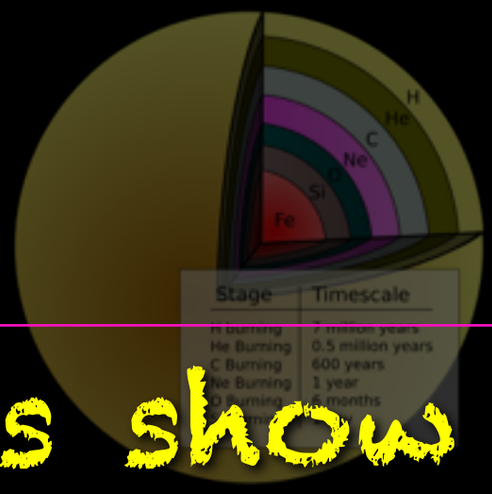
First sources of ionizing photons

Chemical Enrichment

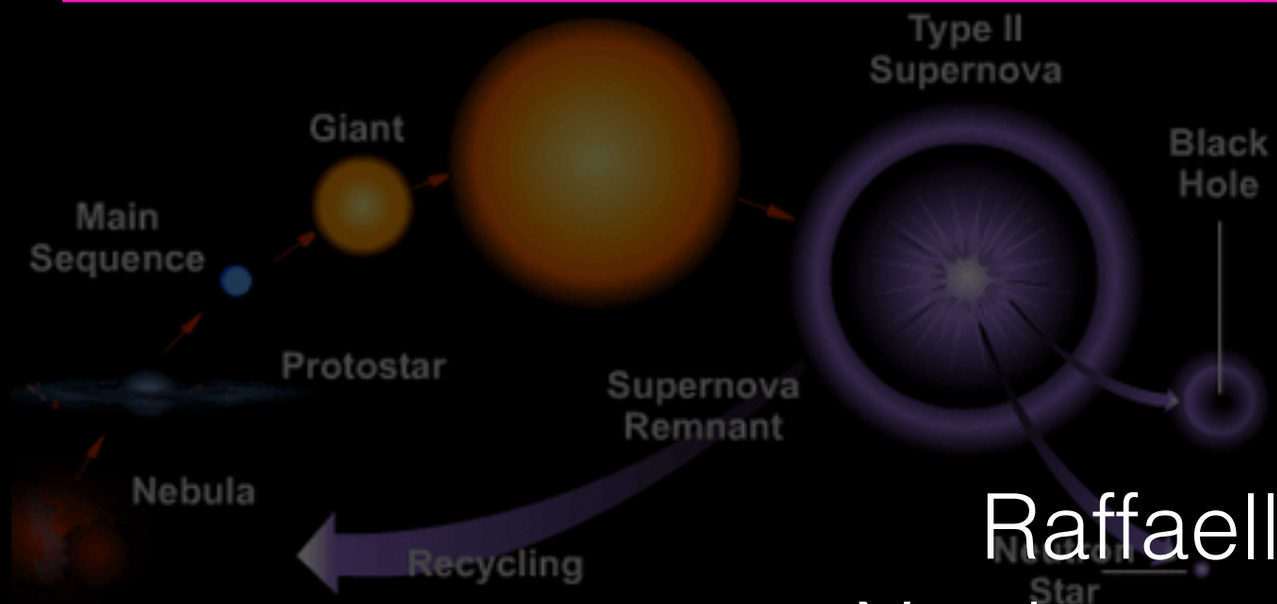


Galaxy Feedback

Deposition of Radiative+ Mechanical Energy

Massive Stars show evidence for enhanced and/or episodic mass-loss at the end of their life

Endpoint of Stellar Evolution

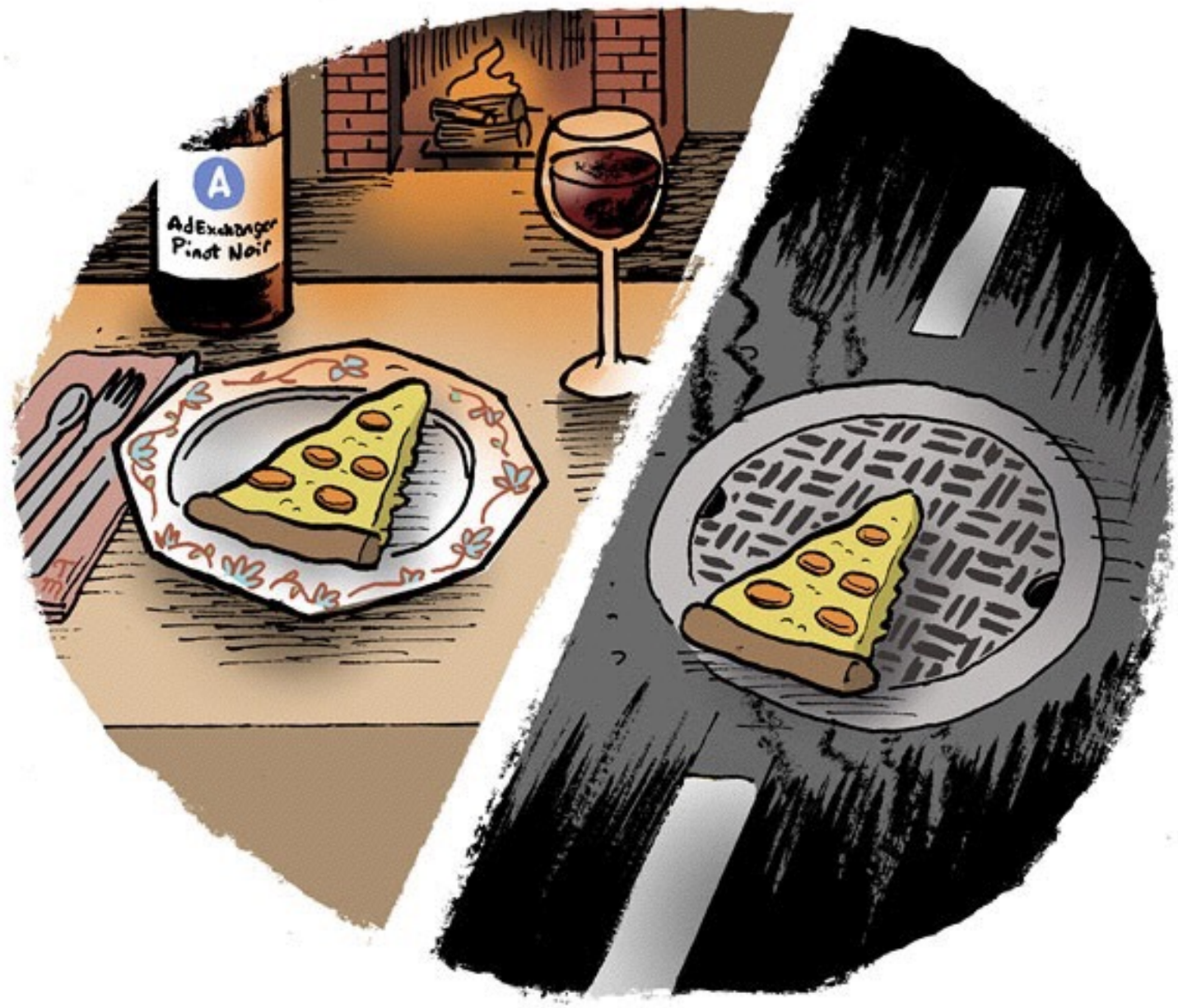


They produce the most Extreme Objects

Laboratories of Extreme Physics (jets)

Sources of GWs and Neutrinos

Raffaella Margutti
Northwestern University



Context Matters

Ib/c

IIn
SLSNe-IIn

Ibn

Enhanced
Mass-Loss
Smith 14

IIP

IIb

Ib/c

IIn

SLSNe-IIn

Ibn

Enhanced
Mass-Loss
Smith 14

IIP

IIb

H-poor

Ib/c

Ibn

Enhanced
Mass-Loss
Smith 14

IIb

IIn
SLSNe-IIn

IIP

H-poor

H-rich

Ib/c

SN2014C + SLSN-I

IIn

SLSNe-IIn

Ibn

Enhanced
Mass-Loss

Smith 14

IIP

IIb

H-poor

H-rich

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

See Poster by Yan for SLSNe

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

See Poster by Yan for SLSNe

SN1987A "ring"

e.g. Sonneborn et al. 1998

IR echoes from distant shells

Smith et al. 2008, 2010b; Miller et al. 2010;

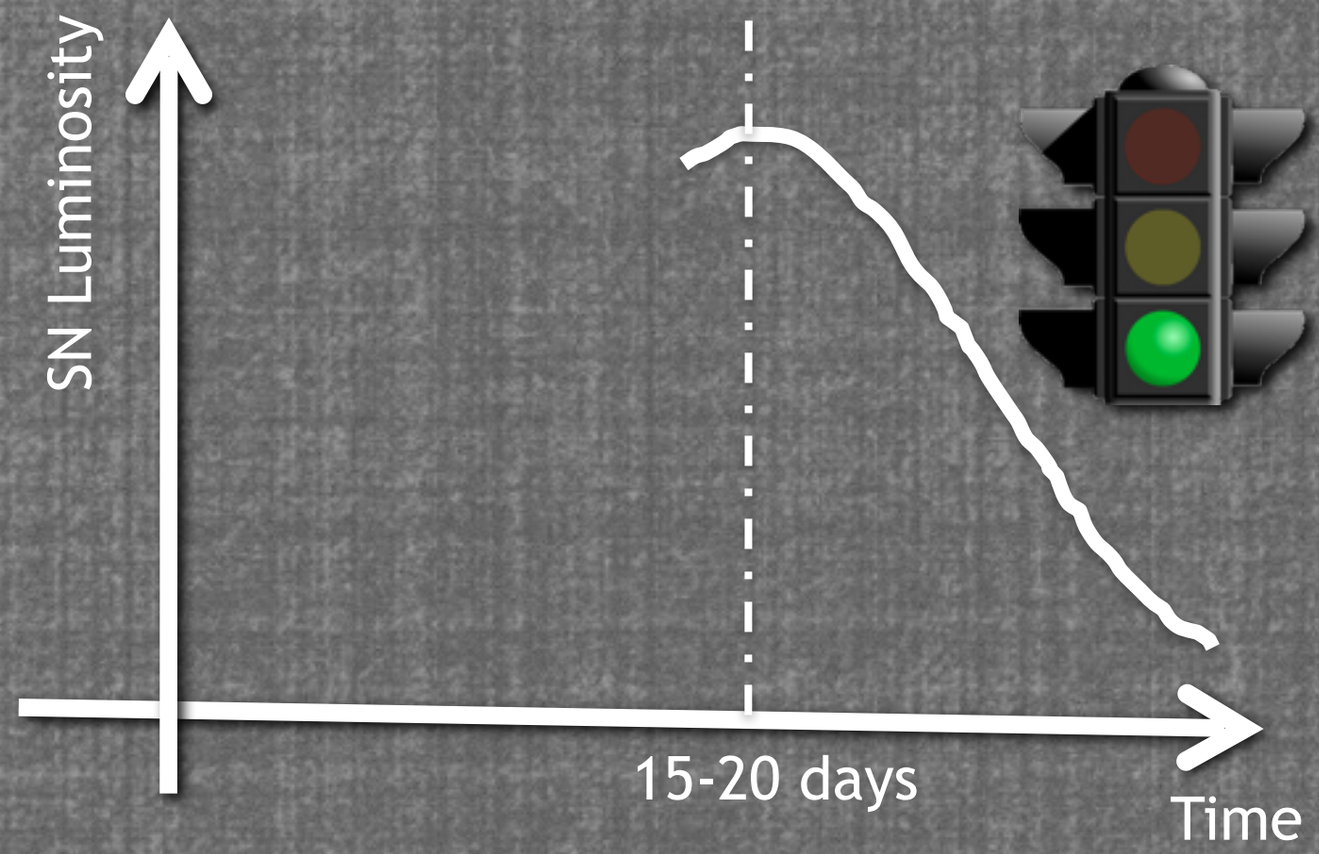
Fox et al. 2011, 2013

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

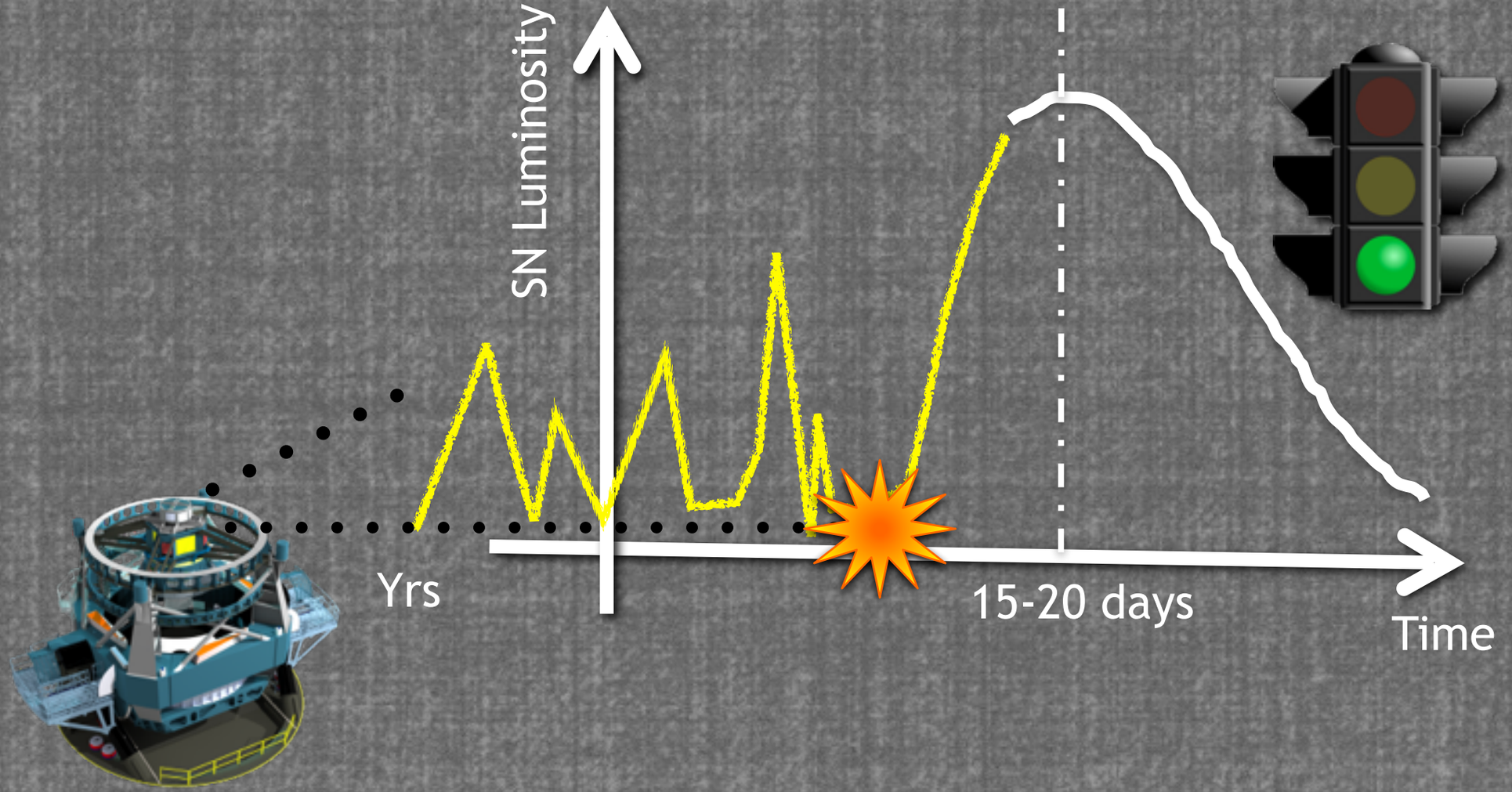


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction



Ib/c

Ibn

Enhanced
Mass-Loss

IIb

IIn
SLSNe-IIn

IIP

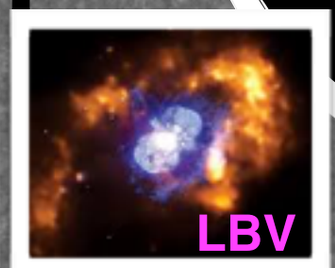
H-poor

H-rich

Ib/c

IIn

SN2010mc, 09ip, 11ht,
SNhunt275
Ofek+, Margutti+, Smith+



Ibn

Enhanced
Mass-Loss

IIP

IIb

H-poor

H-rich

Ib/c

IIn

SN2010mc, 09ip, 11ht

Ofek+, Margutti+, Smith+

Ibn

SN2006jc

Valenti+, Pastorello+

Foley+

Enhanced Mass-Loss

IIP

IIb

H-poor

H-rich

Ib/c

iPTF11qcj
Corsi+

IIn

SN2010mc, 09ip, 11ht
Ofek+, Margutti+, Smith+

Enhanced
Mass-Loss

Ibn

SN2006jc
Valenti+, Pastorello+
Foley+

IIP

IIb

H-poor

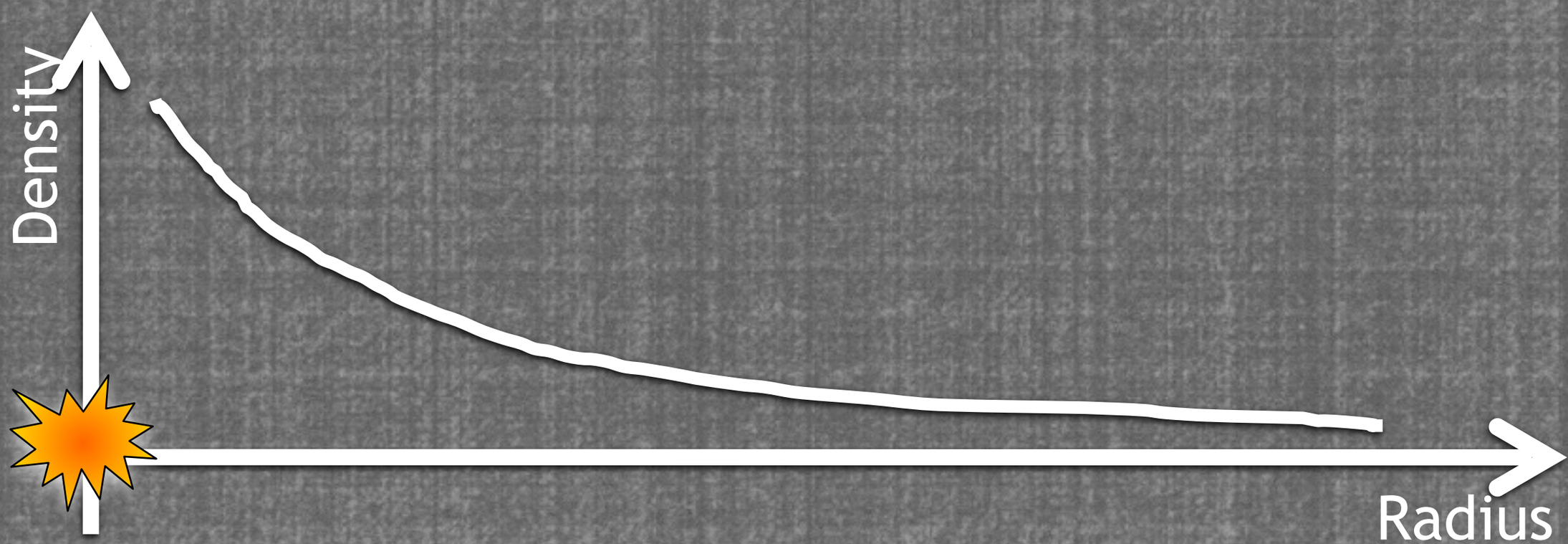
H-rich

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

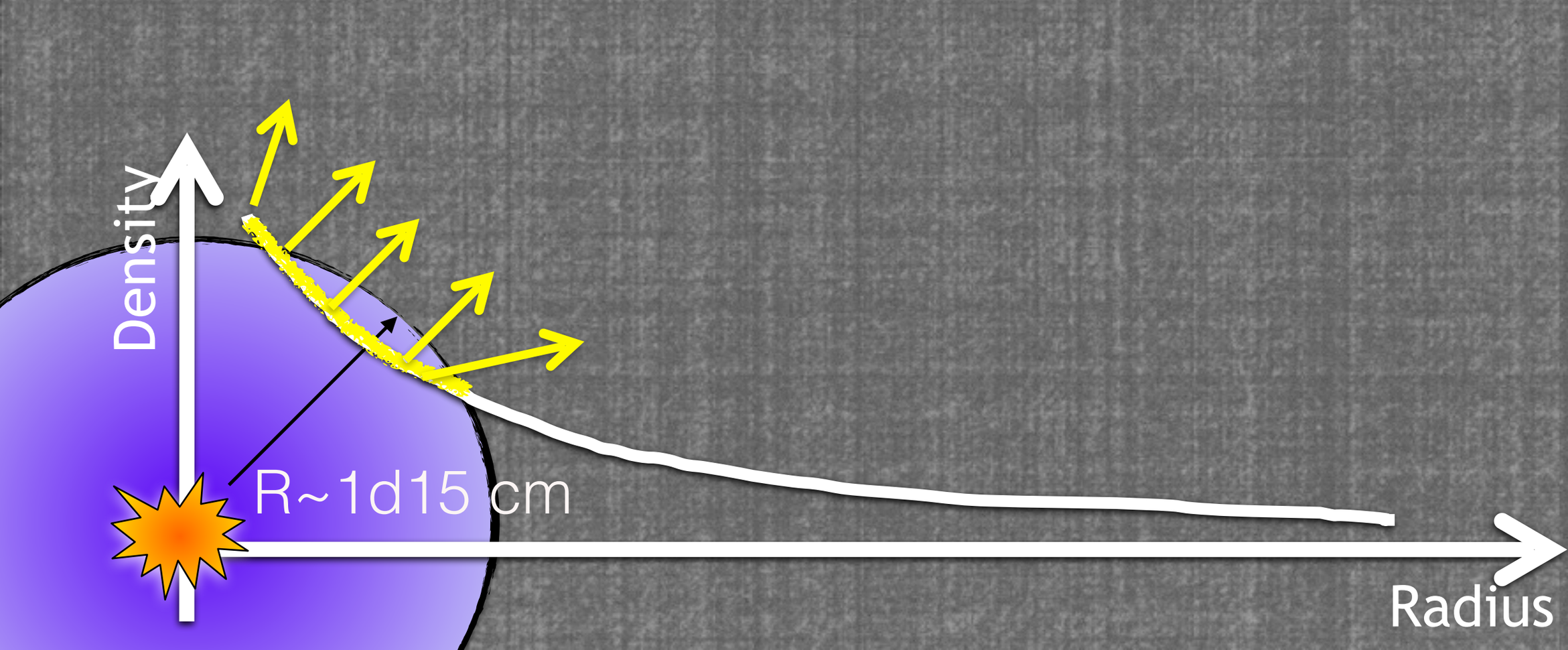


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

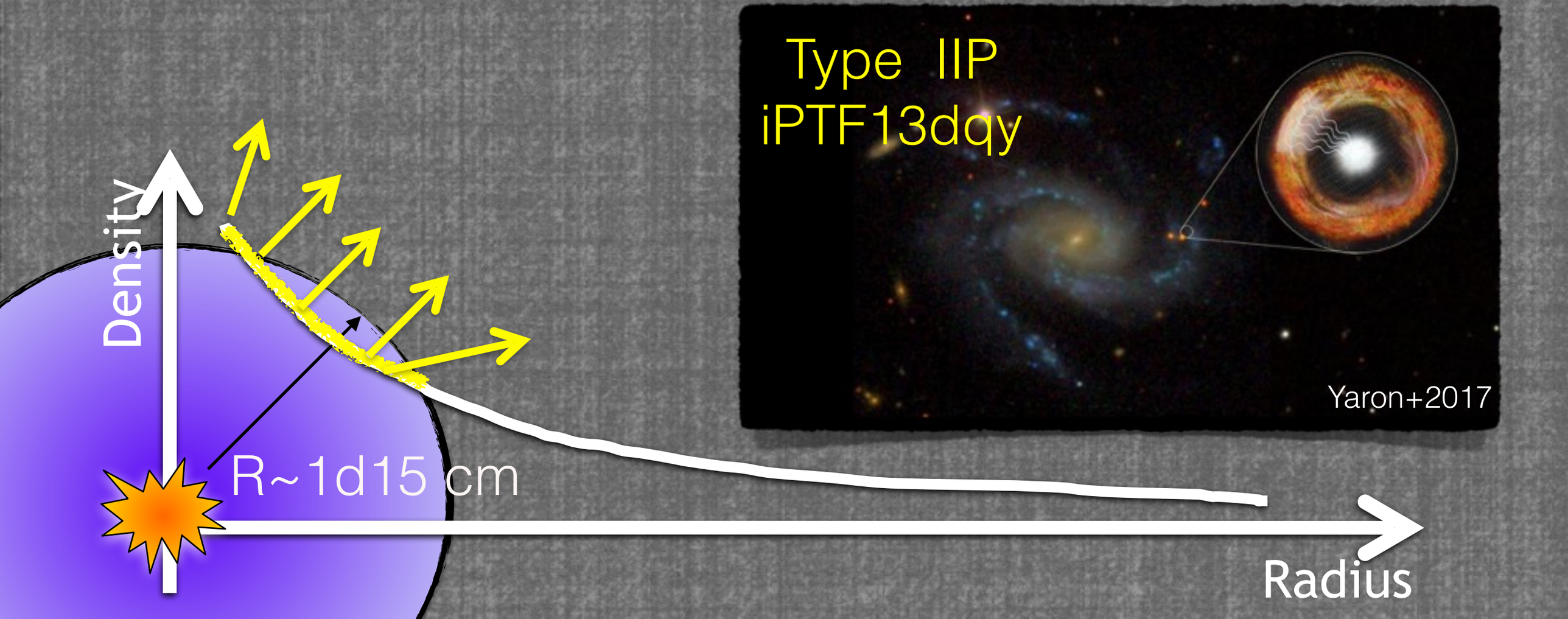


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction



Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

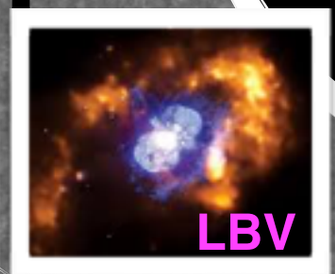
Type IIP
iPTF13dqy

Ib/c

iPTF11qcj
Corsi+

IIn

SN2010mc, 09ip, 11ht
Ofek+, Margutti+, Smith+



Ibn

SN2006jc
Valenti+, Pastorello+
Foley+

Enhanced
Mass-Loss

IIP

iPTF13dqy
Yaron+

IIb

SN2013cu
Gal-Yam+

H-poor

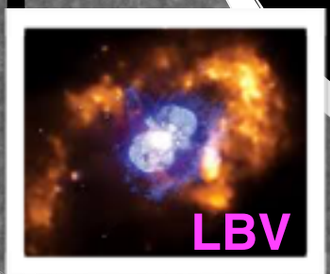
H-rich

Ib/c

iPTF11qcj
Corsi+

IIn

SN2010mc, 09ip, 11ht
Ofek+, Margutti+, Smith+



Ibn

SN2006jc
Valenti+, Pastorello+
Foley+

Enhanced
Mass-Loss

IIP

iPTF13dqy
Yaron+

IIb

SN2013cu
Gal-Yam+

H-poor

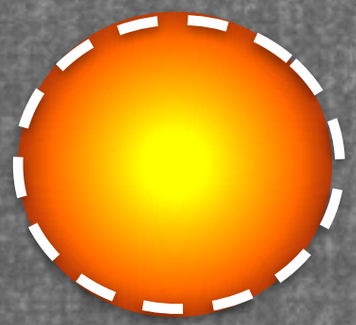
H-rich

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction



Supergiant

Wolf-Rayet

$\sim 10^{4}$-10^{5} yrs

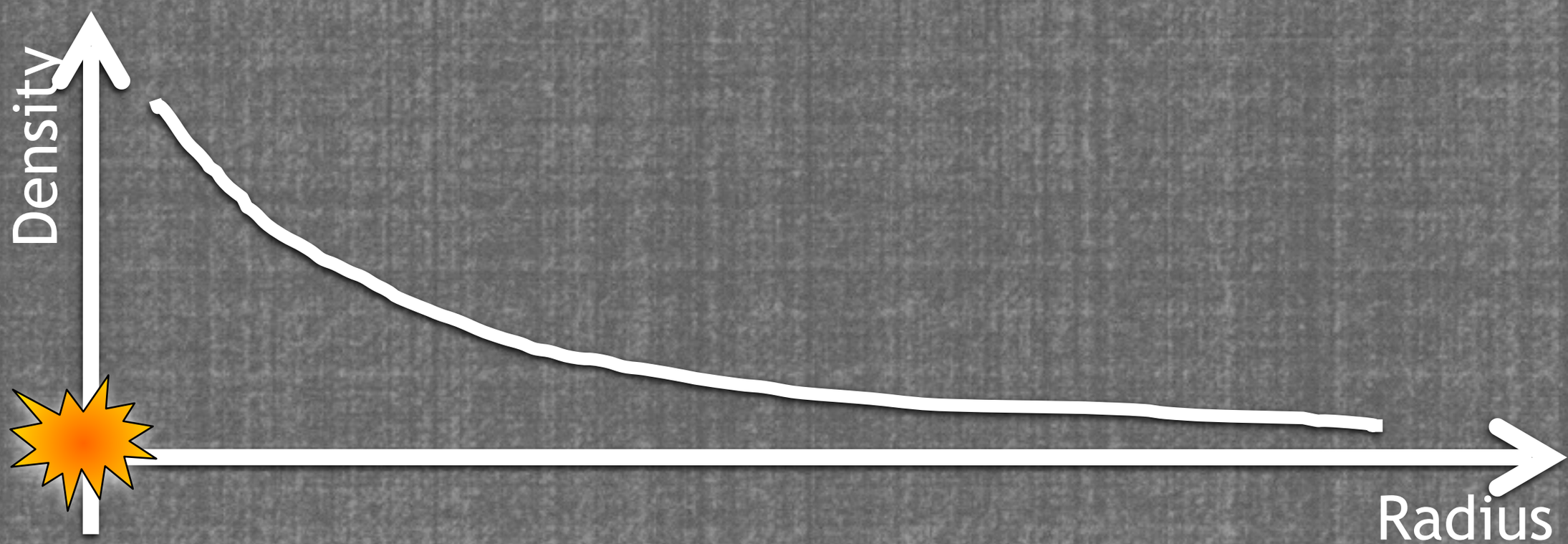
SN Explosion

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

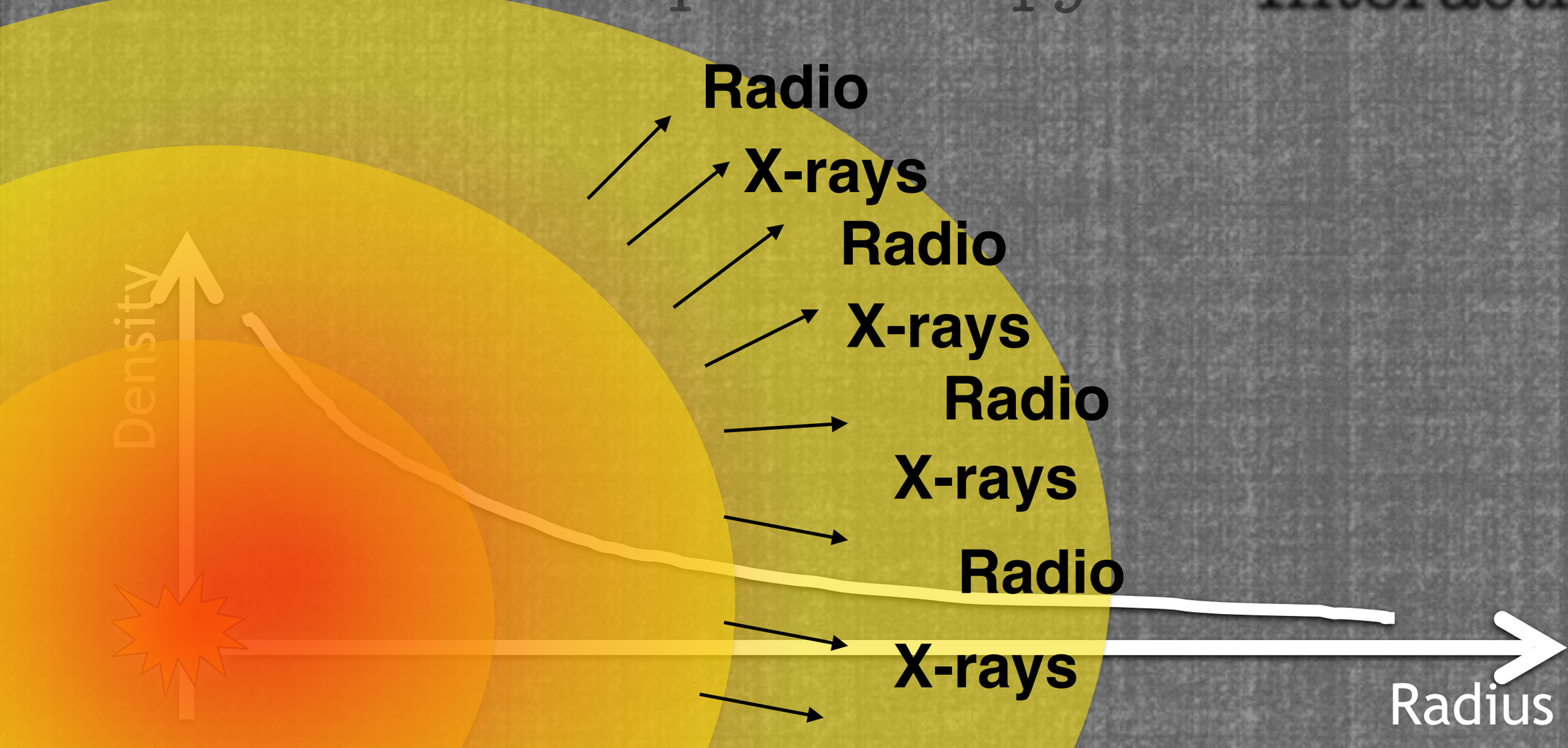


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

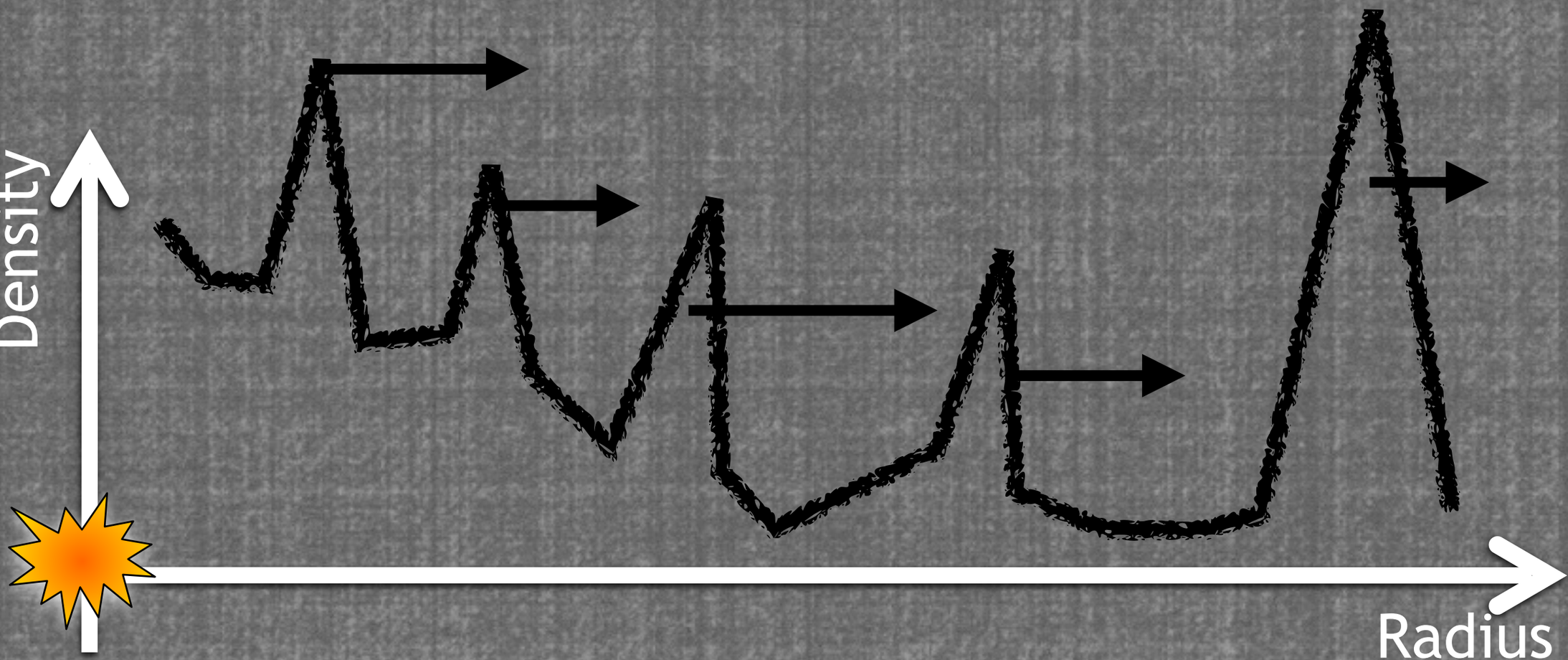


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

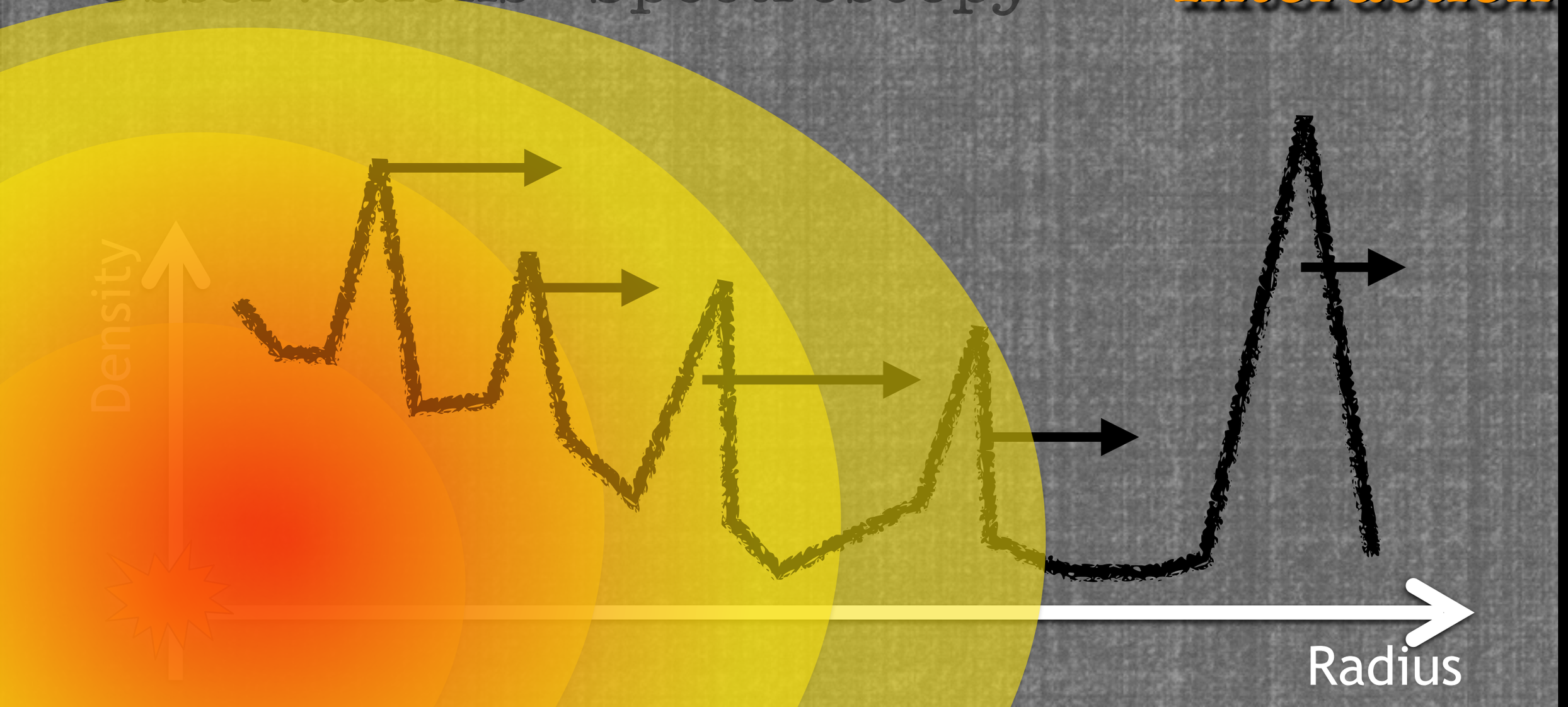


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction



Vshock >> Vejection

(Vshock/Vejection) t

Margutti+17

Ib/c

Corsi+

WR

LBV

IIn

SN2010mc, 09ip, 11ht

Ofek+, Margutti+, Smith+

Enhanced Mass-Loss

Ibn

SN2006jc

Valenti+, Pastorello+

Foley+

RSG

IIP

iPTF13dqy

Yaron+

YSG

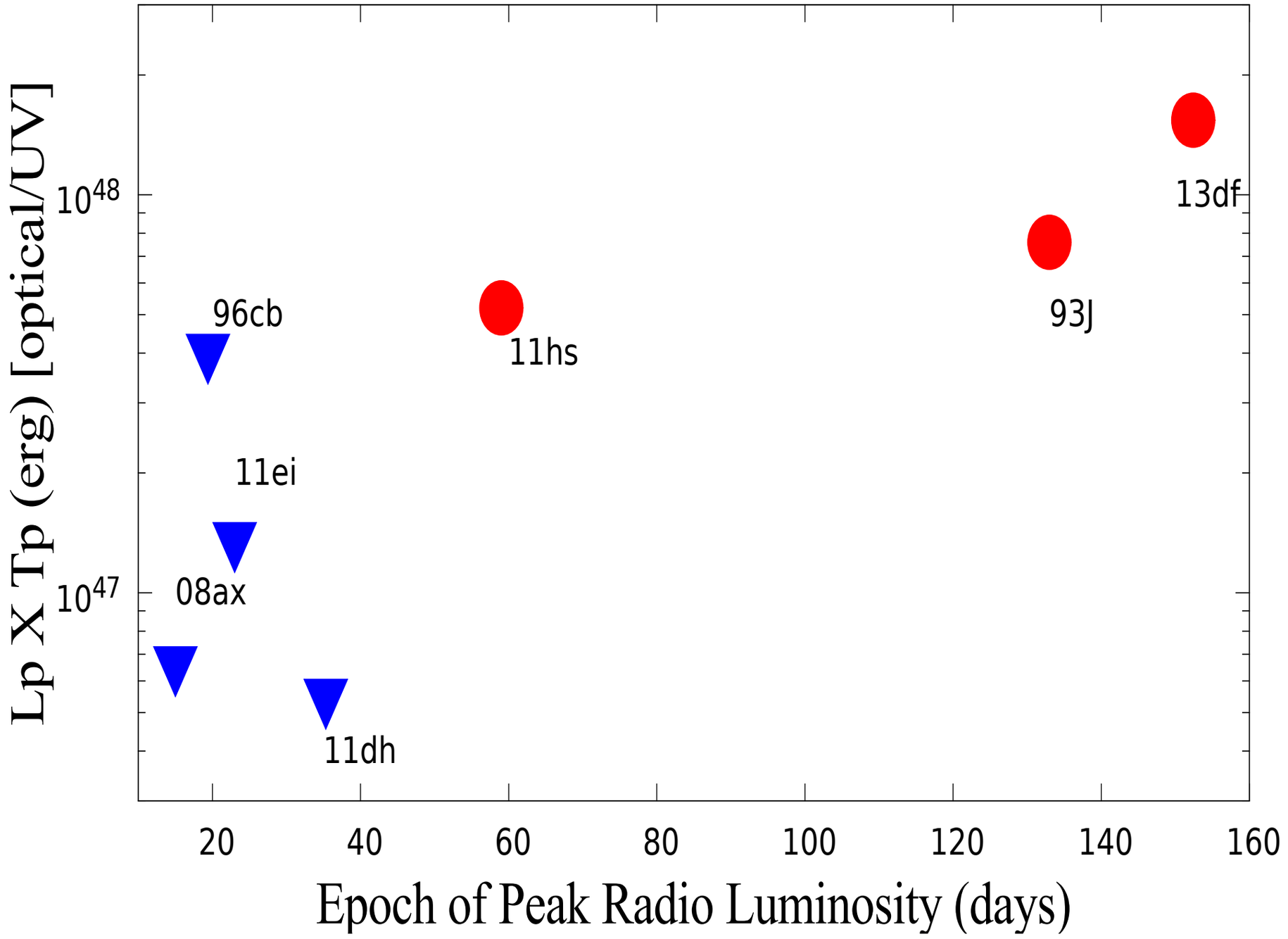
IIb

Kamble+16

H-poor

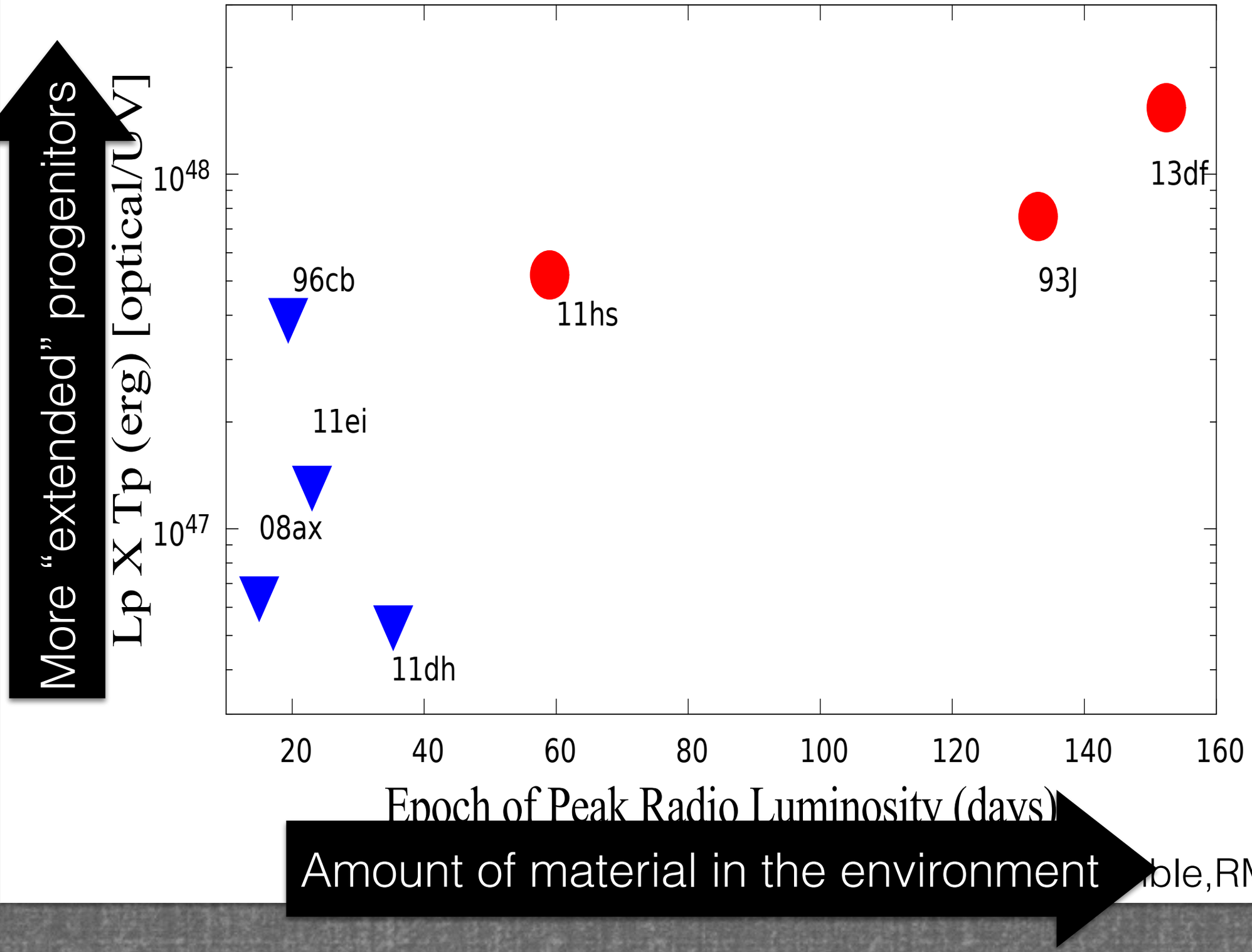
H-rich

Type IIb SNe



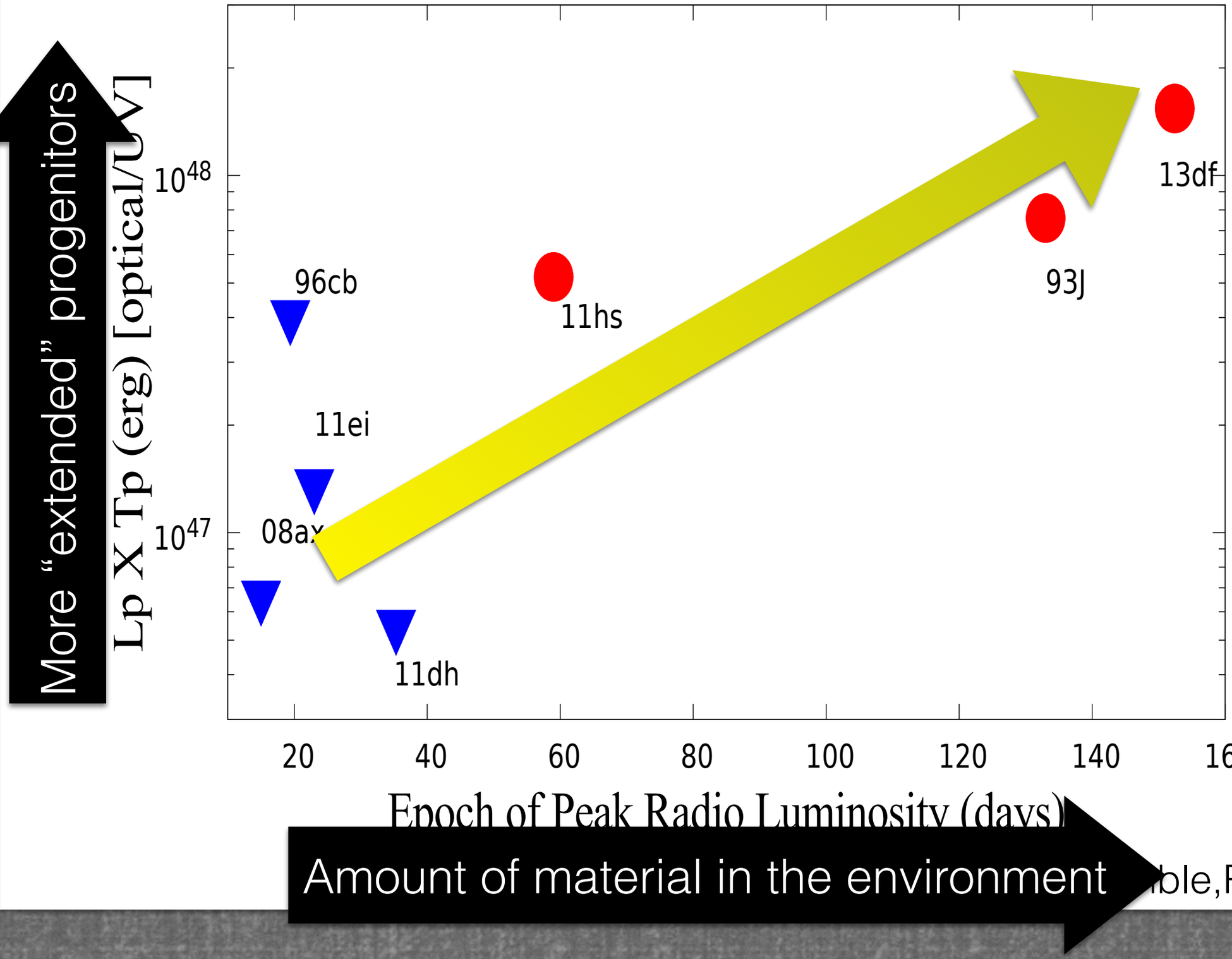
Kamble,RM+16

Type IIb SNe



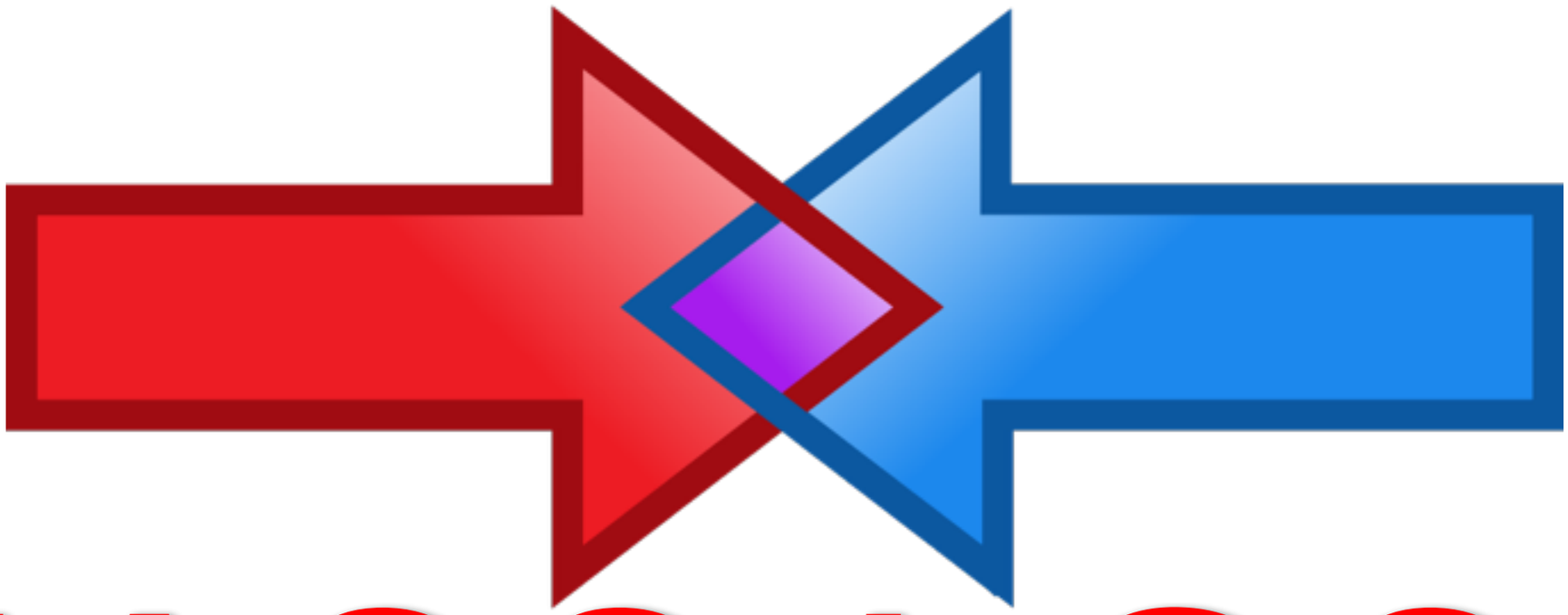
ble,RM+16

Type IIb SNe



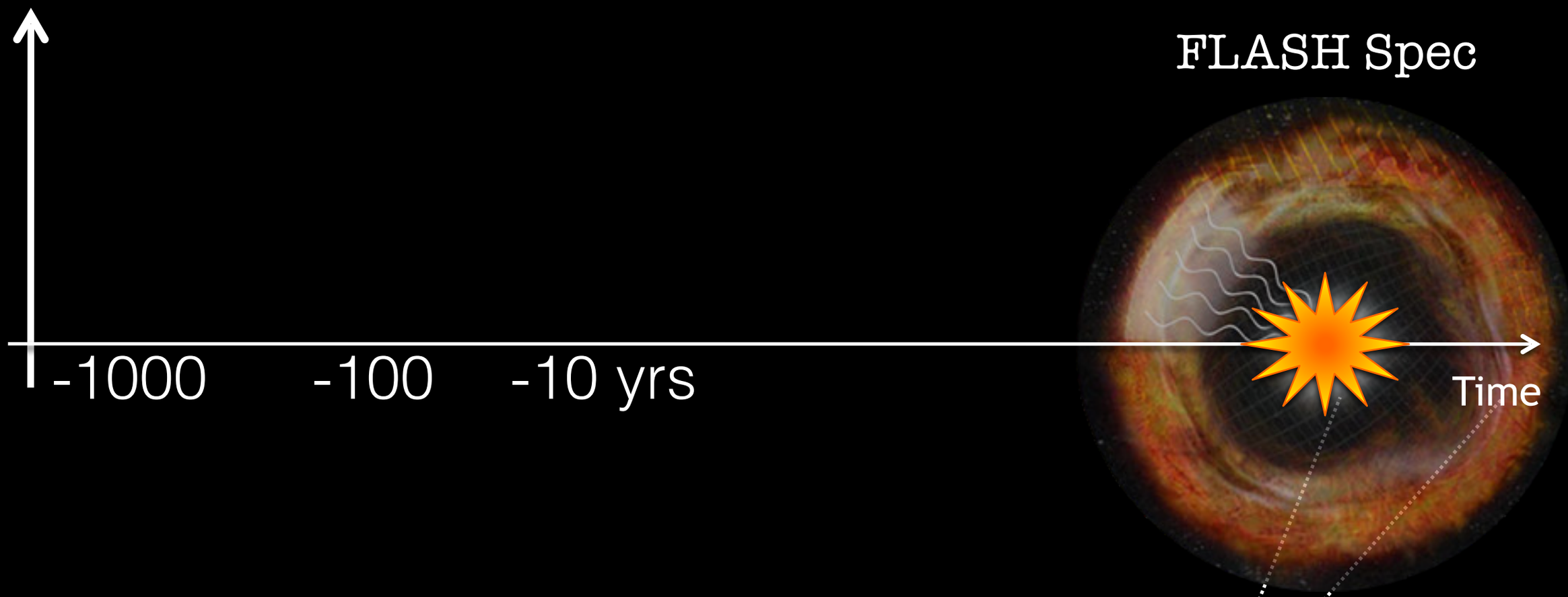
ble,RM+16

Progenitor Structure



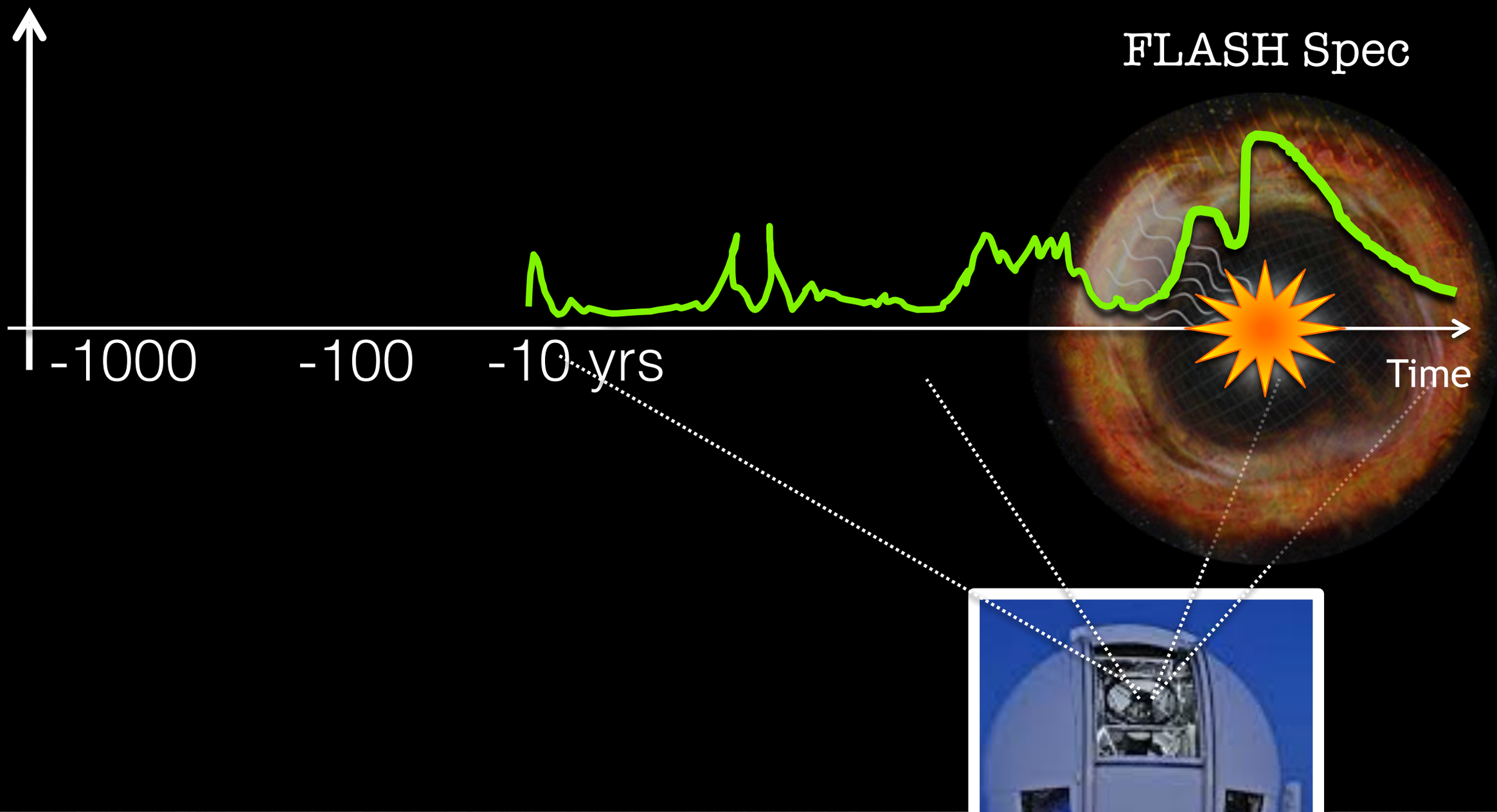
MASS LOSS

Mass Loss in Massive Stars



Direct Imaging

Mass Loss in Massive Stars

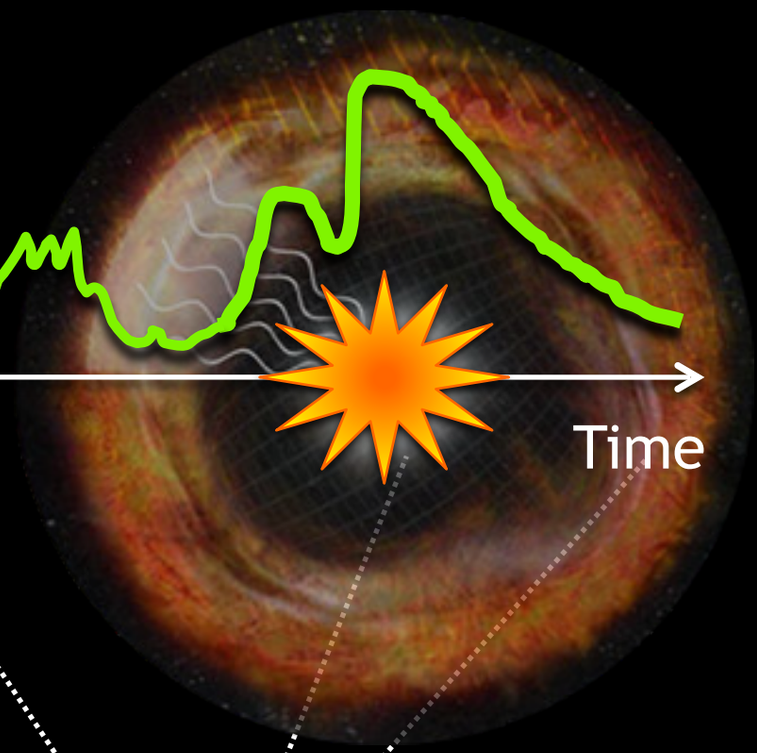


Direct Imaging

Mass Loss in Massive Stars

SN shock as a probe

FLASH Spec

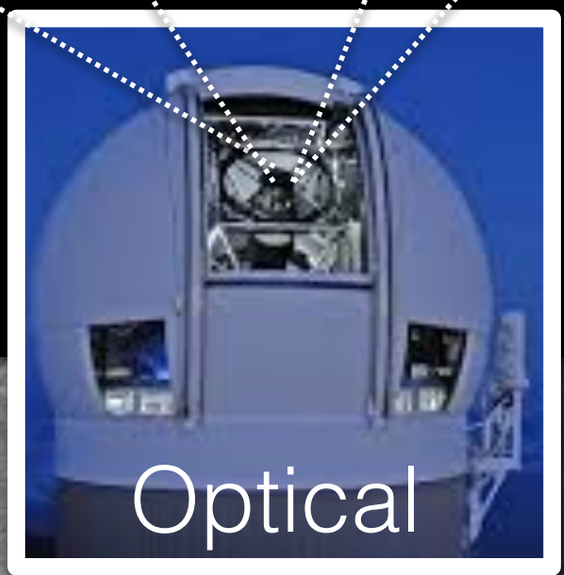


-1000 -100 -10 yrs

Time

X-rays

Radio



Optical

Direct Imaging

Mass Loss in Massive Stars

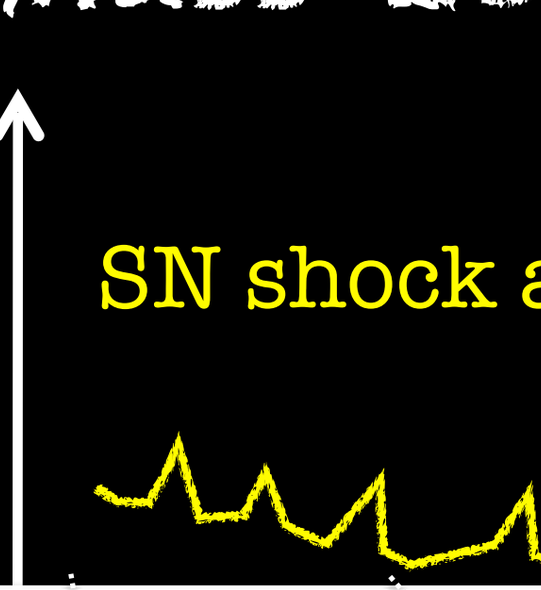
FLASH Spec

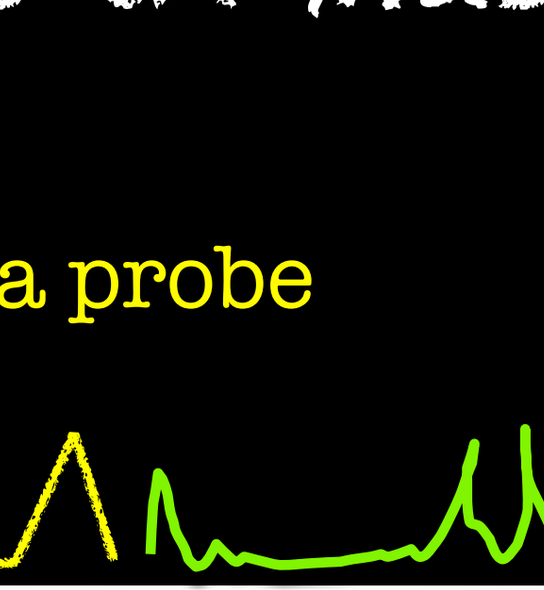
SN shock as a probe

-1000 -100 -10 yrs

Time

Nuclear Burning Sequence



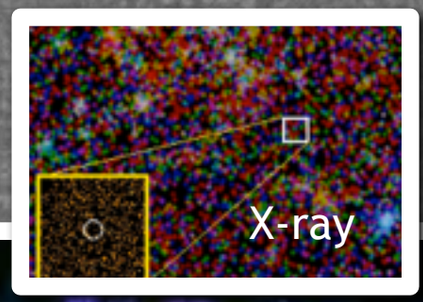


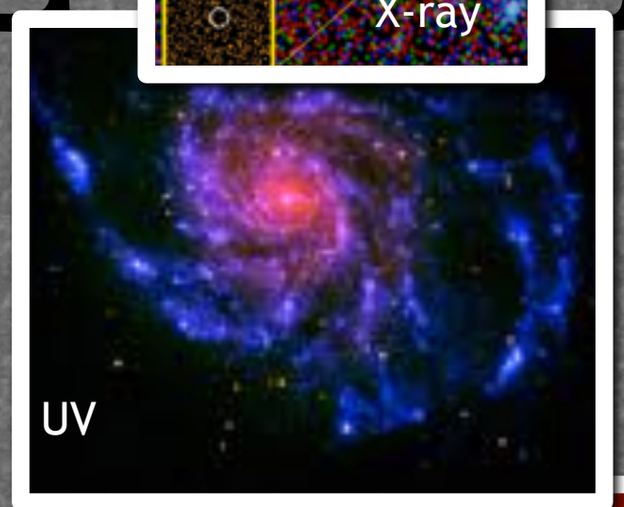
Direct Imaging

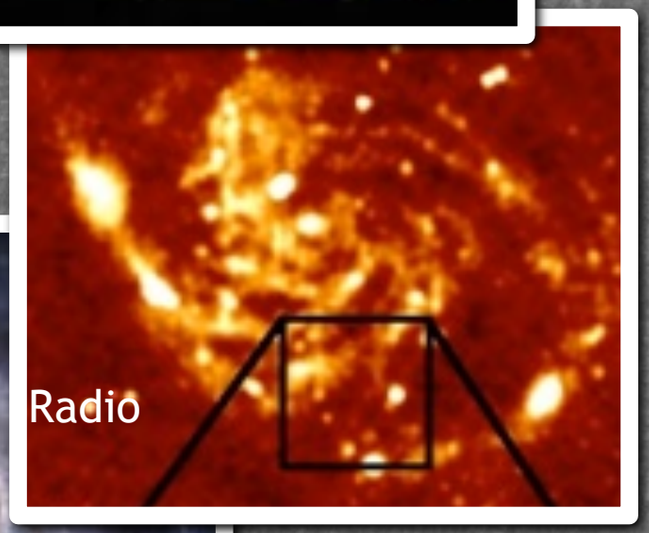
MASS LOSS– Massive Stars

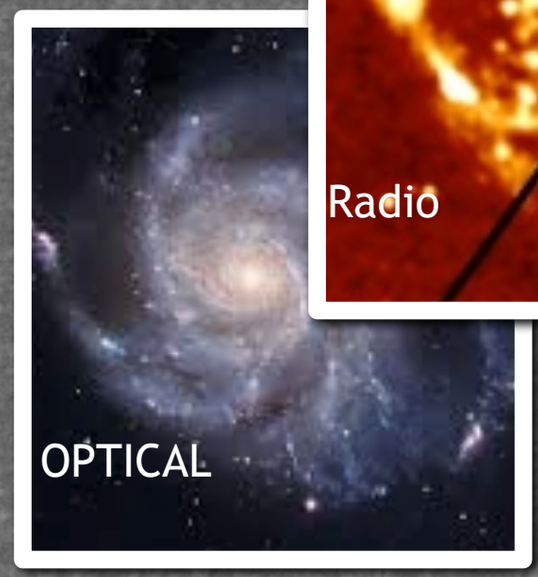
The KNOWLEDGE GAP

The KNOWLEDGE GAP









Margutti+17

Ib/c

Corsi+

WR

LBV

IIn

SN2010mc, 09ip, 11ht

Ofek+, Margutti+, Smith+

Enhanced Mass-Loss

Ibn

SN2006jc

Valenti+, Pastorello+

Foley+

RSG

IIP

iPTF13dqy

Yaron+

YSG

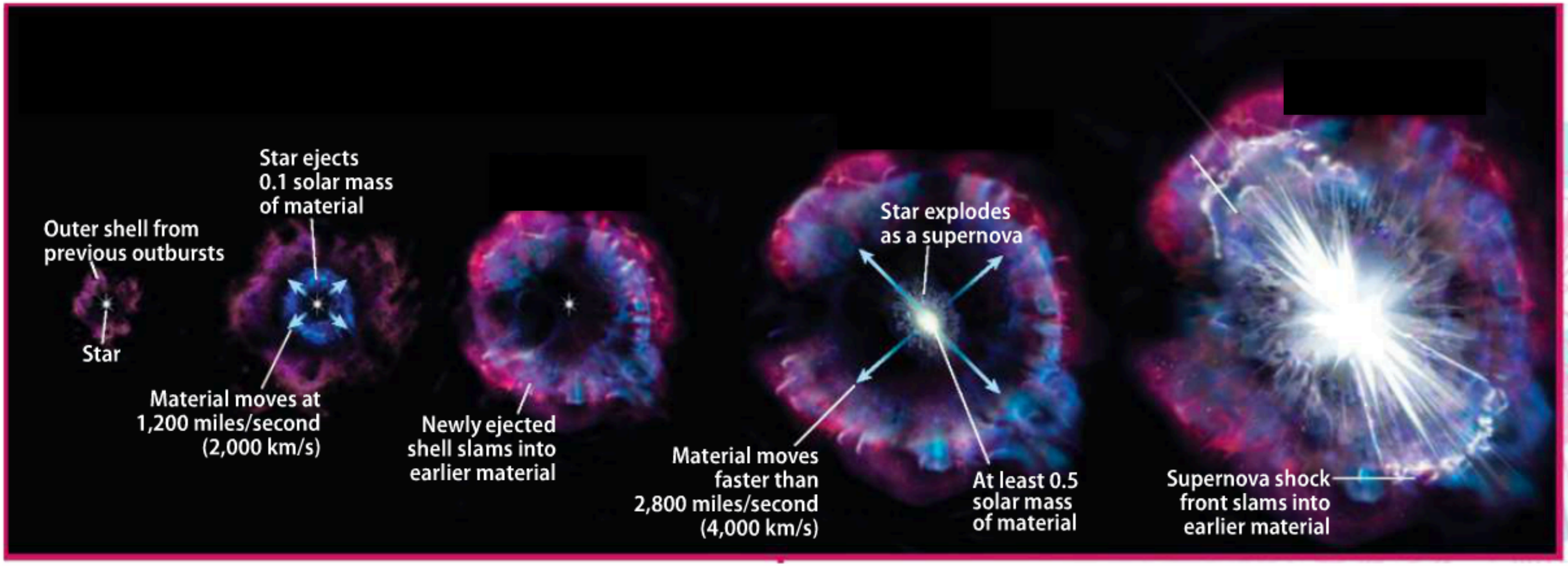
IIb

Kamble+16

H-poor

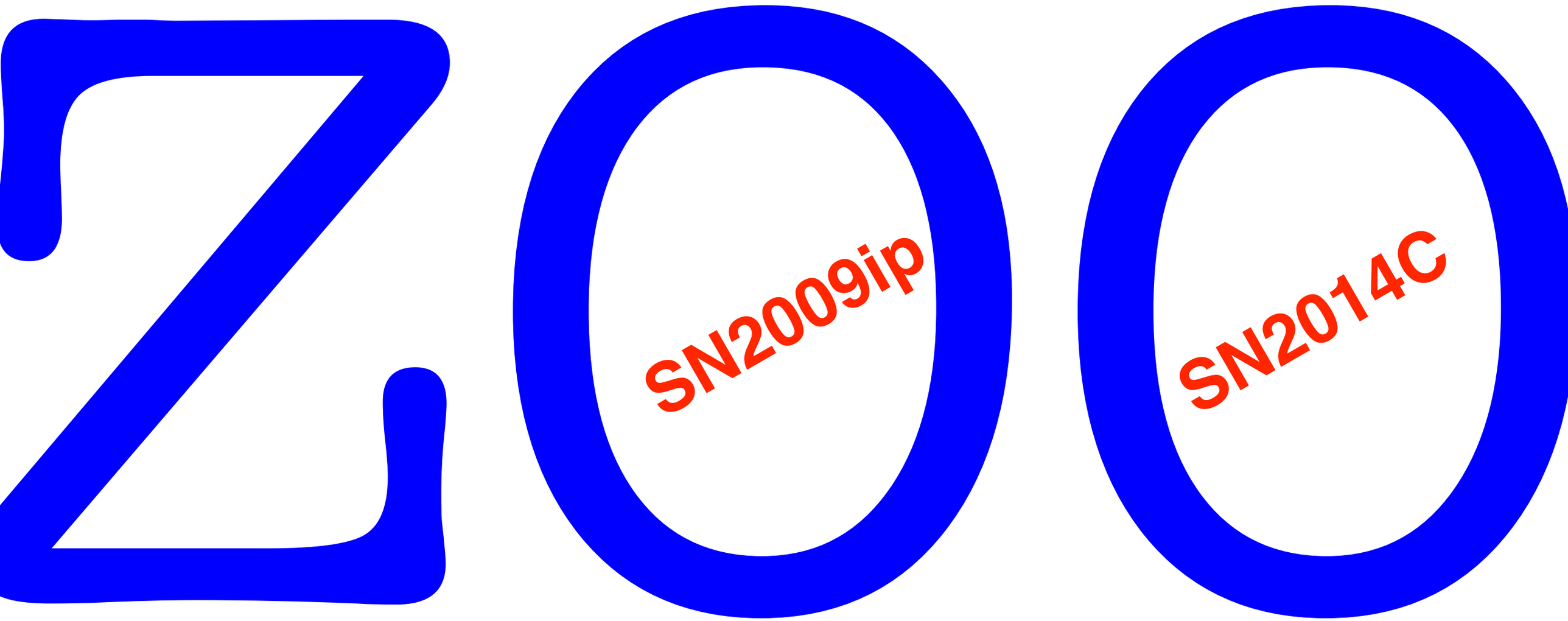
H-rich

THE MESSAGE:

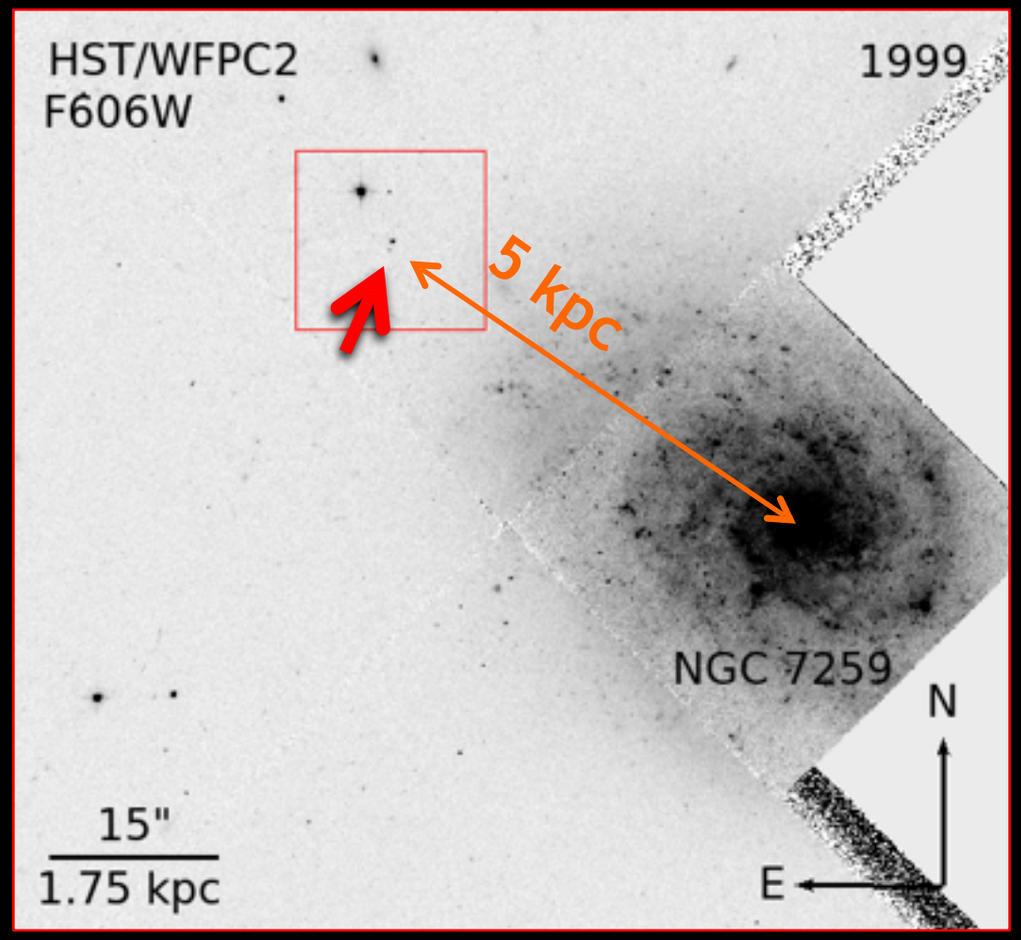


(SOME) Massive Stars experience Enhanced/Episodic Mass Loss when approaching core-collapse

ZOOM in


700
SN2009ip
SN2014C

SN2009ip
Type-IIn



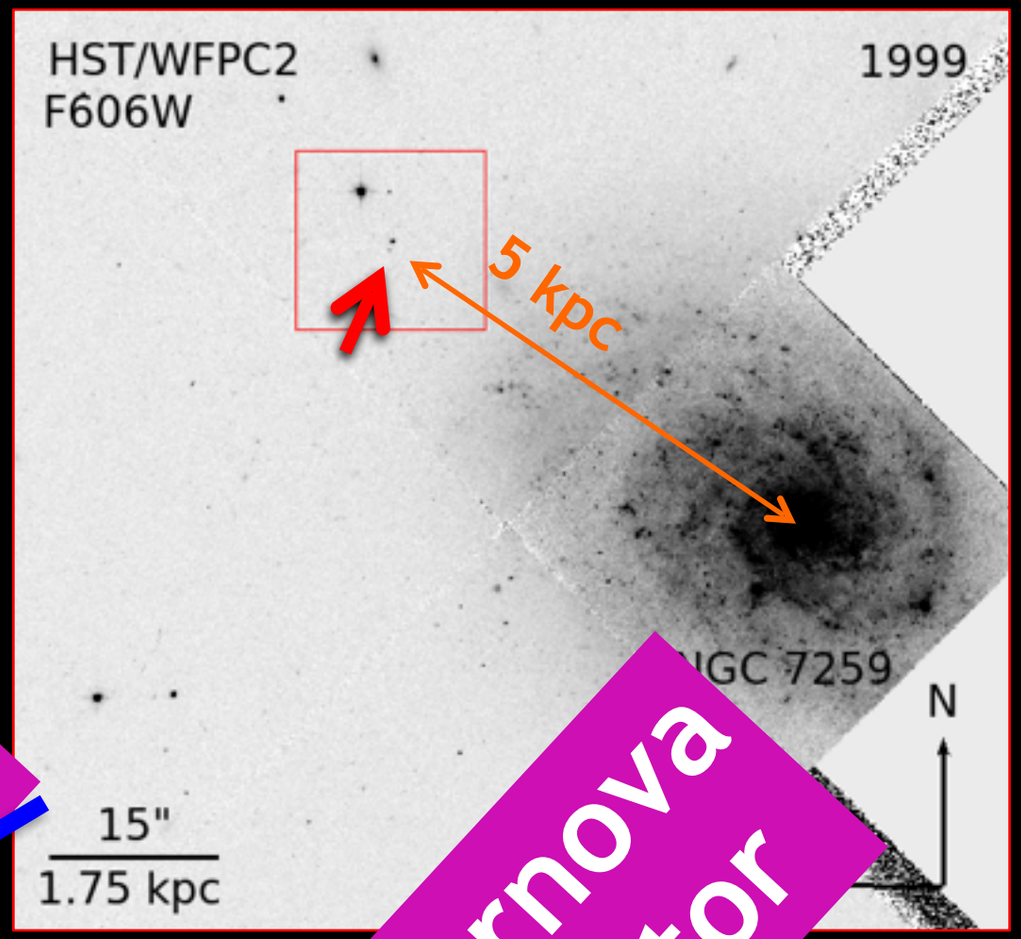
★Distance of 24 Mpc

★In the outskirts of NGC7259

★Sub-solar metallicity environment 0.4<Z<0.9 Zsun

Mauerhan++, Smith++, Margutti+, Pastorello+,Foley+, Prieto+, Fraser+

SN2009ip
Type-IIn



★Distance of 24 Mpc

★In the outskirts of NGC7259

★Sub-solar metallicity environment 0.4<Z<0.9 Zsun

Discovery

Supernova

Outburst

Outburst

Outburst

Supernova Impostor

Explosion1

Supernova

Aug 2009

Jul 2010

Sep 2010

May 2011

Oct 2011

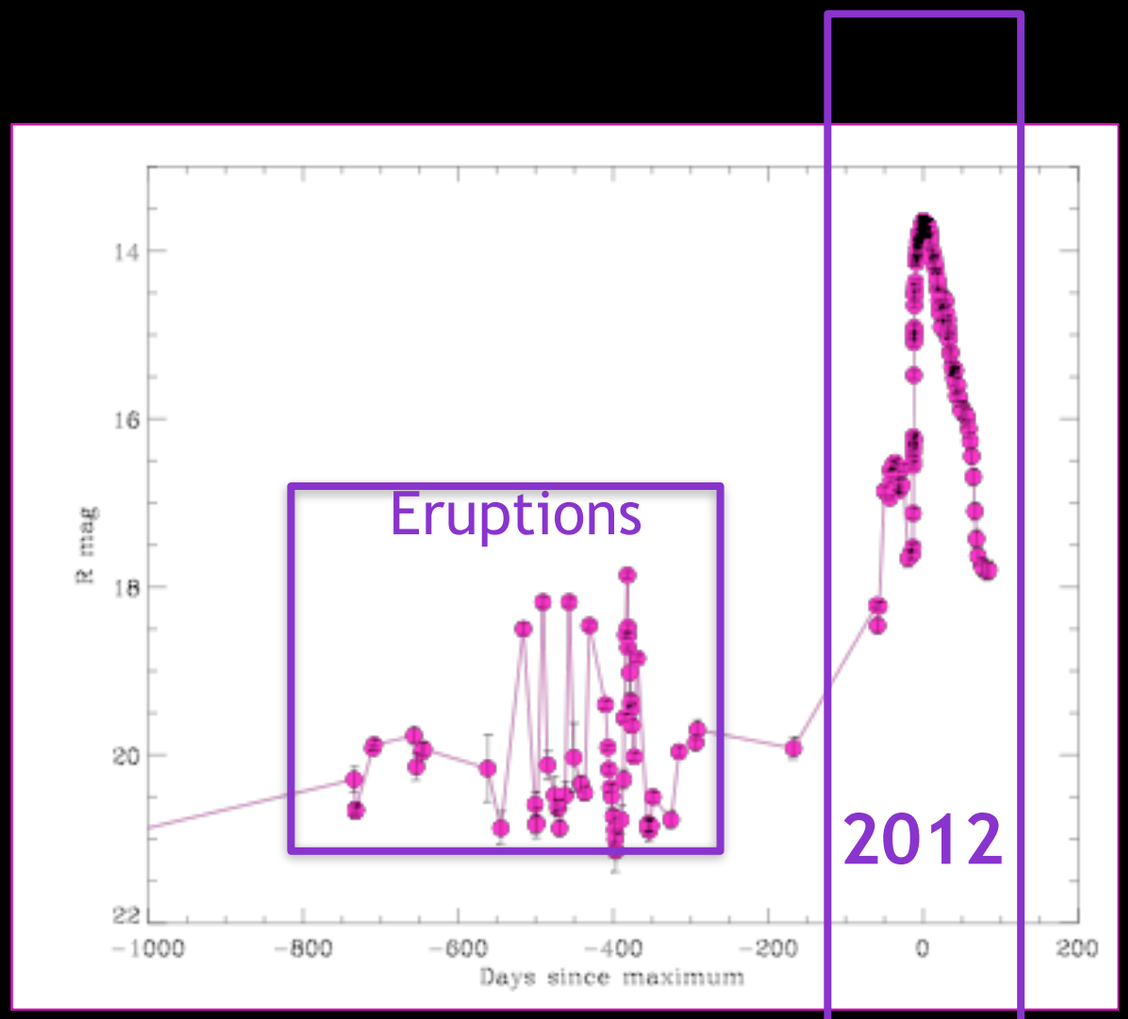
Aug 2012

Sep 2012

Now

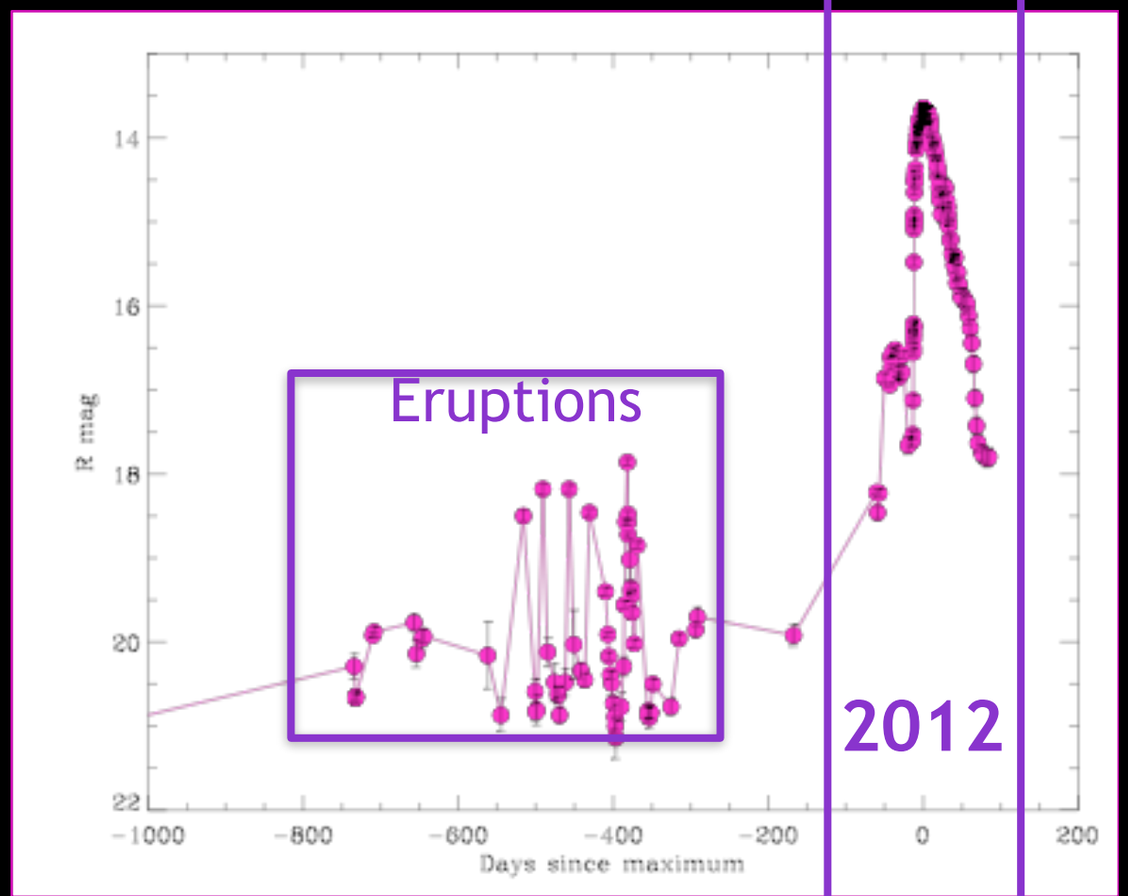
Mauerhan++, Smith++, Margutti+, Pastorello+,Foley+, Prieto+, Fraser+

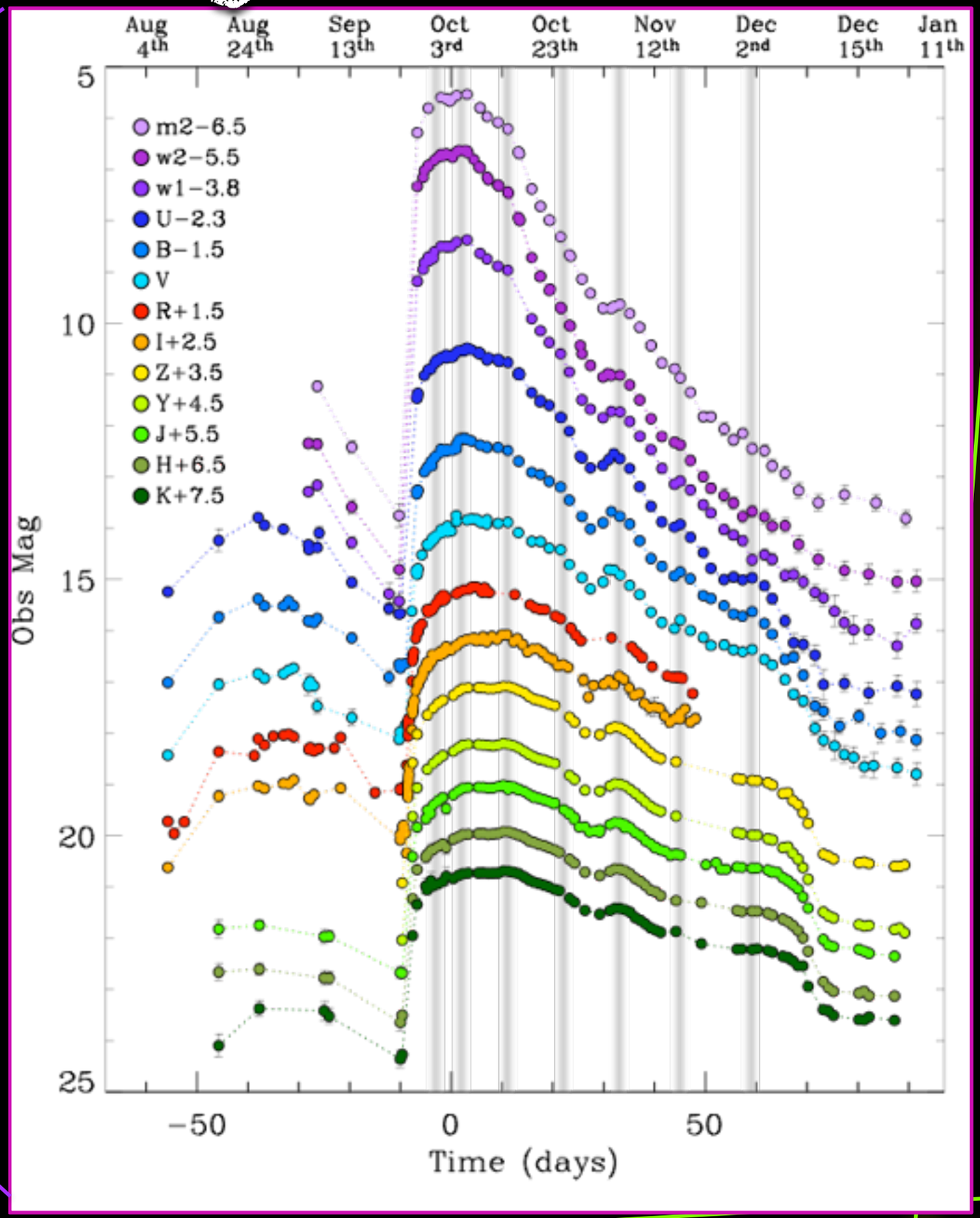
UV-Optical-NIR light-curve



Margutti+ 2014

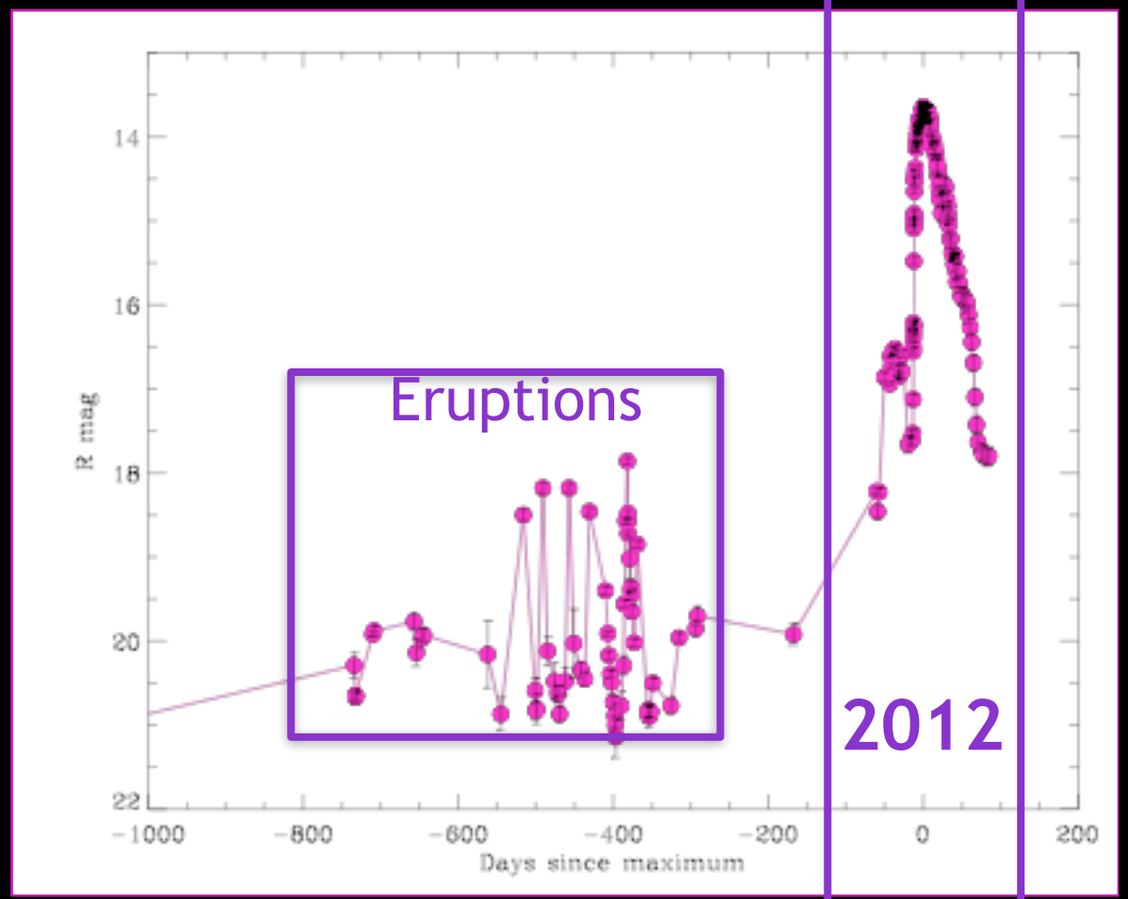
UV-Optical-NIR light-curve

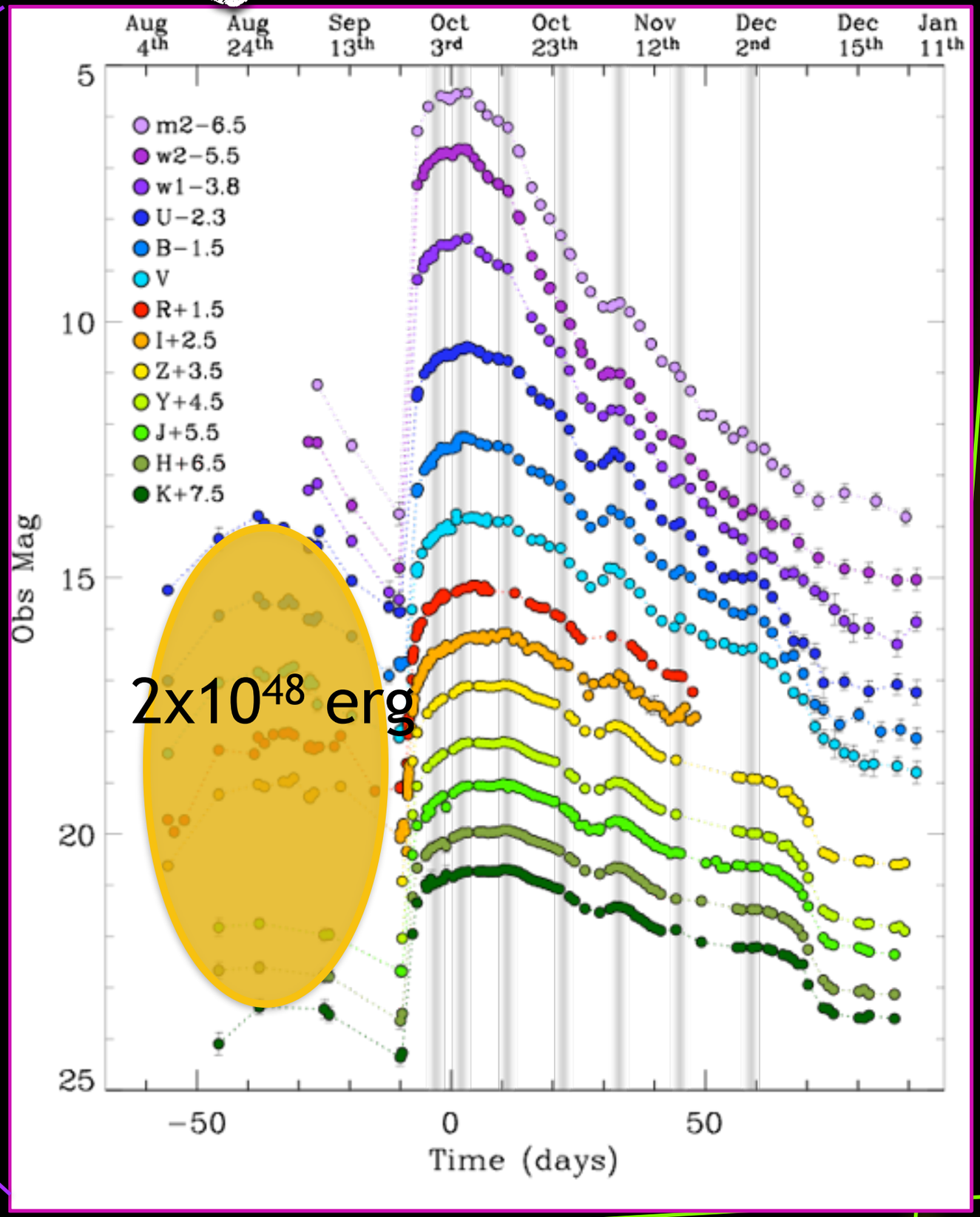




Margutti+ 2014

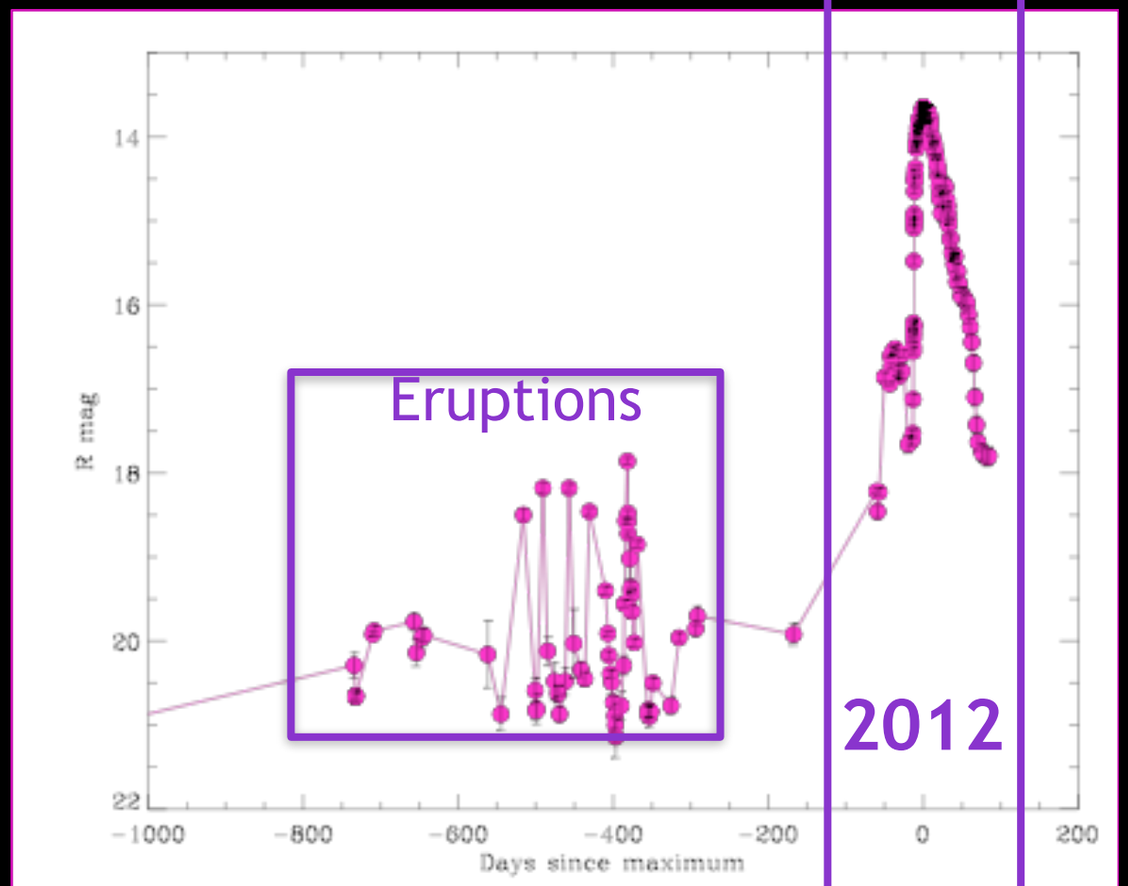
UV-Optical-NIR light-curve

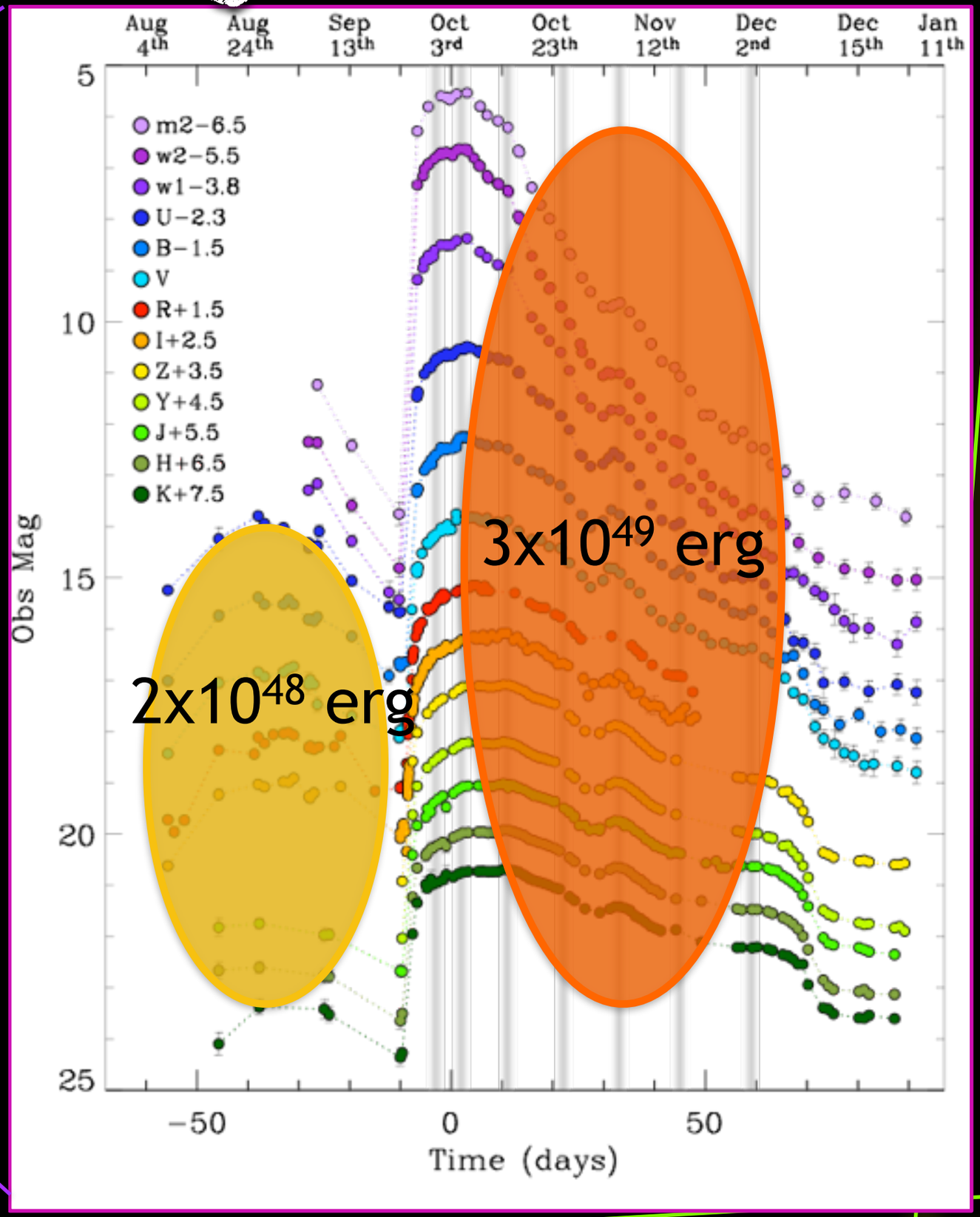




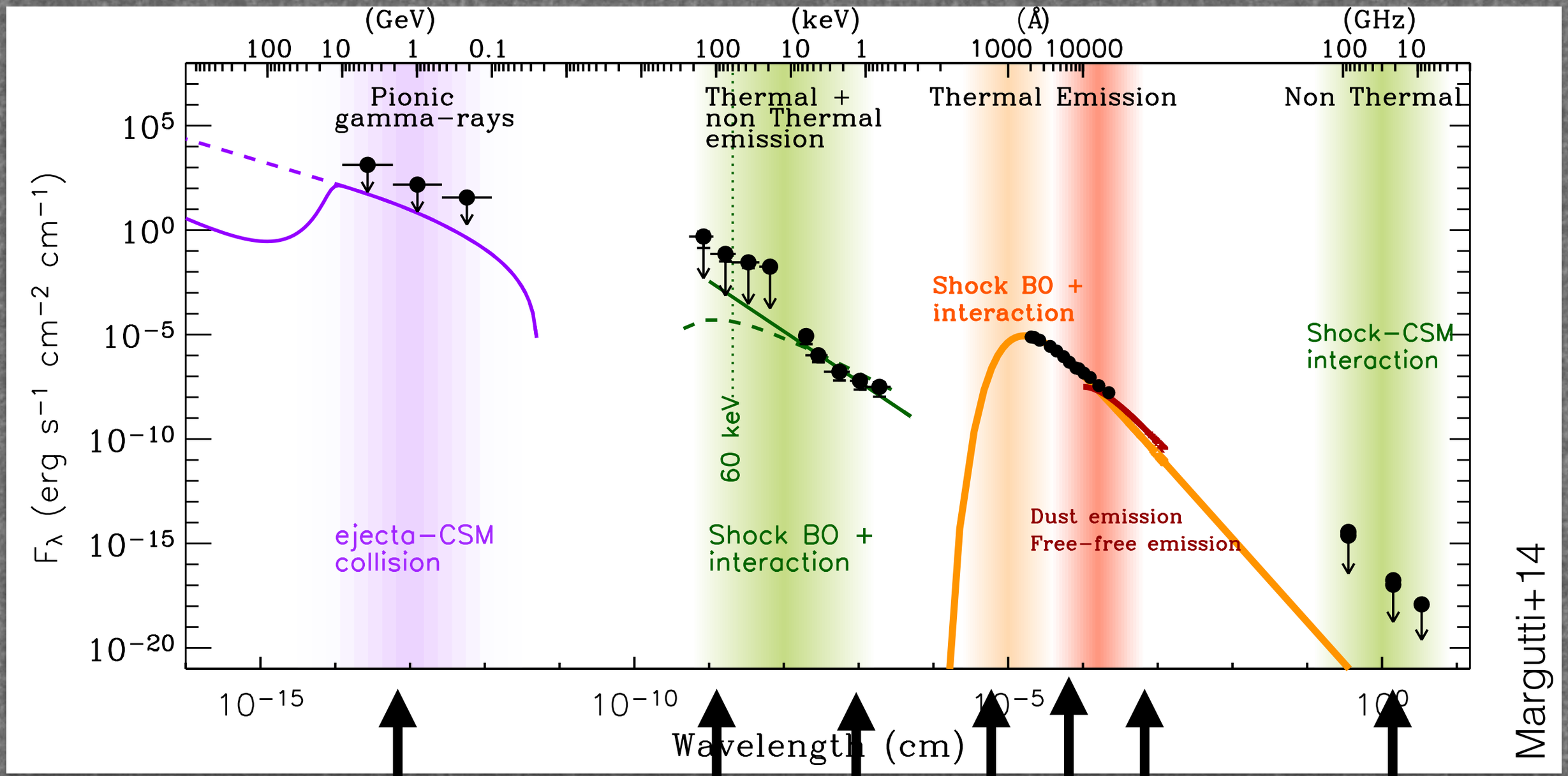
Margutti+ 2014

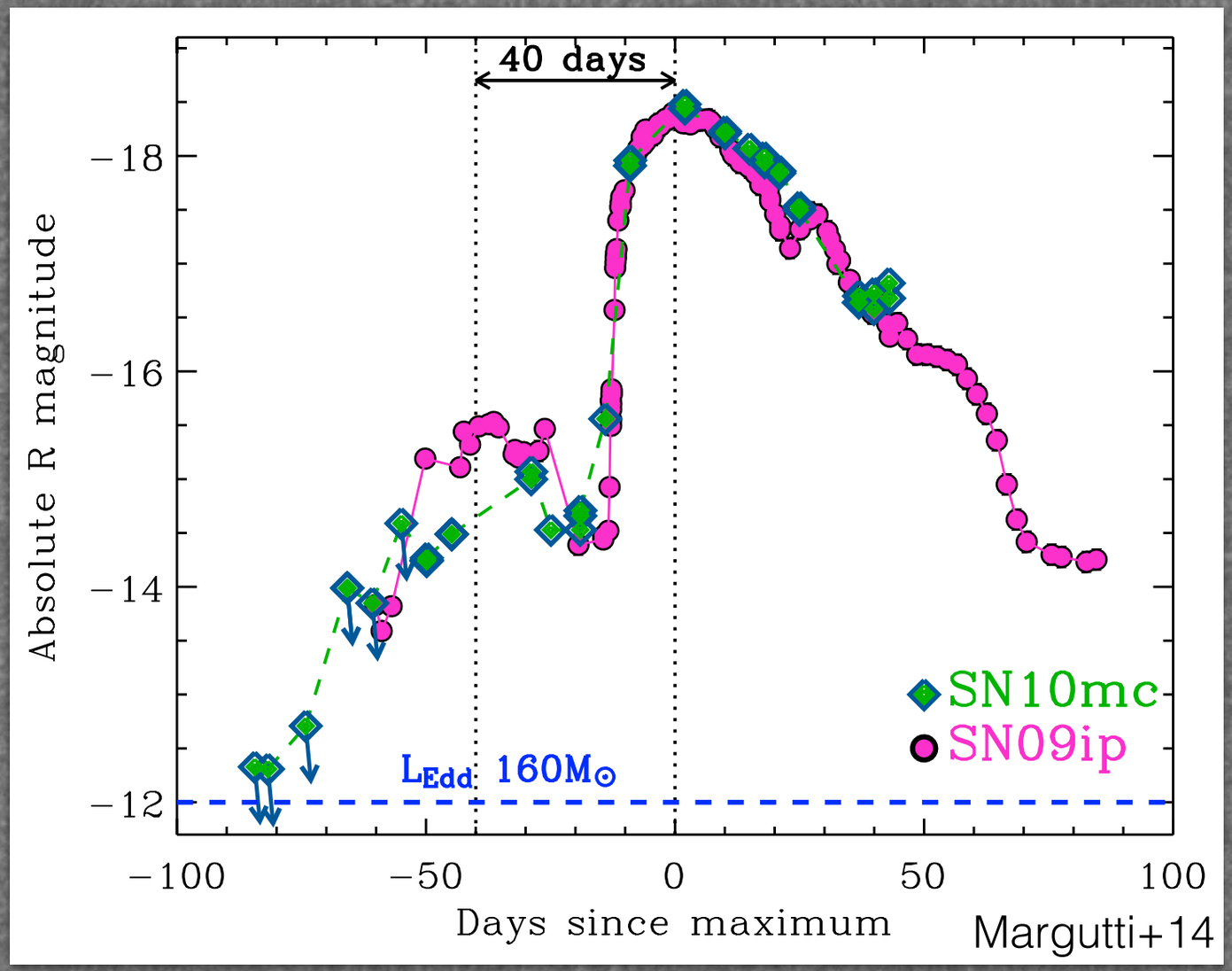
UV-Optical-NIR light-curve

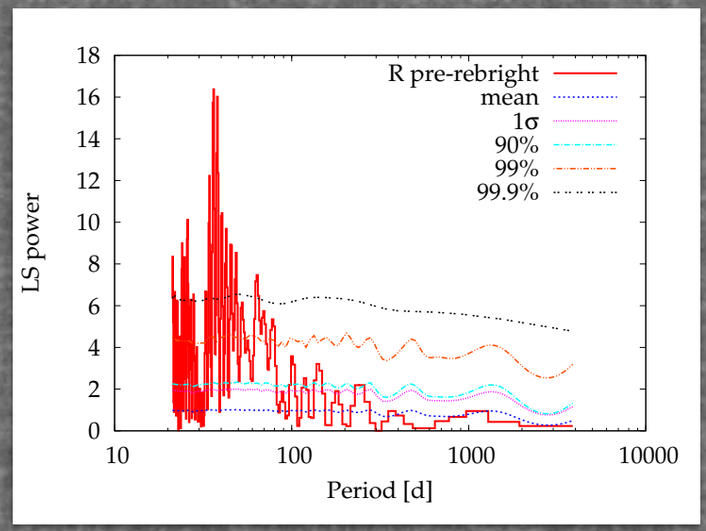




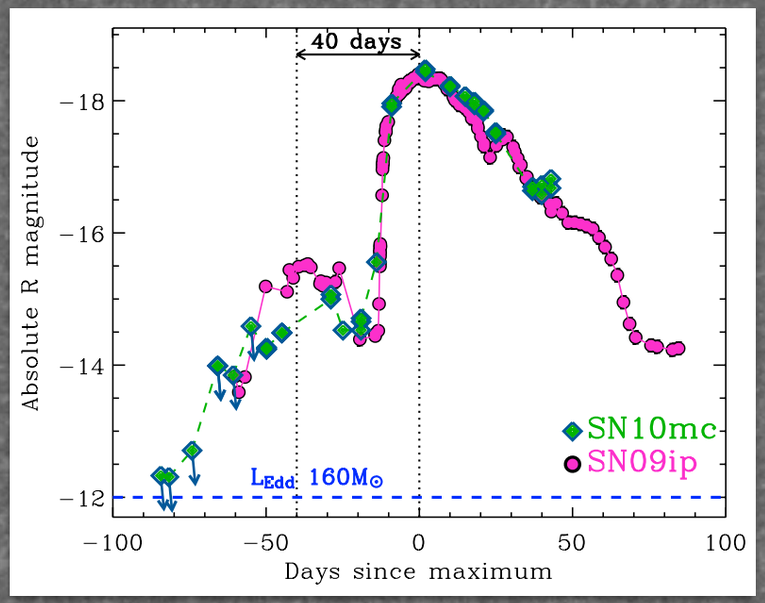
Margutti+ 2014

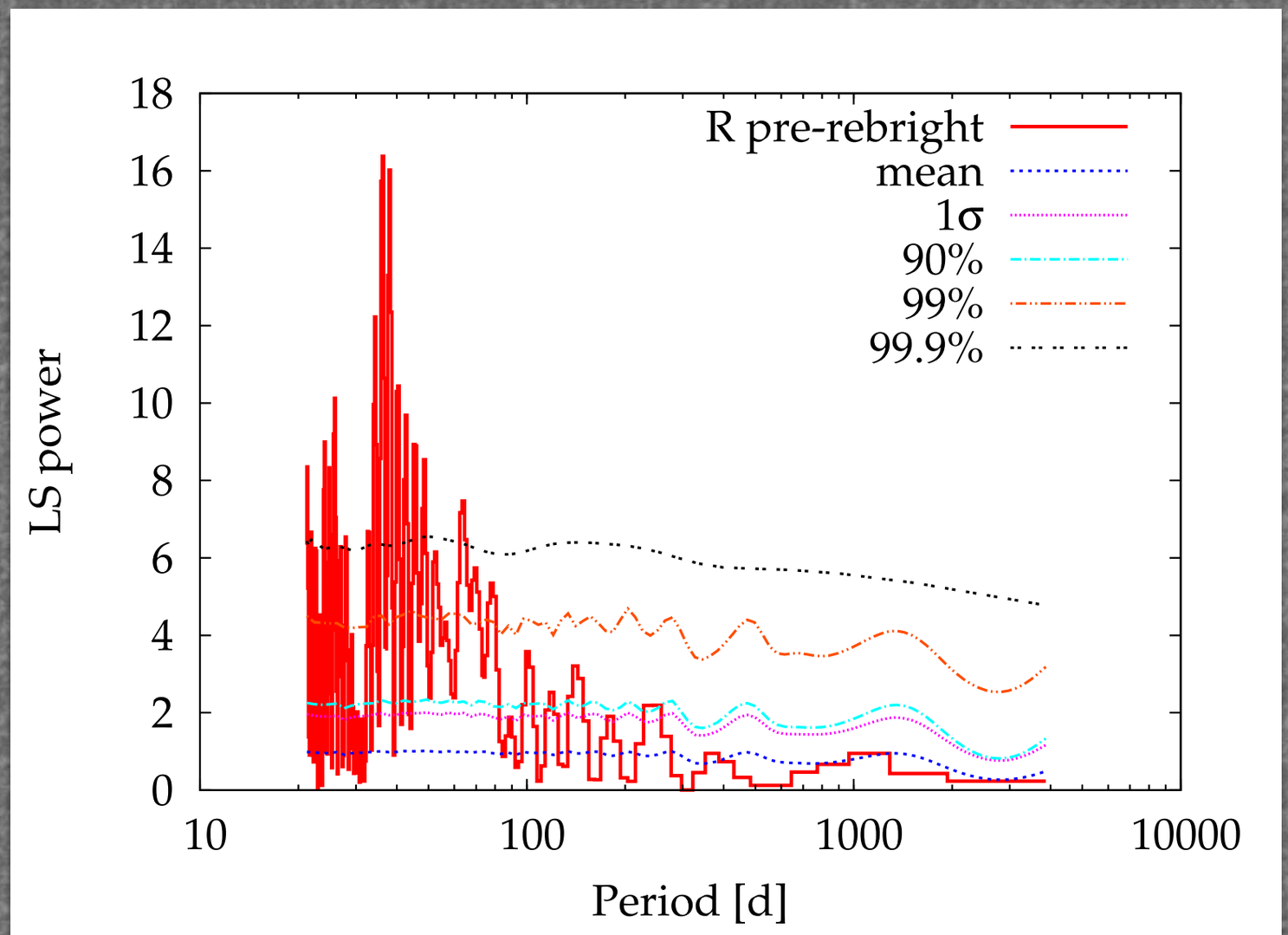

(GeV)
100 10 1 0.1
(keV)
100 10 1
(Å)
1000 10000
(GHz)
100 10
Pionic
gamma−rays
Thermal +
non Thermal
emission
Thermal Emission
Non Thermal
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
F_λ (erg s^{-1} cm^{-2} cm^{-1})
60 keV
Shock BO +
interaction
Shock−CSM
interaction
Dust emission
Free−free emission
ejecta−CSM
collision
Shock BO +
interaction
10^{-15}
10^{-10}
10^{-5}
10^{0}
Wavelength (cm)
Margutti+14
Gamma-Rays
Hard X-rays
Soft X-rays
UV
Optical
NIR
Radio





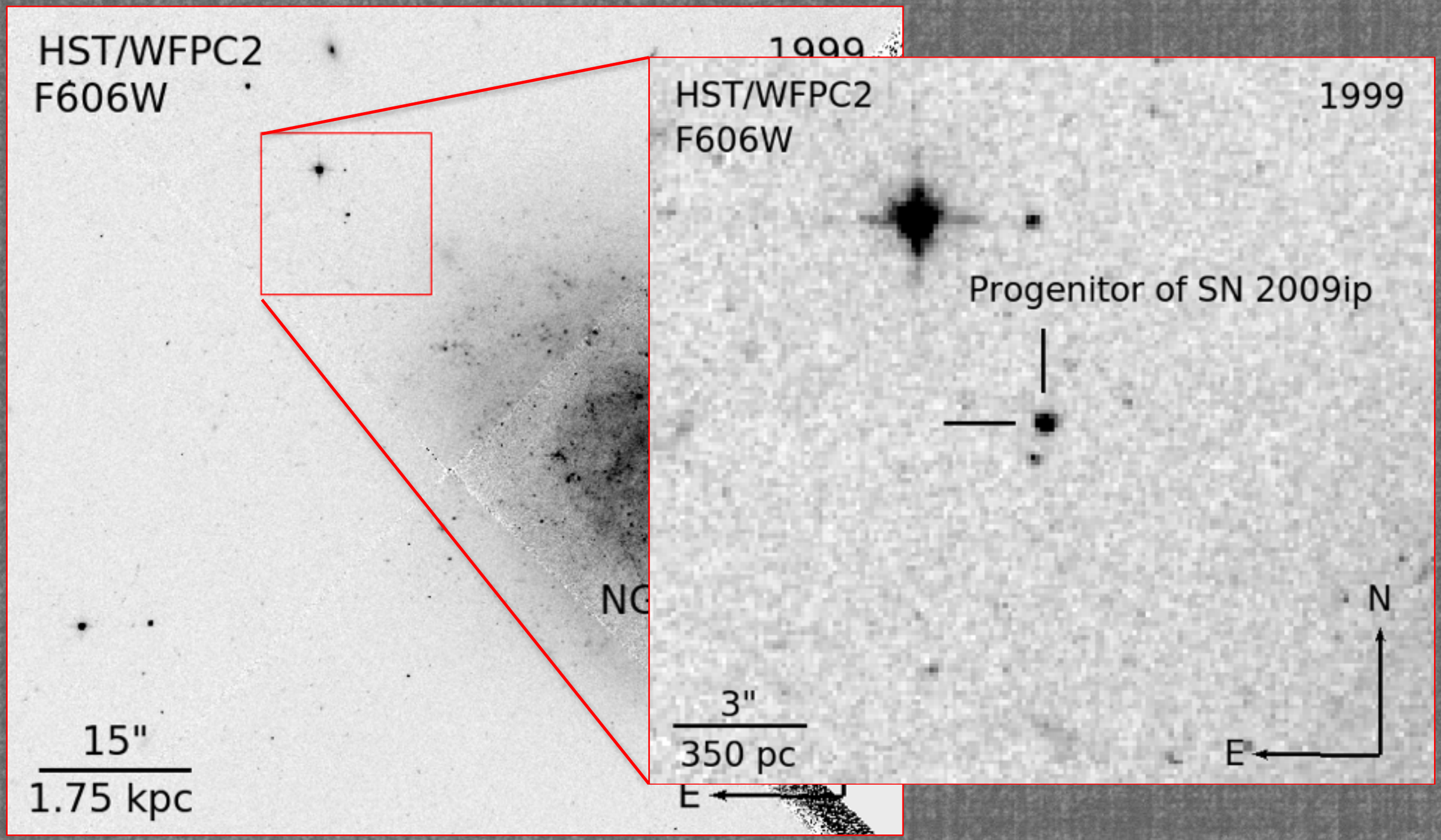
-- Causal connection between the two events
-- “SIMPLE” mechanism
-- Important channel for mass loss





Presence of a **dominant time-scale** common to eruption episodes and the major explosion, shared by completely independent events

→40 days



Massive star: M> 60 Msun

Smith et al, 2010; Foley et al., 2011

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

Optical

X-rays

SN2014C
Type Ib SN

pre-explosion

post-explosion

Credit:
NSA/JPL press release

Margutti et al., 2017

Ib/c

SN2014C

IIn

WR

LBV

Enhanced Mass-Loss

RSG

IIP

iPTF13dqy
Yaron+

Ibn

SN2006jc
Valenti+, Pastorello+
Foley+

YSG

IIb

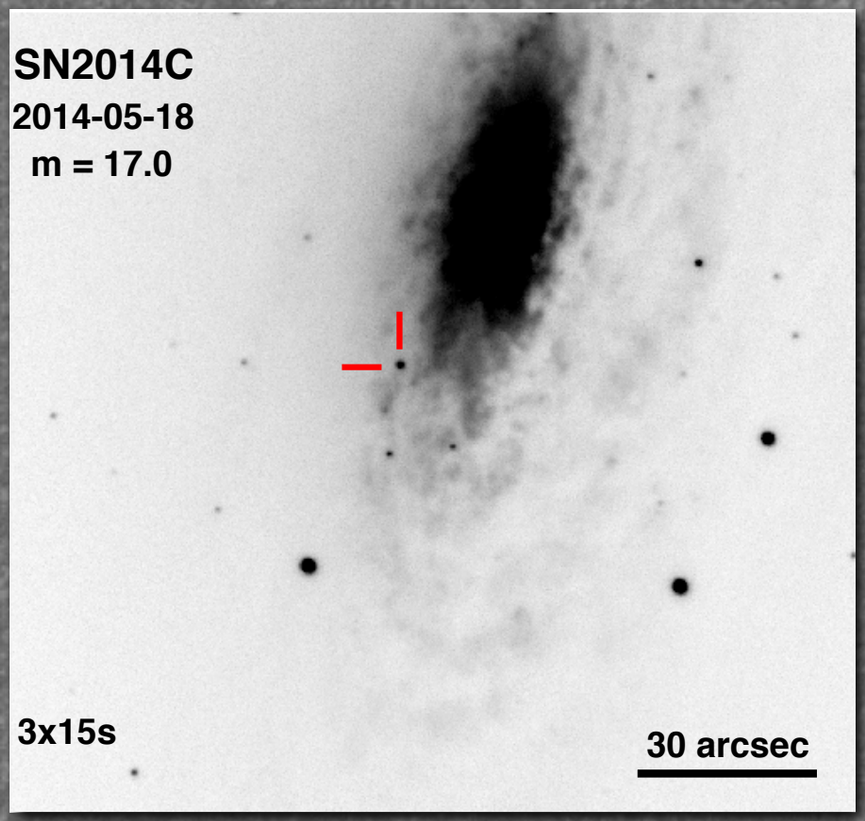
Kamble+16

H-poor

H-rich

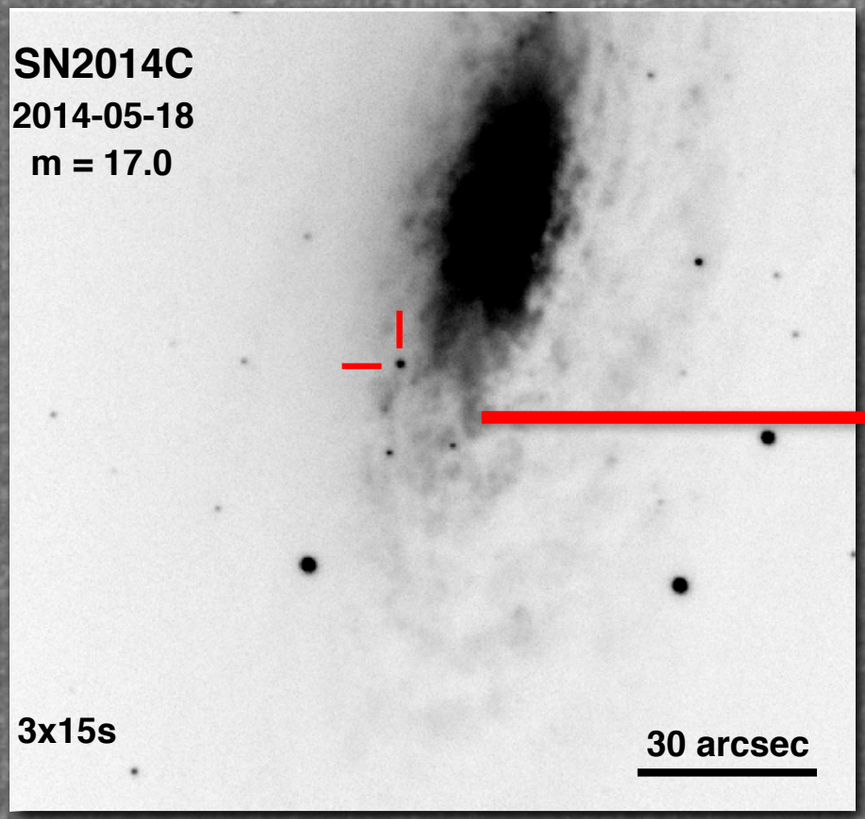
SN2014C: a normal Ib SN

dist=15.7 Mpc

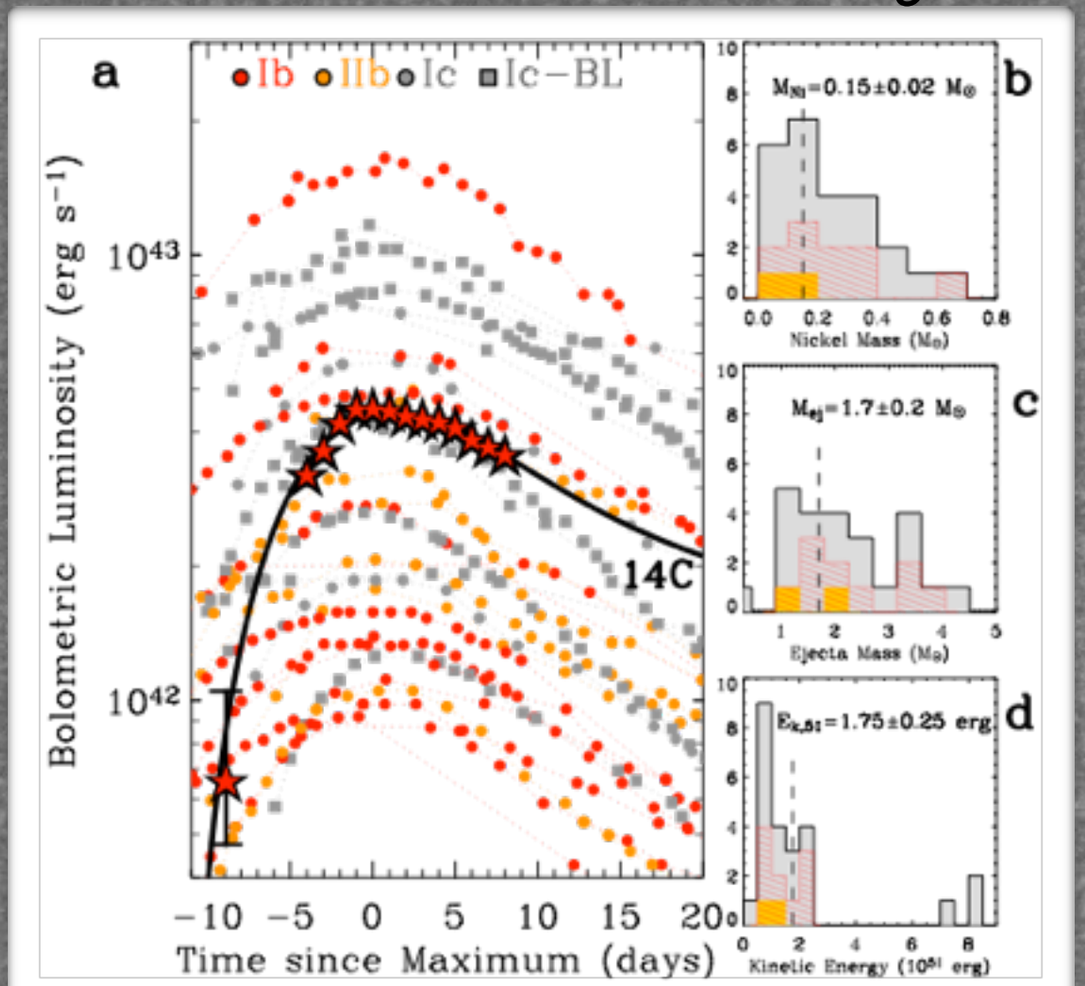


SN2014C: a normal Ib SN

dist=15.7 Mpc



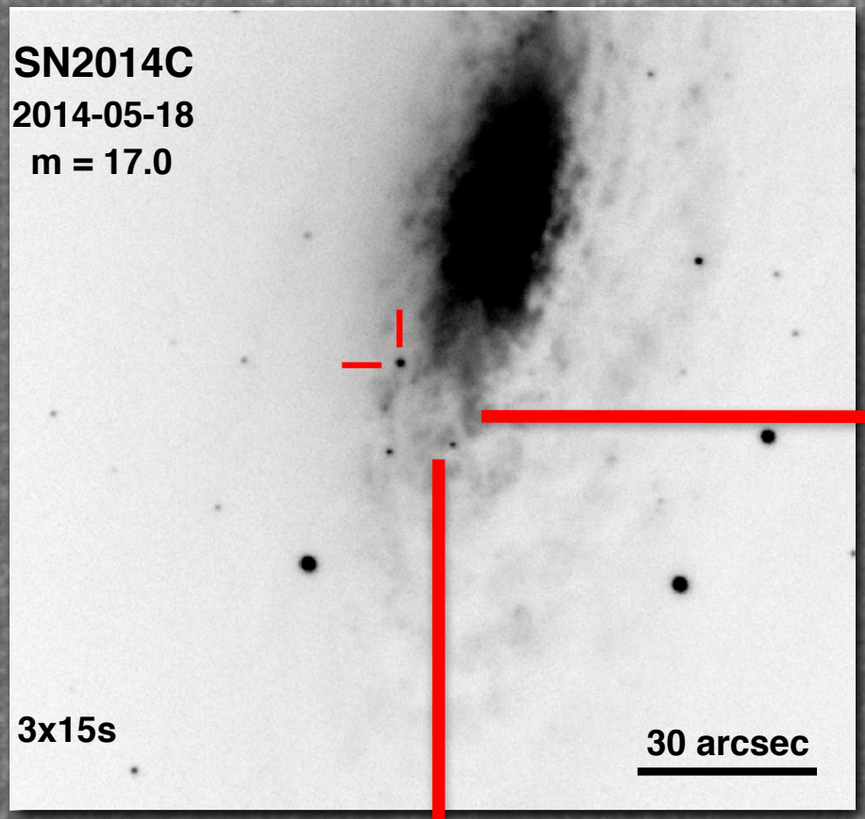
Bolometric Luminosity



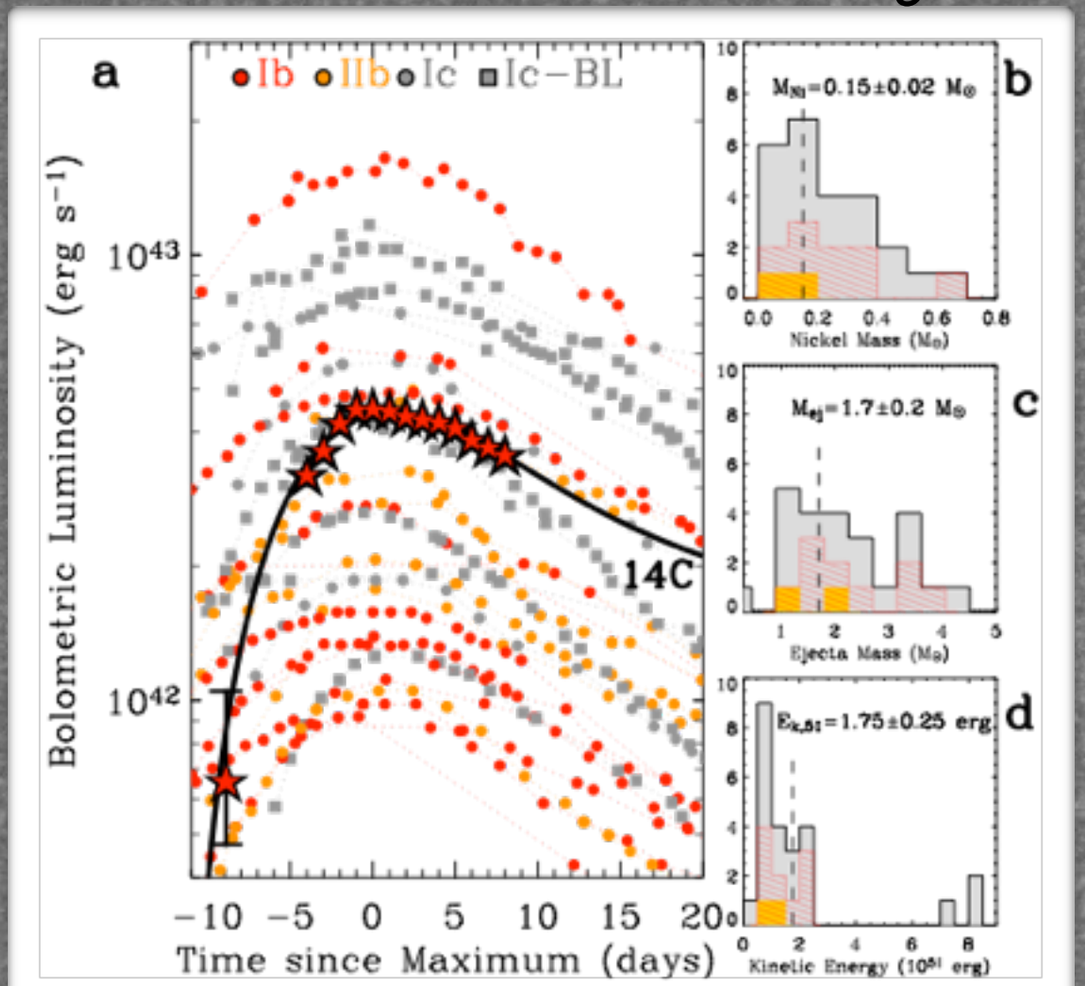
RM+17

SN2014C: a normal Ib SN

dist=15.7 Mpc

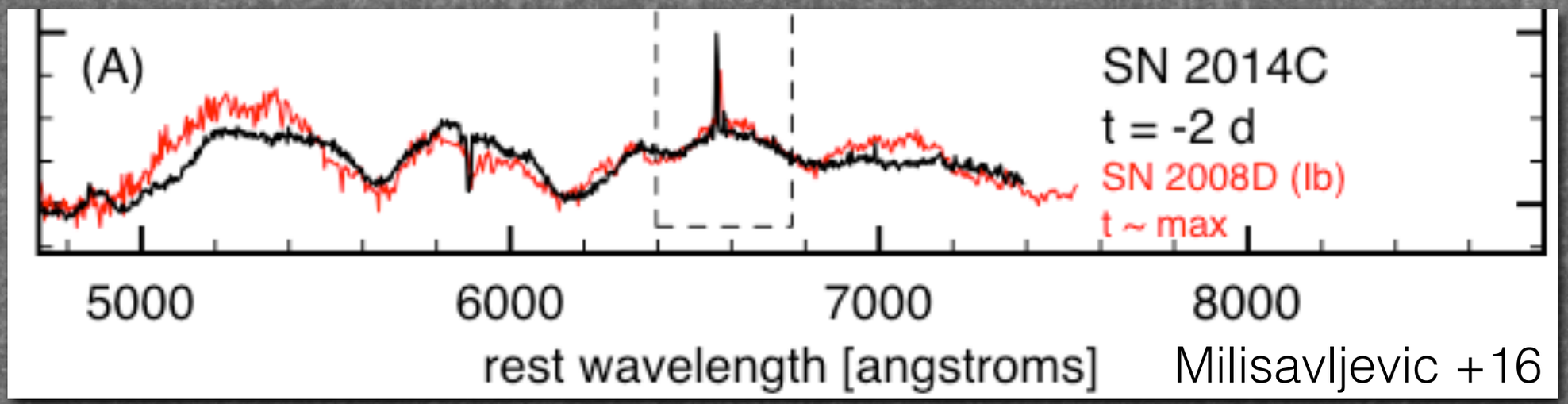


Bolometric Luminosity



RM+17

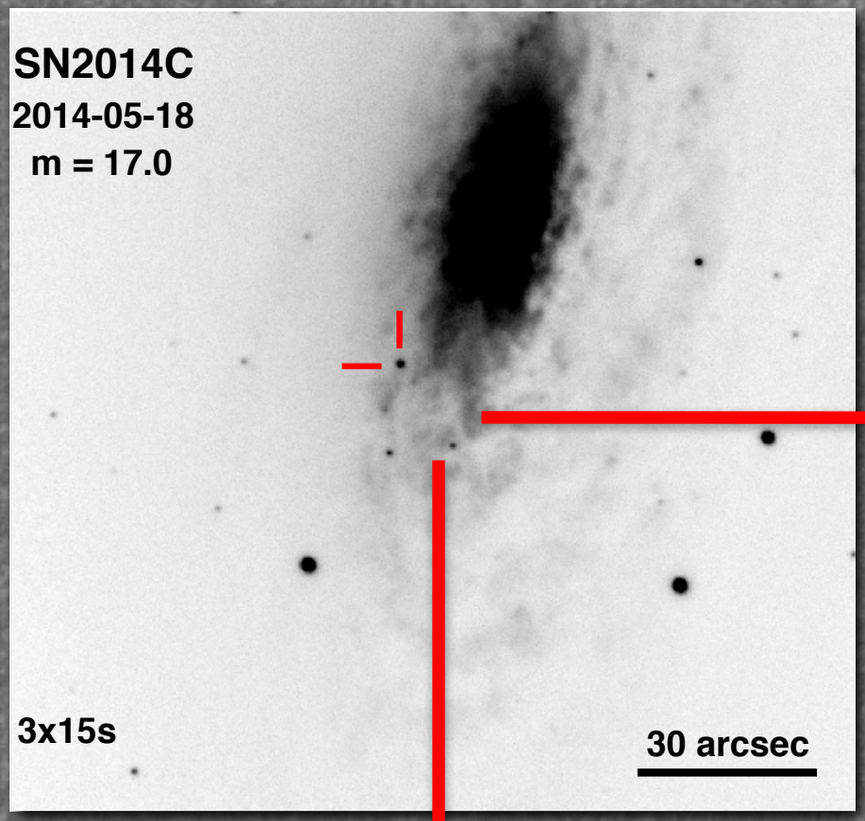
Optical Spectrum at max



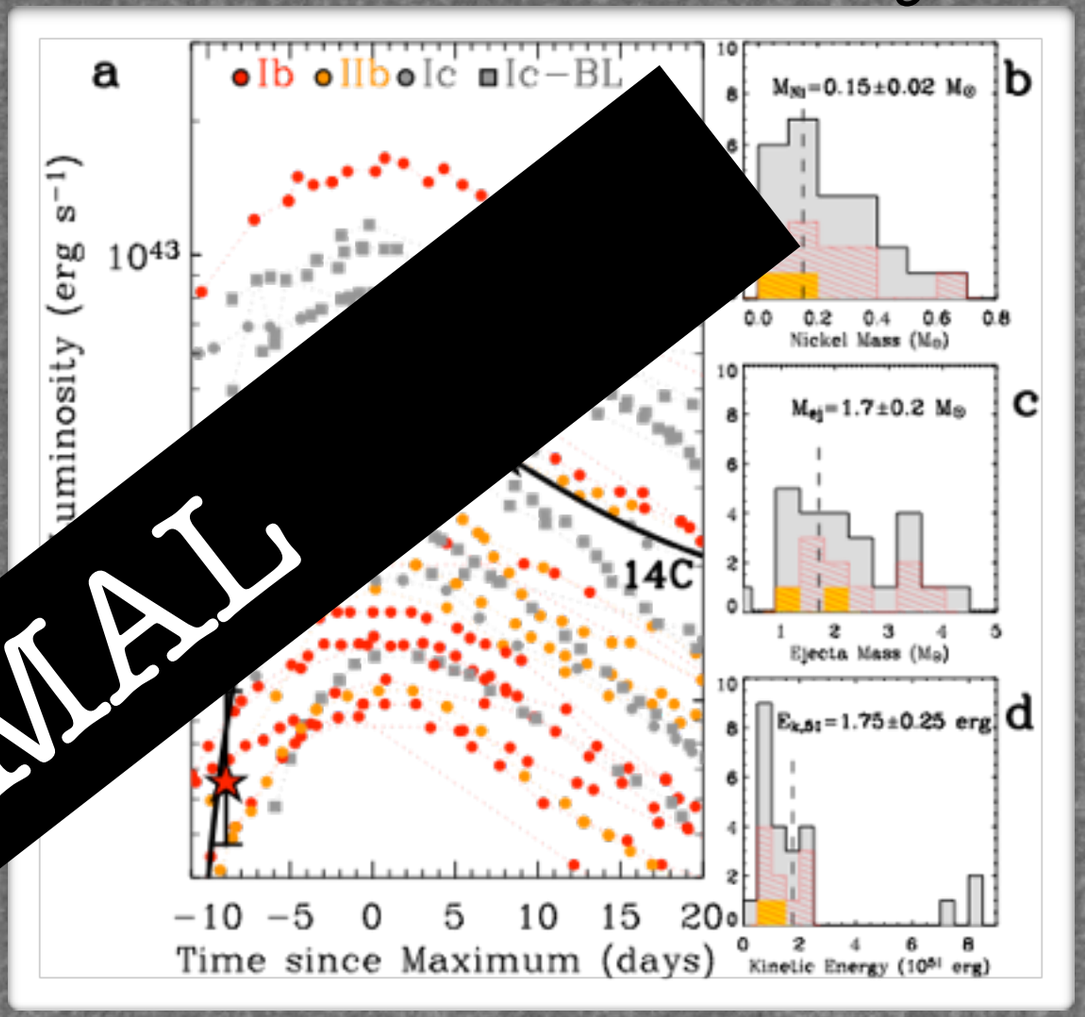
Milisavljevic +16

SN2014C: a normal Ib SN

dist=15.7 Mpc



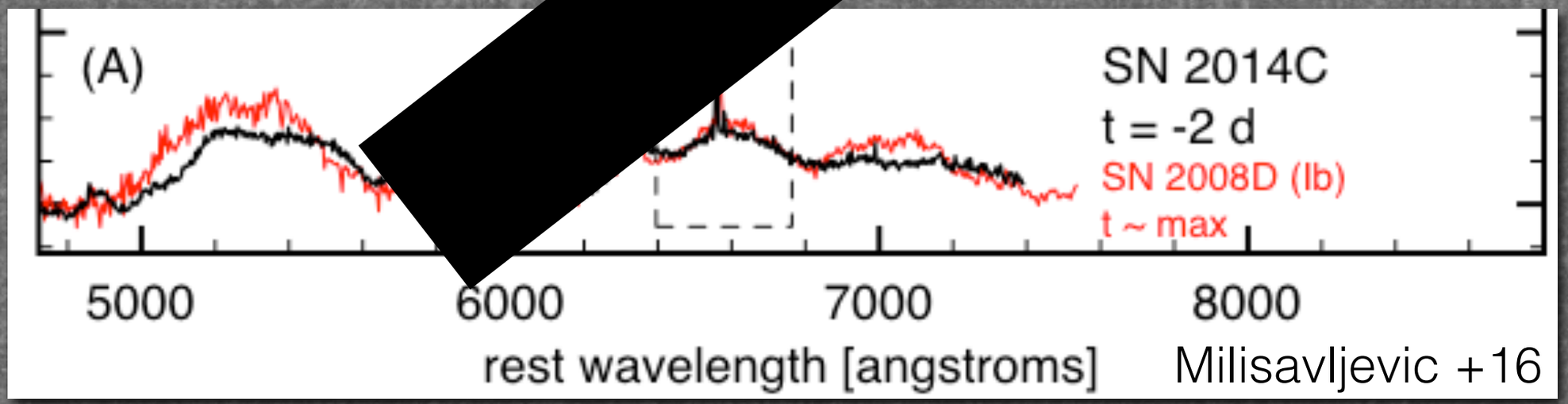
Bolometric Luminosity



RM+17

NORMAL

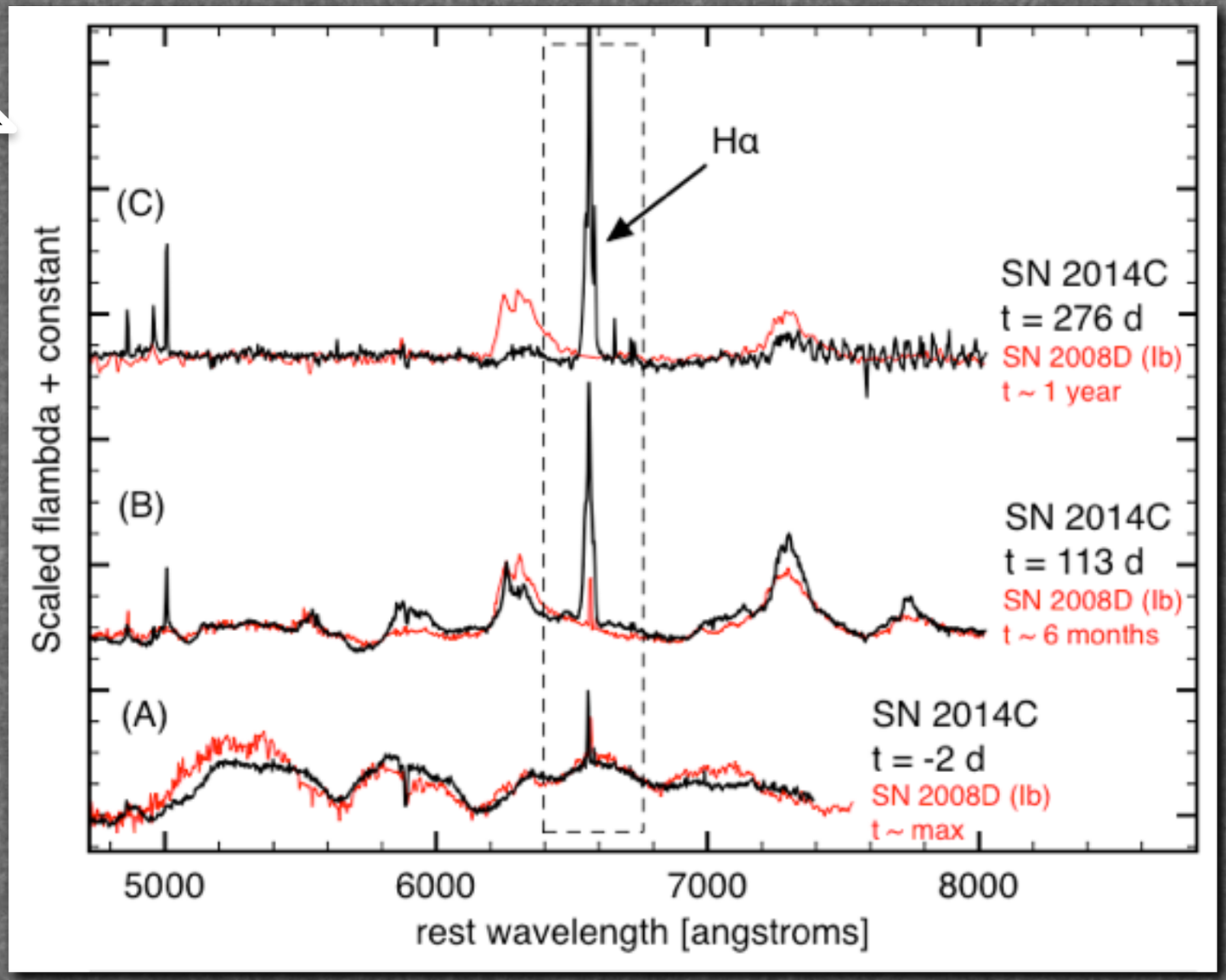
Optical Spectrum at



Milisavljevic +16

SN2014C-Optical

TIME

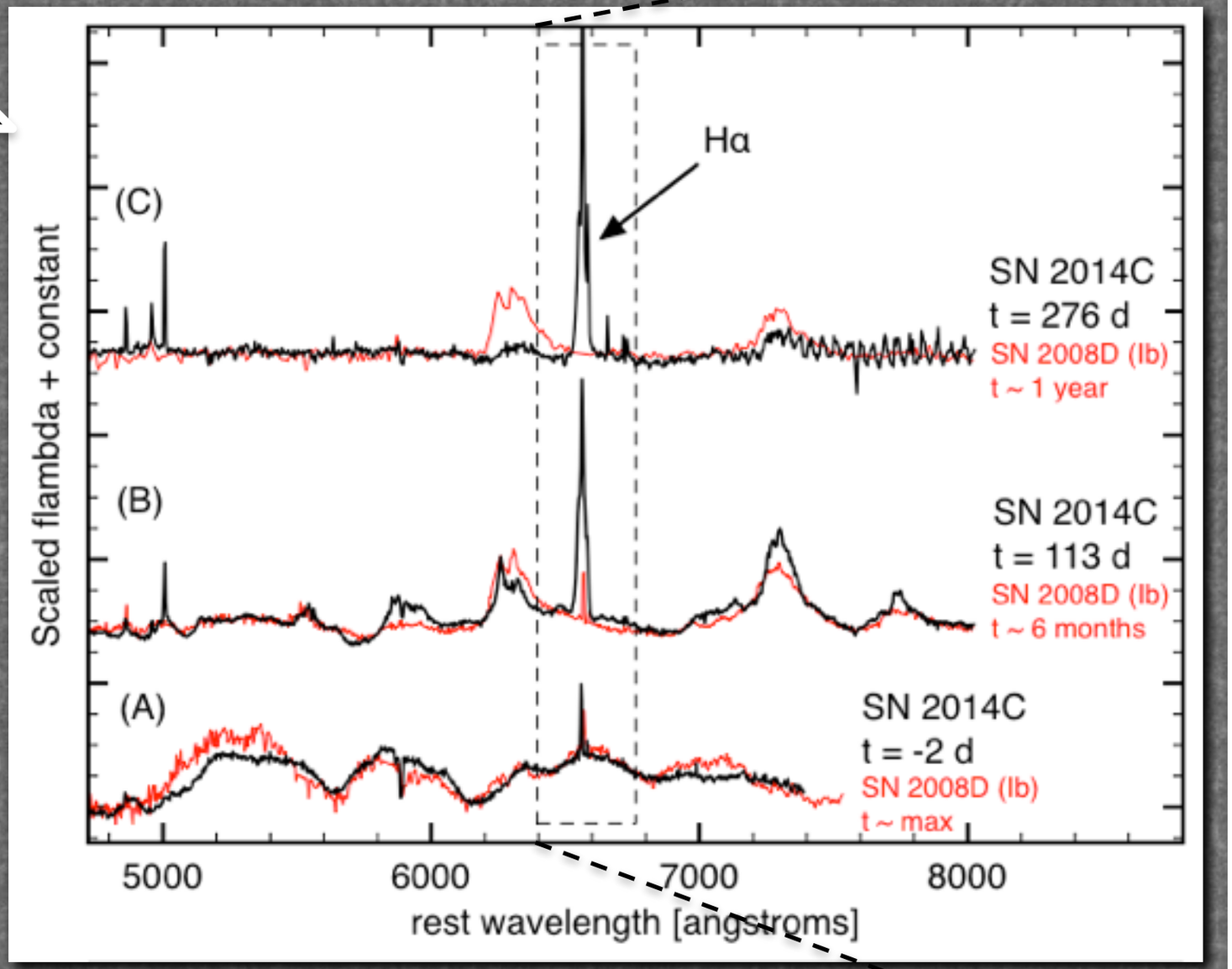


Milisavljevic, RM+17

Development of H-features with time

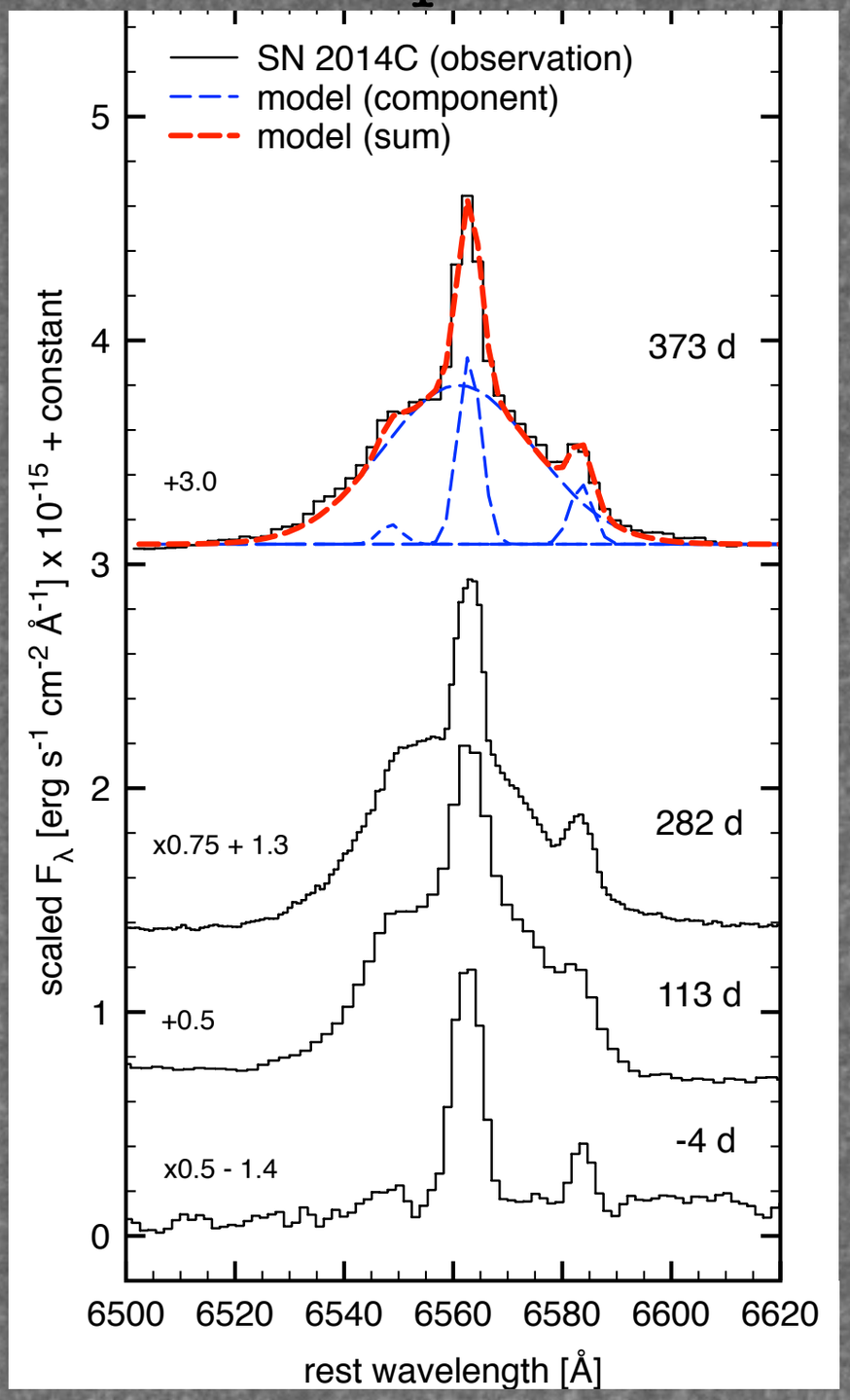
SN2014C-Optical

TIME



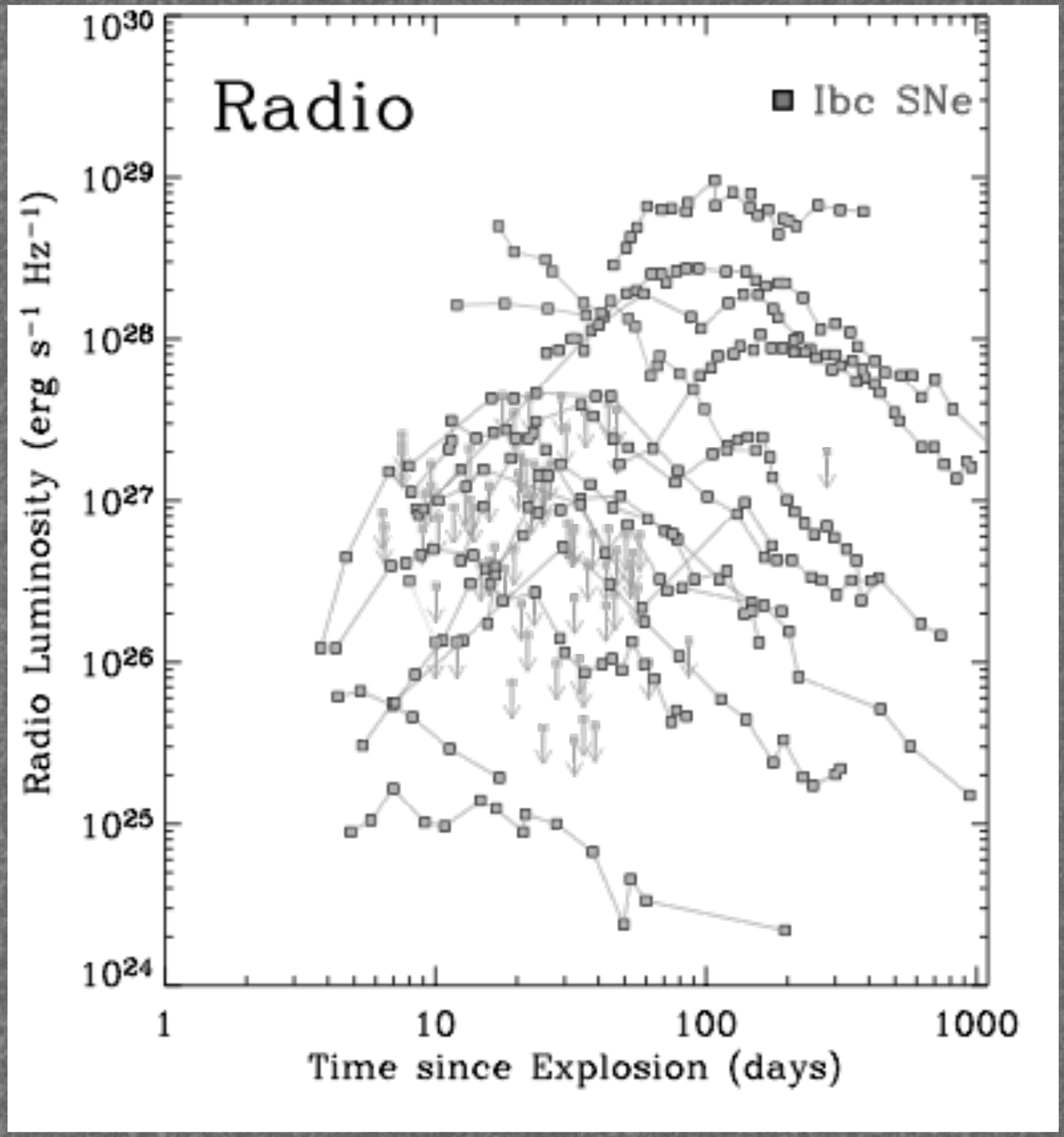
Milisavljevic, RM+17

Halpha



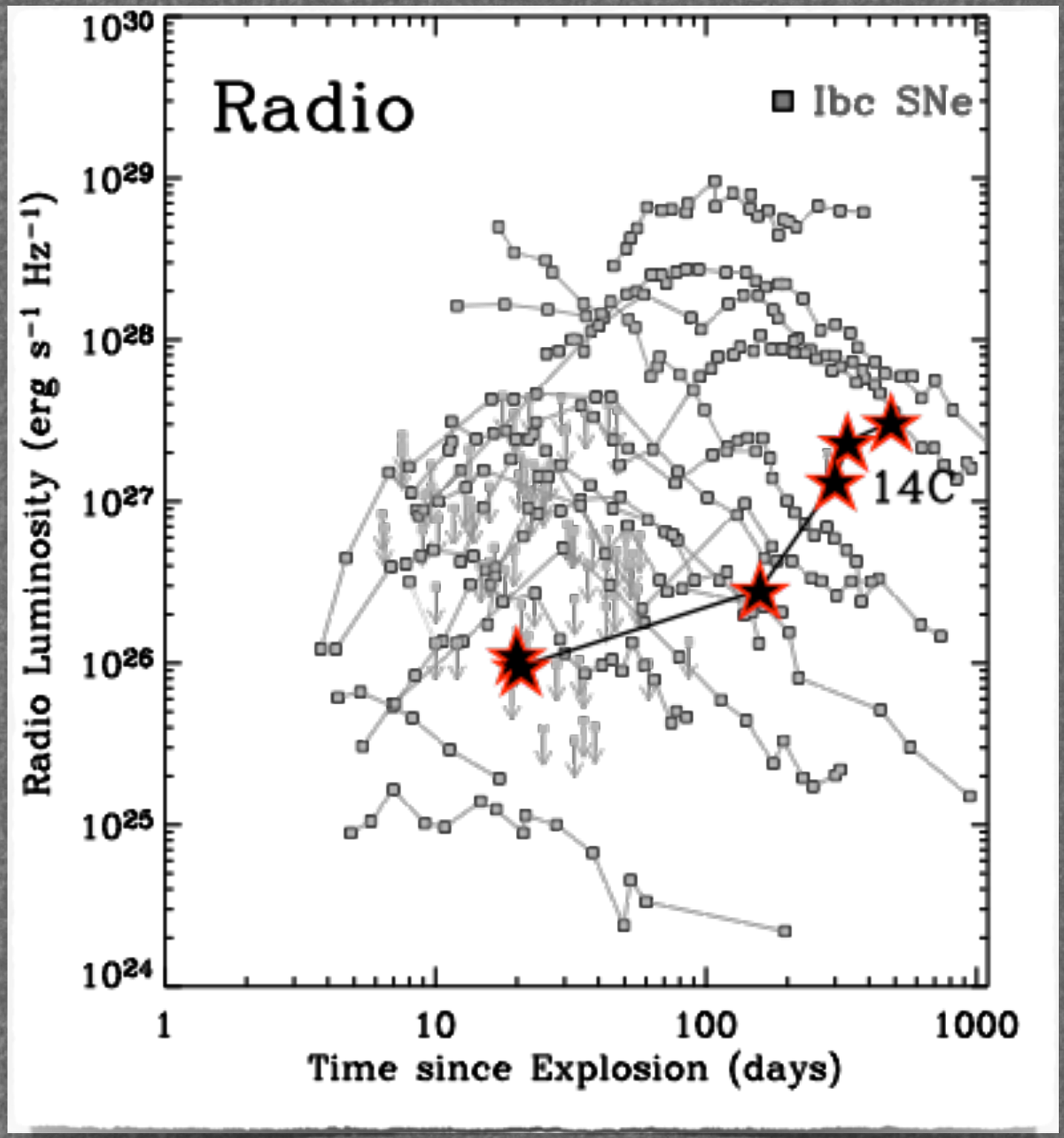
Development of H-features with time

SN2014C-Radio



RM+16

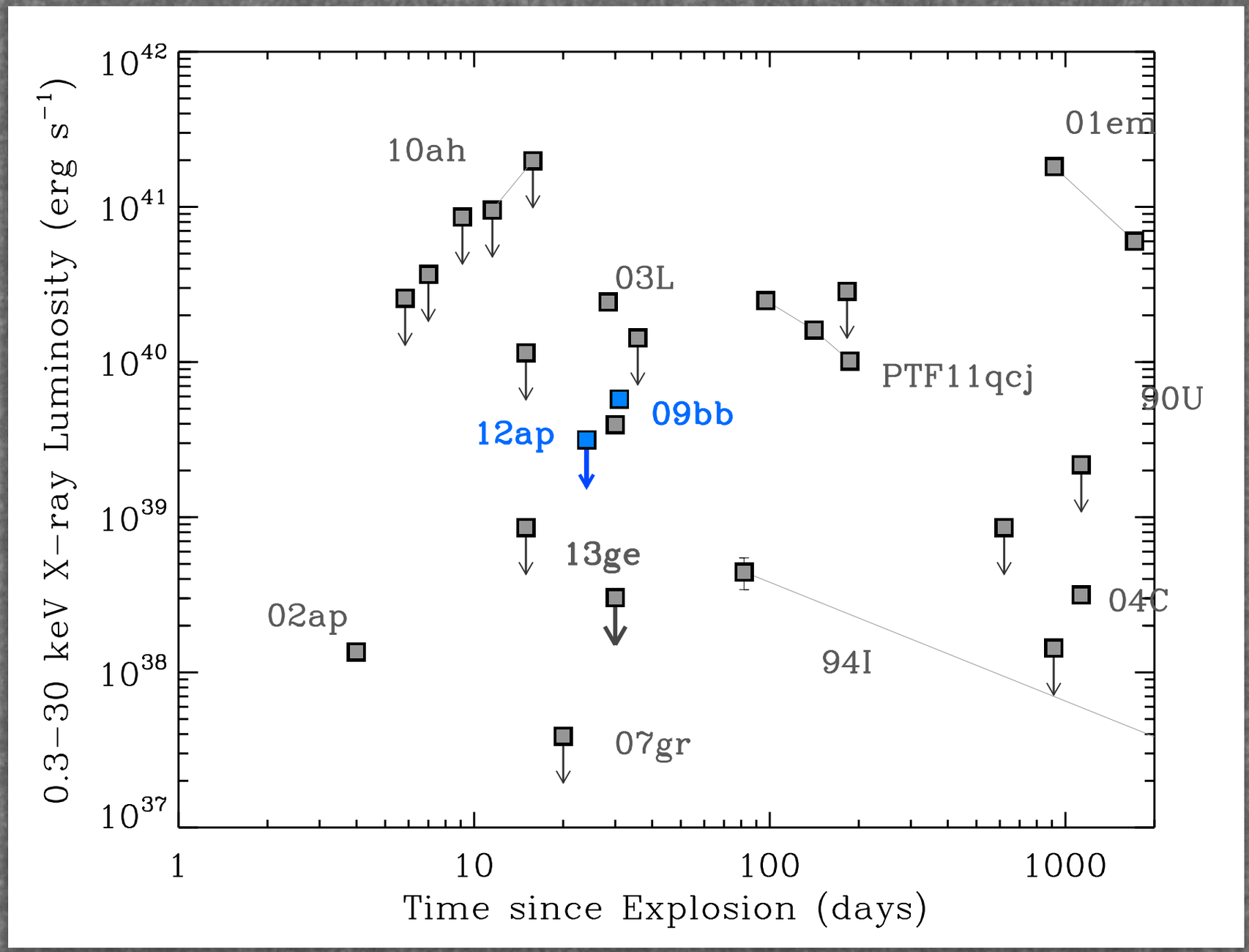
SN2014C-Radio



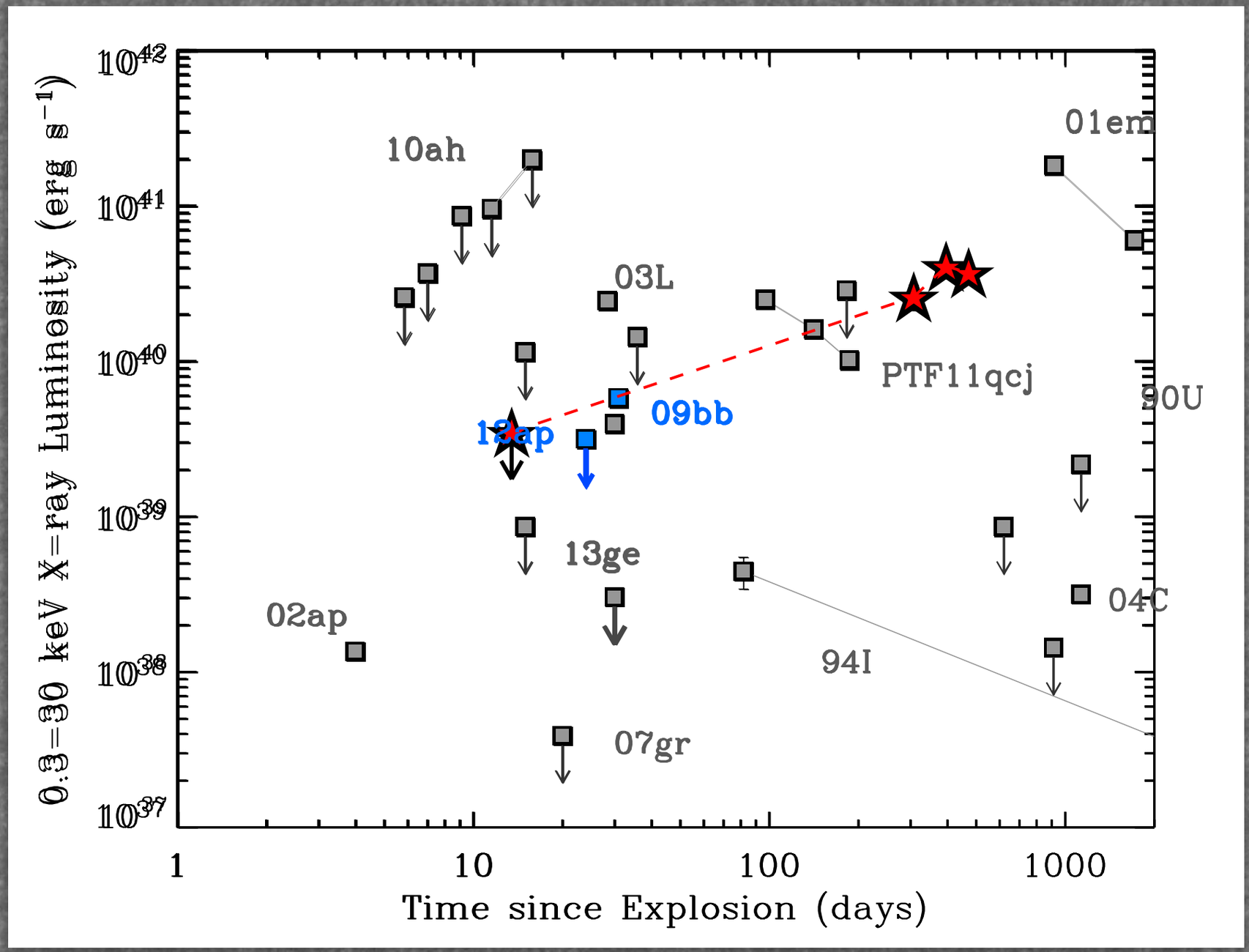
RM+16

Radio Luminosity INCREASES w. time!

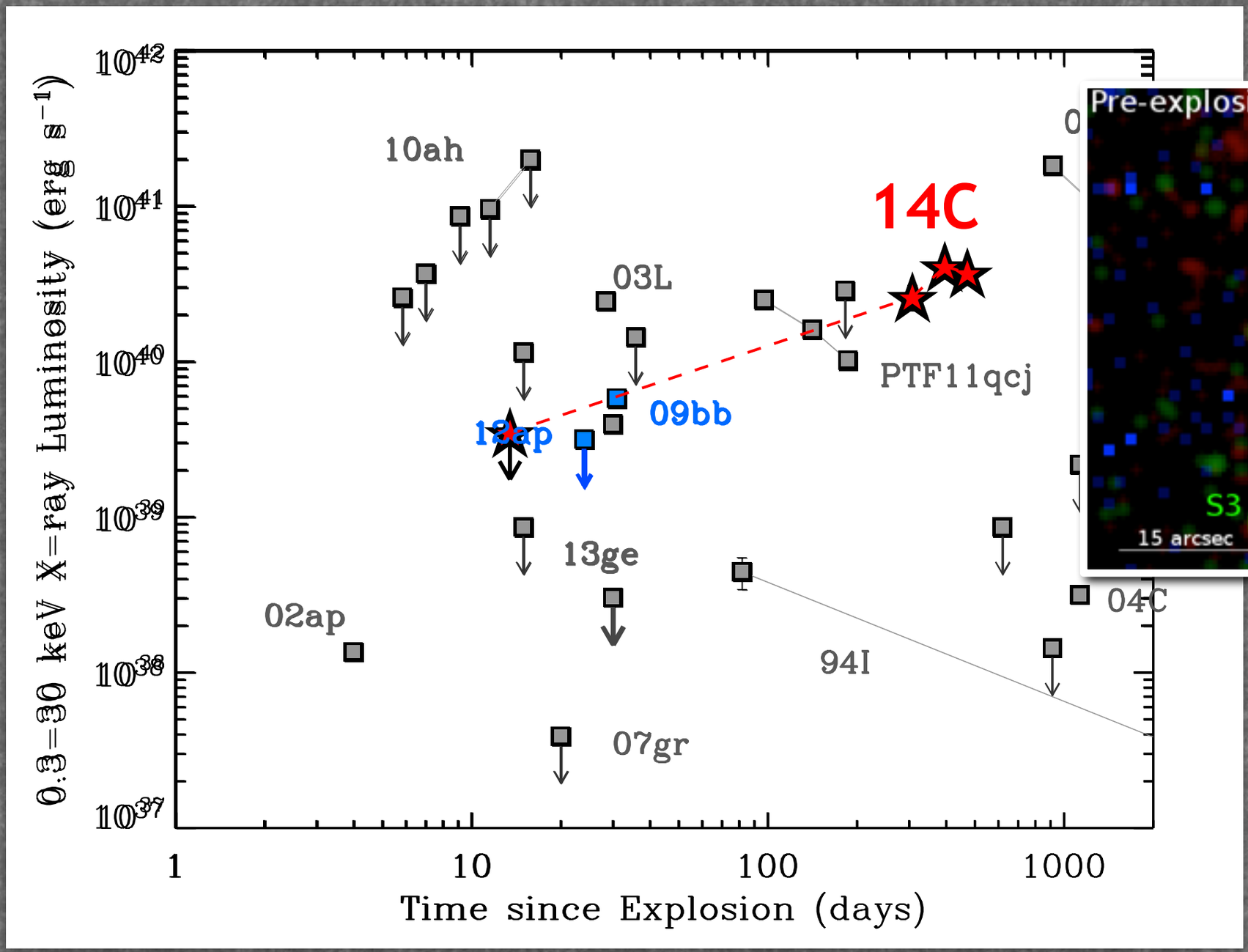
SN2014C-X-rays (soft+hard)

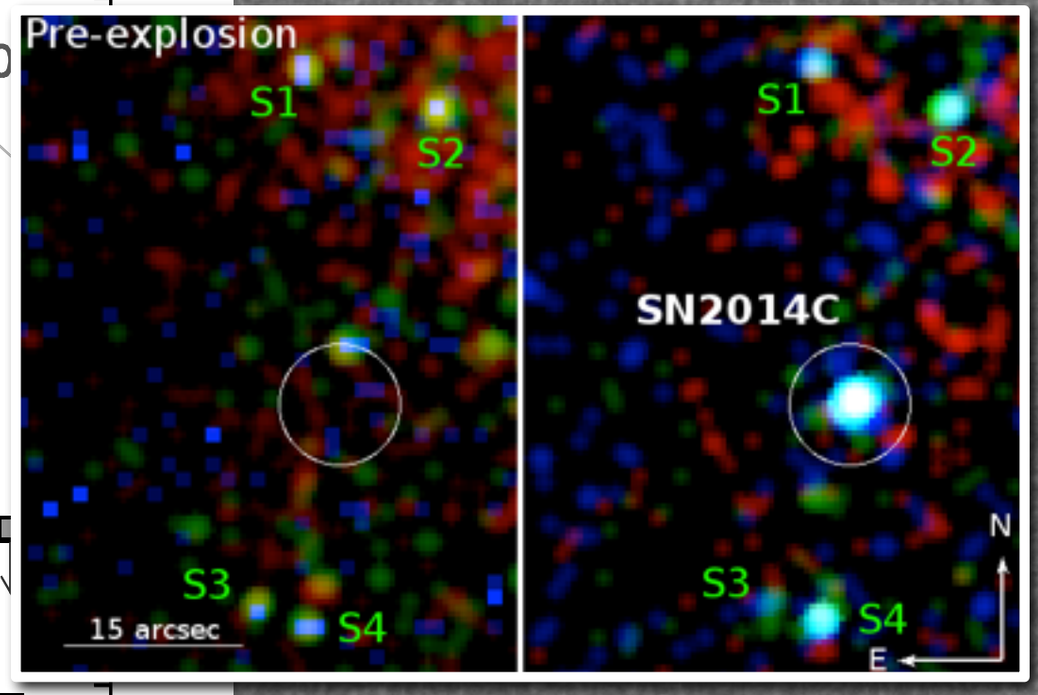


SN2014C-X-rays (soft+hard)



SN2014C-X-rays (soft+hard)

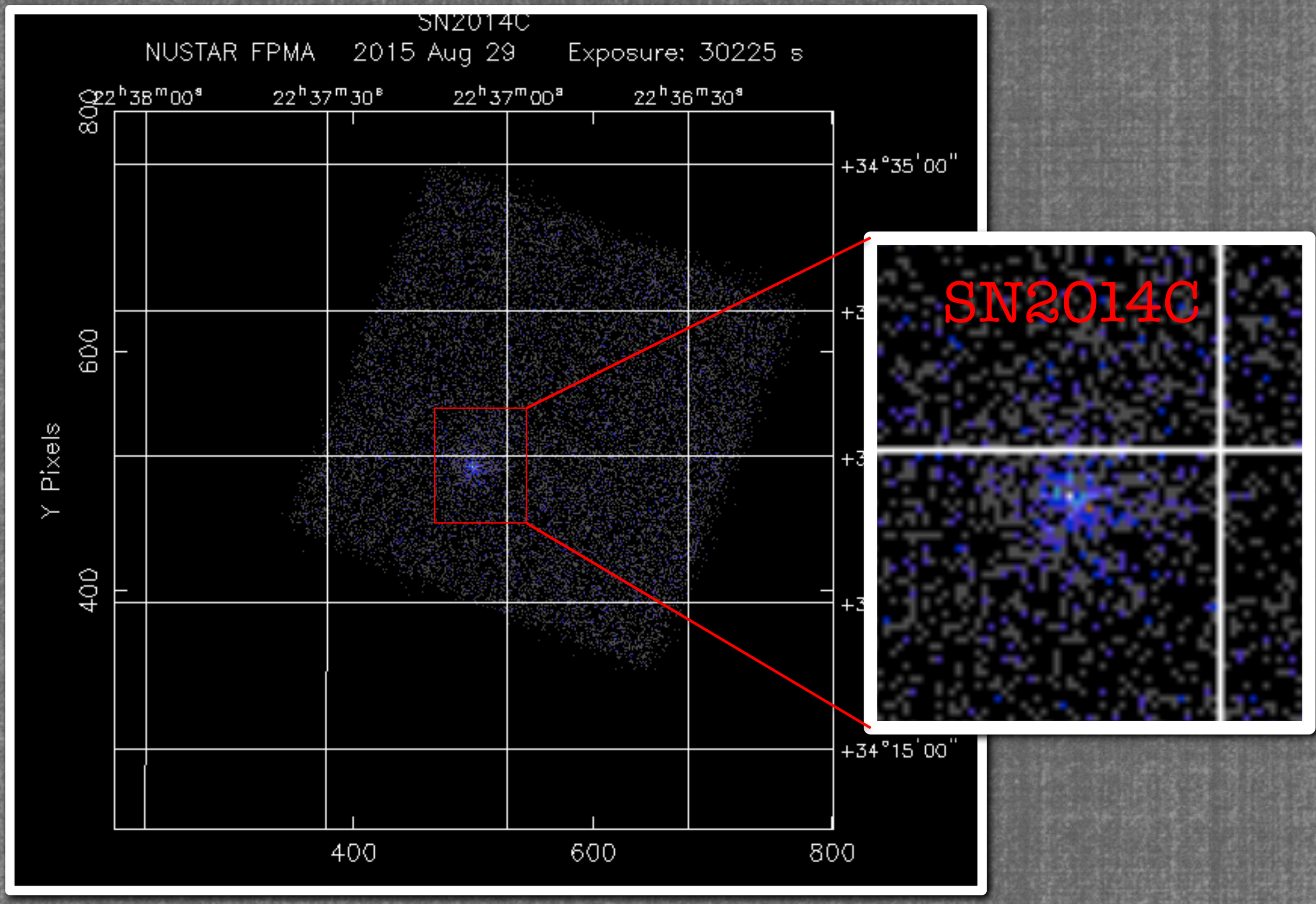


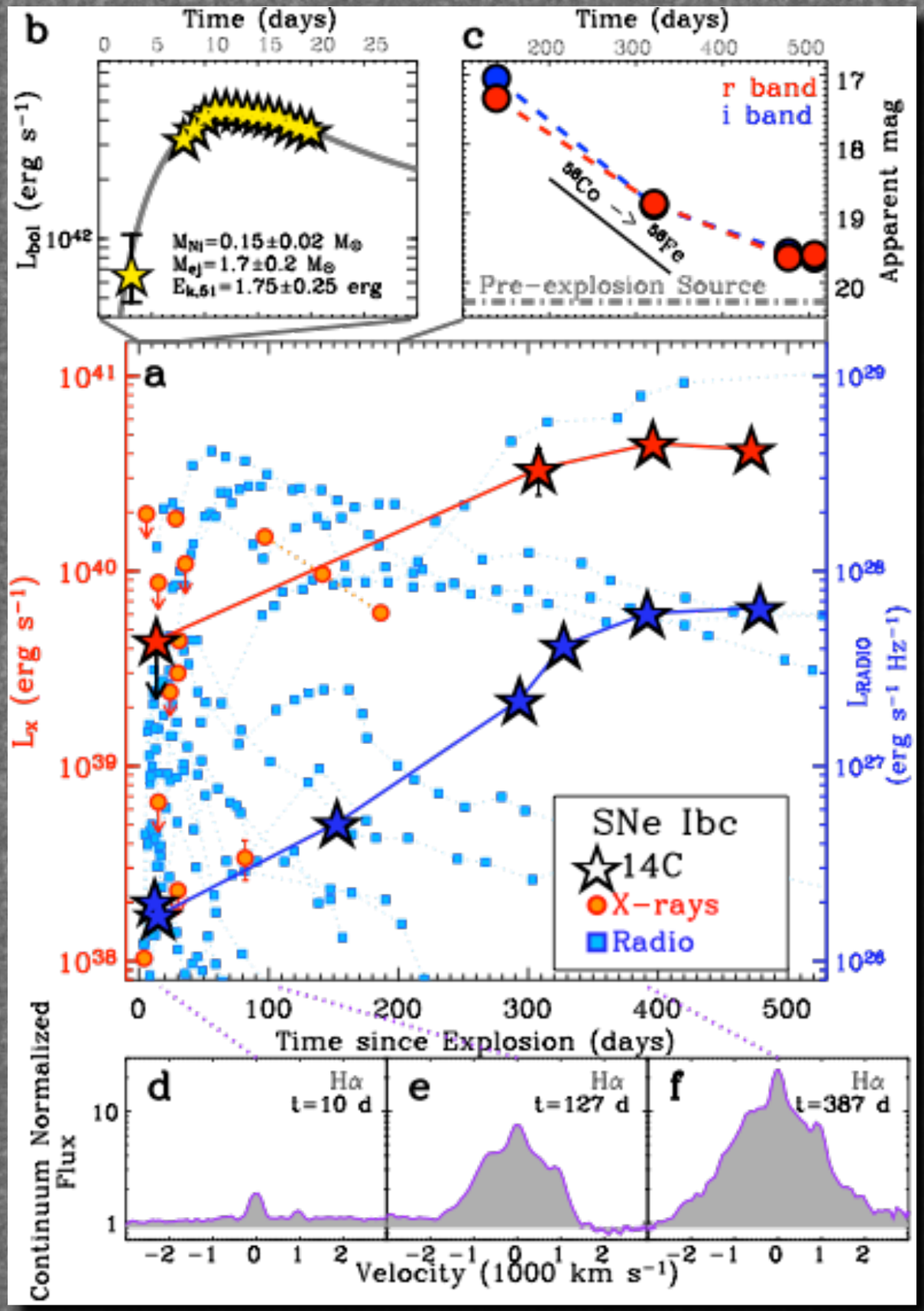


RM+16

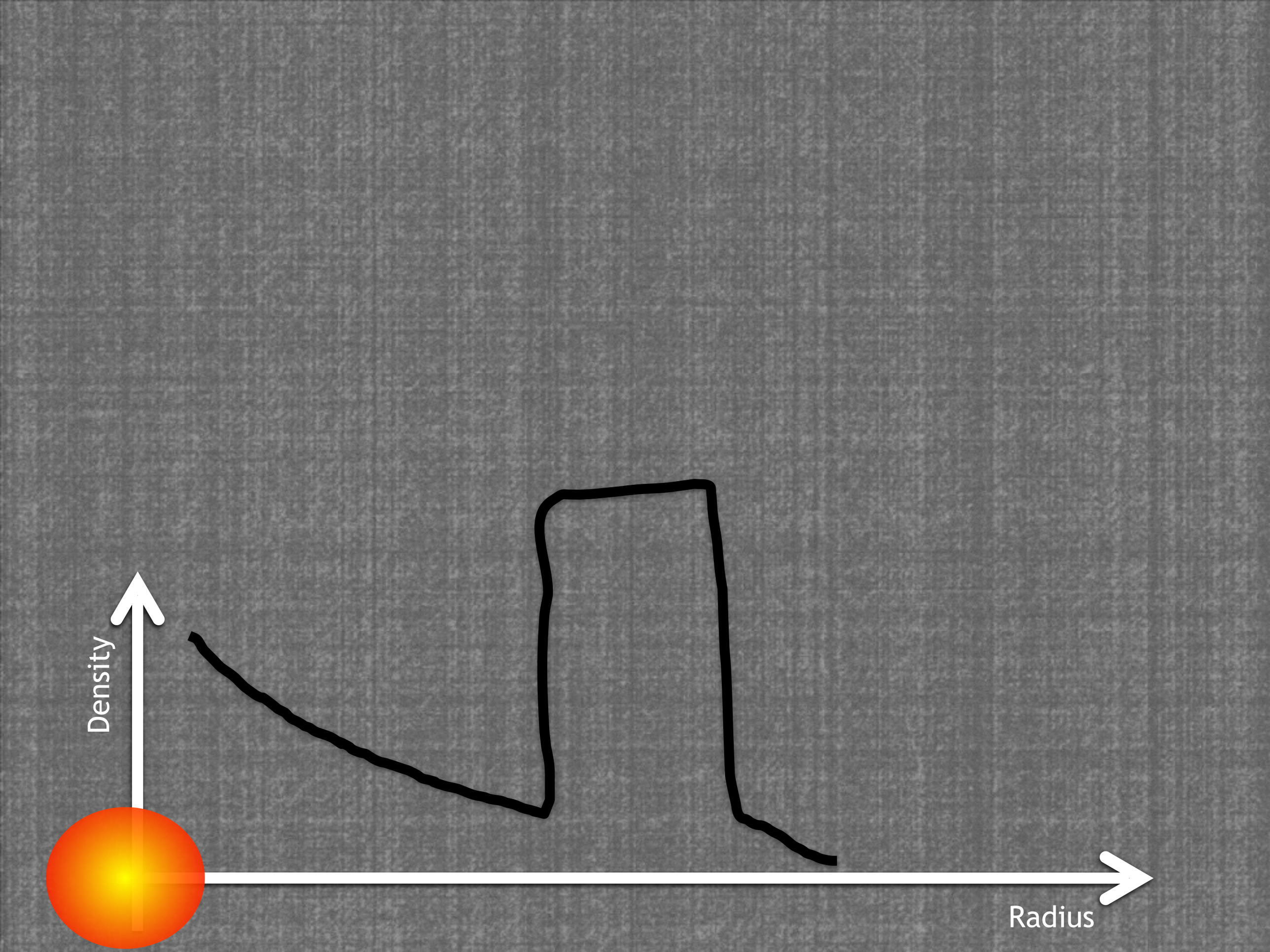
Rising X-ray Luminosity!

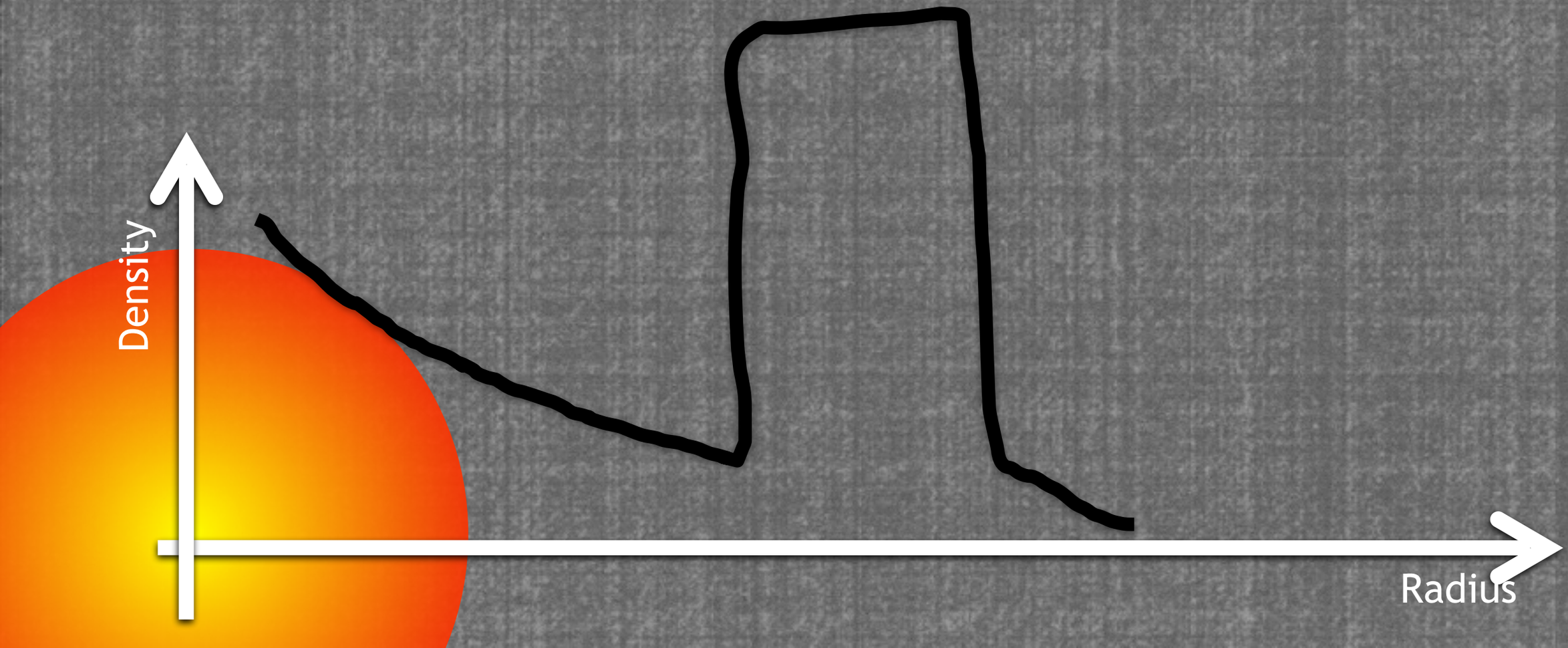
NuSTAR (3-80 keV)

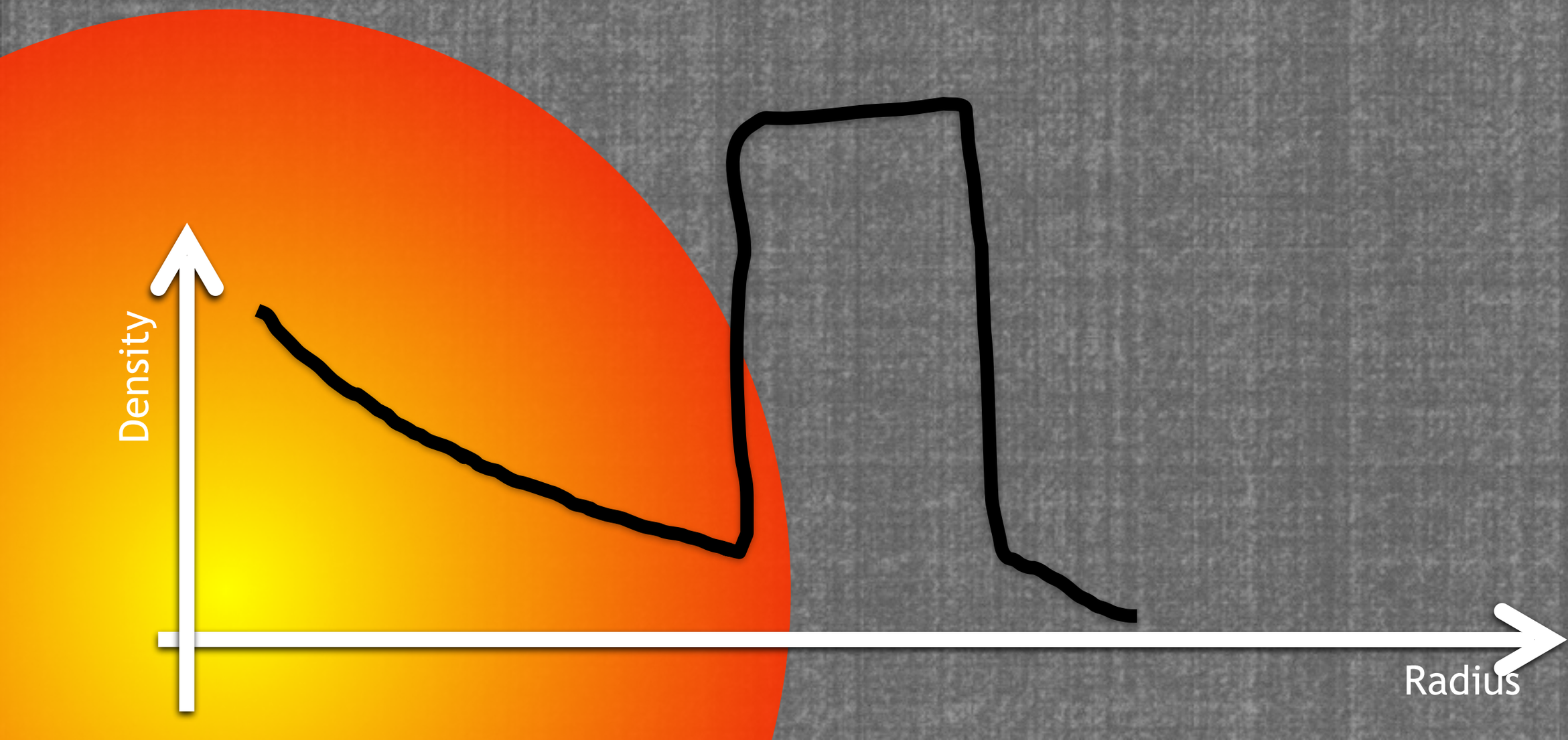




Type I SN ⟶ Type II SN


Density
Radius


Density
Radius


Density
Radius

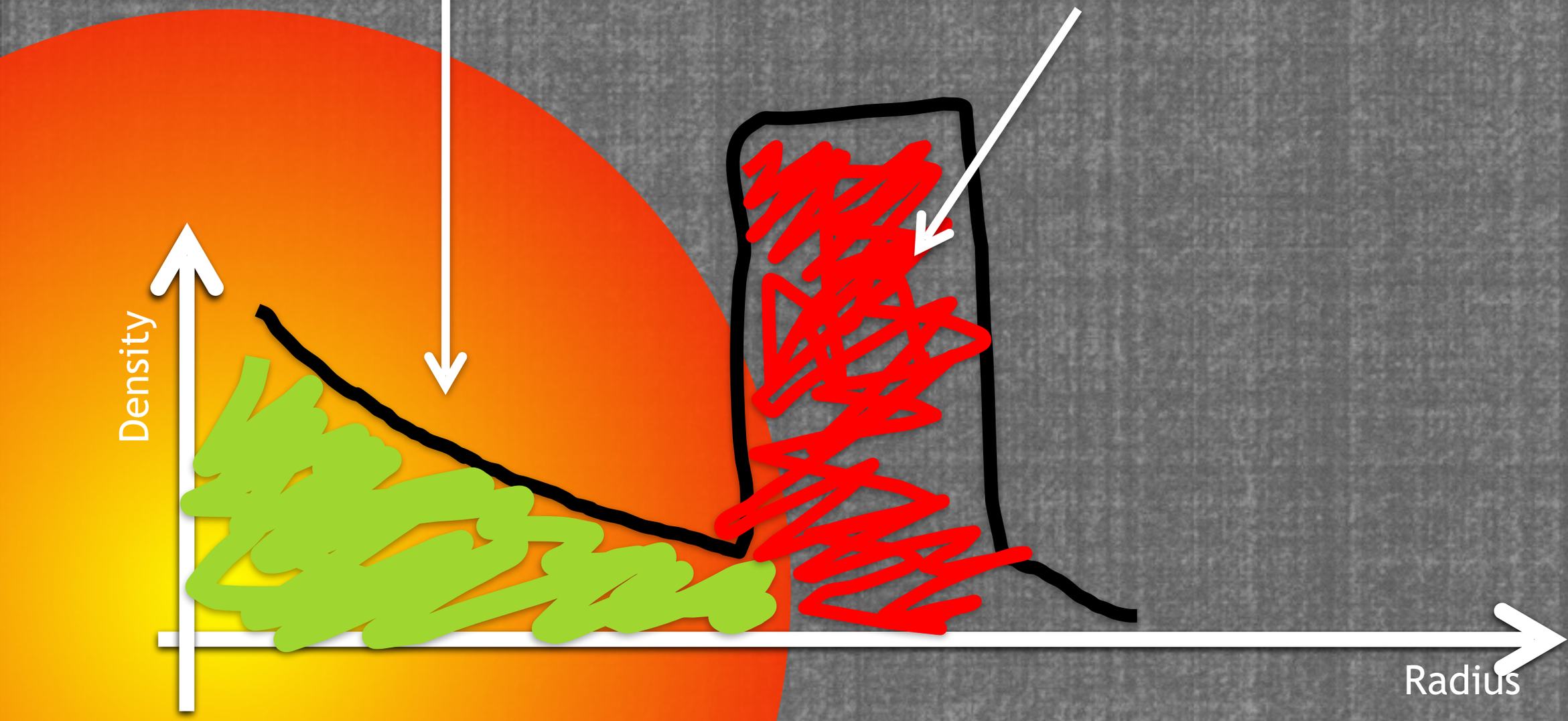
H-poor medium

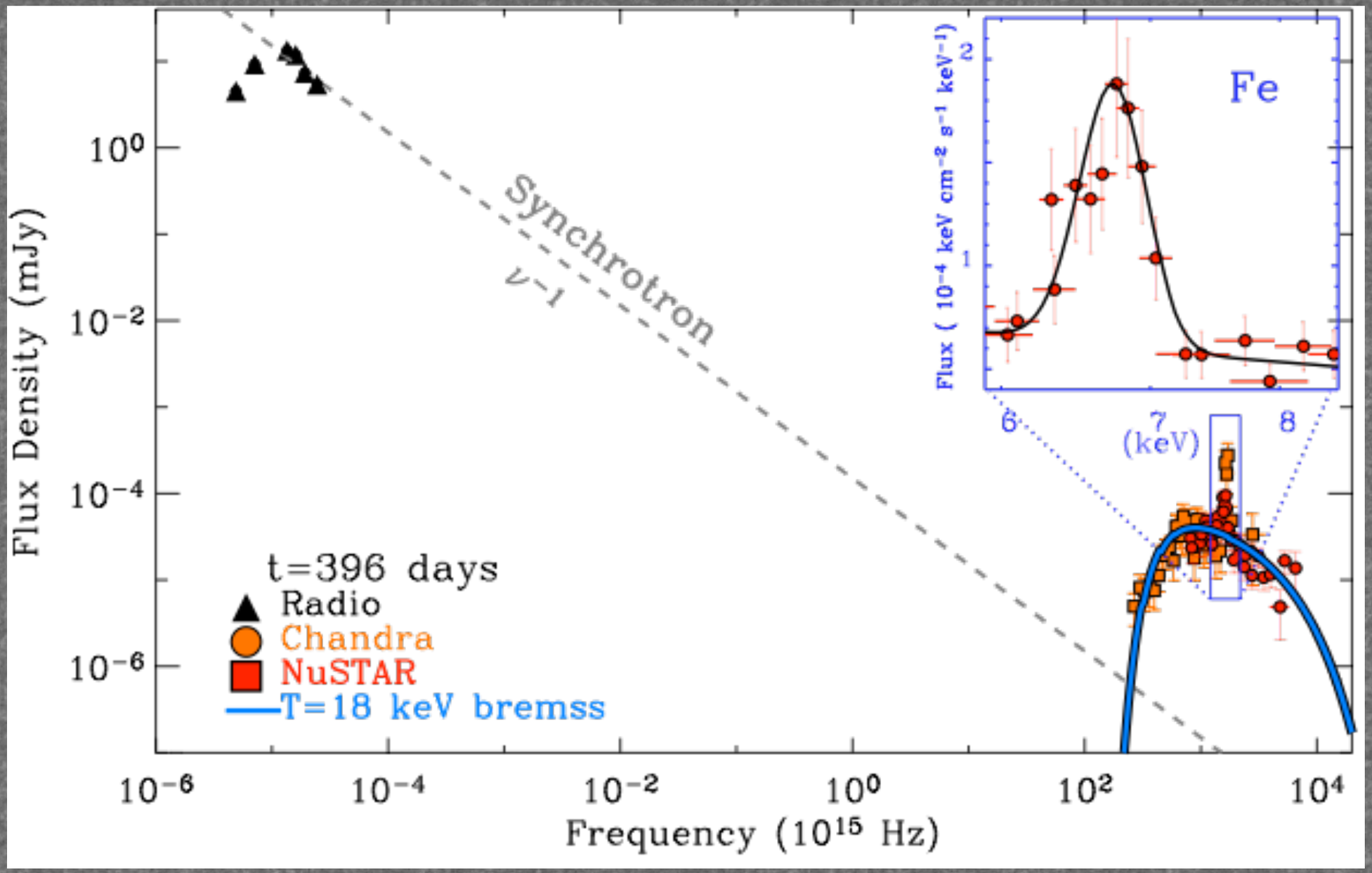
Density

Radius

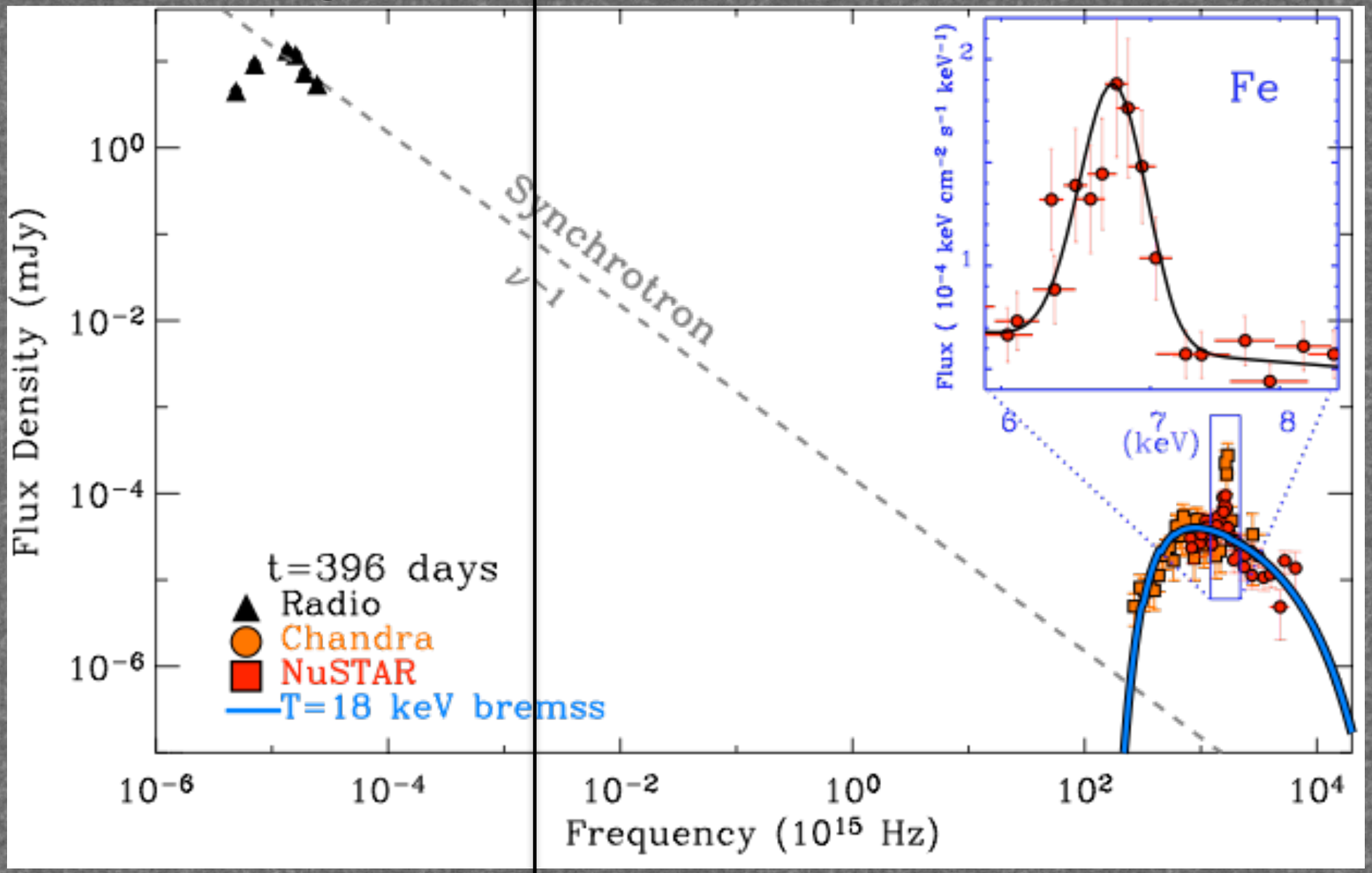
H-poor medium

High-density H-rich medium




Synchrotron
ν^{-1}
t=396 days
Radio
Chandra
NuSTAR
T=18 keV bremss
Flux Density (mJy)
Frequency (10^{15} Hz)
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Fe
Flux (10^{-4} keV cm^{-2} s^{-1} keV^{-1})
(keV)
6
7
8

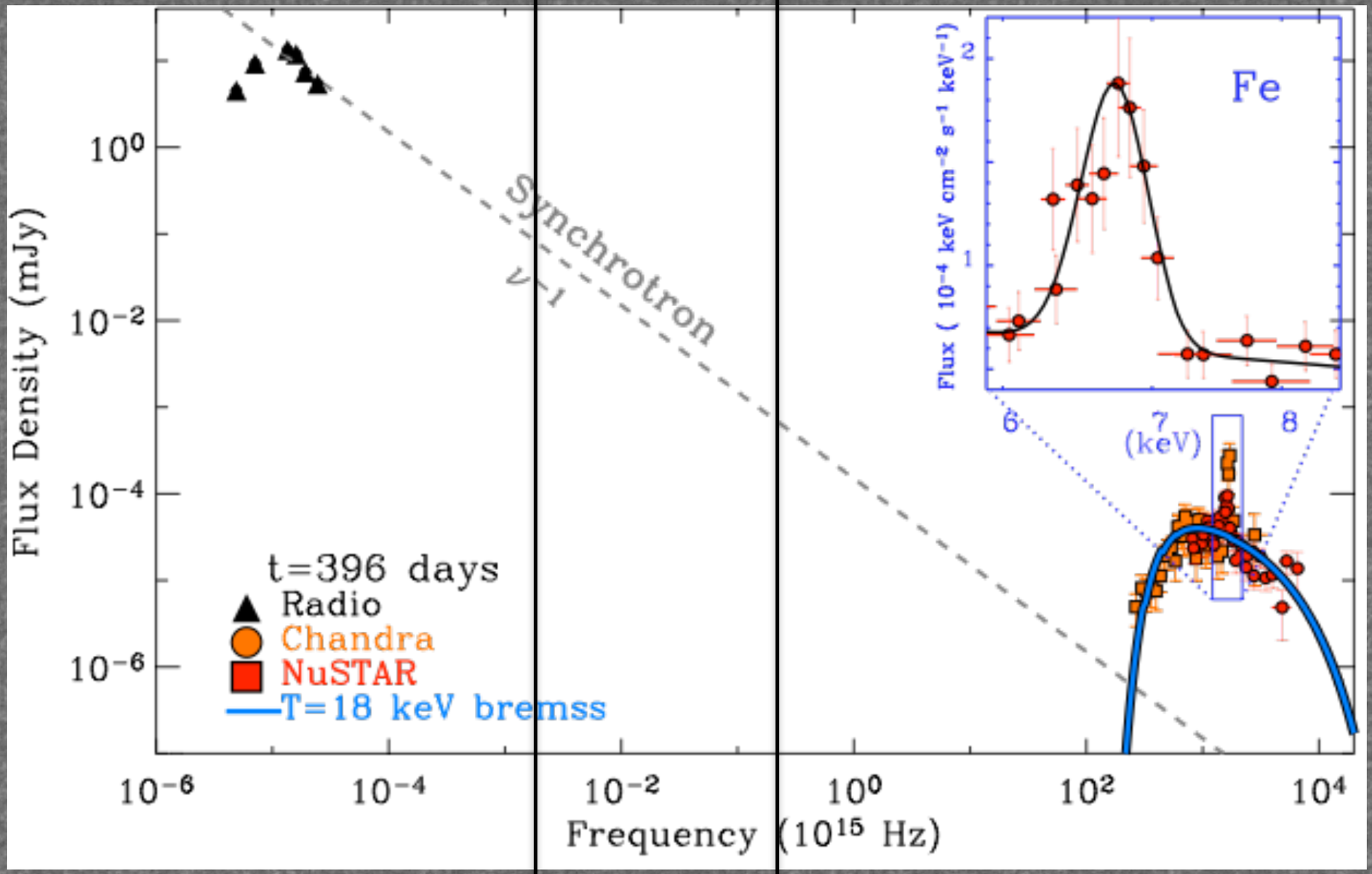
RADIO



Synchrotron

RADIO

X-RAY



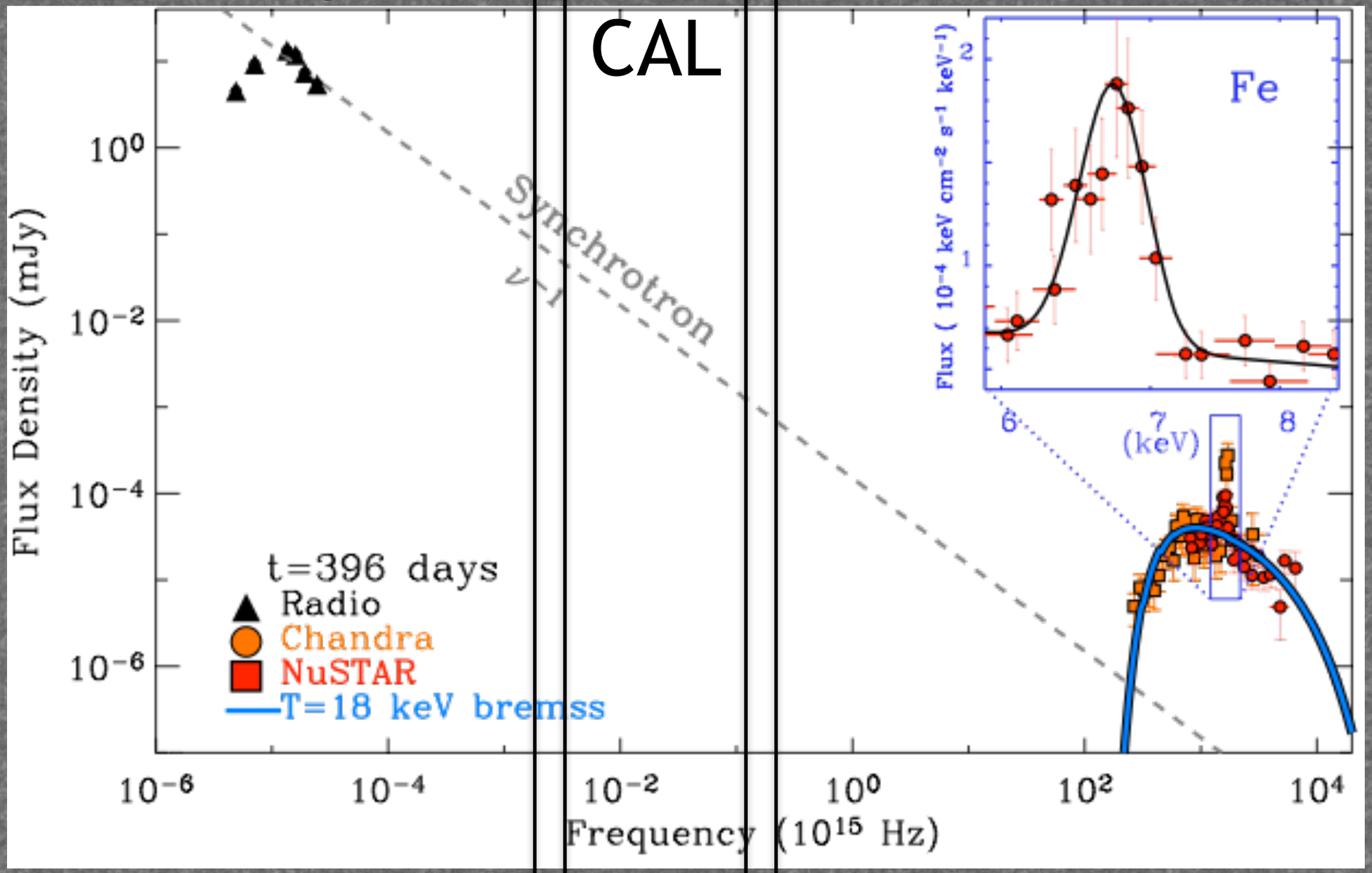
Synchrotron

Bremsstrahlung

RADIO

OPTI CAL

X-RAY



Synchrotron

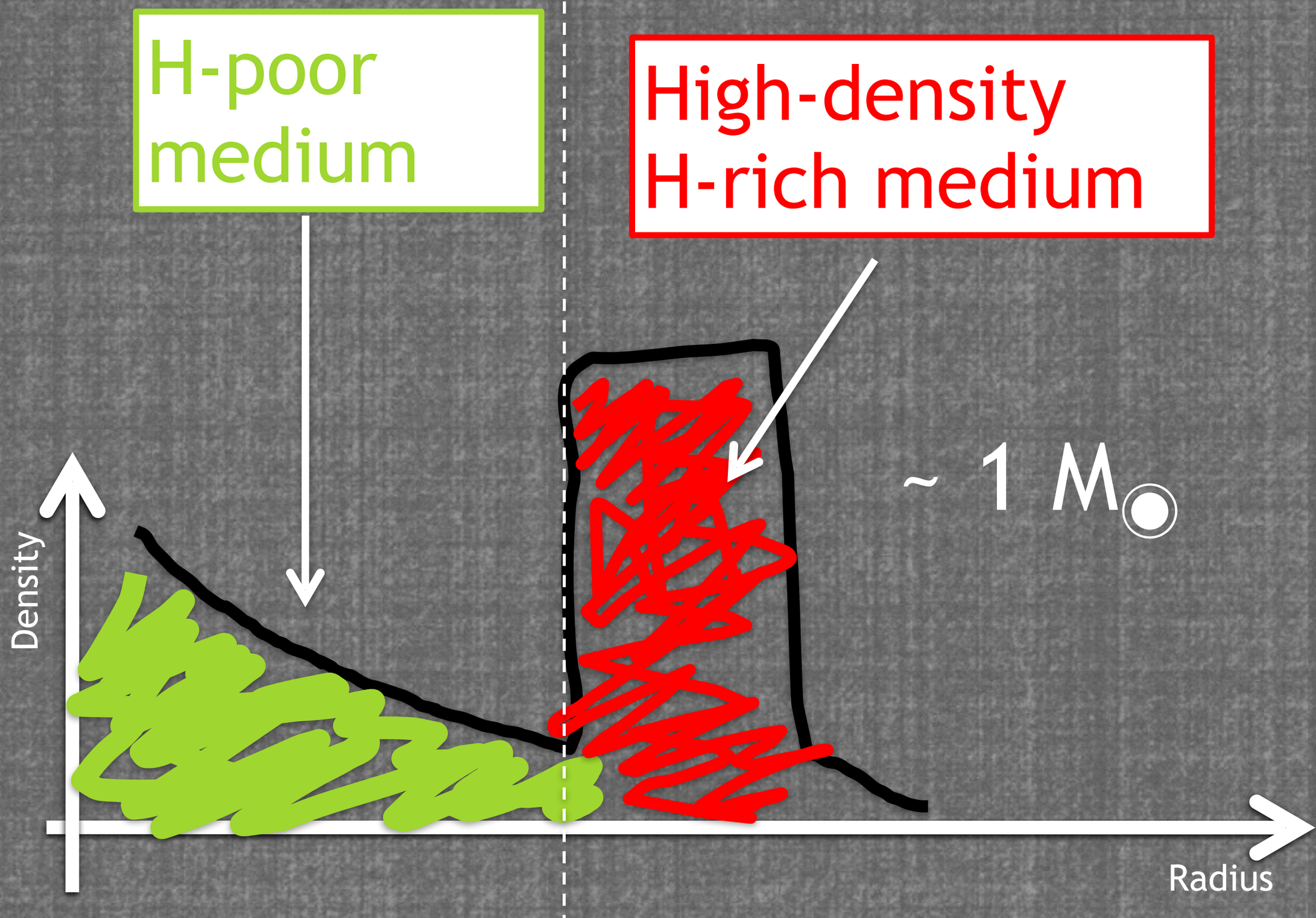
Bremsstrahlung

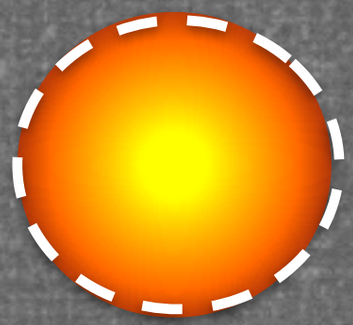
R~ 5 10^{16} cm

H-poor medium

High-density H-rich medium

~ 1 $M_\odot$



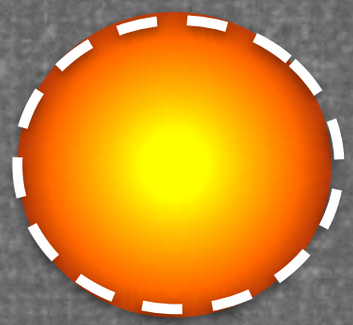


Supergiant

Wolf-Rayet

~10^4-10^5 yrs

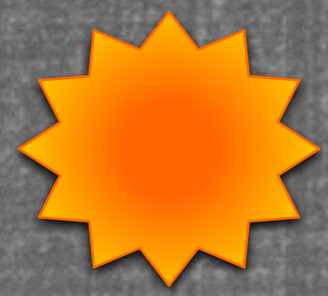
SN Explosion



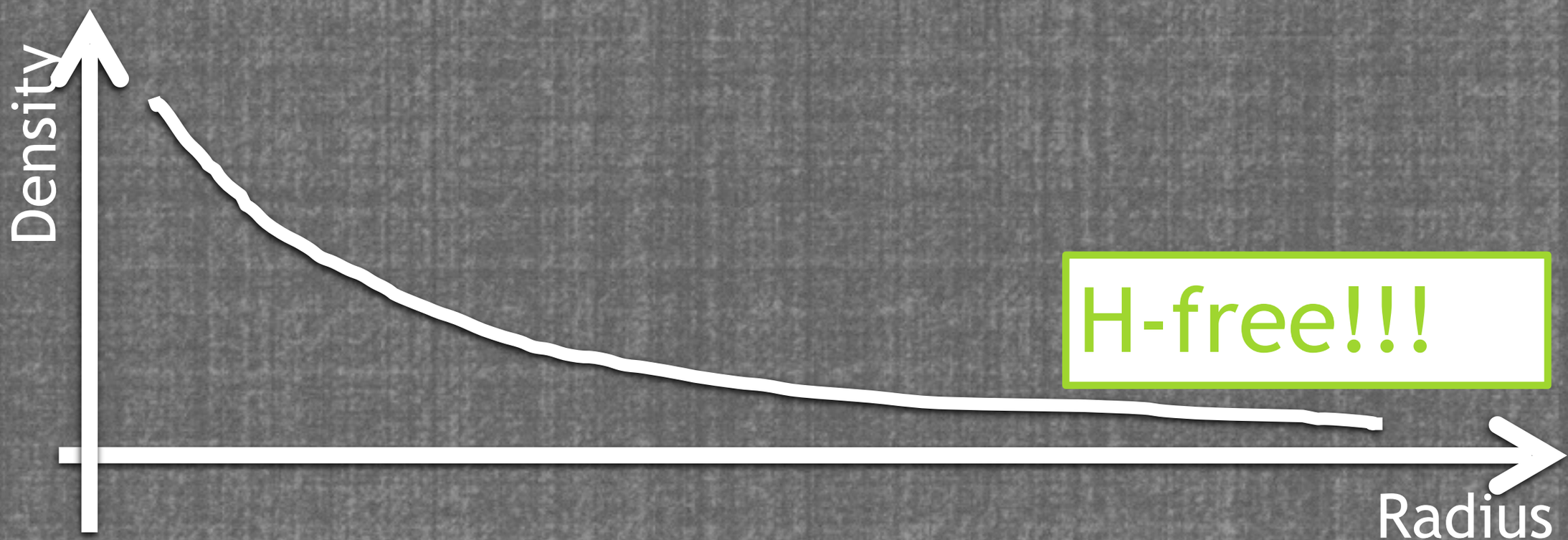
Supergiant

Wolf-Rayet

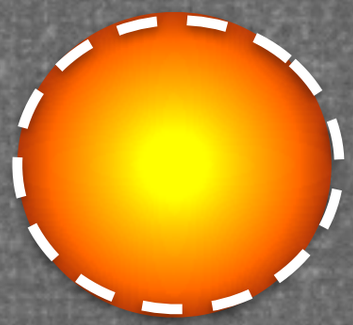
~10^{4}-10^{5} yrs



SN Explosion



MASS LOSS– Massive Stars

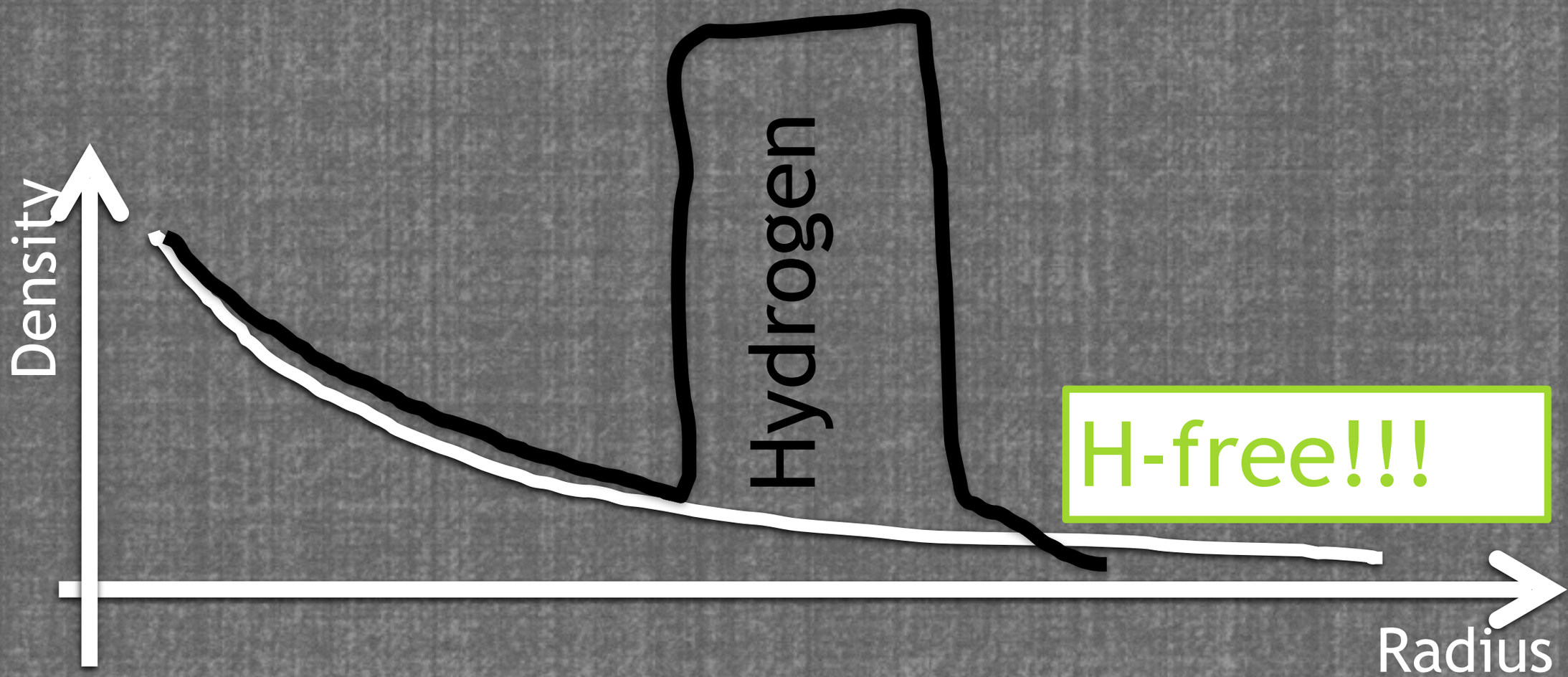


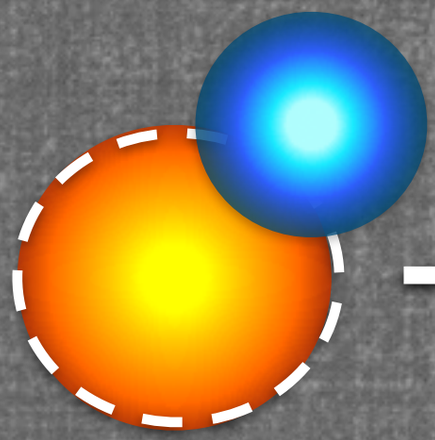
Supergiant

Wolf-Rayet

~10^{4}-10^{5} yrs

SN Explosion



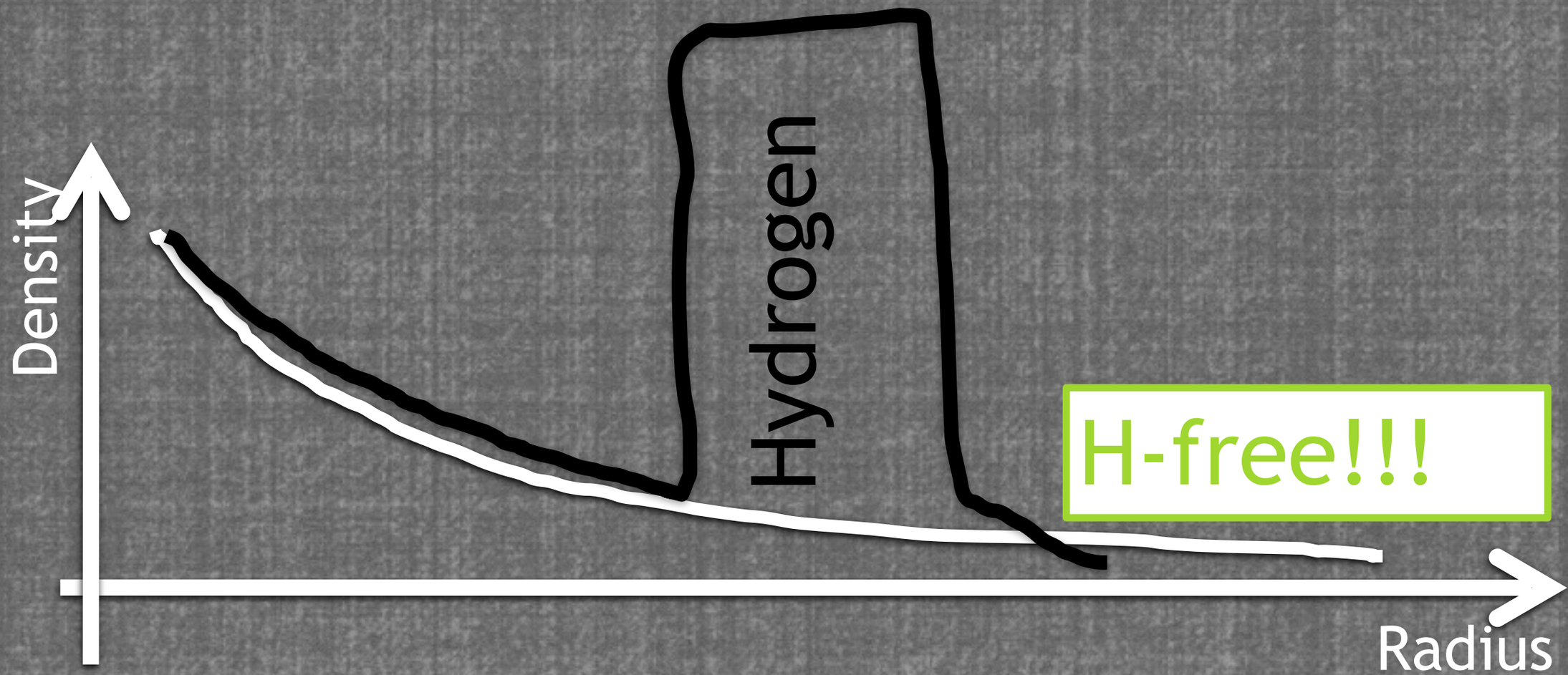


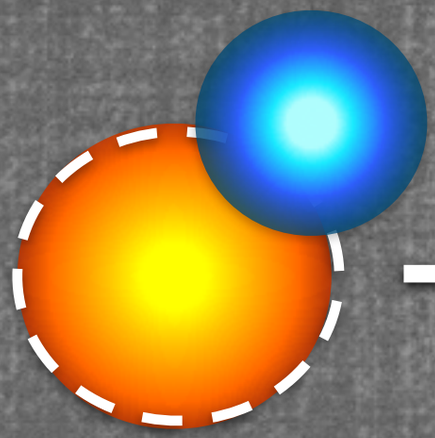
Supergiant

Wolf-Rayet

~10^{4}-10^{5} yrs

SN Explosion



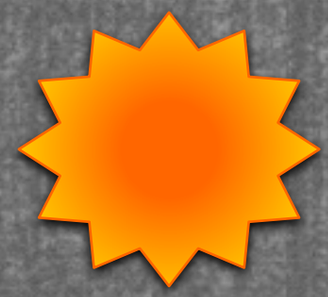


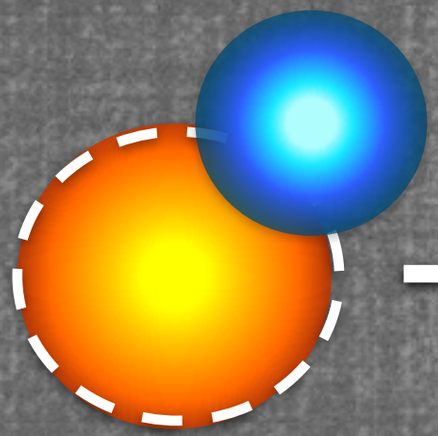
Supergiant

Wolf-Rayet

~10^4-10^5 yrs

1000 yrs



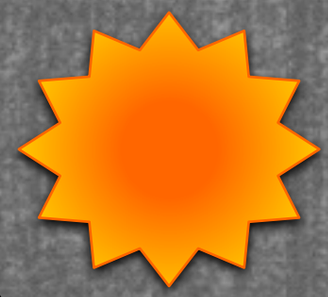


Supergiant

Wolf-Rayet

~10^4-10^5 yrs

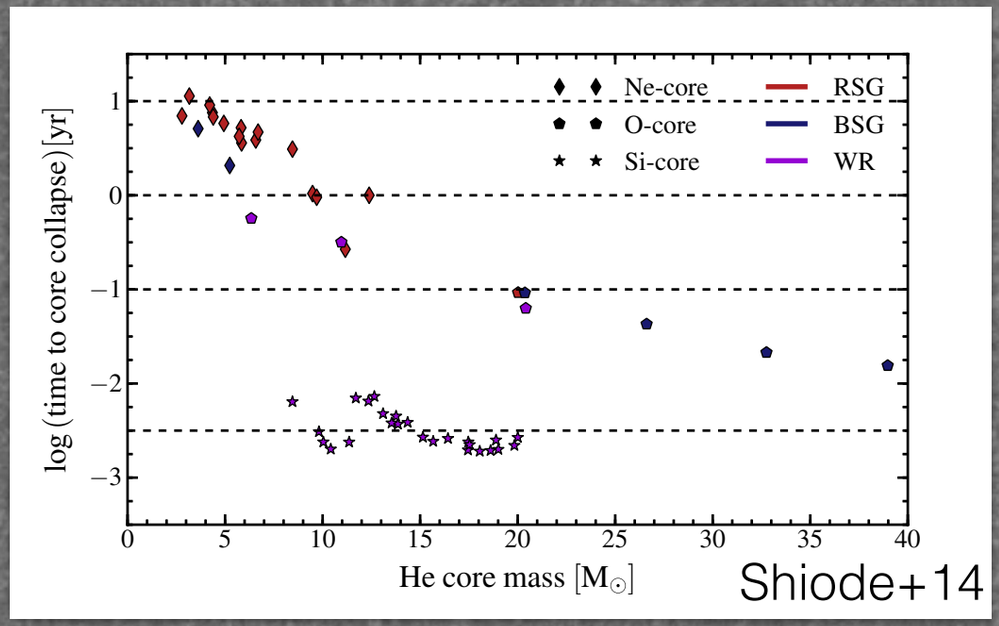
1000 yrs

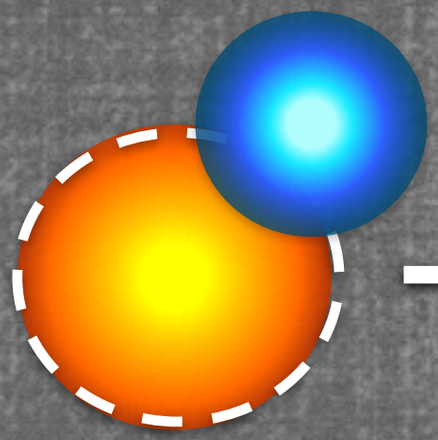


Nuclear Burning Instabilities

MASS LOSS– Massive Stars

Internal Gravity Waves

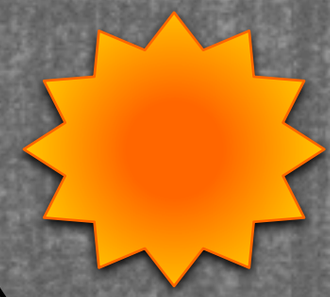




Supergiant

Wolf-Rayet
~10^4-10^5 yrs

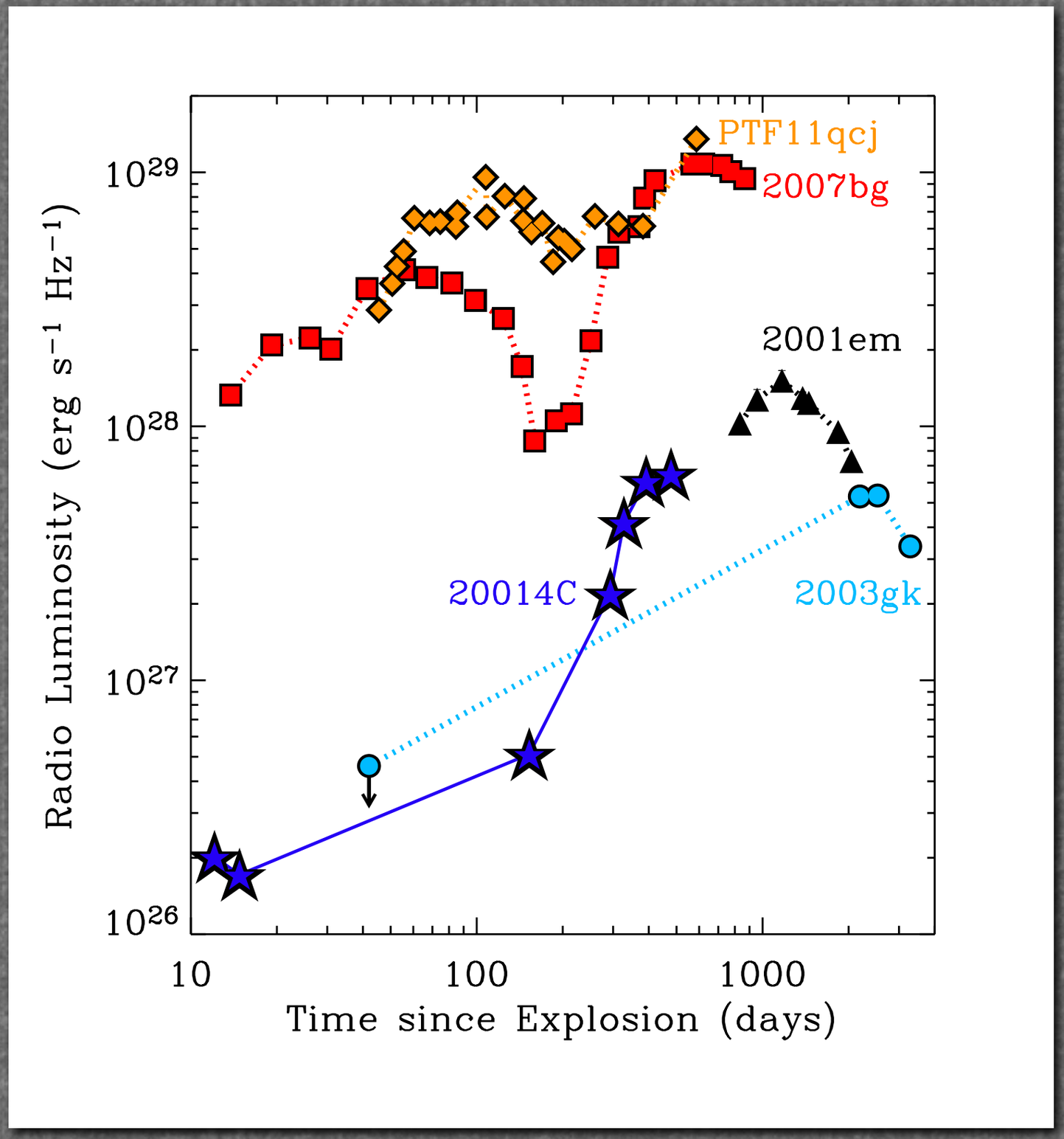
1000 yrs



Nuclear Burning Instabilities

MASS LOSS– Massive Stars

Non thermal Radio emission Ibc

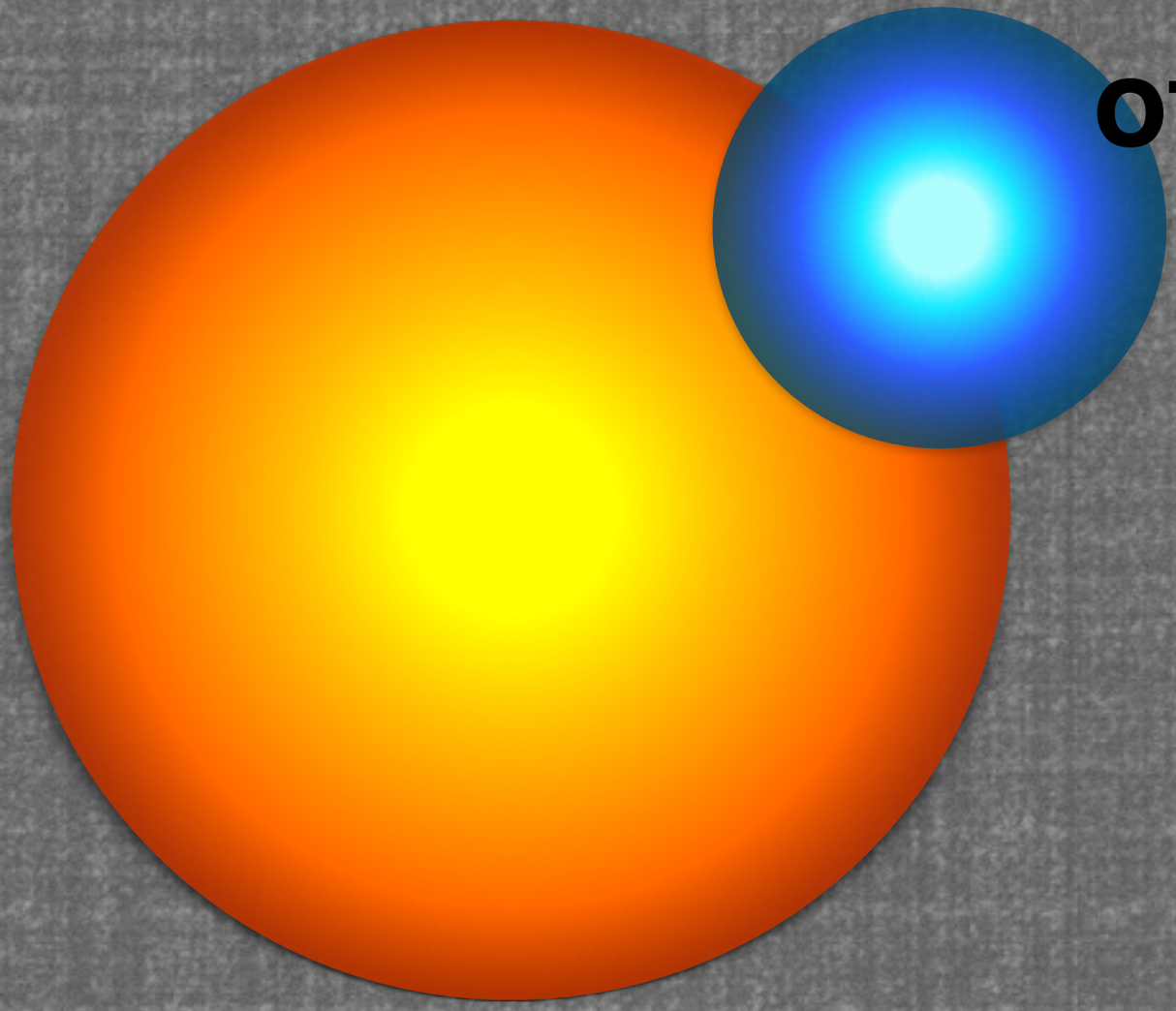


~10%

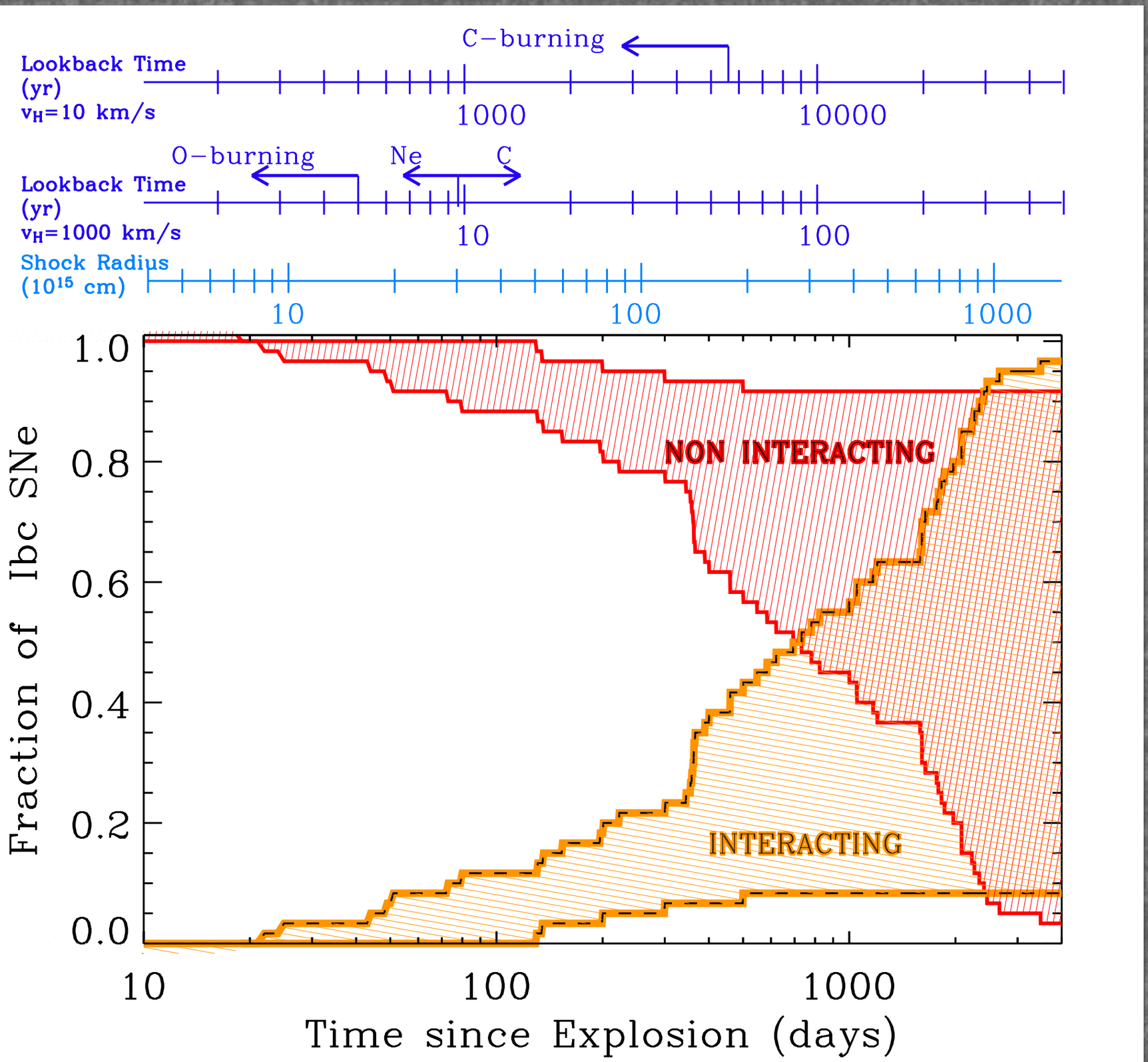
Margutti+17

Binary Population Synthesis

S. de Mink, M. Zapartas

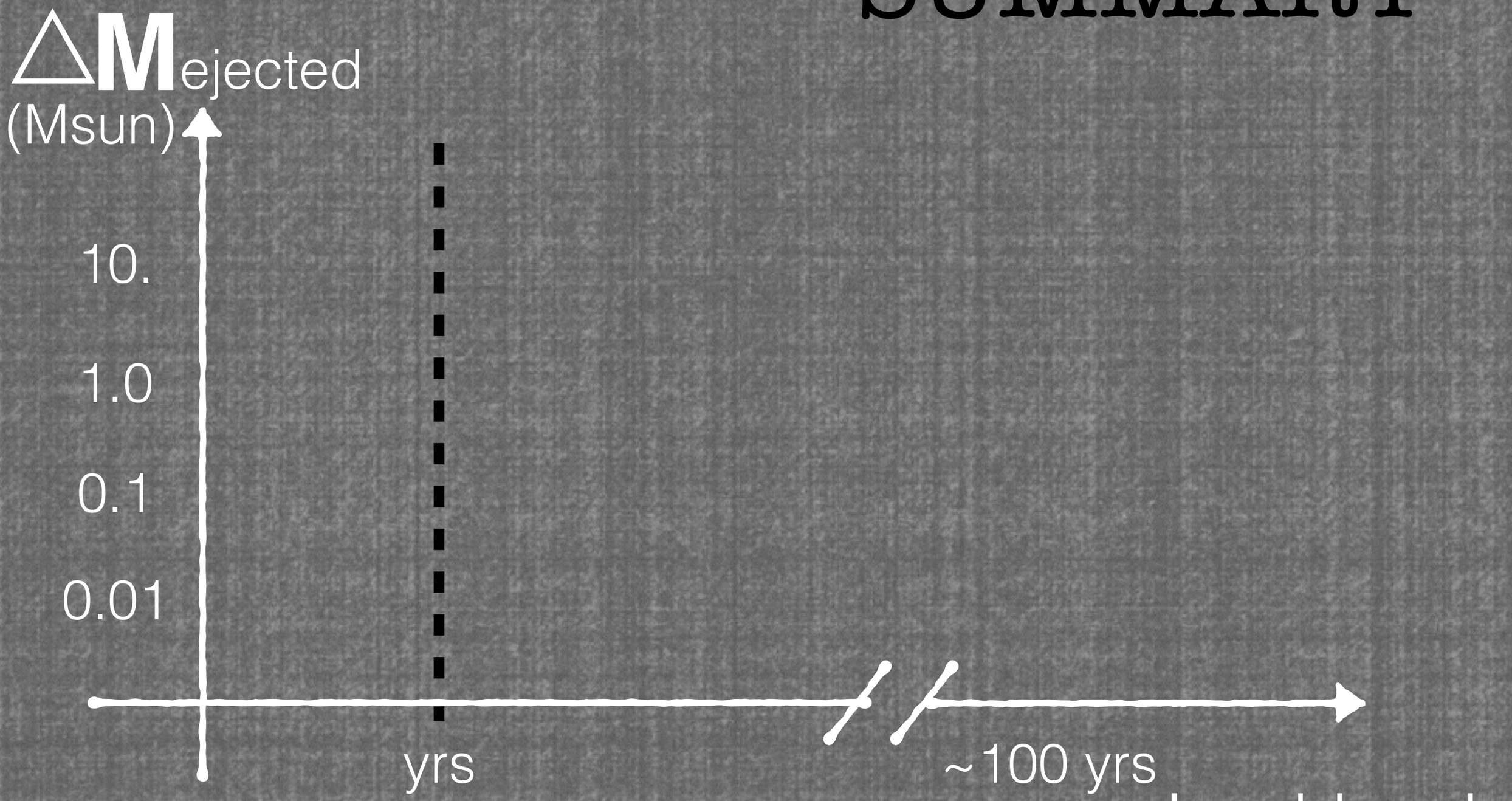


~6.5% [3.5-10%] of Ib/c progenitors go through CE evolution within ~ few 1000 yr before collapse

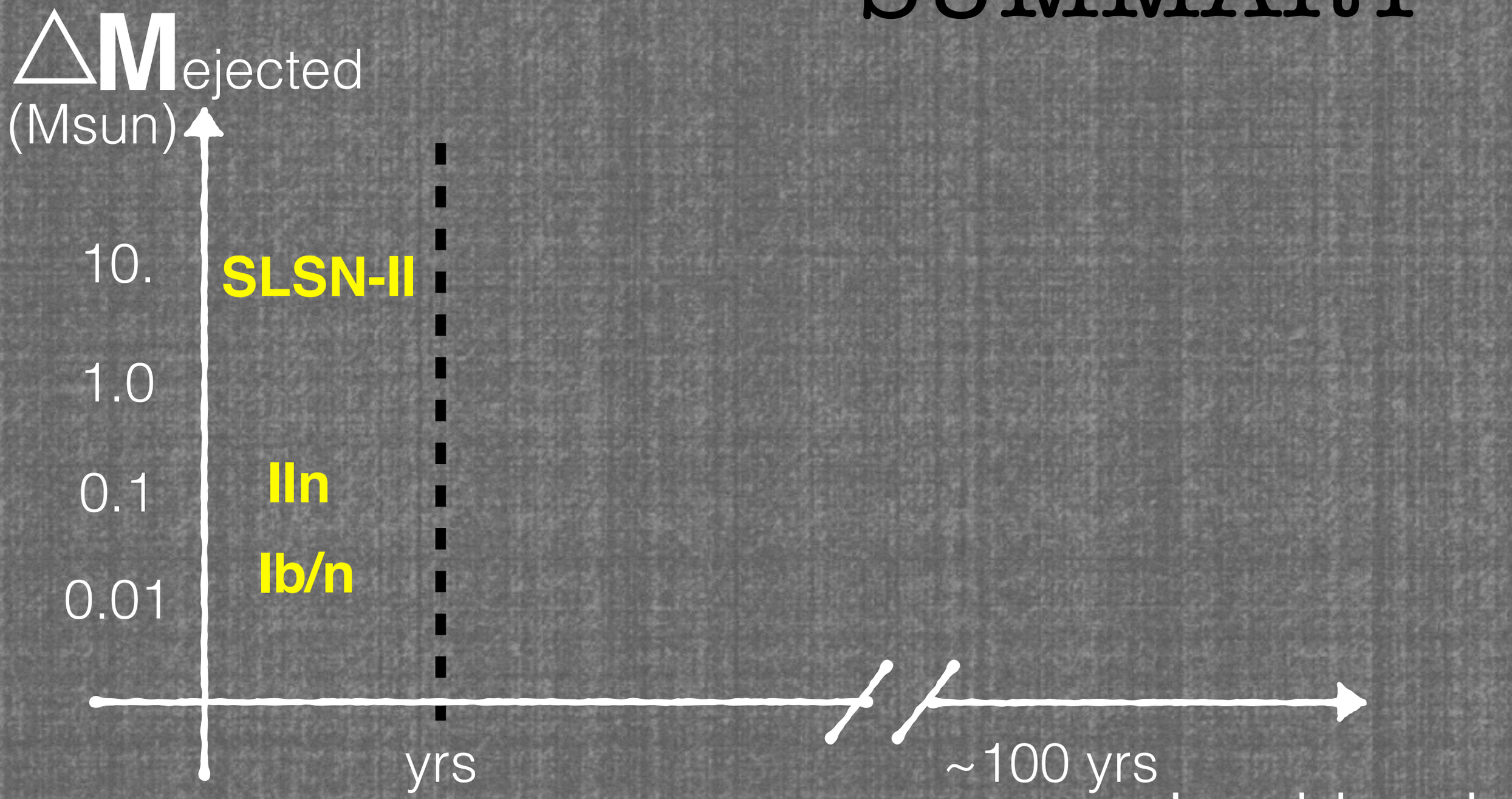

C−burning
Lookback Time
(yr)
v_H=10 km/s
1000
10000
O−burning
Ne
C
Lookback Time
(yr)
v_H=1000 km/s
10
100
Shock Radius
(10^{15} cm)
10
100
1000
1.0
0.8
0.6
0.4
0.2
0.0
Fraction of Ibc SNe
NON INTERACTING
INTERACTING
10
100
1000
Time since Explosion (days)

Margutti+17

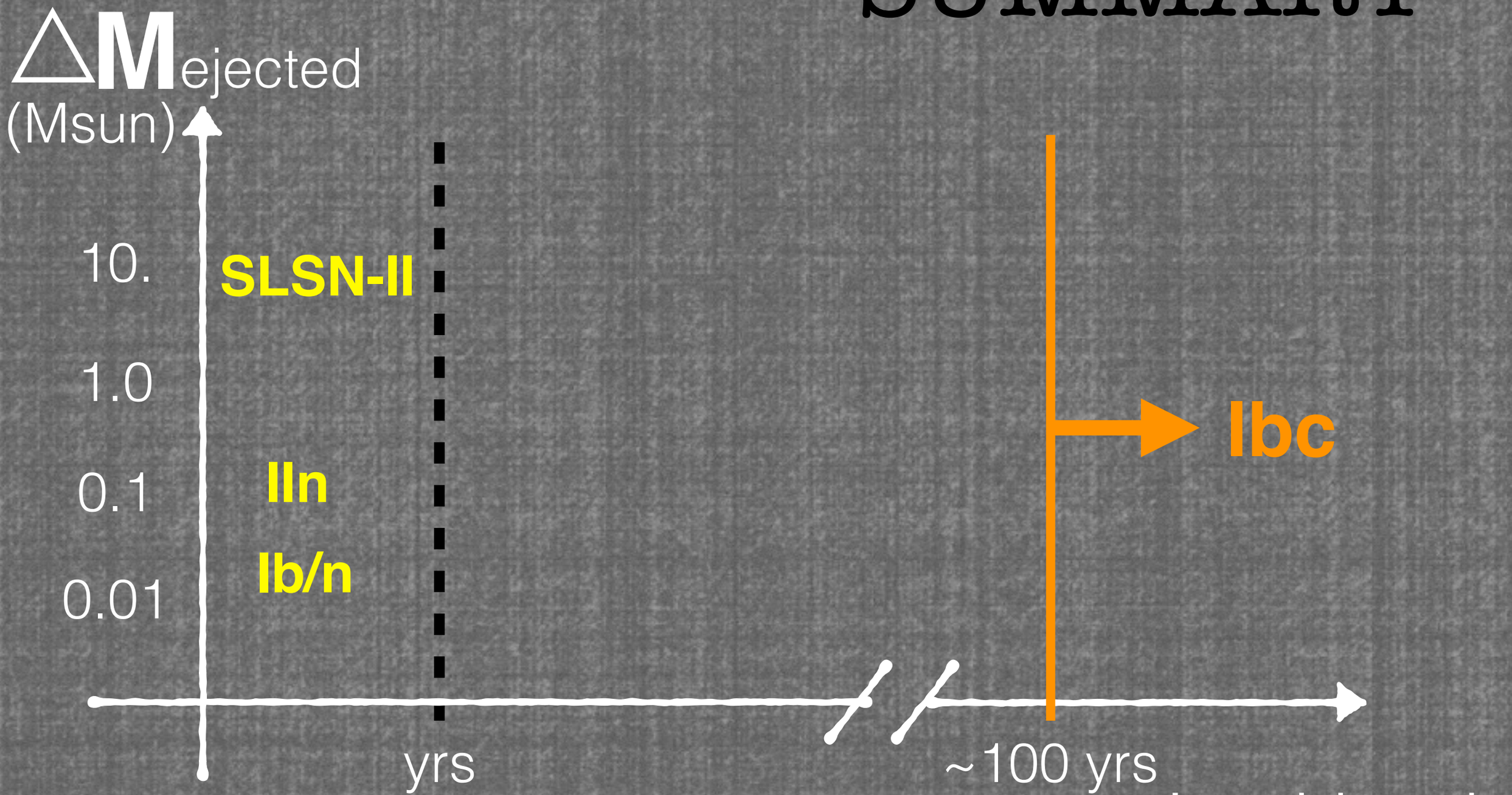
SUMMARY



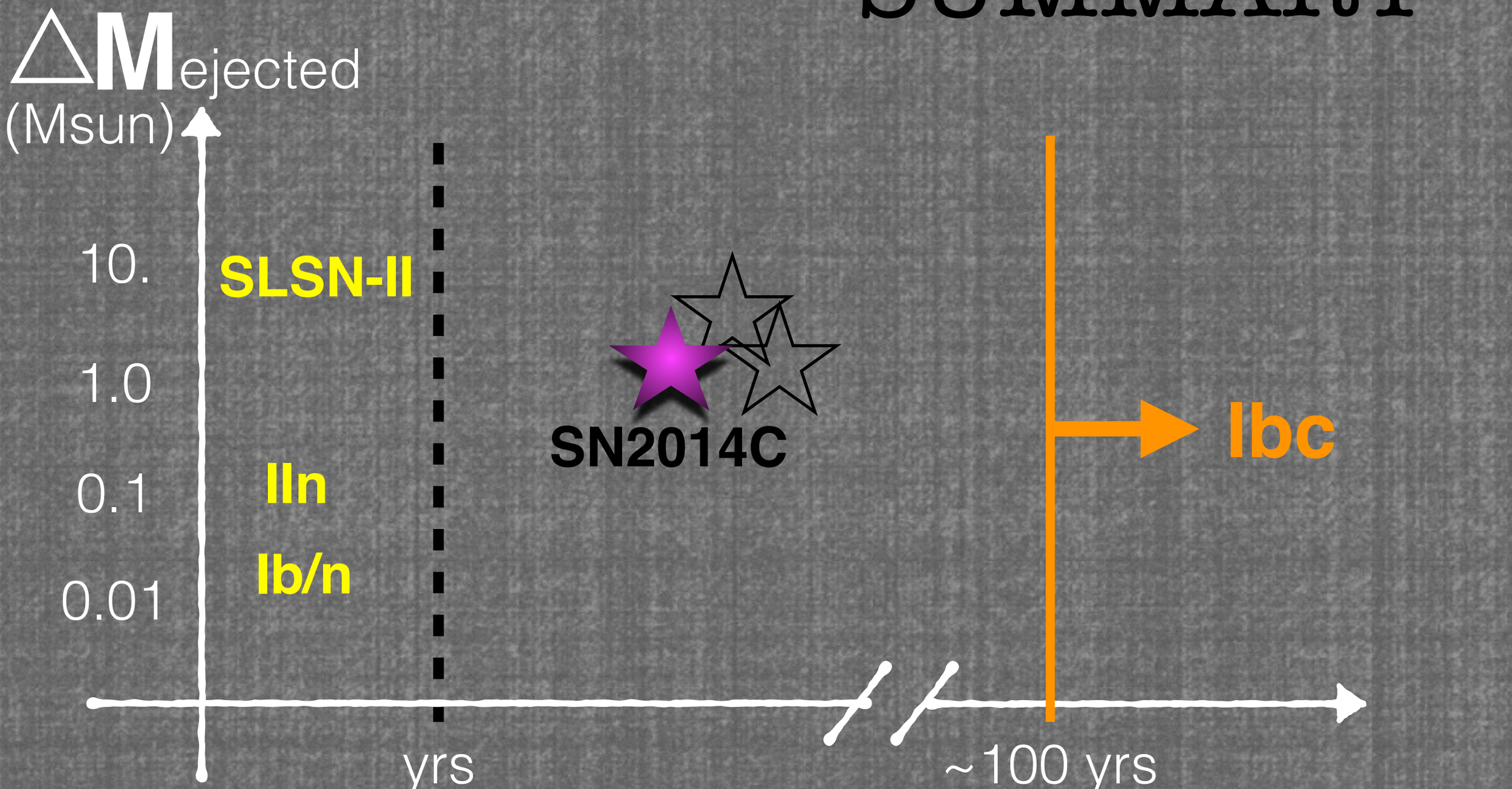
SUMMARY


△Mejected
(Msun)
10.
1.0
0.1
0.01
SLSN-II
IIn
Ib/n
yrs
~100 yrs
Lookback
Time

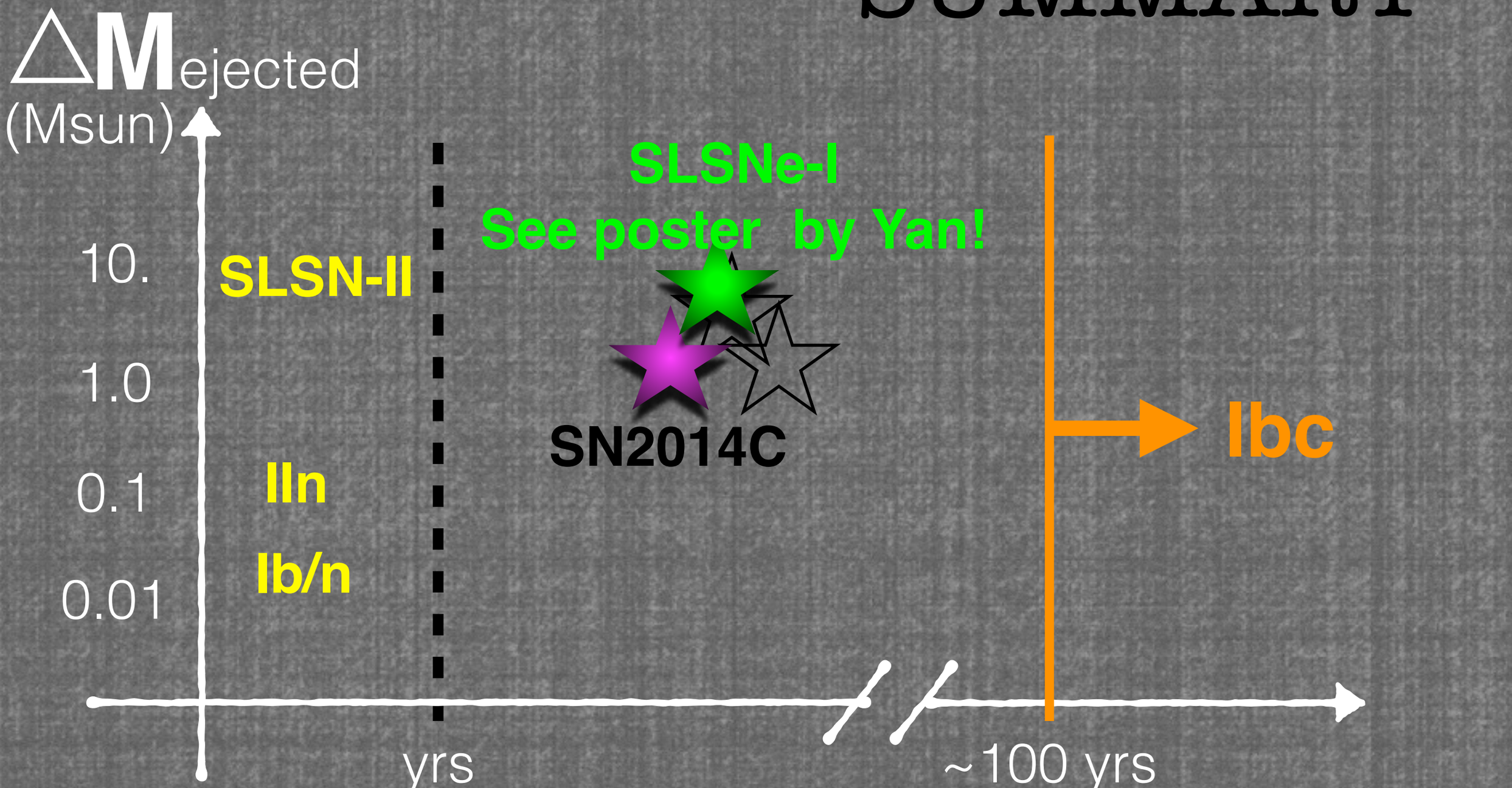
SUMMARY

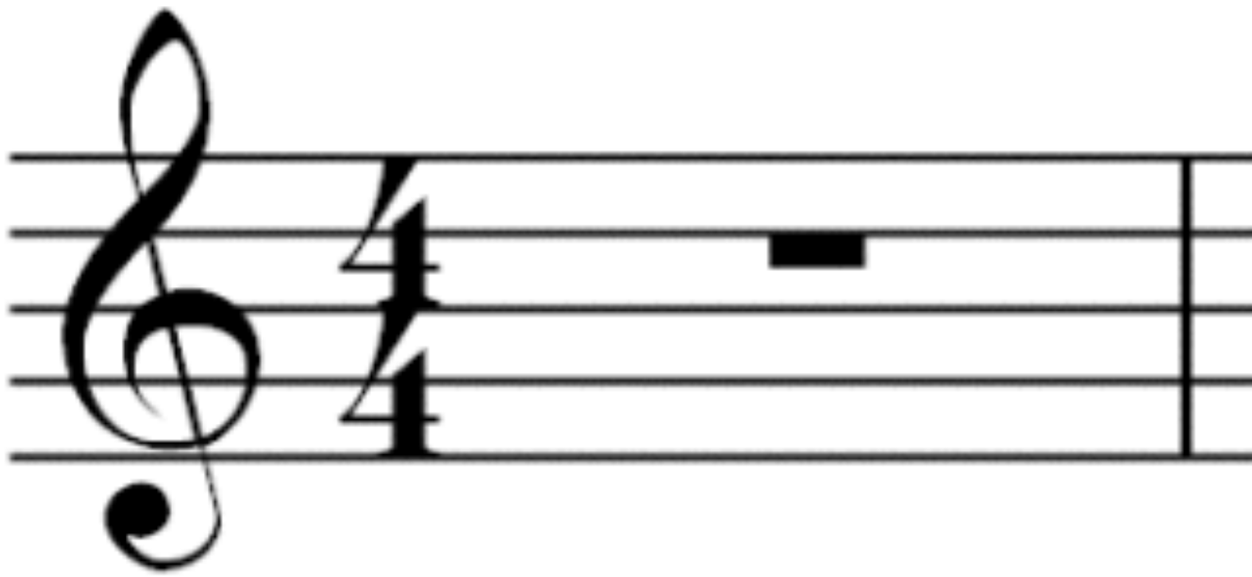

△Mejected
(Msun)
10.
1.0
0.1
0.01
SLSN-II
IIn
Ib/n
Ibc
yrs
~100 yrs
Lookback
Time

SUMMARY


△Mejected
(Msun)
10.
1.0
0.1
0.01
SLSN-II
IIn
Ib/n
SN2014C
Ibc
yrs
~100 yrs
Lookback
Time

SUMMARY


ΔMejected
(Msun)
10.
1.0
0.1
0.01
SLSN-II
IIn
Ib/n
SLSNe-I
See poster by Yan!
SN2014C
Ibc
yrs
~100 yrs
Lookback
Time

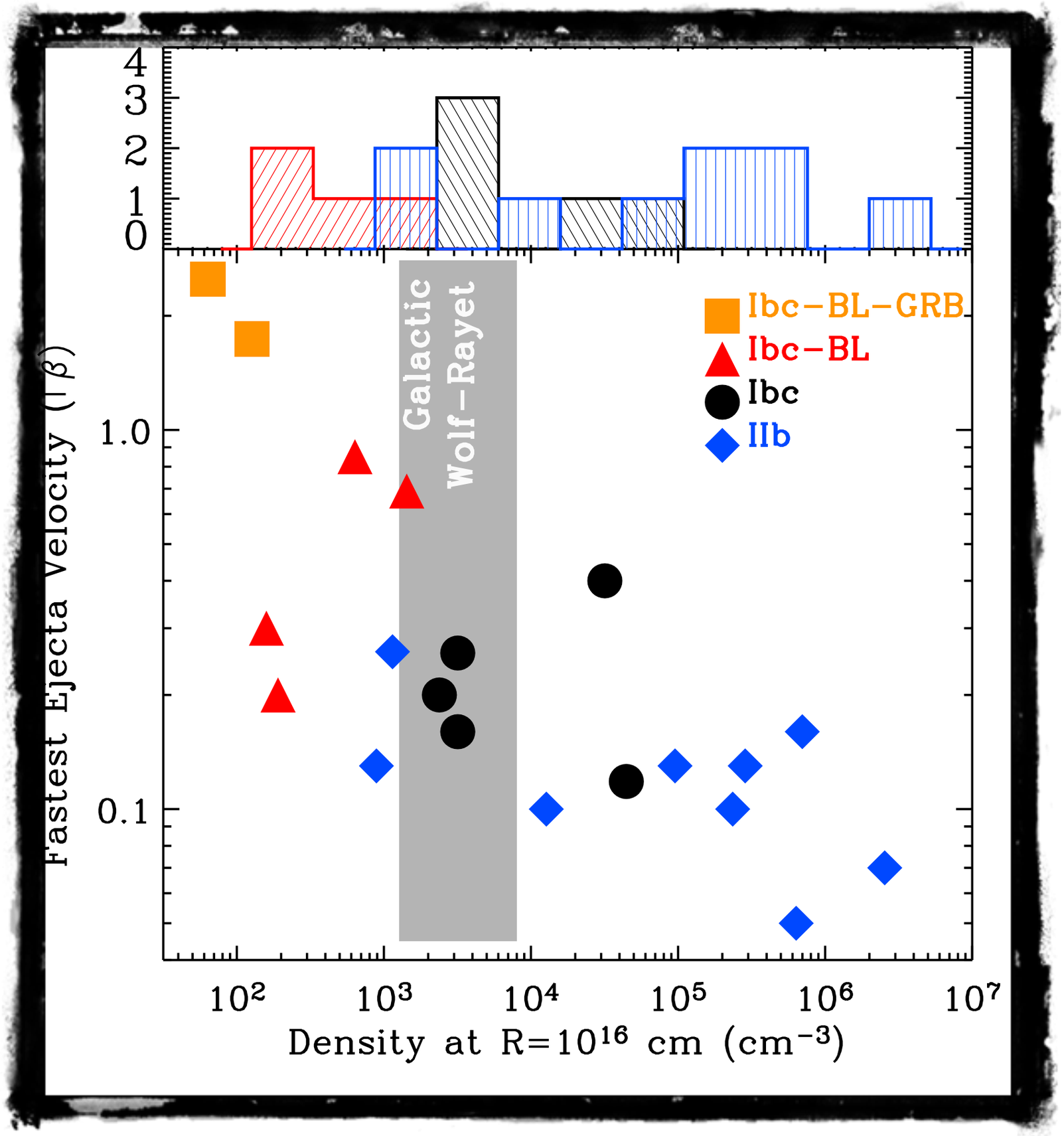


“…The END

is where we start from…”

The Little Gidding by

BACK UP SLIDES



Margutti et al., in prep