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 $p \sim n^{5/3}$).

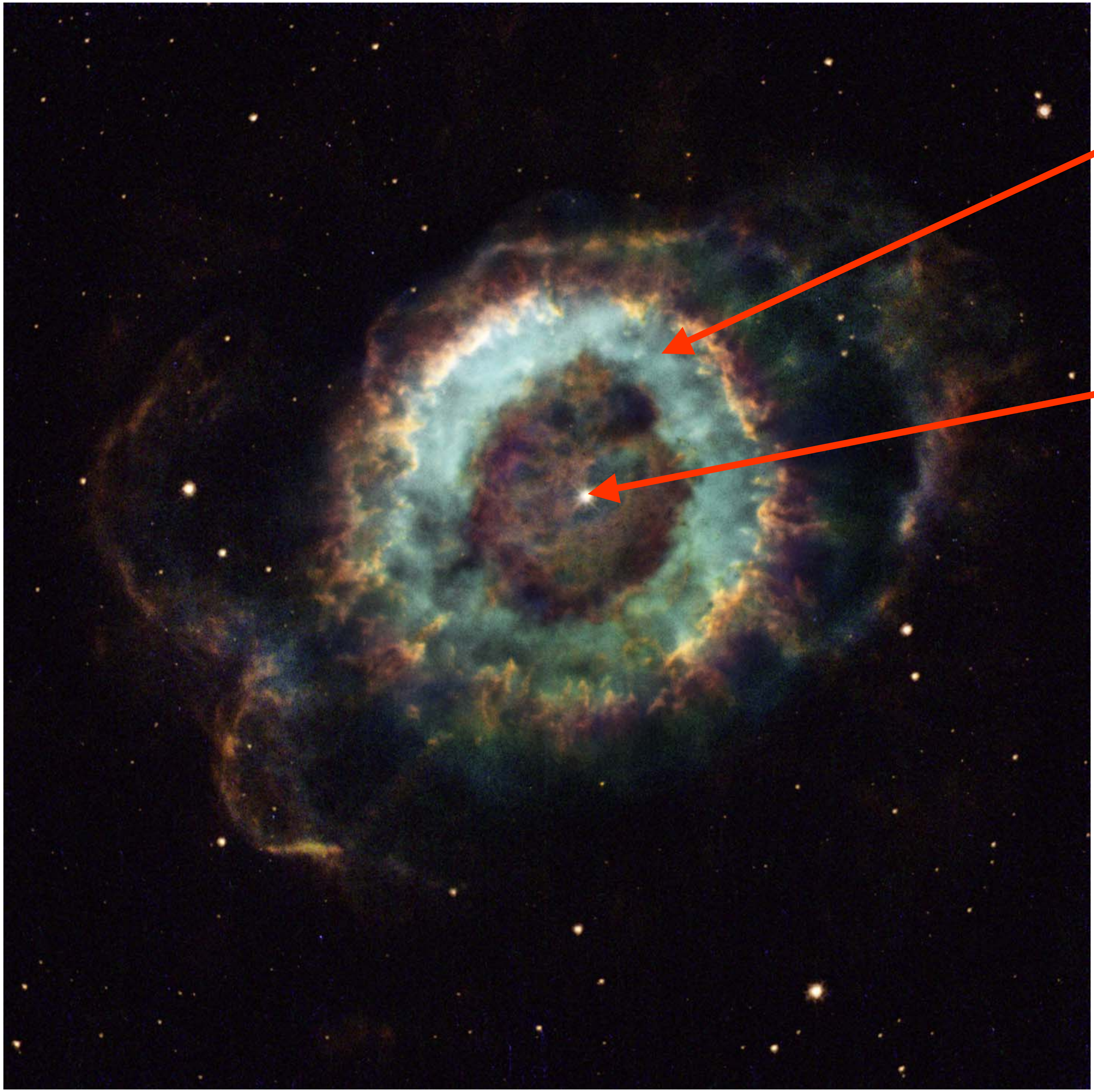
For N=Z $M_{Ch}=1.46\ M_0$

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- 8 M_0	He burning	C,O		
8-12 M_0	C burning	O,Ne,Mg		
> 8-12 M_0	Si burning	Fe	$M>M_{Ch}$	**collapse**

How can 8-12M_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”

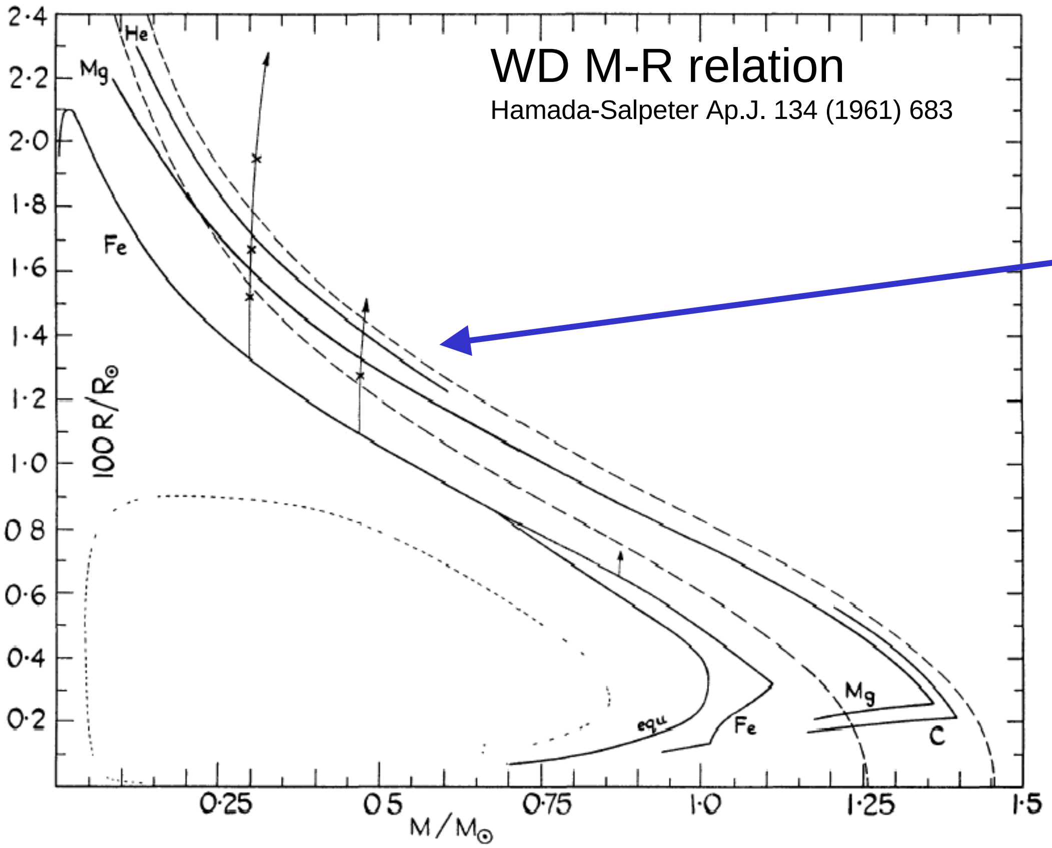
image: HST
Little Ghost Nebula
distance 2-5 kLy
blue: OIII
green: HII
red: NII

Why “white dwarf” ?

- core shrinks until degeneracy pressure sets in and halts collapse

→ star is HOT (gravitational energy !)

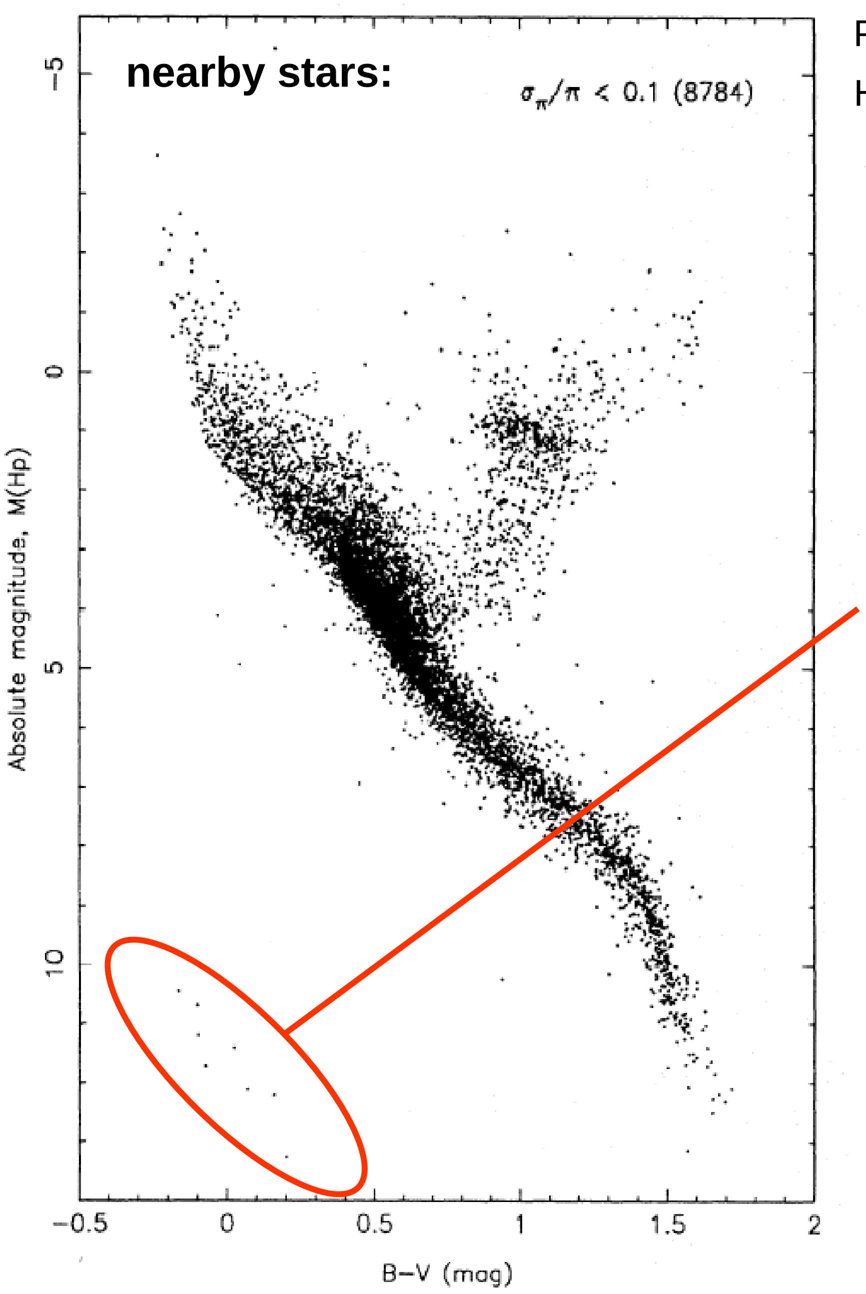
→ star is small



WD M-R relation

Hamada-Salpeter Ap.J. 134 (1961) 683

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

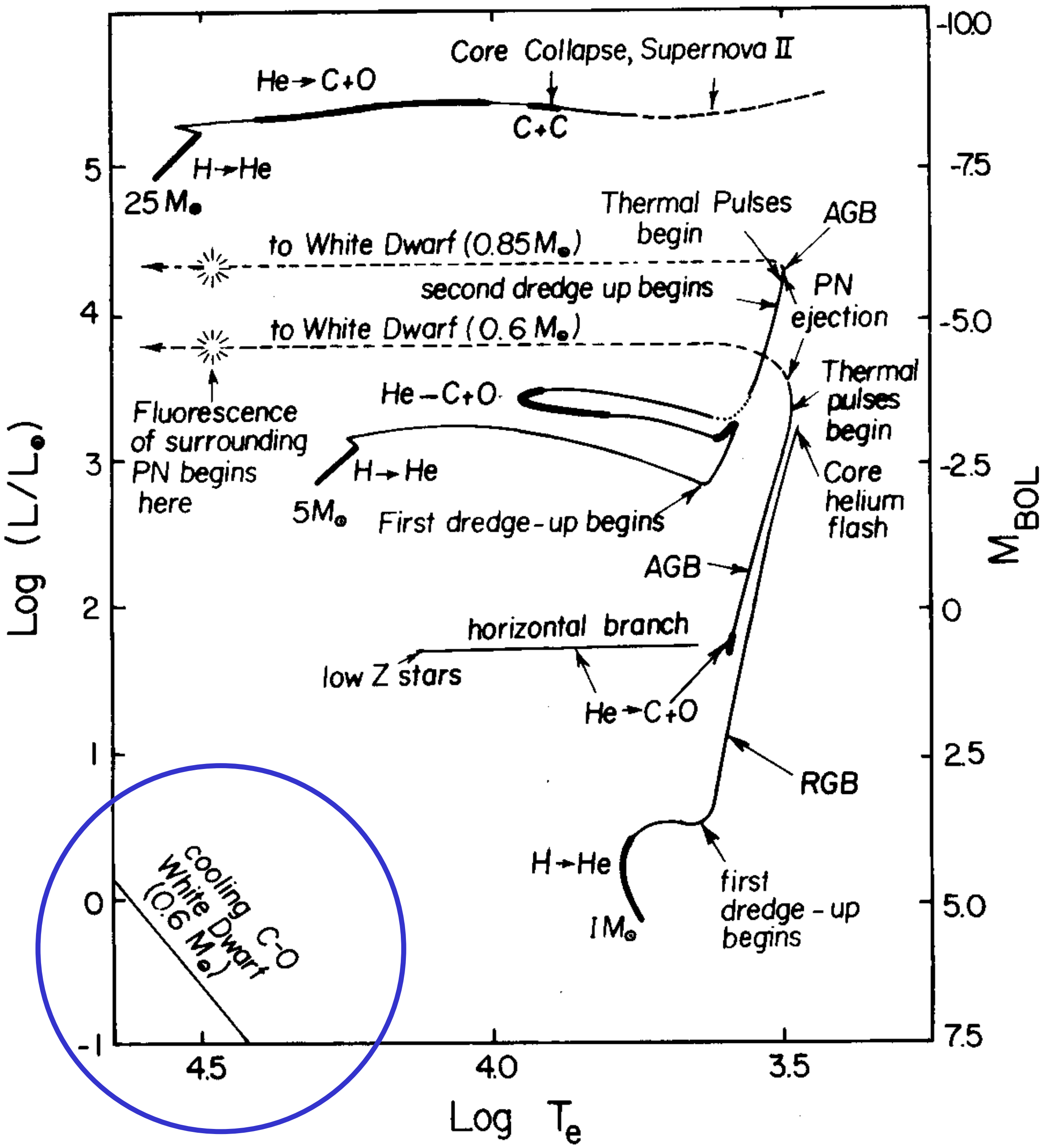


Perryman et al. A&A 304 (1995) 69

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:

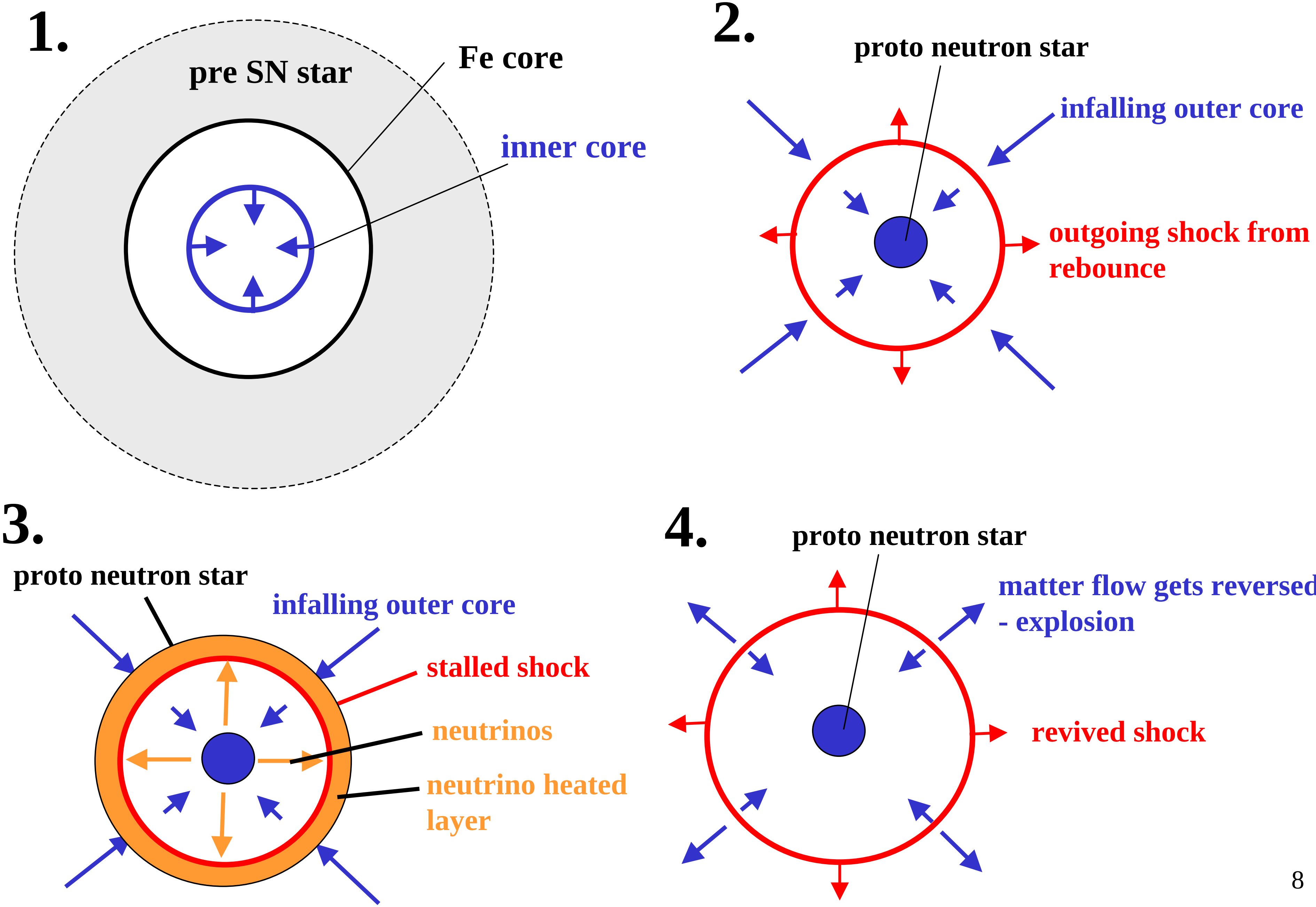
Further collapse heats star and CO or ONeMg burning ignites explosively

→ **Whole star explodes – no remnant**

b) collapsing Fe core in massive star (but not too massive) → neutron star

Fe cannot ignite, but collapse halted once densities of ~2x nuclear density are reached (repulsive nuclear force)

core collapse supernova mechanism



1.

pre SN star

Fe core

inner core

2.

proto neutron star

infalling outer core

outgoing shock from rebounce

3.

proto neutron star

infalling outer core

stalled shock

neutrinos

neutrino heated layer

4.

proto neutron star

matter flow gets reversed - explosion

revived shock

A star ready to die

Neutron
star forms
(size ~ 10 km radius)

Matter evaporated off the hot neutron star

r-process site ?

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: ~10^{51} ergs (= 1 foe = 1 Bethe)
Luminosity : ~10^{9-10} L_0

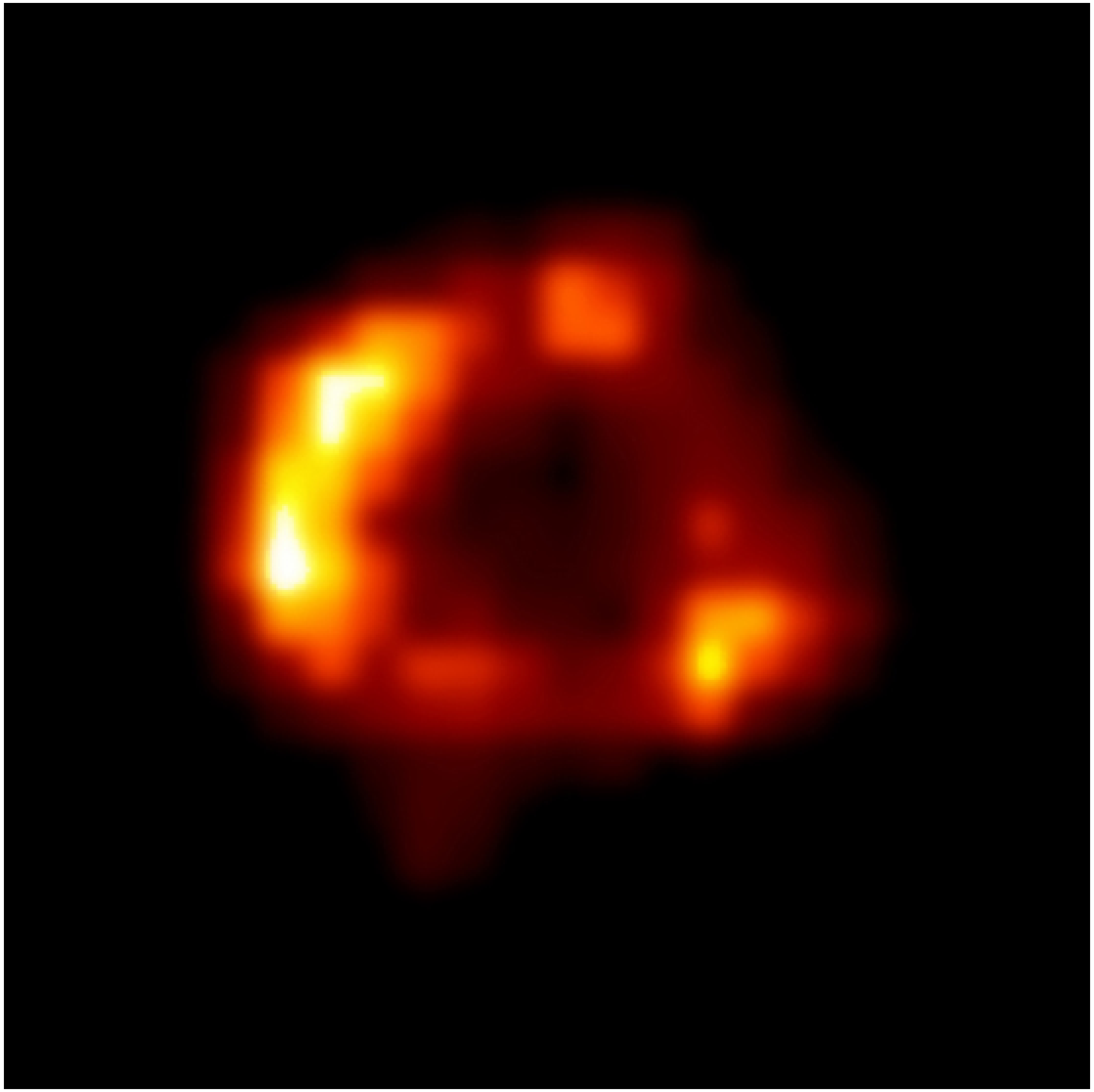
2. Frequency:

~ 1-10 per century and galaxy

Tarantula Nebula in LMC (constellation Dorado, southern hemisphere)
size: ~2000ly (1ly ~ 6 trillion miles), disctance: ~170000 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

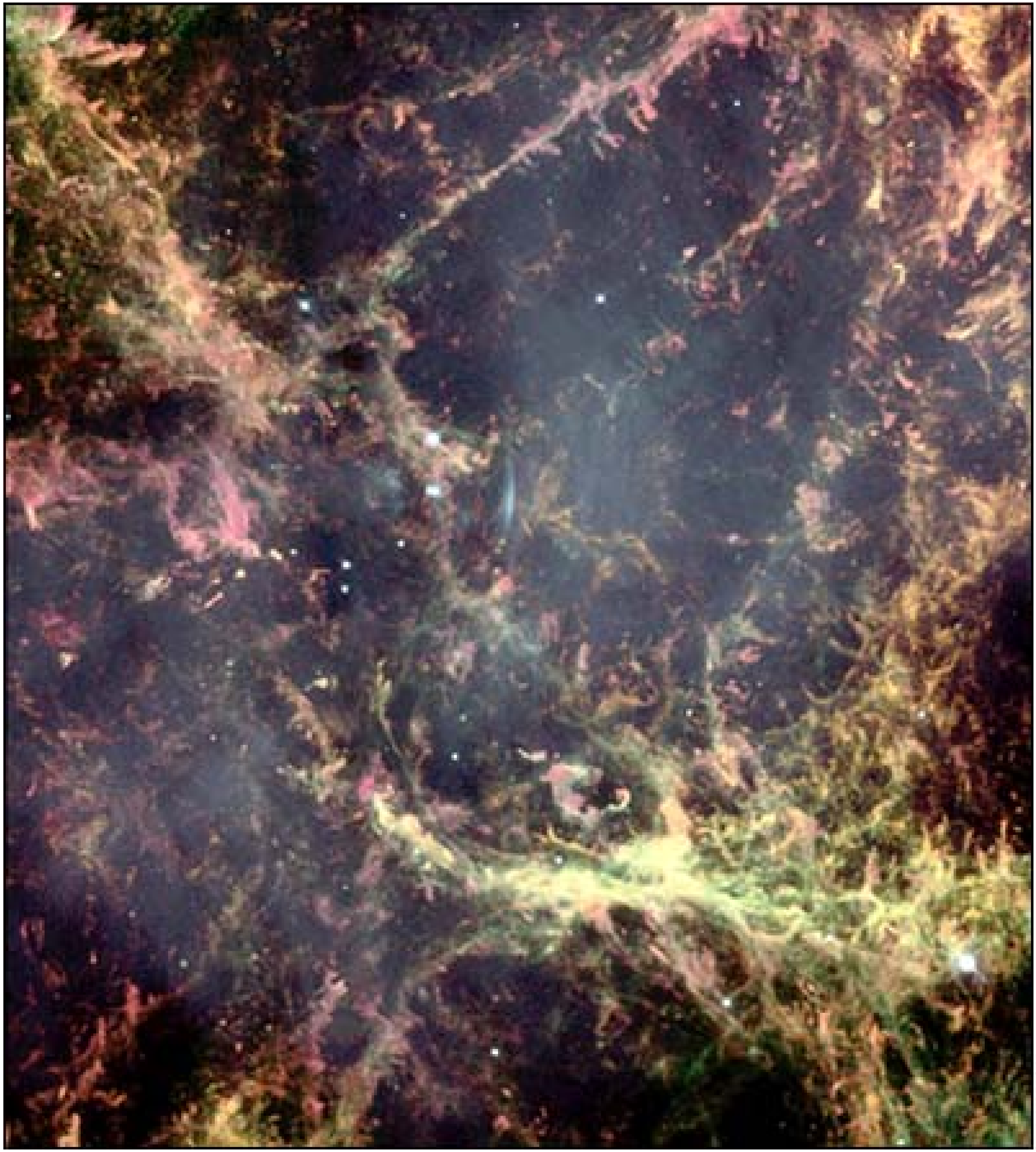


Shock wave hits inner ring of material and creates intense X-ray radiation

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

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

© European Southern Observatory

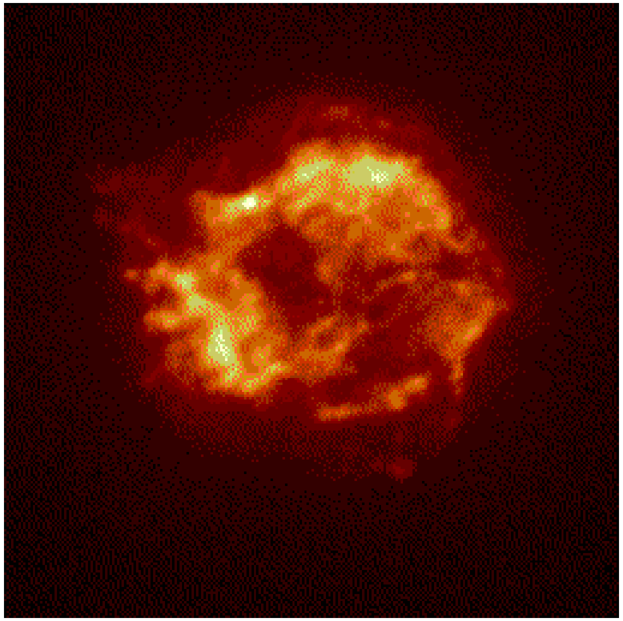

(NASA)

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

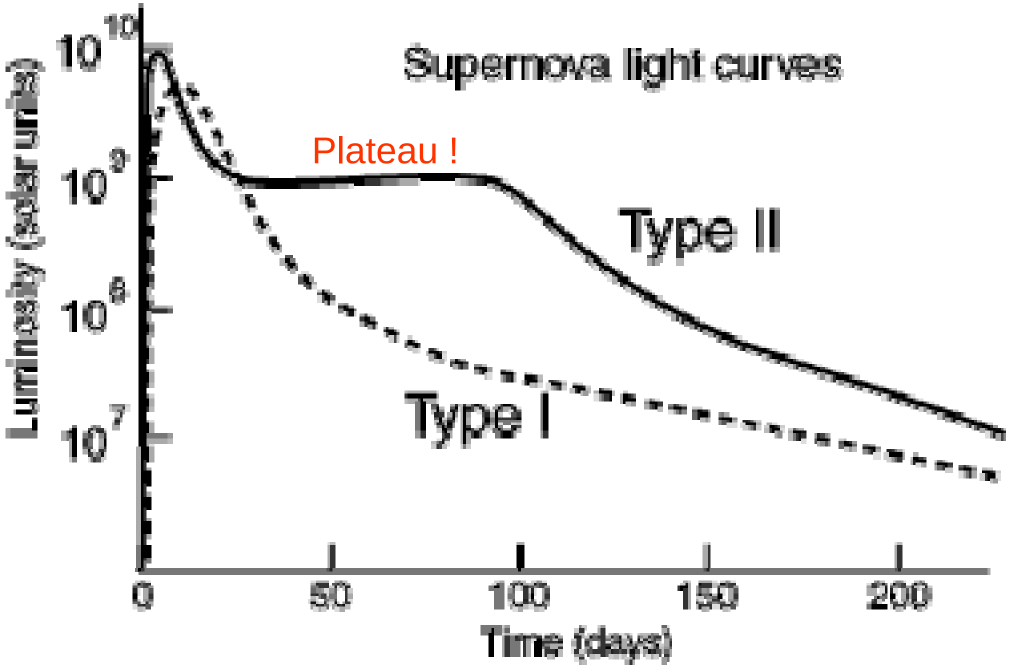
Why are there different types ? **Answer: progenitor stars are different**

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

Type I: 2 possibilities:

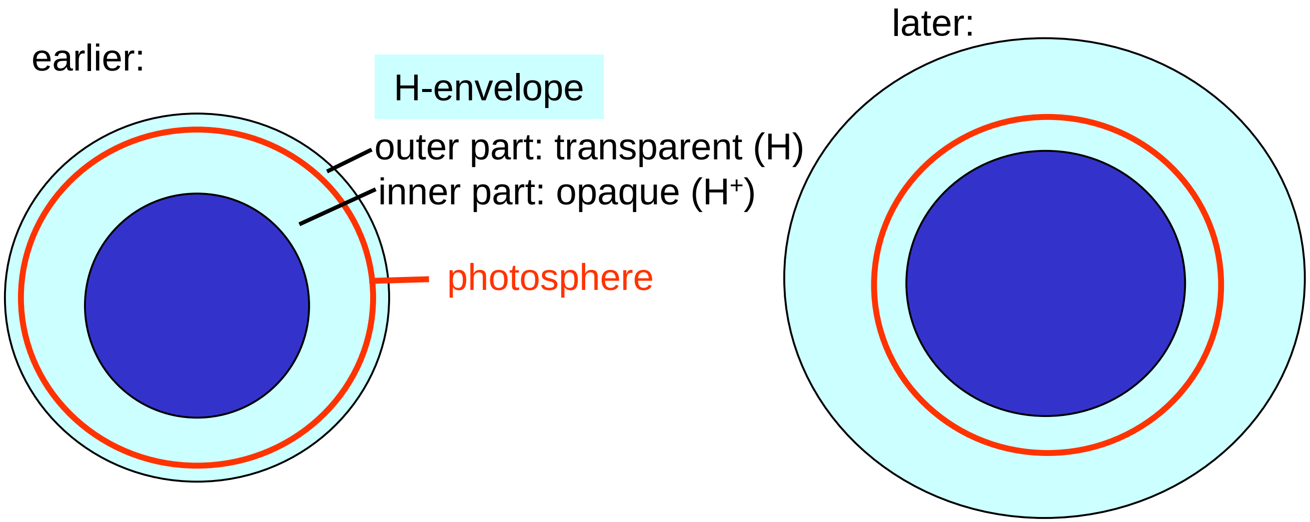
Ia: **white dwarf accreted** matter from companion

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:



earlier:

H-envelope

outer part: transparent (H)

inner part: opaque (H^+)

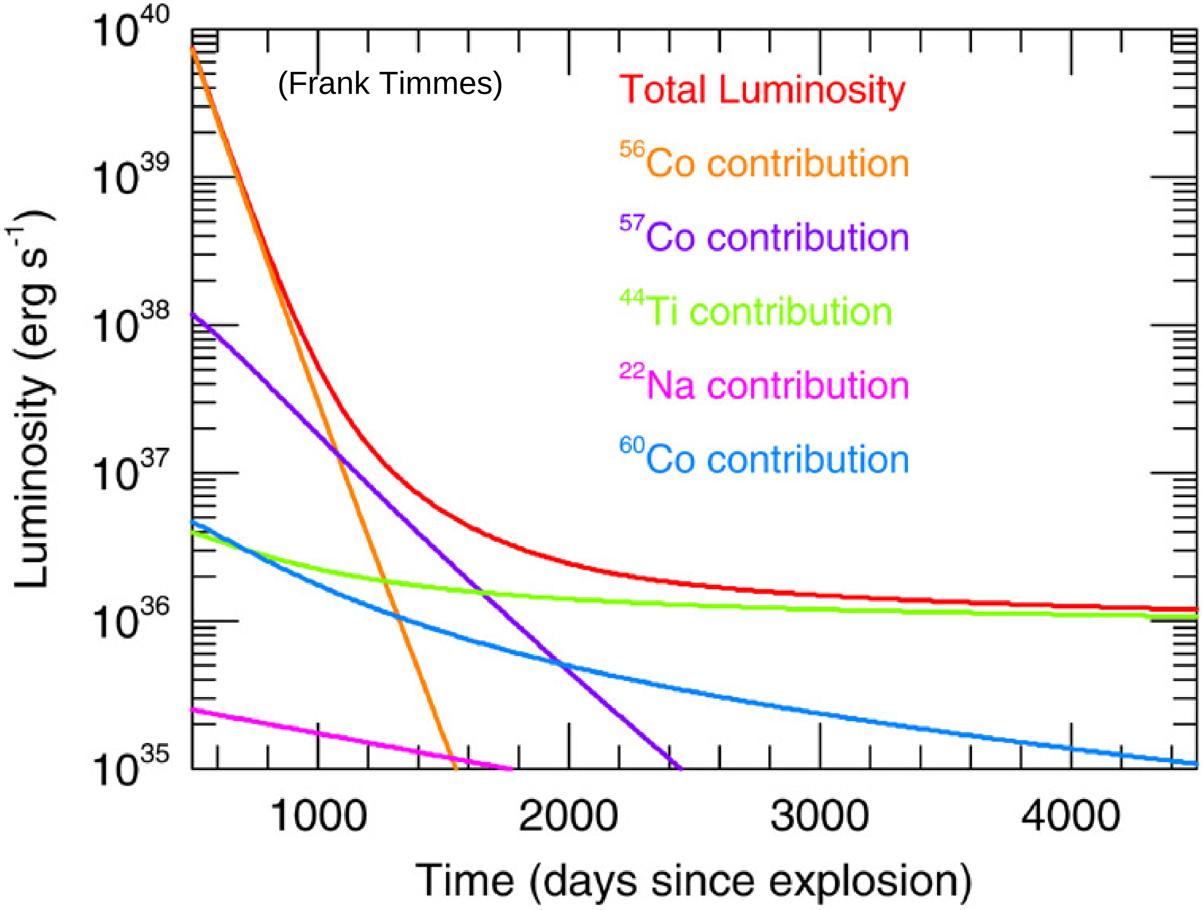
photosphere

later:

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)

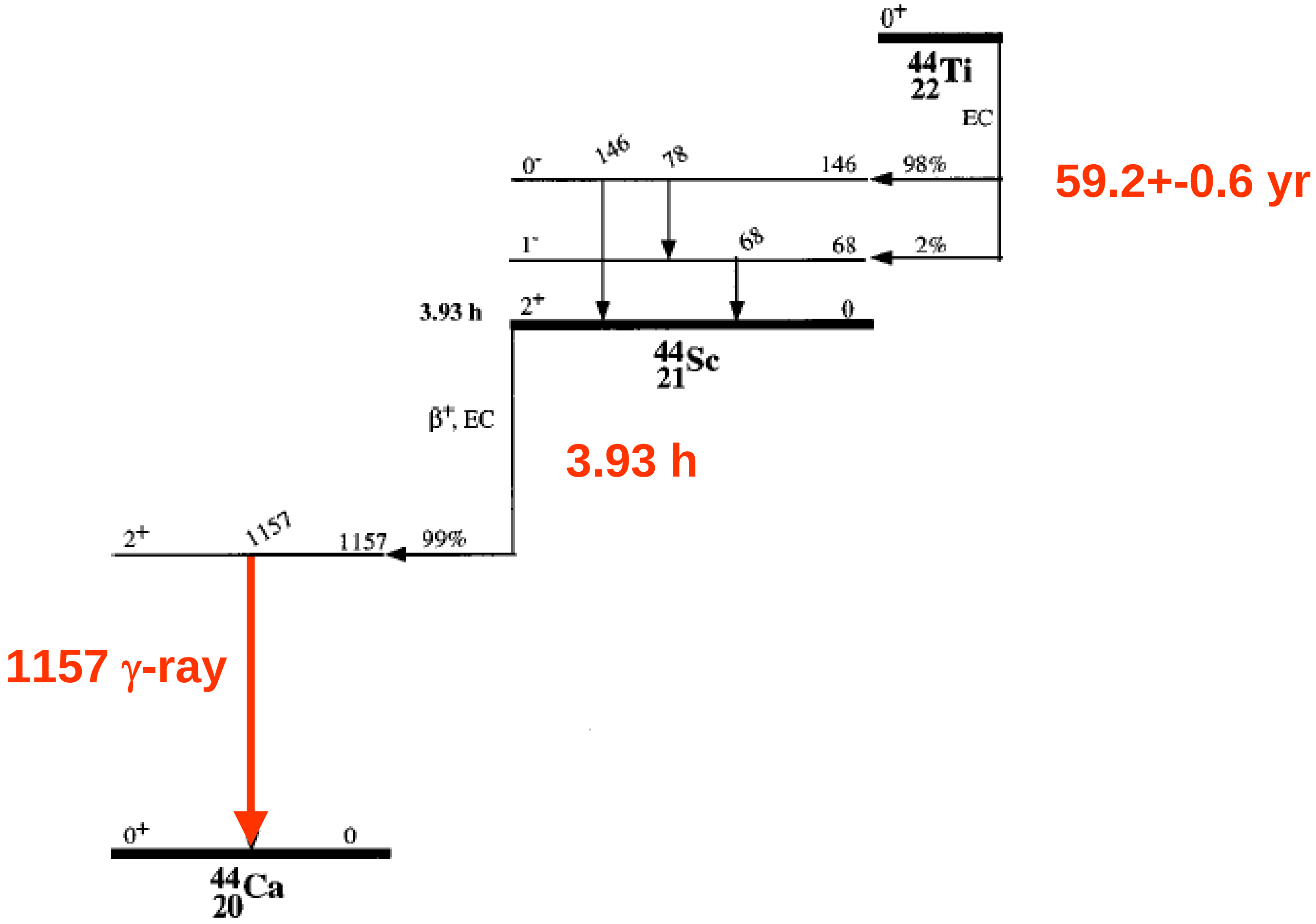
There is another effect that extends SN light curves: Radioactive decay !

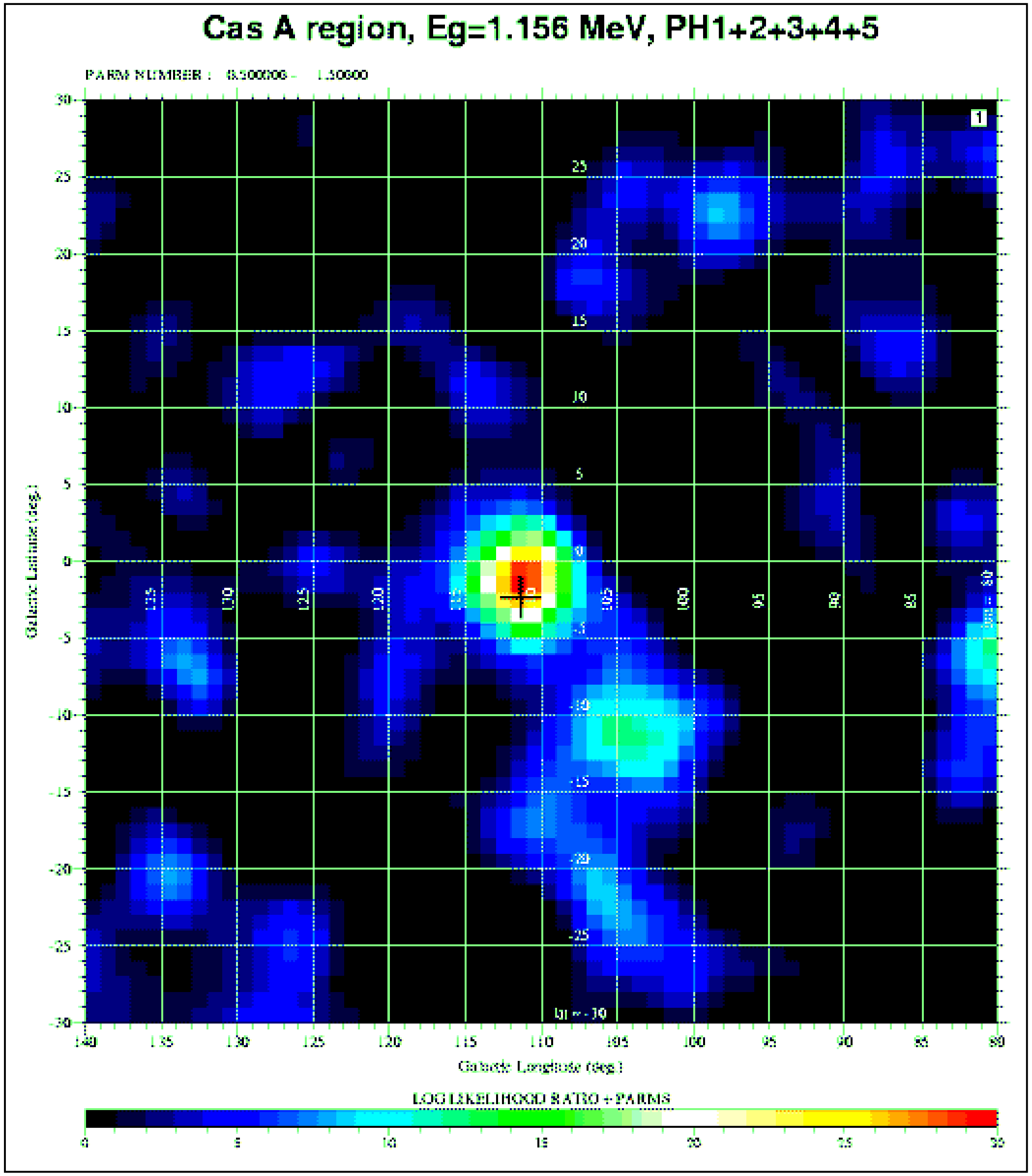


→ Radioactive isotopes are produced during the explosion

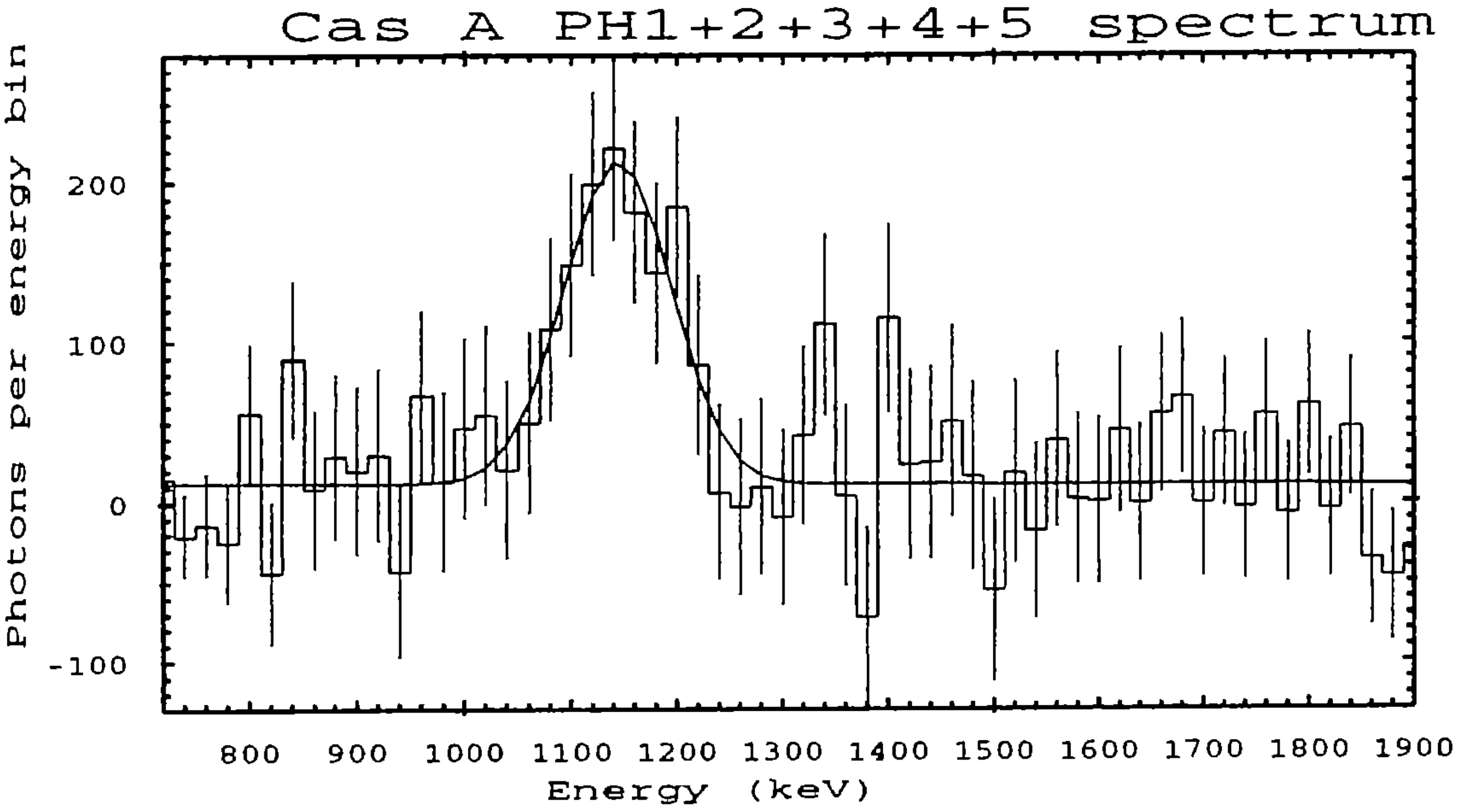
→ there is explosive nucleosynthesis !

44Ti


0+
$^{44}_{22}$Ti
EC
0-
146
78
146
98%
59.2+-0.6 yr
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



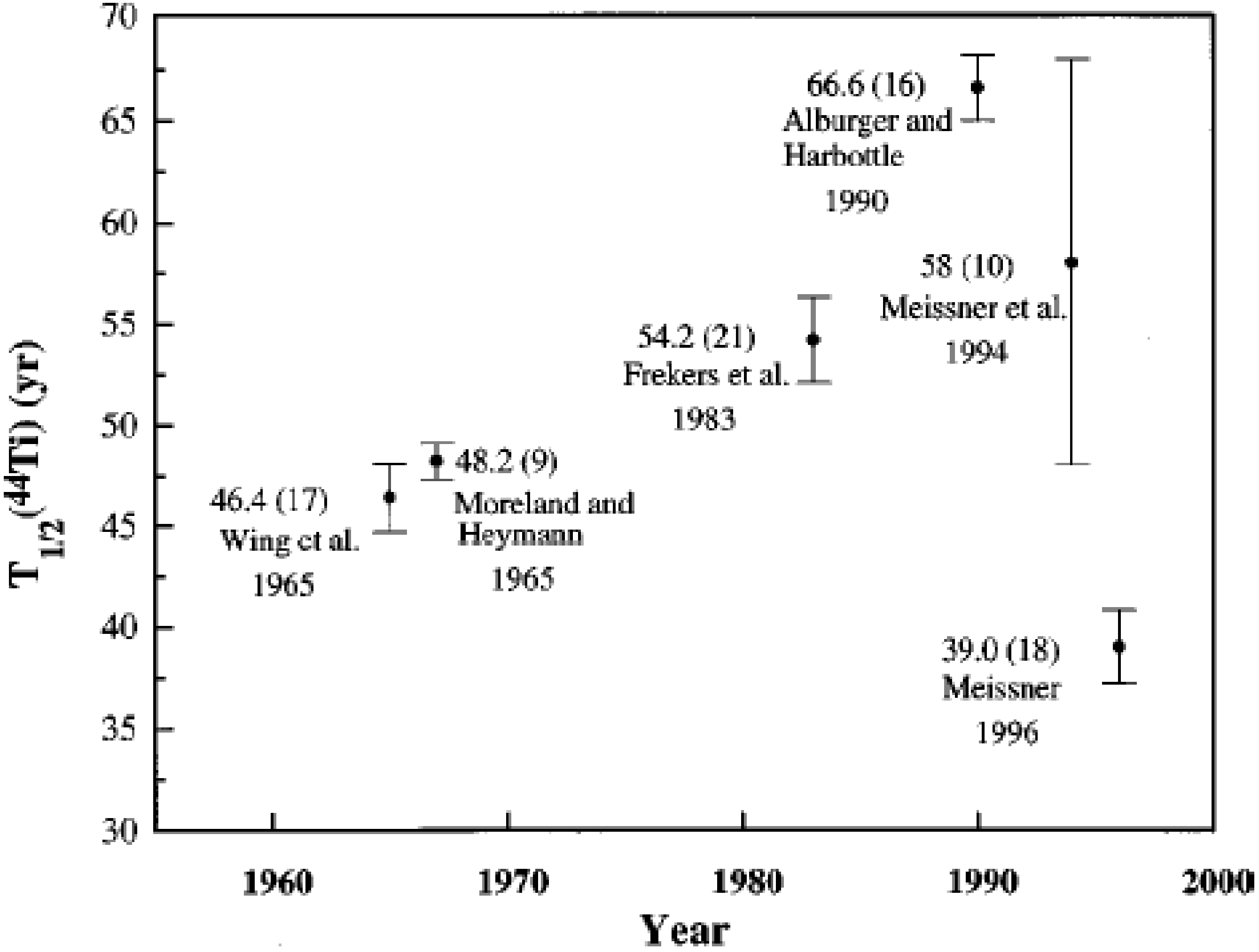
Distance 10,000 ly



Iyudin et al. 1997

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:

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

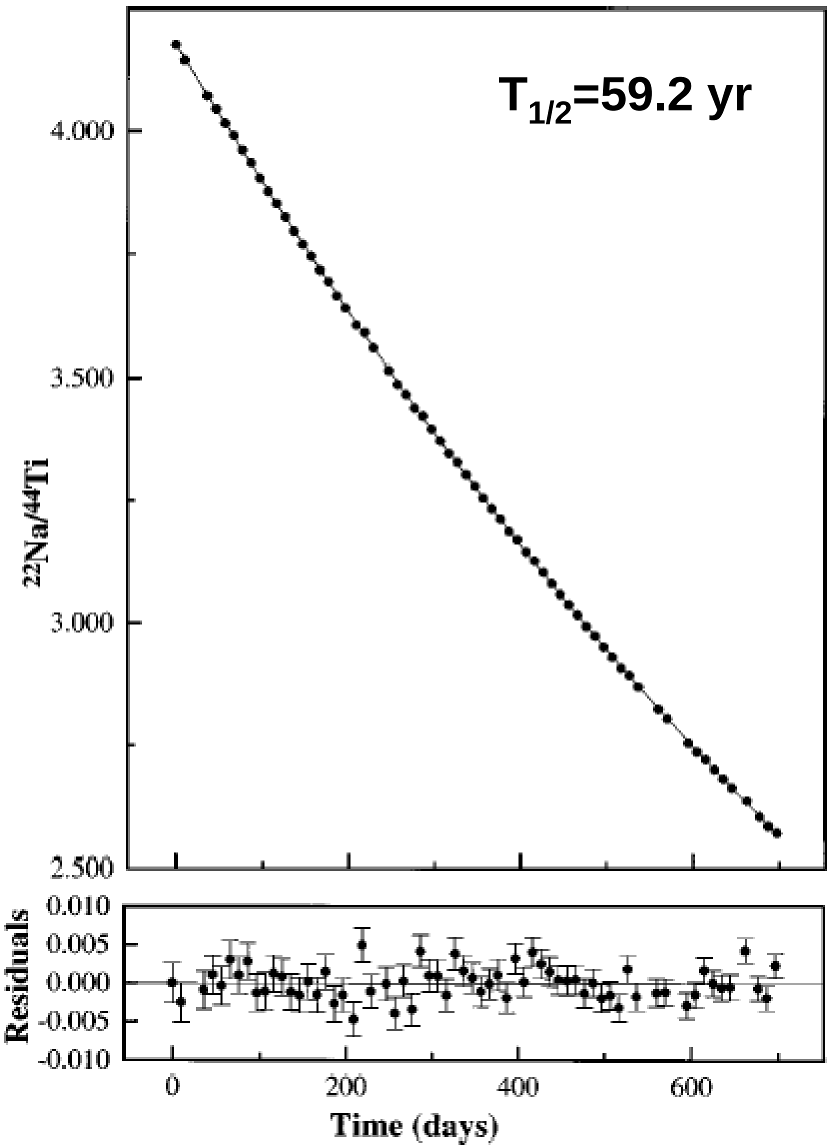
activity = decays per second:

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

Measure A with γ-ray detector as a function of time A(t) to determine N_0 and λ

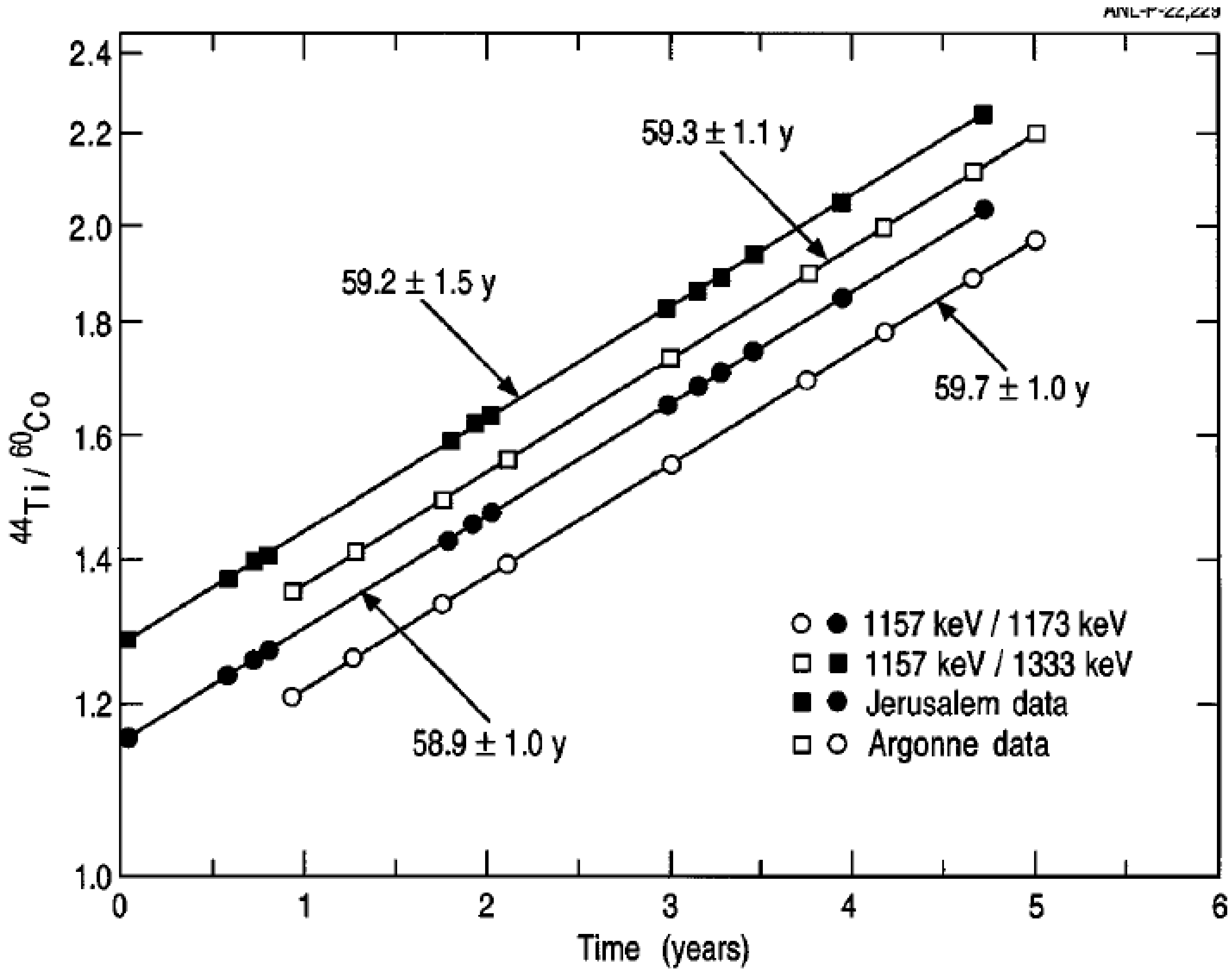
$$\lambda = \frac{\ln 2}{T_{1/2}}$$

Berkeley:



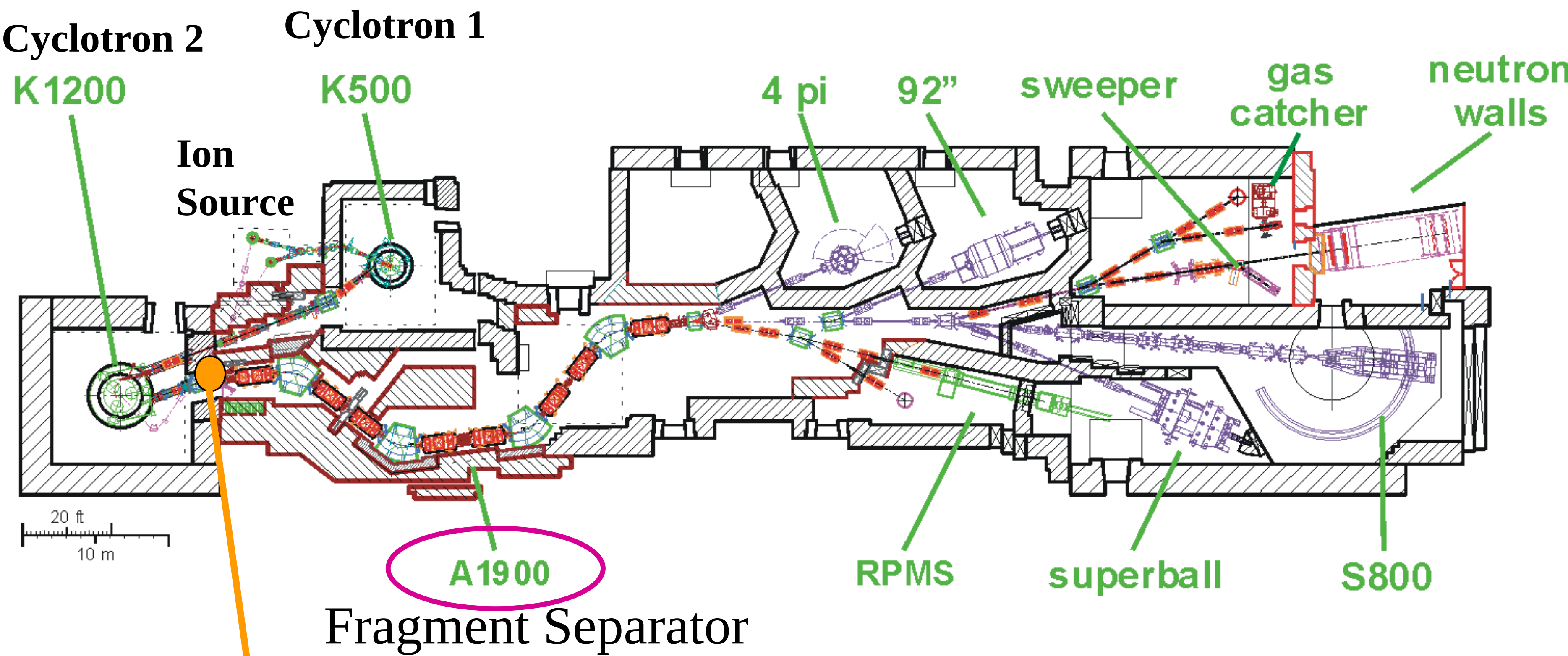
Norman et al. PRC57 (1998) 2010

ANL:

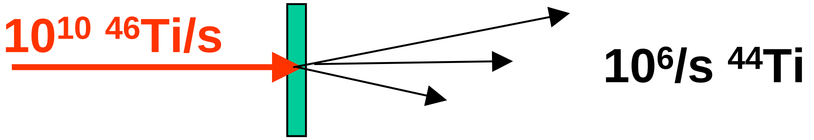


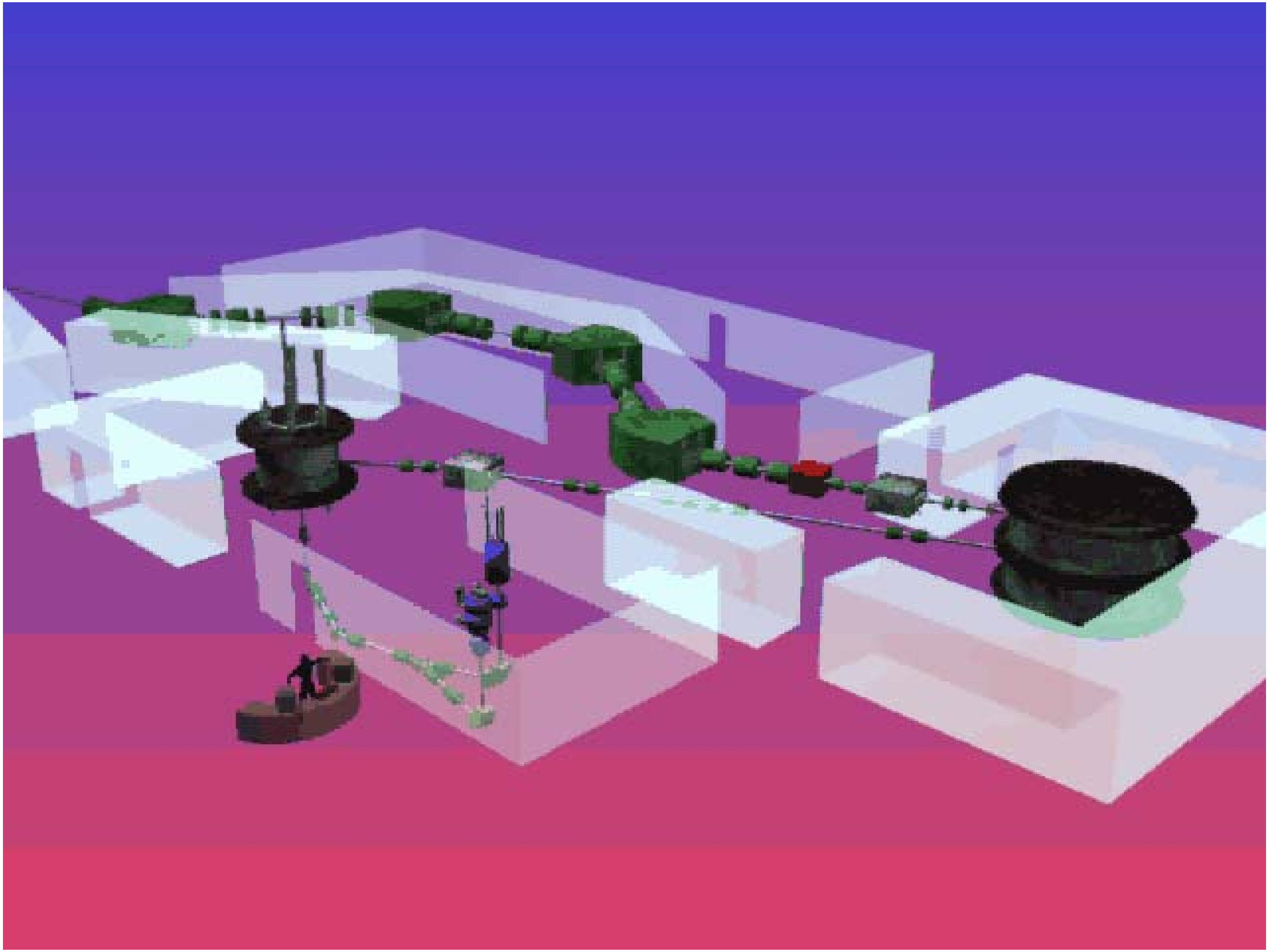
Ahmad et al. PRL 80 (1998) 2550

National Superconducting Cyclotron Facility at Michigan State University



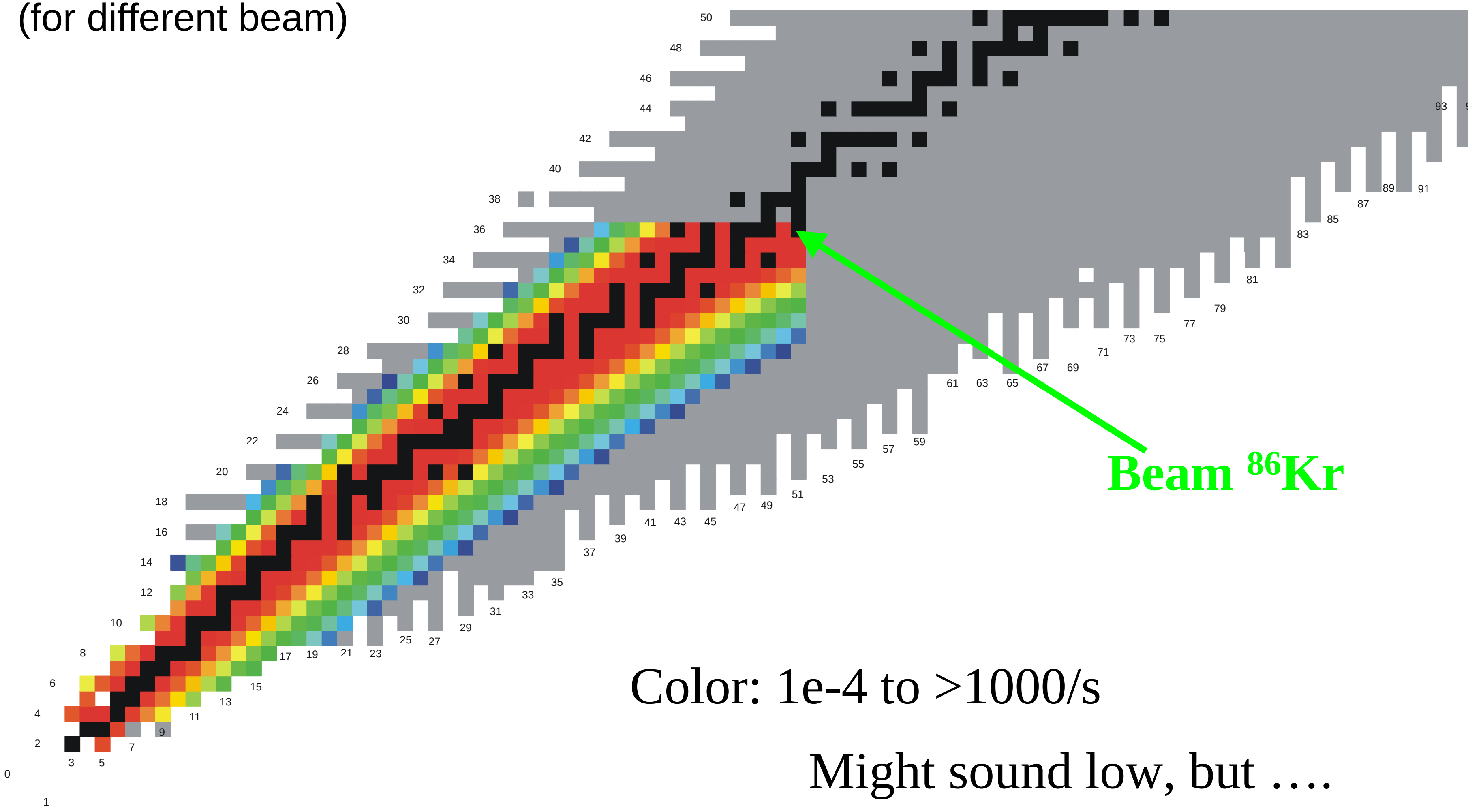
Make ^{44}Ti by fragmentation of ^{46}Ti beam





Fast beam feature 1: production of broad range of beams

Example: Fragmentation Technique
(for different beam)



Beam ^{86}Kr

Color: 1e-4 to >1000/s

Might sound low, but ….

Method 2:

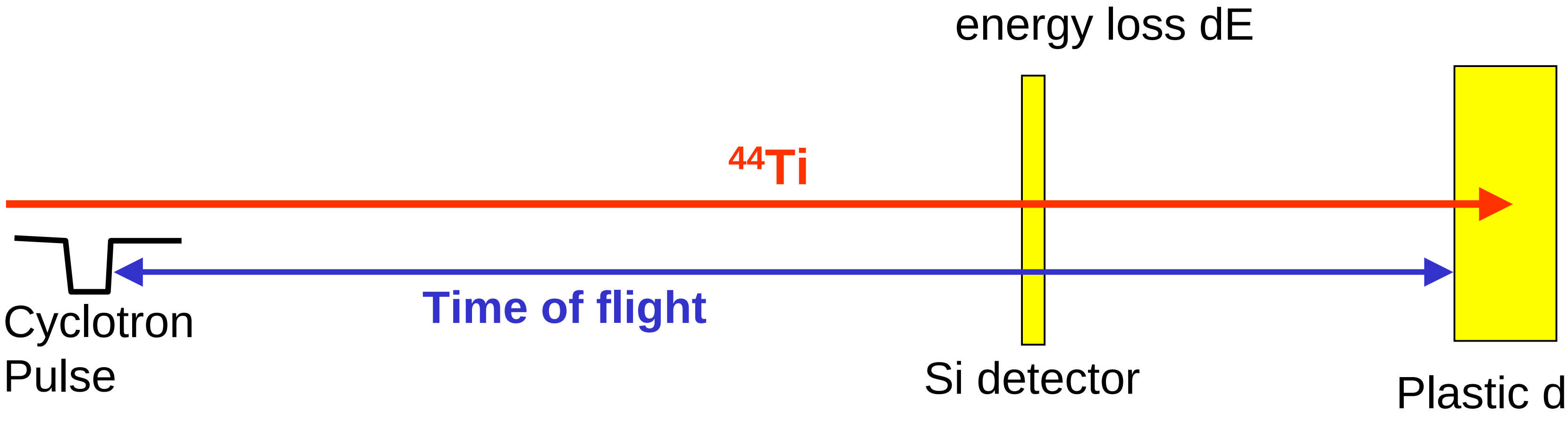
Measure A AND N_0 at a one time

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

Standard Setup:

^{44}Ti

Use this setup from time to time:



energy loss dE

^{44}Ti

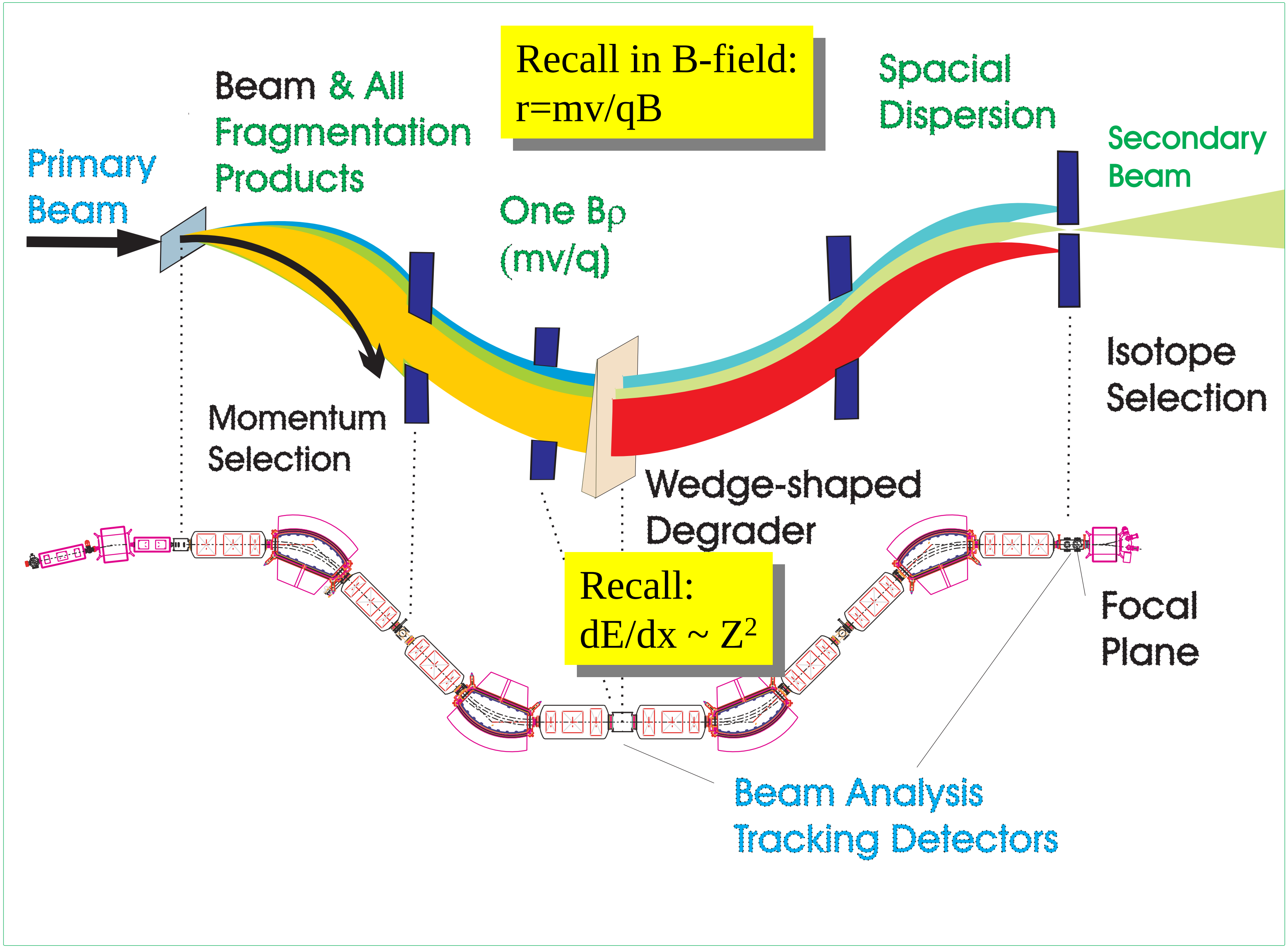
Cyclotron
Pulse

Time of flight

Si detector

Plastic det.

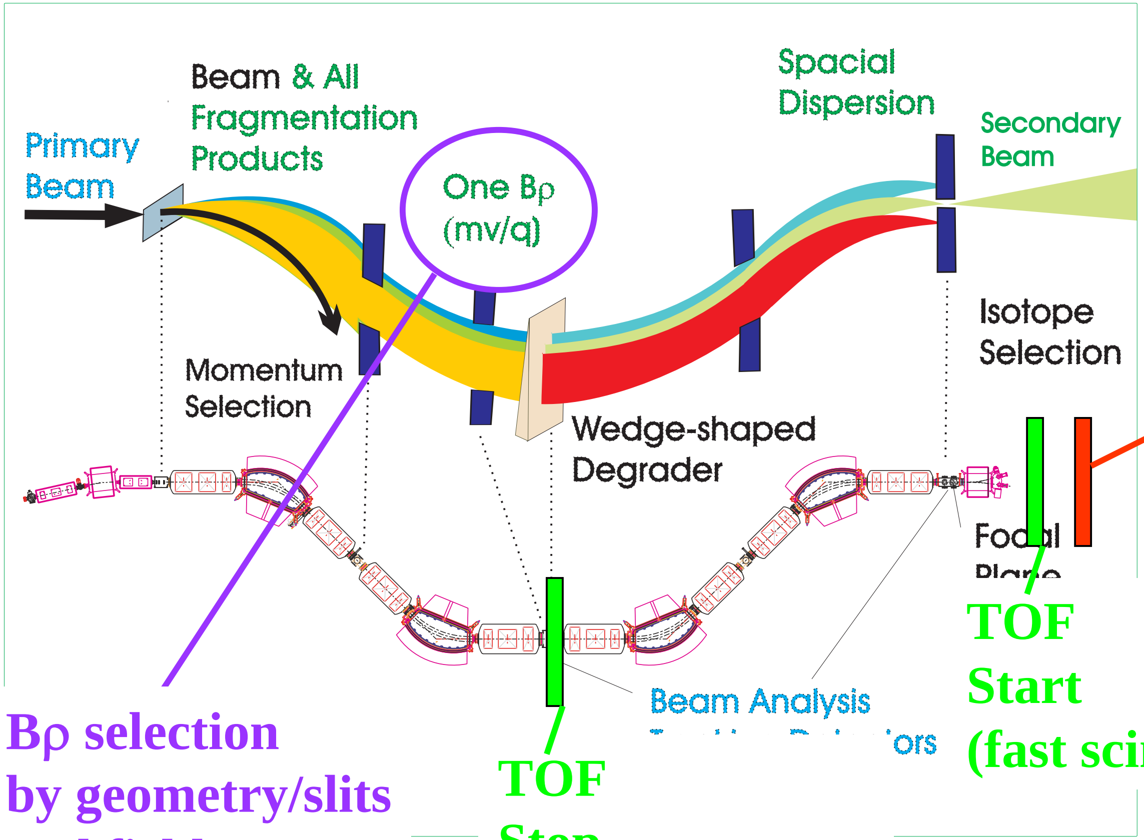
Fast beam feature 2: high selectivity – step1: Separator



Recall in B-field:
r=mv/qB

Recall:
dE/dx ~ Z^2

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)

measure m/q:

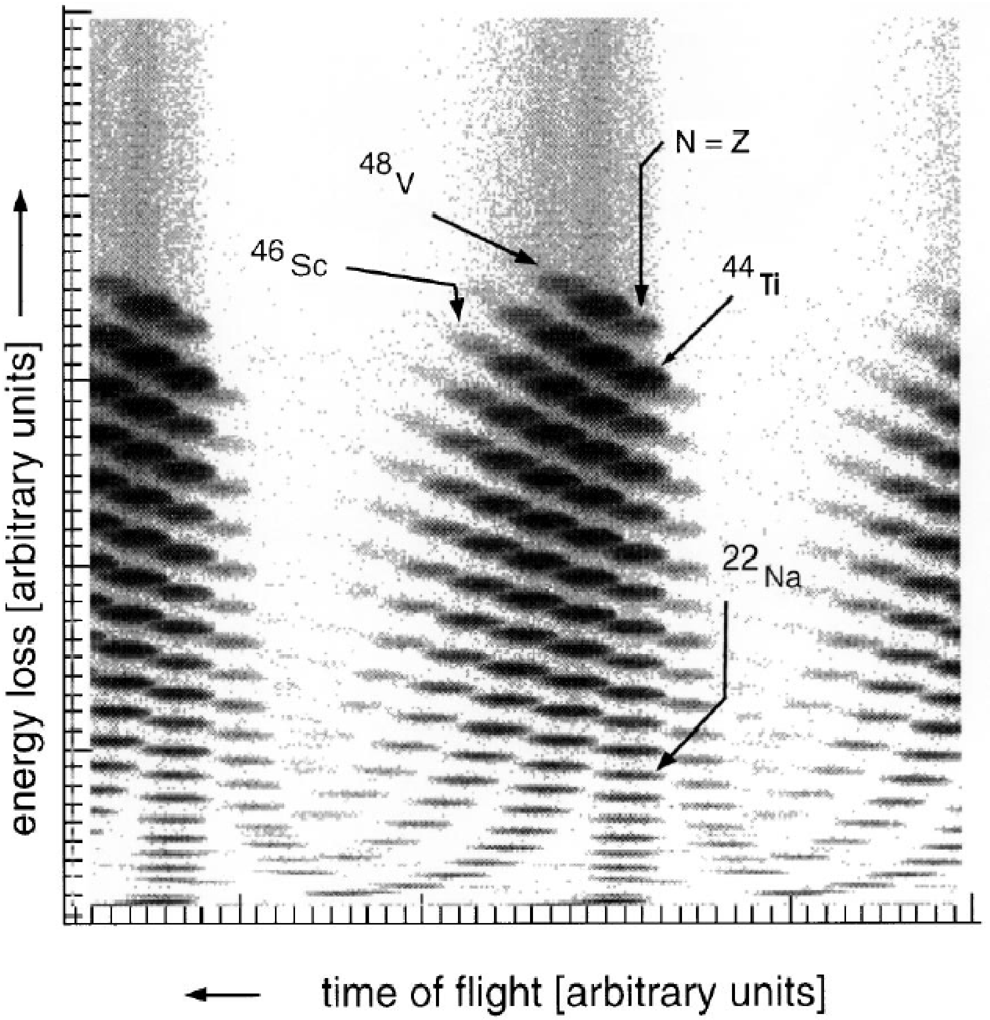
Bρ = mv/q (relativistic Bρ=γmv/q !)

m/q = **Bρ**/v

└─ v=d/**TOF**

Measure Z:

dE ~ Z^2



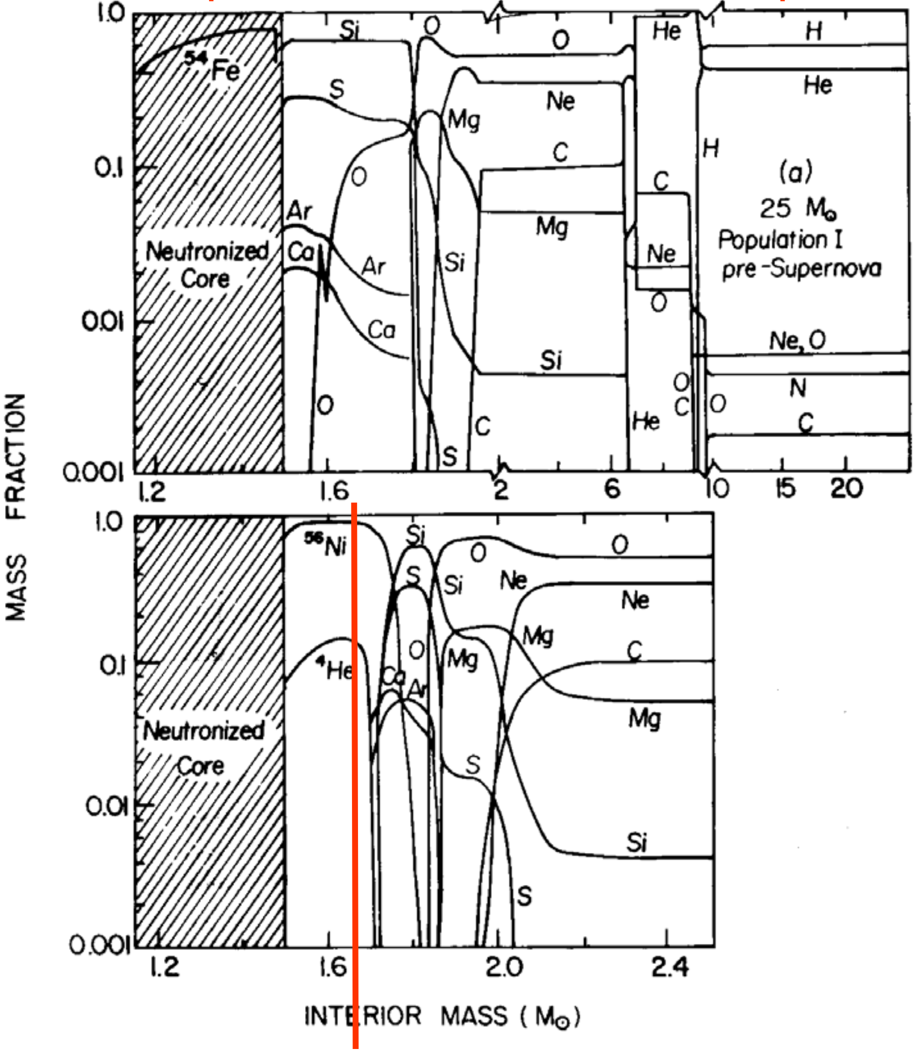
→ determine number of implanted ^{44}Ti

→ 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)

Explosive Si burning:

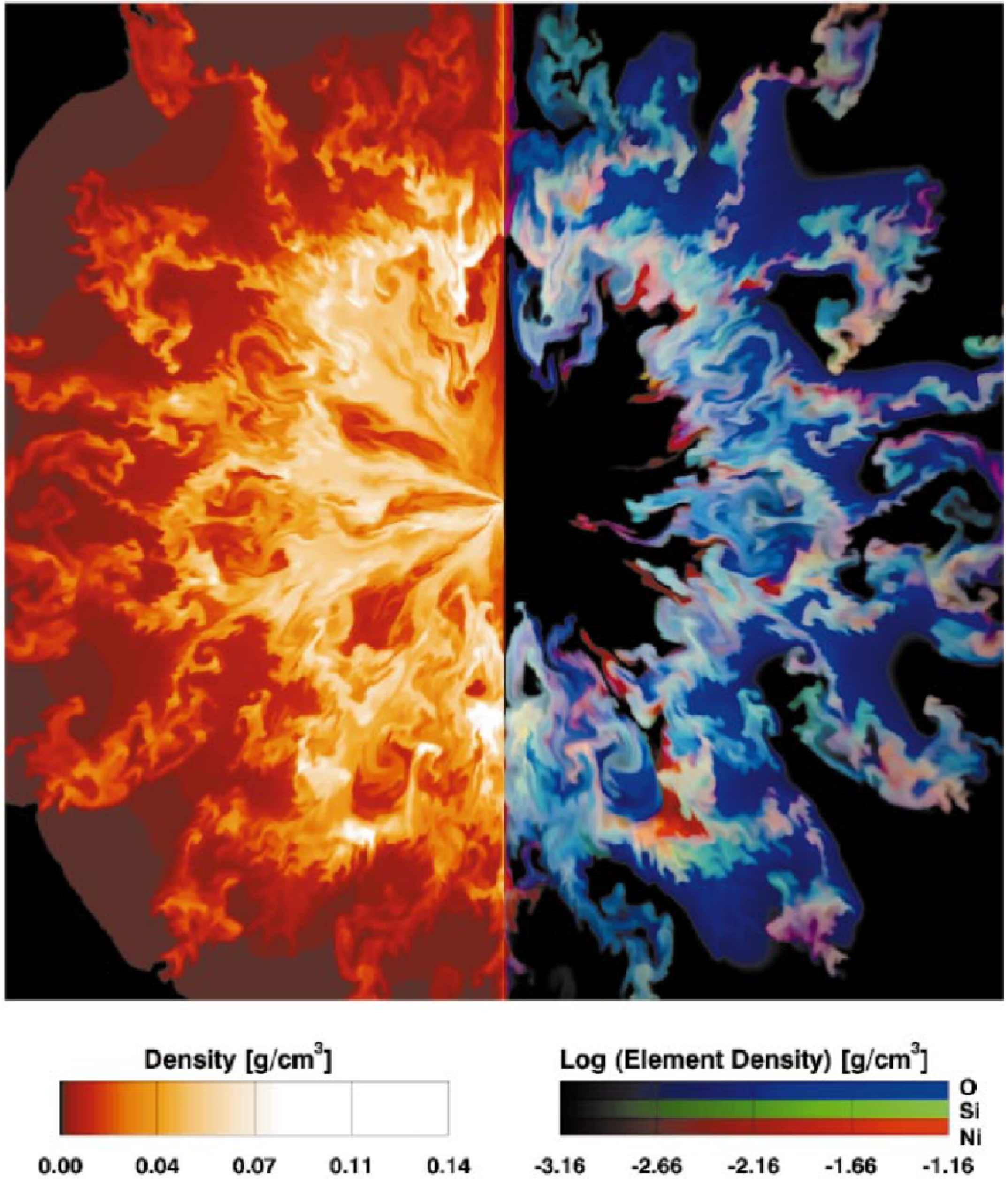
Deepest layer: full NSE ^{28}Si → ^{56}Ni

Further out: α-rich freezeout

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

→ result: lots of α-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

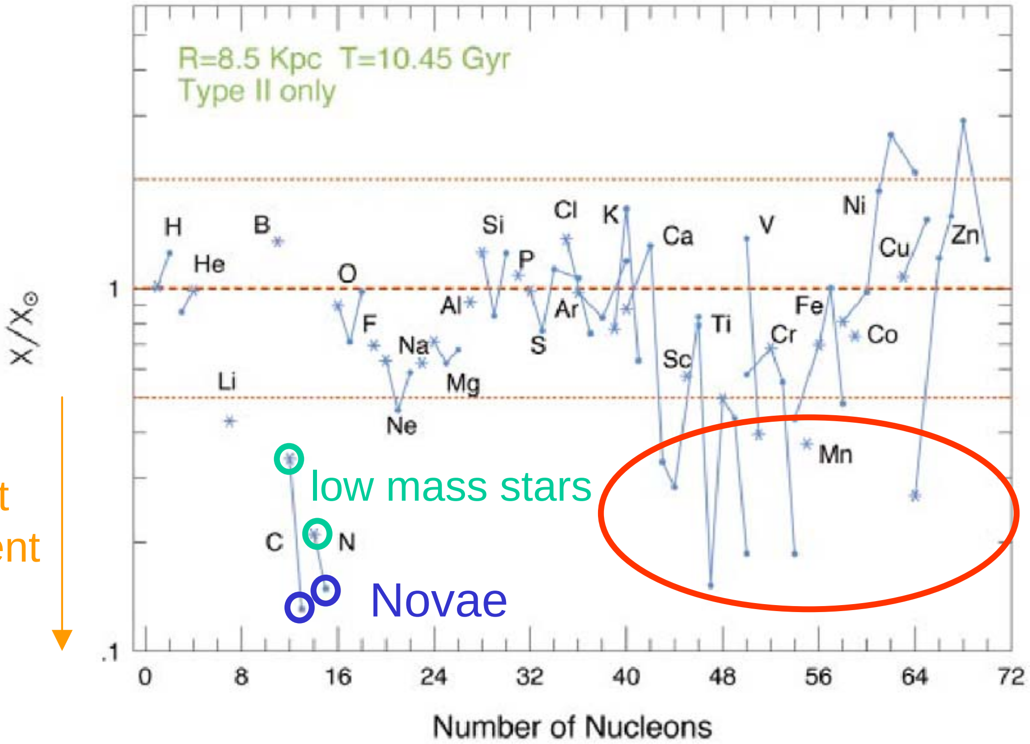
Contribution of Massive Stars to Galactic Nucleosynthesis

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

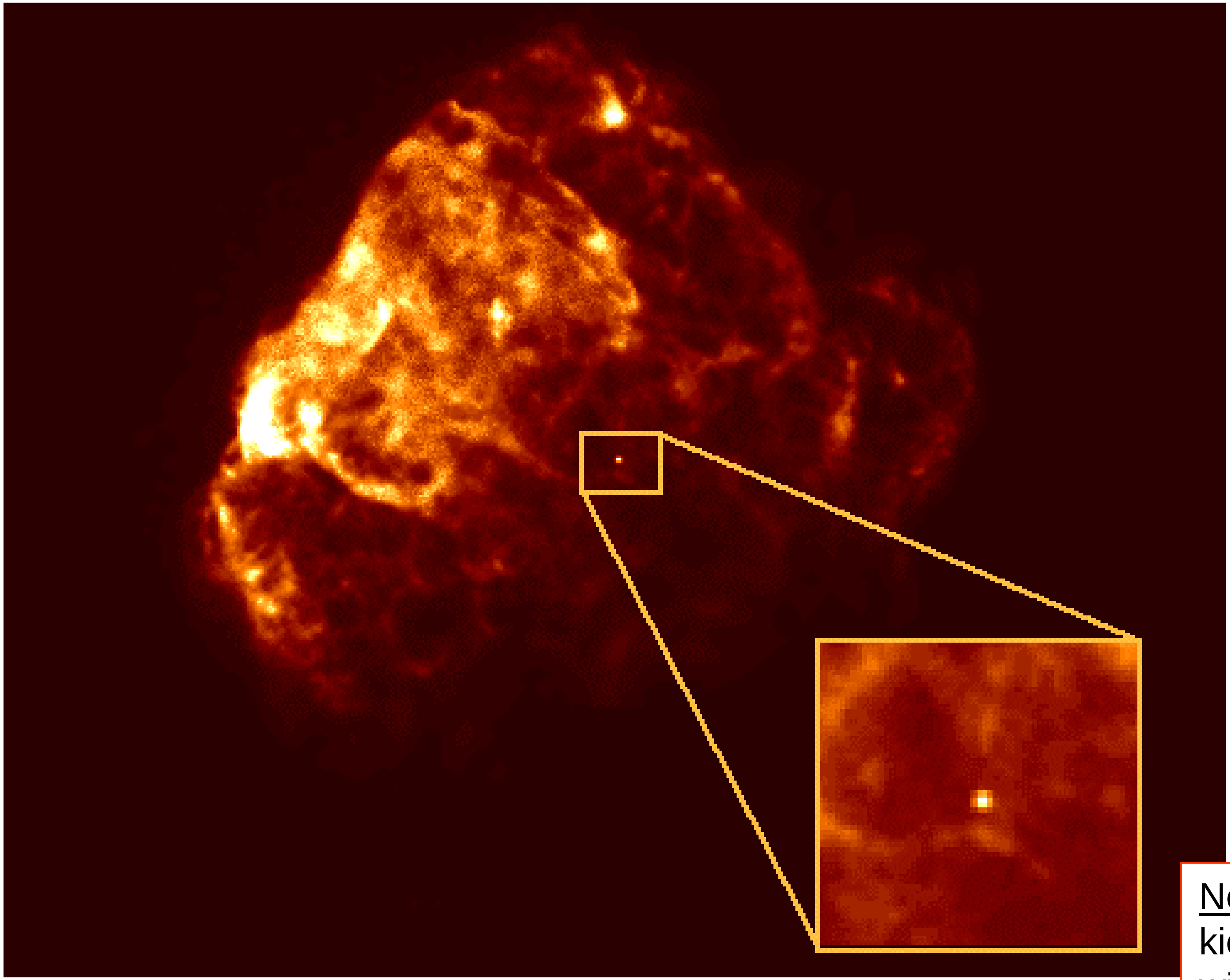


"Problem" zone
these nuclei are not
produced in sufficient
quantities

Type Ia supernovae

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

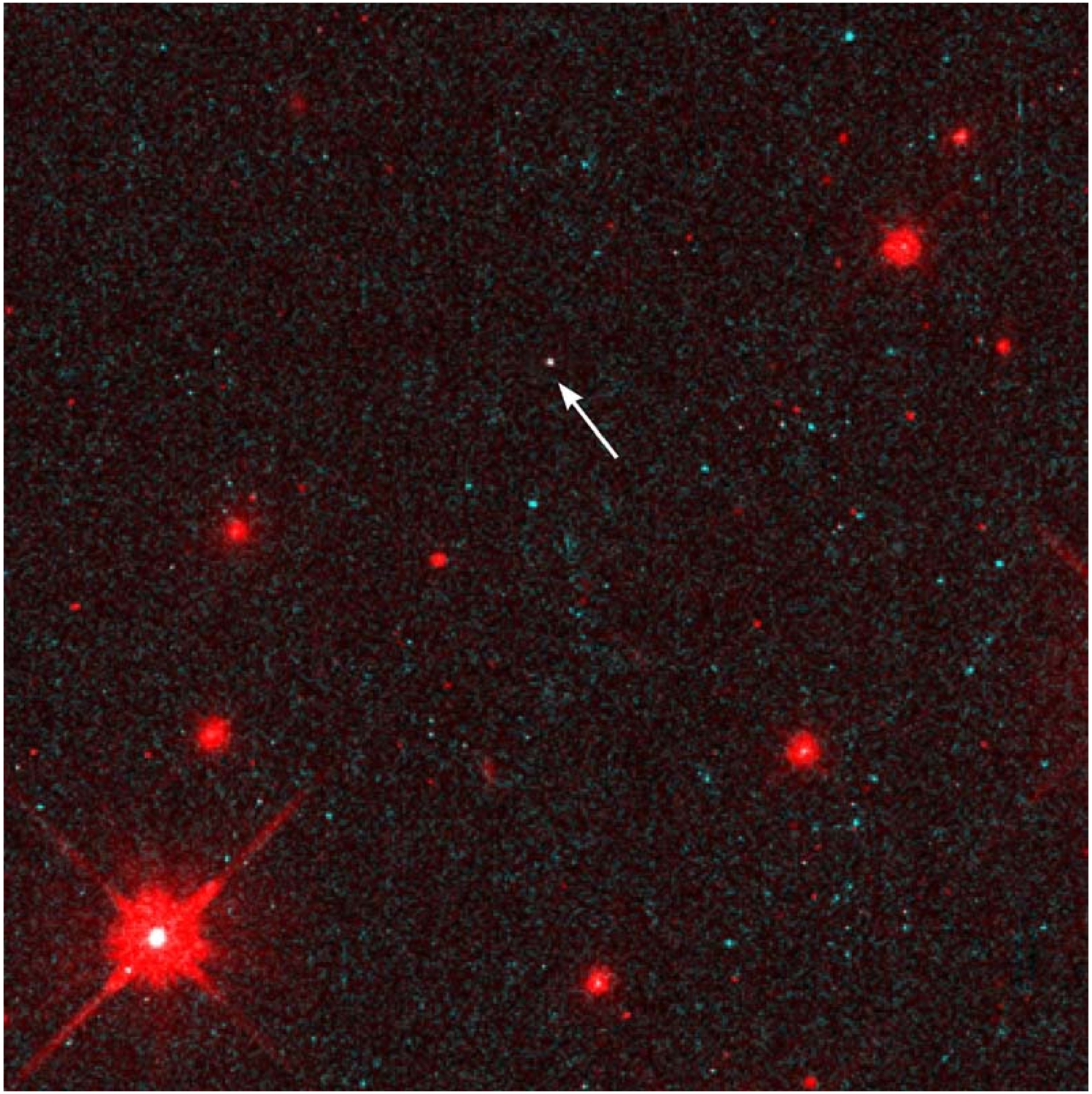
Supernova remants – neutron stars



Neutron star
kicked out
with ~600 mi/s

SN remnant Puppis A (Rosat)

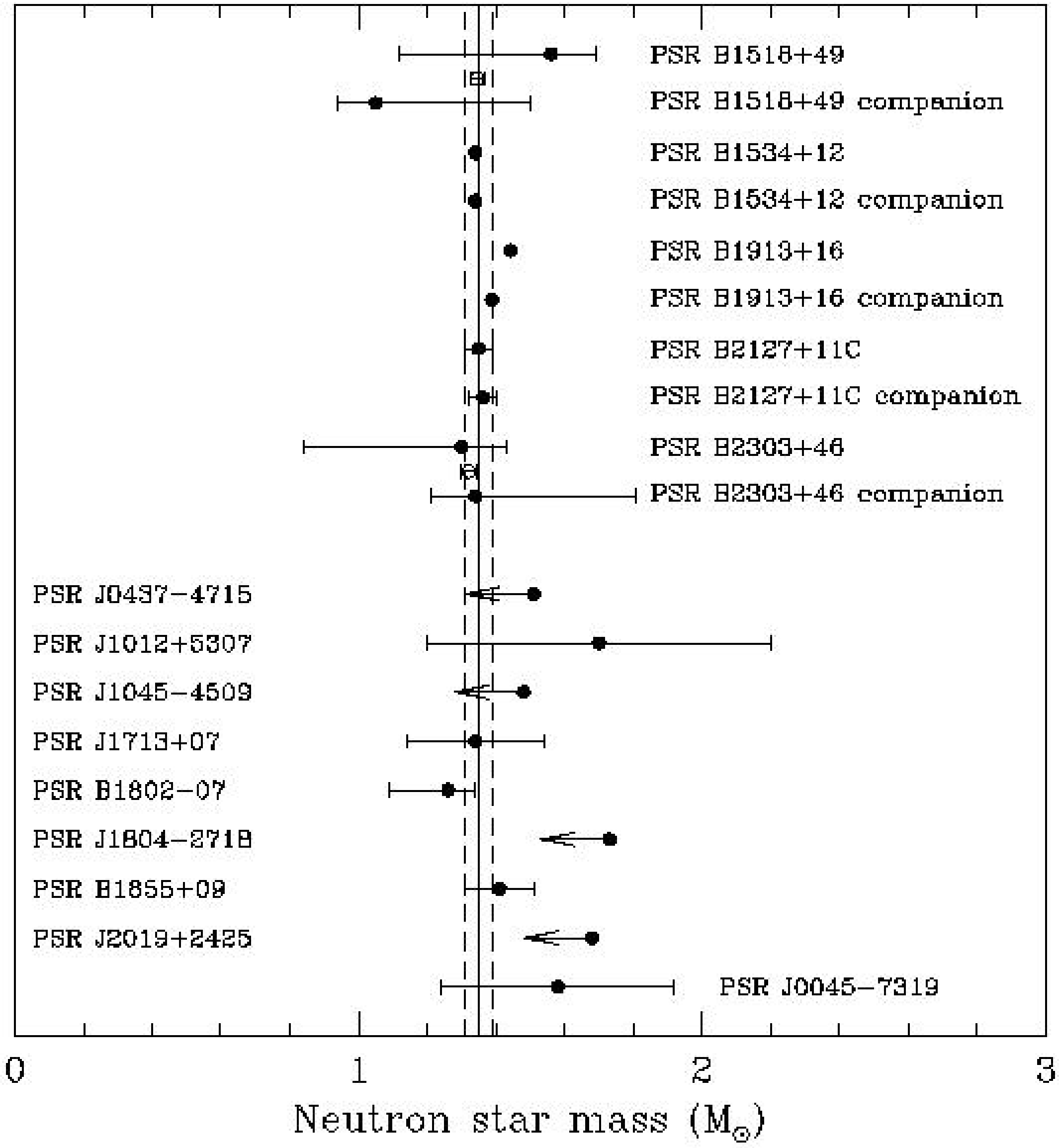
An isolated neutron star seen with HST:



Its estimated that there are ~100’s of millions of neutron stars in our Galaxy

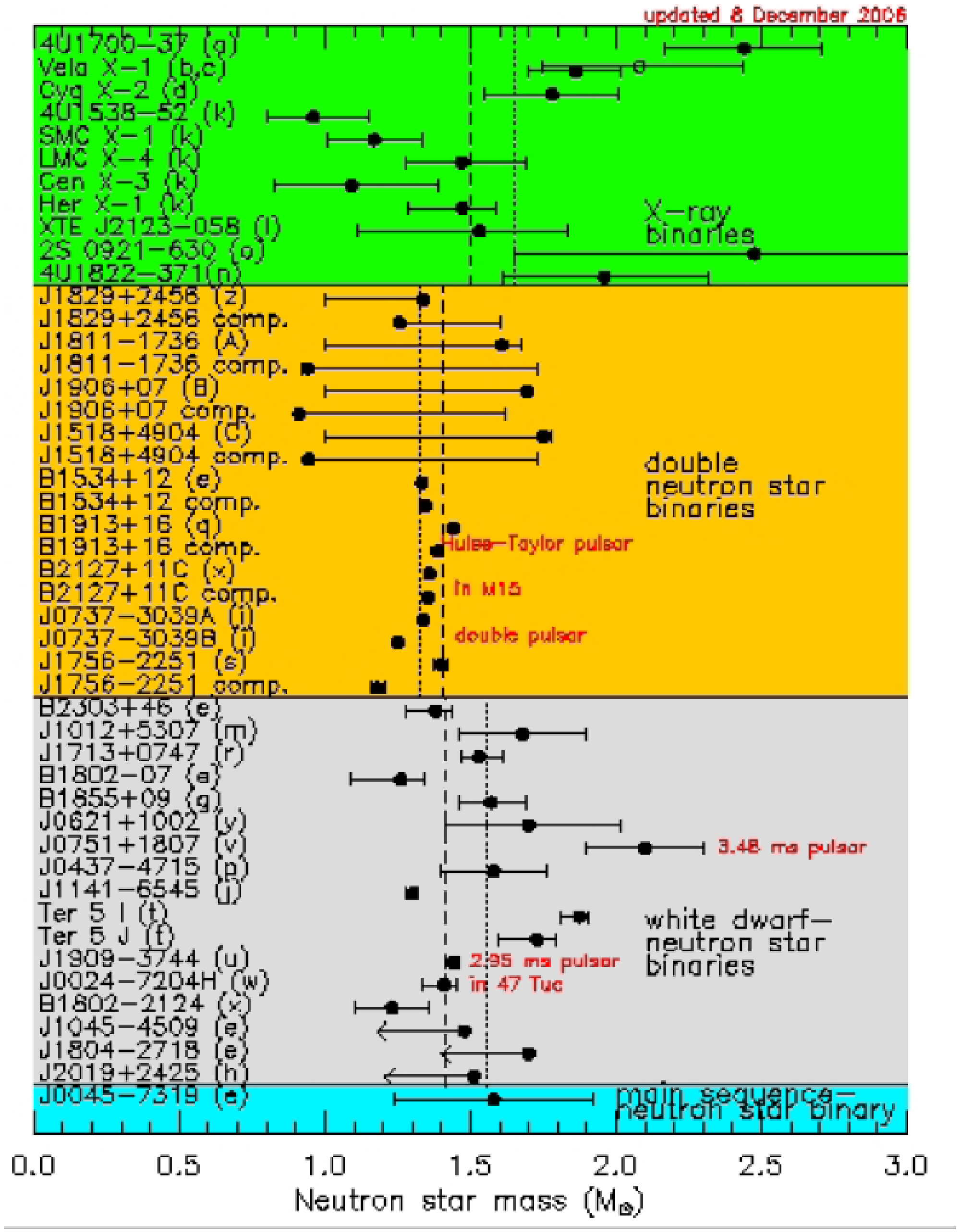
Neutron star properties

Mass:

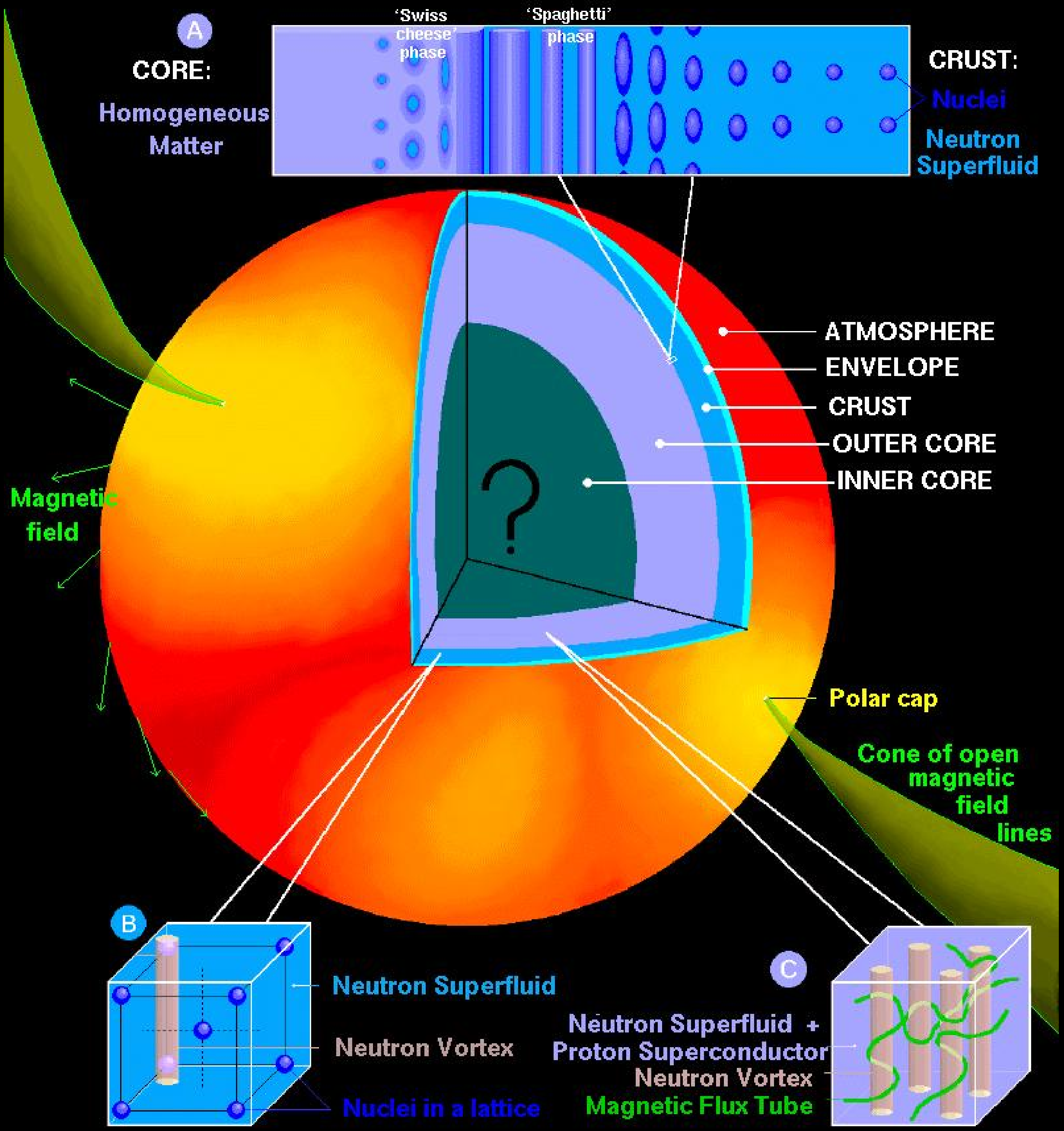


Radius:

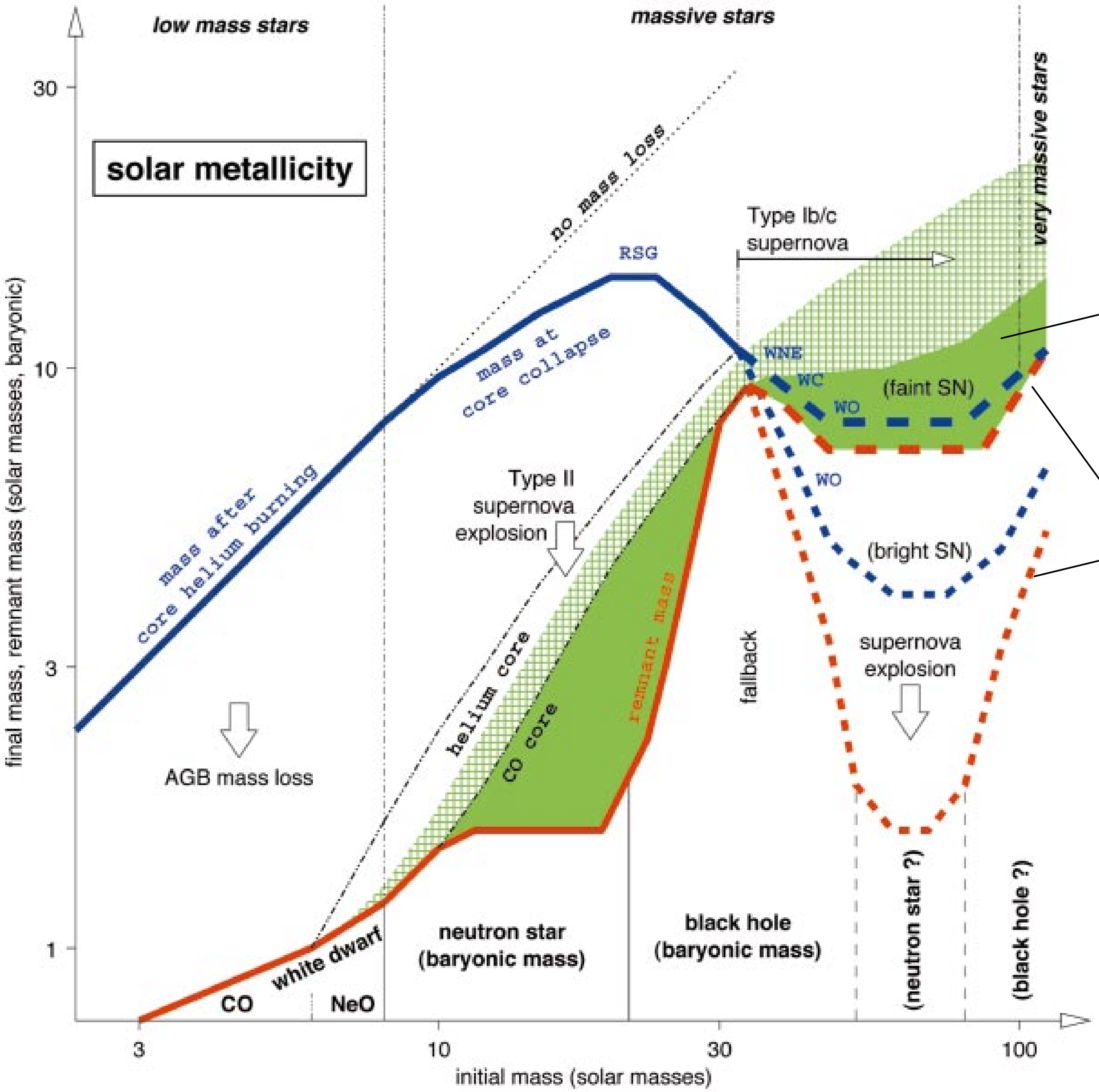
~10 km !


updated 8 December 2006
4U1700−37 (a)
Vela X−1 (b,c)
Cyg X−2 (d)
4U1538−52 (k)
SMC X−1 (k)
LMC X−4 (k)
Cen X−3 (k)
Her X−1 (k)
XTE J2123−058 (l)
2S 0921−630 (o)
4U1822−371(n)
X−ray binaries
J1829+2456 (z)
J1829+2456 comp.
J1811−1736 (A)
J1811−1736 comp.
J1906+07 (B)
J1906+07 comp.
J1518+4904 (C)
J1518+4904 comp.
B1534+12 (e)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737−3039A (i)
J0737−3039B (i)
J1756−2251 (s)
J1756−2251 comp.
double neutron star binaries
Hulse−Taylor pulsar
in M15
double pulsar
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802−07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (v)
J0437−4715 (p)
J1141−6545 (j)
Ter 5 I (t)
Ter 5 J (f)
J1909−3744 (u)
J0024−7204H (w)
B1802−2124 (x)
J1045−4509 (e)
J1804−2718 (e)
J2019+2425 (h)
3.48 ms pulsar
2.95 ms pulsar
in 47 Tuc
white dwarf−neutron star binaries
J0045−7319 (e)
main sequence−neutron star binary
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)

A NEUTRON STAR: SURFACE and INTERIOR



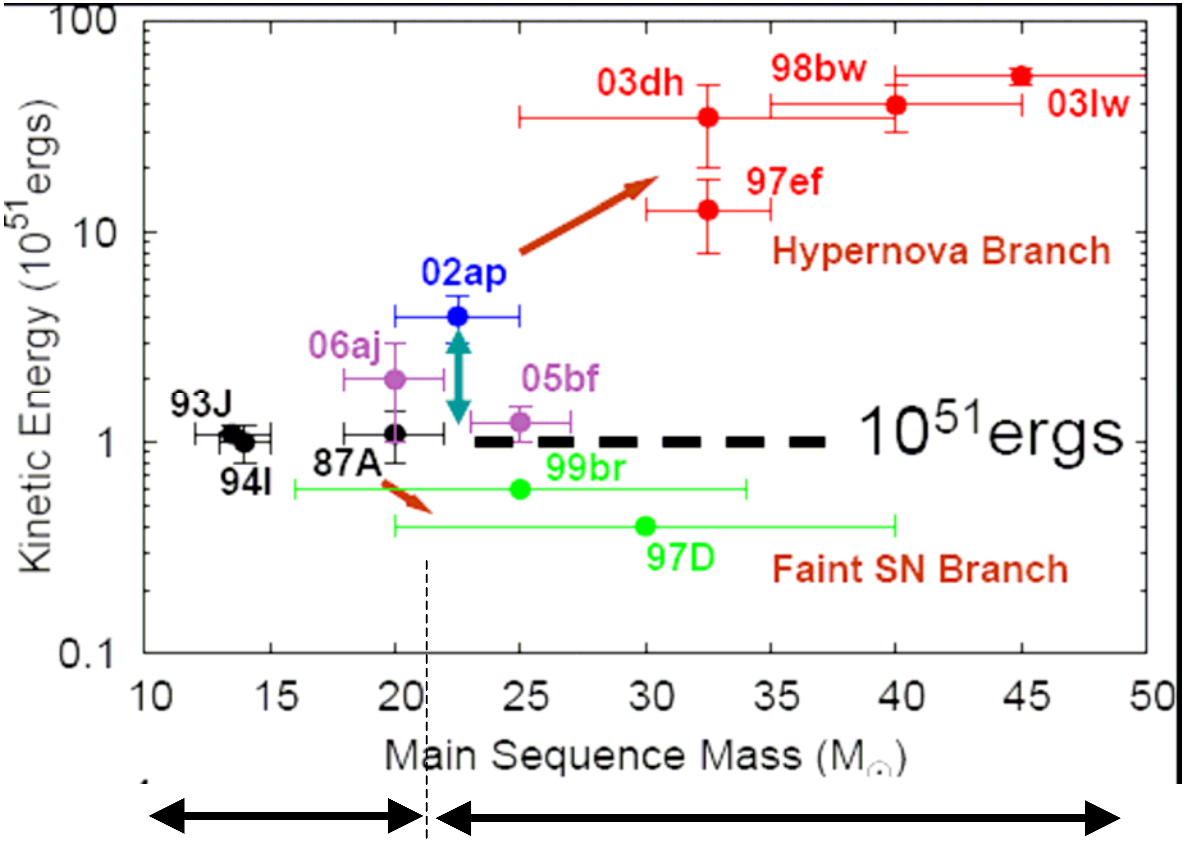
Mass loss and remnants



Nucleosynthesis of Z>2

Different choices of mass loss rates

Hypernovae and faint SN

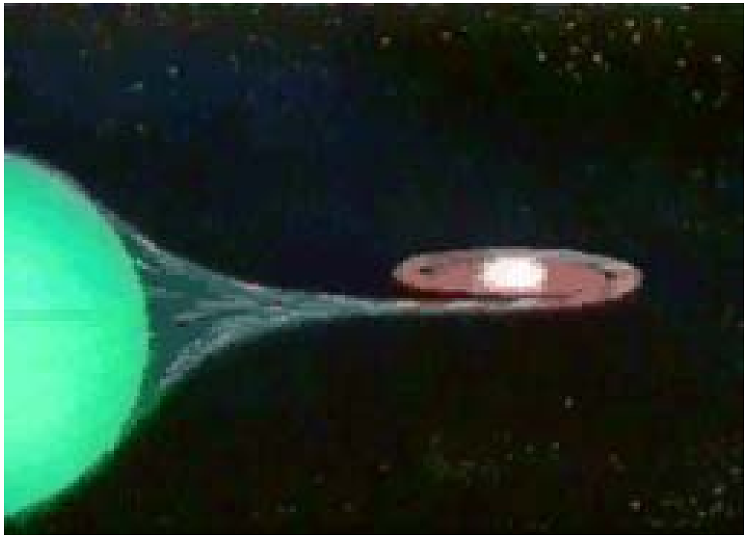


GRBs?

NS
(bounce driven SN)

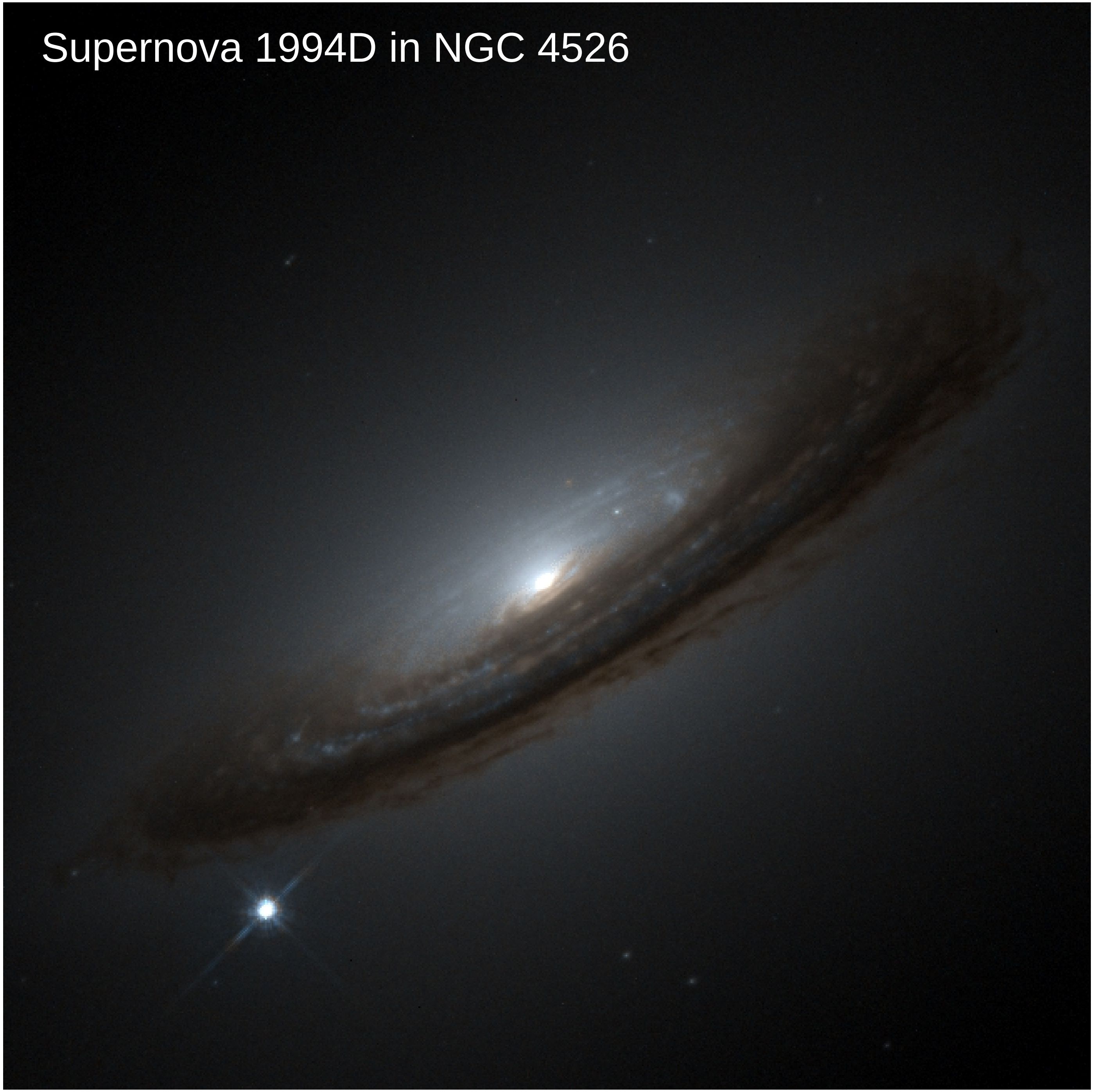
BH
(L (jet) driven SN)

Type Ia supernovae



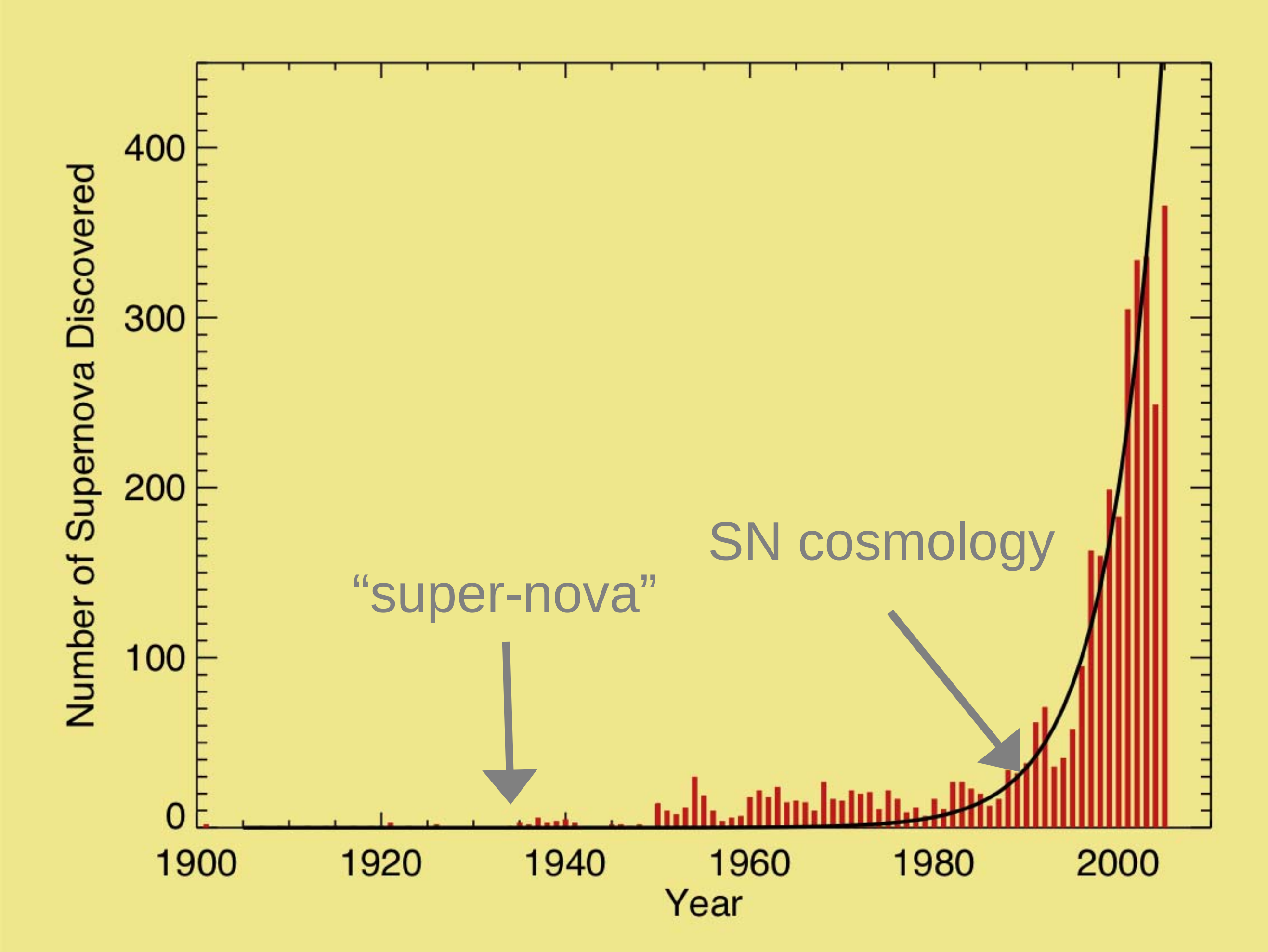
white dwarf accreted matter and grows beyond the Chandrasekhar limit

→ star explodes – no remnant



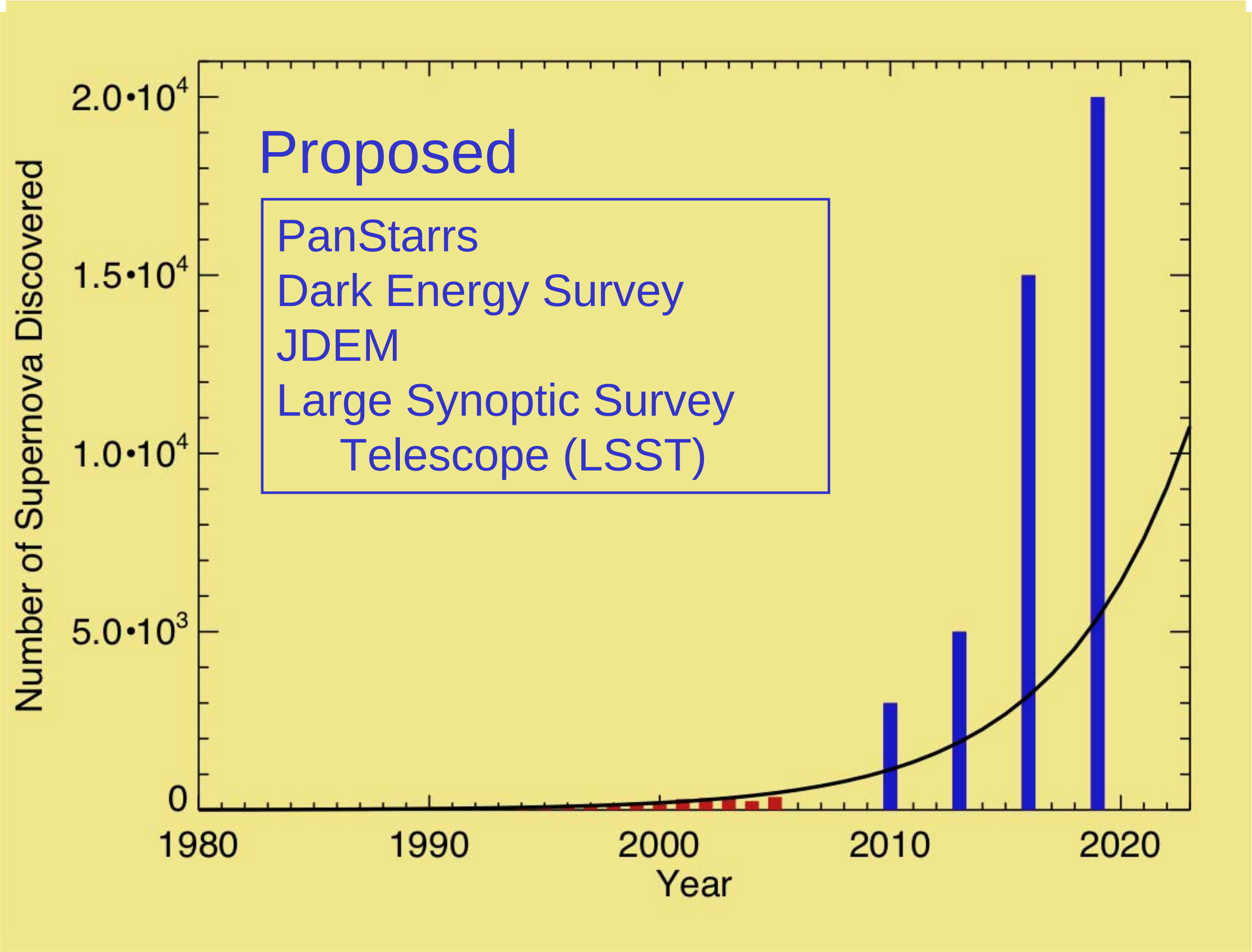
Supernova 1994D in NGC 4526

Discovery rate of type Ia supernovae



D. Kasen, presentation

Discovery rate of type Ia supernovae

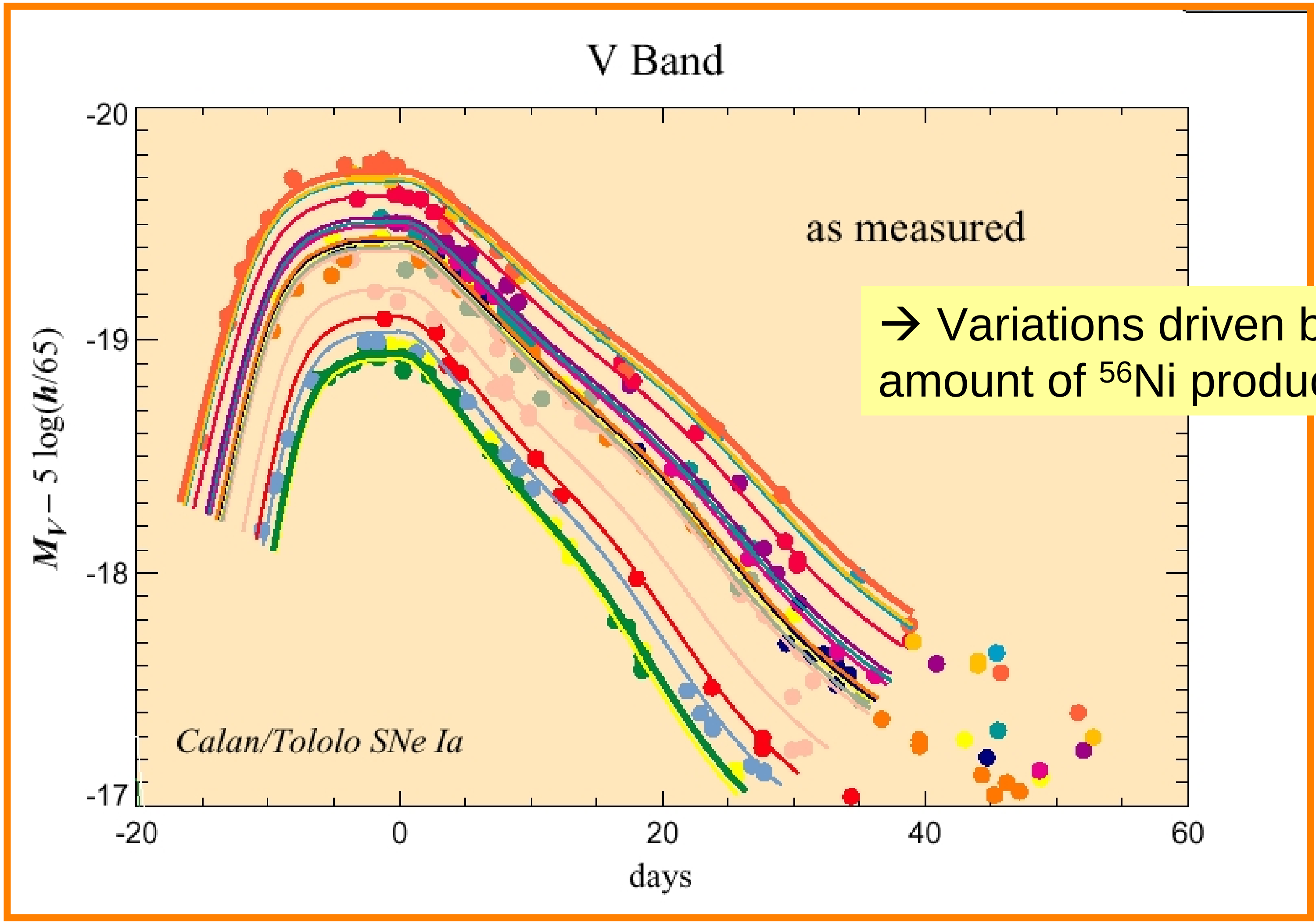


Proposed

PanStarrs
Dark Energy Survey
JDEM
Large Synoptic Survey
Telescope (LSST)

D. Kasen, presentation

Absolute brightness variations of type Ia supernovae



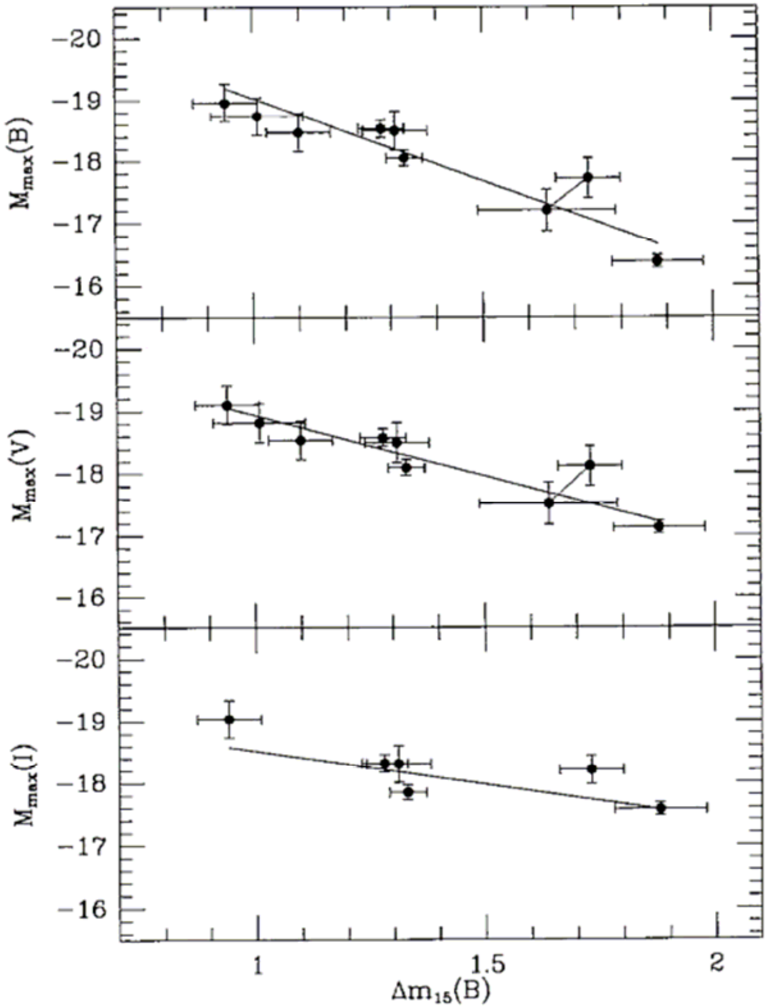
→ Variations driven by amount of ^{56}Ni produced

Origin of variations?

Timmes, Brown, Truran 2003: ^{22}Ne ~ Z (why?) (^{22}Ne has 10 protons and 12 neutrons !)
→ presence of ^{22}Ne reduces Ye below 0.5 and therefore the amount of ^{56}Ni produced

Phillips relation:

Decline rate $\Delta m_{15}(B)$: magnitude decline during first 15 days in B-band is related to ABSOLUTE peak brightness M_{max}:

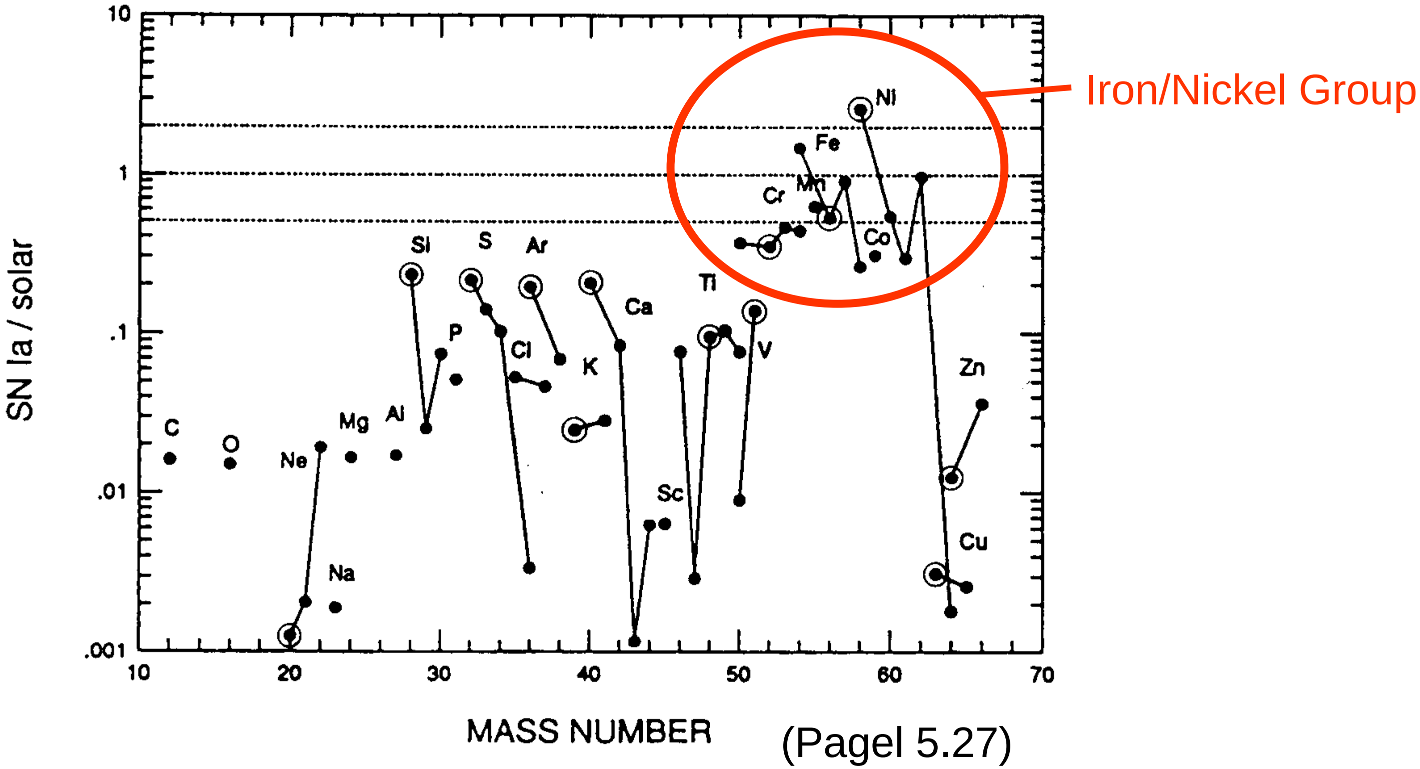


Phillips, ApJ413(1993)105

→ Can use type Ia's as standard candles !

Nucleosynthesis contribution from type Ia supernovae

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



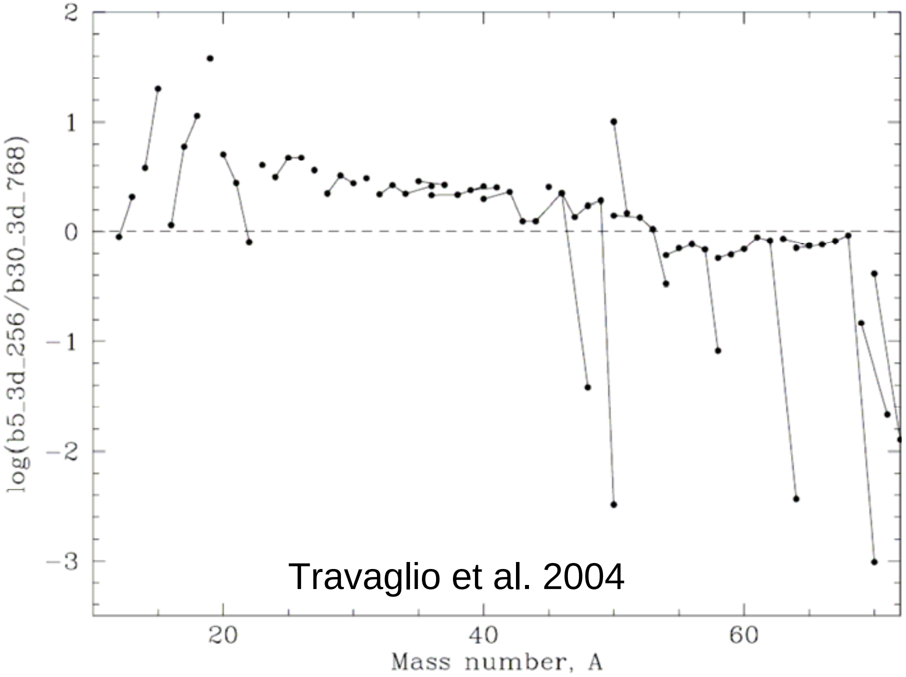
Iron/Nickel Group

(Pagel 5.27)

→ Has to be consistent with solar abundances
→ Nucleosynthesis is a prime constraint for models

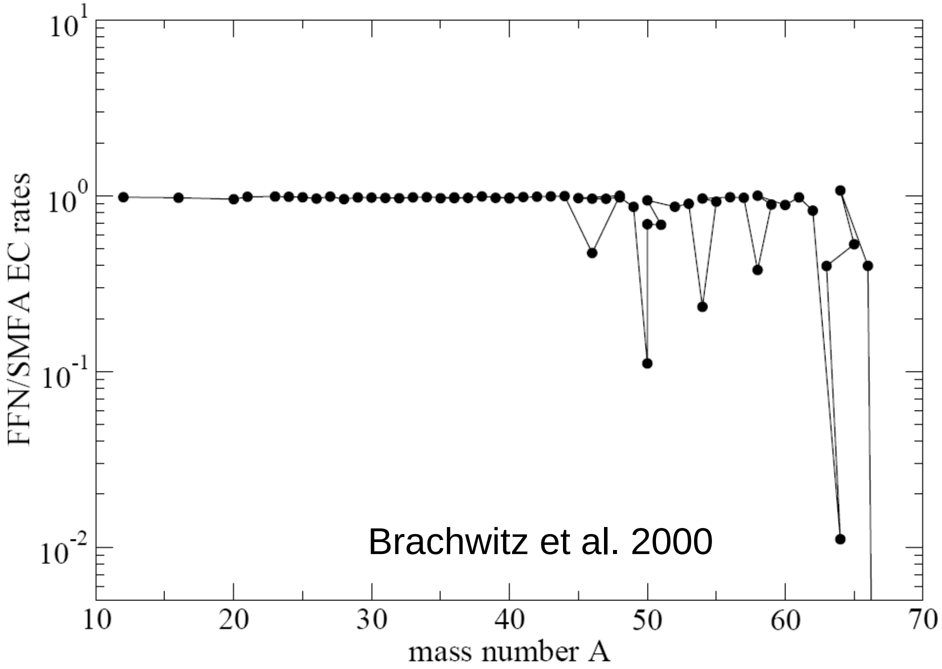
Sensitivity of type Ia supernova nucleosynthesis

Different models: 5 bubbles/30 bubbles



Travaglio et al. 2004

Different nuclear models for EC rates



Brachwitz et al. 2000

Nucleosynthesis is one important diagnostic tool for SN type Ia models

→ Need experimental EC rates to use it
→ EC rates might also matter directly in explosion (currently explored)
→ EC rates are also an ingredient for core collapse SN models