Discovery Frontiers in the New Era of Time Domain Multi-Messenger Astrophysics

Raffaella Margutti
Northwestern University

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

Discovery Frontiers in the New Era of Time Domain Multi-Messenger Astrophysics

The turbulent Mass-Loss History of Massive Stars at the end of their lives

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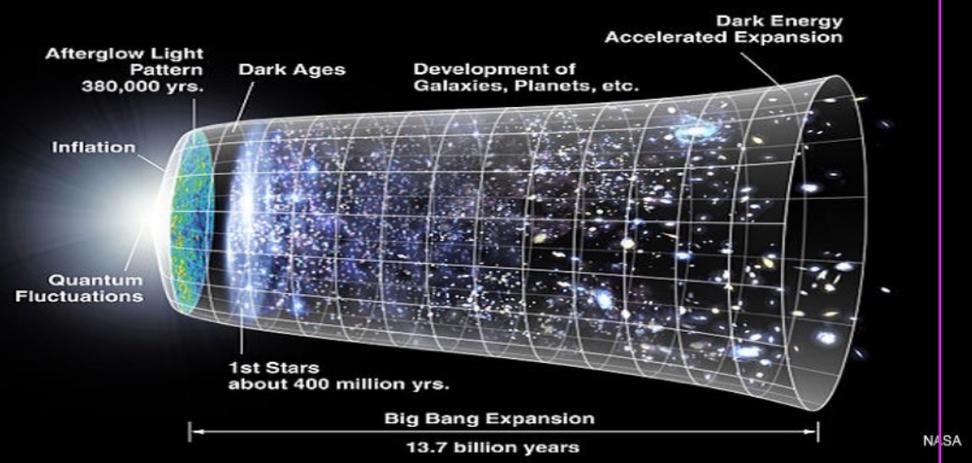
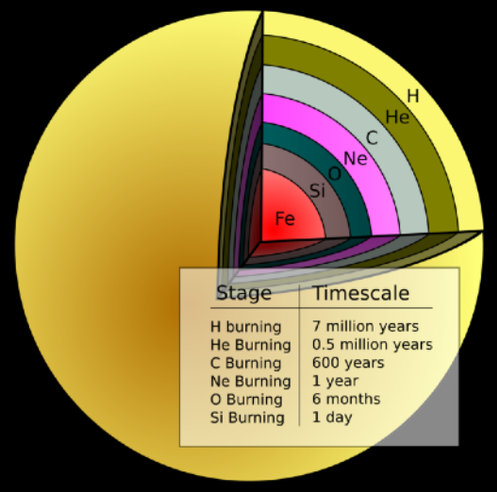
Cosmology: Distance Ladders



First sources of ionizing photons

Chemical Enrichment

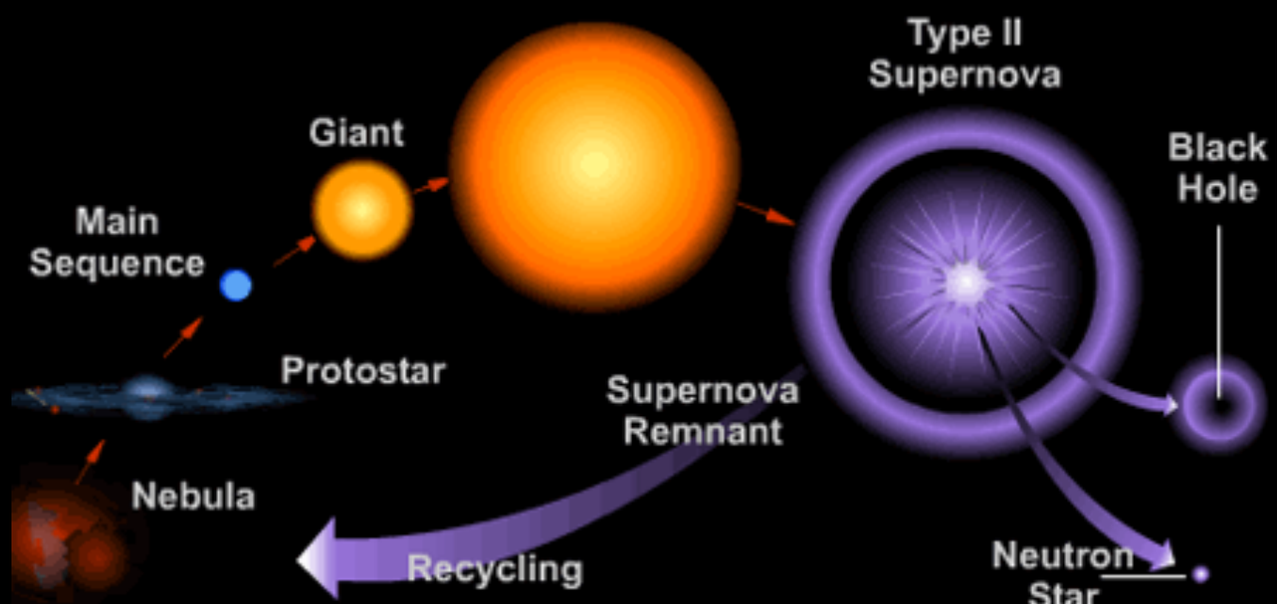


Galaxy Feedback

Deposition of Radiative+ Mechanical Energy

Explosive Transients

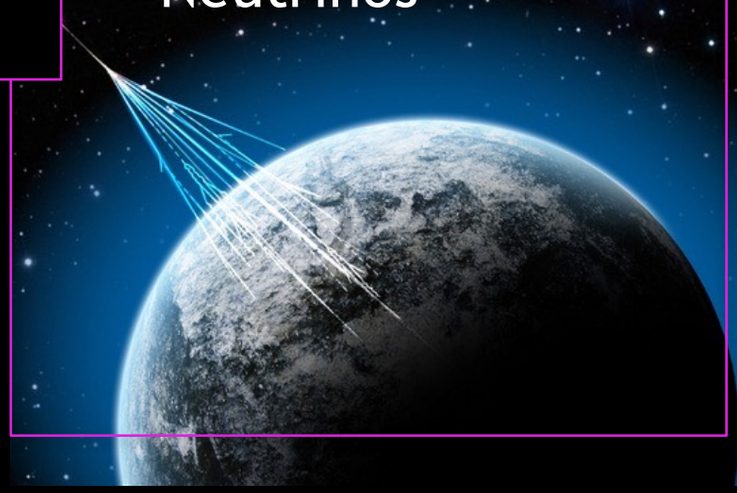
Endpoint of Stellar Evolution



They produce the most Extreme Objects

Laboratories of Extreme Physics (jets)

Sources of GWs and Neutrinos



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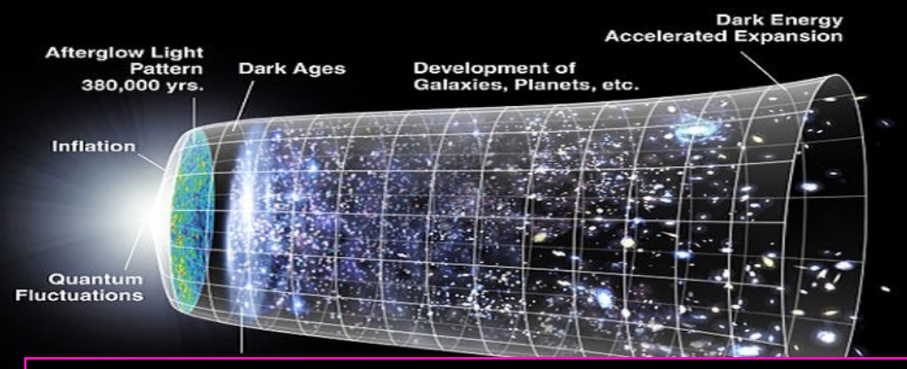

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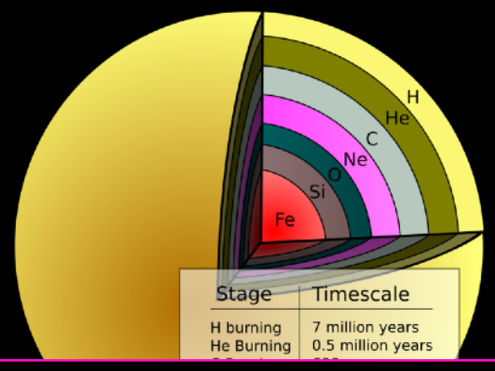
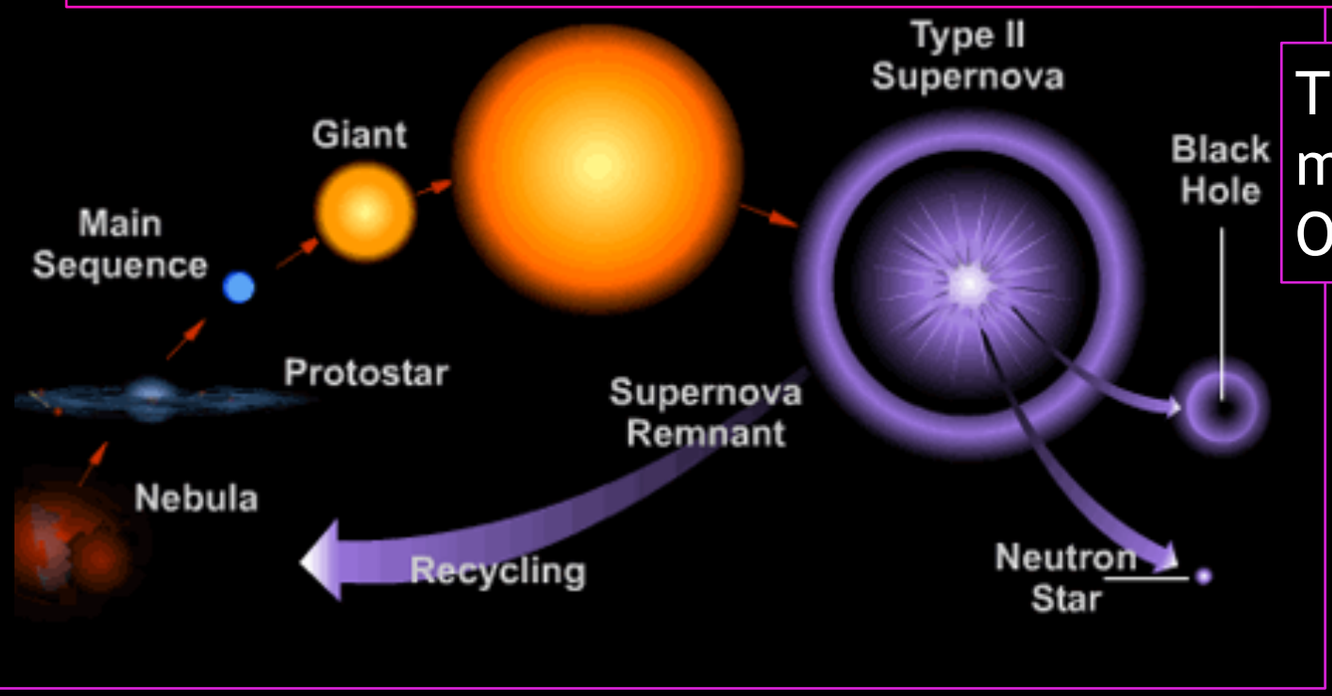


Galaxy Feedback

F

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



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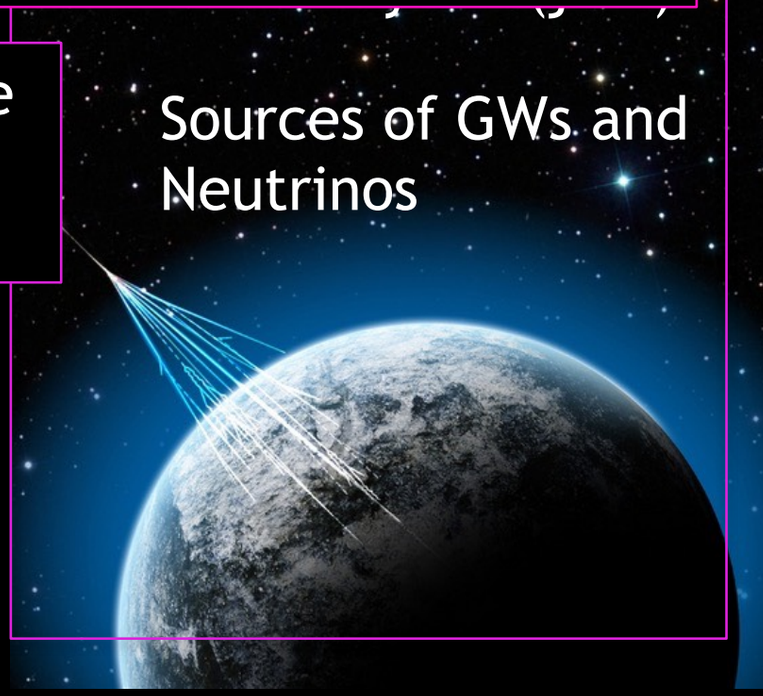

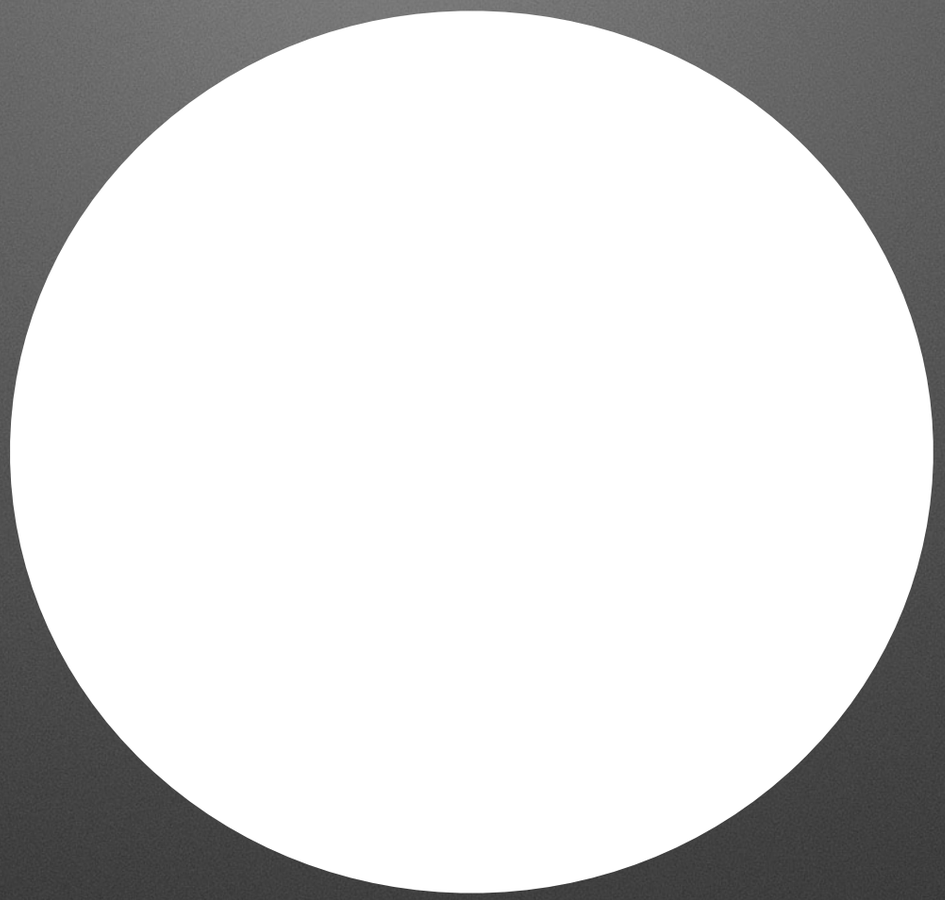

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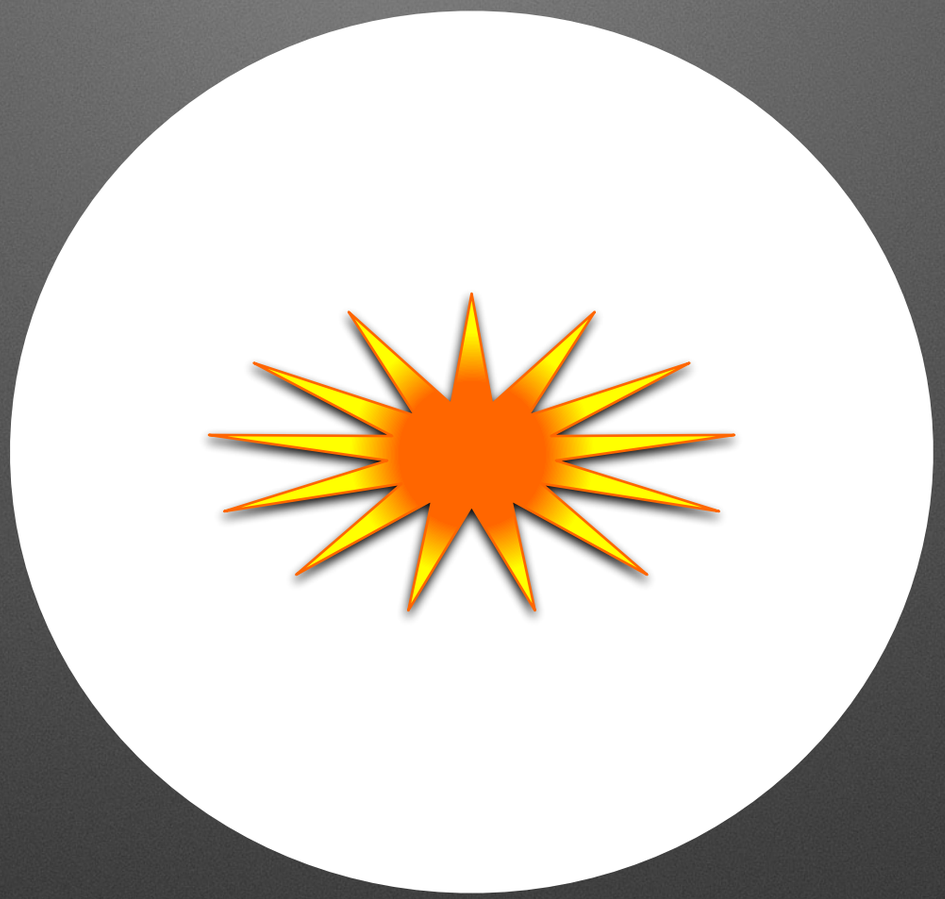

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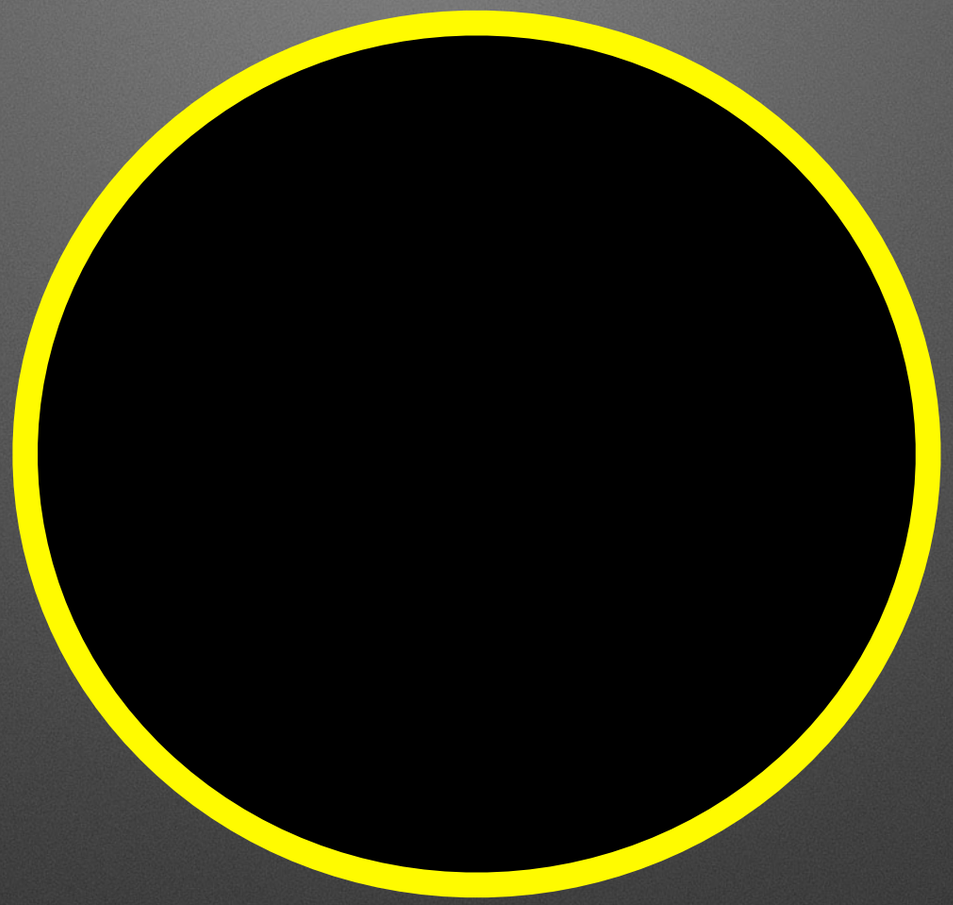

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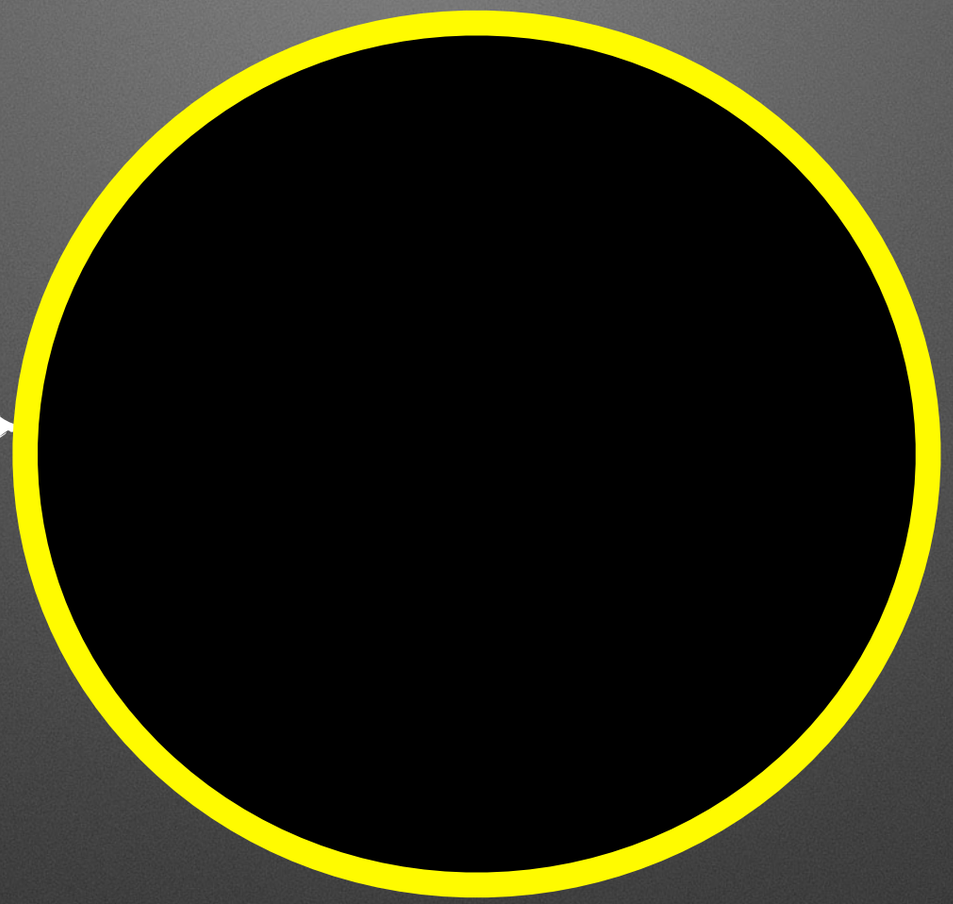

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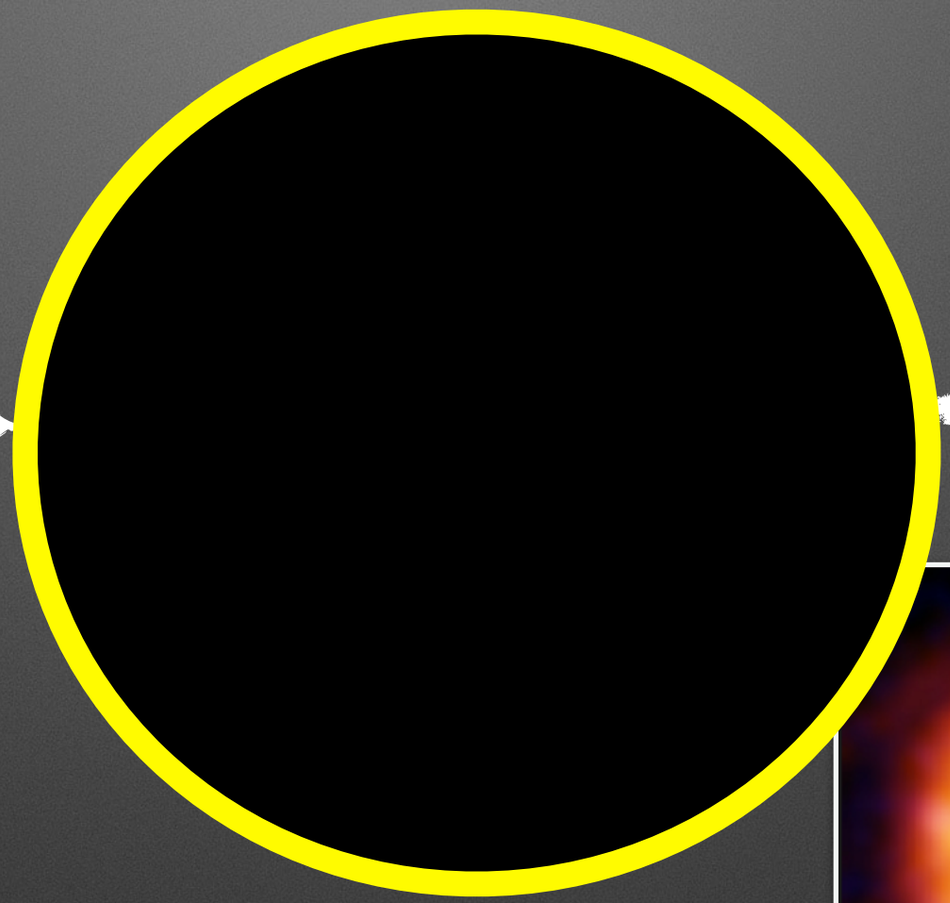

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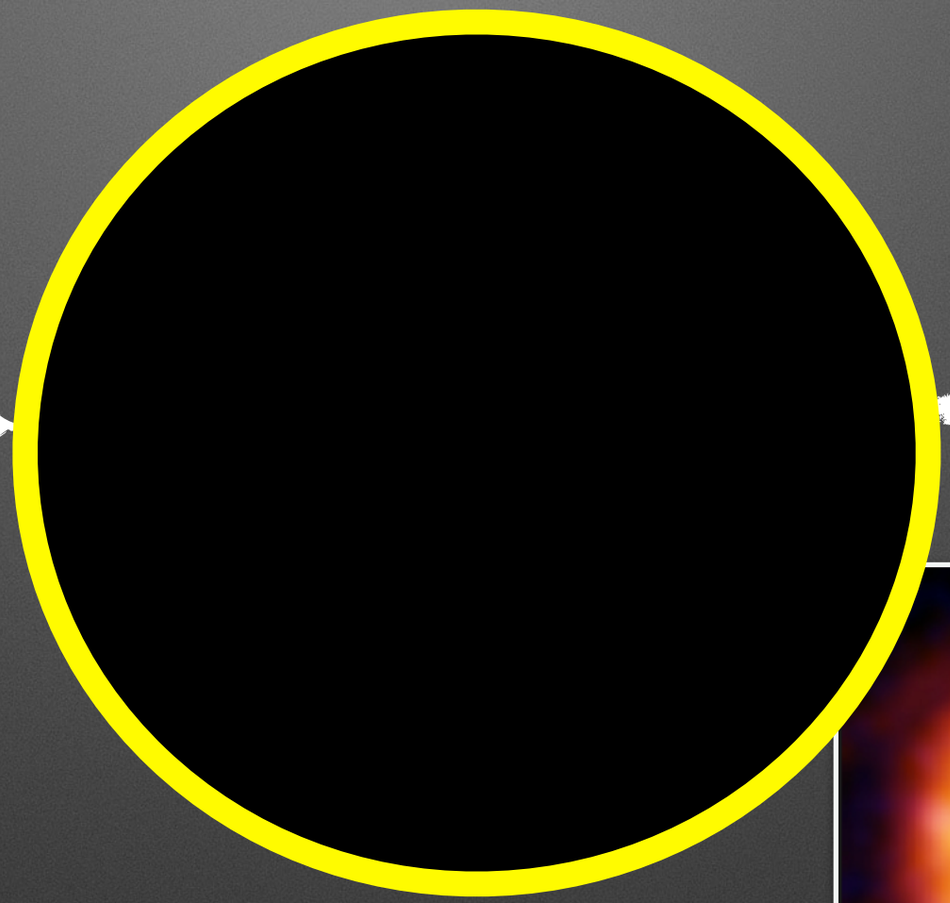
γ- X-rays UV/Optical/NIR Radio

?



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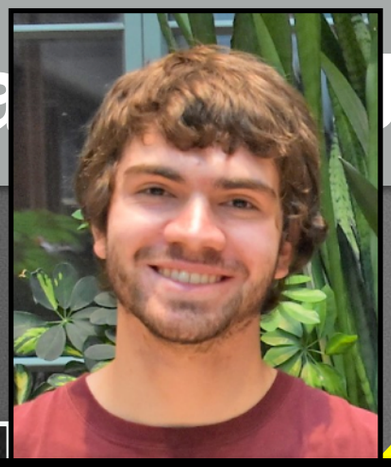
Lindsay de Marchi
gradstudent



Angelo Bastas
undergrad

X-ray UV/Optical/NIR Radio

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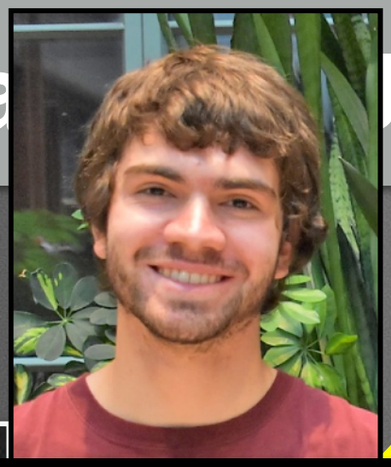

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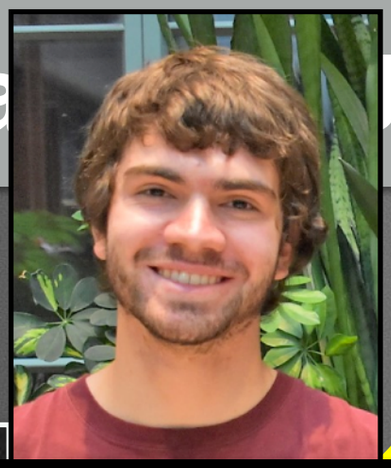

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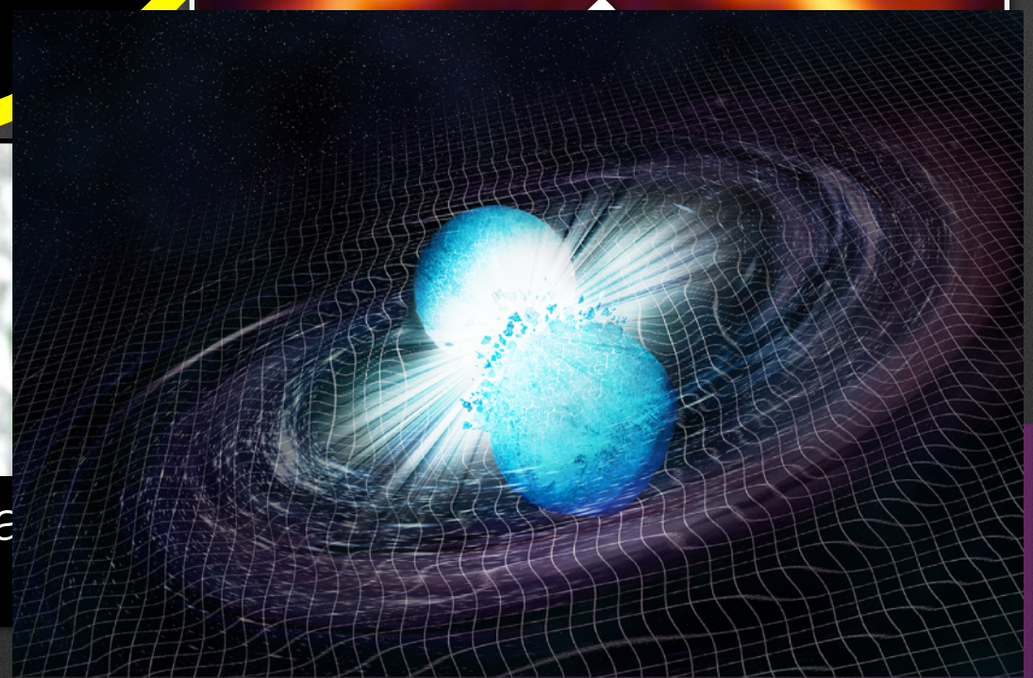

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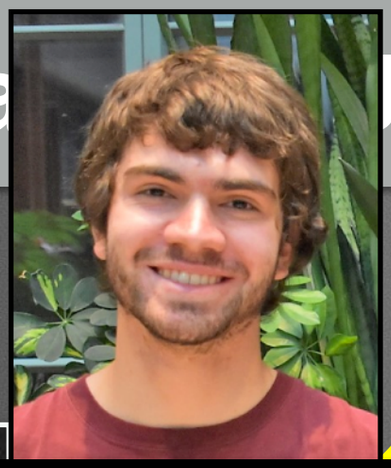

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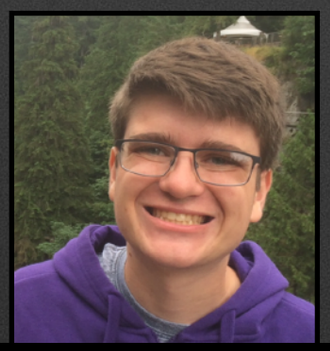

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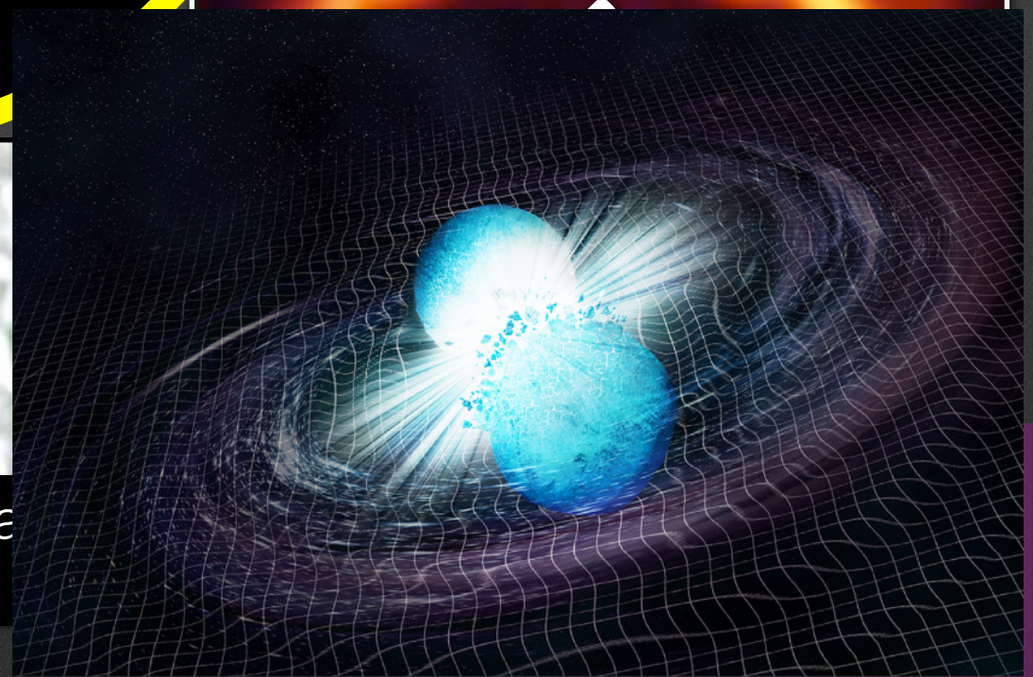

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γ- X-rays UV/Optical/NIR Radio

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NS

?

BH

~ 1000 yr

γ- X-rays UV/Optical/NIR Radio

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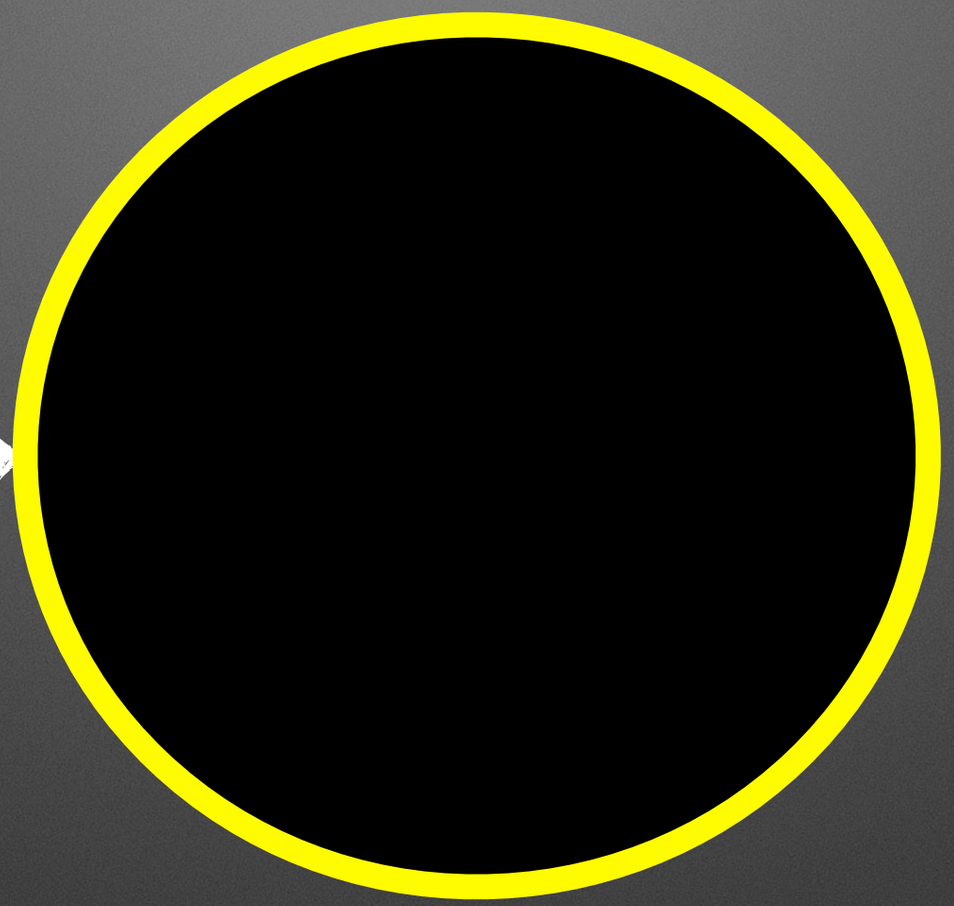


~ 1000 yr

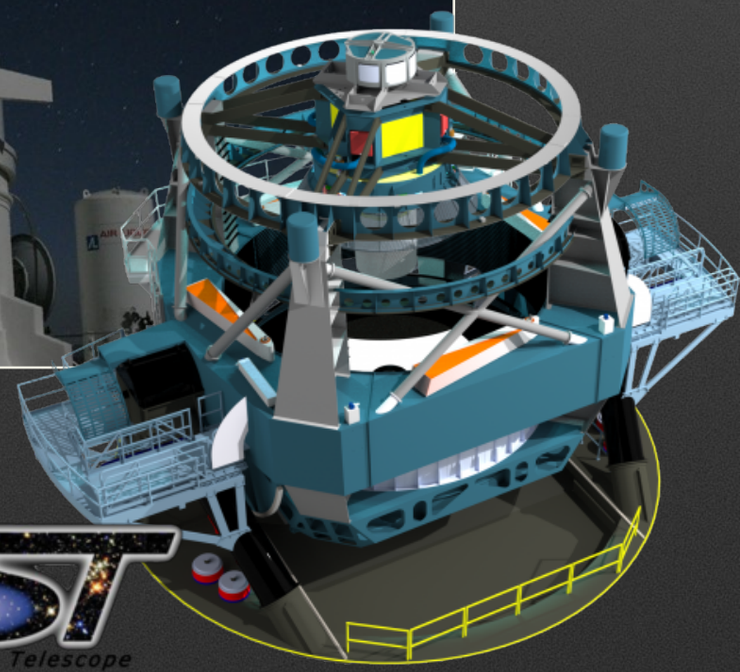
Why NOW?

1. Technological Revolution ==> Time Domain Astrophysics

PanSTARRS

Zwicky Transient Facility

+ many others!



LSST
Large Synoptic Survey Telescope

Why NOW?

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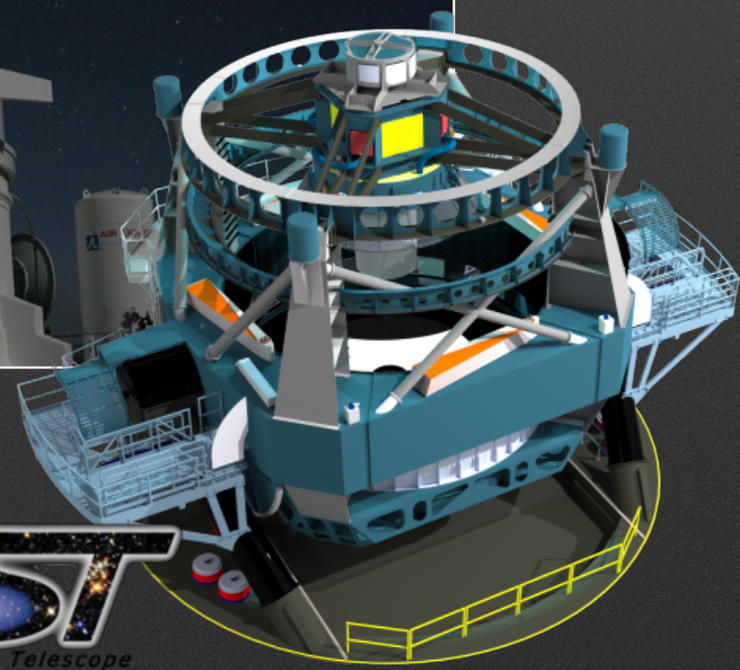
SKA
SQUARE KILOMETRE ARRAY

+ many others!



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Where do we stand?

Where do we go?

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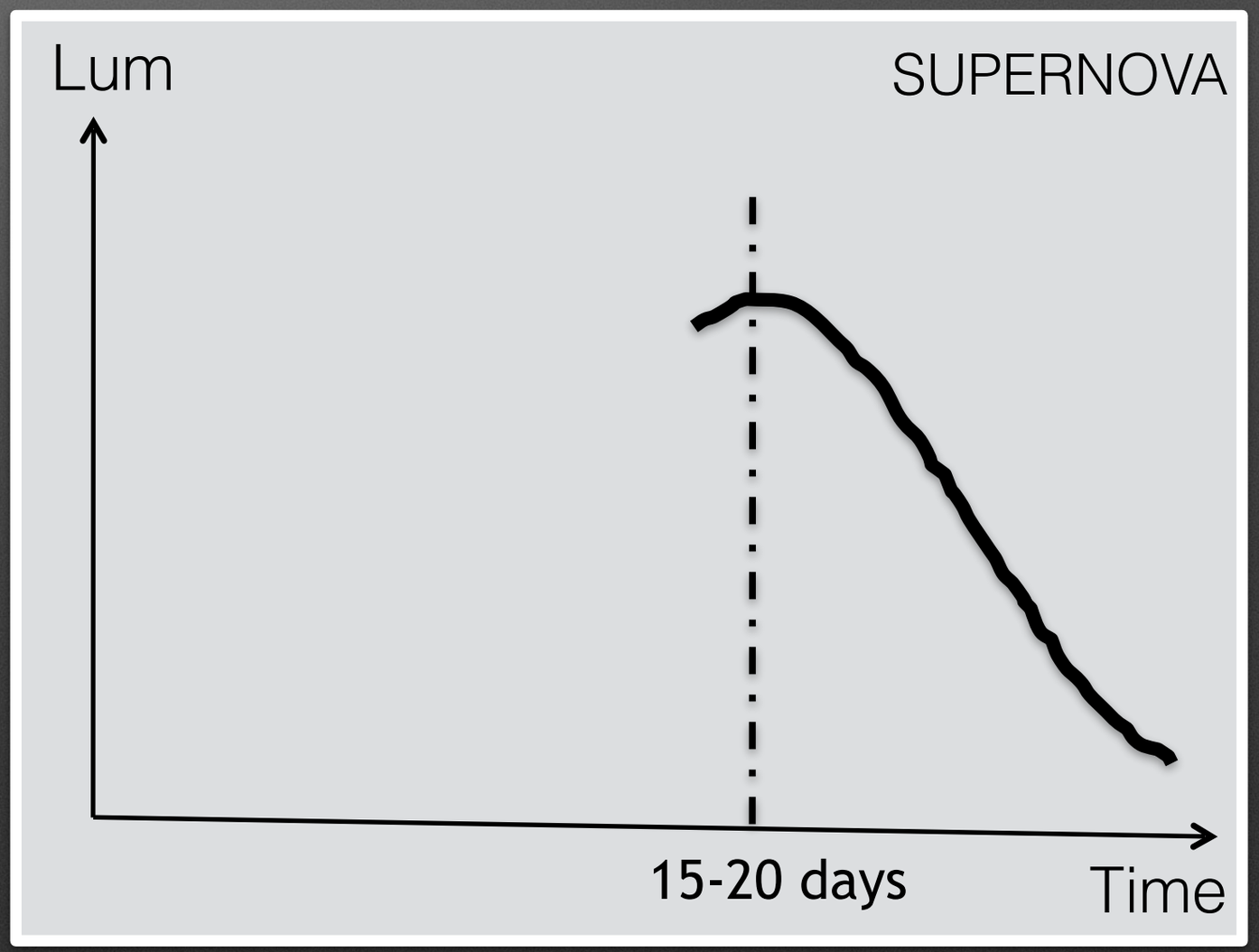
Explore a new parameter space in already known transients
(Rise-time science; pre-SN science; shock break out science)



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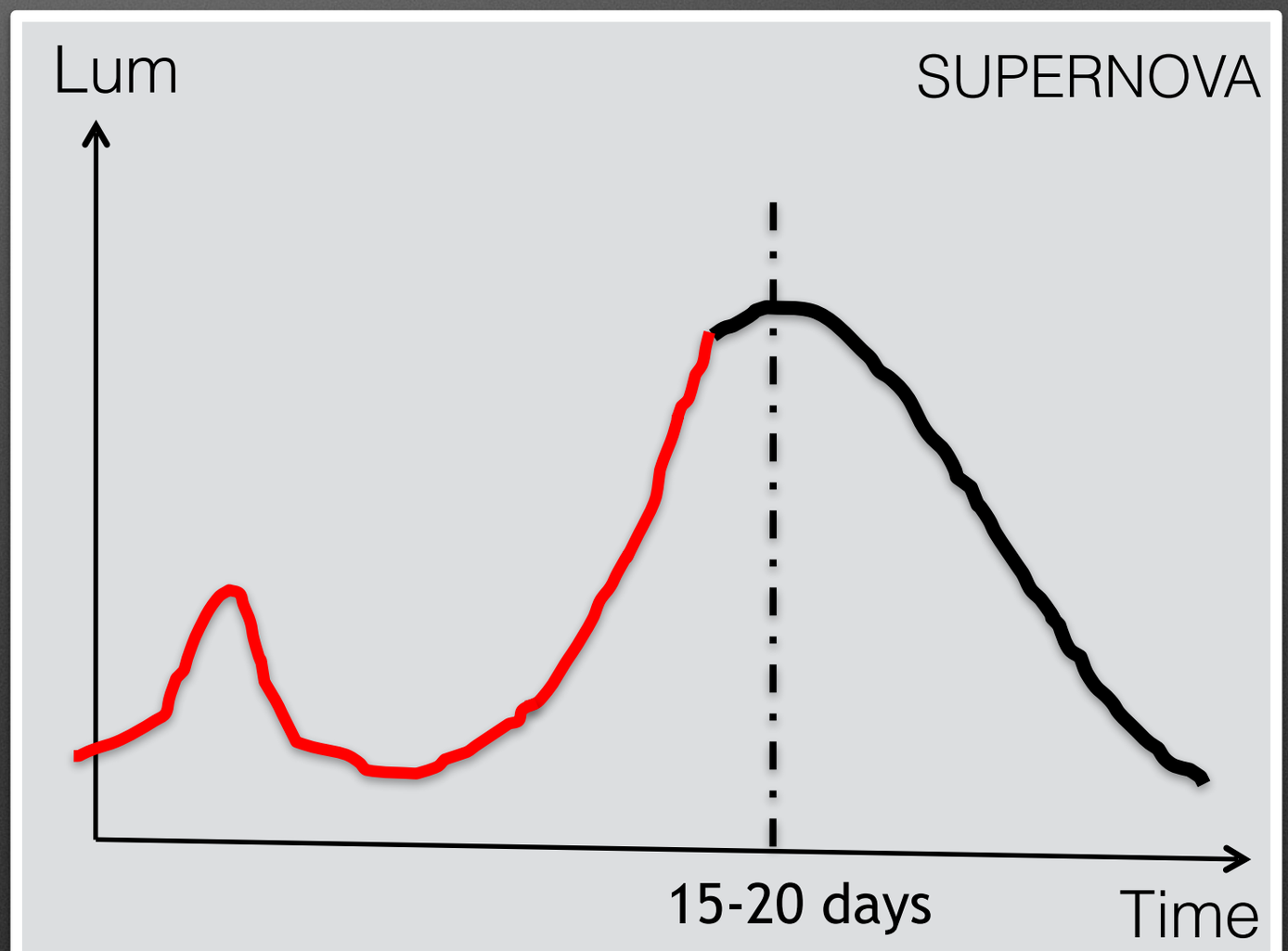

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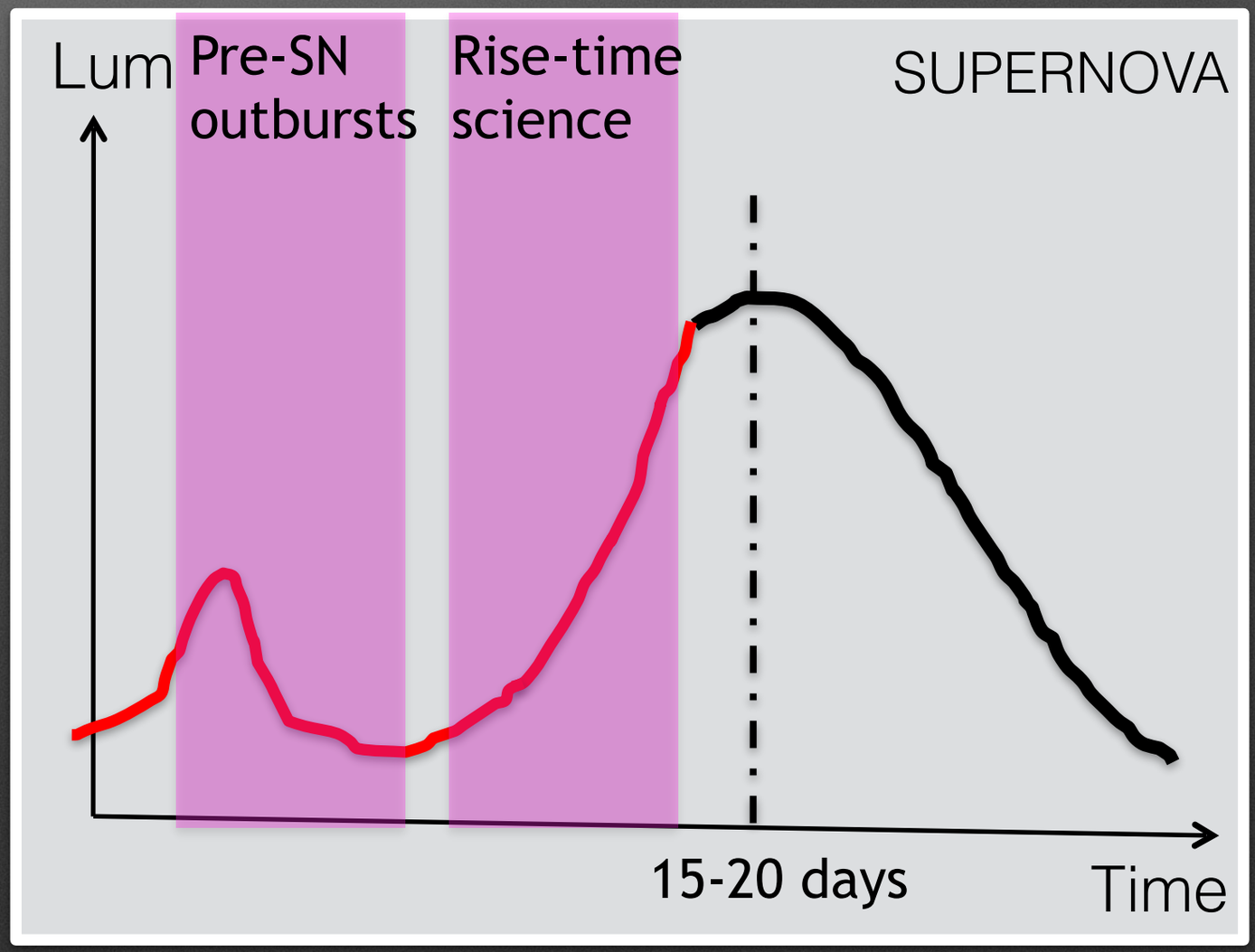

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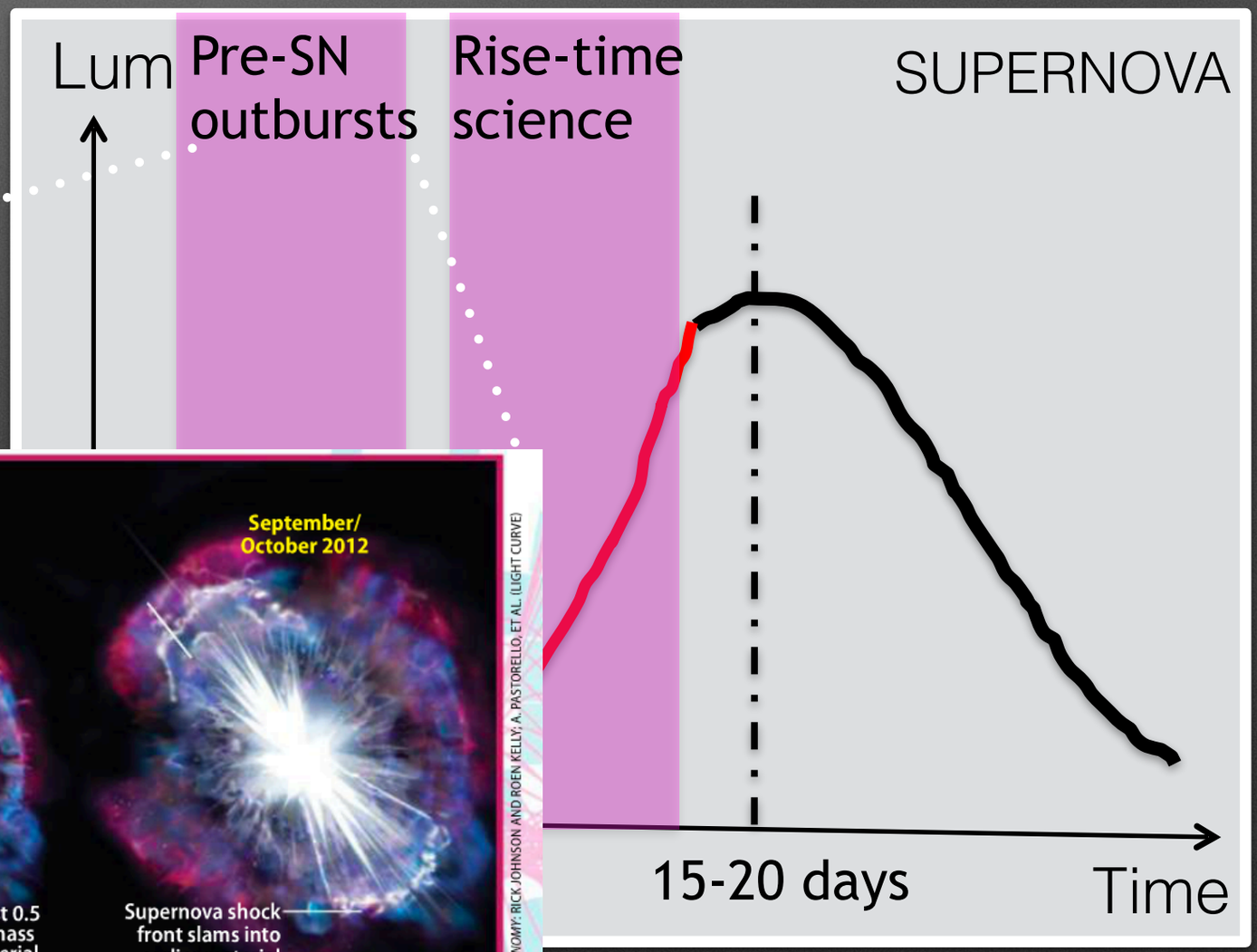

Margutti Astronomy Magazine 2014

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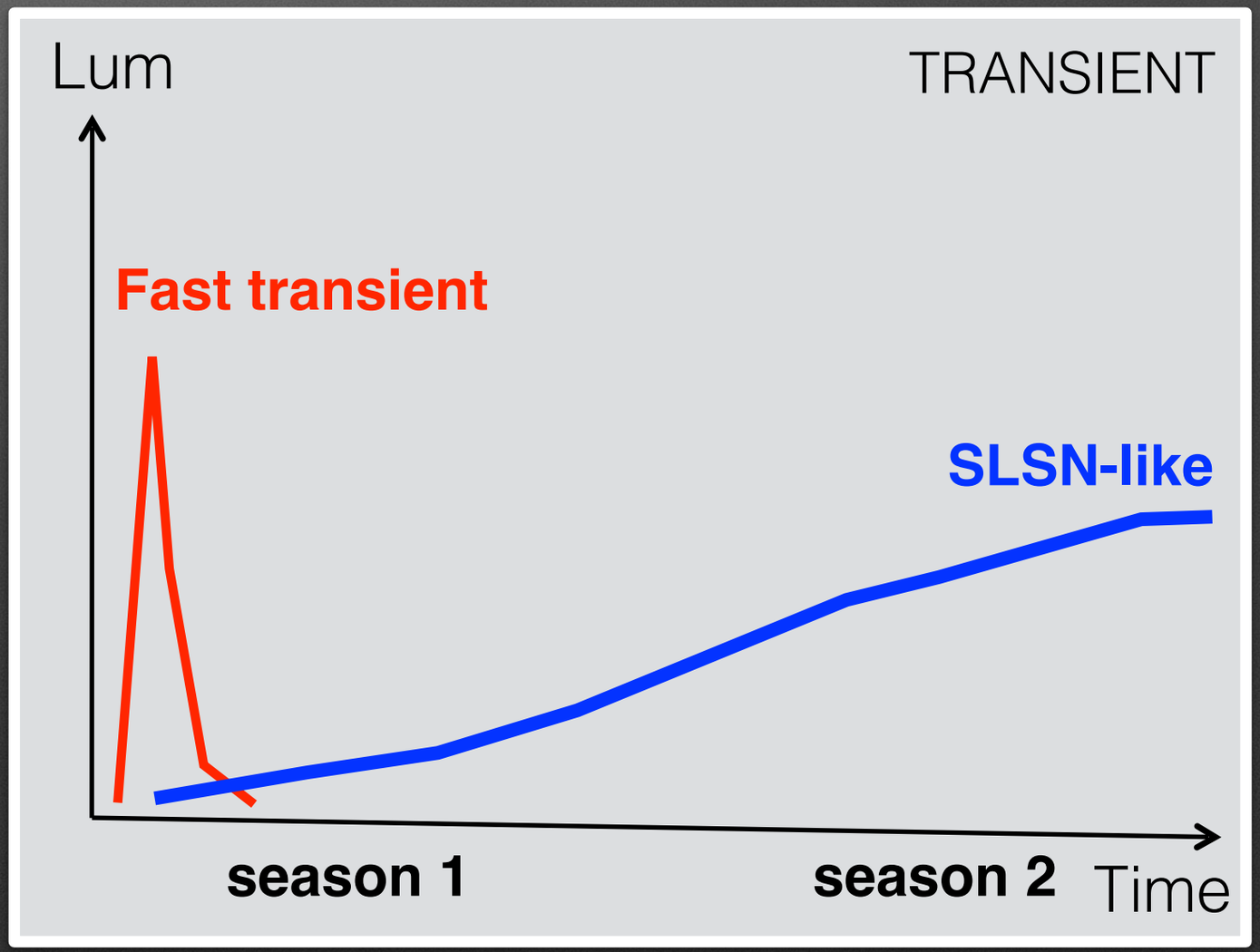
Discovery of **NEW type of transients** (e.g. SLSNe, very fast evolving transients)



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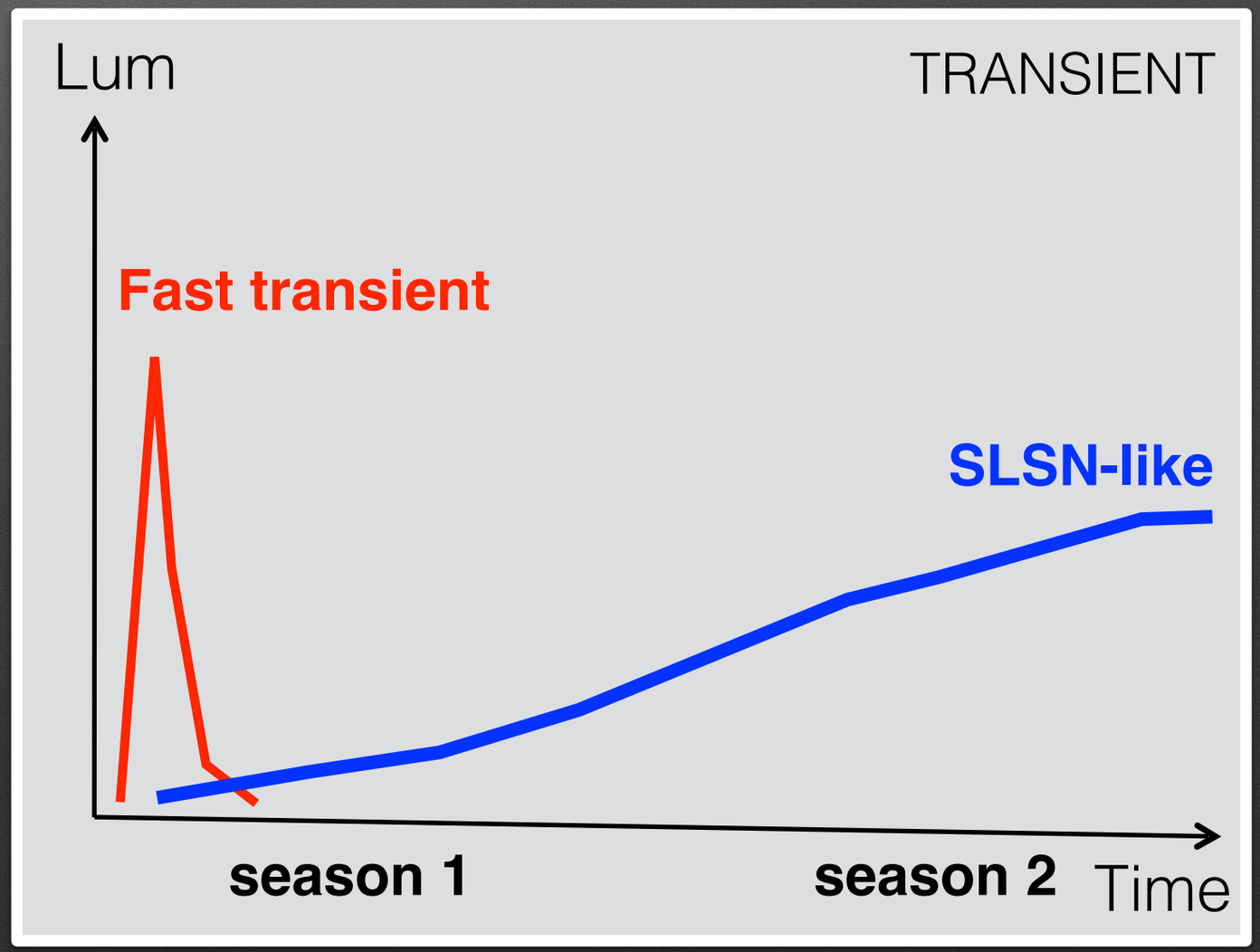

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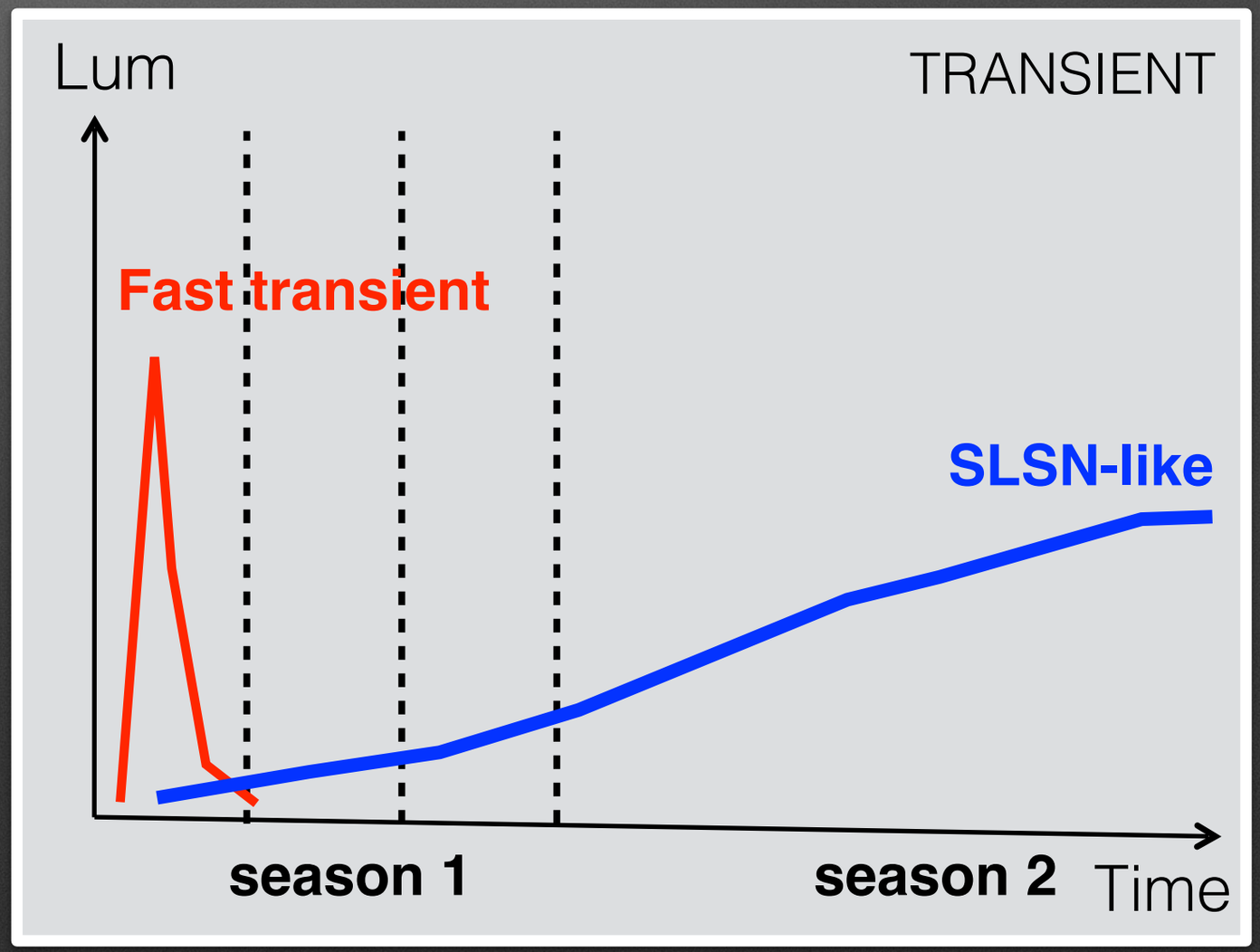

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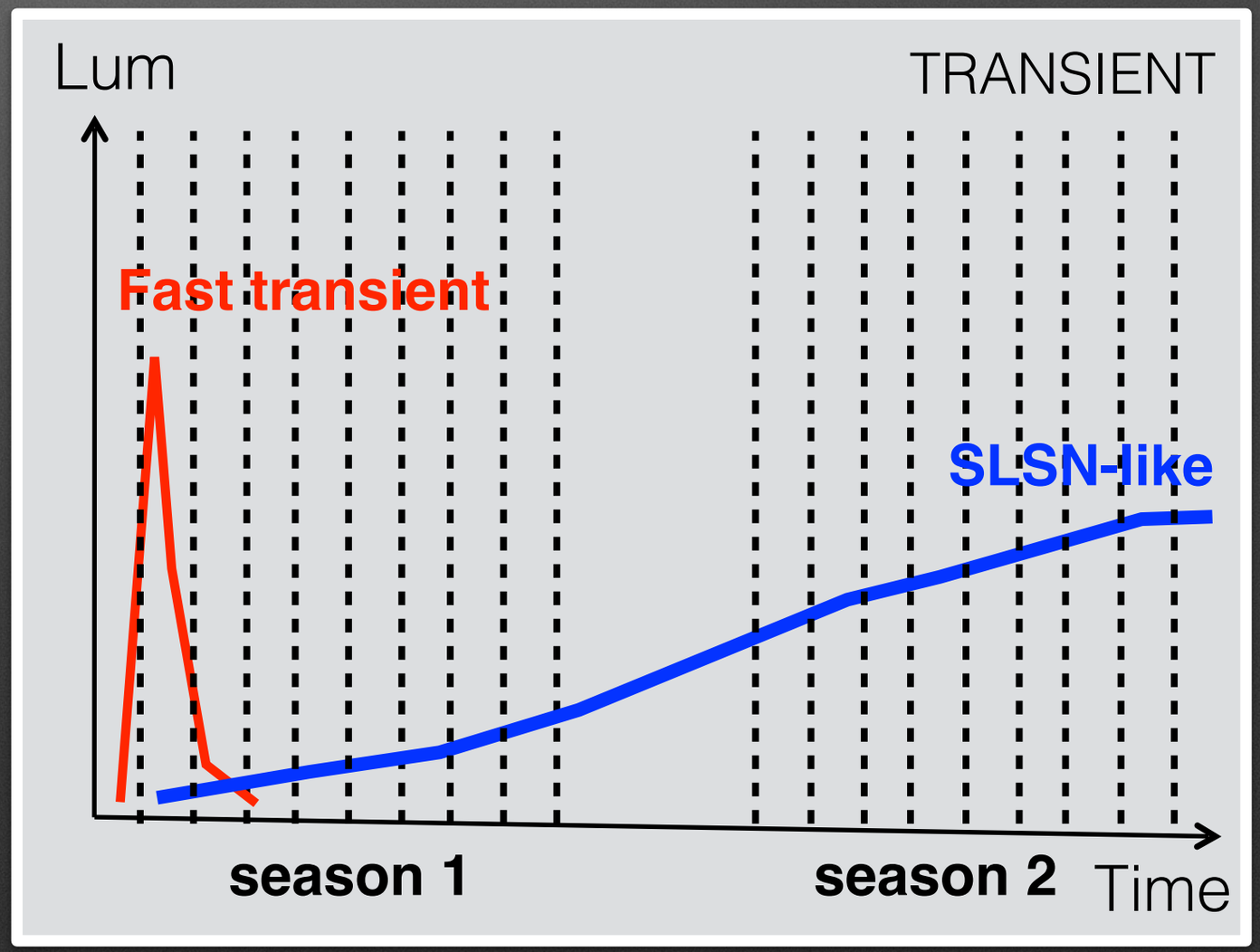

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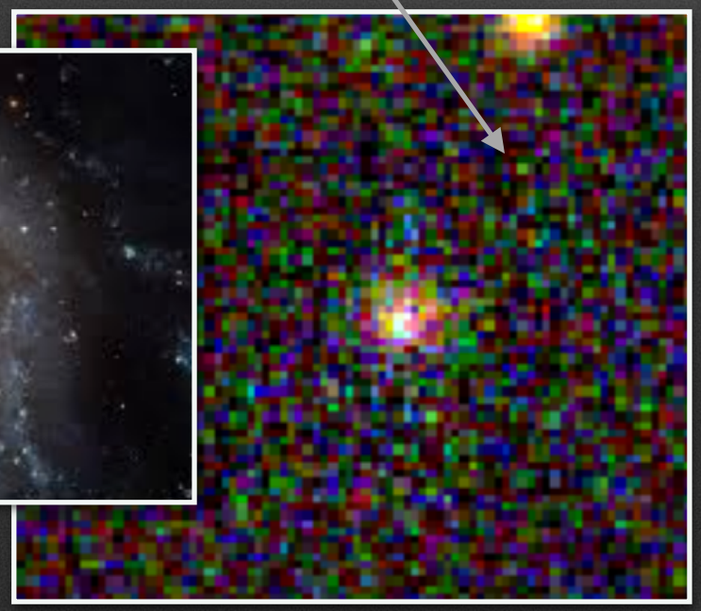
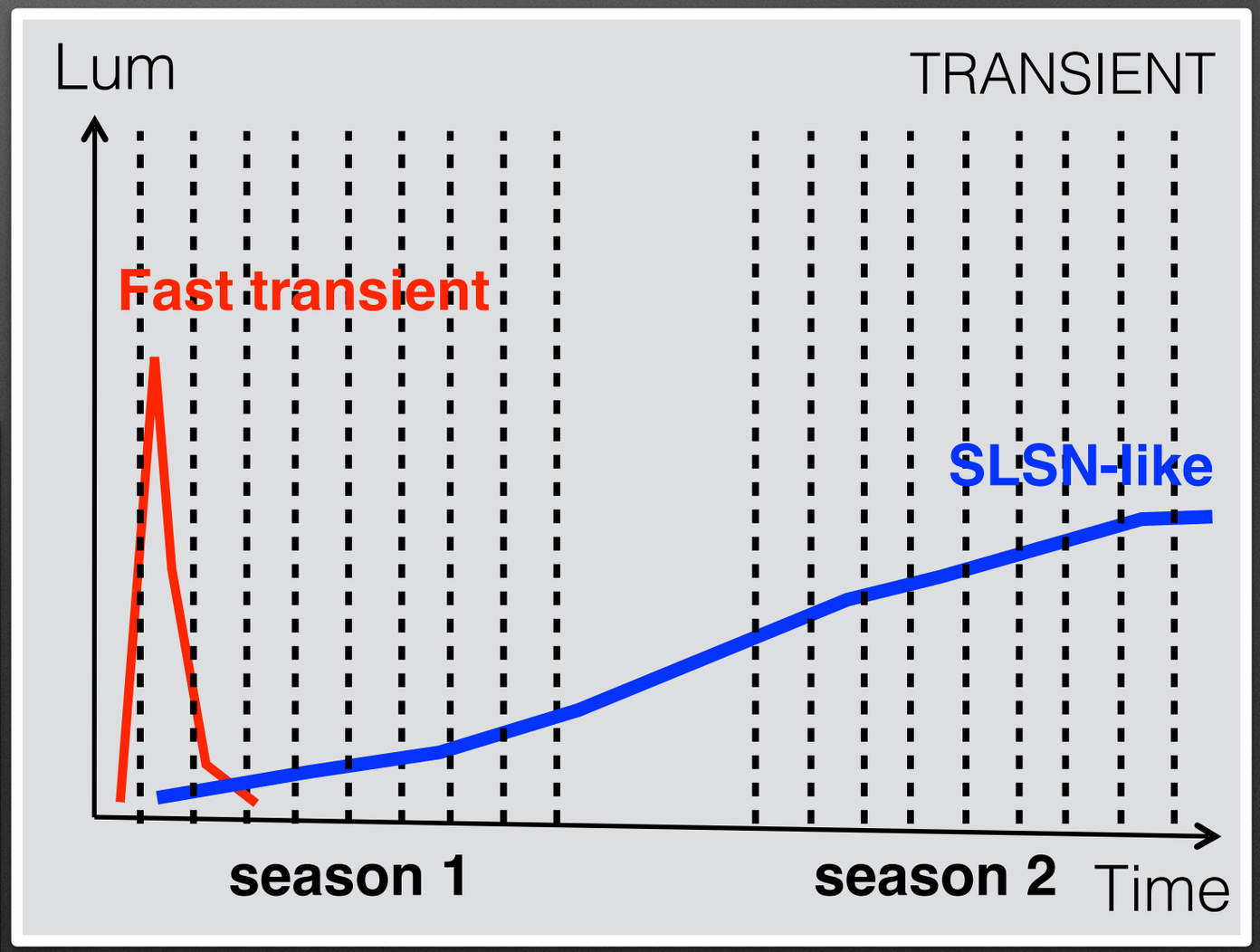
Time scales

Untargeted search





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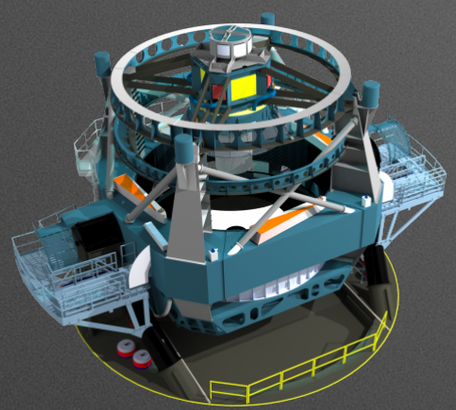

Explore a new parameter space in already known transients
(Rise-time science; pre-SN science; shock break out science)

Discovery of **NEW type of transients**
(e.g. SLSNe, very fast evolving transients)

2. Multi-Wavelength Astrophysics

Multi-messenger Astrophysics
(neutrinos, GW)

γ- X-rays UV/Optical/NIR Radio

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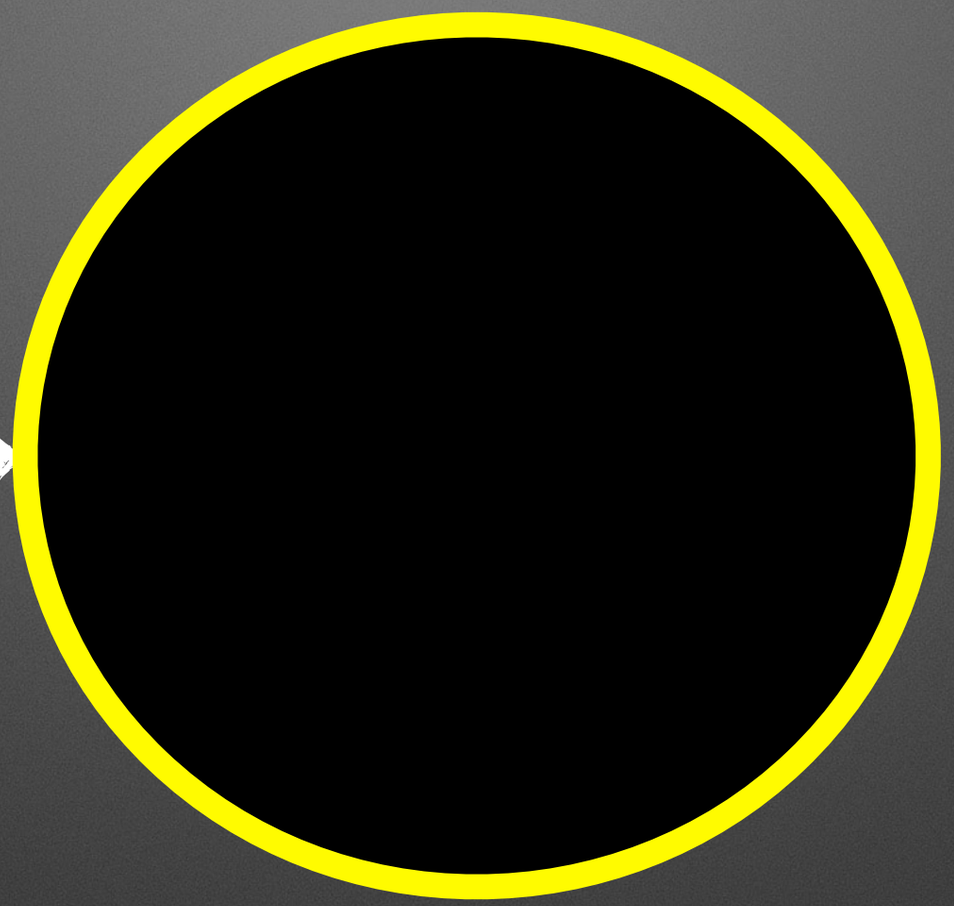


~ 1000 yr

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

SN1987A "ring"

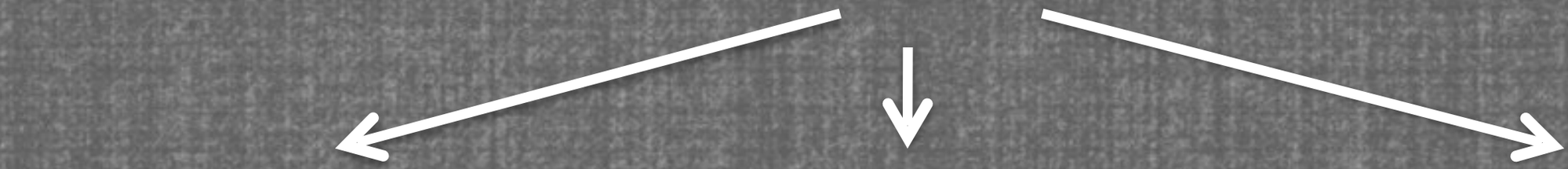
See Talk that follows!

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

The last years before explosion

Direct Observations

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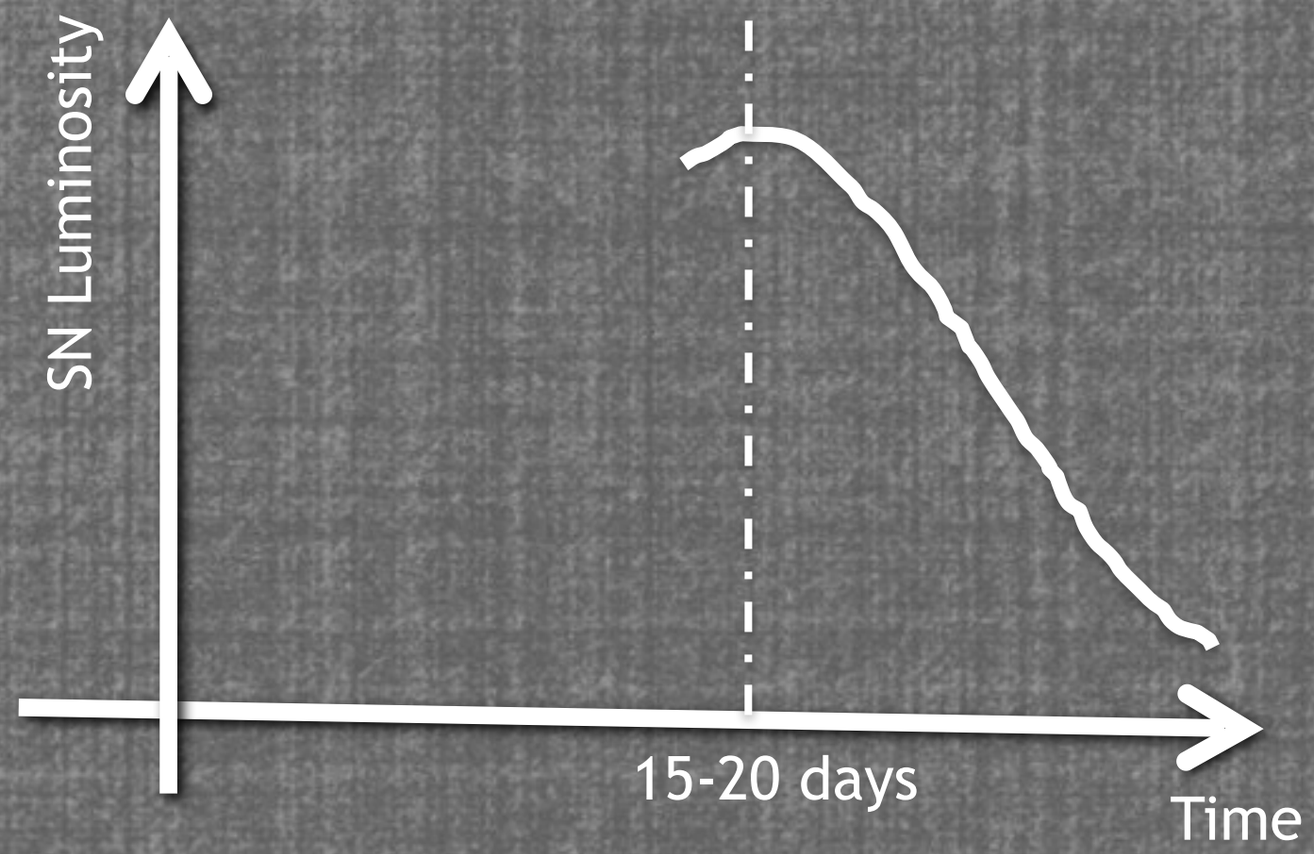
Shock Interaction



The last years before explosion

Direct Observations

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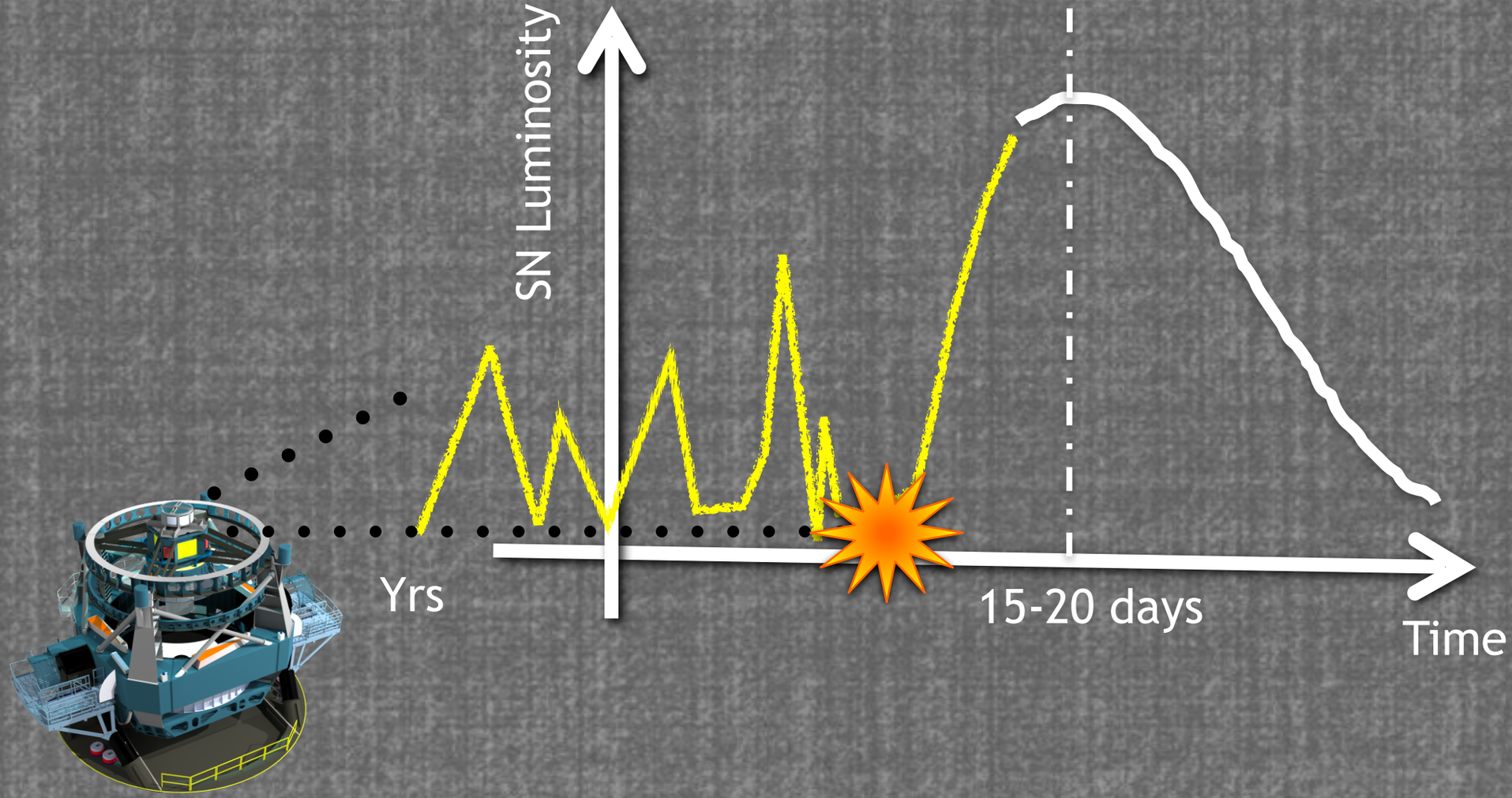
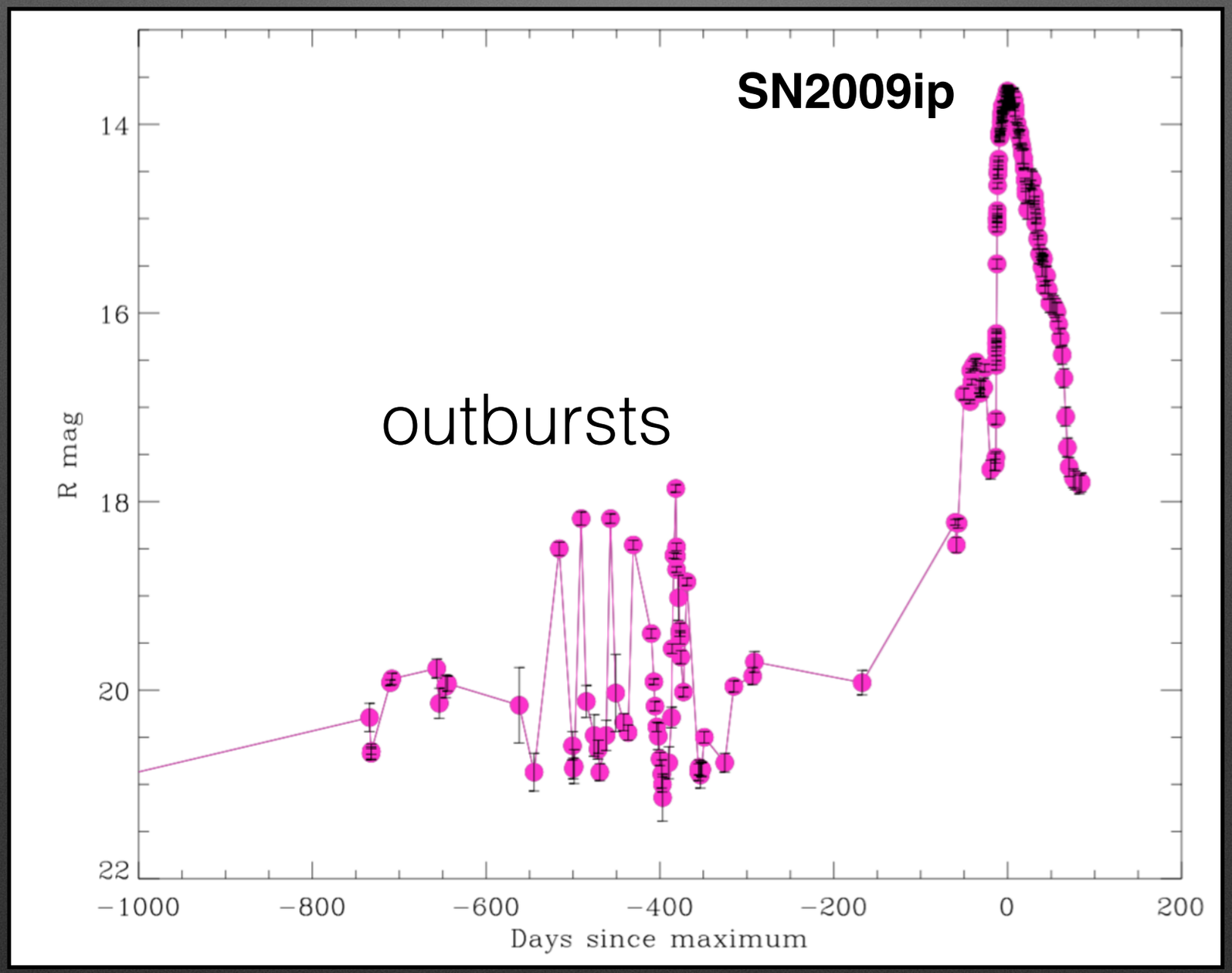


Pre-SN outbursts are common among H-rich progenitors

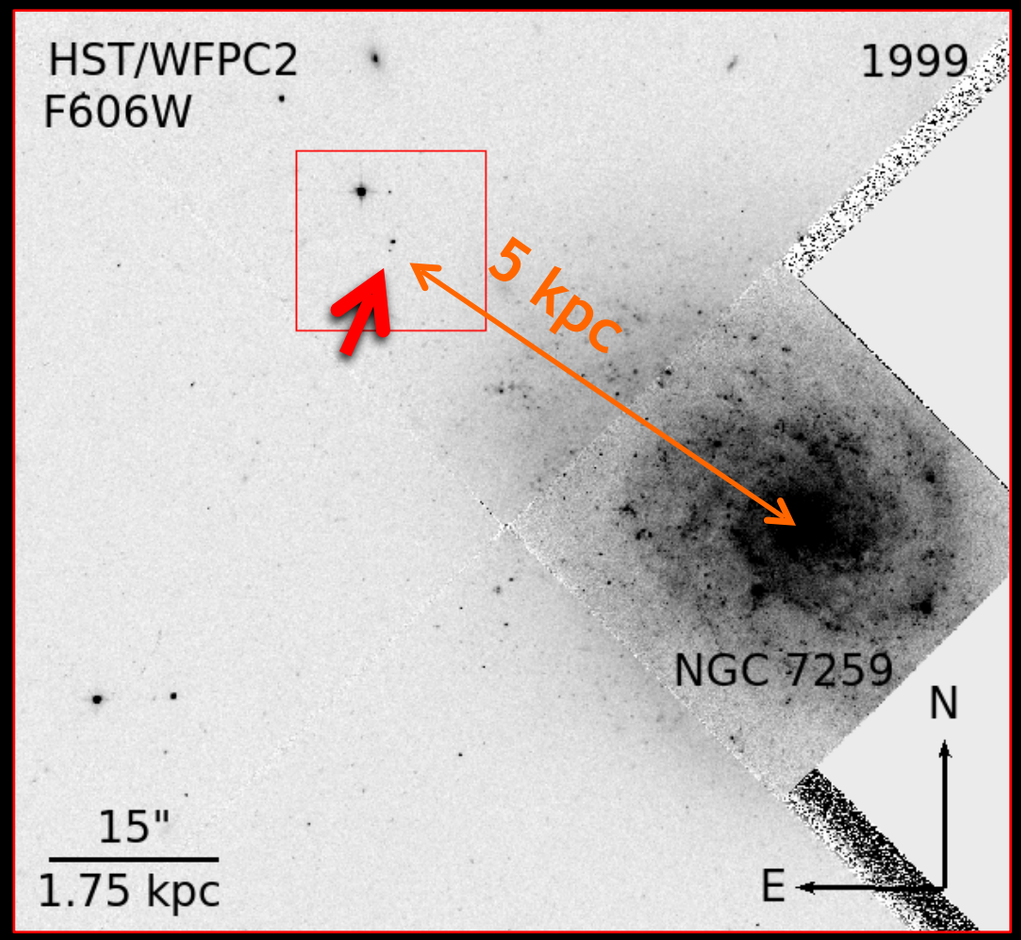
E.g. Margutti+14, Ofek+14, Smith+15



Margutti+14

This is common, but maybe only among very massive stars?

SN2009ip
Type-IIn



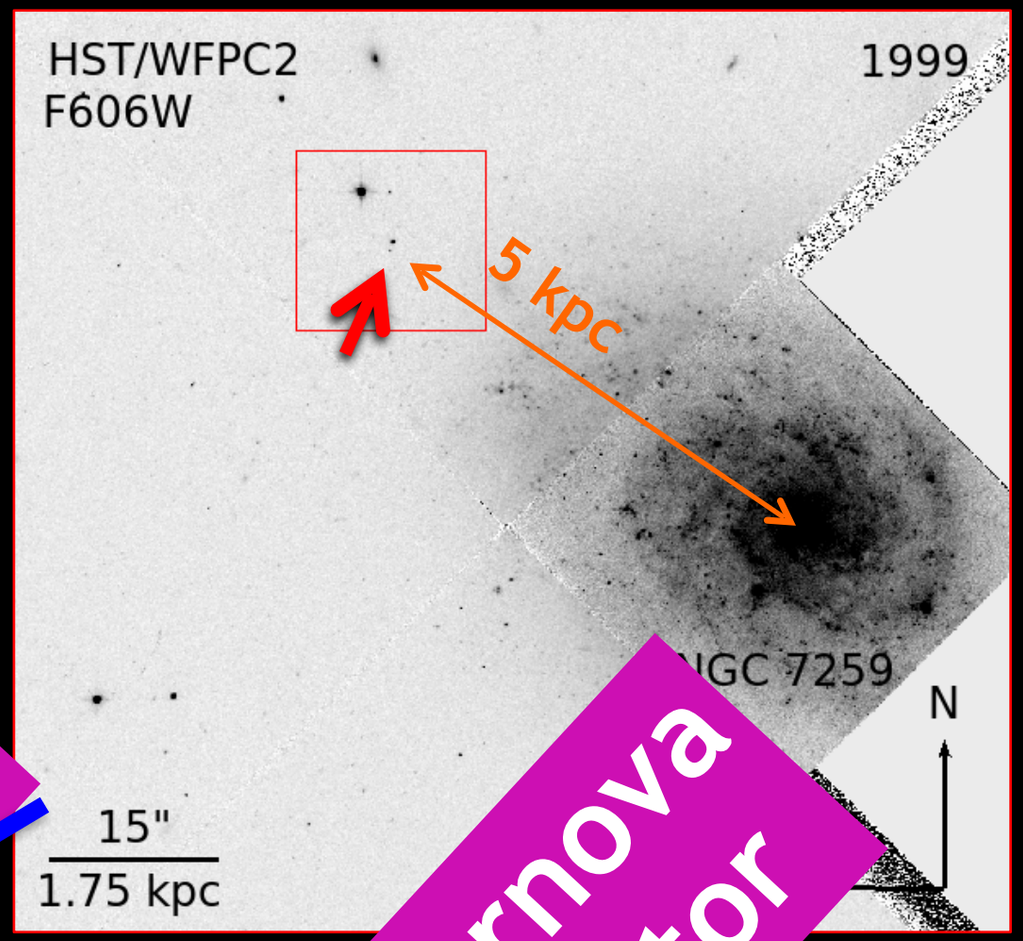
★Distance of 24 Mpc

★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



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Discovery

Outburst

Outburst

Outburst

Explosion1

Ex

Supernova

Supernova Impostor

Supernova

Aug 2009

Jul 2010

Sep 2010

May 2011

Oct 2011

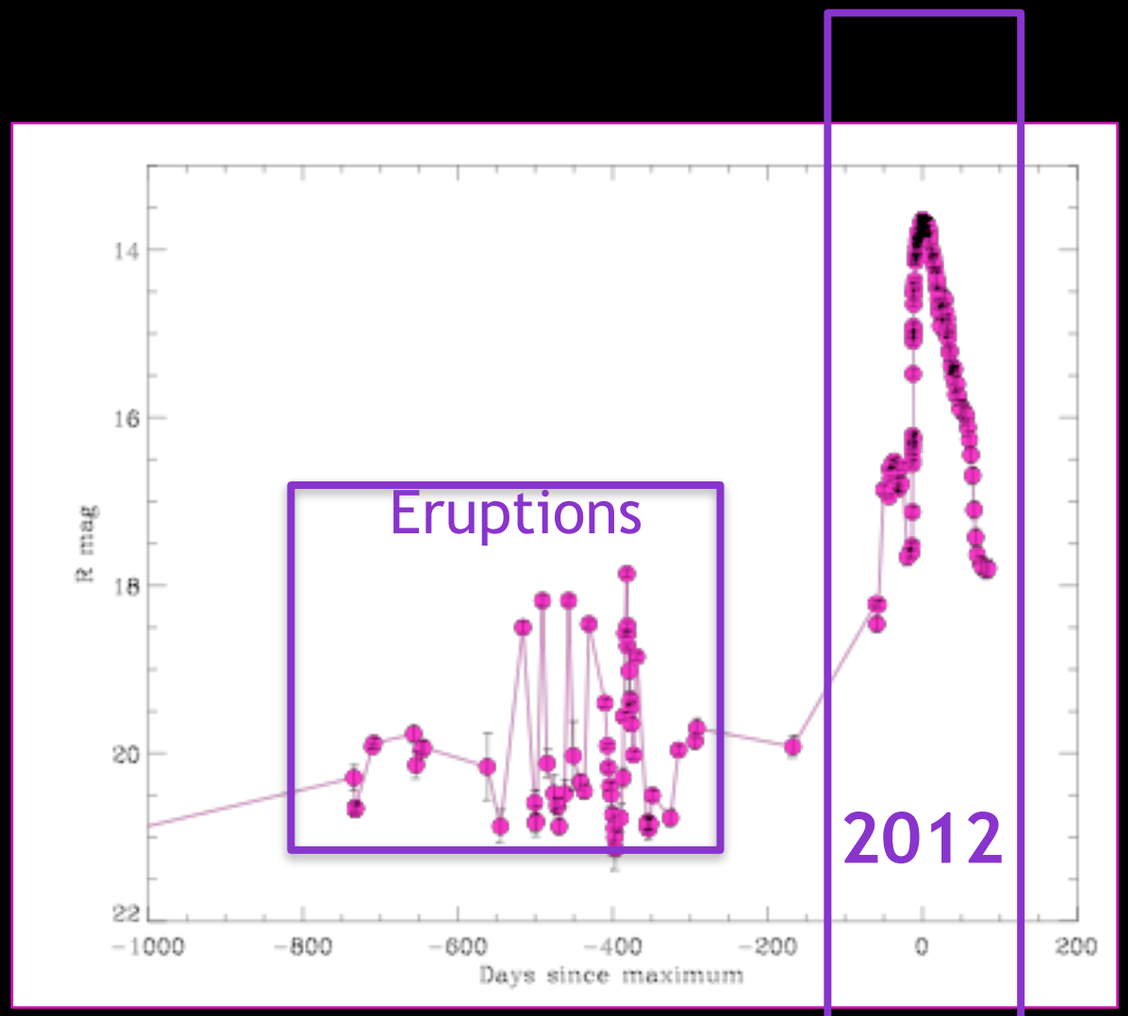
Aug 2012

Sep 2012

Now

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

UV-Optical-NIR light-curve



Margutti+ 2014

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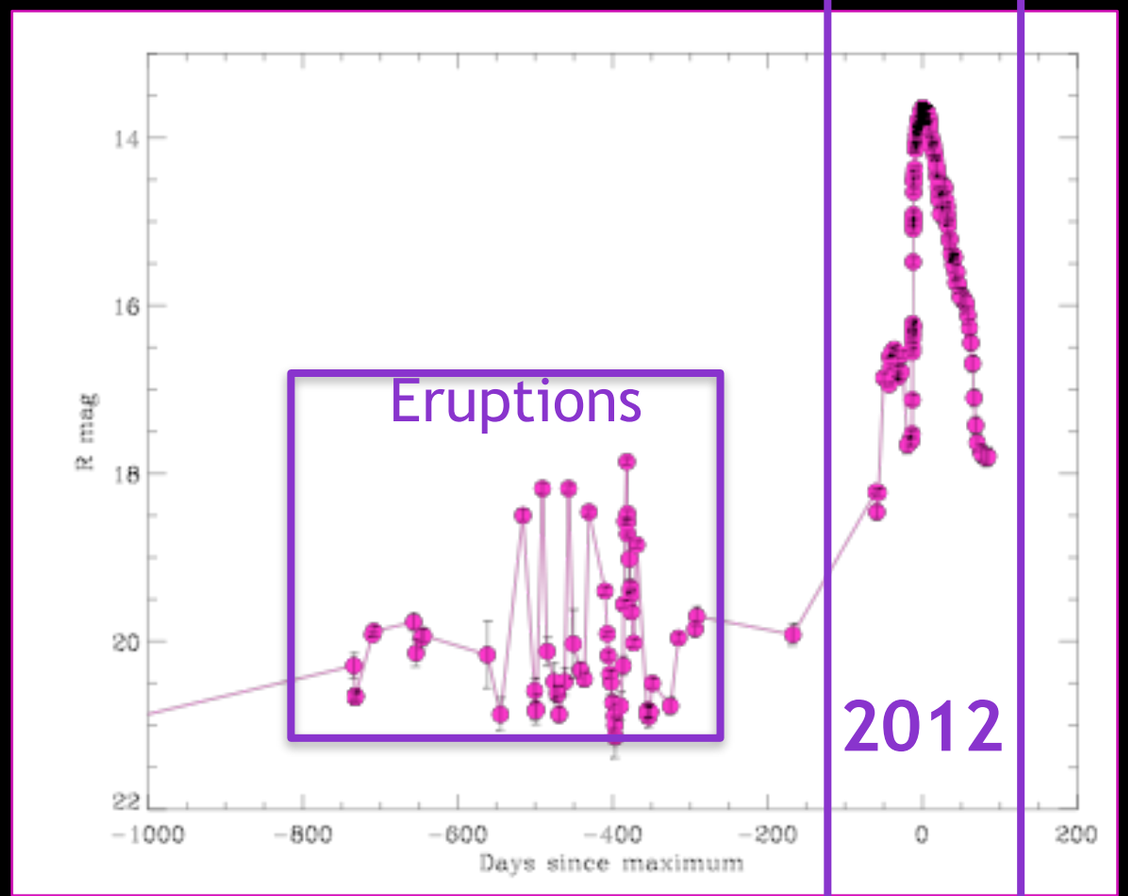
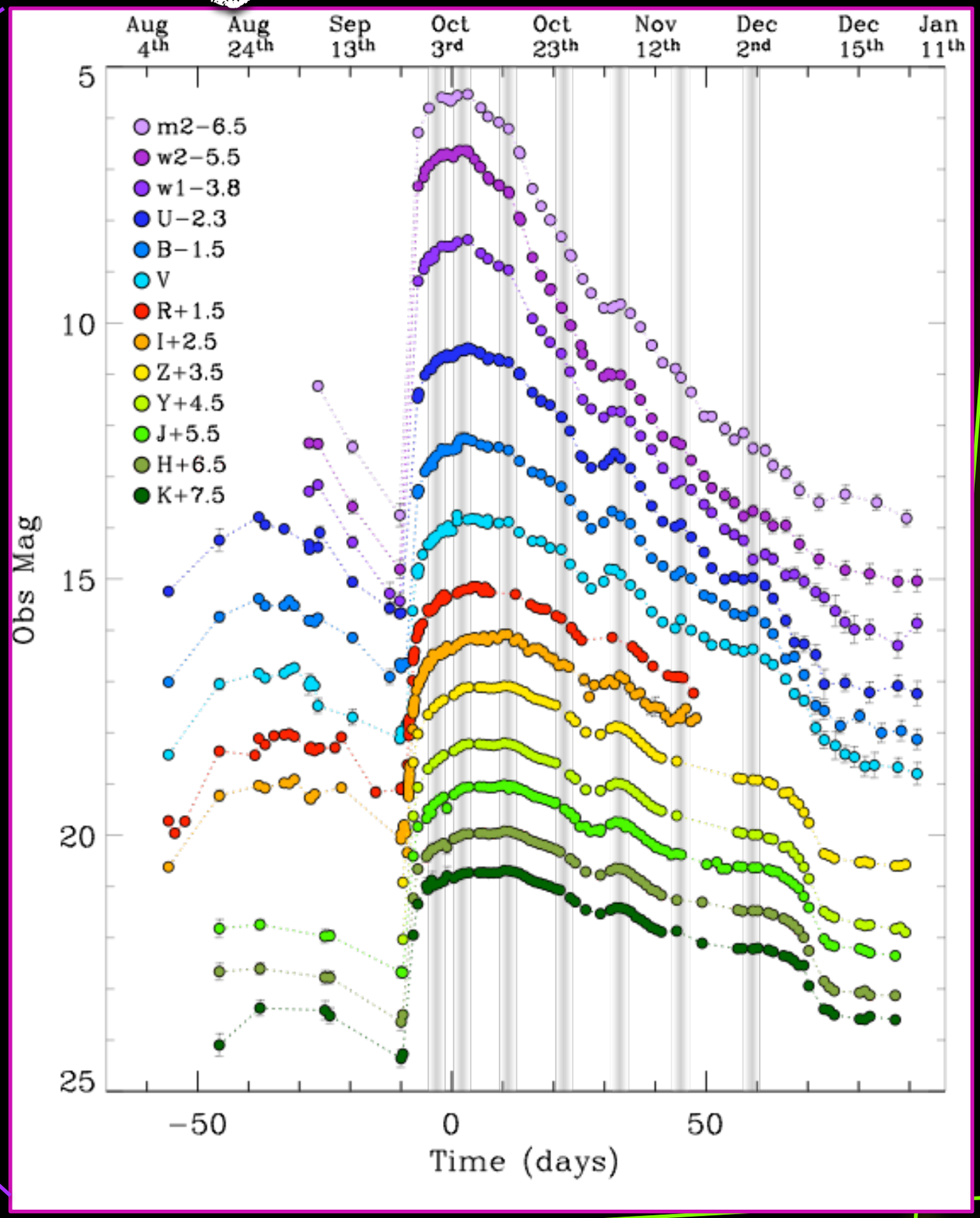
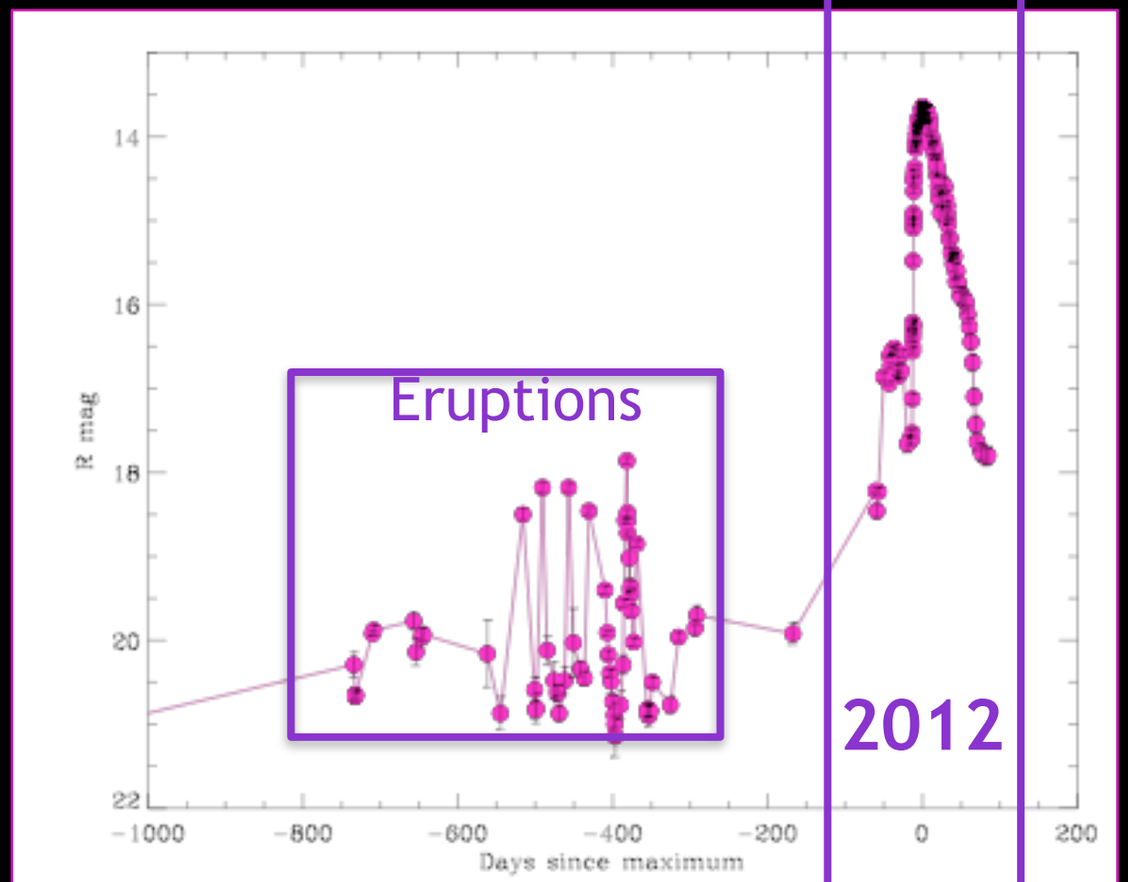
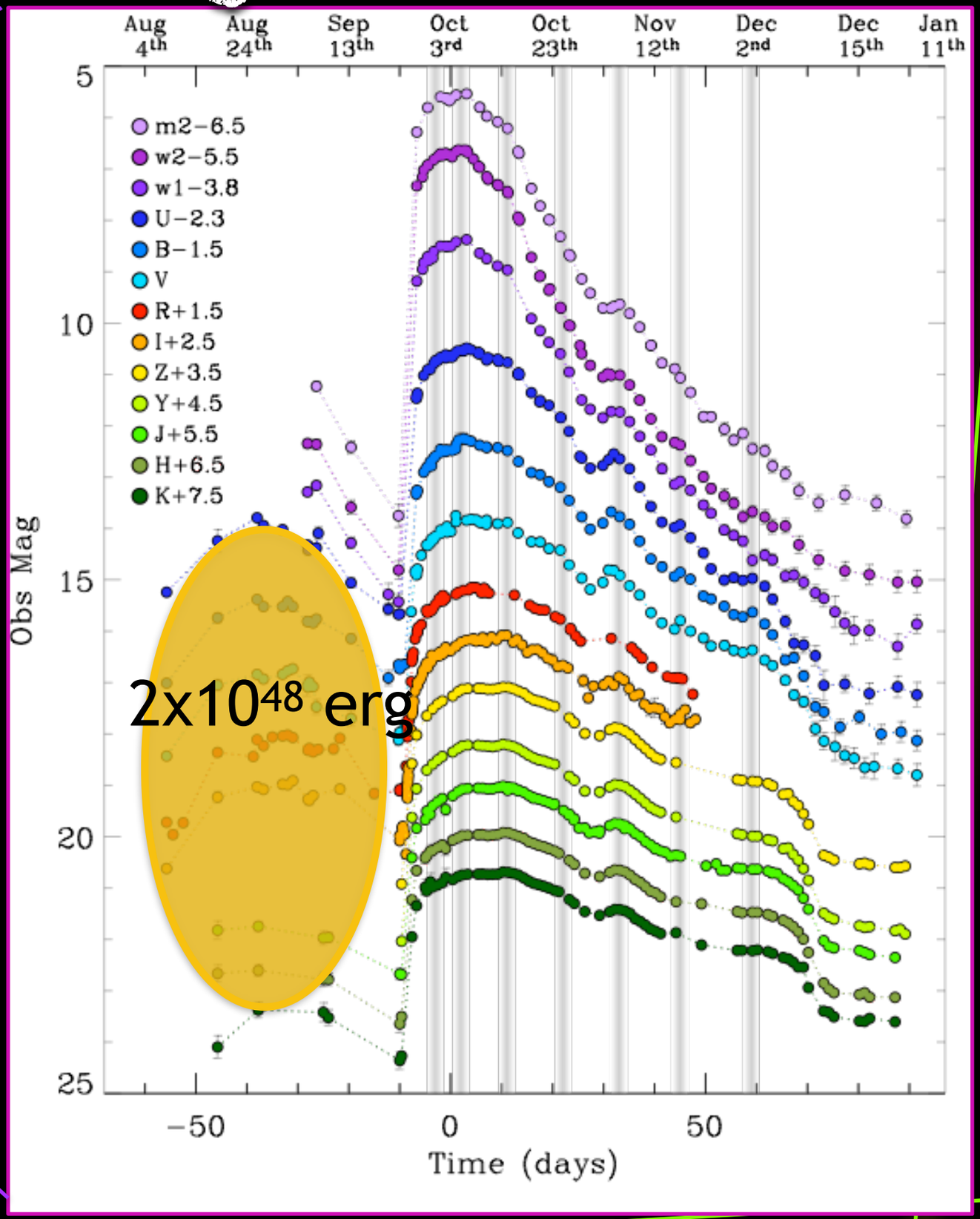




Margutti+ 2014

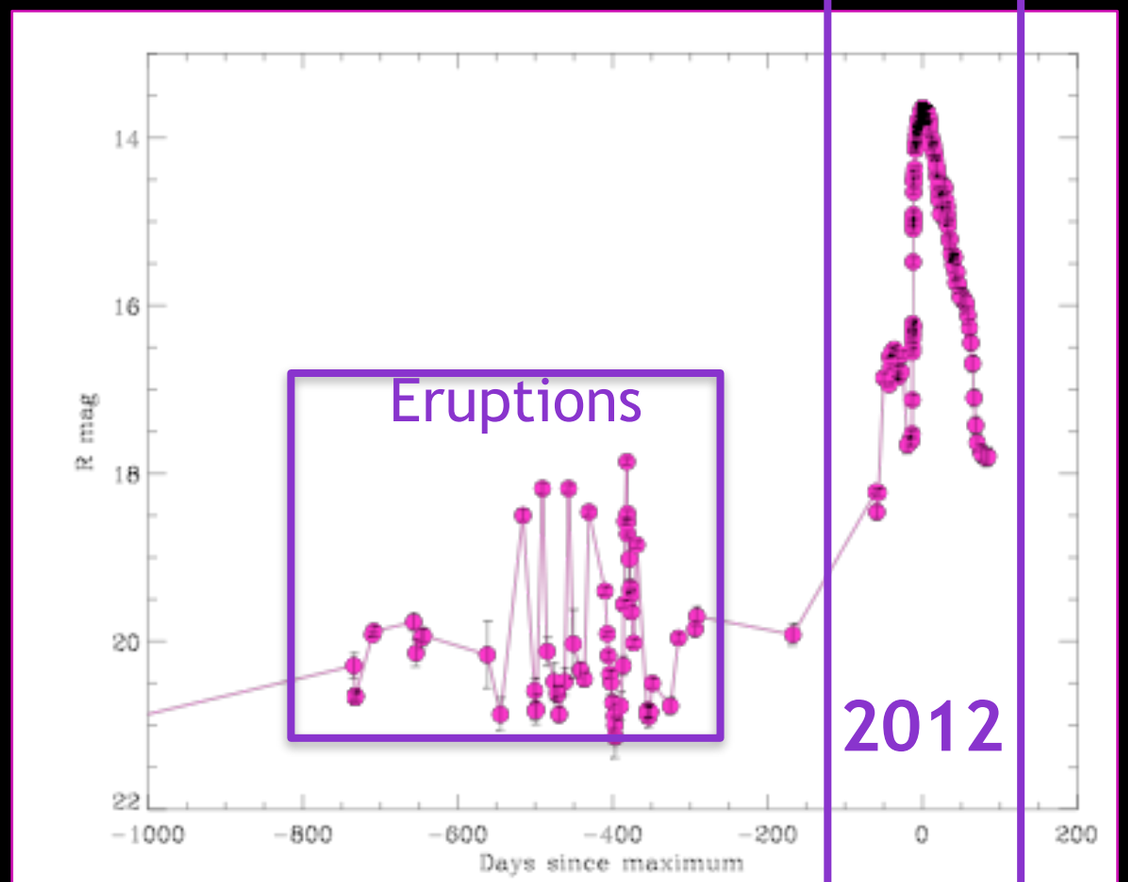
UV-Optical-NIR light-curve

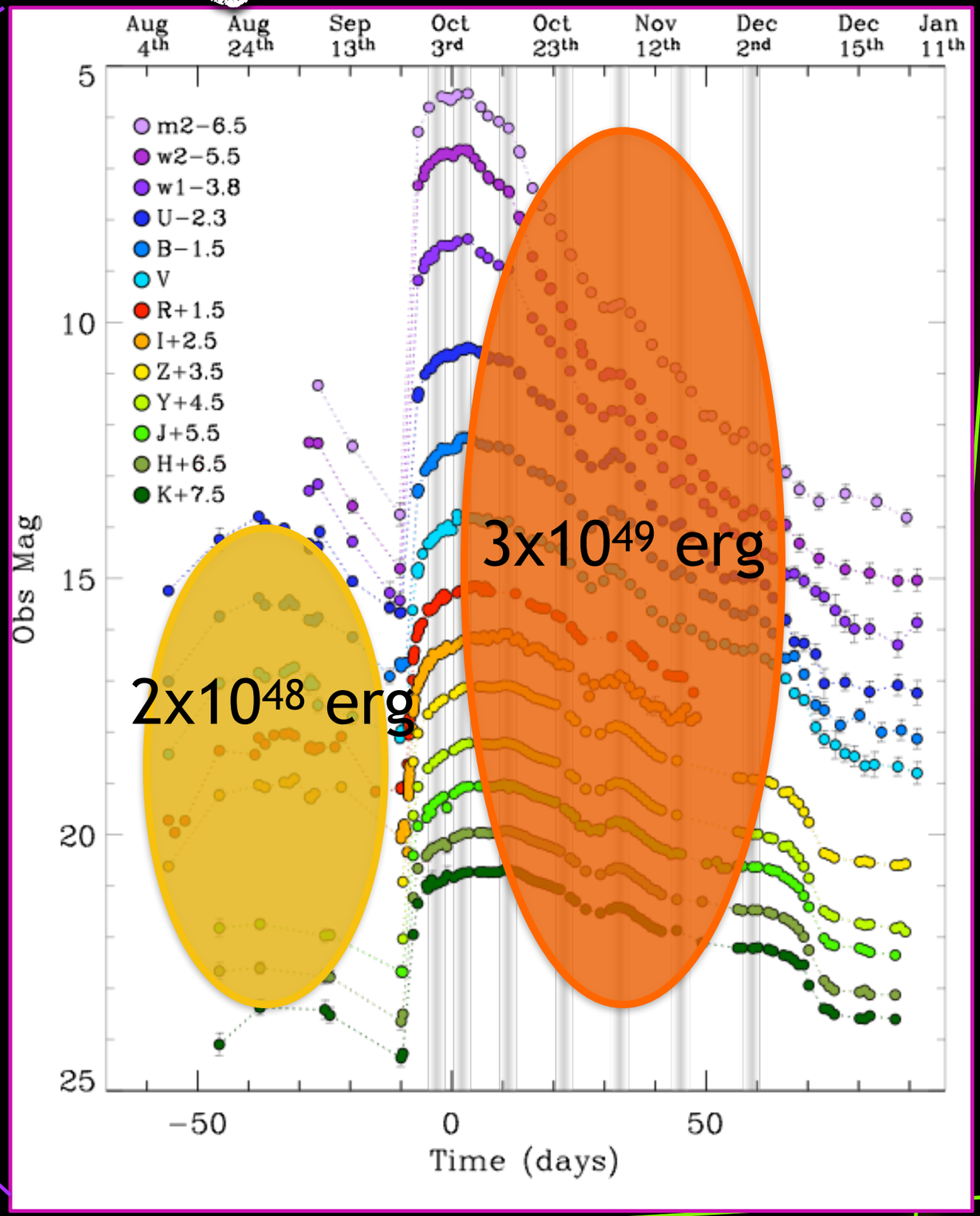




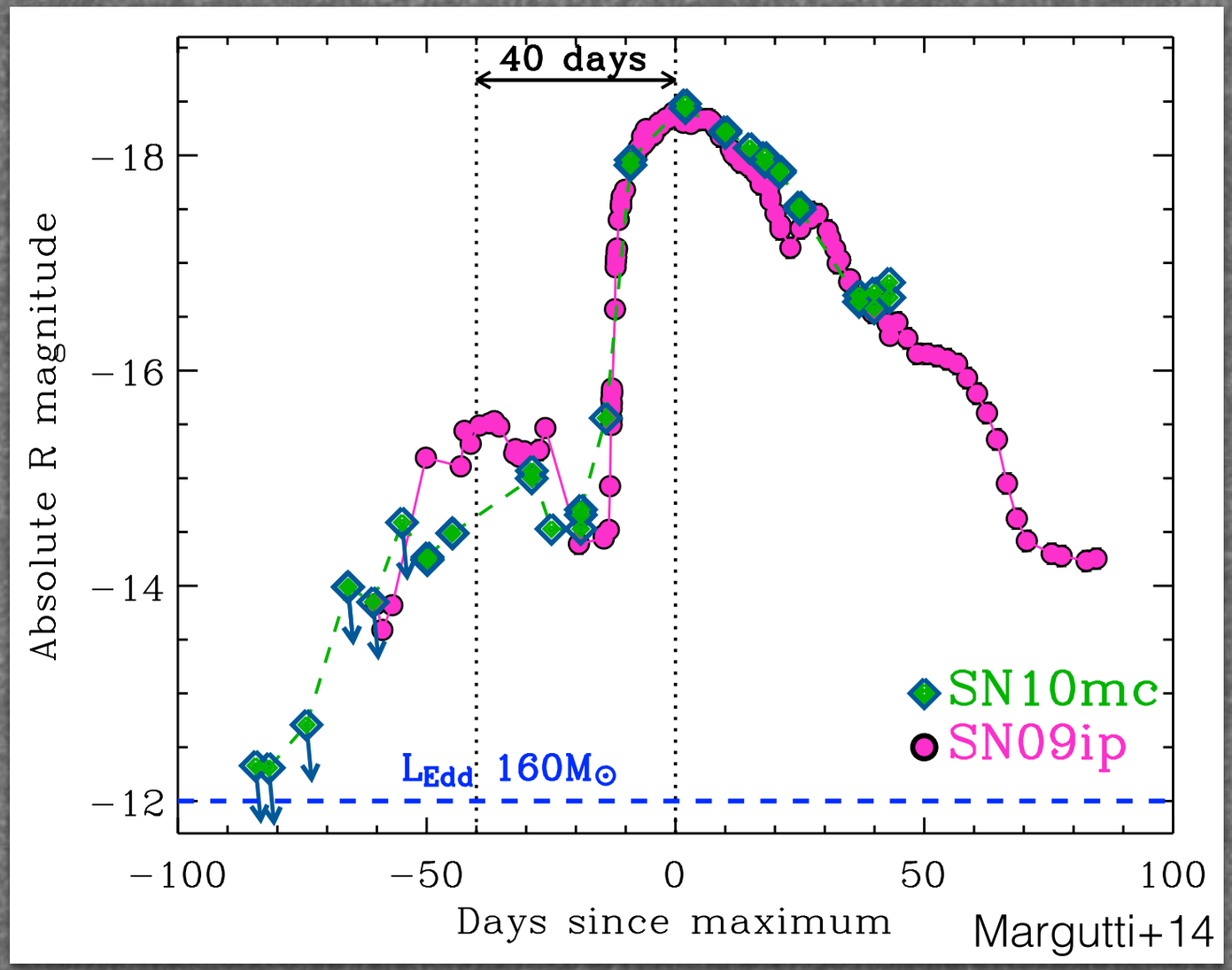
Margutti+ 2014

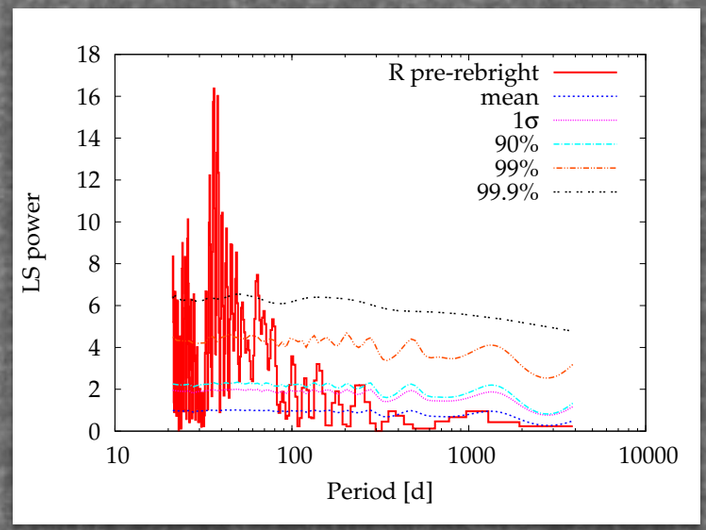
UV-Optical-NIR light-curve



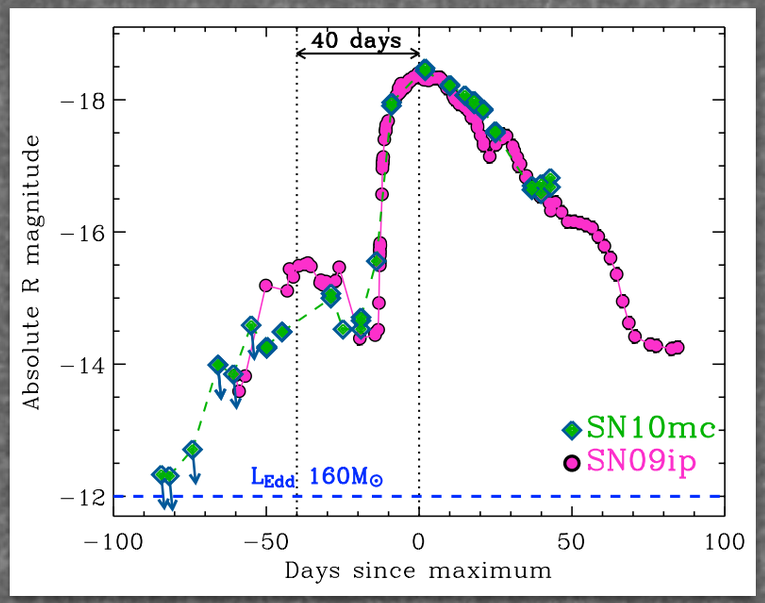


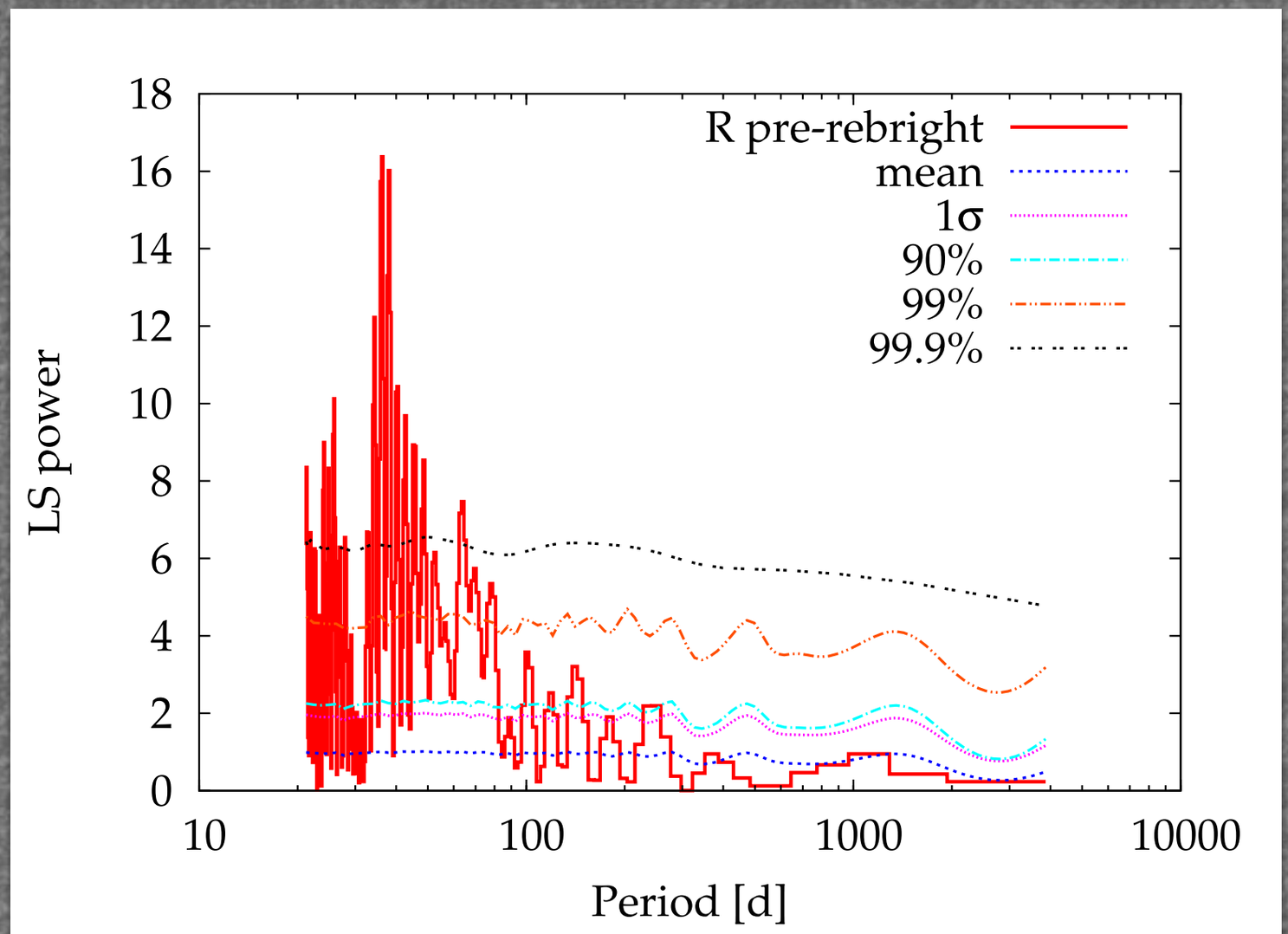
Margutti+ 2014





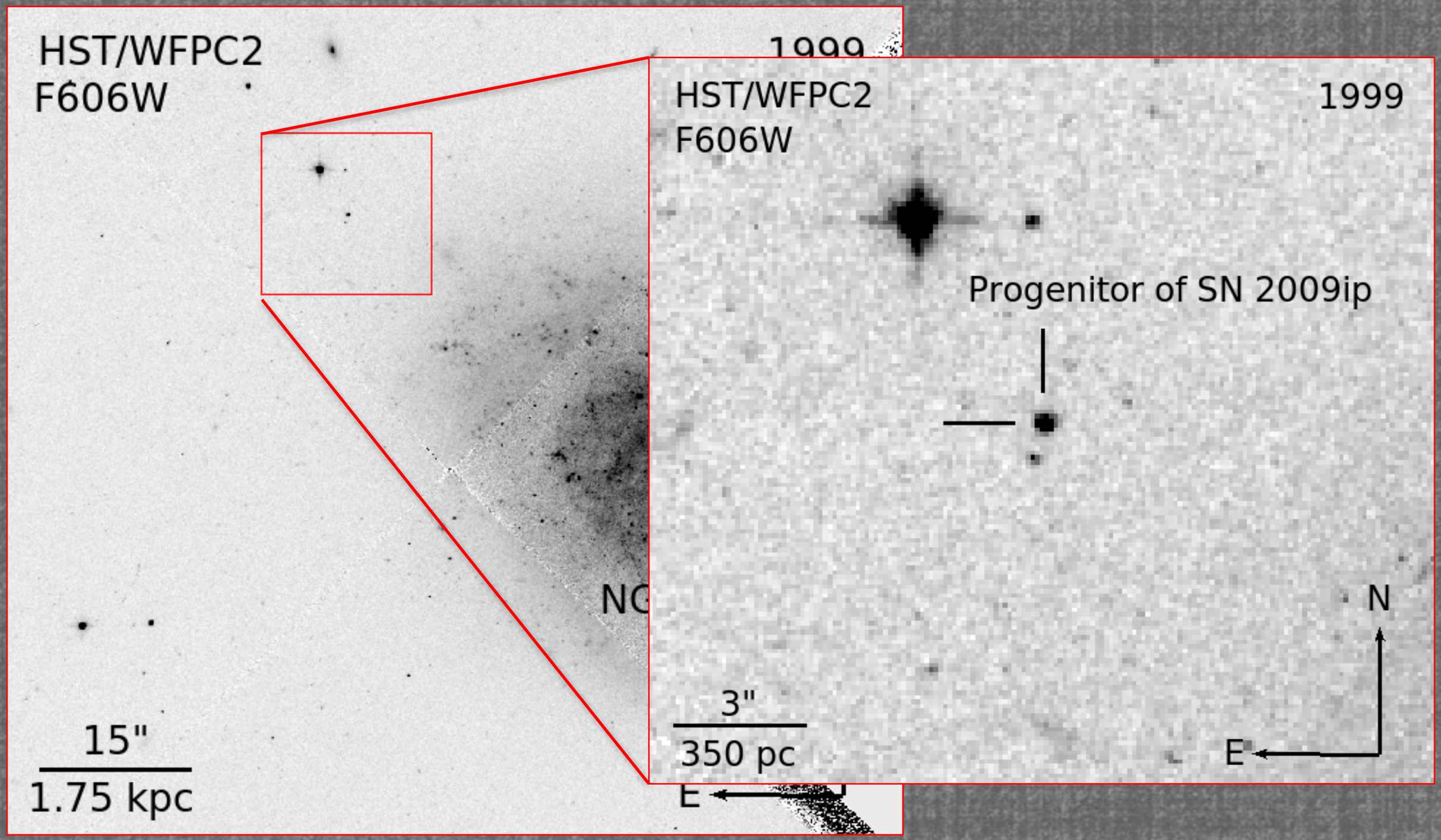
-- Causal connection between the two events
-- “SIMPLE” mechanism
-- Important channel for mass loss





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

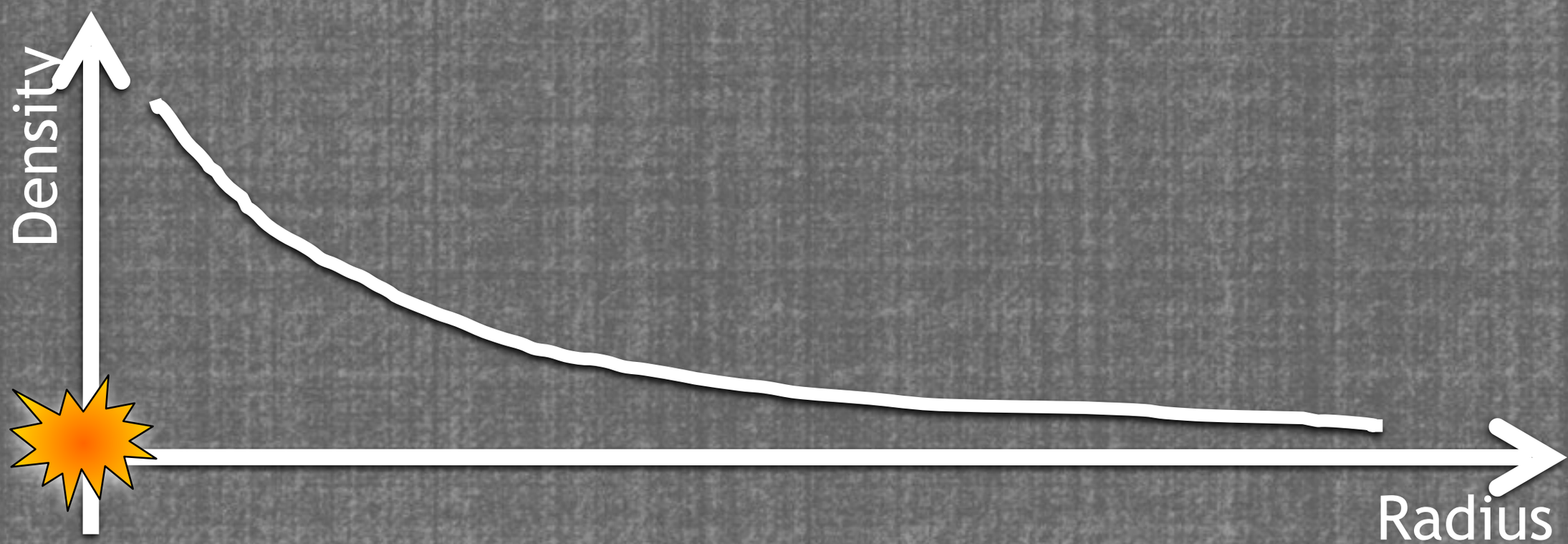
"It sort of makes you stop and think, doesn't it."

The last years before explosion

Direct Observations

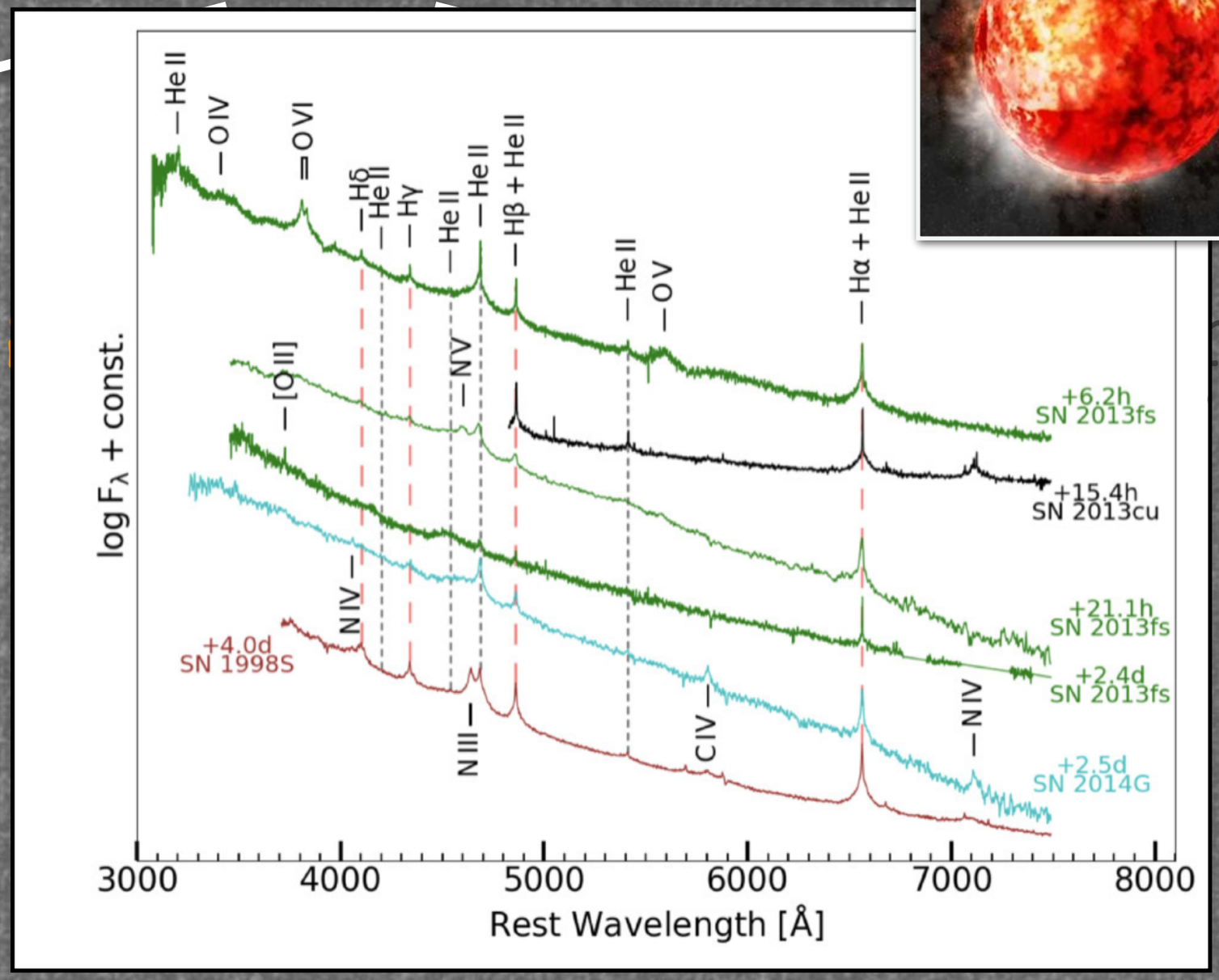
Flash Spectroscopy

Shock Interaction

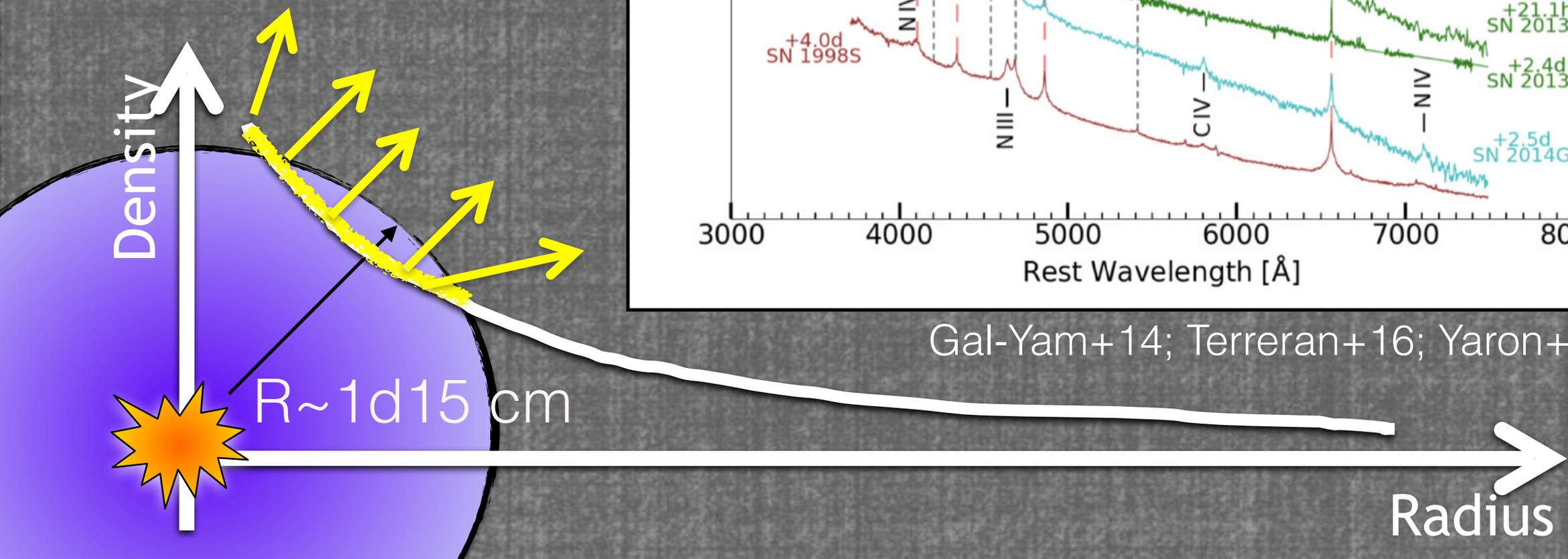


The last years before explosion

Direct Observations



Gal-Yam+14; Terreran+16; Yaron+17

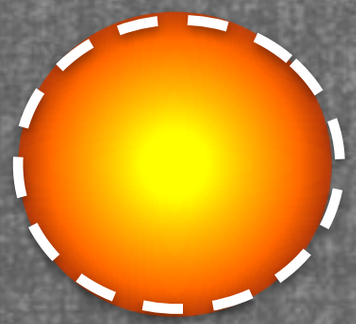


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction



Supergiant

Wolf-Rayet

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

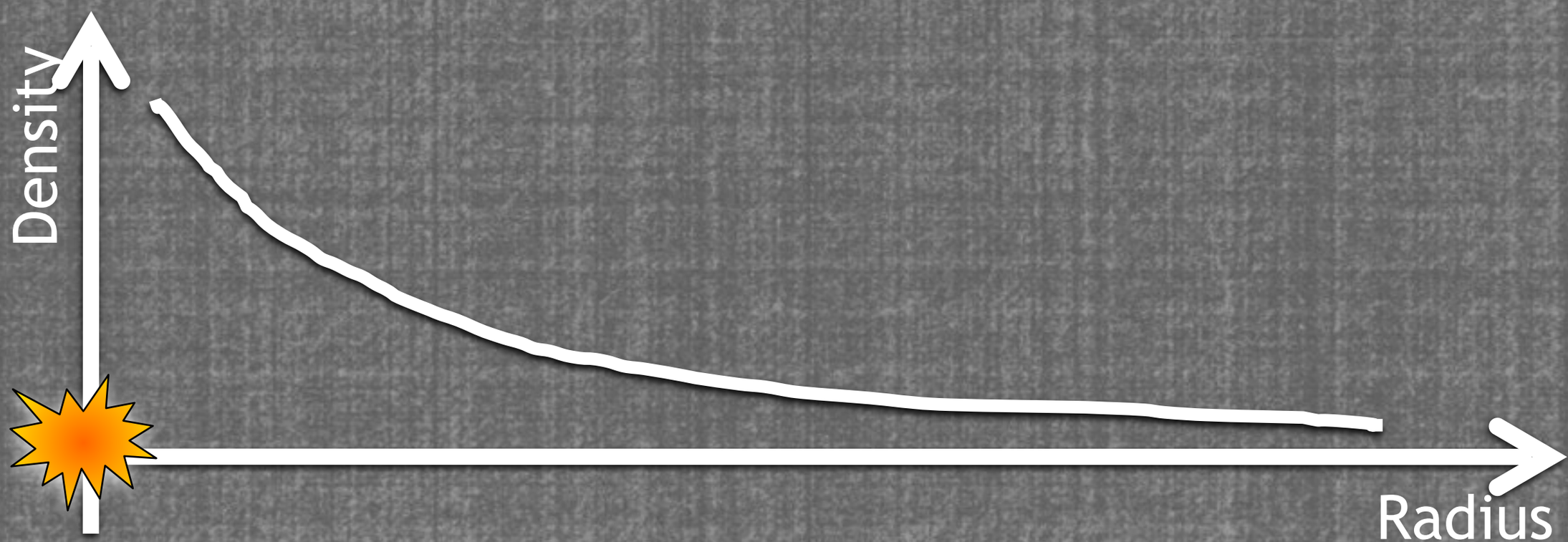
SN Explosion

Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

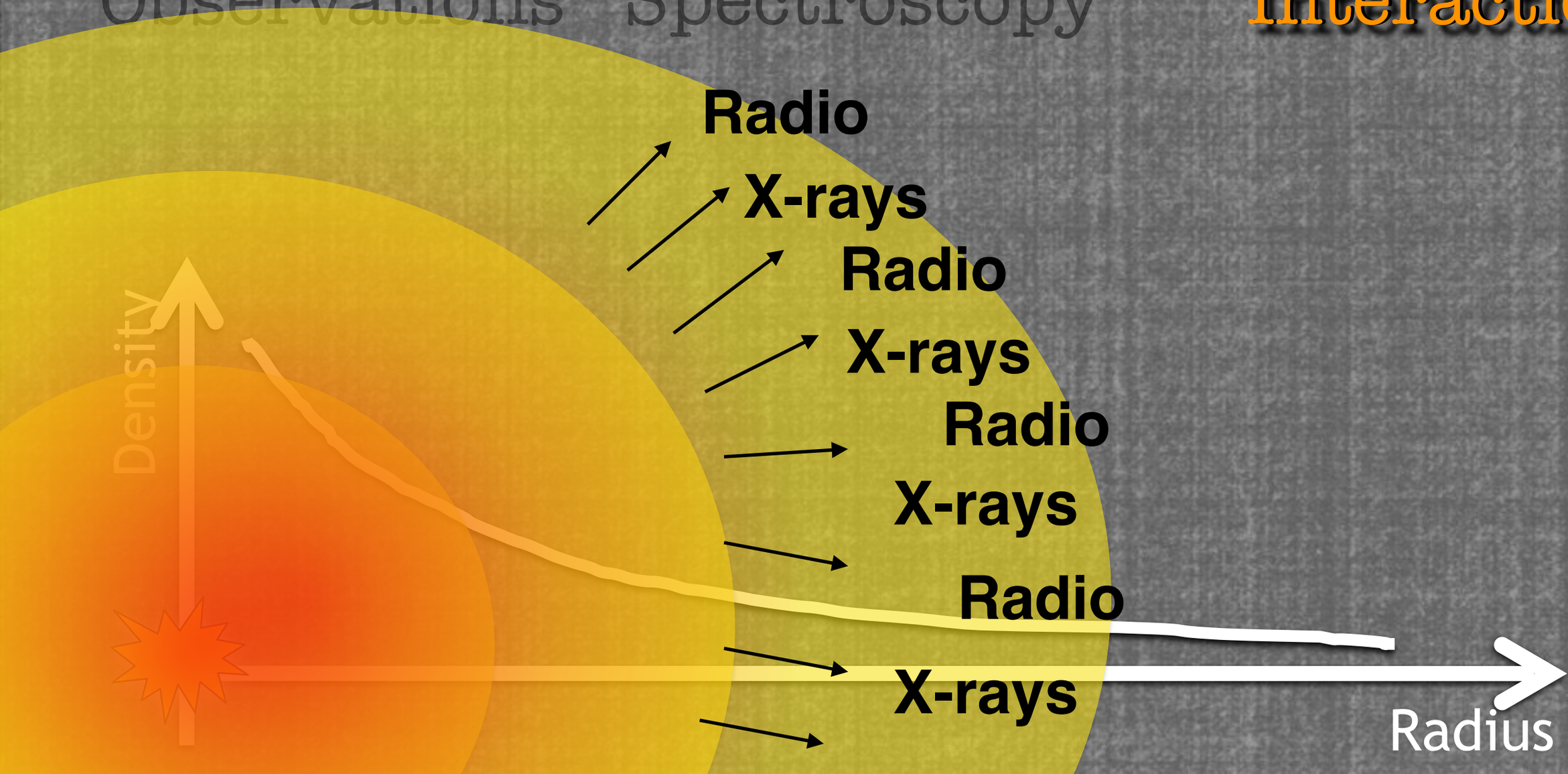


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

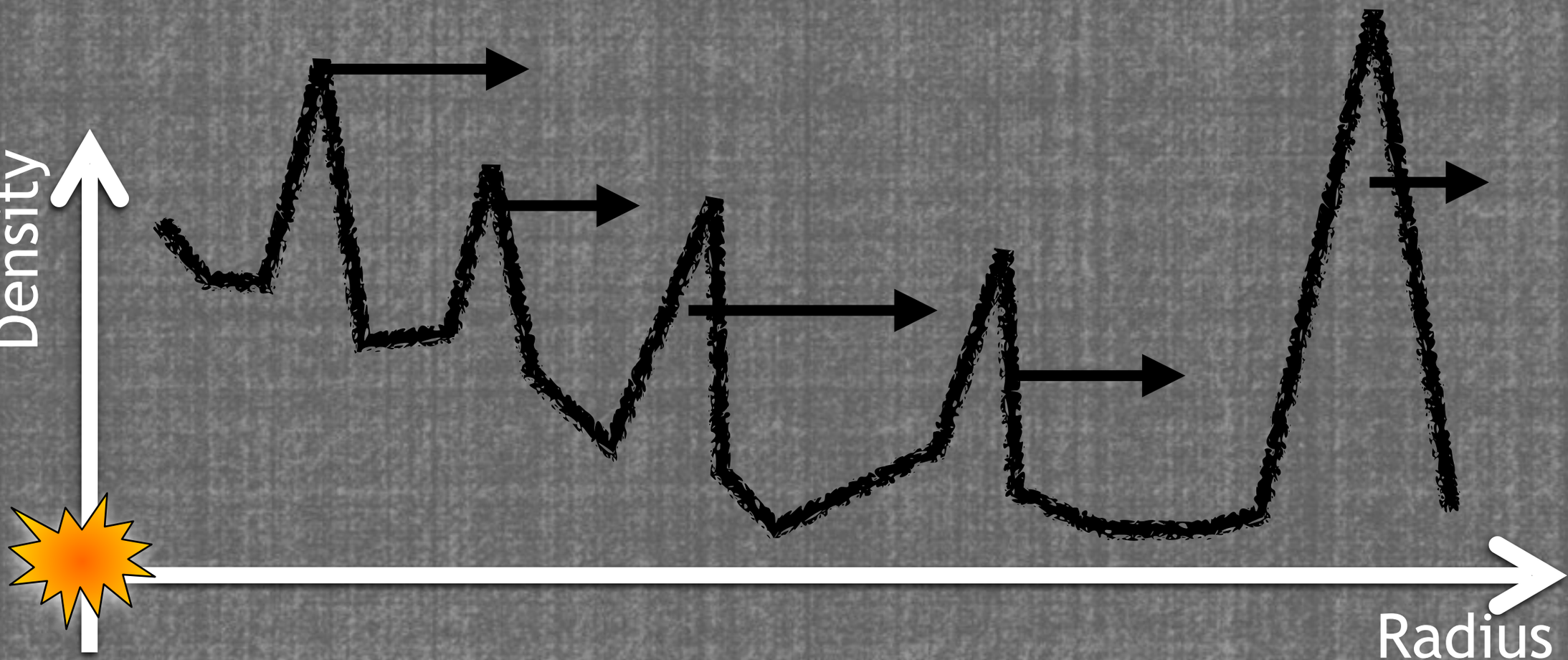


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

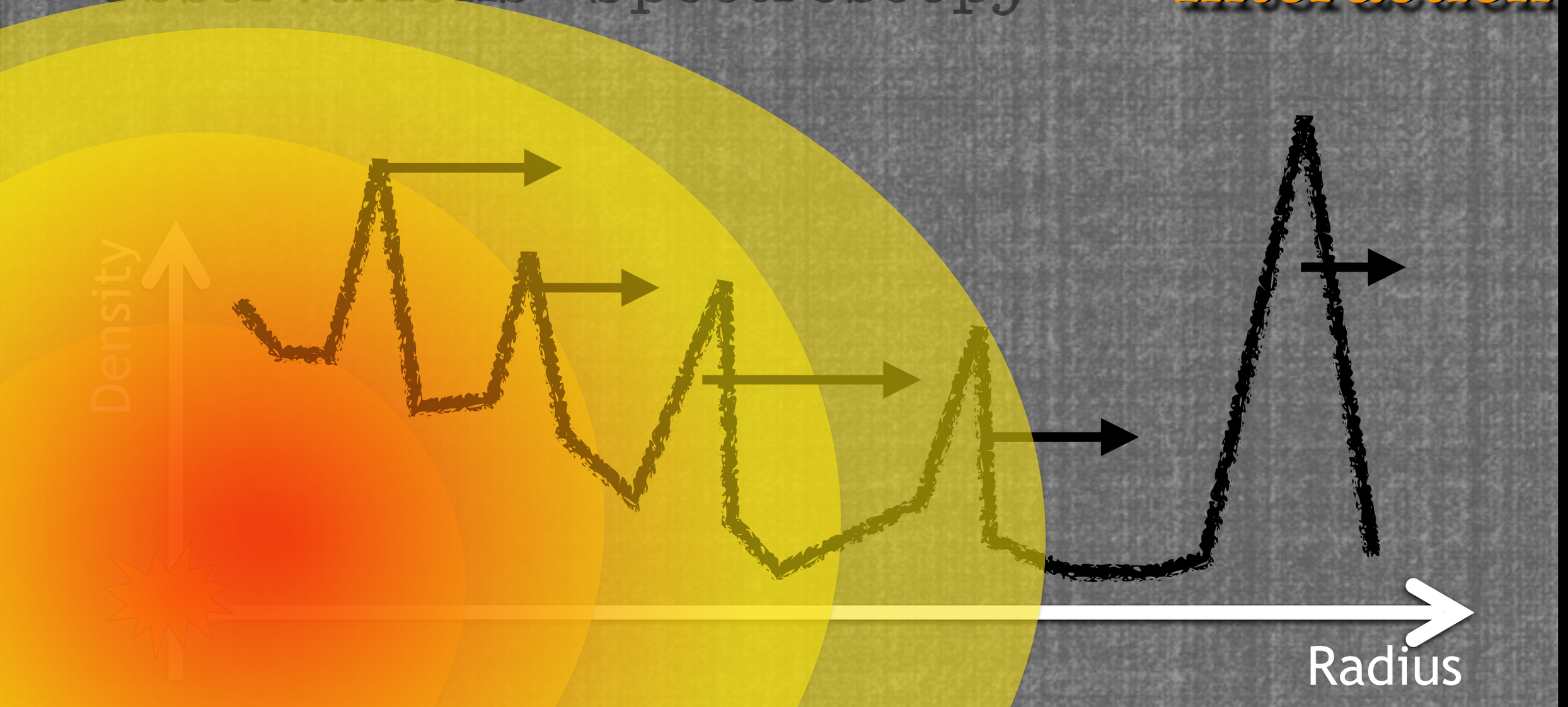


Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

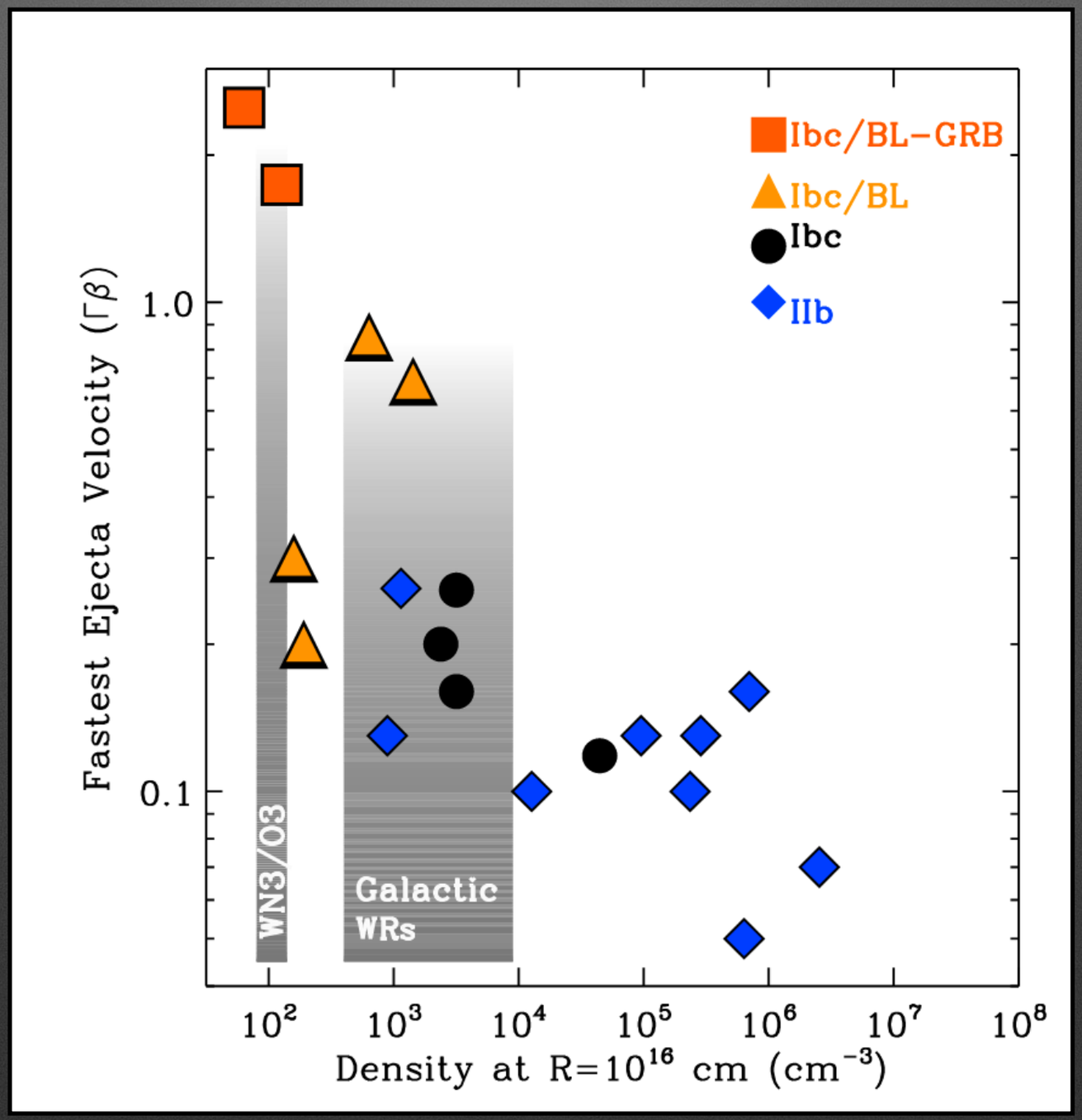


MASS LOSS– Massive Stars

Vshock >> Vejection

(Vshock/Vejection) t

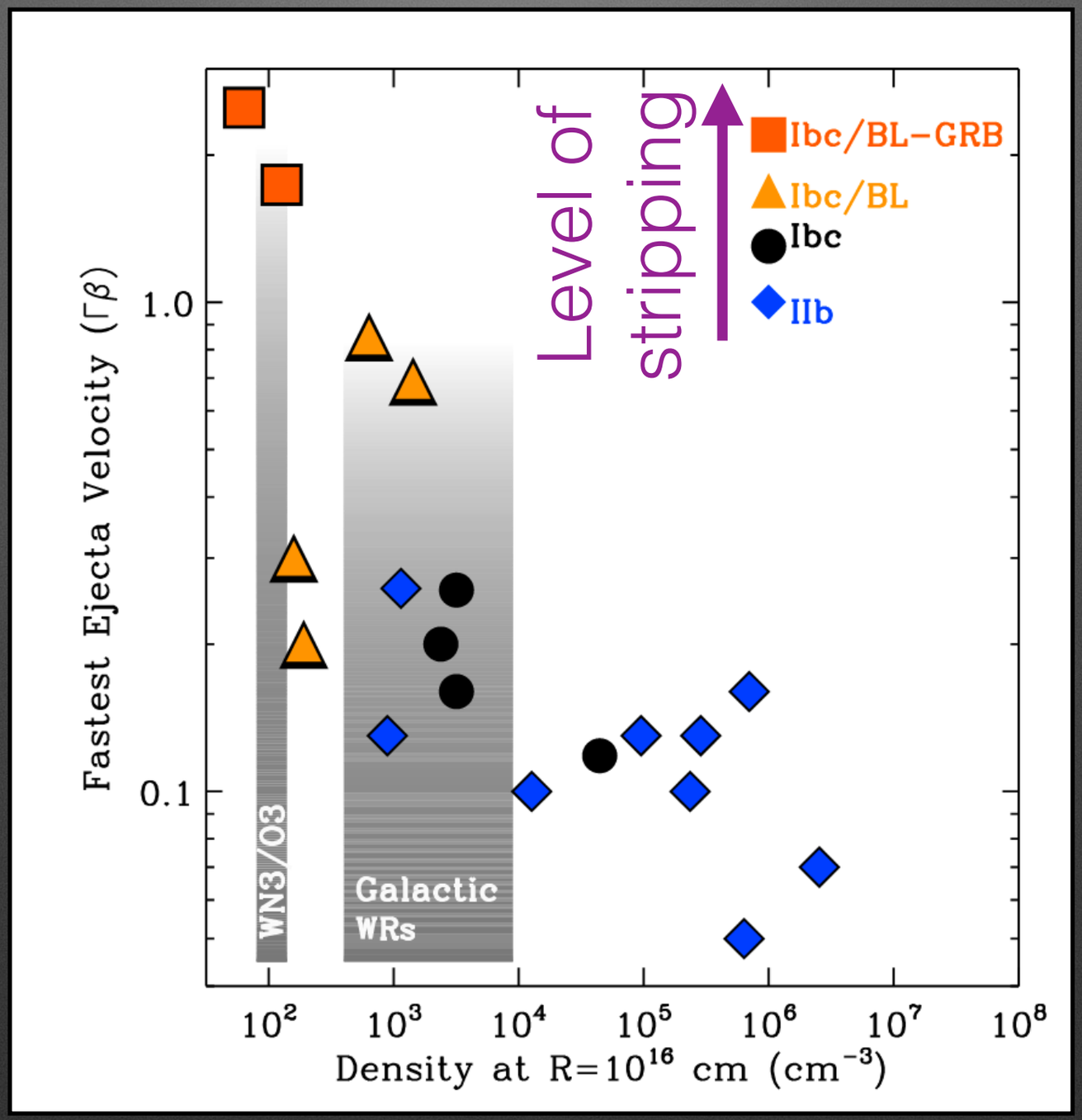
Connecting the structure of the star at collapse with recent mass-loss history (II)



Drout+16, Margutti+18, Terreran+18

=Mdot/Vwind

Connecting the structure of the star at collapse with recent mass-loss history (II)



Drout+16, Margutti+18, Terreran+18

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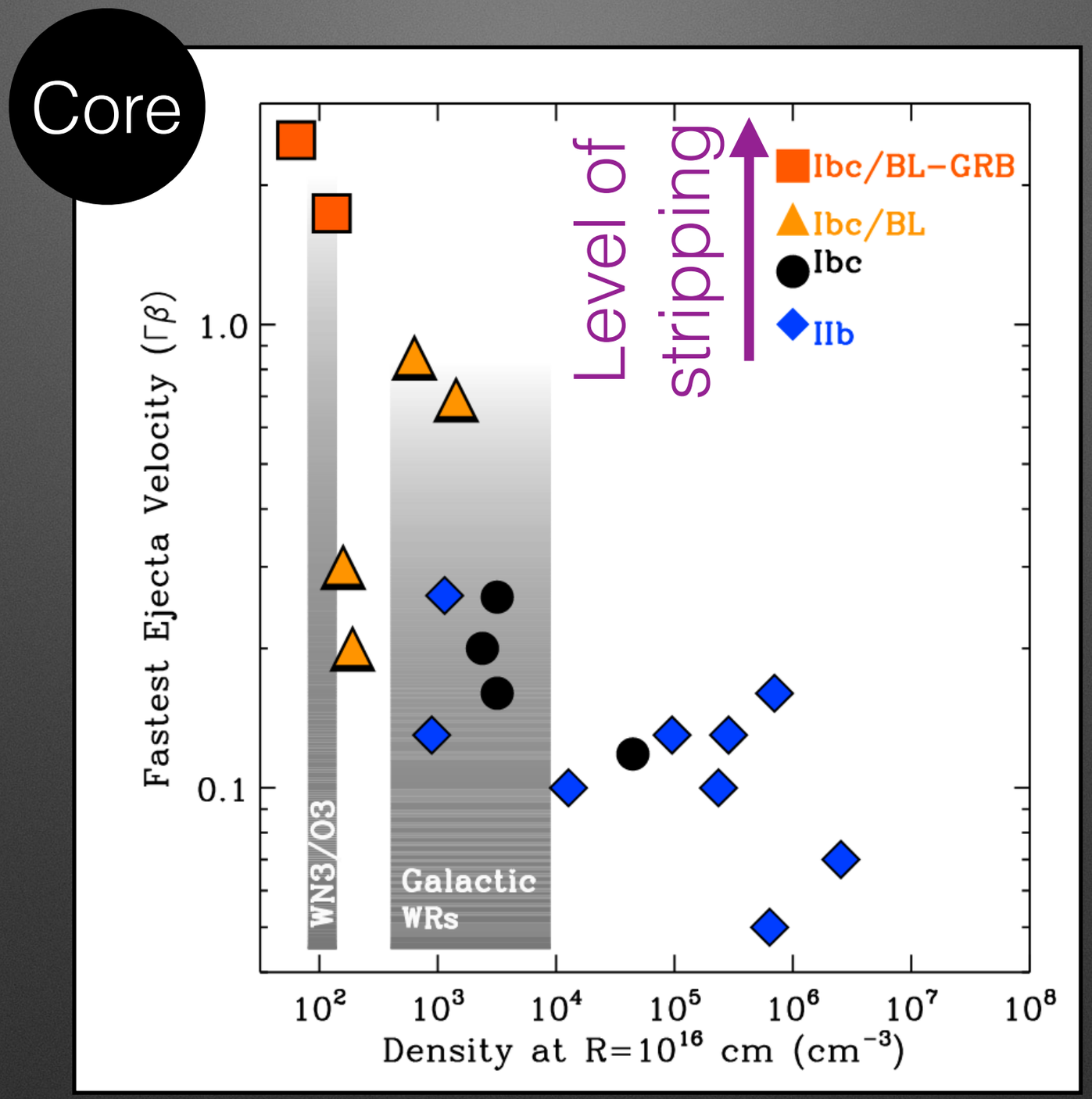

Drout+16, Margutti+18, Terreran+18

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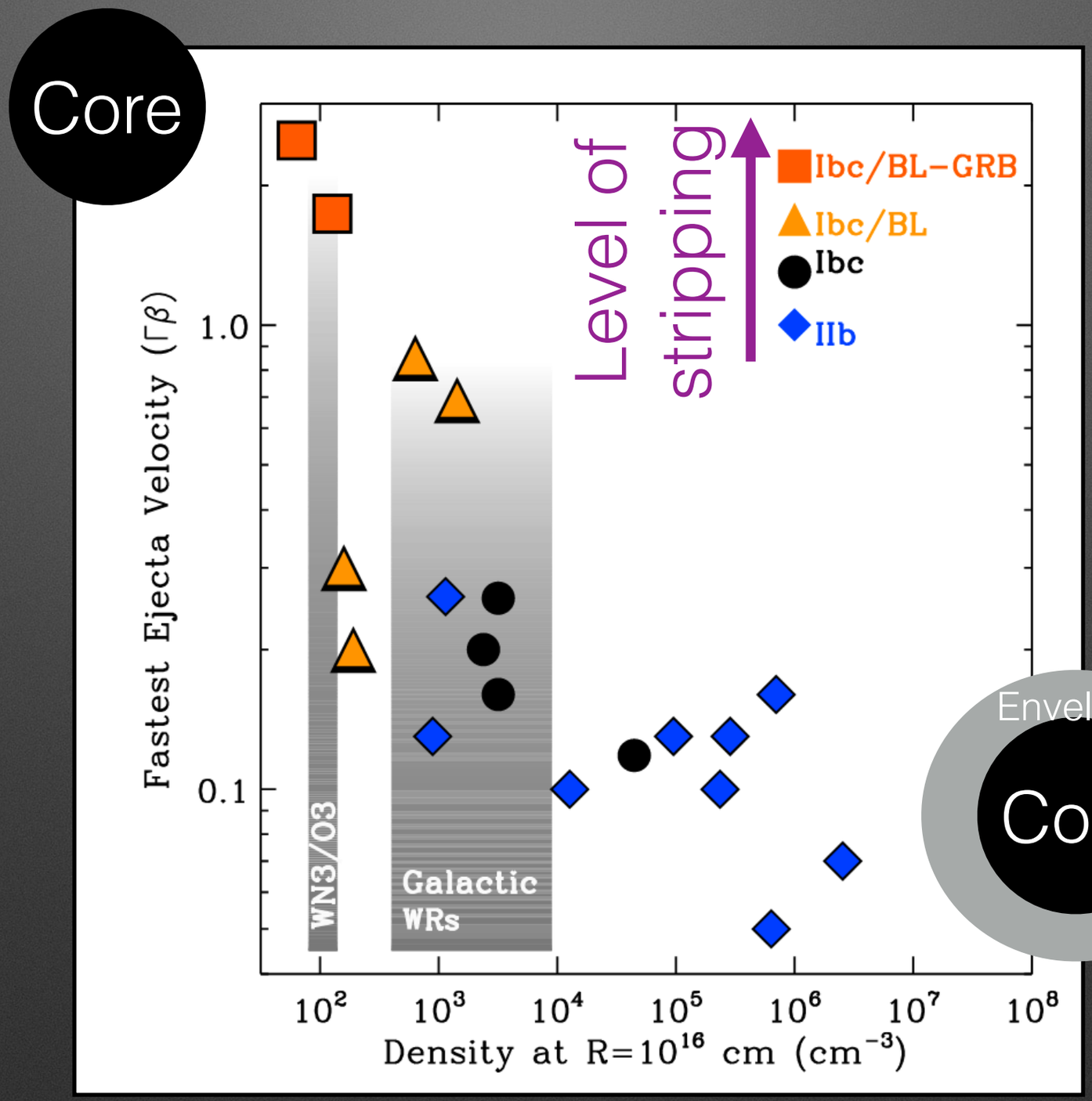
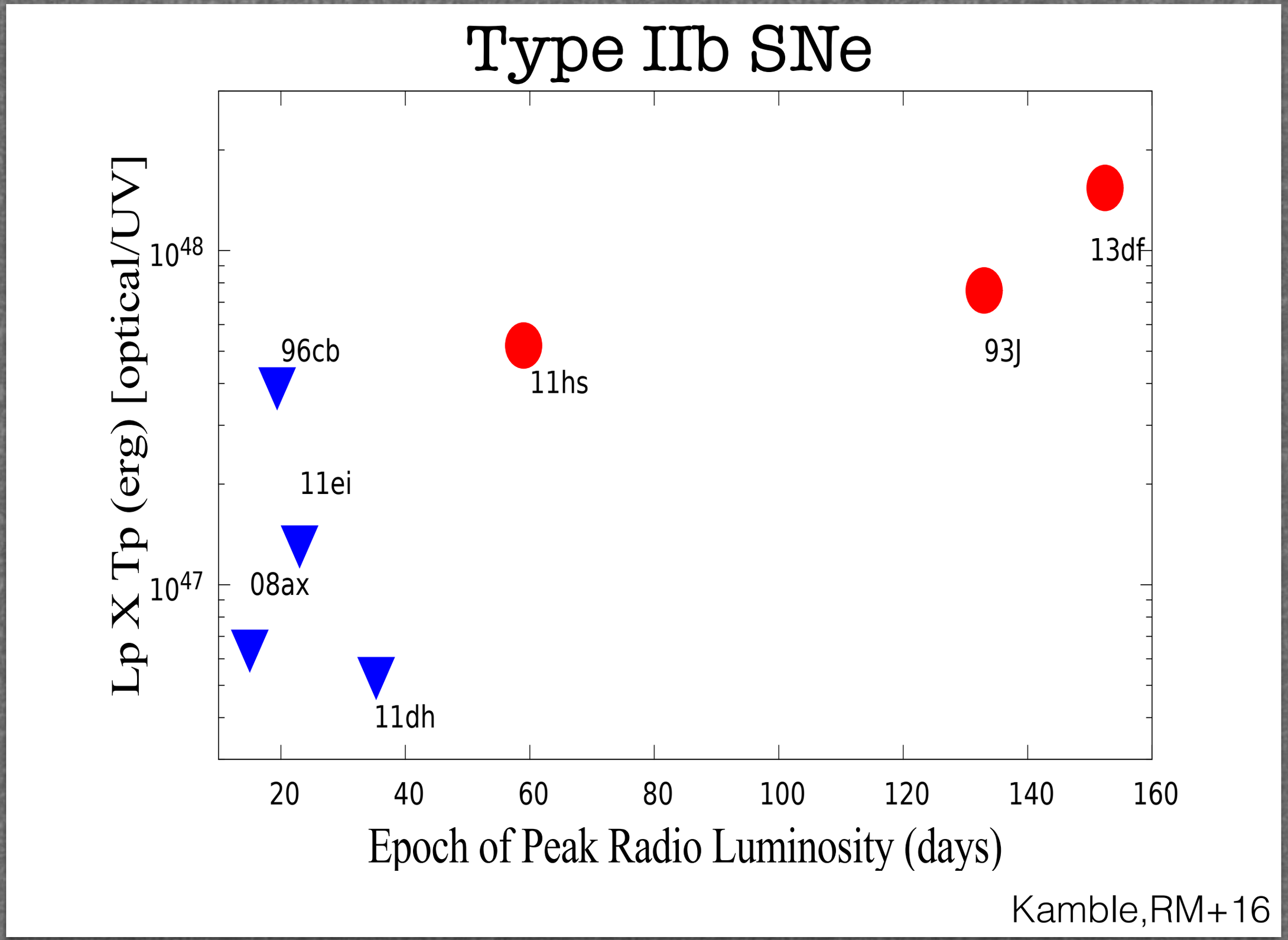
Connecting the structure of the star at collapse with recent mass-loss history (II)



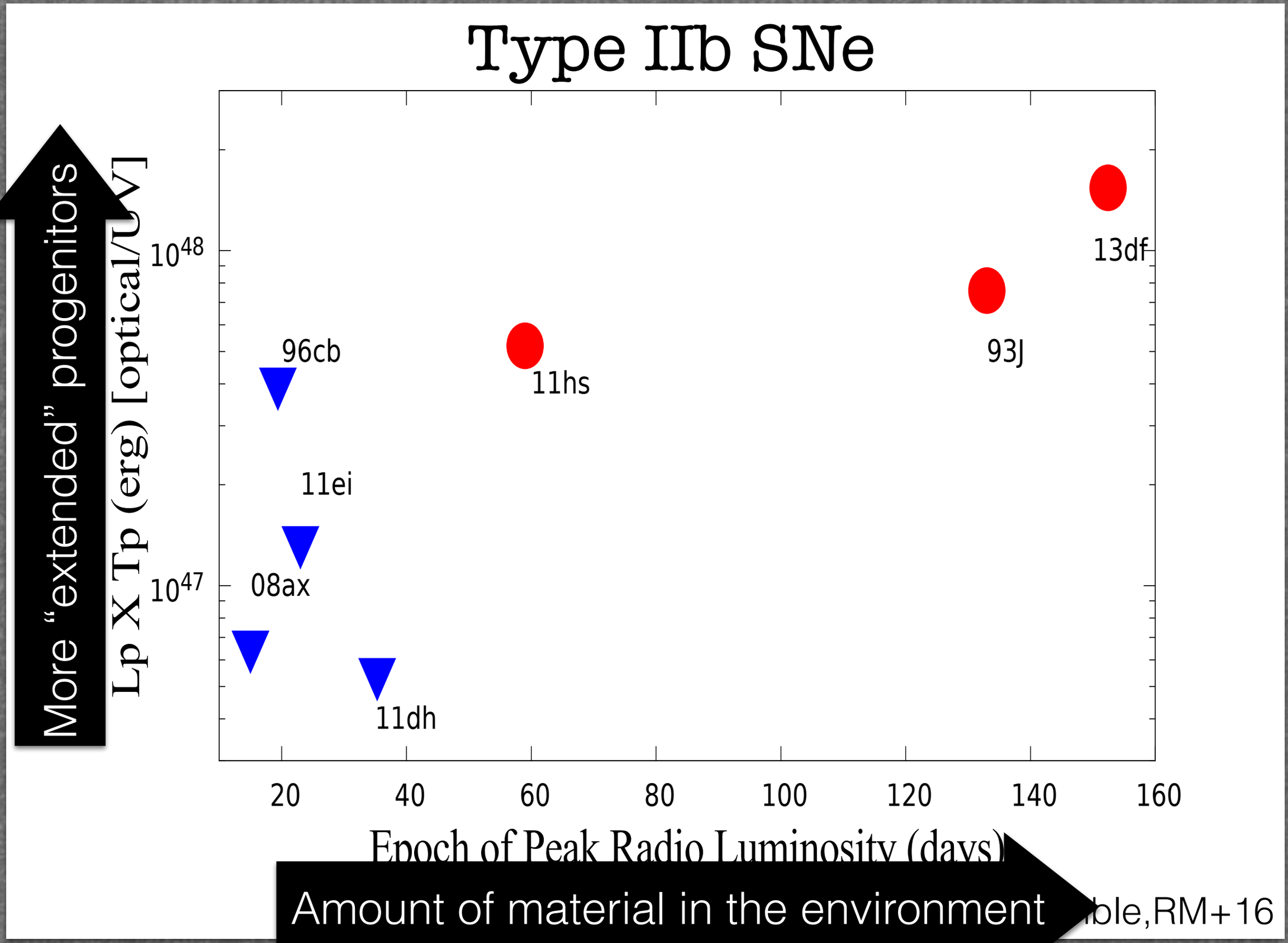
=Mdot/Vwind

Drout+16, Margutti+18, Terreran+18

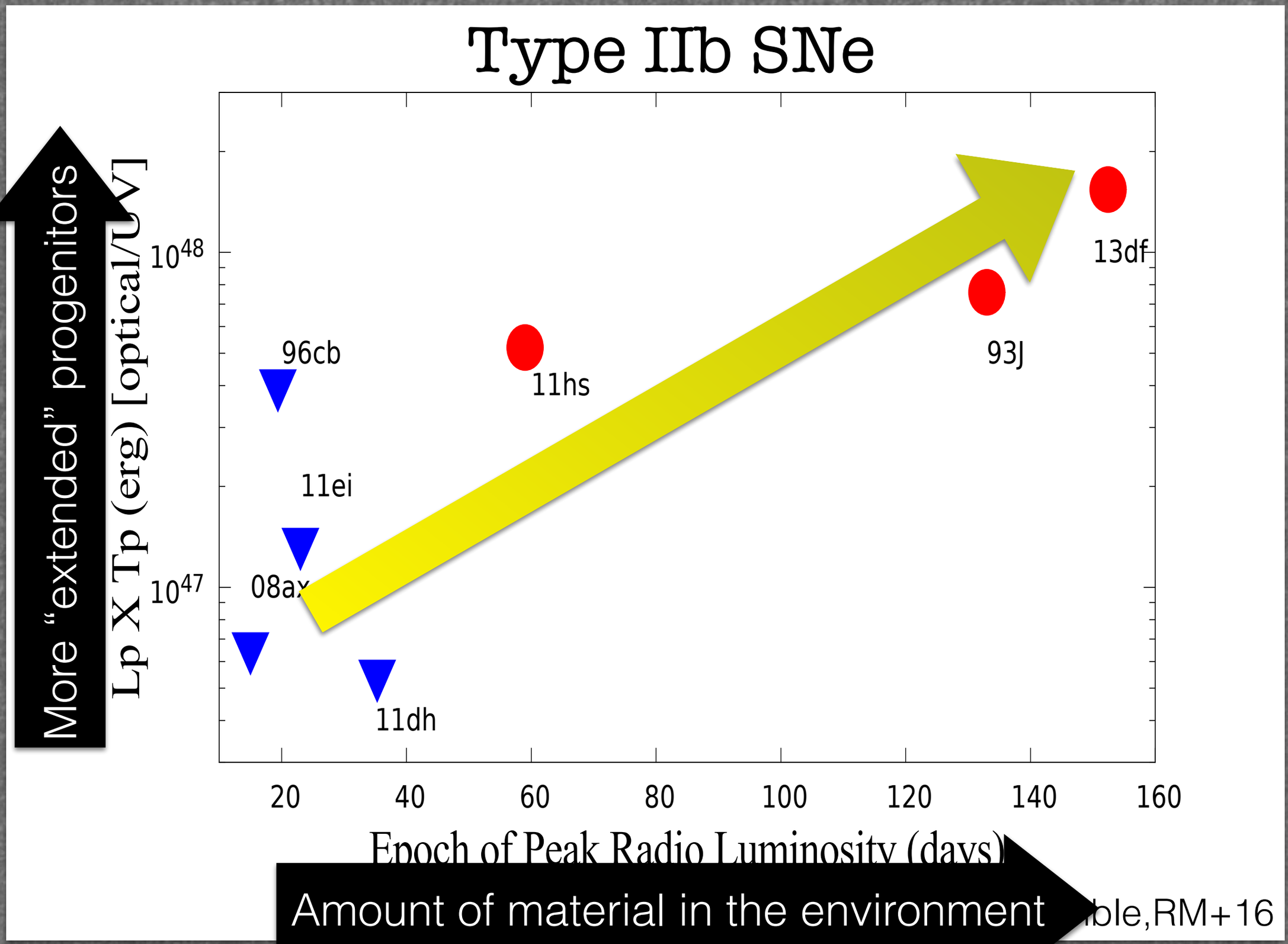
Connecting the structure of the star at collapse with recent mass-loss history (I)



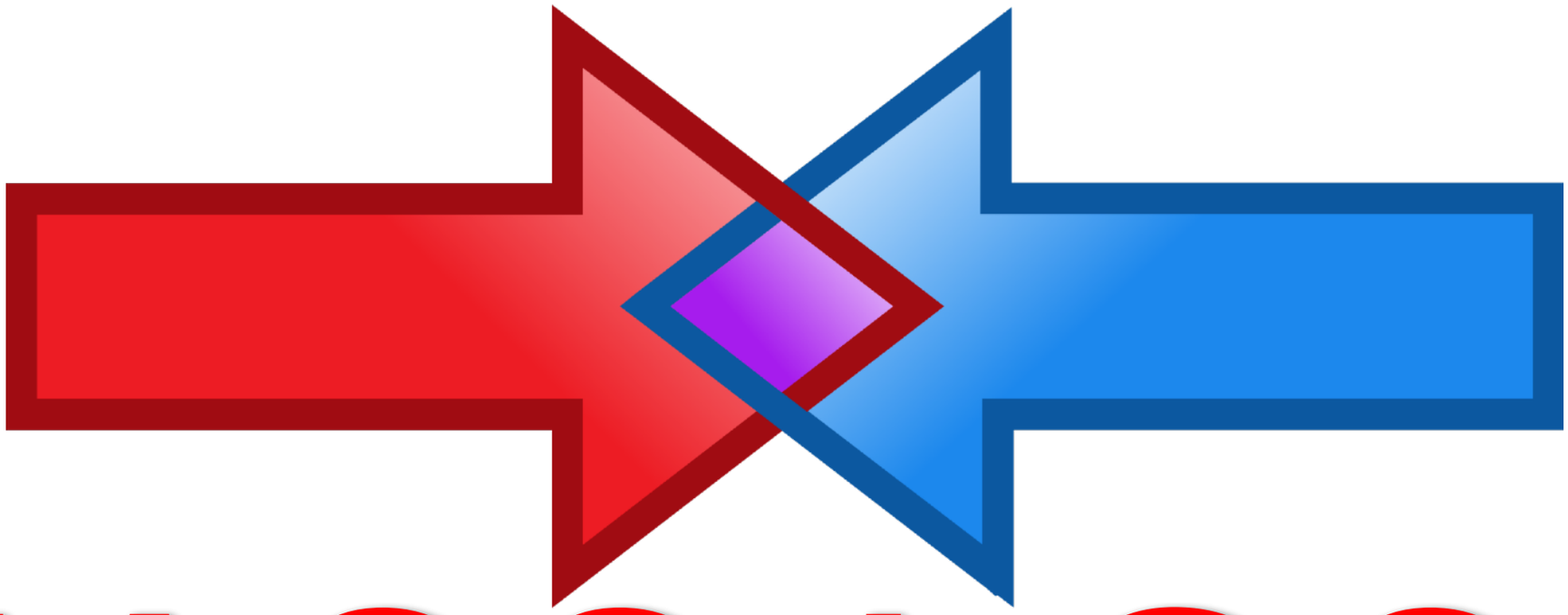
Connecting the structure of the star at collapse with recent mass-loss history (I)



Connecting the structure of the star at collapse with recent mass-loss history (I)



Progenitor Structure



MASS LOSS

Back to the Drawing Board:

Exploding Star challenges decades-long understanding of how massive stars evolve and die

Optical

Supernova 2014C

X-rays

Chandra

Chandra

pre-explosion

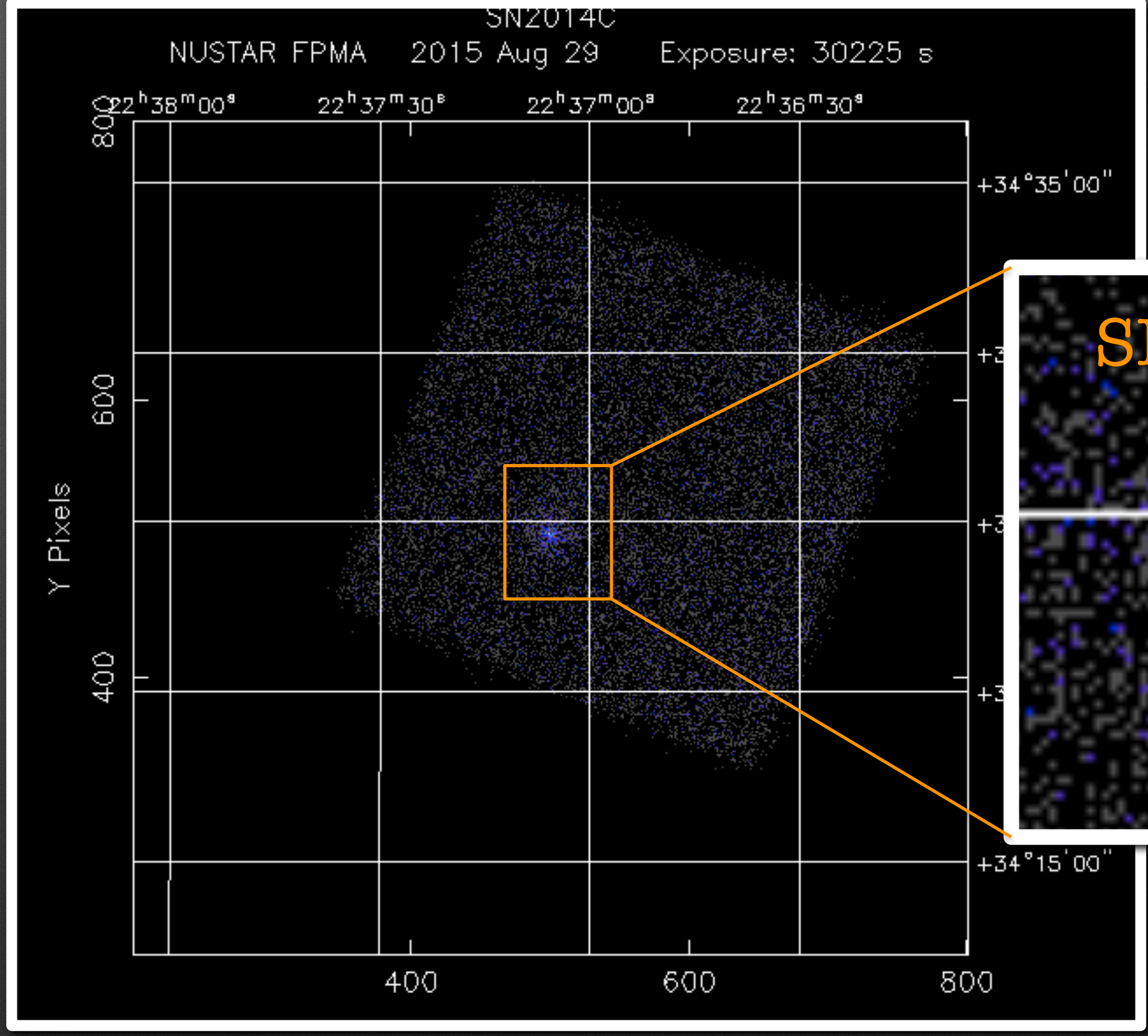
Chandra

post-explosion

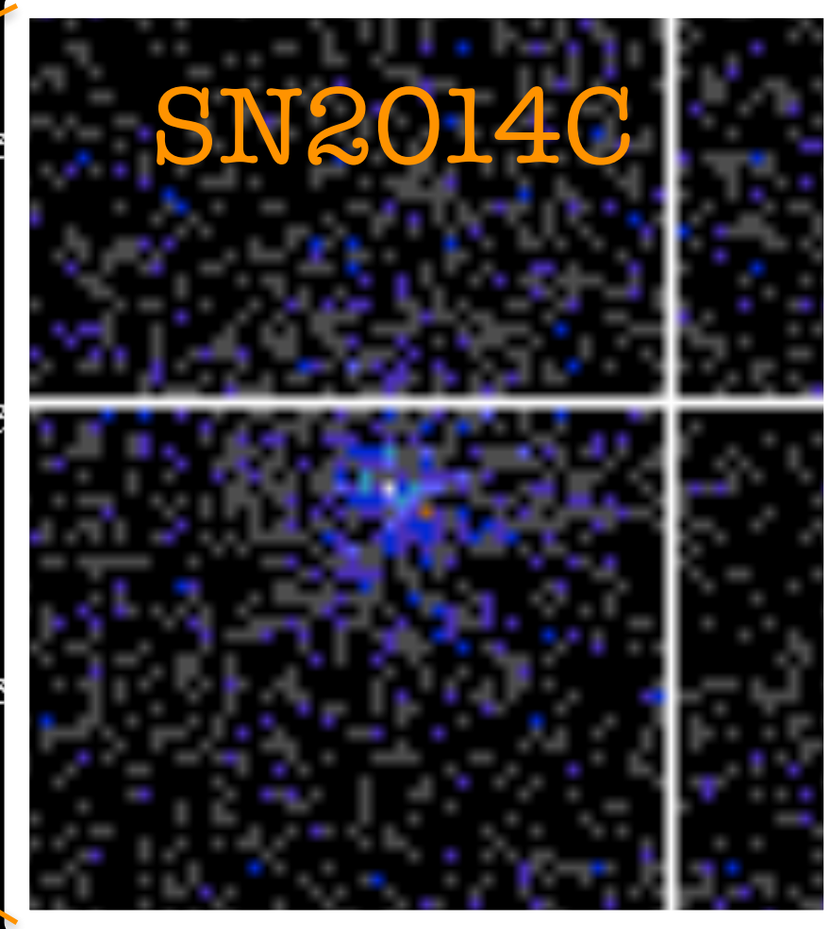
Credit:
NASA/CXC/CIERA/R.Margutti et al

#space
http://go.nasa.gov/2jWc8Ua

NuSTAR (3-80 keV)

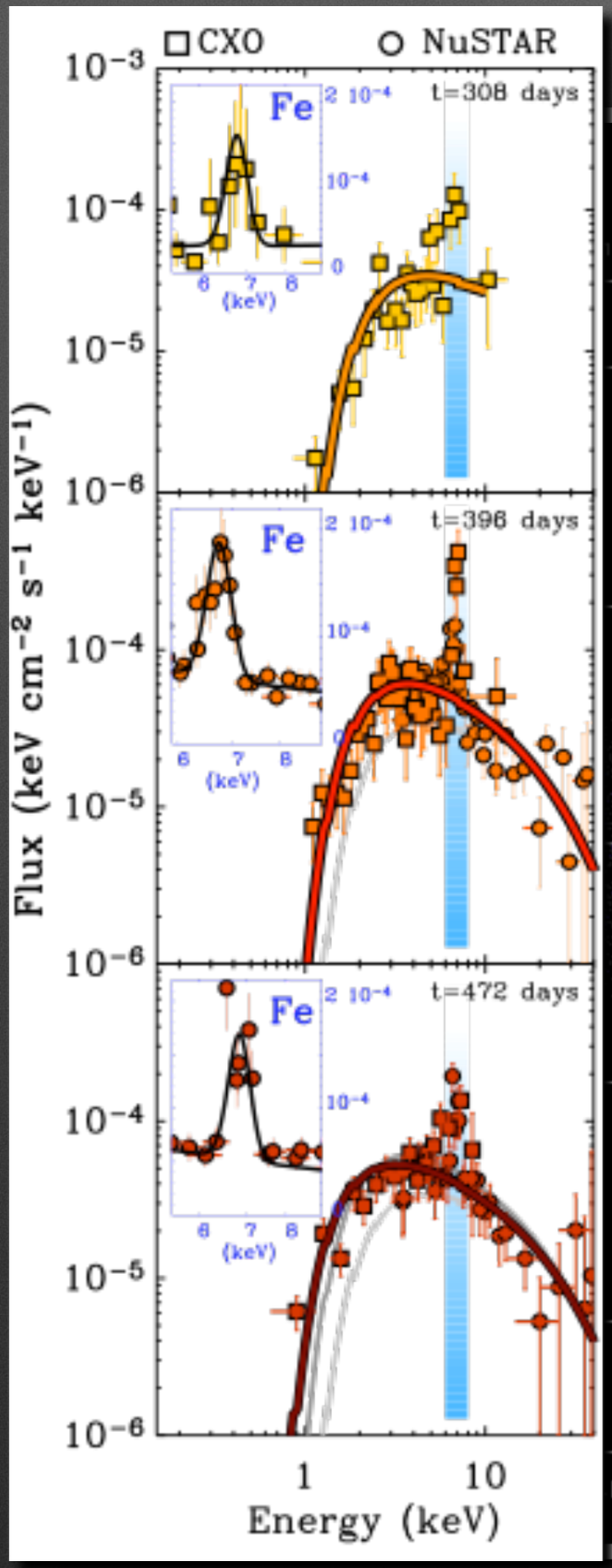


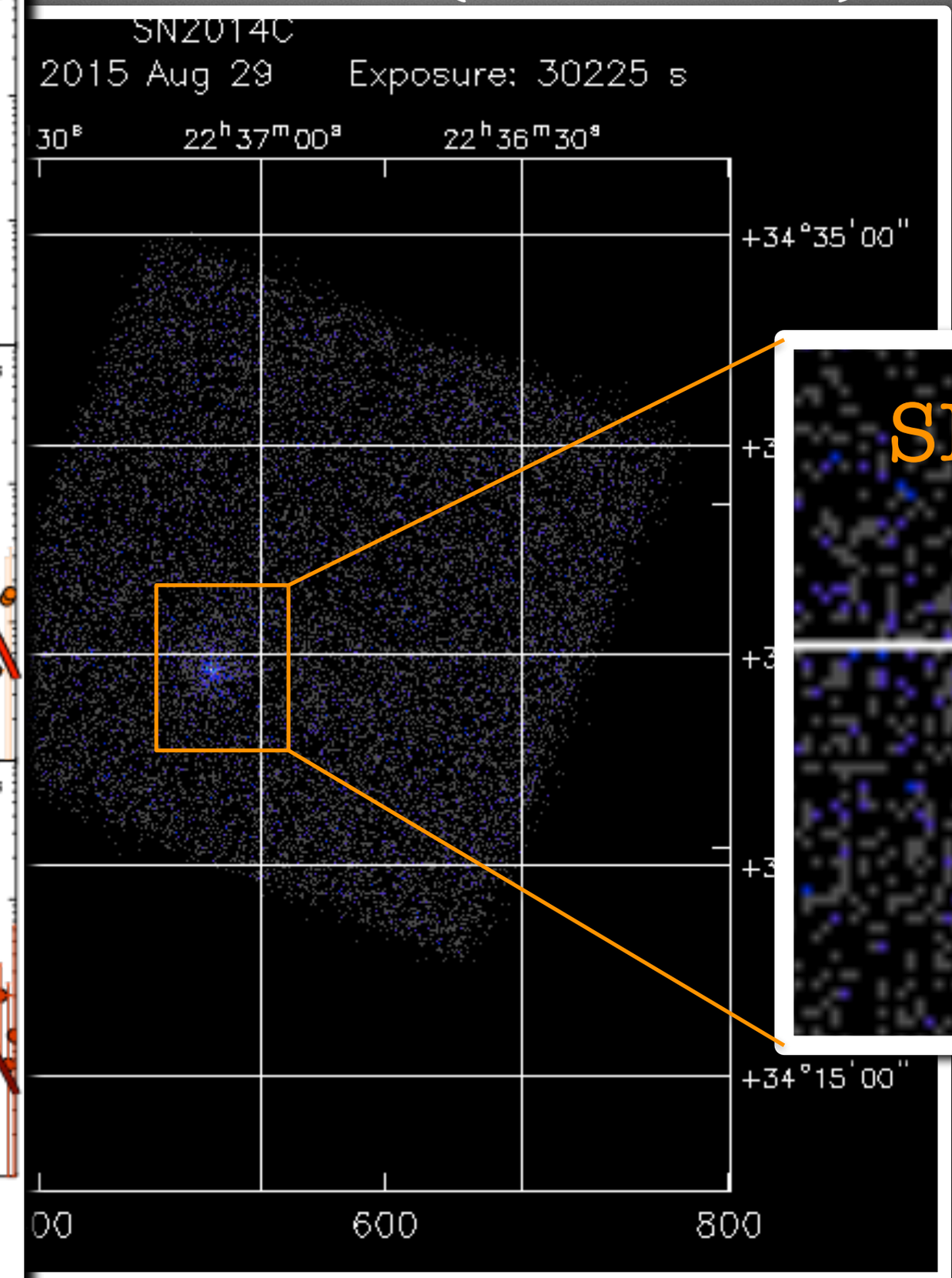
RM+17



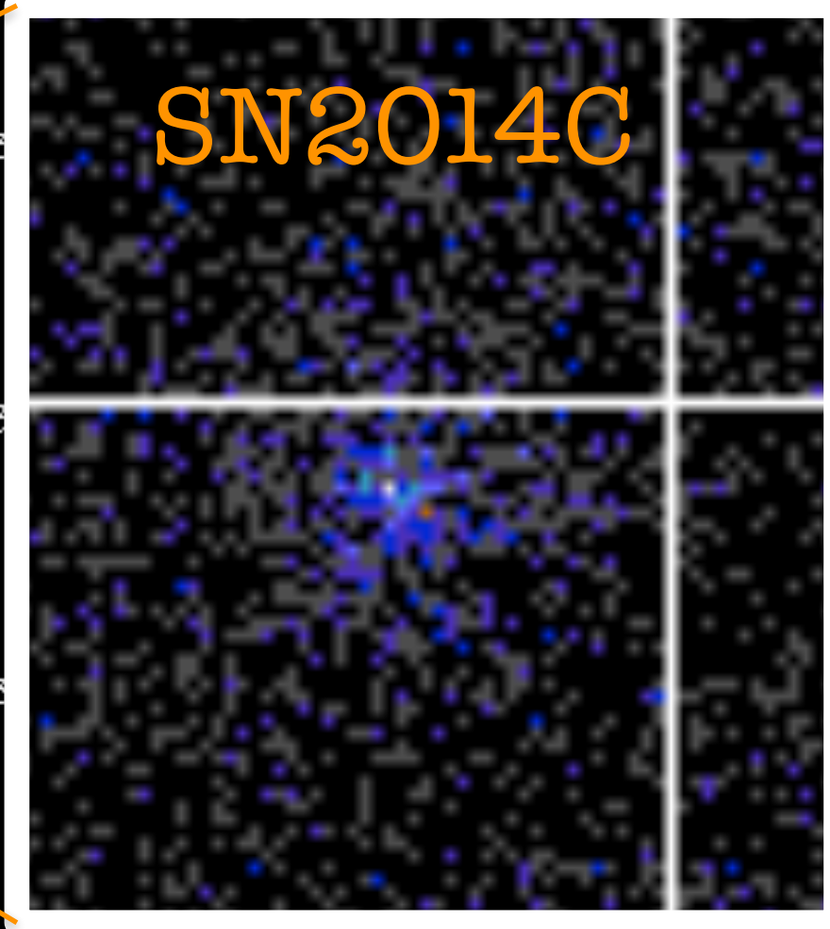
First hard X-ray image and years-long campaign of a young extragalactic core-collapse SN

NuSTAR (3-80 keV)

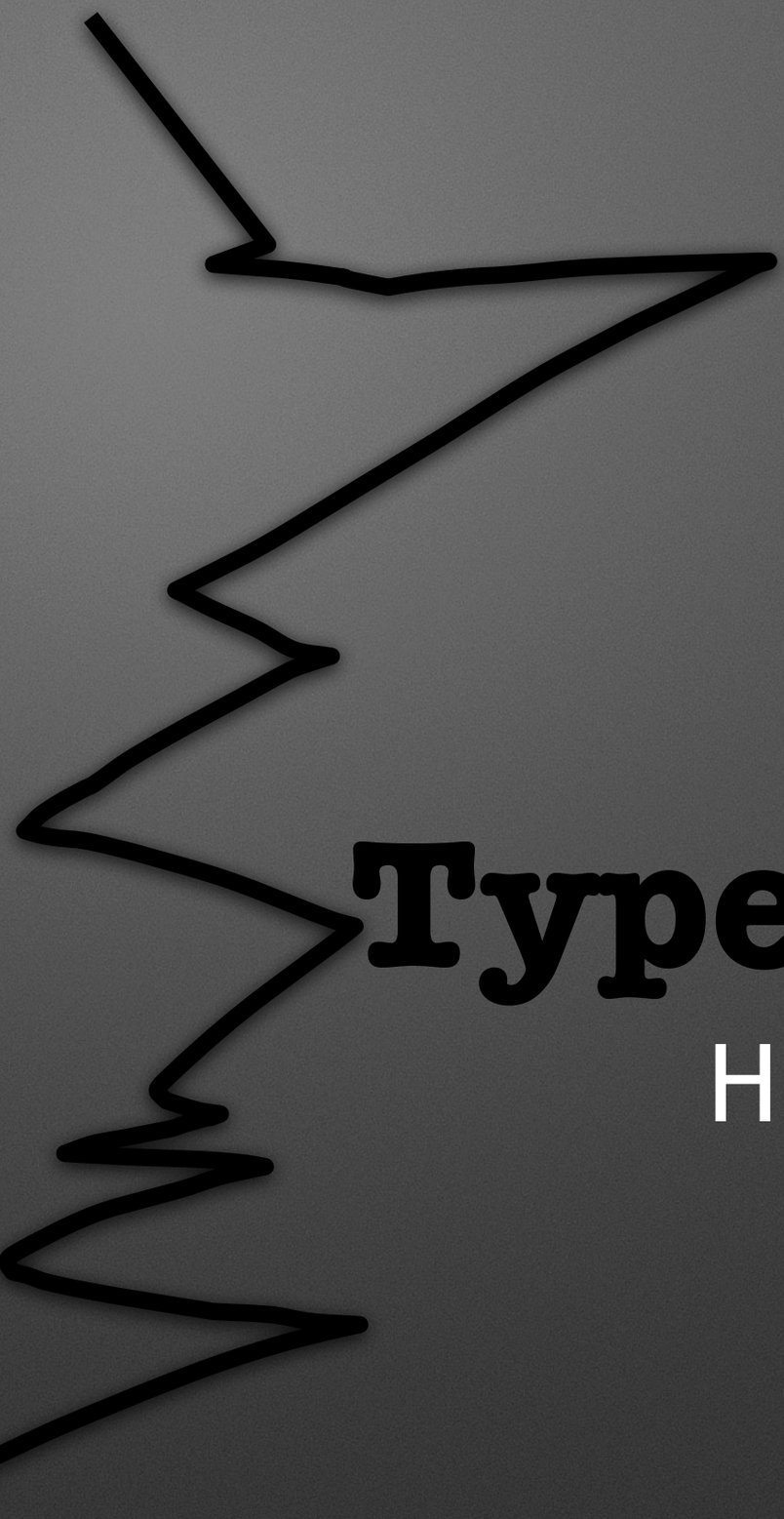




RM+17



First hard X-ray image and years-long campaign of a young extragalactic core-collapse SN



Type I SN

H-poor

Type II SN

H-rich

SN2014C

Type I SN

H-poor

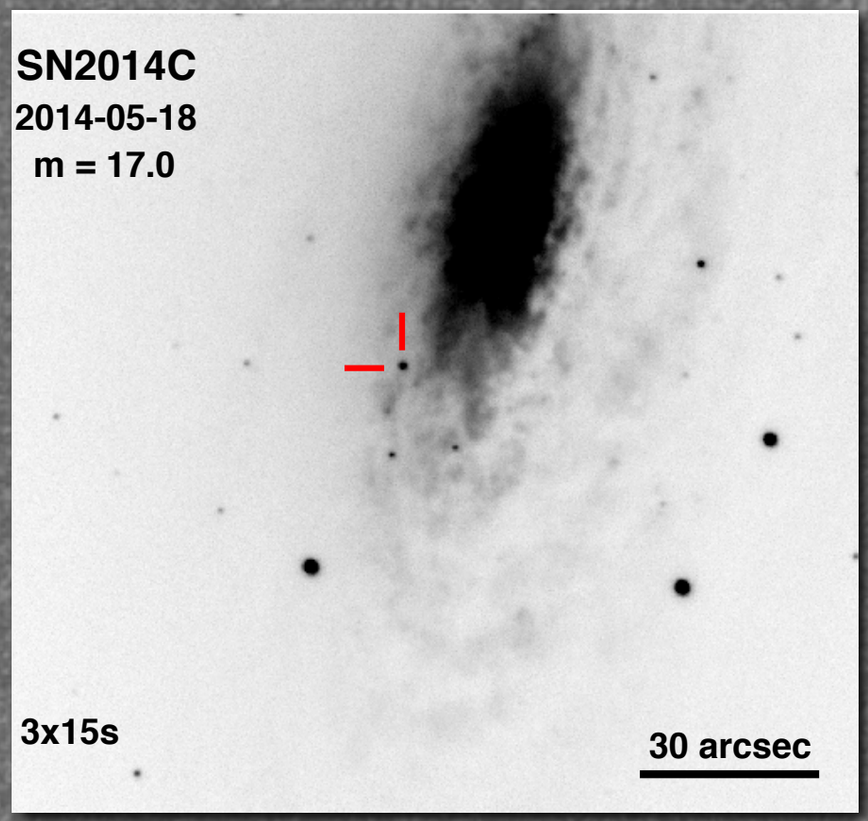
Type II SN

H-rich

Margutti+ 2017, ApJ, 835, 140
Tinyanont et al., 2016
Anderson et al., 2016
Milisavlejvic, RM et al., 2015, ApJ, 815, 120

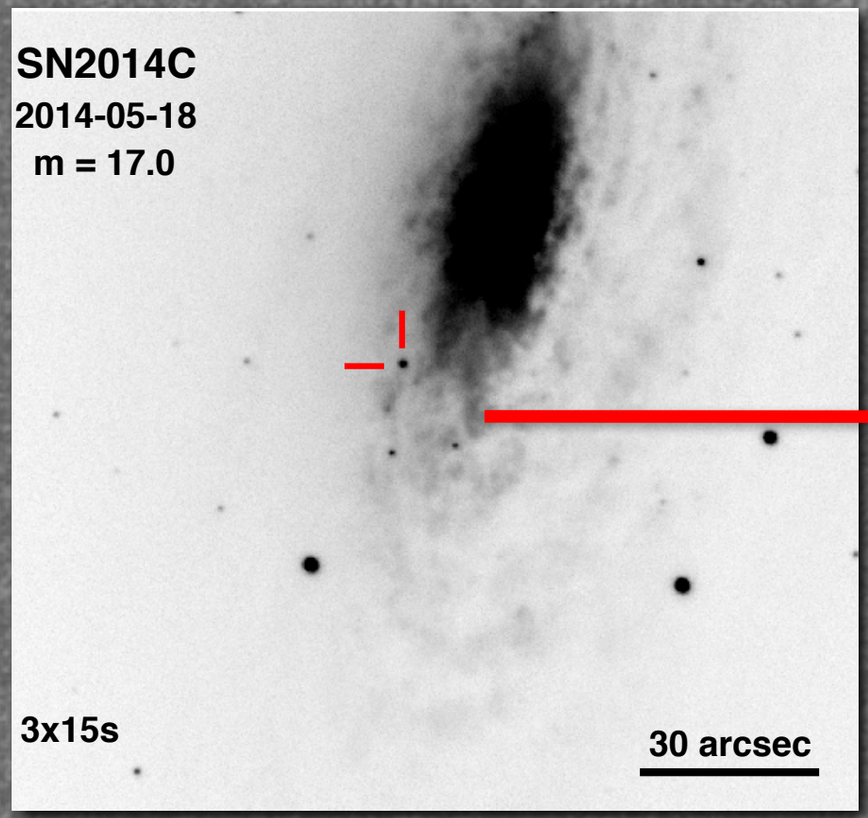
SN2014C: a normal H-stripped SN

dist=15.7 Mpc

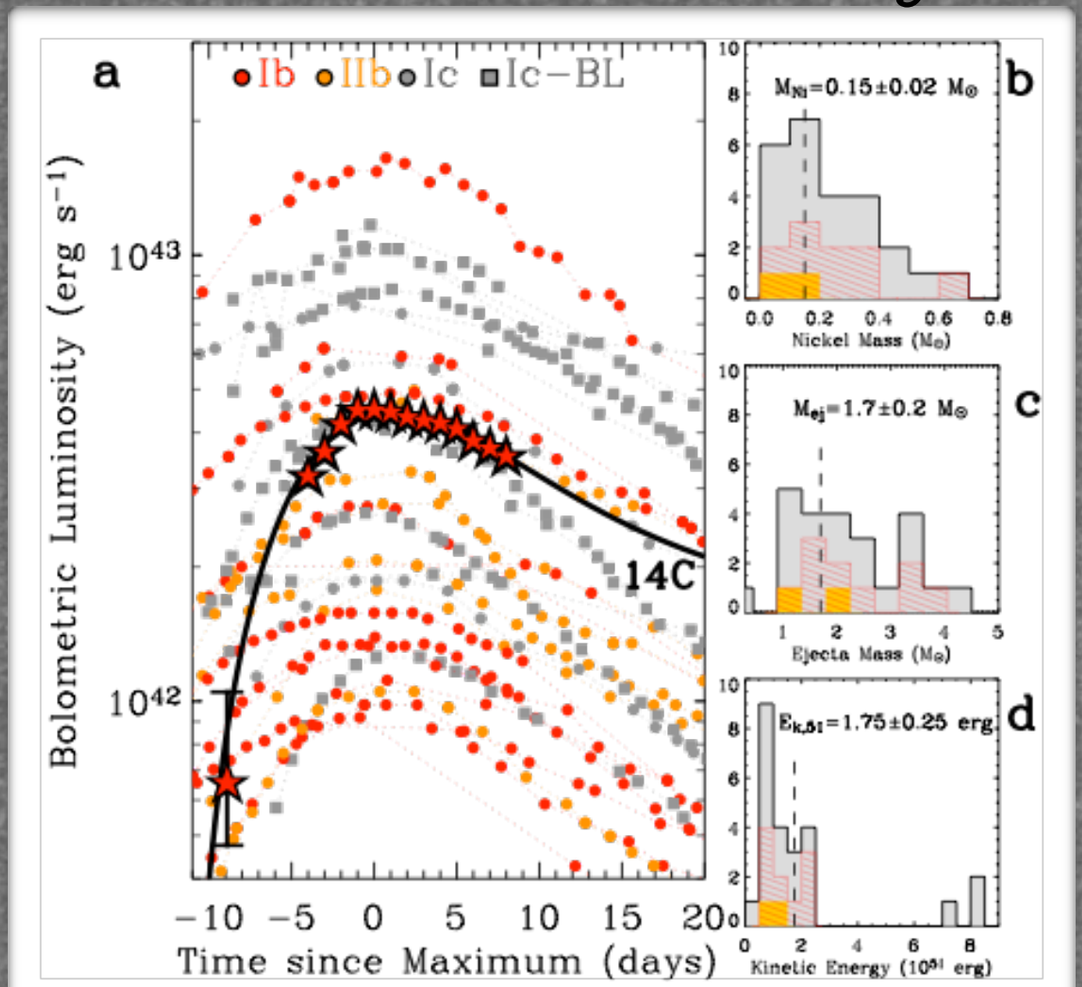


SN2014C: a normal H-stripped SN

dist=15.7 Mpc



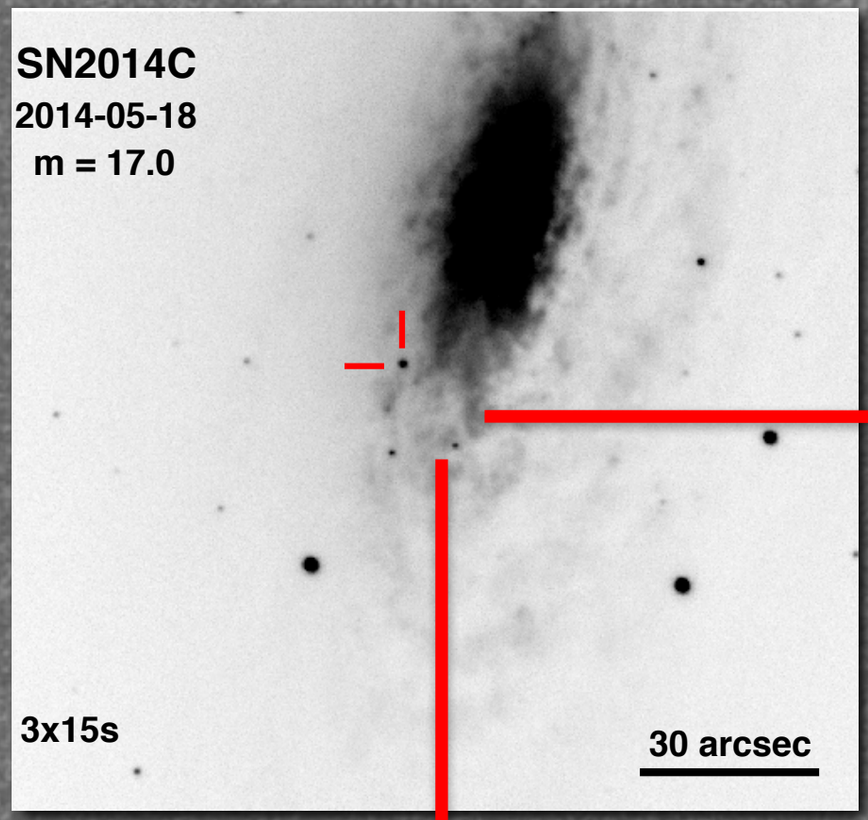
Bolometric Luminosity



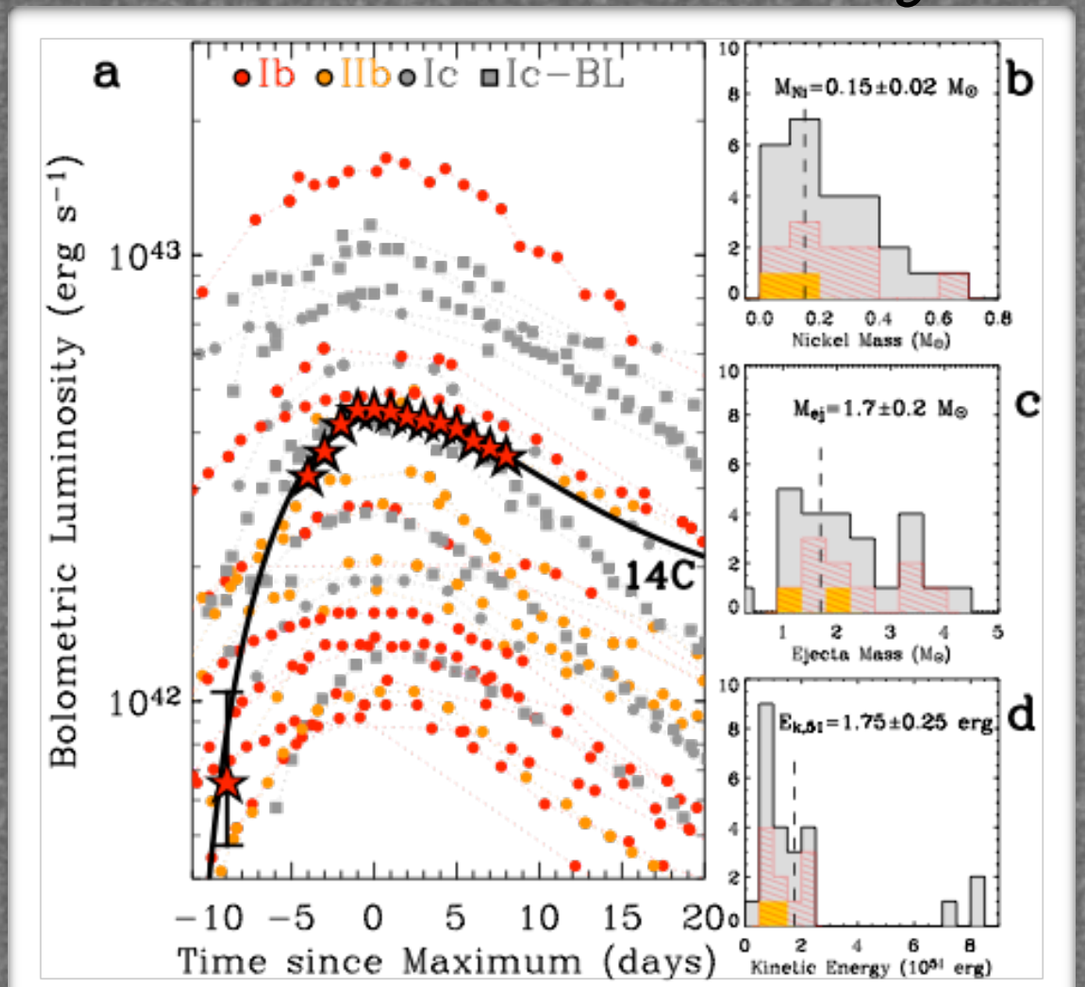
RM+16

SN2014C: a normal H-stripped SN

dist=15.7 Mpc

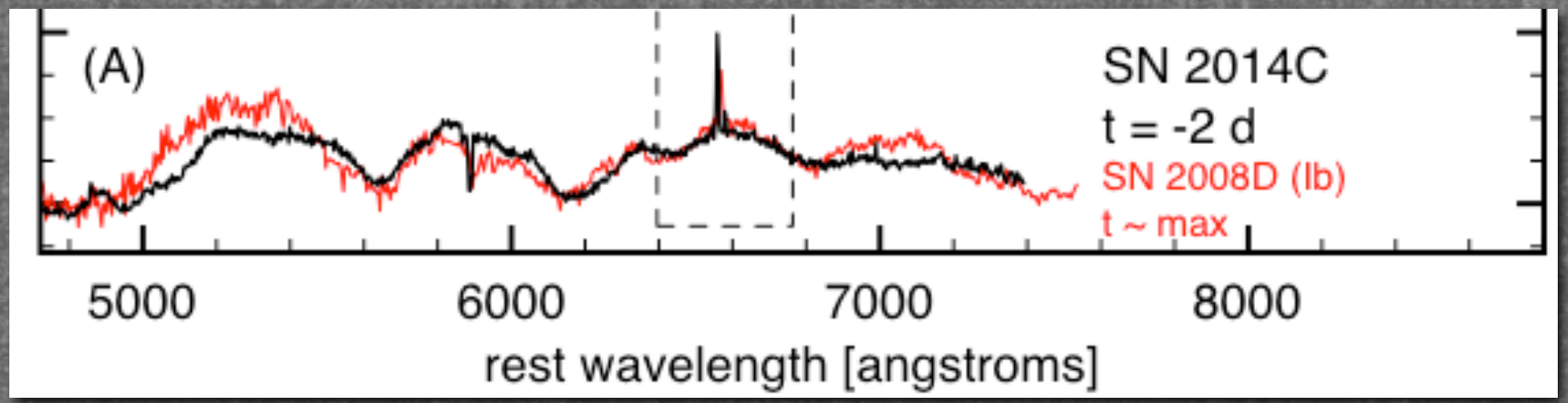


Bolometric Luminosity



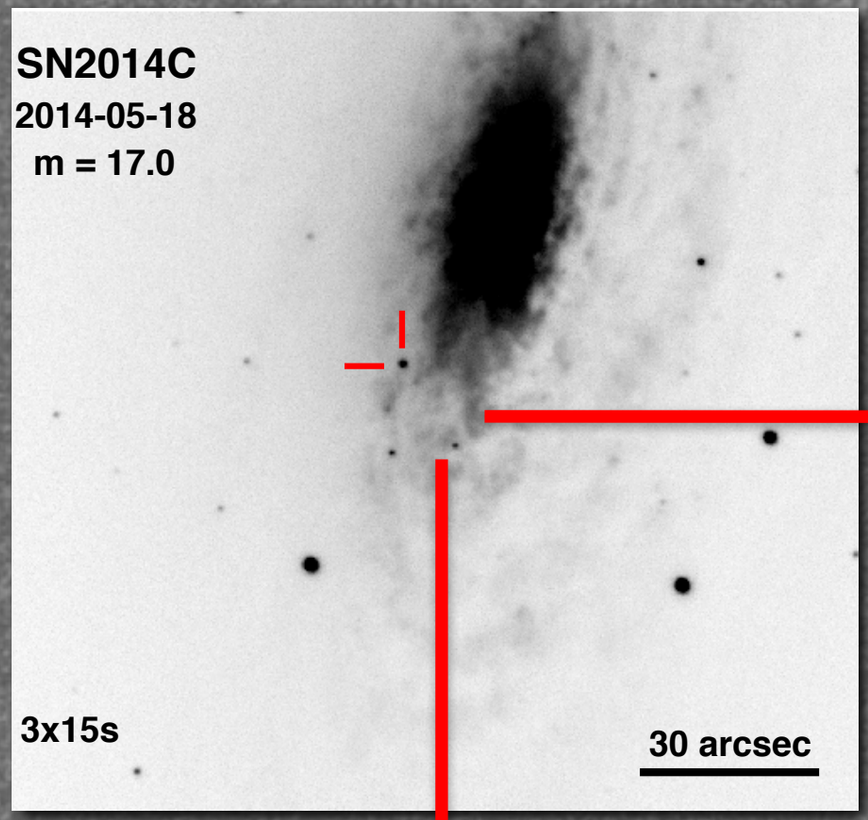
RM+16

Optical Spectrum at max

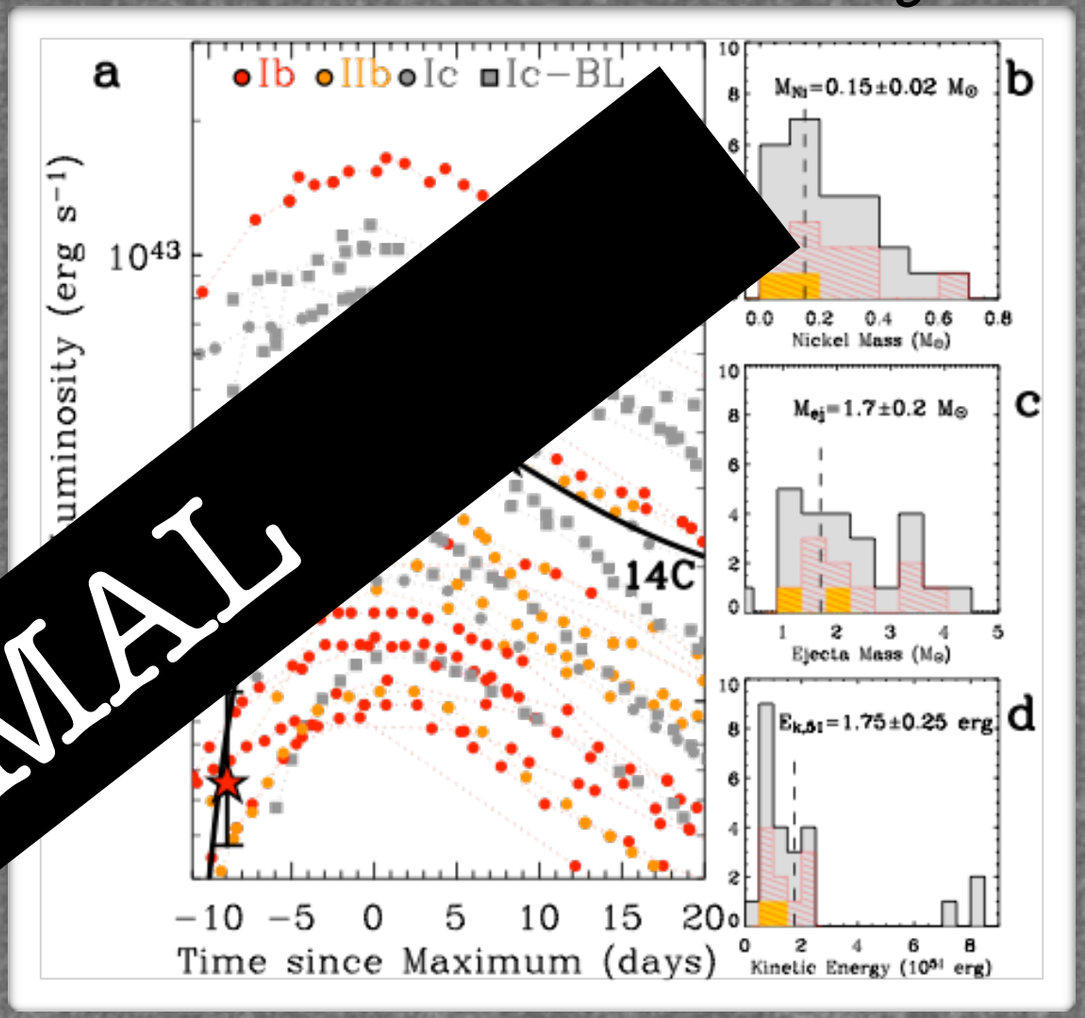


SN2014C: a normal H-stripped SN

dist=15.7 Mpc

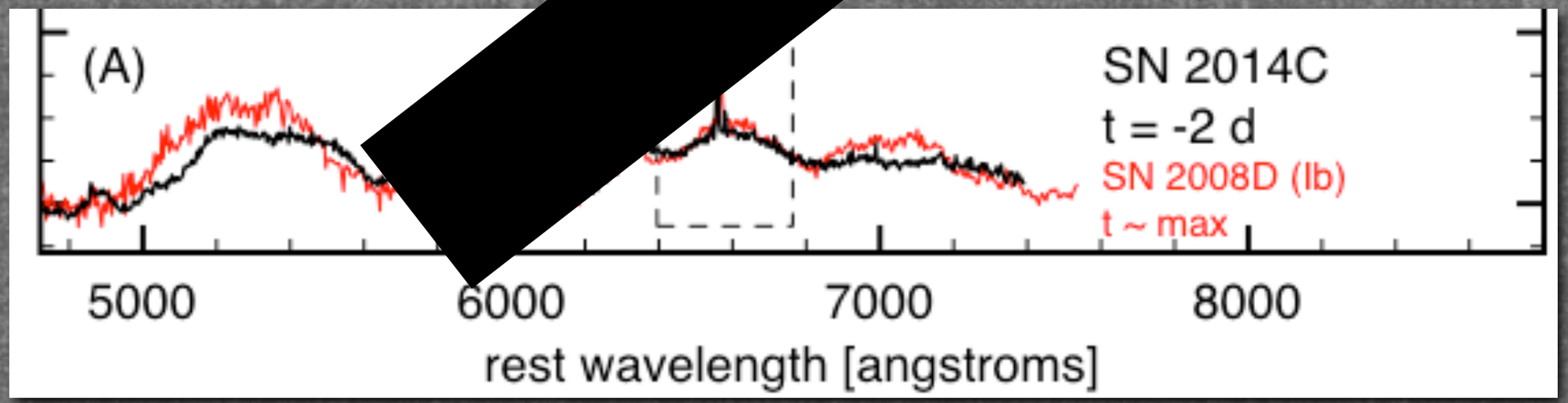


Bolometric Luminosity



RM+16

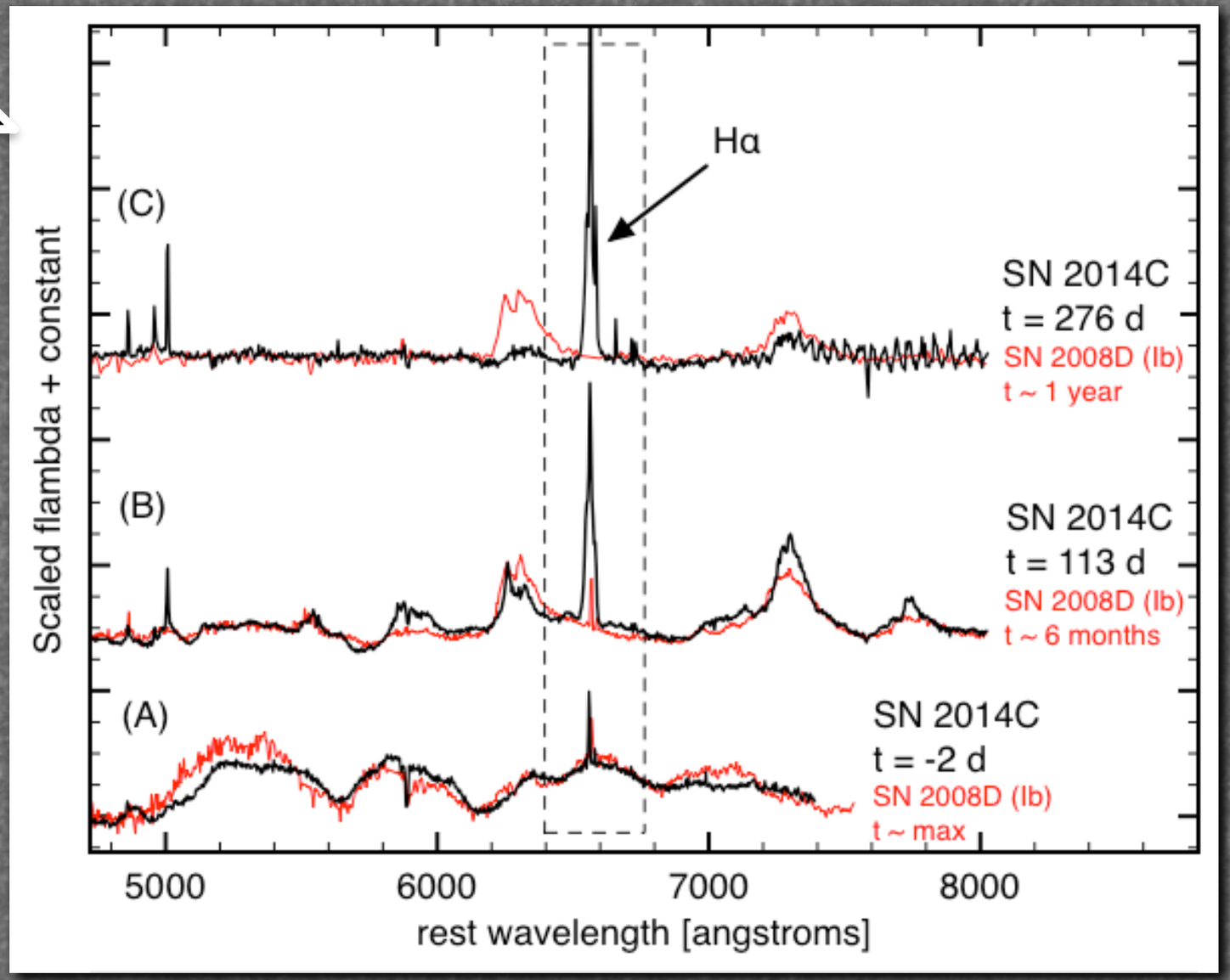
Optical Spectrum at



NORMAL

SN2014C-Optical

TIME

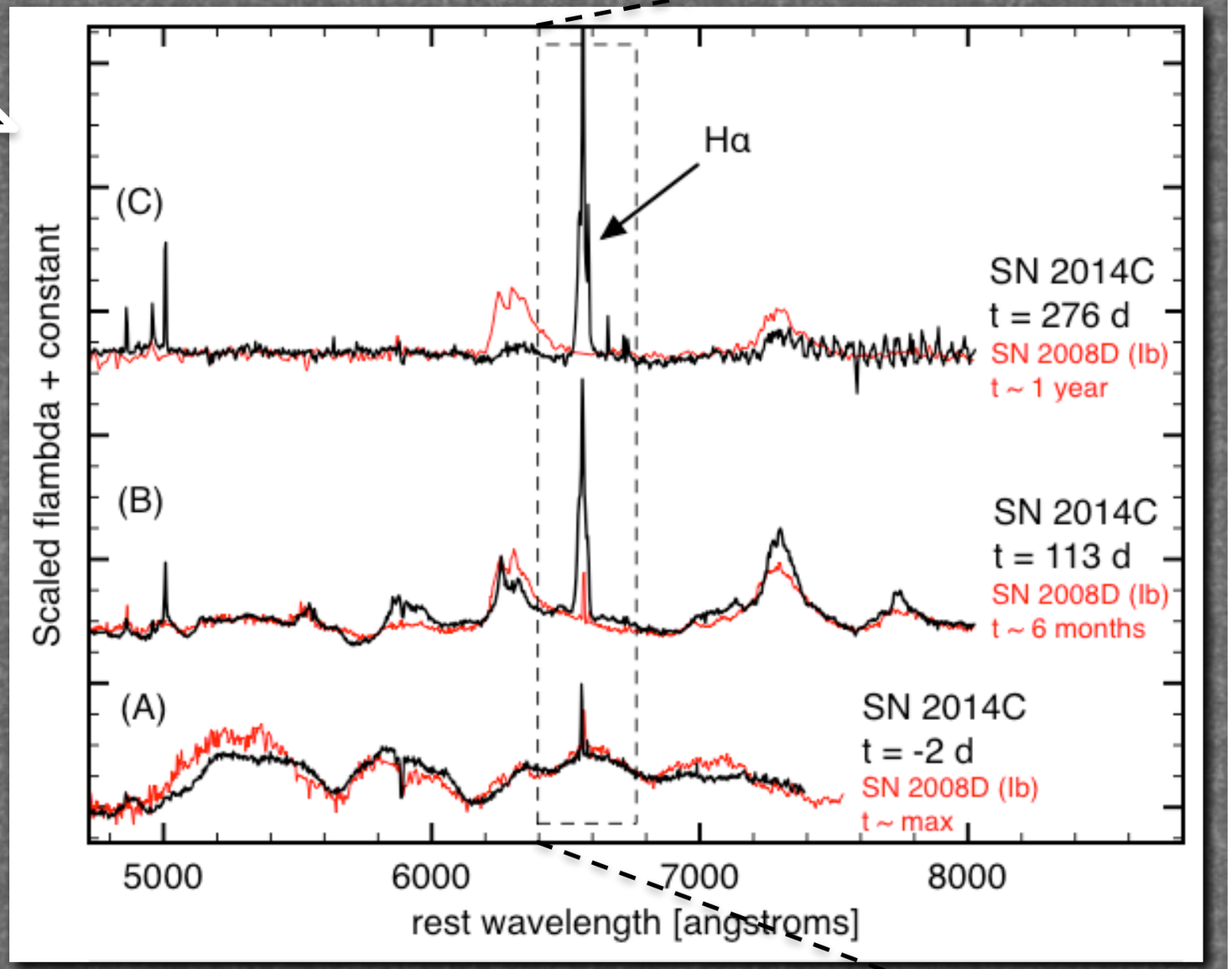


Milisavljevic, RM+16

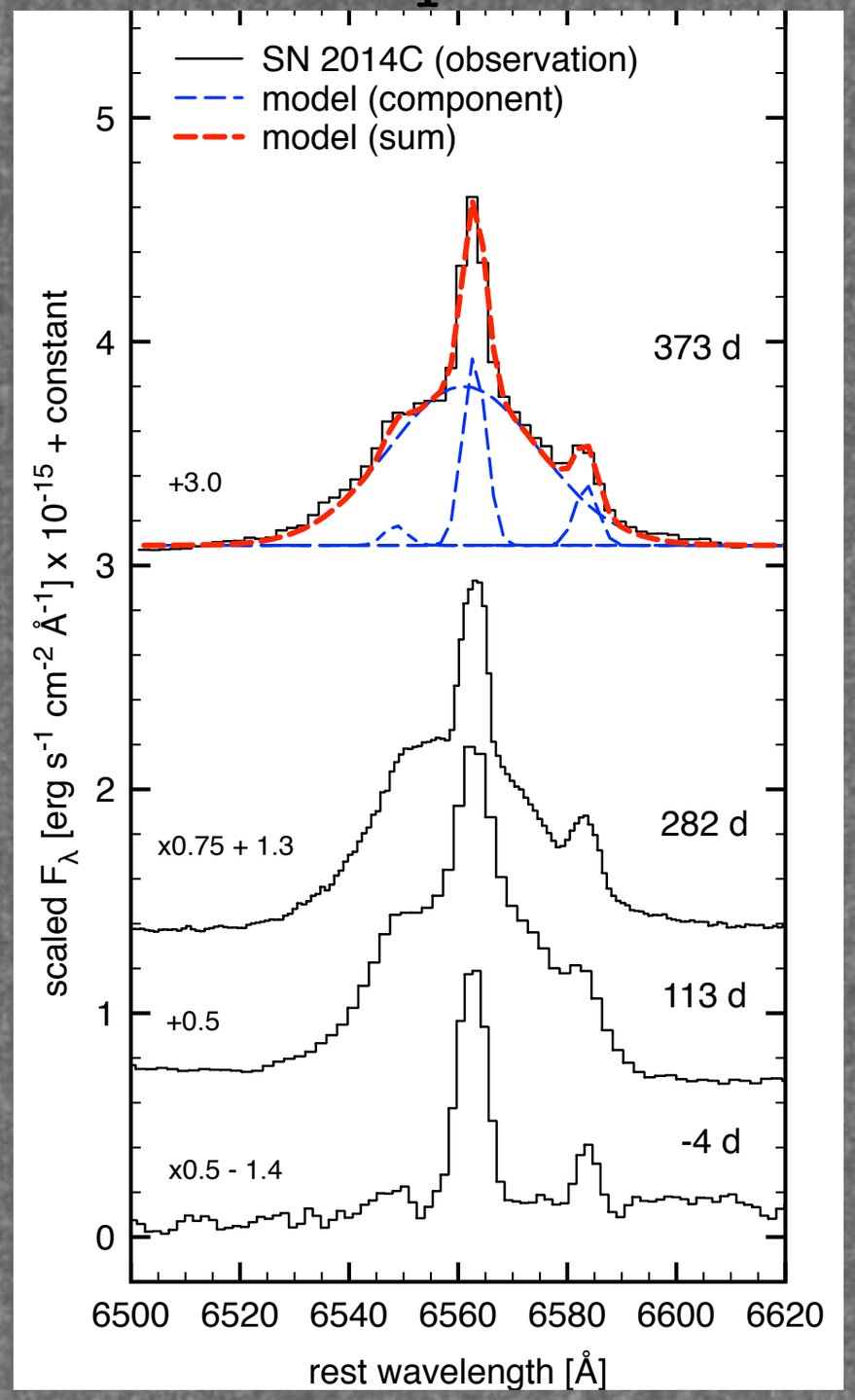
Development of H-features with time

SN2014C-Optical

TIME



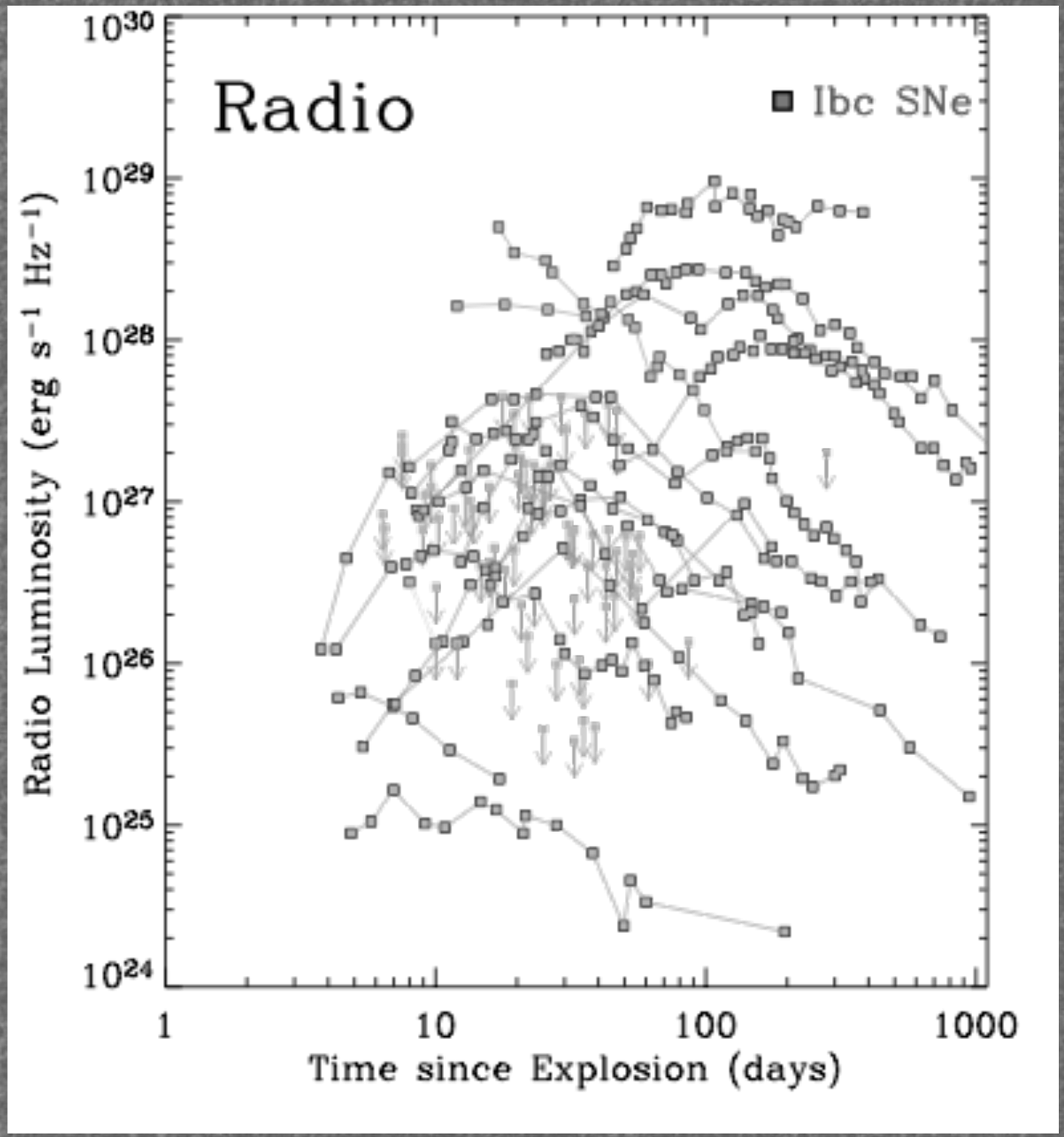
Halpha



Milisavljevic, RM+16

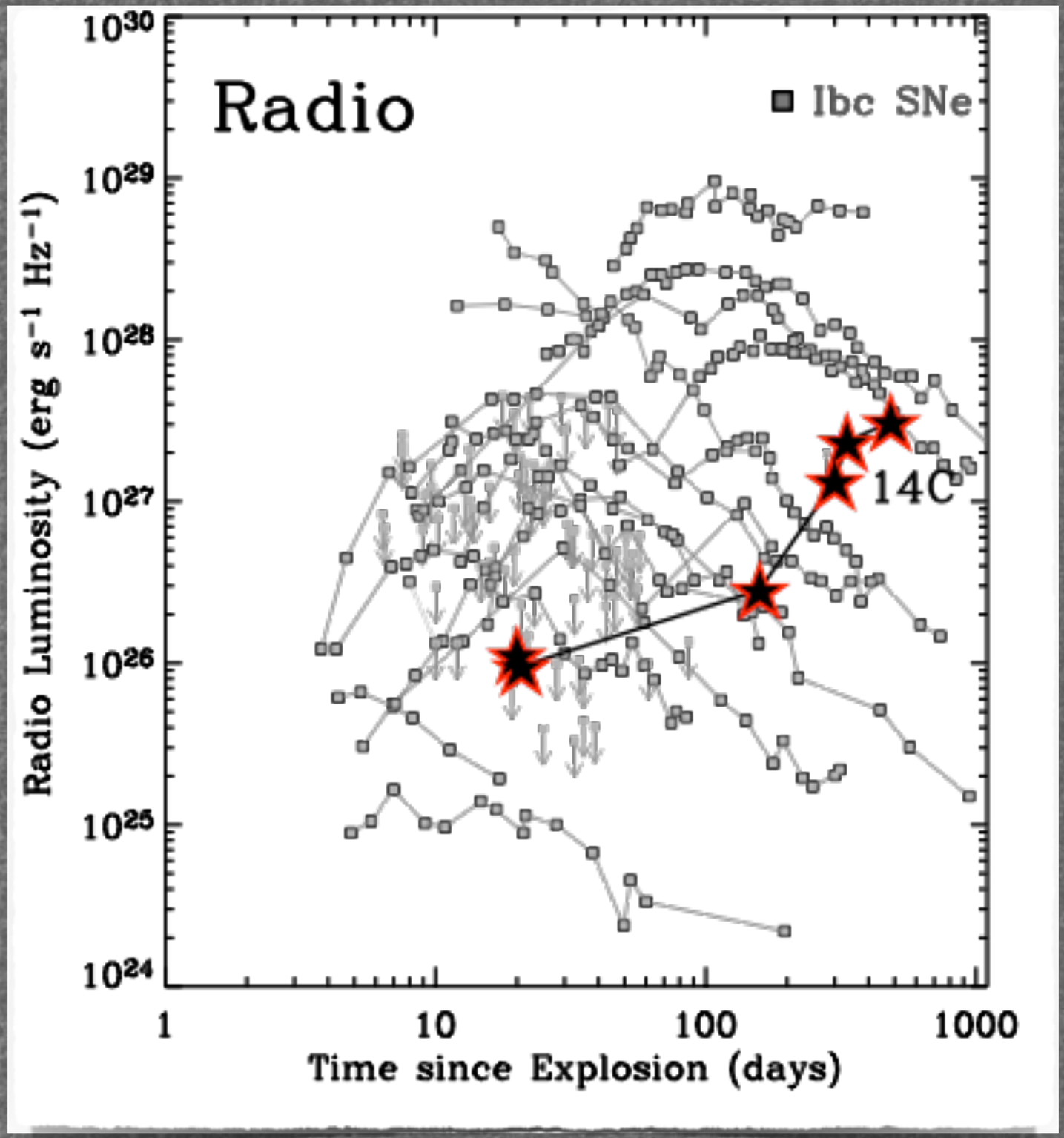
Development of H-features with time

SN2014C-Radio



RM+17

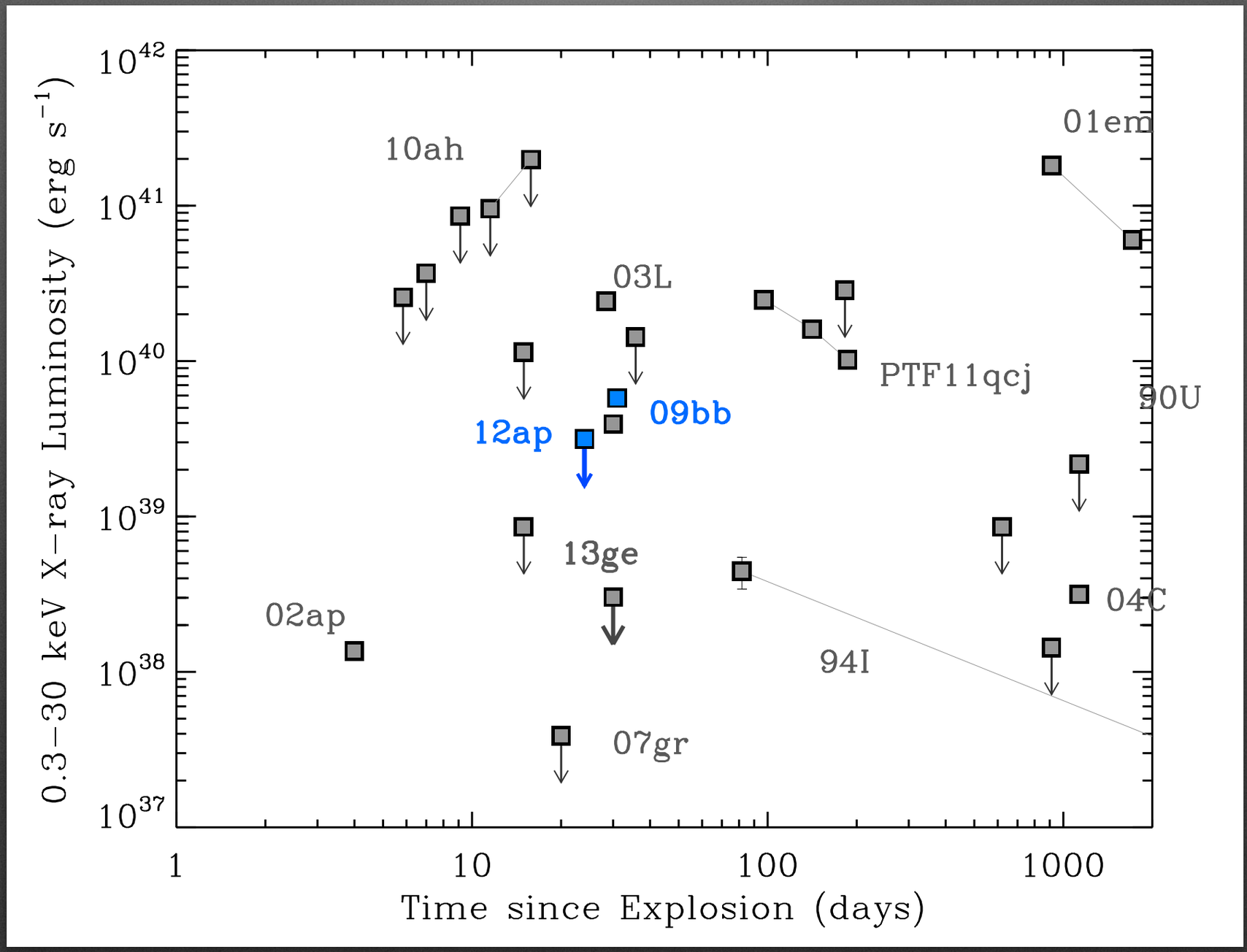
SN2014C-Radio



RM+17

Radio Luminosity INCREASES w. time!

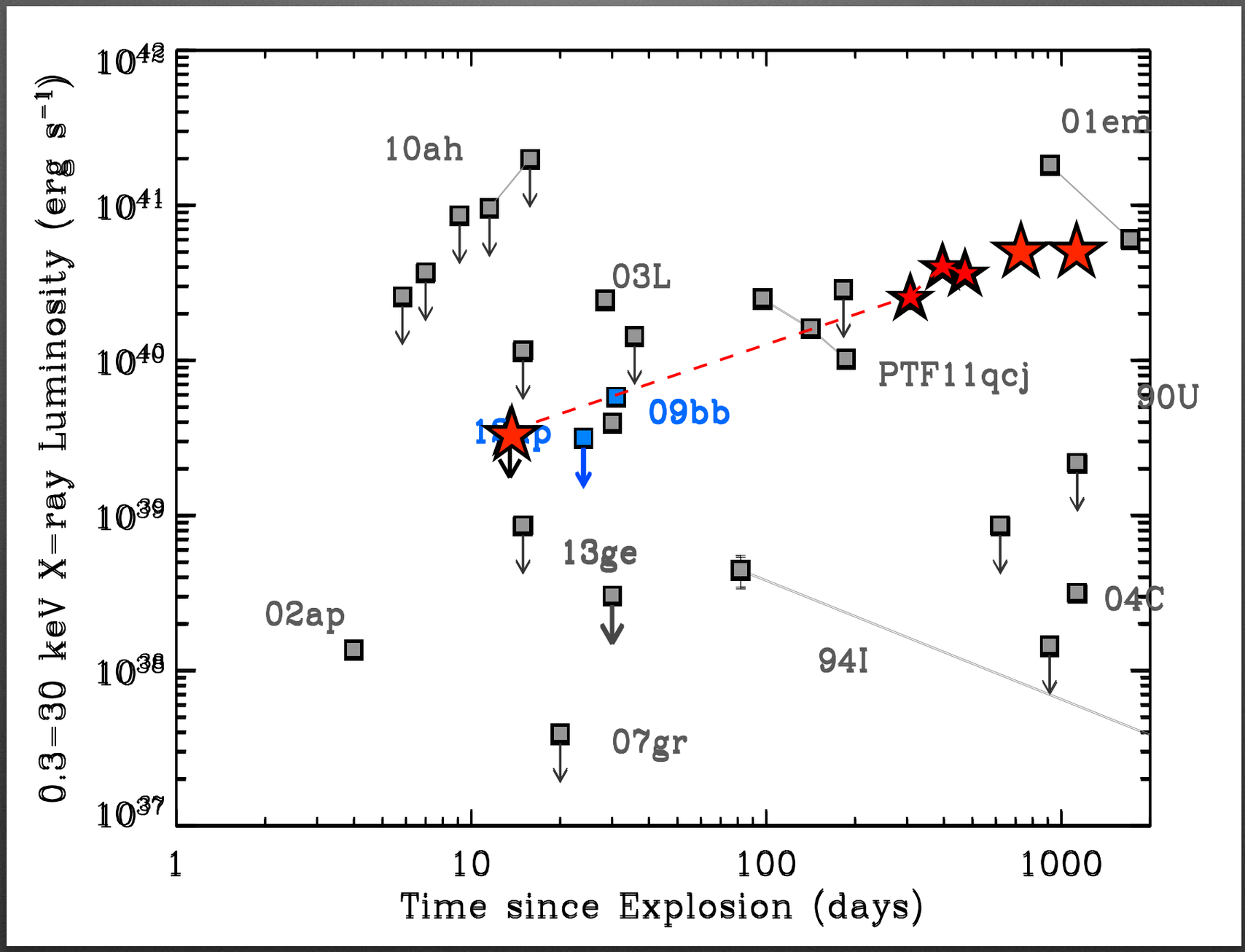
SN2014C-X-rays (soft+hard)



RM+17, Brethauer, RM , in prep.

X-ray Luminosity INCREASES w. time!

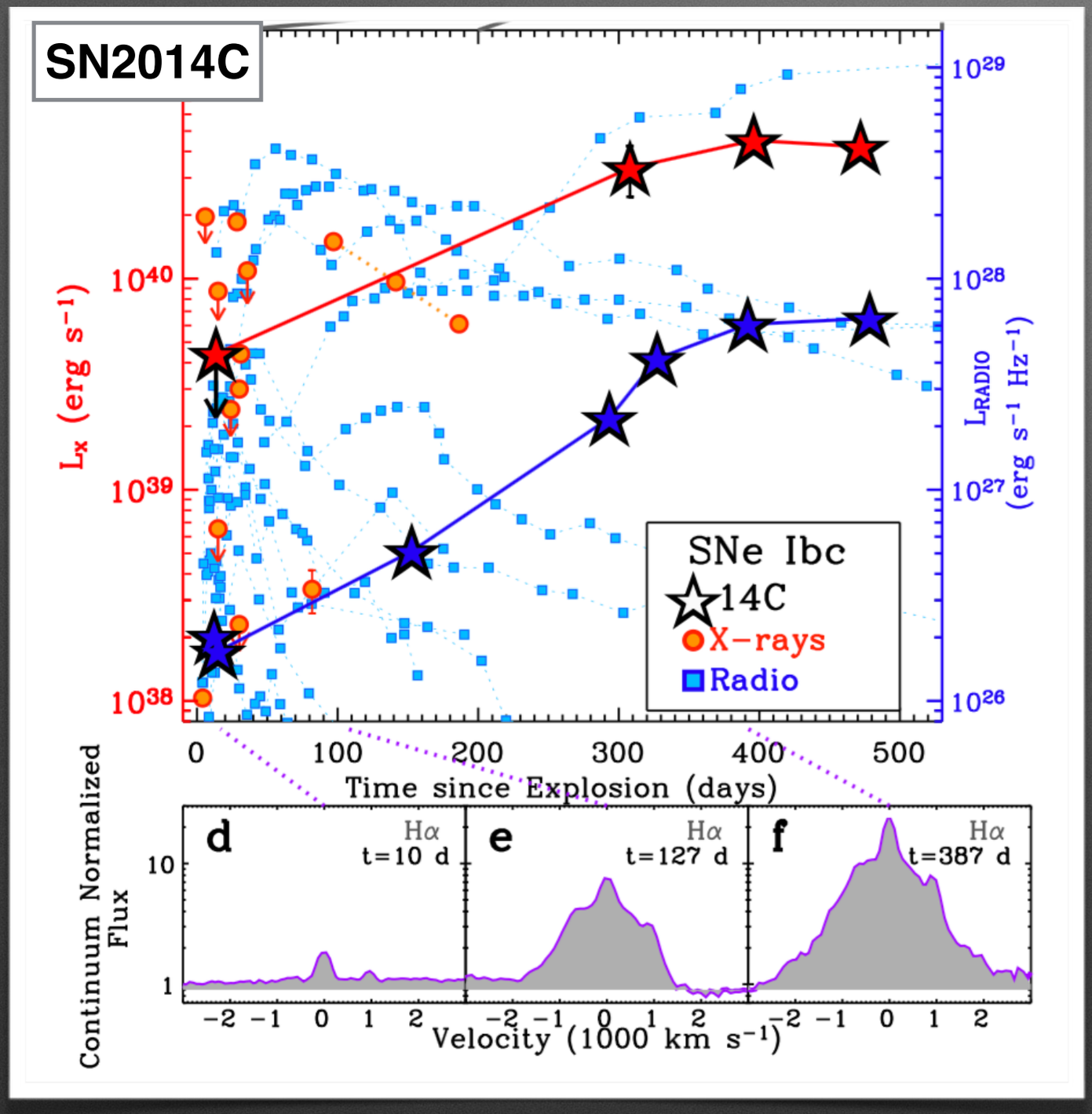
SN2014C-X-rays (soft+hard)



RM+17, Brethauer, RM , in prep.

X-ray Luminosity INCREASES w. time!

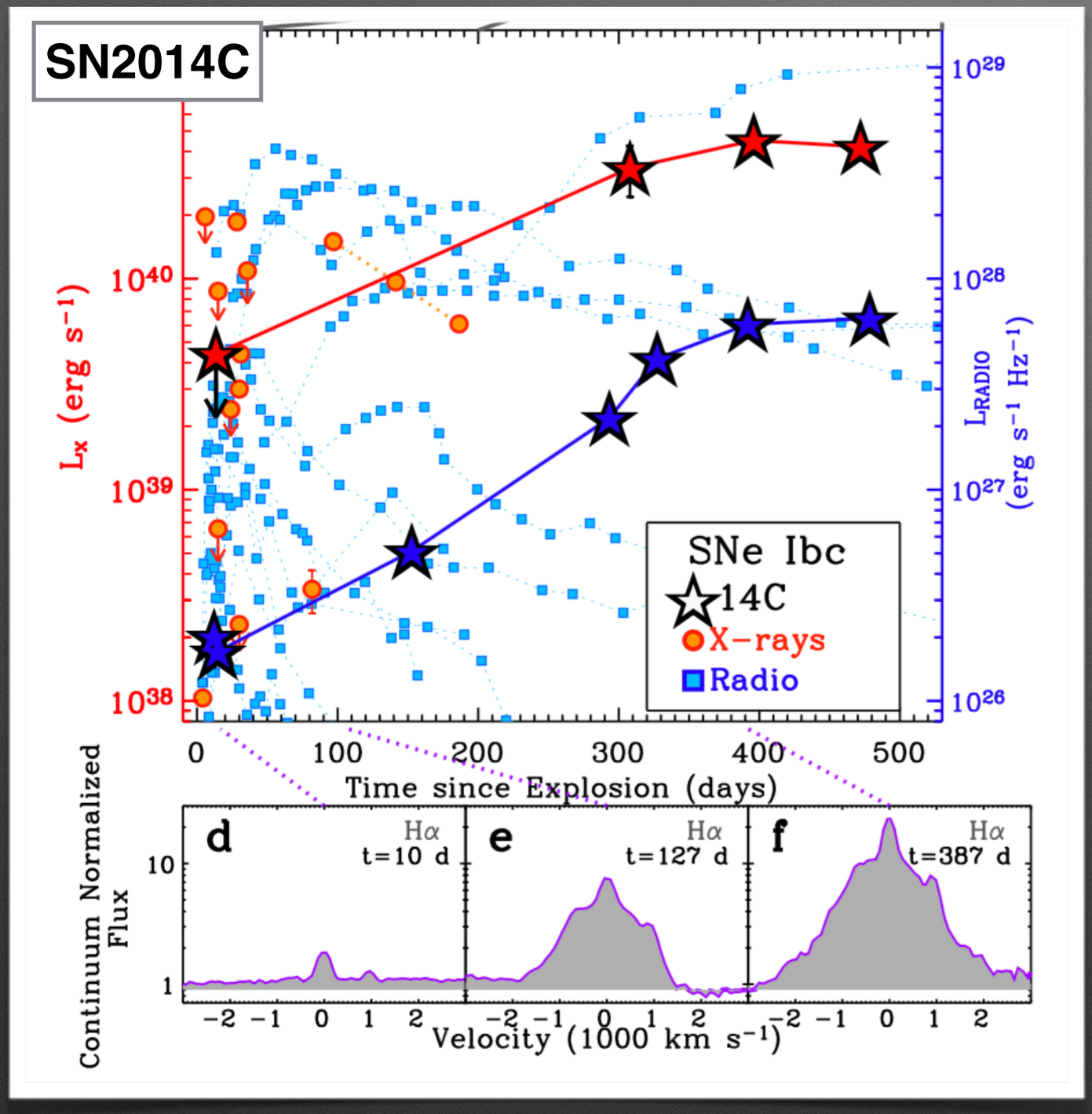
Shock interaction with H-rich shell

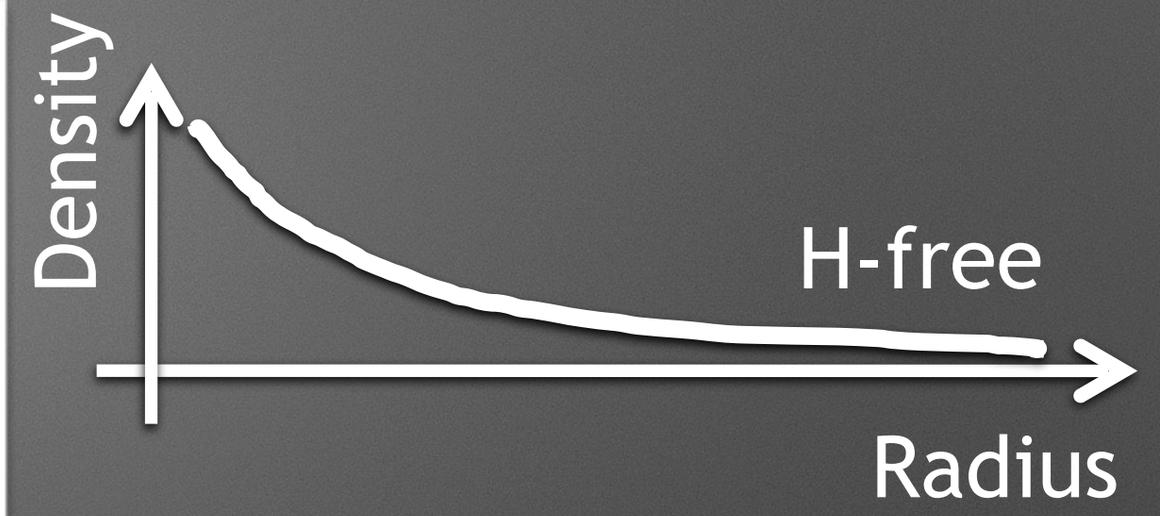


Type I ⟶ Type II

(H-poor) (H-rich)

Shock interaction with H-rich shell

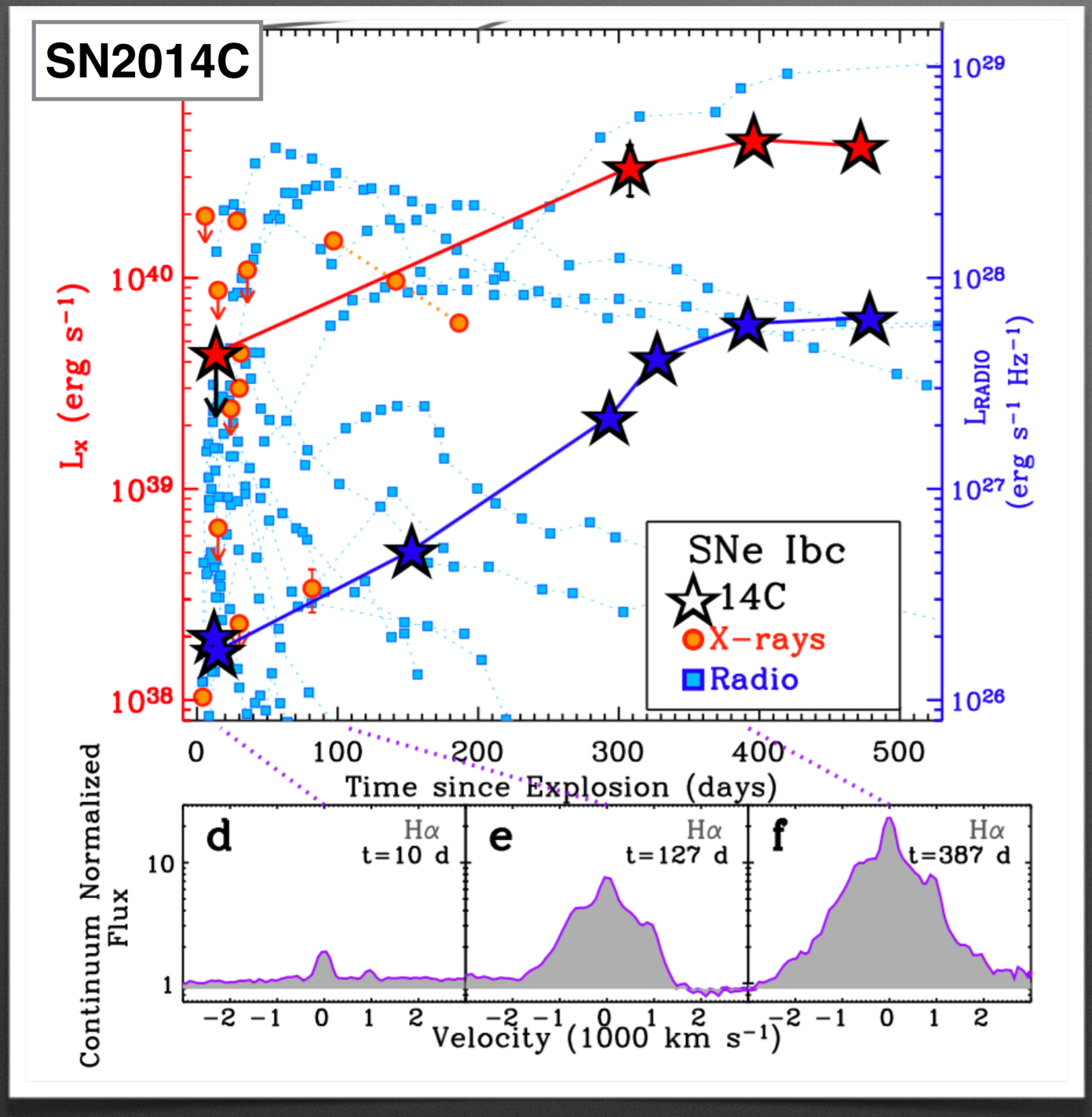


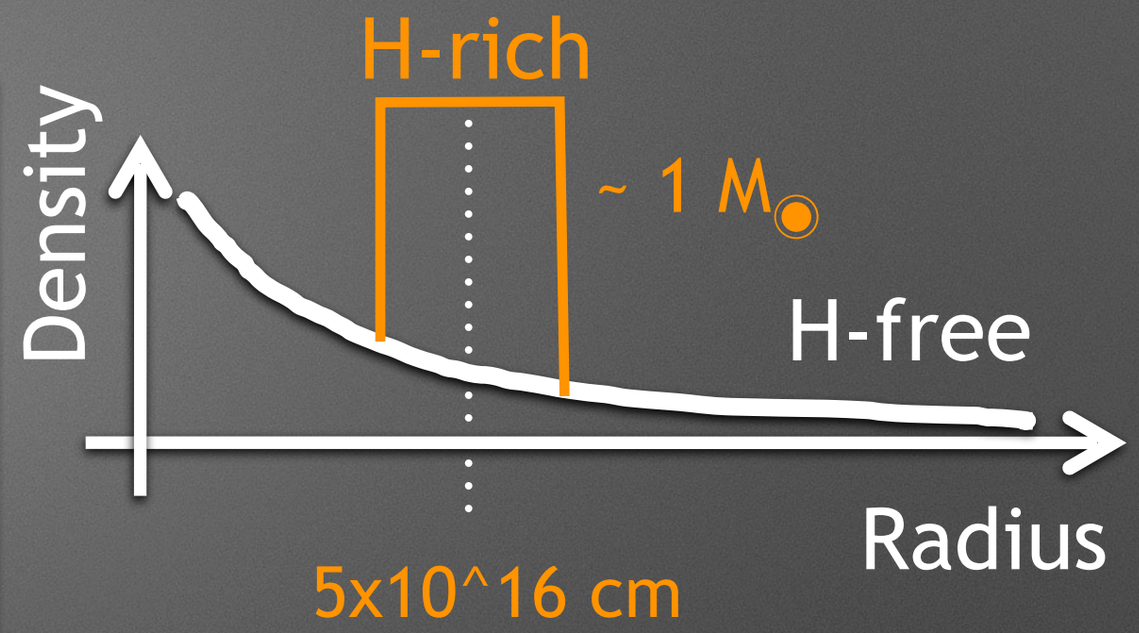


Type I ⟶ Type II

(H-poor) (H-rich)

Shock interaction with H-rich shell

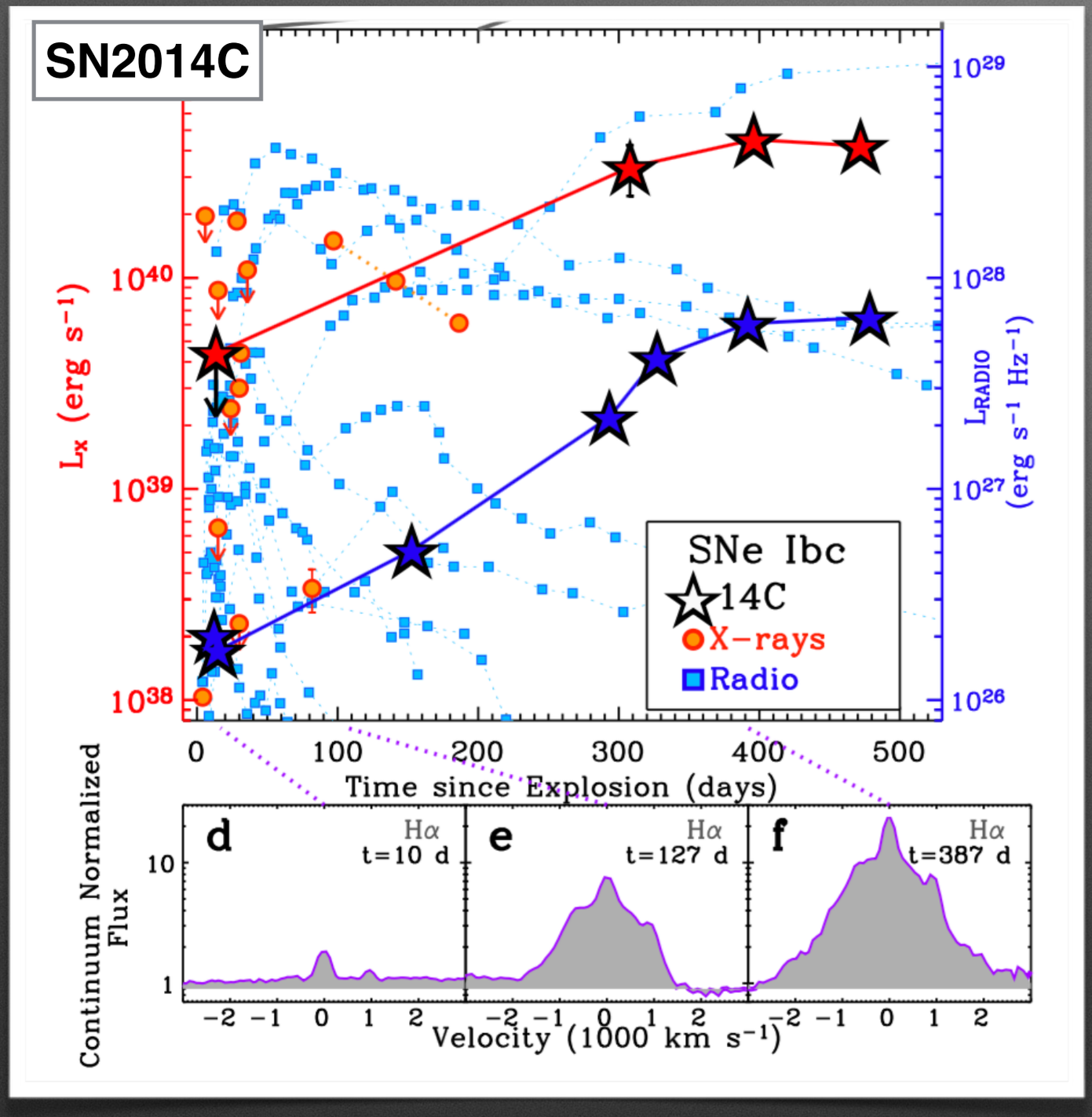


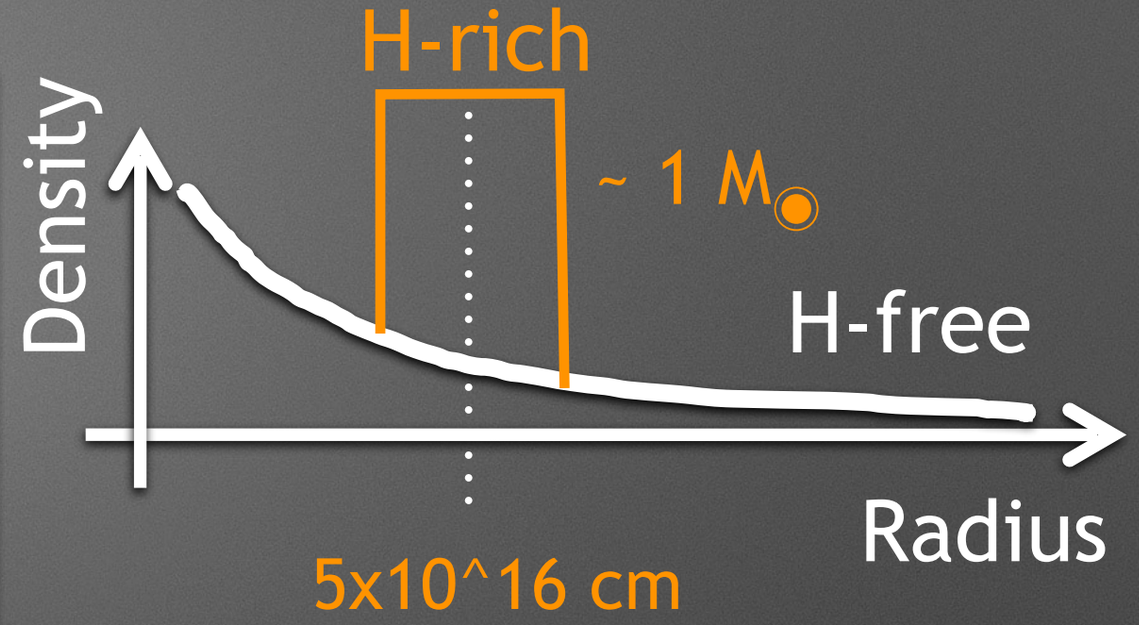


~20-2000 yrs before collapse

Type I (H-poor) ⟶ Type II (H-rich)

Shock interaction with H-rich shell



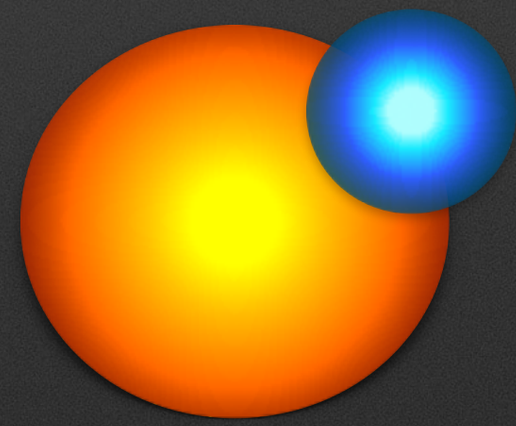


~20-2000 yrs before collapse

WHY?

Nuclear Burning Instabilities

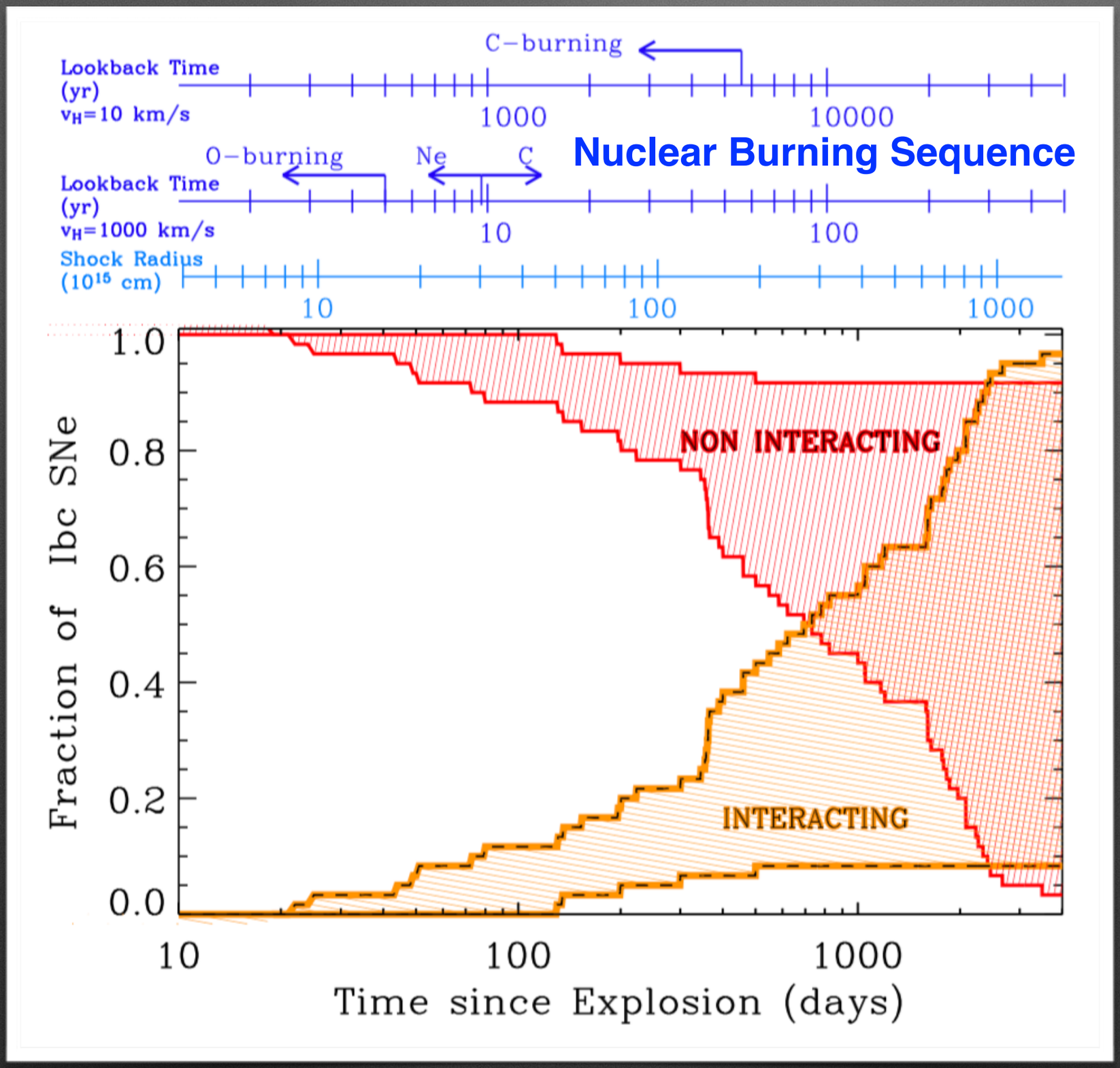
Binary evolution

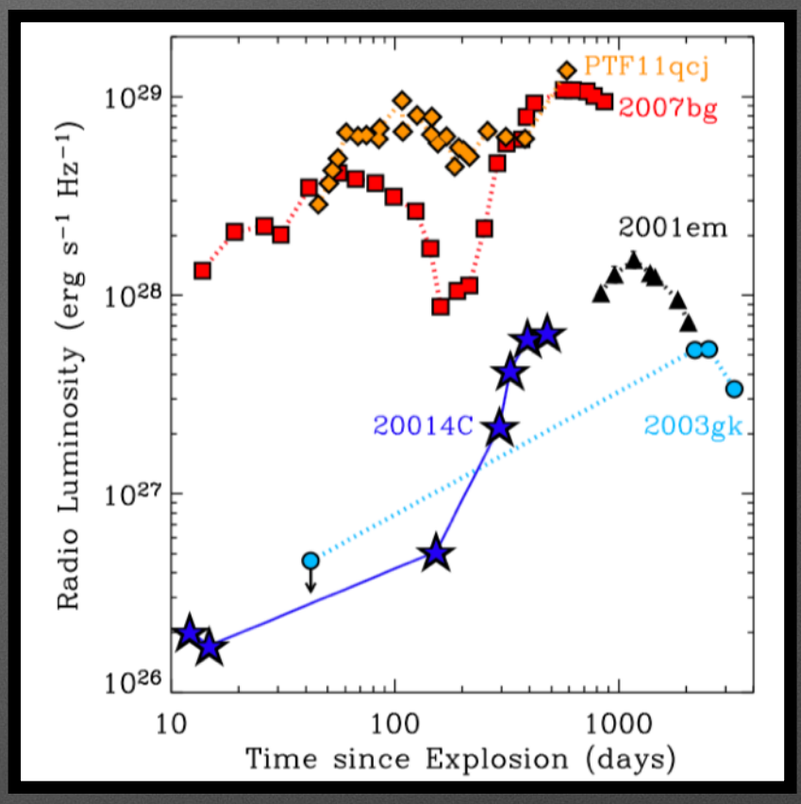


Type I → Type II

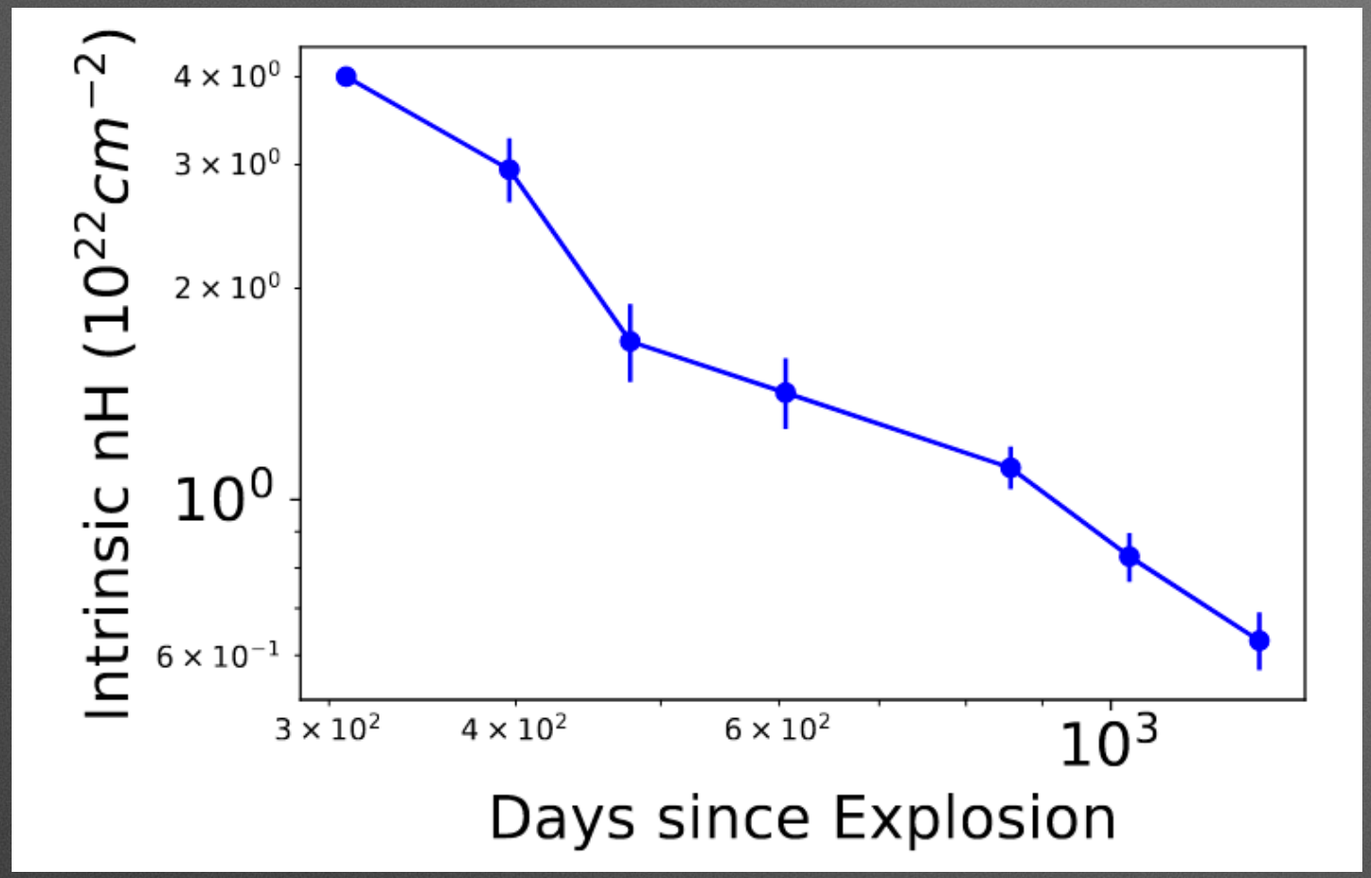
(H-poor) (H-rich)

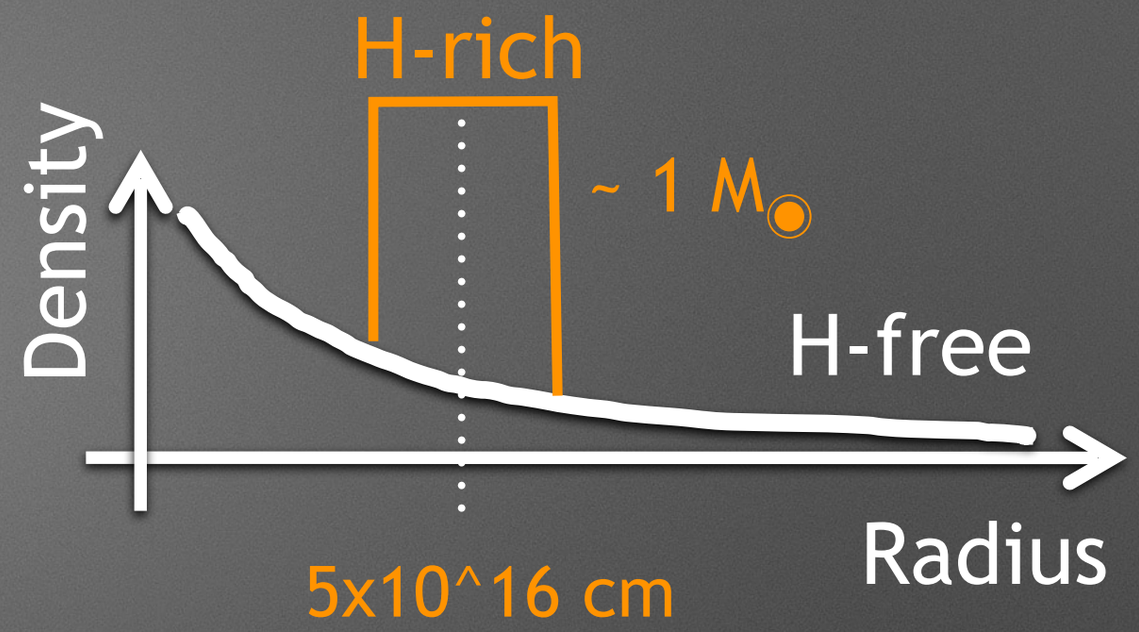
At least 10% of progenitors of normal H-poor SNe experience outbursts just before core-collapse



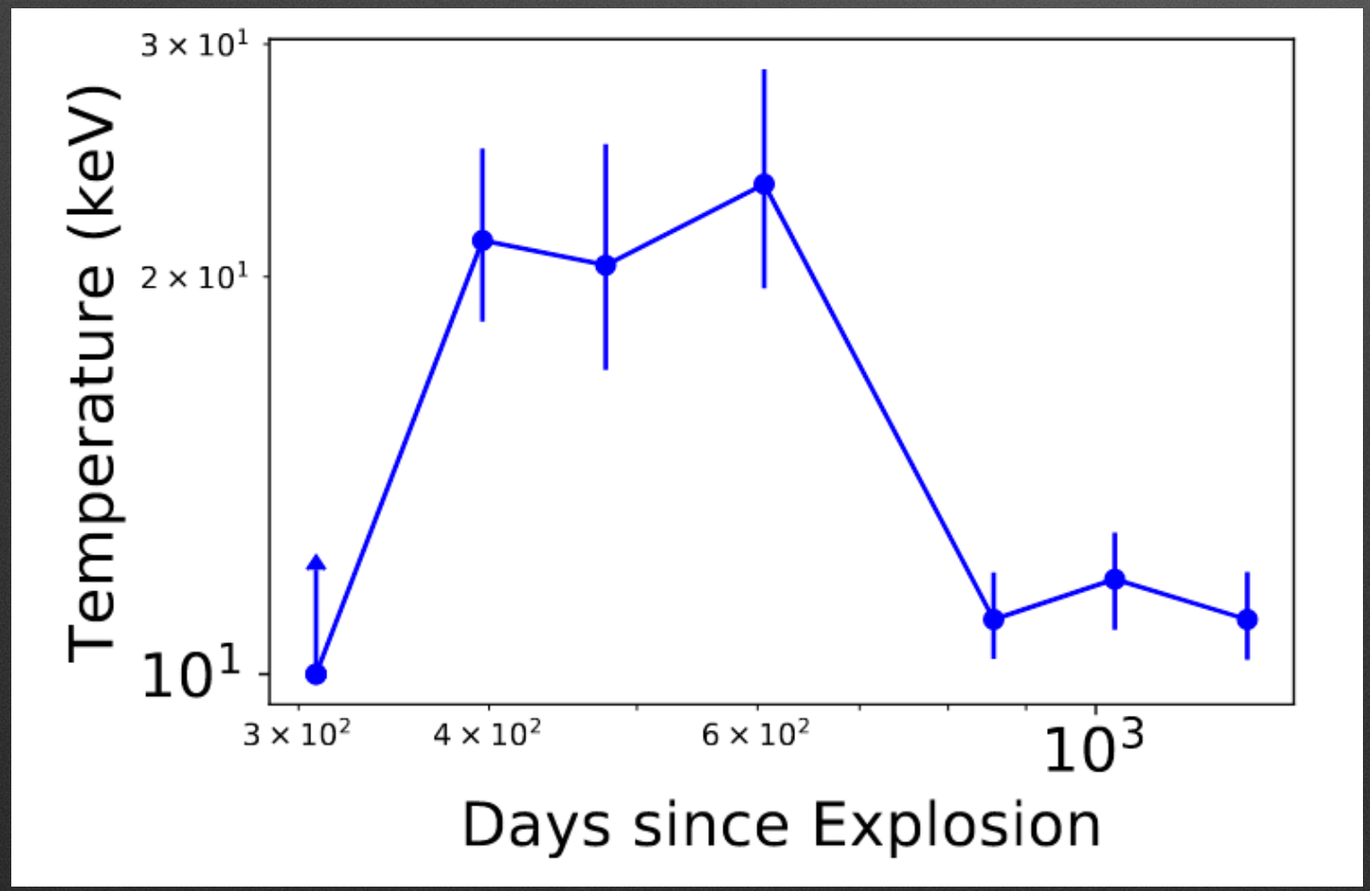


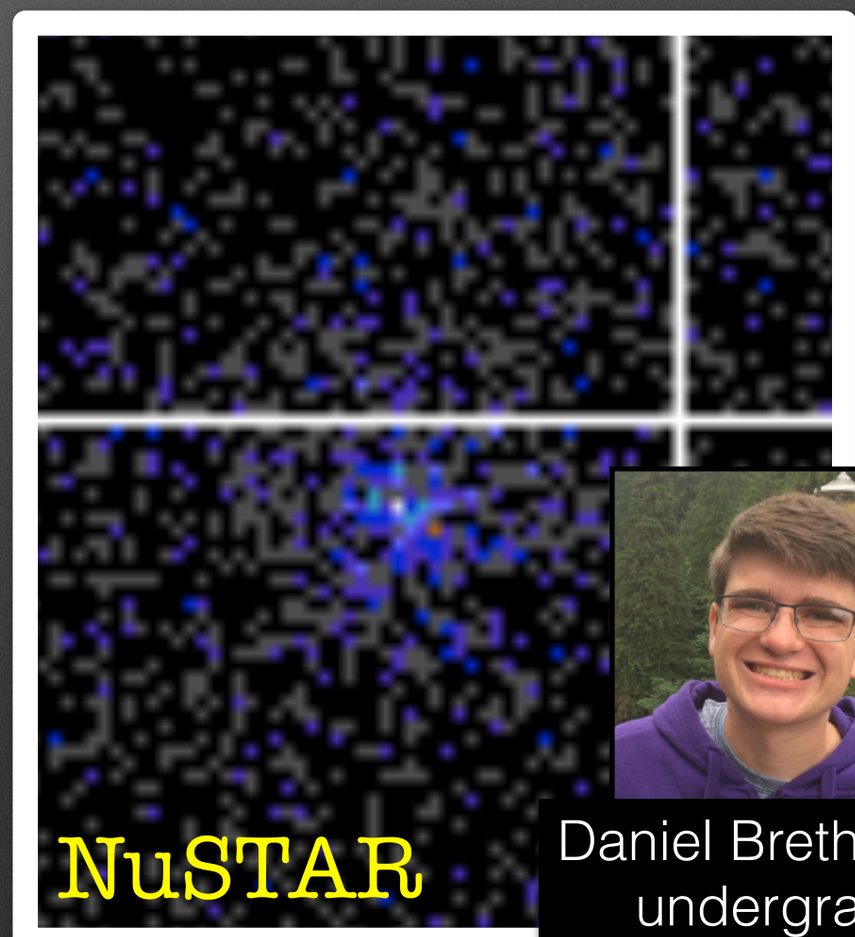
Update on SN2014C





~20-2000 yrs before collapse





Daniel Brethauer
undergrad

The last thousand years...

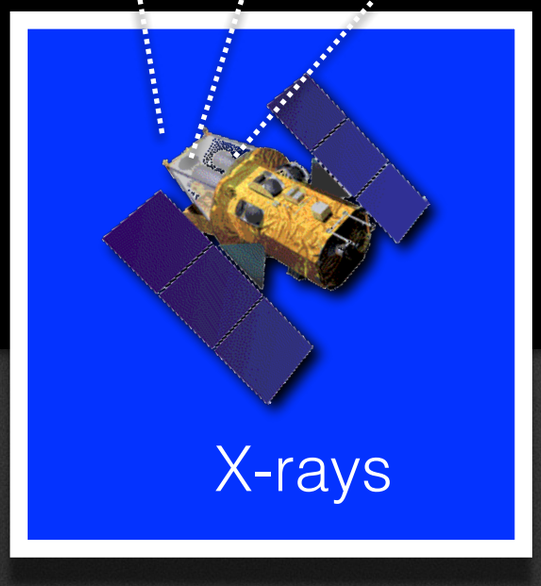
SN shock as a probe

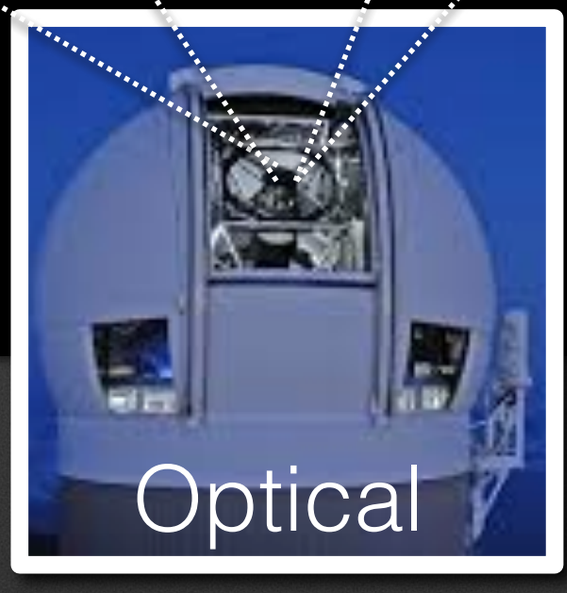
FLASH Spec

-1000 -100 -10 yrs

Time

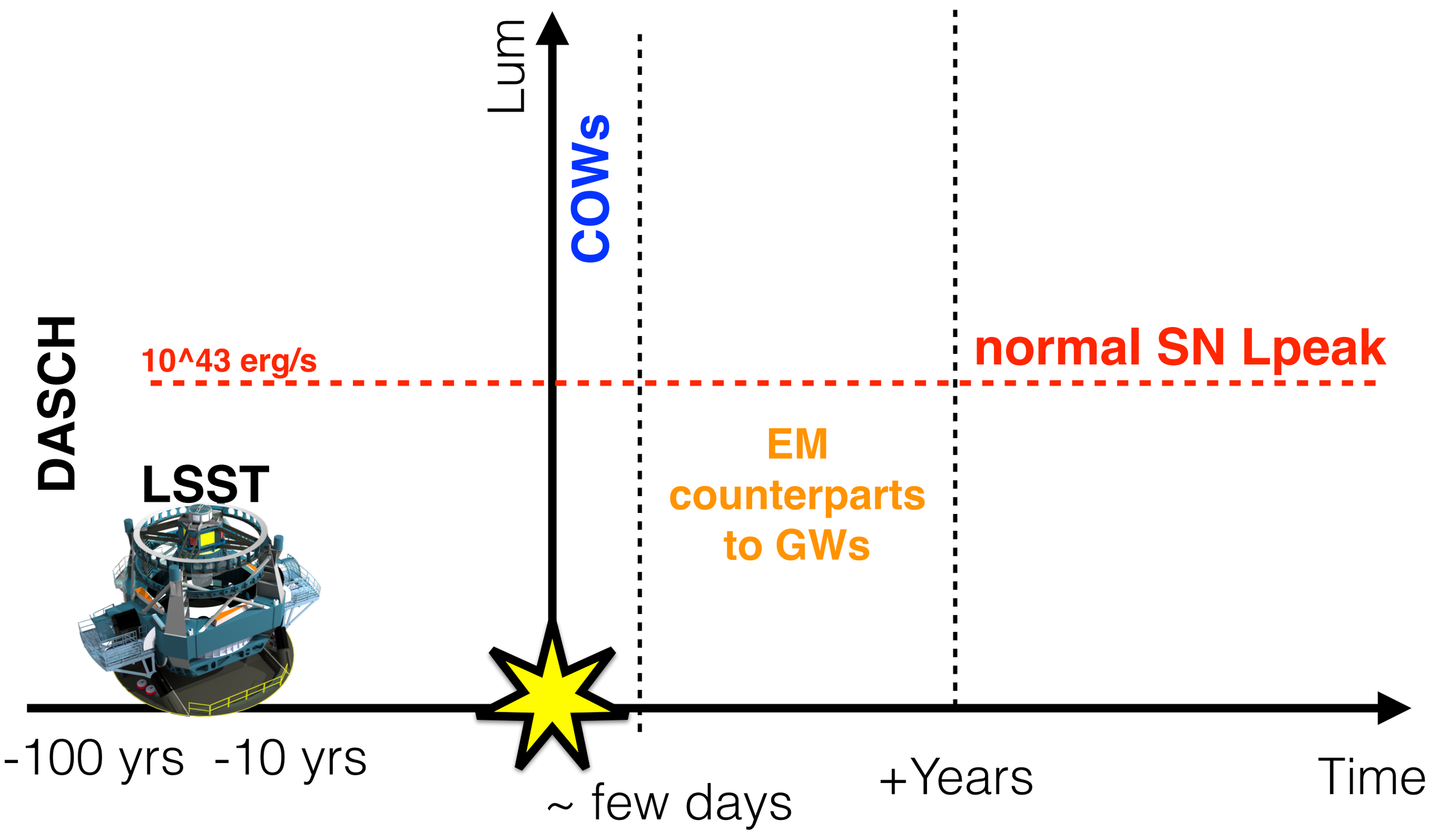
Nuclear Burning Sequence



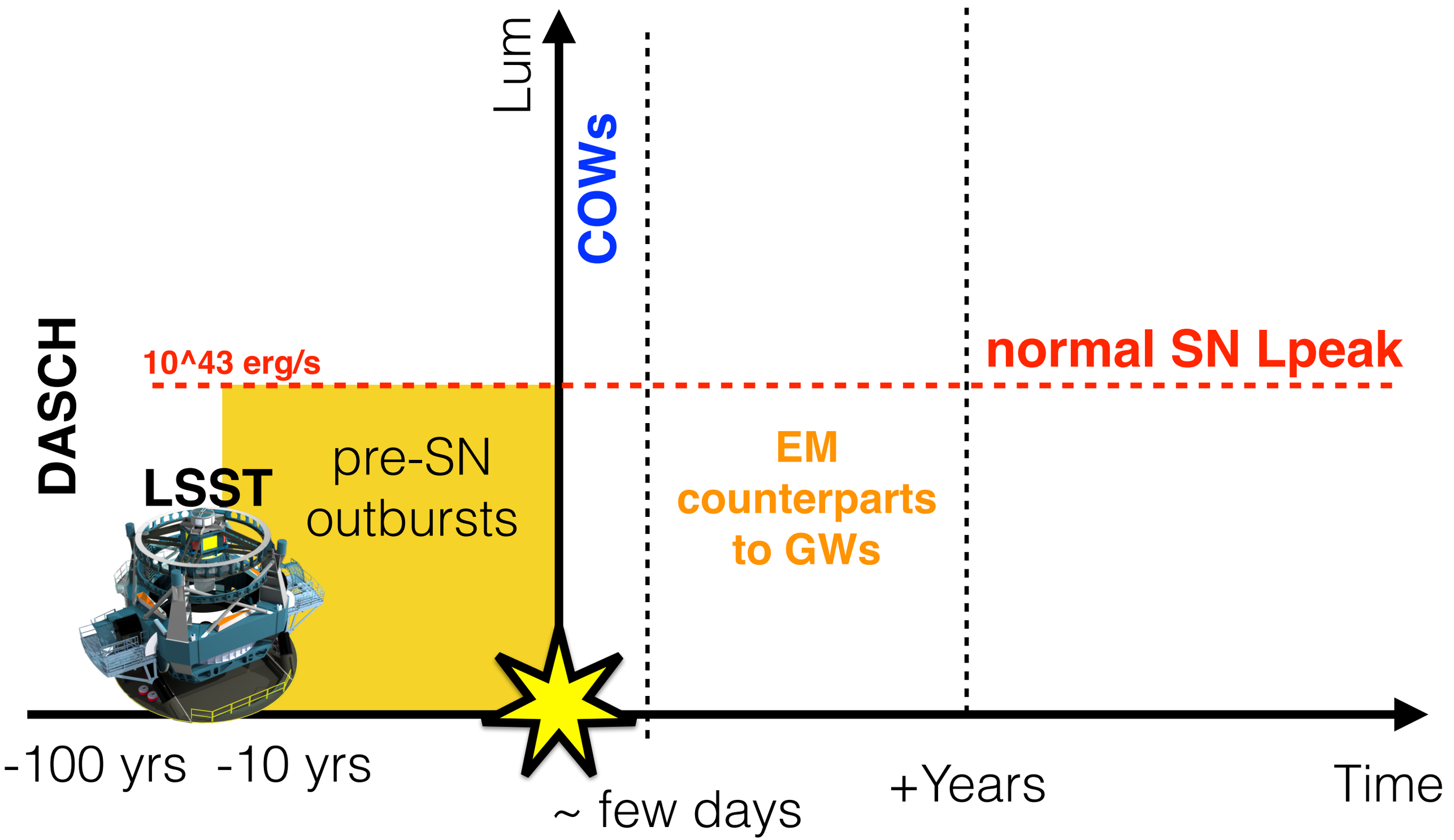


Direct Imaging

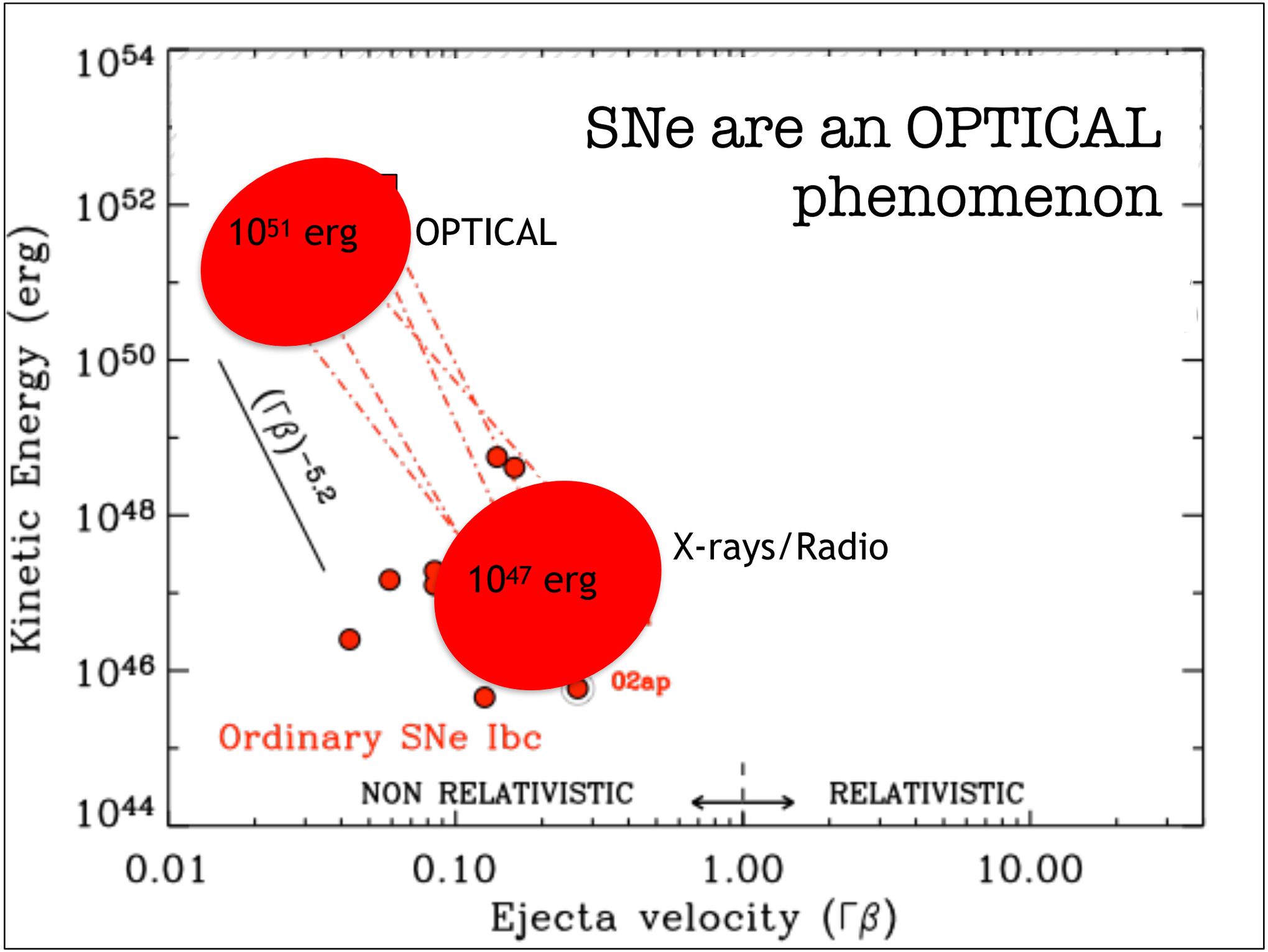
Discovery Phase Space of Astronomical Transients



Discovery Phase Space of Astronomical Transients

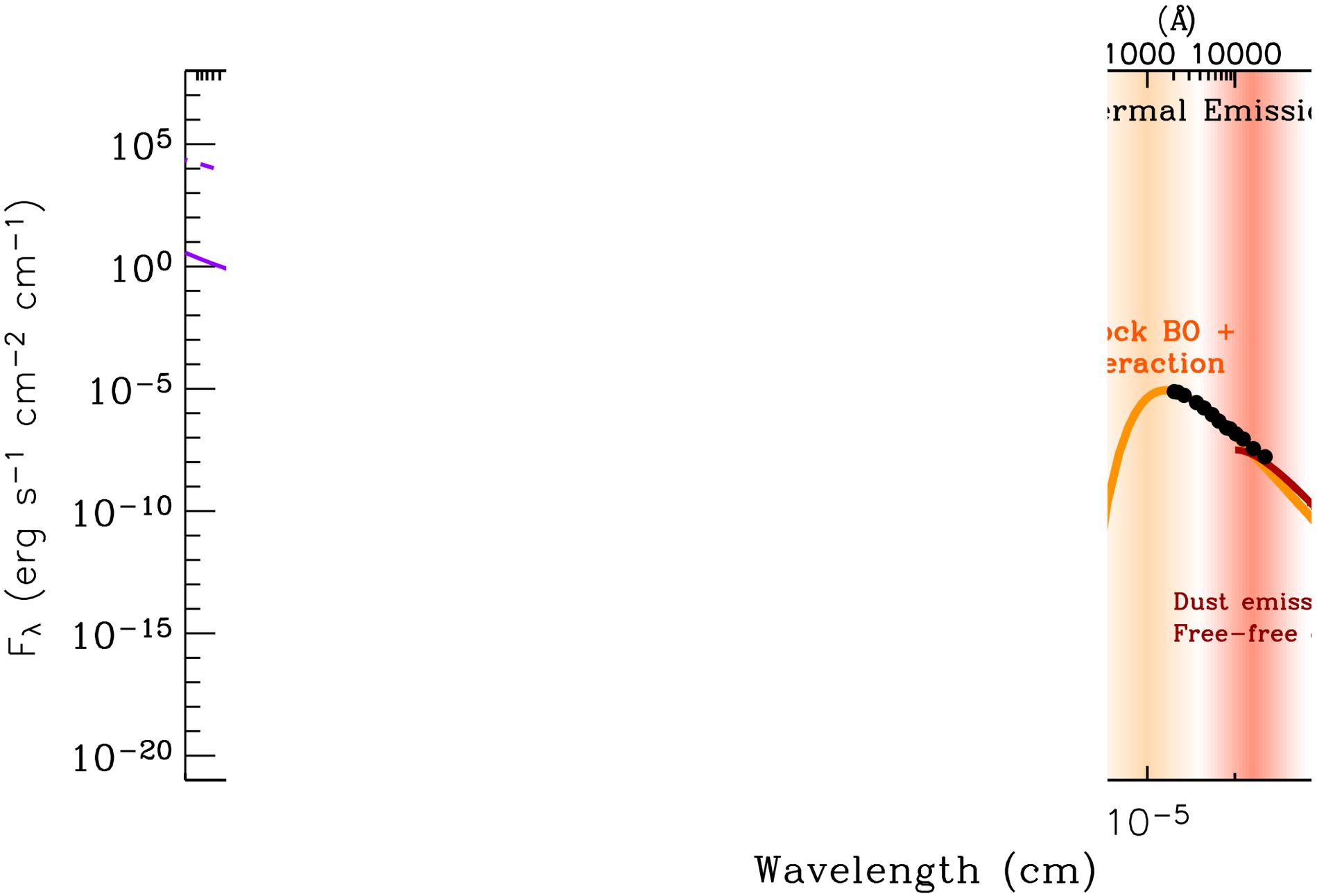


Energy partitioning



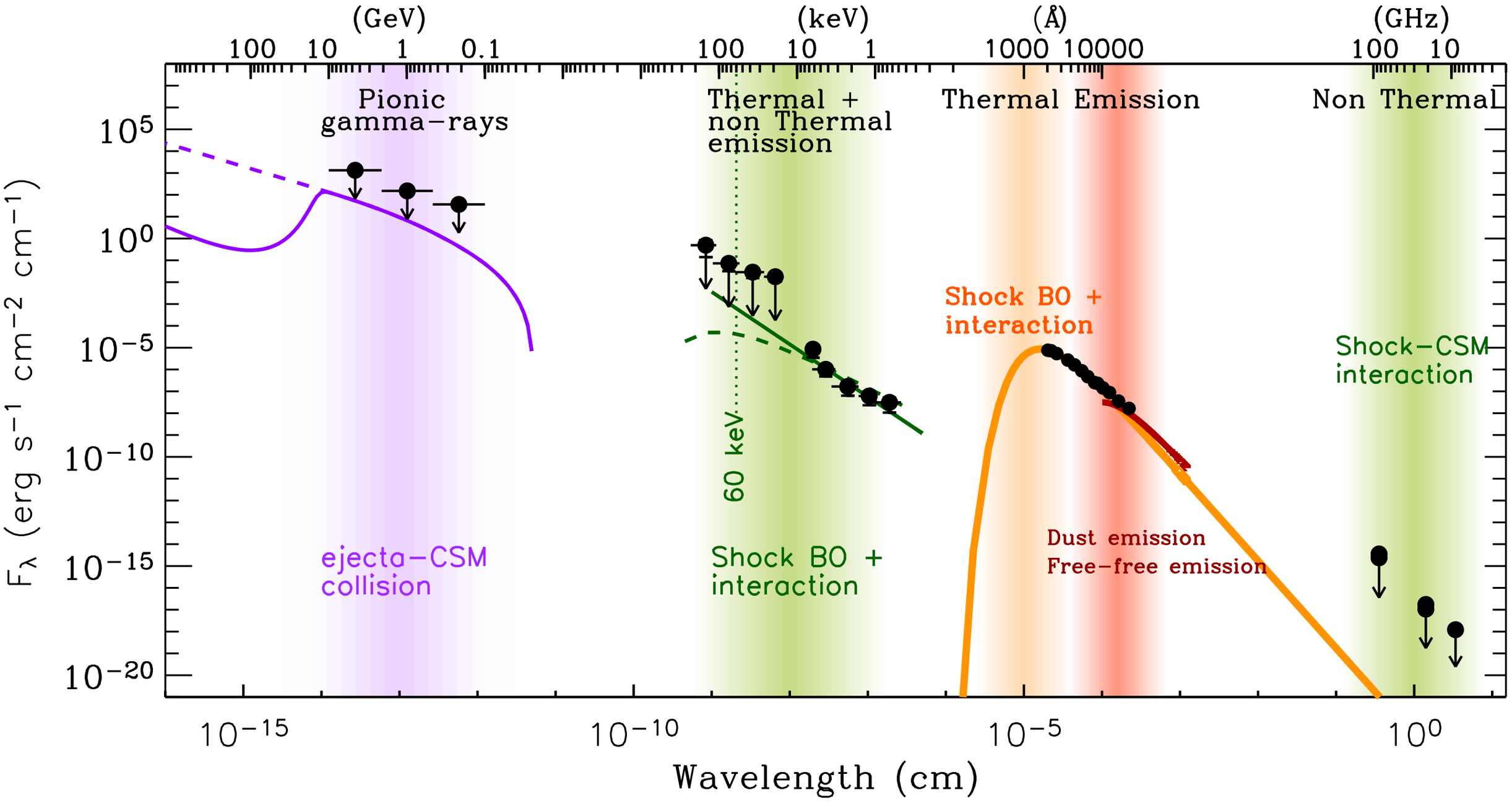
Margutti +13,

Gamma-ray to Radio SED of SN2009ip at peak



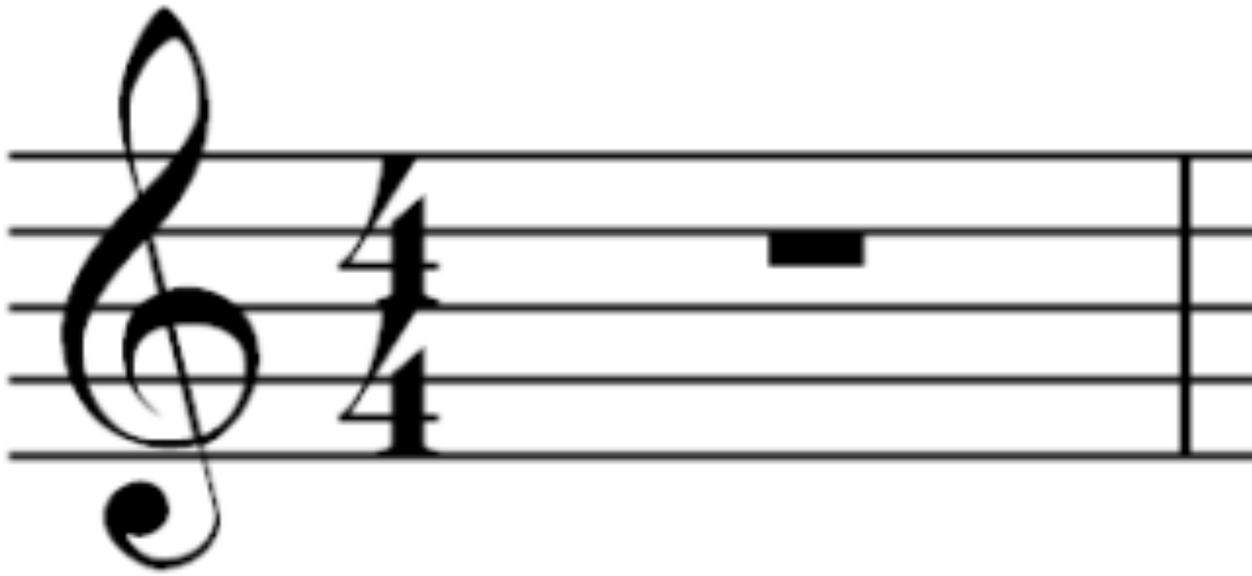
RM+14

Gamma-ray to Radio SED of SN2009ip at peak



RM+14

Thanks to: VERITAS, Fermi, Swift, NuSTAR, XMM, Chandra, HST, ALMA, SMA, VLA, CARMA, GMRT, ATCA, Keck, MMT, SOAR for supporting our investigation.



"...The END

is where we start from..."

The Little Gidding by T.S. Eliot

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CIERA

CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

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August 19 - 22, 2019 | #HOTWIREDVI

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Register by June 17, 2019

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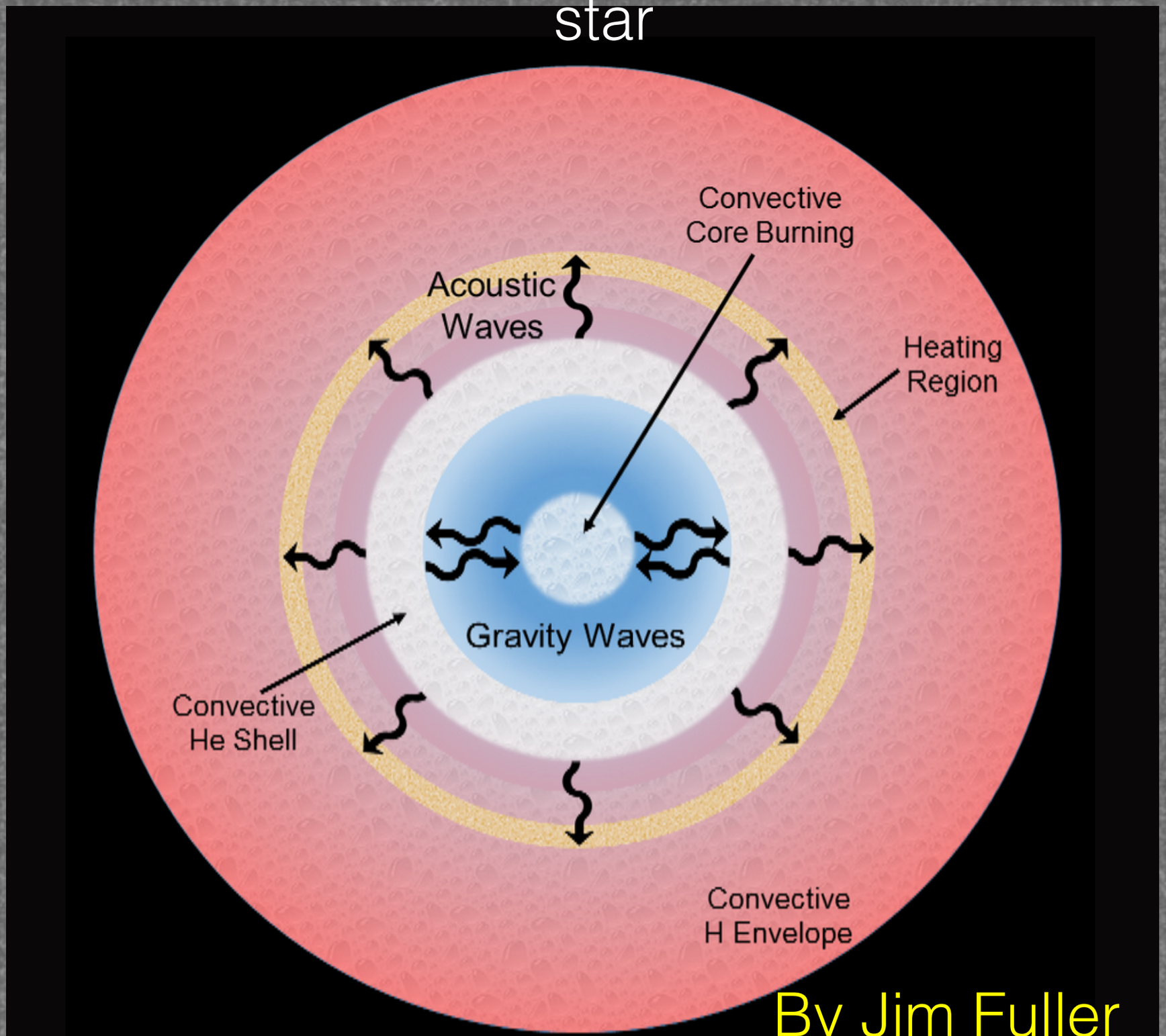
Back up

Cartoon picture showing how waves excited in the core of a star can travel into the envelope of a star, where they deposit enough energy to power an eruption from the surface of the star



By Jim Fuller