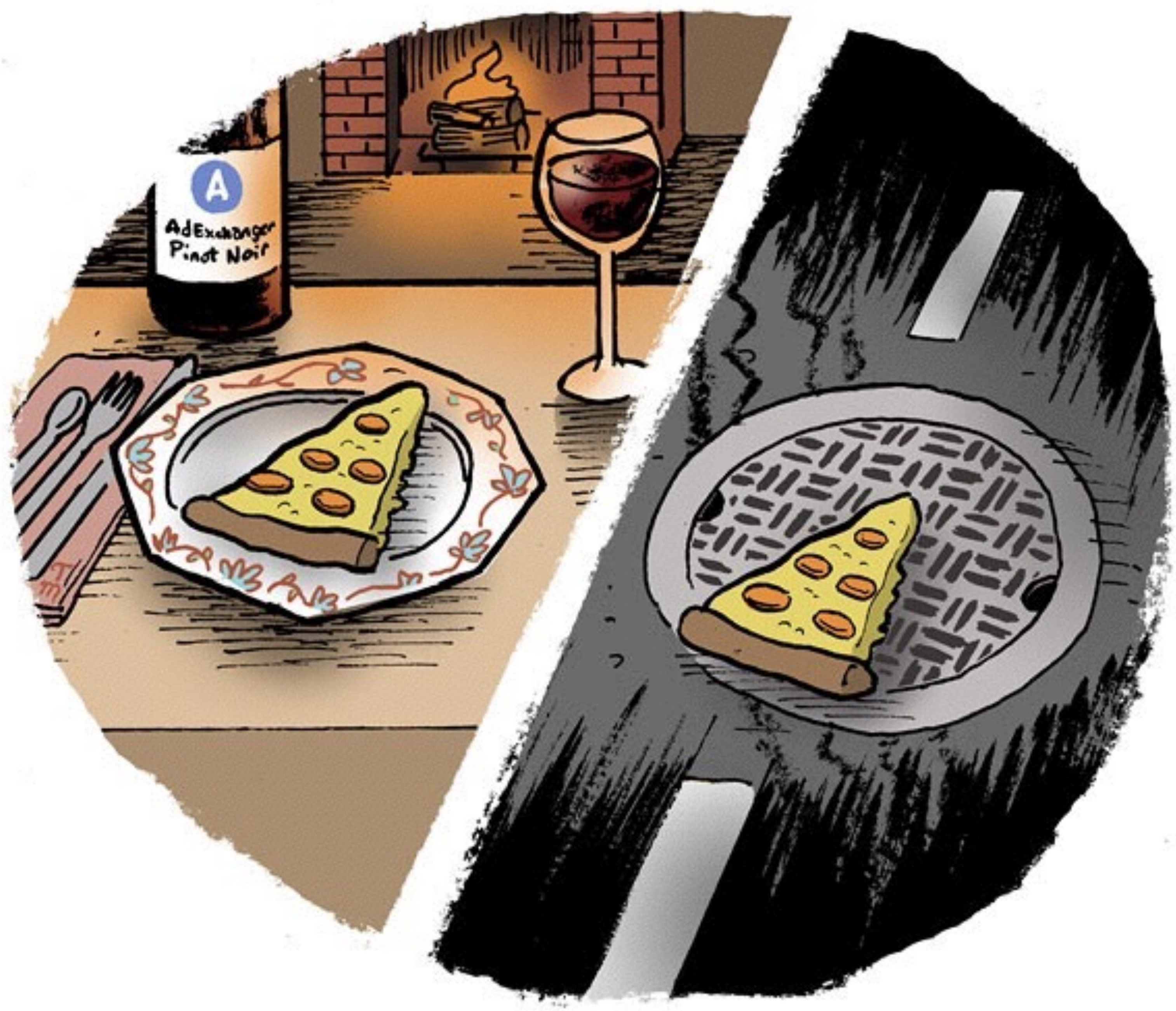
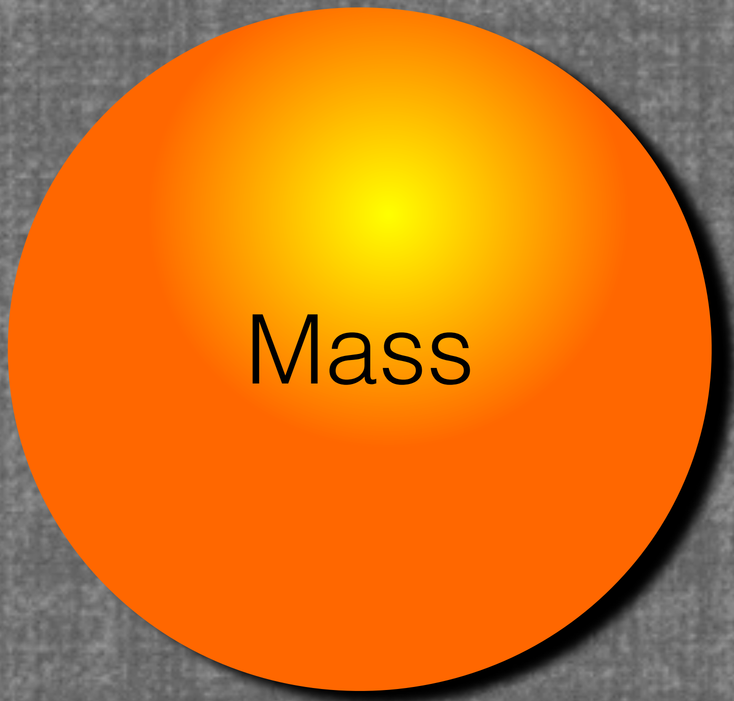
Multi-Wavelength observations of Stellar Explosions

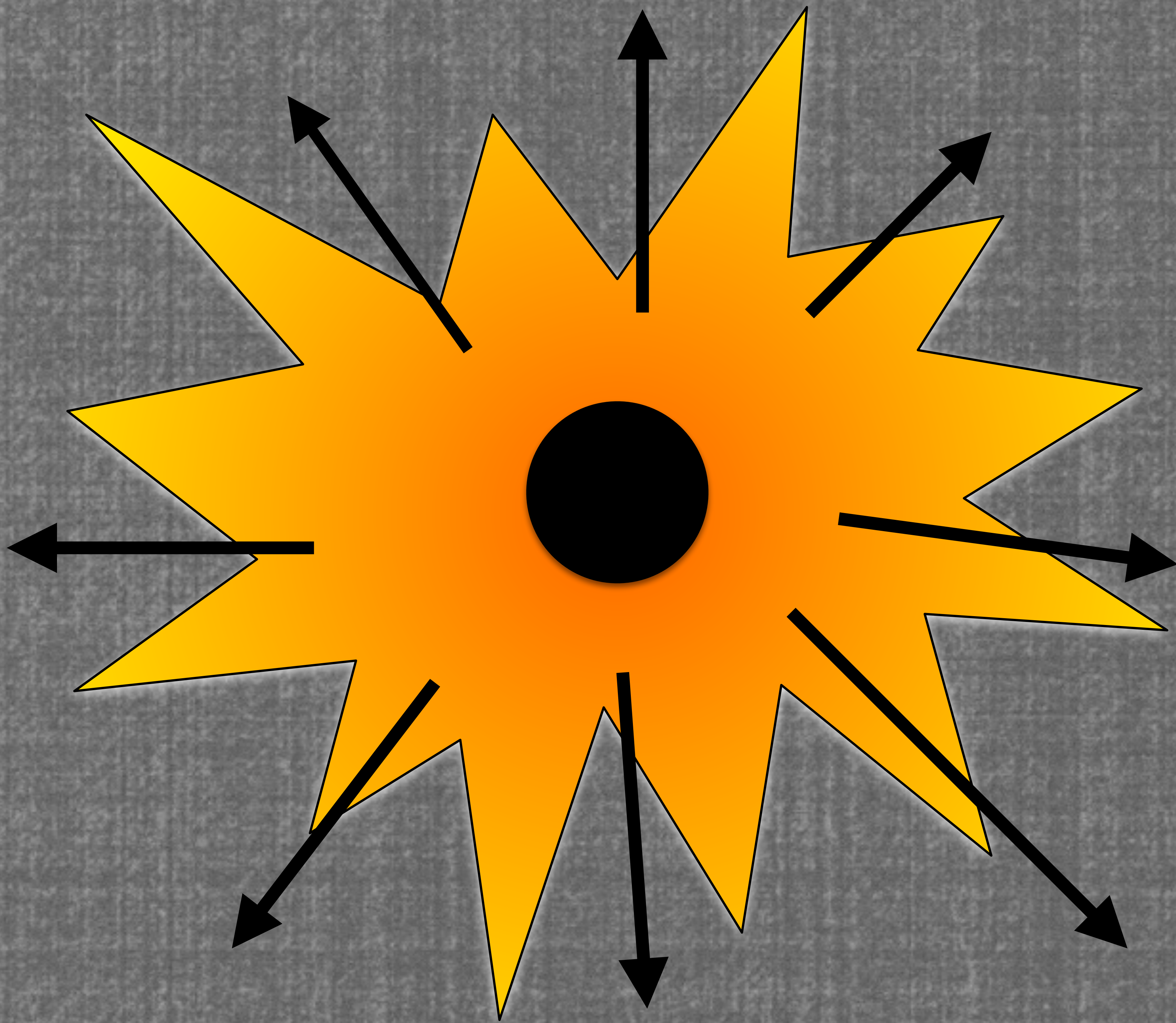
Raffaella Margutti
(JA Fellow, NYU)

"We always find something, eh Didi, to give us the impression we exist?"



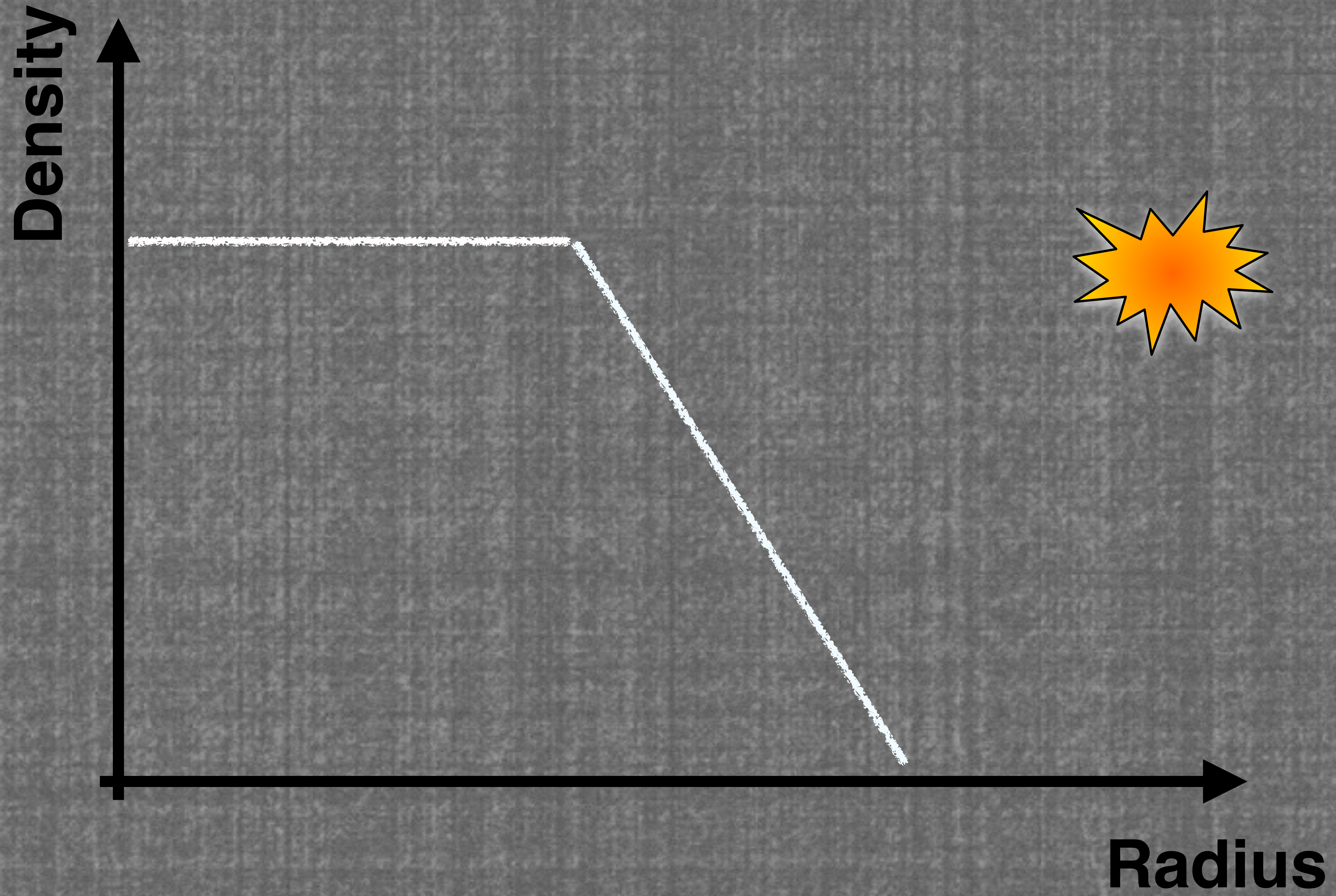
Context Matters


Mass



Compact object + Ejecta

SN Ejecta profile



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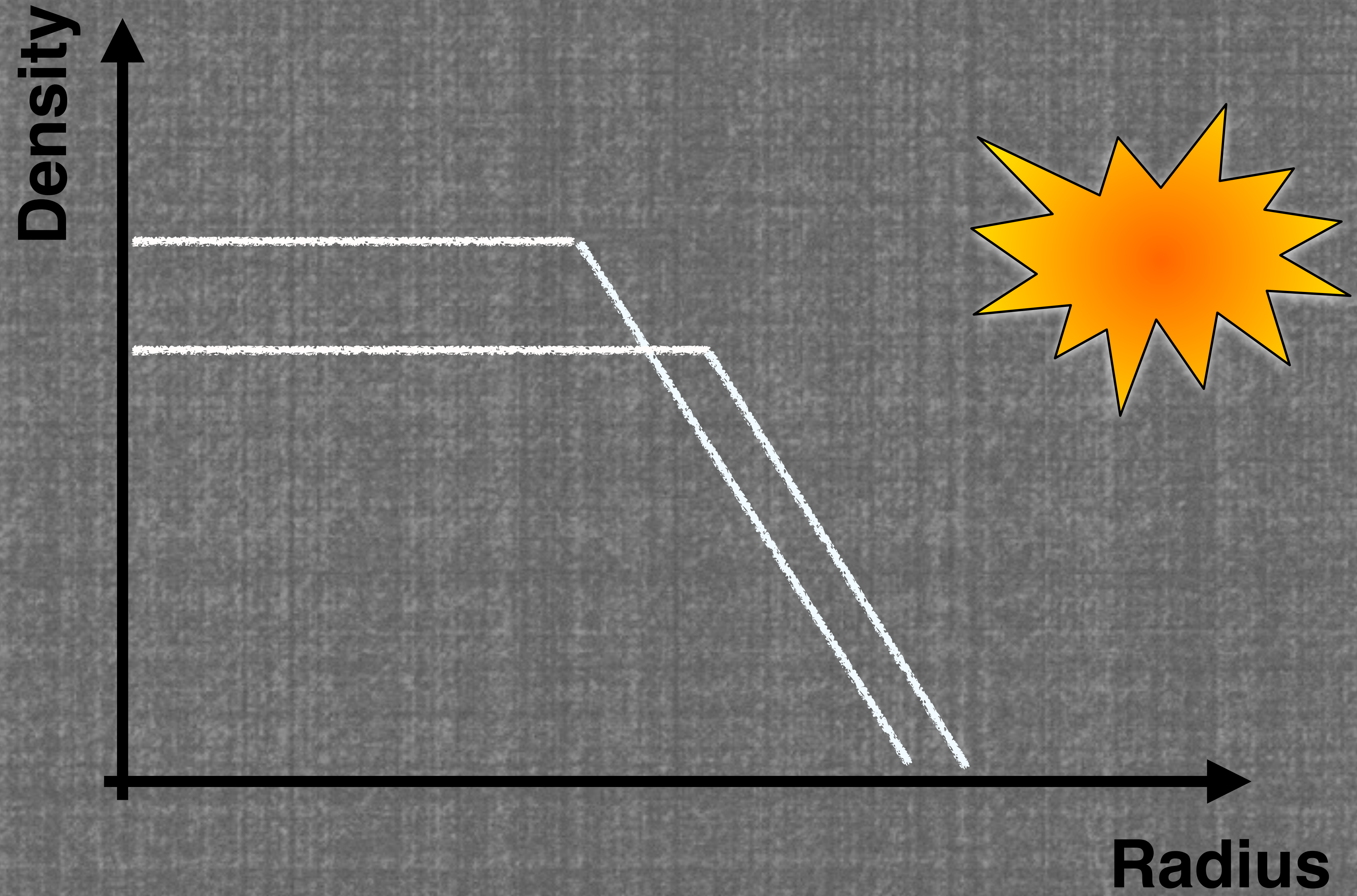

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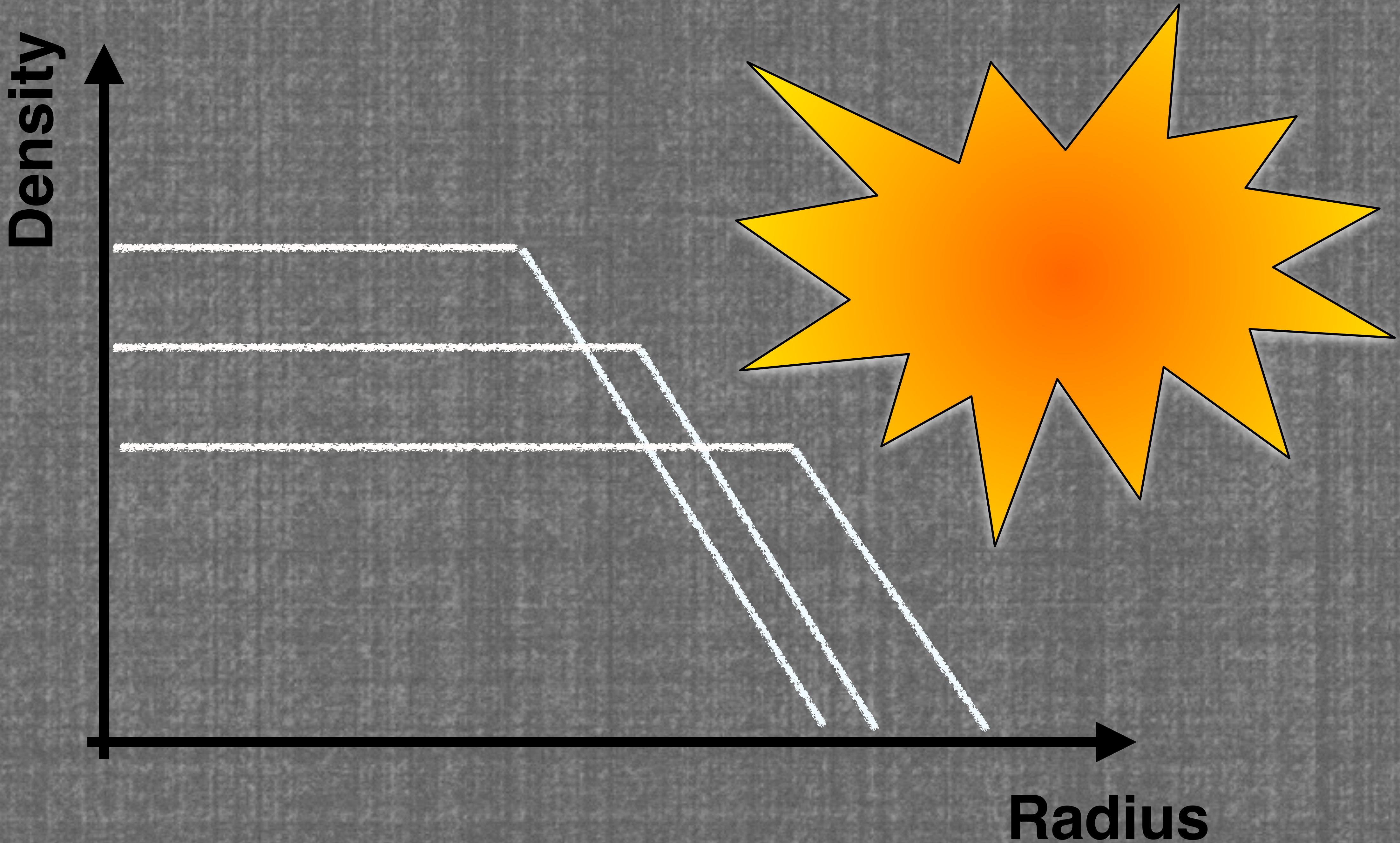
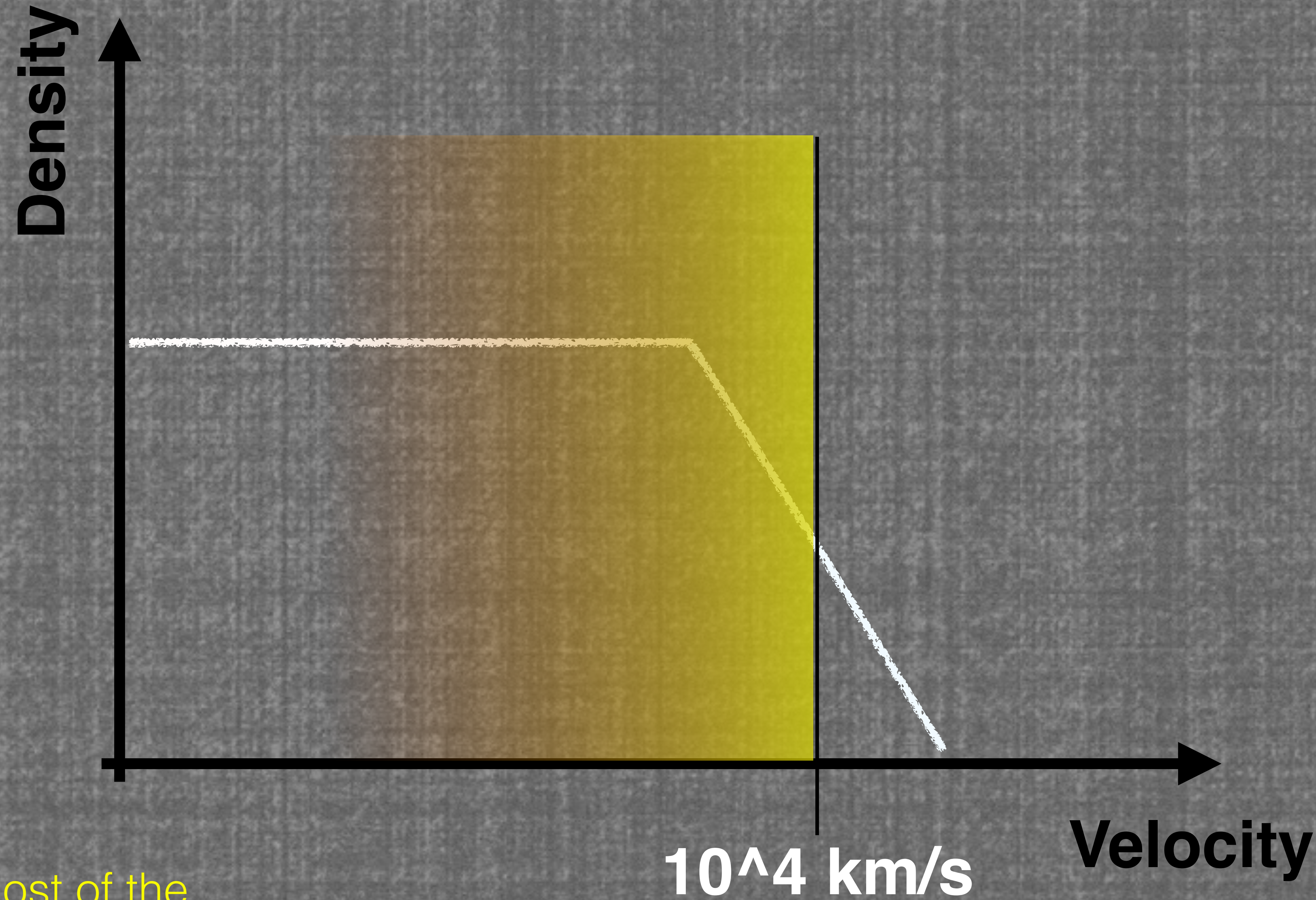


homologous expansion

R=vxt

SN Ejecta profile

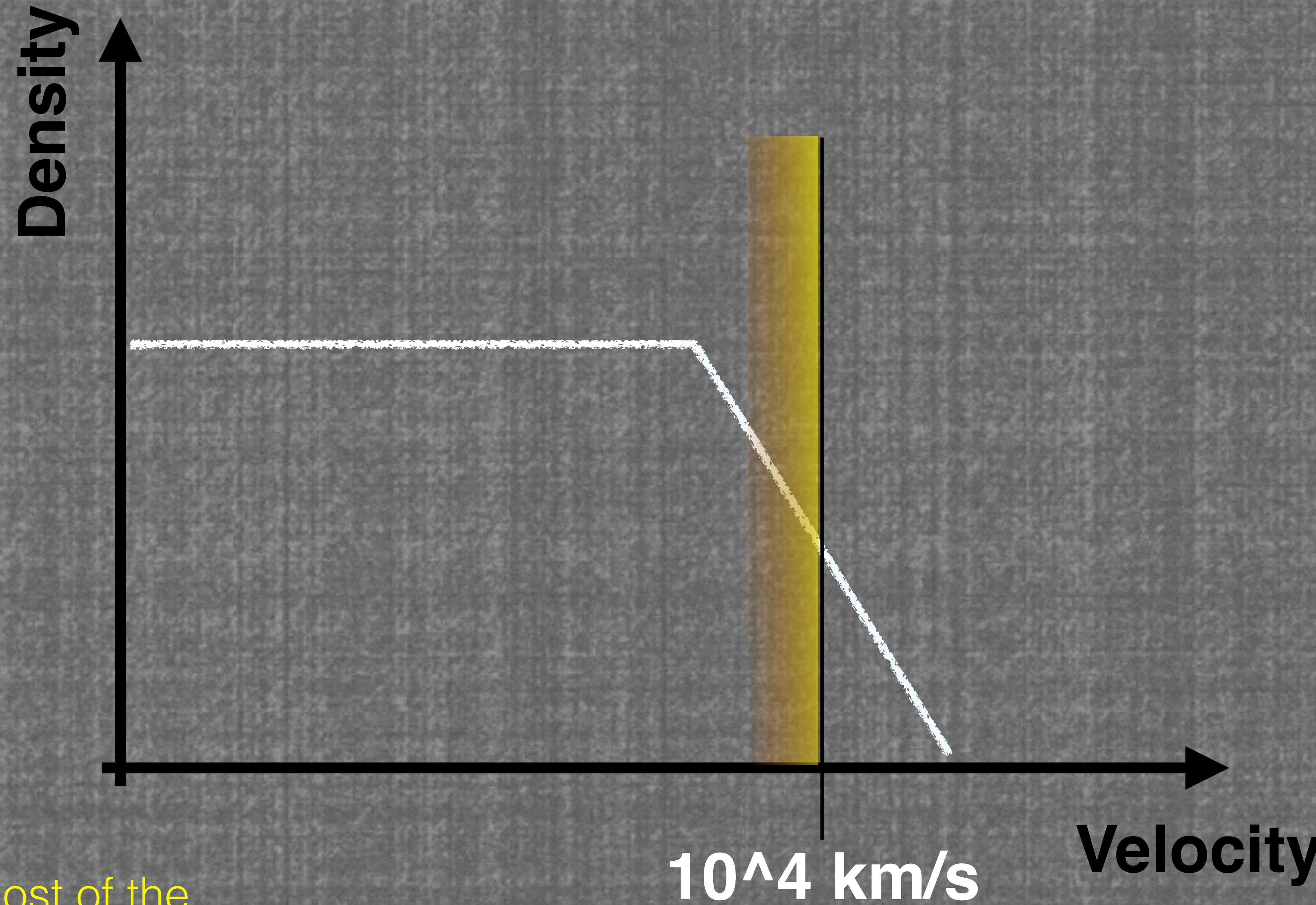


"Carries" most of the Energy

Tracks the bulk of ejecta material

Thermal Emission (UV-Optical-IR)

SN Ejecta profile



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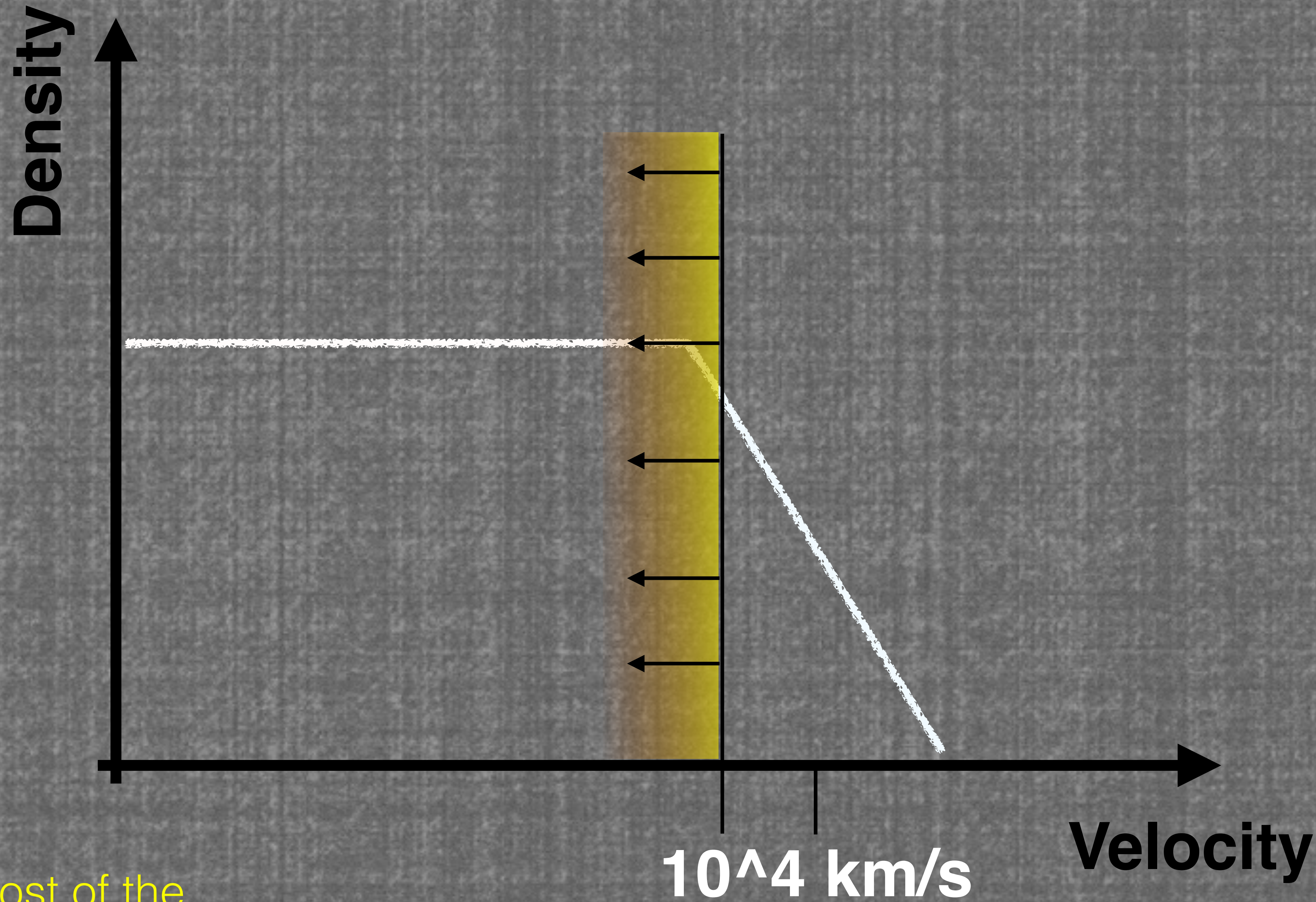

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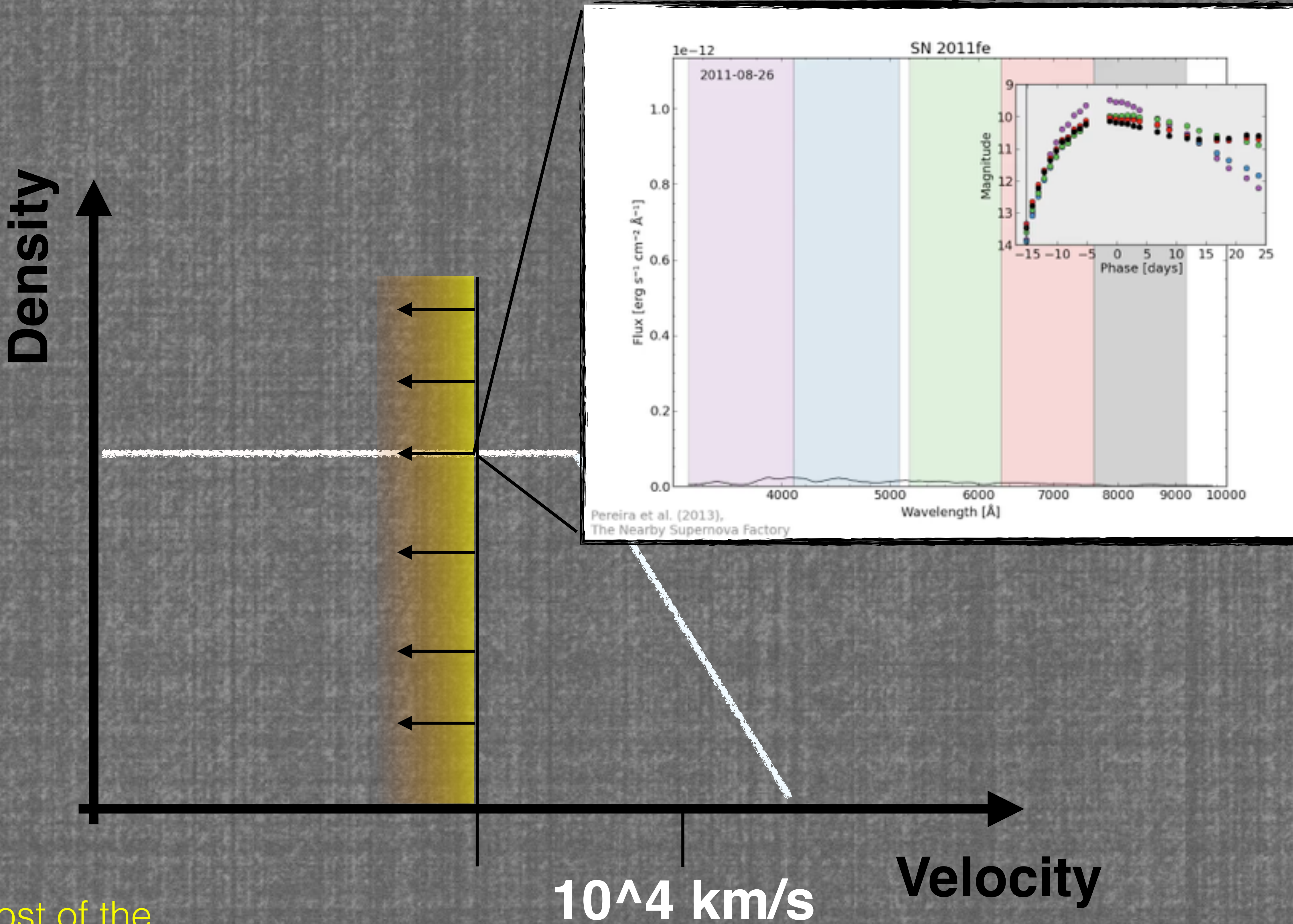

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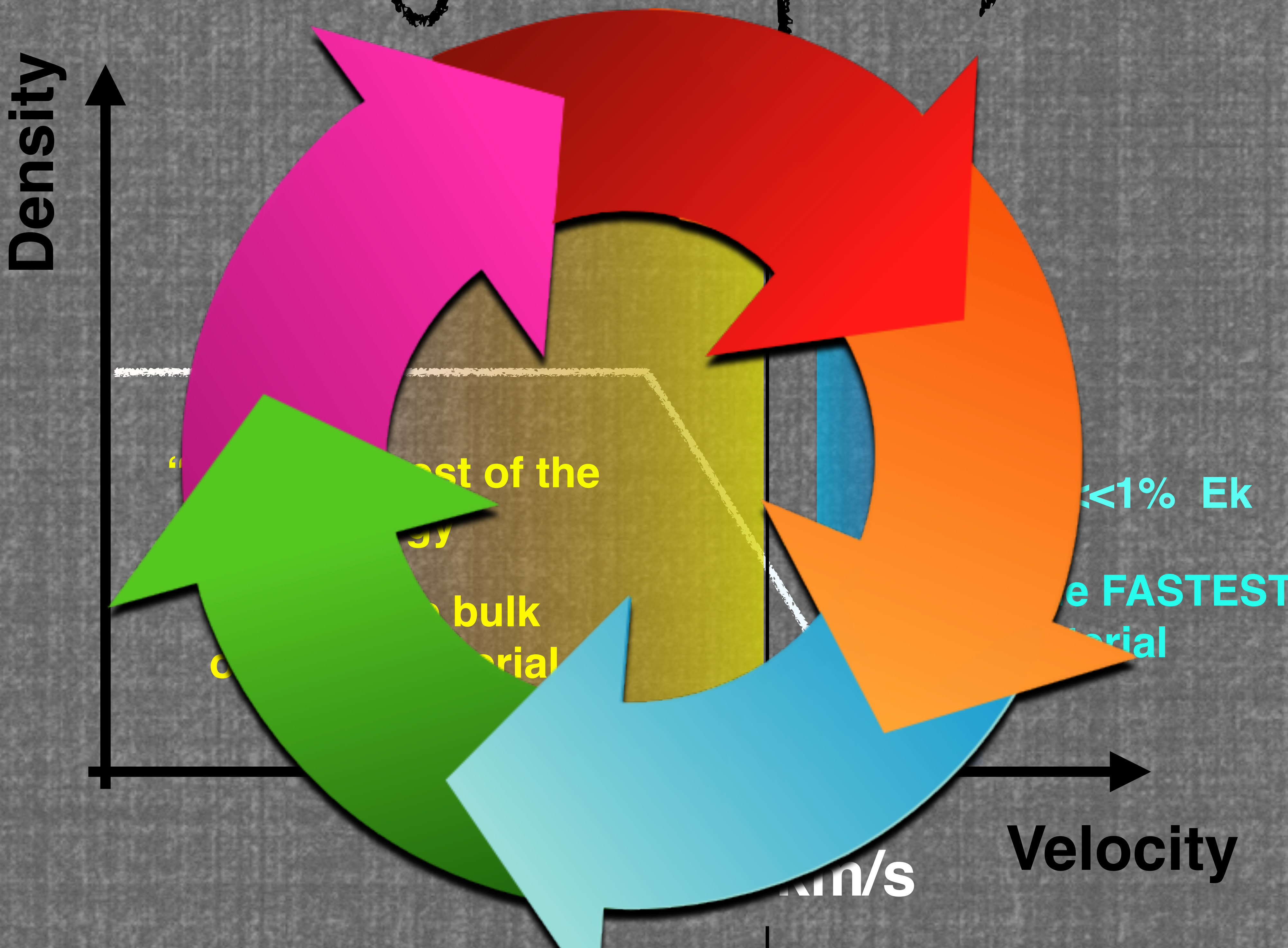
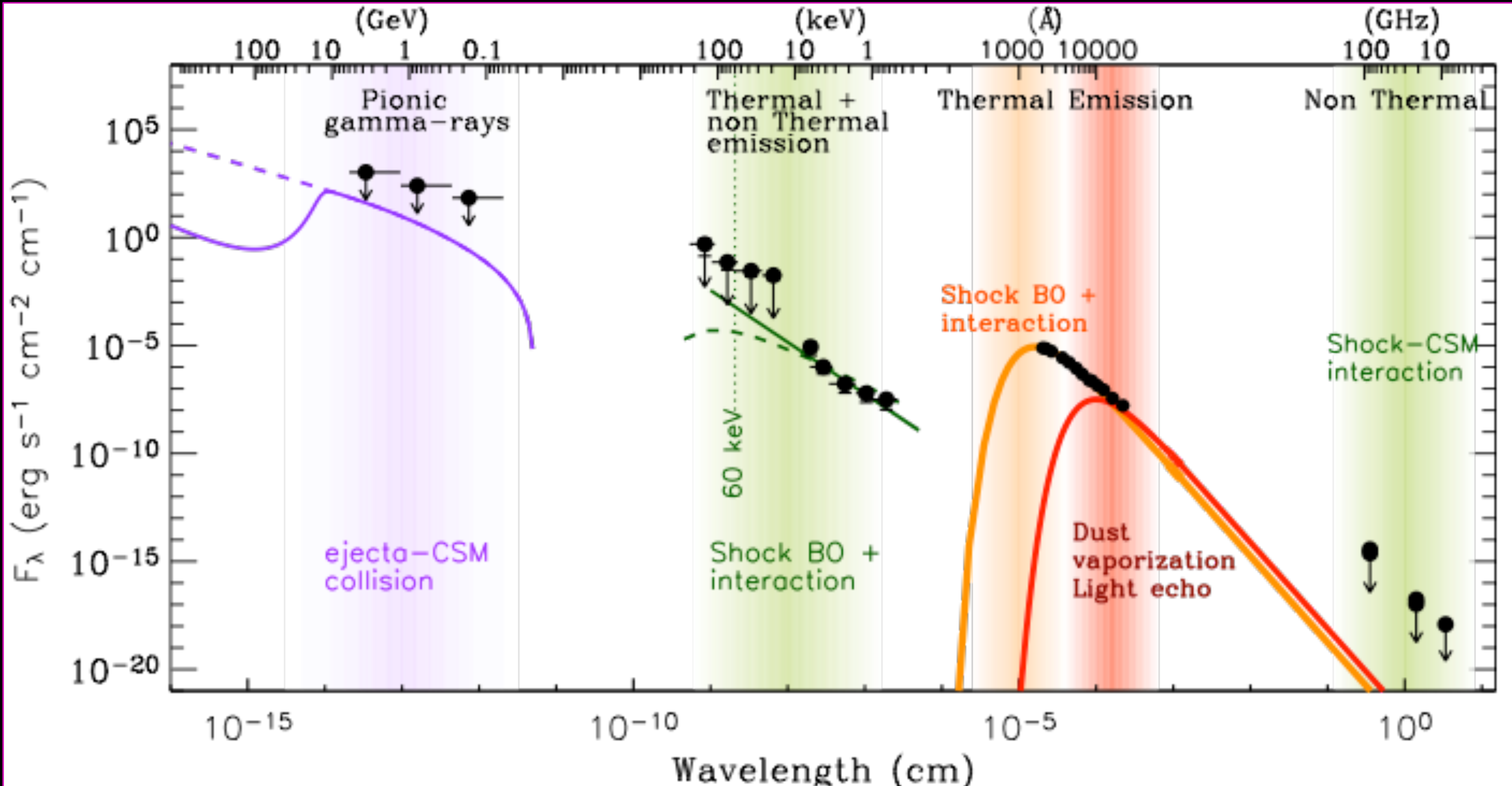


Thermal Emission (UV-Optical-IR)

Radio (non-thermal) X-rays

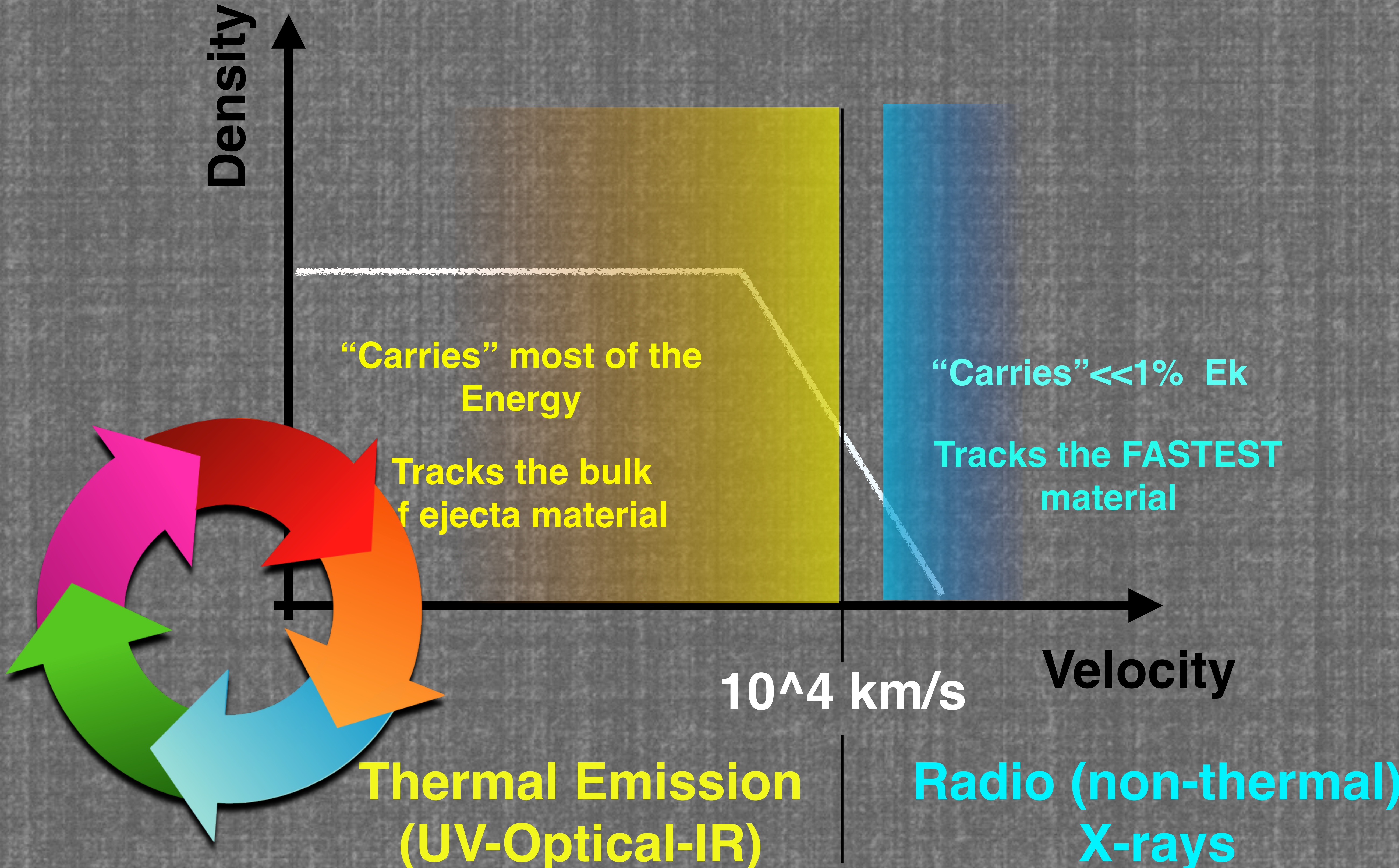
Broad-band SED of SN2009ip around peak:

Margutti+14



gamma-rays X-rays UV-OPTICAL-IR RADIO

SN Ejecta profile

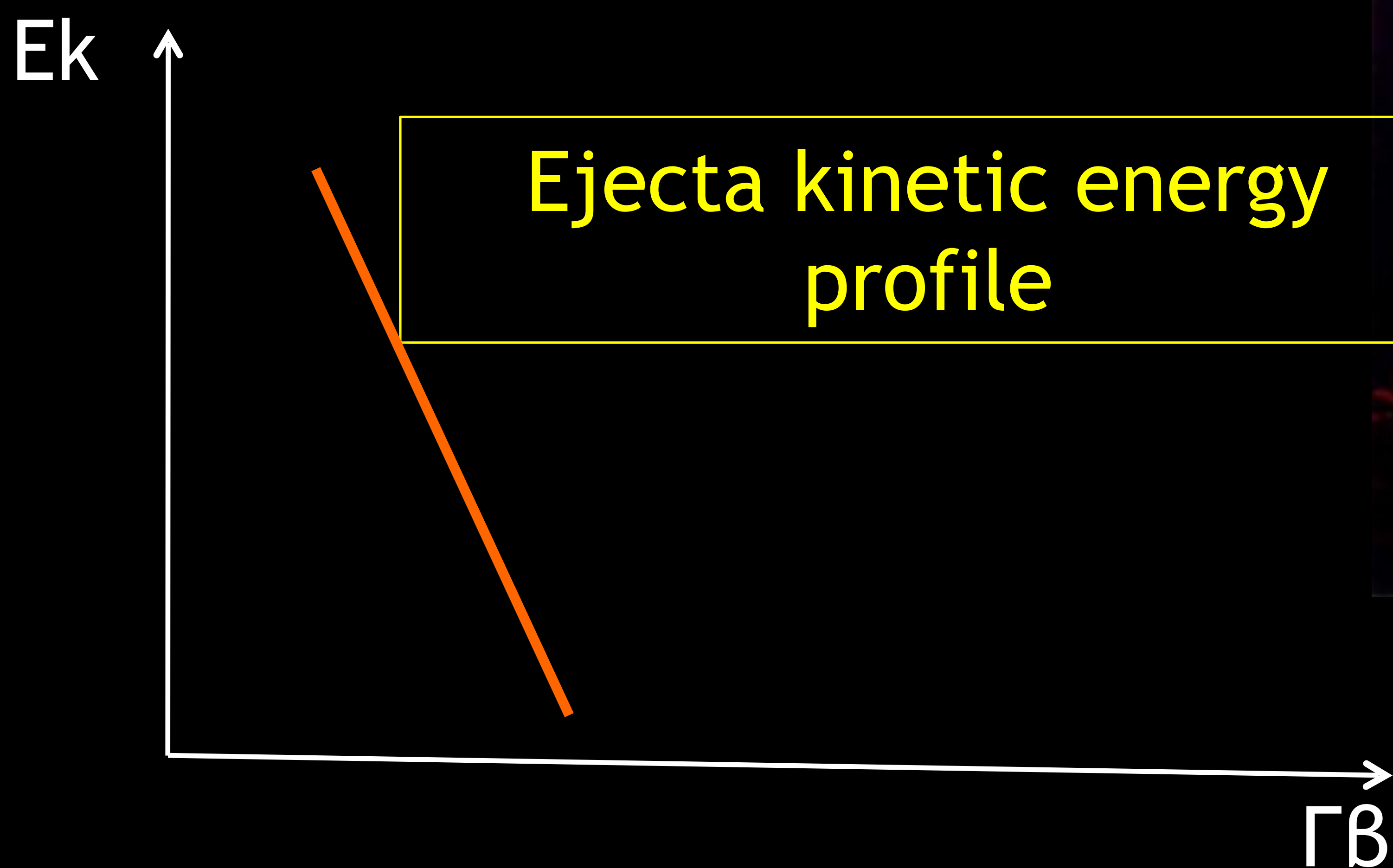


"It sort of makes you stop and think, doesn't it."

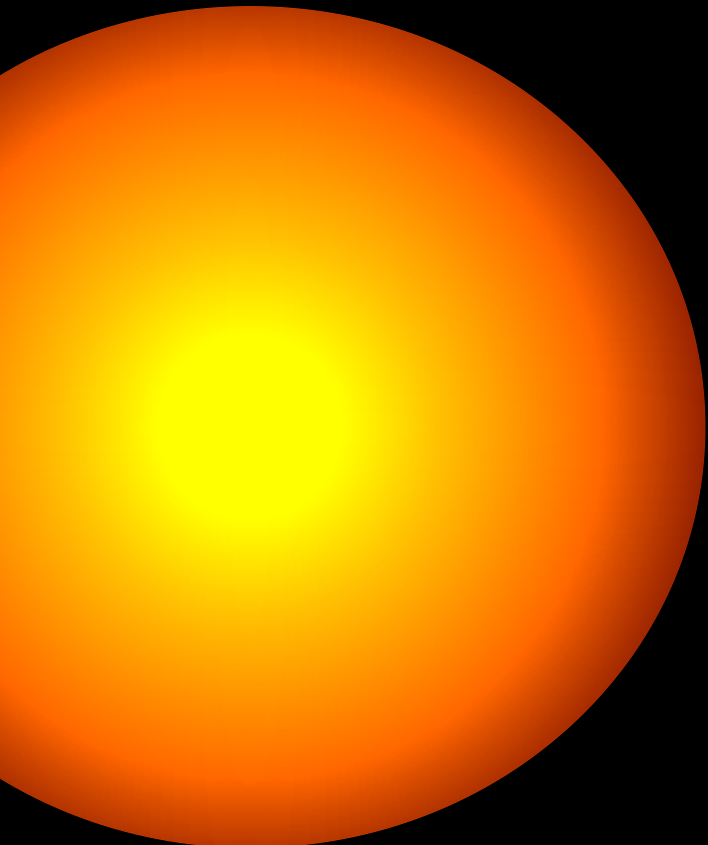
Multi-Wavelength observations of Stellar Explosions

- Engine-driven Stellar Explosions
- Strongly Interacting SNe
- Super-Luminous SNe

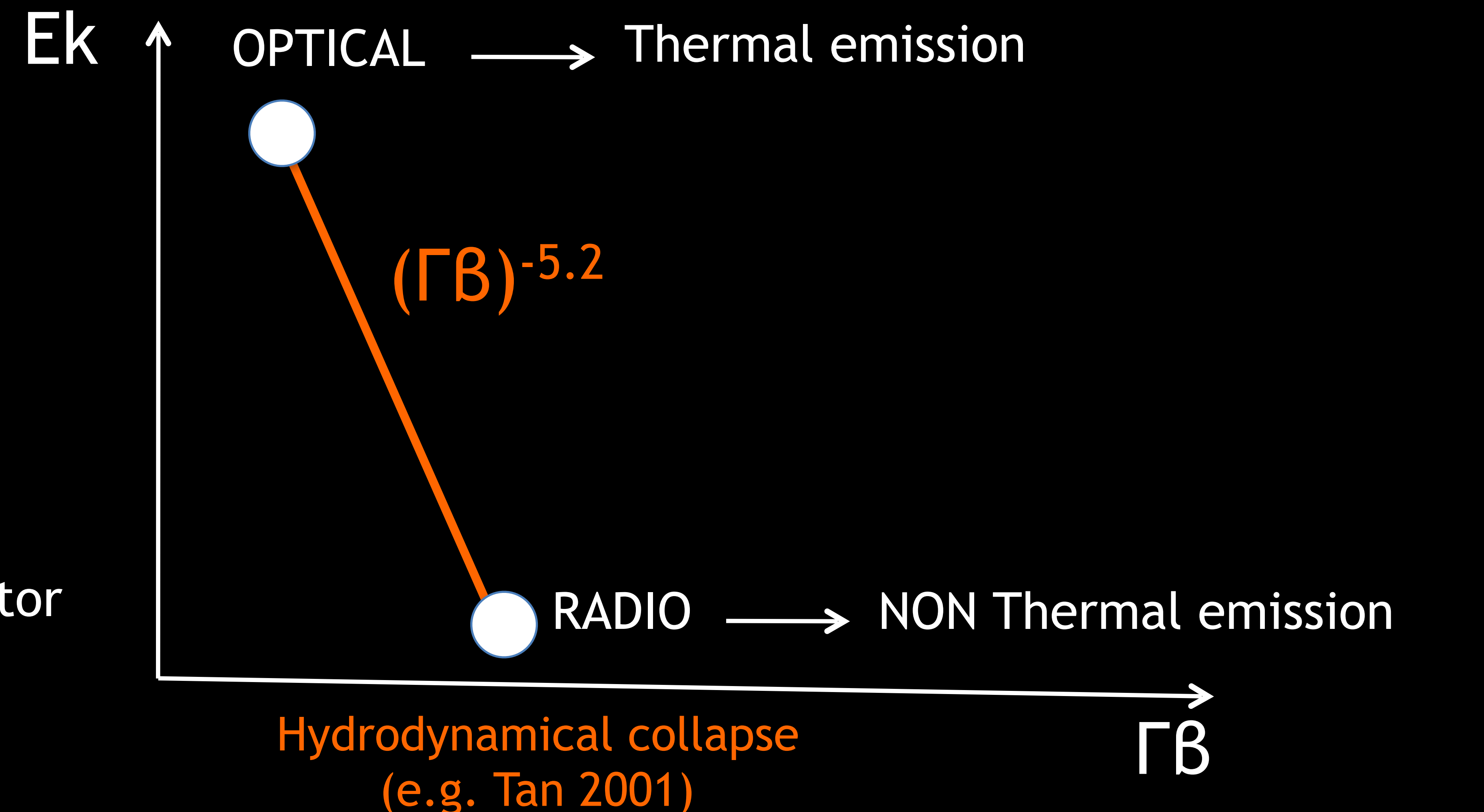
Ejecta kinetic energy profile

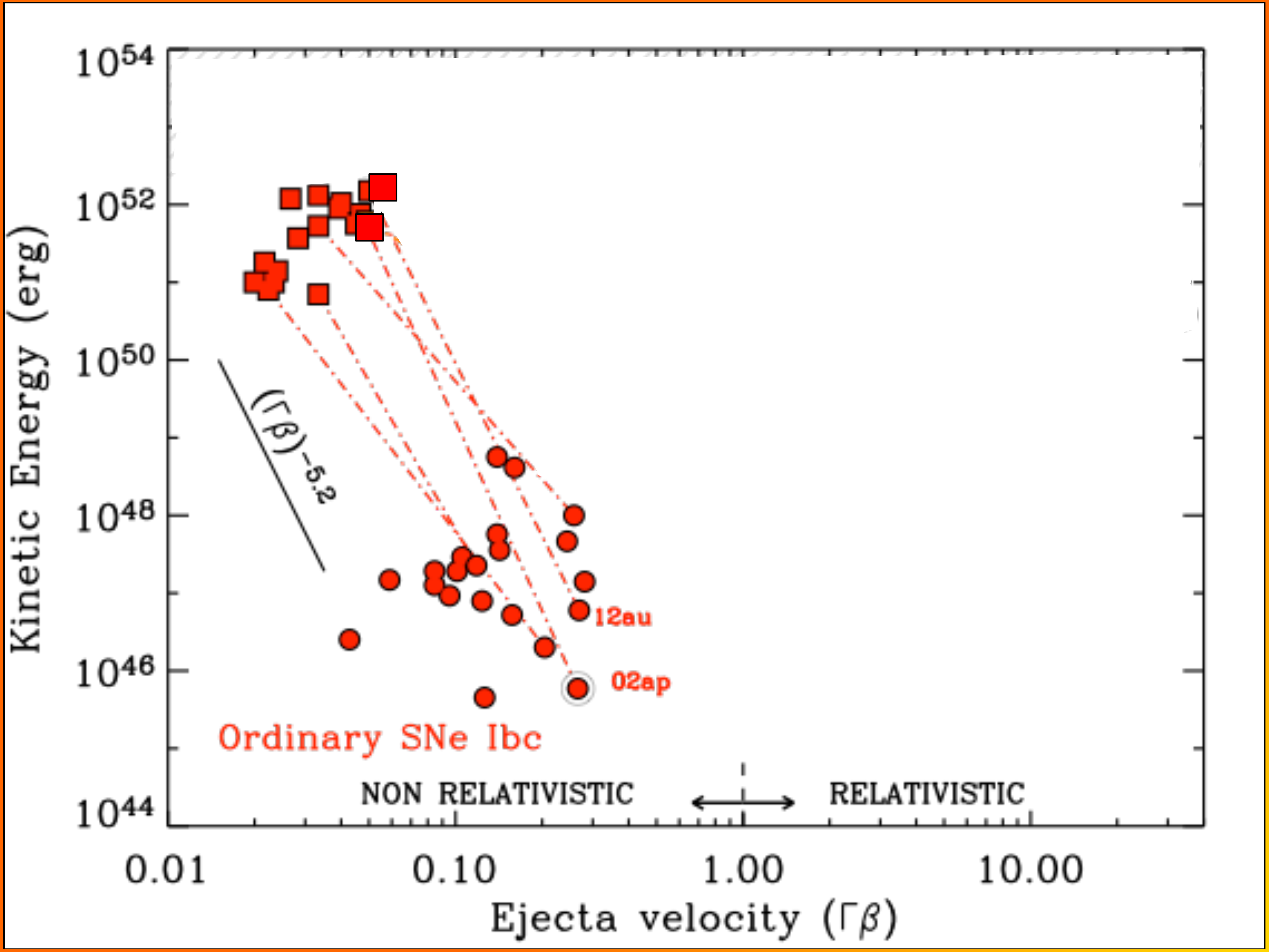


Ejecta kinetic energy profile



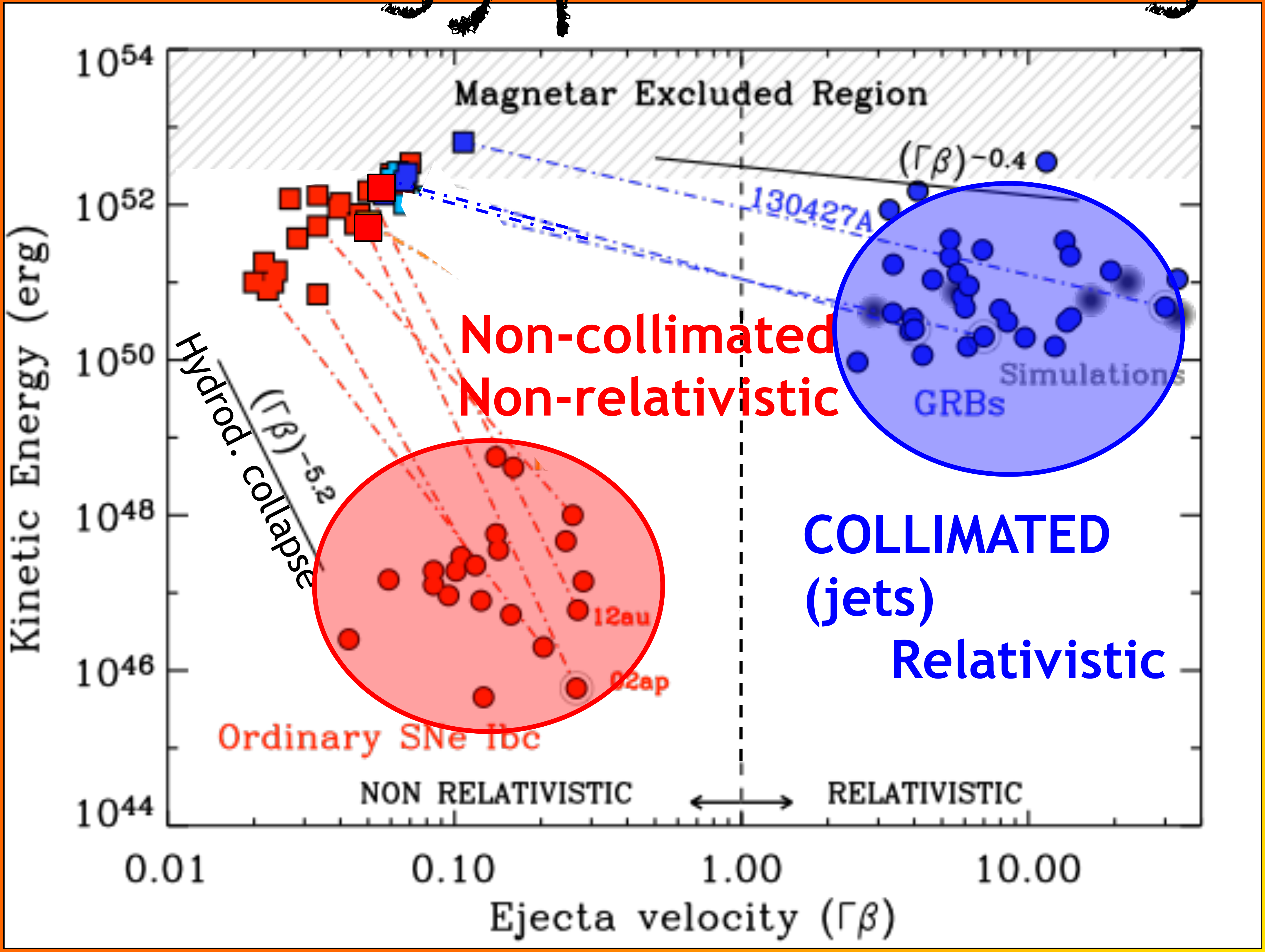
Hydrogen-stripped progenitor
Core-collapse



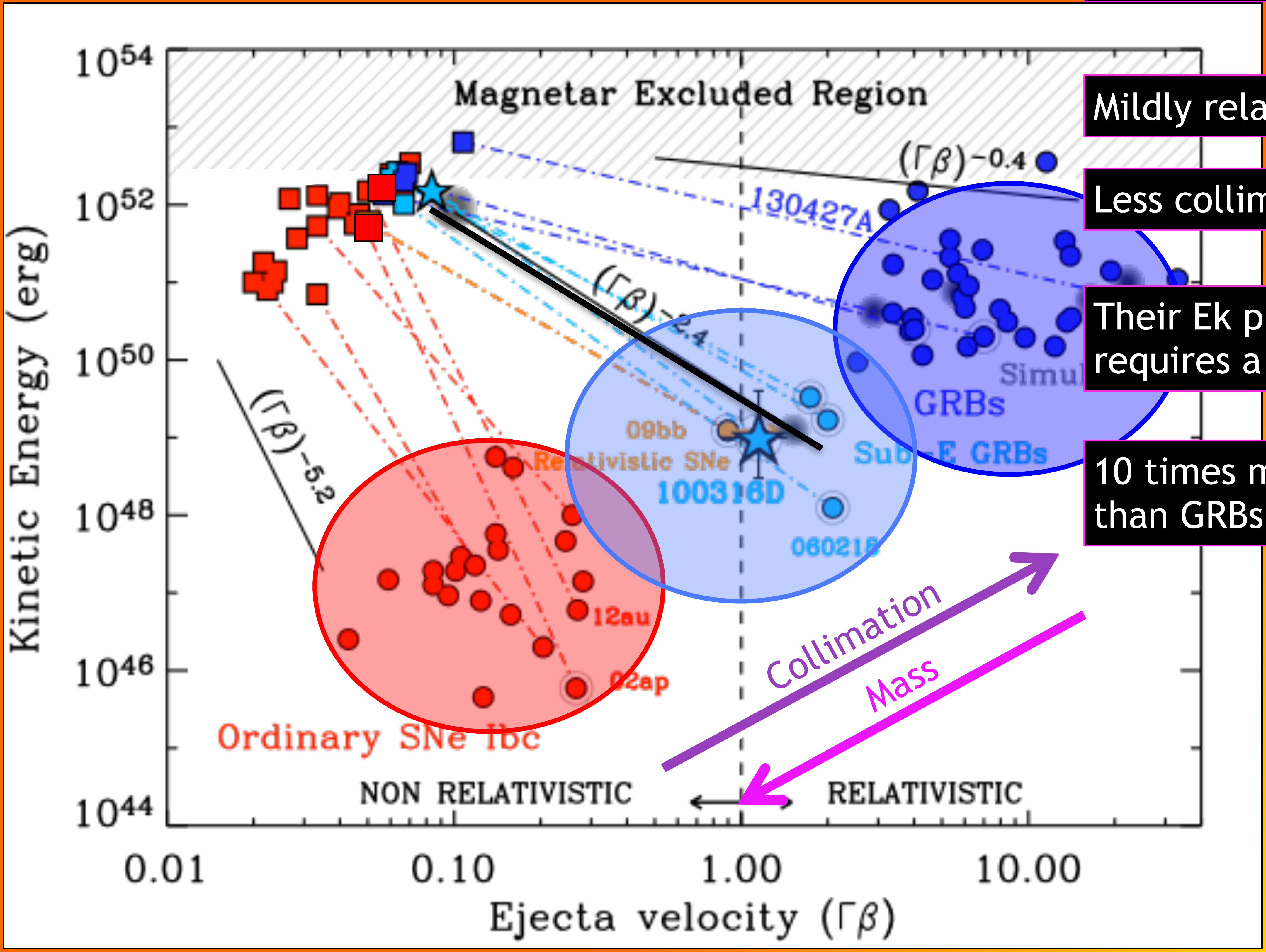


Margutti +13, +14; Kamble +13; Soderberg +06, +10

Energy partitioning



-->Continuum



Less energetic than GRBs (local universe)

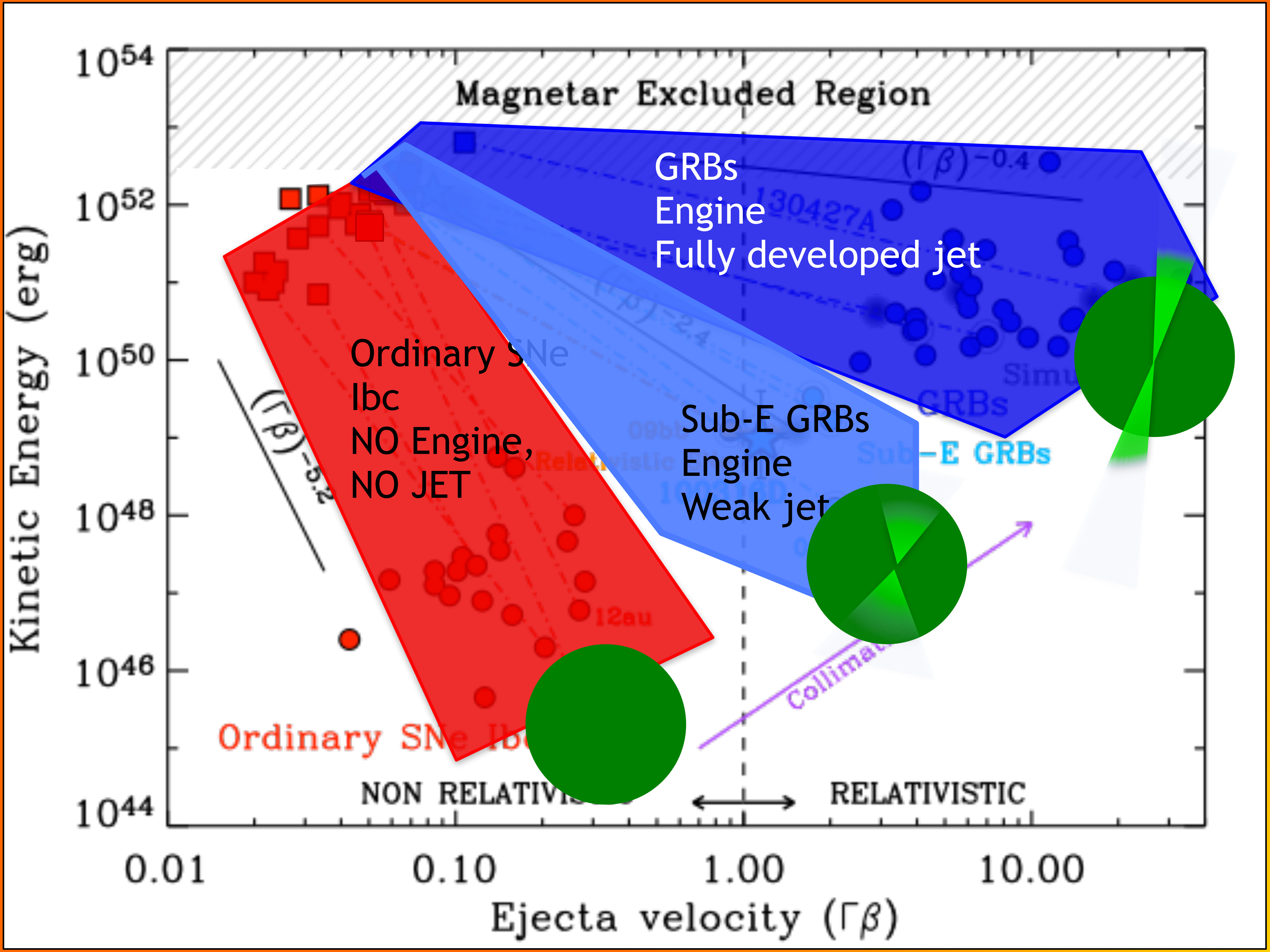
Mildly relativistic

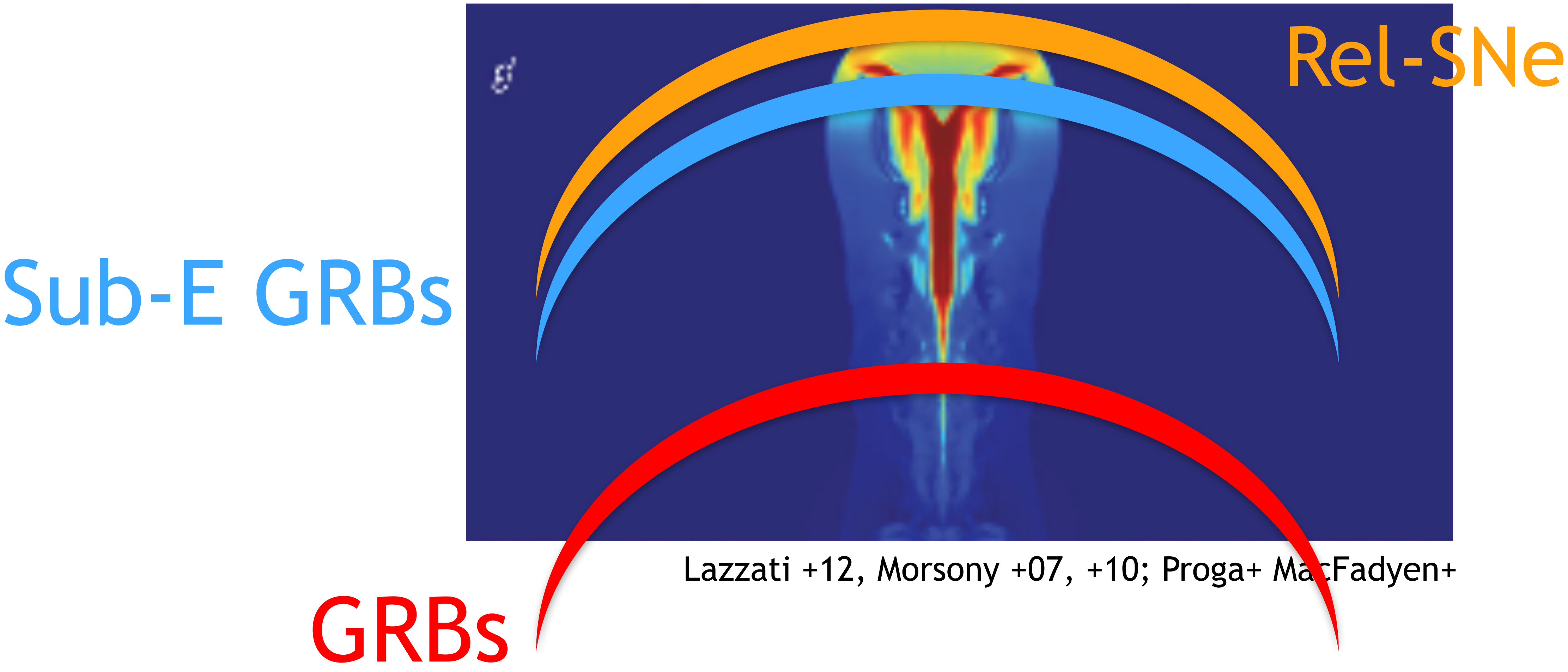
Less collimated than GRBs

Their Ek profile still requires a CE

10 times more common than GRBs

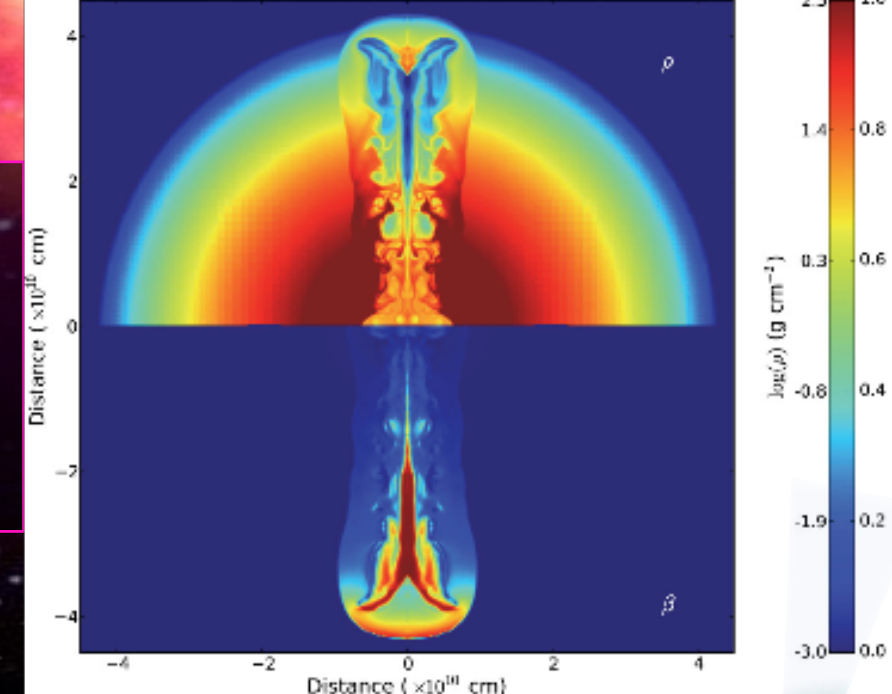
The big picture: H-stripped explosions





Lazzati +12, Morsony +07, +10; Proga+ MacFadyen+

The ZOO of engine-driven explosion



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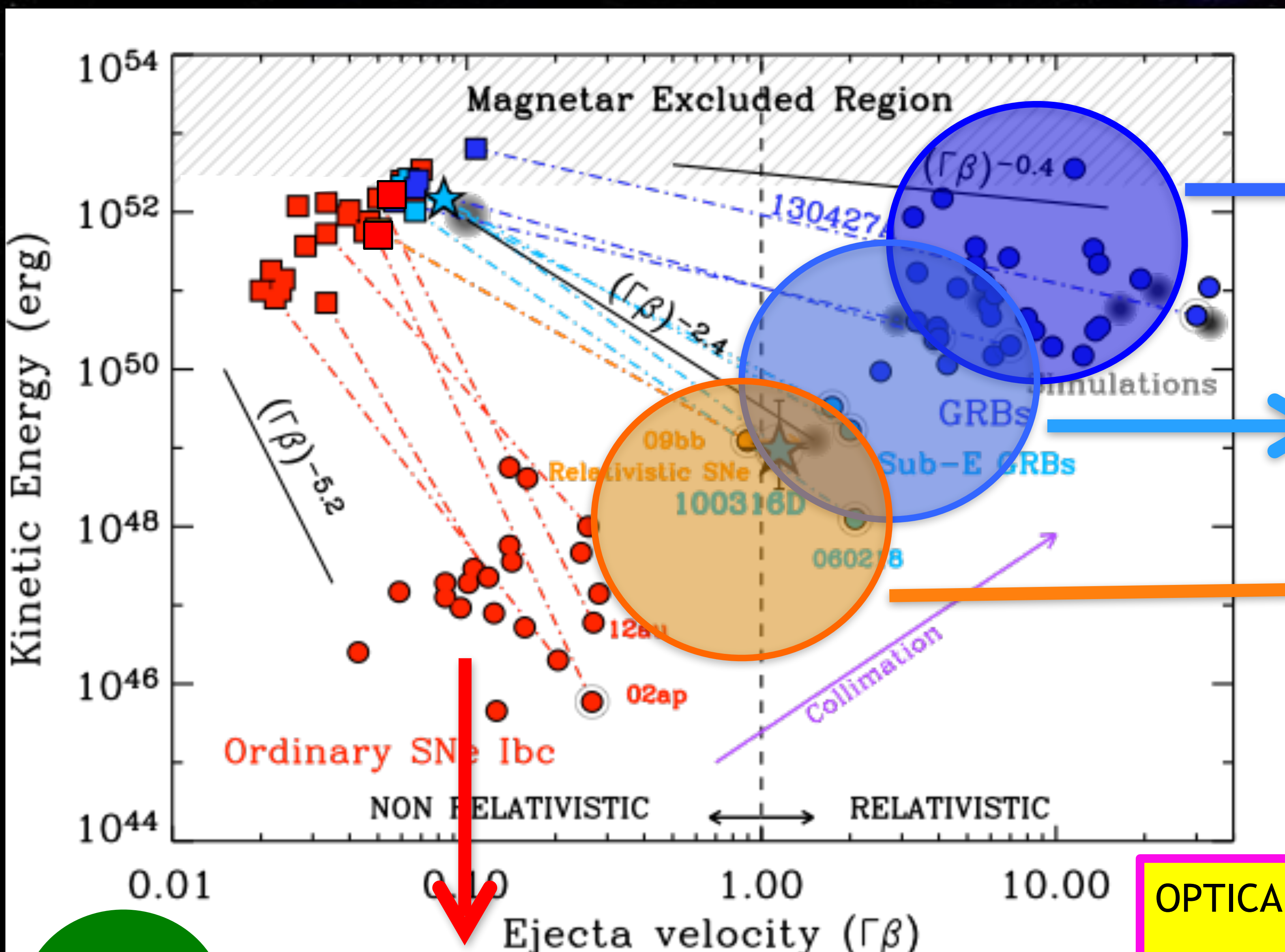


Fully successful jet break out

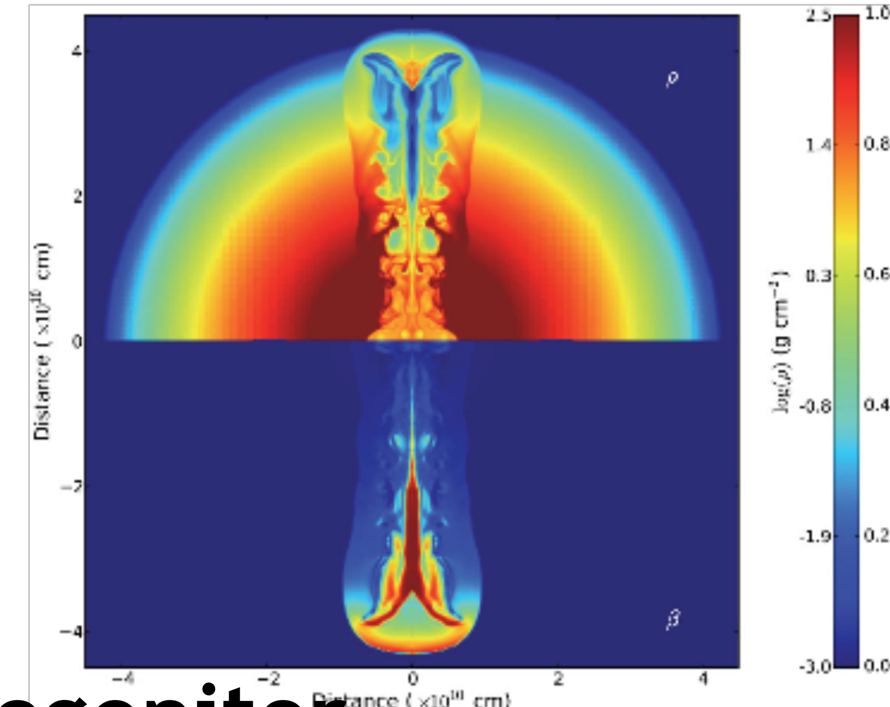
Barely successful jet break out

Barely failed jet break out

Consistent with hydrodynamical explosion (No need for a jet/engine)

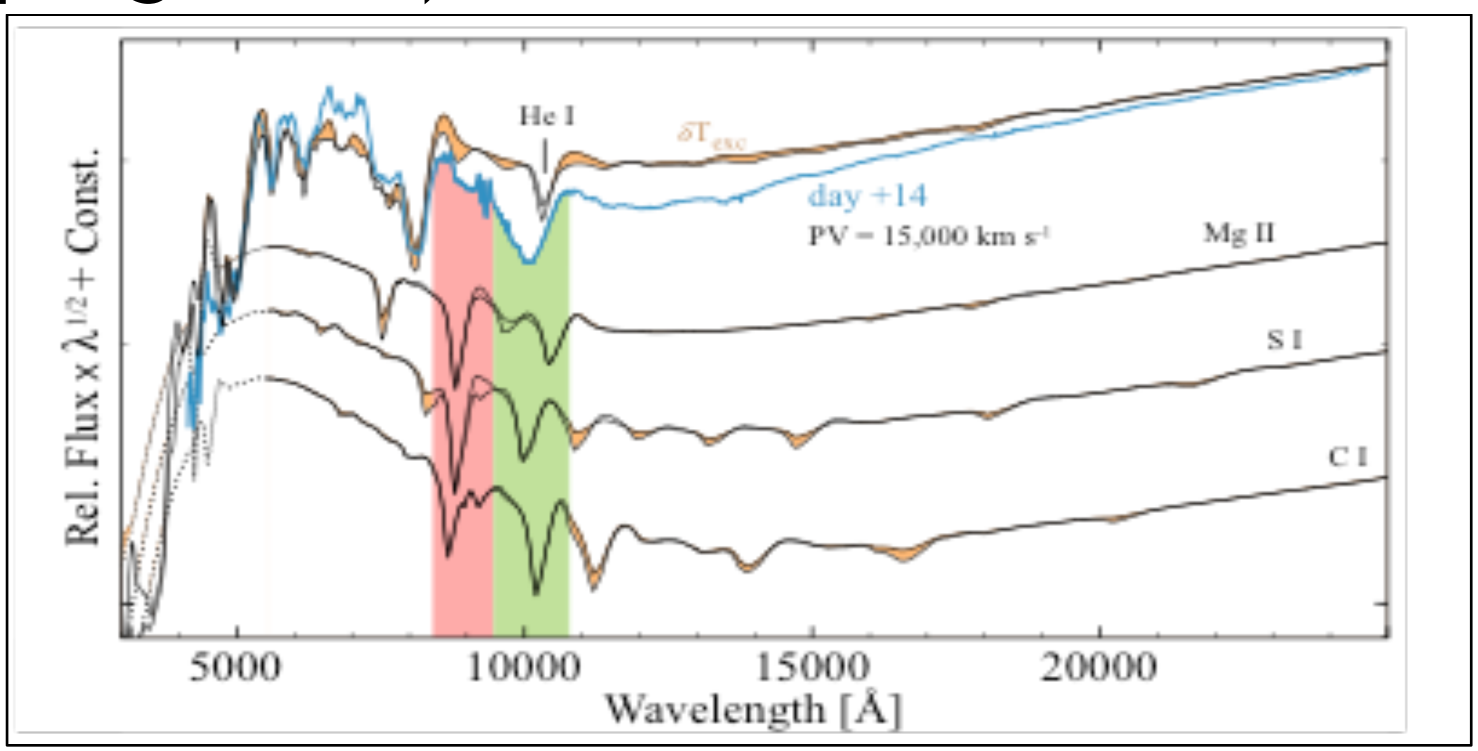
OPTICAL→ (phot) energetic of the explosion
(spec) composition + environment
RADIO→ Engine vs. no engine
X-rays→ Jet breakout vs. no breakout

Why a jet fails to breakout?

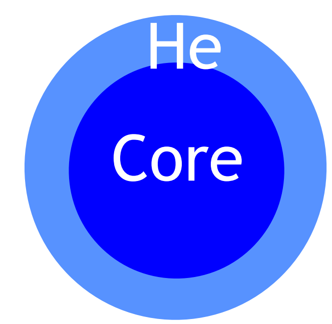


Shorter engine life-time
(same progenitor)

Larger progenitor
(same engine life-time)

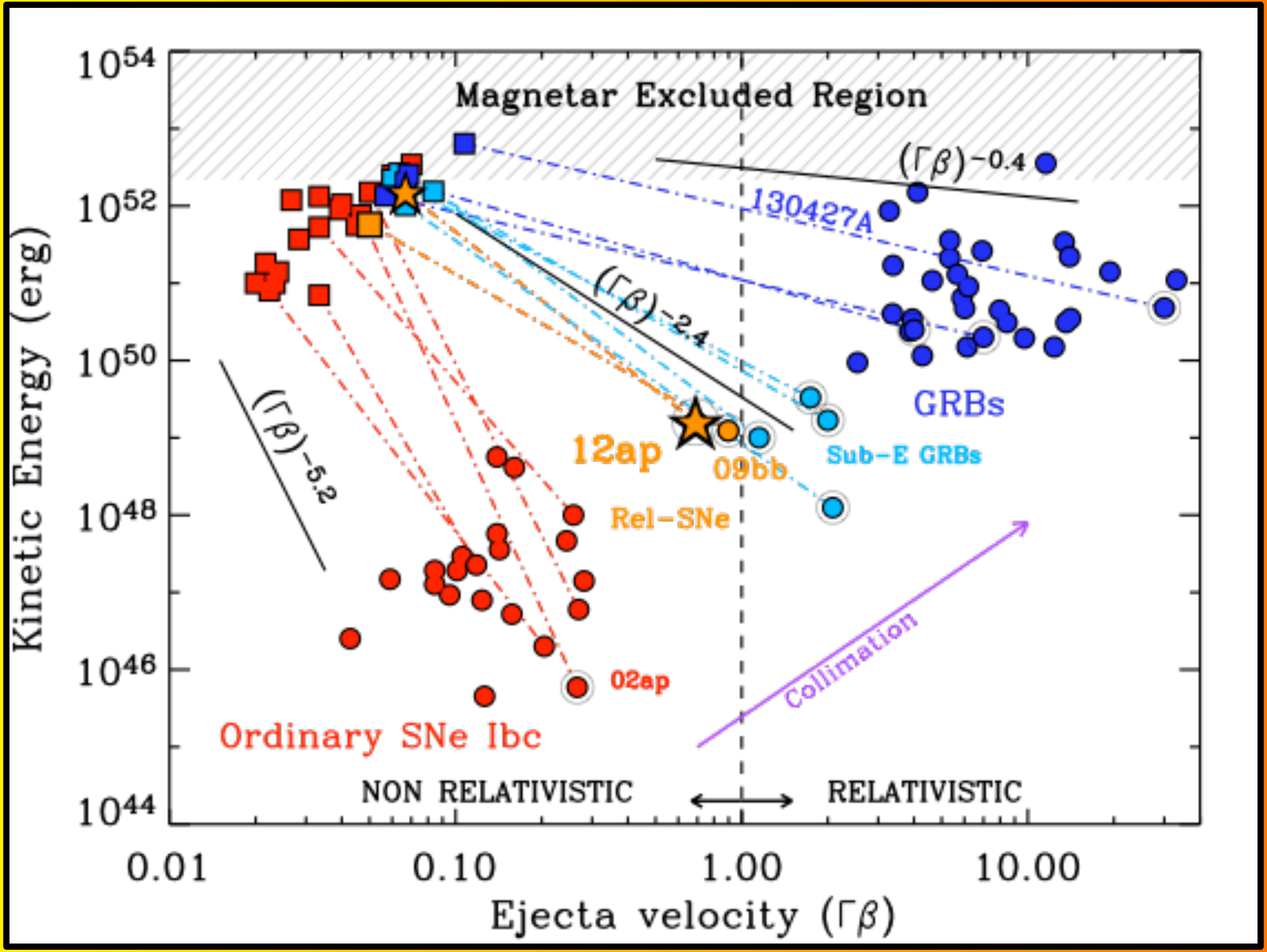


Milisavljevic, RM +14



RELATIVISTIC SUPERNOVAE HAVE SHORTER-LIVED CENTRAL ENGINES OR MORE EXTENDED PROGENITORS: THE CASE OF SN 2012AP

R. Margutti[1], D. Milisavljevic[1], A. M. Soderberg[1], C. Guidorzi[2], B. J. Morsony[3], N. Sanders[1], S. Chakraborti[1], A. Ray[5], A. Kamble[1], M. Drout[1], J. Parrent[1], A. Zauderer [1], L. Chomiuk[4]



Margutti +14b

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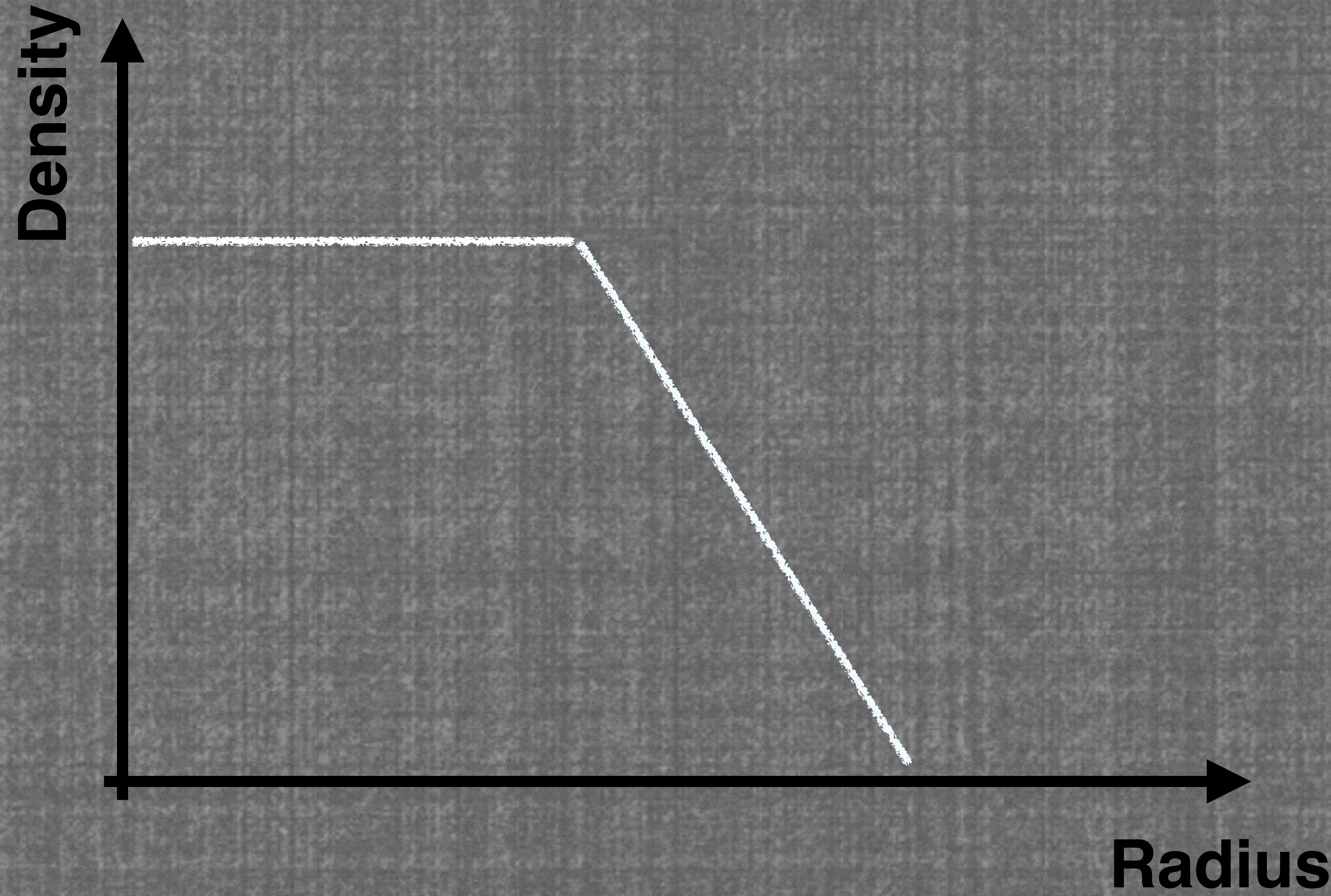
SN Ejecta profile



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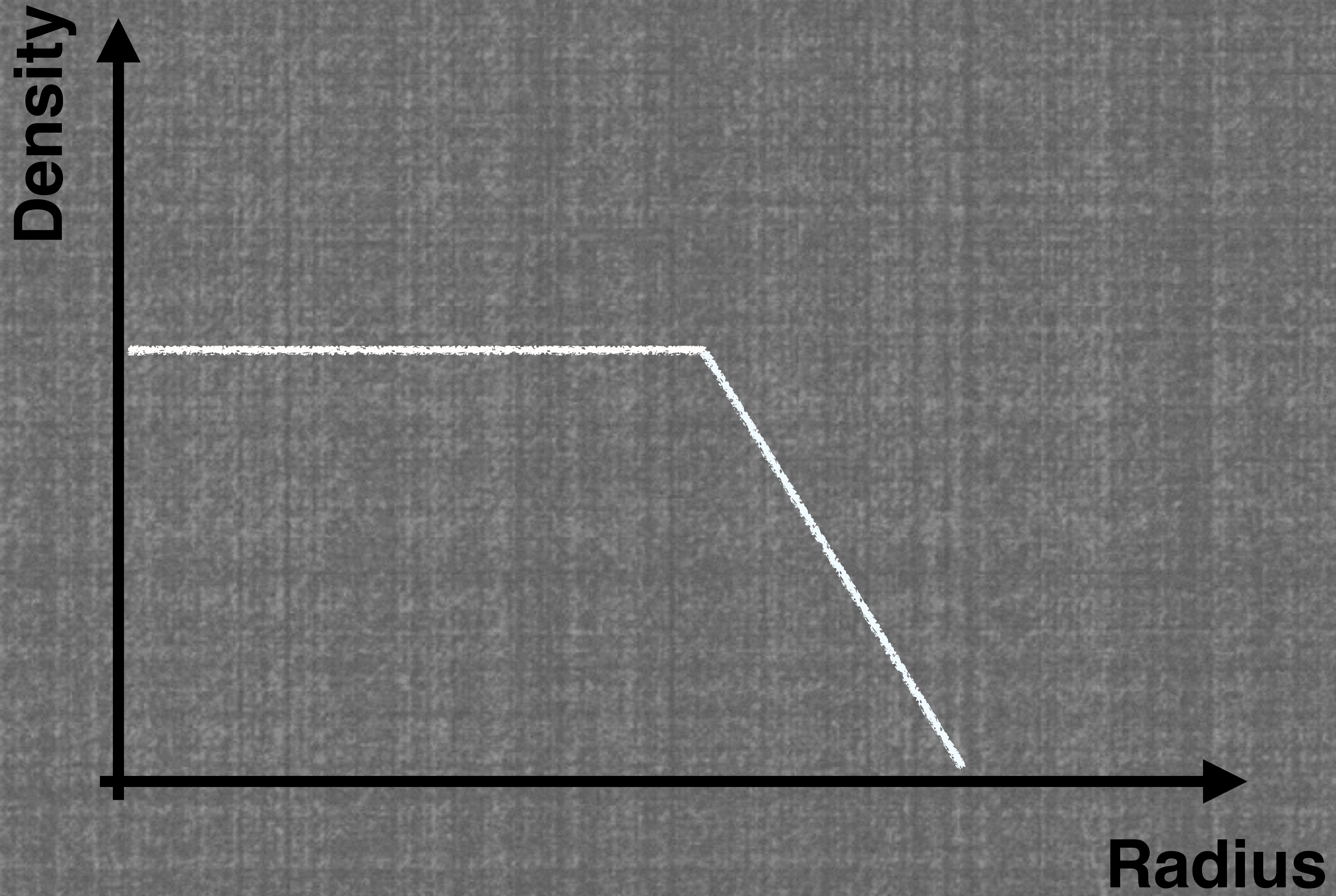

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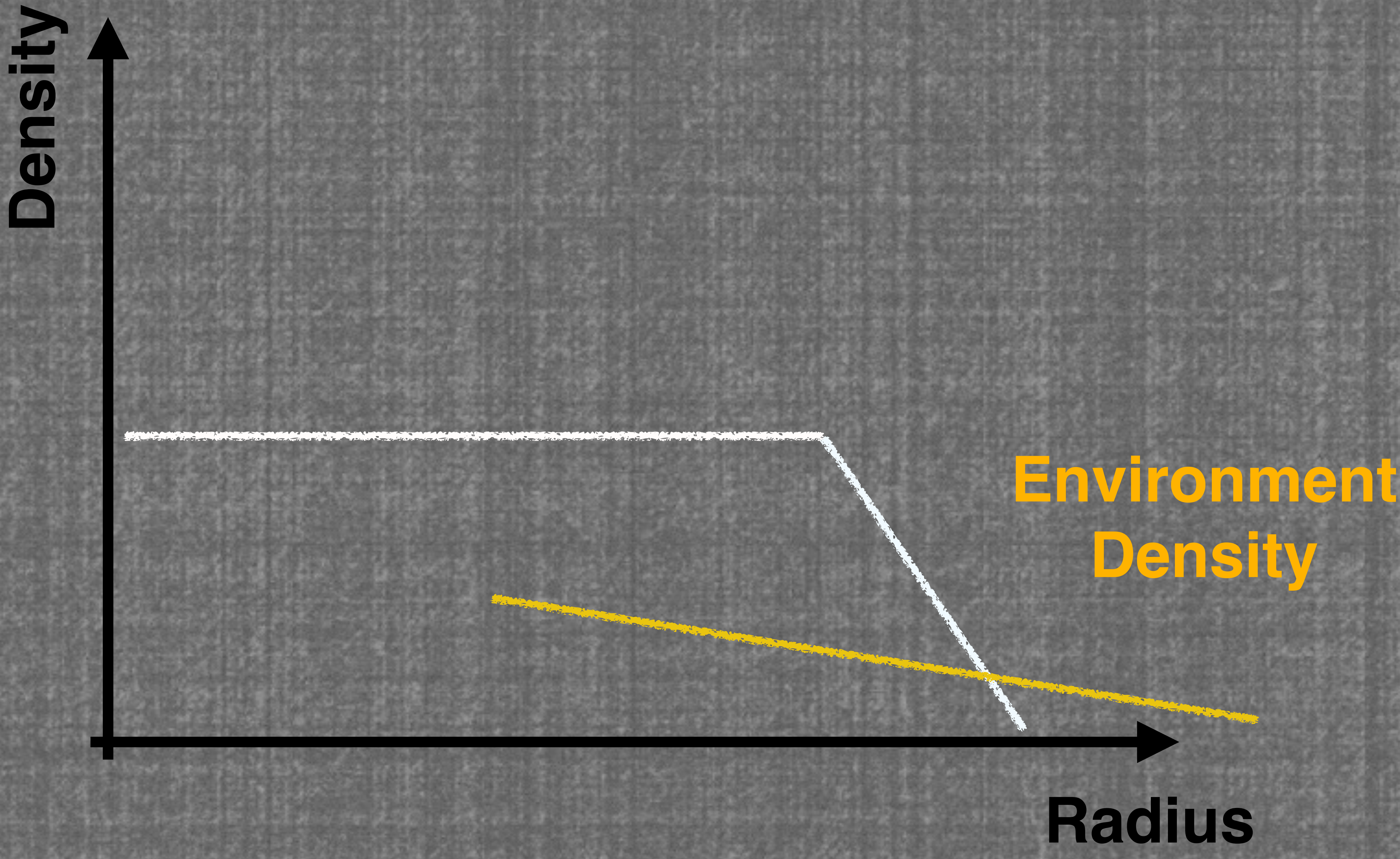

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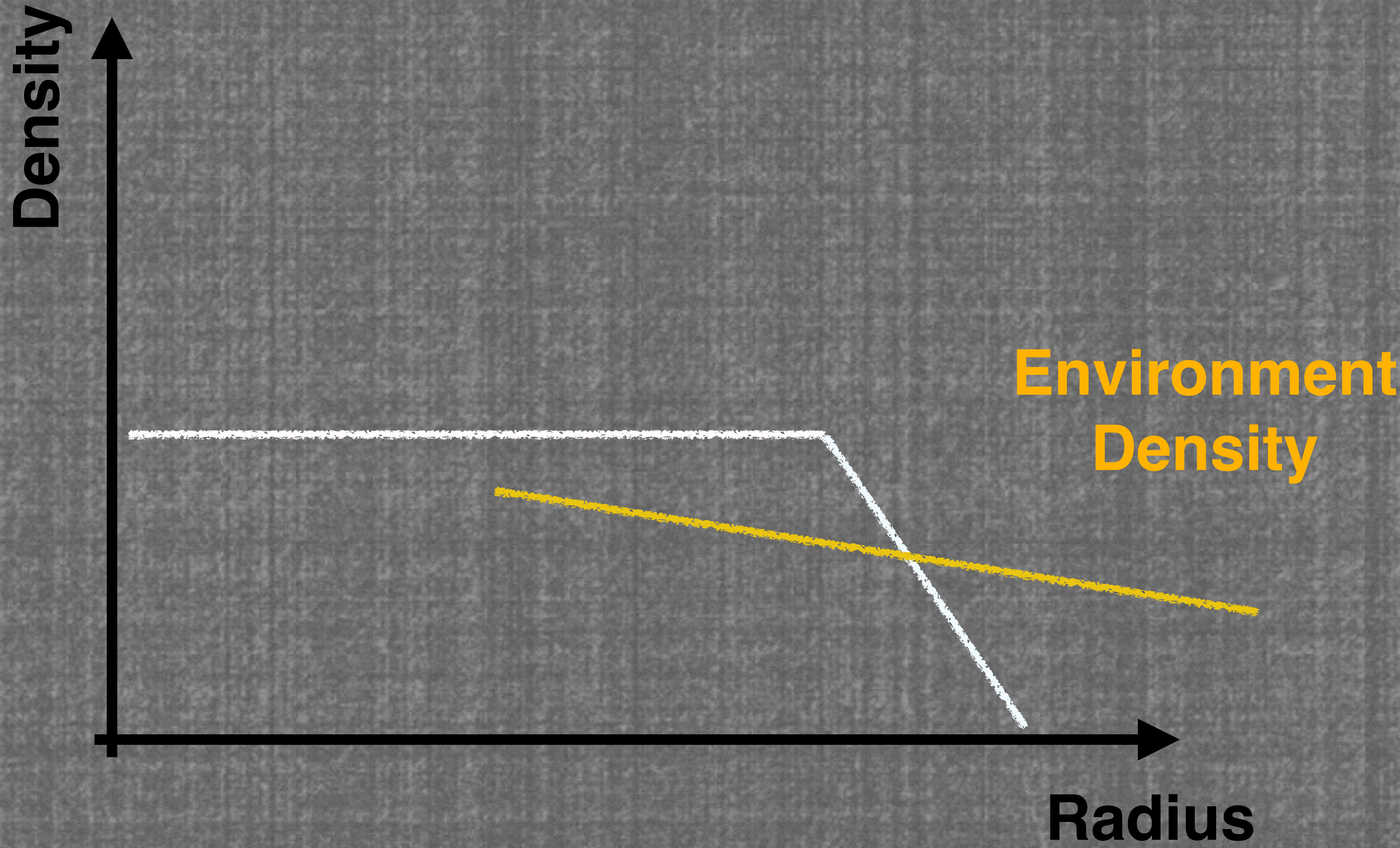
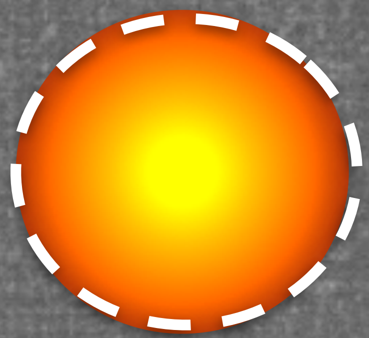


Expected Evolution from Stellar tracks:

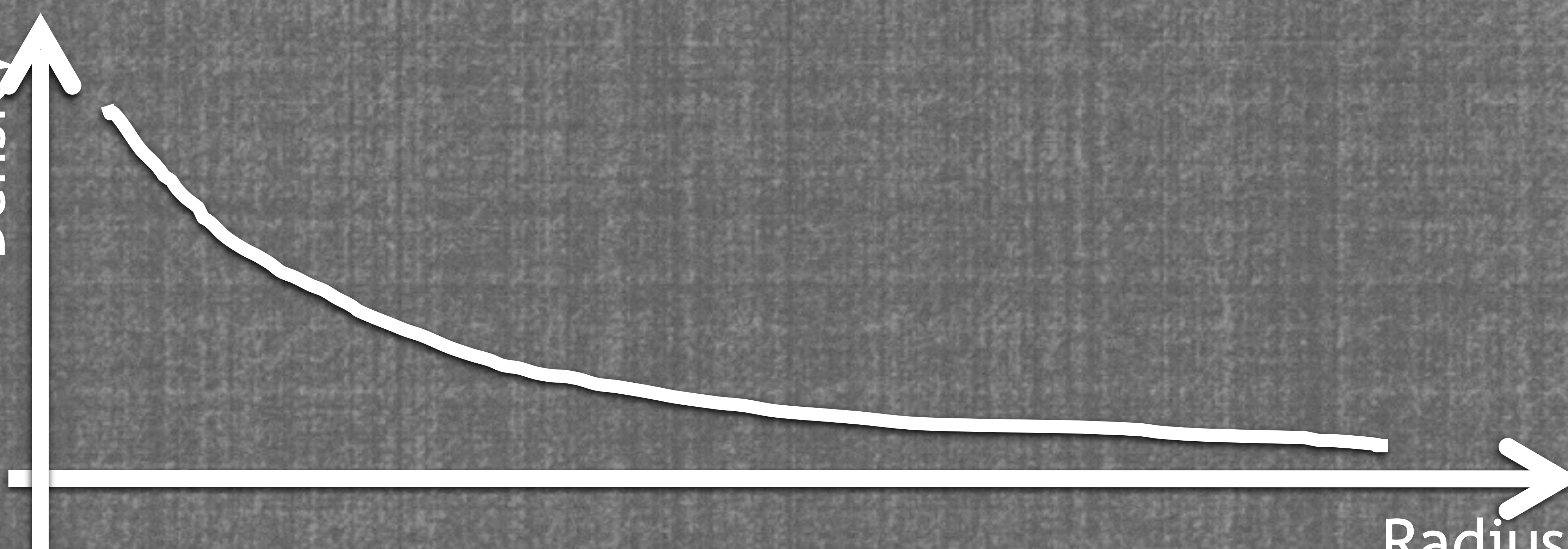


Supergiant

Wolf-Rayet

~10^4-10^5 yrs

SN Explosion



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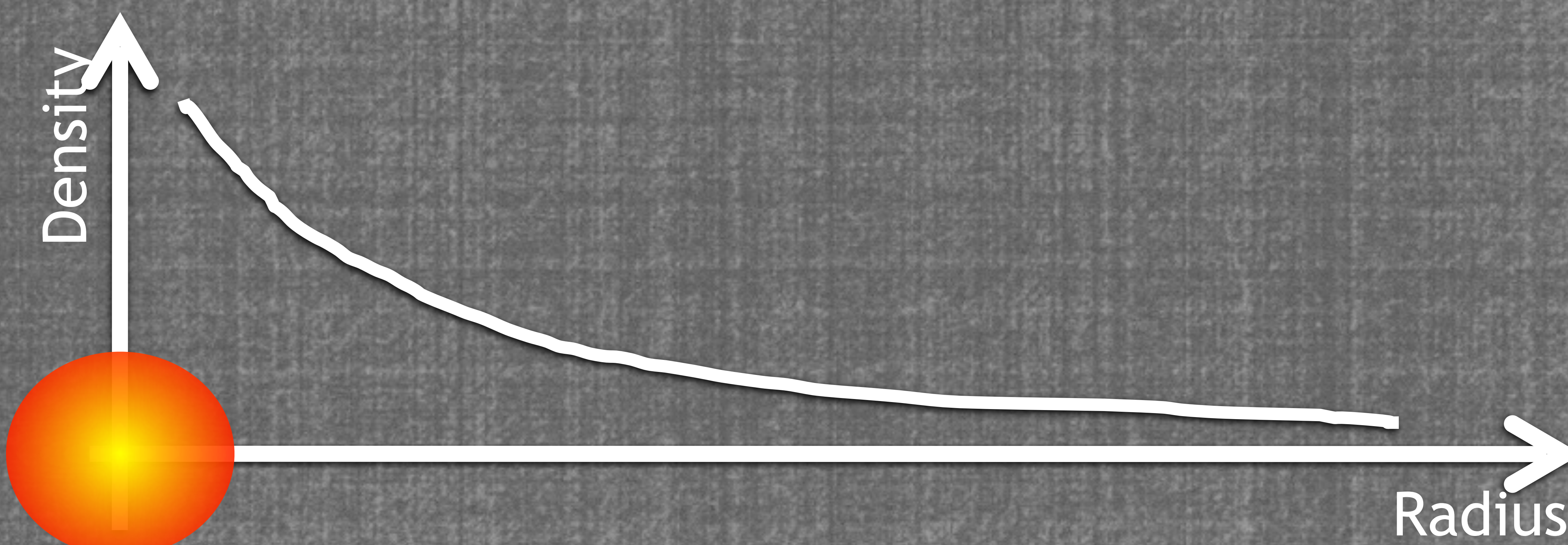

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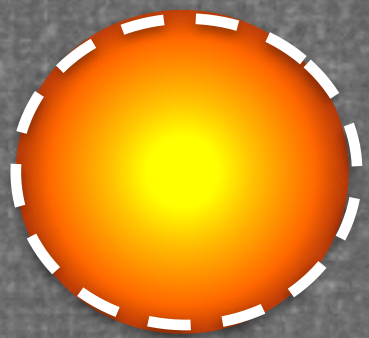

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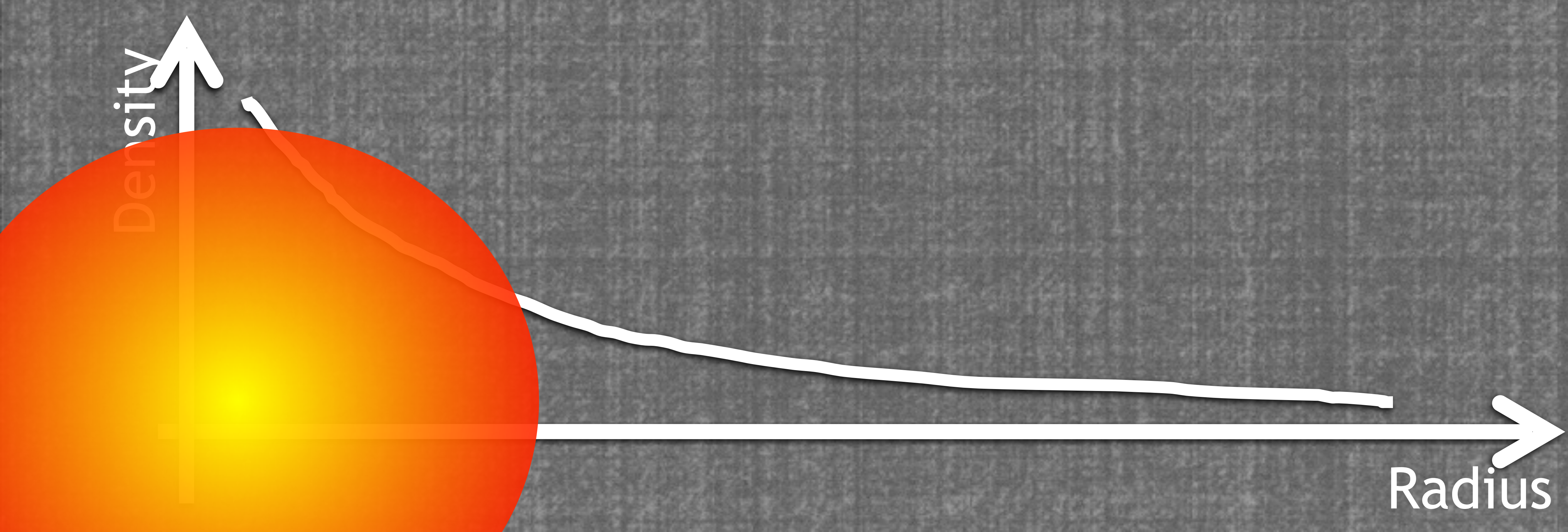

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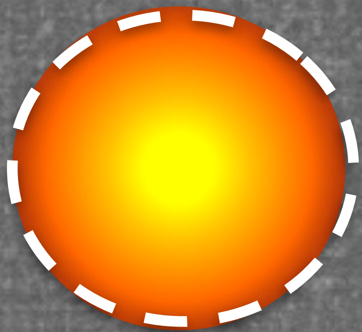

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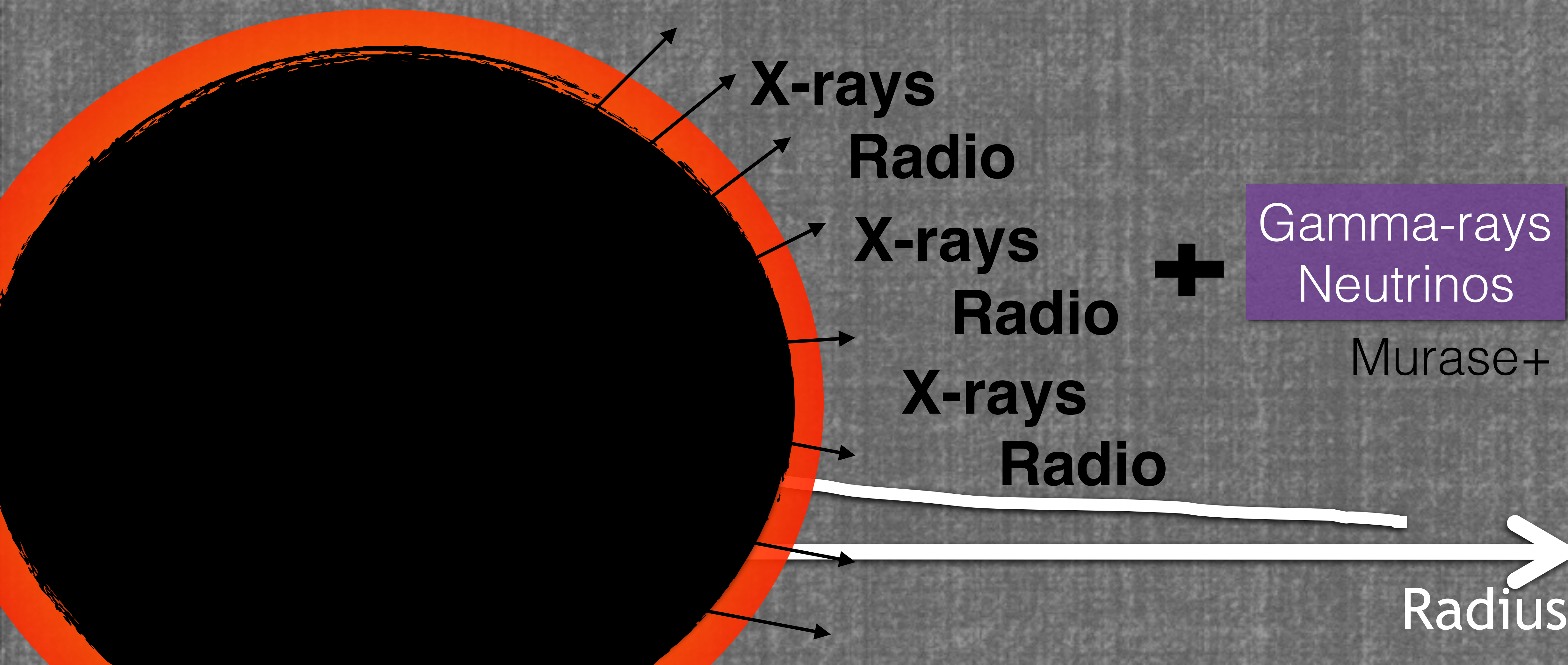
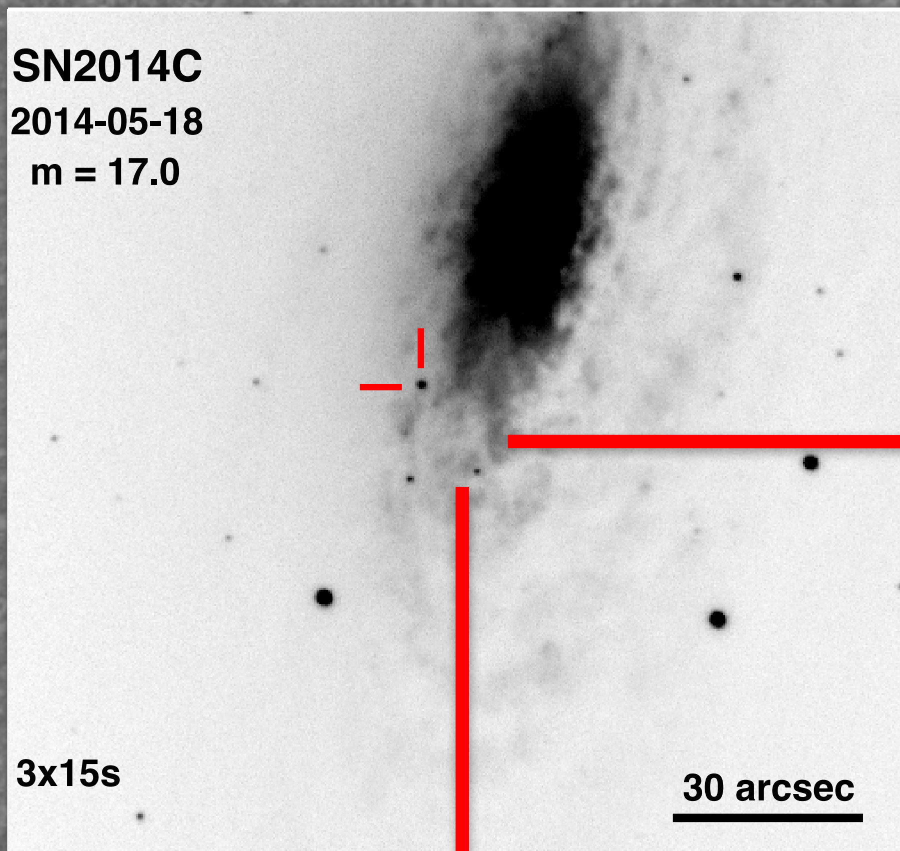


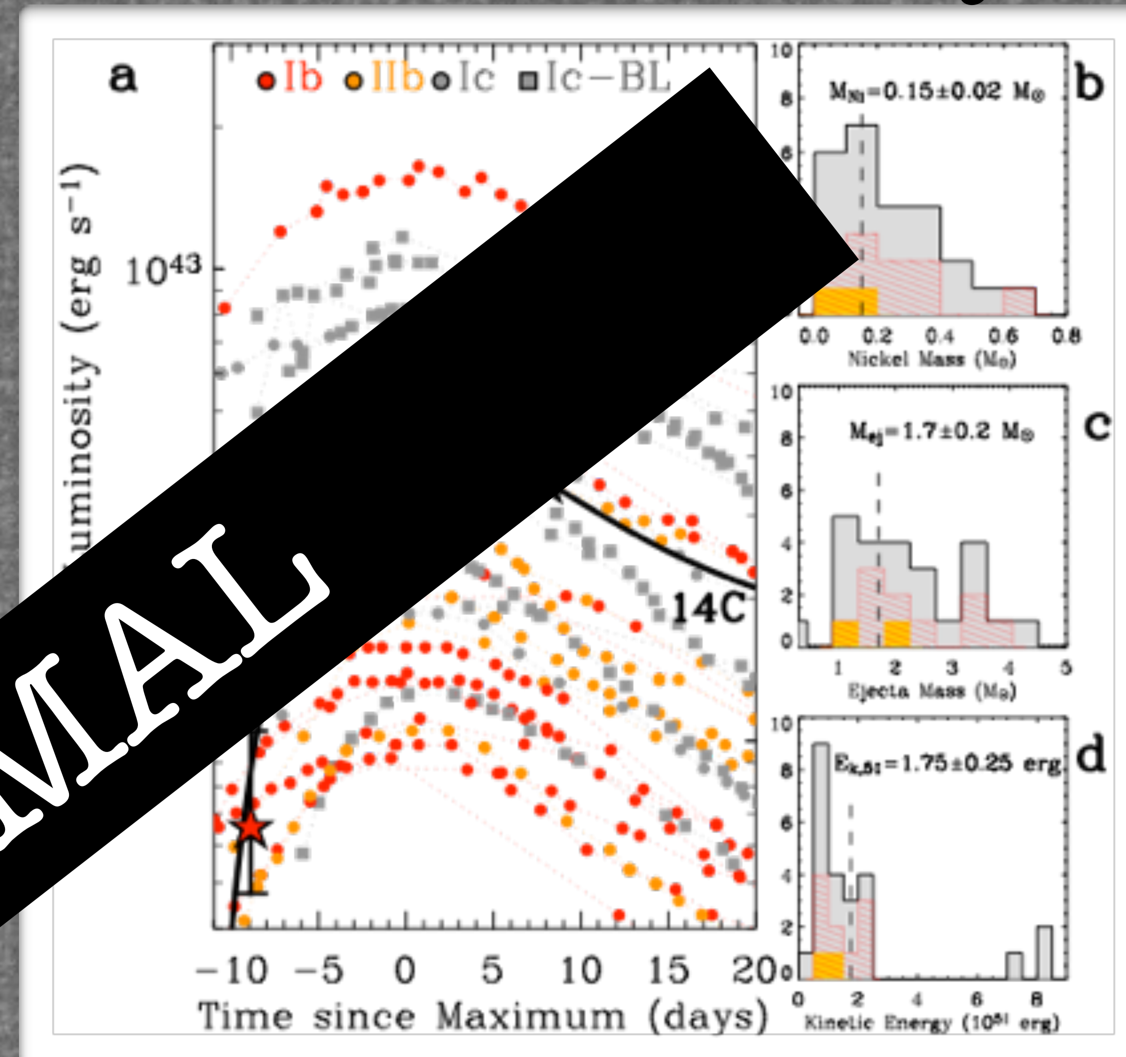
...in real-time...

SN2014C: a normal Ib SN

dist=15.7 Mpc



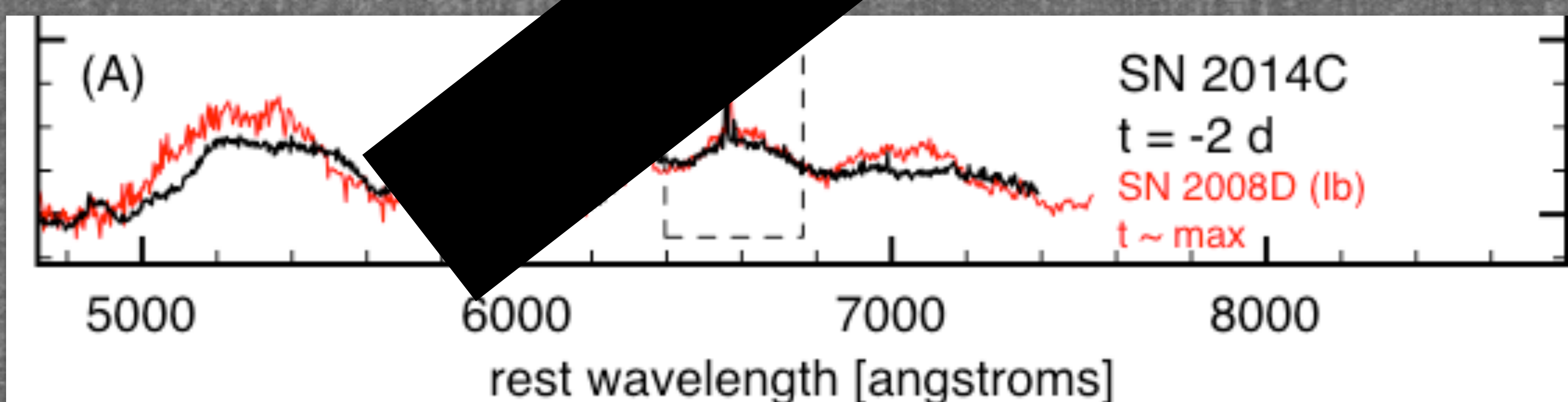
Bolometric Luminosity



RM+16

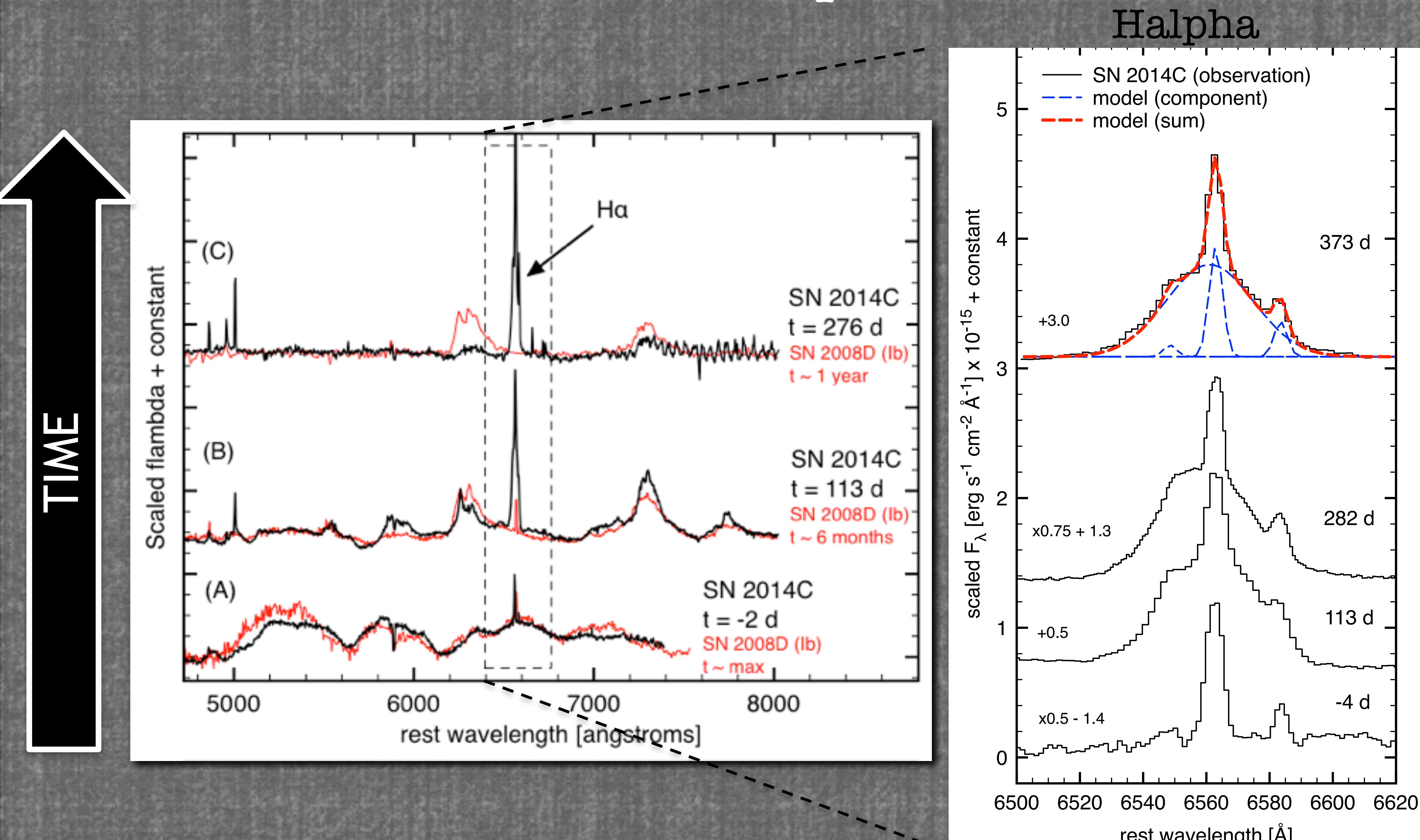
NORMAL

Optical Spectrum at



Milisavljevic, RM+15

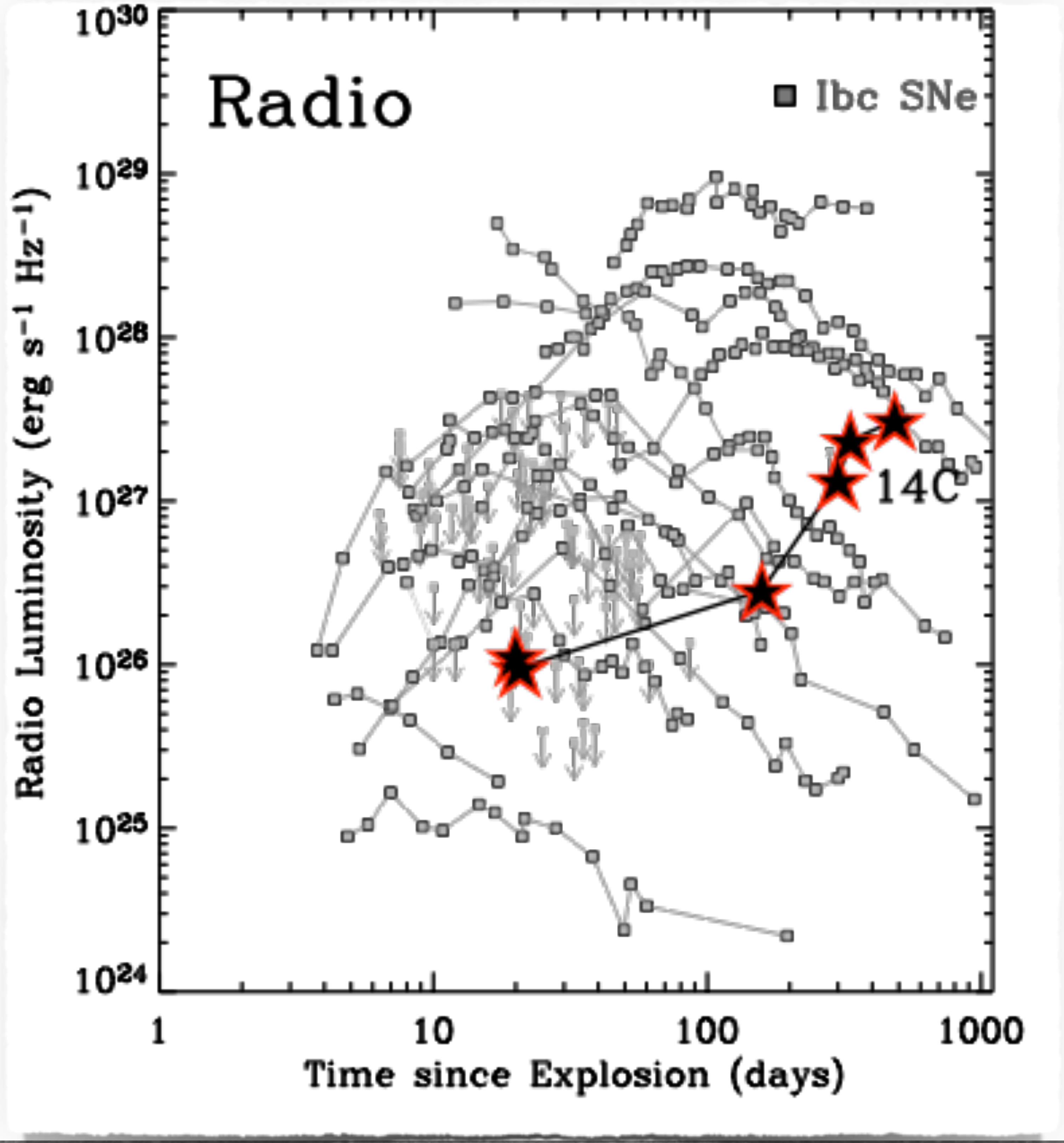
SN2014C-Optical



Milisavljevic, RM+15

Development of H-features with time

SN2014C-Radio

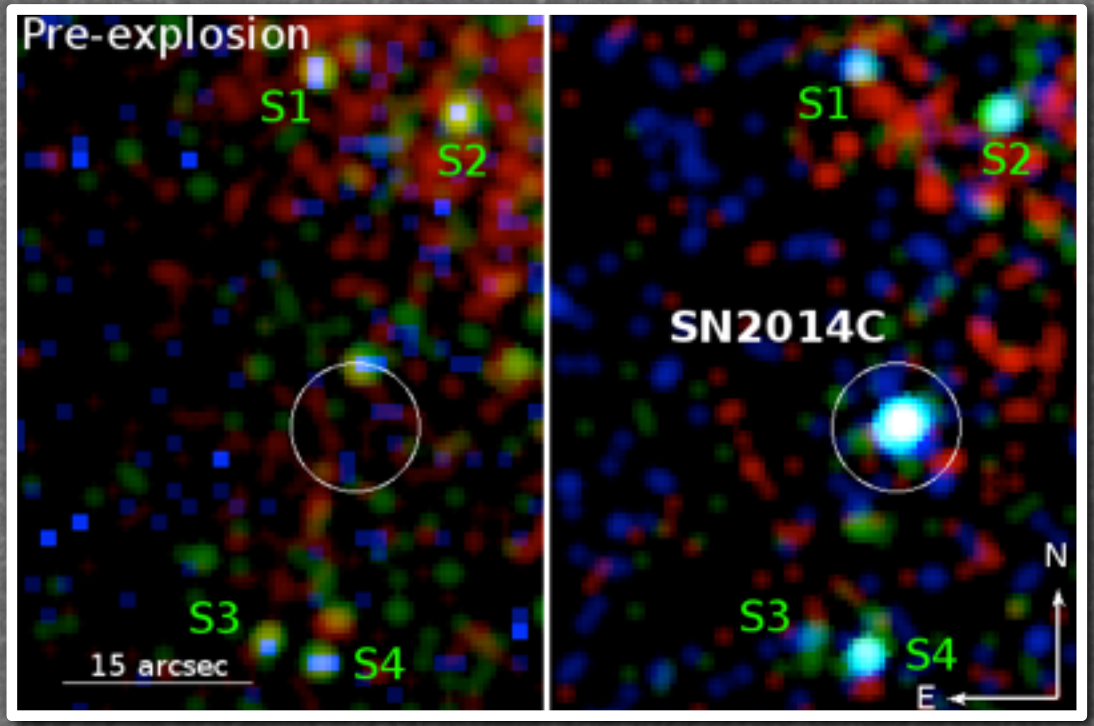


RM+16

Radio Luminosity INCREASES w. time!

SN2014C-X-rays (soft+hard)

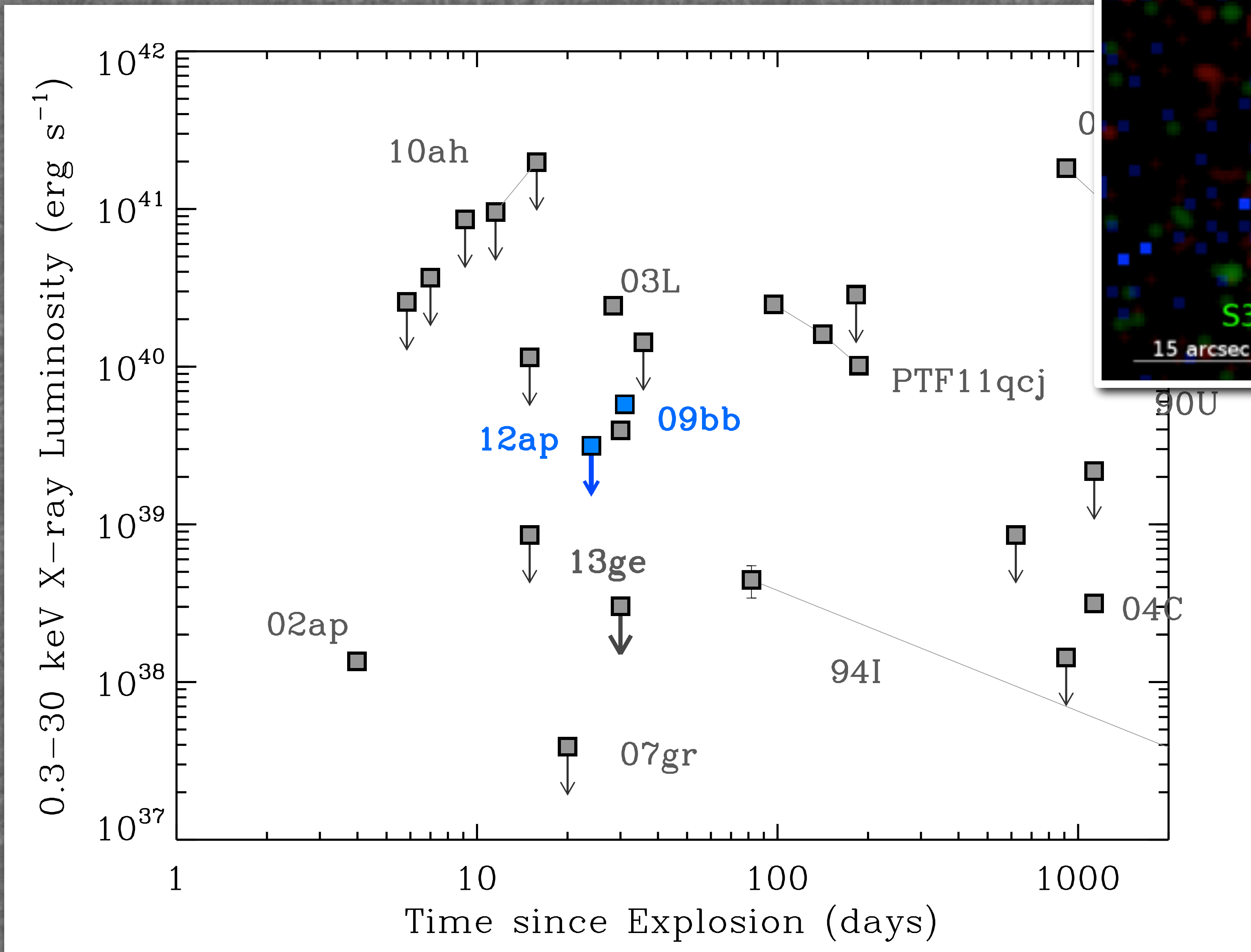
Chandra

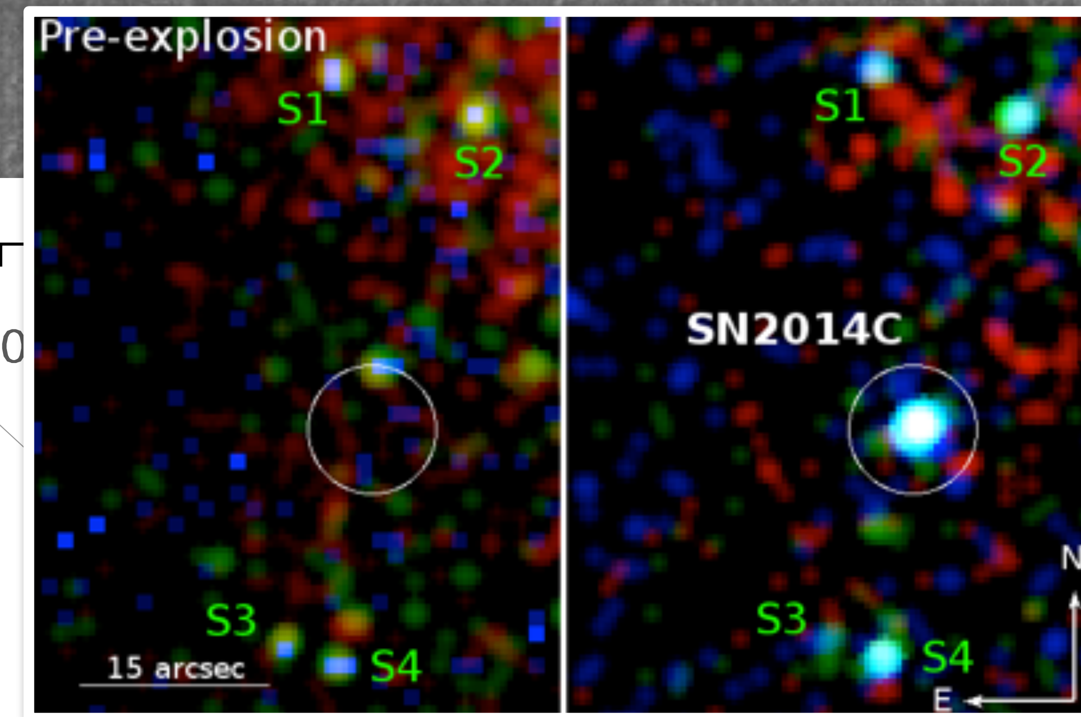


RM+16

FIRST Hstripped-SN ever detected at hard X-rays!

SN2014C-X-rays (soft+hard)





RM+16

Rising X-ray Luminosity!

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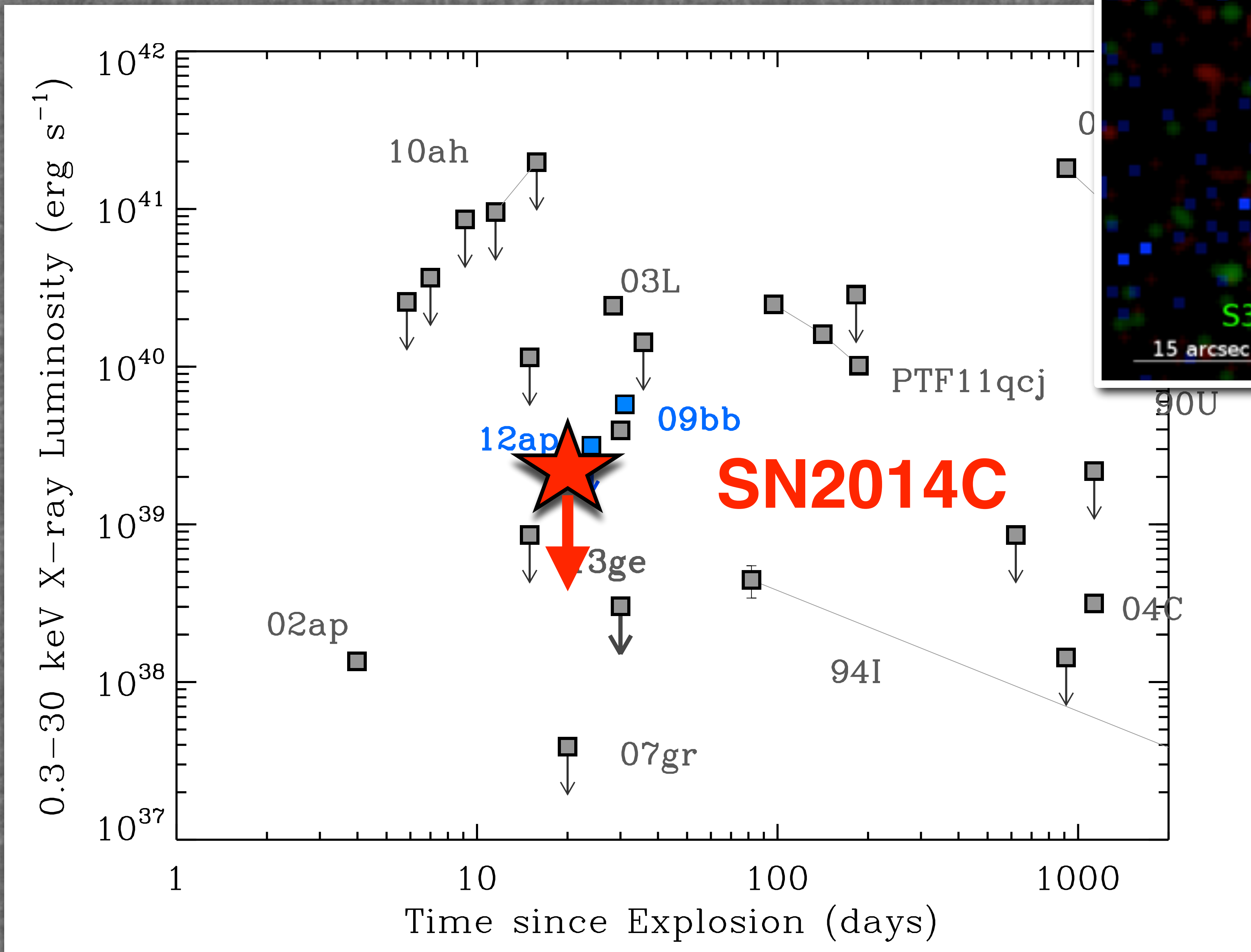

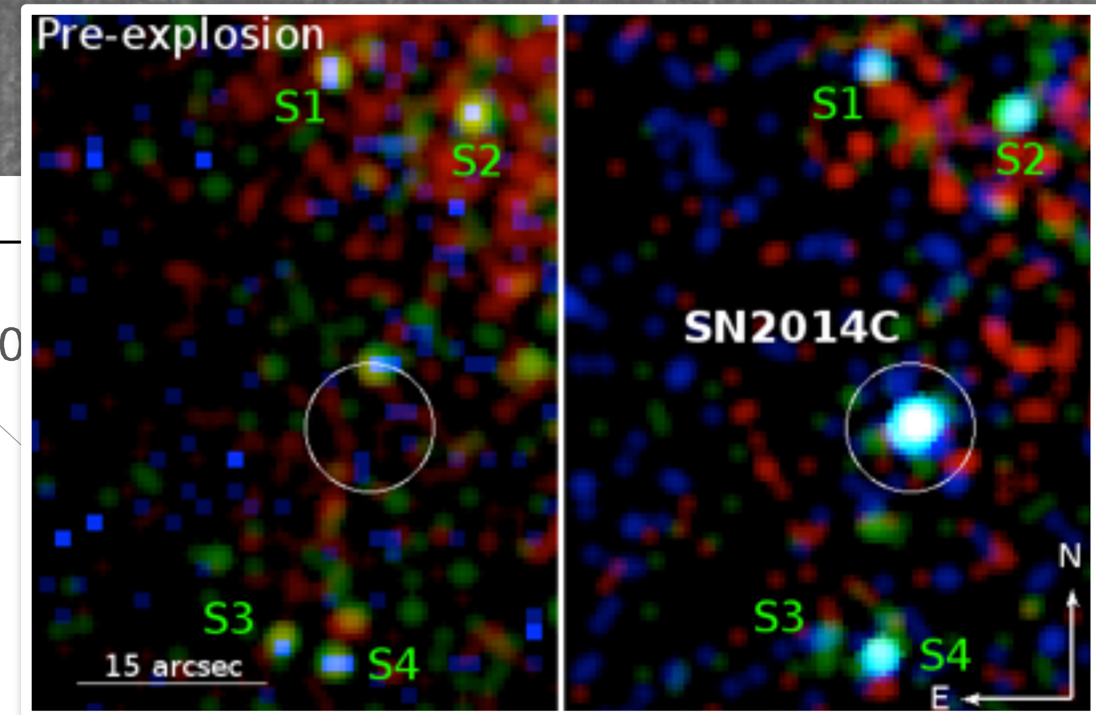

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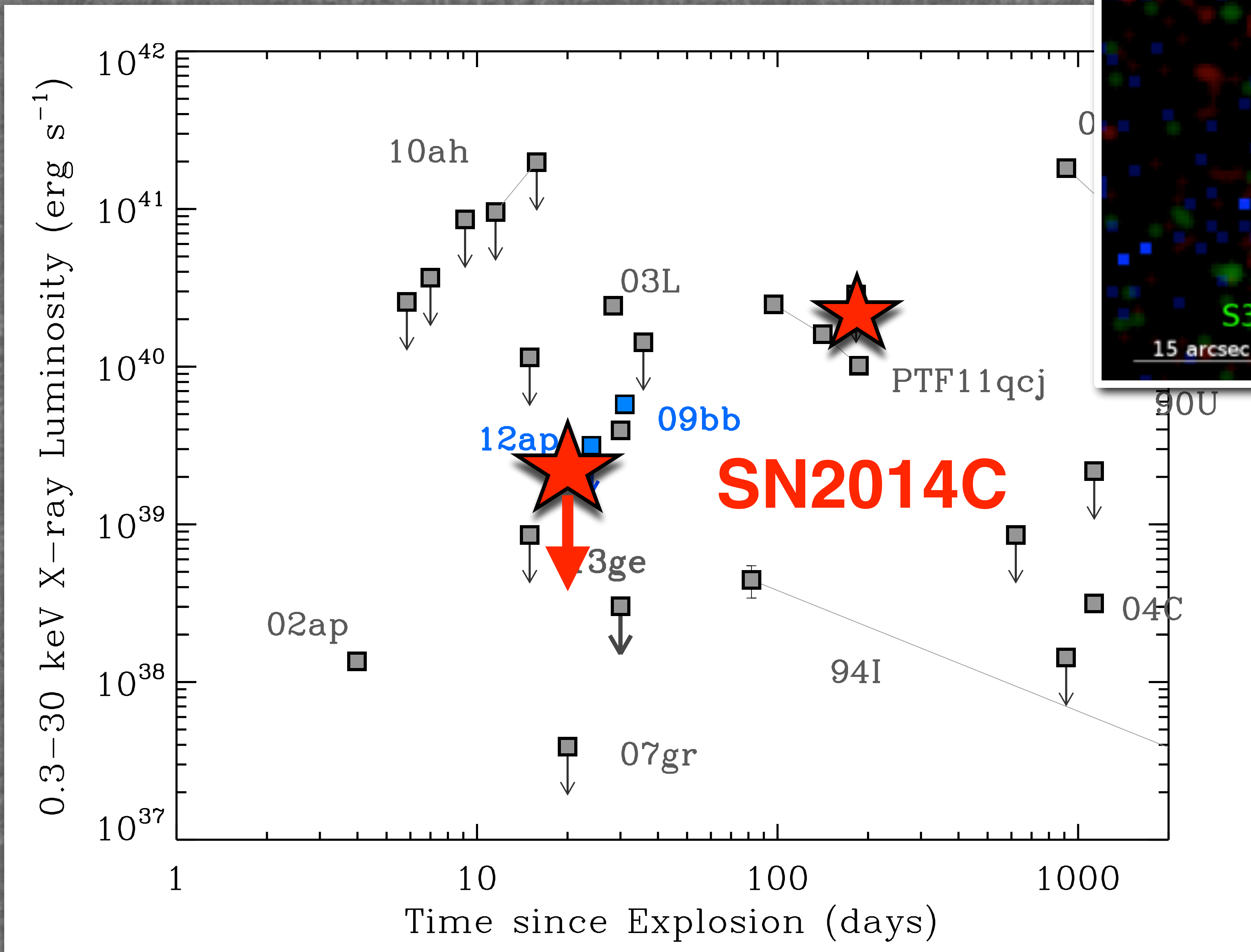

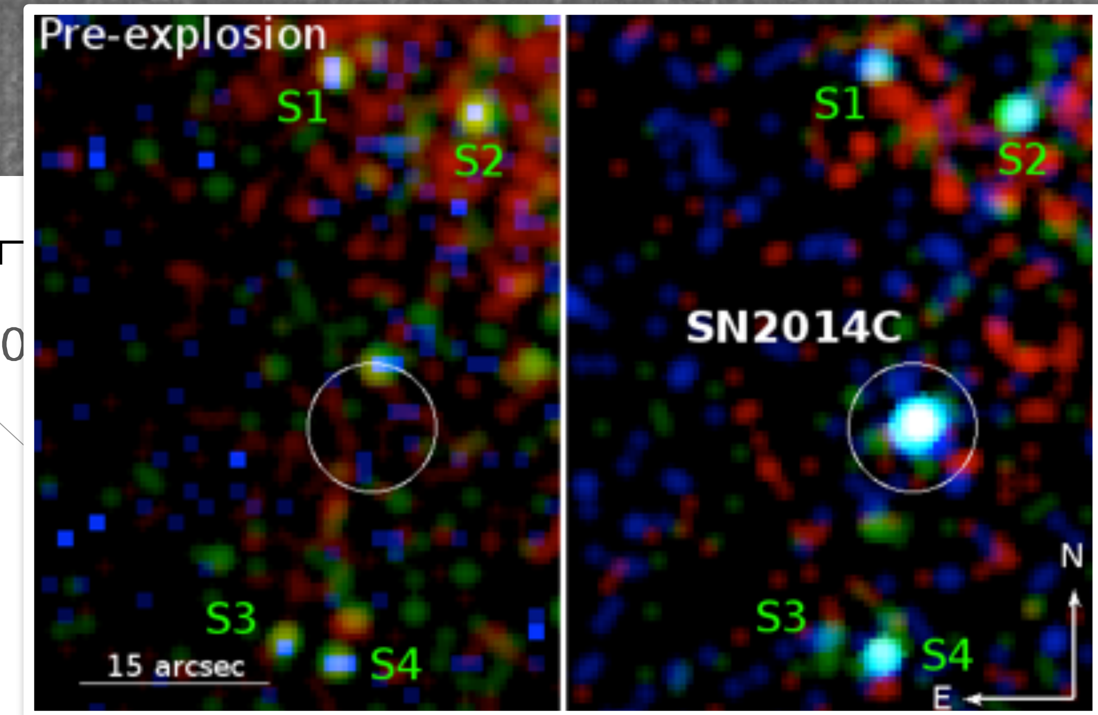

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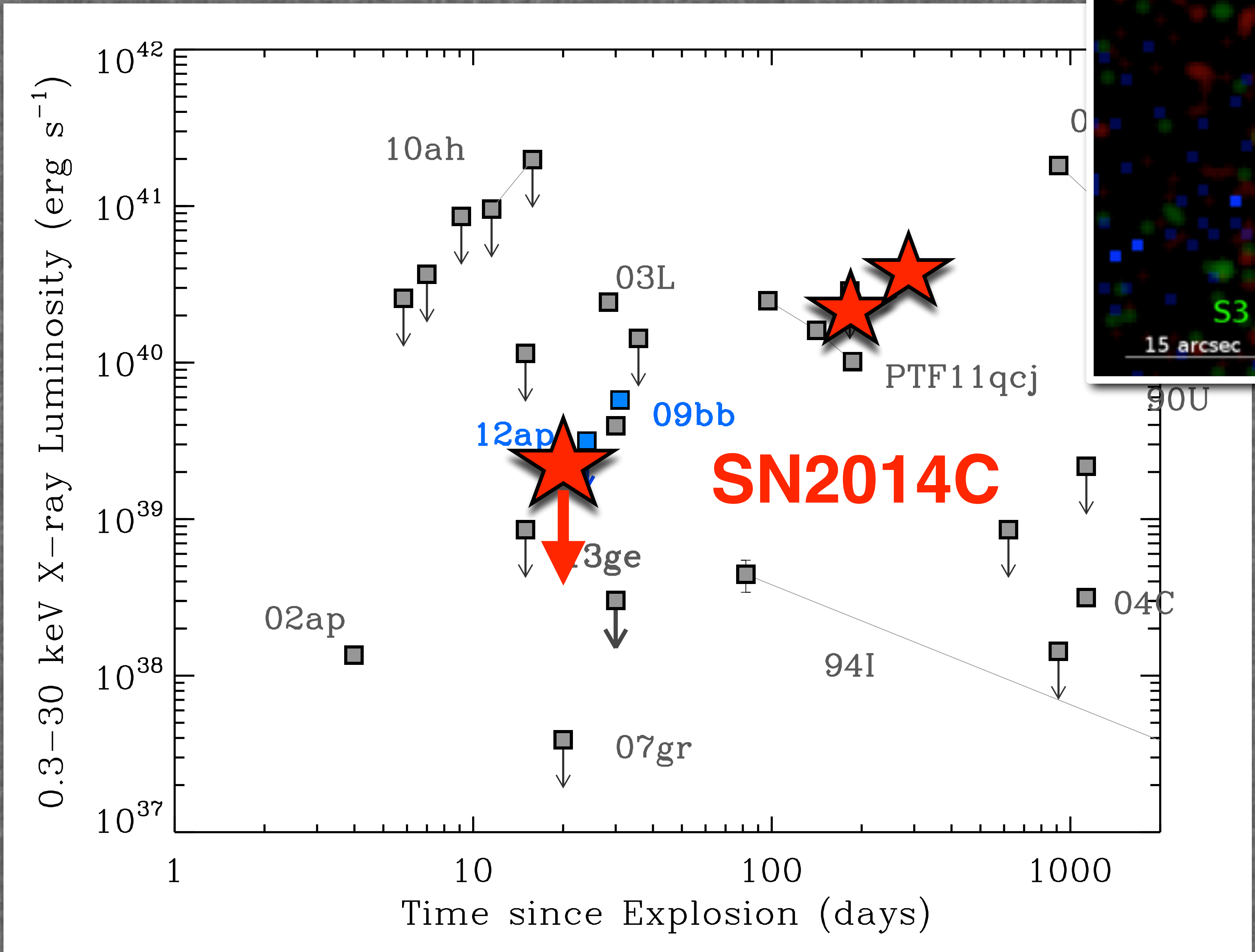

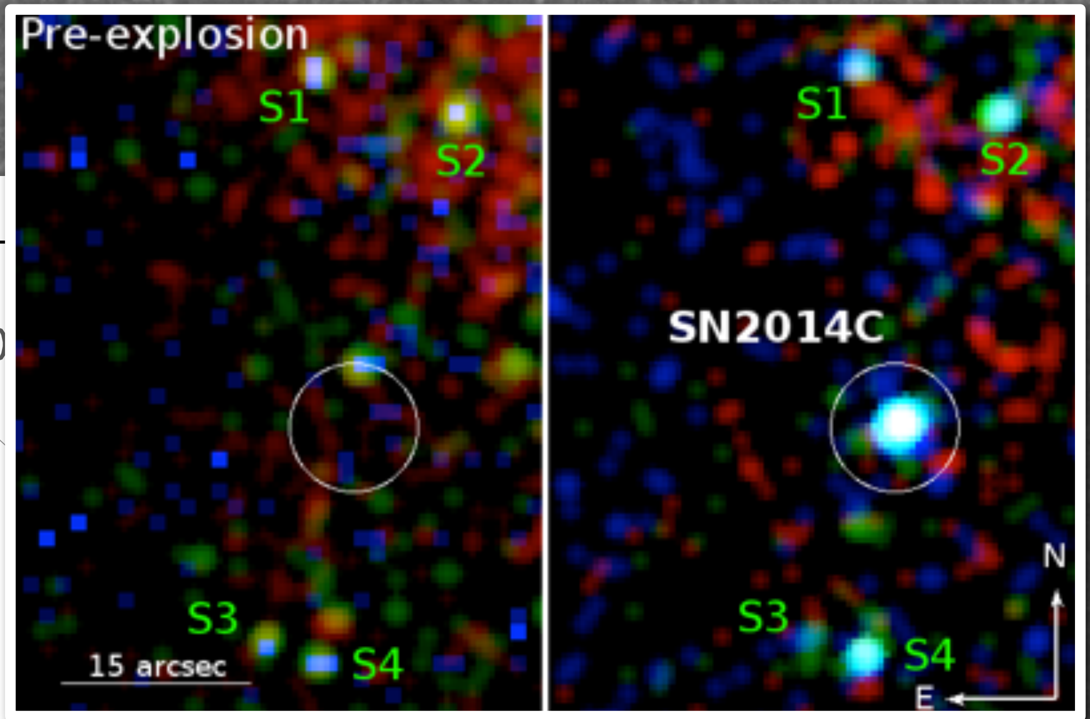

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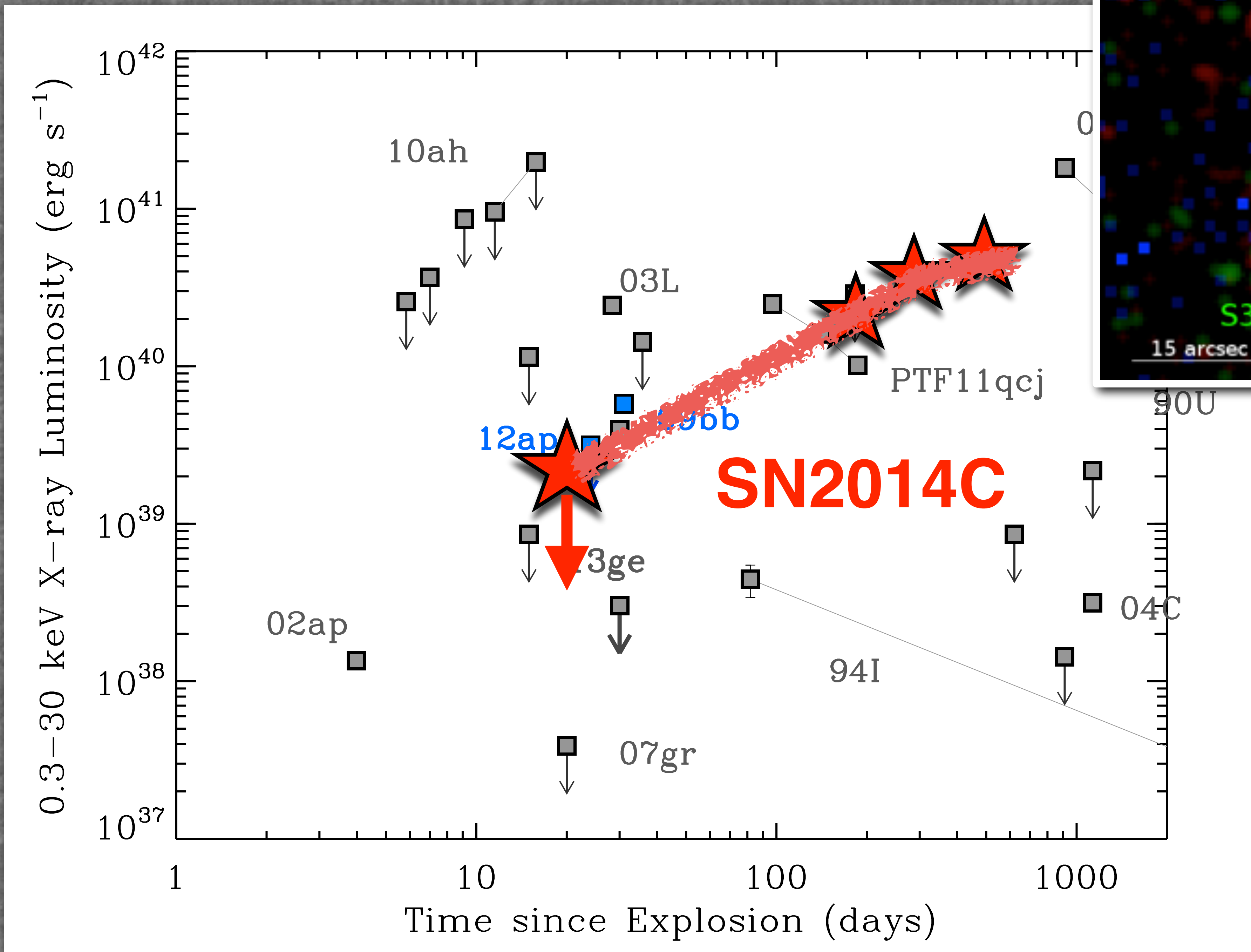

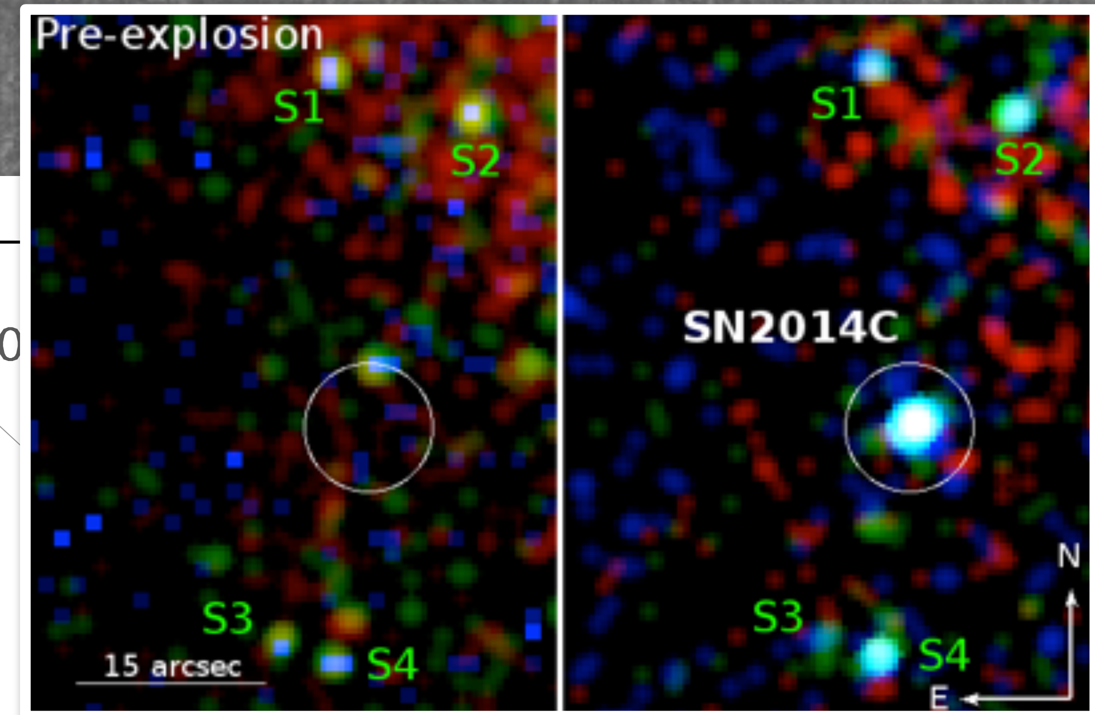

RM+16

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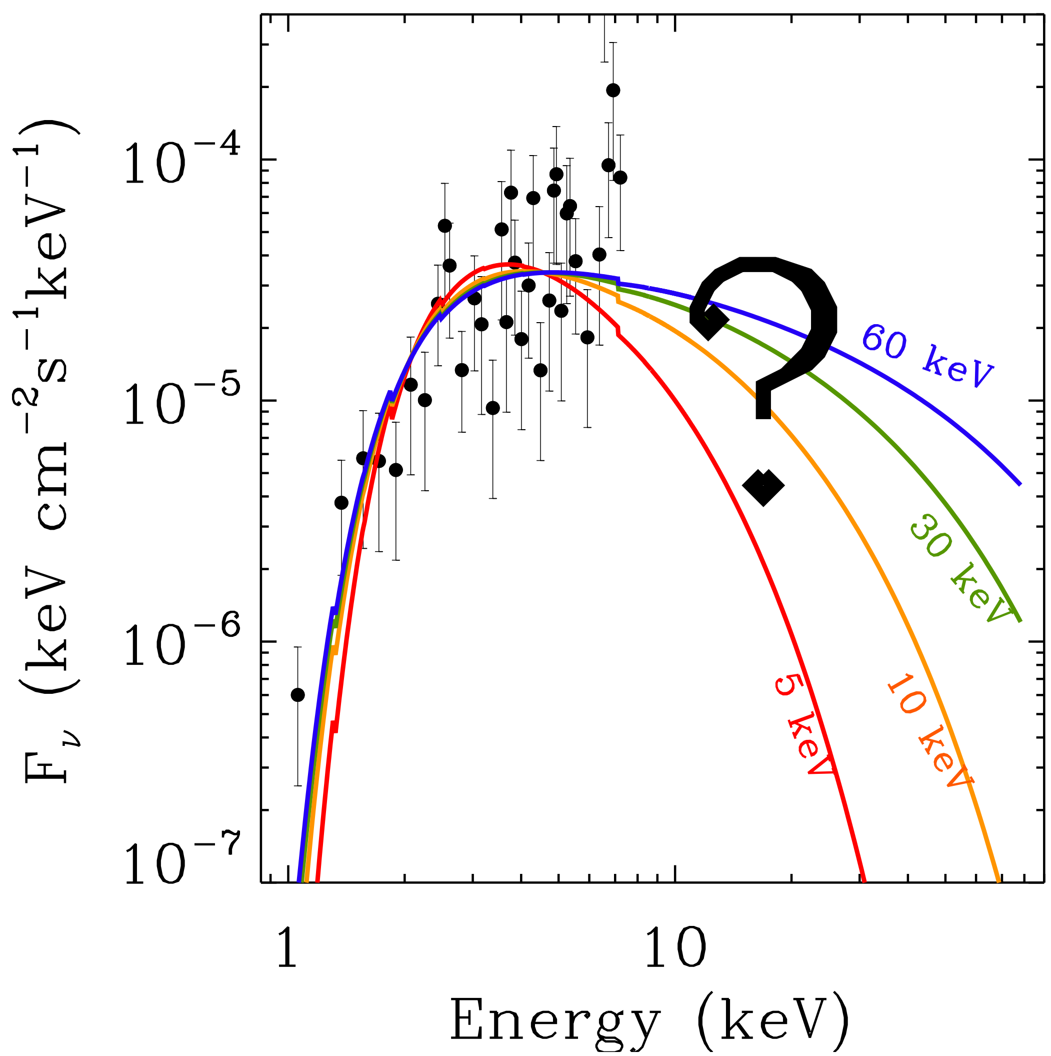
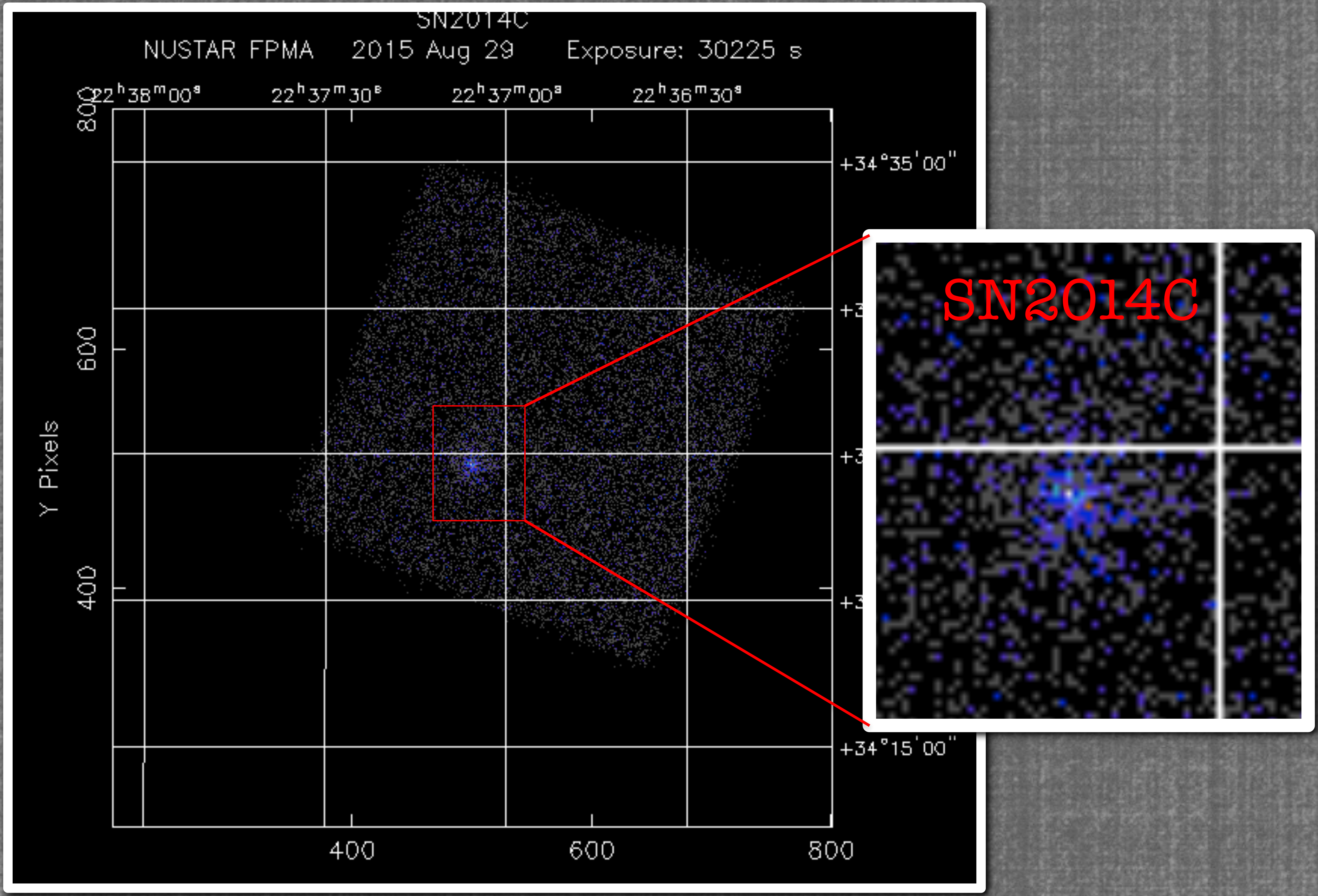
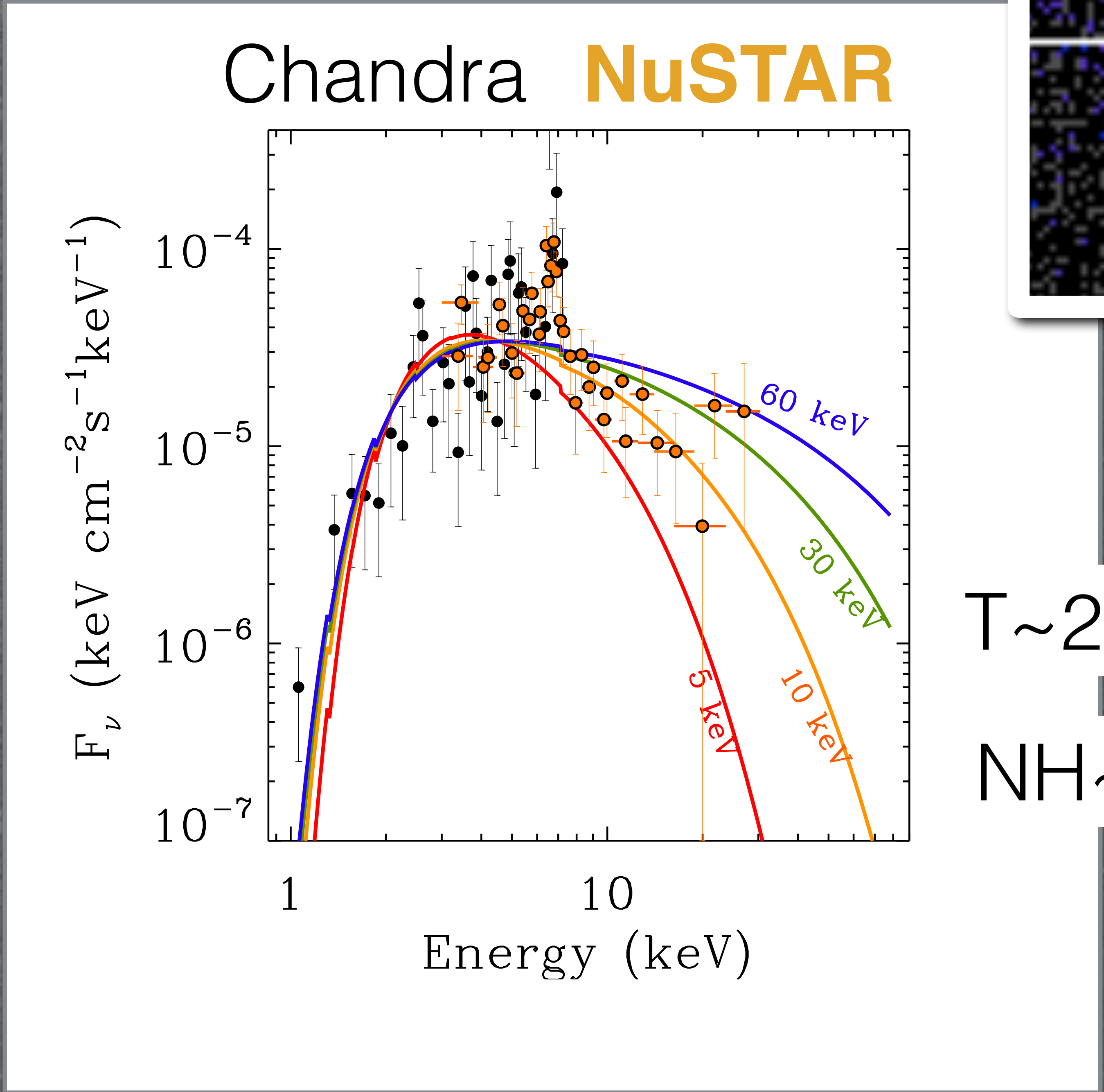
Chandra

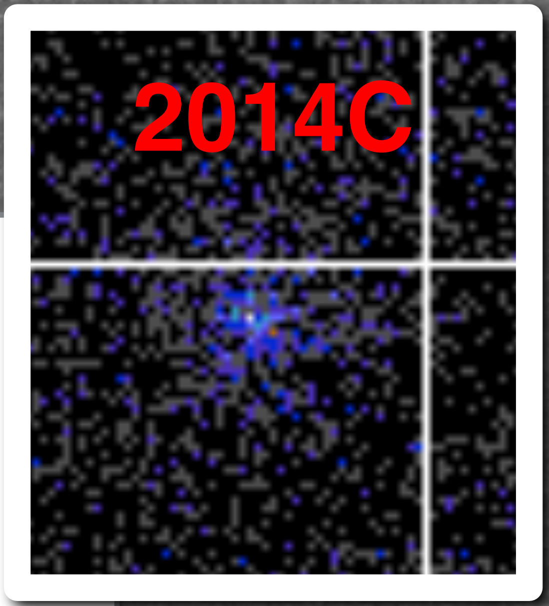


10^{-4}
10^{-5}
10^{-6}
10^{-7}
F_ν (keV cm^{-2}s^{-1}keV^{-1})
1
10
Energy (keV)
60 keV
30 keV
10 keV
5 keV
?

NuSTAR (3-80 keV)



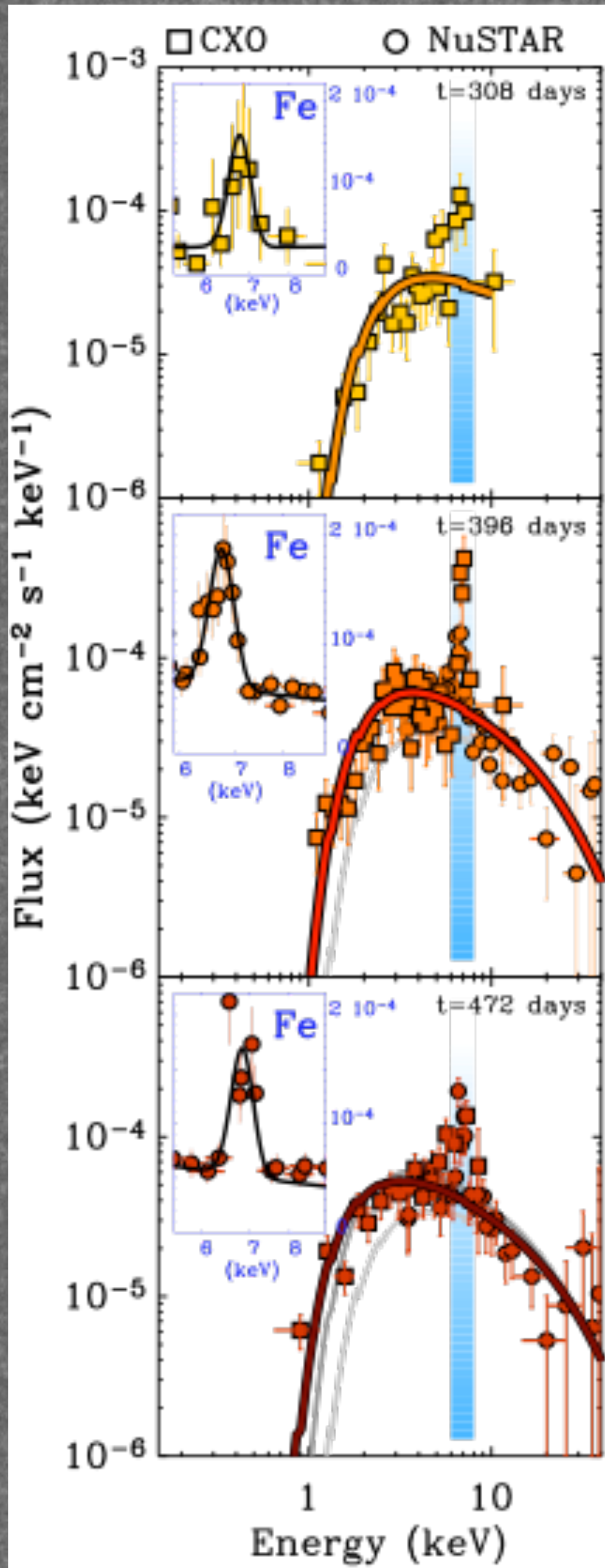




T~20 keV

NH~4d22 cm-2

Chandra+NuSTAR



RM+16

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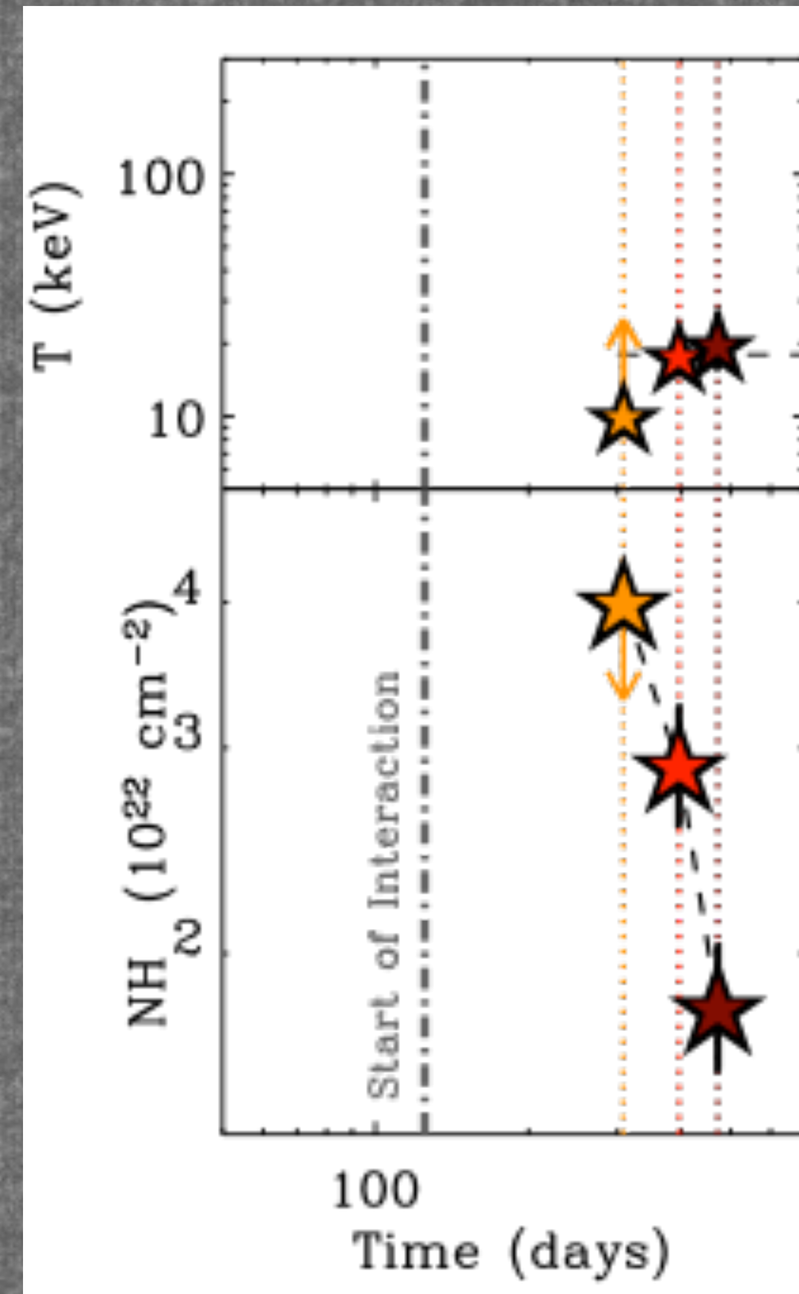
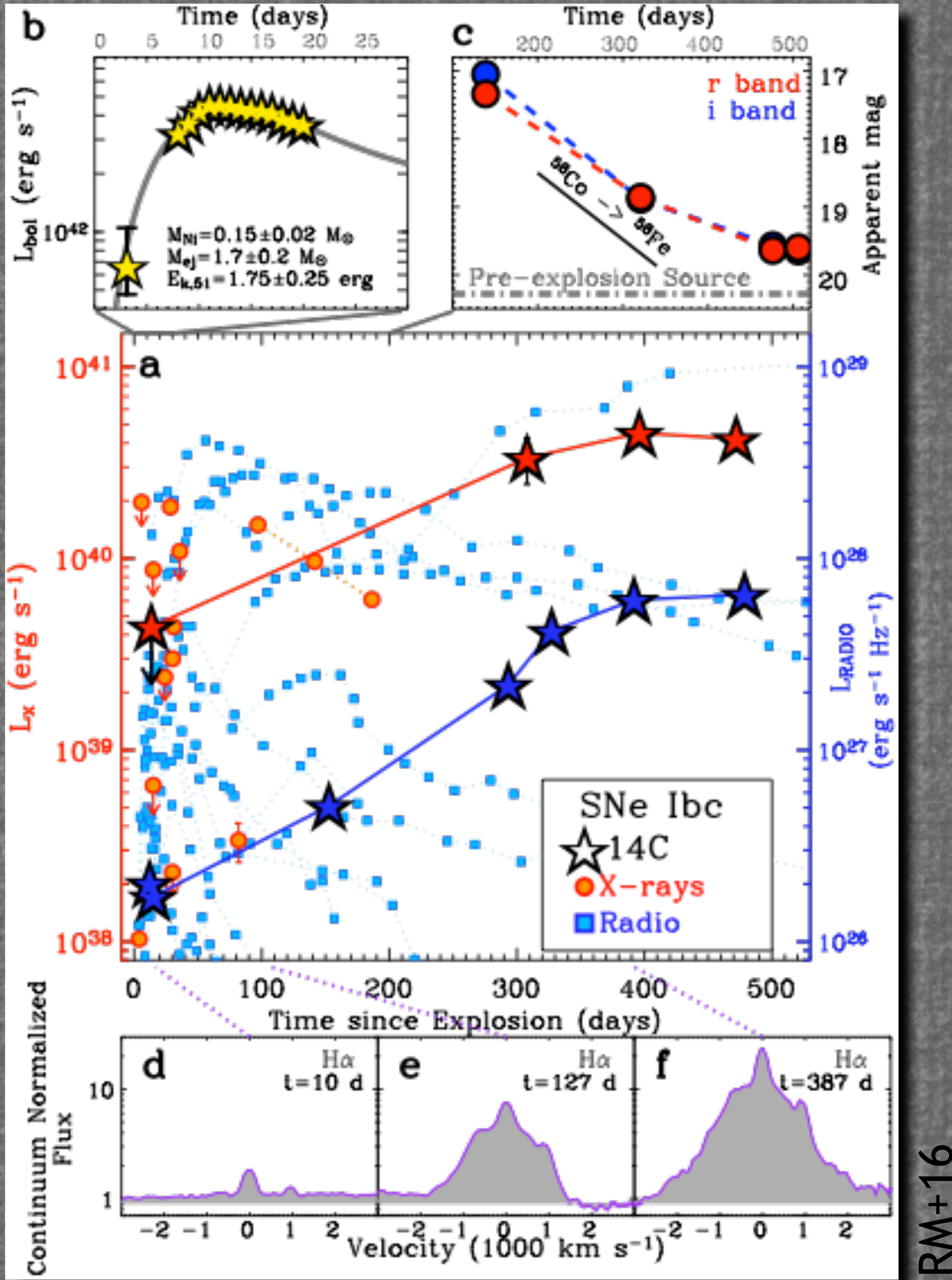
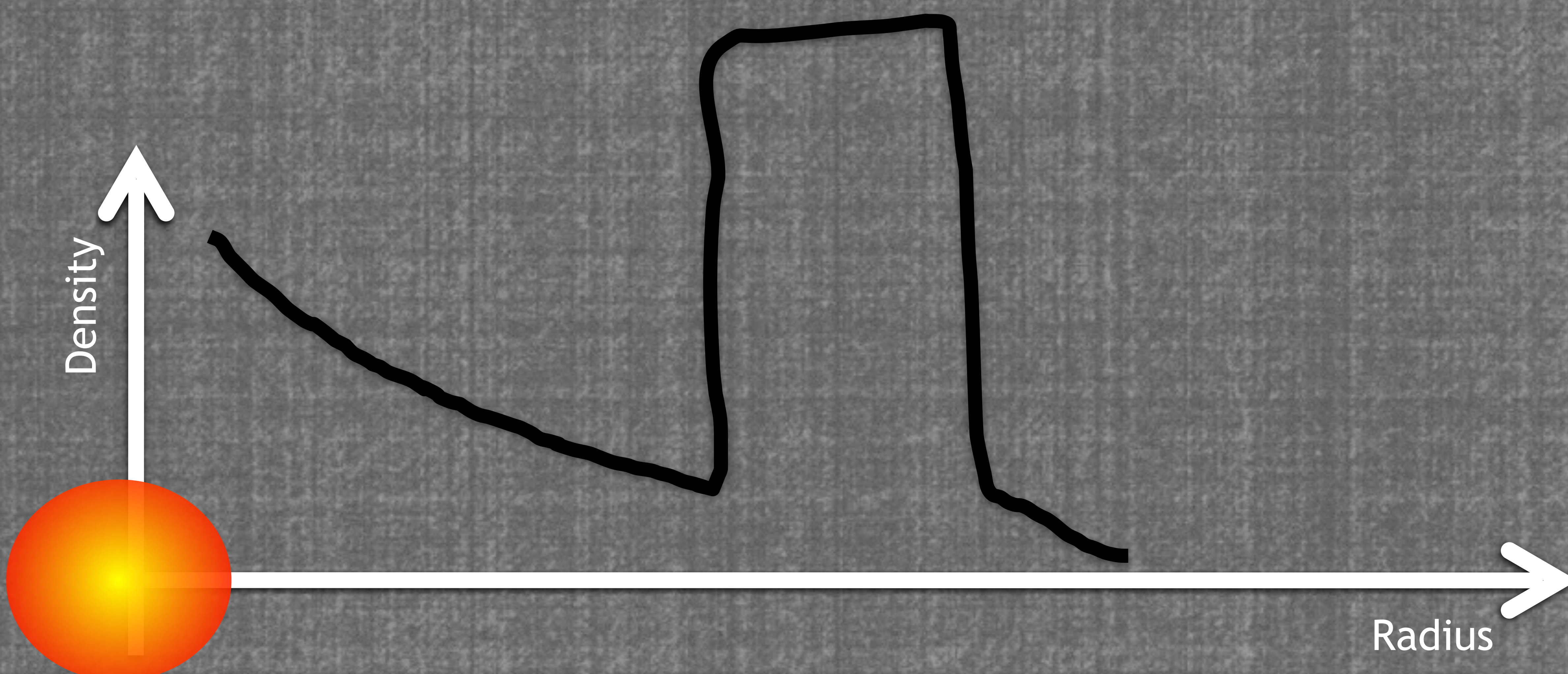


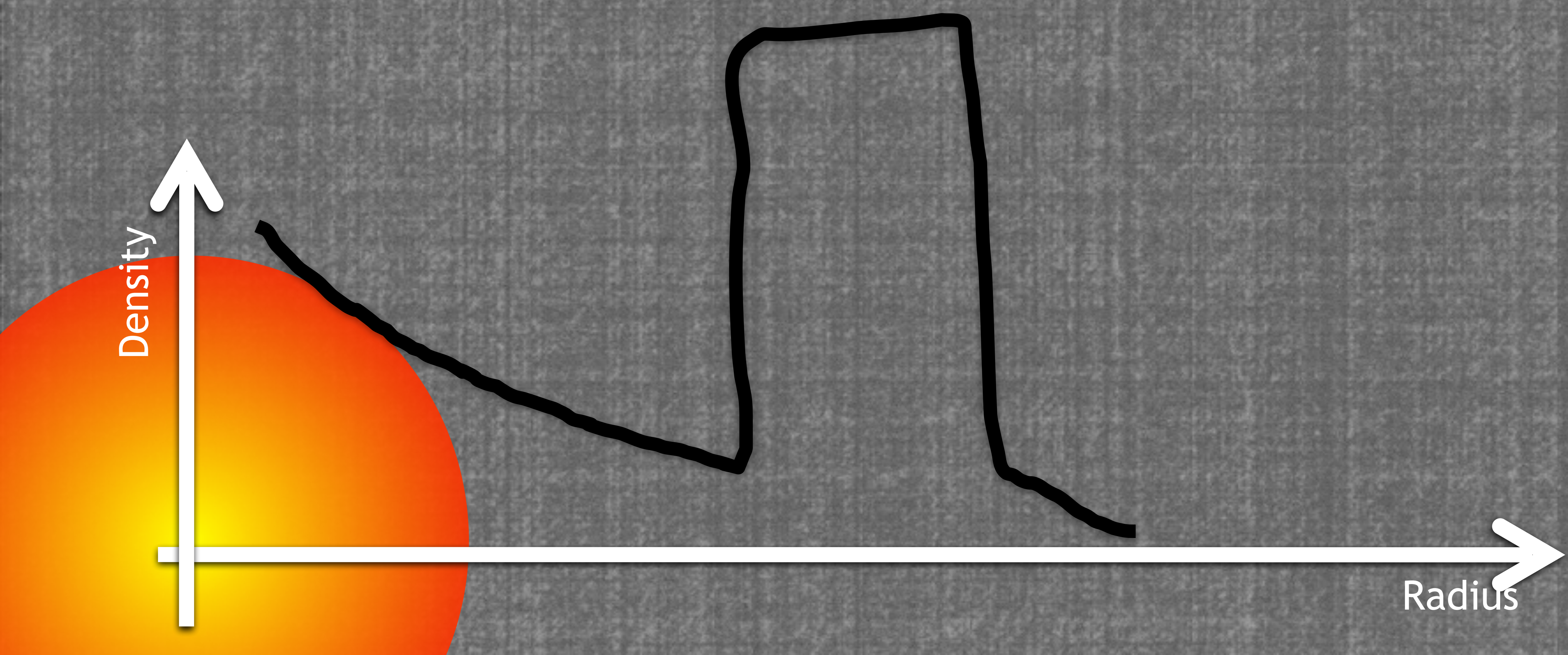
Direct Constraints on the shock dynamics!

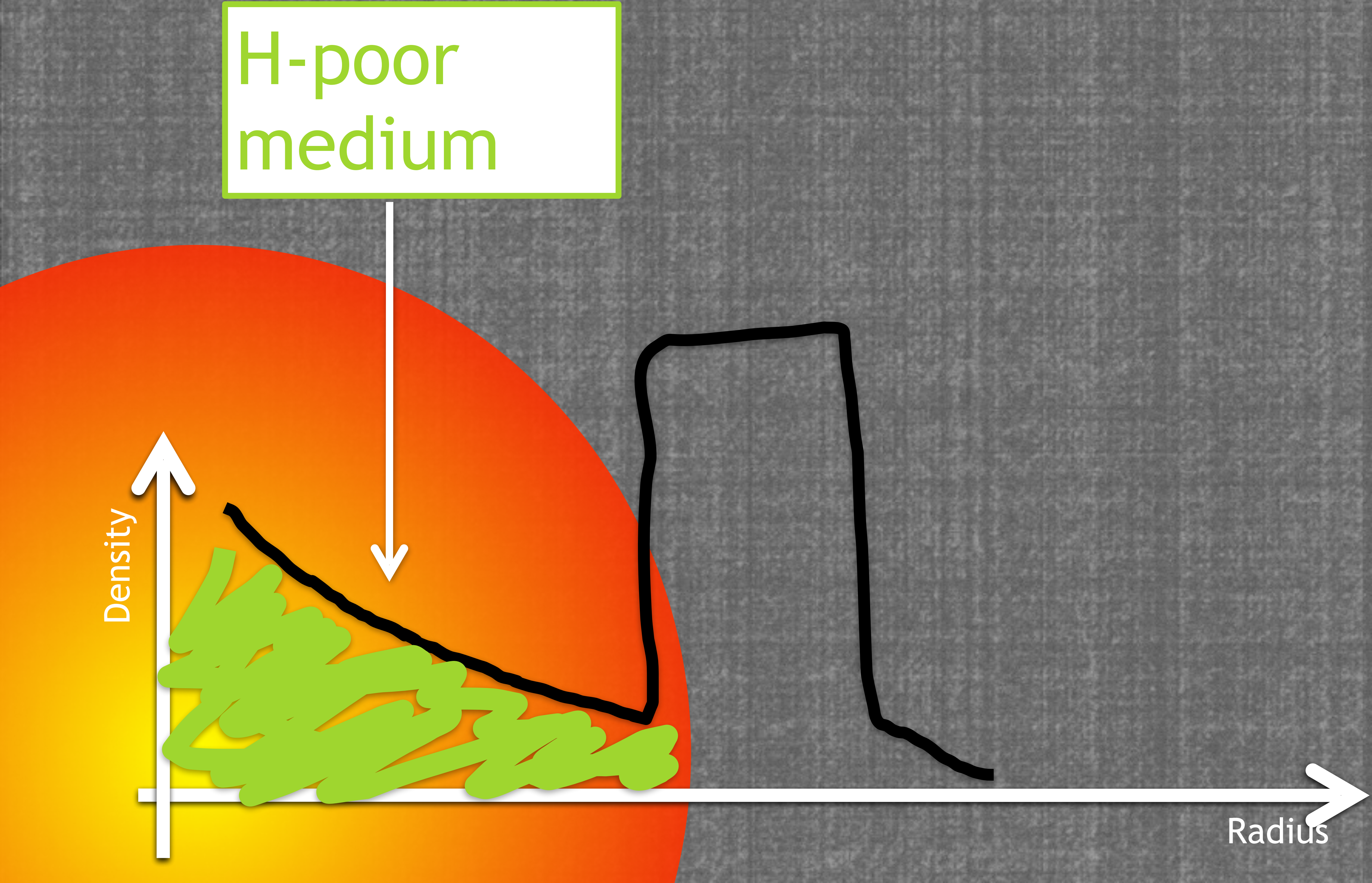


Type I SN ⟶ Type II SN

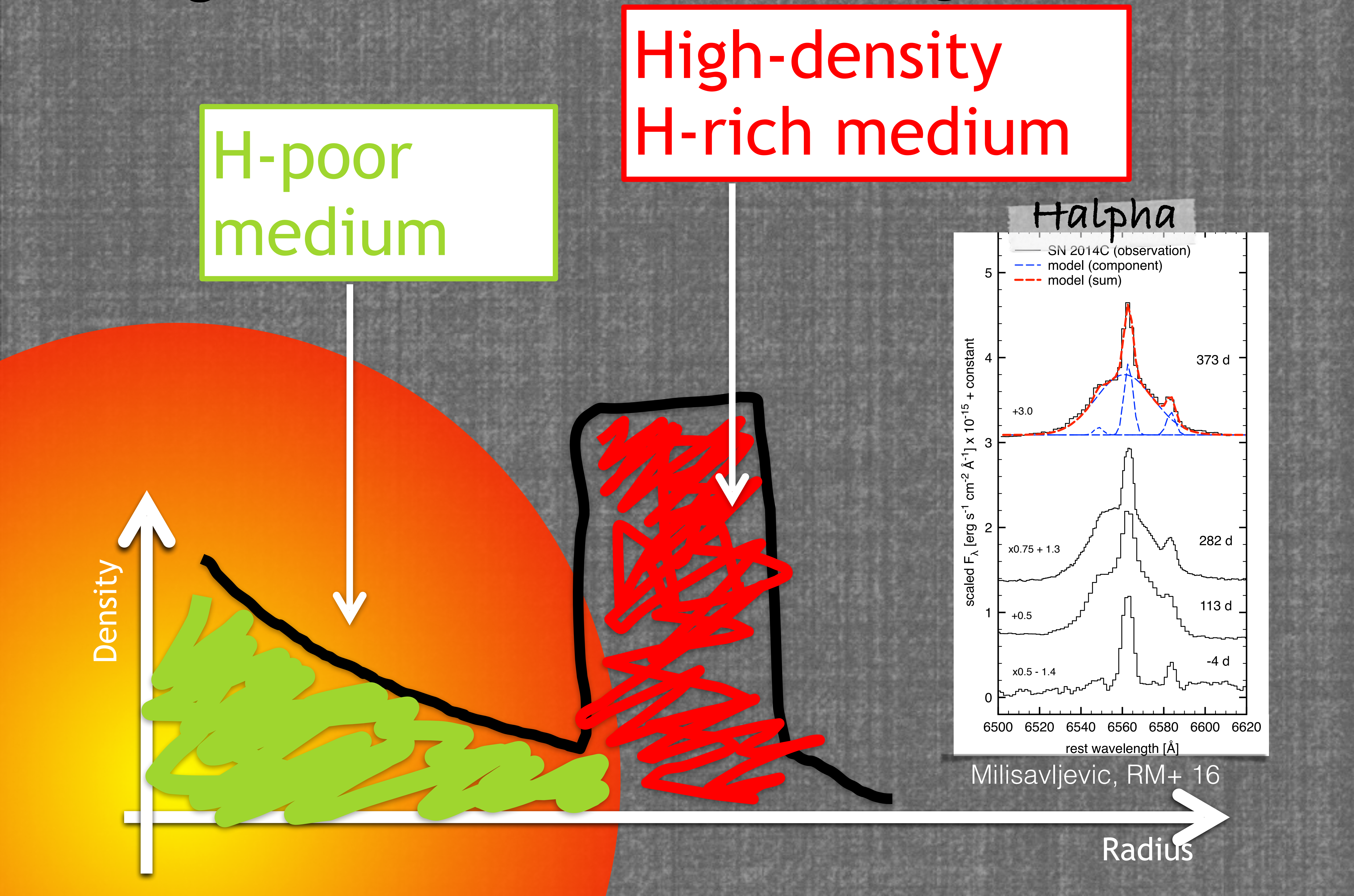


Density
Radius


Density
Radius

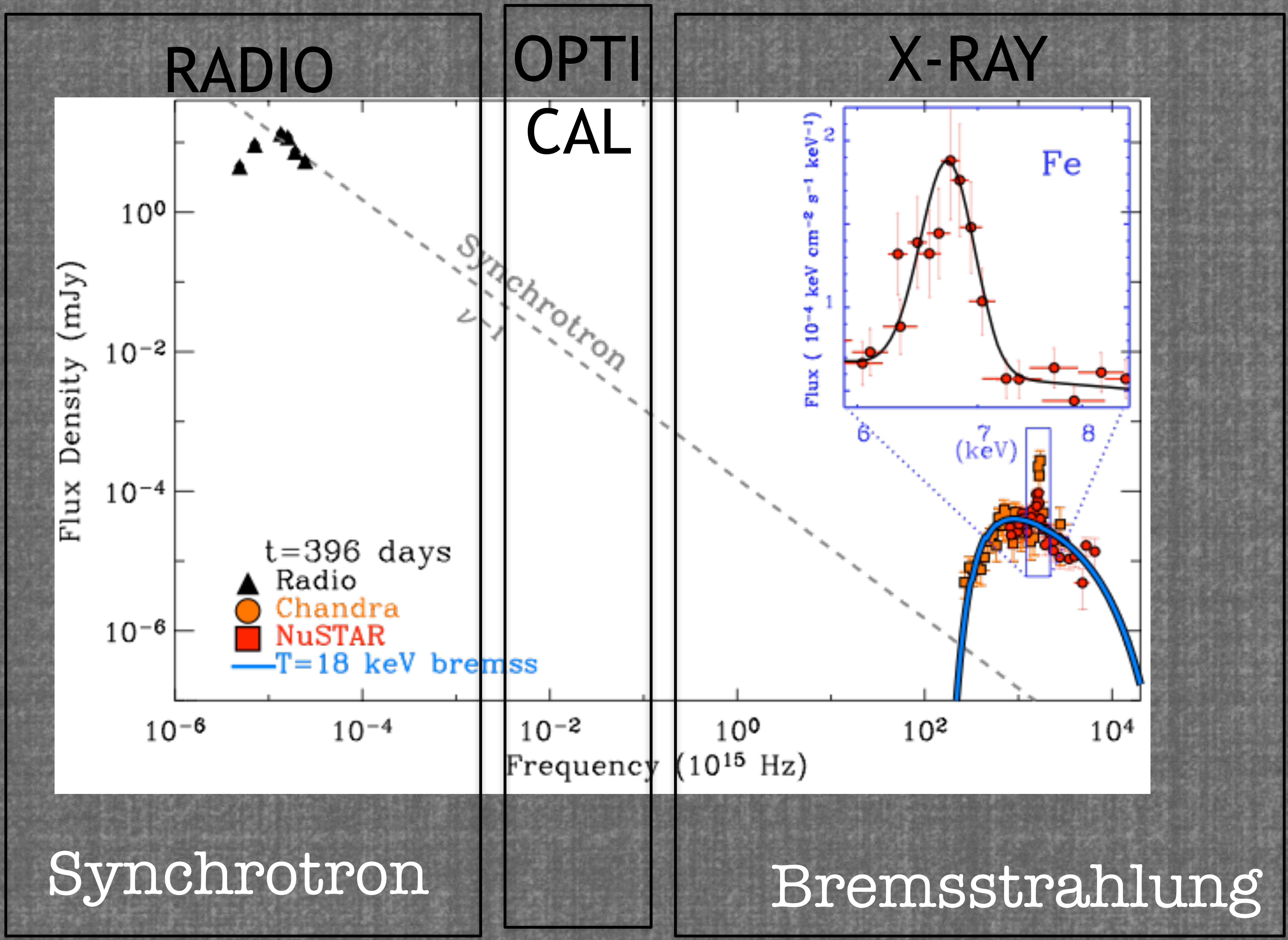

H-poor medium
Density
Radius

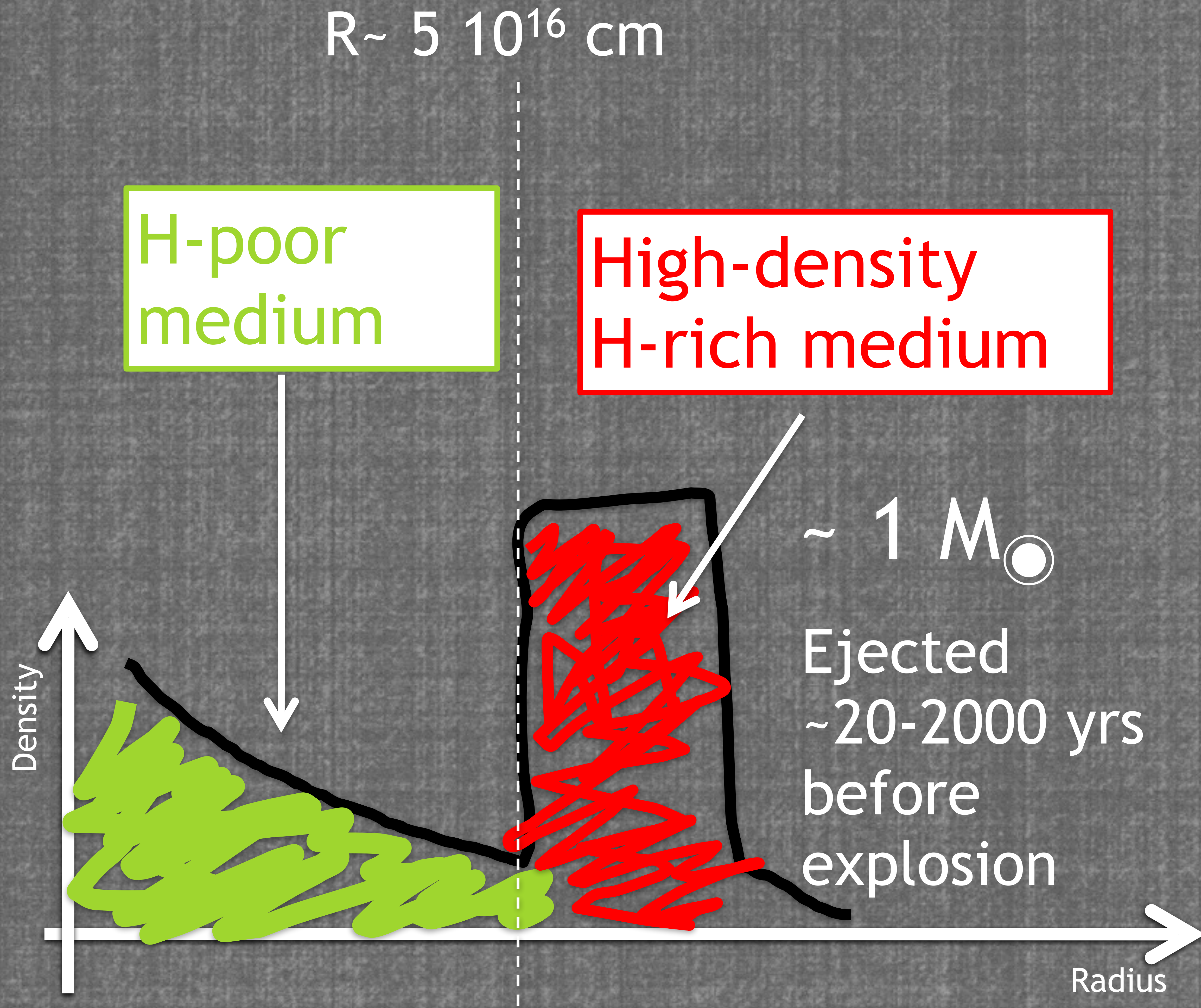
Type I → Type II



Milisavljevic, RM+ 16

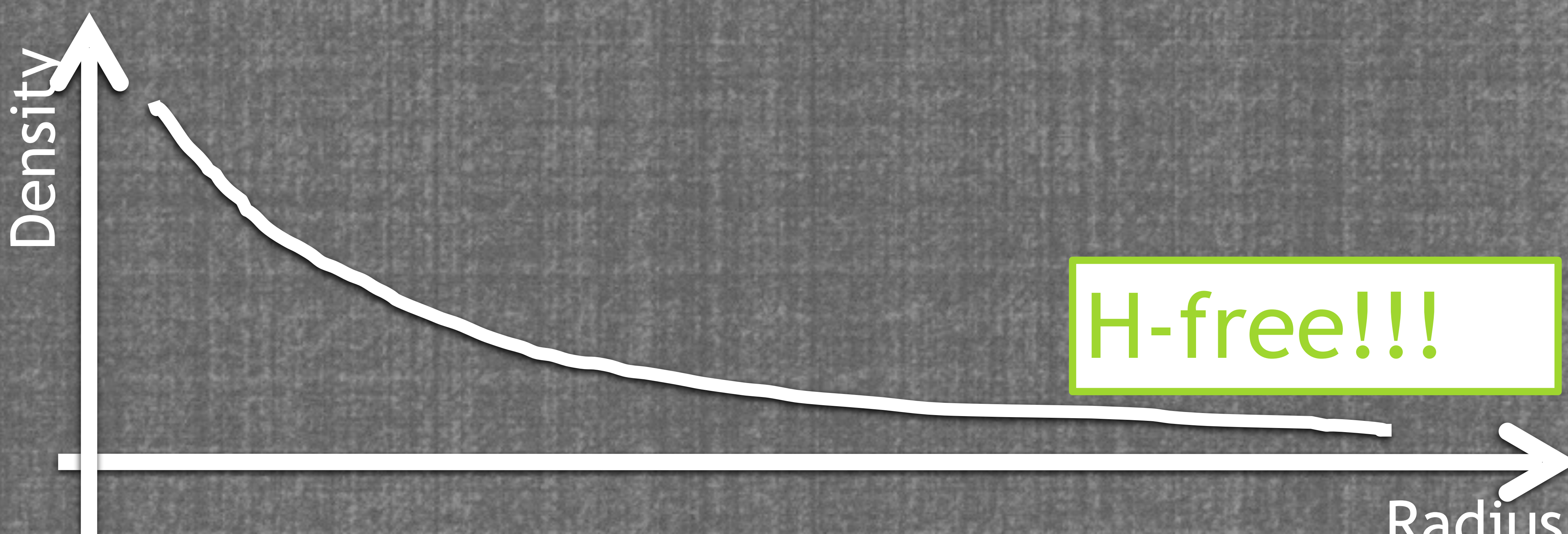
Multi-wavelength Follow Up



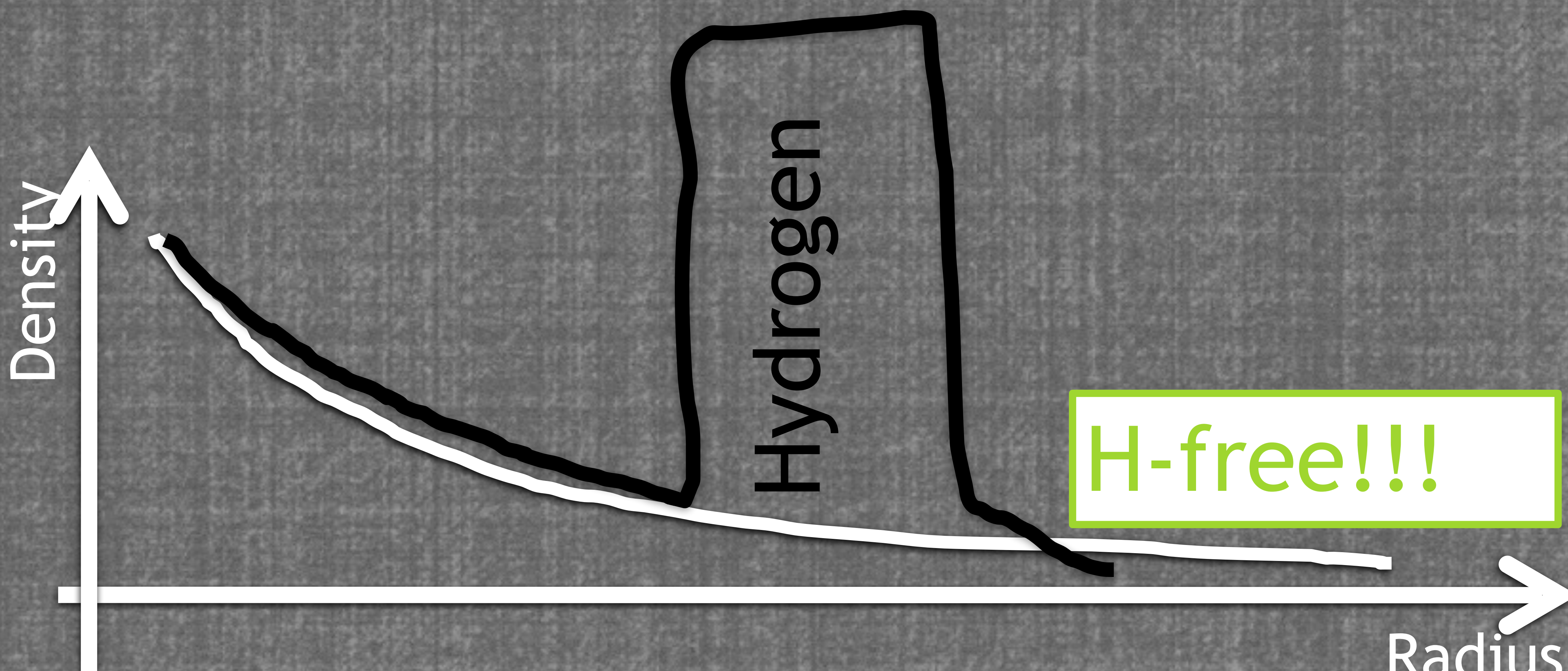

R~ 5 10^16 cm
H-poor medium
High-density H-rich medium
~ 1 M⊙
Ejected ~20-2000 yrs before explosion
Density
Radius

Why ?

Expected Evolution from Stellar tracks:



Expected Evolution from Stellar tracks:



Why so important?

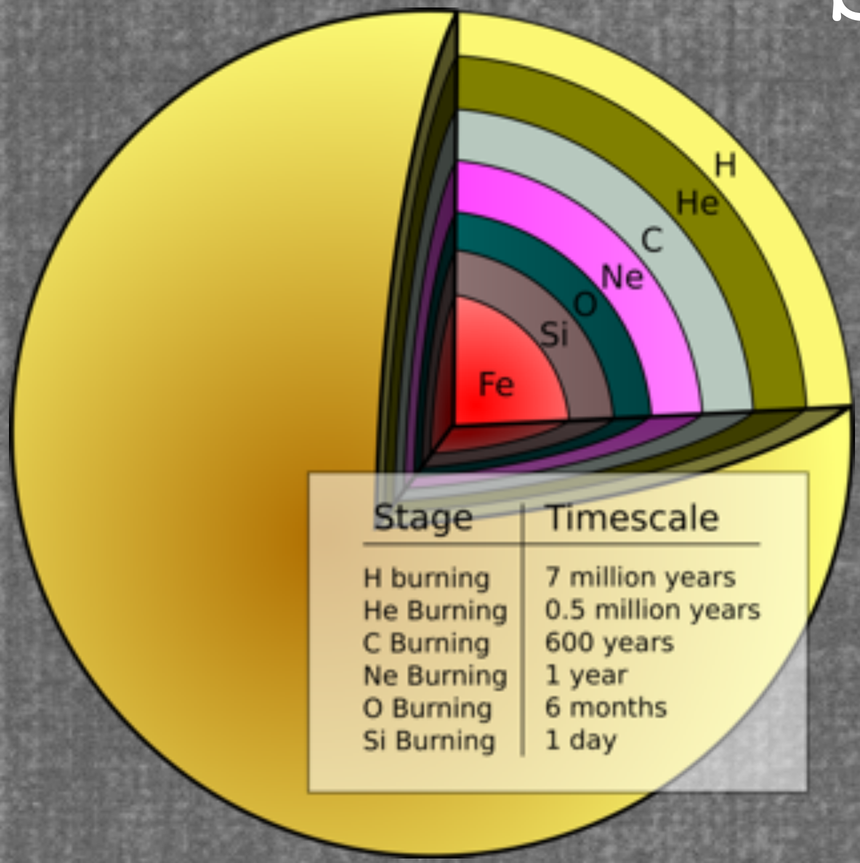
Mass - Loss

↓

Stellar Structure at Collapse

↓

"Explodability" of a Star



Why so important?

Young SN shocks as particle accelerators

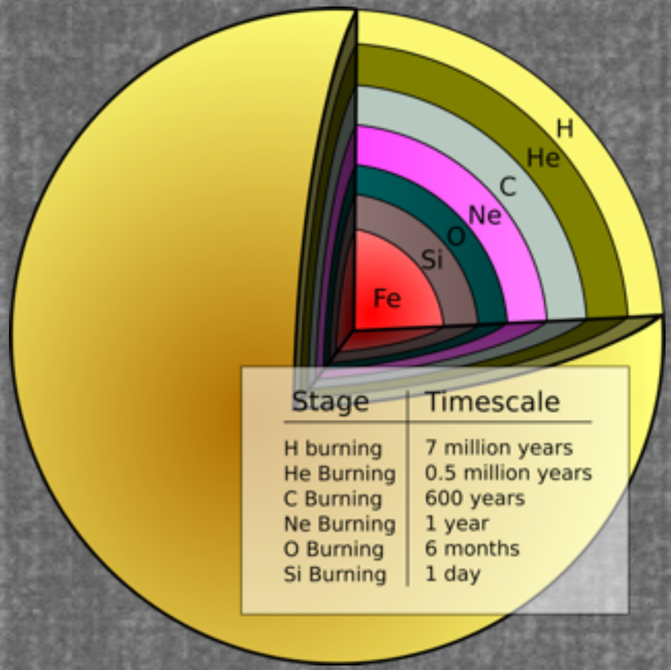
Mass - Loss

Chemical Enrichment of the Universe

Stellar Structure at Collapse

"Explodability" of a Star

Impact our understanding of the **Star Formation History** of the Universe.



Multi-Wavelength observations of Stellar Explosions

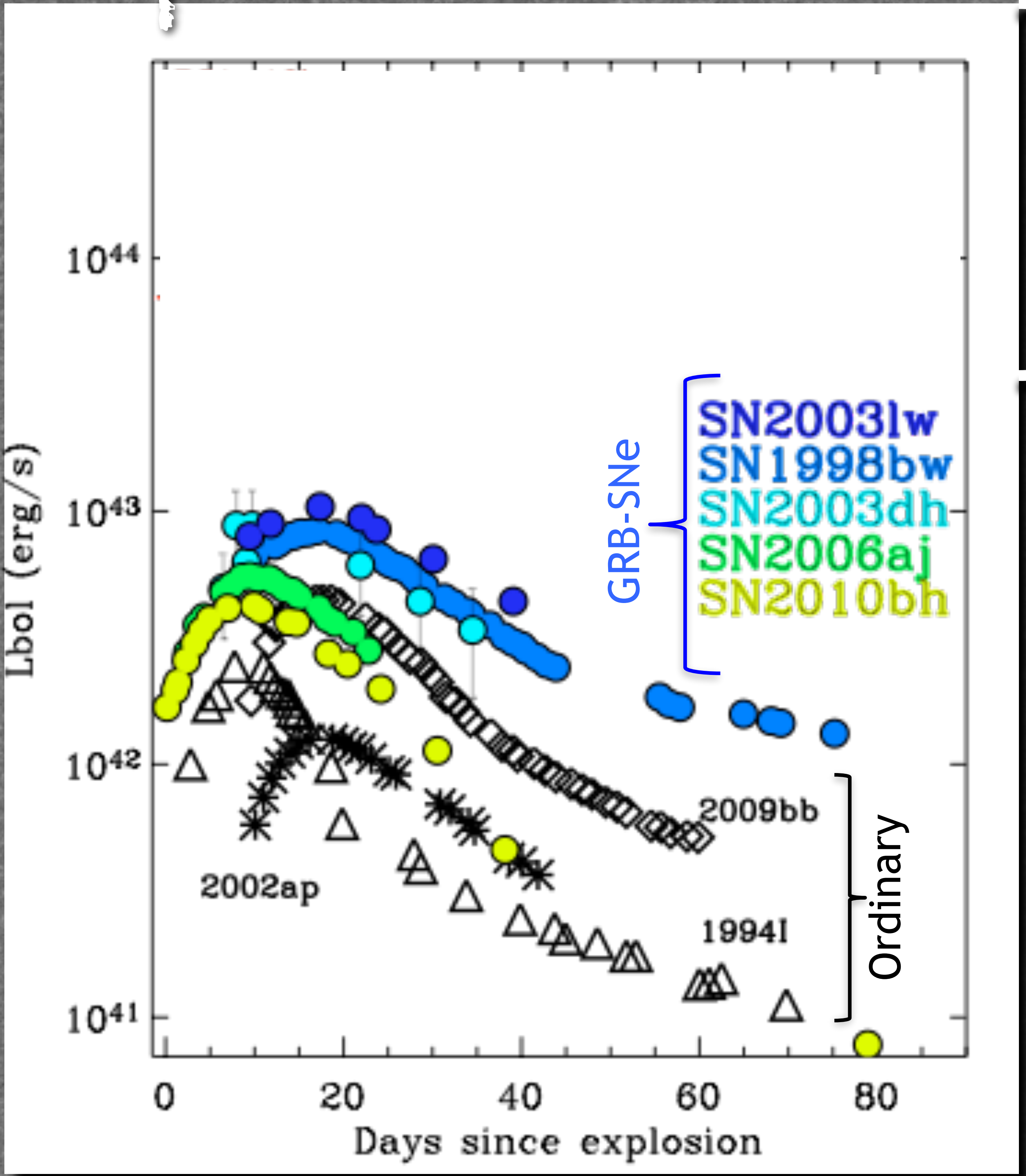
- Engine-driven Stellar Explosions
- Strongly Interacting SNe
- Super-Luminous SNe

RESULTS from:

The first systematic search for Super-Luminous X-rays from Super-Luminous SNe

Margutti et al., in prep.

Super-Luminous SNe



$E_{rad} = 10^{51}$ erg

$E_K = 10^{52}$ erg

What Source of Energy powers SLSNe ?

ENERGY SOURCE- SUPERLUMINOUS

What powers SLSNe?

Interaction

E.g. Chevalier 2011
Pan & Loeb 2013

^{56}Ni

Gal-Yam 2009

Magnetar

Kasen & Bildsten 2010
Woosley 2010

What powers SLSNe?

Interaction
E.g. Chevalier 2011
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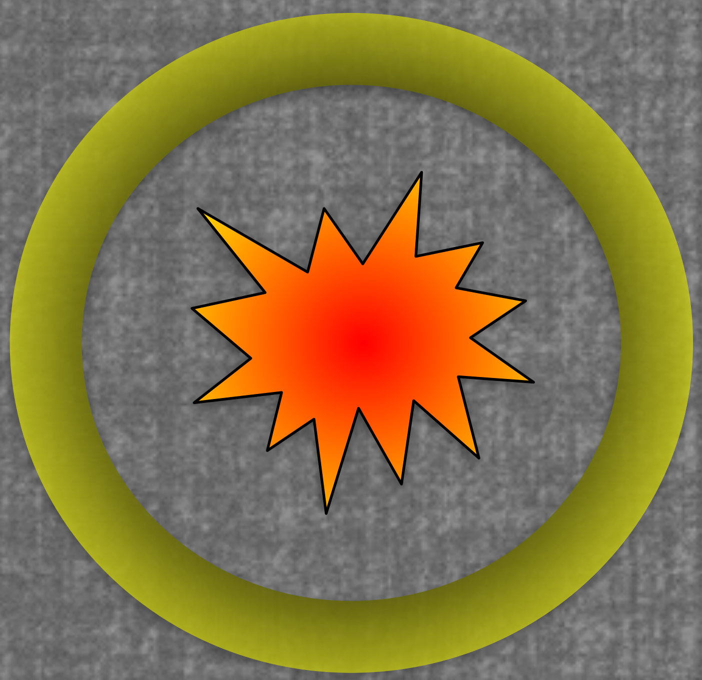
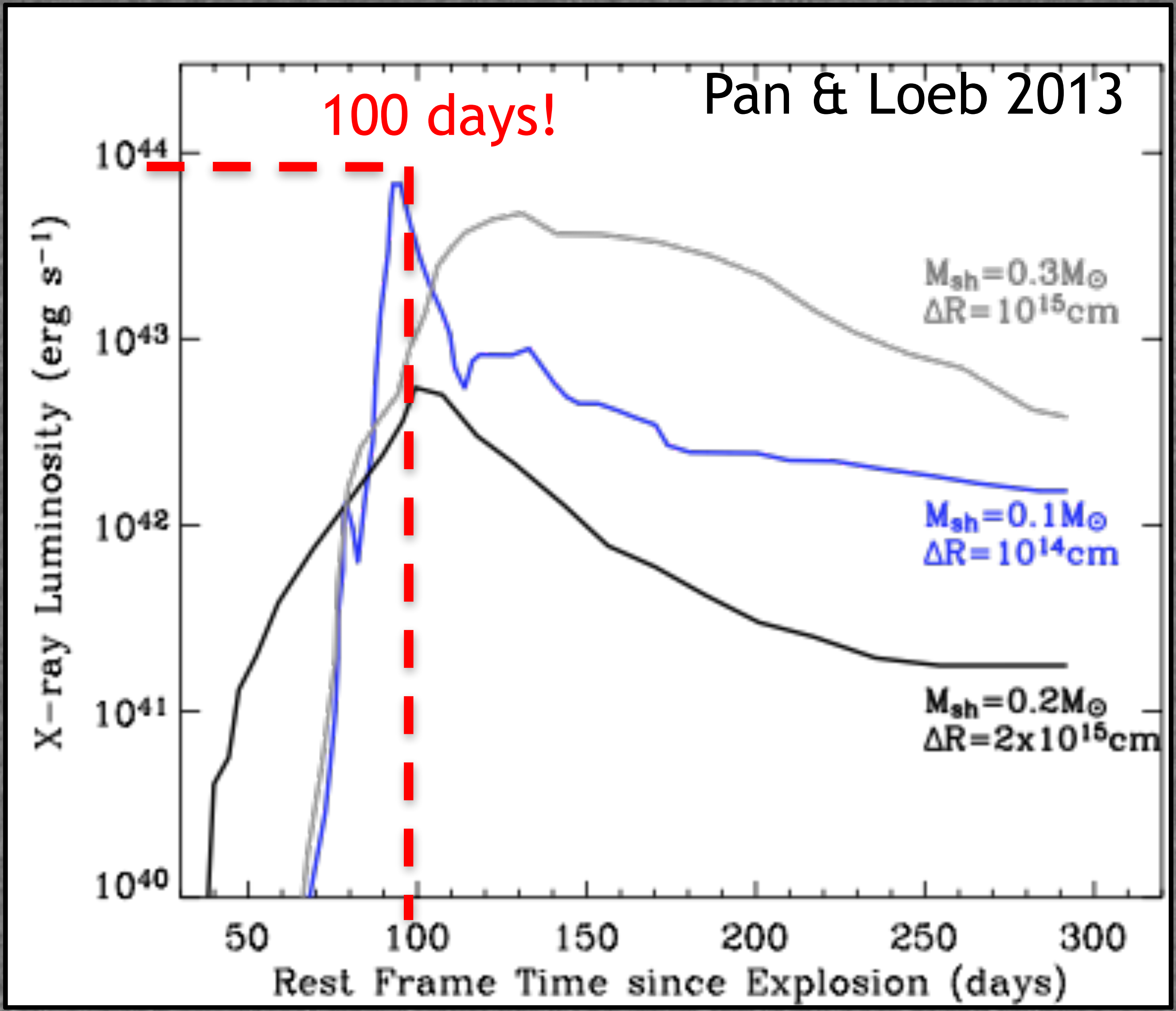


Increased Efficiency



What powers SLSNe?

Interaction
E.g. Chevalier 2011
Pan & Loeb 2013

^{56}Ni
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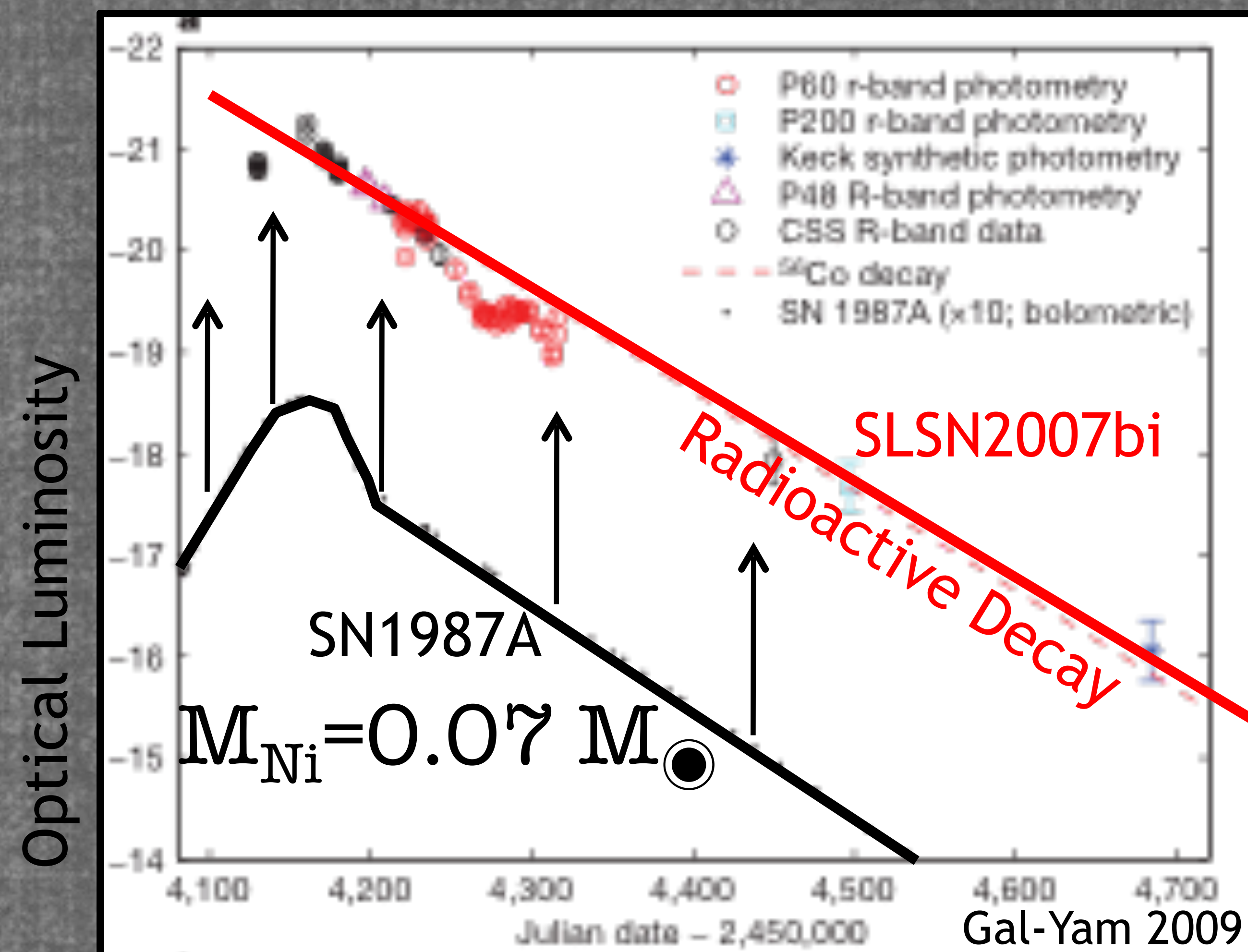


X-rays from shock interaction with an ordinary medium
→ Super-Luminous X-rays are *not* a natural expectation

Late-time optical observations

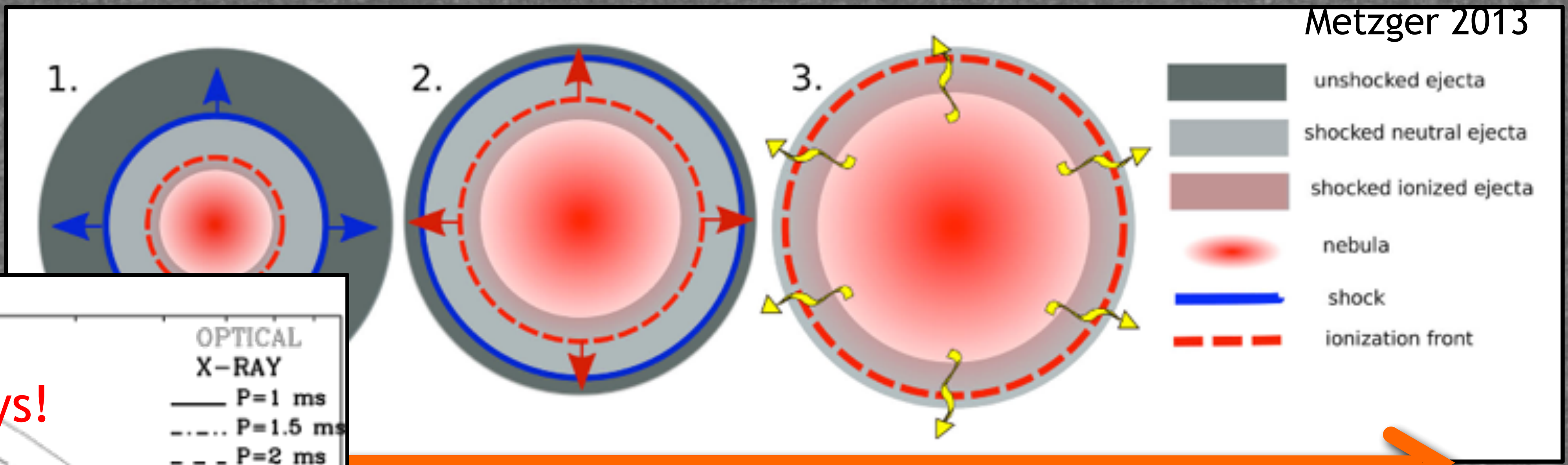
$4M_\odot < {}^{56}Ni < 7M_\odot$

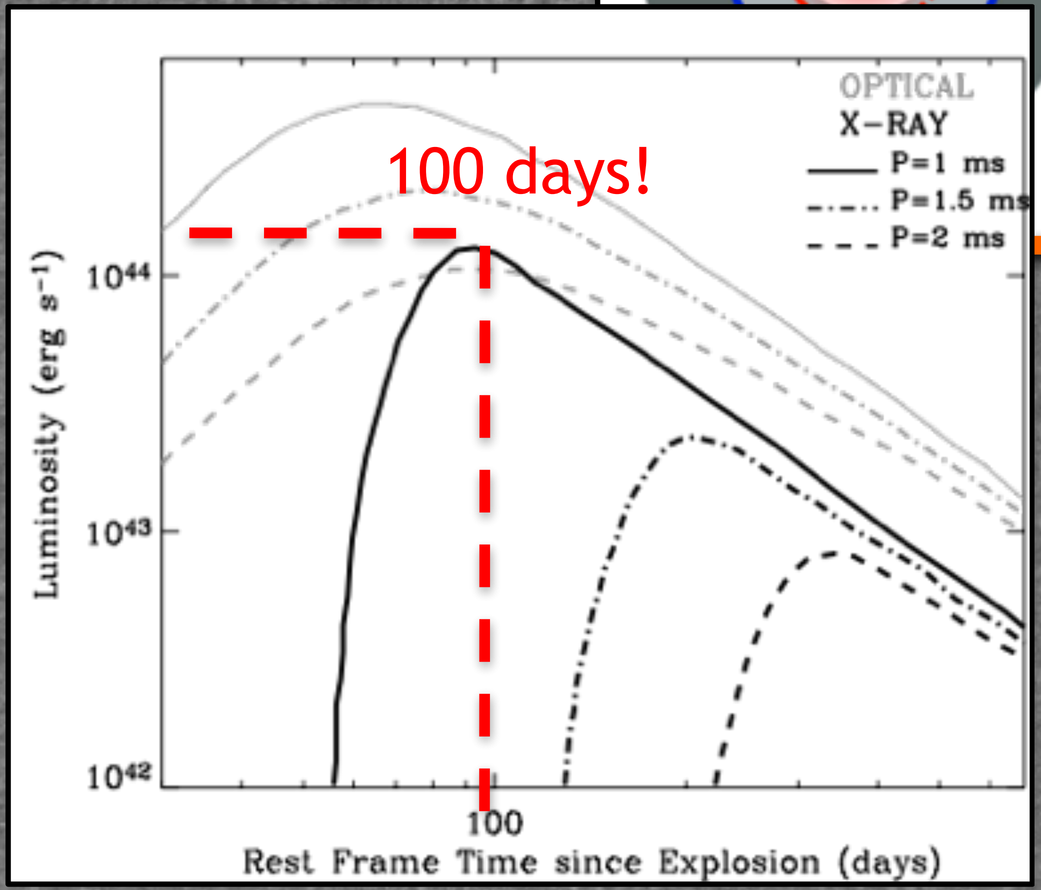
What powers SLSNe?

Interaction
E.g. Chevalier 2011
Pan & Loeb 2013

^{56}Ni
Gal-Yam 2009

Magnetar
Kasen & Bildsten 2010
Woosley 2010





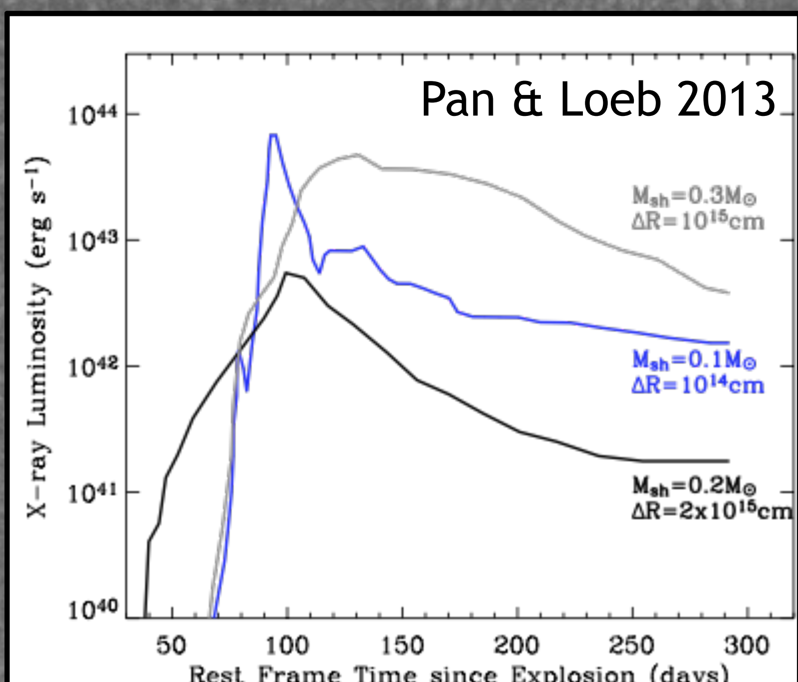
TIME

"The problem is completely specified by the properties of the pulsar and of the ejecta"
Metzger 2013

What powers SLSNe?

Interaction

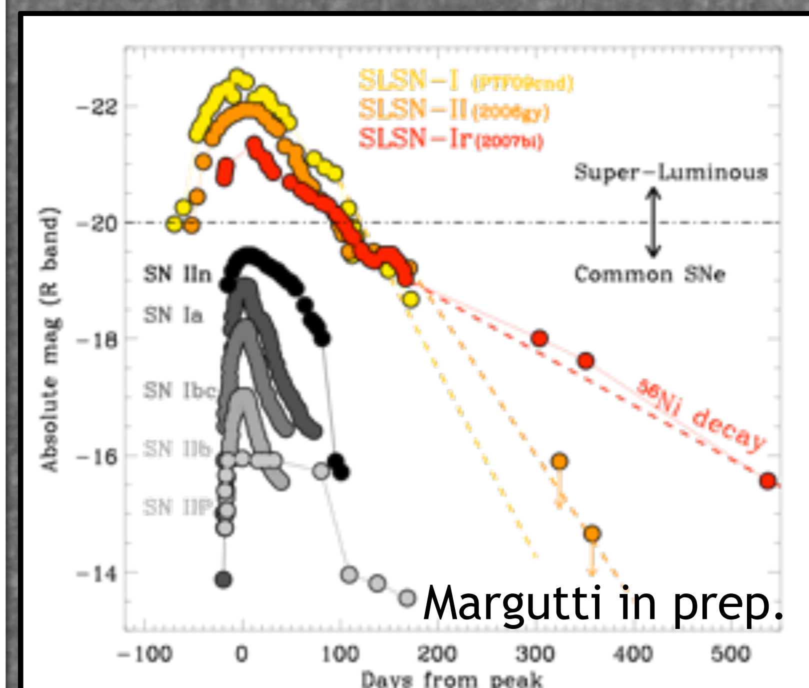
E.g. Chevalier 2011
Pan & Loeb 2013



X-rays

^{56}Ni

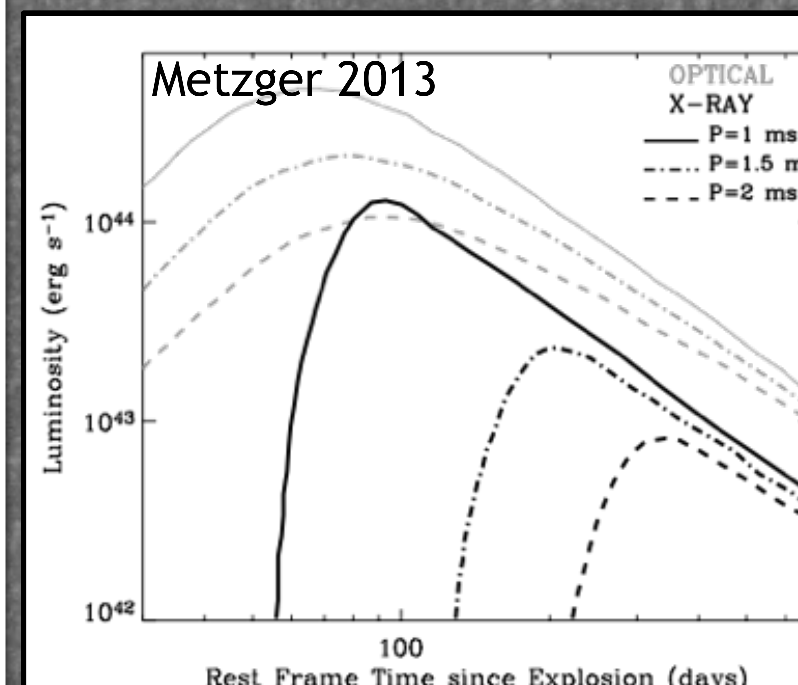
E. g. Gal-Yam 2009
(Pair Instability Explosions)



Optical

Magnetar

E.g. Kasen & Bildsten 2010
Woosley 2010

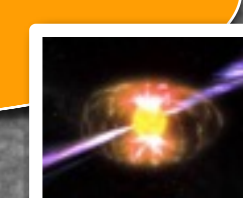


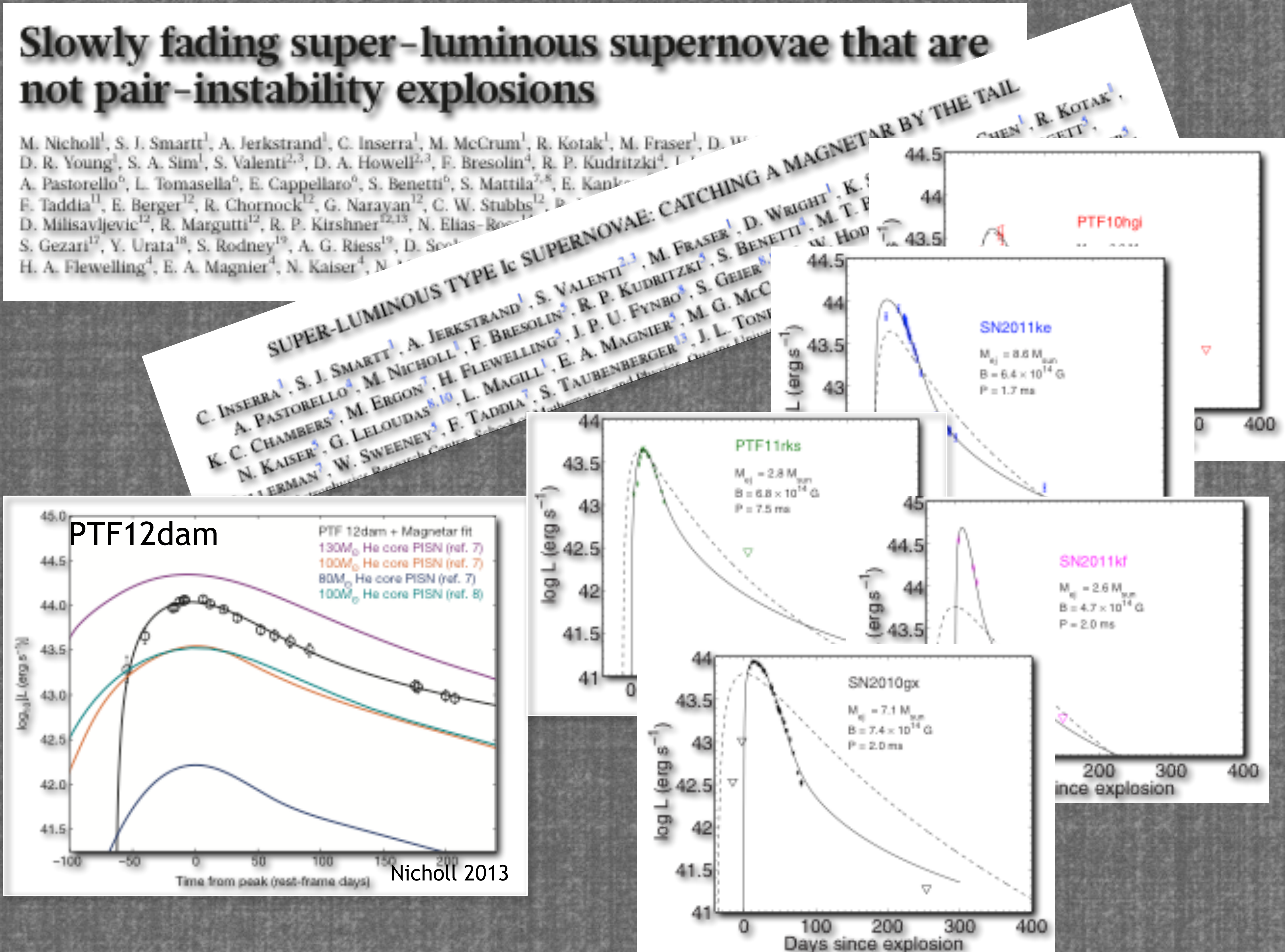
X-rays+Optical

Increased Efficiency

More "Ordinary Fuel"

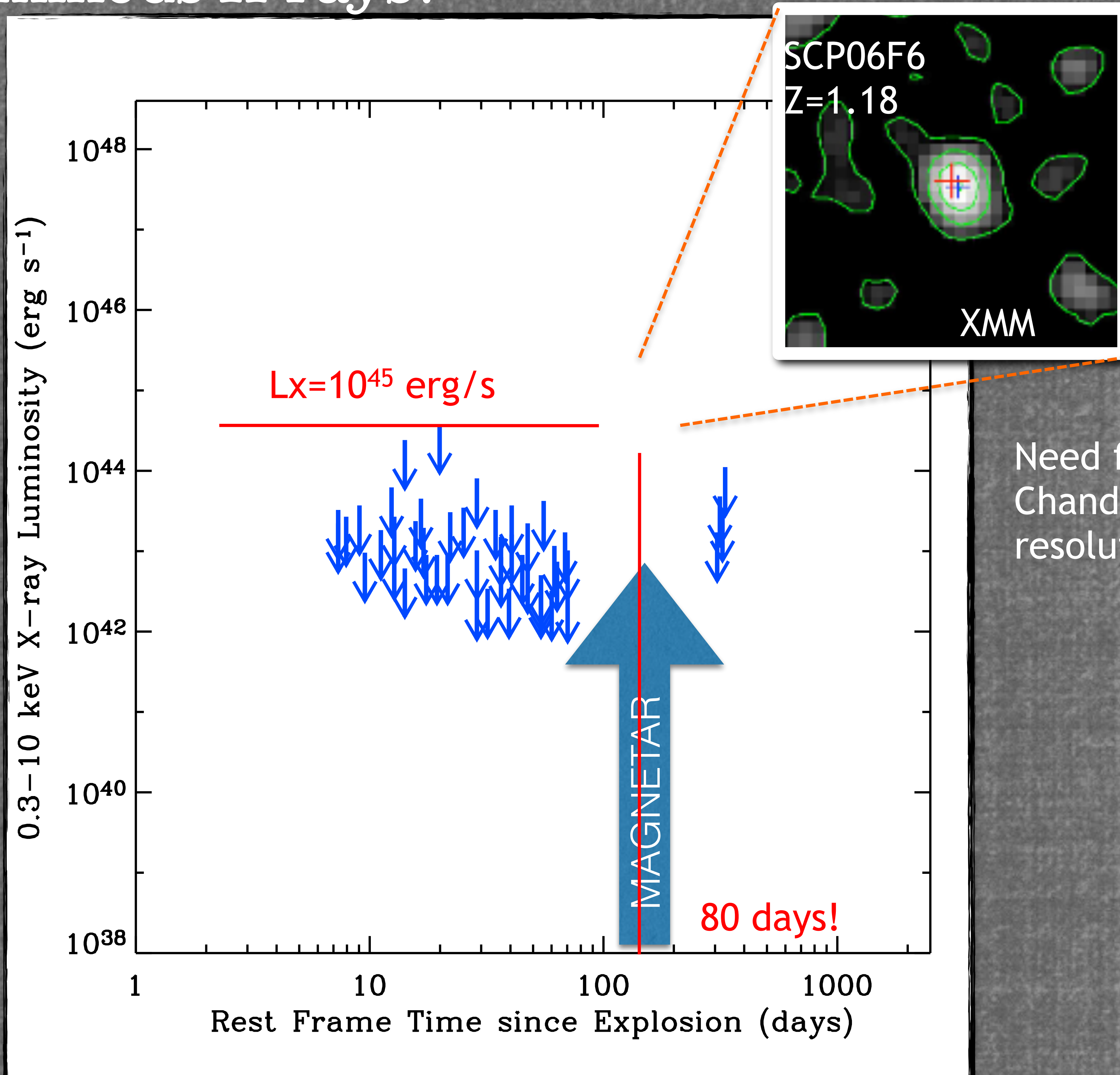
Extra Energy Source



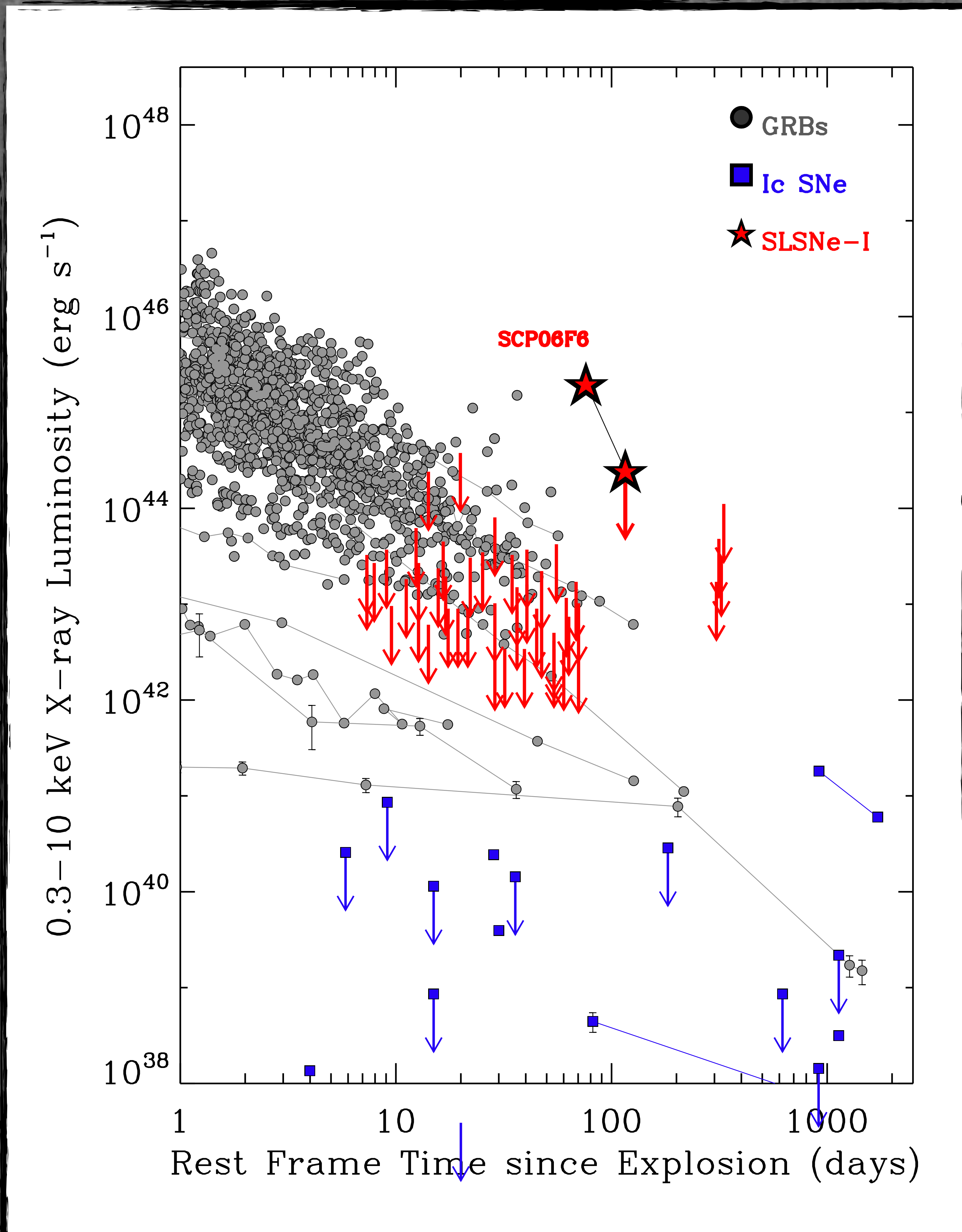

Slowly fading super-luminous supernovae that are not pair-instability explosions
SUPER-LUMINOUS TYPE Ic SUPERNOVAE: CATCHING A MAGNETAR BY THE TAIL
PTF12dam
PTF 12dam + Magnetar fit
130M☉ He core PISN (ref. 7)
100M☉ He core PISN (ref. 7)
80M☉ He core PISN (ref. 7)
100M☉ He core PISN (ref. 8)
Time from peak (rest-frame days)
Nicholl 2013
PTF10hgi
SN2011ke
PTF11rks
SN2011kf
SN2010gx
log L (erg s−1)
Days since explosion

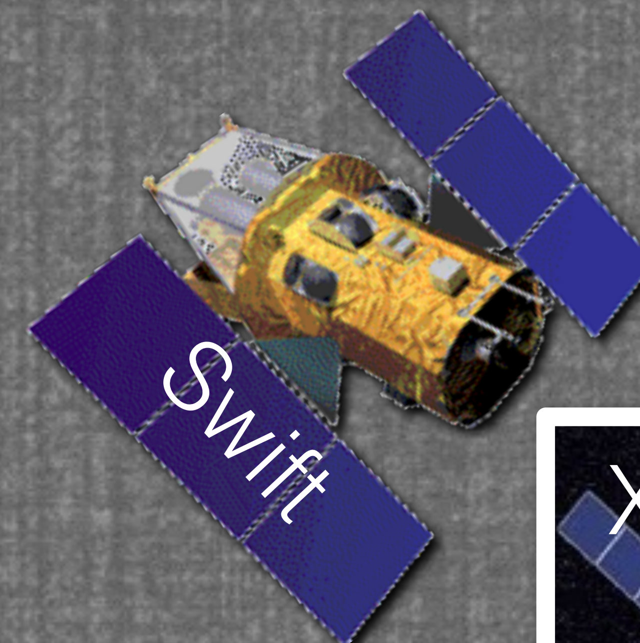
Super-Luminous X-rays!

Levan 2013



Need for Chandra angular resolution!

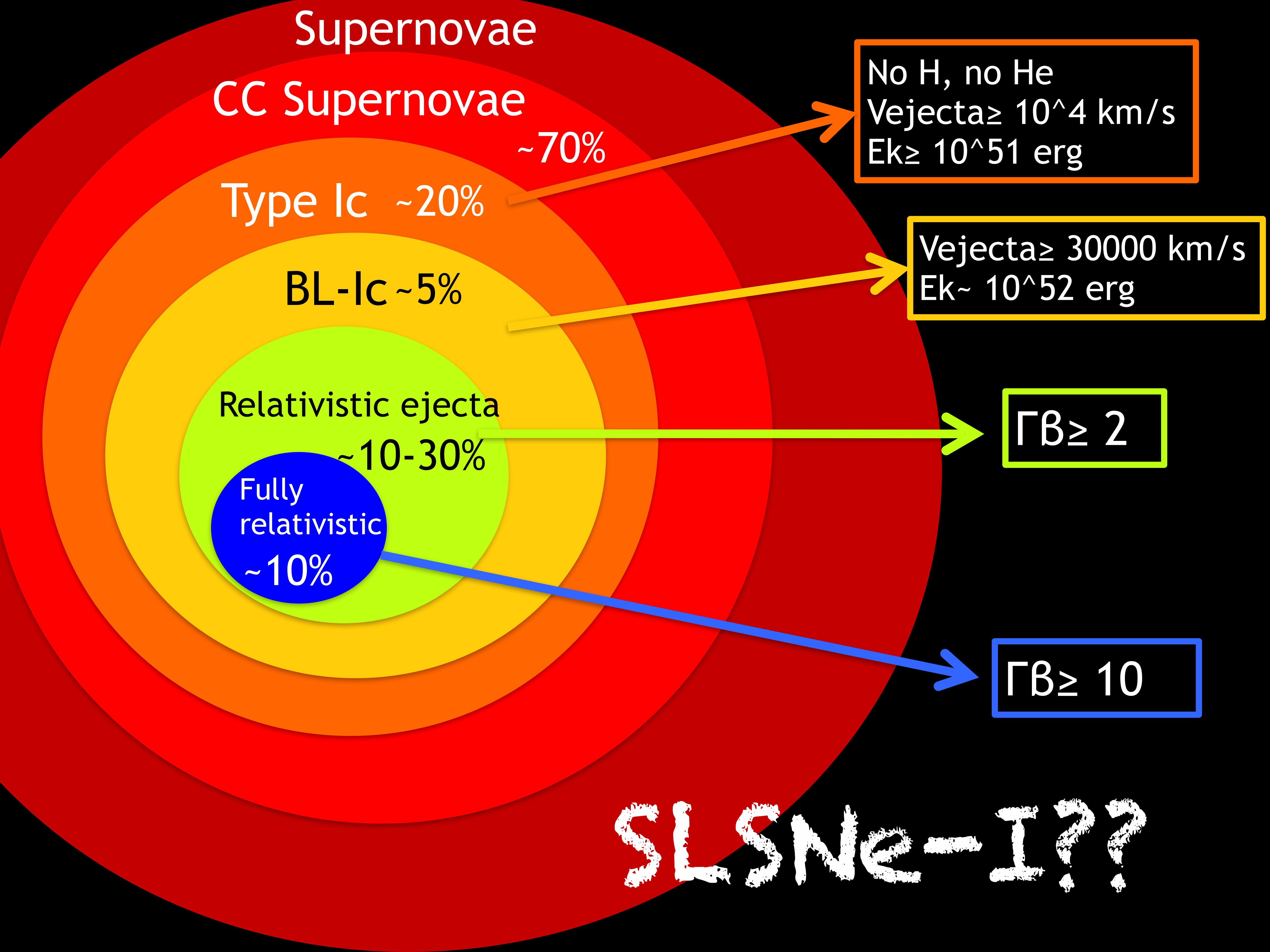

GRBs
Ic SNe
SLSNe-I
SCP06F6
10^{48}
10^{46}
10^{44}
10^{42}
10^{40}
10^{38}
0.3−10 keV X−ray Luminosity (erg s^{-1})
1
10
100
1000
Rest Frame Time since Explosion (days)


Swift

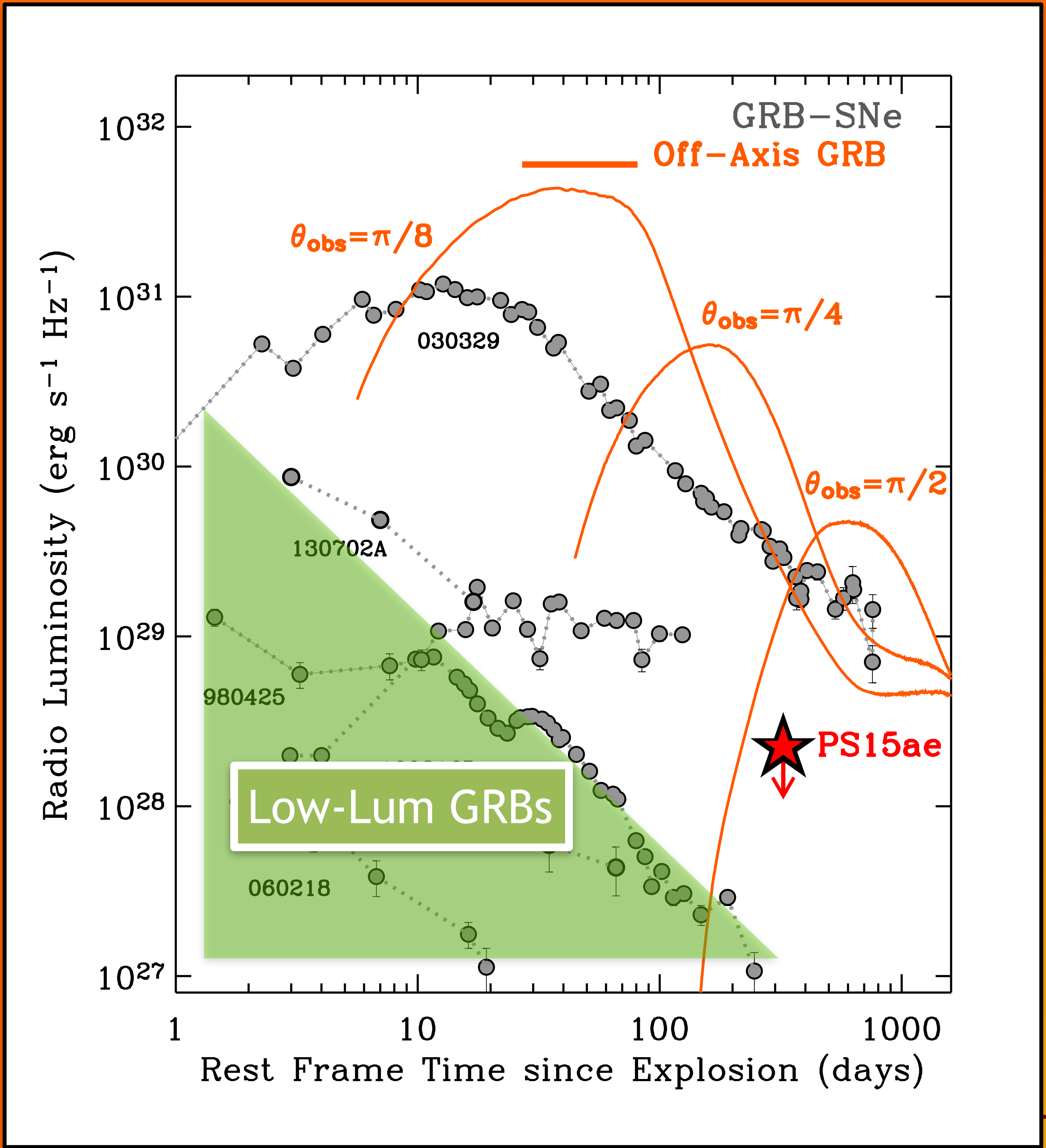

XMM


Chandra

We did detect X-rays at the location of 2 SLSNe-I


Supernovae
CC Supernovae
~70%
Type Ic ~20%
BL-Ic ~5%
Relativistic ejecta
~10-30%
Fully
relativistic
~10%
No H, no He
Vejecta≥ 10^4 km/s
Ek≥ 10^51 erg
Vejecta≥ 30000 km/s
Ek~ 10^52 erg
Γβ≥ 2
Γβ≥ 10
SLSNe-I??

SLSNe-I and off-axis GRBs



Nicholl+16

Eiso= 1d53 erg

n= 1 cm-3

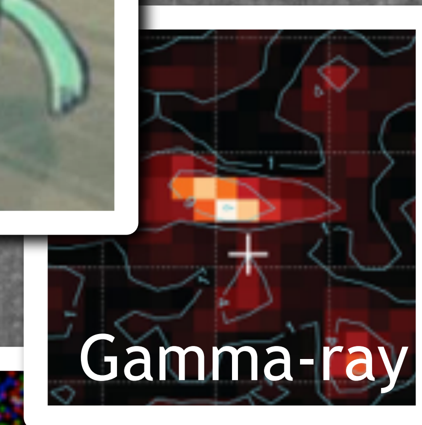
Theta_jet= 10 deg

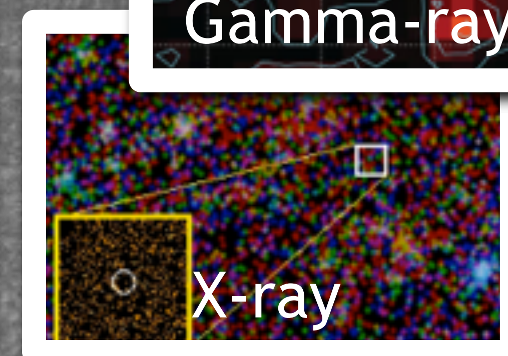
Radio

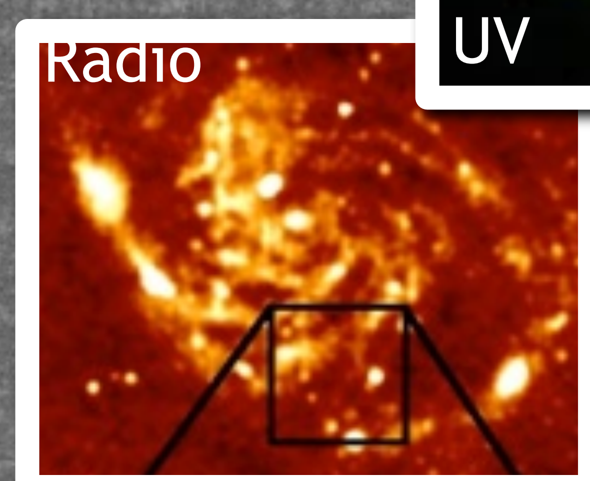
Multi-Wavelength observations of Stellar Explosions

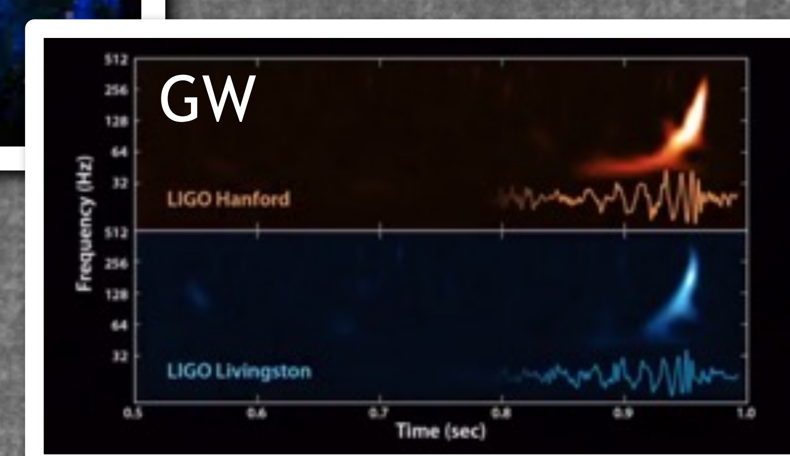
- Engine-driven Stellar Explosions
- Strongly Interacting SNe
- Super-Luminous SNe

The KNOWLE DGE GA P









"…The END

is where we start from…"

The Little Gidding by T. S. Eliot

Thanks to Chandra, XMM, Swift, NuSTAR, VLA, VLBI,
CARMA, SMA, GMRT
for their generous support to our investigation