Supernovae:

Remarkable Physics Triggering Extraordinary Stellar Explosions

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Mount Stromlo Observatory

Australian National University

What is a Supernova?

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No formal definition!

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latin: *Super* + *Nova*

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A cataclysmic event which irreversibly disrupts or transforms a star or stellar remnant on the time scale of a day or less...

The Many Paths to a Supernovae

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The Core Collapse of a Masive Star
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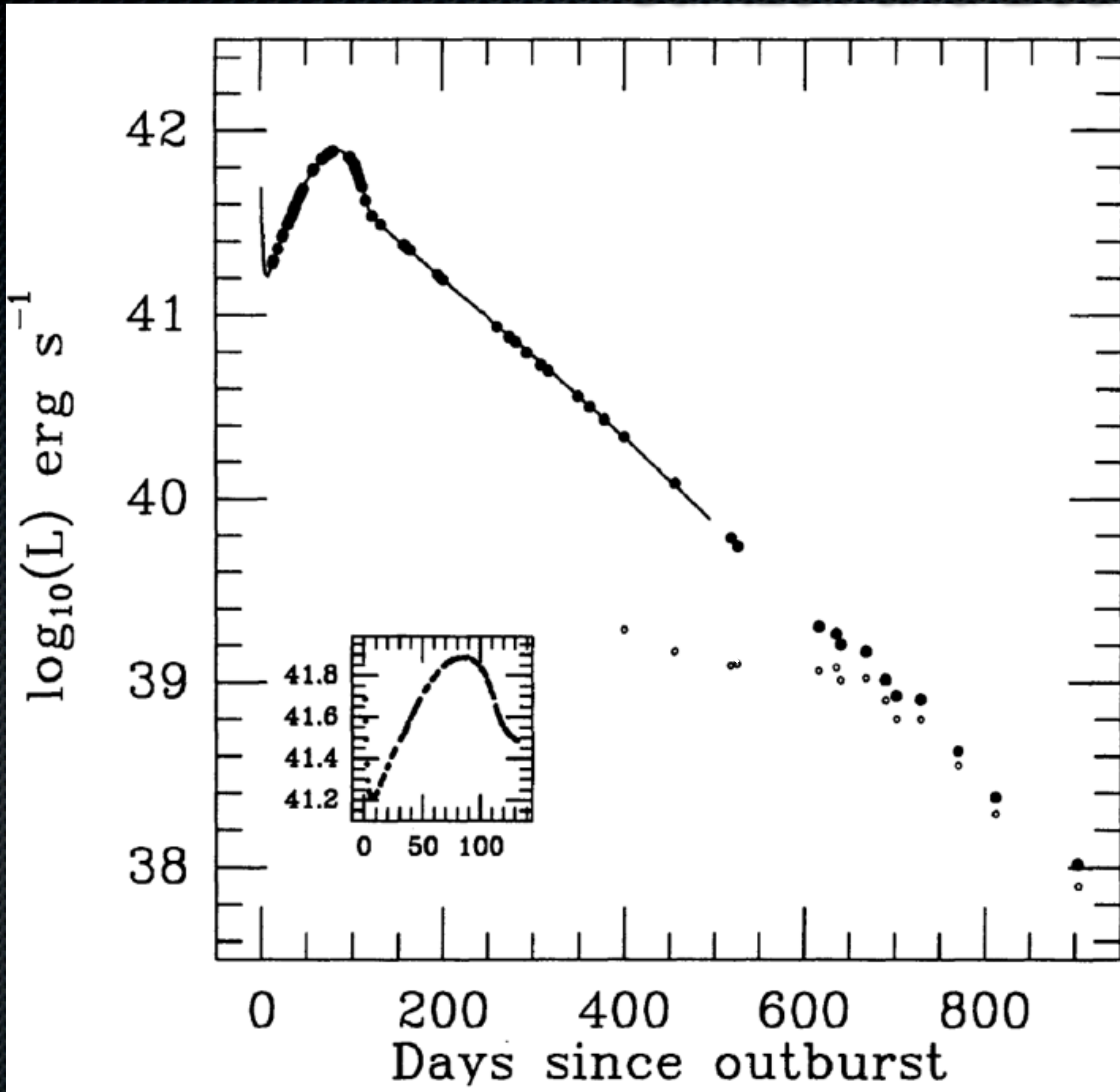
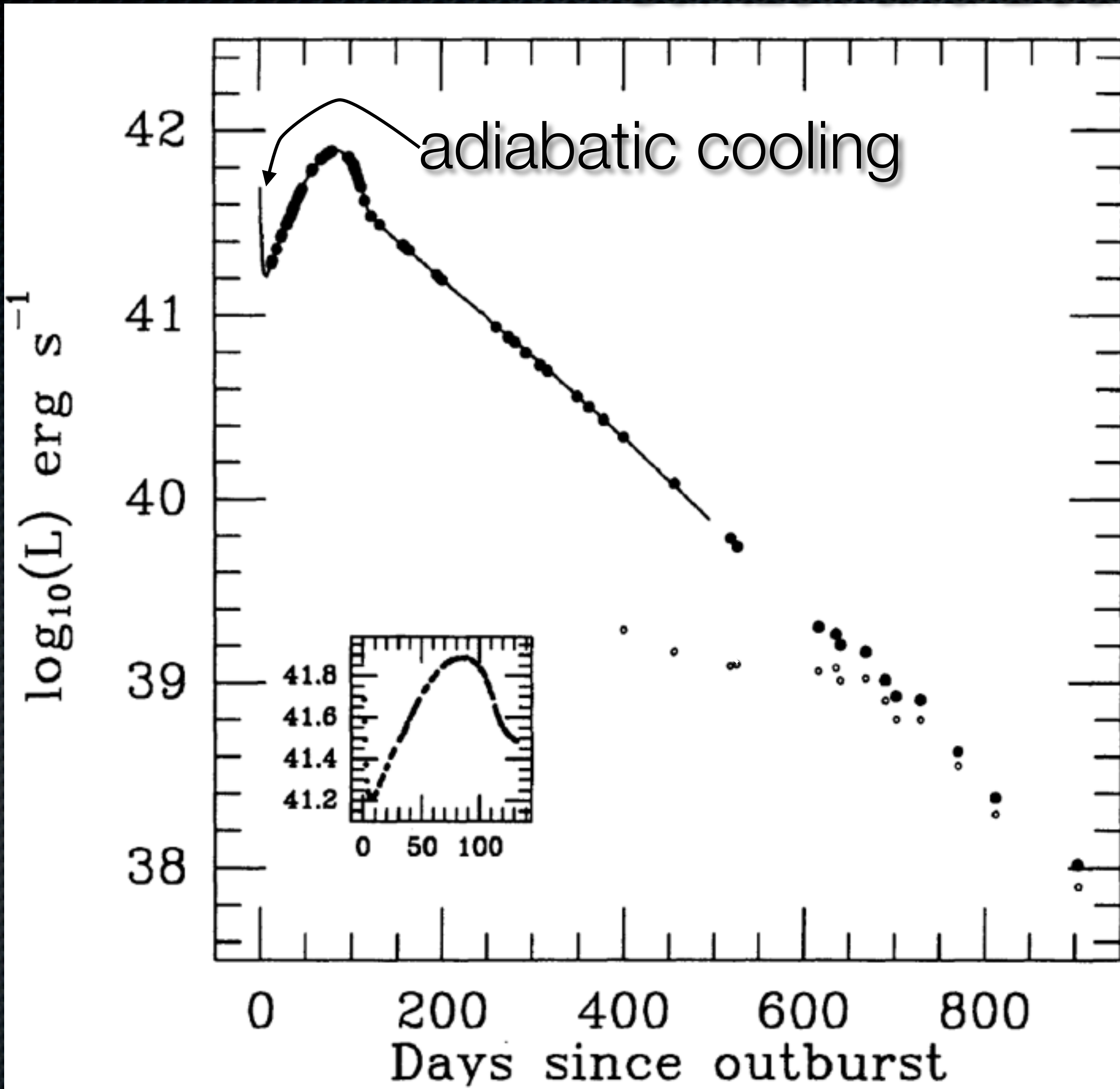
Suntzeff and Bouchet 1990



Suntzeff and Bouchet 1990



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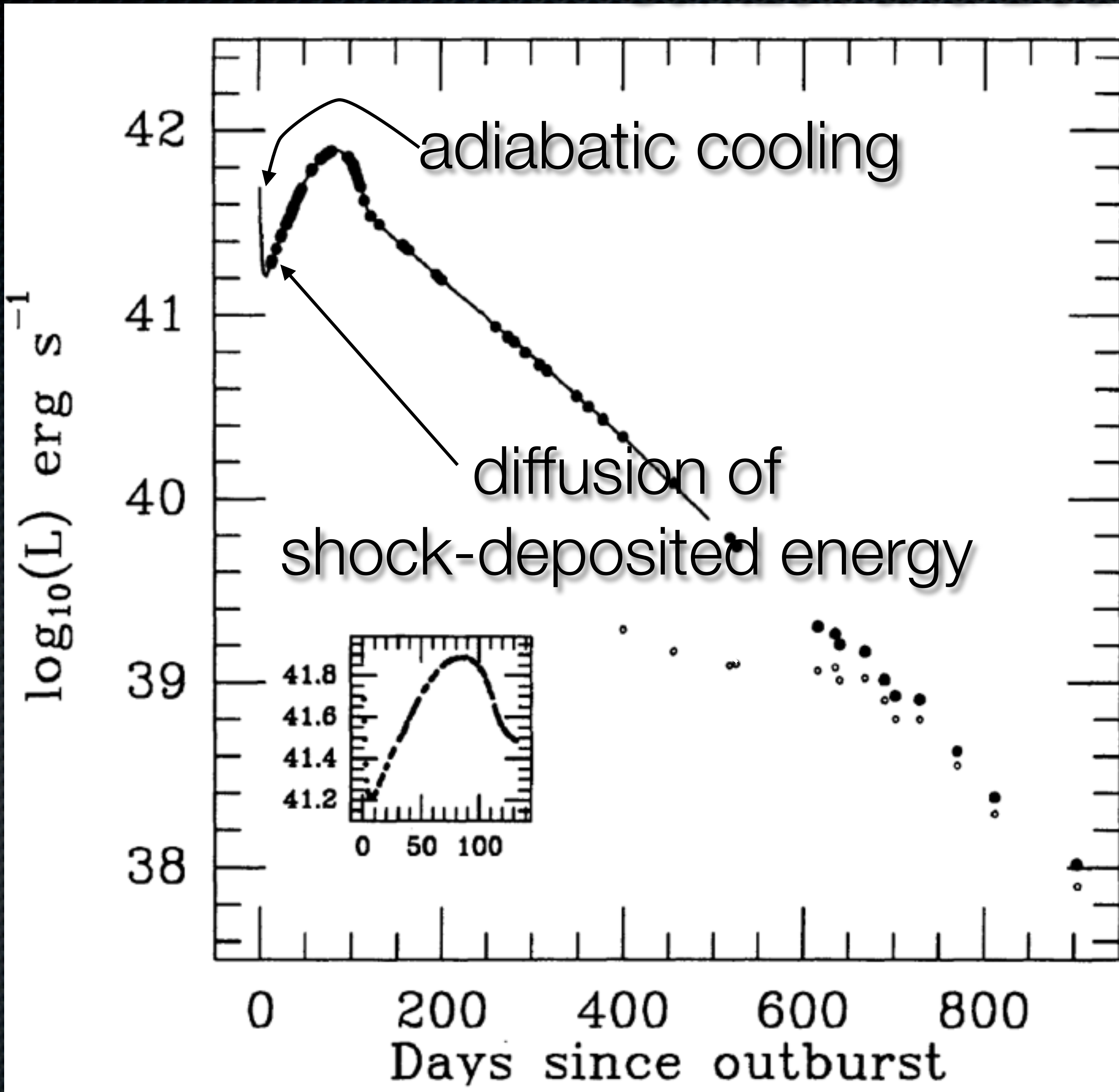
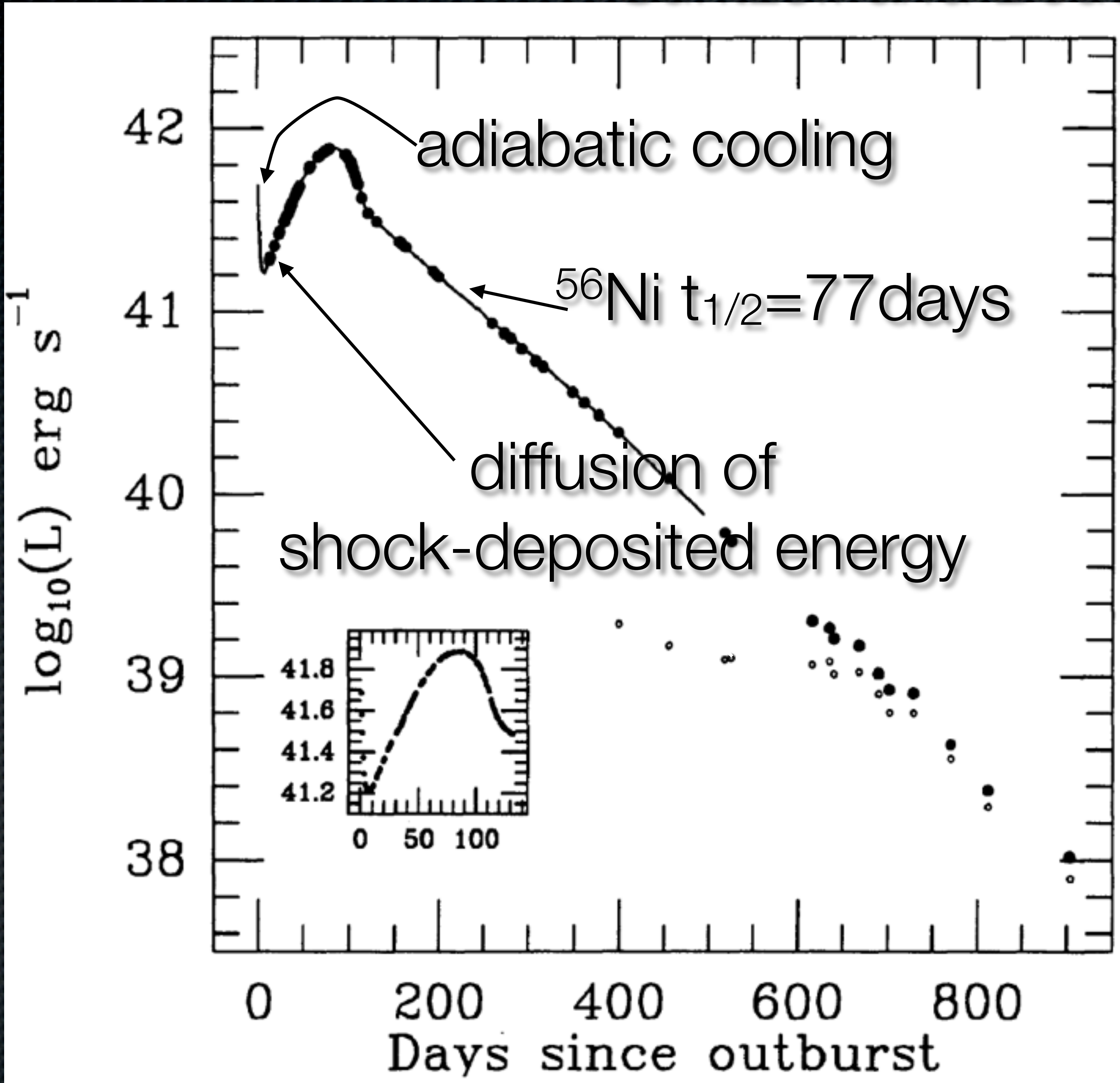


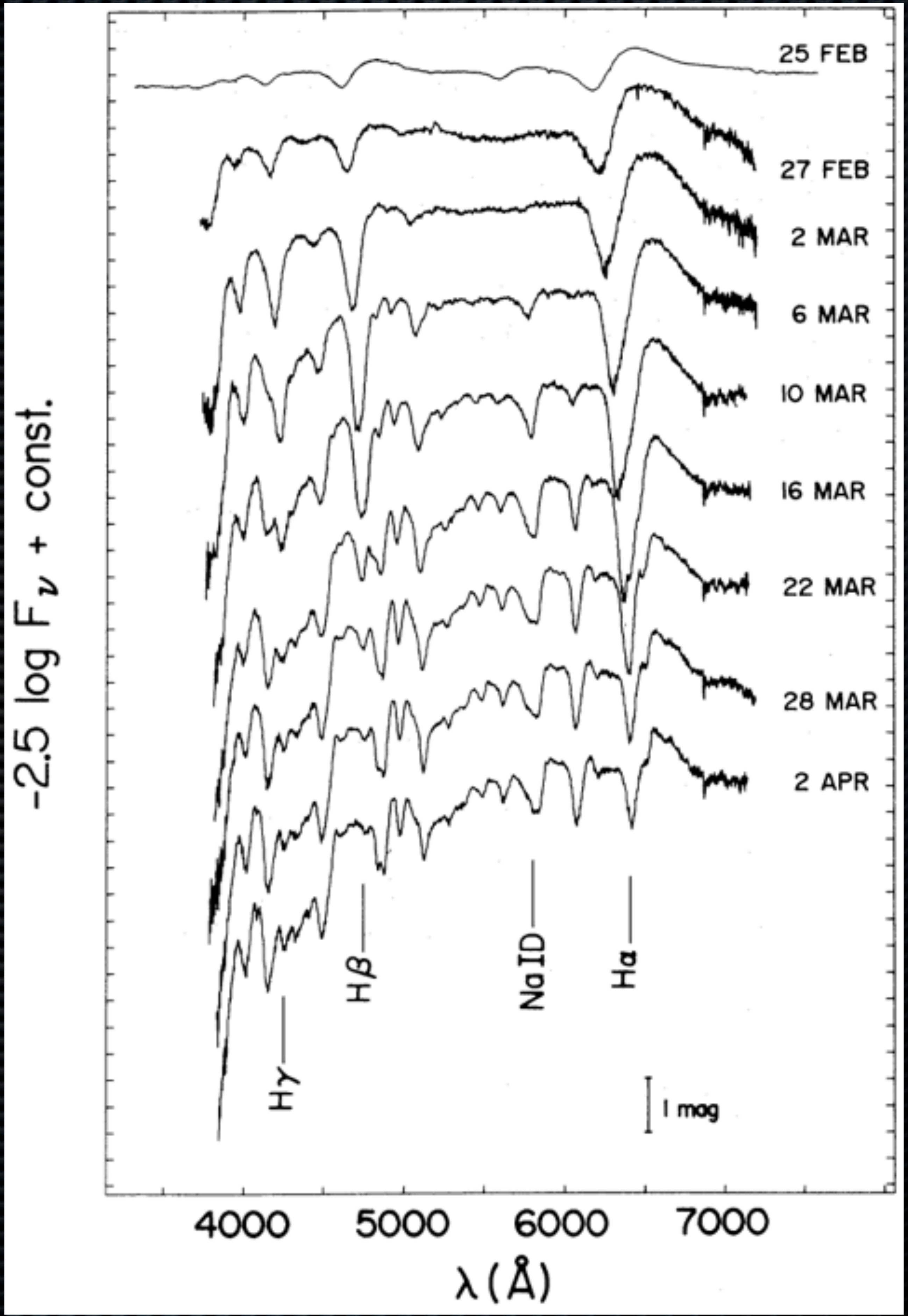

adiabatic cooling
^{56}Ni $t_{1/2}$=77days
diffusion of
shock-deposited energy
$\log_{10}(L)$ erg s^{-1}
42
41
40
39
38
41.8
41.6
41.4
41.2
0 50 100
0
200
400
600
800
Days since outburst

Spectral Evolution of SN 1987A

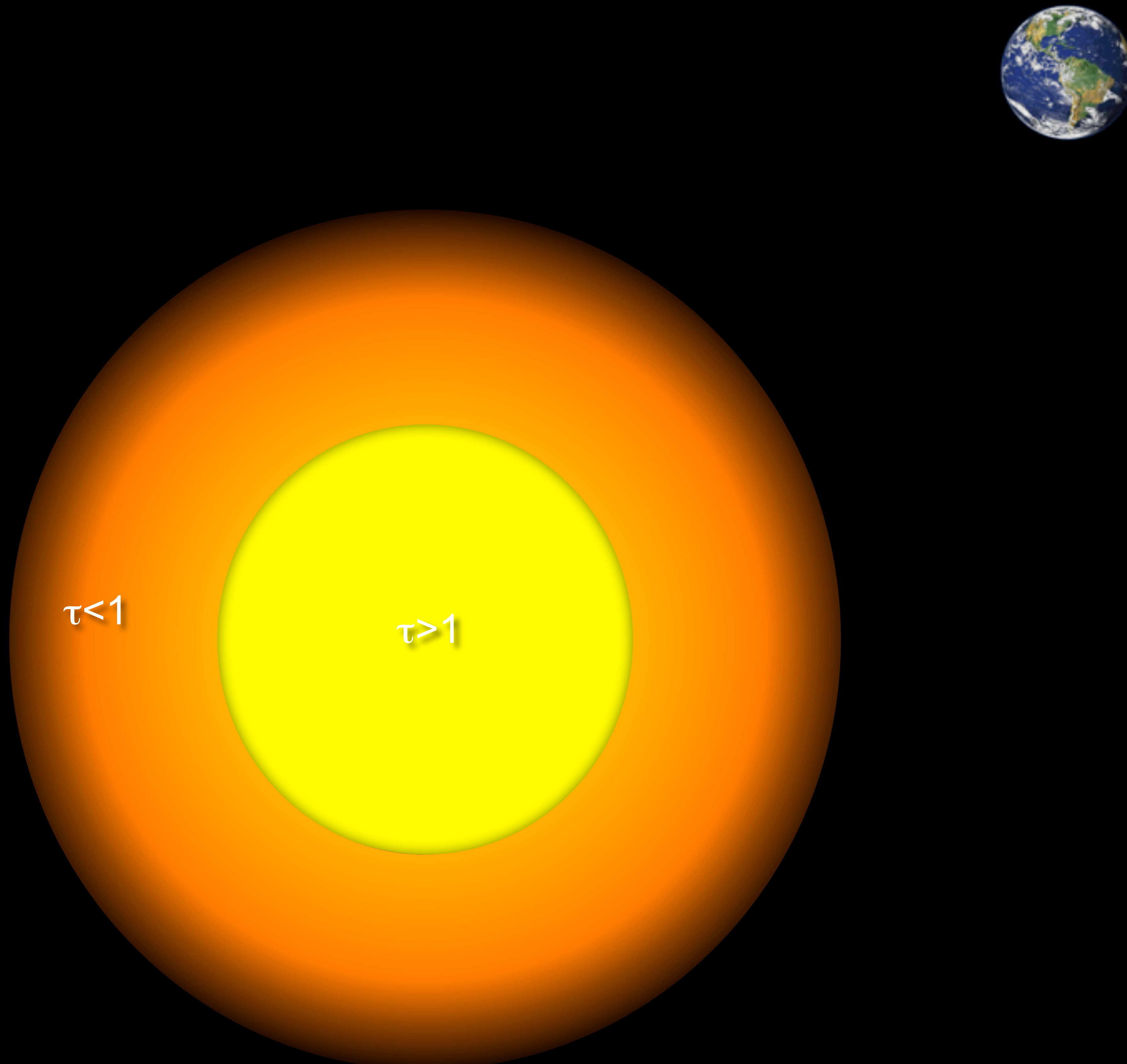
T: 15000K...5000K

vel: 20000 km/s ...

2000 km/s



Blanco et al 1987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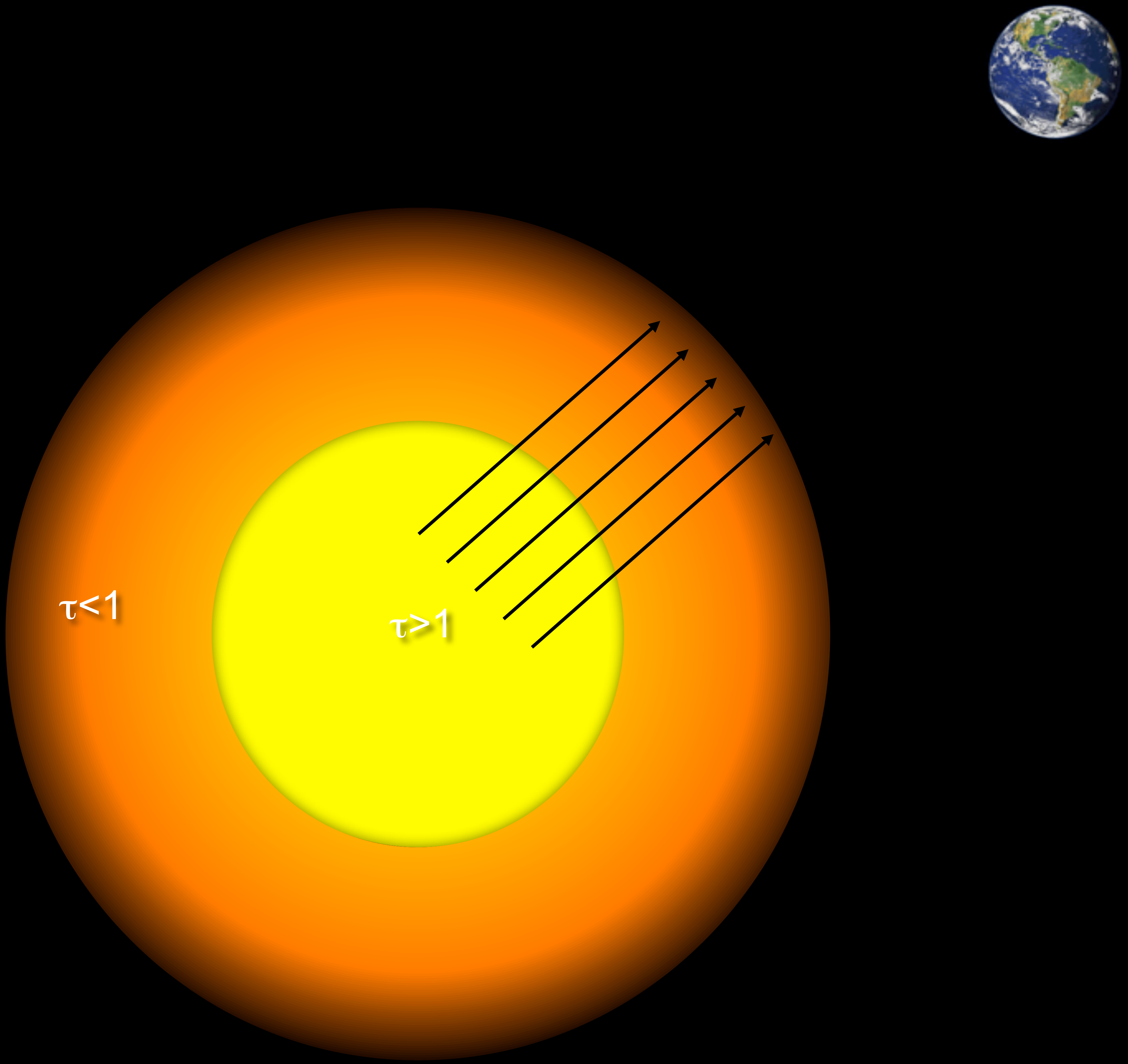
τ>1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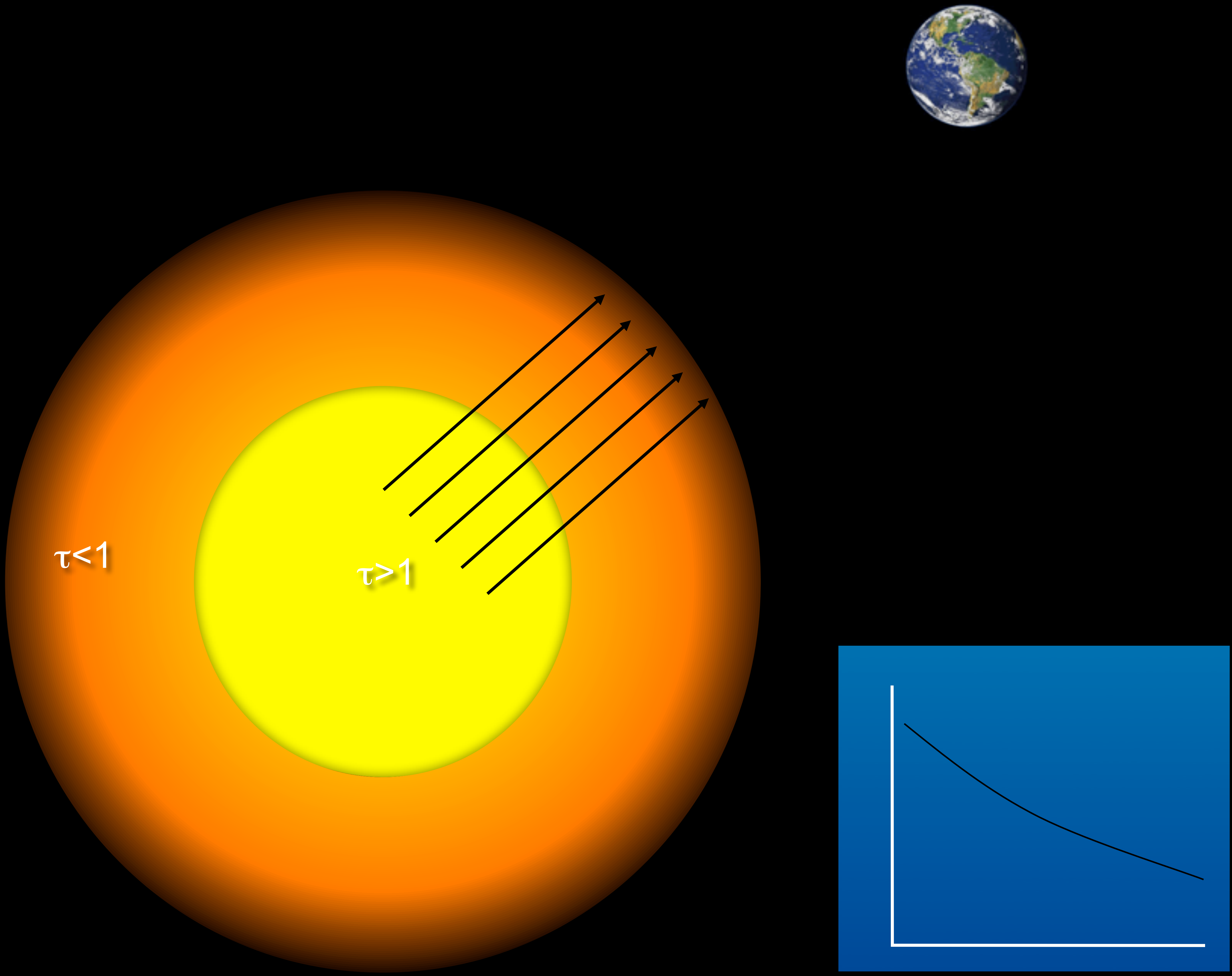
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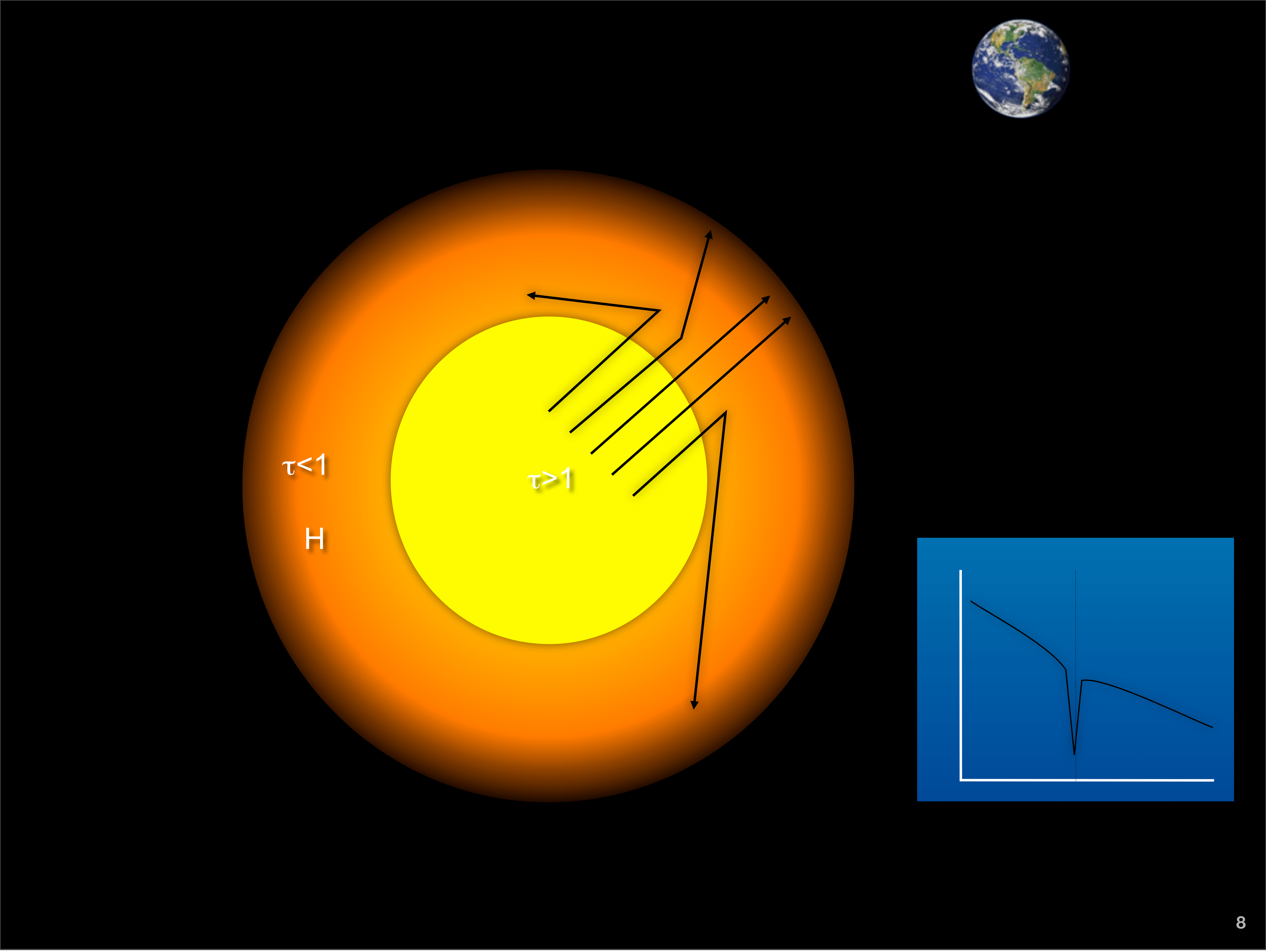
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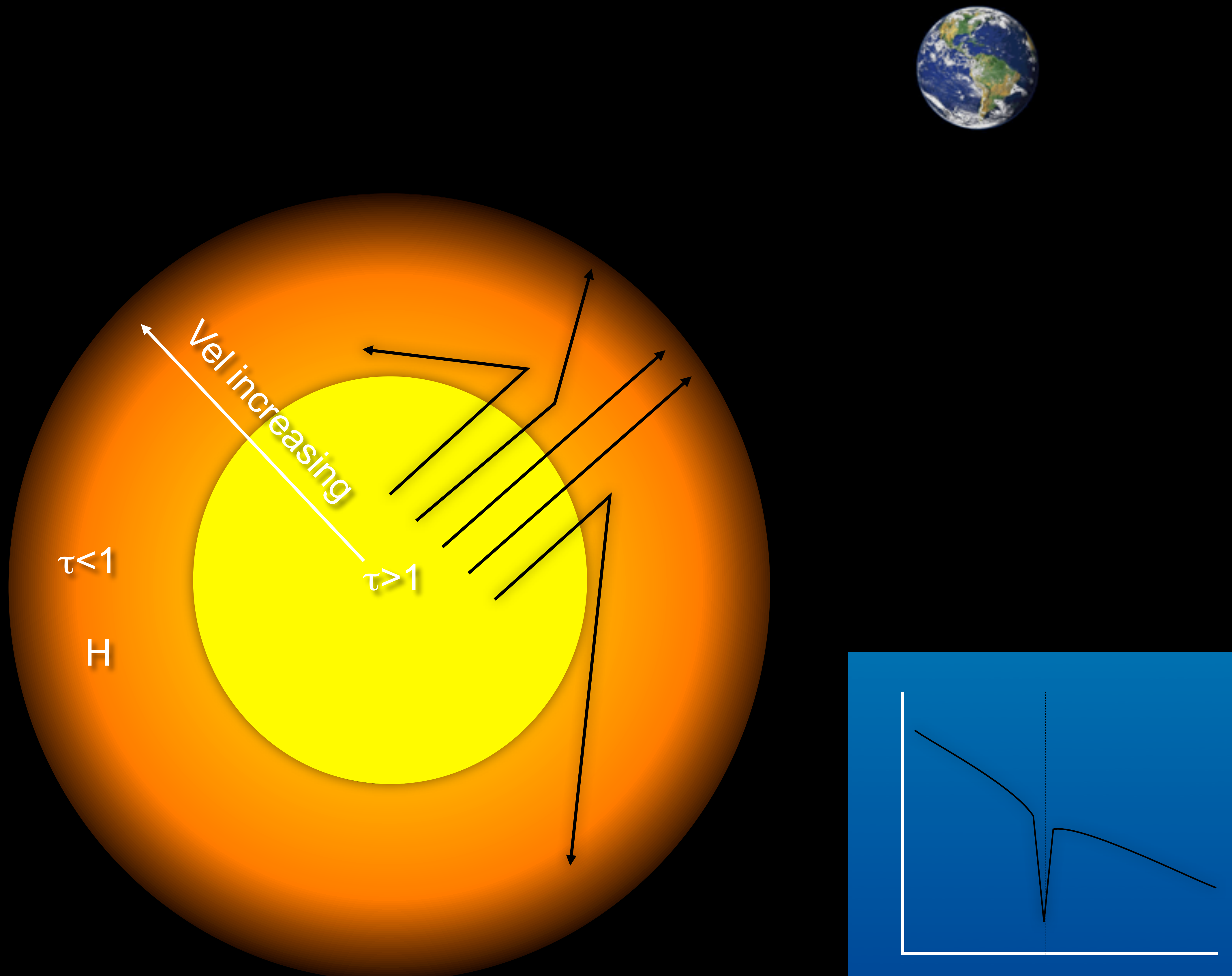
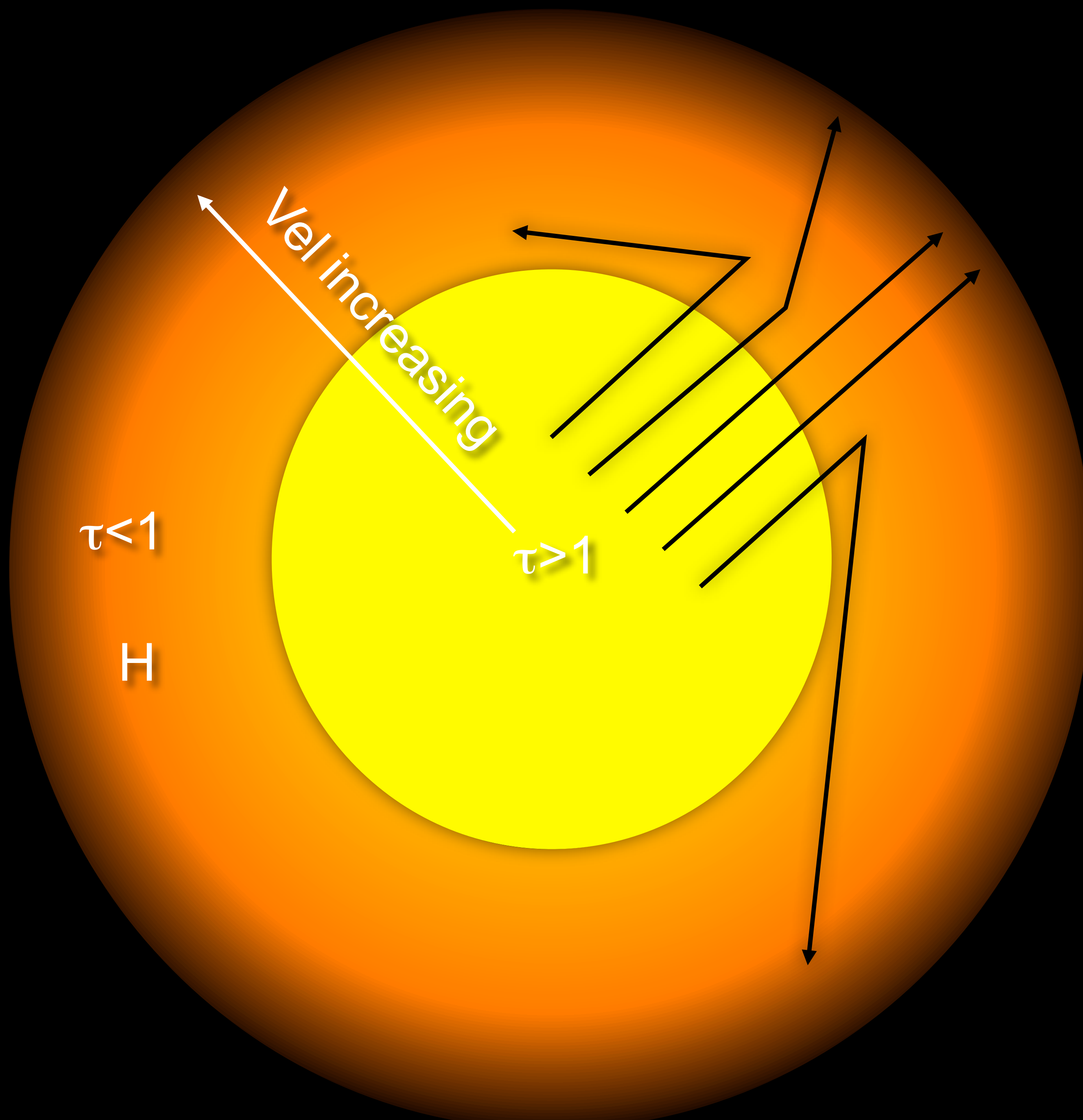
H
τ>1


Vel increasing
τ<1
τ>1
H



Vel increasing
τ<1
H
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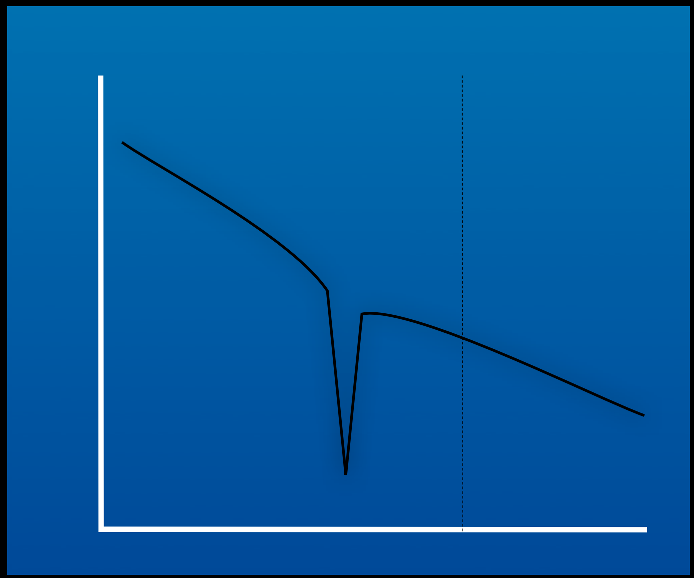
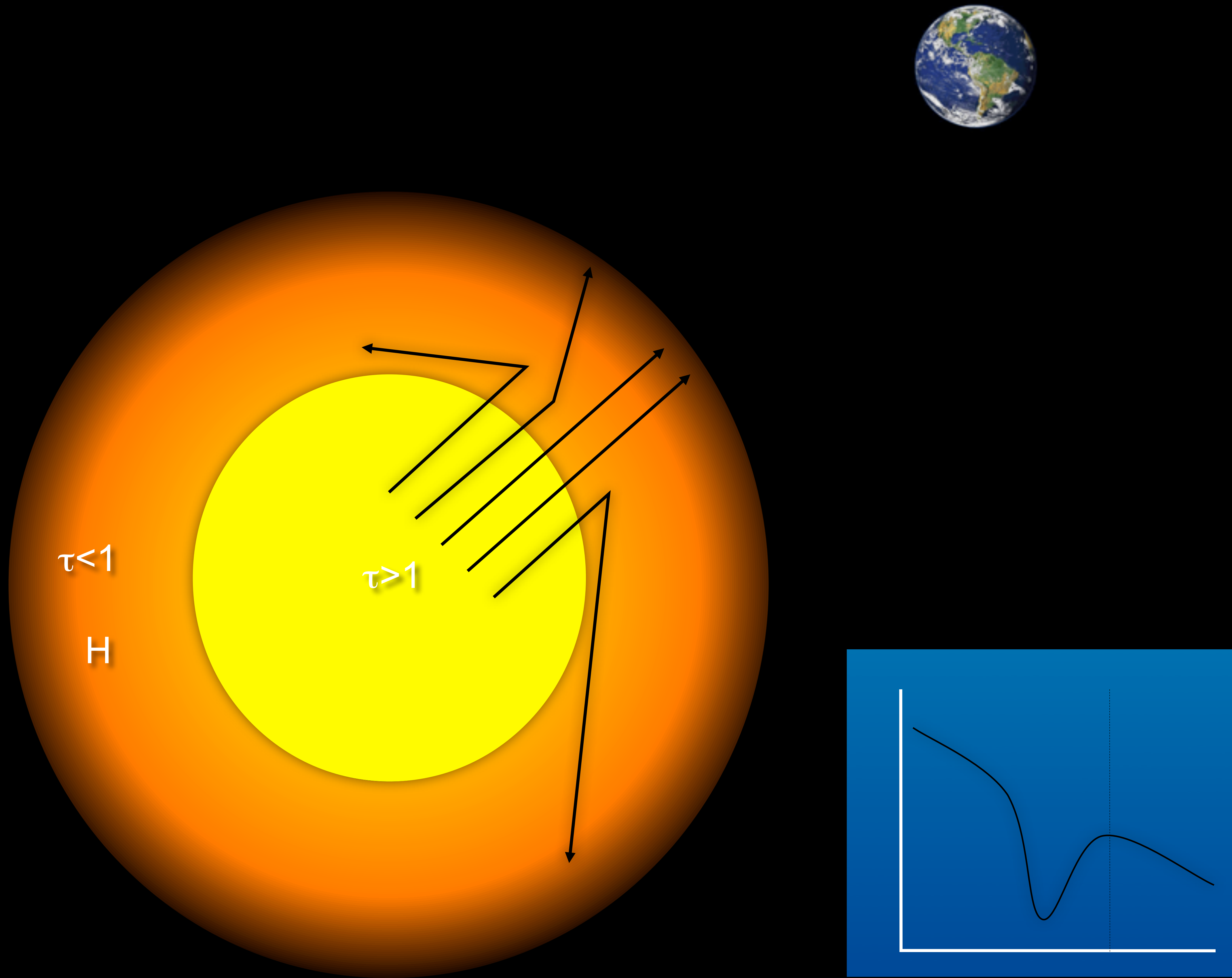
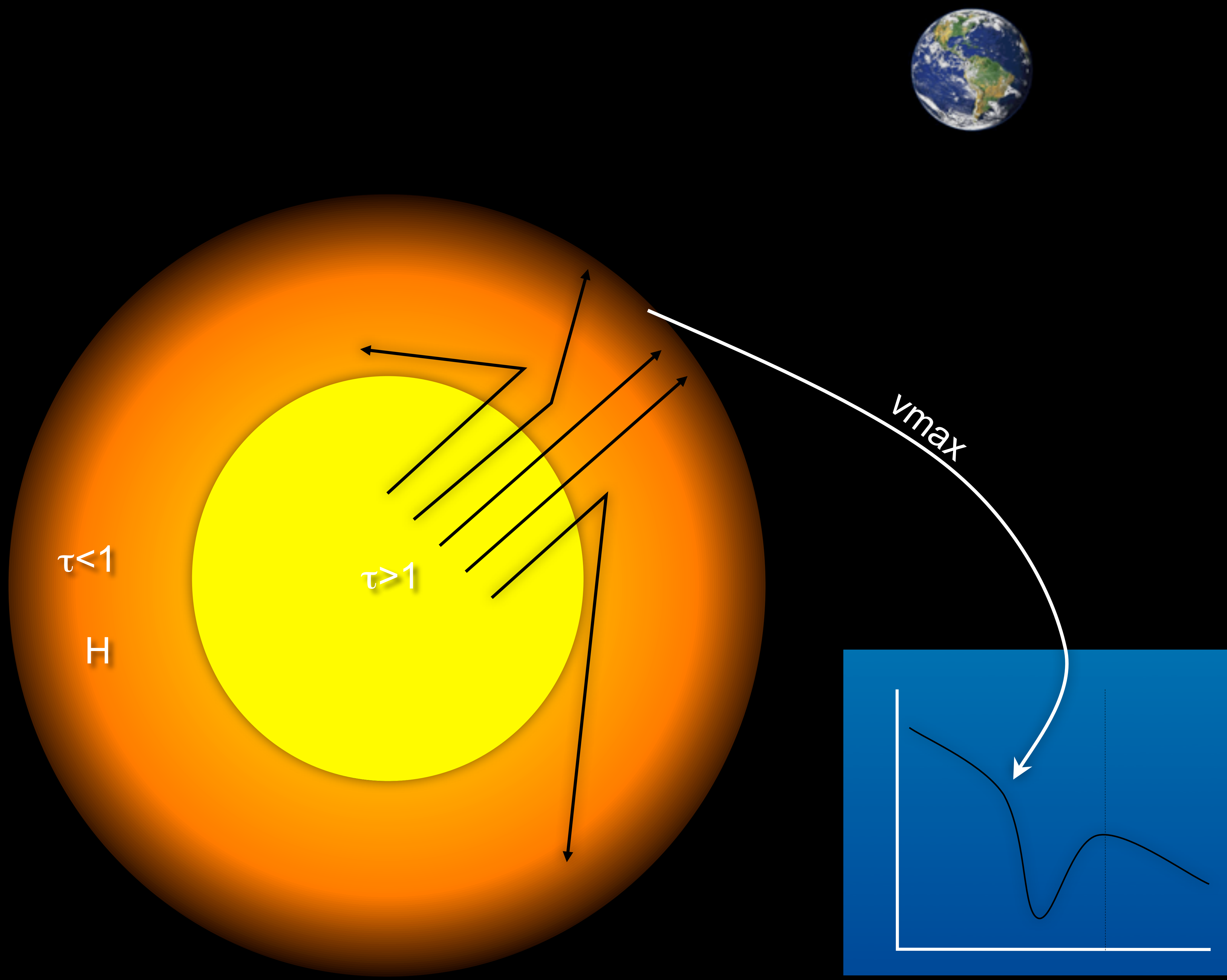
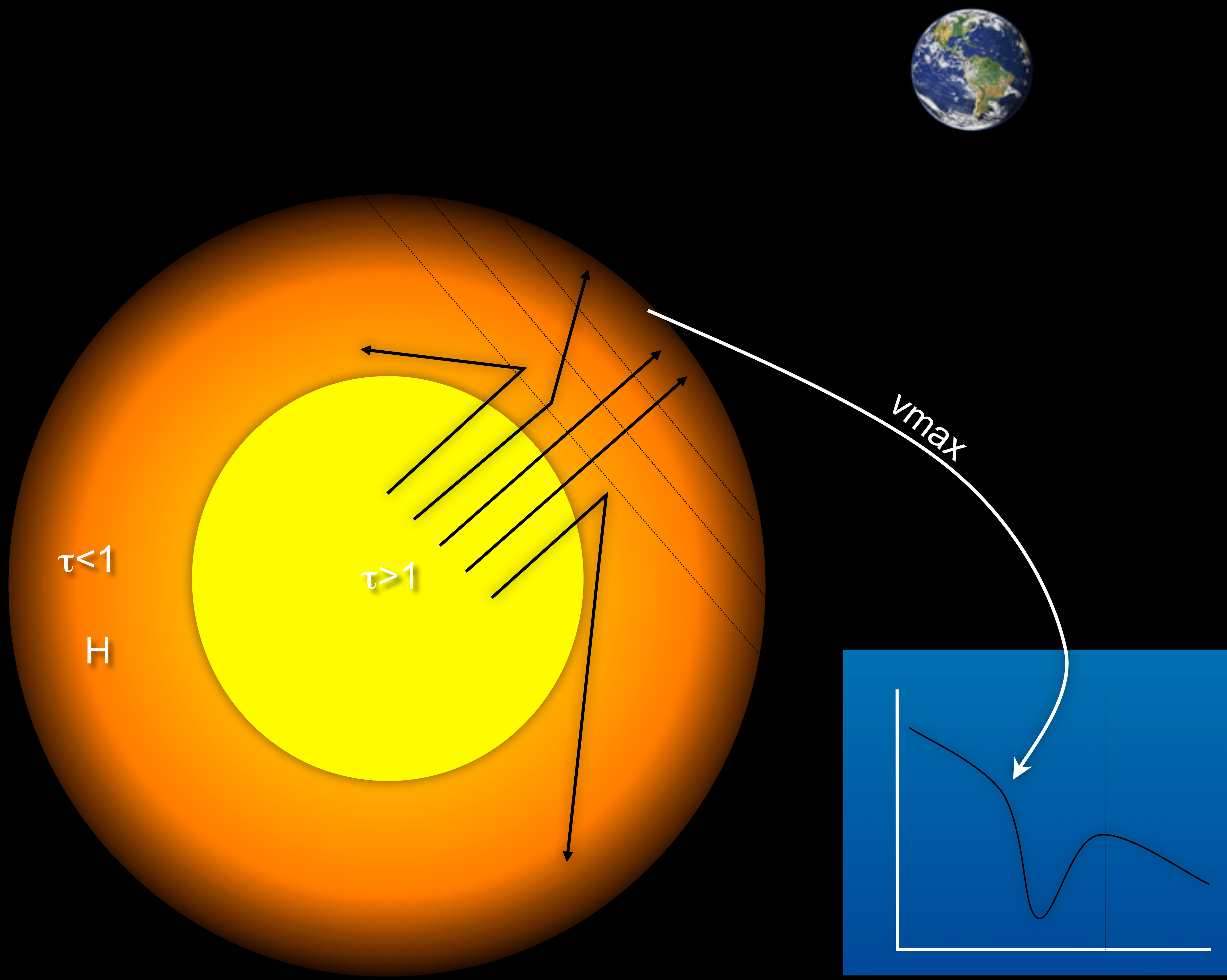
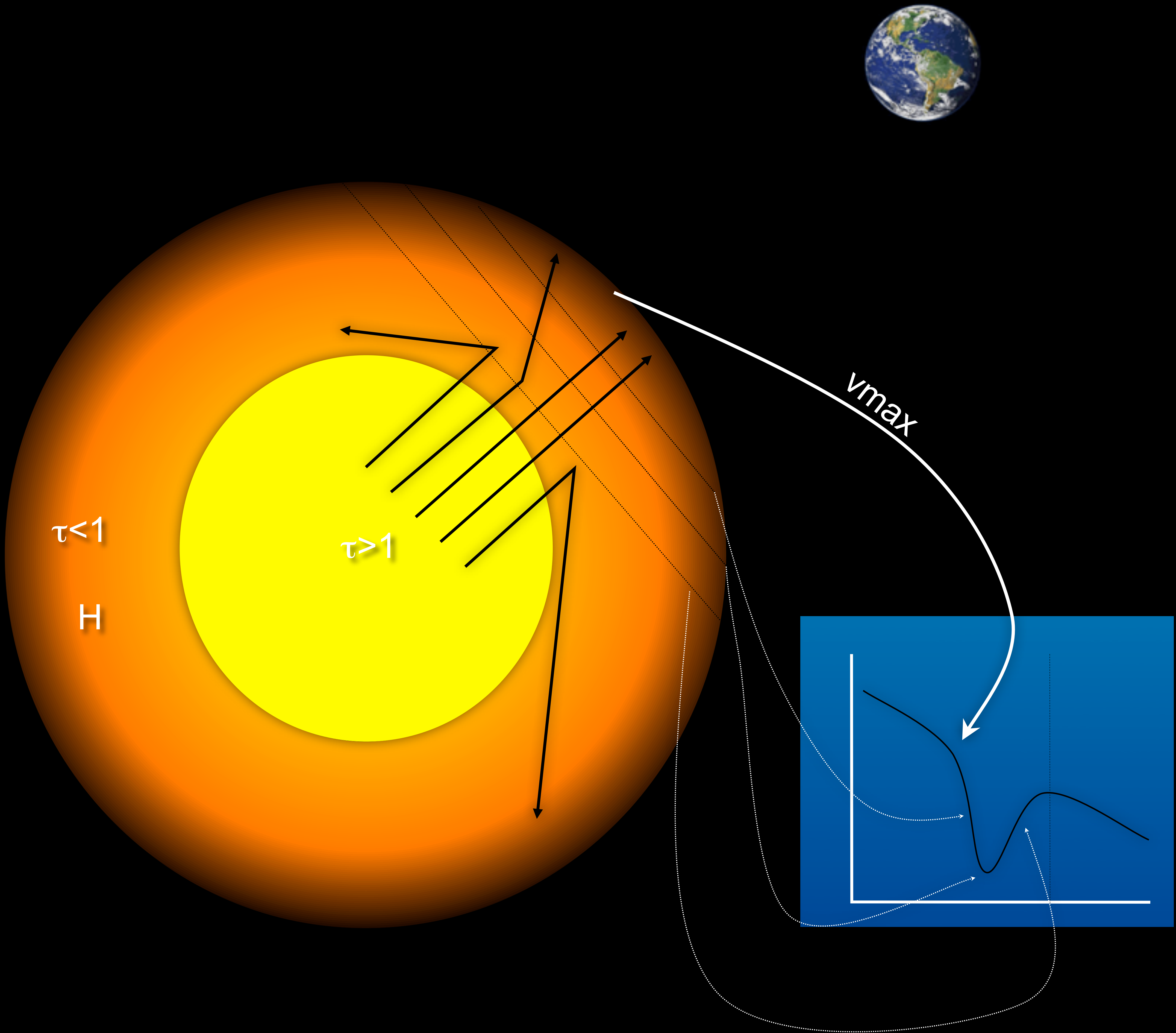


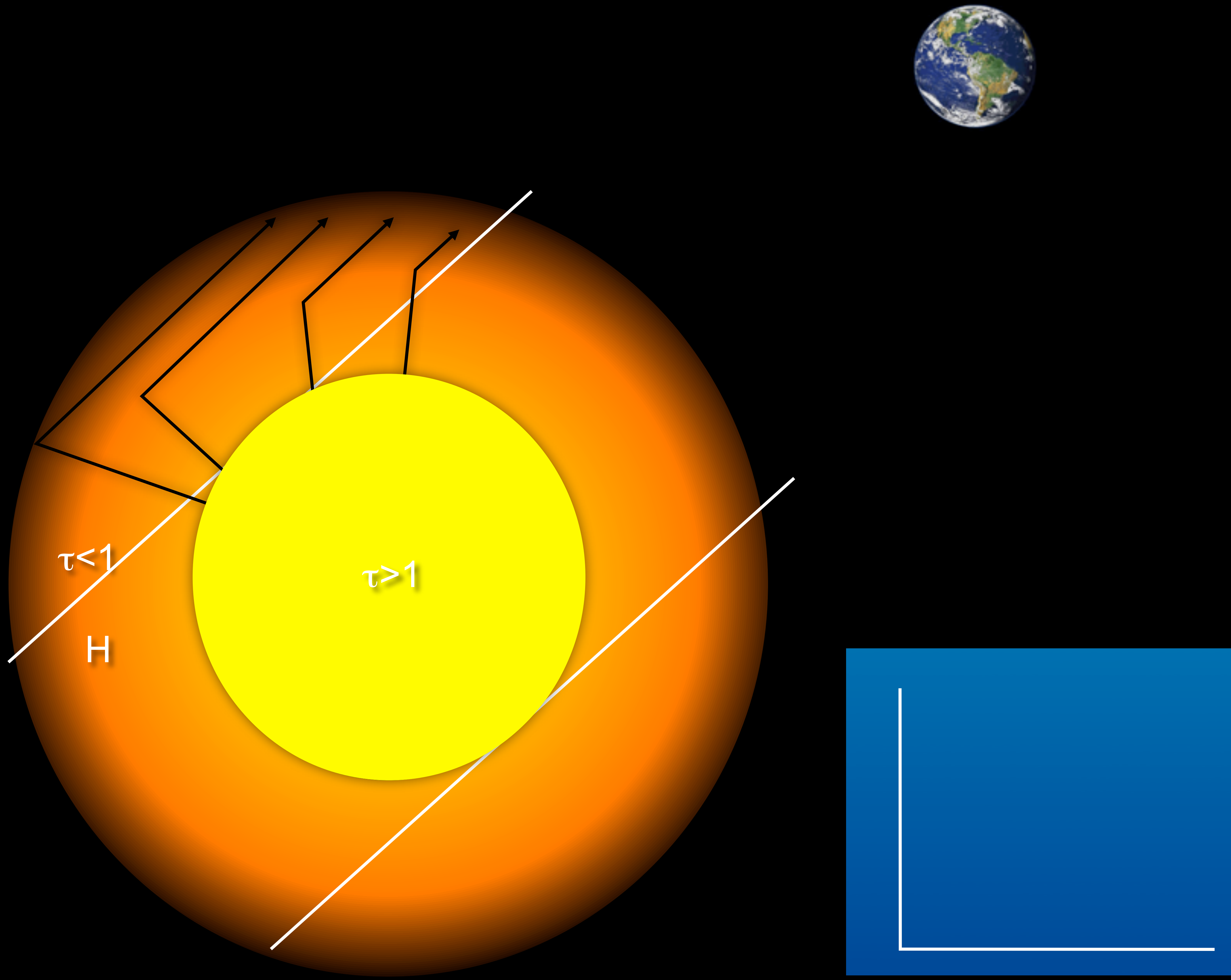

τ<1
H
τ>1

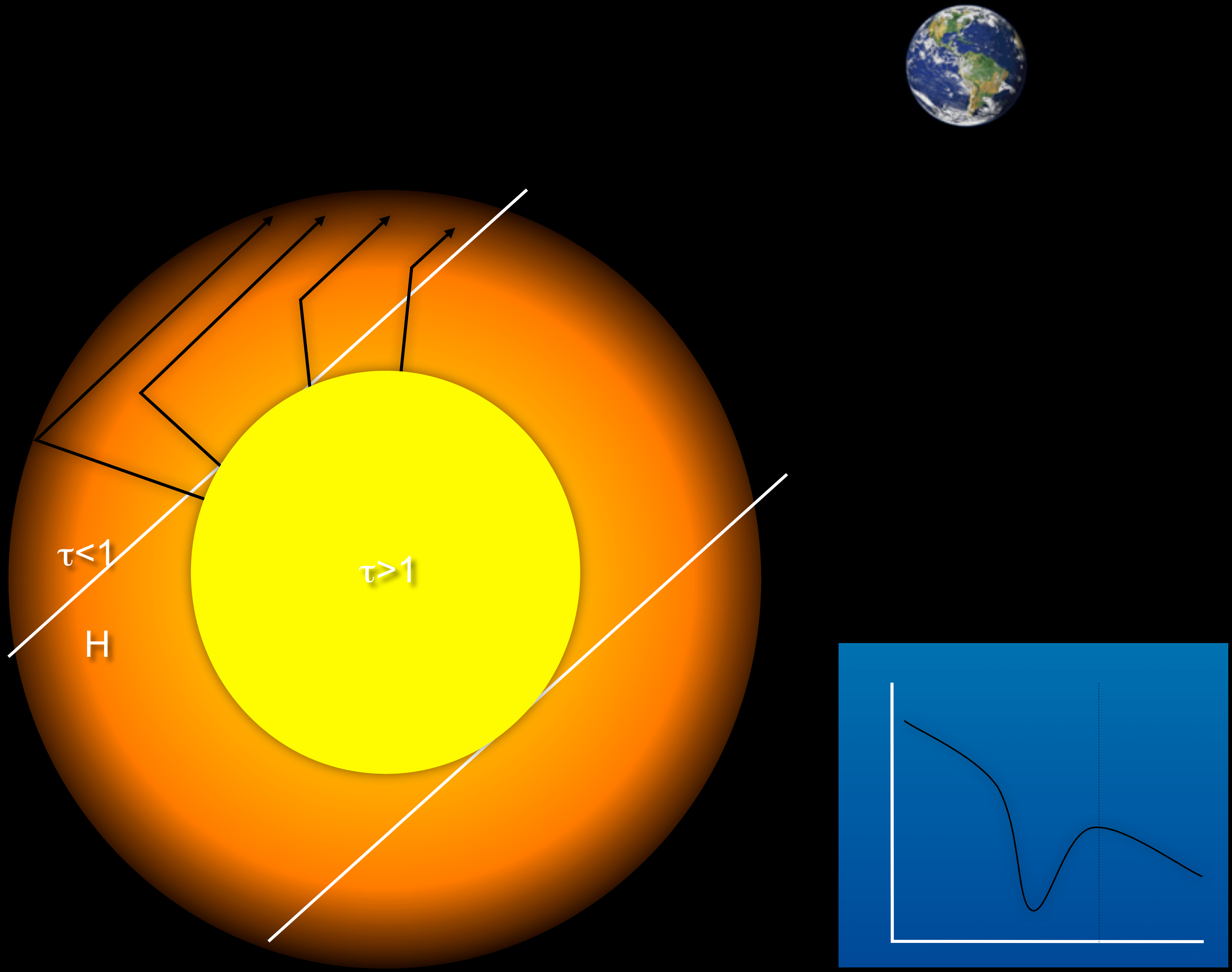

τ<1
H
τ>1
vmax

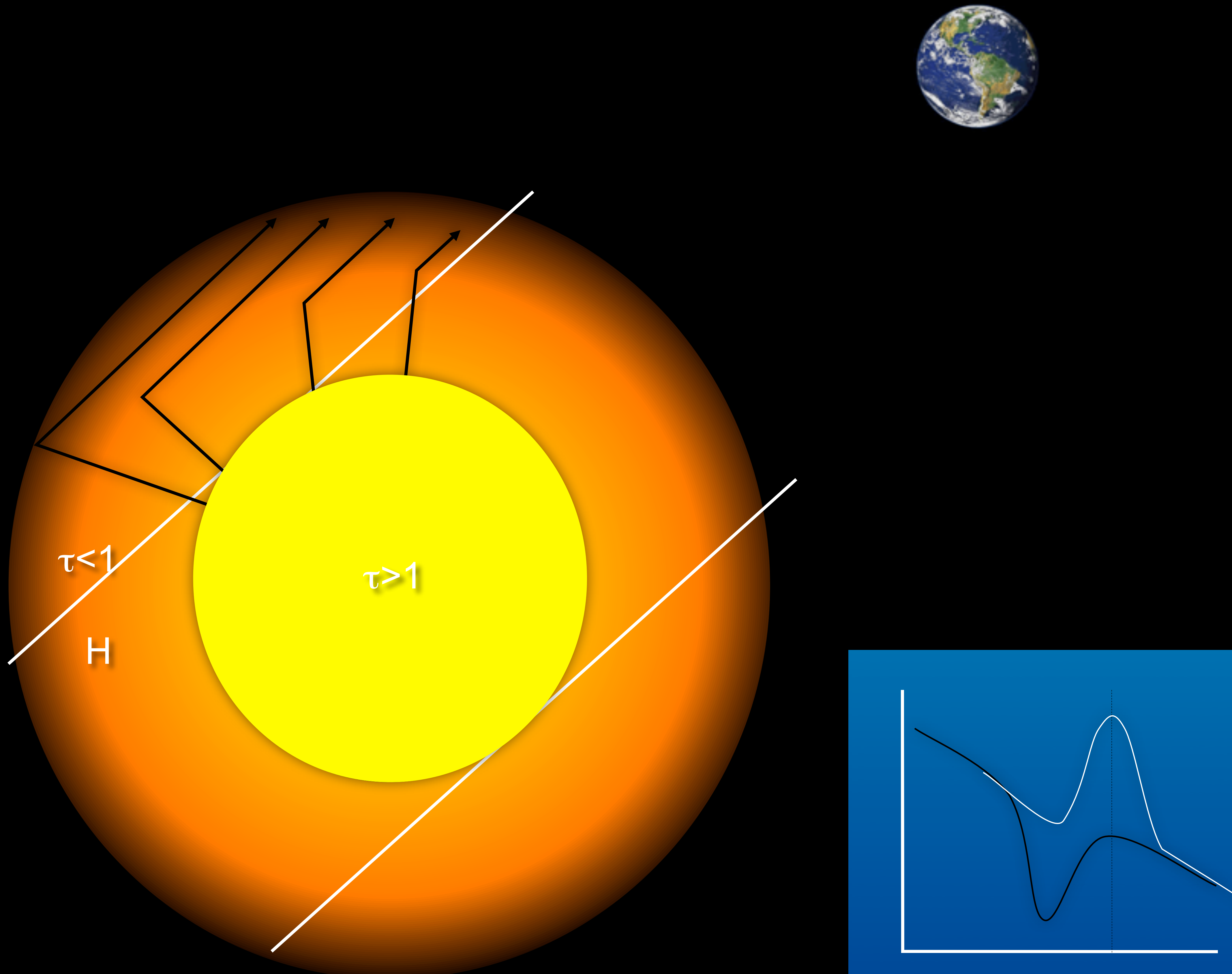

τ<1
H
τ>1
vmax

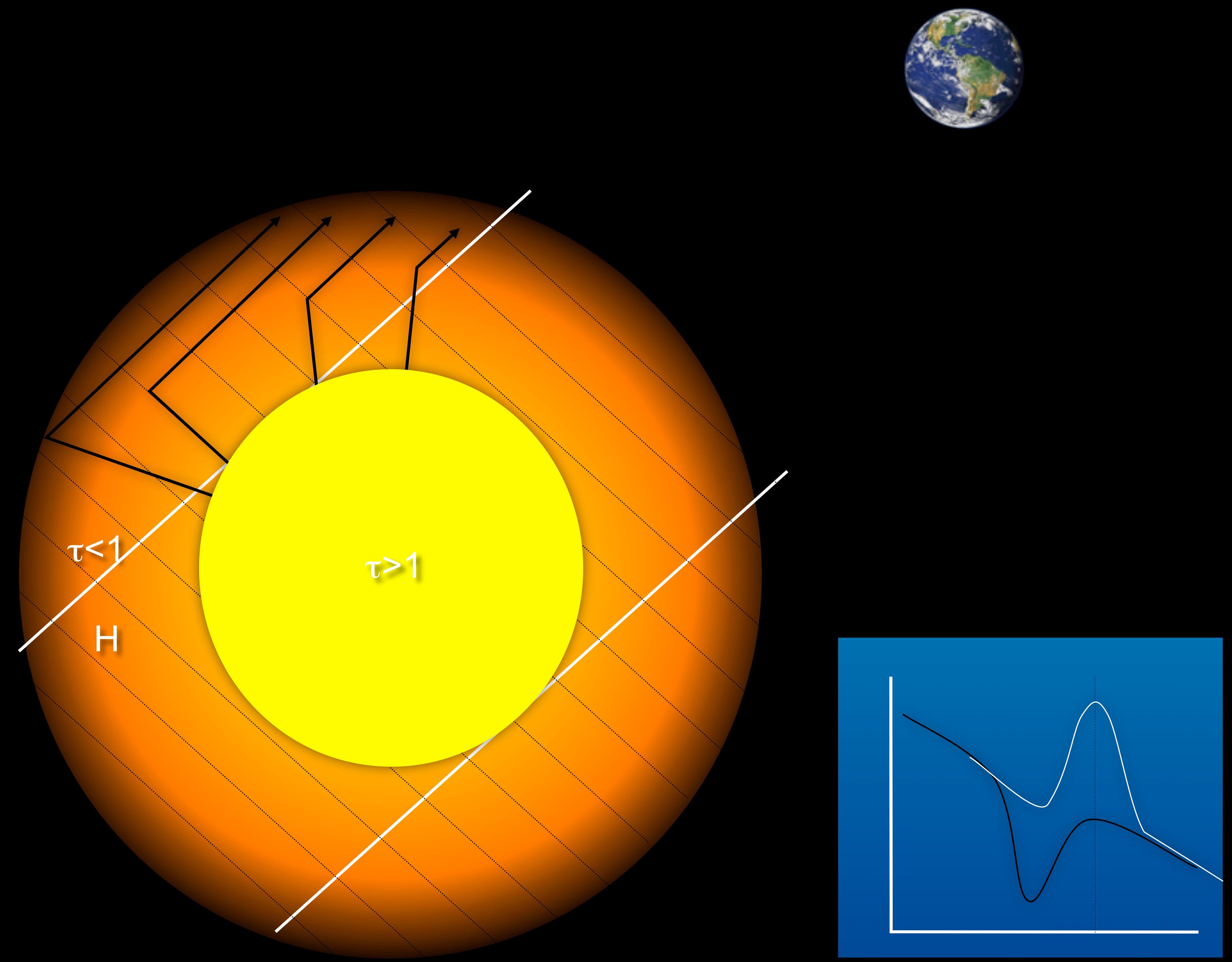


τ<1
H
τ>1
vmax


τ<1
τ>1
H


τ<1
τ>1
H


τ<1
τ>1
H


τ<1
H
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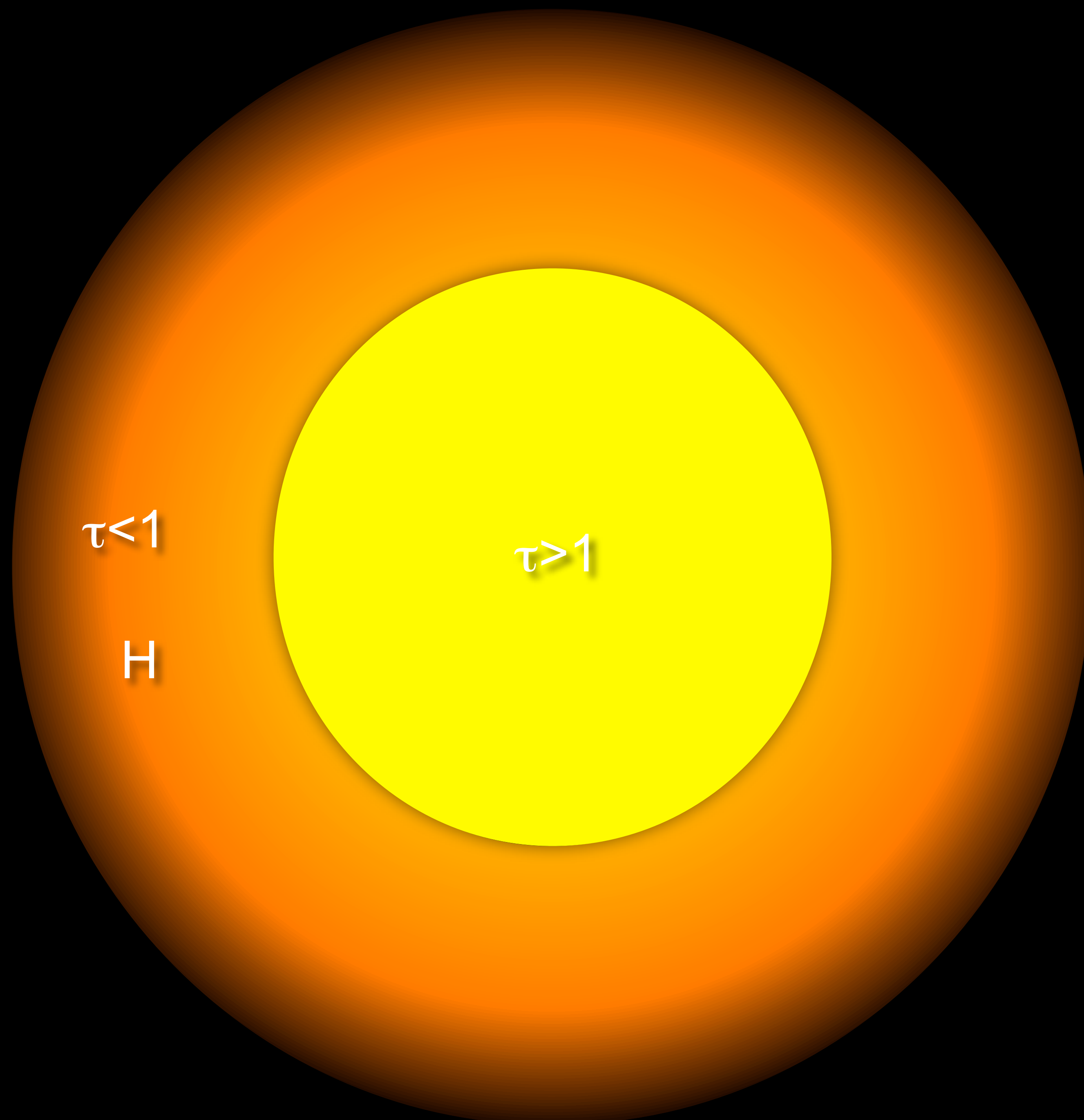

τ<1
H
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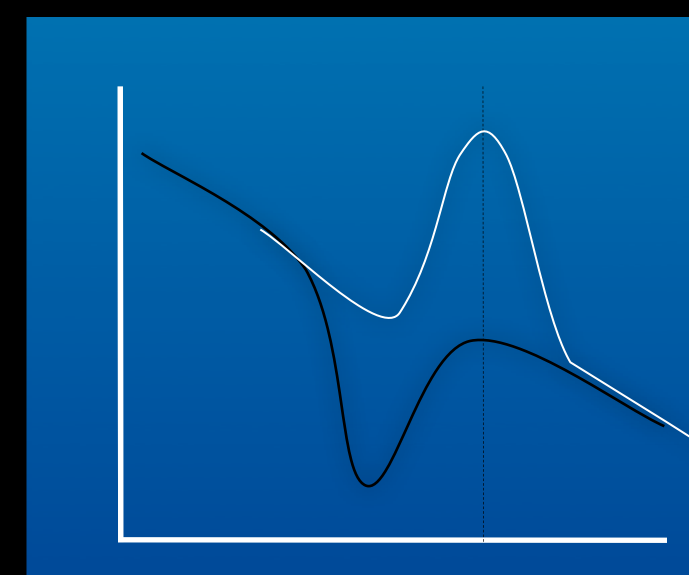

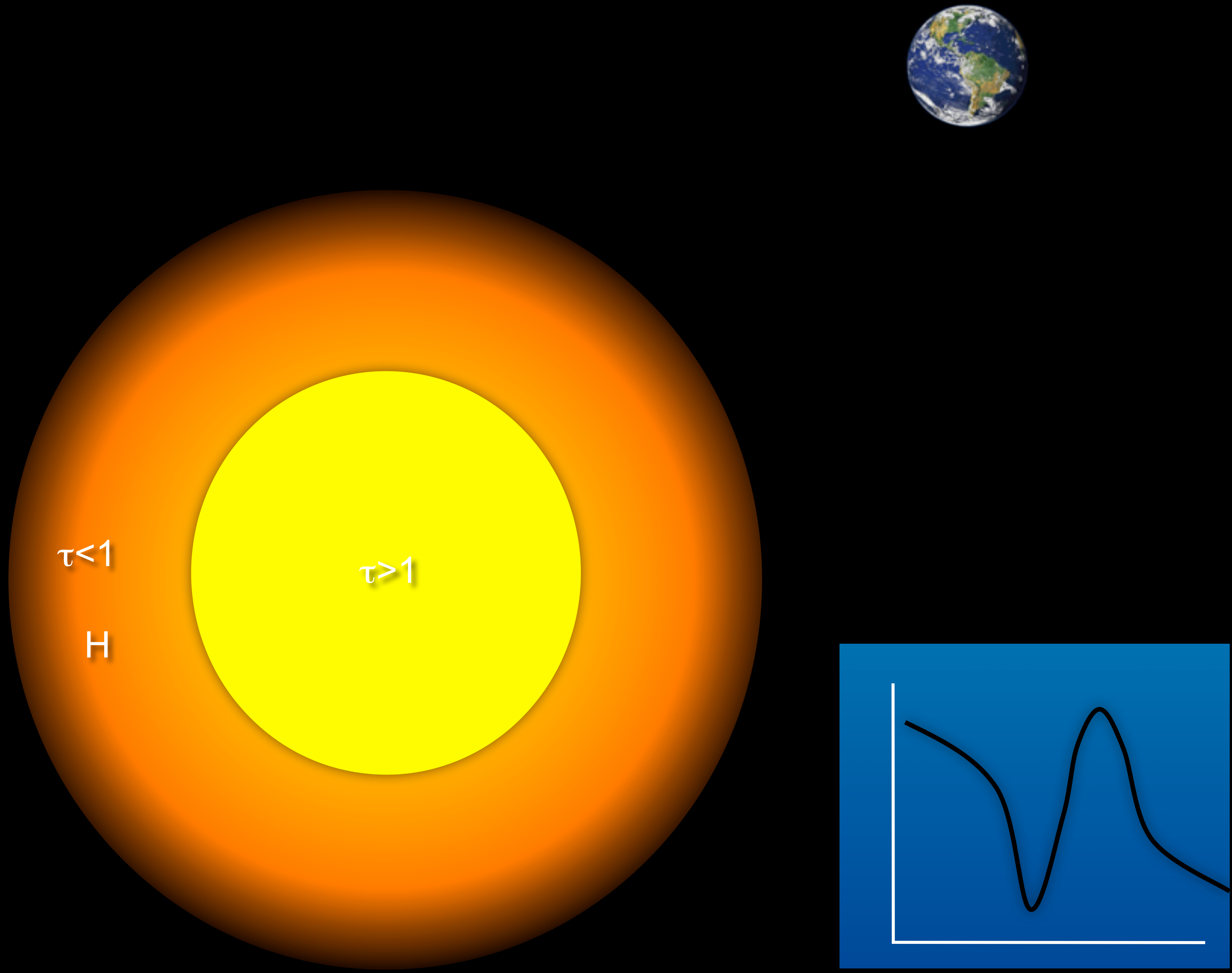
τ<1
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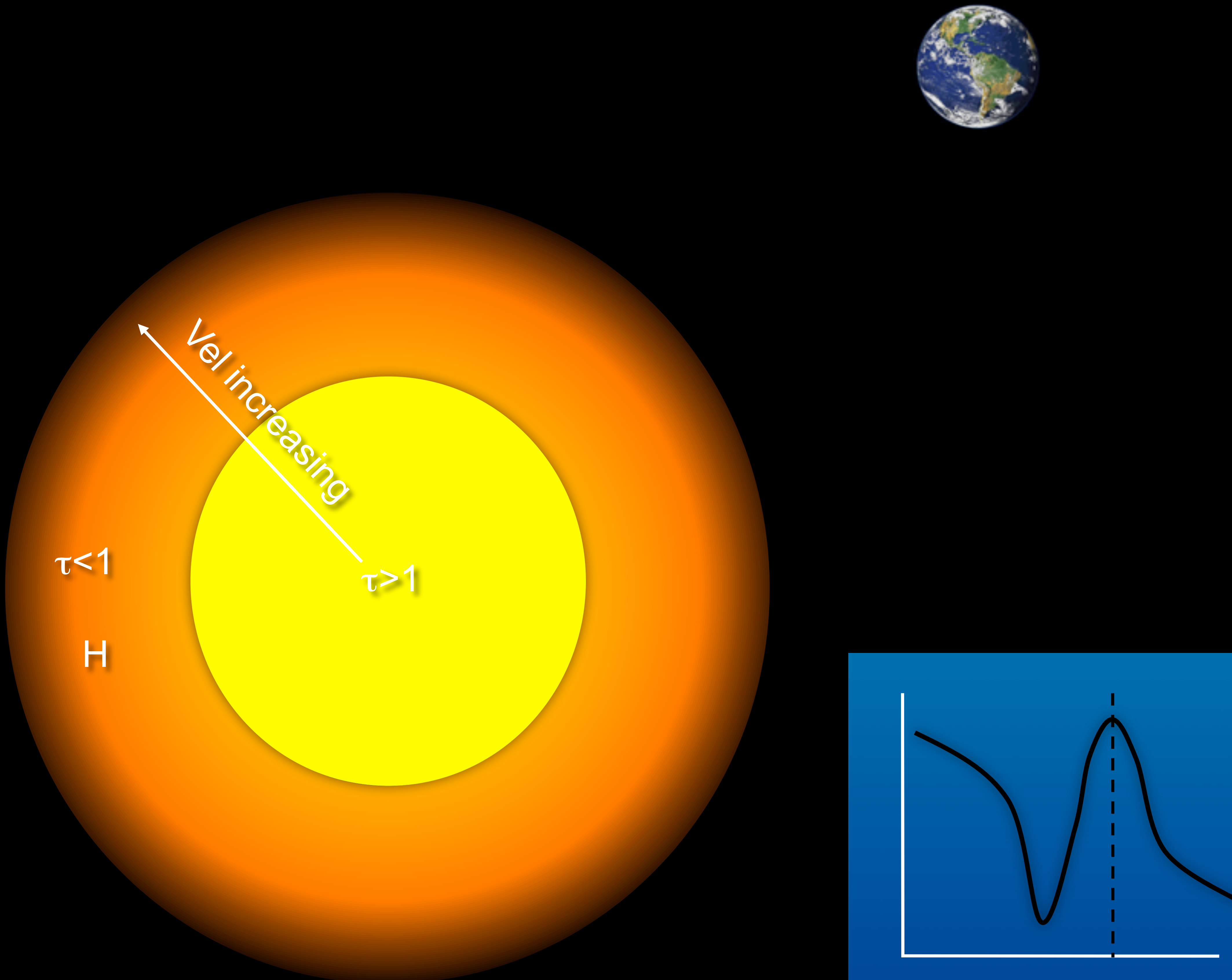
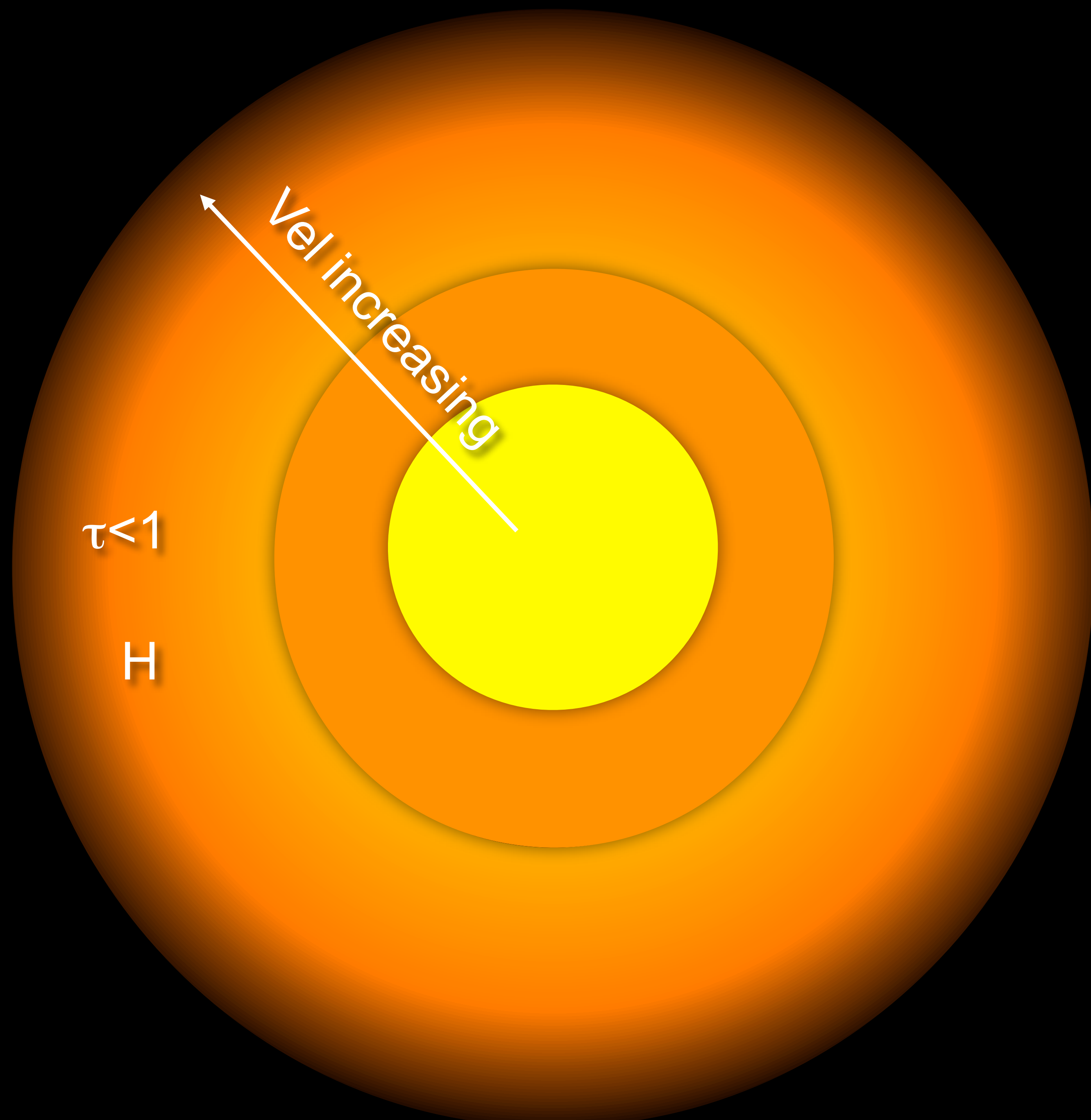

Vel increasing
τ<1
H
τ>1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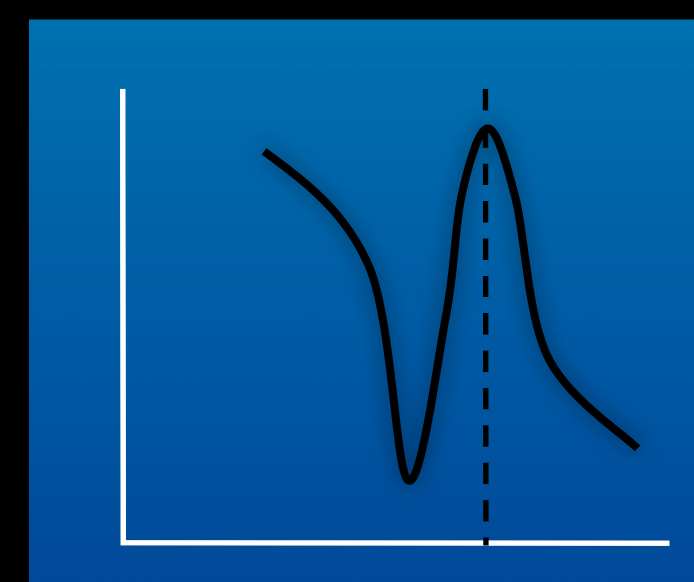
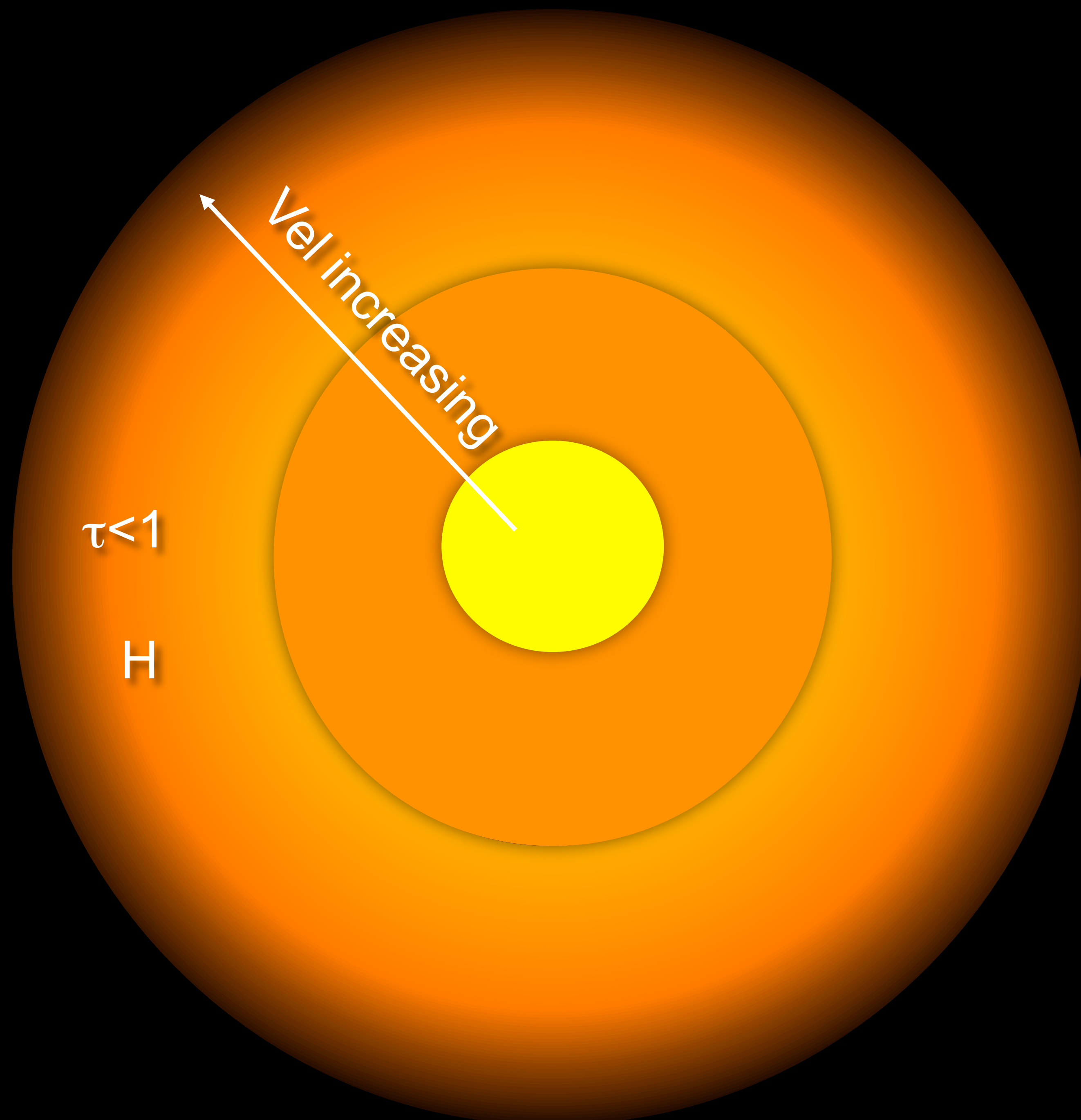
H

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τ<1
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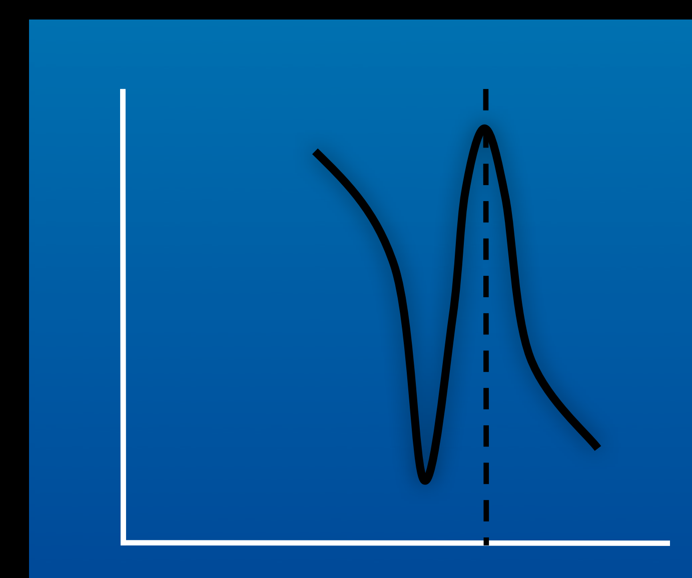


- So SN 1987A was a hot ball of expanding Hydrogen, Helium, with smaller amounts (Solar Abundance more or less) of heavier elements.
- As it aged, the expanding ball cooled from 15000 K to 5000K,
- And the photosphere moved inward from gas travelling more than 20,000km/s to about 2000 km/s

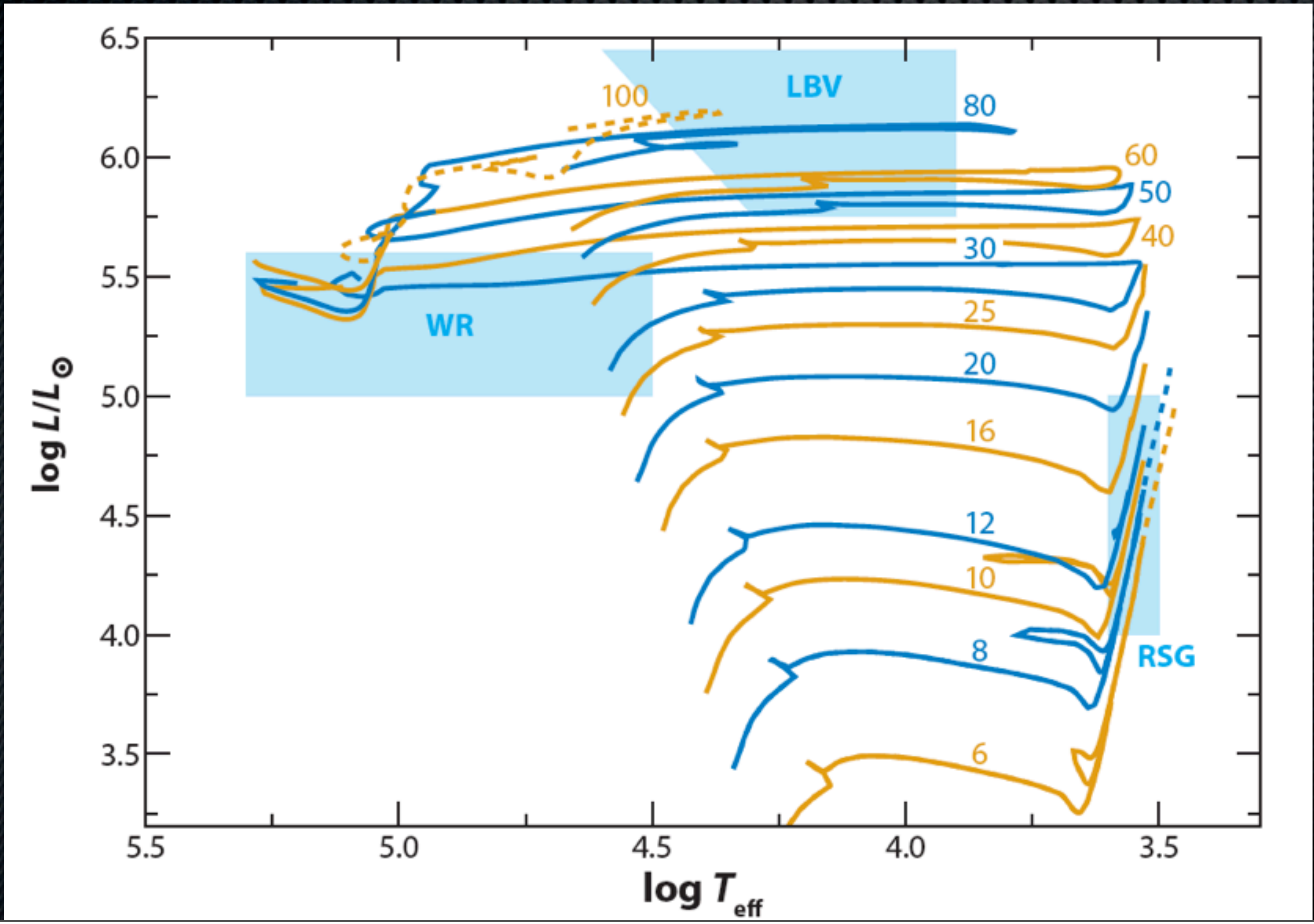
Model the system...

- Evolve a star
- Inject Energy in its center and let a hydrodynamics code follow the shock wave to expand the object
- Use a radiation Transfer code to model the spectrum of the object.
- Add some additional energy from due to ^{56}Ni

SN 1987A: 15 Solar Mass Blue Super Giant with 10^{51}ergs (10^{44} Watts) of Energy and $0.07M_\odot$ ^{56}Ni

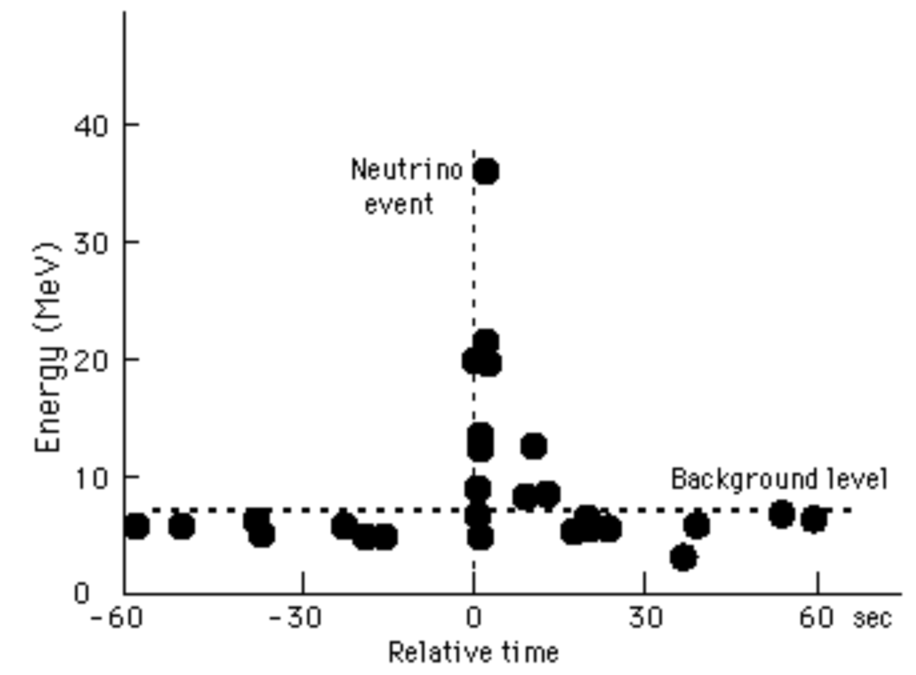
But Life is not simple...

Stellar evolution codes do not predict a star should be a blue supergiant when it explodes...



Event	Event time (s)	Electron energy (MeV)	Electron angle (degrees)
Kamiokande II:			
1	0.0	20.0±2.9	18±18
2	0.107	13.5±3.2	40±27
3	0.303	7.5±2.0	108±32
4	0.324	9.2±2.7	70±30
5	0.507	12.8±2.9	135±23
6	0.686	6.3±1.7	68±77
7	1.541	35.4±8.0	32±16
8	1.728	21.0±4.2	30±18
9	1.915	19.8±3.2	38±22
10	9.219	8.6±2.7	122±30
11	10.433	13.0±2.6	49±26
12	12.439	8.9±1.9	91±39
IMB:			
1	0.0	38±7	80±10
2	0.41	37±7	44±15
3	0.65	28±6	56±20
4	1.14	39±7	65±20
5	1.56	36±9	33±15
6	2.68	36±6	52±10
7	5.01	19±5	42±20
8	5.58	22±5	104±20

[a] The first events were detected on February 23, 1987, at about 7 hr 36 m UT. The angle in the last column is relative to the direction of the LMC. The errors are estimated 1σ uncertainties.



Core Collapse
Engine

Core Collapse Engine

Core Collapse Engine

Oxygen Burning

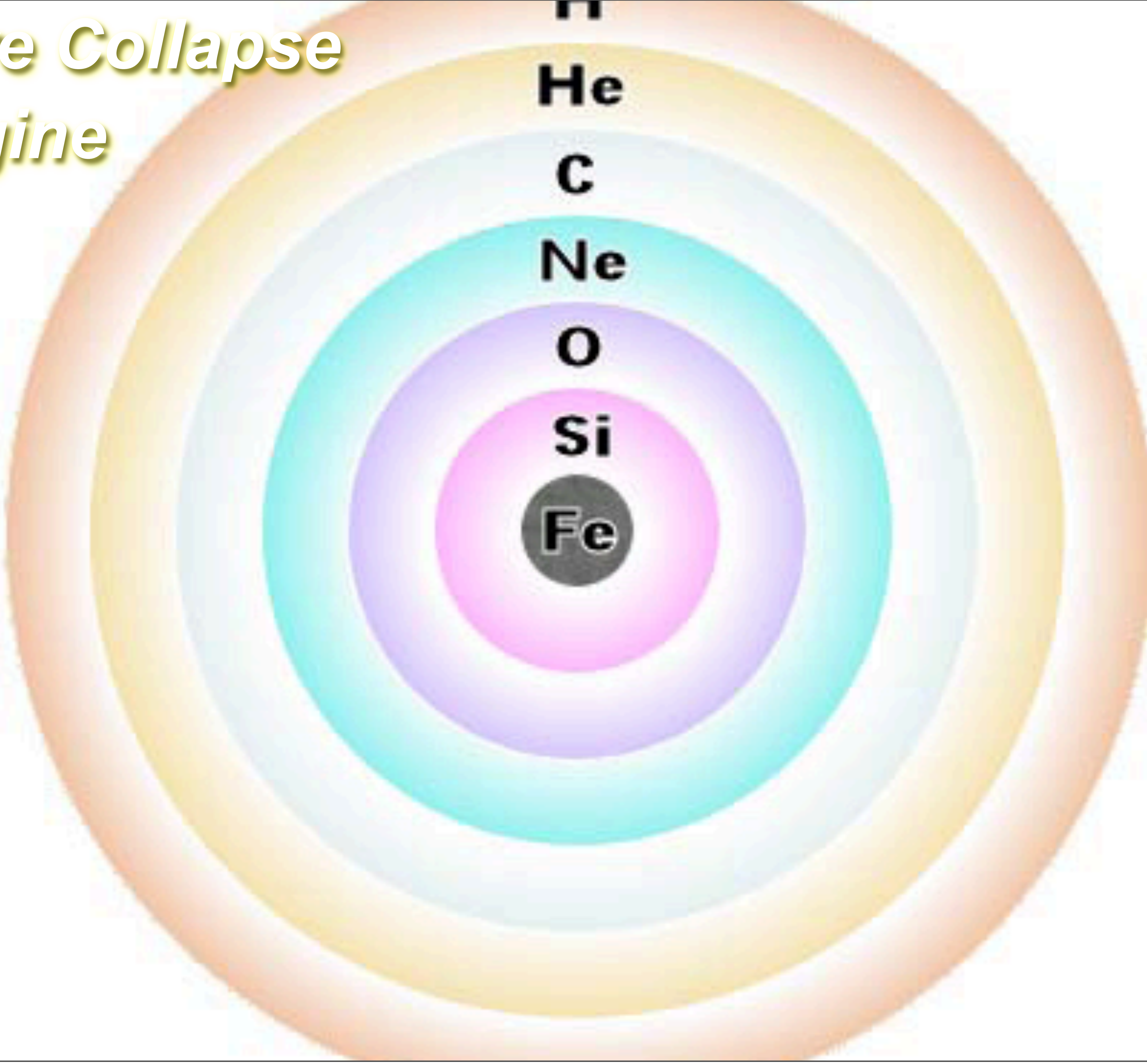
Core Collapse Engine

Oxygen Burning
Silicon Burning

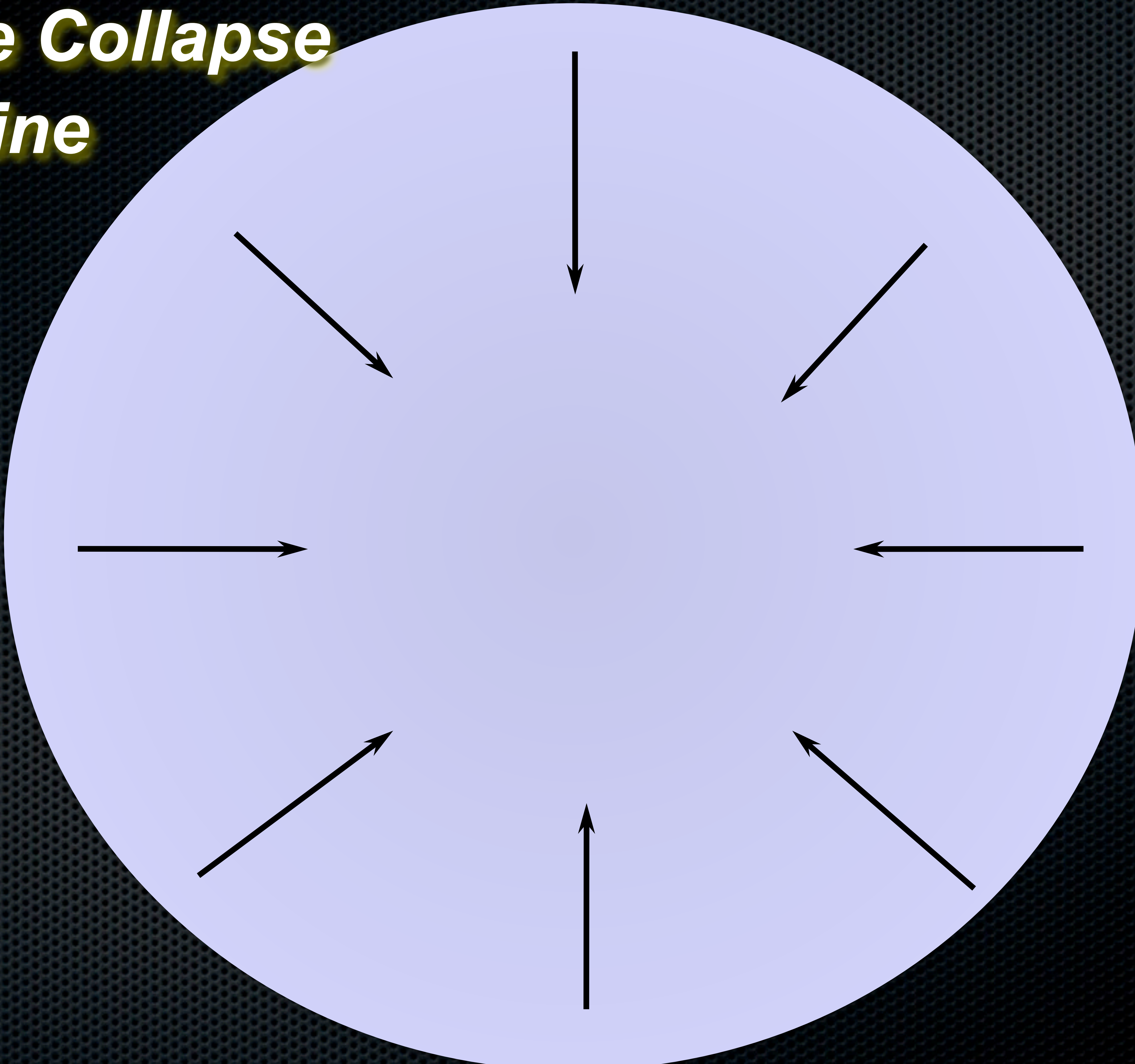
Core Collapse Engine

Oxygen Burning
Silicon Burning
Iron Burning

Core Collapse Engine



Core Collapse Engine



Core Collapse Engine

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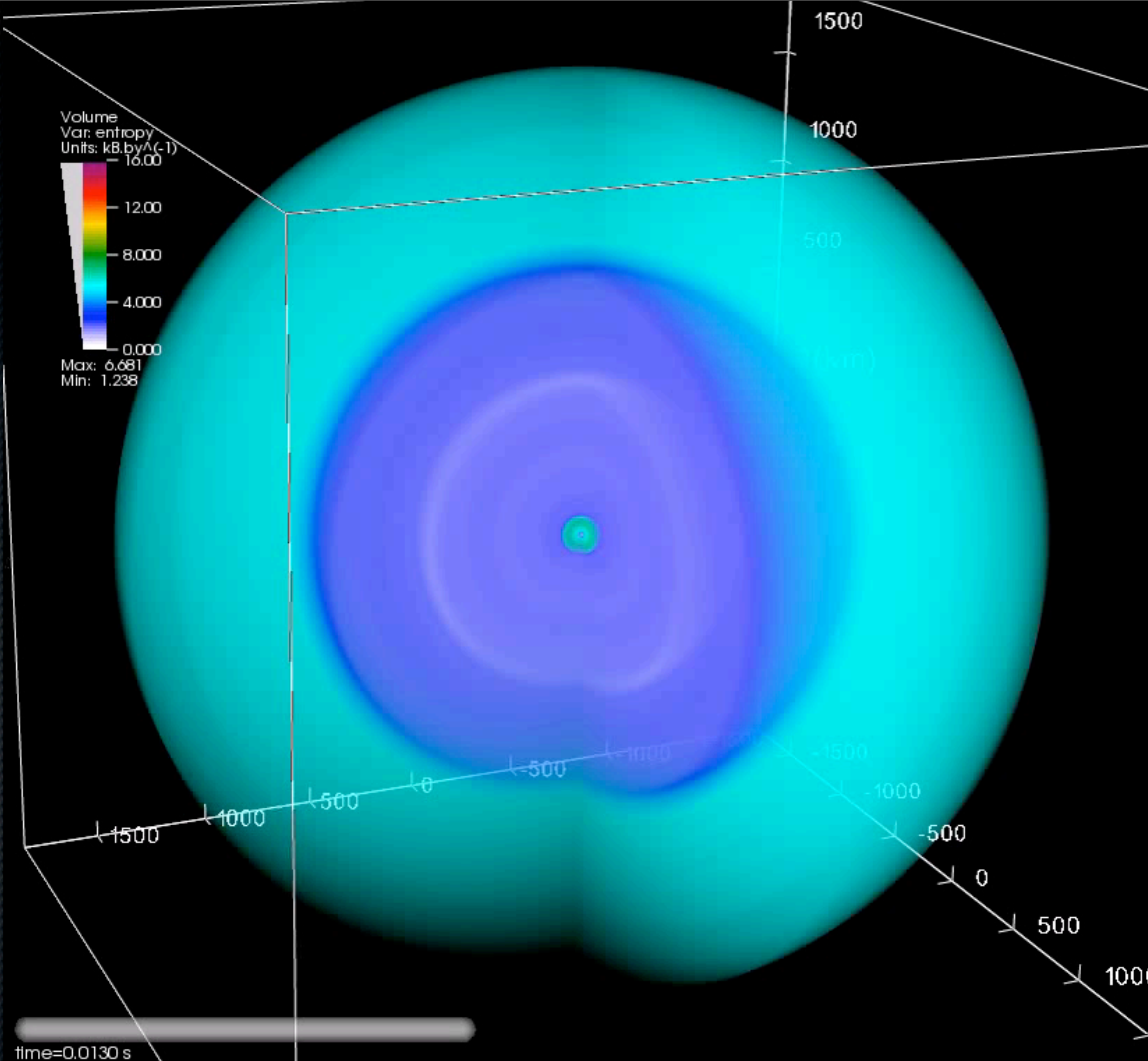
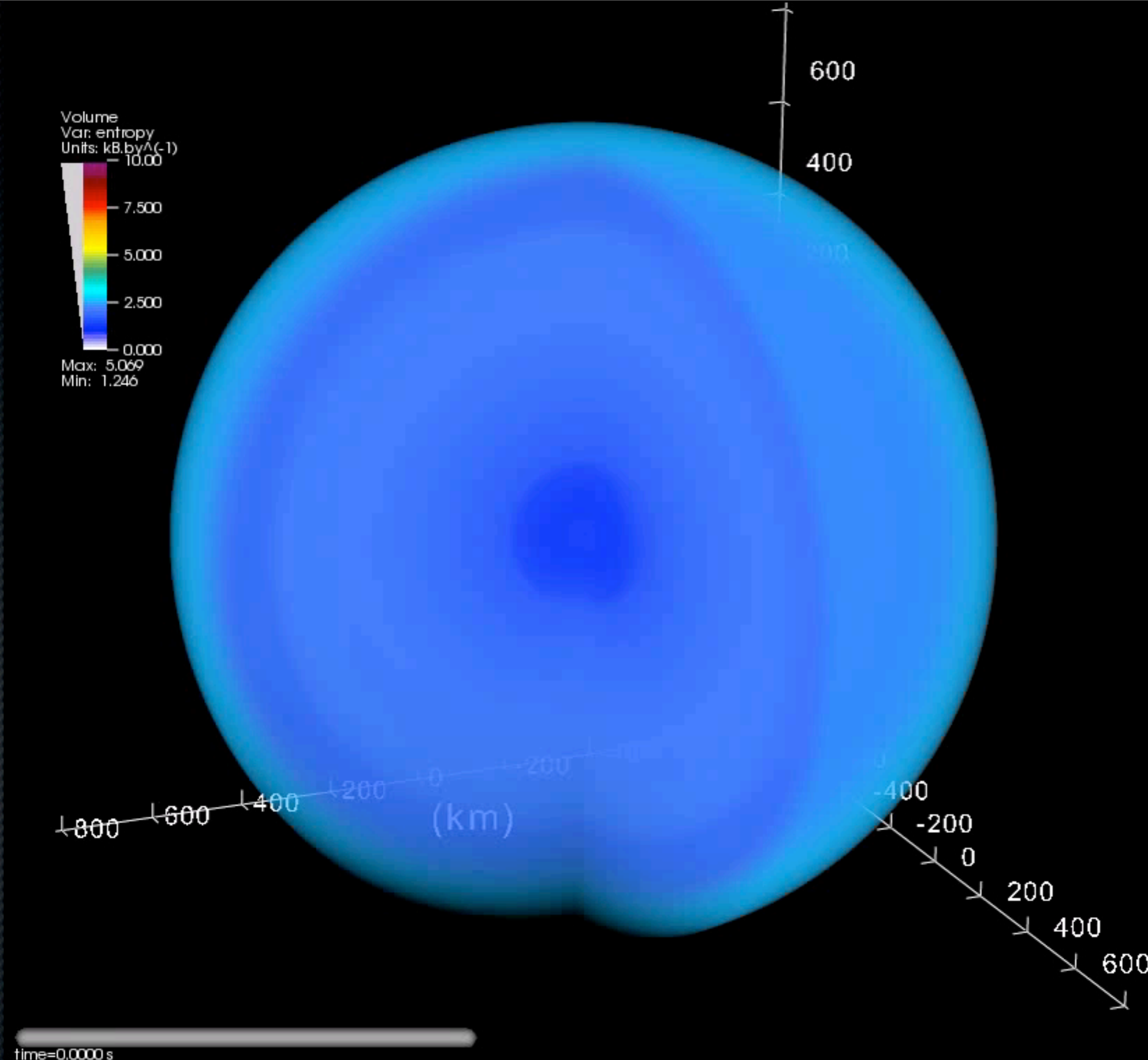

Volume
Var: entropy
Units: kB.by^(-1)
16.00
12.00
8.000
4.000
0.000
Max: 6.681
Min: 1.238
1500
1000
500
1500
1000
500
0
-500
-1000
-1500
-1000
-500
0
500
1000
time=0.0130 s


Volume
Var: entropy
Units: kB.by^(-1)
10.00
7.500
5.000
2.500
0.000
Max: 5.069
Min: 1.246
600
400
800
600
400
200
(km)
-400
-200
0
200
400
600
time=0.0000 s

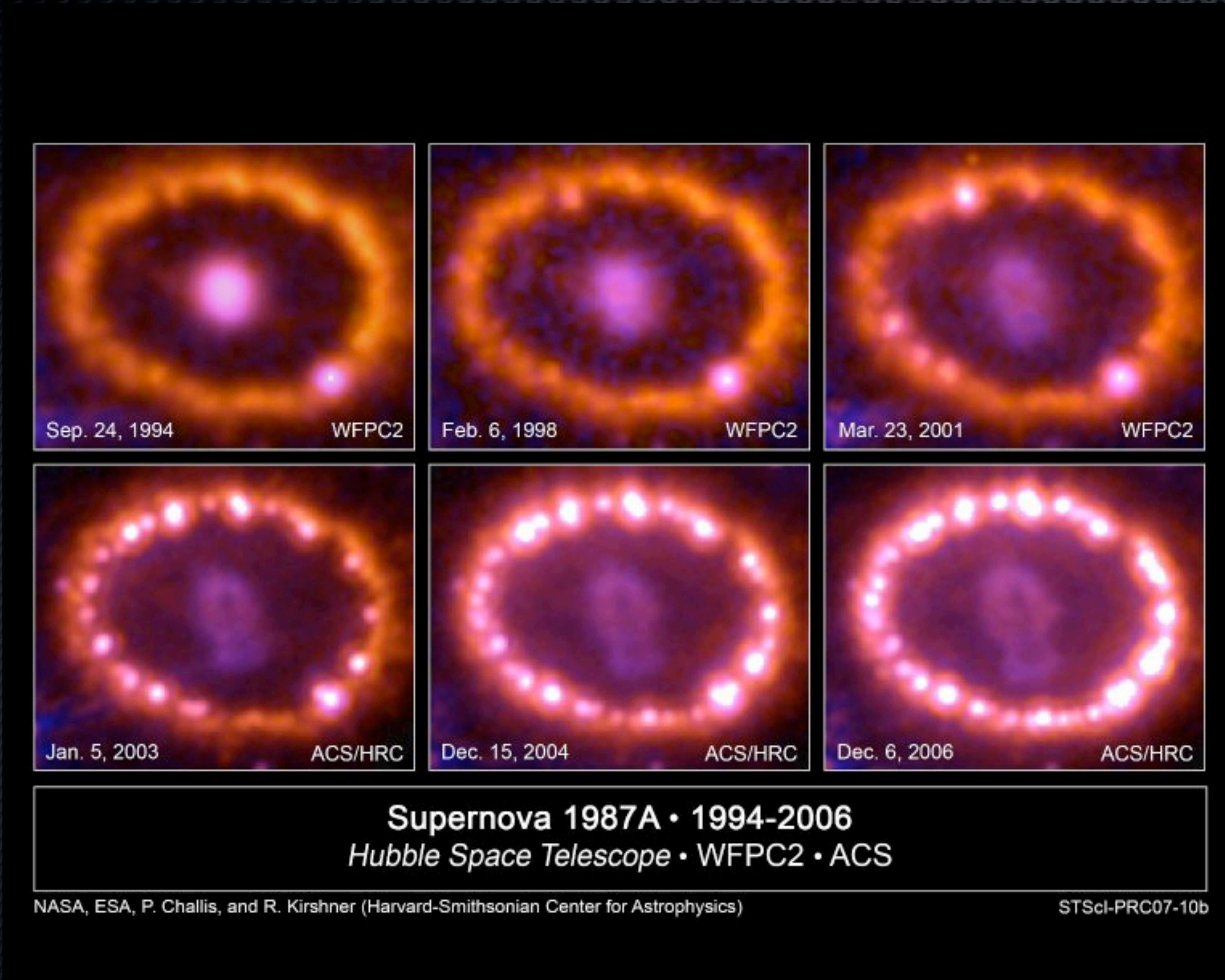
Picture is not yet clear

- Various Groups can get 8-11 $M_{\odot}$ Stars to explode

  Because Graviational Binding Energy is less

- But with higher mass stars, how and when objects explode depends on who is blowing them up.
- Yet, we are pretty sure that some of these do explode as Supernovae - like SN 1987A

SN 1987A inner core



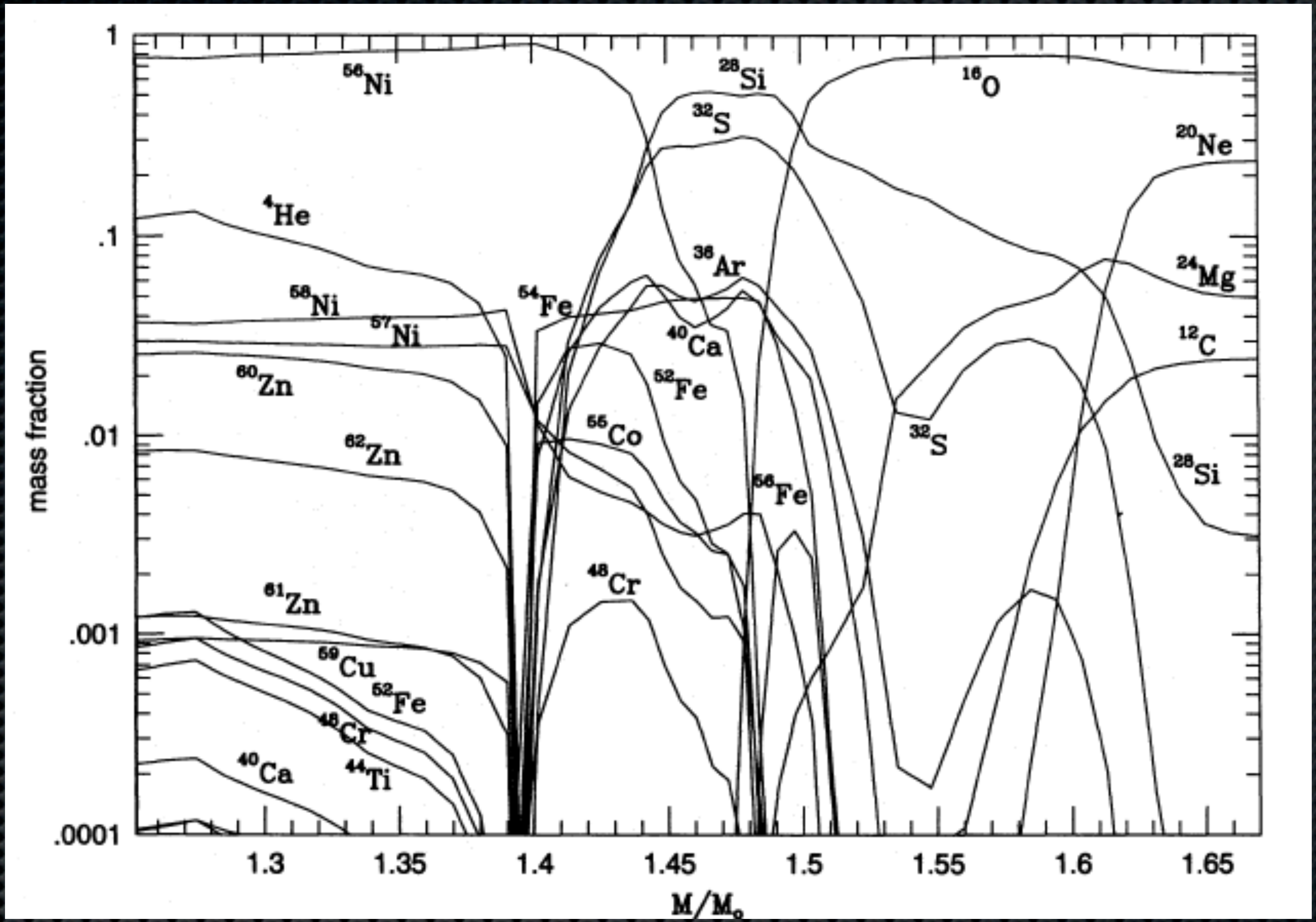
Nucleosynthesis in Core Collapse Objects

- Core Supernovae are thought to be responsible for enriching the Universe with most elements between Carbon and Uranium
- Yields as a function of mass are key input to people who model the chemical evolution of the Universe

Nuclear Yields

- Take models of Stars of 8,9,10...40,50,60 $M_\odot$
- Explode them simply, by putting an impulse of energy in their centre.
- Calculate nucleosynthesis in 1-d
- Play with mass cut to give appropriate ^{56}Ni amounts and where data not available, make physical guess, or choose to match observations.
- Integrate using number of stars as a function of mass.

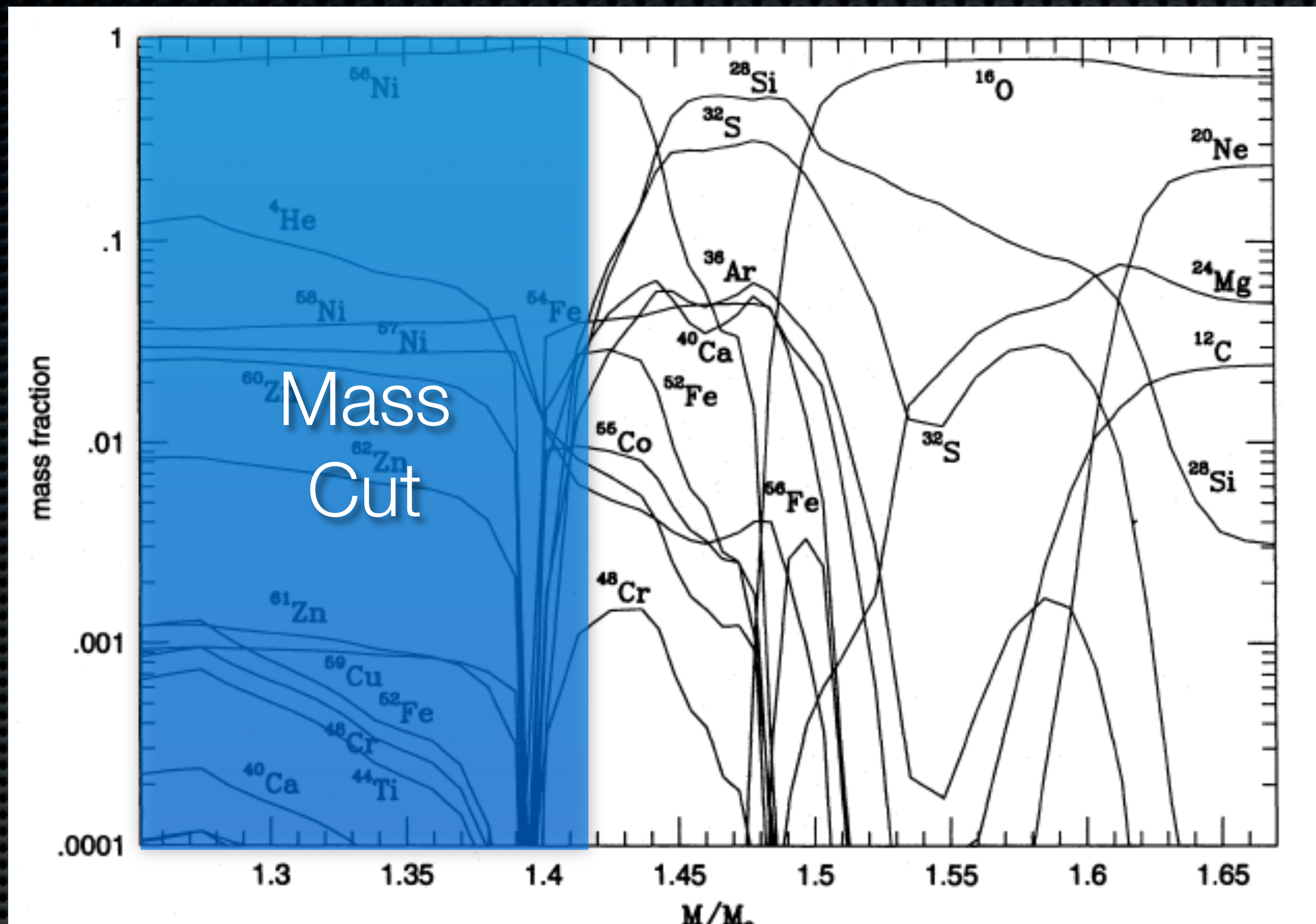
Seems to work! - at least in the average. But we know the physics is so much more complicated... Dangerous to assume these are right - especially when applied to individual stars.



Yield of a 13M☉ Star

Thielemann, Nomoto, & Hashimoto

Chieffi and Limongi (04), Woosley Weaver 95



Yield of a 13M$_\odot$ Star

Thielemann, Nomoto, & Hashimoto

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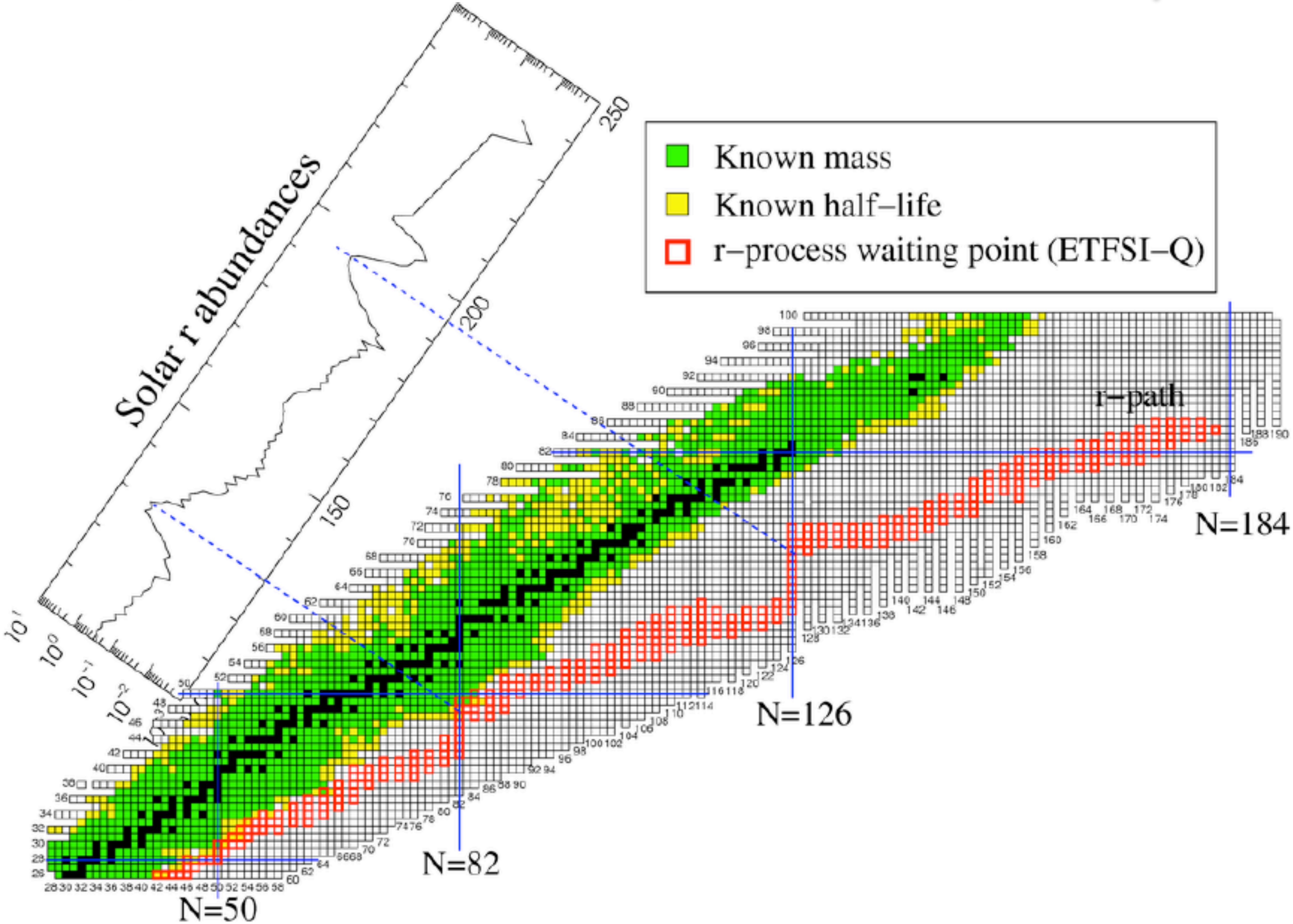
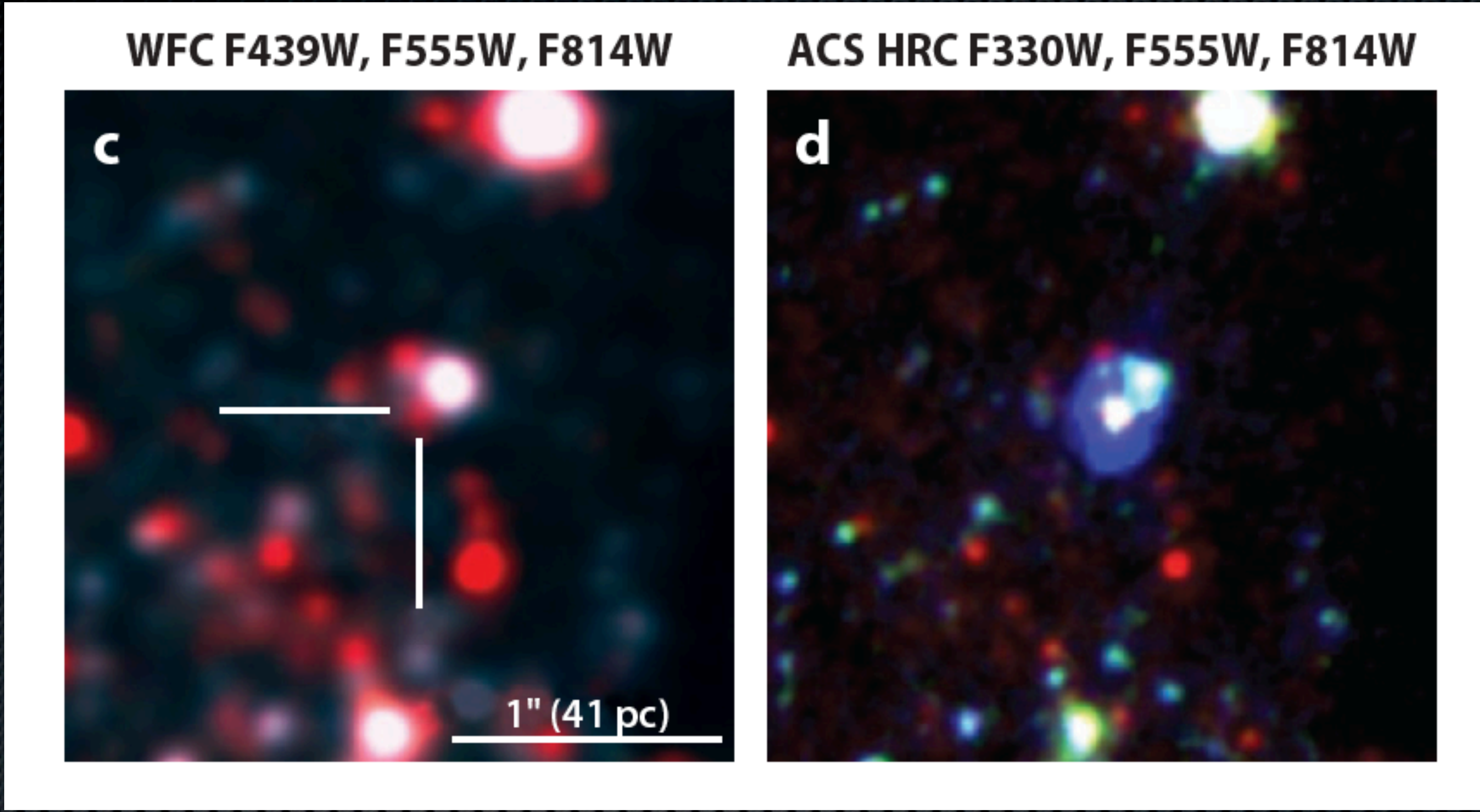
The R-Process - Heavy Elements
Assumed, but not shown to occur in Core Collapse SN

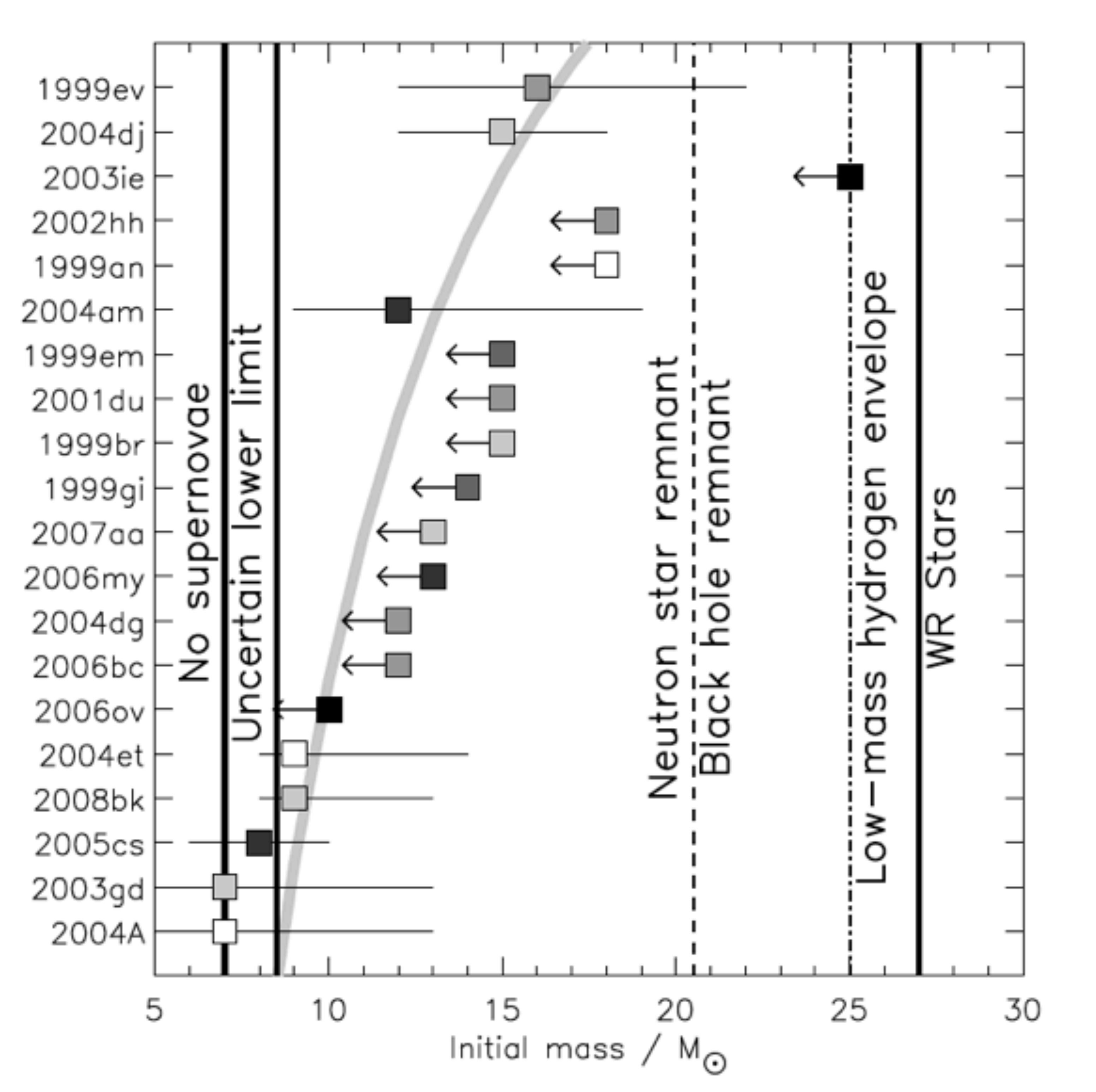




So what explodes as a SN II

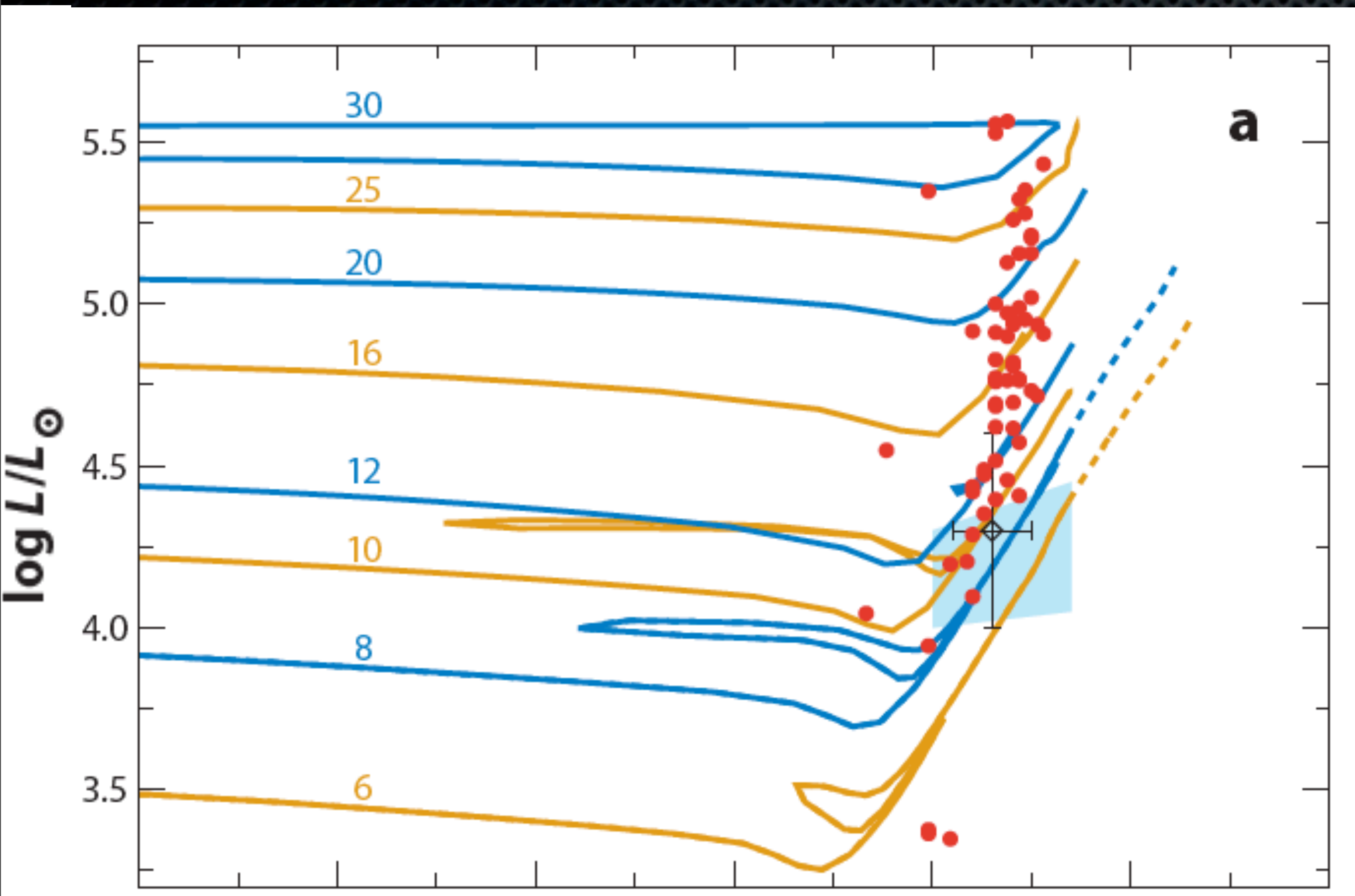
HST (and some 8-m) images of galaxies before stars explode

Smartt 10 ARAA



Low mass limit for SN II: 8.5±1 M$_\odot$ Smartt 10 ARAA

High mass limit for SN II????: 16.5±1.5M$_\odot$

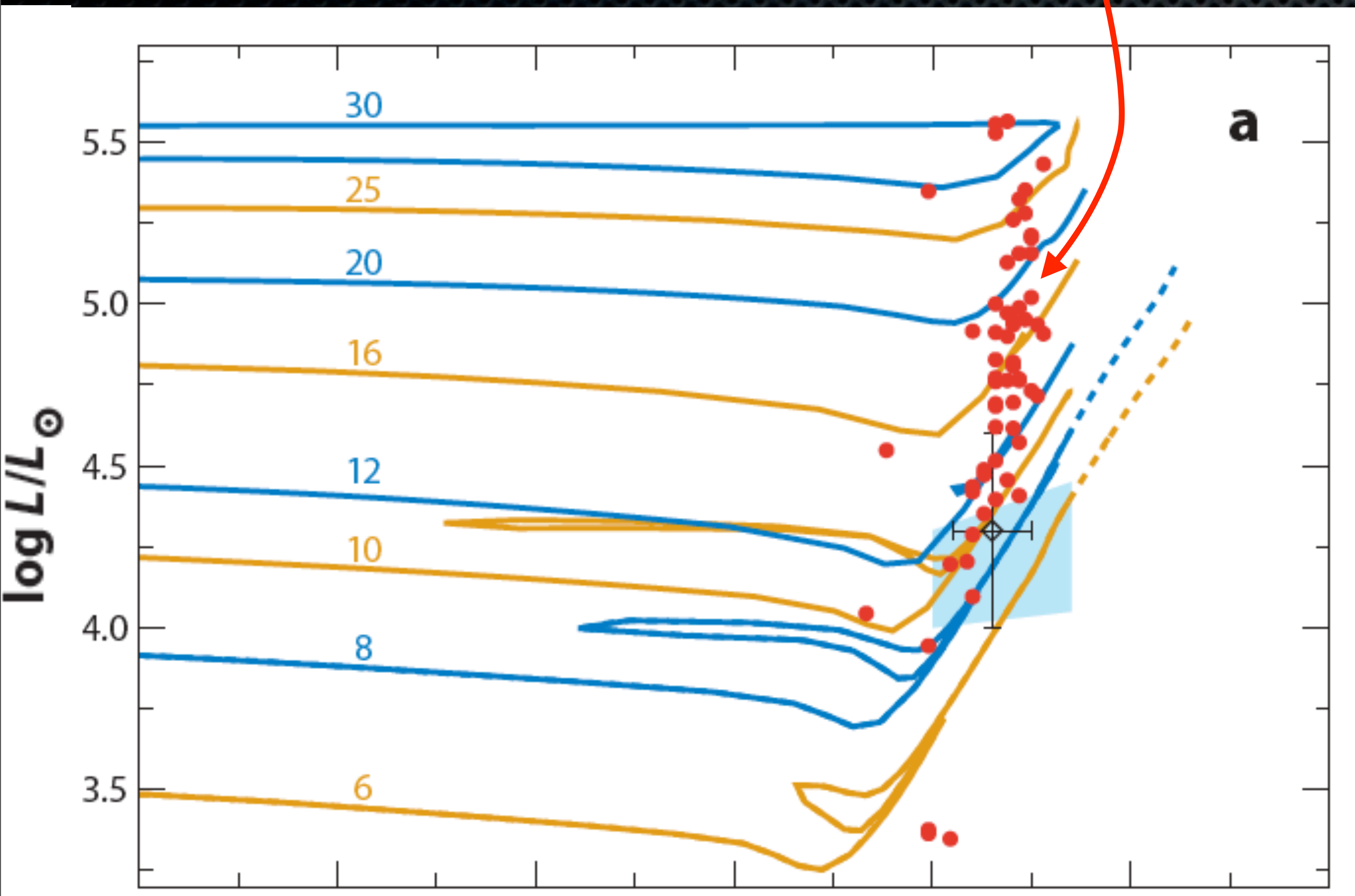


There are stars larger than 16 M⊙ which should core collapse.

Perhaps they do not explode!

Smartt 10 ARAA

Red Giants in Milky Way



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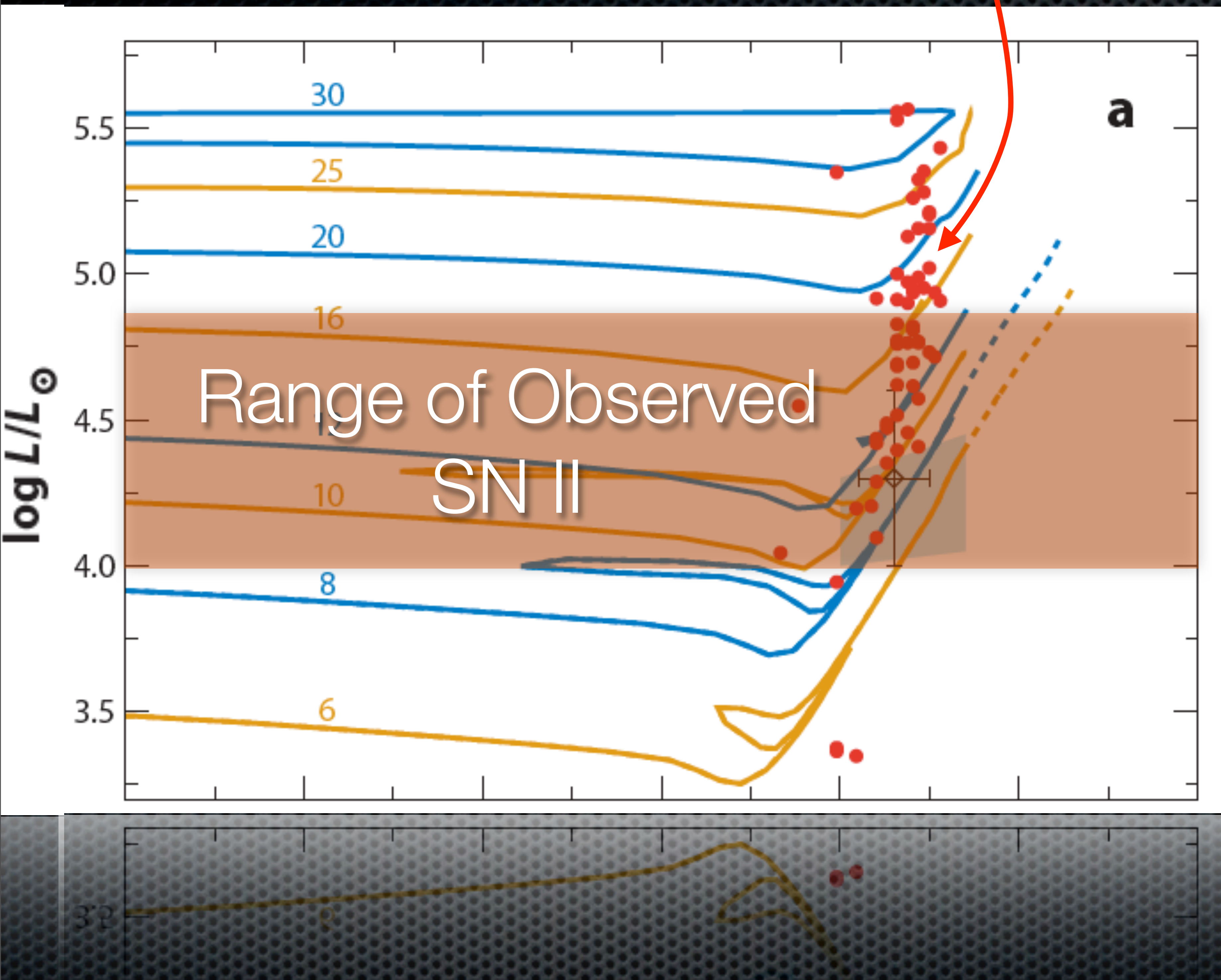

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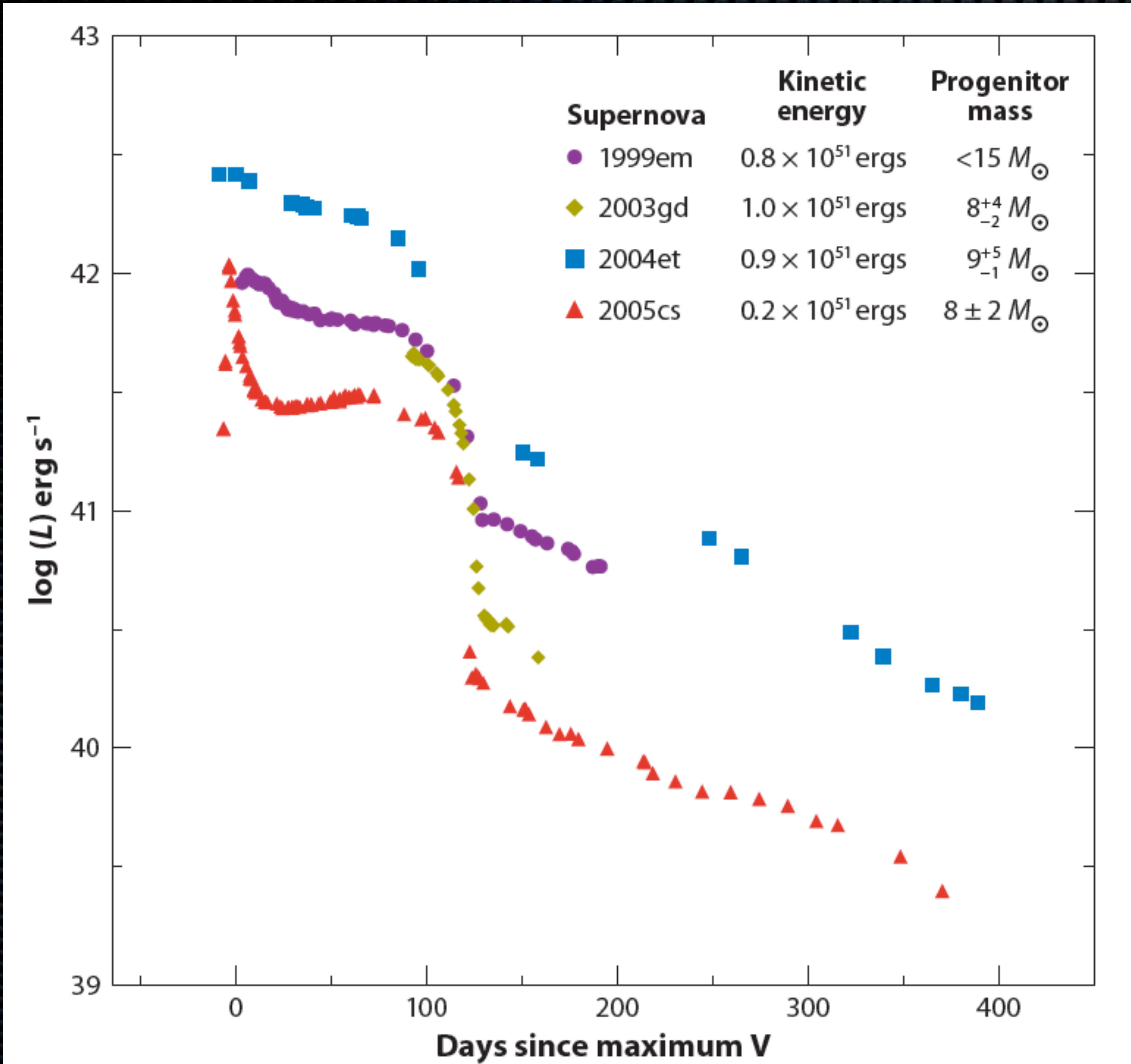
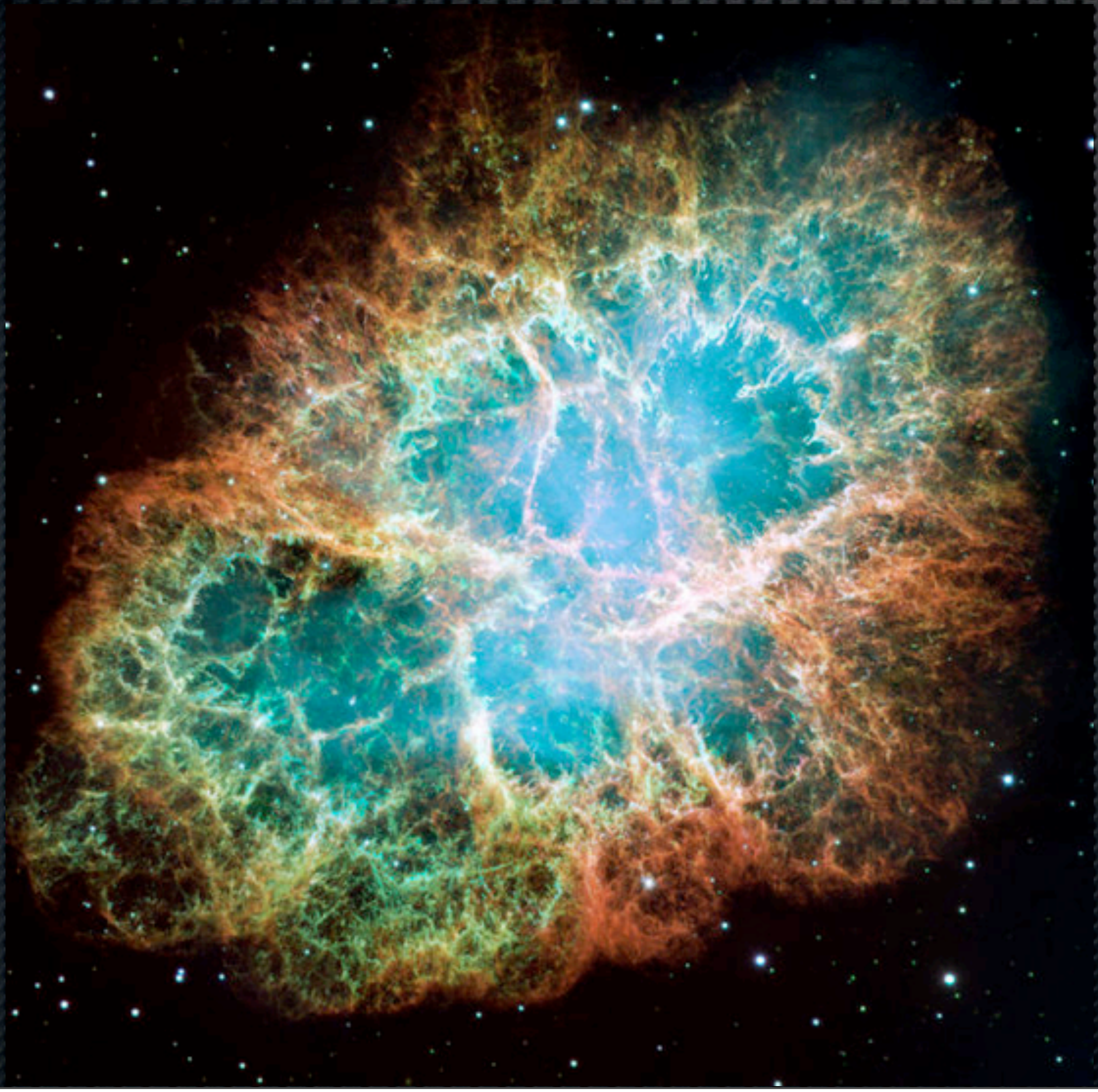


SN Explosions seem to vary greatly for stars of similar mass.

Perhaps two types of Core Collapse?

Electron Capture Supernova



Nomoto 84

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Core Collapse Engine

Mg-Ne-O core becomes degenerate

$$e^- + {}^{20}Ne \rightarrow \nu + {}^{20}F$$

$$e^- + {}^{24}Mg \rightarrow \nu + {}^{24}Na$$

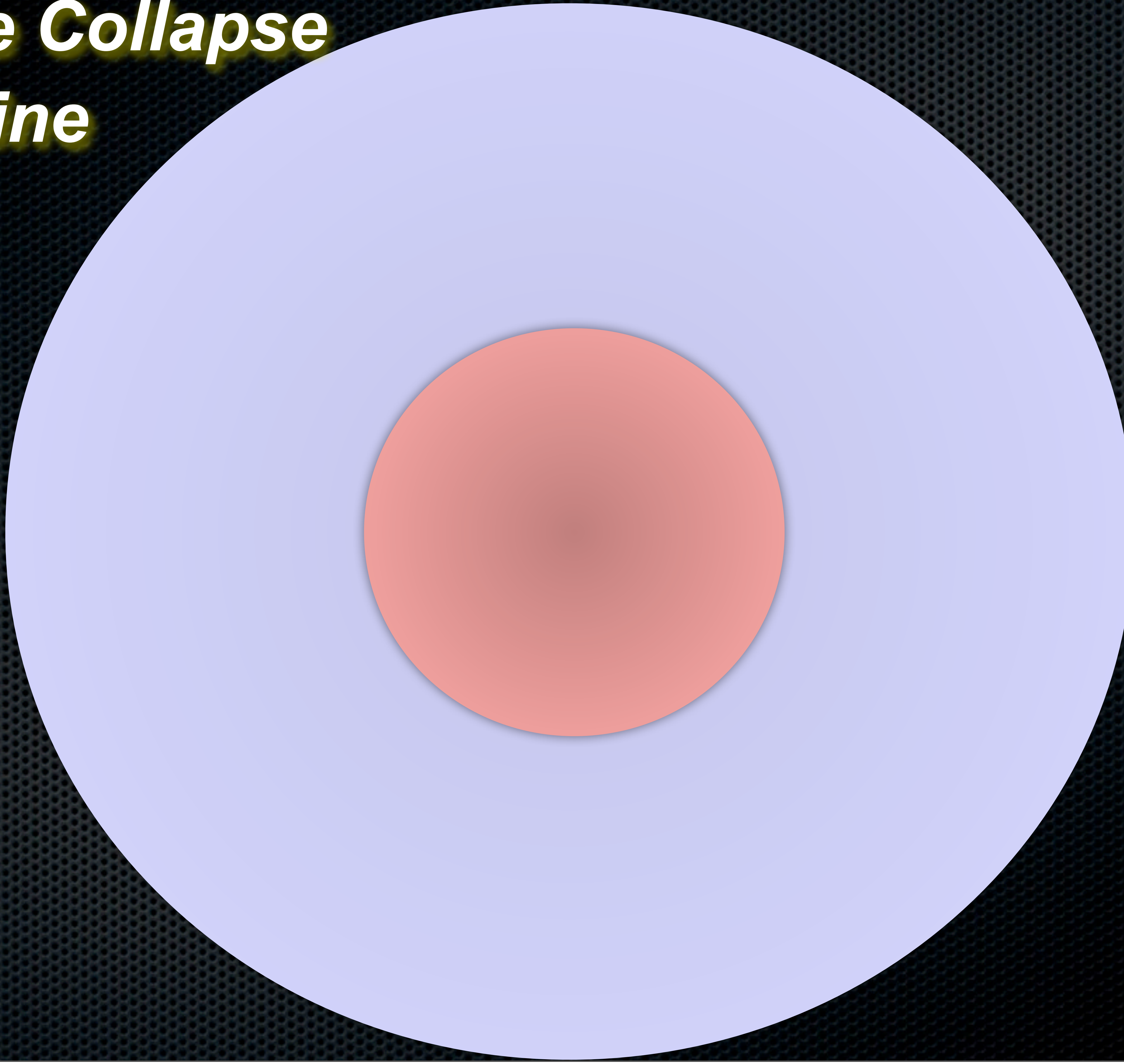
Core Collapse Engine

Mg-Ne-O core becomes degenerate

$$e^- + {}^{20}Ne \rightarrow \nu + {}^{20}F$$

$$e^- + {}^{24}Mg \rightarrow \nu + {}^{24}Na$$

Core Collapse Engine



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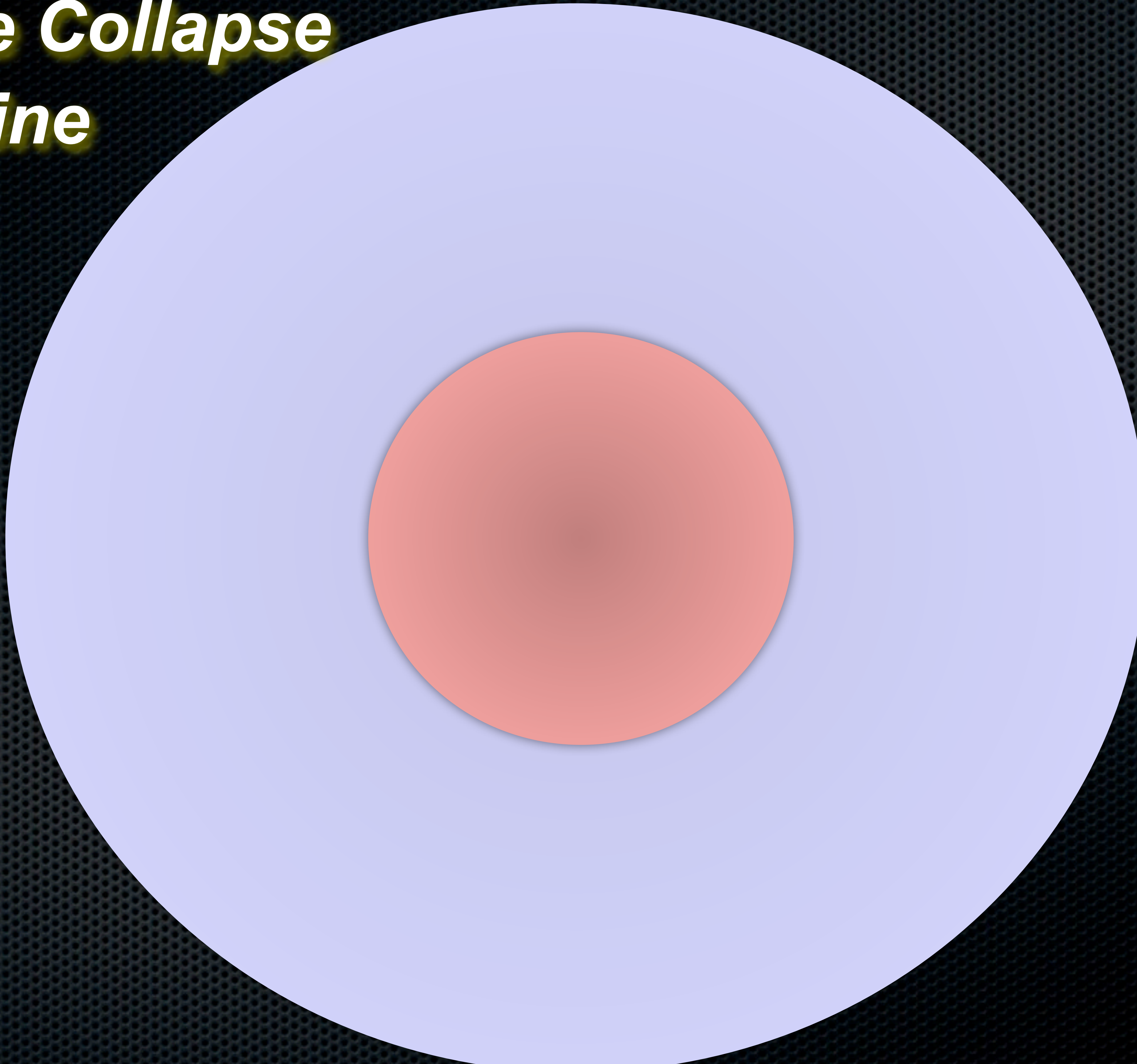
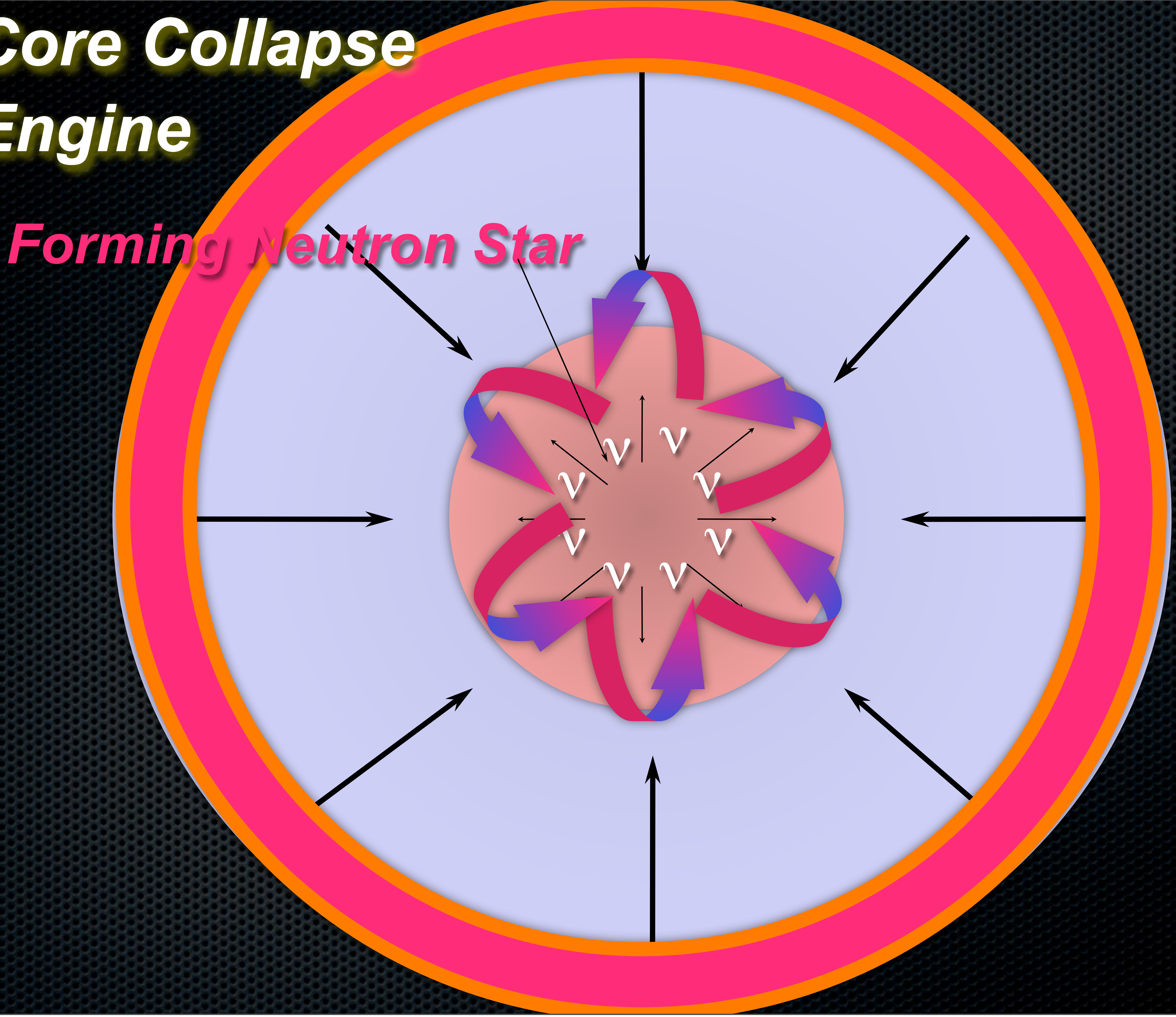


Core Collapse Engine



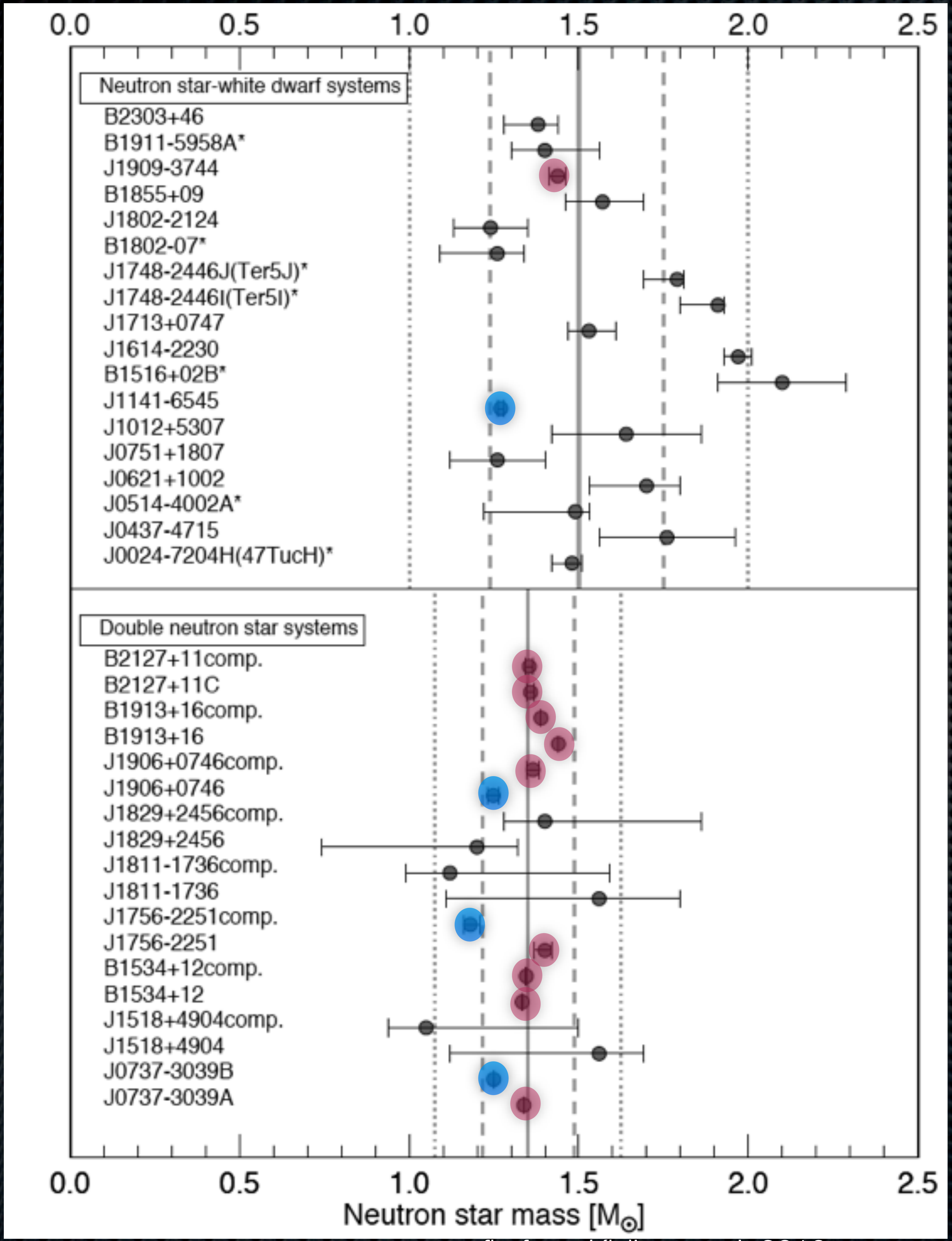


fig from Kiziltan et al. 2010

Mass measurements of Neutron stars from Pulsar Studies

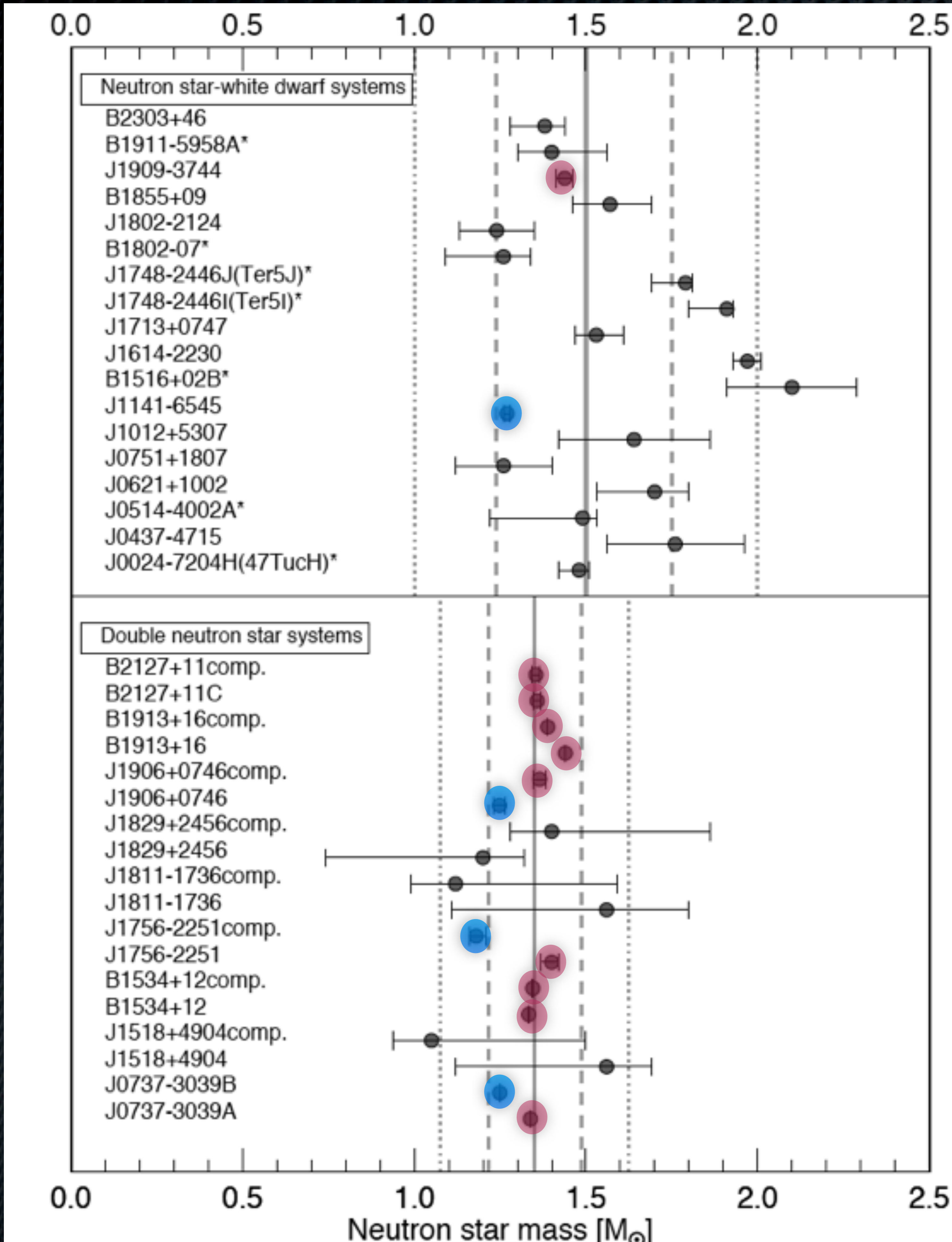


fig from Kiziltan et al. 2010

Mass measurements of Neutron stars from Pulsar Studies

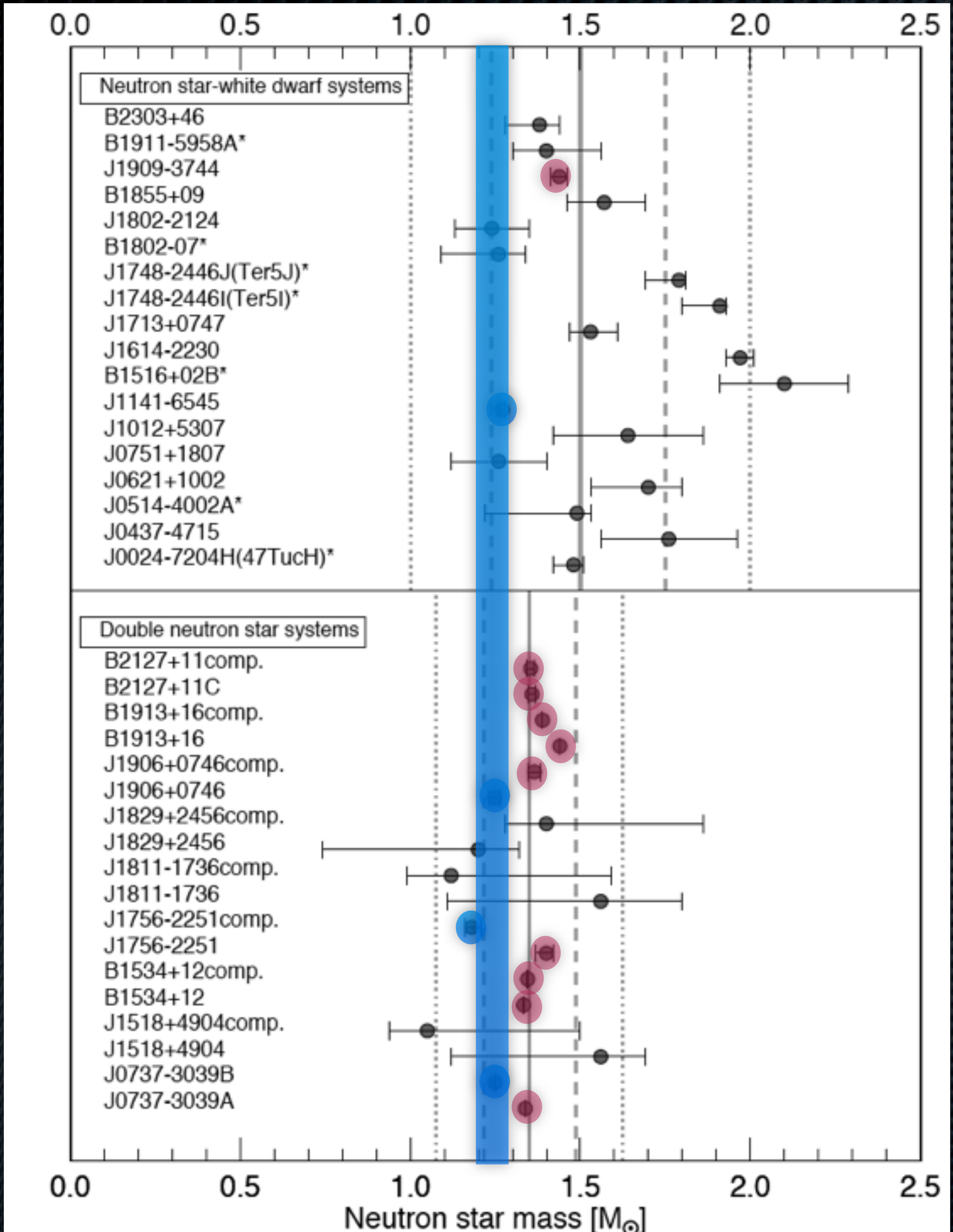


fig from Kiziltan et al. 2010

Friday, 22 July 2011

Mass measurements of Neutron stars from Pulsar Studies

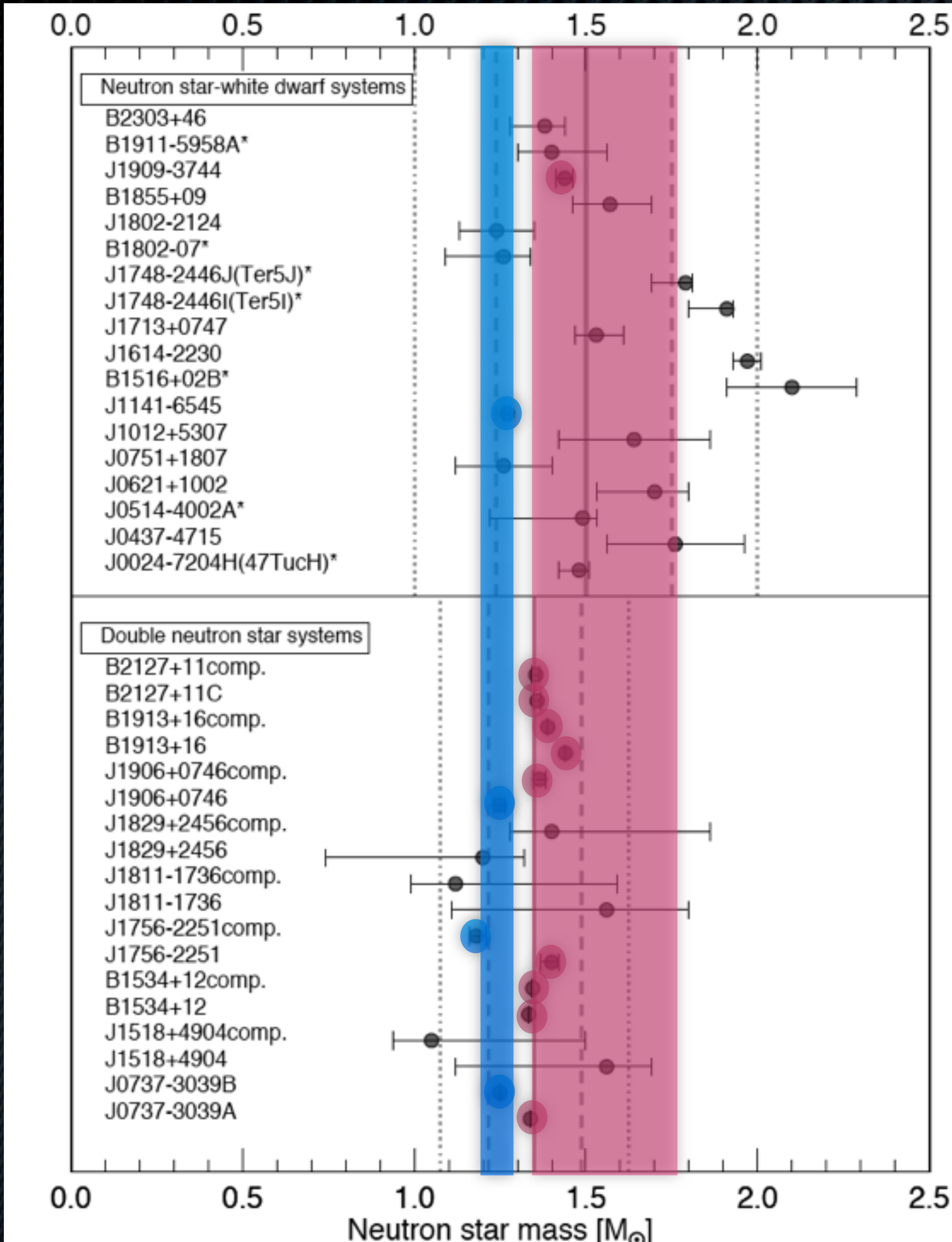


fig from Kiziltan et al. 2010

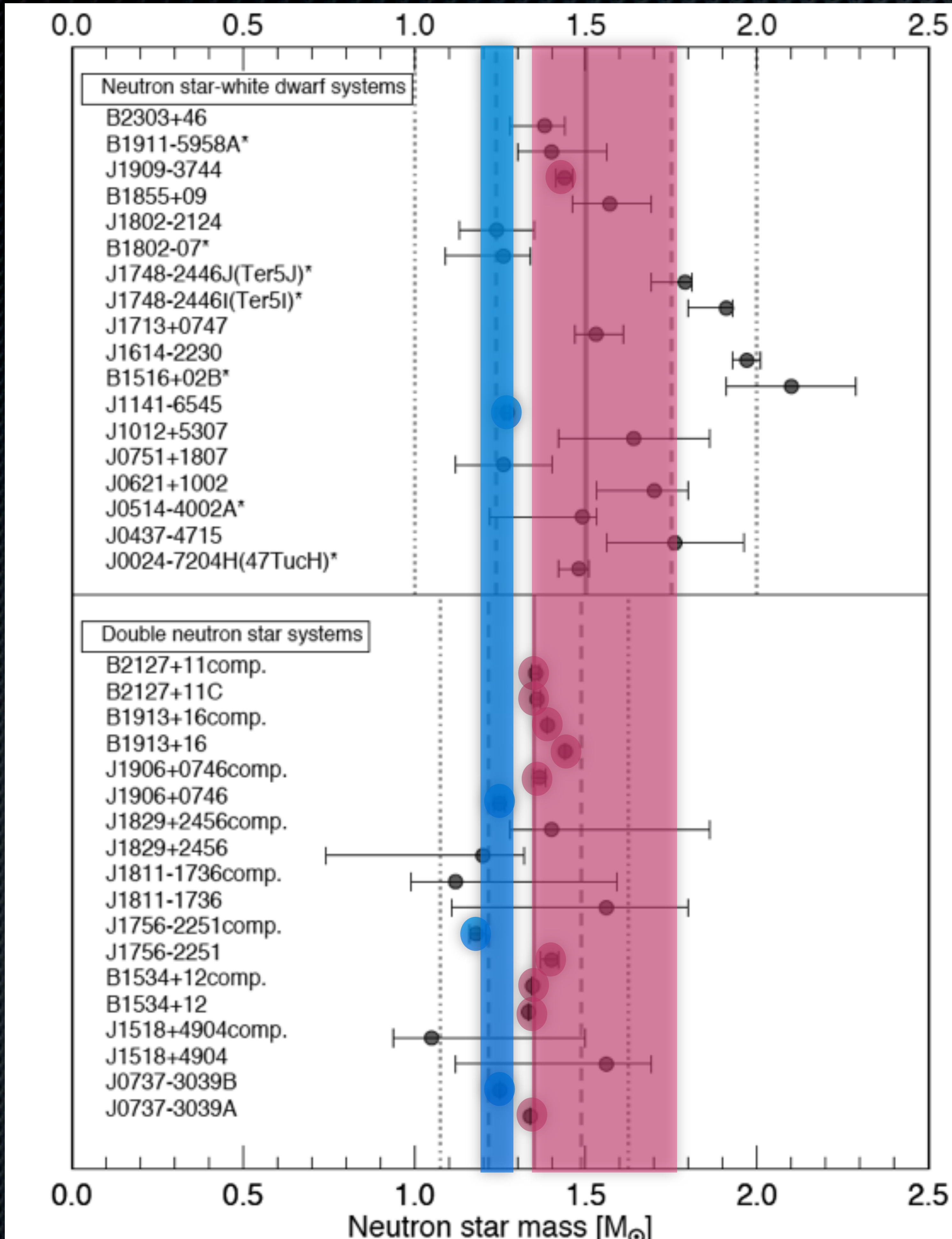


fig from Kiziltan et al. 2010

Mass measurements of Neutron stars from Pulsar Studies

O-Ne-Mg electron capture SNe should produce lower mass Neutron stars - preferred in binaries (Podsiadlowkski 2004)

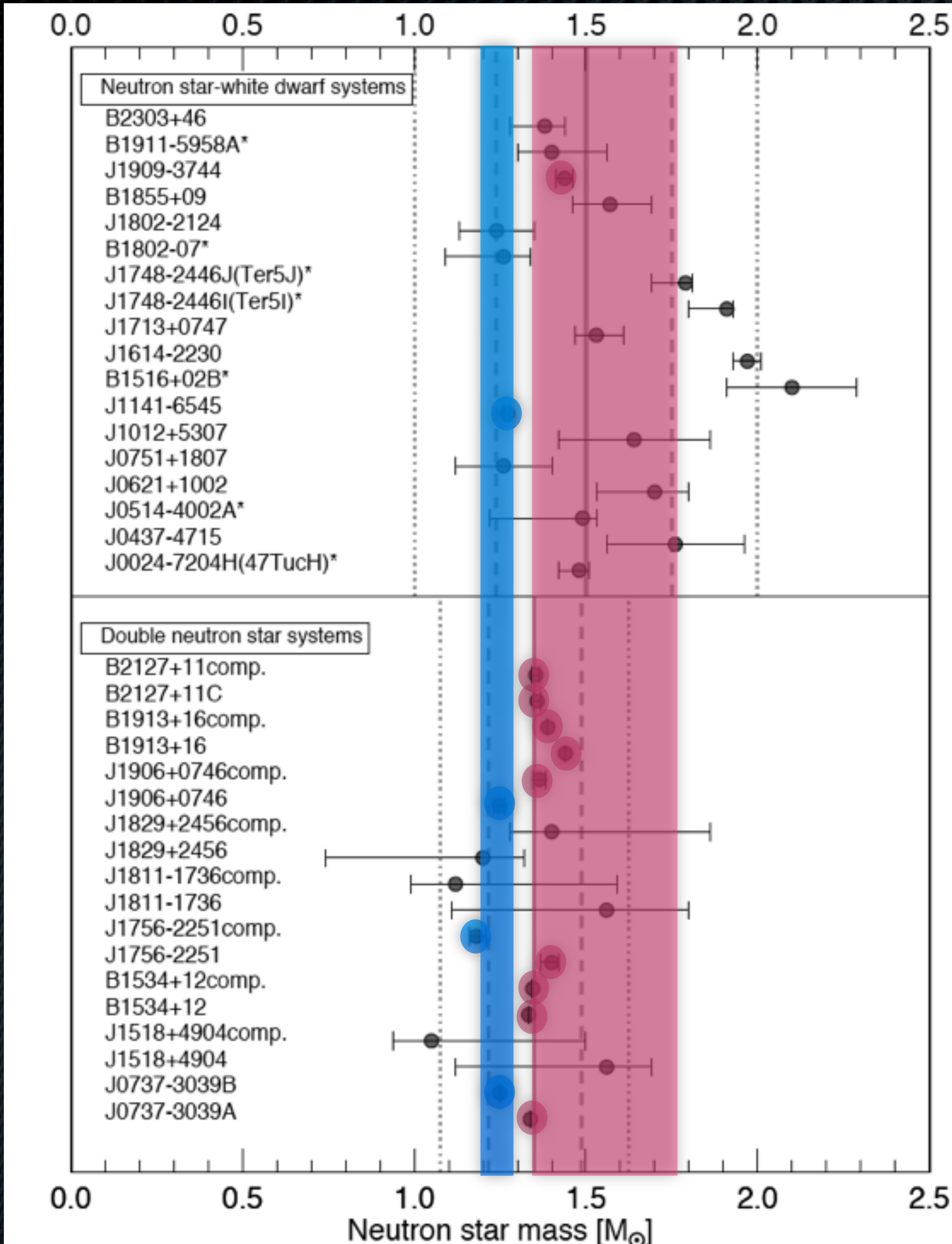


fig from Kiziltan et al. 2010

Mass measurements of Neutron stars from Pulsar Studies

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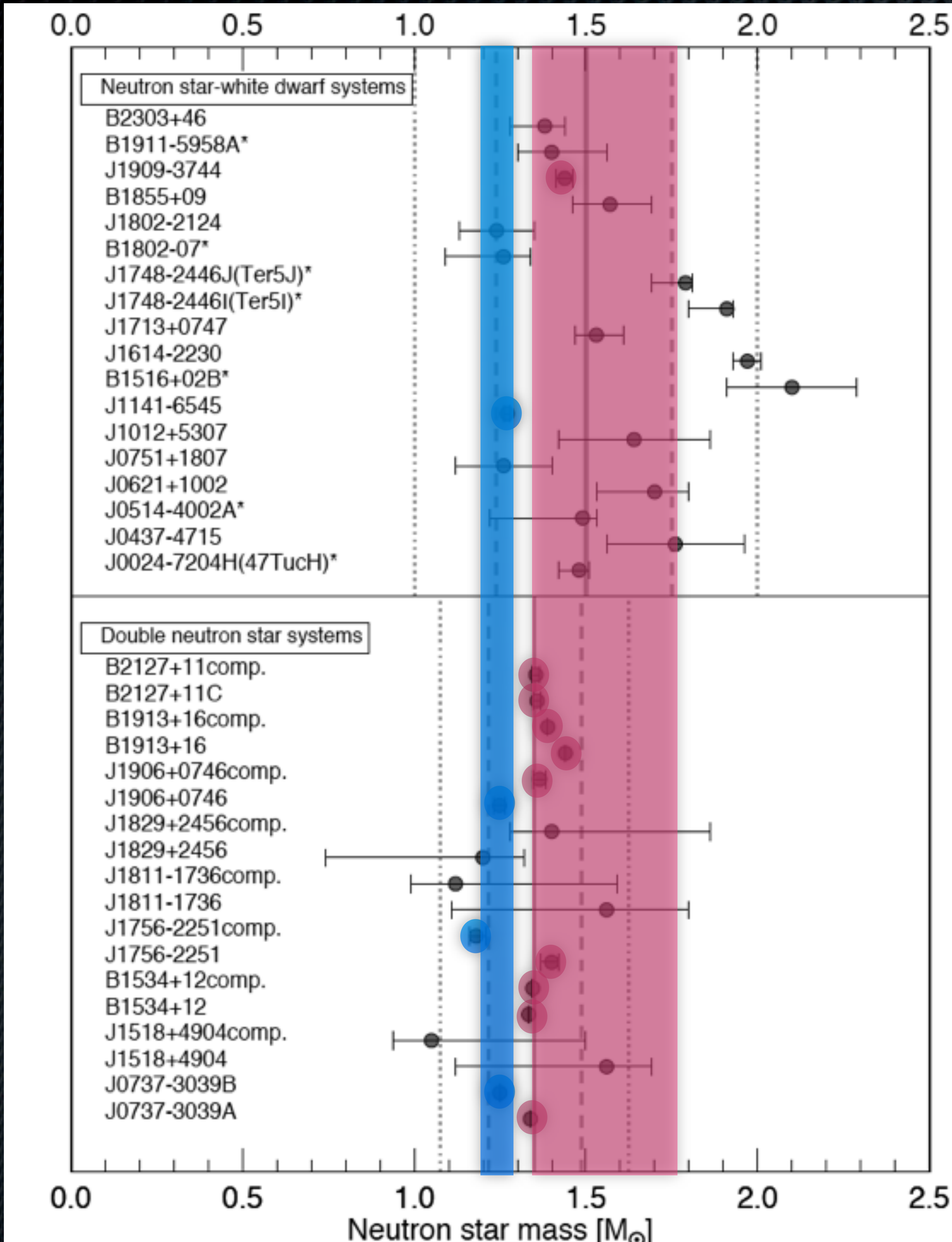
Very large Neutron stars are a recent mystery.



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Mass measurements of Neutron stars from Pulsar Studies

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Very large Neutron stars are a recent mystery.

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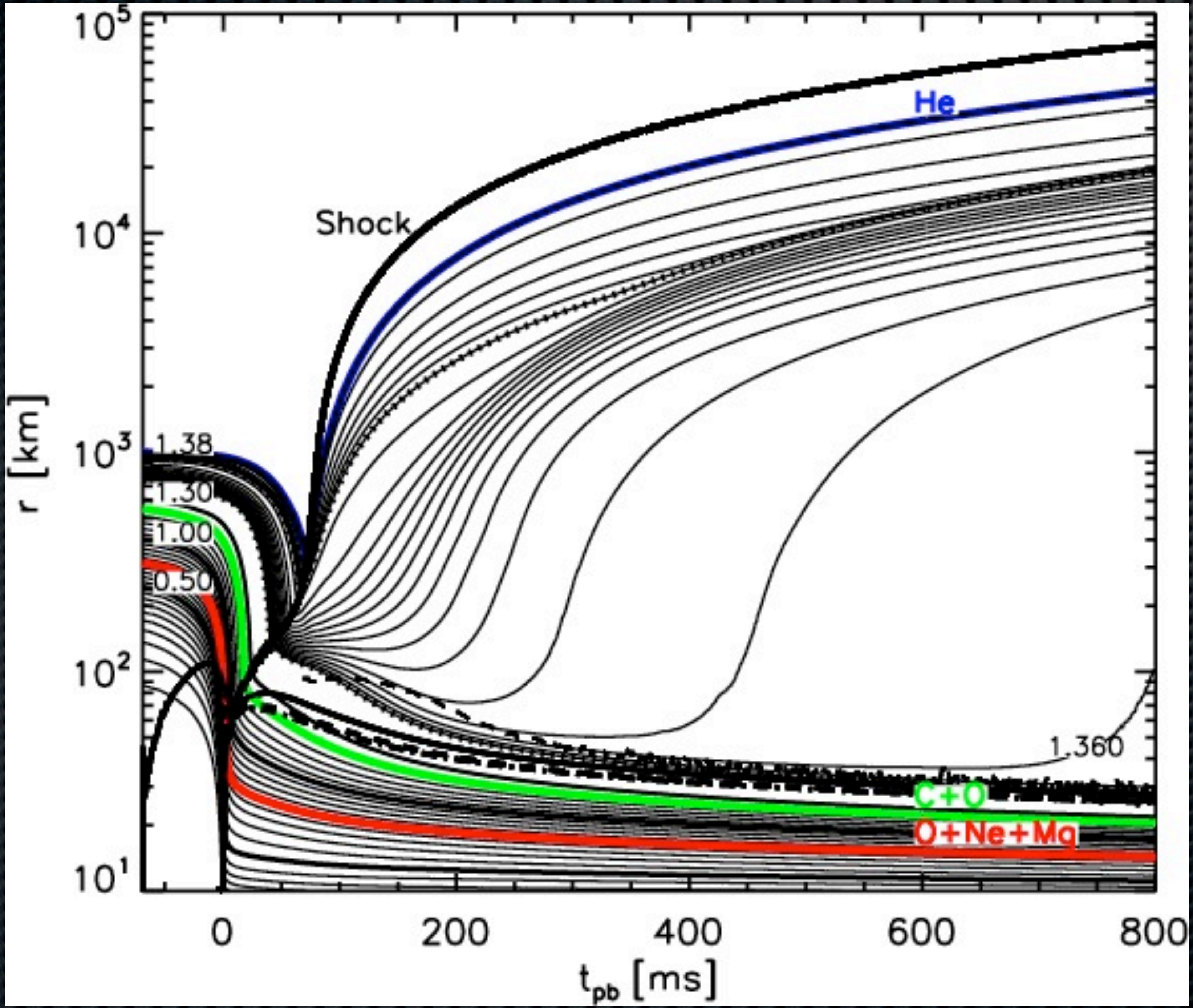
Electron Capture SN



Janka et al 2006... Explode like others and produces larger neutron stars, but weak explosions..

But if true, where do the low mass Neutron Stars come from?

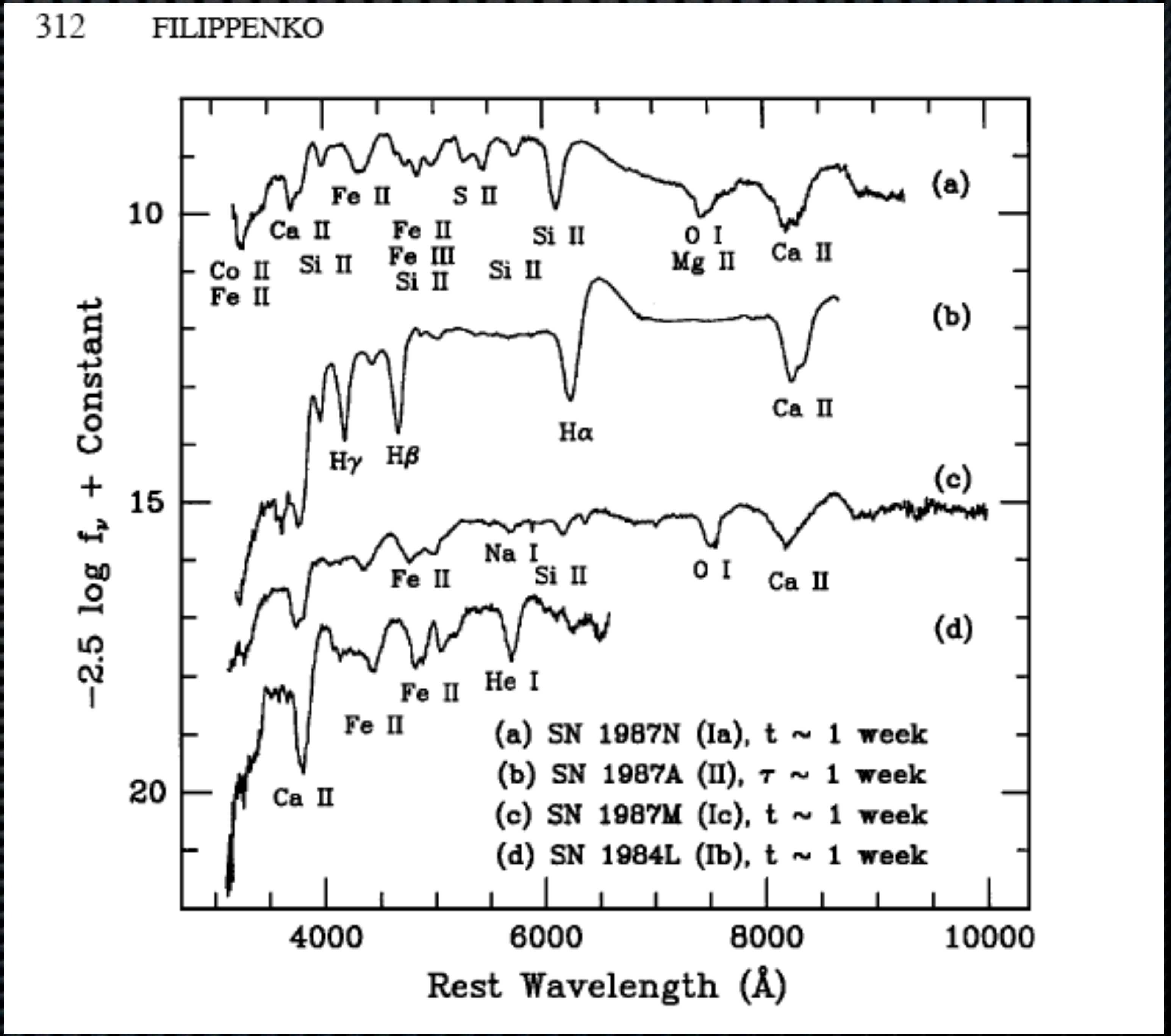
Rates of SN within 30 Mpc

Type	per year	fraction
SN II	6	43%
SN Ib/c	3.2	23%
SN Ia	3.7	27%
Others	0.9	7%

adapted from
Smartt et al 09

SN Ib/c

- Little or no Hydrogen
- Occur in star forming galaxies near the sites star formation
- Have wide range of ejected masses
- Do not have identified progenitors



What Makes SN Ib/c?

Massive Stars?

lose mass due to radiative driven winds and are known as Wolf Rayet Stars.

State of star at explosion can give range of explosions.

- ✓ SN Ib/c occur near H II regions
- ☐ Too many compared to Wolf Rayet Numbers
- ☐ Mant SN only have 2-4 ejected mass - too small
- ☐ No progenitor detections yet.

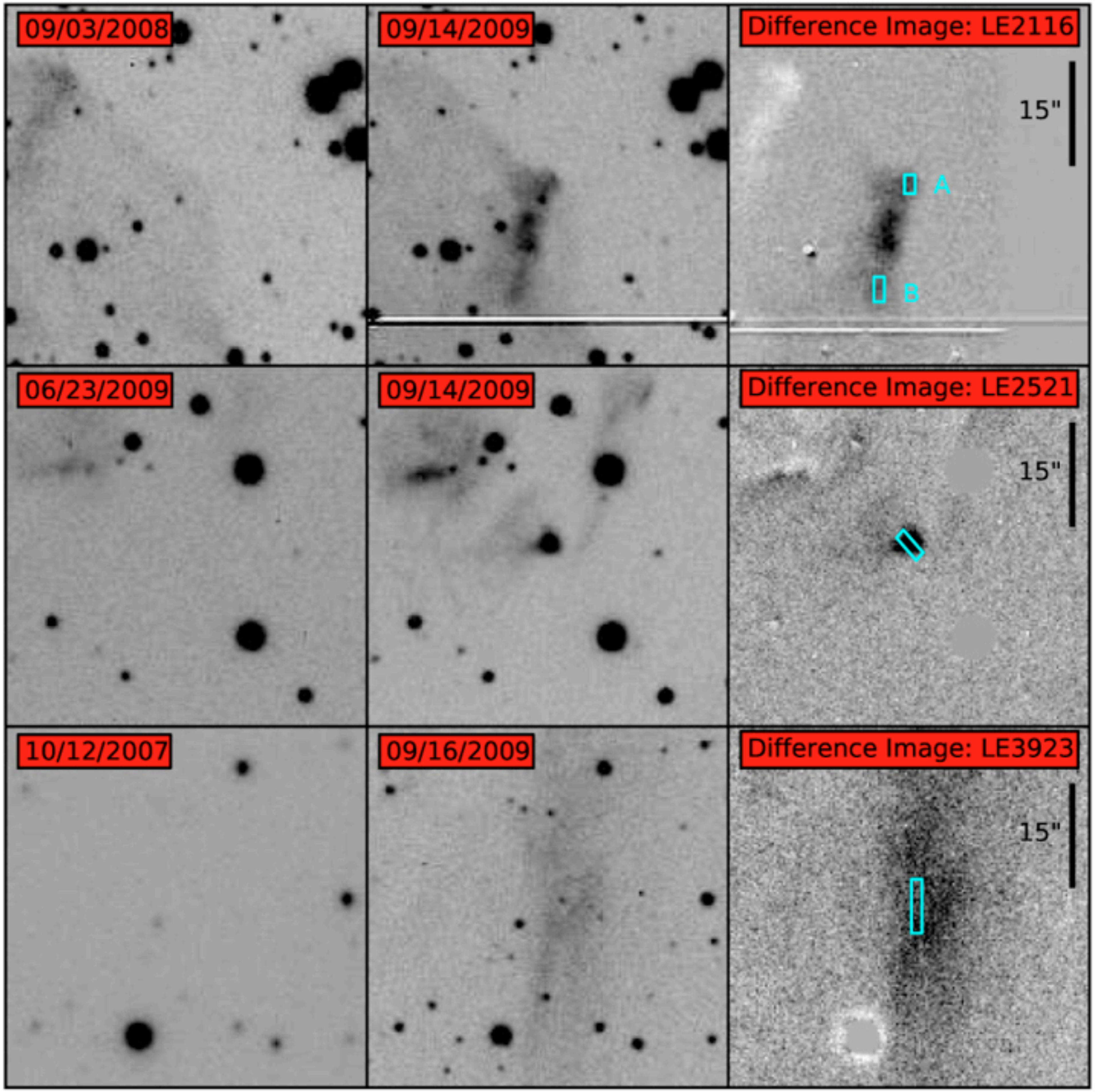
What Makes a typical SN Ib/c?

Binary Stars?

Interaction causes stars to shed most or all of their envelopes

>30% of all massive stars are in appropriate binaries

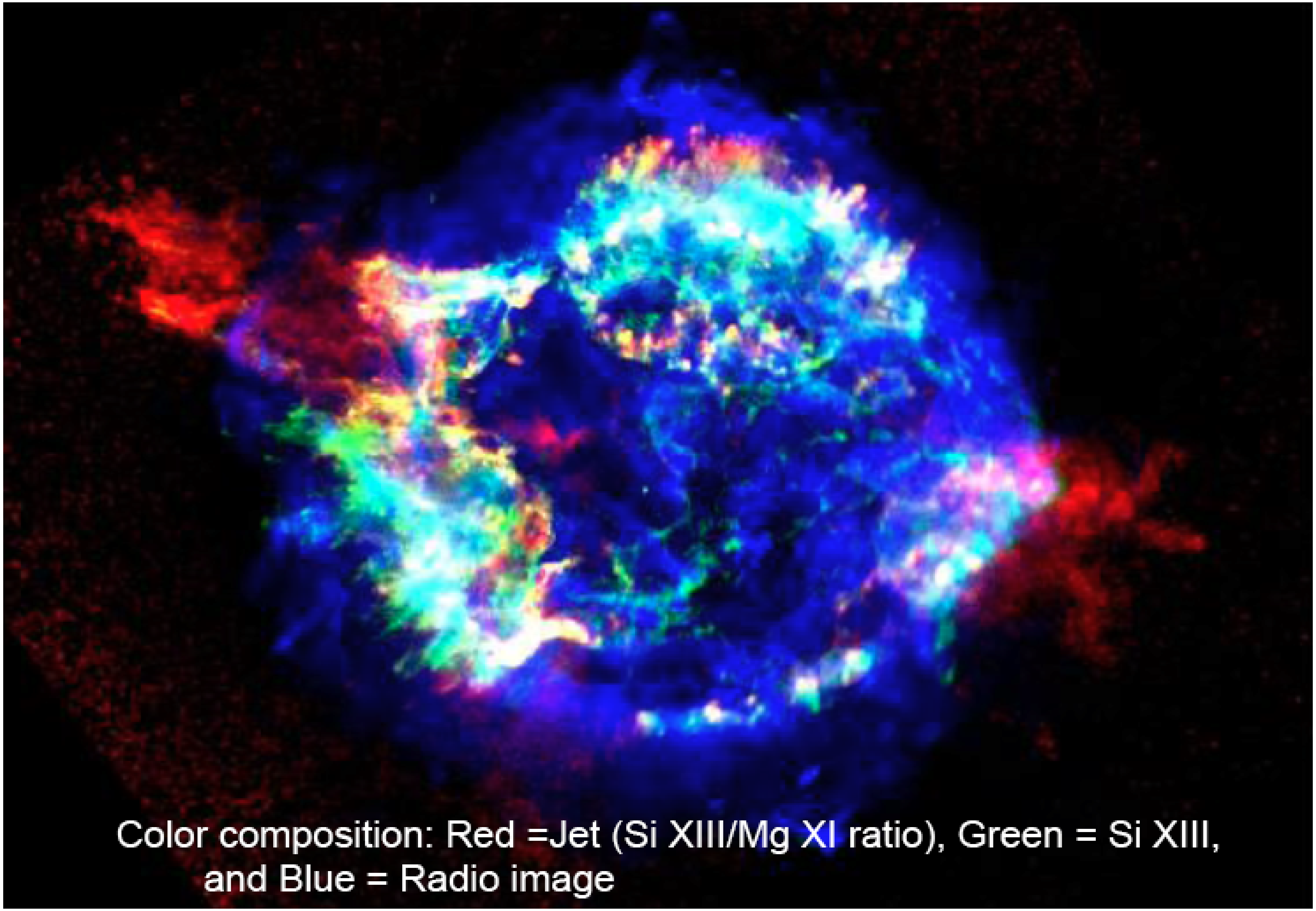
- ☐ SN Ib/c occur near H II regions
- ☑ Right Numbers
- ☑ many SN only have 2-4 ejected mass
- ☑ No detections yet.
- ☑ 93J and 87A?



Light echoes allow us to look into the past

Cas A was a IIb -a SN II that turned into a SN Ib
Krause 08
Rest 09

The X-ray properties of the jets show them to be chemically different from the rest of the remnant's outlying ejecta.



Vink 2004

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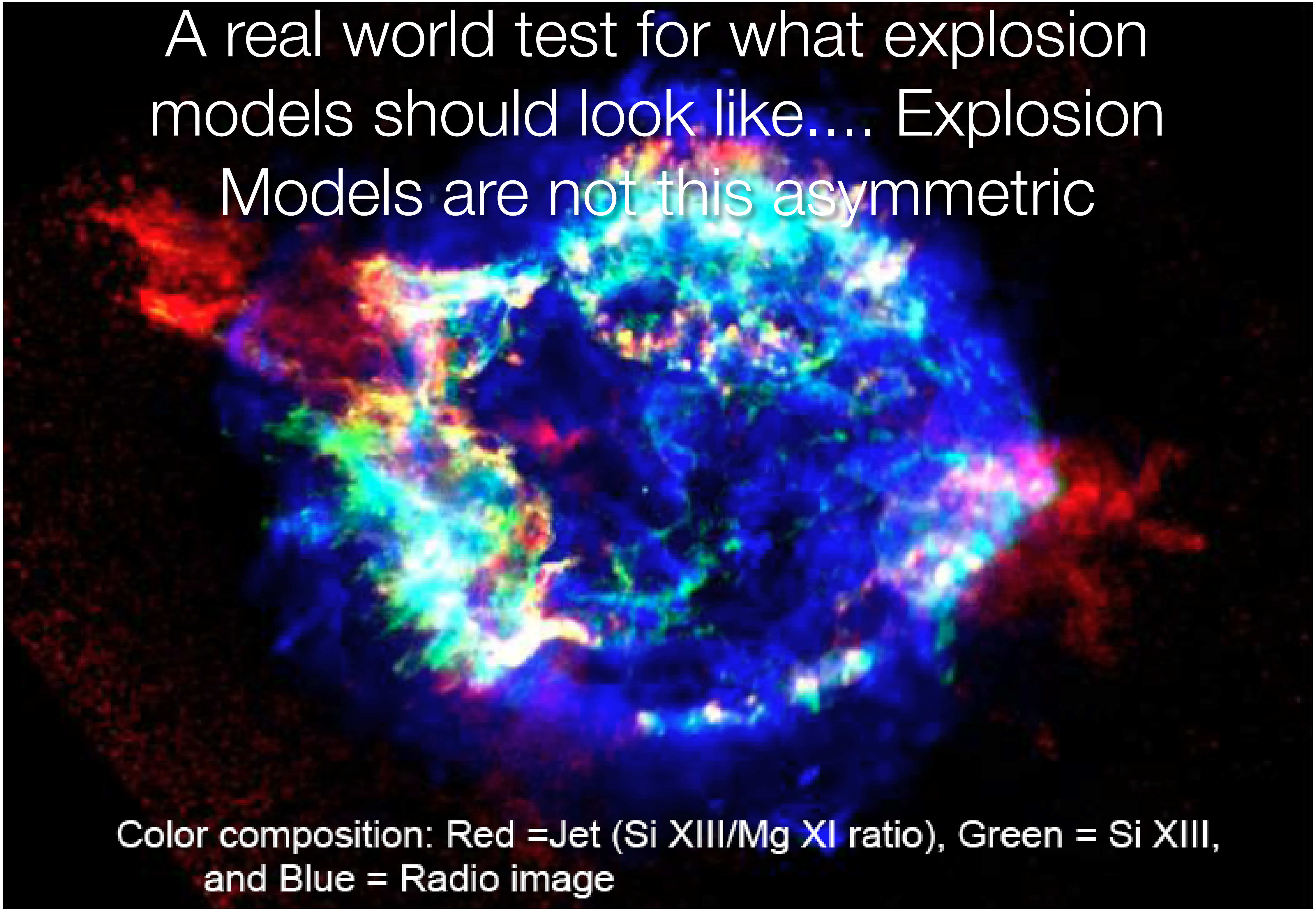


Vink 2004

Core Collapse SNe

- Overall picture more or less clear
  - Stars between 8-16M explode as SN via core collapse - some after Fe burning, some via electron capture on O-Ne-Mg cores
  - Core collapse mechanism where neutrinos interacting with infalling material seems to be able to explode lowest mass stars.
- But questions remains
  - Where are the high mass SN II? R-process?
  - How do larger mass cores explode, or do they not?
  - Are SN Ib/c's binaries, the massive stars, or a mix?

SN Ia

SN Ia

Show a remarkable homogeneity with respect to

- Light Curve Shape
- Absolute Magnitude
- Spectral Evolution

SN Ia

Show a remarkable homogeneity with respect to

- Light Curve Shape
- Absolute Magnitude
- Spectral Evolution

Boring

SN Ia

Show a remarkable homogeneity with respect to

- Light Curve Shape
- Absolute Magnitude
- Spectral Evolution

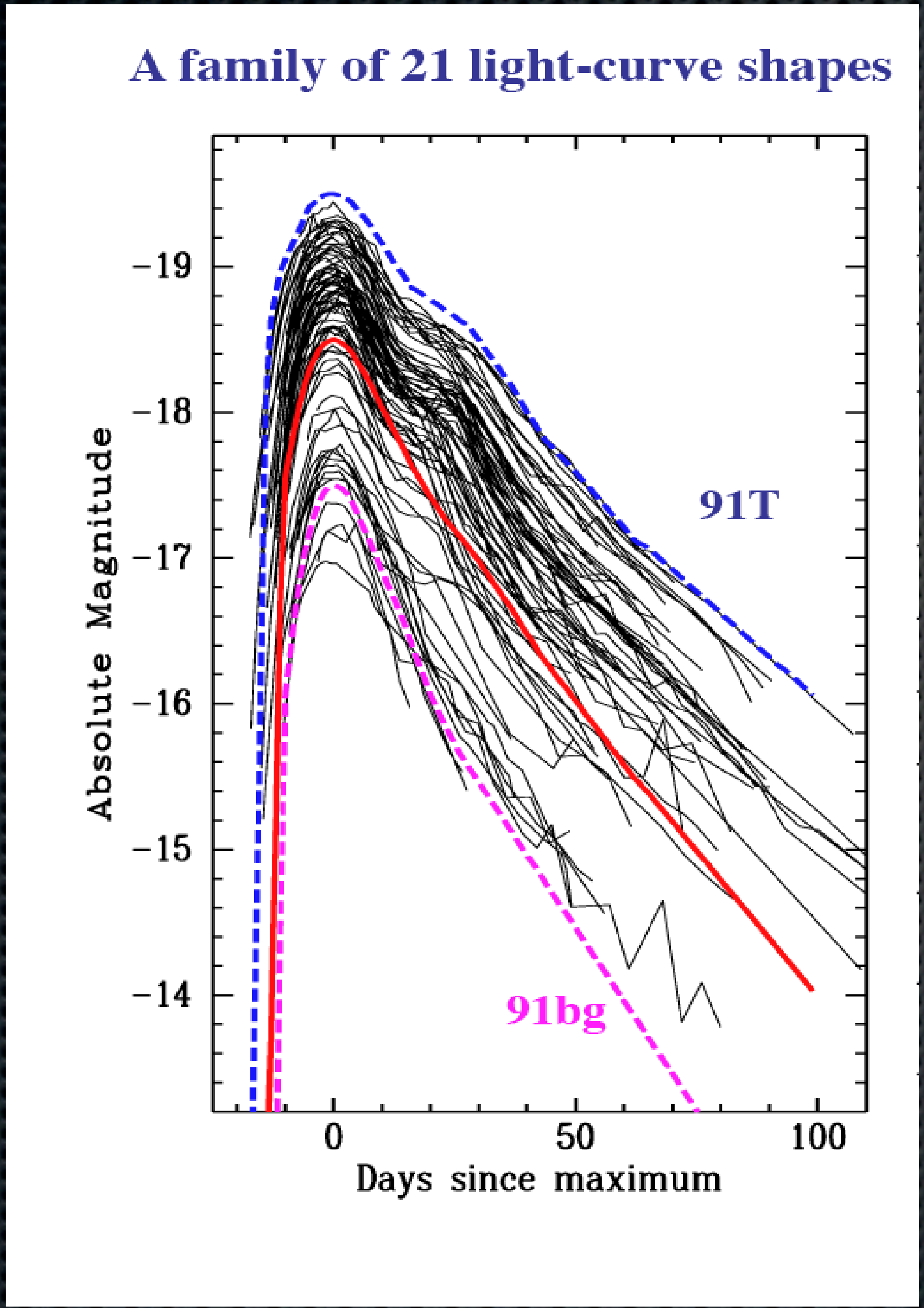
Boring

But all Type Ia SN are not the same...

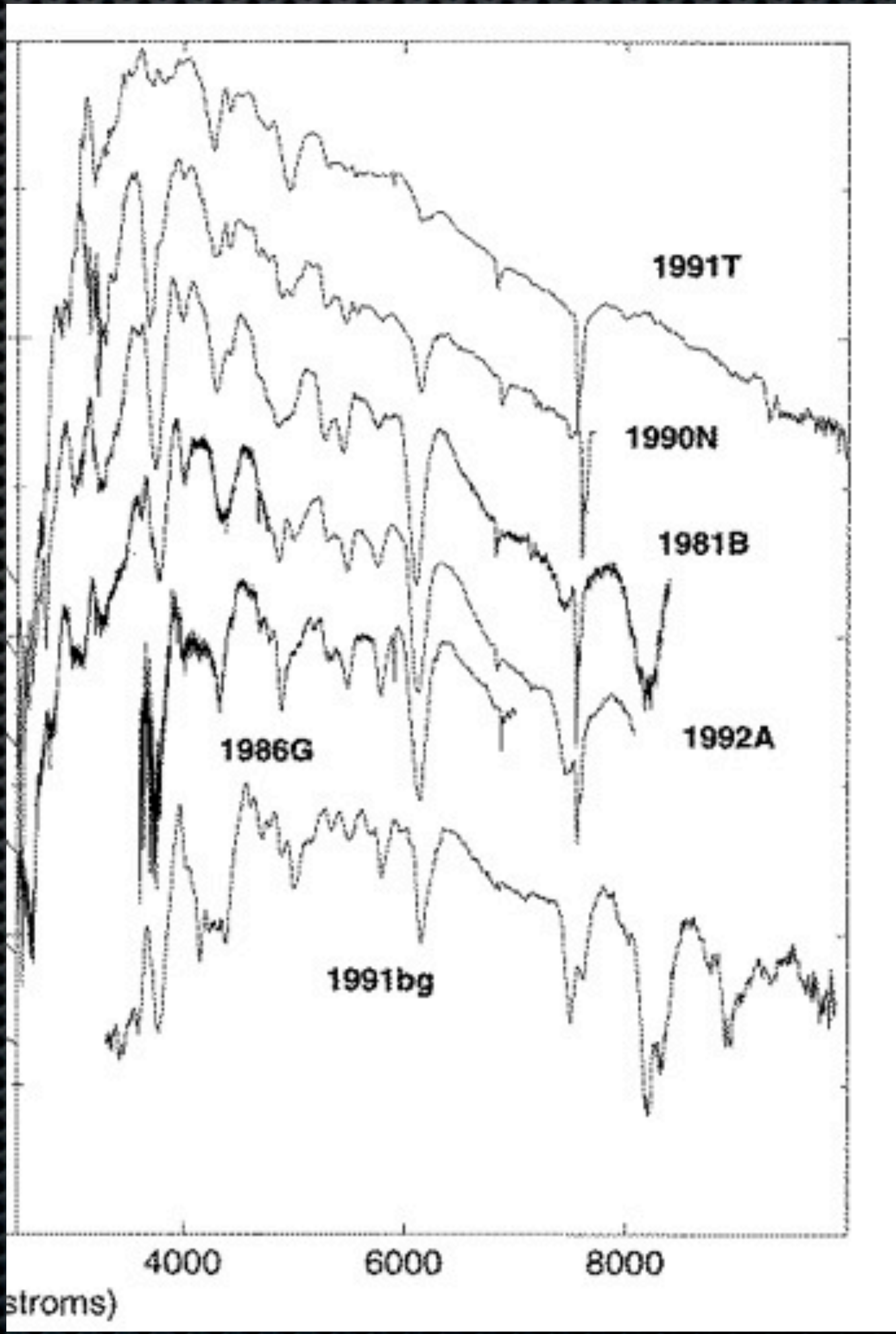
SNe Ia Are Not All Identical

- **Light Curves Show Variety within a theme**
  - ***Exhibit a relationship between light curve width and Absolute Magnitude***
- **Spectra Show Variety also within a theme**
  - ***Exhibit a spectral sequence related to Temperature and composition of the ejecta***

SN Ia Observations



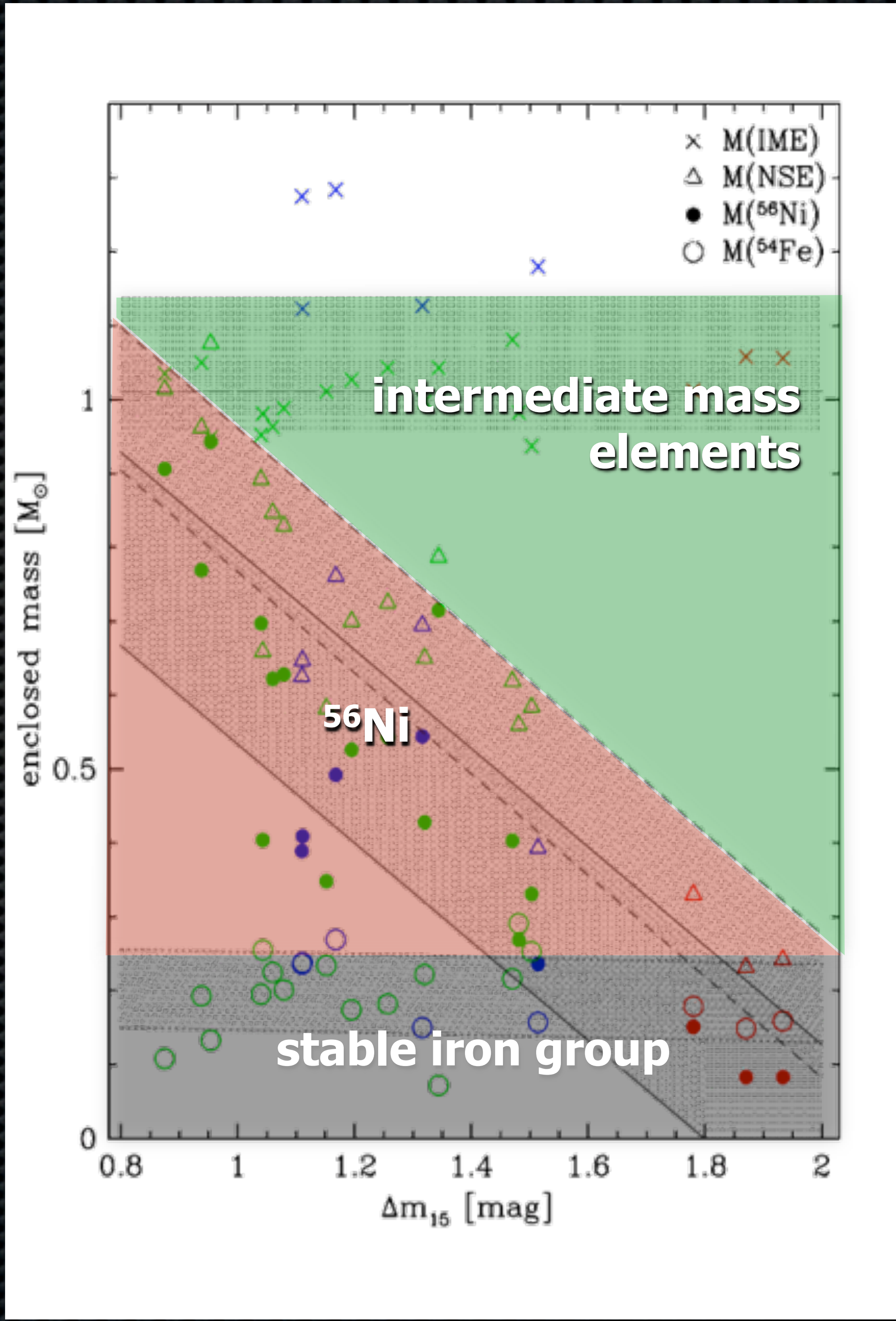
Filippenko 09



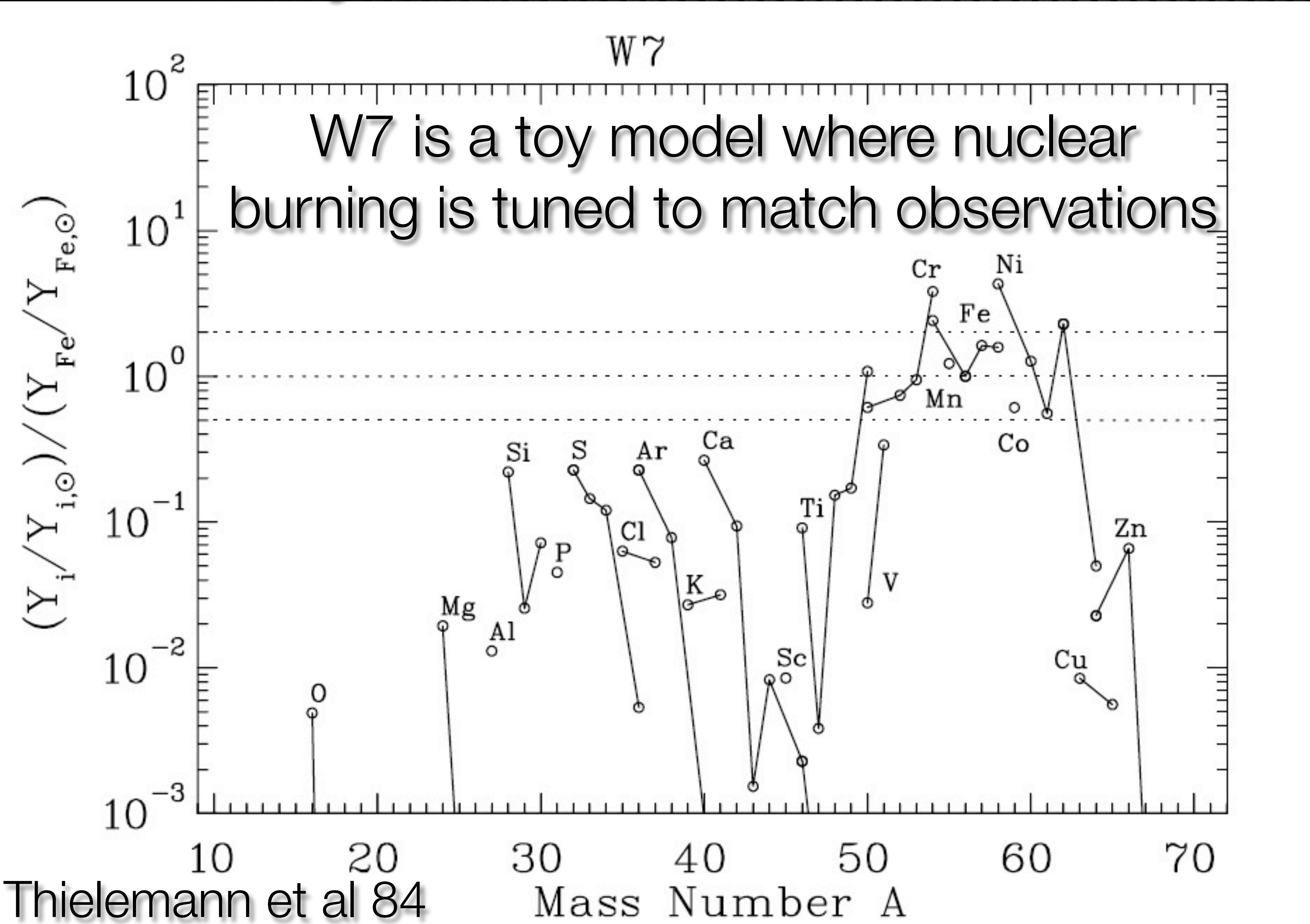
Nugent 95

Nucleosynthetic Production

- Mazzali et al. used light curves and spectra to estimate synthesized material in SN Ia
- Constant amount of stable Fe group, Constant Mass, but Intermediate Mass to Nuclear Stable Equilibrium varies...



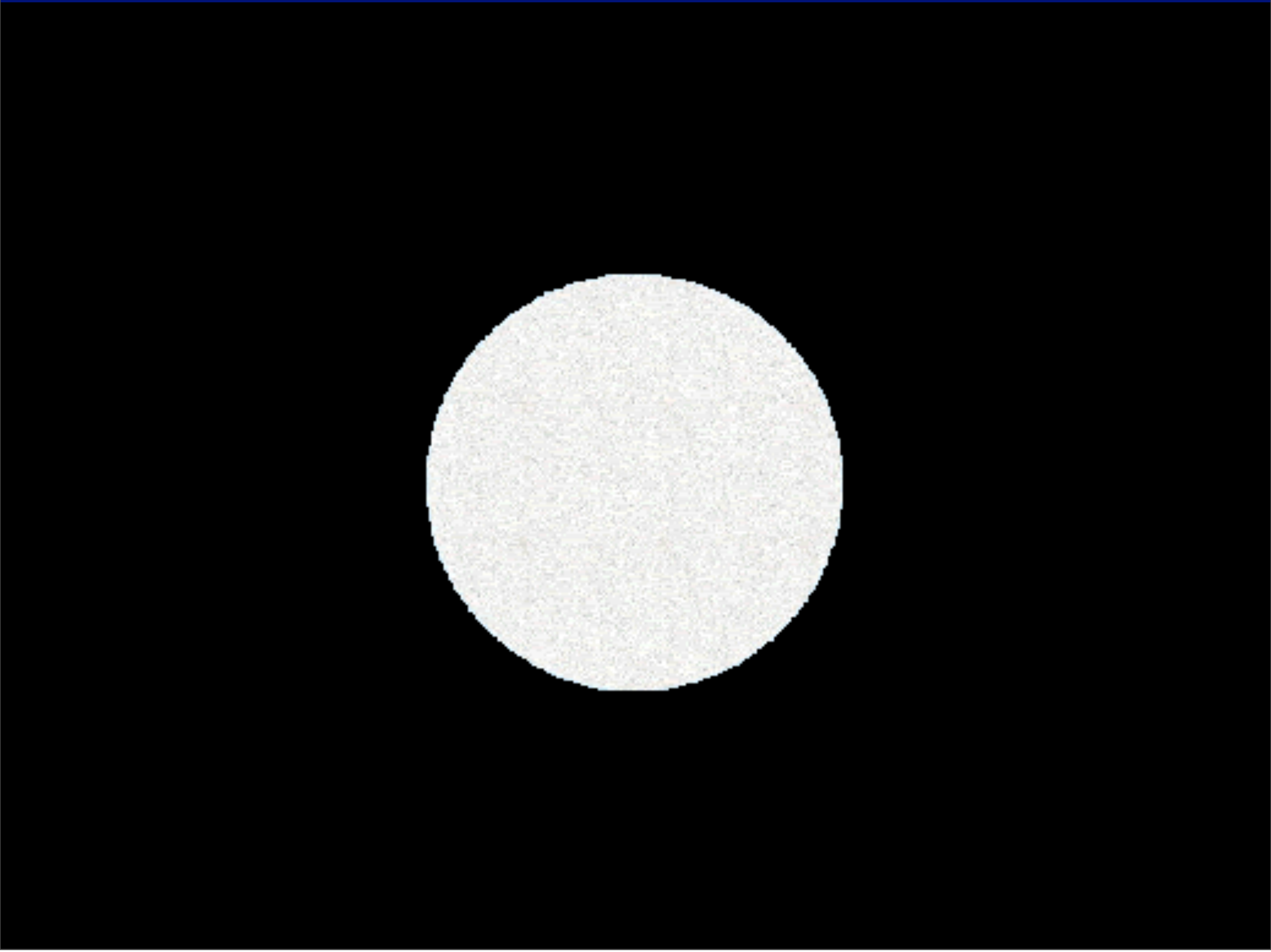
Nuclesynthetic Production in SN Ia



Thielemann et al 84

SN Progenitor Possibilities

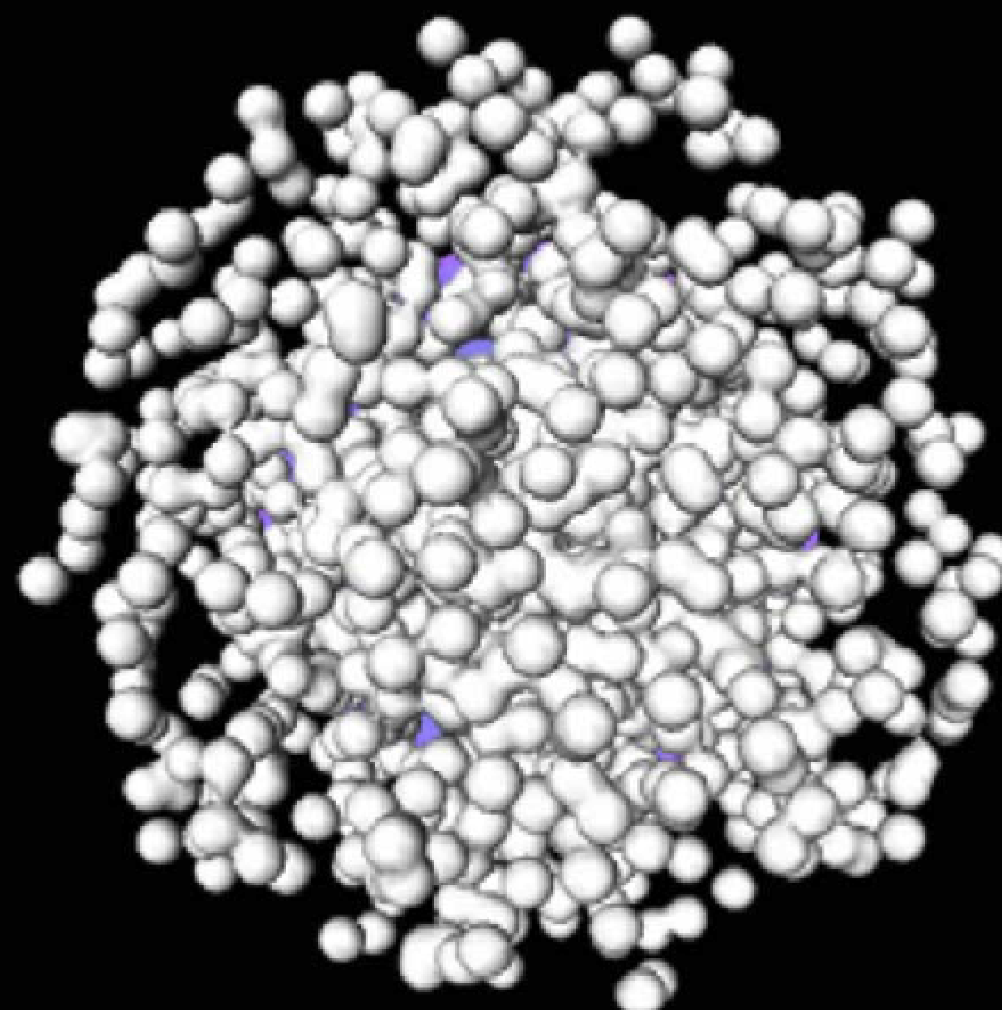
- **WD Accretes material from friend and exceeds 1.38 $M_\odot$ (Odds on favourite)**
  - accretion rates need to be very specific so Novae explosions do not cause Mass-loss
- **WD-WD merger exceeds 1.38 $M_\odot$ (Long shot)**
  - long thought to lead to neutron star, Pakmor '10 suggest two 0.9$M_\odot$ can lead to a sub-luminous Ia-like event.
- **WD accretes Helium, sub 1.38$M_\odot$ edge-lit detonation**
  - on again, off-again possibility. Sim '10, Fink '10 seem to show it could work?



0 days

Deflagration SN Ia simulation

t = 0.025 sec

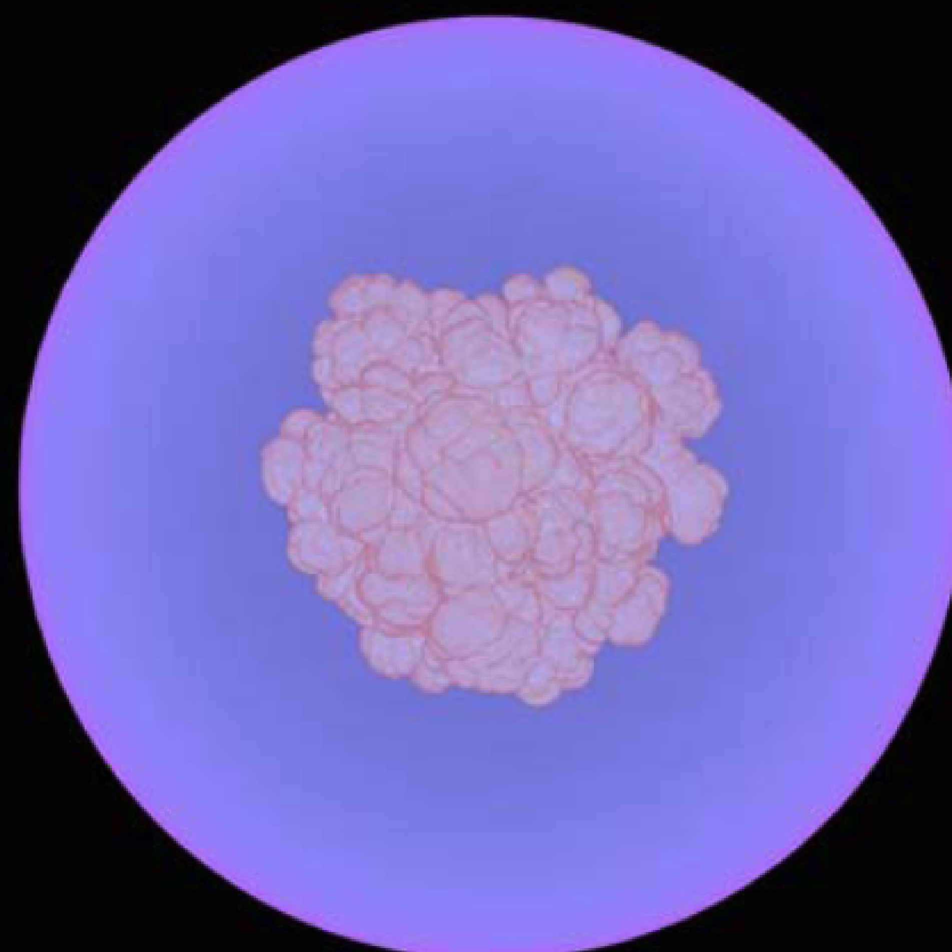


Deflagration SN Ia simulation

t = 0.200 sec

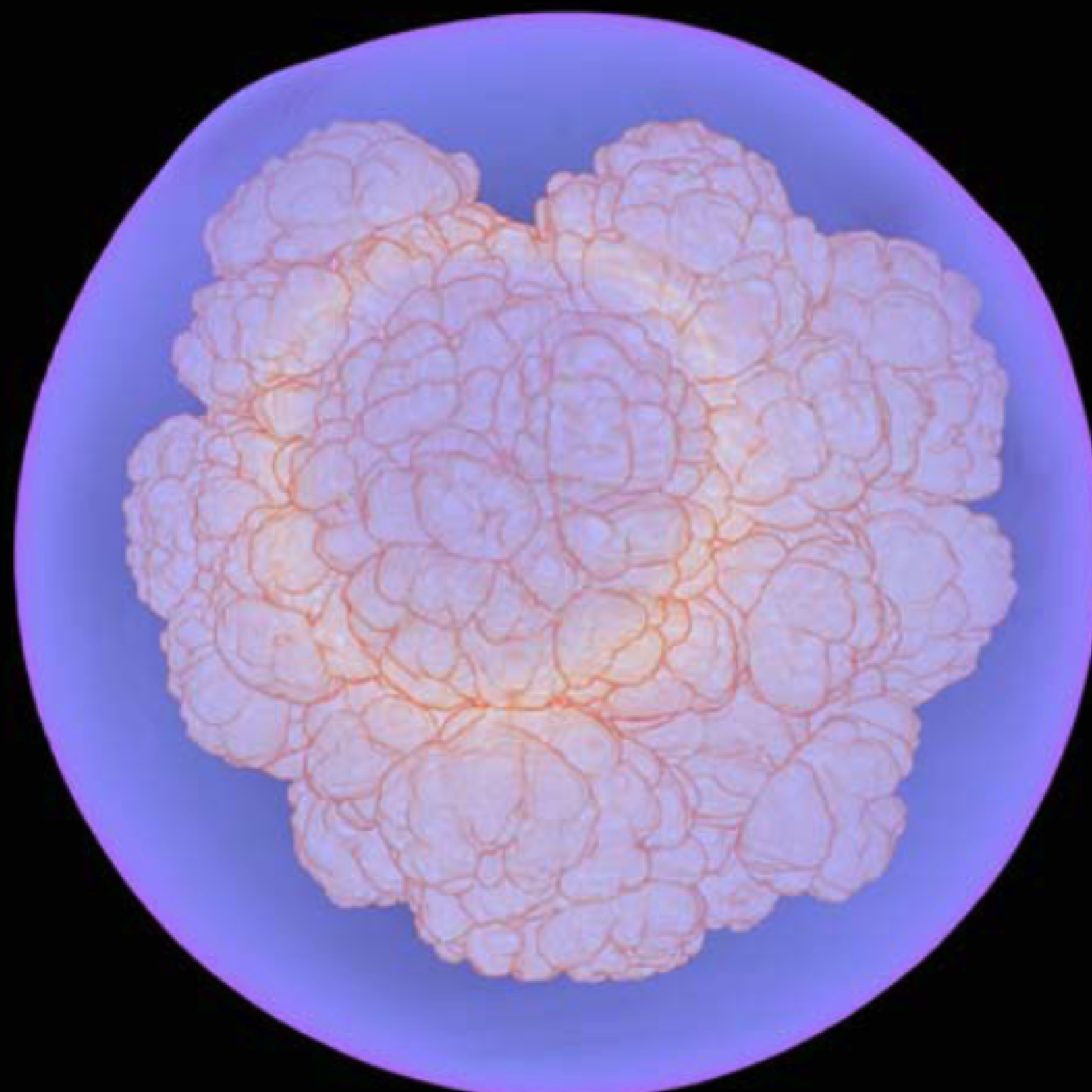
Deflagration SN Ia simulation

t = 0.600 sec



Deflagration SN Ia simulation

t = 1.000 sec

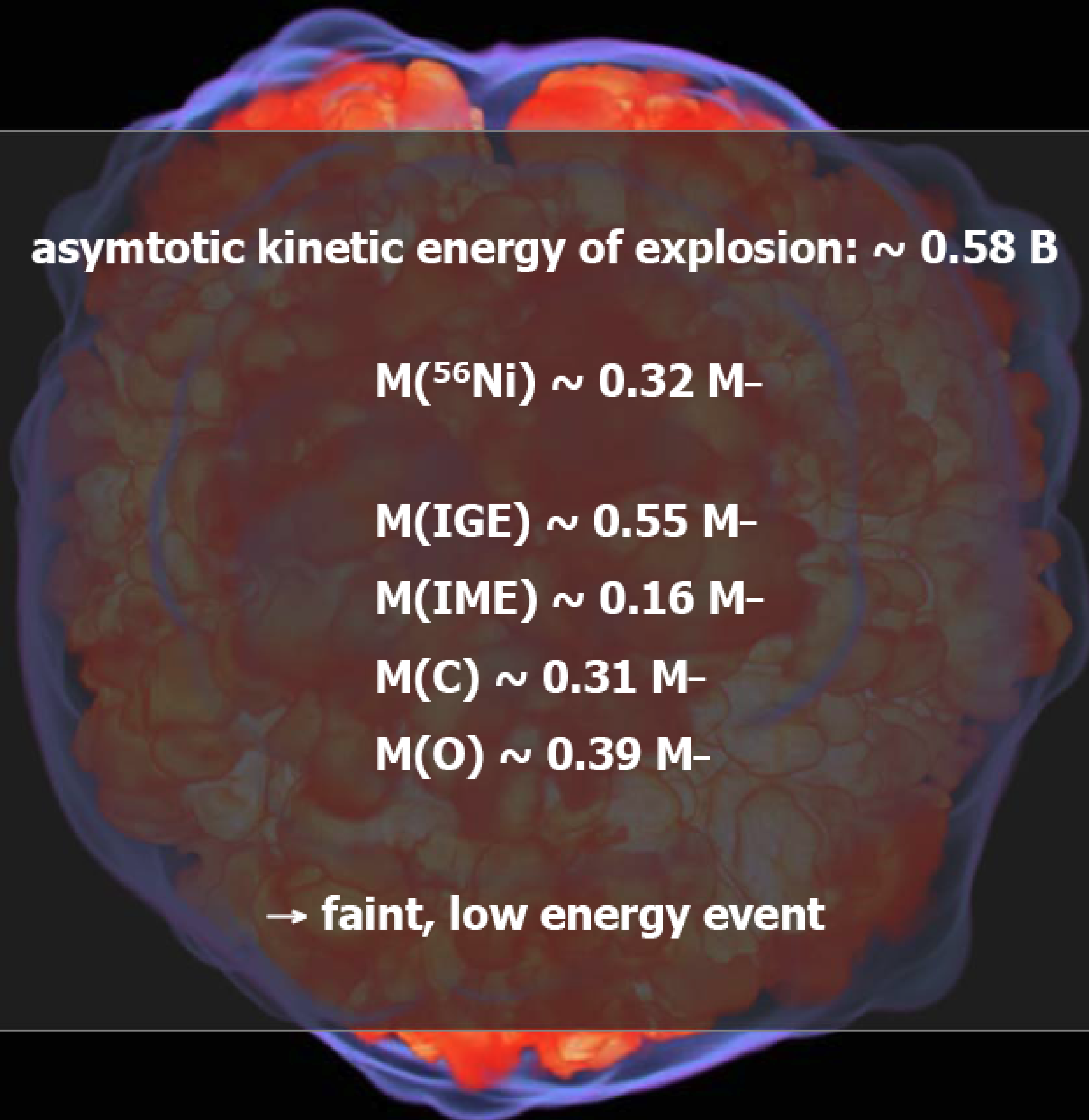


Deflagration SN Ia simulation

Friedrich Röpke, MPA

Deflagration SN Ia simulation

t = 3.000 sec



asymtotic kinetic energy of explosion: ~ 0.58 B

M(^{56}Ni) ~ 0.32 M–

M(IGE) ~ 0.55 M–

M(IME) ~ 0.16 M–

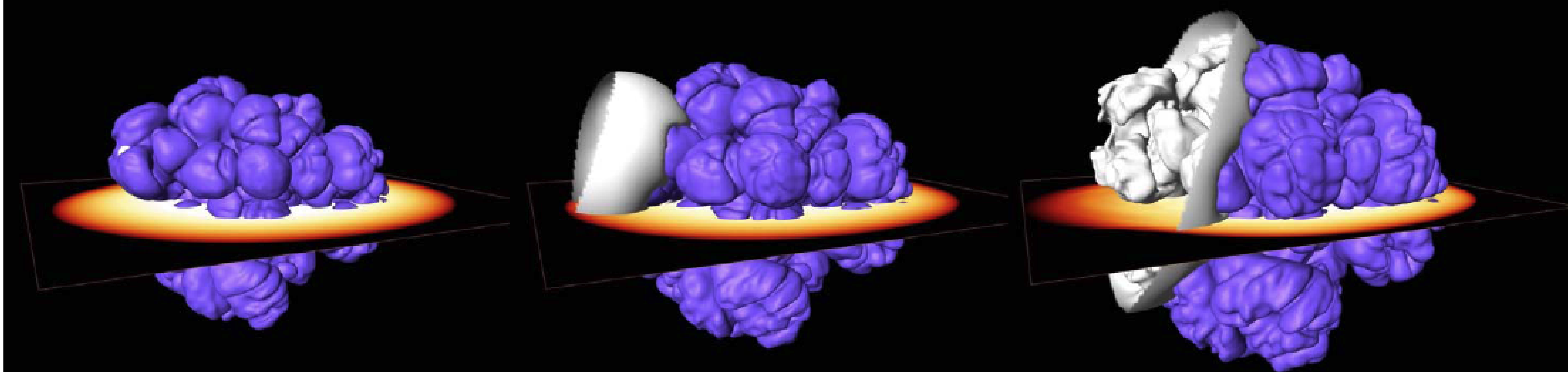
M(C) ~ 0.31 M–

M(O) ~ 0.39 M–

→ faint, low energy event

Khoklov 1991

Delayed detonation models



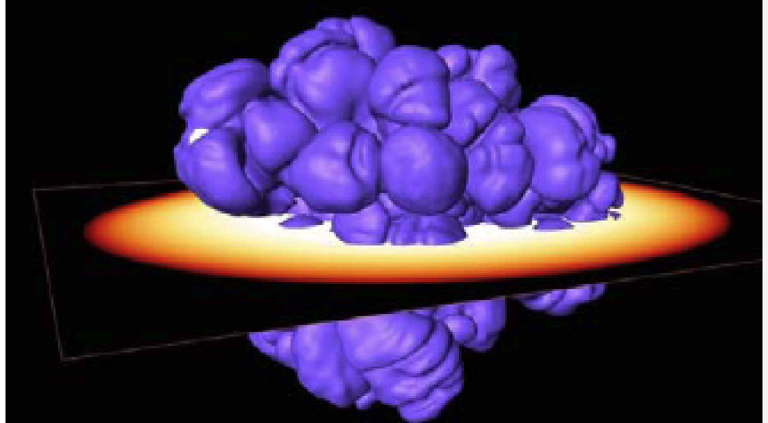
FR & Niemeyer, 2007
Mazzali et al., 2007

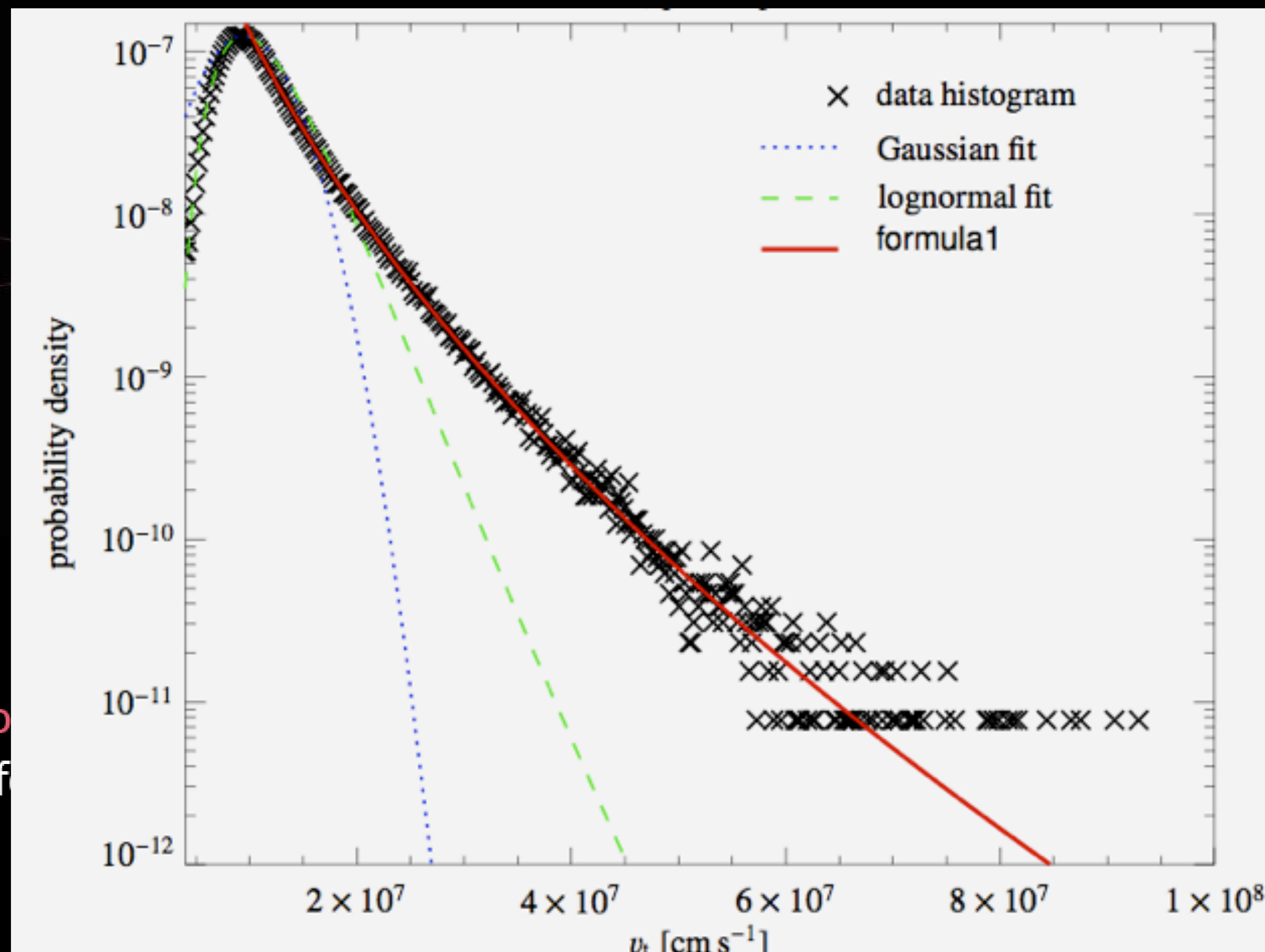
preliminary test calculations:

- promising candidate for explaining normal to bright SNe Ia

Khoklov 1991

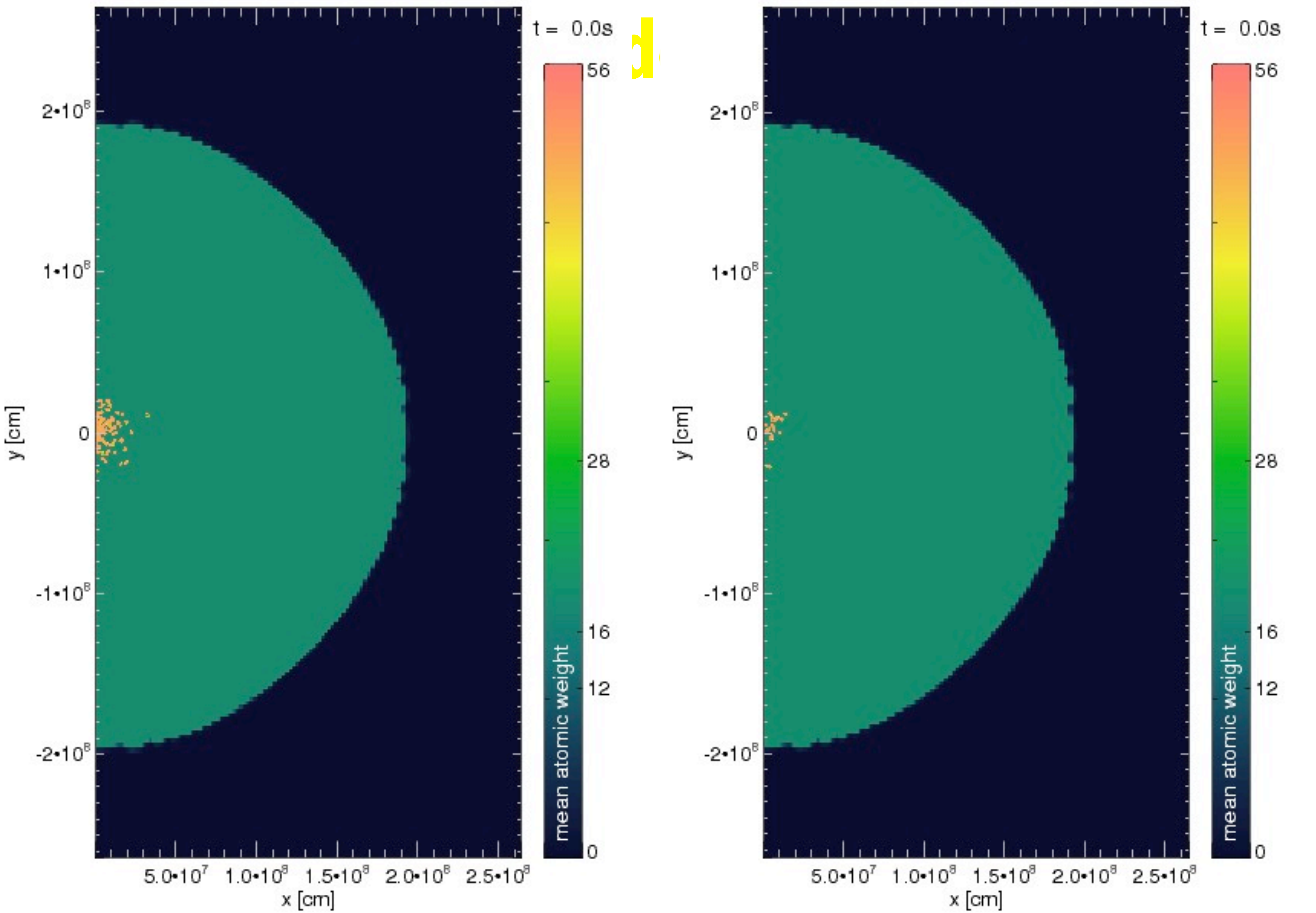
Delayed detonation models





preliminary test calculatio

- promising candidate f



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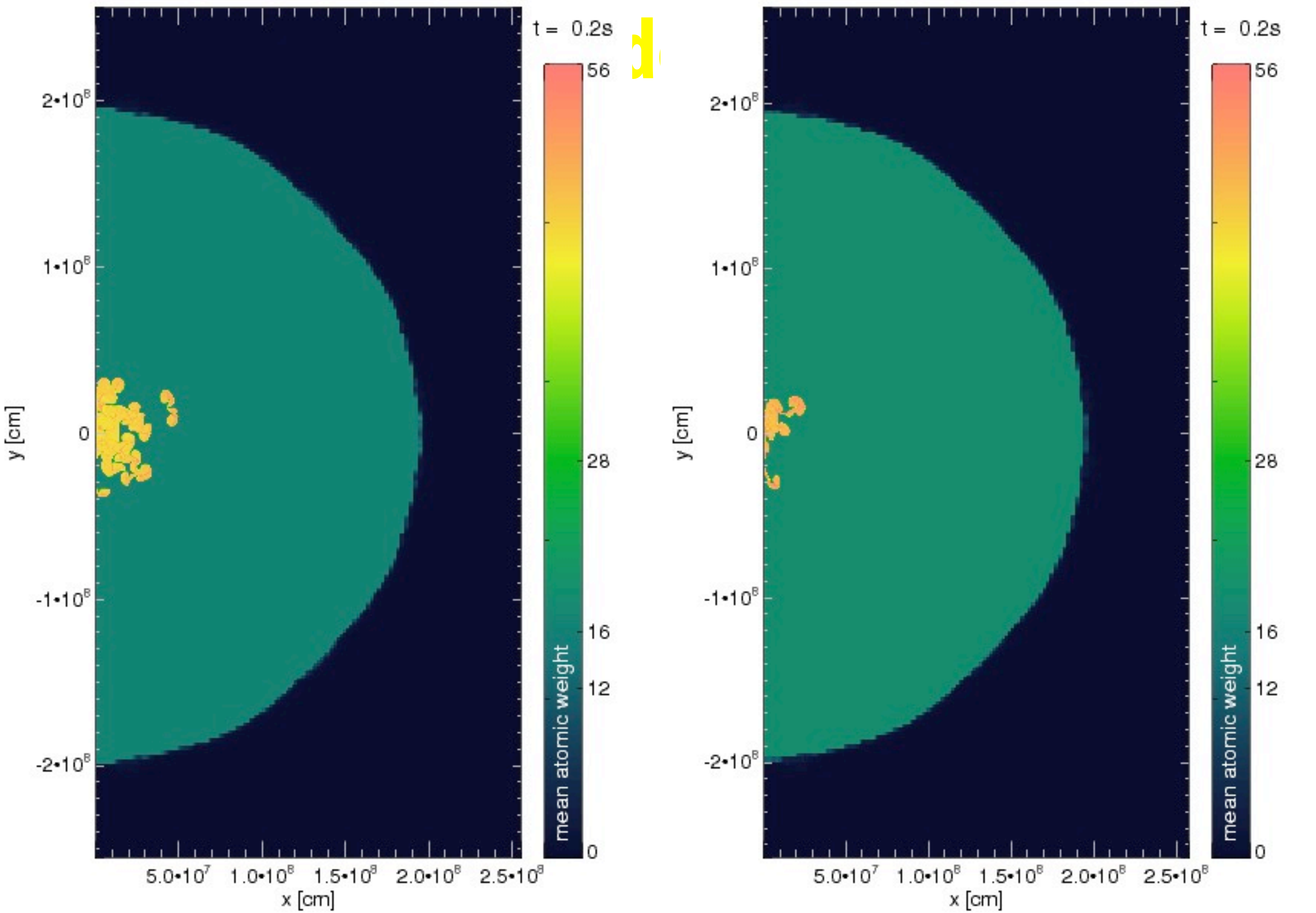
56
28
16
12
0
mean atomic weight
2•10^8
1•10^8
0
-1•10^8
-2•10^8
y [cm]
5.0•10^7
1.0•10^8
1.5•10^8
2.0•10^8
2.5•10^8
x [cm]
t = 0.0s
56
28
16
12
0
mean atomic weight
2•10^8
1•10^8
0
-1•10^8
-2•10^8
y [cm]
5.0•10^7
1.0•10^8
1.5•10^8
2.0•10^8
2.5•10^8
x [cm]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16
12
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y [cm]
x [cm]
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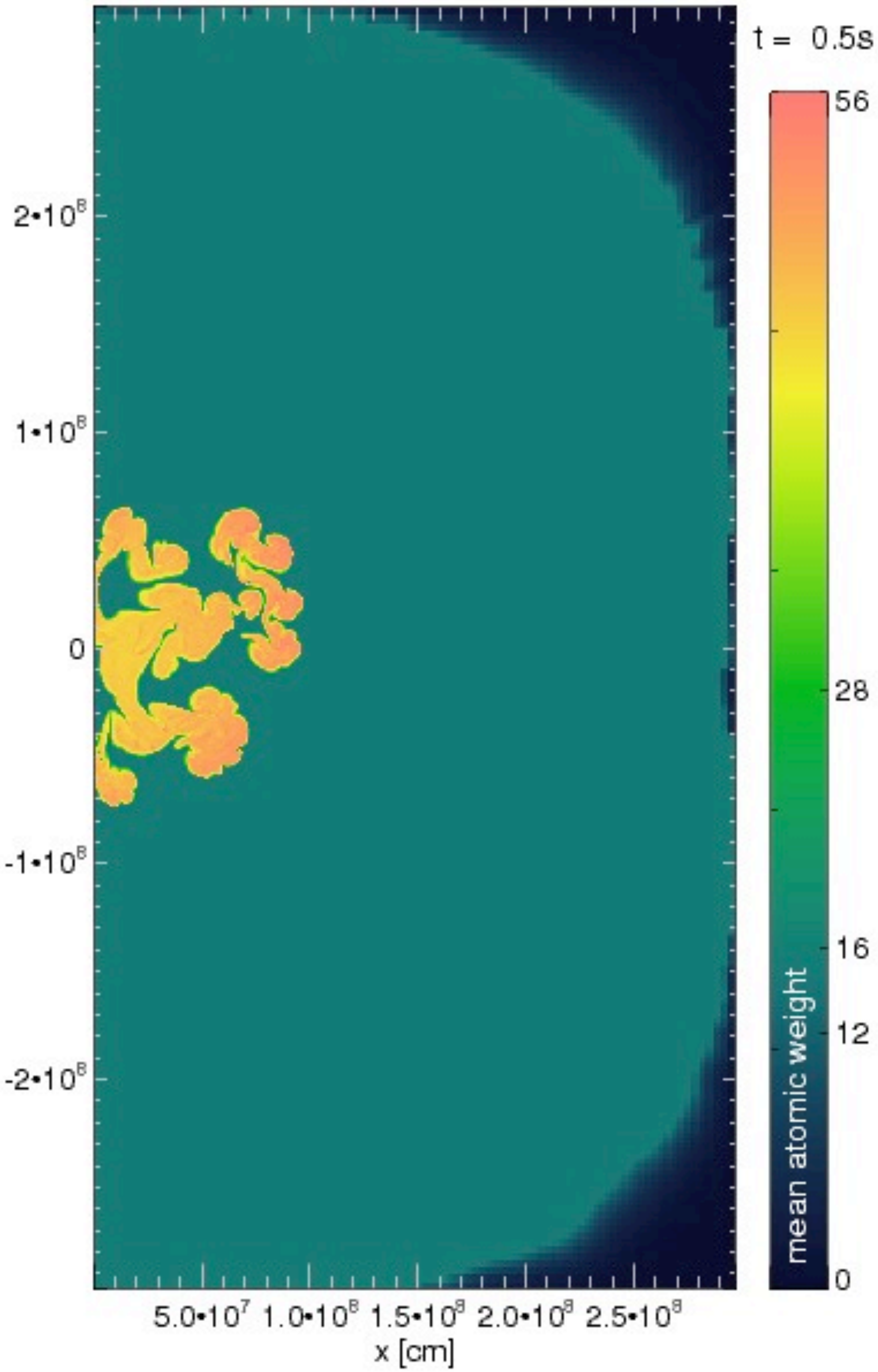
-2•10^8
5.0•10^7
1.0•10^8
1.5•10^8
2.0•10^8
2.5•10^8
t = 0.2s
56
28
16
12
0
mean atomic weight
y [cm]
x [cm]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28
16
12
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x [cm]
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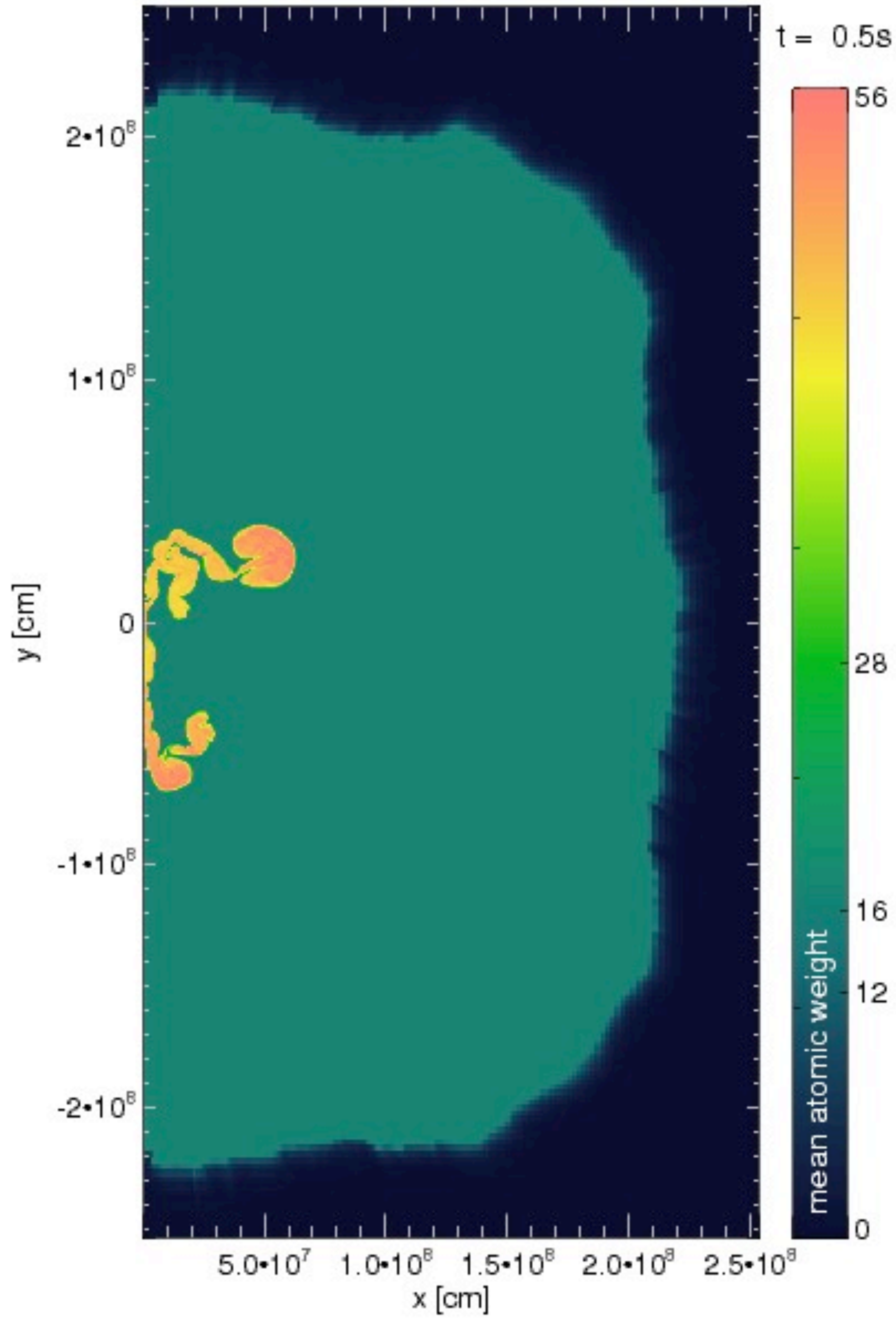
-1•10^8
-2•10^8
5.0•10^7 1.0•10^8 1.5•10^8 2.0•10^8 2.5•10^8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28
16
12
0
mean atomic weight
y [cm]
x [cm]
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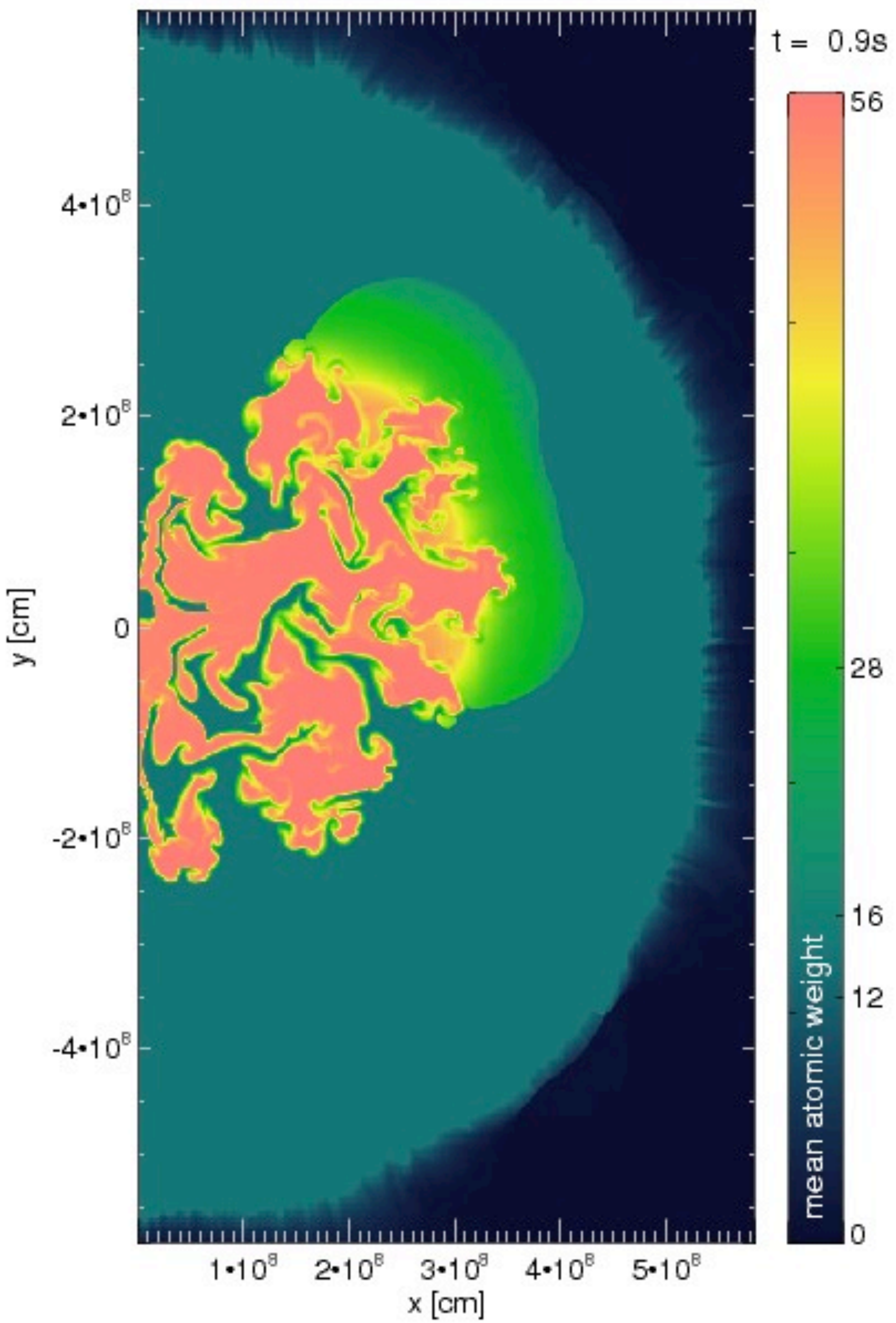
0
-1•10^8
-2•10^8
5.0•10^7 1.0•10^8 1.5•10^8 2.0•10^8 2.5•10^8



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16
12
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x [cm]
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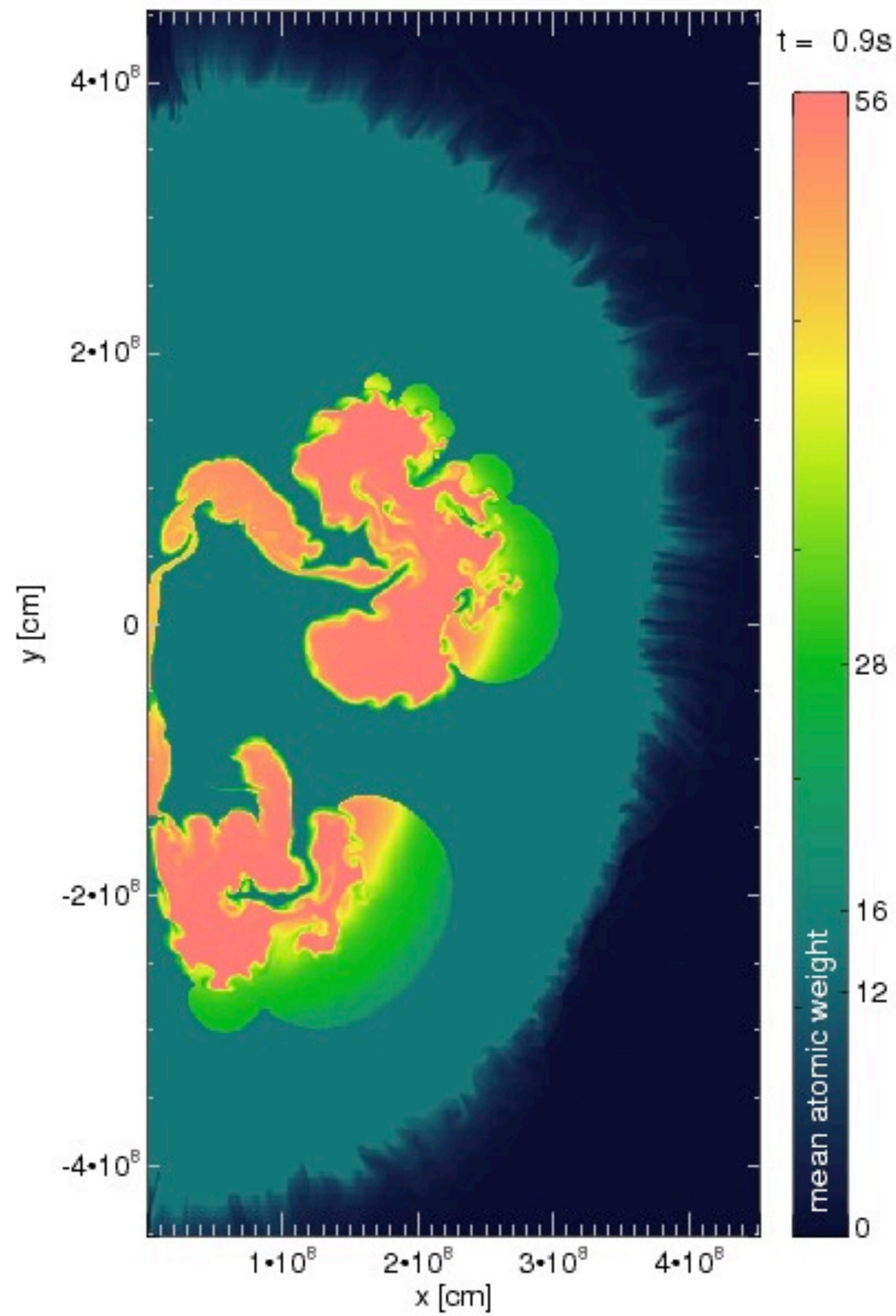
1•10^8
2•10^8
3•10^8
4•10^8
5•10^8



t = 0.9s
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28
16
12
0
mean atomic weight
y [cm]
x [cm]
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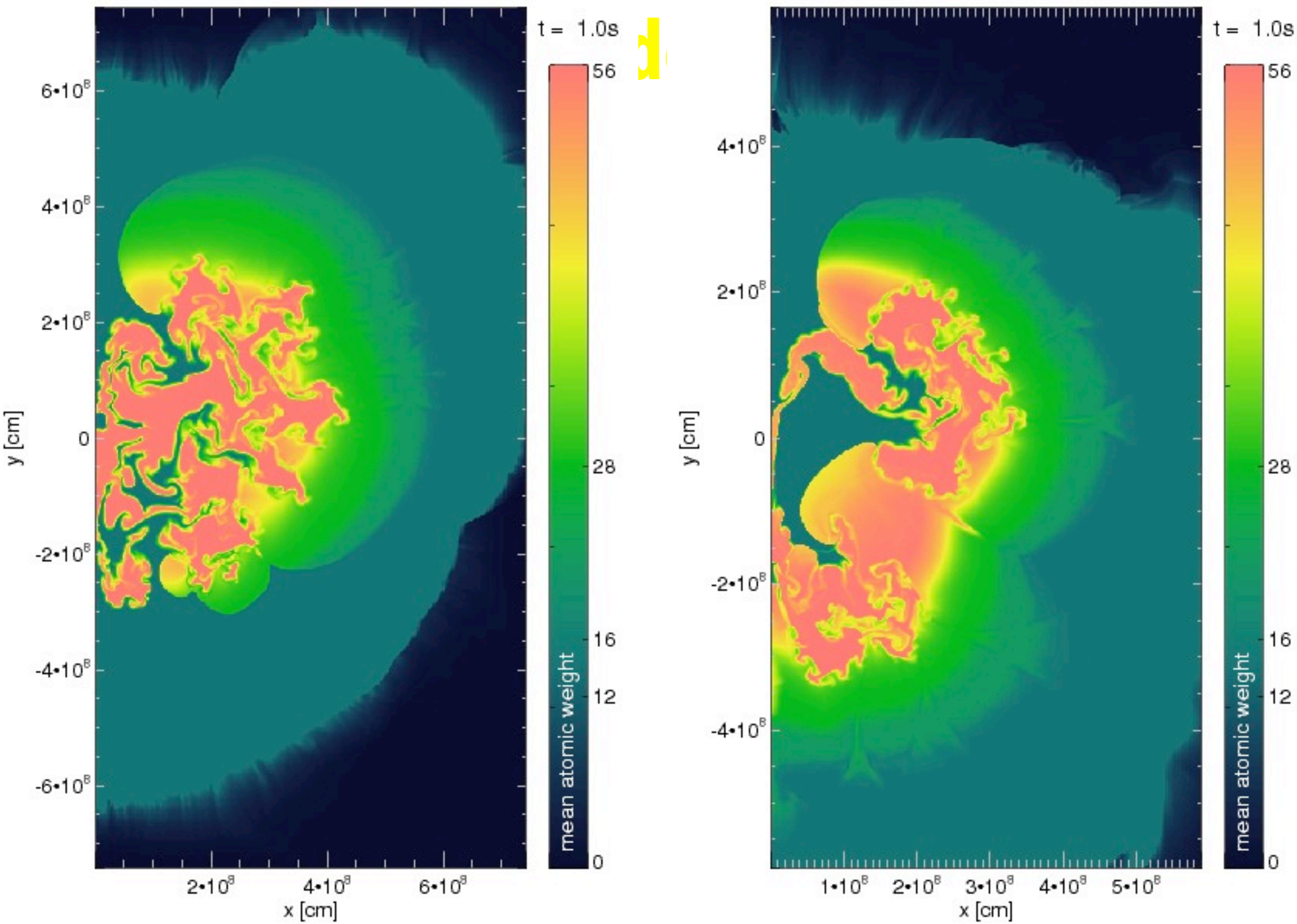
2•10^8
0
-2•10^8
-4•10^8
1•10^8
2•10^8
3•10^8
4•10^8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mean atomic weight
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x [cm]
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0
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-4•10^8
-6•10^8
2•10^8
4•10^8
6•10^8
t = 1.0s
56
28
16
12
0
mean atomic weight
y [cm]
x [cm]
4•10^8
2•10^8
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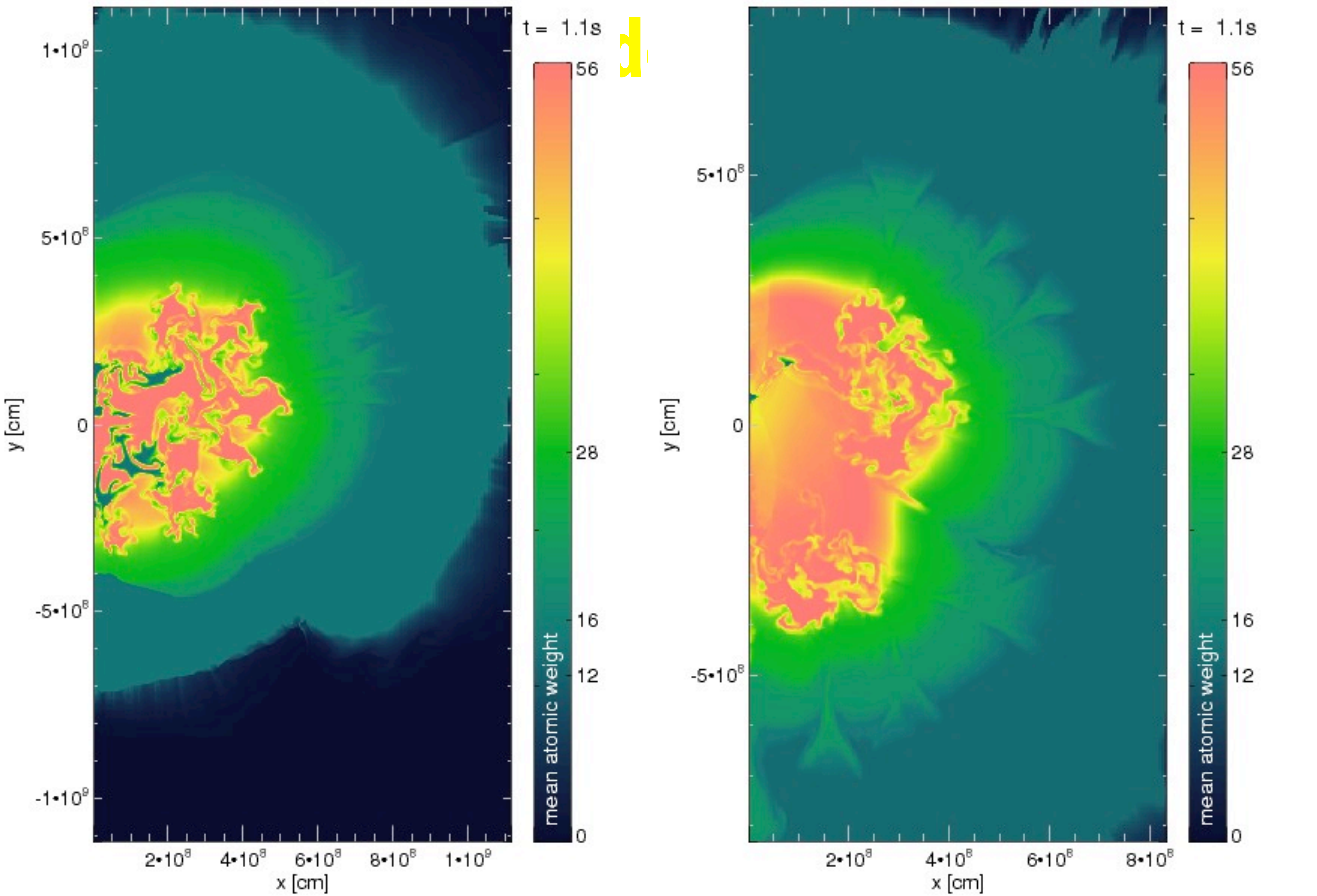
-2•10^8
-4•10^8
1•10^8
2•10^8
3•10^8
4•10^8
5•10^8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16
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x [cm]
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5•10⁸
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-1•10⁹
2•10⁸
4•10⁸
6•10⁸
8•10⁸
1•10⁹
t = 1.1s
56
28
16
12
0
mean atomic weight
y [cm]
x [cm]
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0
-5•10⁸
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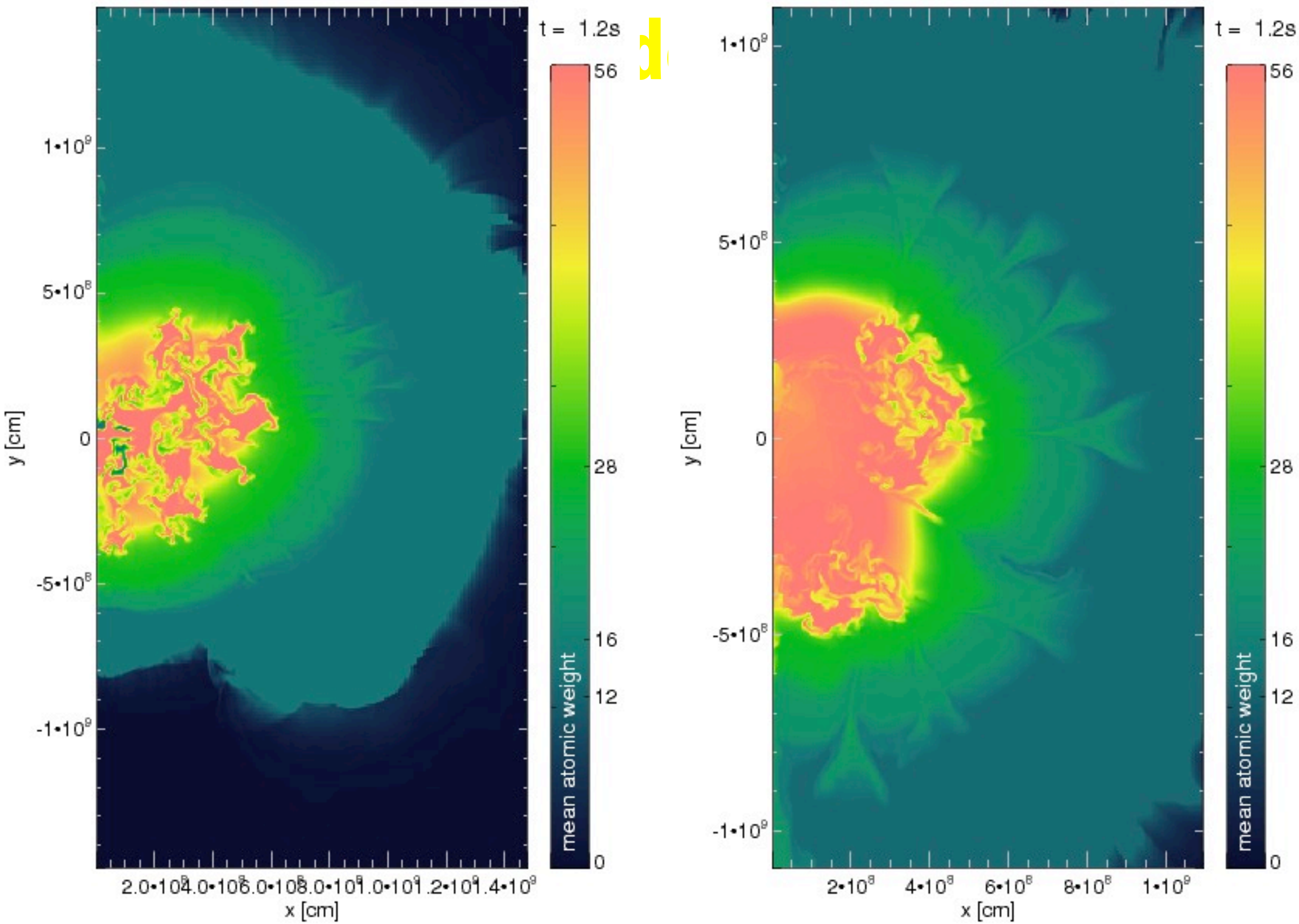
4•10⁸
6•10⁸
8•10⁸


t = 1.2s
56
28
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mean atomic weight
y [cm]
x [cm]
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5•10^8
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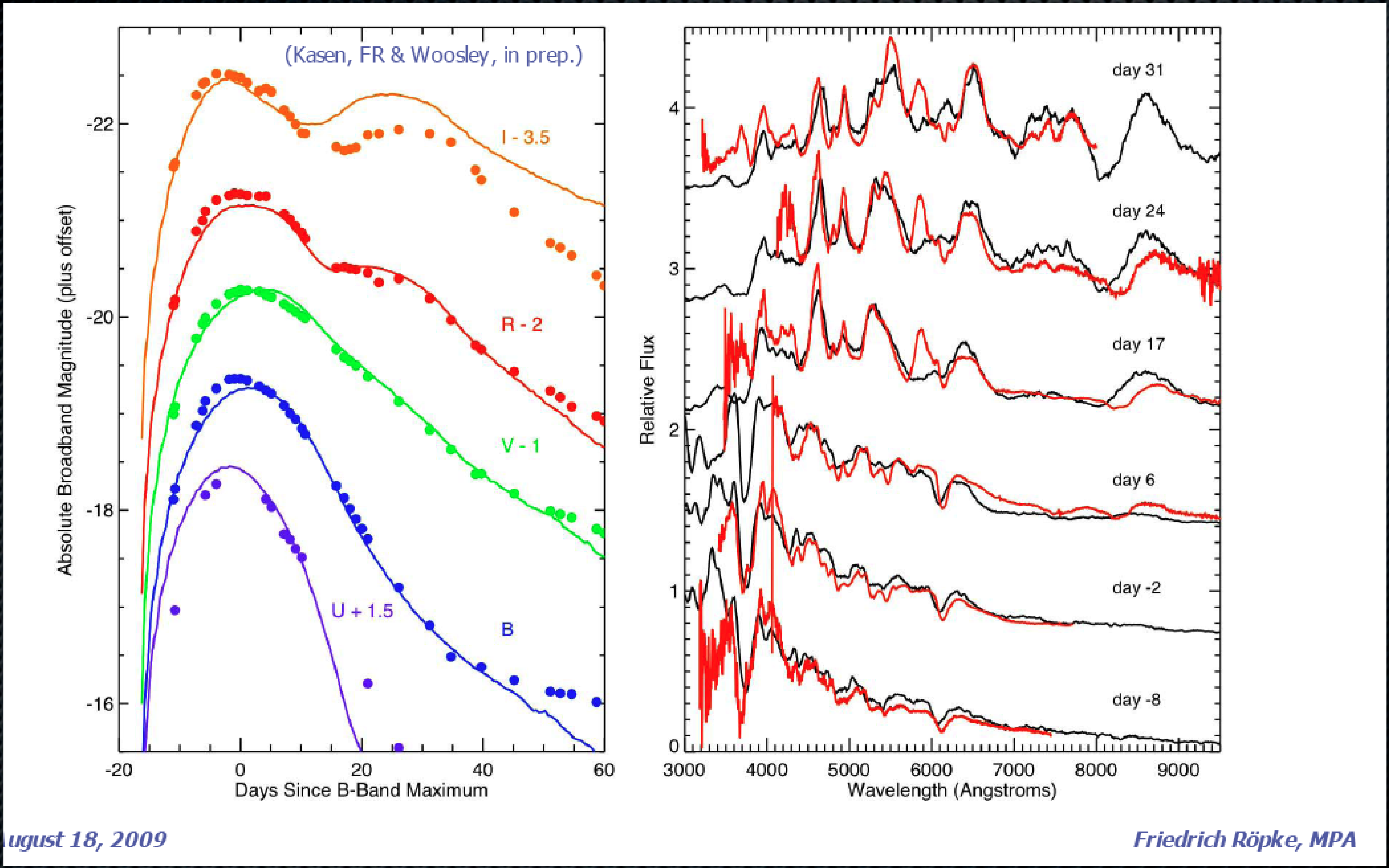
-5•10^8
-1•10^9
2•10^8
4•10^8
6•10^8
8•10^8
1•10^9

Delayed Detonation Models

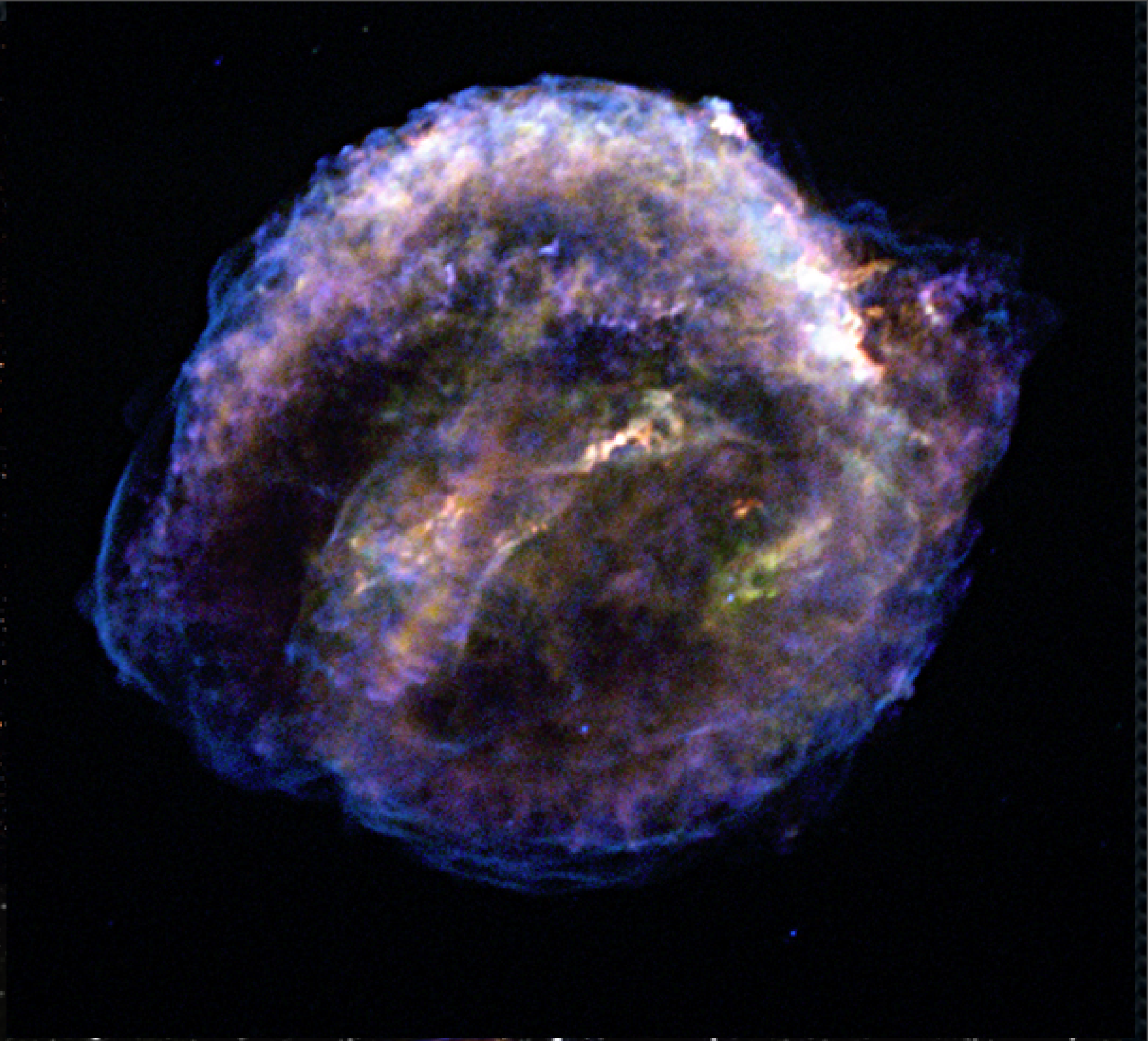


Hoflich and Khoklov - Kasen Ropke and Woosley

SN Remnants

and DD models fit remnants well (Badenes et al)

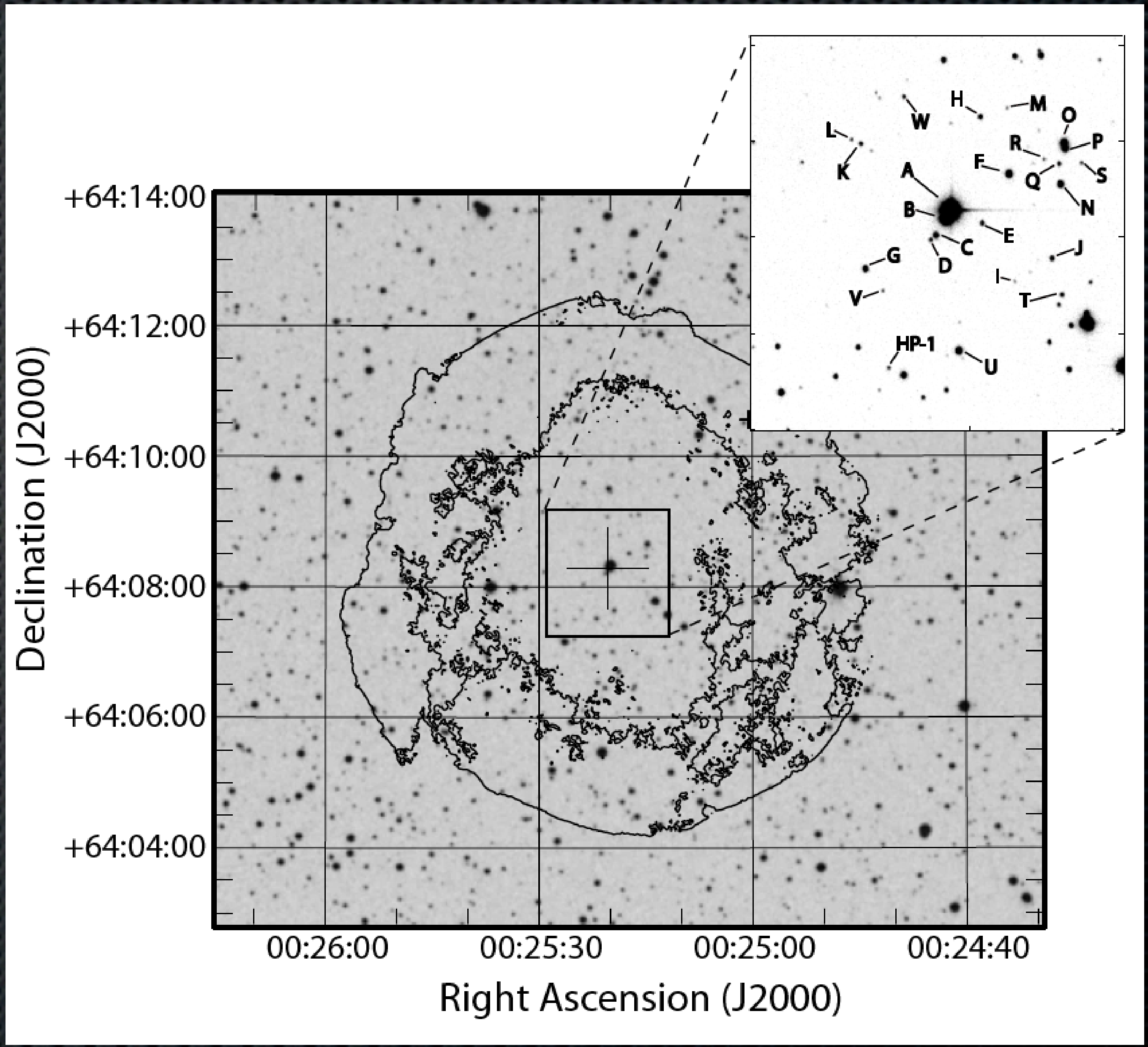
SN Remnants



and DD models fit remnants well (Badenes et al)

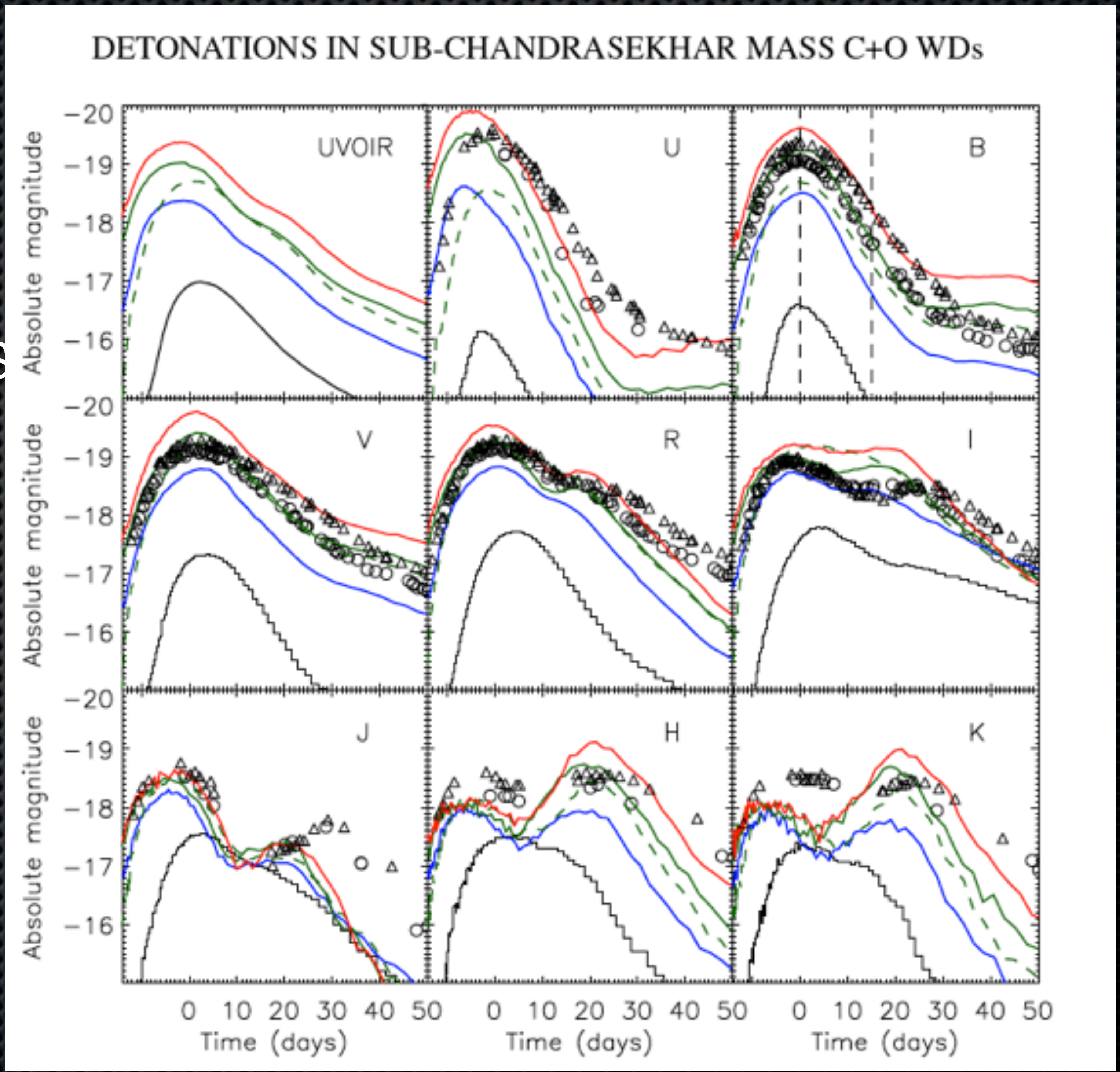
One Problem? Where are the Progenitors

Ruiz-Lapuente and Kerzendorf et al. Searched for star that donated mass. I believe no obvious candidates at this point, and they should be obvious From their motion and rotation, unless it is a helium star.



Maybe Helium Detonations

- Light curves and spectra more or less look OK at least for brightest objects
- But where are the less massive ones?
- leaves a very faint secondary He star.



Livne ...Sim et al 2010

Maybe two White Dwarfs?

Are there enough progenitors?

☑ Maybe, but hard to know

Do they give the right Age distribution?

☑ Probably OK

Do they explode?

☐ Answer has typically been no...But hard problem, which out of desperation is being looked at again in detail. Some might. Most would say most do not, and the ones that do, don't look like normal Ia (but maybe like the faintest SN Ia)

So a Major Mystery remains What makes a SN Ia?

Delayed Detonation Explosions look good, except they should leave their donor star as a calling card, some hydrogen left-over from the explosion, and probably a signature in the light curve - none of which are seen.

edge-lit Helium Detonations - low mass, unclear if there are enough, and why SN Ia are so homogenous

and White-Dwarf White-Dwarf mergers remain possibilities, but not clear that they can explain the bulk of SN Ia which are observed.

I suspect SN Ia population may potentially be a mix...

Largest Bangs in the Universe....Since the Big One.

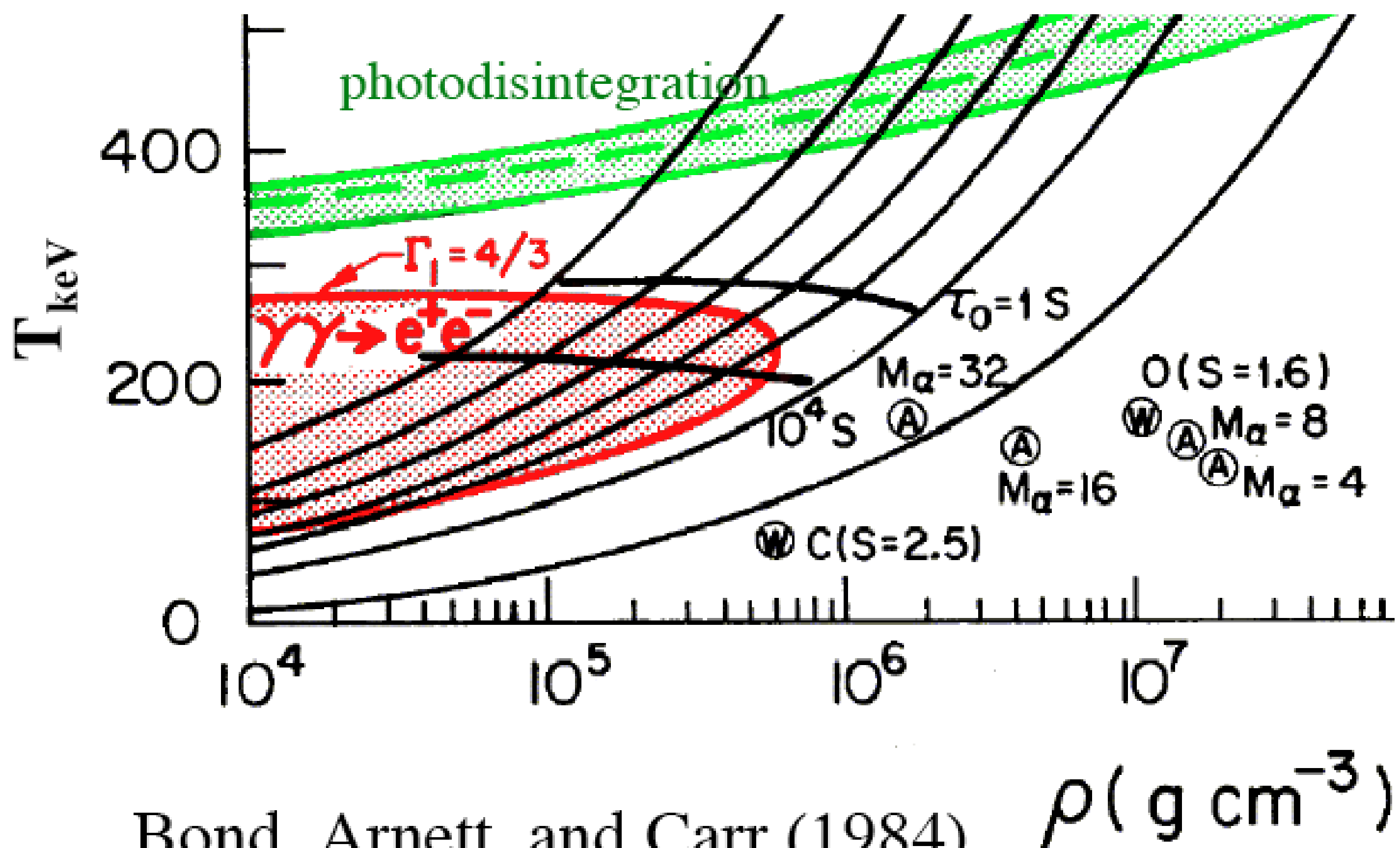
There exist very rare events which are extremely energetic. These include

Pair Production Supernova

Gamma Ray Bursts (two types)

Pair Instability

Stars of sufficiently high mass (central entropy) encounter a structural instability ($\Gamma < 4/3$) and collapse following the end of helium burning. Explosive C, O, Si burning can reverse the implosion and make a thermonuclear explosion



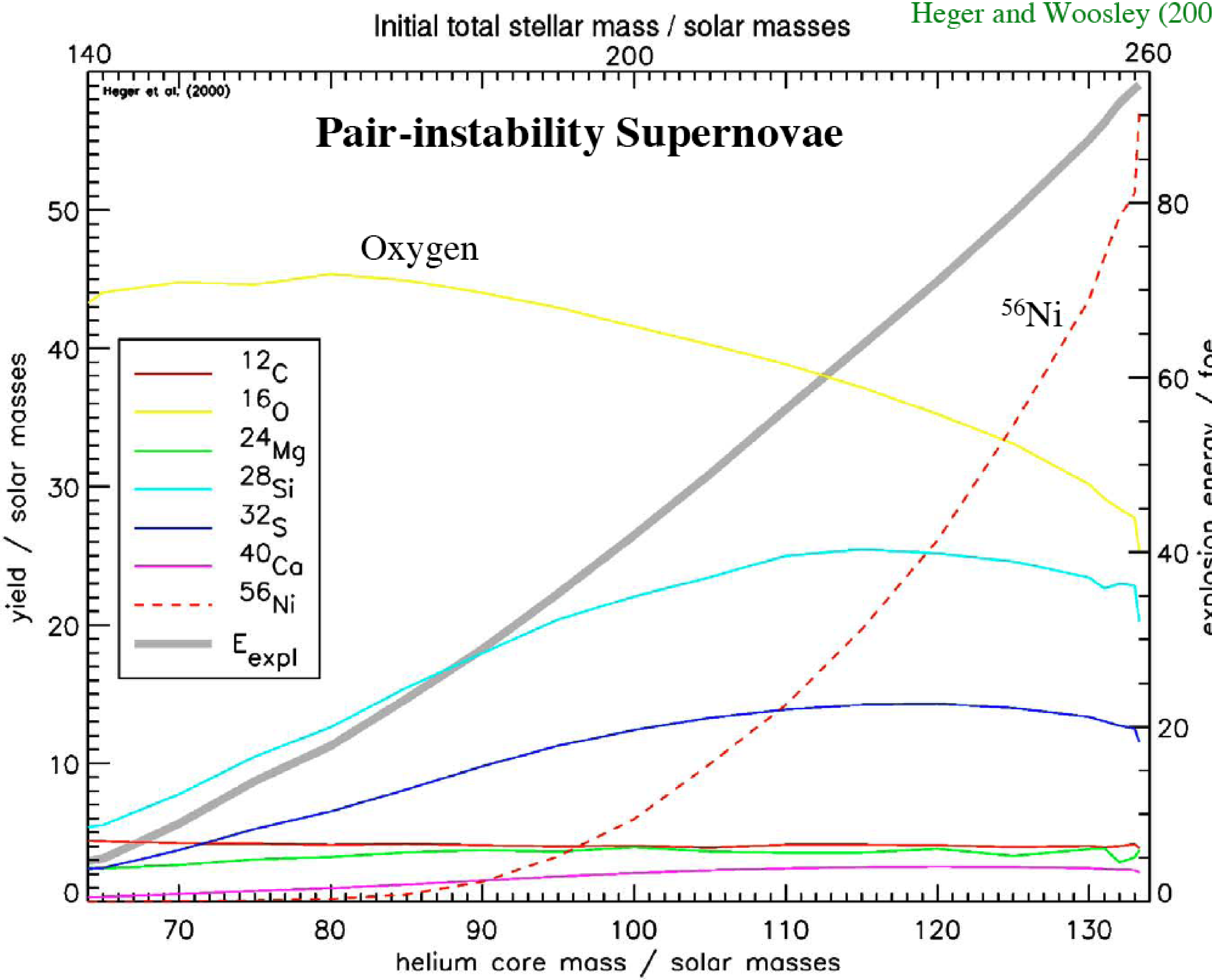
Bond, Arnett, and Carr (1984)

$$\text{BE} \sim \frac{GM^2}{R}$$

Nuclear energy $\sim f\ M$

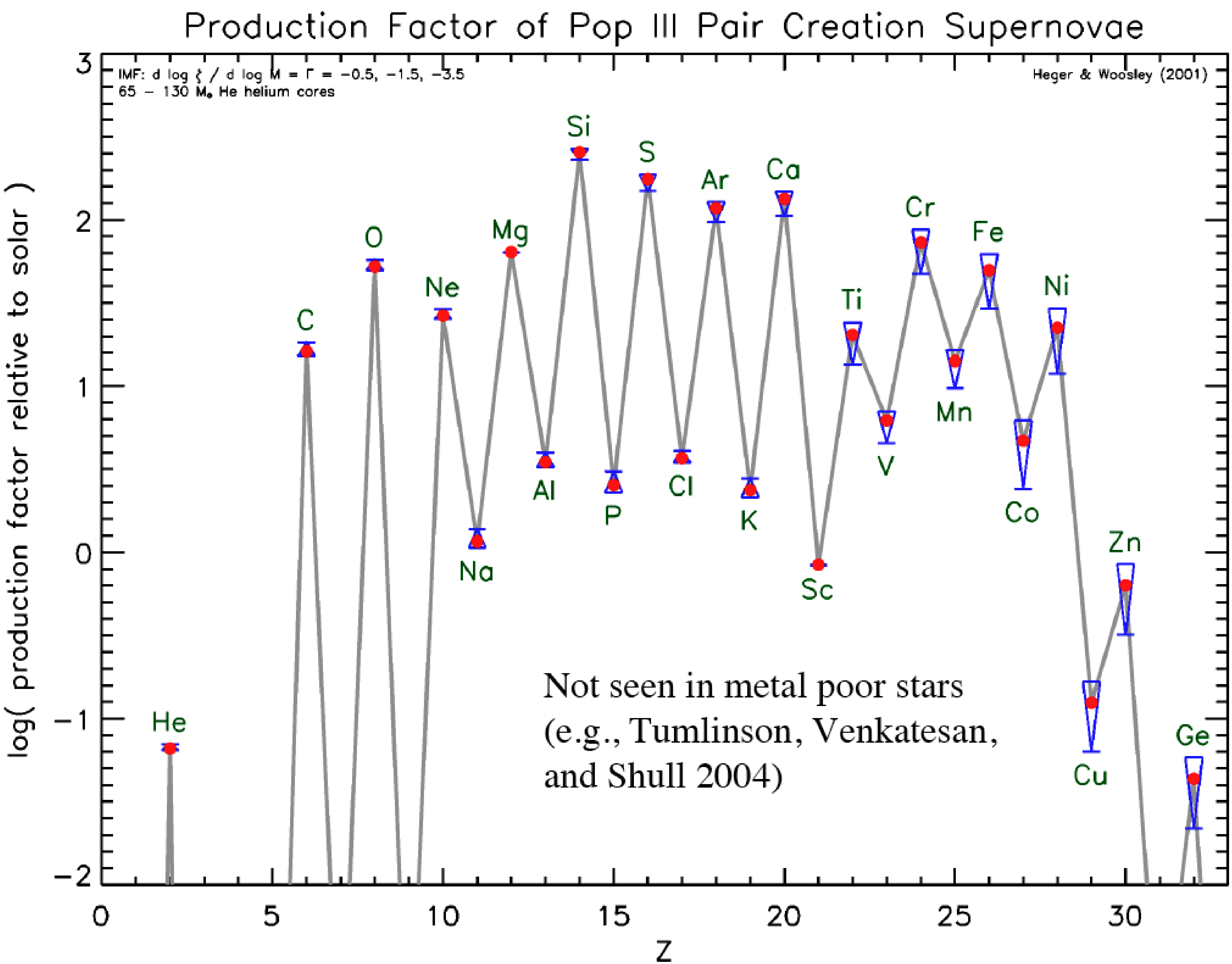
Above some mass hard to explode

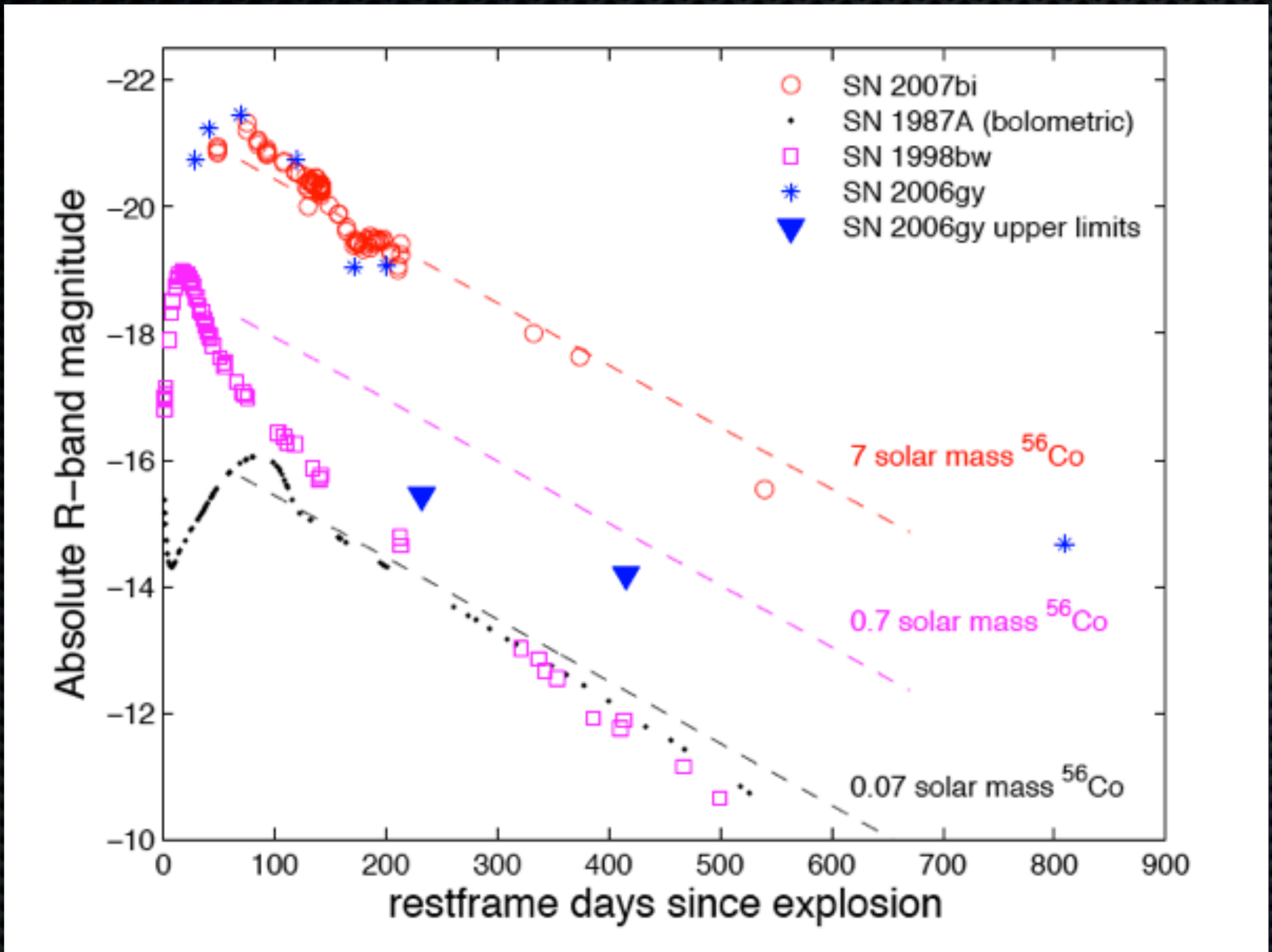
Heger and Woosley (2002)



Complications:

- Did they, do they ever exist and what was the heaviest?
- Mass loss: Eta Carina or $\dot{M} \propto Z^n \rightarrow 0$ as $Z \rightarrow 0$
- Convection and convective dredge up. Primary nitrogen production leads to red supergiant, otherwise blue. RSG may lose mass even at $Z = 0$.
- Rotation - increases He core mass, increases mixing and mass loss and may dominate the explosion mechanism in some mass range
- Binary - lose envelope?


Production Factor of Pop III Pair Creation Supernovae
IMF: d log ξ / d log M = Γ = −0.5, −1.5, −3.5
65 − 130 M☉ He helium cores
Heger & Woosley (2001)
log(production factor relative to solar)
Z
He
C
O
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ge
Not seen in metal poor stars
(e.g., Tumlinson, Venkatesan,
and Shull 2004)



But they do seem to be seen in Nature

at least something that looks like them - but very rare

Gamma Ray Bursts

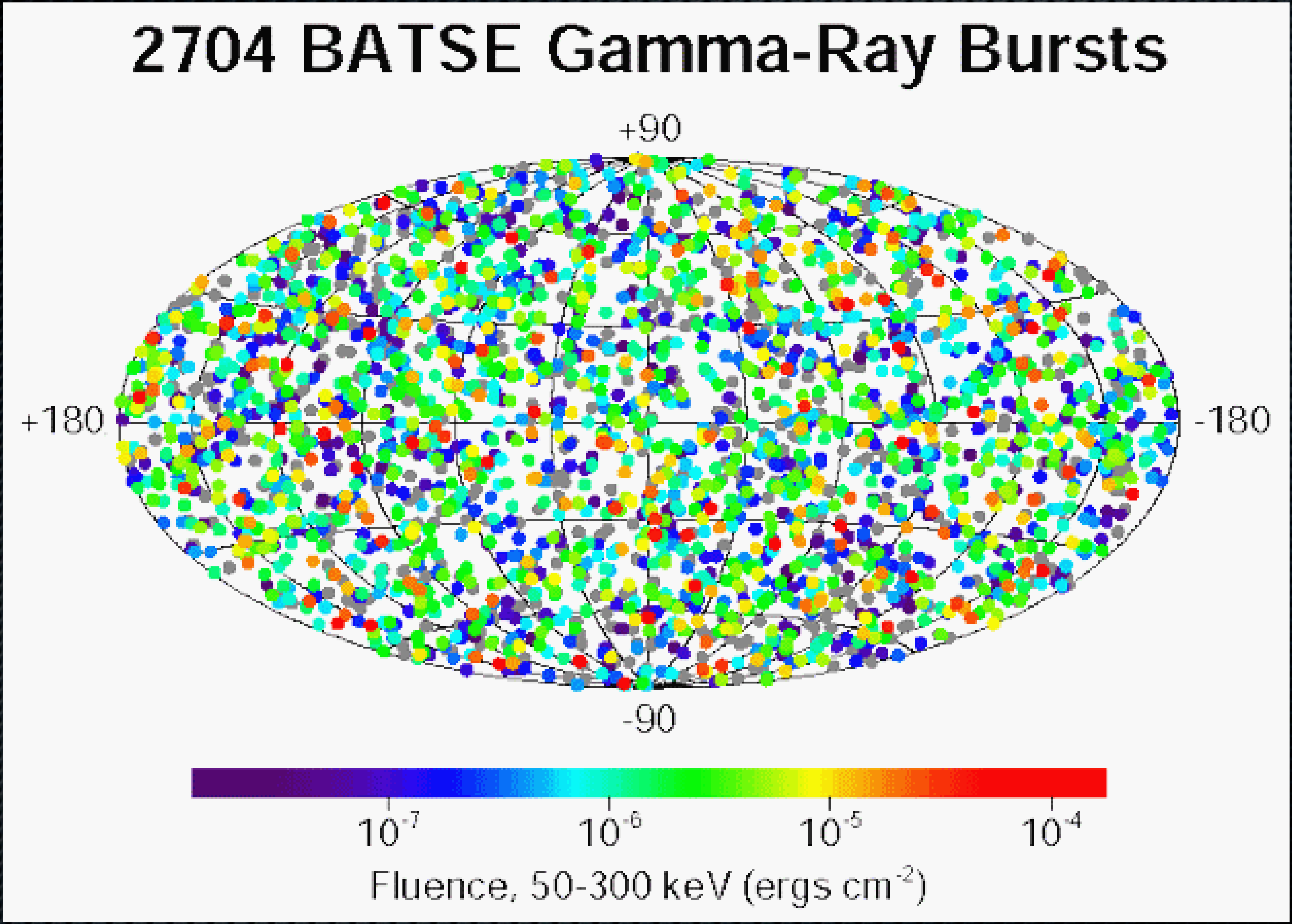
THE DISCOVERY

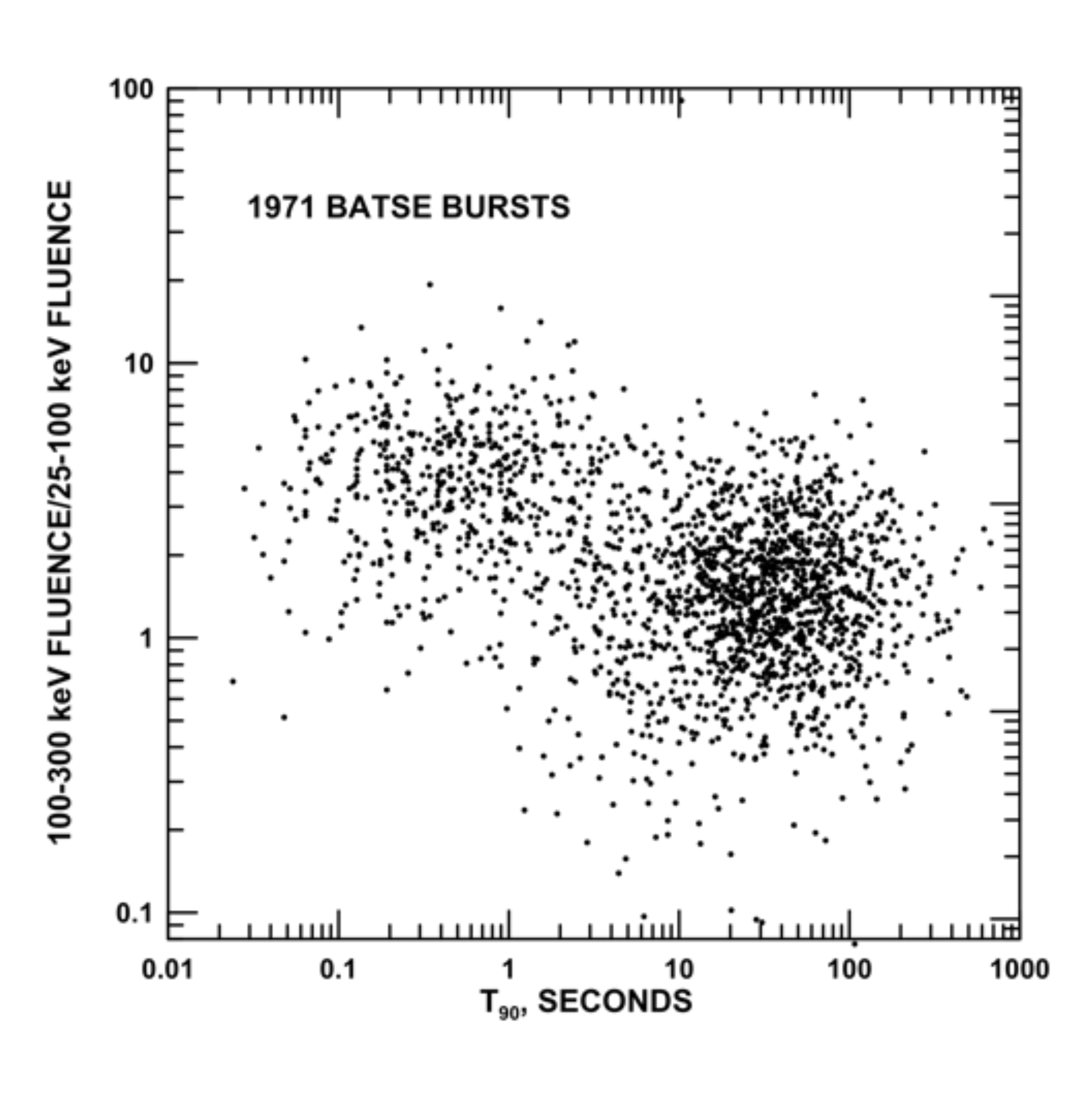
Gamma-Ray Bursts (GRBs) are Short (few seconds) bursts of 100keV-few MeV.

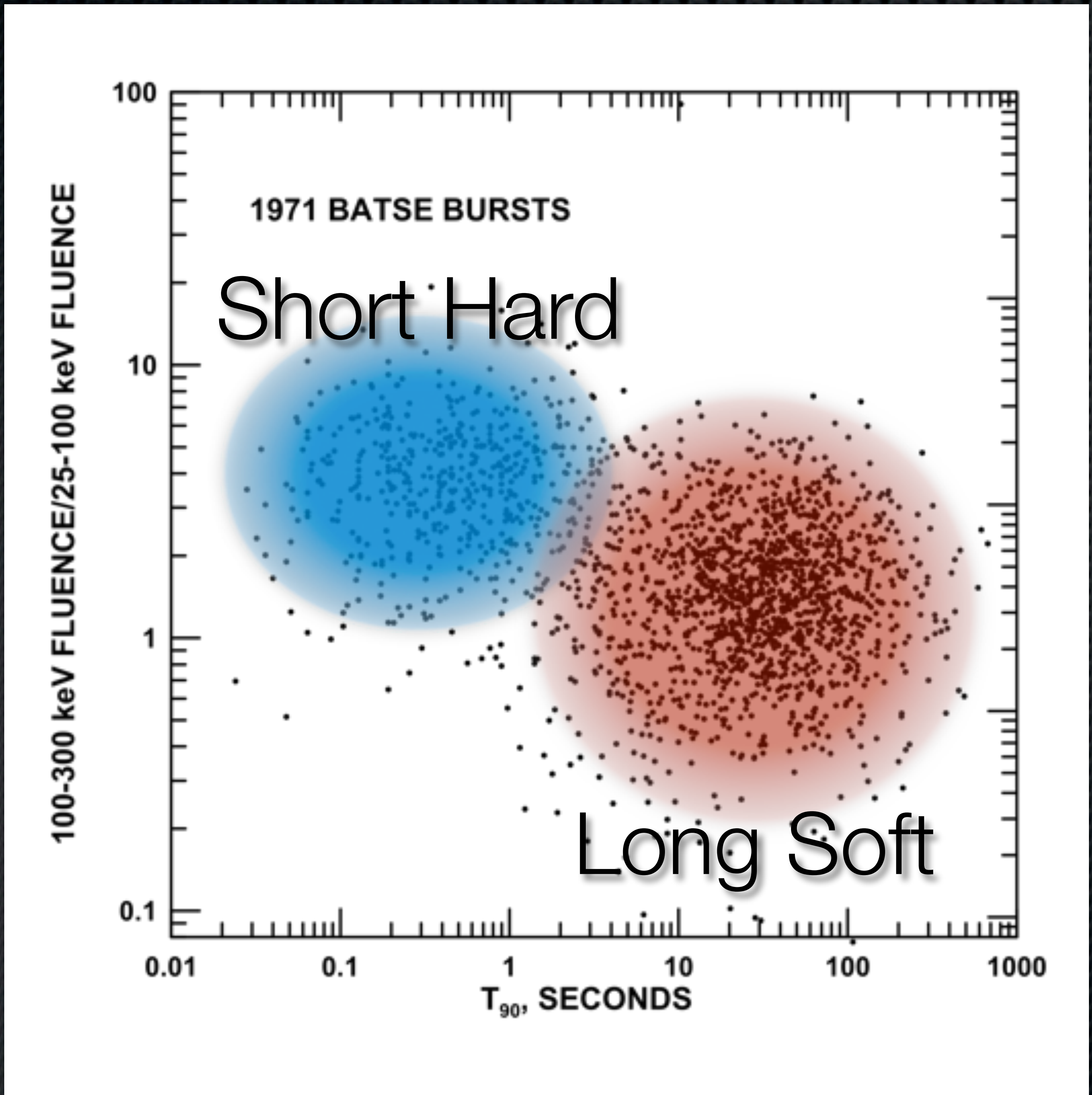
They were discovered accidentally by Klebesadal Strong and Olson in 1967 using the Vela satellites

(defense satellites sent to monitor Atomic Bomb tests).

- The discovery was reported for the first time only in 1973.

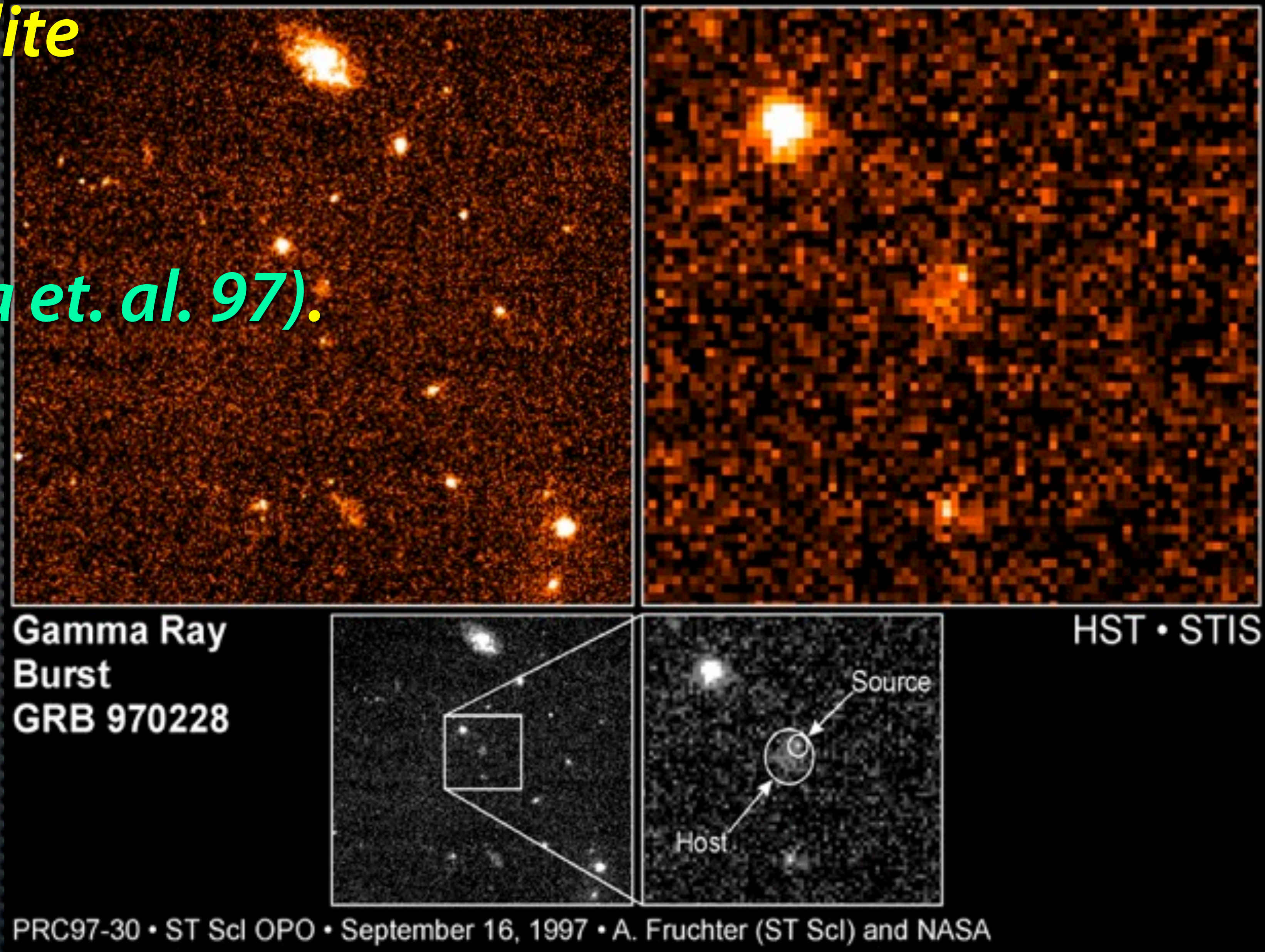

2704 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10-7
10-6
10-5
10-4
Fluence, 50-300 keV (ergs cm-2)


1971 BATSE BURSTS
100-300 keV FLUENCE/25-100 keV FLUENCE
T_{90}, SECONDS
100
10
1
0.1
0.01
0.1
1
10
100
1000


1971 BATSE BURSTS
Short Hard
Long Soft
100-300 keV FLUENCE/25-100 keV FLUENCE
T90, SECONDS
100
10
1
0.1
0.01
0.1
1
10
100
1000

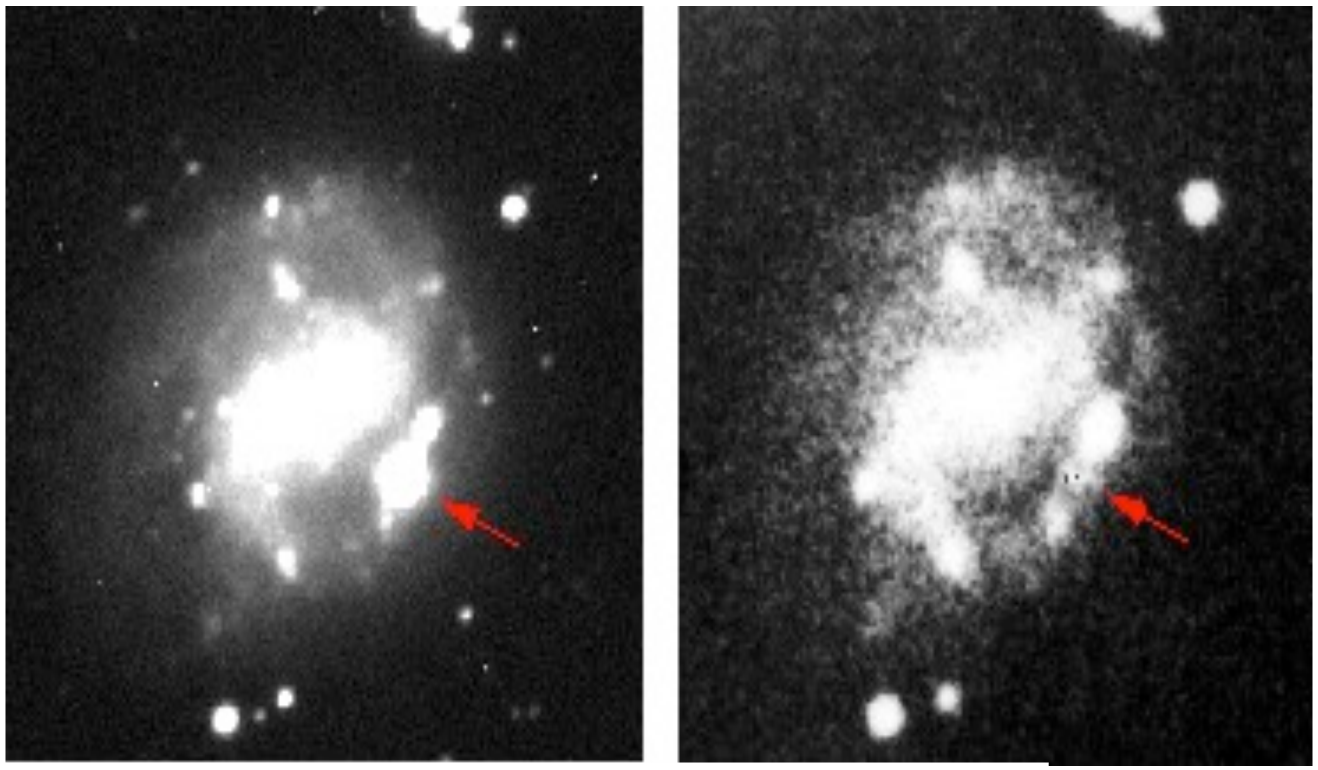
Cosmological Origin!

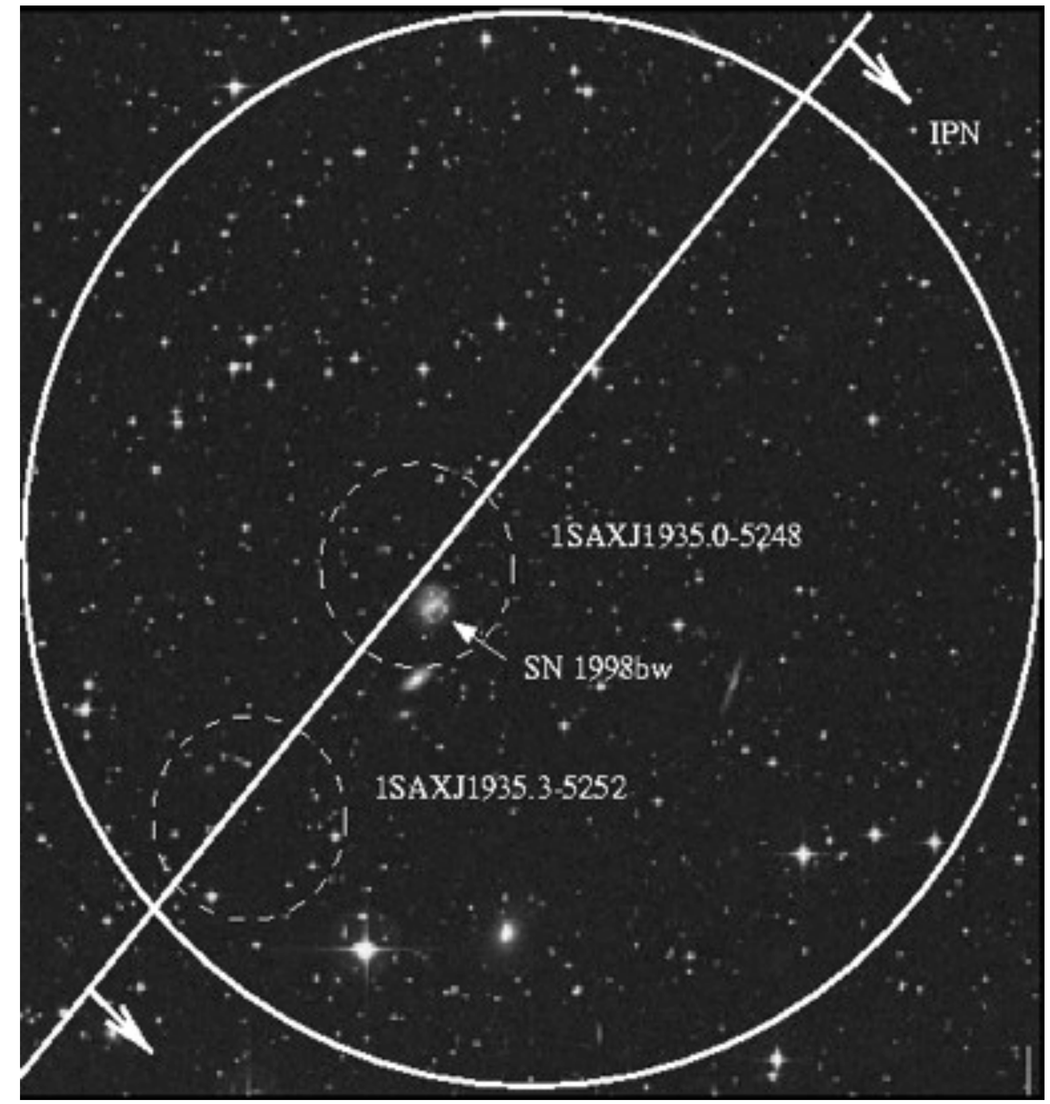
- *The Italian/Dutch satellite BeppoSAX discovered x-ray afterglow on 28 February 1997 (Costa et. al. 97).*
- *Immediate discovery of Optical afterglow (van Paradijs et. al 97).*

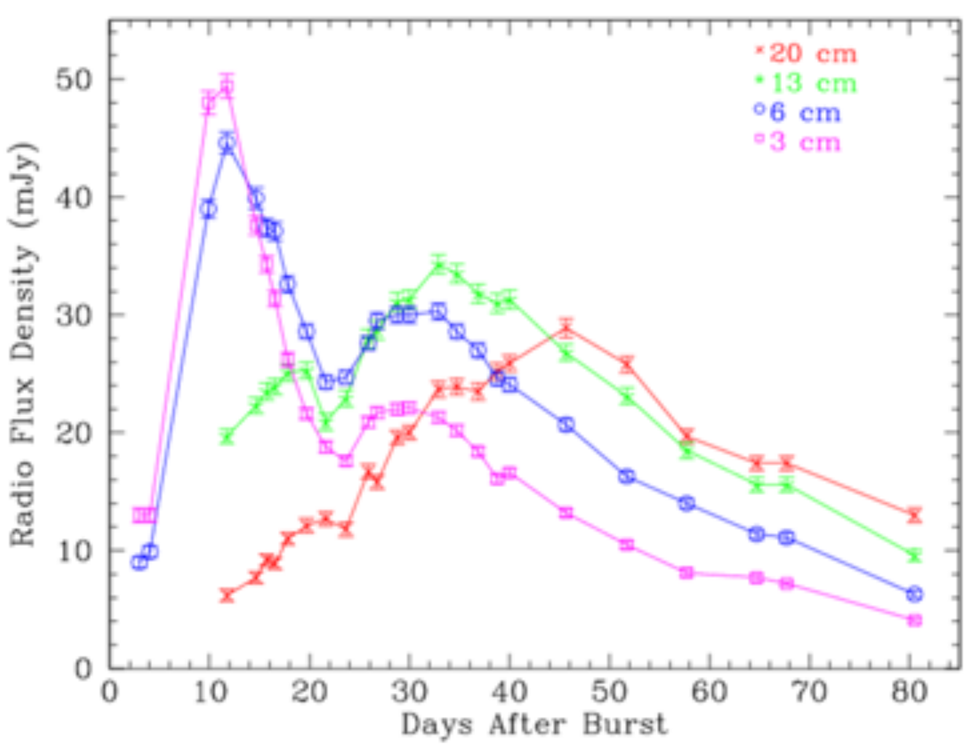


SN 1998bw was discovered in Gamma Rays

Beppo-Sax

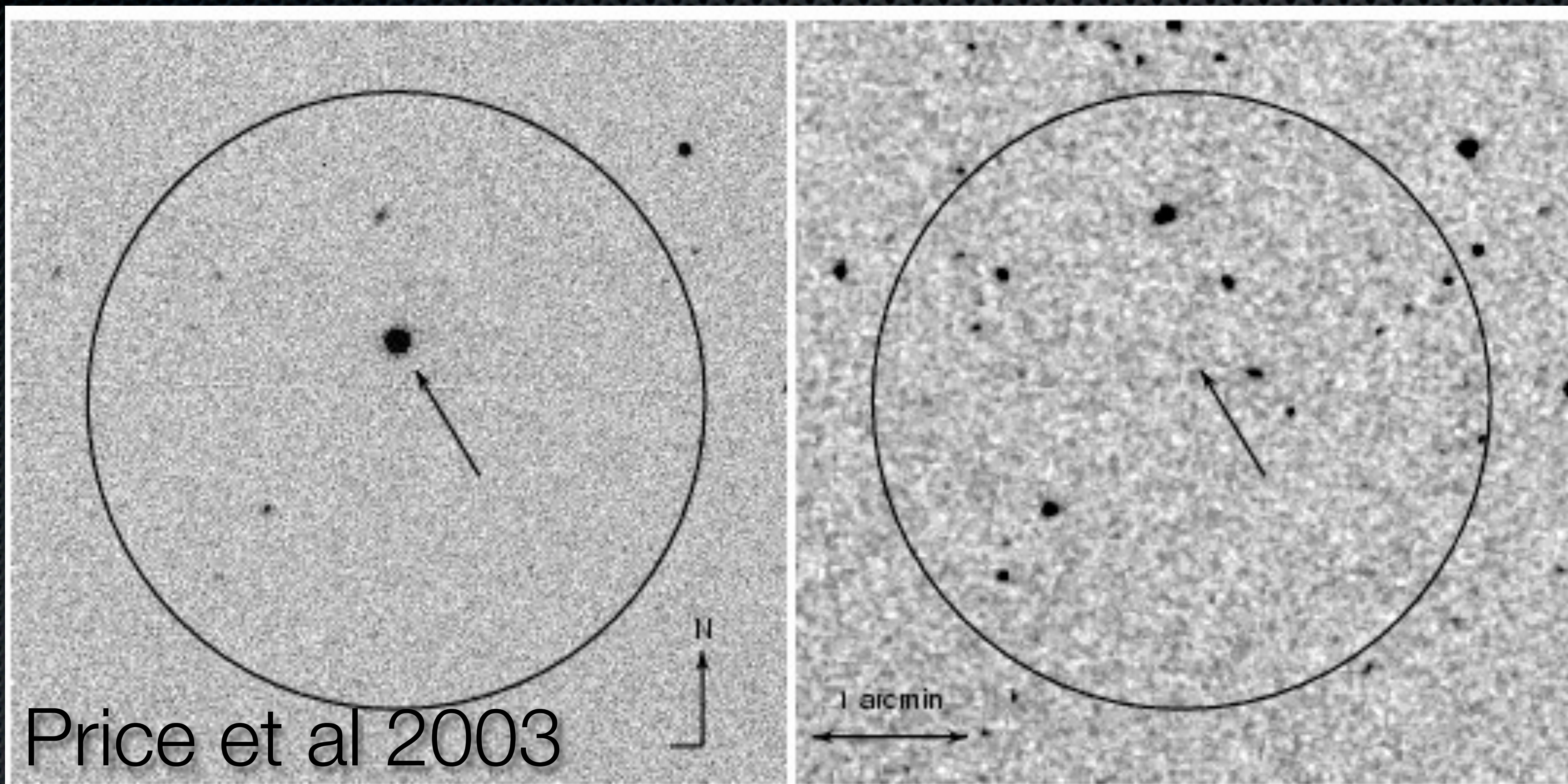






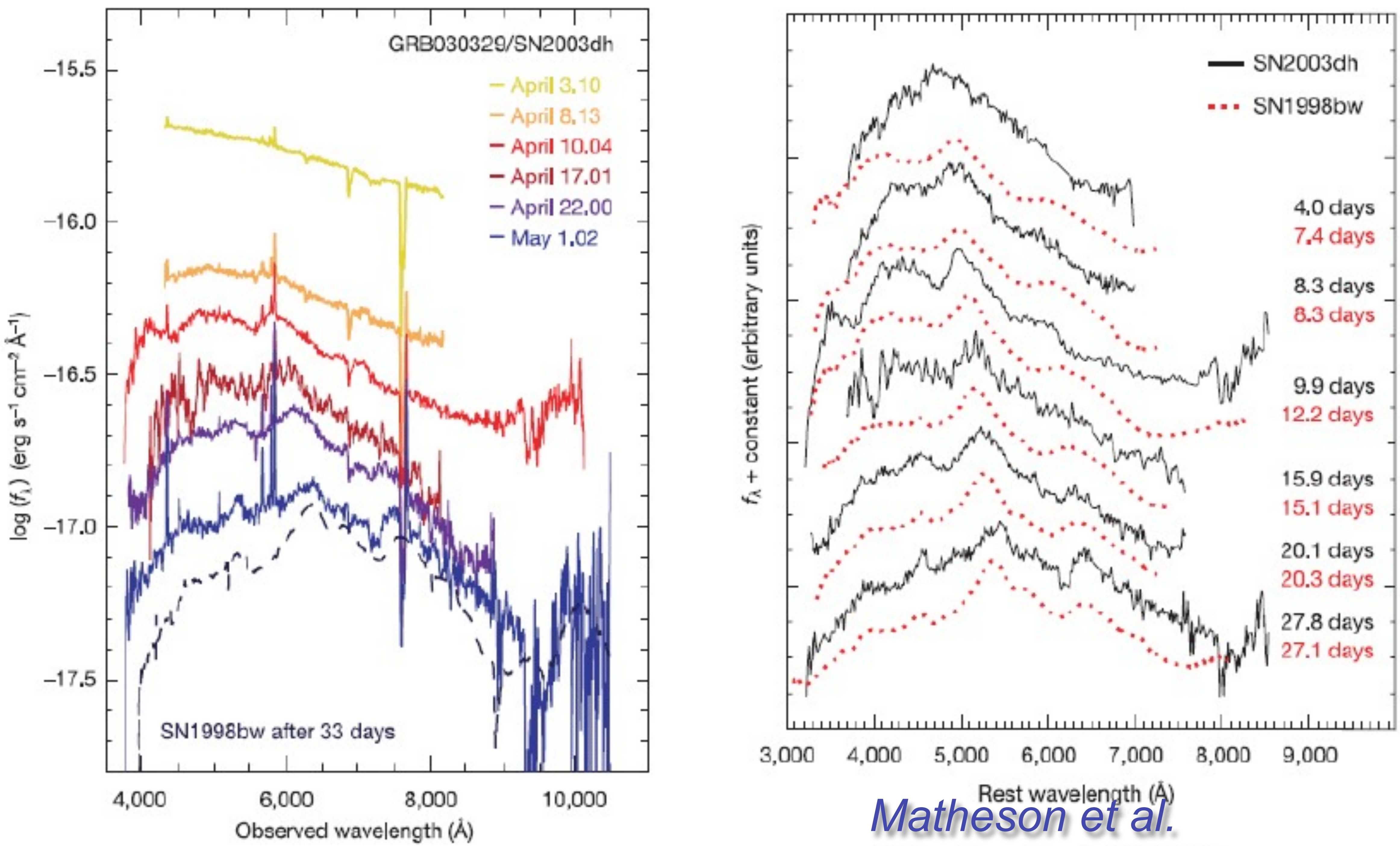
Brightest Radio SN ever –
Measurement indicate relativistic Ejecta… funny very high velocity
Spectrum … within a day of GRB

SN 2003dh was also discovered in Gamma Rays and it was more typical GRB



Price et al 2003

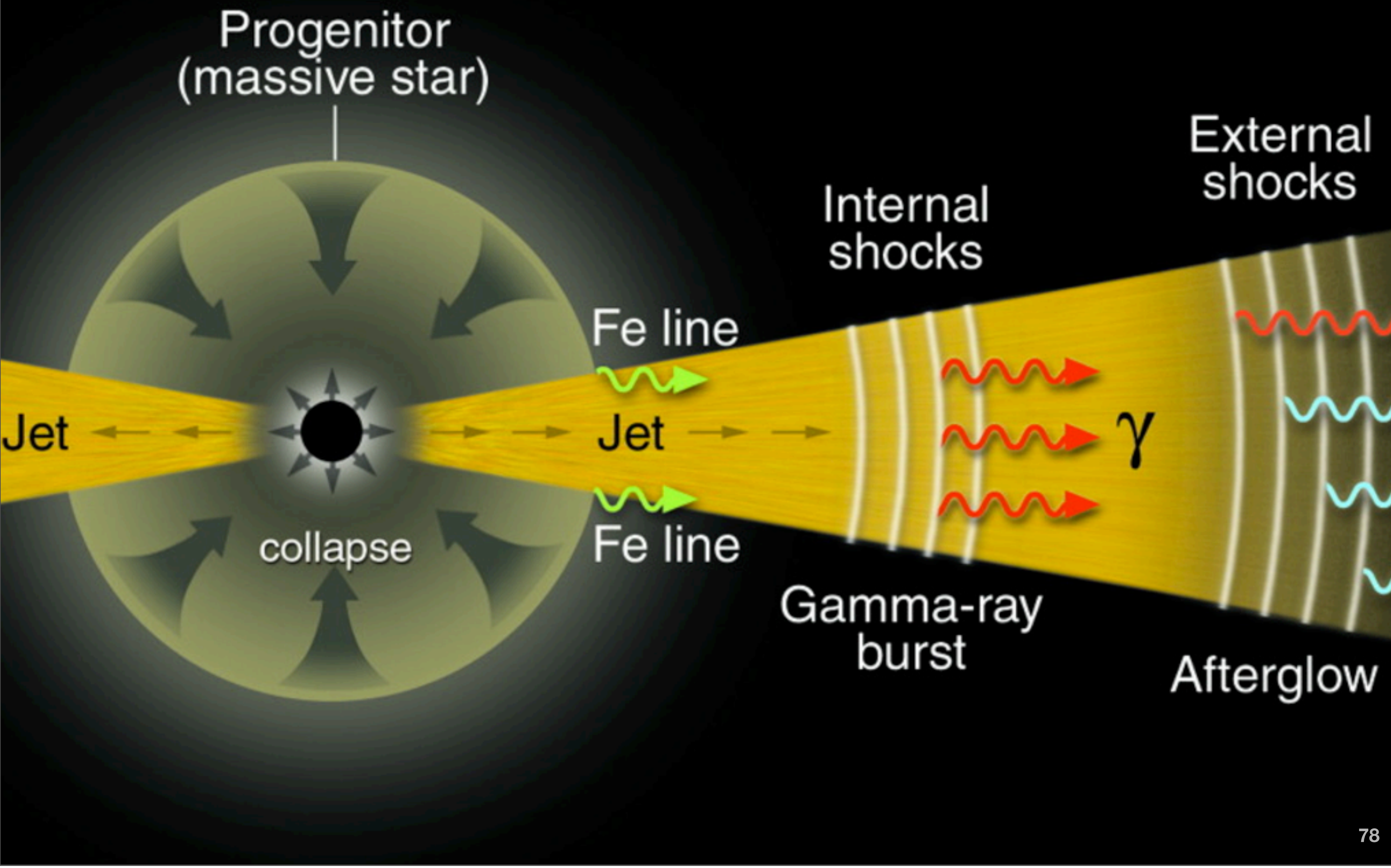
SN 2003dh was also discovered in Gamma Rays and it was more typical GRB



Matheson et al.

Hjorth et al (2003)

Toy Model for GRB



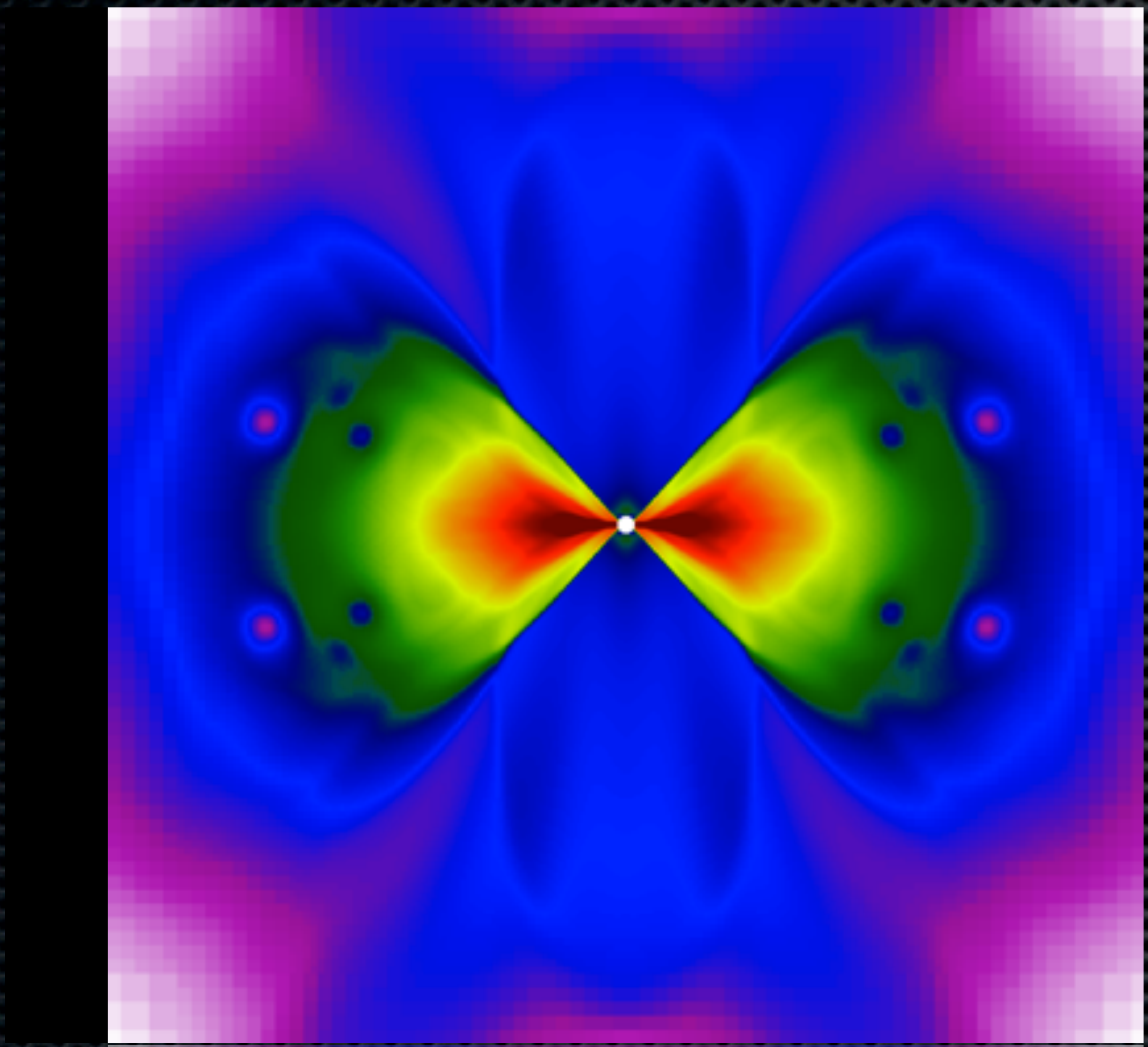
Do all Long GRBs have a SN?

- Only a few normal GRBs seen close enough
- Faint GRBs have all had a SN
- At present, GRB-SNe seem to be energetic Ib/c SN... that have a wide dispersion in energy and mass
- There are a few cases where no SN has been seen.

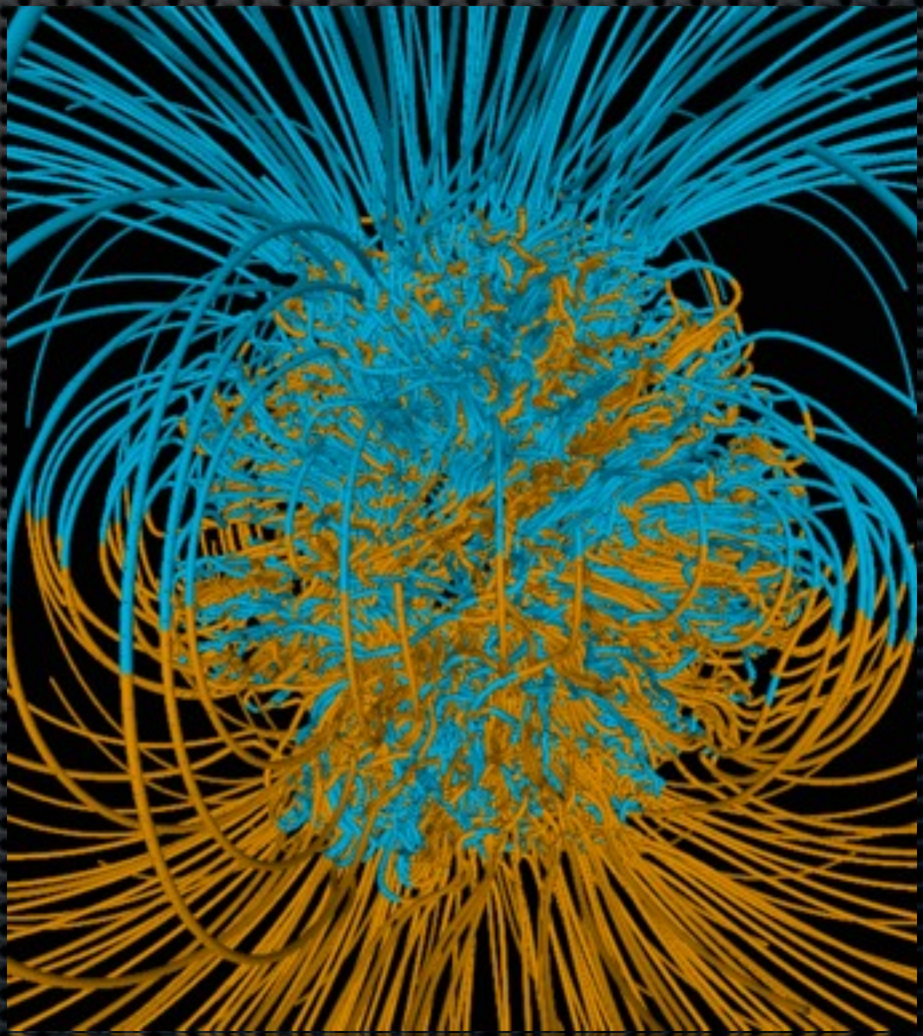
GRBs formed by some very massive stars. Possibly some form blackholes directly, with no explosion. (This is a prediction of collapsar model)

Today, there are two principal models being discussedcfor GRBs of the "long-soft" variety:

The collapsar model



The millisecond magnetar

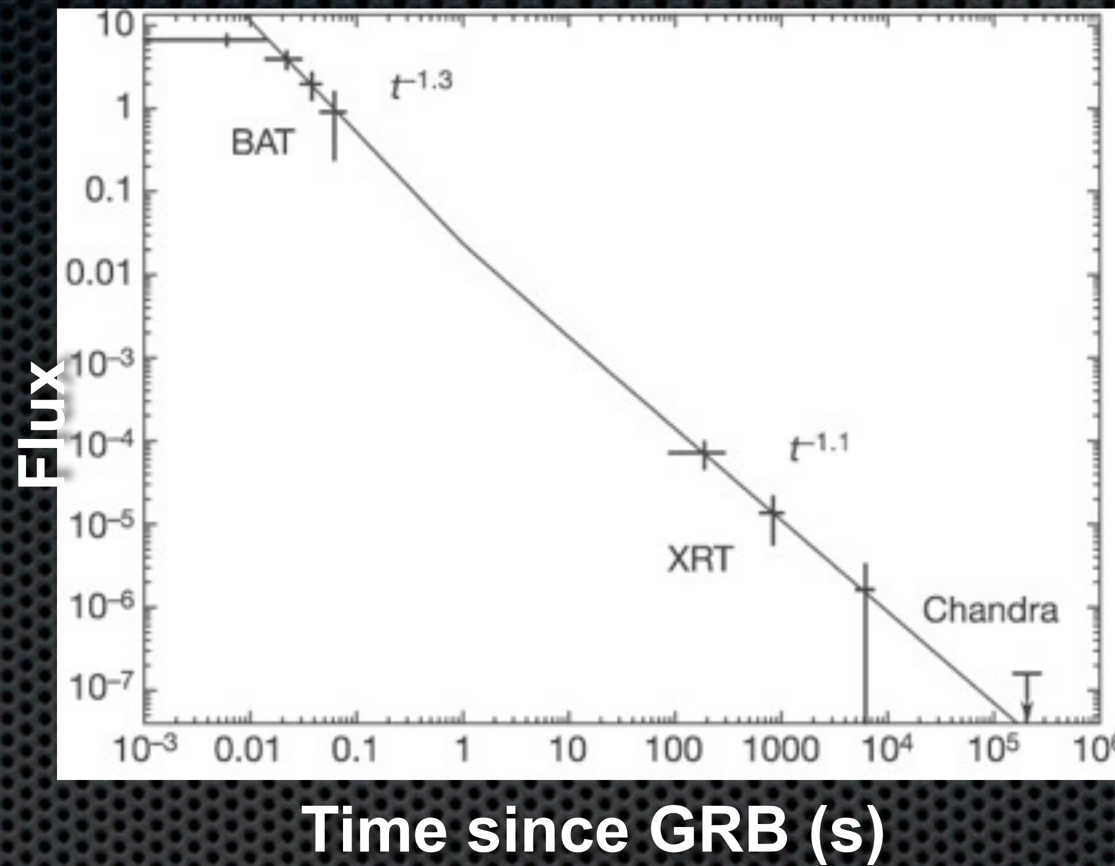


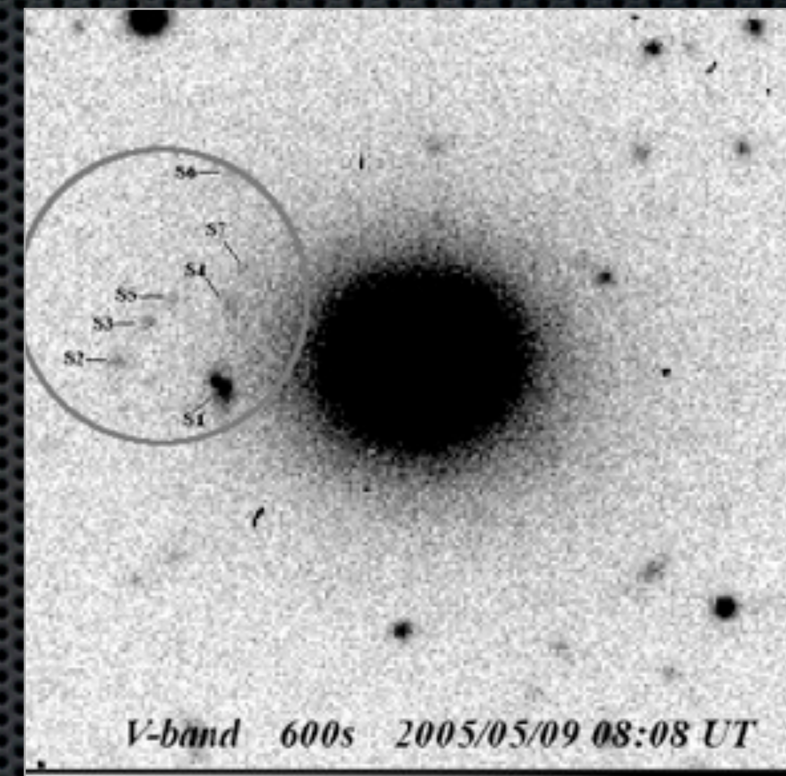
The ultimate source of energy in both is rotation and both produce relativistic jets

Short Hard Bursts

GRB 050509B first short GRB X-ray afterglow very faint!

Gehrels et al. 2005





GRB 050724 - the bright one: optical + X-ray

- z = 0.258

Short Hard Bursts

In 2005 - 2006, several short hard bursts were localized by SWIFT and HETE-2 and coordinated searches for counterparts were carried out. The bursts were GRB 050509b ($z = 0.2248$, elliptical galaxy), 050709 ($z = 0.161$) and 050724 ($z = 0.258$)

- The bursts were either on the outskirts of galaxies or in old galaxies with low star formation rate
- There was no accompanying supernova
- The redshifts were much lower than for the long soft bursts and thus the total energy was about two orders of magnitude less (because they are shorter as well as closer).
- All this is consistent with the merging neutron star (or merging black hole neutron star) paradigm.

But Life is not so simple

- Since then, many Short GRBs have been found at high redshift, with the same energy as Long GRBs (Maybe two things make Short GRBs)
- And emission several hours was seen in Gamma Rays, which violates predictions of Neutron Star merger (which take a few seconds)...This now maybe explained from debris taking a long time to fall onto the merged Blackhole..

And a lot more to come

- The transient Universe is being explored at a rate 100 times fast than a few years ago with Palomar Transit Factory, Pan Starrs, SkyMapper, and eventually LSST surveying the sky

- Lots of stuff will be found, but I think the big questions around SN II, SN Ia remain the most interesting - because they are the things that influence the evolution of universe