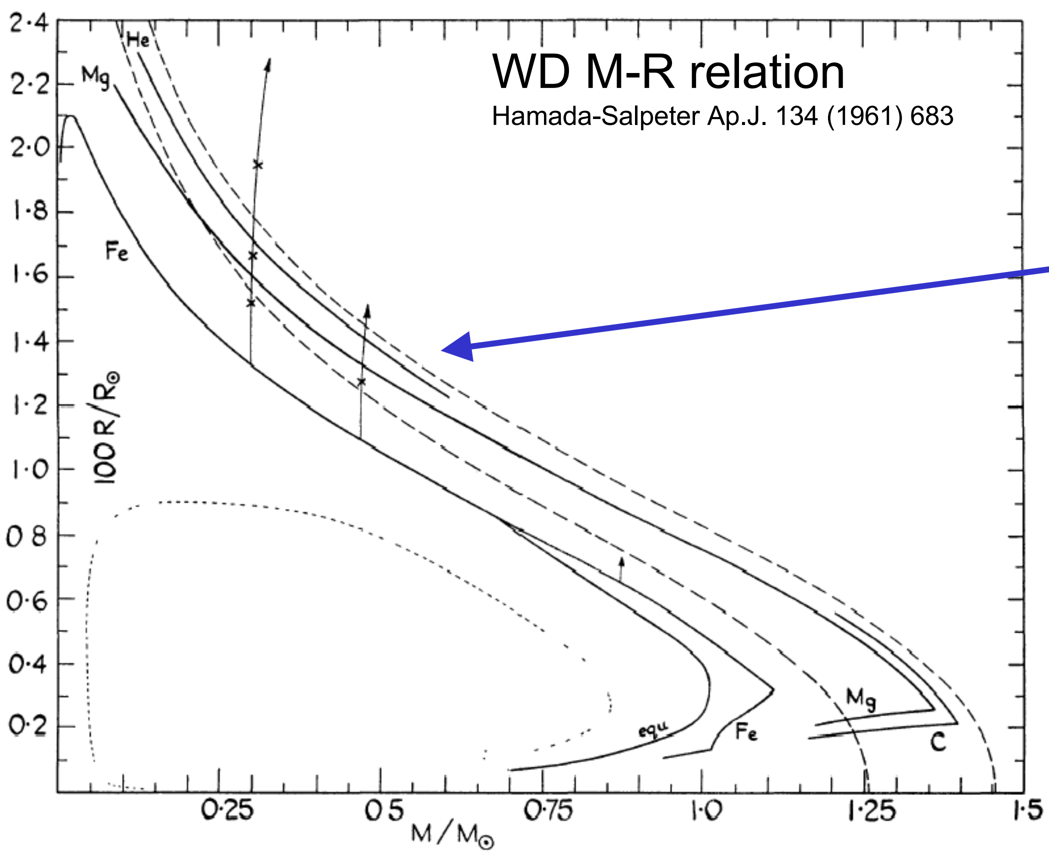
image: HST
Little Ghost Nebula
distance 2-5 kLy
blue: OIII
green: HII
red: NII

# Why “white dwarf” ?

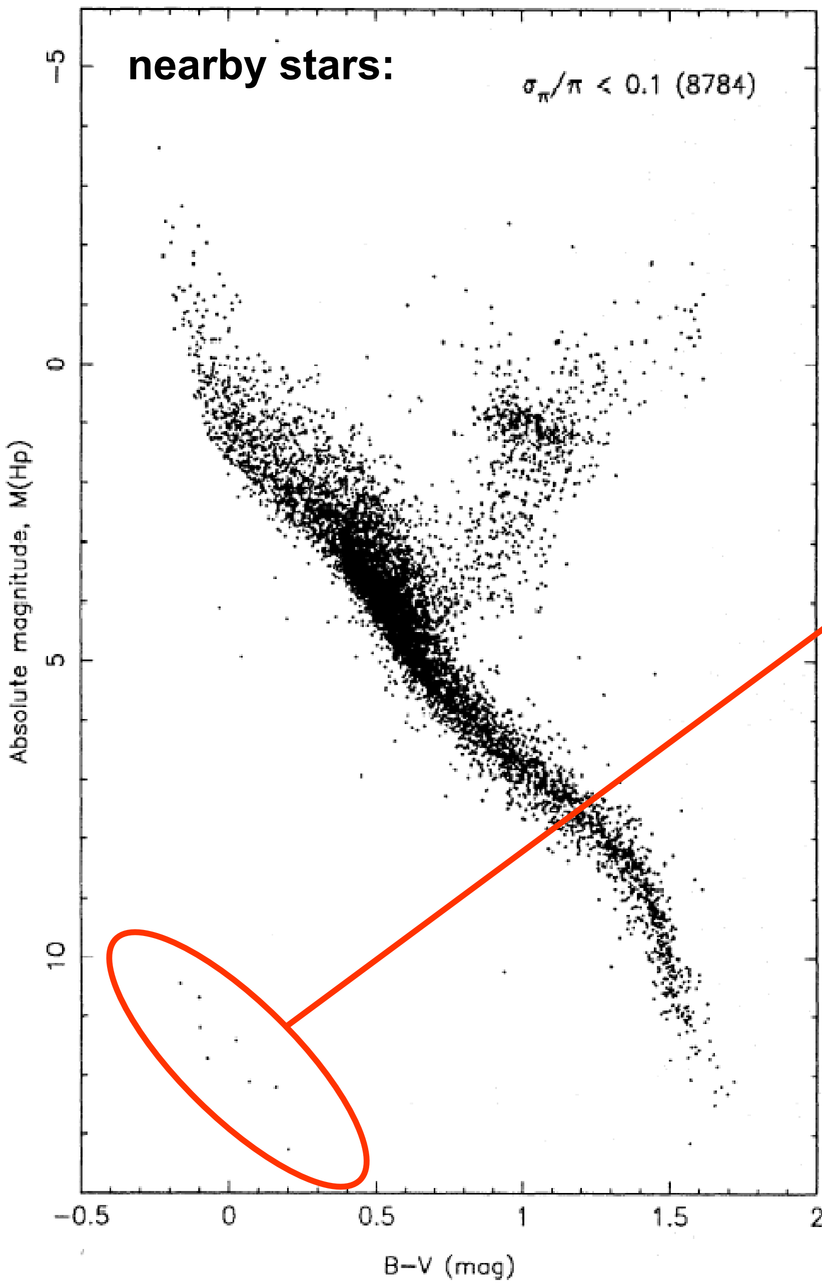
• core shrinks until degeneracy pressure sets in and halts collapse

→ star is HOT (gravitational energy !)

→ star is small




$$\boxed{R \sim M^{-1/3}}$$

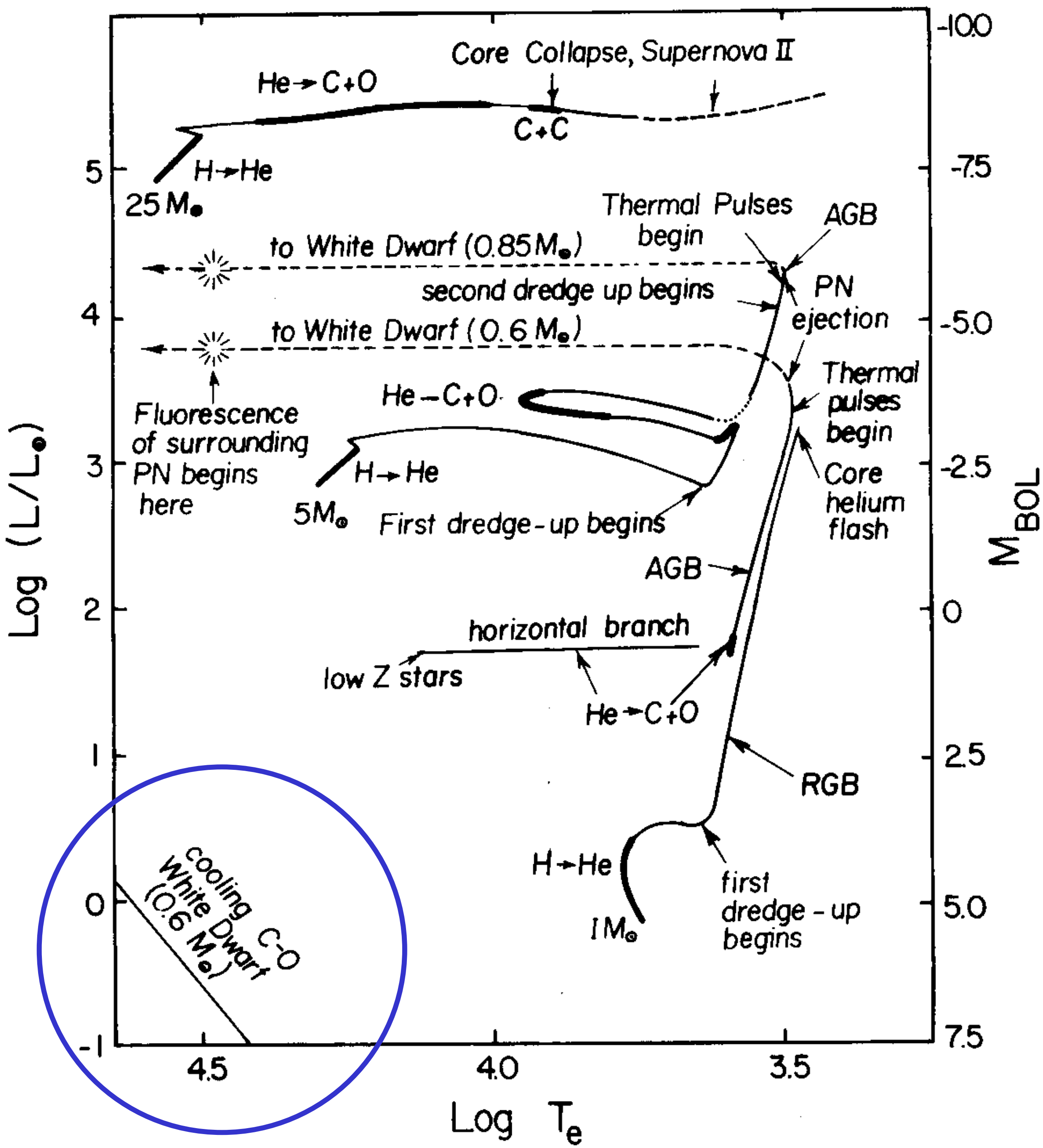



Perryman et al. A&A 304 (1995) 69

HIPPARCOS distance measurements

Where are the white dwarfs ?

there (small but hot white (B~V))




Pagel, Fig. 5.14

# Supernovae

If a stellar core grows beyond its Chandrasekhar mass limit, it will collapse.

Typically this will result in a **Supernova explosion**
→ at least the outer part of a star is blown off into space

But why would a collapsing core explode ?

**a) CO or ONeMg cores that accrete matter from a companion star can get beyond the Chandrasekhar limit:**

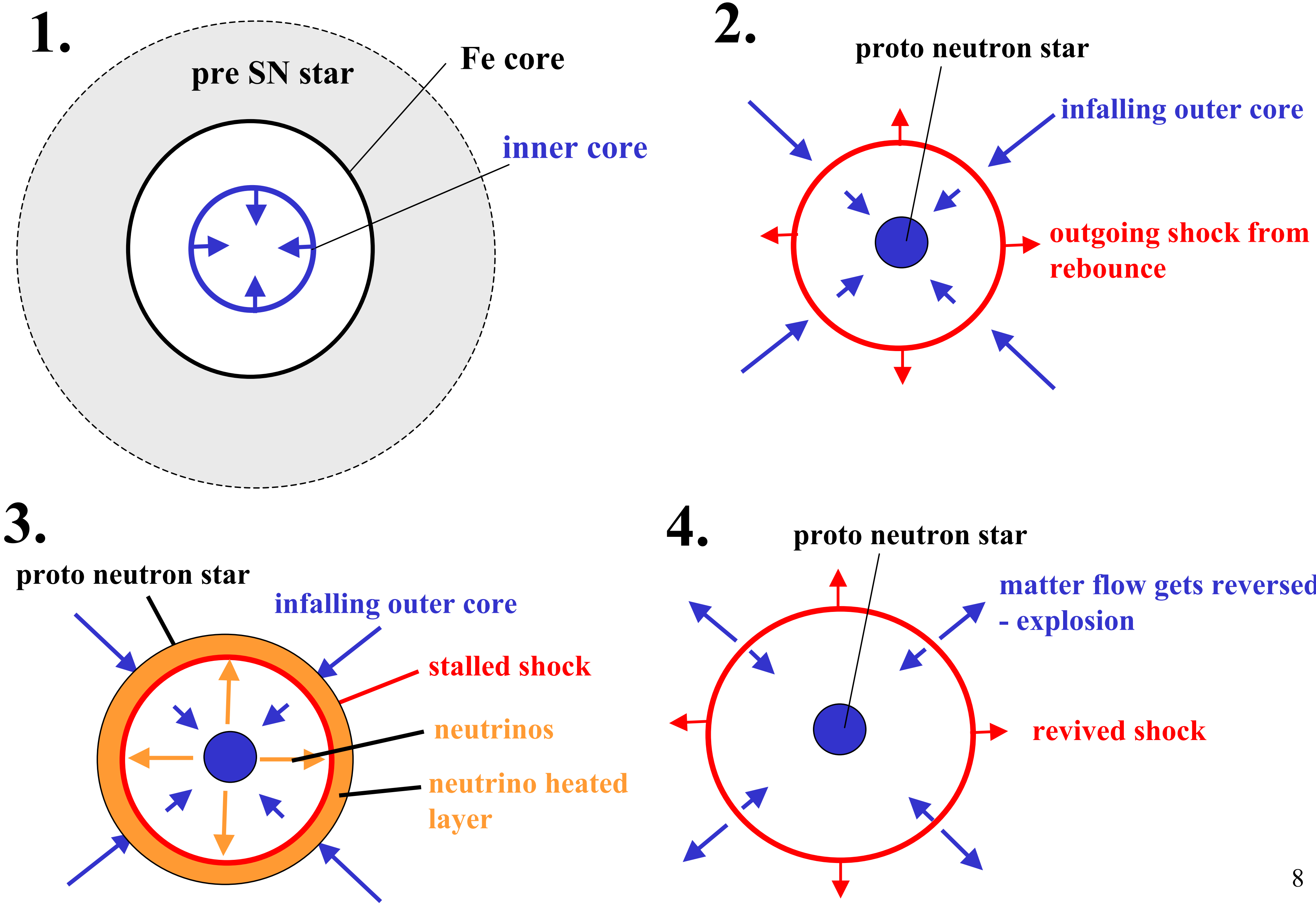
Further collapse heats star and CO or ONeMg burning ignites explosively

→ **Whole star explodes – no remnant**

**b) collapsing Fe core in massive star**

Fe cannot ignite, but collapse halted by degenerate NUCLEON gas at a radius of ~10 km

# core collapse supernova mechanism



## Some facts about Supernovae:

### 1. Luminosity:

Supernovae might be the brightest objects in the universe, and can outshine a whole galaxy (for a few weeks)

**Energy of the visible explosion: $\sim 10^{51}$ ergs**
**Luminosity : $\sim 10^{9-10}$ $L_0$**

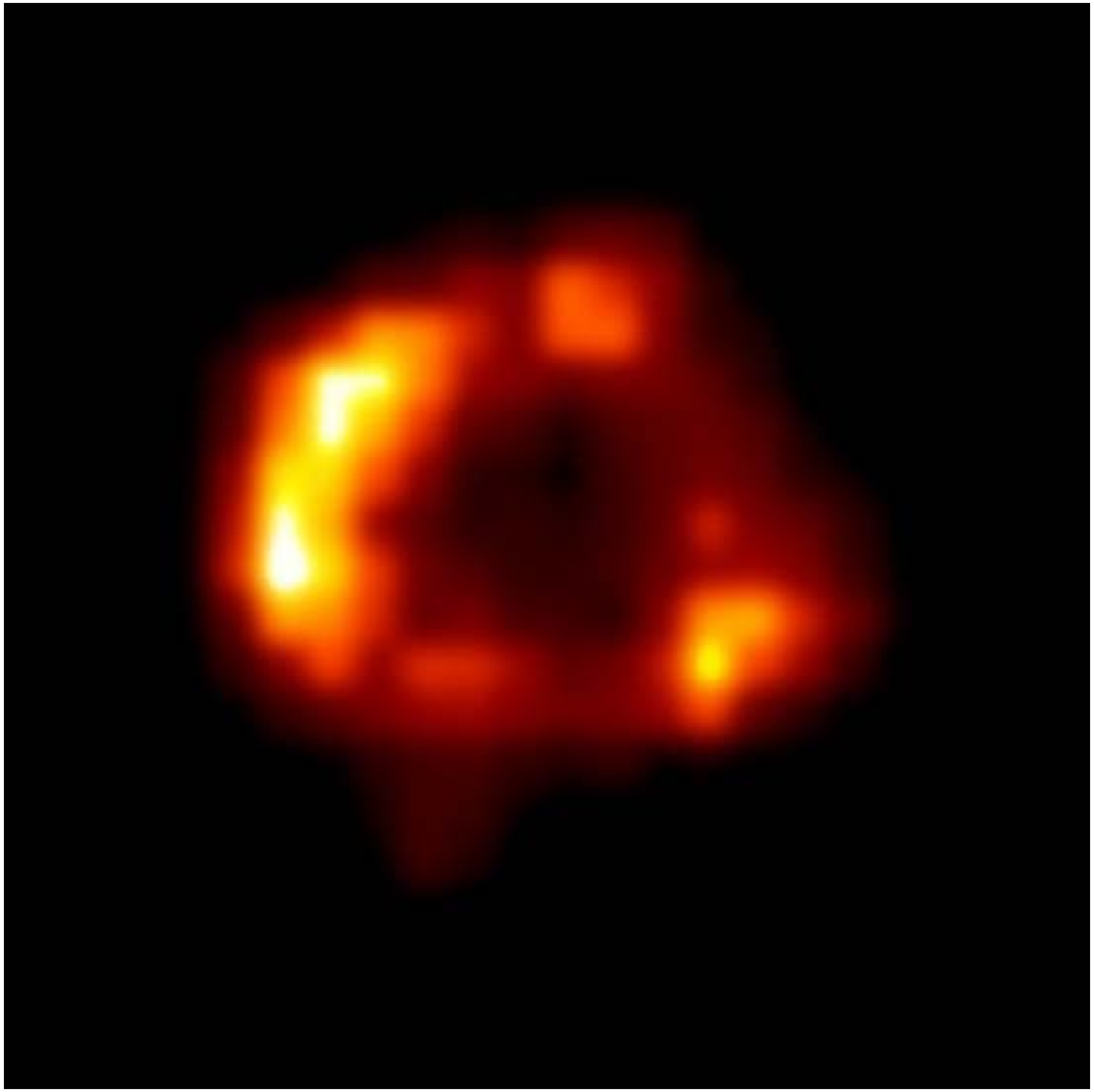
### 2. Frequency:

**~ 1-10 per century and galaxy**

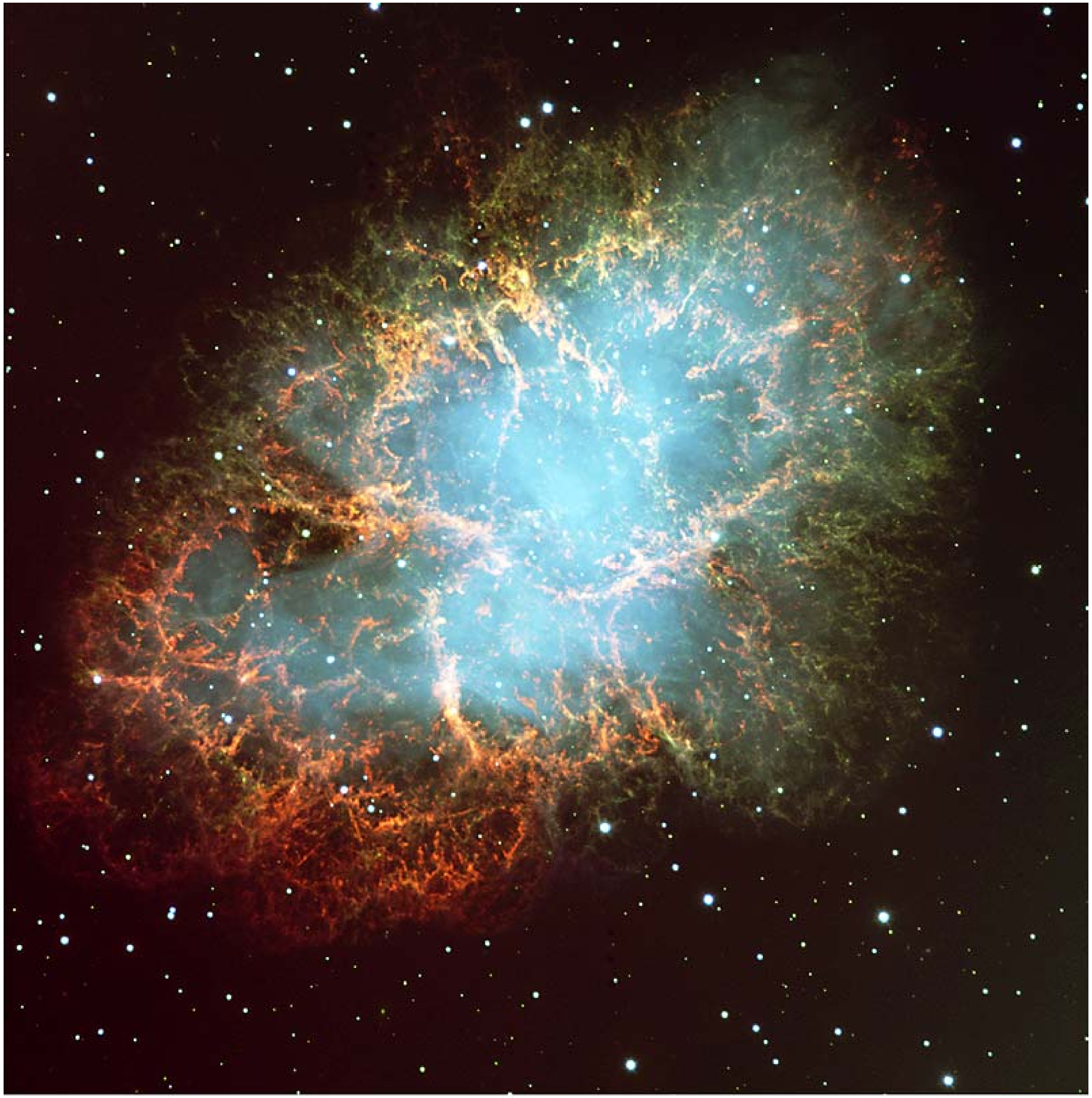

Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~180000 ly


Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~180000 ly

Supernova 1987A seen by Chandra X-ray observatory, 2000

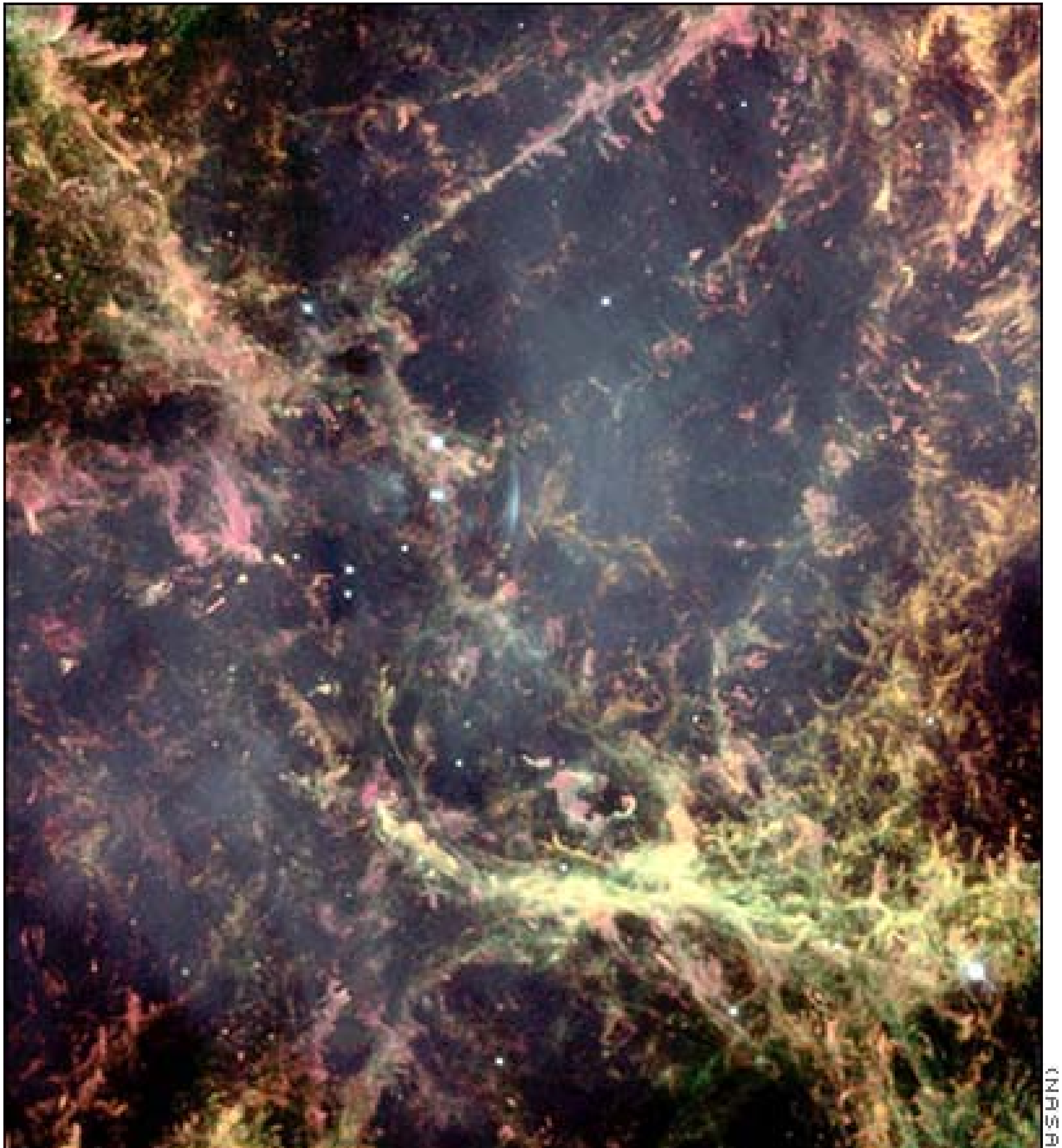


Shock wave hits inner ring of material and creates intense X-ray radiation



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 ( 17 November 1999 )

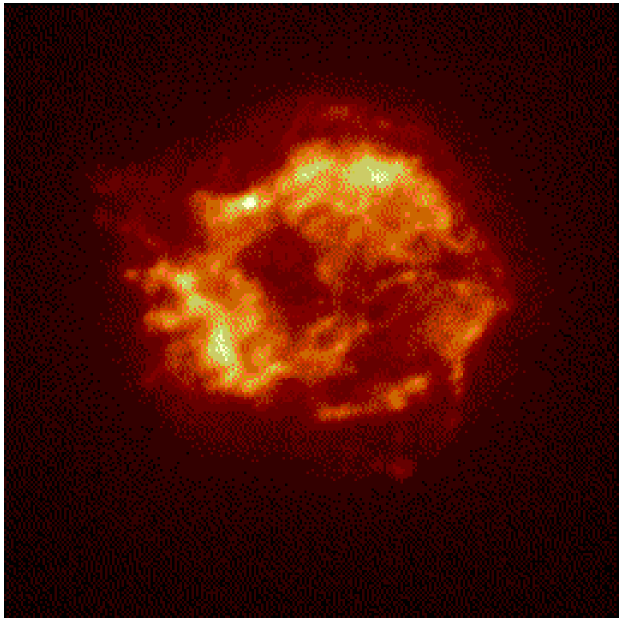



HST picture

Crab nebula
SN July 1054 AD
Dist: 6500 ly
Diam: 10 ly,
pic size: 3 ly
Expansion: 3 mill. Mph
(1700 km/s)
Optical wavelengths
Orange: H
Red : N
Pink : S
Green : O

Pulsar: 30 pulses/s

# Cas A supernova remnant



… seen over 17 years

youngest supernova in our galaxy – possible explosion 1680
(new star found in Flamsteeds catalogue)

## 3. Observational classes (types):

| | |
|---|---|
| **Type I** | no hydrogen lines |
| | depending on other spectral features there are sub types Ia, Ib, Ic, ... |
| **Type II** | hydrogen lines |

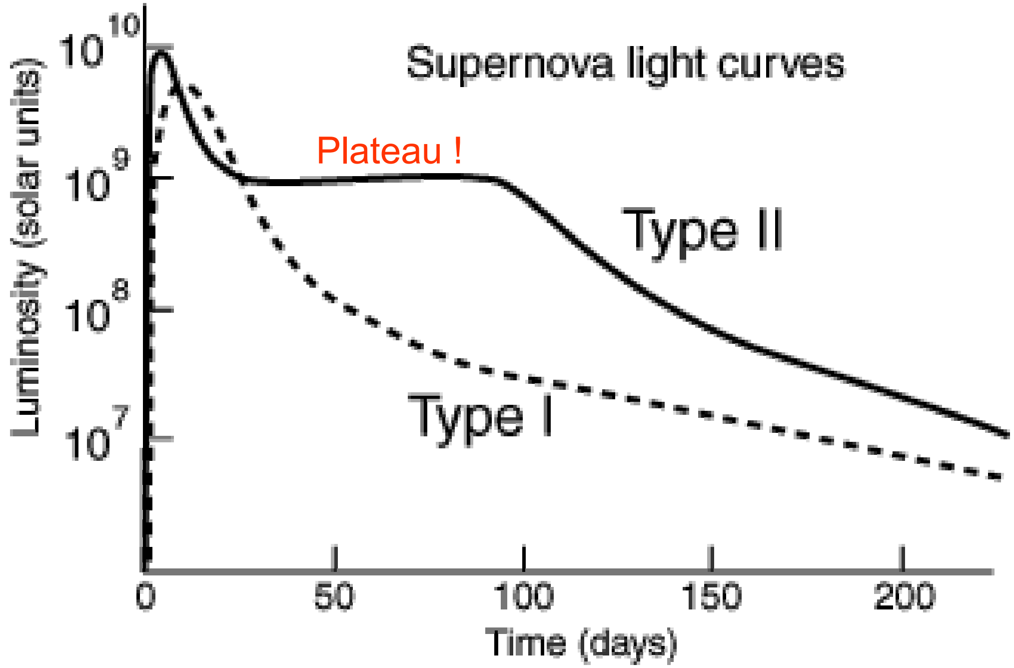
**Why are there different types ?** **Answer: progenitor stars are different**

**Type II:** **collapse of Fe core** in a normal massive star (H envelope)

**Type I:** 2 possibilities:

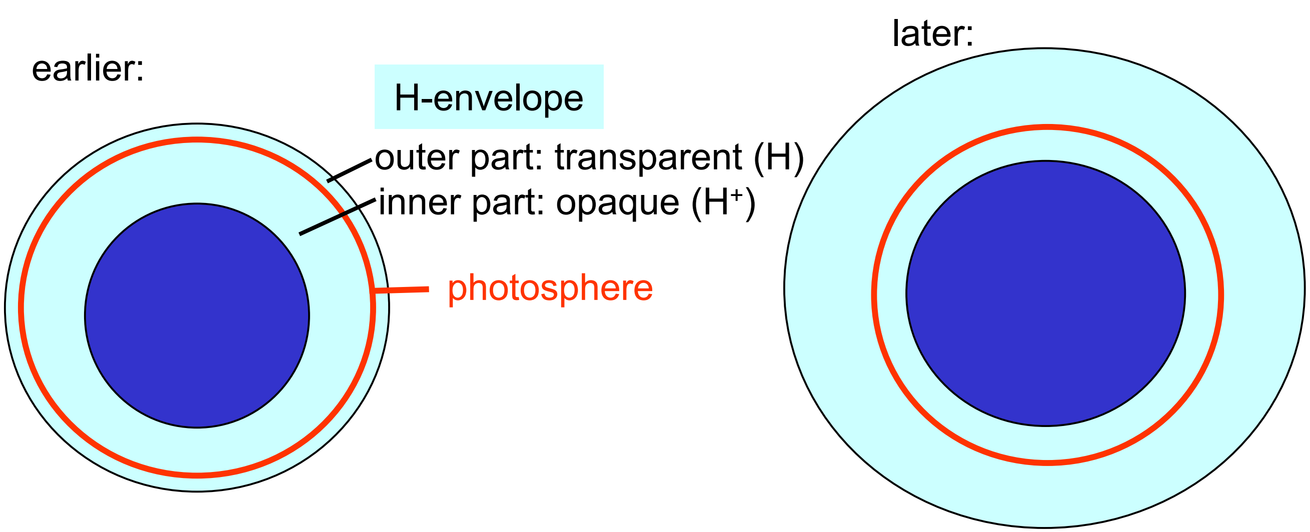
**Ia:** **white dwarf accreted** matter from companion

**Ib,c** **collapse of Fe core** in star that blew its H (or He) envelope into space prior to the explosion




Adapted from Chaisson & McMillan

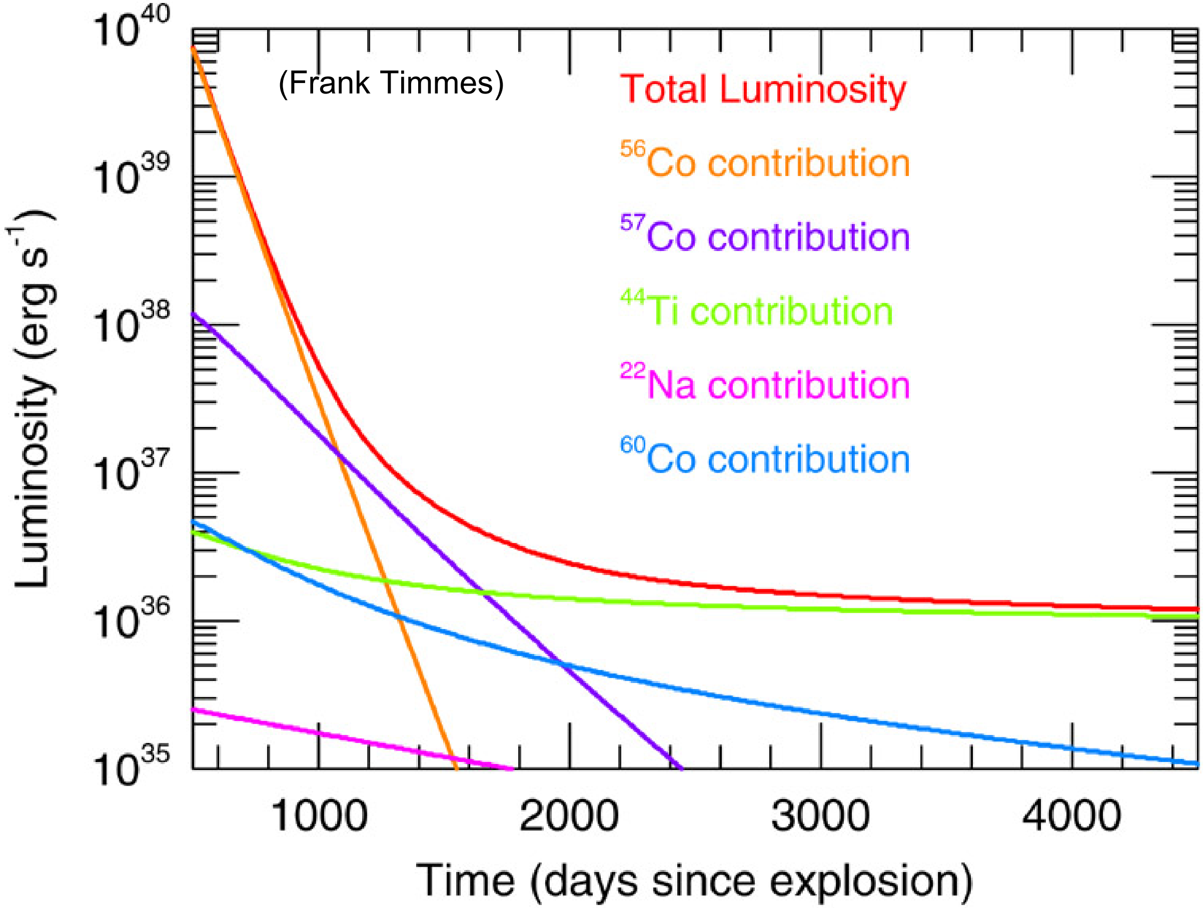
**Origin of plateau:**




As star expands, photosphere moves inward along the T=5000K contour (H-recombination)

T,R stay therefore roughly fixed = Luminosity constant (as long as photosphere wanders through H-envelope)

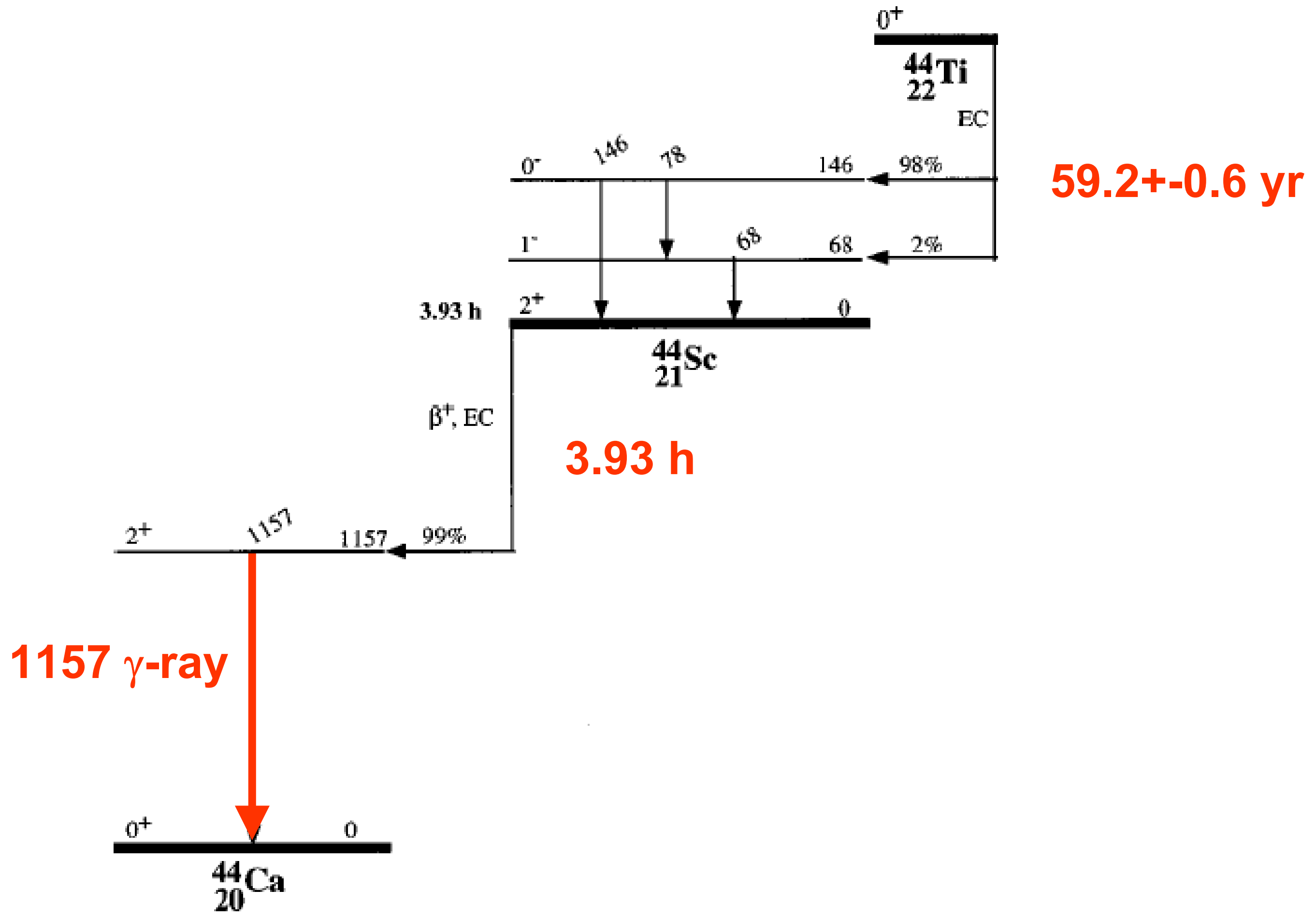
There is another effect that extends SN light curves: Radioactive decay !



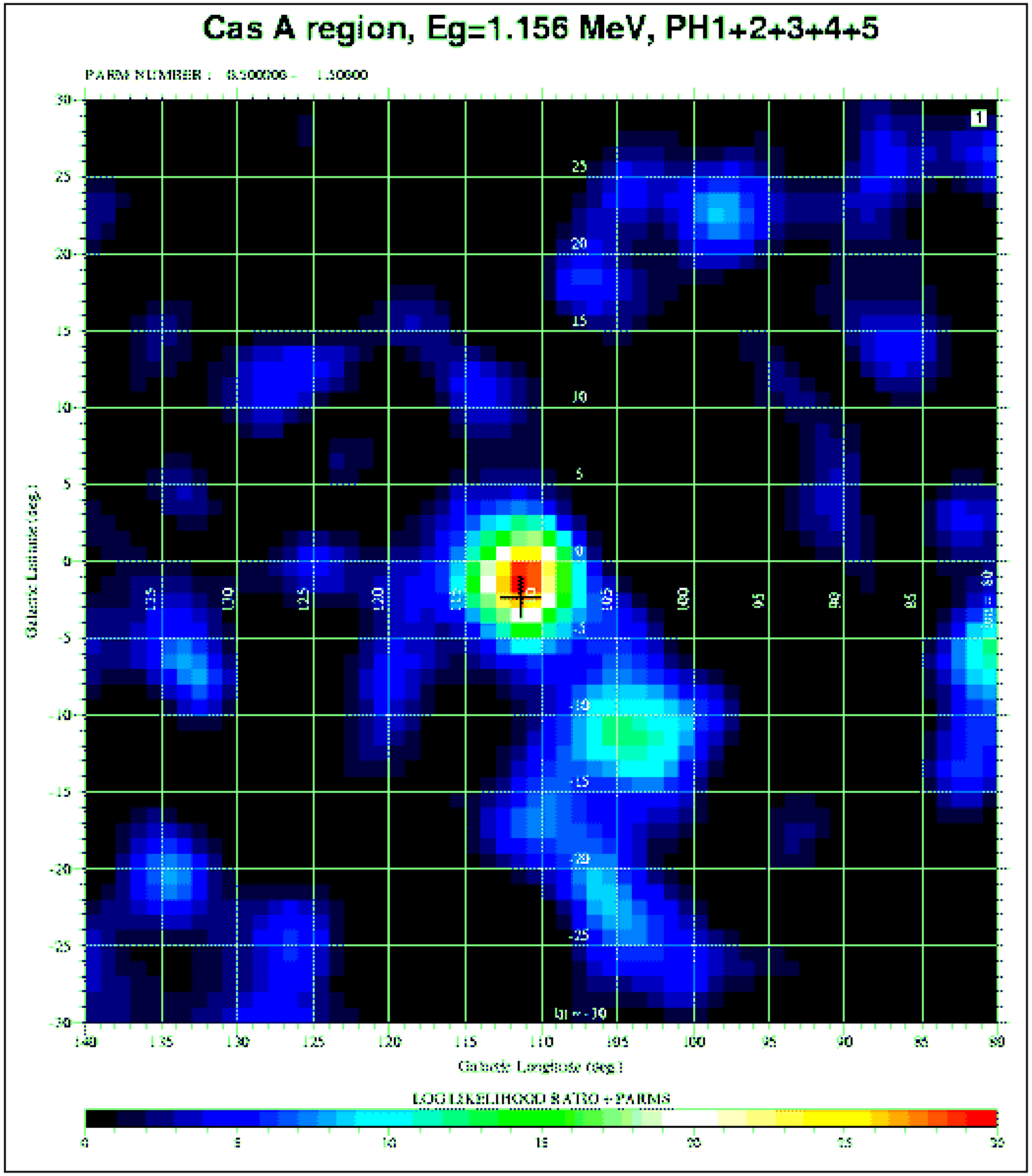

→ Radioactive isotopes are produced during the explosion

→ there is explosive nucleosynthesis !

# 44Ti



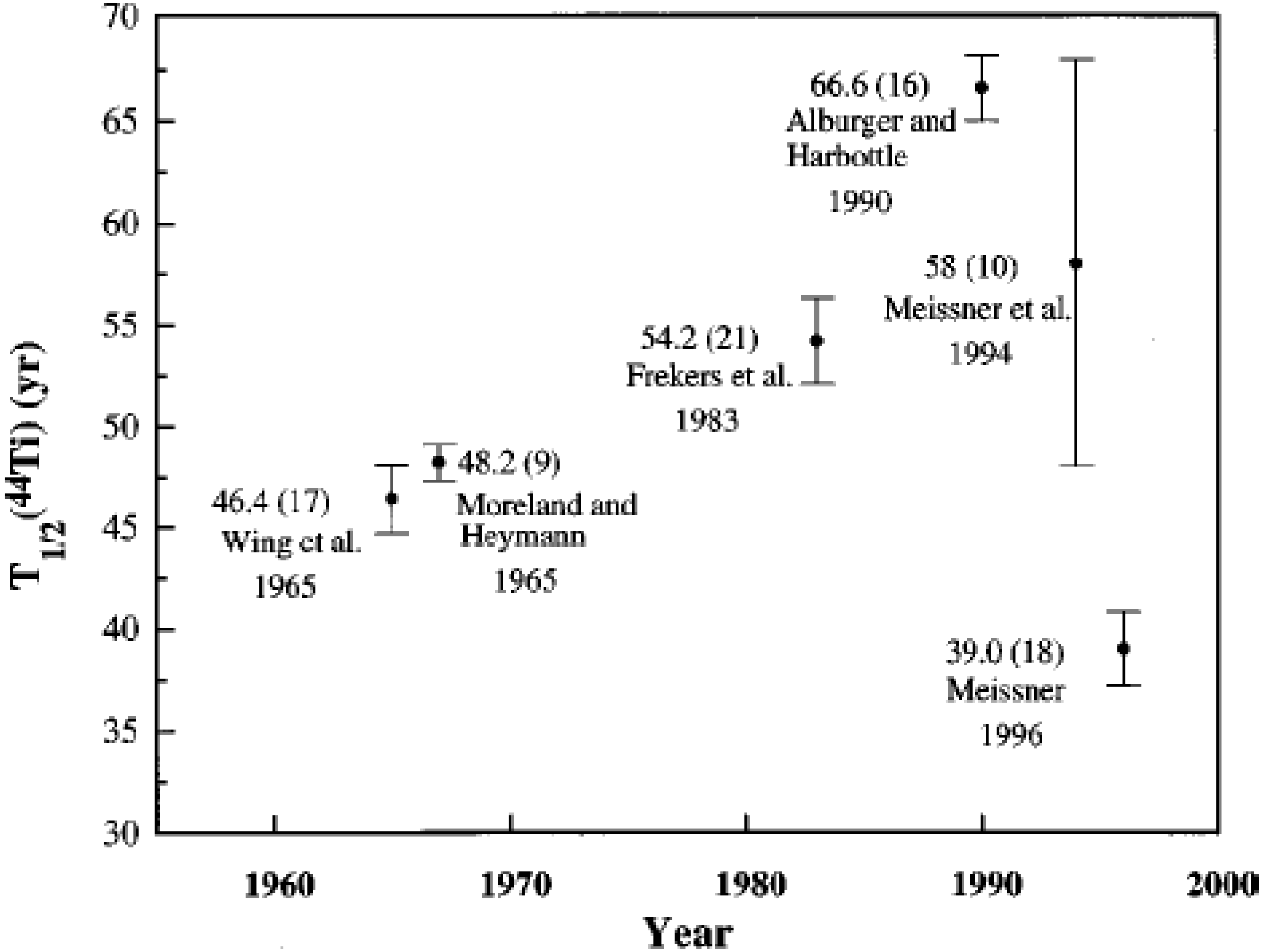
0+
$^{44}_{22}$Ti
EC
59.2+-0.6 yr
0-
146
78
146
98%
1-
68
68
2%
3.93 h
2+
0
$^{44}_{21}$Sc
β+, EC
3.93 h
2+
1157
1157
99%
1157 γ-ray
0+
0
$^{44}_{20}$Ca




Distance 10,000 ly

# Measure the half-life of $^{44}$Ti

It's not so easy: Status as of 1997:



## Method 1:

Prepare sample of 44Ti and measure activity as a function of time

number of sample nuclei N:

$$N(t) = N_0 e^{-\lambda t}$$

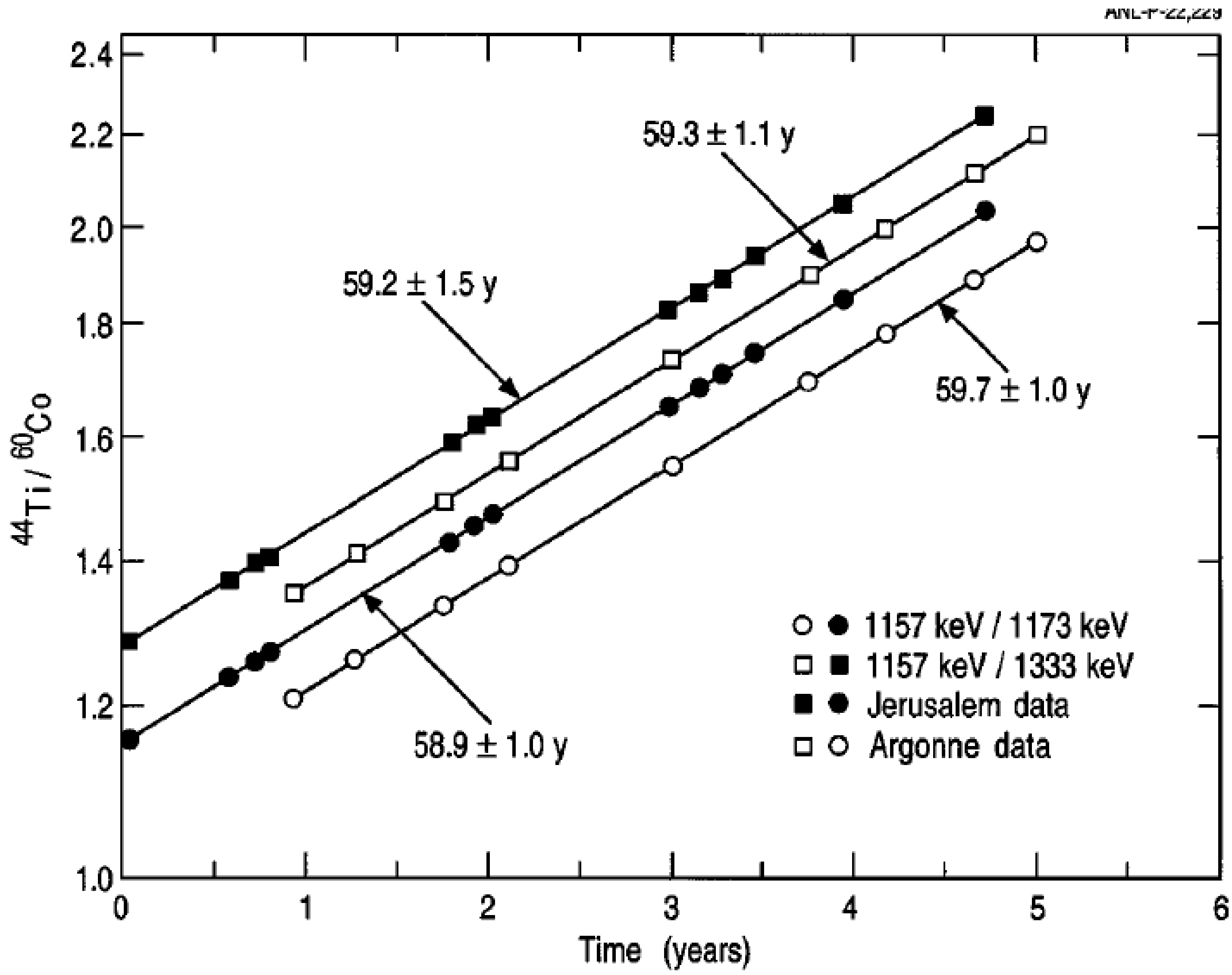
activity = decays per second:

$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$$

Measure A with $\gamma$-ray detector as a function of time A(t) to determine $N_0$ and $\lambda$

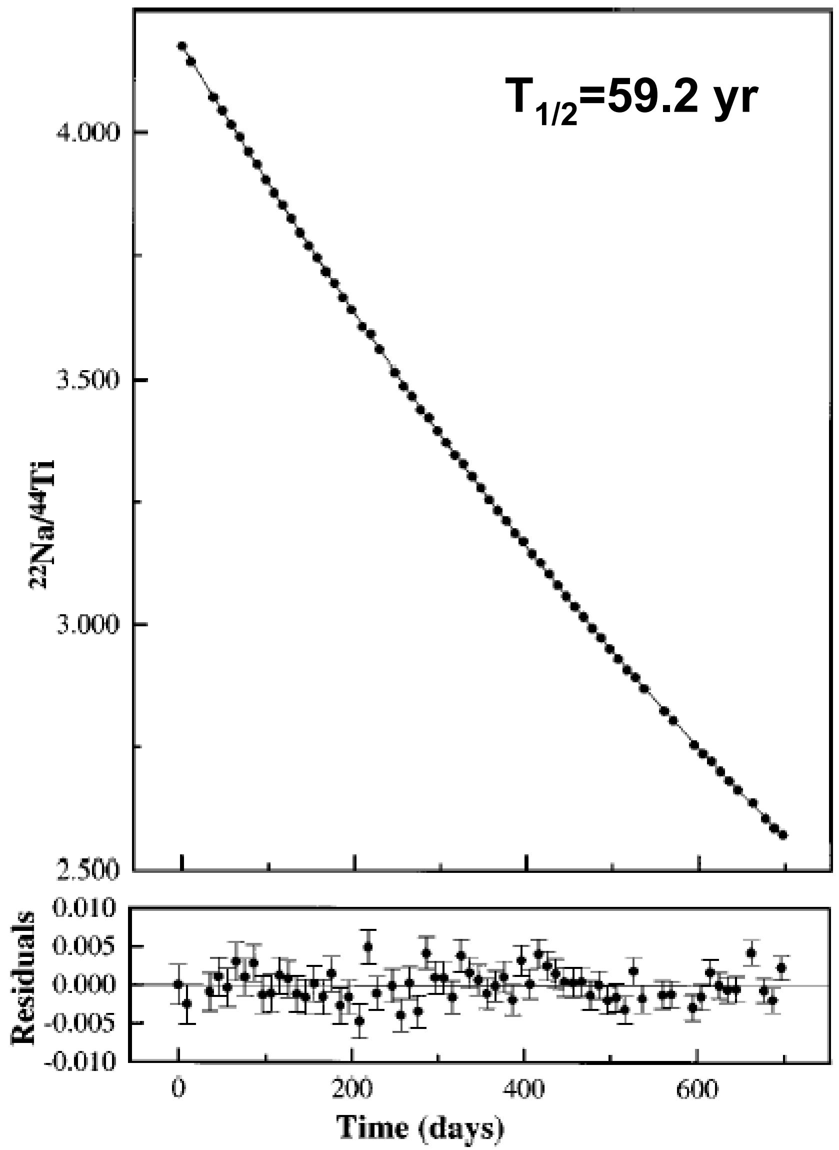
$$\lambda = \frac{\ln 2}{T_{1/2}}$$

ANL:



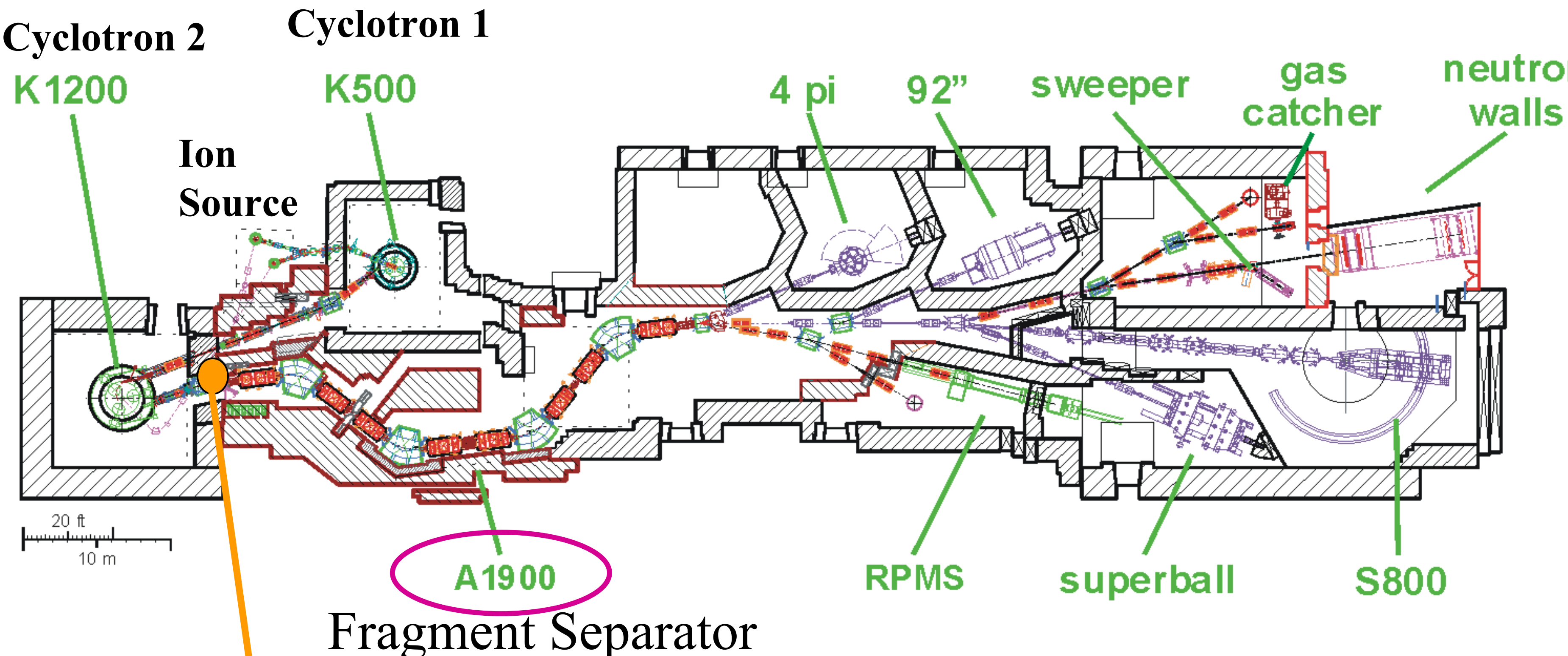

Ahmad et al. PRL 80 (1998) 2550

Berkeley:

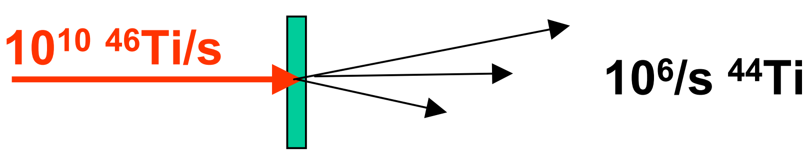



Norman et al. PRC57 (1998) 2010

# National Superconducting Cyclotron Facility at Michigan State University

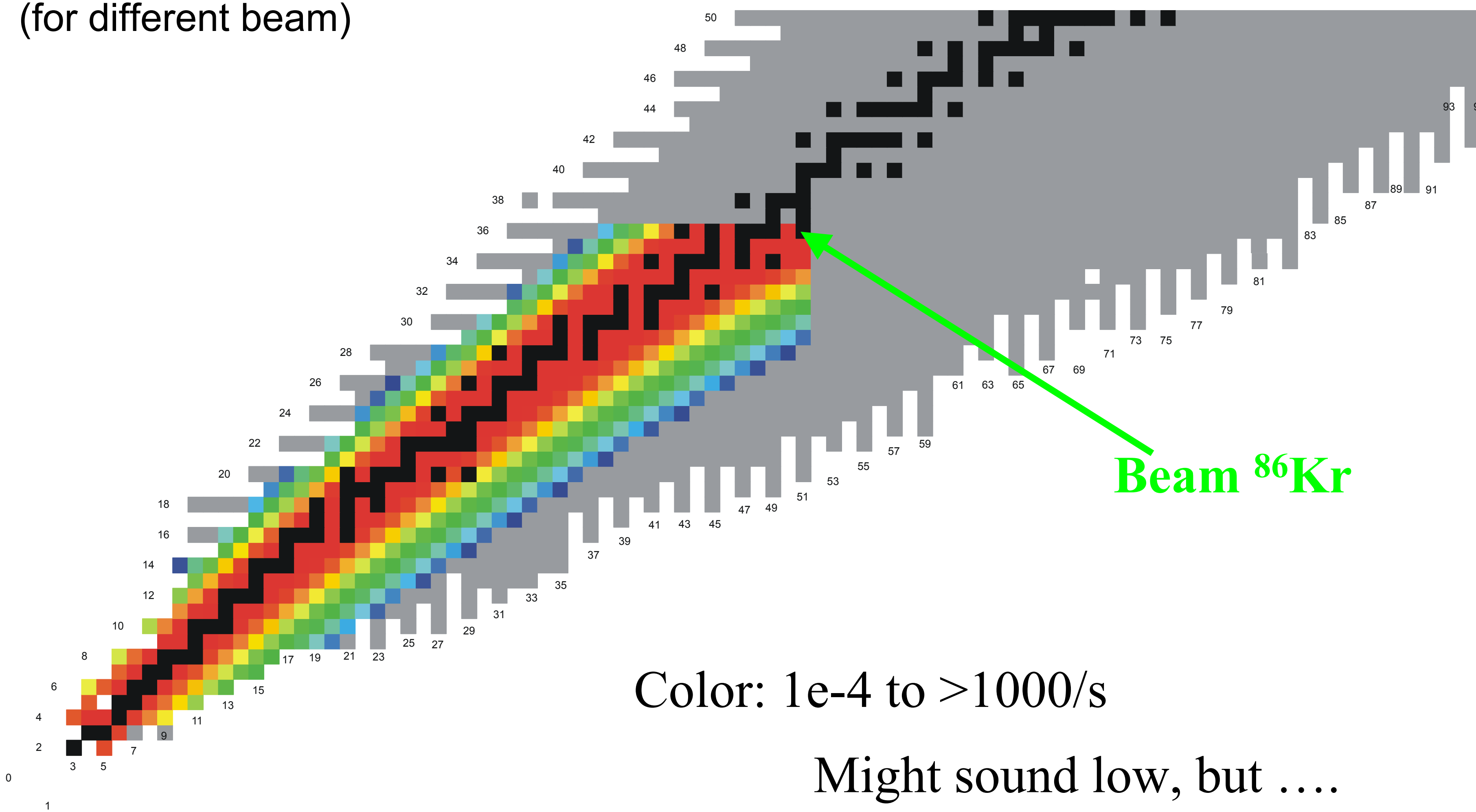



Make $^{44}$Ti by fragmentation of $^{46}$Ti beam



# Fast beam feature 1: production of broad range of beams

Example: Fragmentation Technique
(for different beam)




Color: 1e-4 to >1000/s

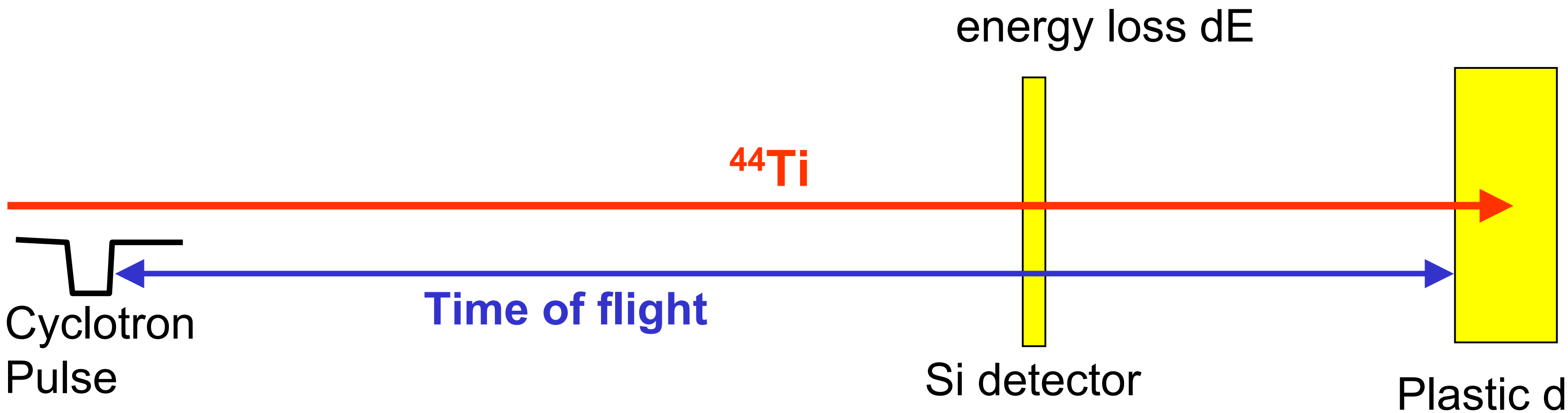
Might sound low, but ….

## Method 2:

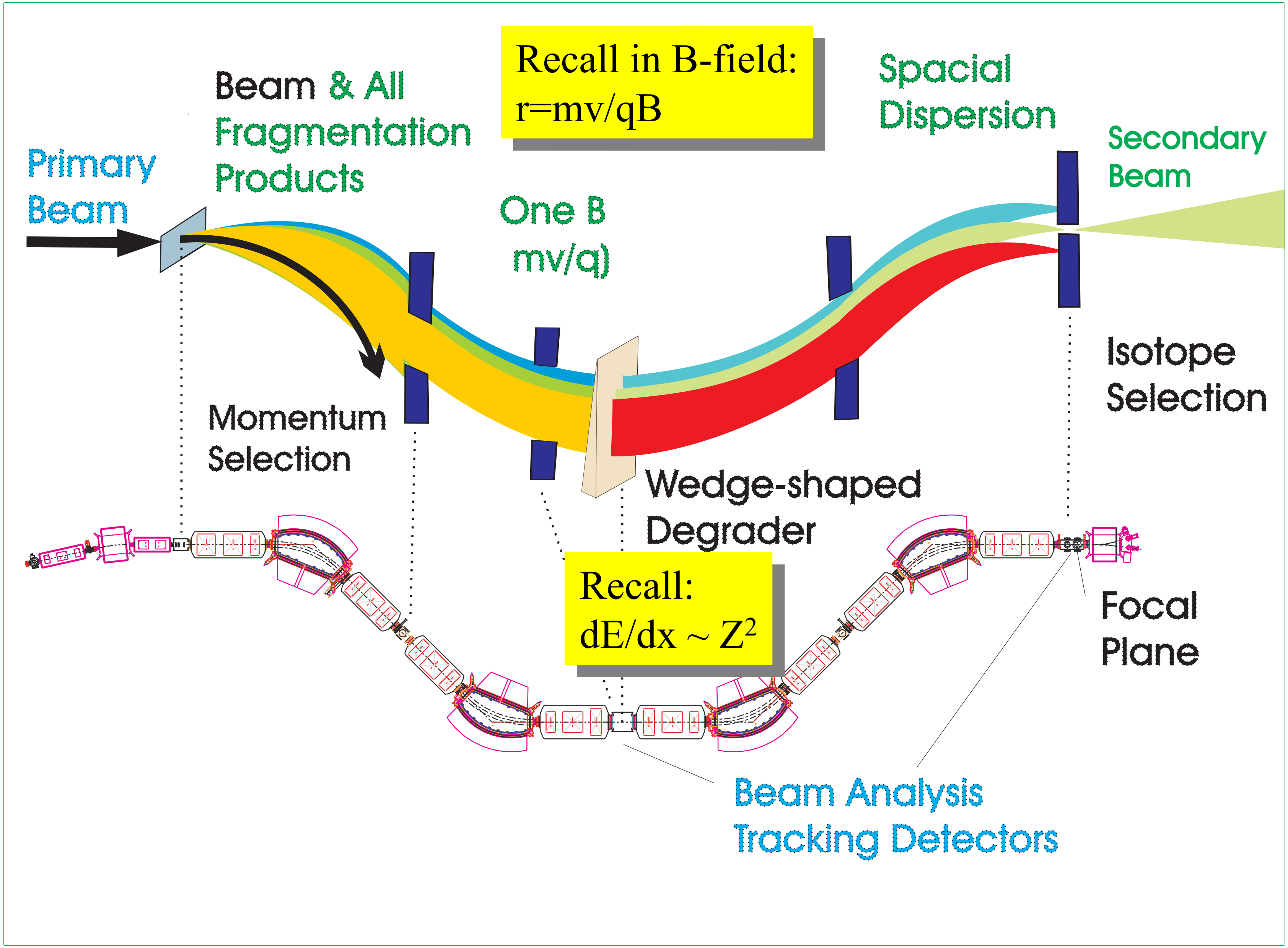
Measure A AND $N_0$ at a one time $$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$$

**Standard Setup:**

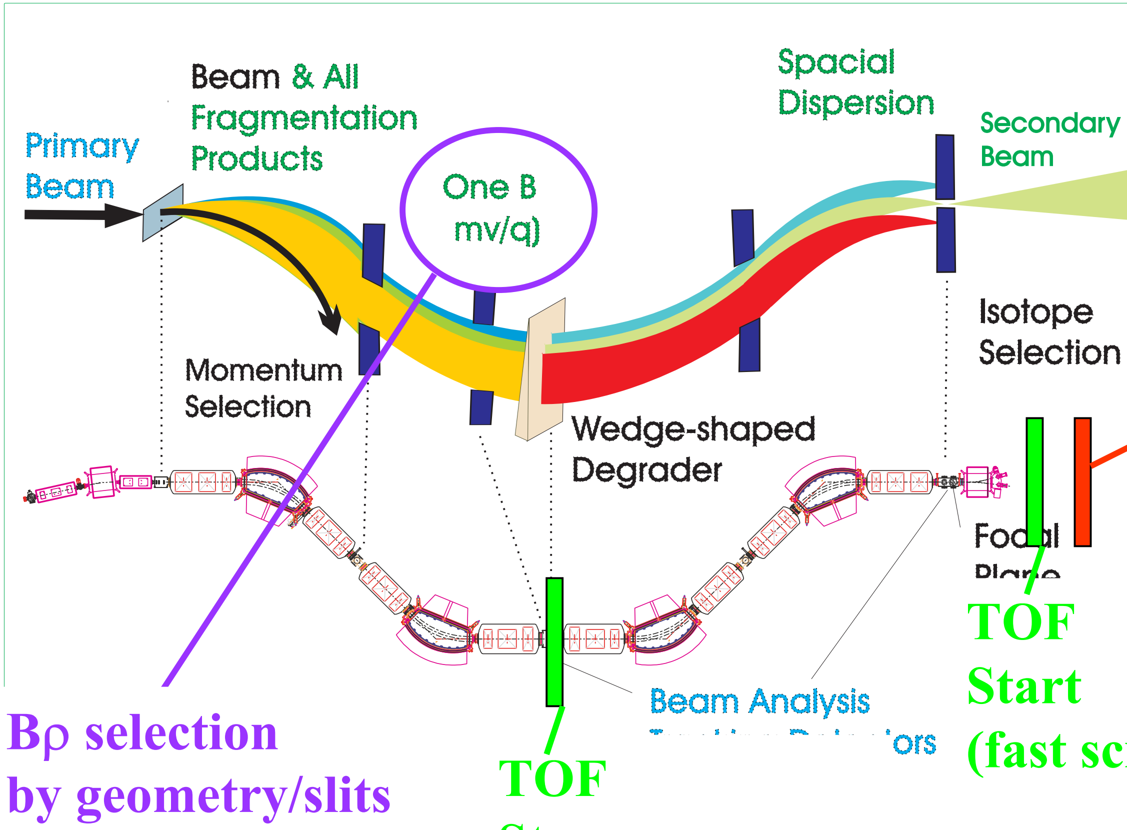

**Use this setup from time to time:**



# Fast beam feature 2: high selectivity – step1: Separator



# Fast beam feature 2: high selectivity – step2: Particle ID




Energy loss dE (Si-PIN diode or ionization chamber)

TOF Start (fast scintillator)

Bρ selection by geometry/slits and fields

TOF Stop (fast scintillator)

<u>measure m/q:</u>

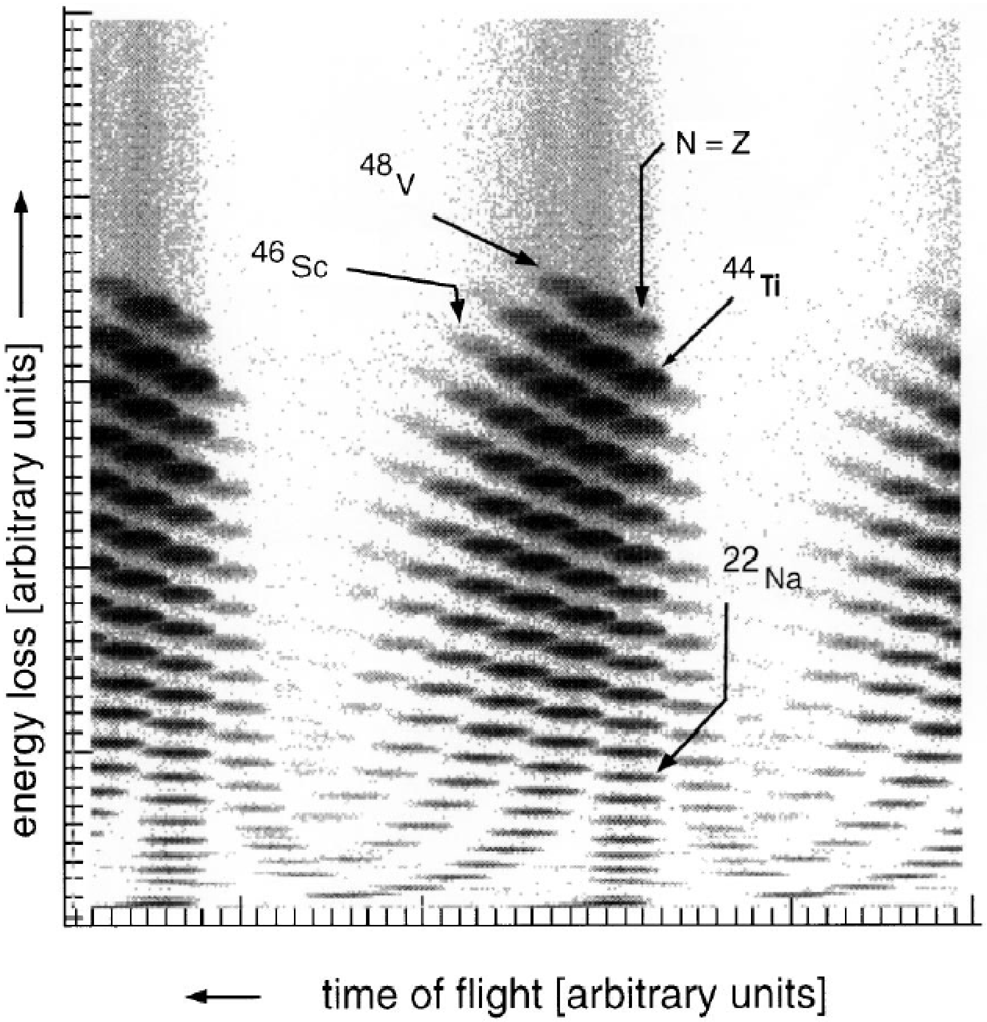
Bρ = mv/q (relativistic Bρ=γmv/q !)

m/q = **Bρ**/v

└ v=d/**TOF**

<u>Measure Z:</u>

$dE \sim Z^2$



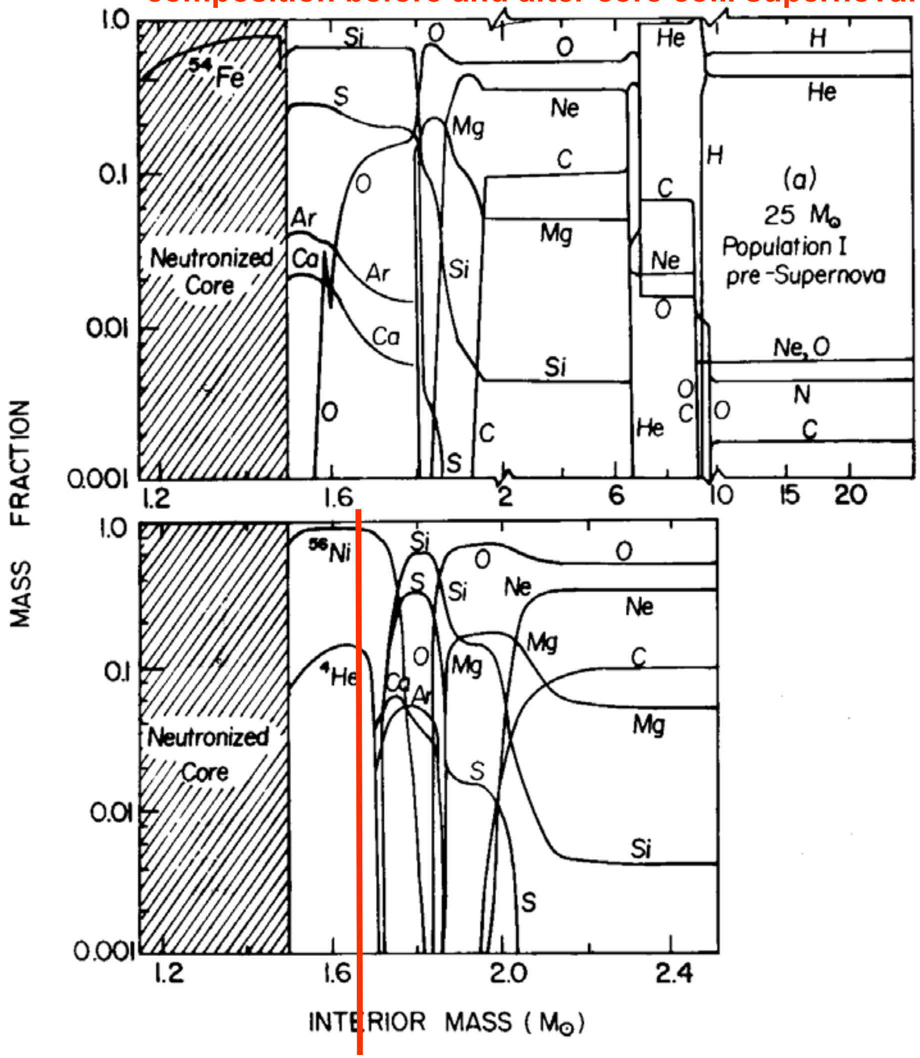

→ determine number of implanted $^{44}$Ti

→ 60.3 +- 1.3 years        Goerres et al. Phys. Rev. Lett. 80 (1998) 2554

# Explosive Nucleosynthesis

Shock wave rips through star and compresses and heats all mass regions

**composition before and after core coll. supernova:**




**mass cut somewhere here**

**not ejected | ejected**

## Explosive C-Si burning

- similar final products
- BUT weak interactions unimportant for >= Si burning (but key in core !!!)\
- BUT somewhat higher temperatures
- BUT Ne, C incomplete (lots of unburned material)

<u>Explosive Si burning:</u>

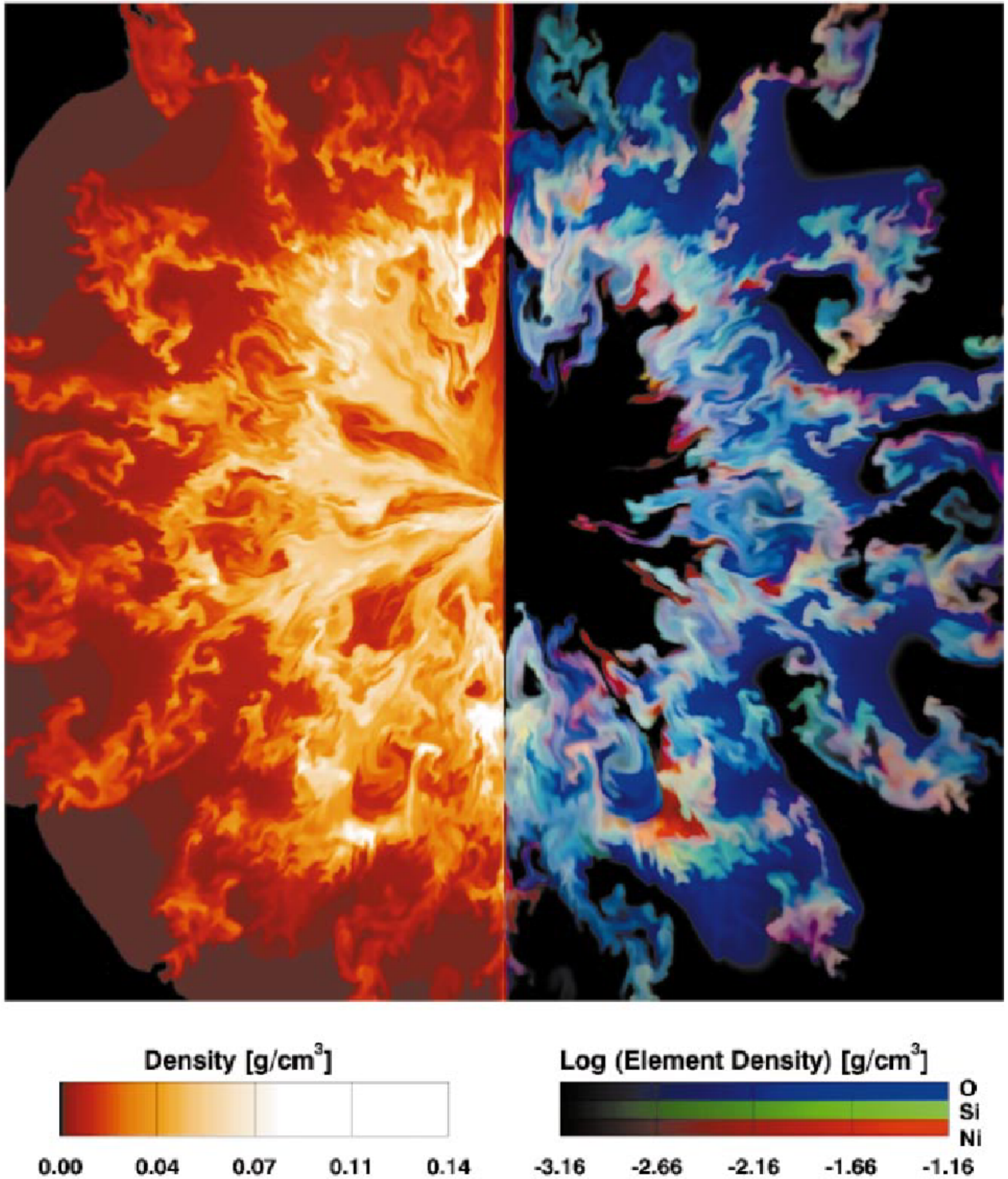
Deepest layer: full NSE $^{28}Si \rightarrow {}^{56}Ni$

Further out: $\alpha$-rich freezeout

- density low, time short → 3$\alpha$ cannot keep up and $\alpha$ drop out of NSE (but a lot are made from 2p+2n !)
- result: after freezeout lots of $\alpha$ !
- fuse slower – once one $^{12}C$ is made quickly captures more

→ result: lots of $\alpha$-nuclei ($^{44}Ti$ !!!)

# The “mass zones” in “reality”:




1170s after explosion, 2.2Mio km width, after Kifonidis et al. Ap.J.Lett. 531 (2000) 123L

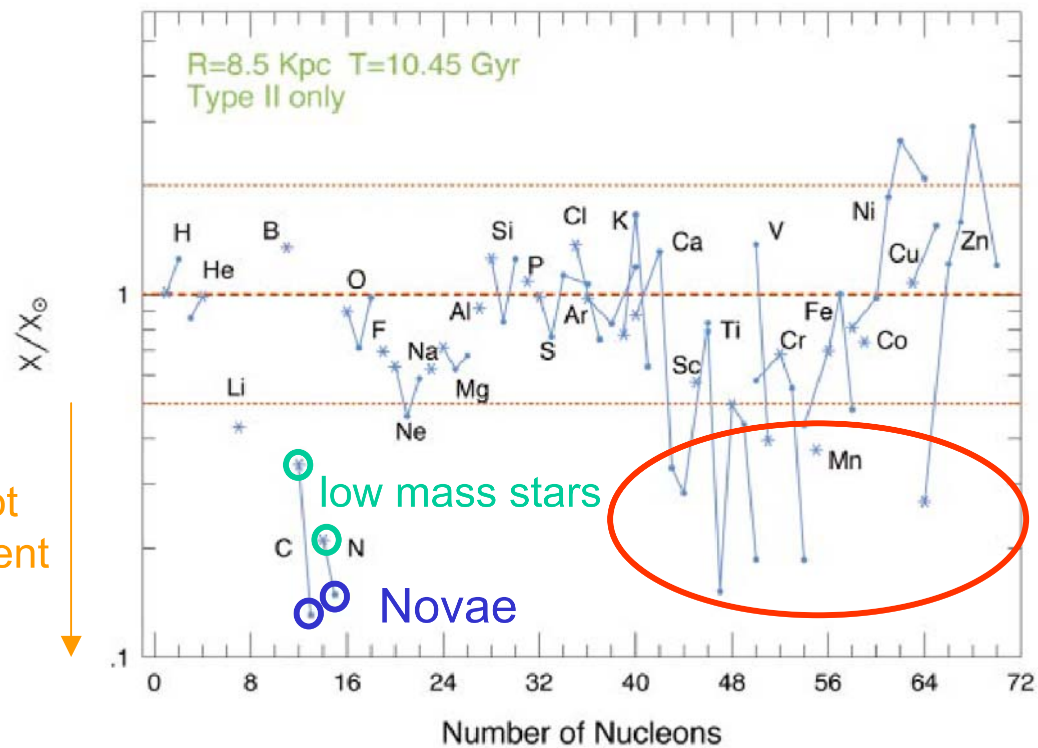
# Contribution of Massive Stars to Galactic Nucleosynthesis

**Displayed is the overproduction factor $X/X_{solar}$**

This is the fraction of matter in the Galaxy that had to be processed through the scenario (massive stars here) to account for todays observed solar abundances.

**To explain the origin of the elements one needs to have**

- **constant overproduction** (then the pattern is solar)
- **sufficiently high overproduction** to explain total amount of elements observed today

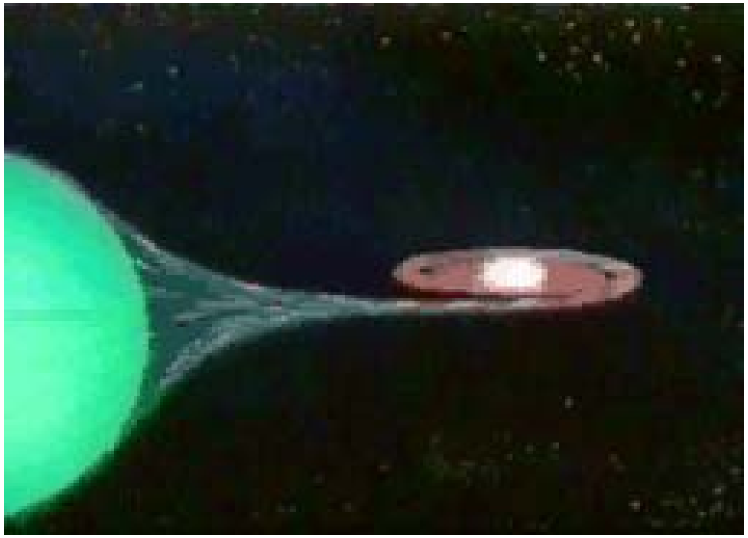



“Problem” zone these nuclei are not produced in sufficient quantities

Type Ia supernovae

calculation with grid of massive stars 11-40$M_0$ (from Woosley et al. Rev. Mod. Phys. 74 (2002)1015)

# Type Ia supernovae

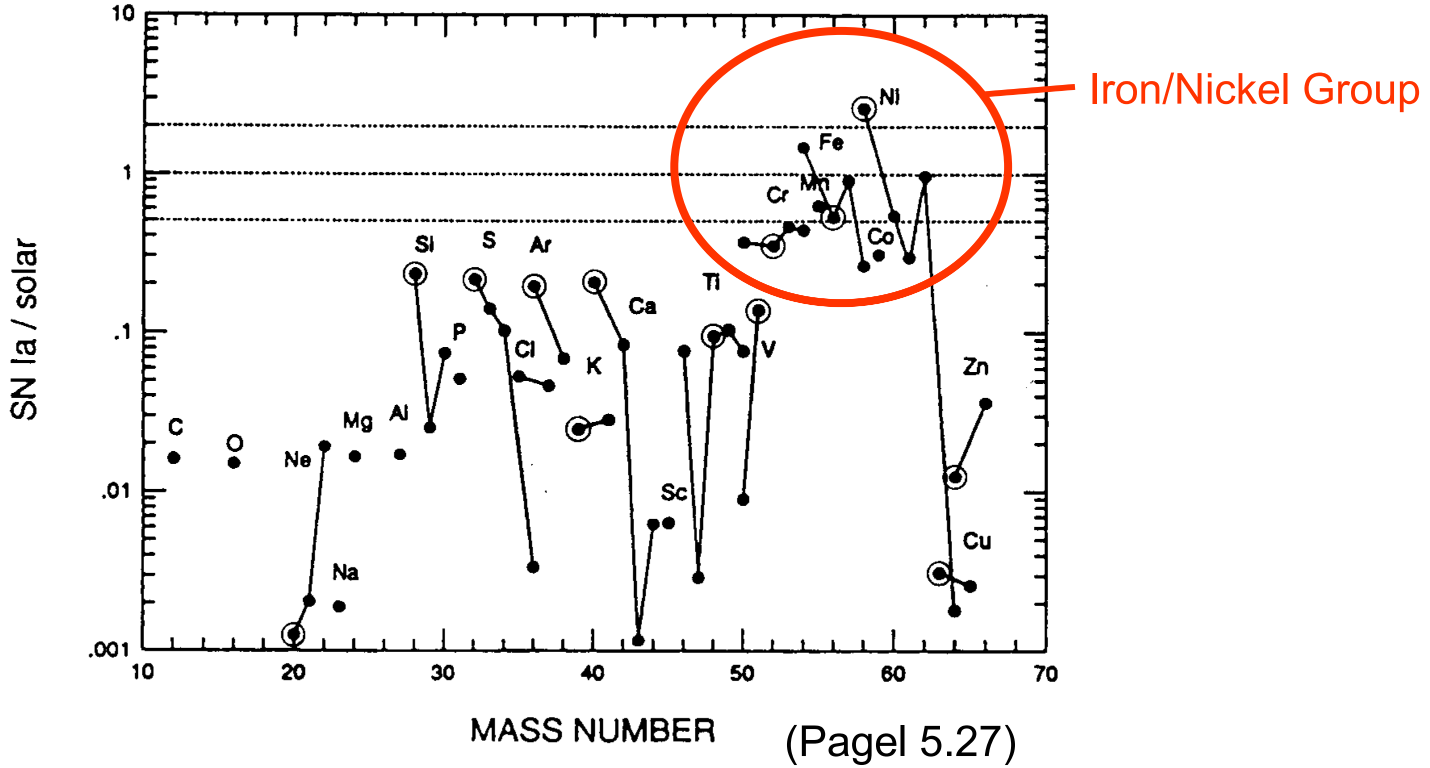


white dwarf accreted matter and grows beyond the Chandrasekhar limit

→ star explodes – no remnant

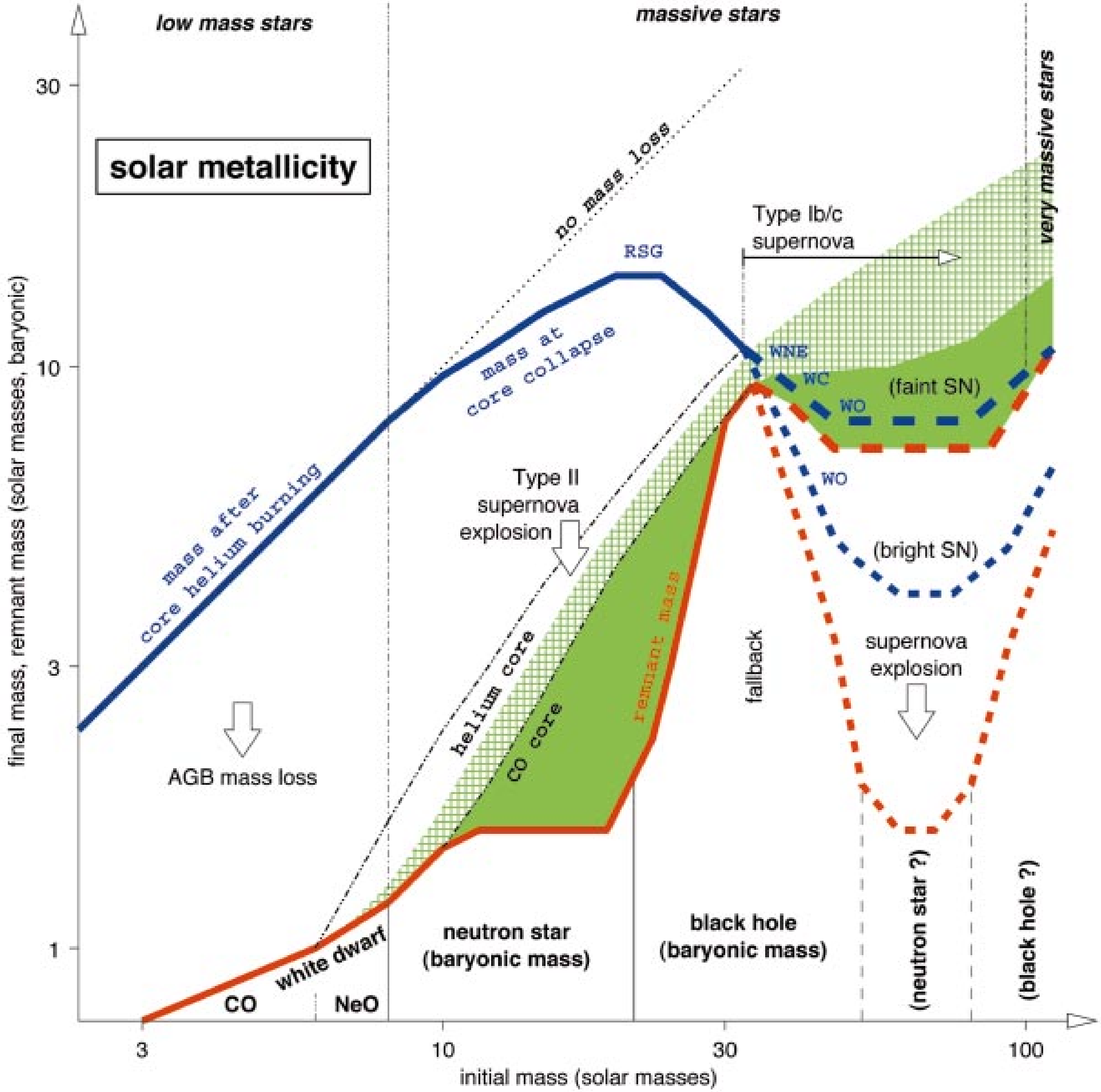
# Nucleosynthesis contribution from type Ia supernovae

CO or ONeMg core ignites and burns to a large extent into NSE

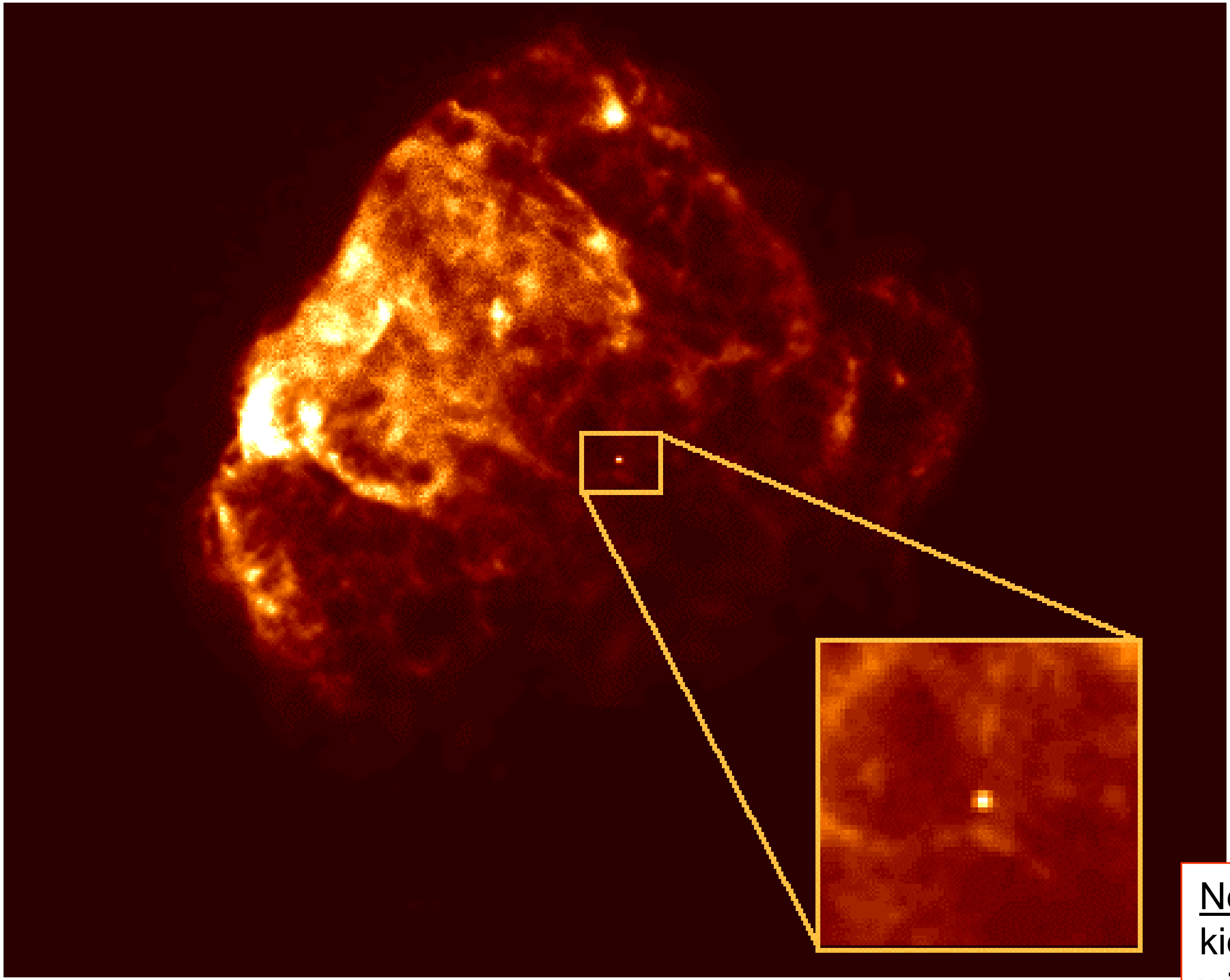



(Pagel 5.27)

# Mass loss and remnants



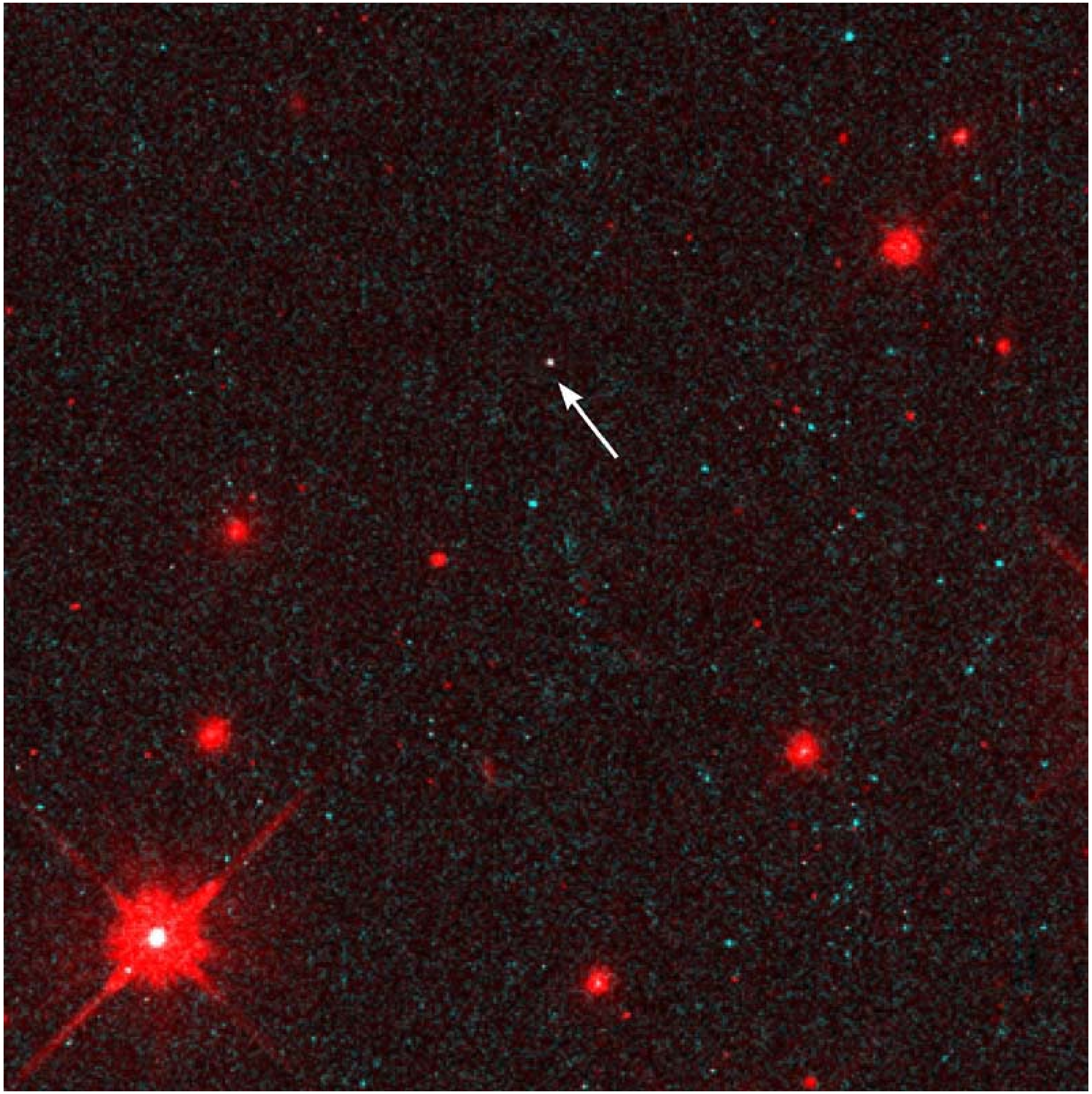
# Supernova remants – neutron stars



Neutron star
kicked out
with ~600 mi/s

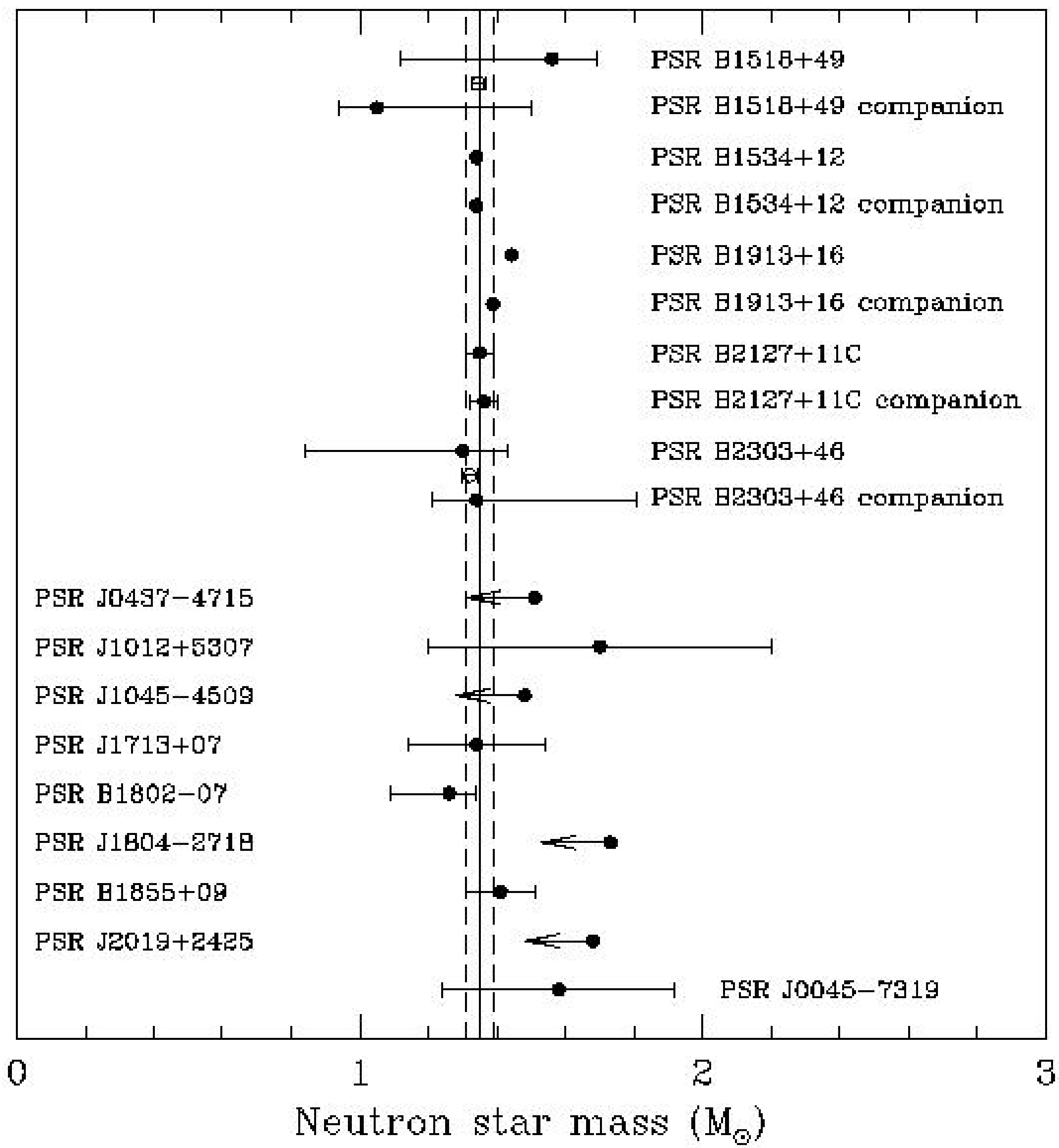
SN remnant Puppis A (Rosat)

An isolated neutron star seen with HST:



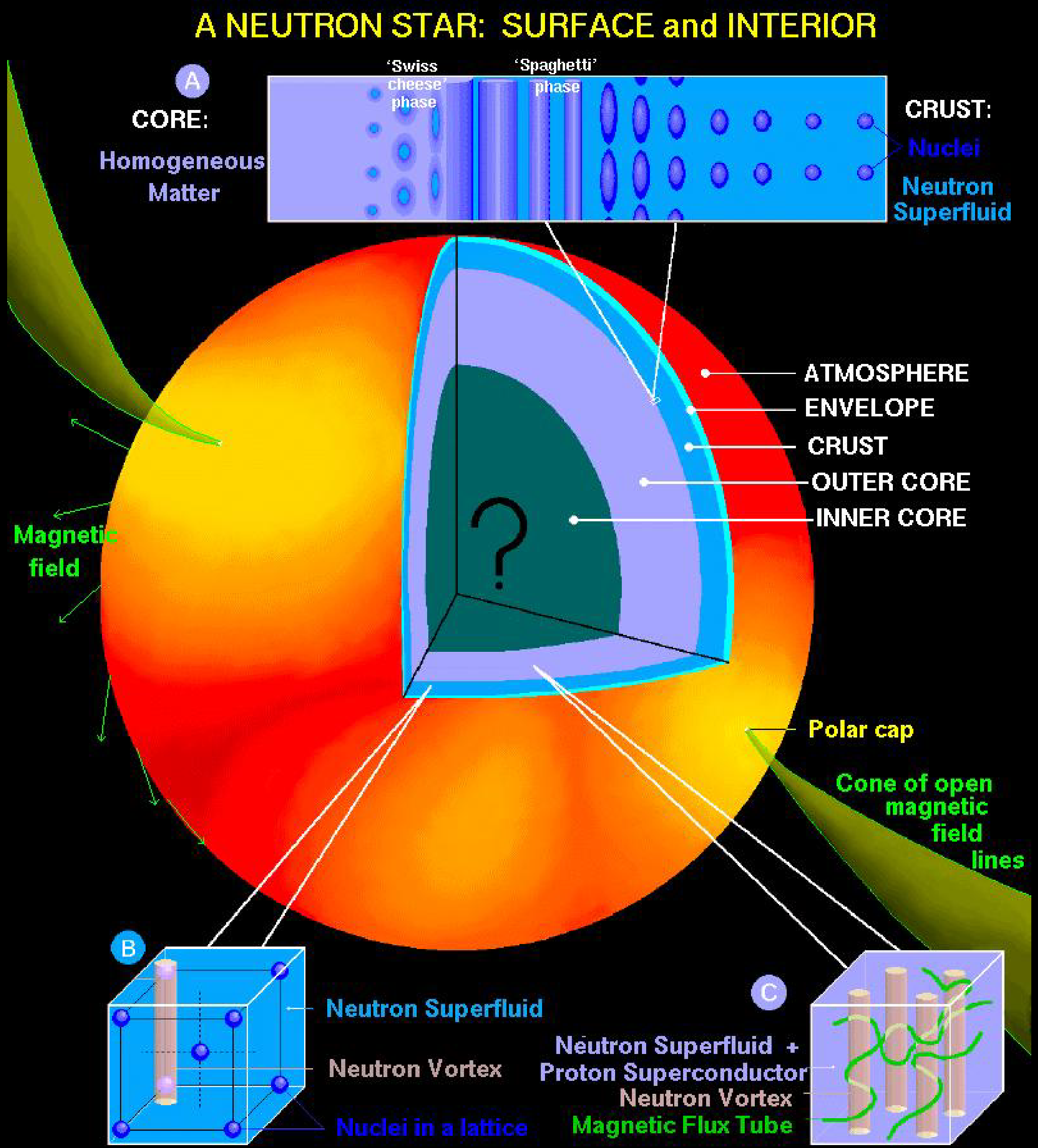
# Neutron star properties

Mass:




Radius:

**~10 km !**



A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid +
Proton Superconductor
Neutron Vortex
Magnetic Flux Tube