



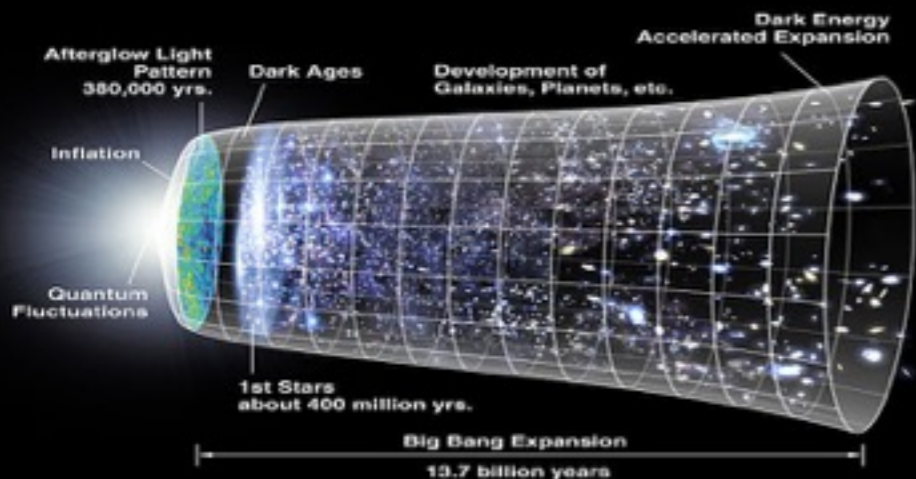
# The Renaissance of Astrophysics:

a landscape of  
opportunities in the  
era of Time-Domain  
Multi-messenger  
investigations

Raffaella Margutti  
UC Berkeley

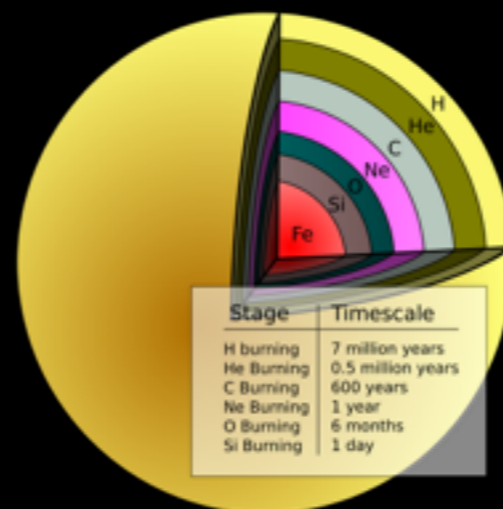
*“We always find something, eh Didi,  
to give us the impression we exist?”*

## Cosmology: Distance Ladders



First sources of ionizing photons

## Chemical Enrichment

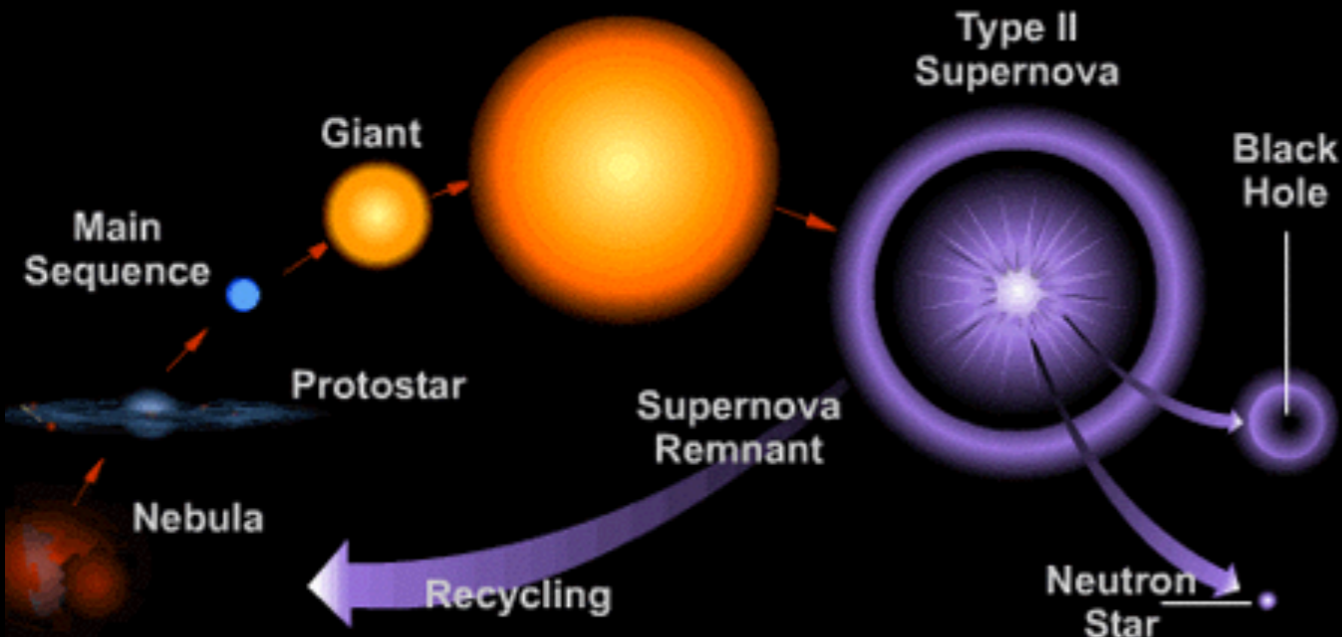


## Galaxy Feedback

Deposition of Radiative+  
Mechanical Energy

# Explosive Transients

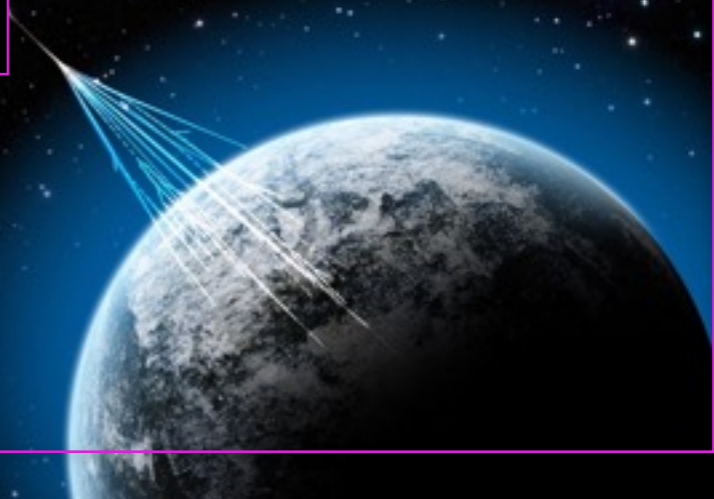
## Endpoint of Stellar Evolution



They produce the  
most Extreme  
Objects

Laboratories of  
Extreme Physics (jets)

Sources of GWs and  
Neutrinos

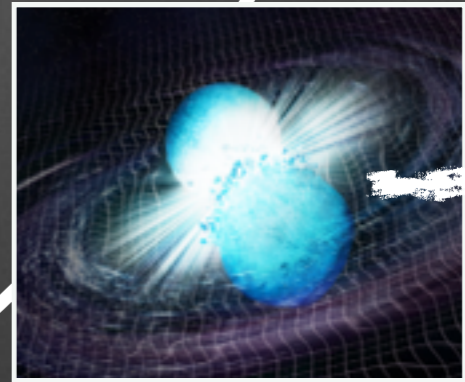
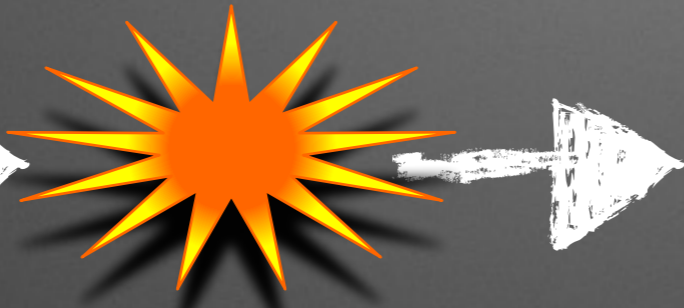




How do massive stars approach their death?

What are the properties of newly-born BHs and NSs?

What powers stellar explosions?



What are the progenitors?

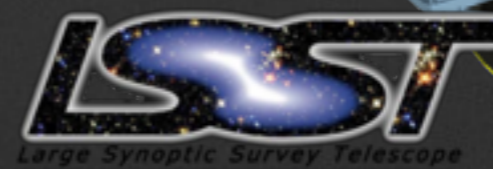
Gravitational Waves  
+ Light

How do compact-object mergers look in the electromagnetic spectrum?



# Why NOW?

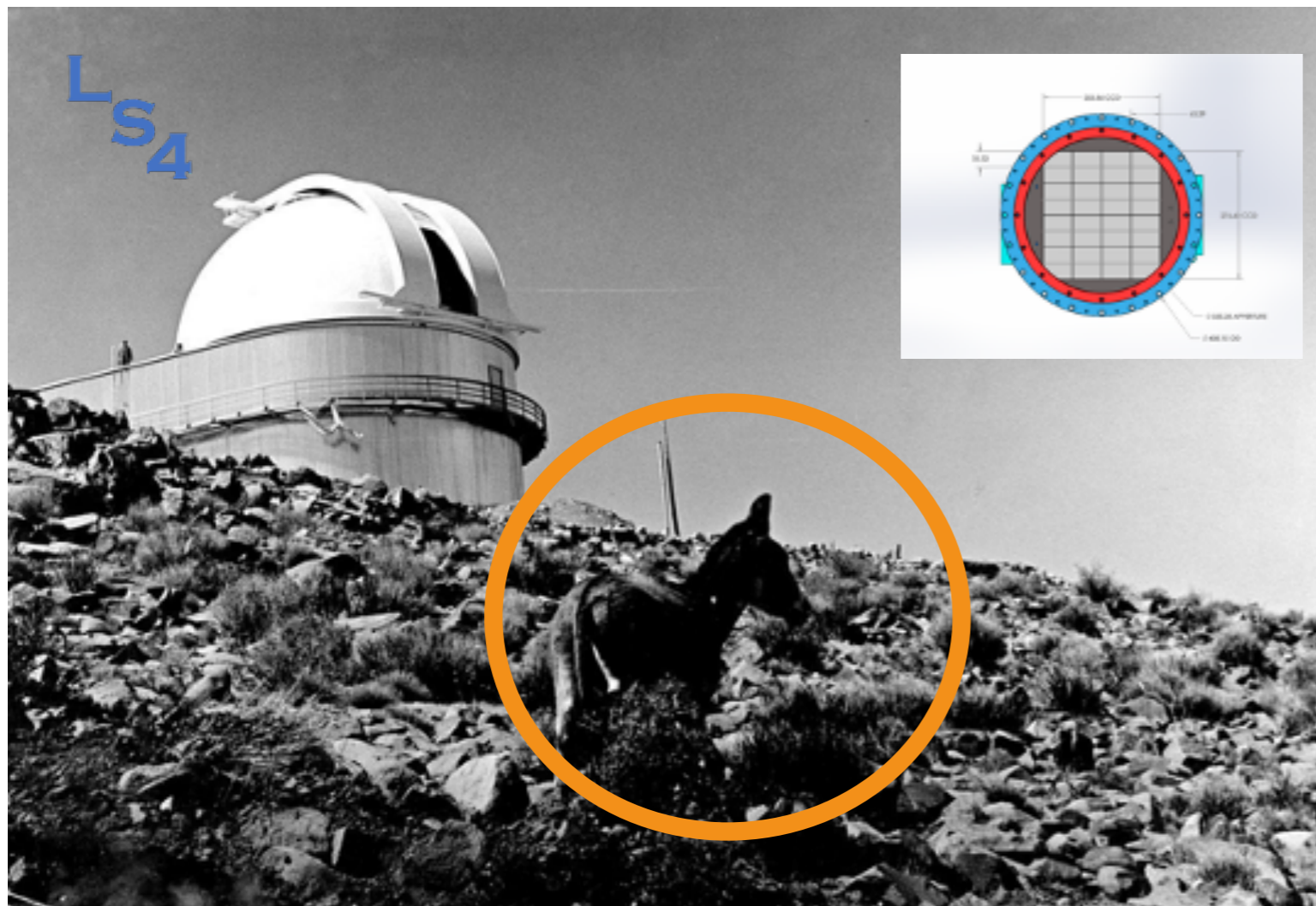
## 1. Technological Revolution ==> Time Domain Astrophysics





# The La Silla Schmidt Southern Survey (LS4), PI P. Nugent

## Quick Facts Summary

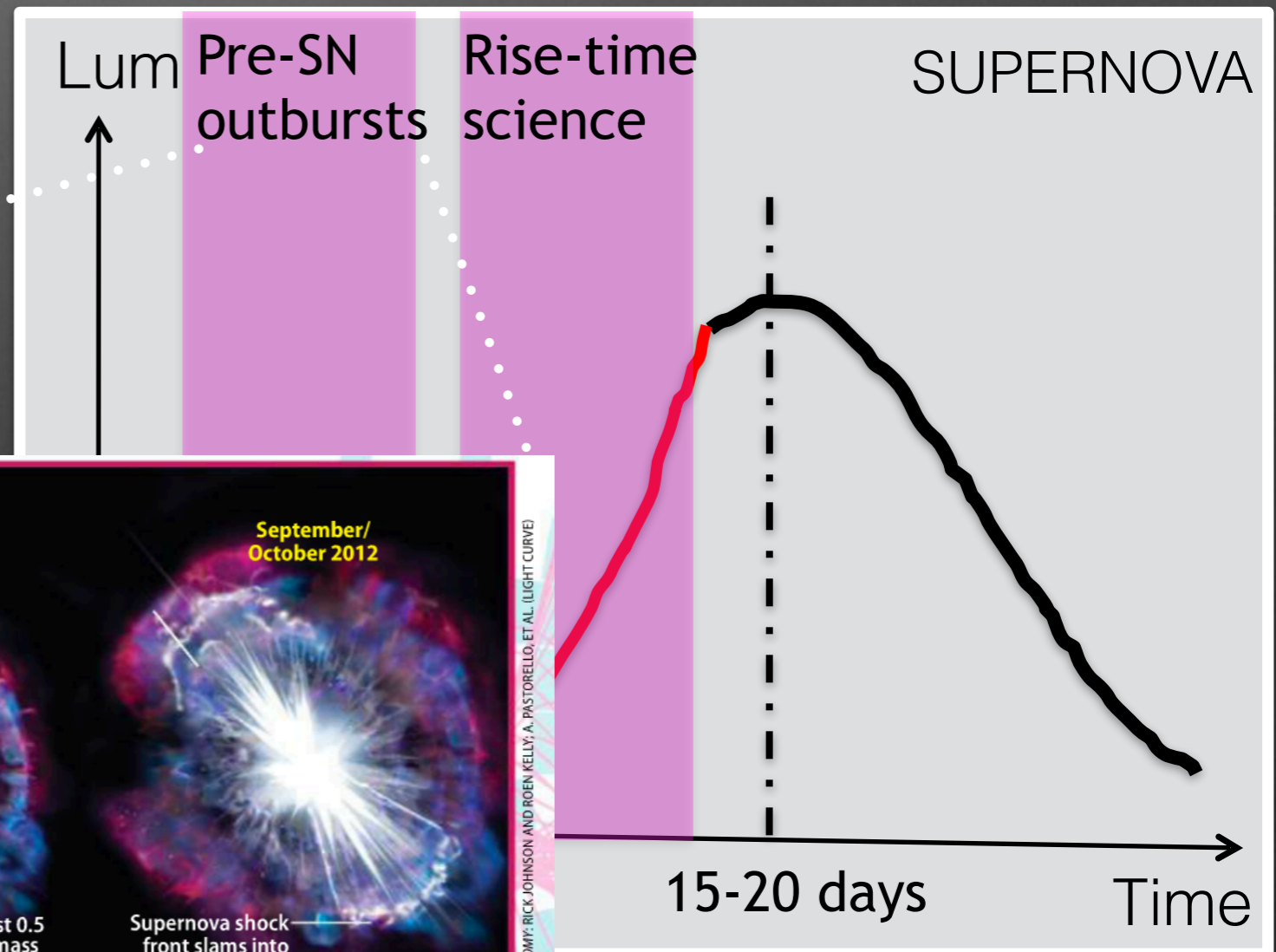


- 20 sq. deg. fov
- 2 fixed filters (g+z)
- 45s exp; 15s read +slew
- g-band: 21.0+/- 0.5
- z-band: 20.0
- 2k-4k sq.deg./night
- ~90% Survey mode
- ~10% ToO's and focused experiments
- ~90 % Real-time public data

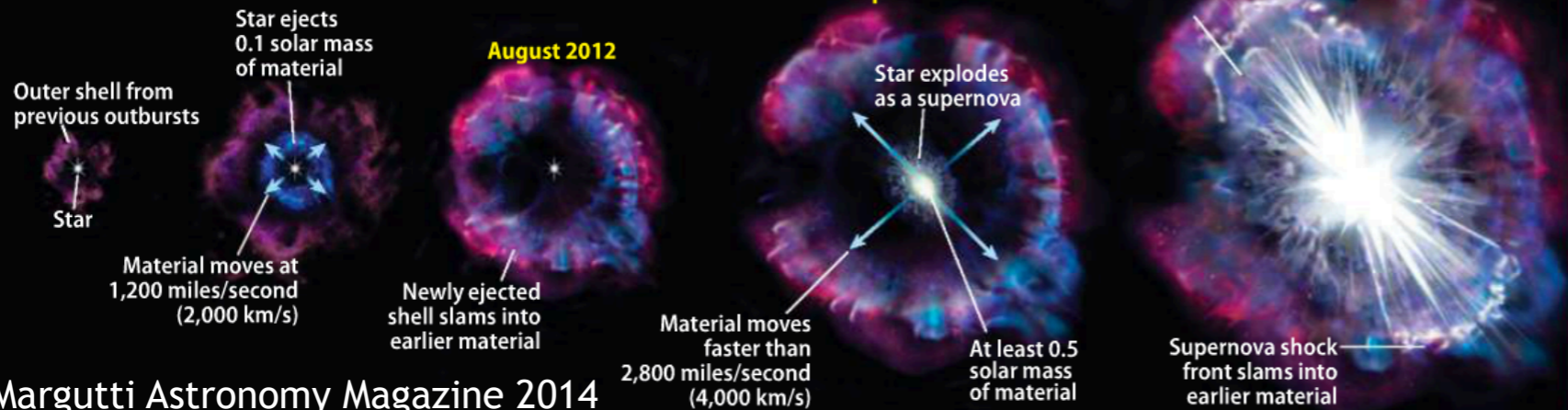
Where do we stand?  
Where do we go?

# 1. Technological Revolution ==> Time Domain Astrophysics

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



## A supernova symphony unraveled?





Where do we stand?  
Where do we go?

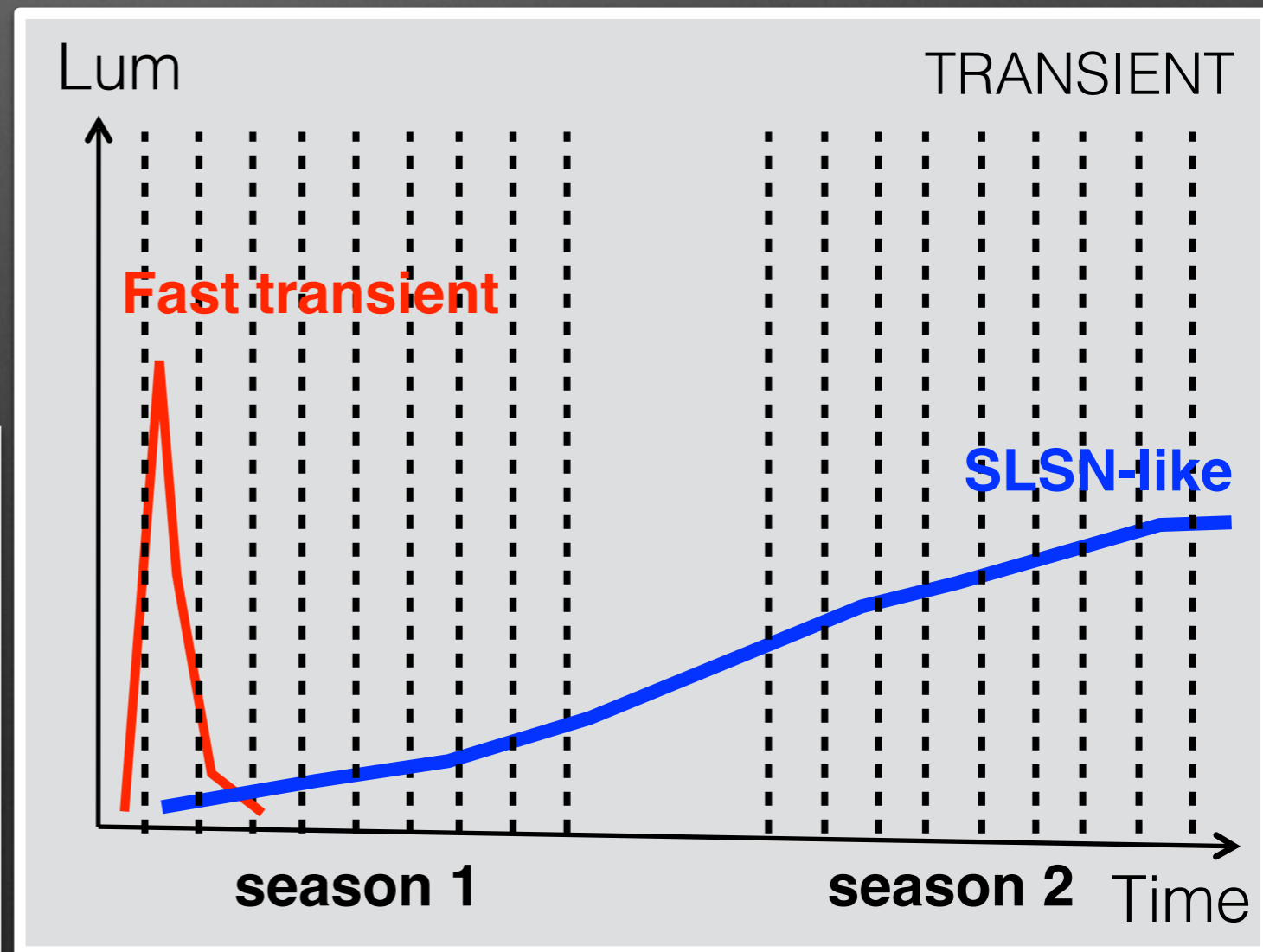
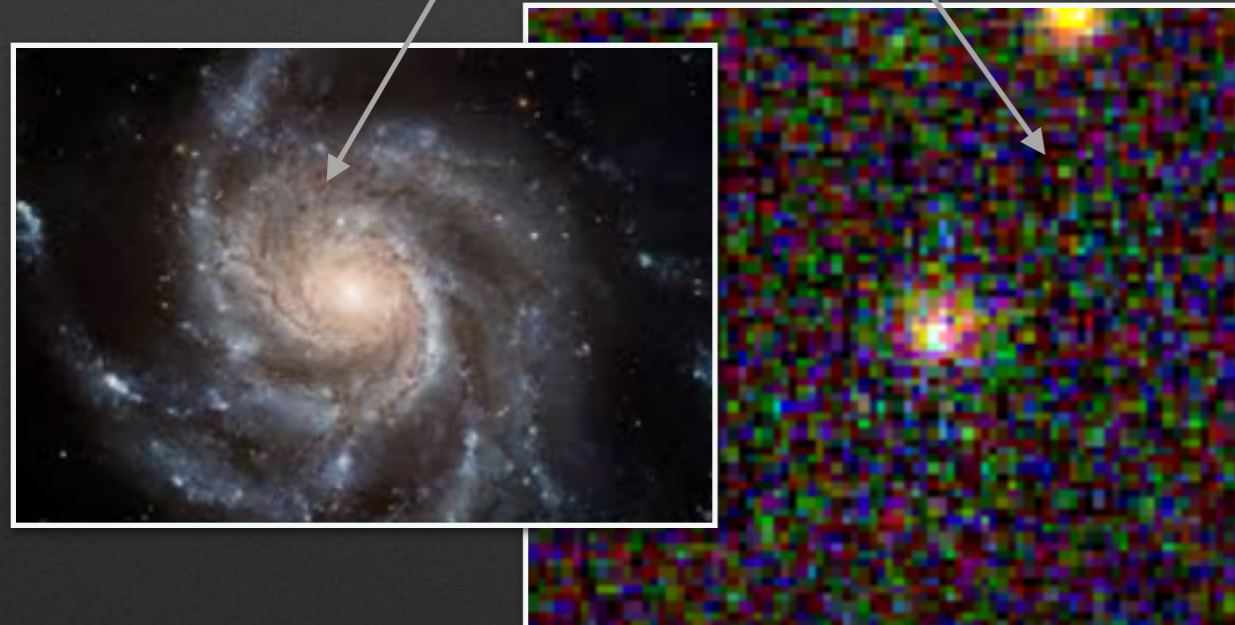
# 1. Technological Revolution ==> Time Domain Astrophysics

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)

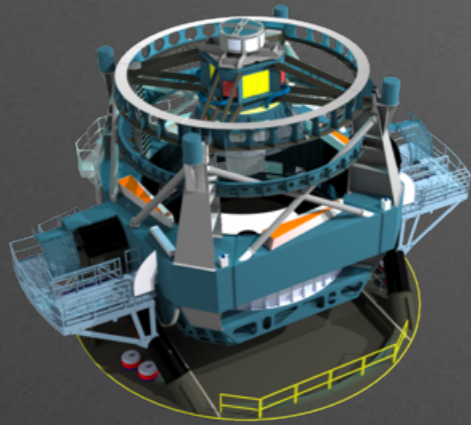
Time scales

Untargeted search



# Why NOW?

## 1. Technological Revolution ==> Time Domain Astrophysics

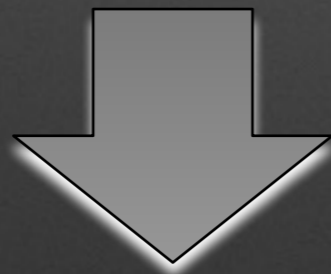


Explore a new parameter space in already known transients  
(Rise-time science; pre-SN science; shock break out science)

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

# DISCOVERY power

## 2. Multi-Wavelength Astrophysics



Multi-messenger Astrophysics  
(neutrinos, GW)

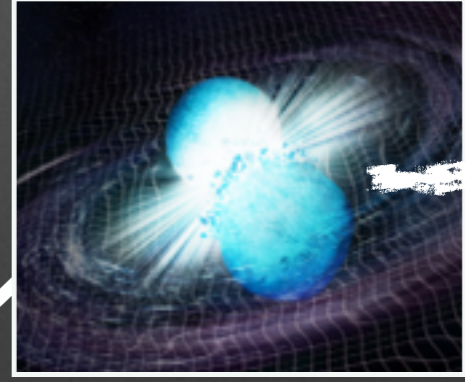
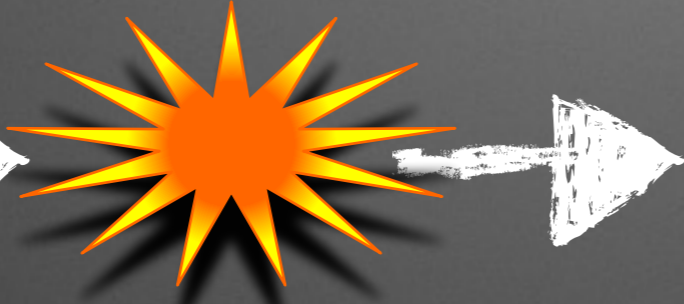
# UNDERSTANDING



How do massive stars approach their death?

What are the properties of newly-born BHs and NSs?

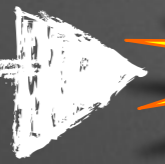
What powers stellar explosions?



What are the progenitors?

Gravitational Waves  
+ Light

How do compact-object mergers look in the electromagnetic spectrum?





No photon left behind...

Inter-Planetary  
Network

INTEGRAL

NuSTAR

XMM

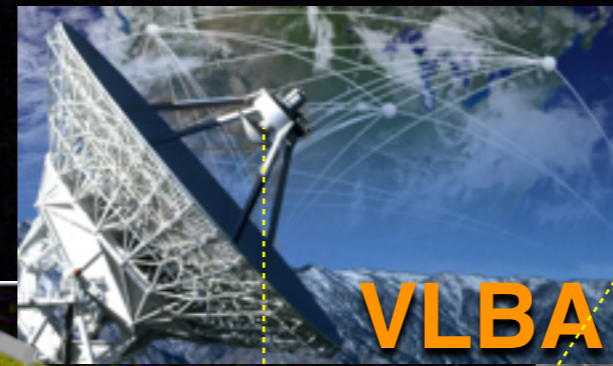
Swift-Gehrels

WIYN

Keck Telescopes

UV/Optical/NIR

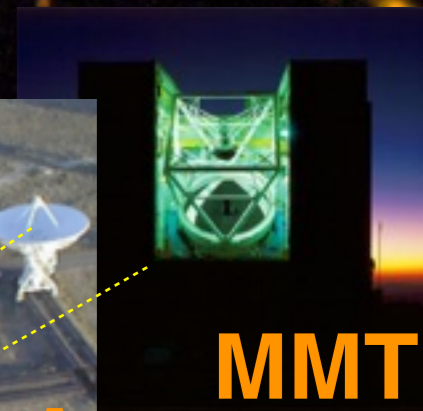
Radio



VLBA



VLA



MMT



UKIRT



Magellan



CTIO



SOAR

18cwo

$\gamma$ -rays

X-rays



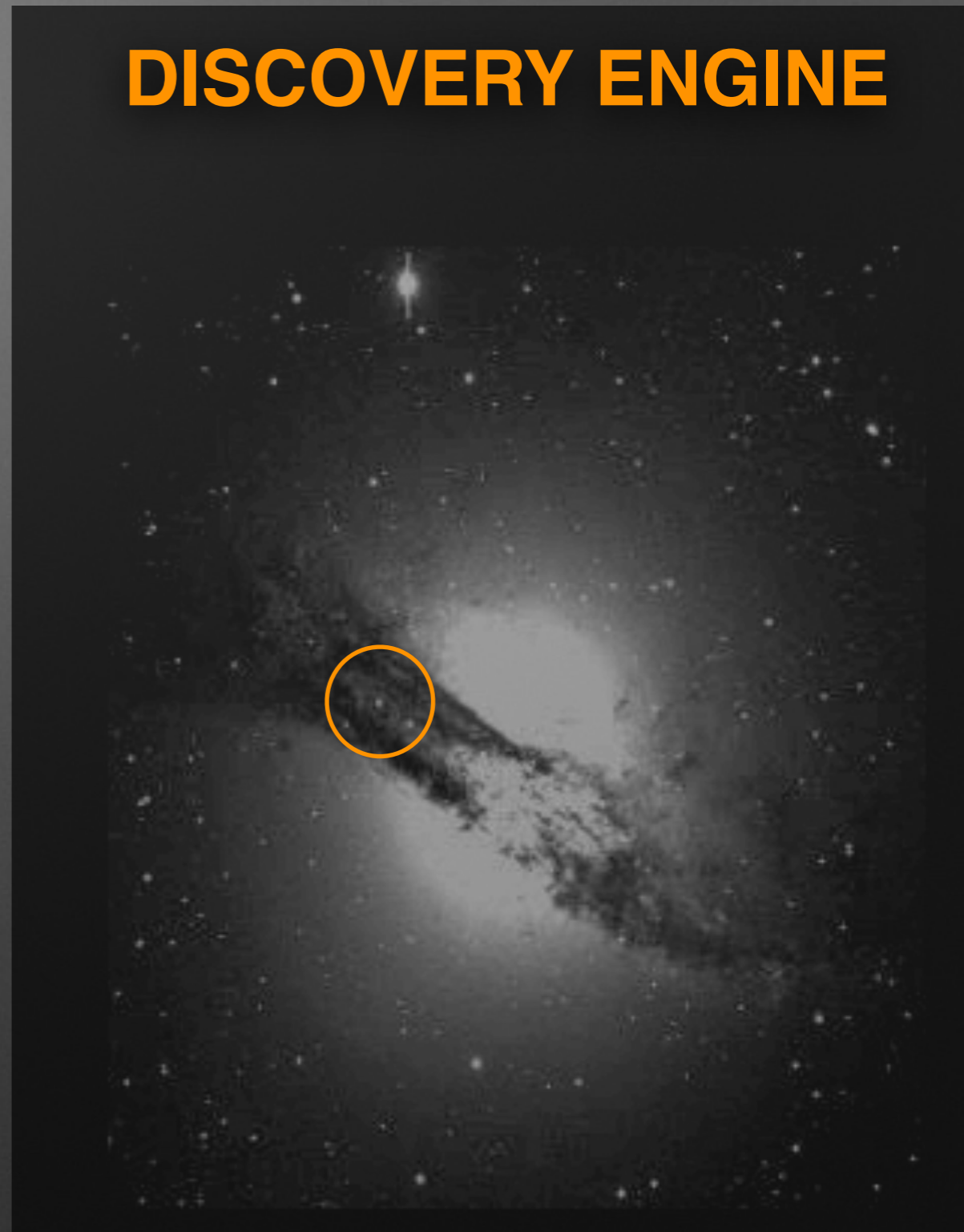


# From Discovery to Understanding: an End-to-End experiment

**FOLLOW UP  
TEAM**



**DISCOVERY ENGINE**



Credit: SSP/Lawrence Berkeley National  
Laboratory's Computer Visualization  
Laboratory

# From Discovery to Understanding: an End-to-End experiment

**FOLLOW UP  
TEAM**



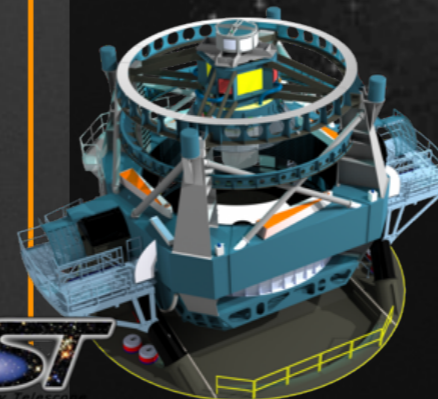
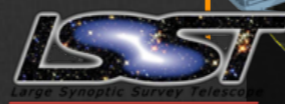
## **DISCOVERY ENGINE**

**YSE** (PS1-2: depth)

**ZTF** (rate)

+

**ARTIFICIAL INTELLIGENCE**  
(HS supported, new approach)



Credit: SSP/Lawrence Berkeley National  
Laboratory's Computer Visualization  
Laboratory



# From Discovery to Understanding: an End-to-End experiment

**FOLLOW UP  
TEAM**



## **DISCOVERY ENGINE**

**YSE** (PS1-2: depth)

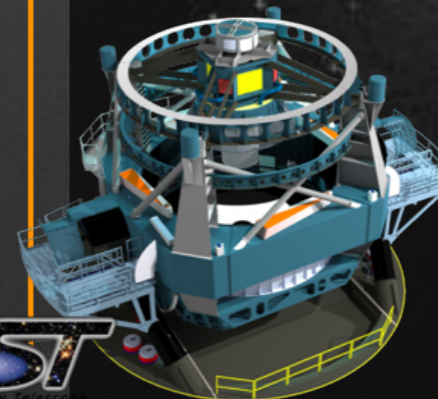
**ZTF** (rate)

+

**ARTIFICIAL INTELLIGENCE**  
(HS supported, new approach)

+

**LIGO** (GW sources)



Credit: SSP/Lawrence Berkeley National  
Laboratory's Computer Visualization  
Laboratory

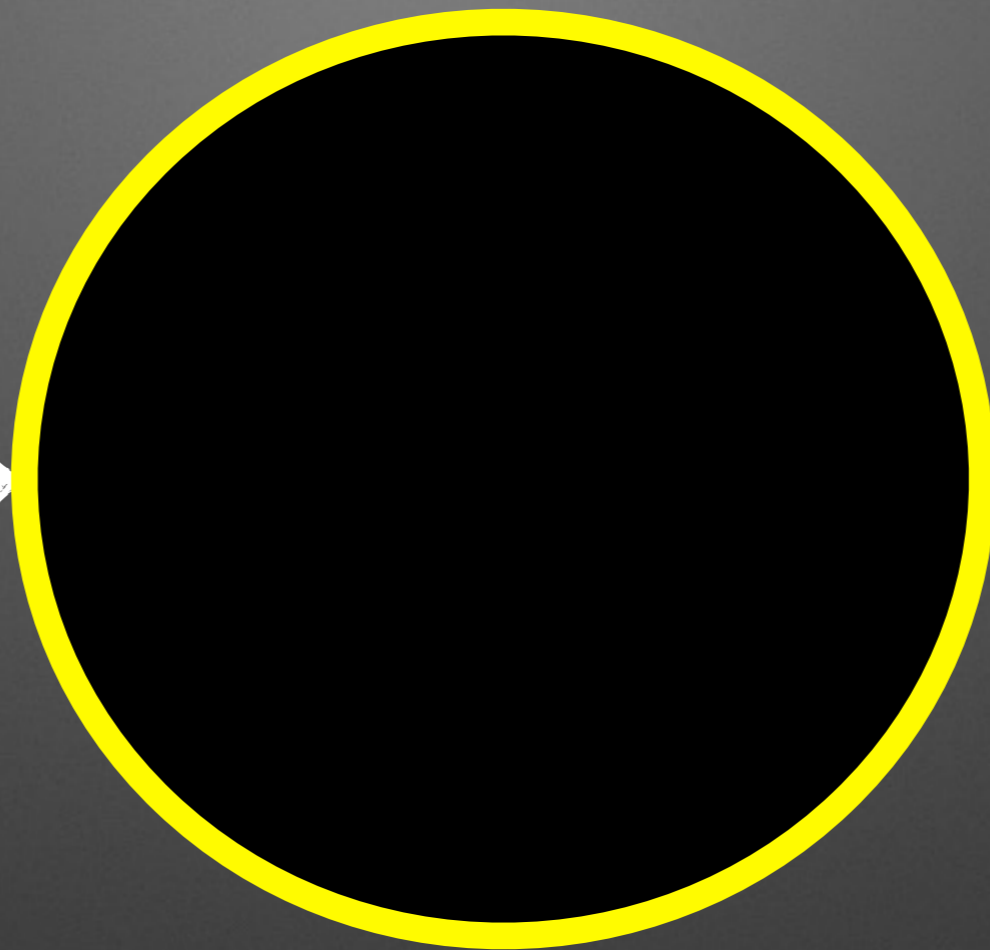


$\gamma$ -rays

X-rays

UV/Optical/NIR

Radio



— — — — —  
~ 1000 yr





# The last years before explosion

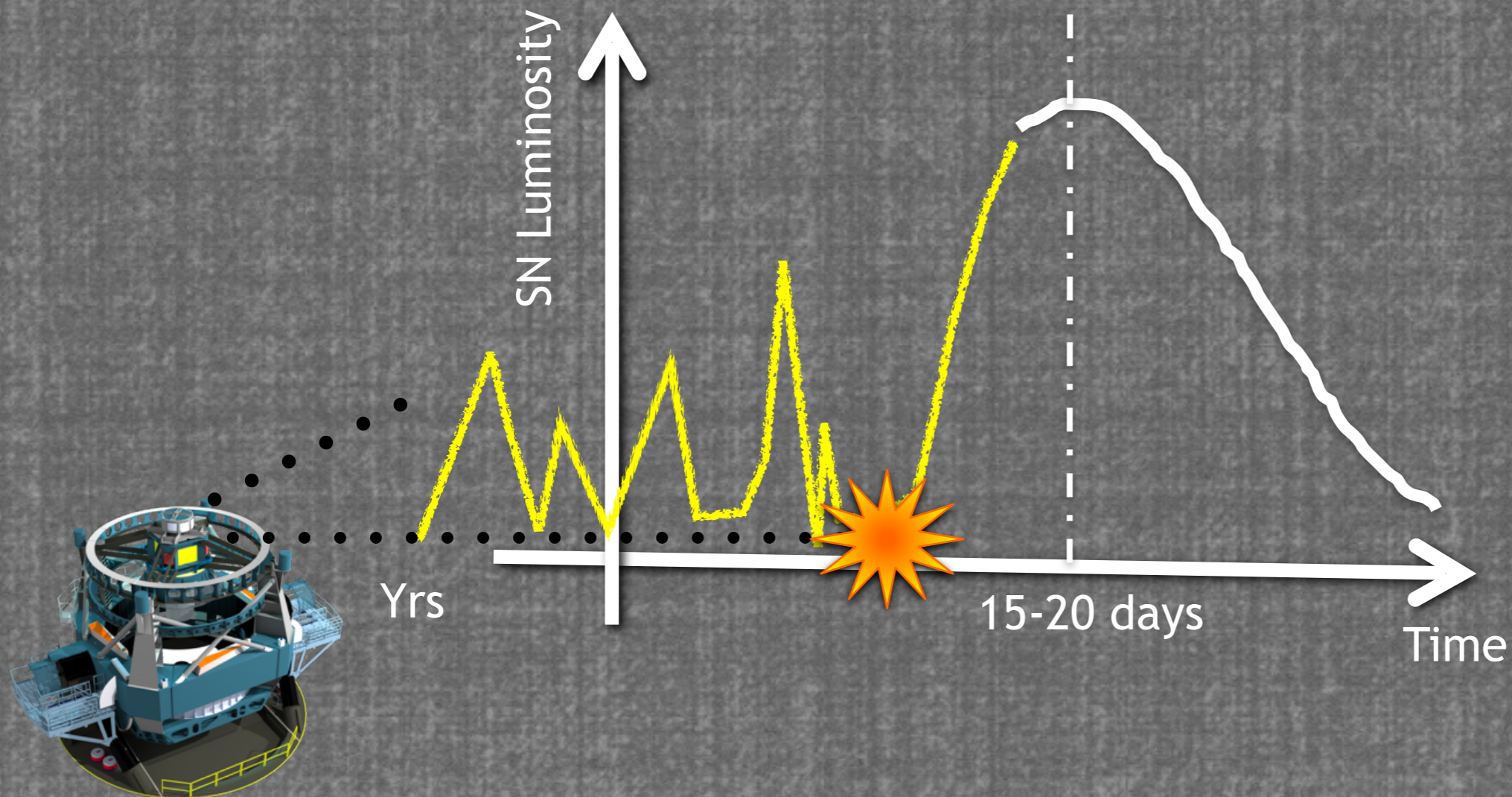
**Direct  
Observations**

Flash

Spectroscopy

Shock

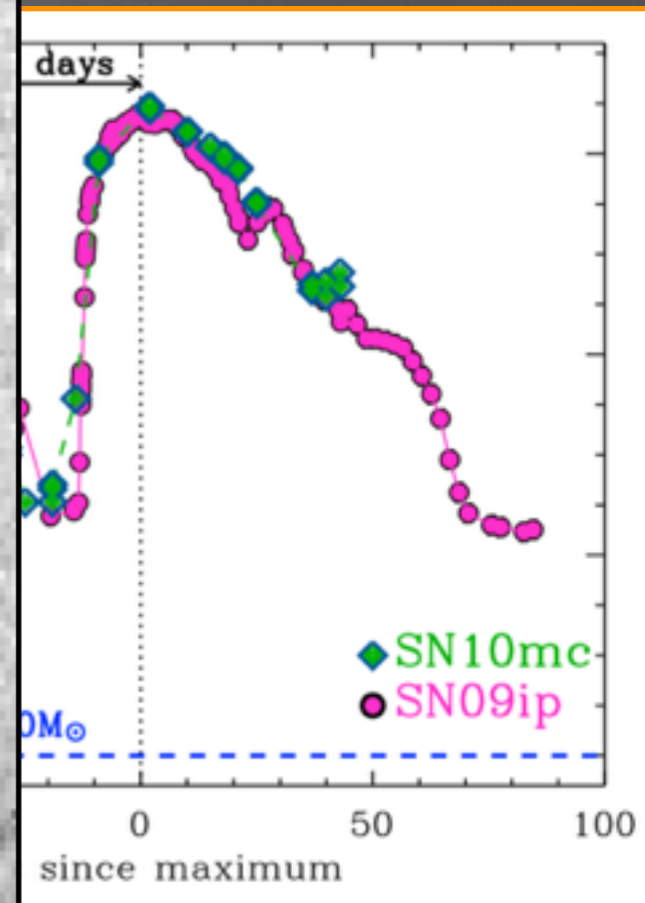
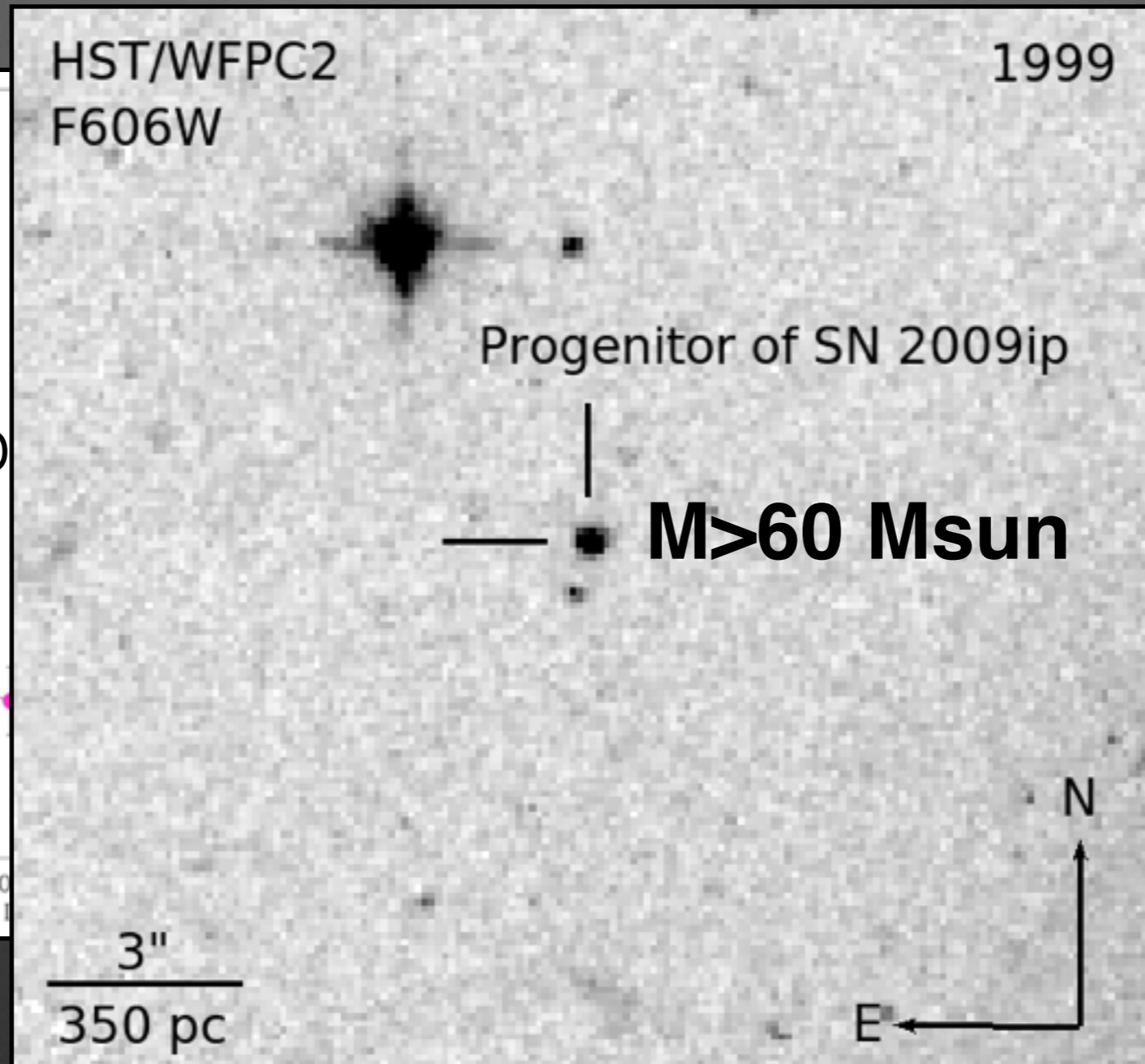
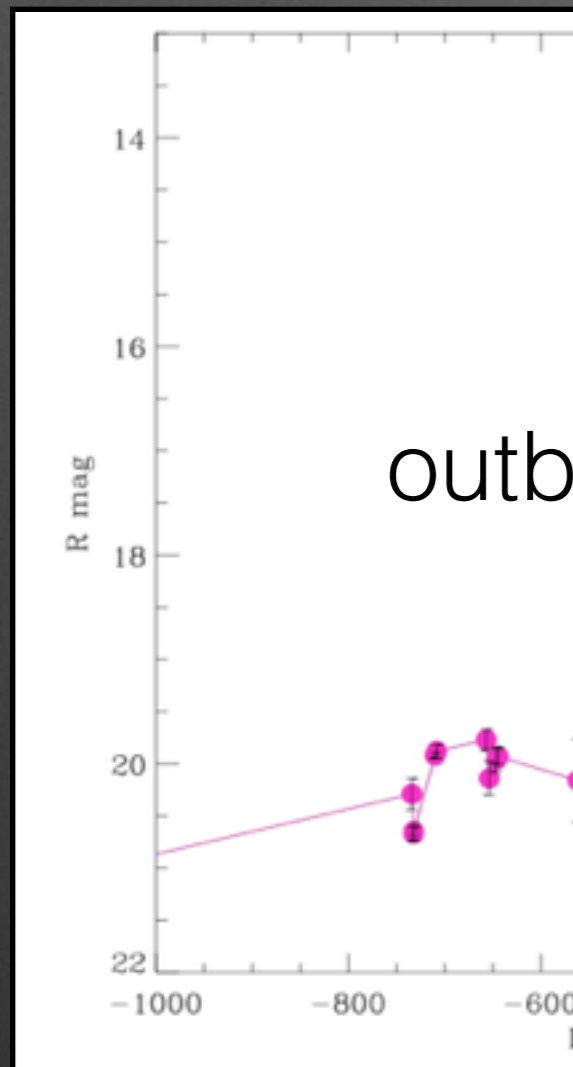
Interaction





# Pre-SN outbursts are common among H-rich progenitors

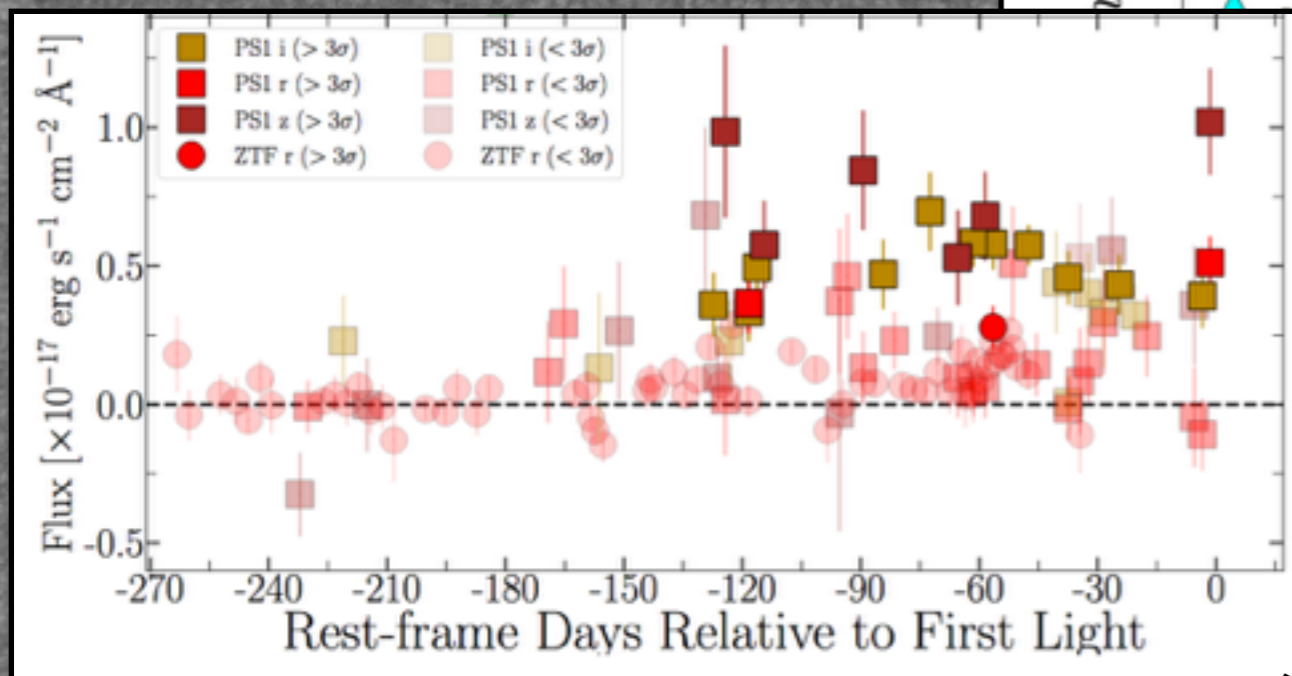
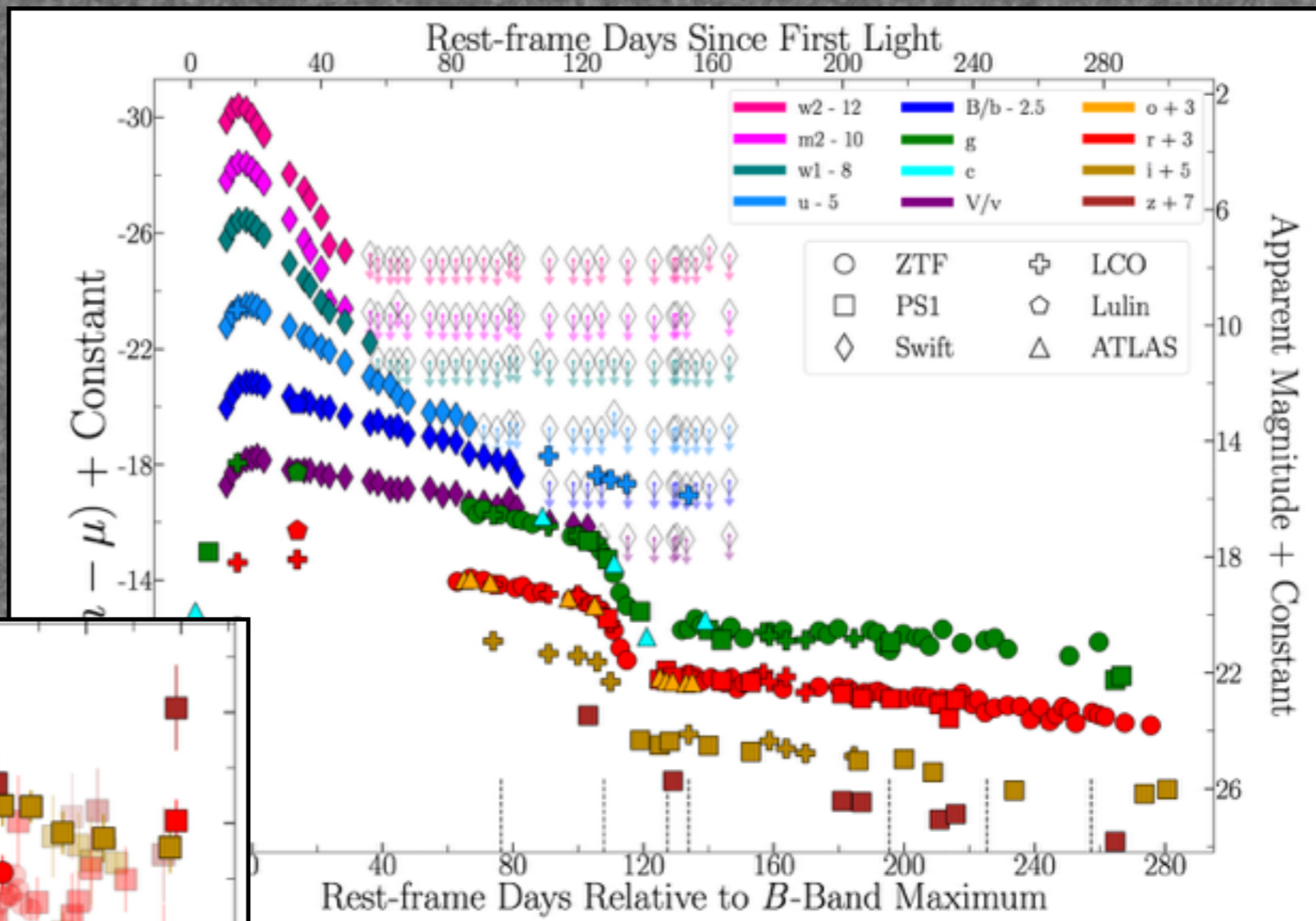
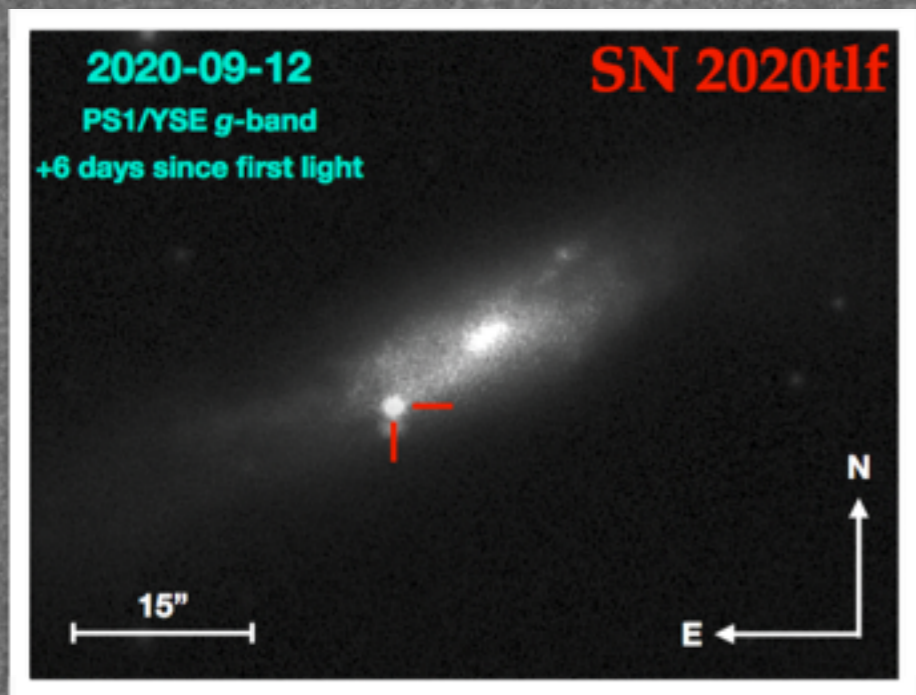
E.g. Margutti+14, Ofek+14, Smith+15



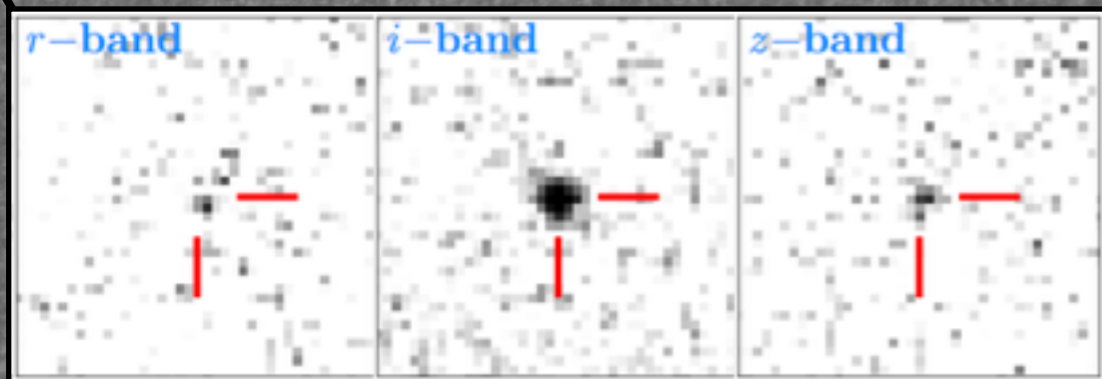
Smith et al, 2010; Foley et al., 2011

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



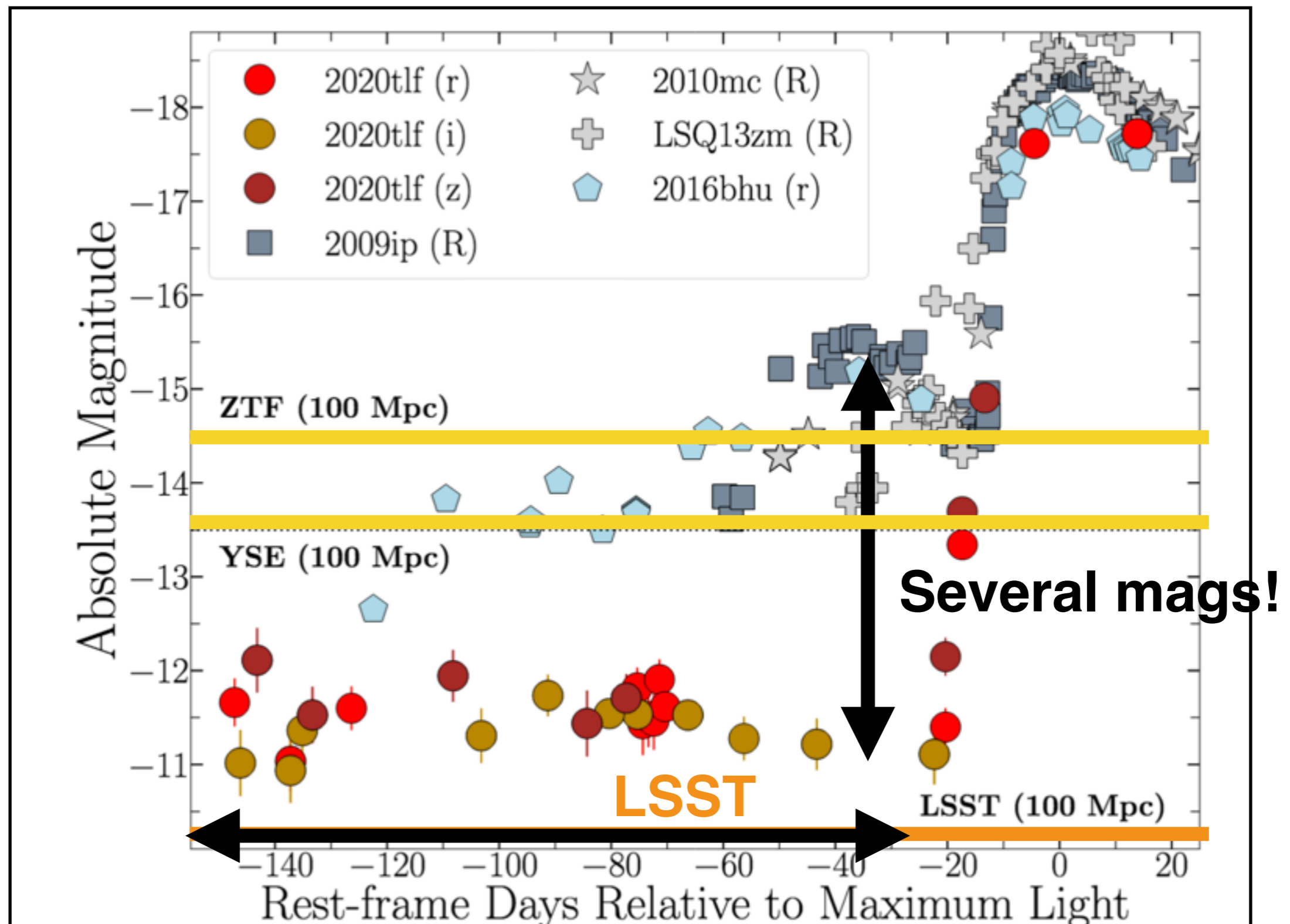


Jacobson-Galan+2021



**Pre-SN “activity”  
for ~100 days before collapse  
in an ordinary Type II SN**

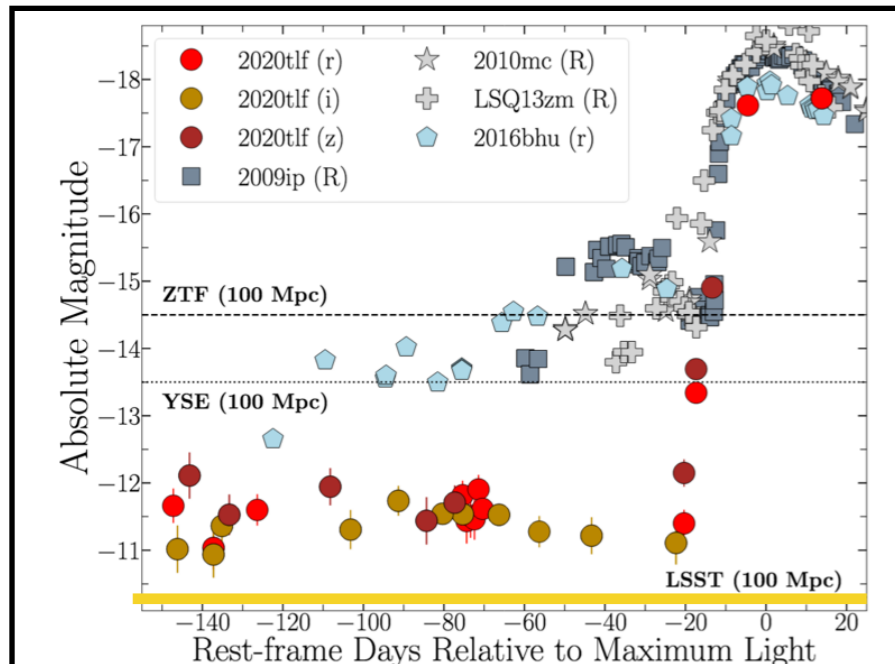
# Pre-SN outburst from the most common core-collapse SN type





# Discovery Phase Space of Astronomical Transients

Jacobson-Galan+2021



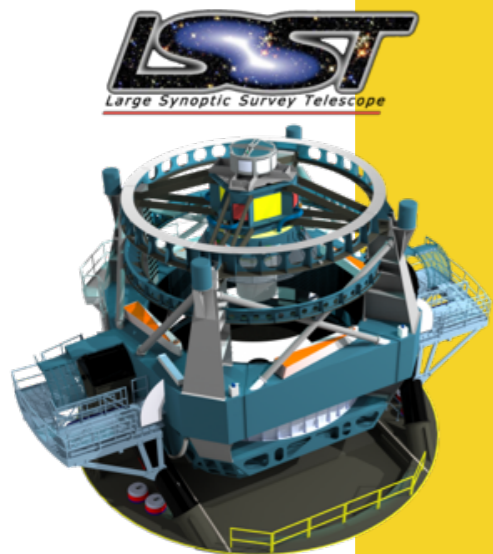
Lum

$10^{43}$  erg/s

normal SN L<sub>peak</sub>

pre-SN  
outbursts

EM  
counterparts  
to GWs



-100 yrs -10 yrs

~ few days

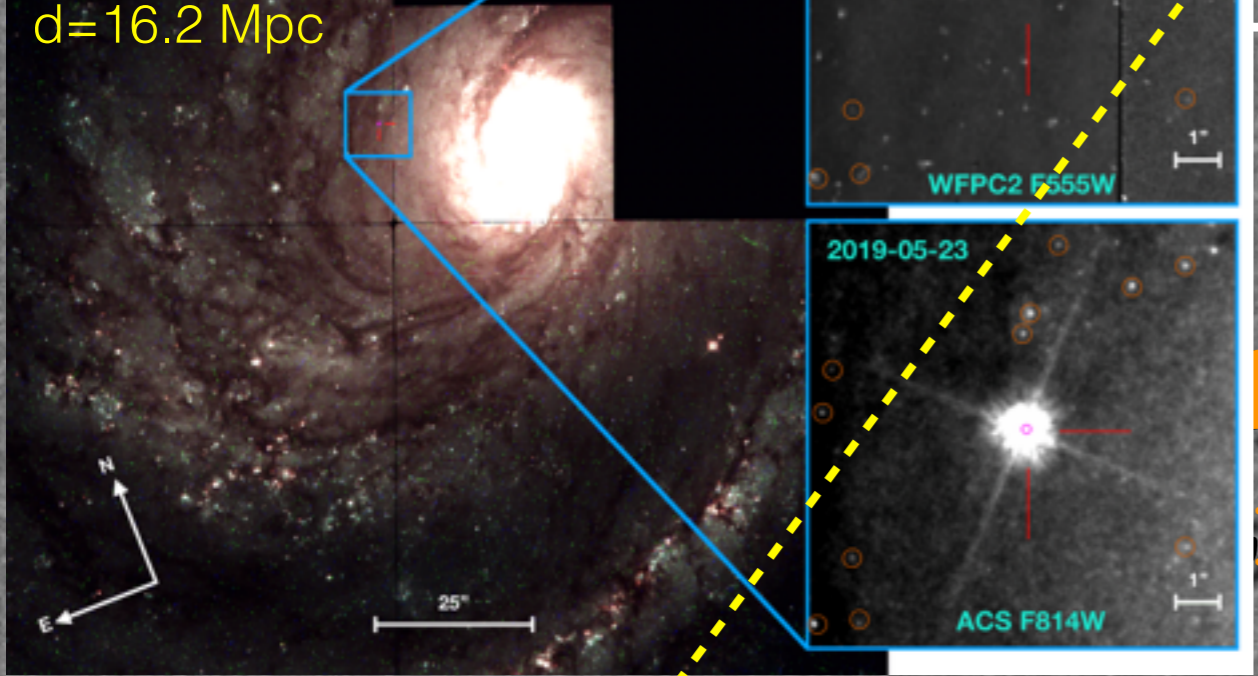
+Years

Time

# SN2019ehk

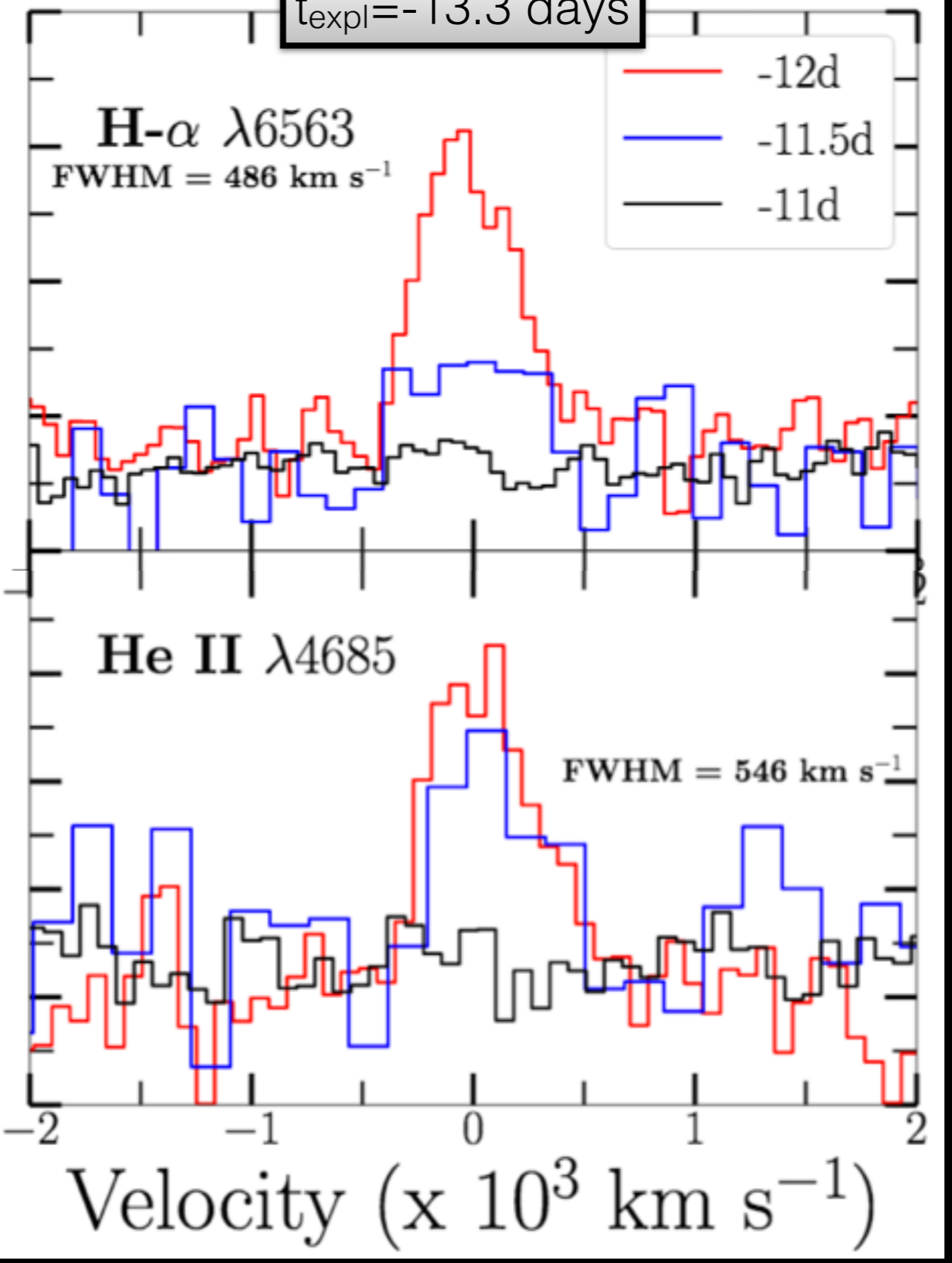
Ca-rich

d=16.2 Mpc

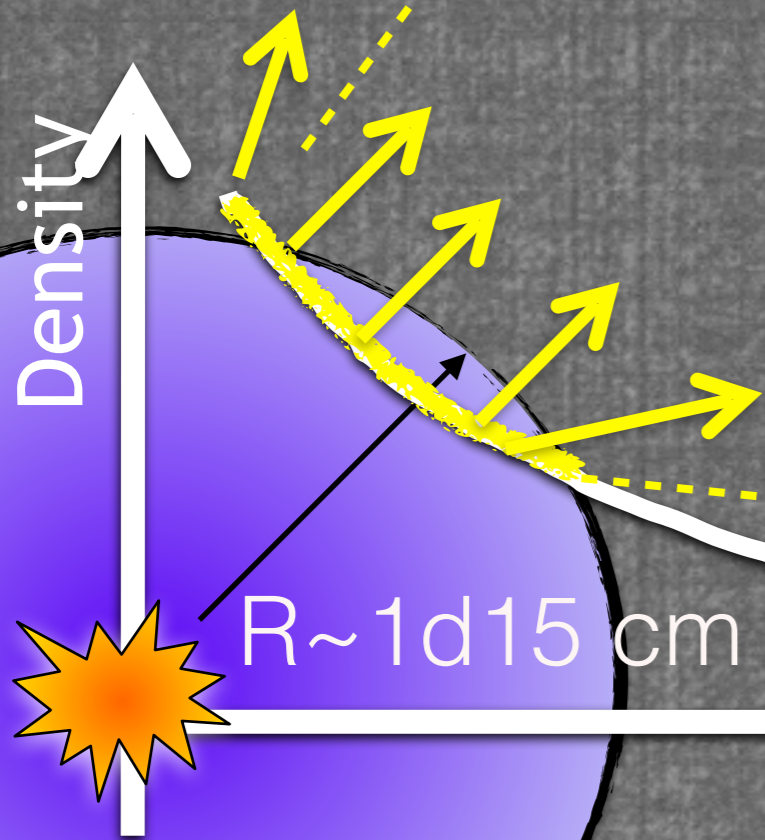


Jacobson-Galan in prep.

$t_{\text{expl}} = -13.3$  days



Jacobson-Galan in prep.

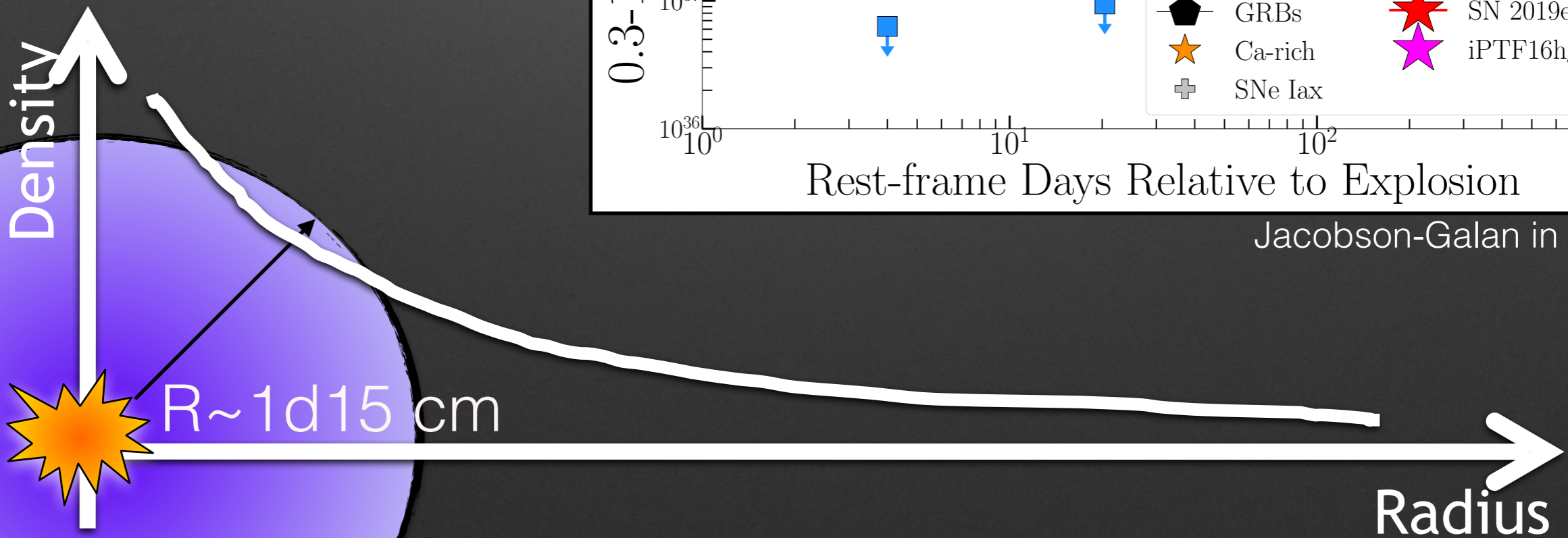
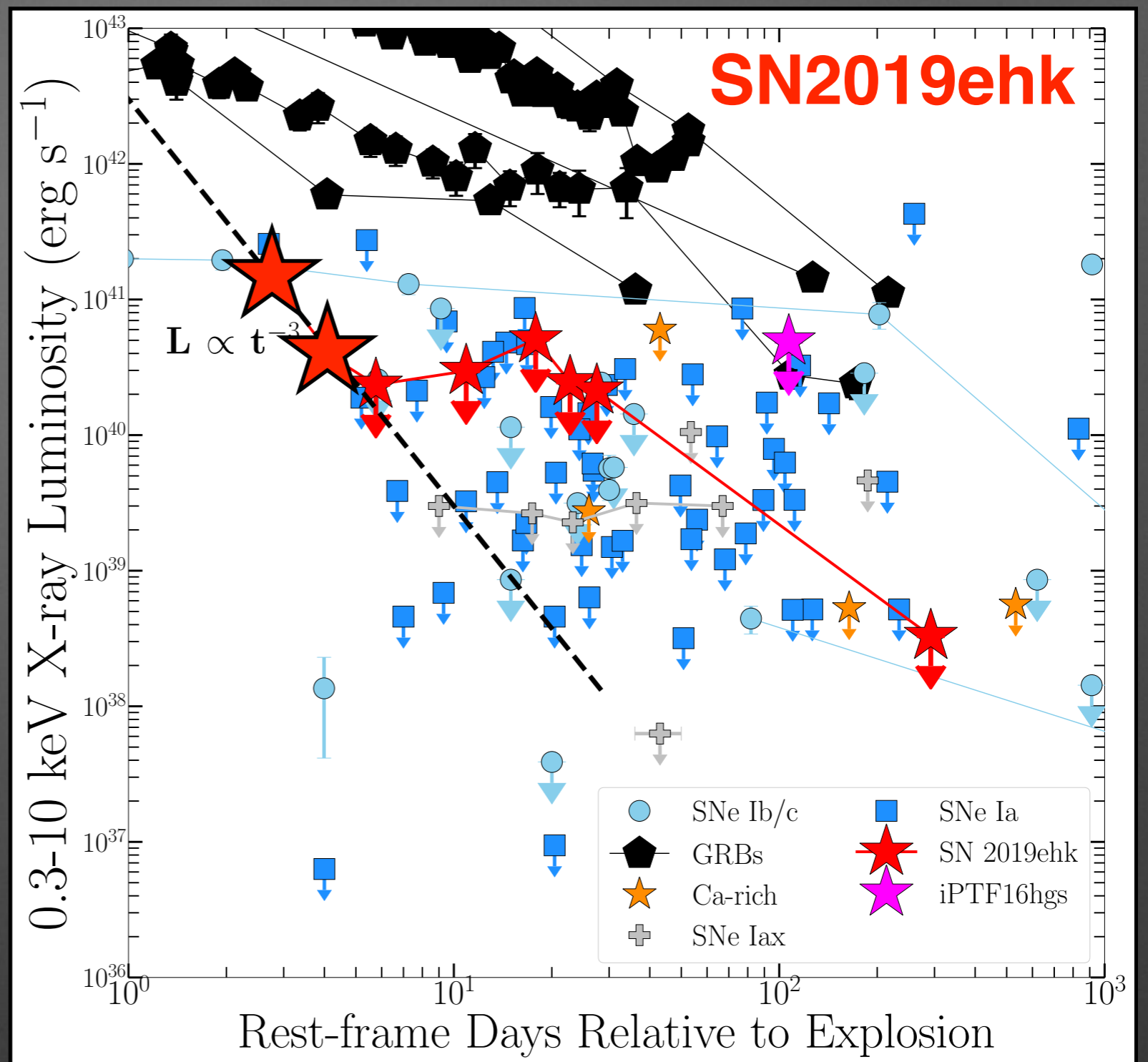


First early-time H detection in a Ca-rich transient



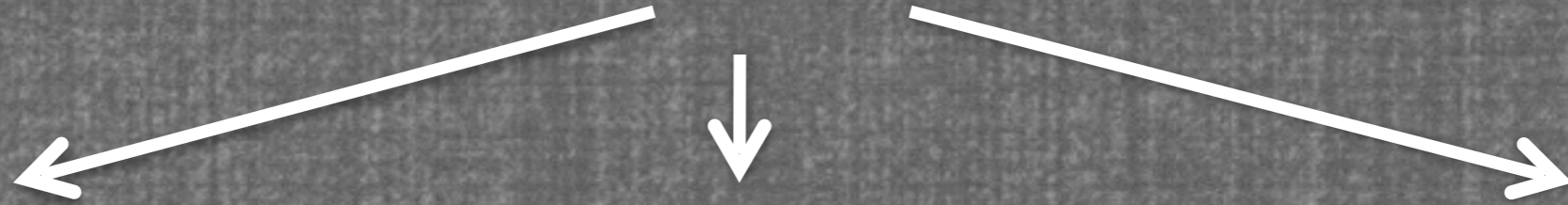
First X-ray detection  
of a Ca-rich transient

$L_x \sim 10^{41}$  erg/s (!!!)





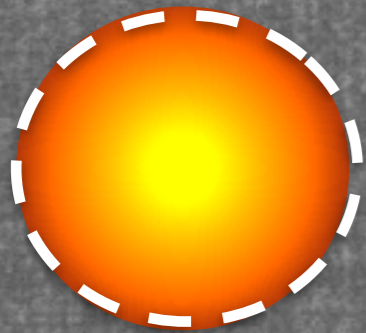
# The last thousands years



Direct  
Observations

Flash  
Spectroscopy

**Shock  
Interaction**



Supergiant



Wolf-Rayet

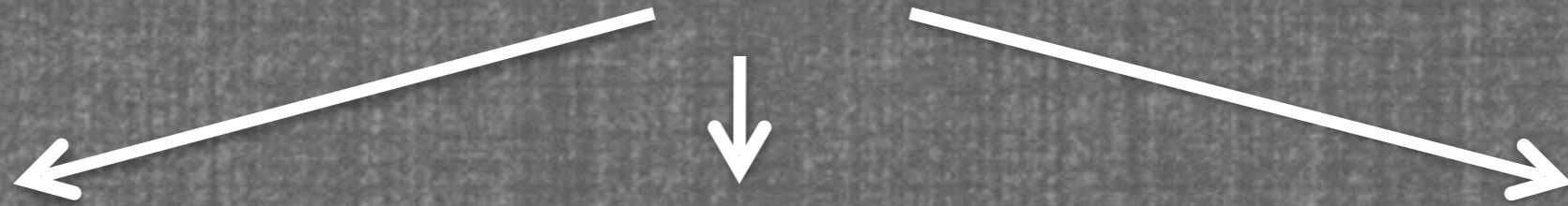
$\sim 10^4\text{-}10^5$  yrs



SN Explosion



# The last thousands years



Direct

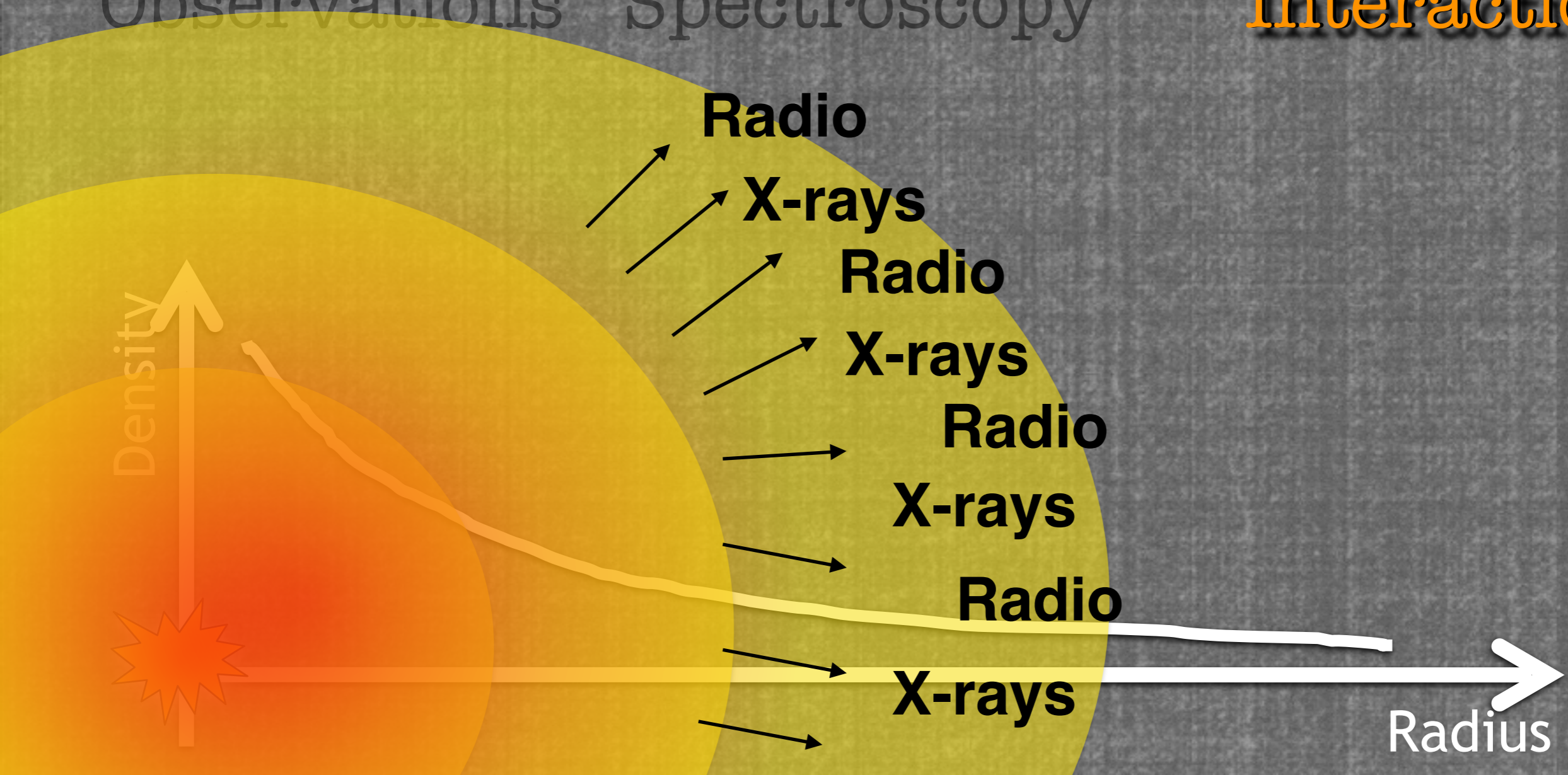
Flash

**Shock**

Observations

Spectroscopy

**Interaction**



**Radio**

**X-rays**

**Radio**

**X-rays**

**Radio**

**X-rays**

**Radio**

**X-rays**

Radius



# The last years before explosion



Direct

Observations

Flash

Spectroscopy

Shock

Interaction

Radio

X-rays

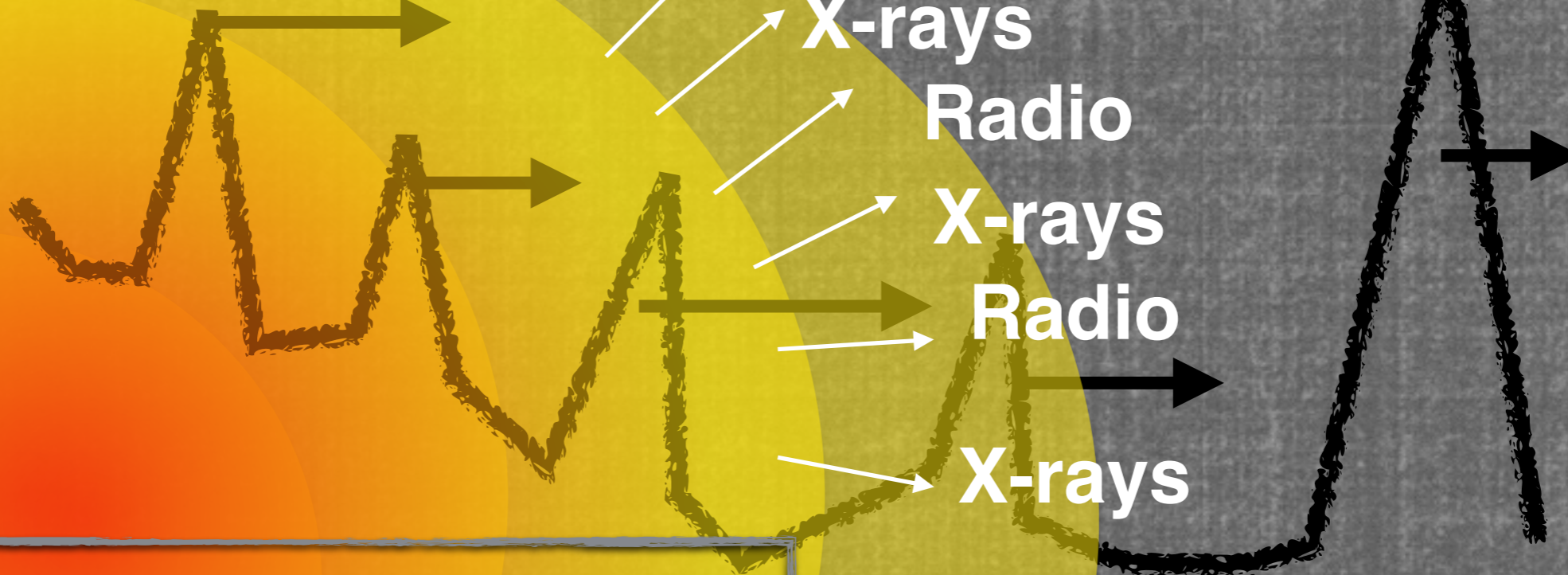
Radio

X-rays

Radio

X-rays

Density



**$V_{shock} \gg V_{ejection}$**

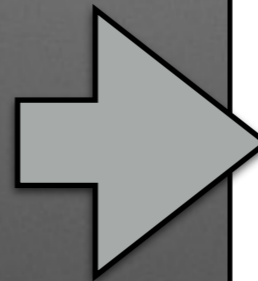
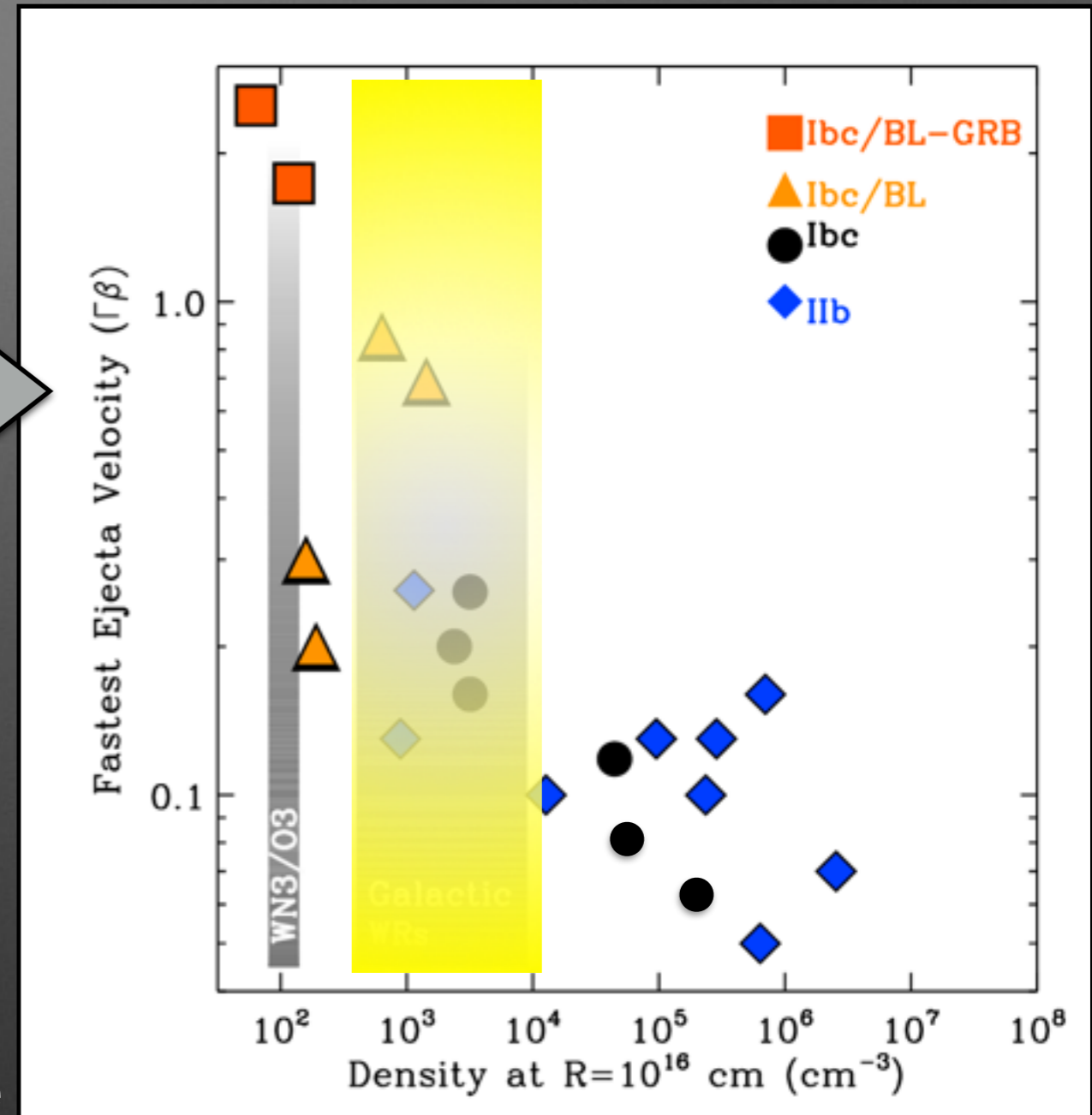
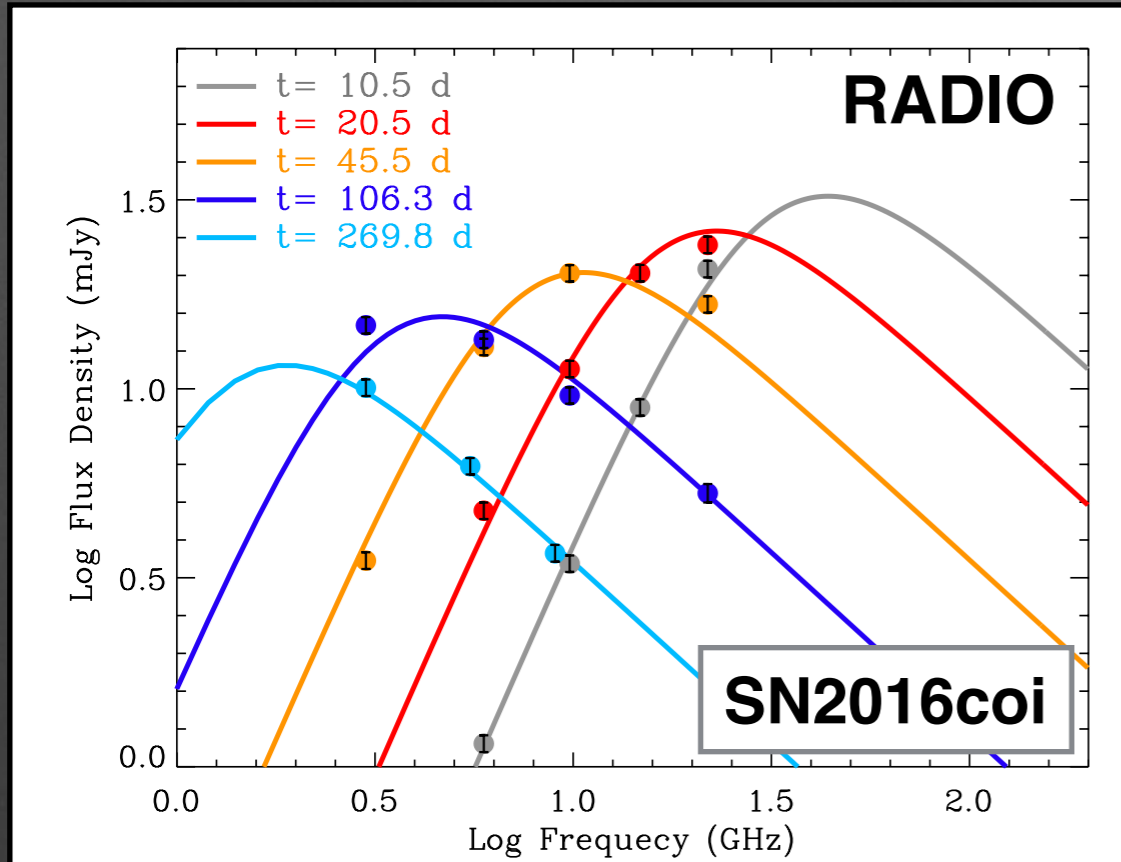
Radius



# A systematic campaign of X-ray/Radio emission from H-stripped SNe

Terreran+18

Margutti+18, Terreran+18, DeMarchi in prep.

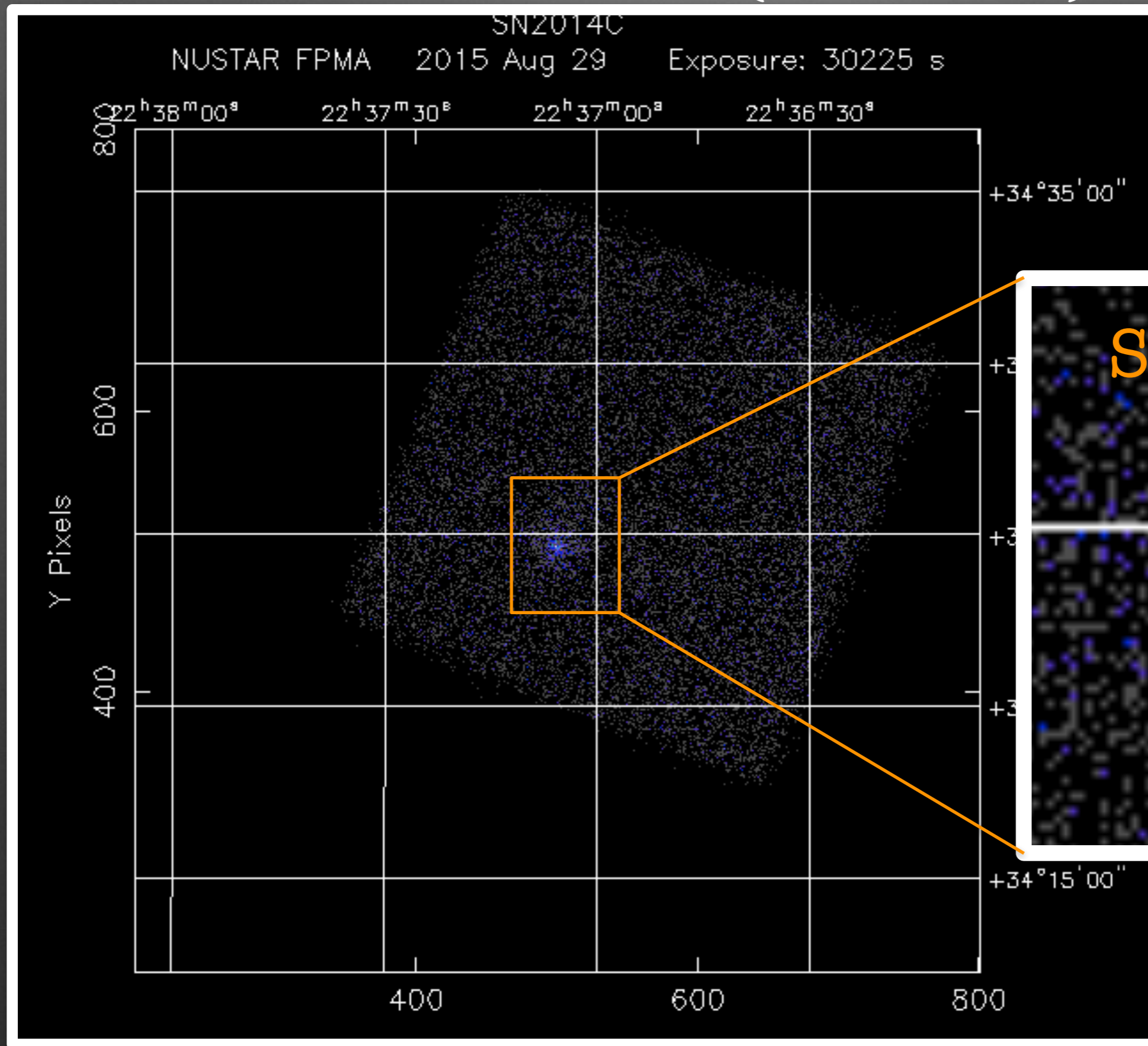


- Wide range of environment densities
- Connection with progenitor structure at the time of stellar demise

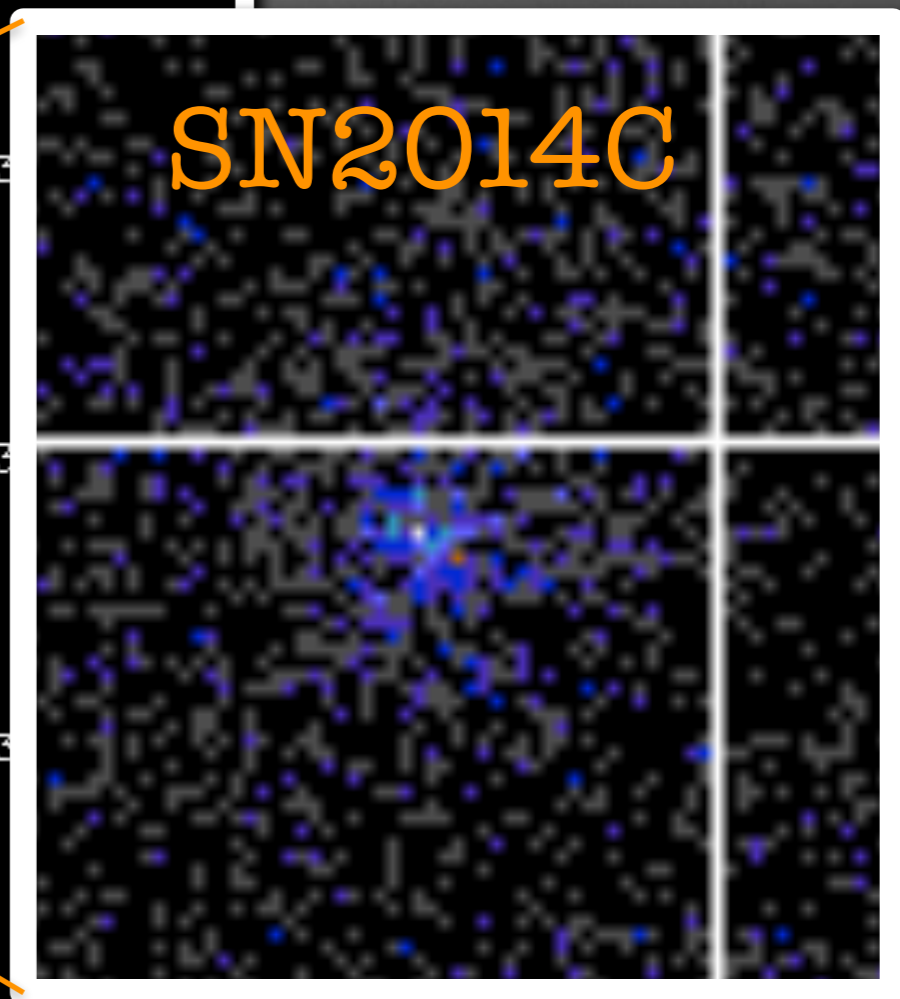
Density

Level of H stripping

# NuSTAR (3-80 keV)



RM+17

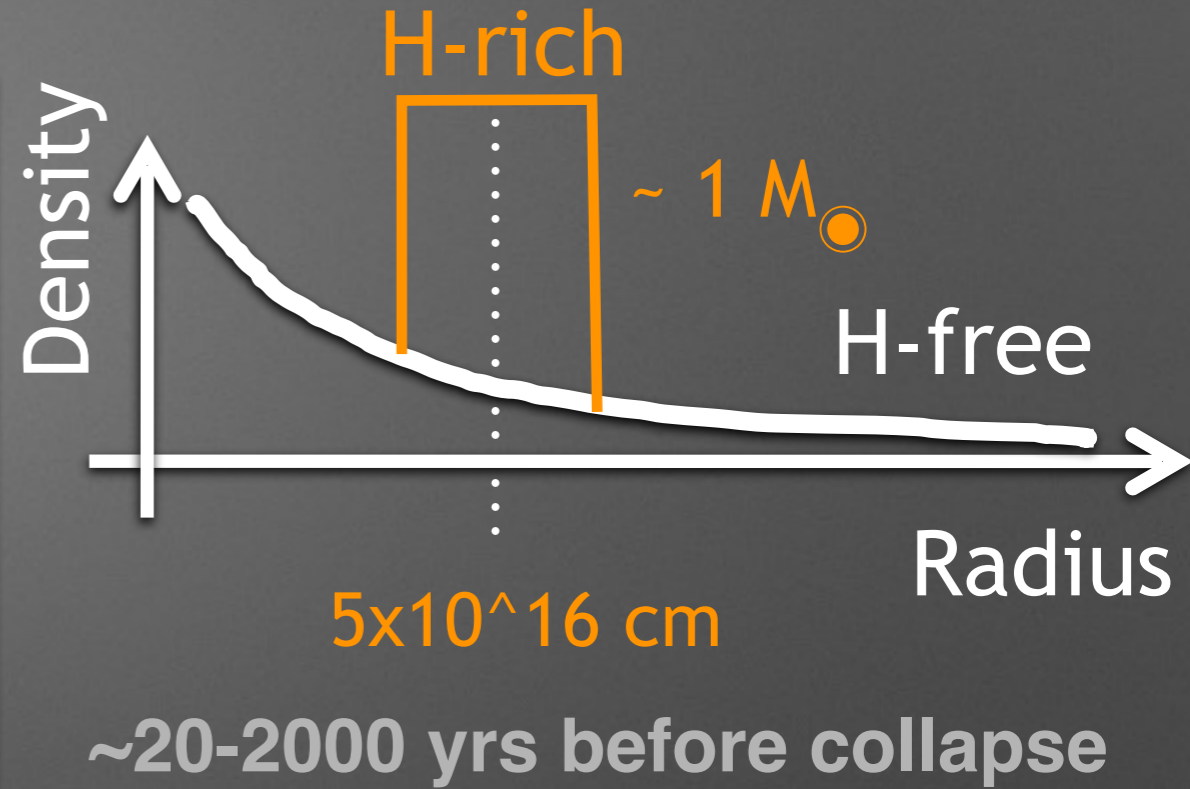
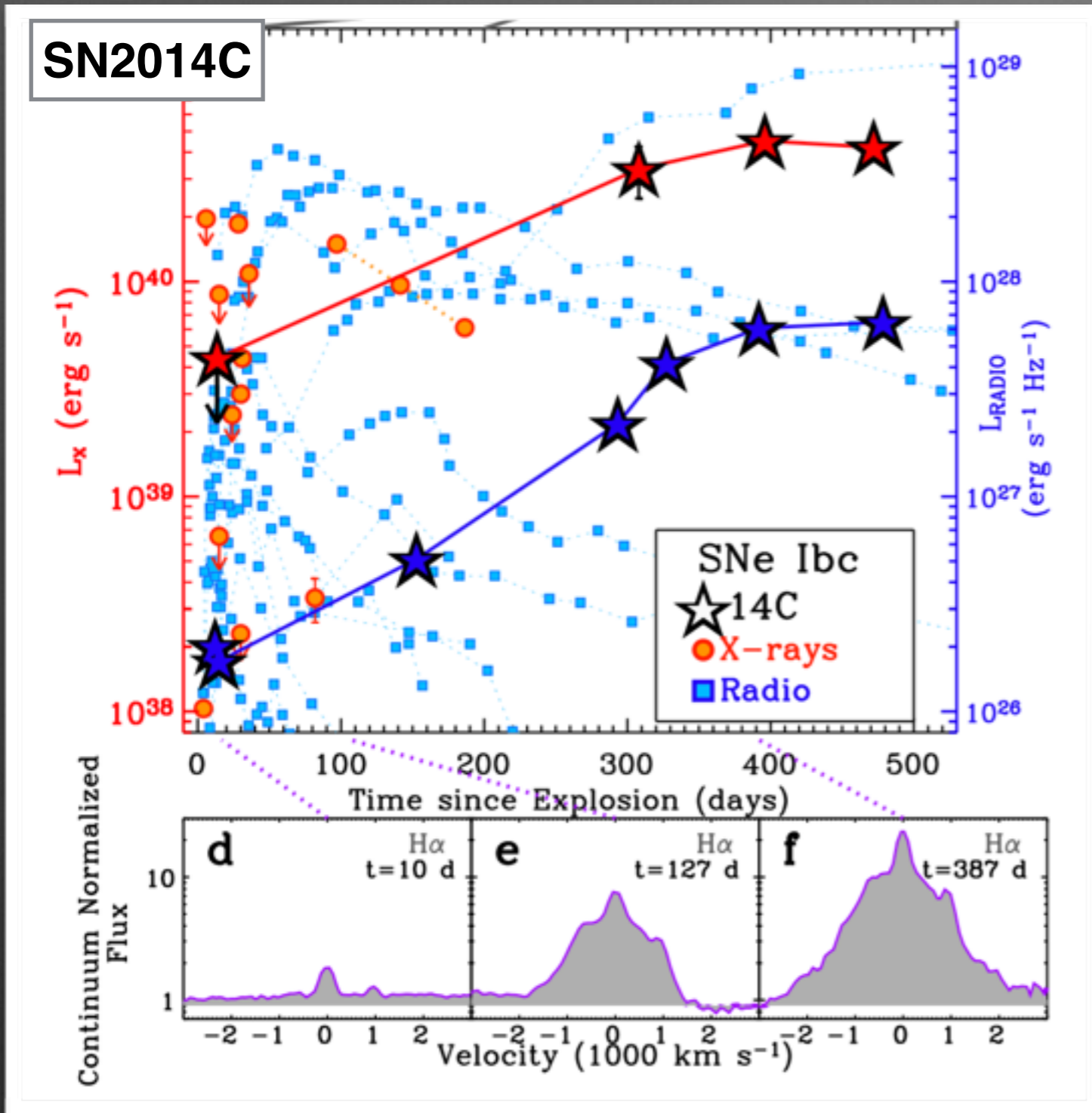


Brethauer+ in prep

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



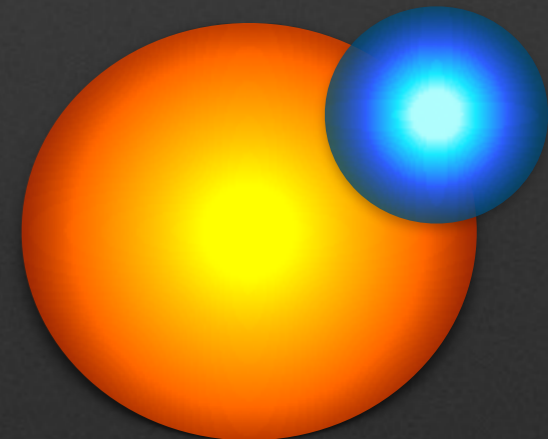
# SN2014C: Shock interaction with H-rich shell



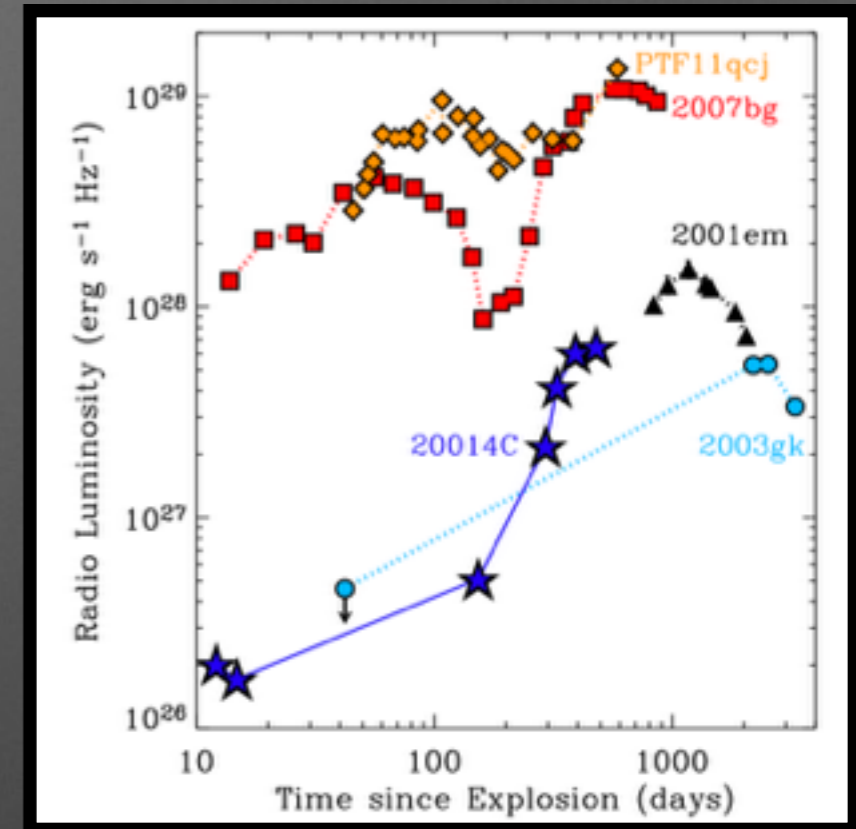
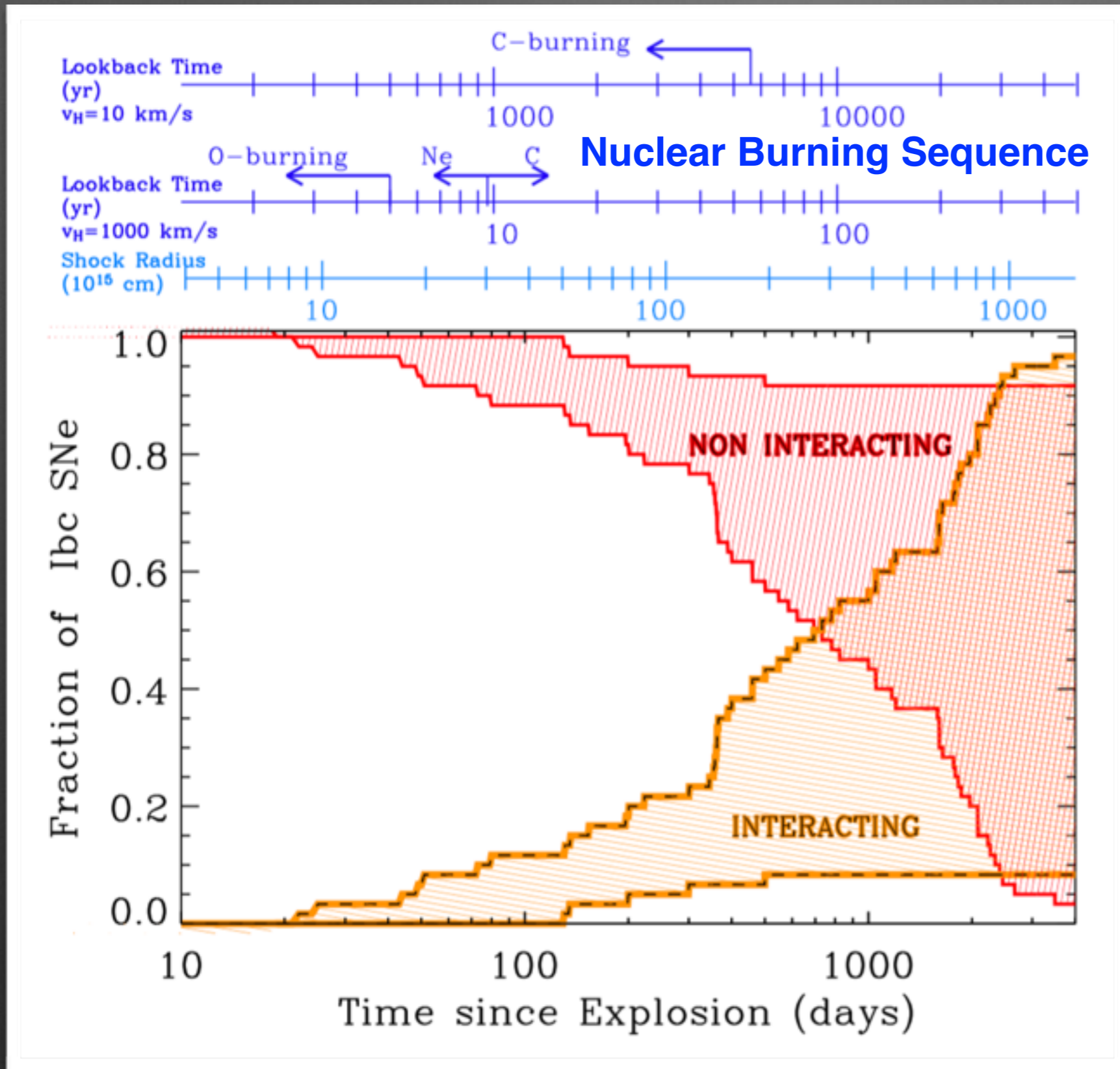
## WHY?

Nuclear Burning Instabilities  
 Binary evolution

Type I (H-poor)  $\longrightarrow$  Type II (H-rich)



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



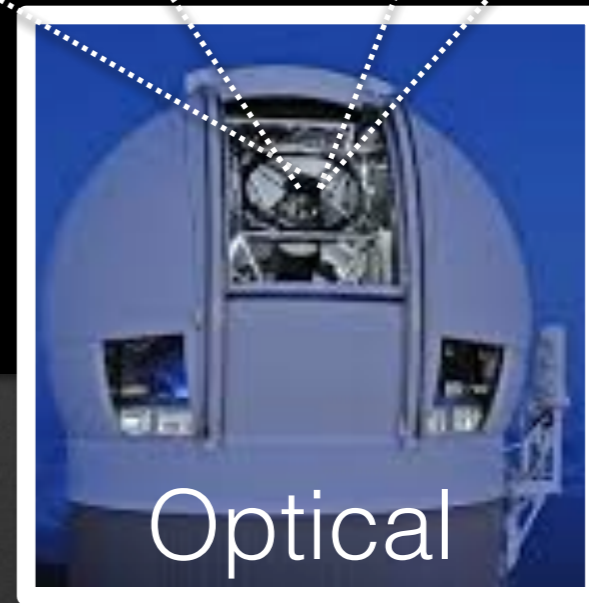
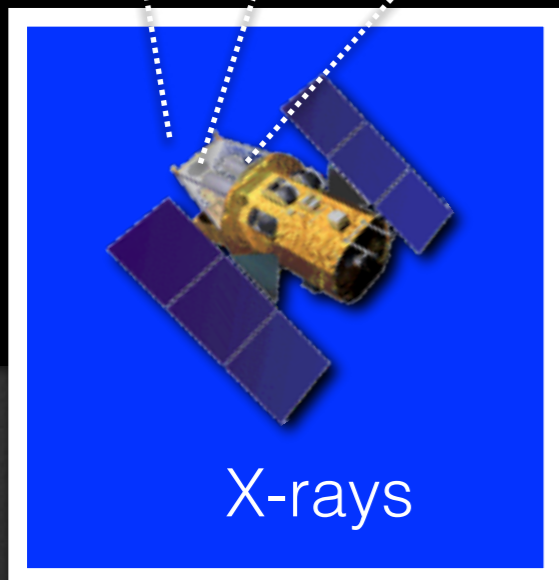
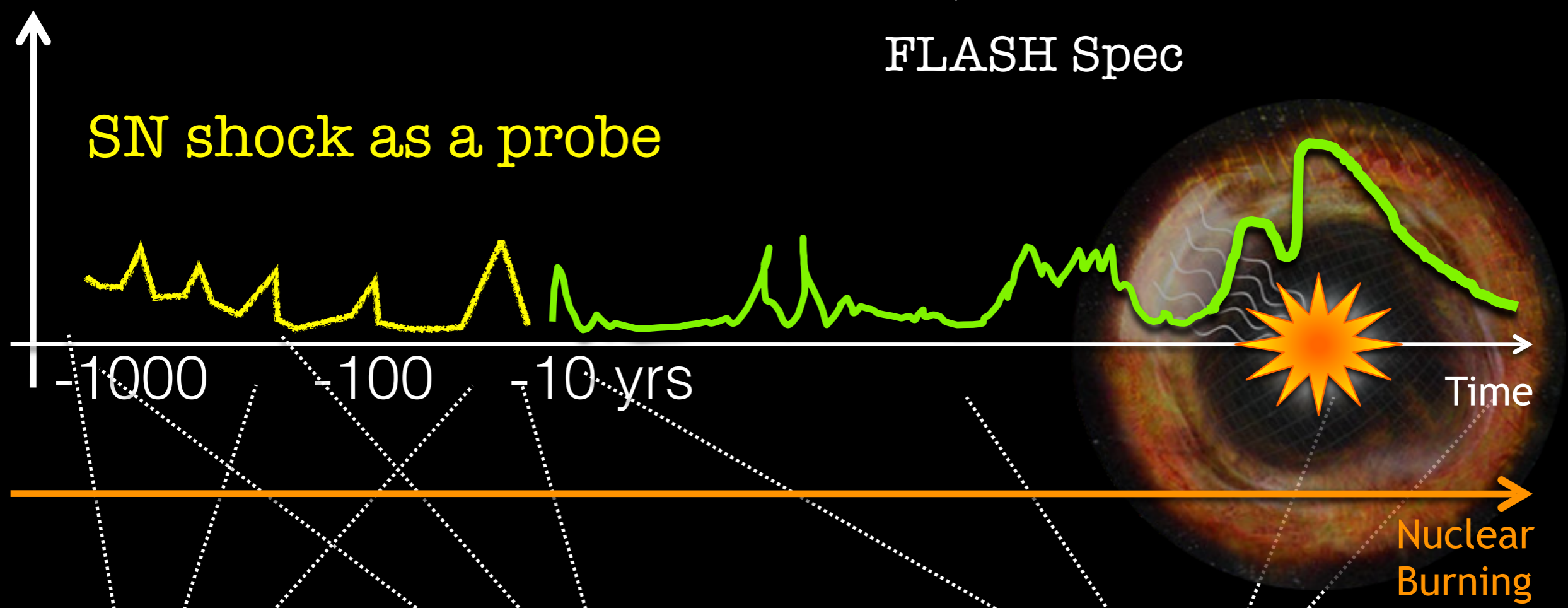
Supernovae with radio re-brightenings



# The Last thousand years...

FLASH Spec

SN shock as a probe



Direct Imaging

# Where do we go from here?

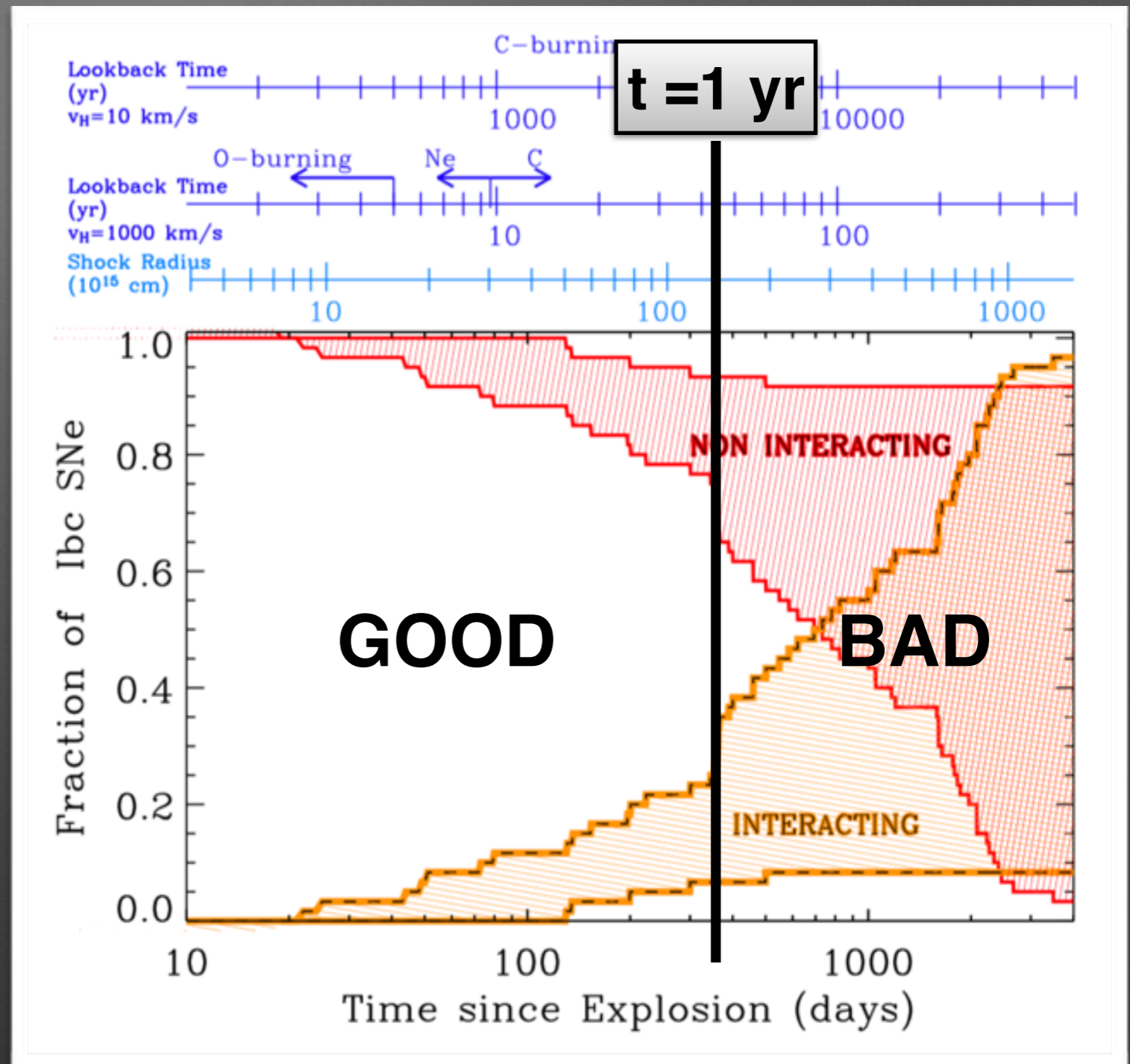


Systematic Radio-to-X-ray monitoring (early+late) of transients

- First X-rays from Ca-rich
- First X-rays from SLSN
- First X-rays/radio from FBOs
- EM from NS-NS merger



New region of the parameter space: non-thermal emission yrs after the explosion

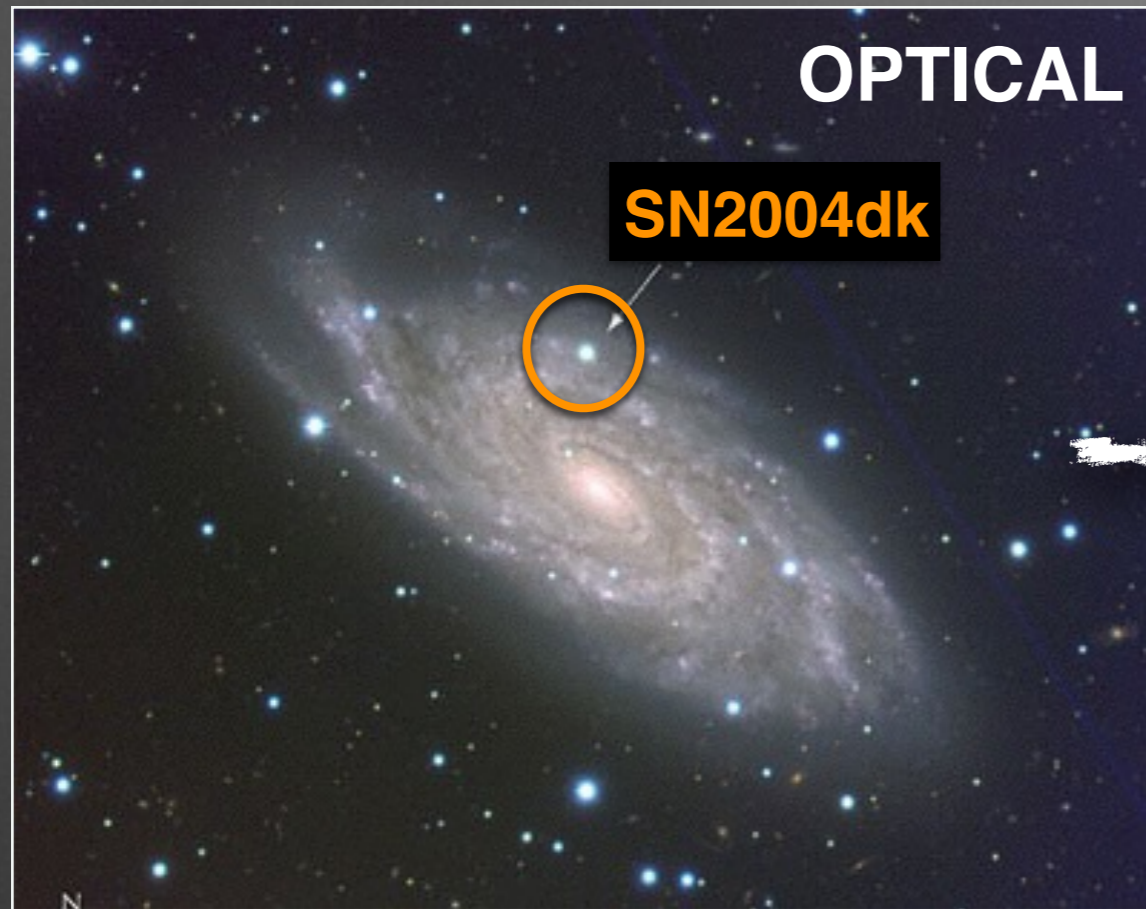




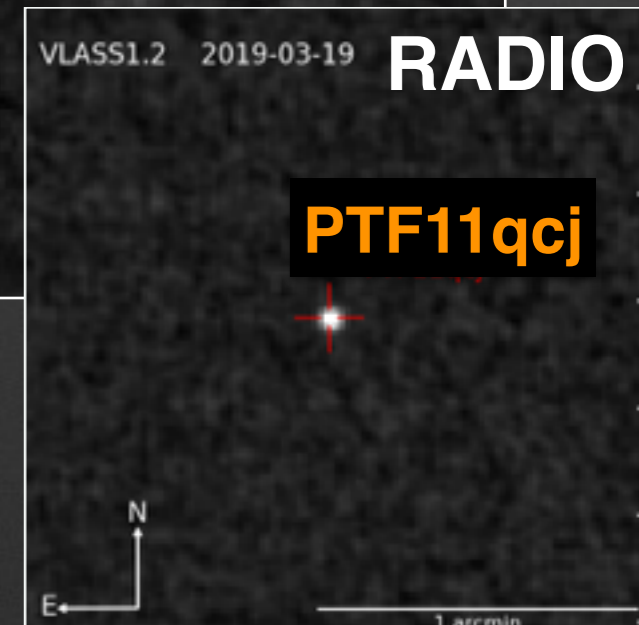
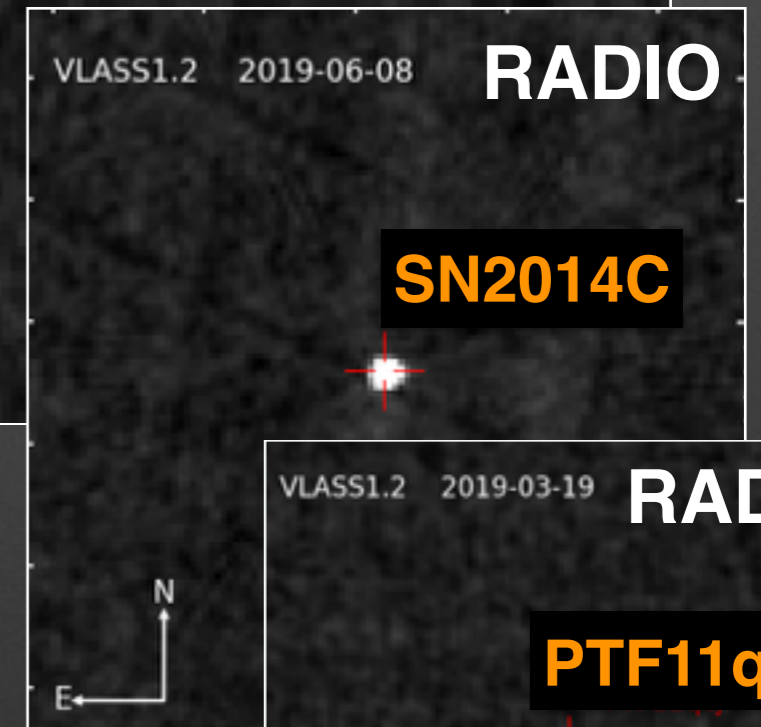
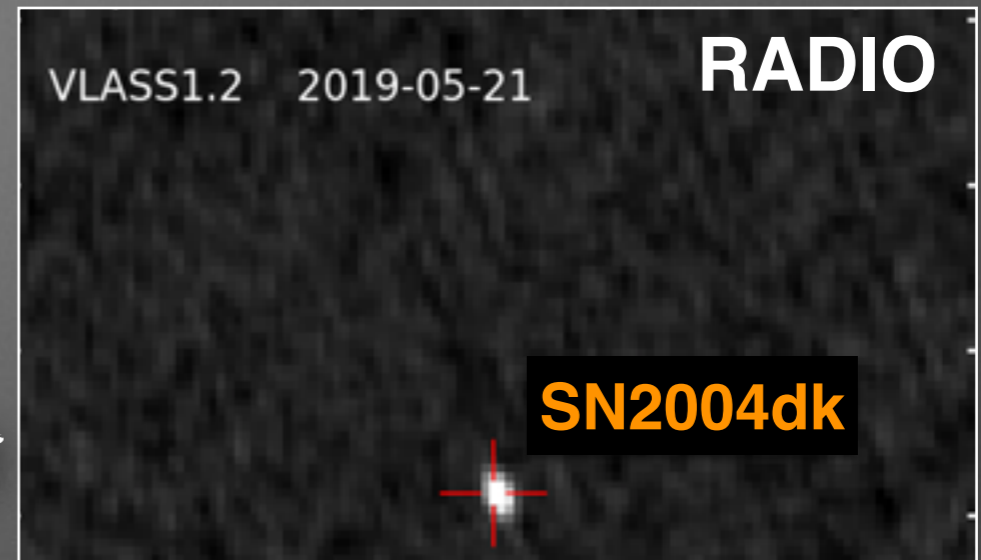
# Where do we go from here?

The VLA Sky Survey (VLASS): 1-3 GHz  $\sim 1$  mJy limit

NEW Algorithm for prompt radio detection.

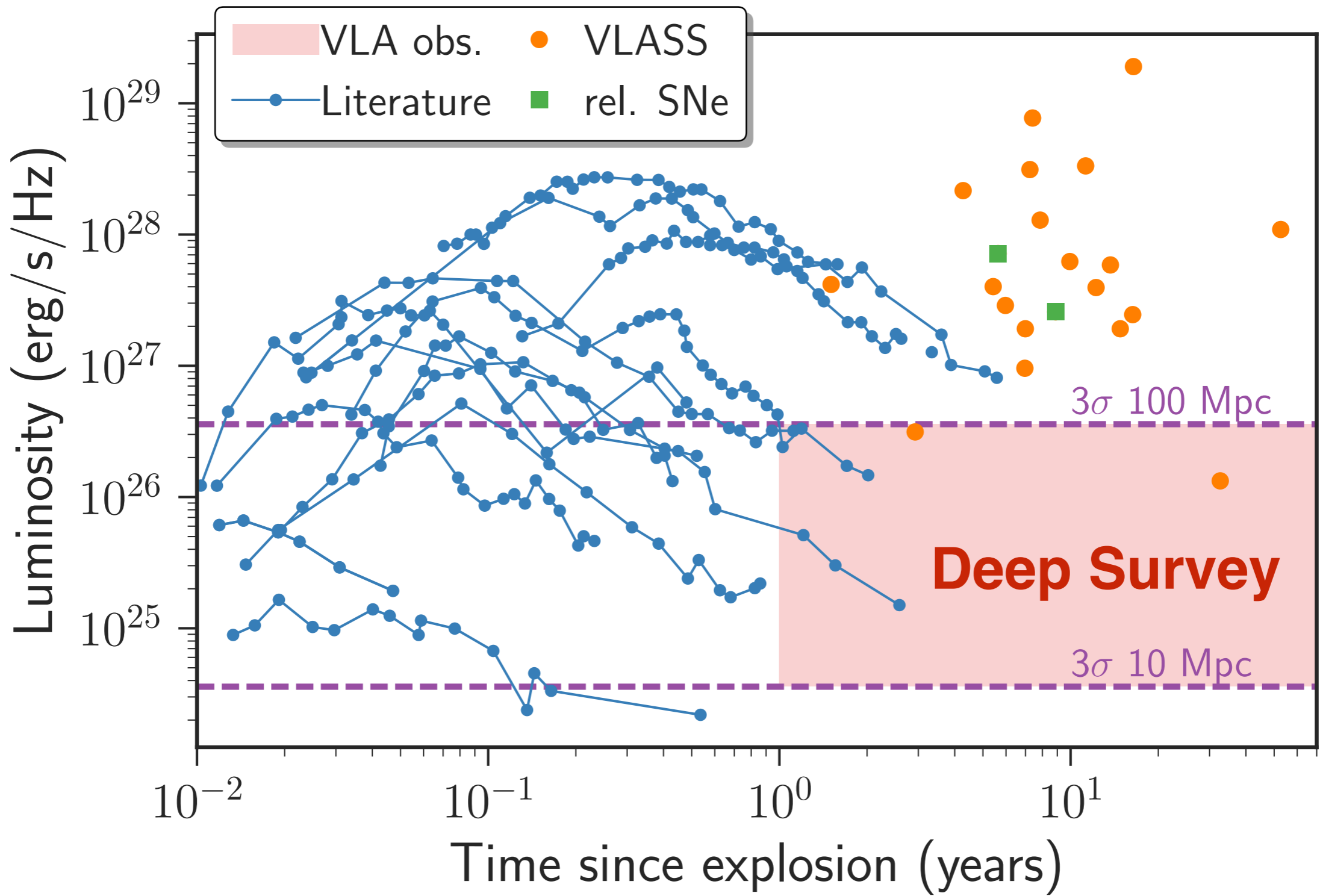


60,000+ Optical SNe



+30 others





Plot by D. Coppejans

Stroh+2021

# Why this is interesting?

## Knowledge GAP

✔ Shock Interaction  
(**unusual** evolutionary path)

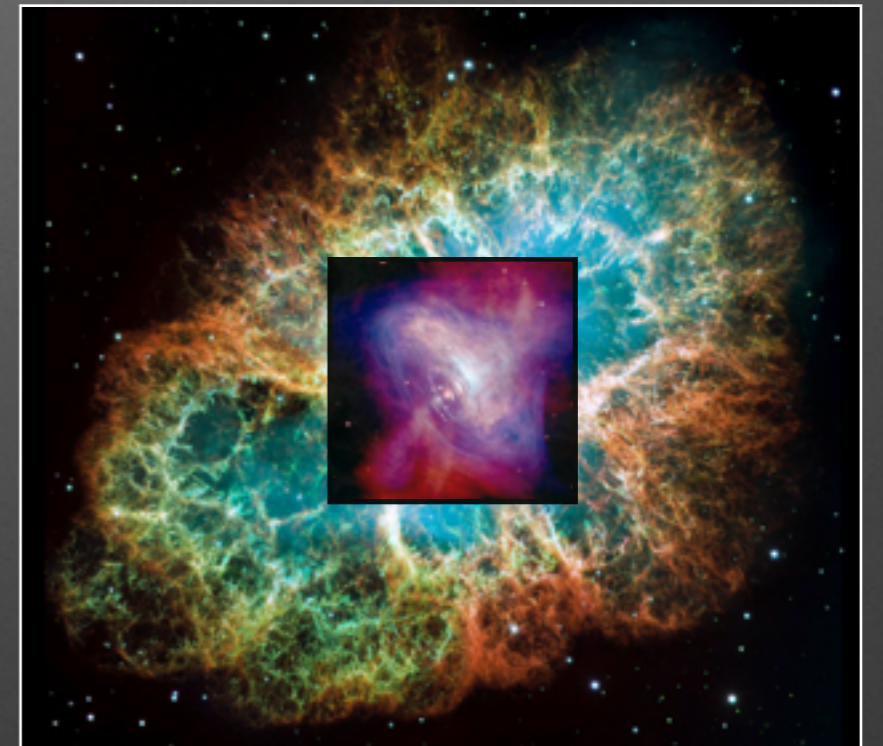
✔ Relativistic **Jets**  
from SNe seen off-axis  
2 CANDIDATES

✔ Emergence of emission  
from a **pulsar-wind nebula**  
1 CANDIDATE

Supernova



Supernova Remnant

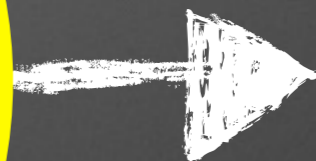
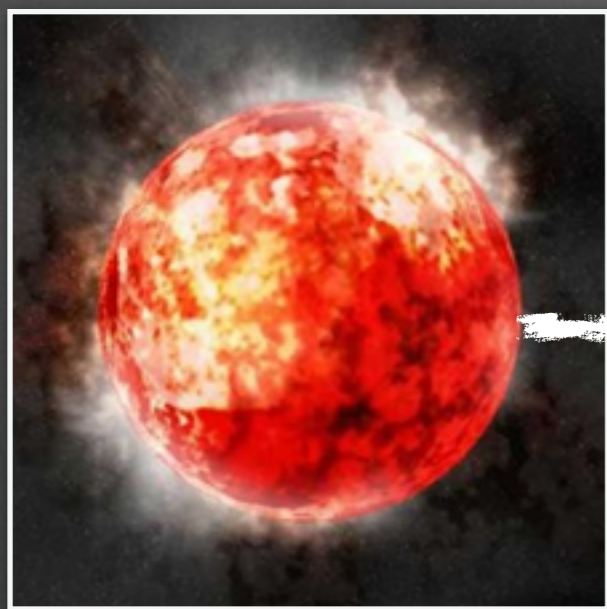


few yrs

~100 yrs

Time





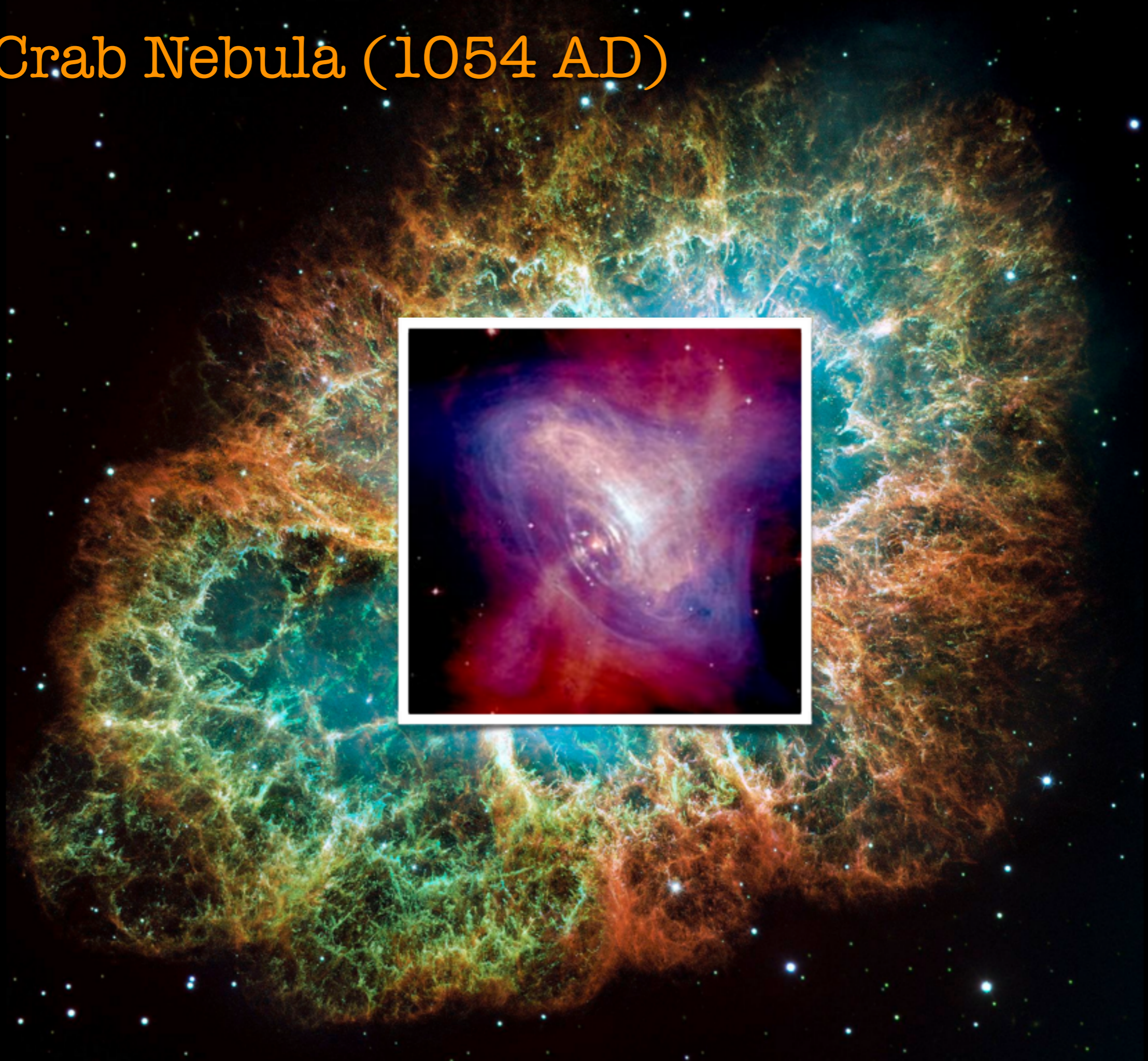
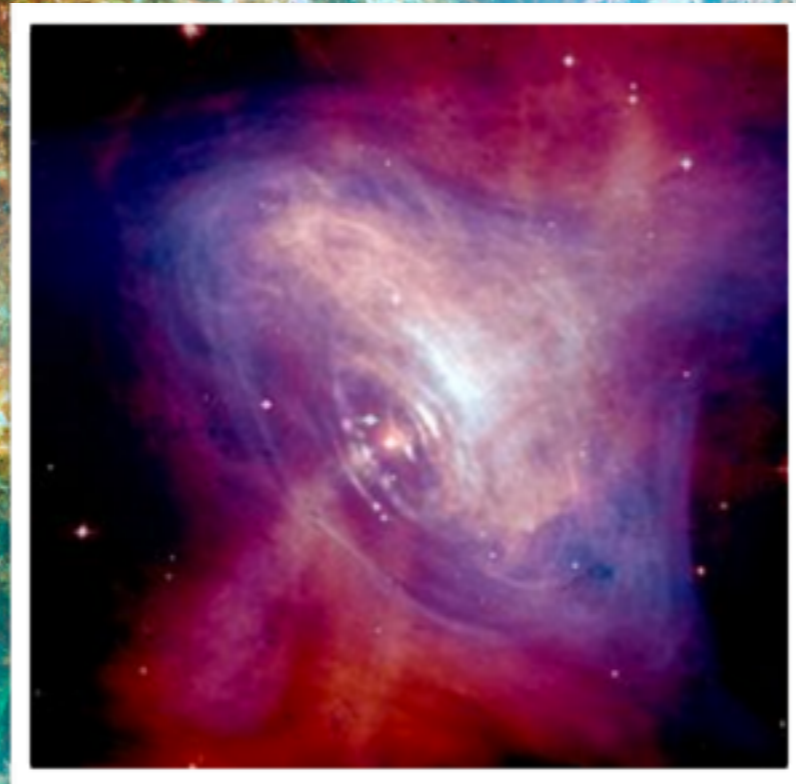
NS



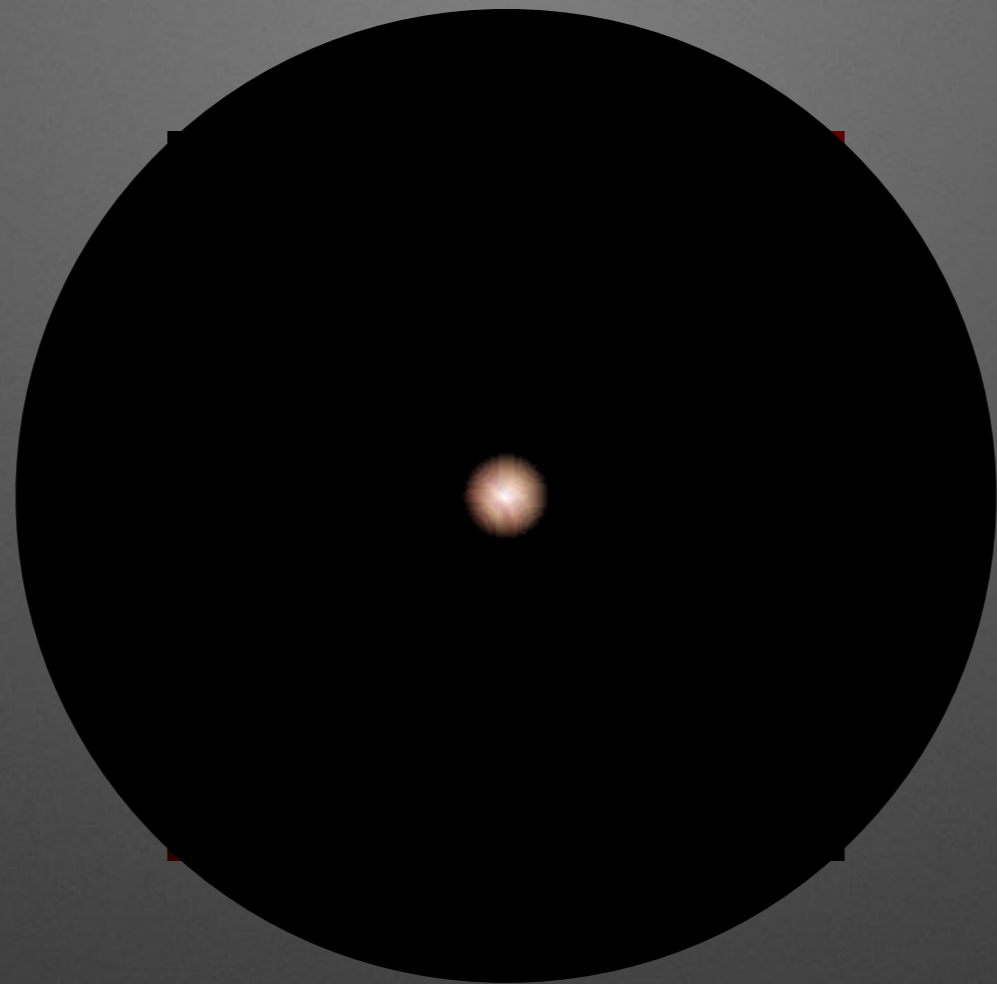
BH



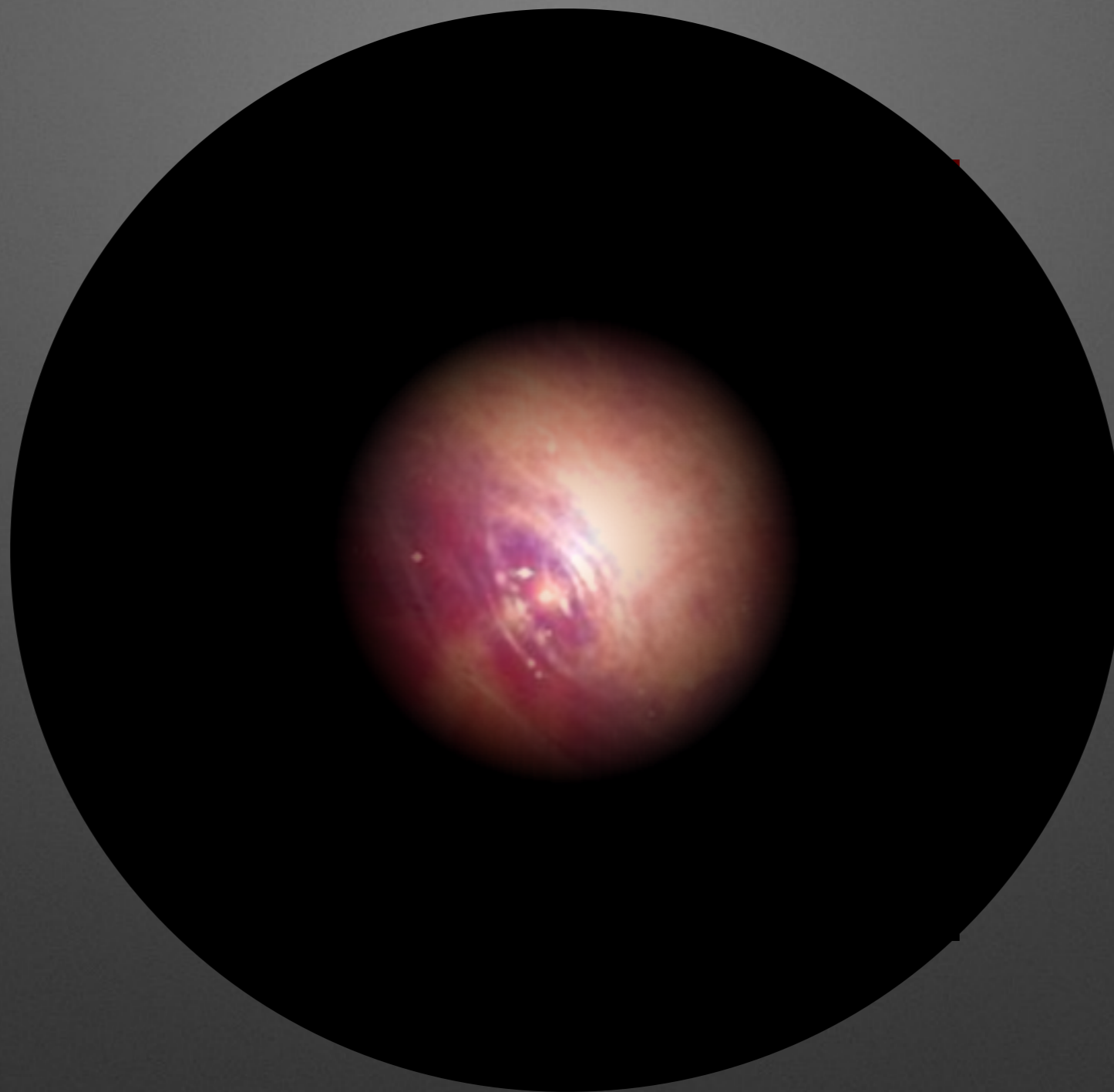
# Crab Nebula (1054 AD)



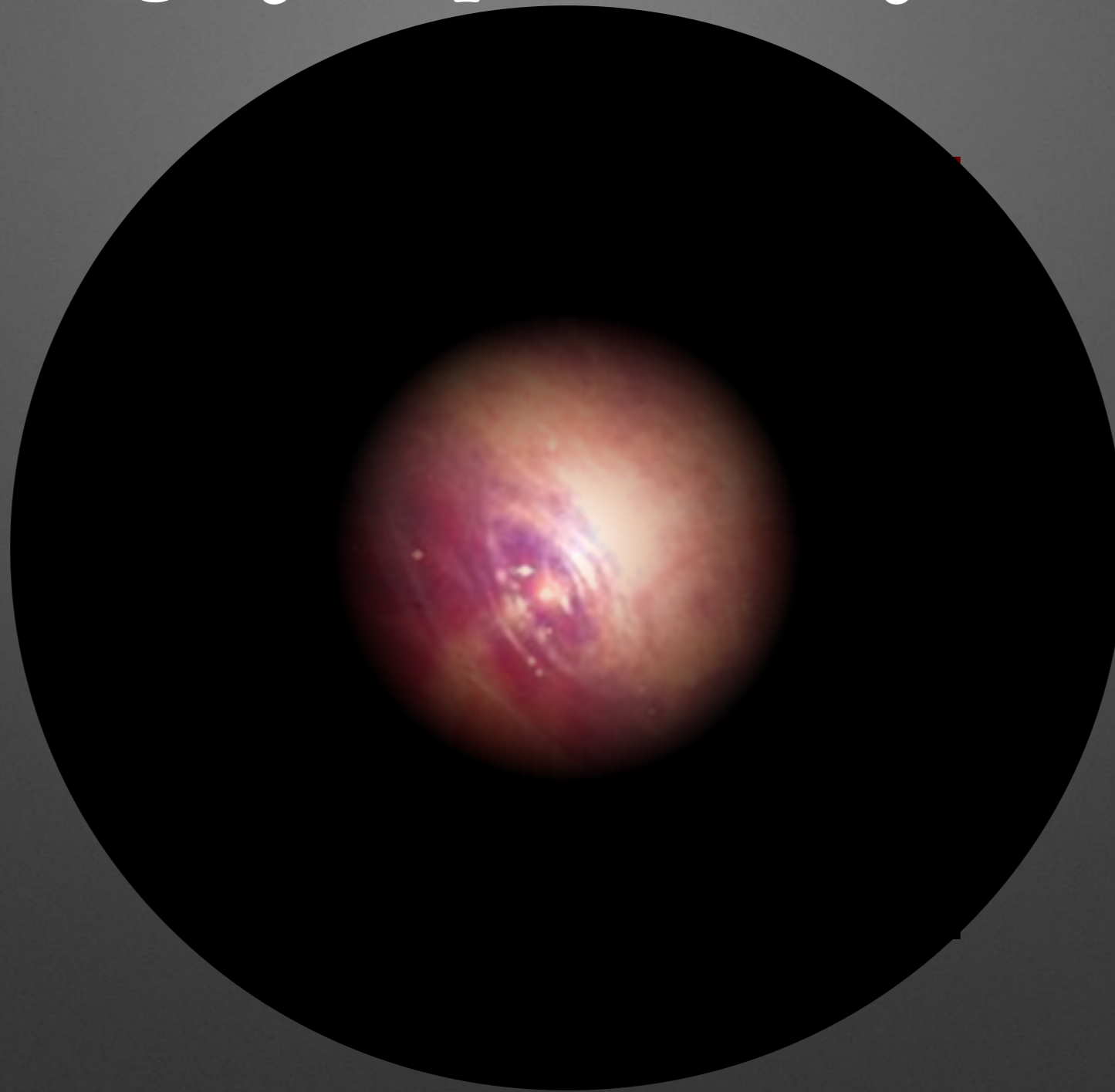








# Transients with Small Ejecta Mass or Highly Aspherical Ejecta





# Transients with Small Ejecta Mass or Highly Aspherical Ejecta

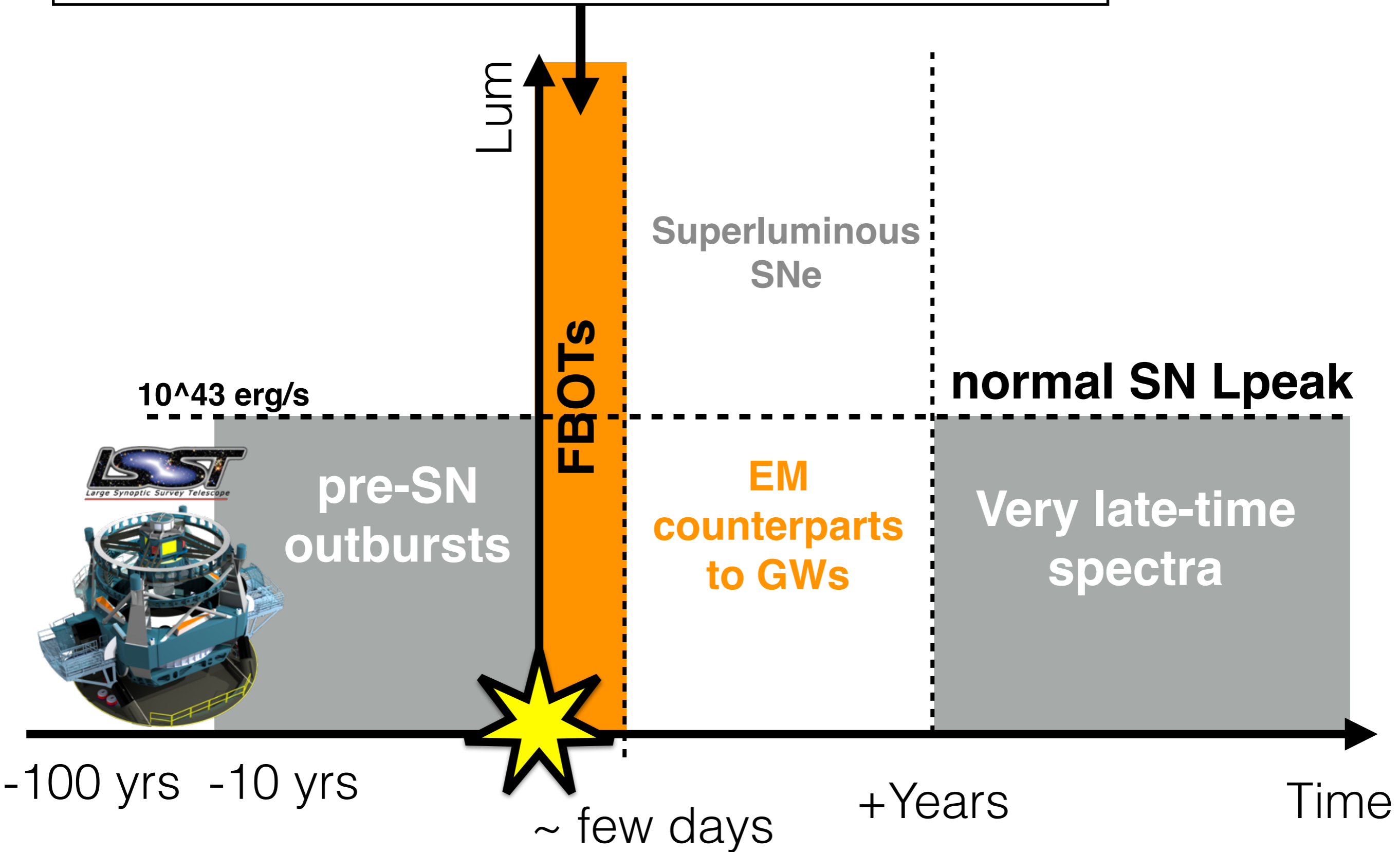


# Transients with Small Ejecta Mass or Highly Aspherical Ejecta



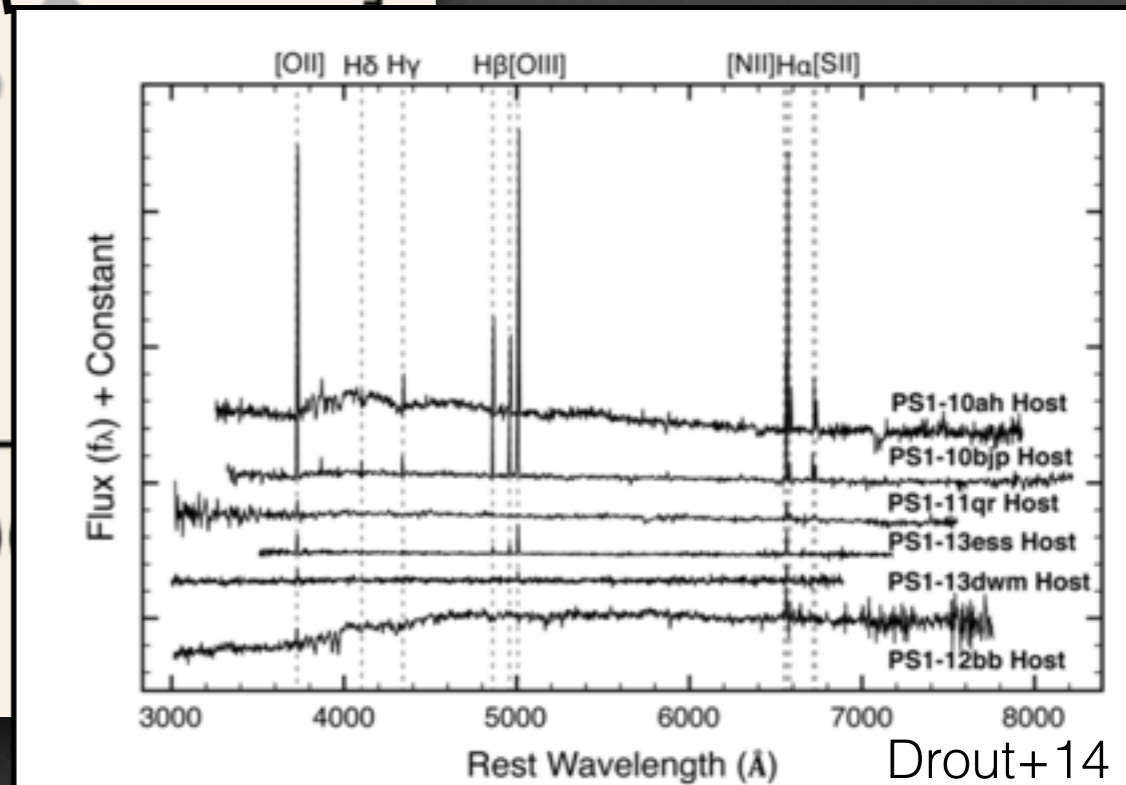
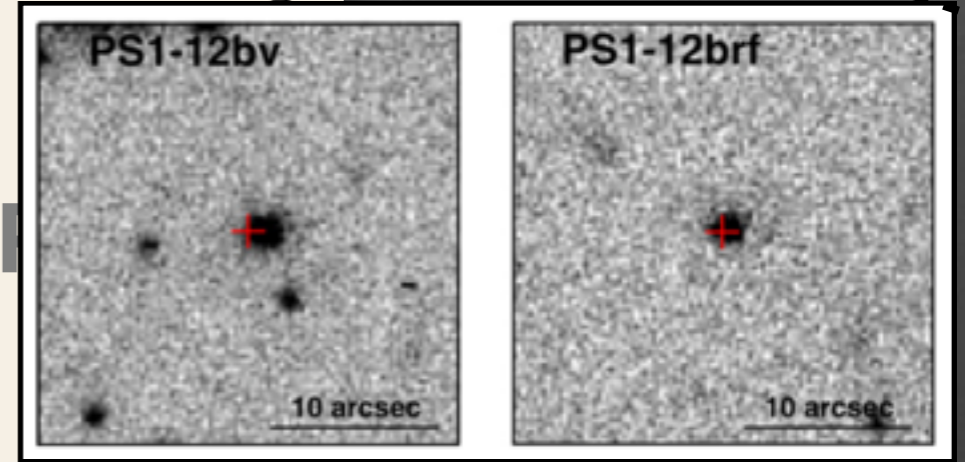
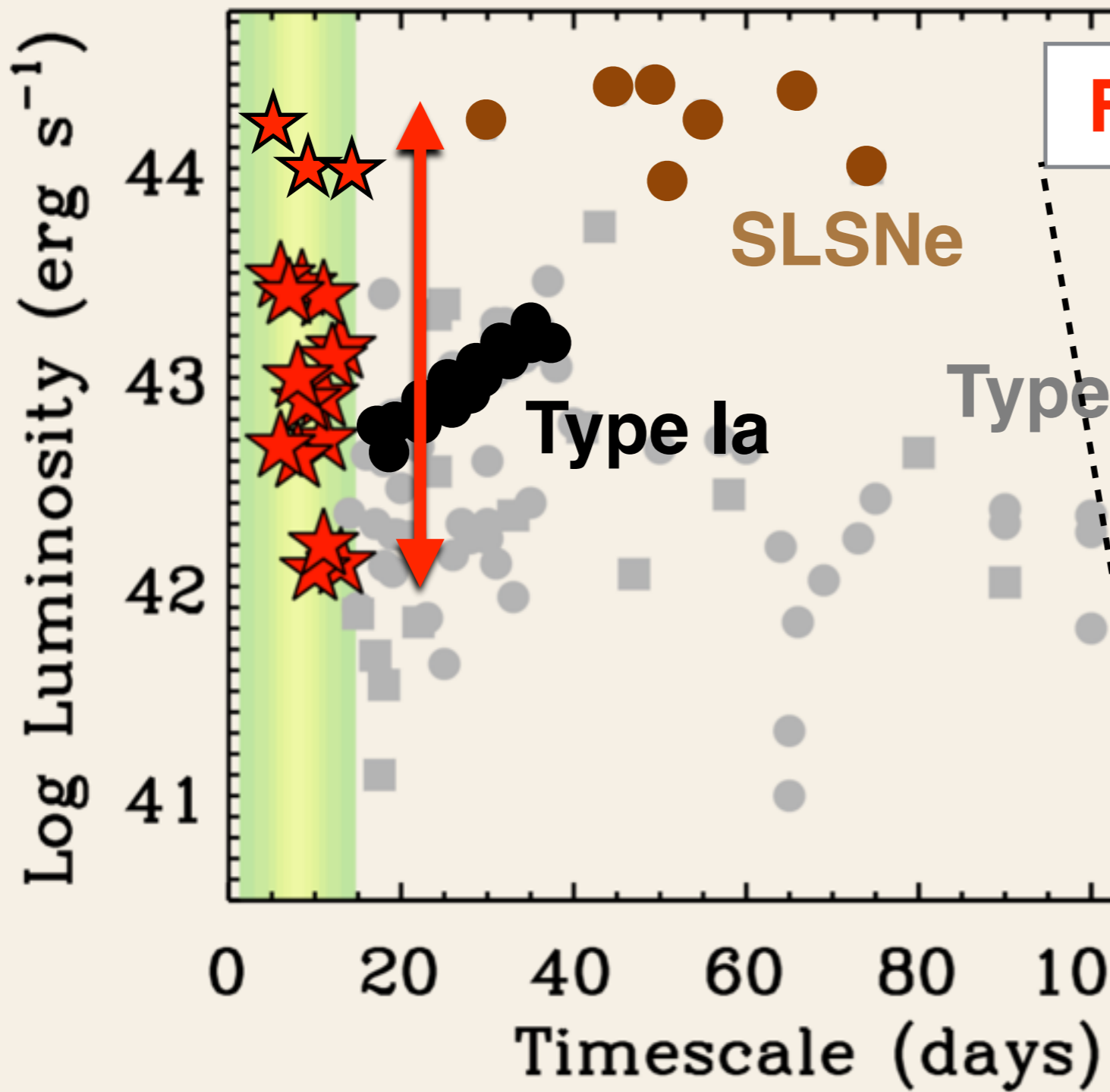


# Fast Blue Optical Transients (FBOTs) (Fast Evolving Optical Transients, FELTs)



# Fast Blue Optical Transients

Sample studies: Drout+14 (PanSTARSS), Tanaka+16 (Subaru), Arcavi+16 (SNLS+PTF), Pursiainen+18 (DECam)





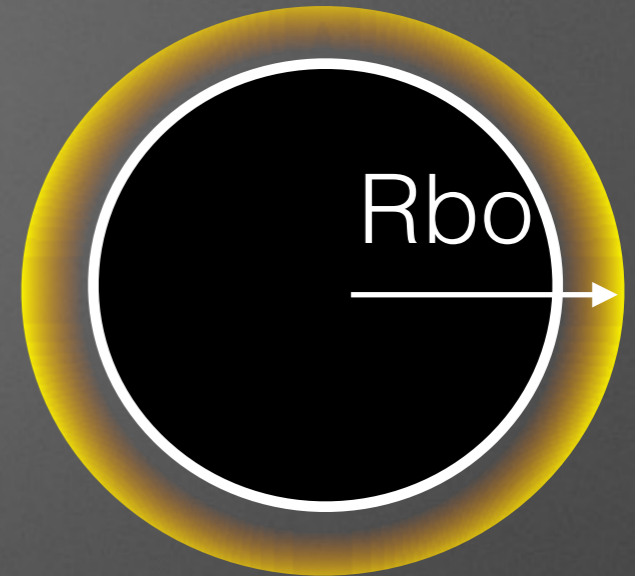
# Fast Time Scales



Central Source of Energy

$$t_{\text{pk}} \approx \left( \frac{M_{\text{ej}} \kappa}{4\pi v_{\text{ej}} c} \right)^{1/2} \approx 2.7 \text{ d} \left( \frac{M_{\text{ej}}}{0.3 M_{\odot}} \right)^{1/2} \left( \frac{v_{\text{ej}}}{0.1 c} \right)^{-1/2}$$

Small  $M_{\text{ej}}$   $\rightarrow$  Ruled out  $^{56}\text{Ni}$



Shock interaction

Break out Radius ( $R_{\text{bo}}$ )

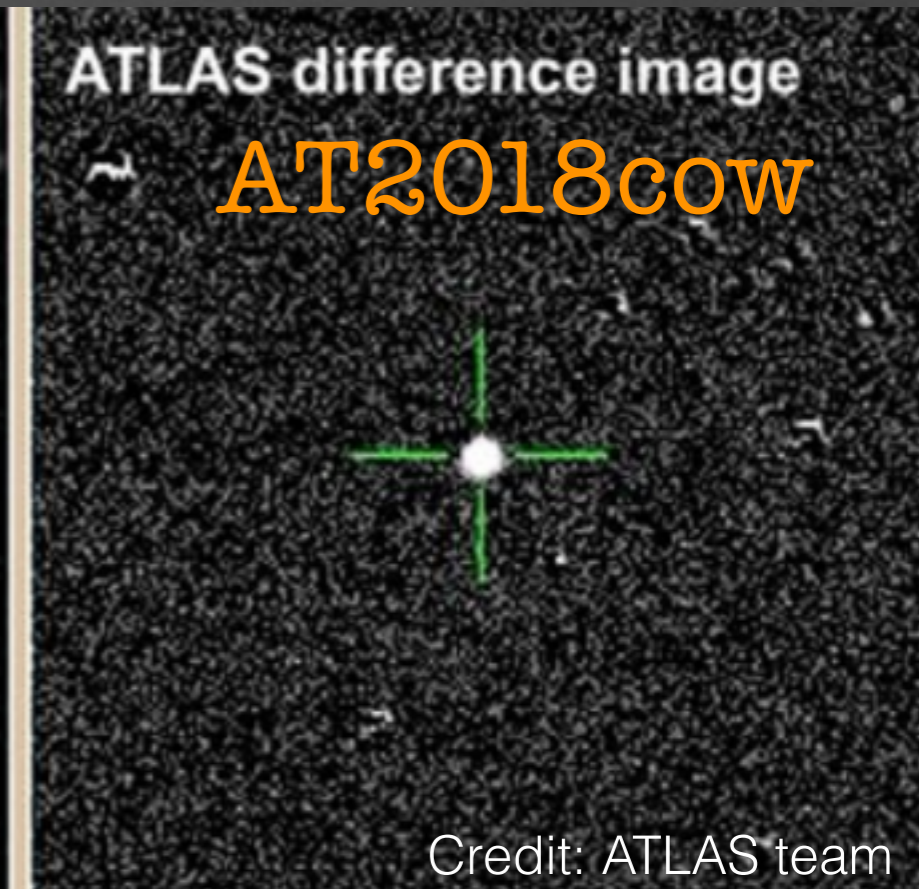
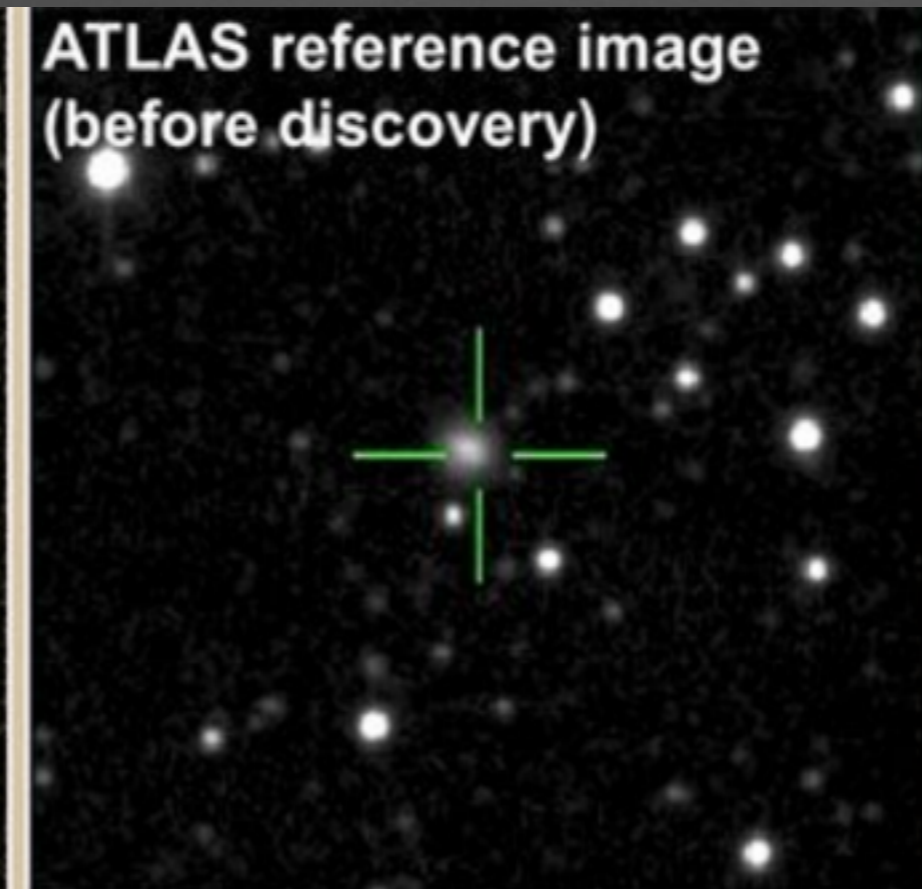
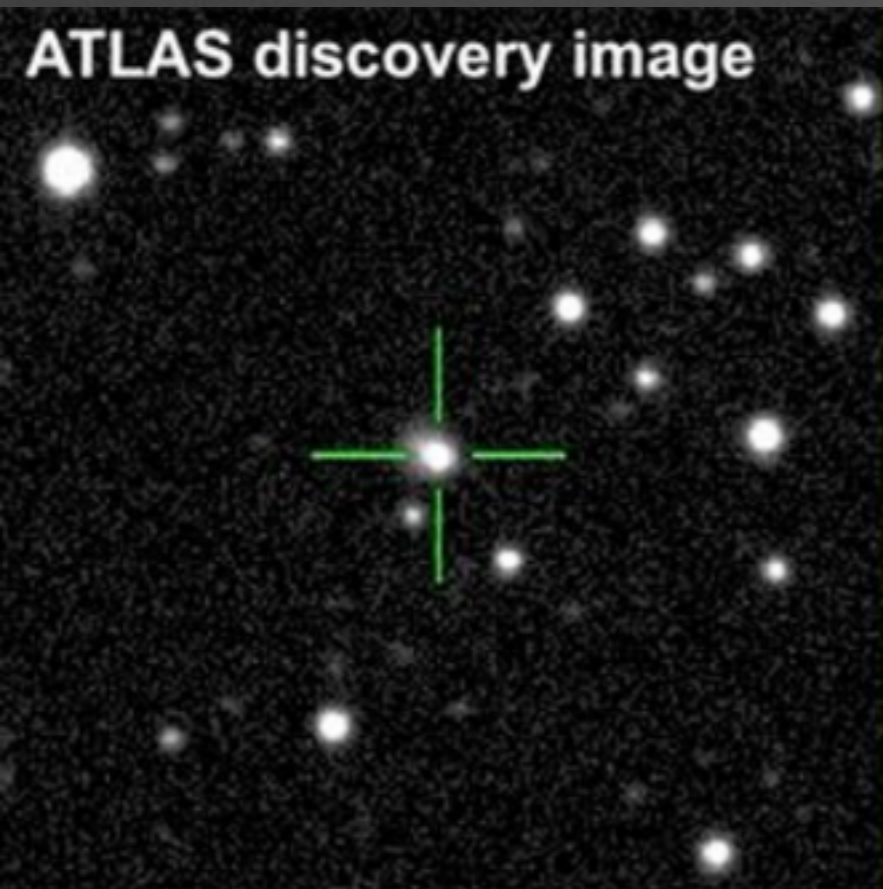
- Cooling with time
- No fast variability time scales
- No relativistic ejecta

No info outside the optical/UV

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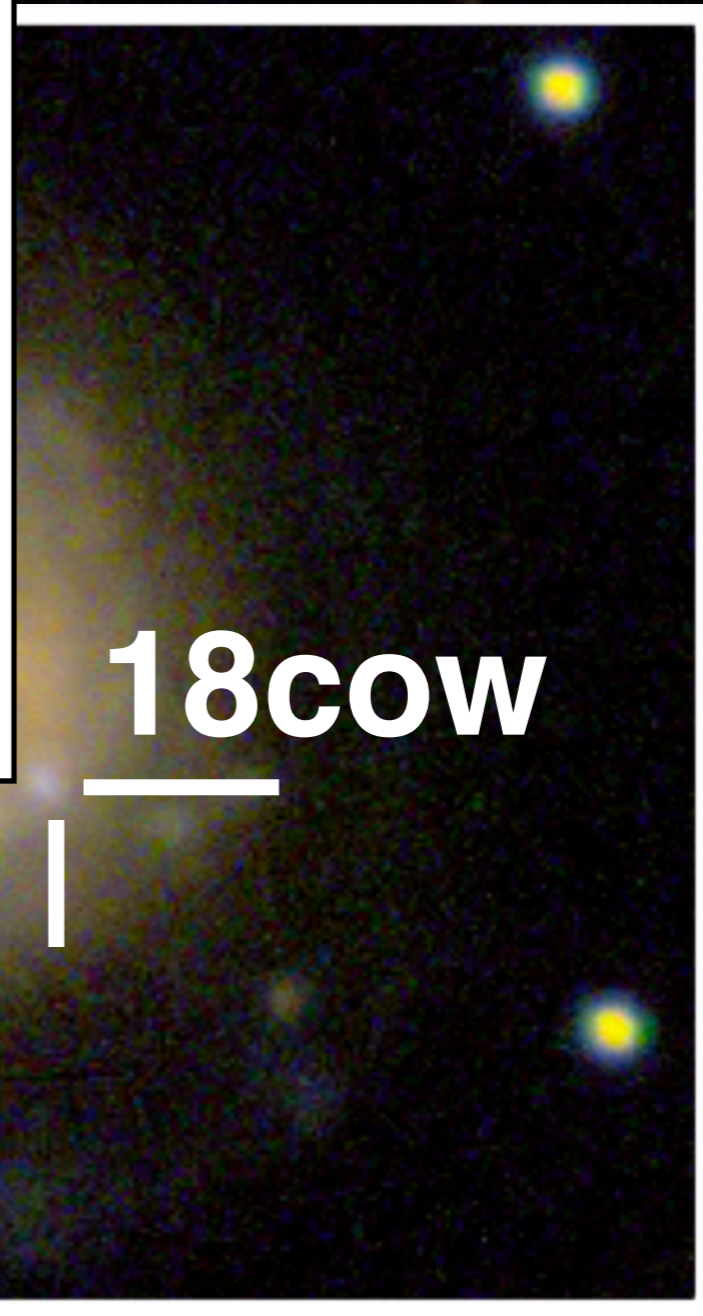
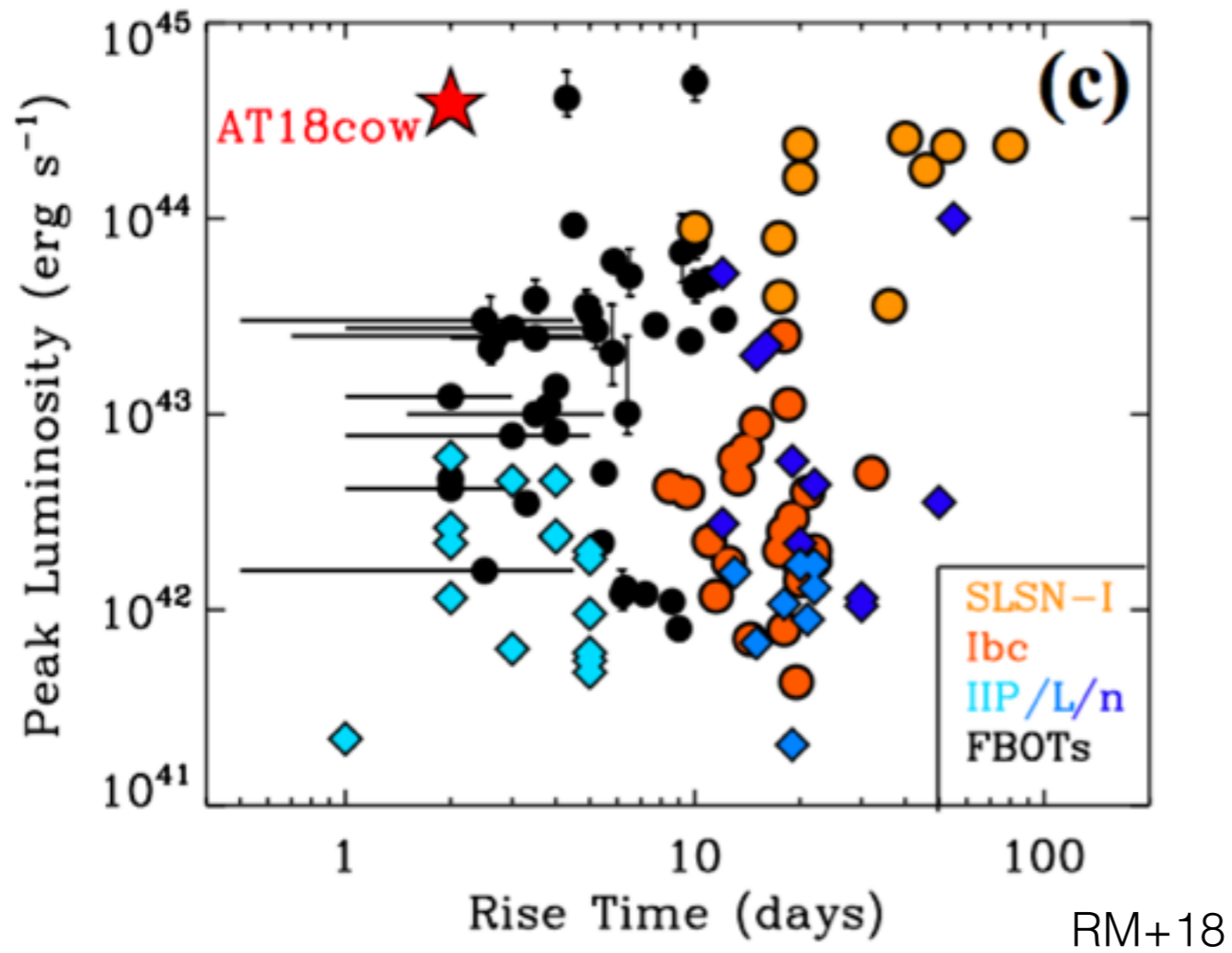
# Holy Cow! Astronomers agog at mysterious new supernova

*An event known as 'Cow' that has rocked astronomy since June likely offers a close look at the birth of a neutron star or black hole.*



Credit: ATLAS team

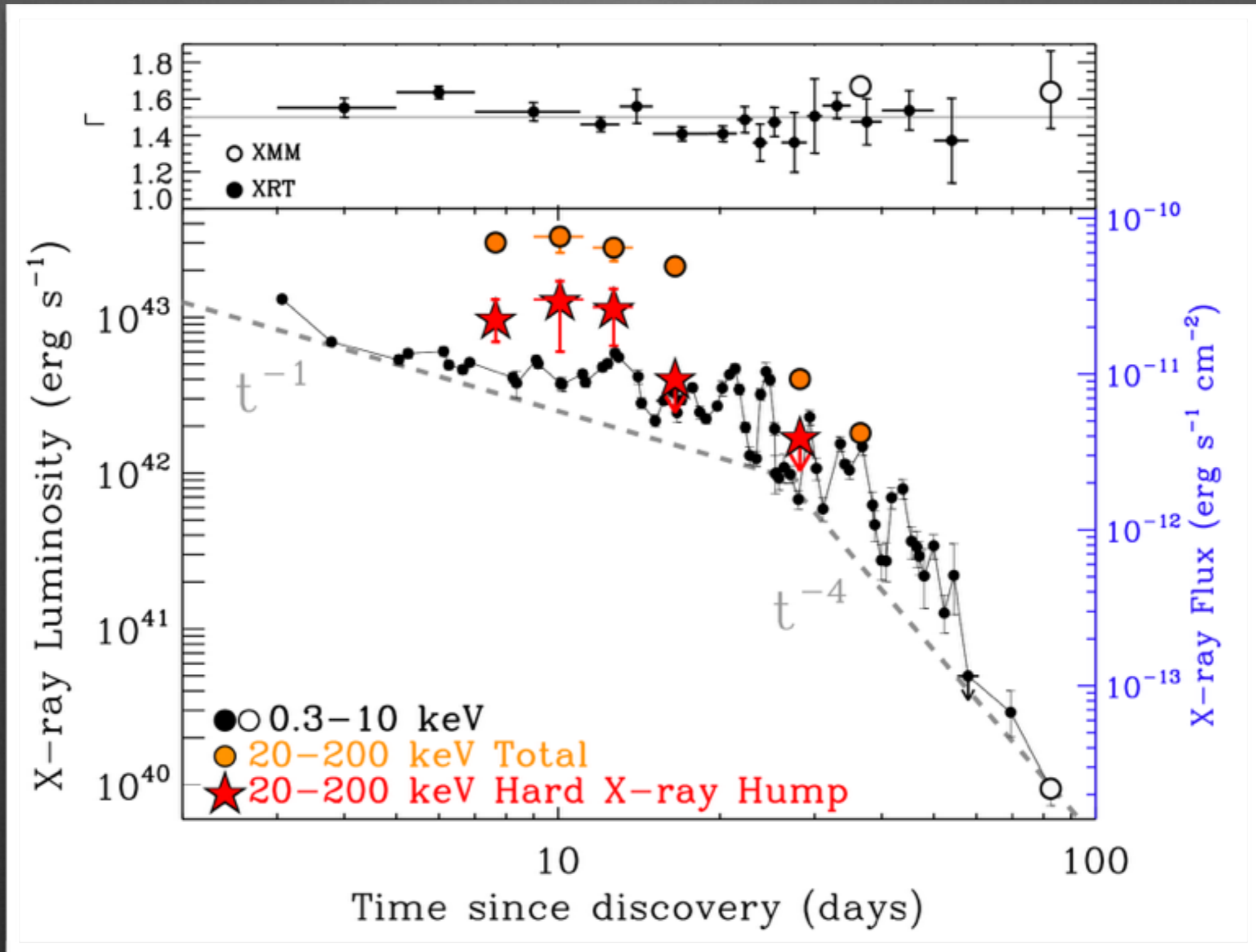




see also Perley+18  
Prentice+18



# Luminous Variable X-rays



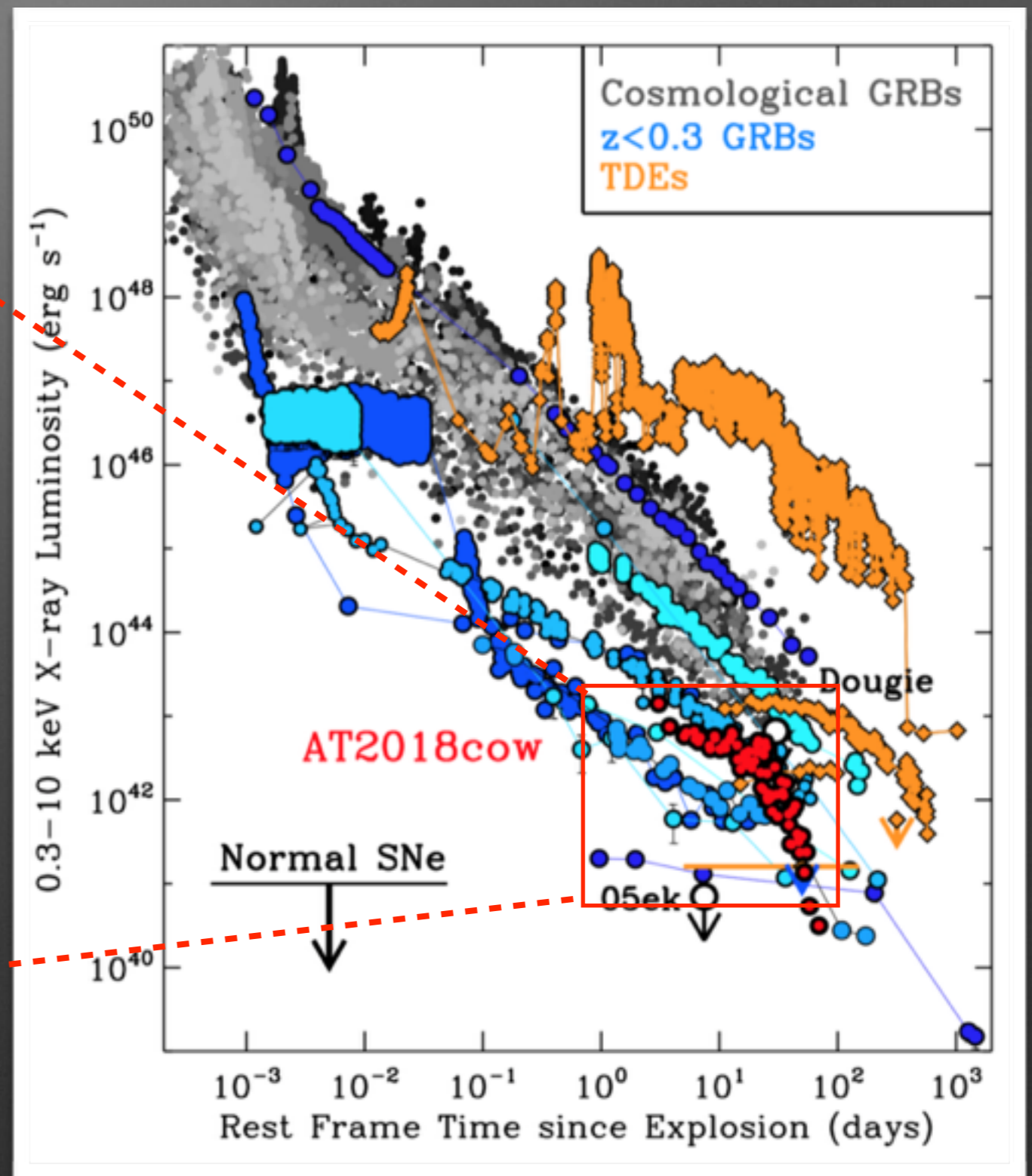
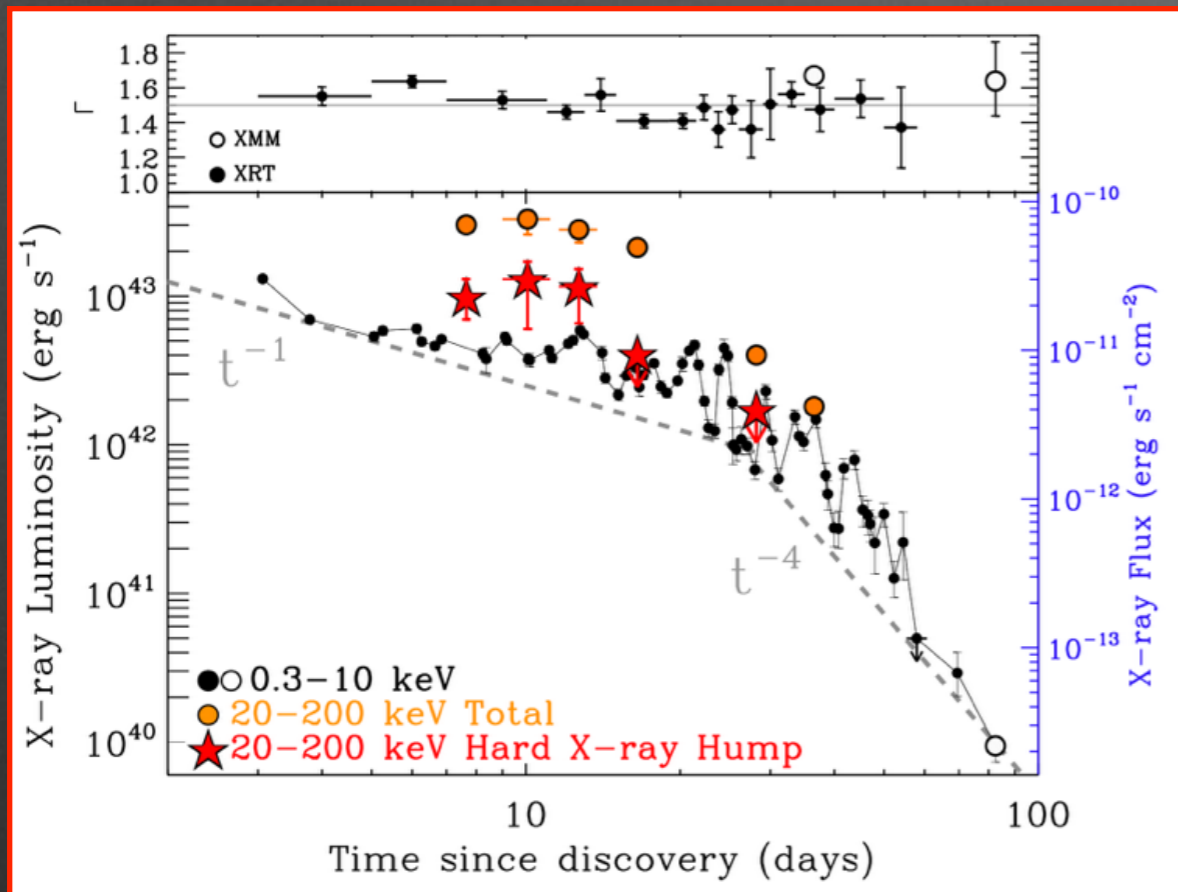
RM+18

see also Kuin+18, Rivera Sandoval+18

Not consistent with shock interaction

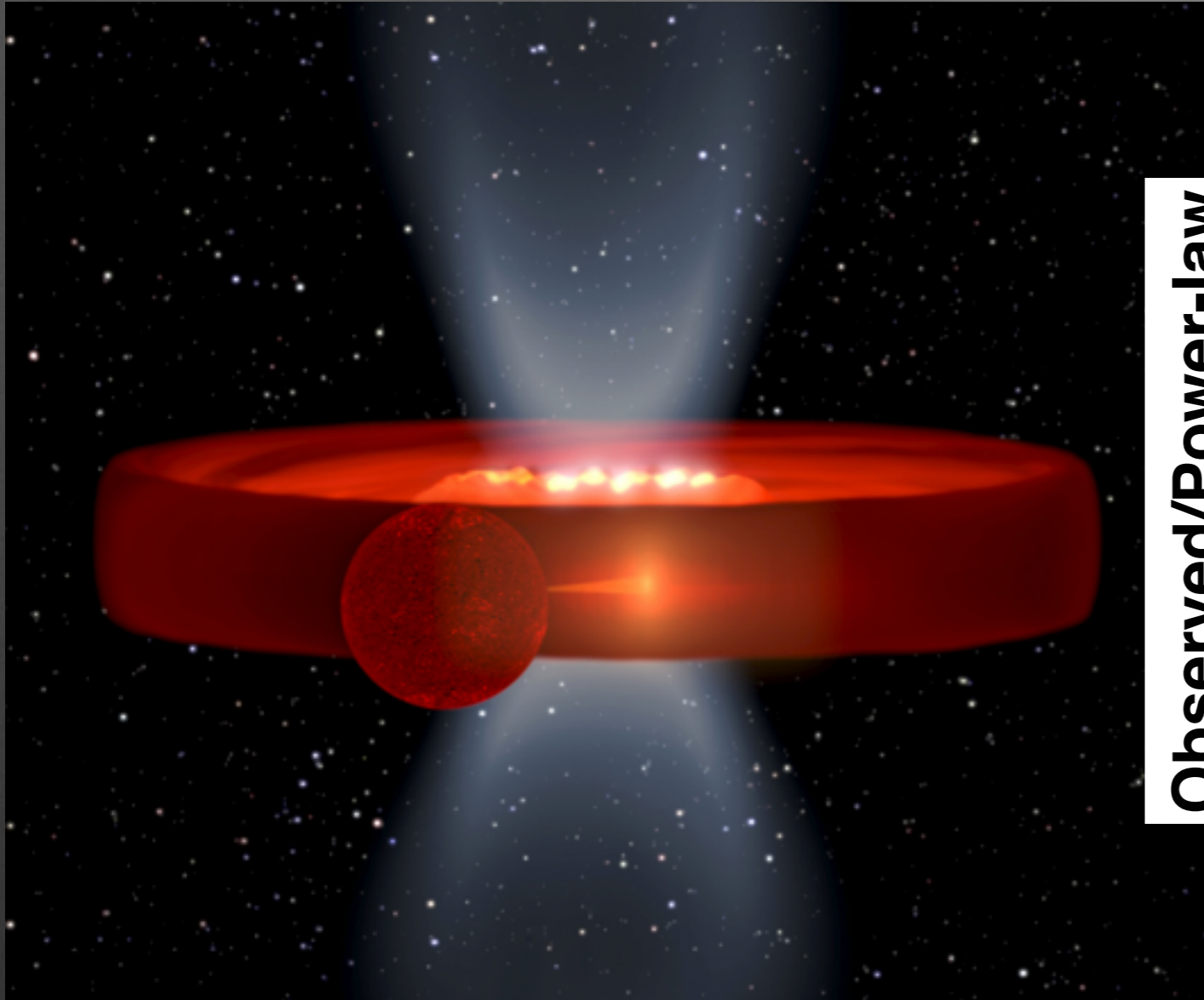


# Luminous Variable X-rays in AT2018cow

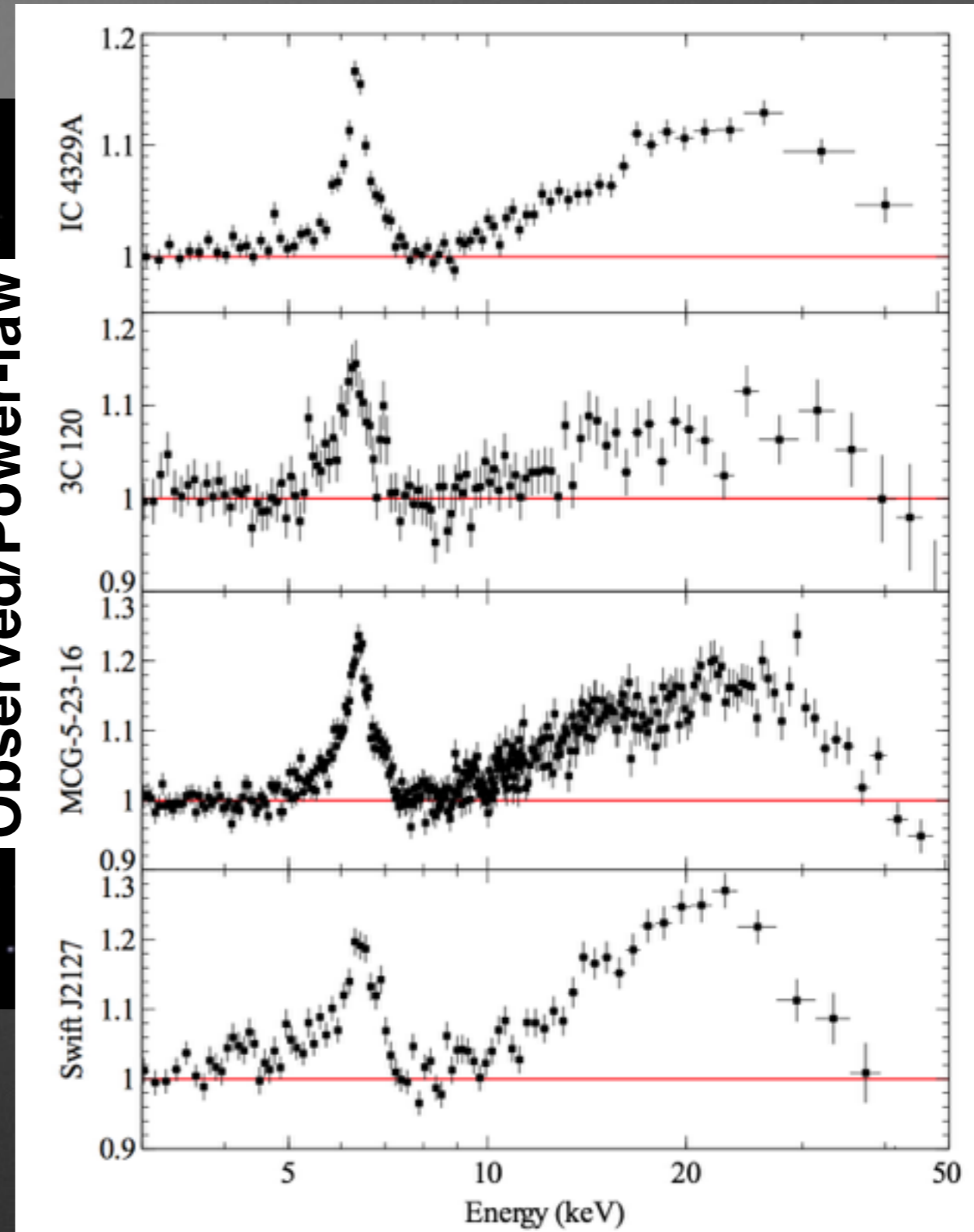


RM+18  
see also Kuin+18, Rivera Sandoval+18

# Compton Hump Spectra



Observed/Power-law





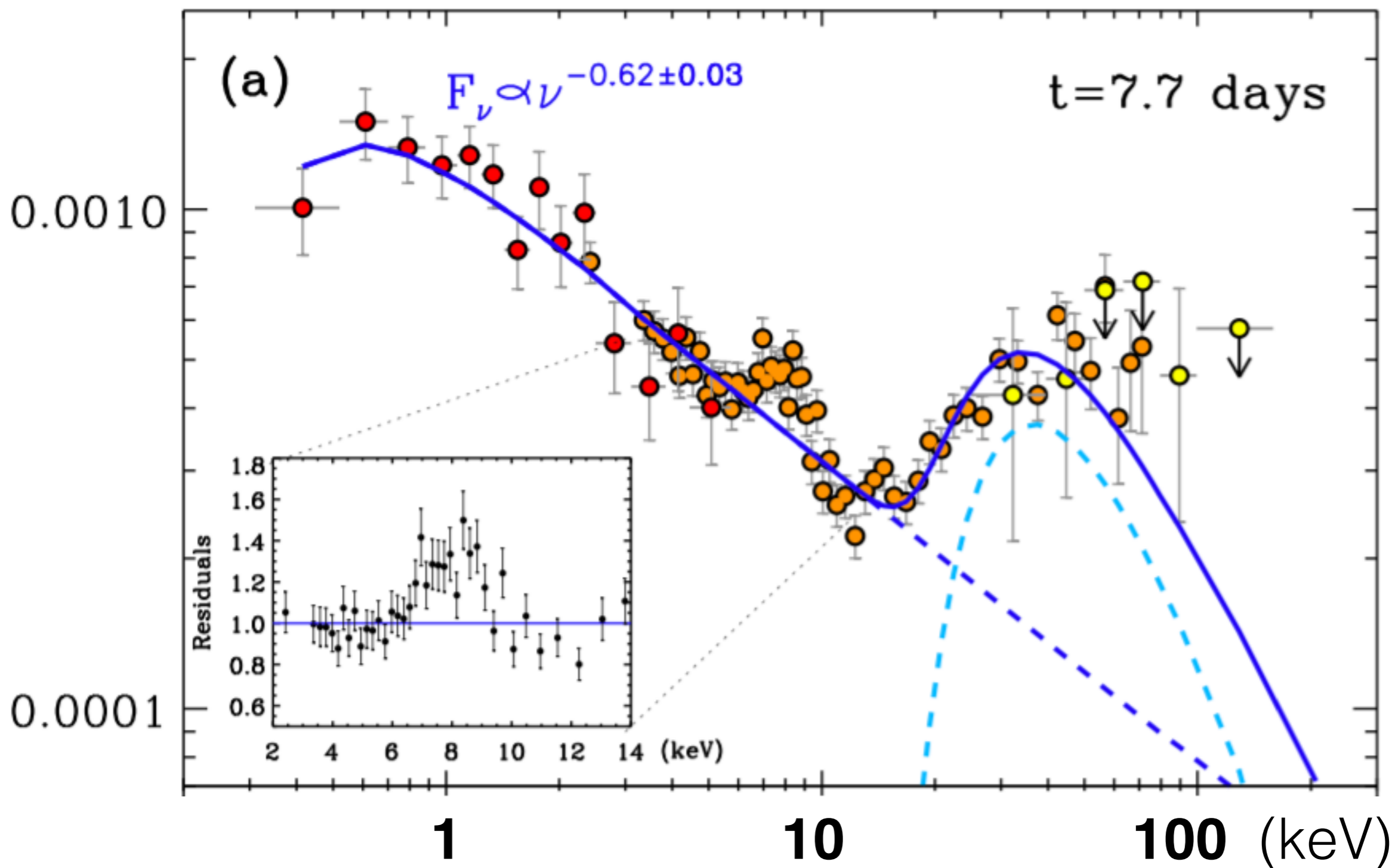
# AT2018cow

● XRT

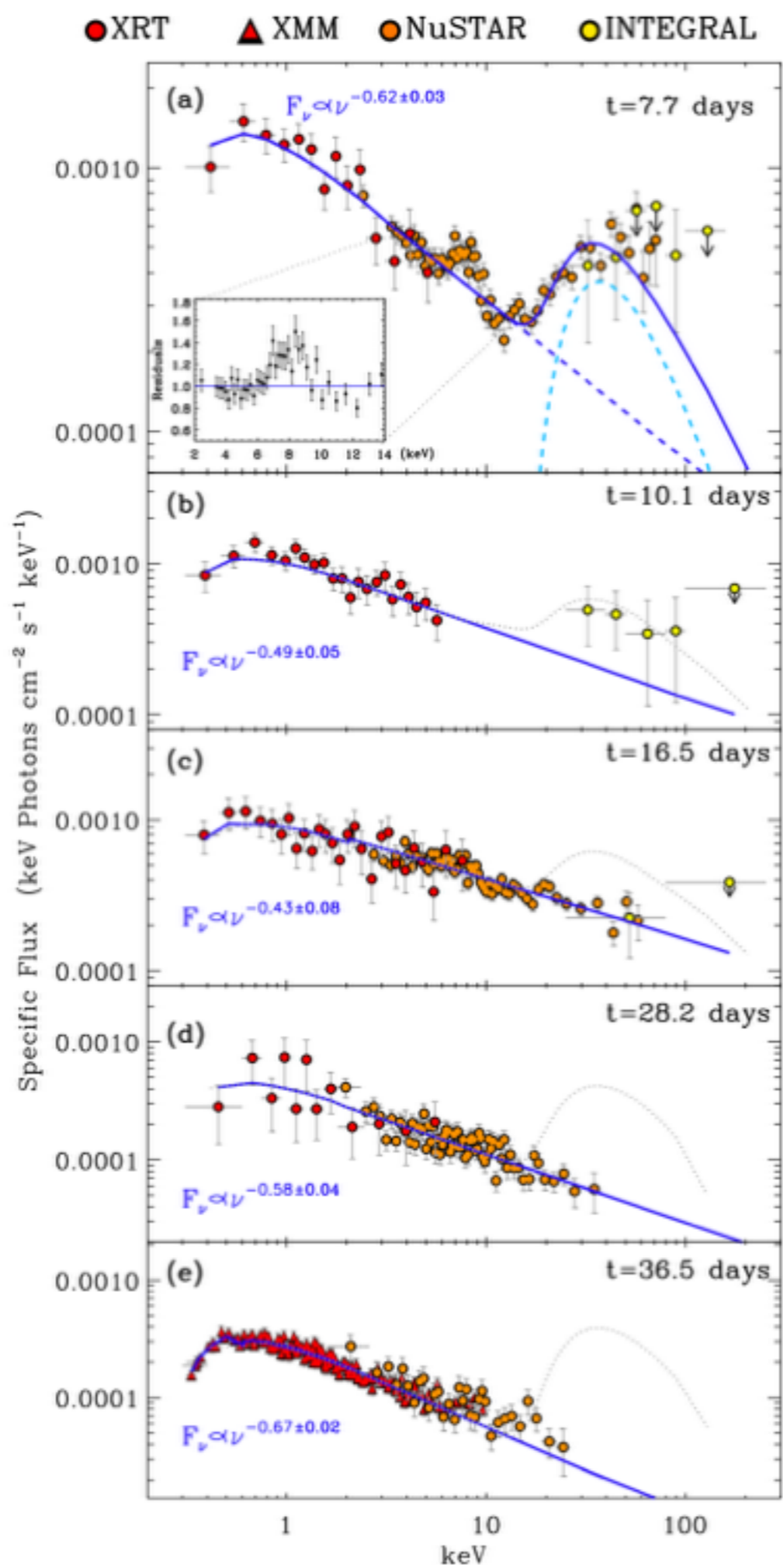
▲ XMM

● NuSTAR

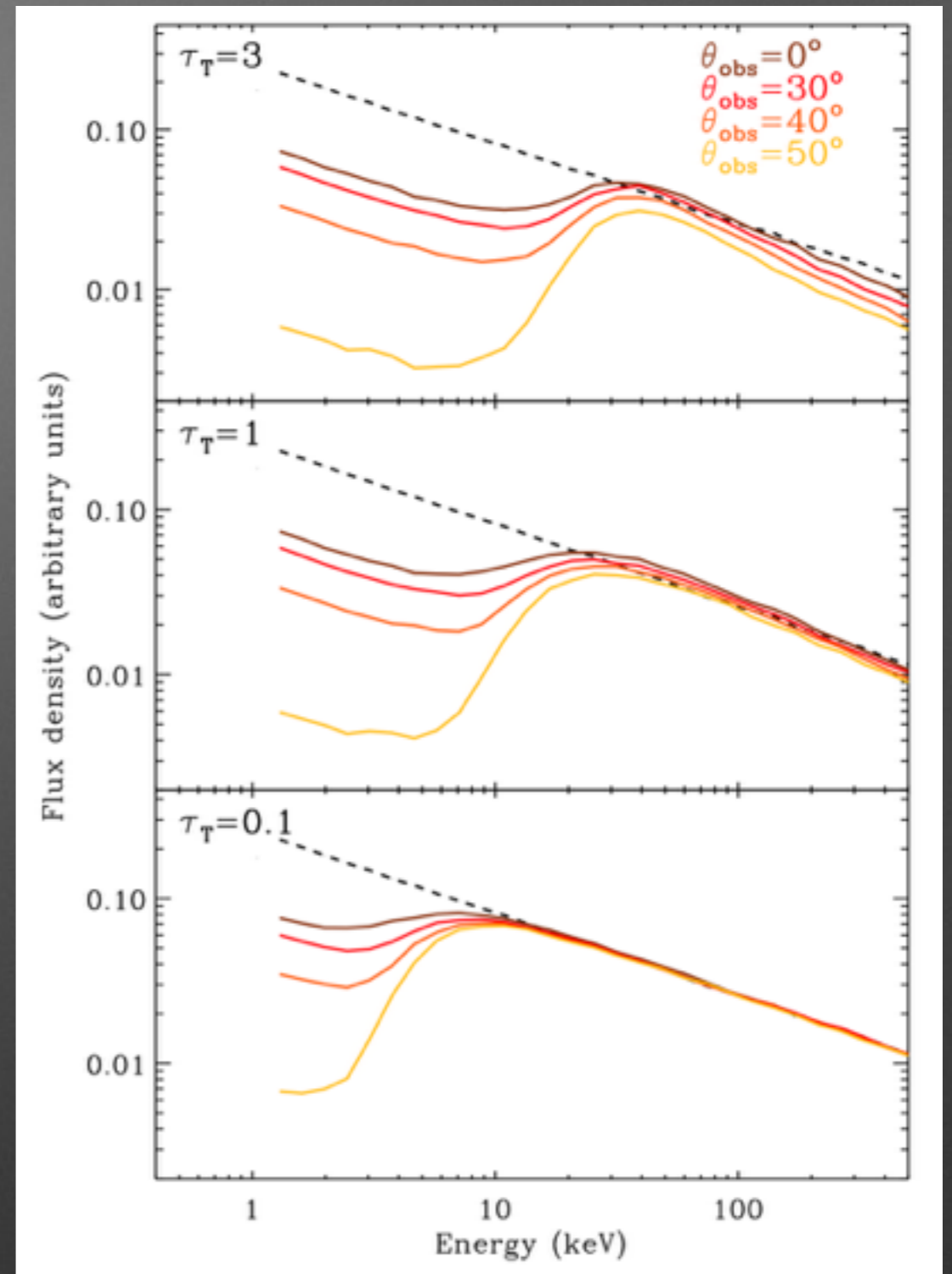
● INTEGRAL



TIME



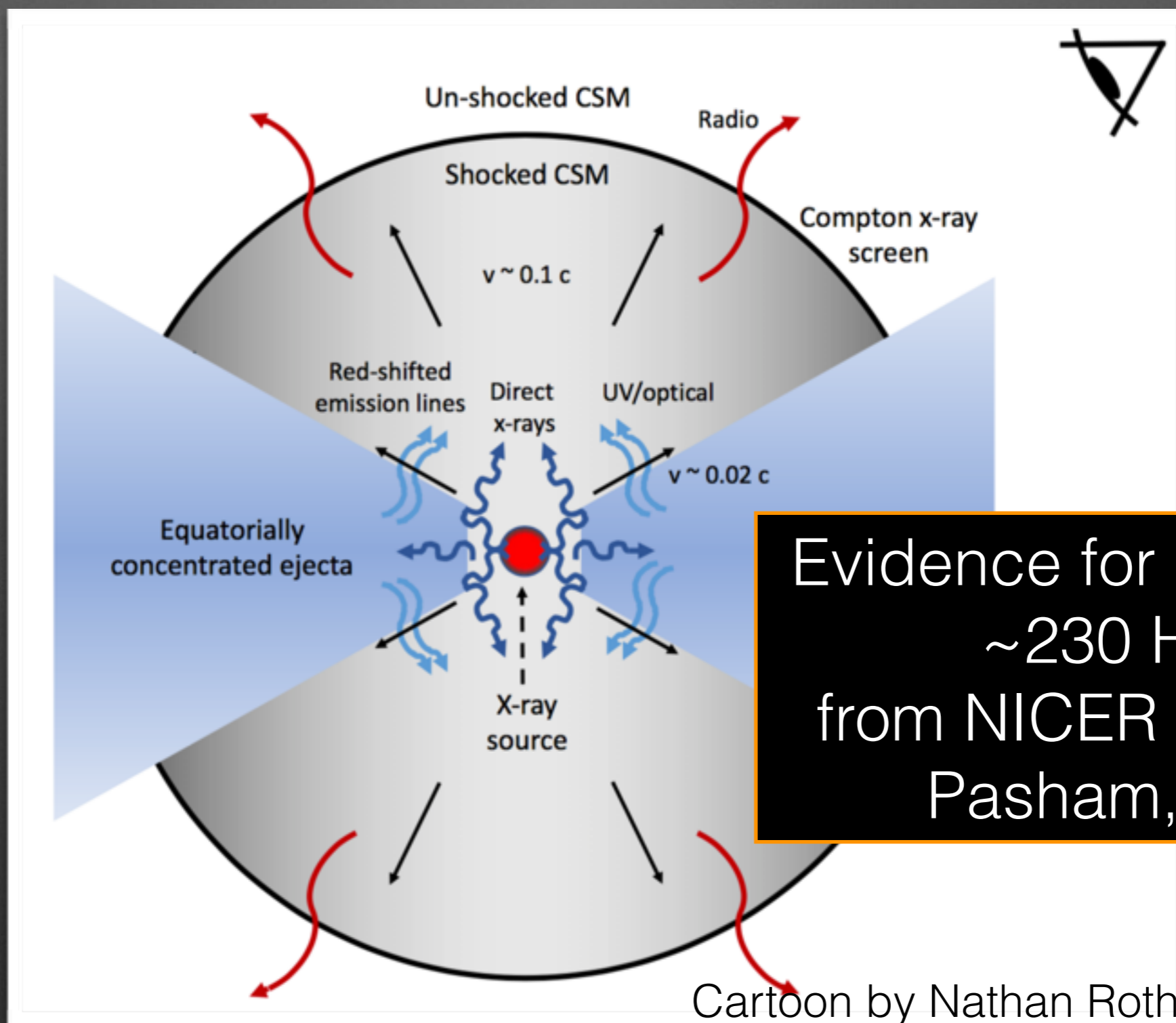
Simulations of transmitted spectrum:



The reprocessing material dilutes with time



There is an 18cow in the sky, it is aspherical and it has an engine



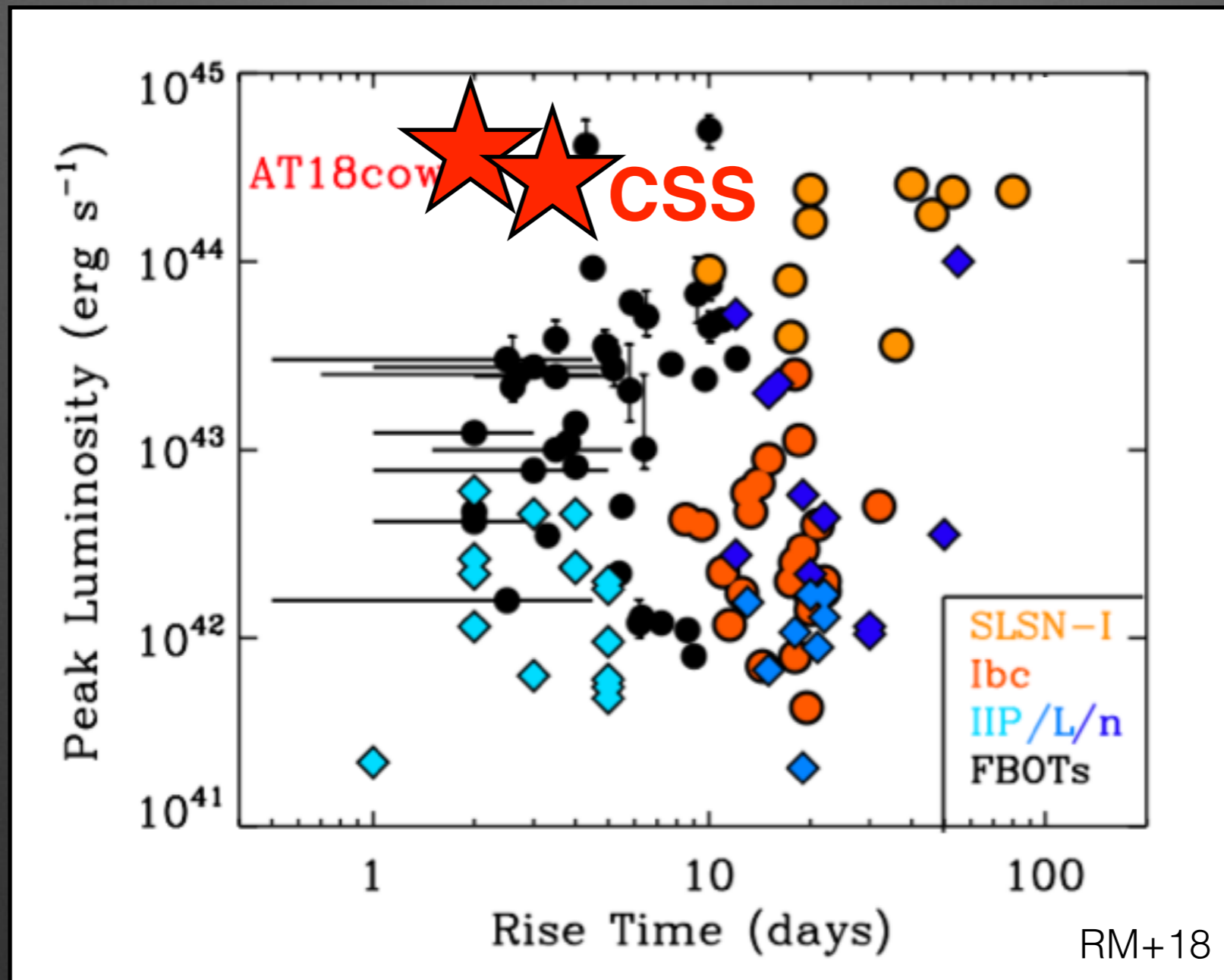
Evidence for QPOs at  $\sim 230$  Hz from NICER obs (by Pasham, D.)

RM+18

Cartoon by Nathan Roth

# Where do we go from here?

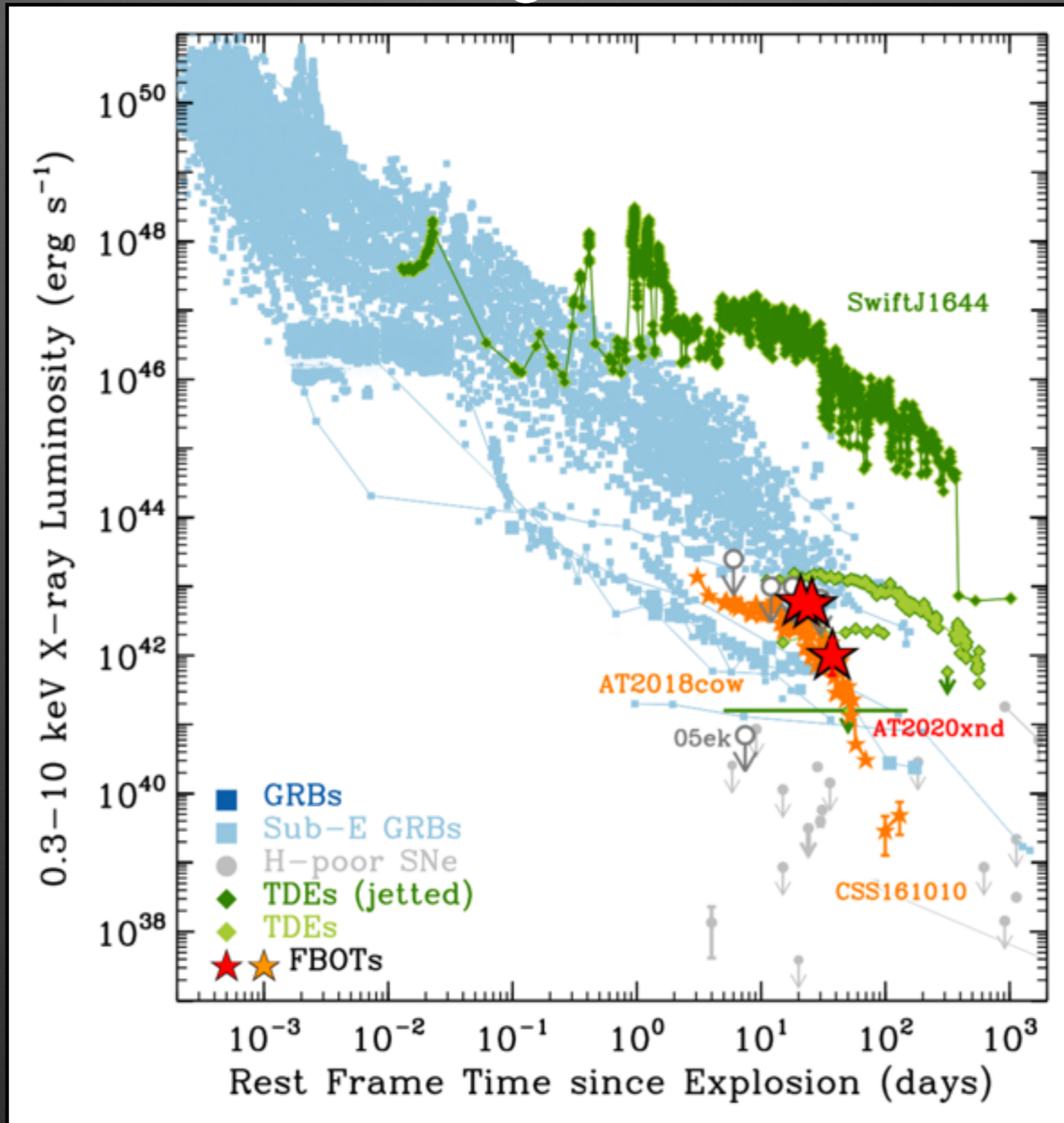
Systematic investigation of very fast evolving transients across the EM spectrum → constraints on newly-born compact-objects



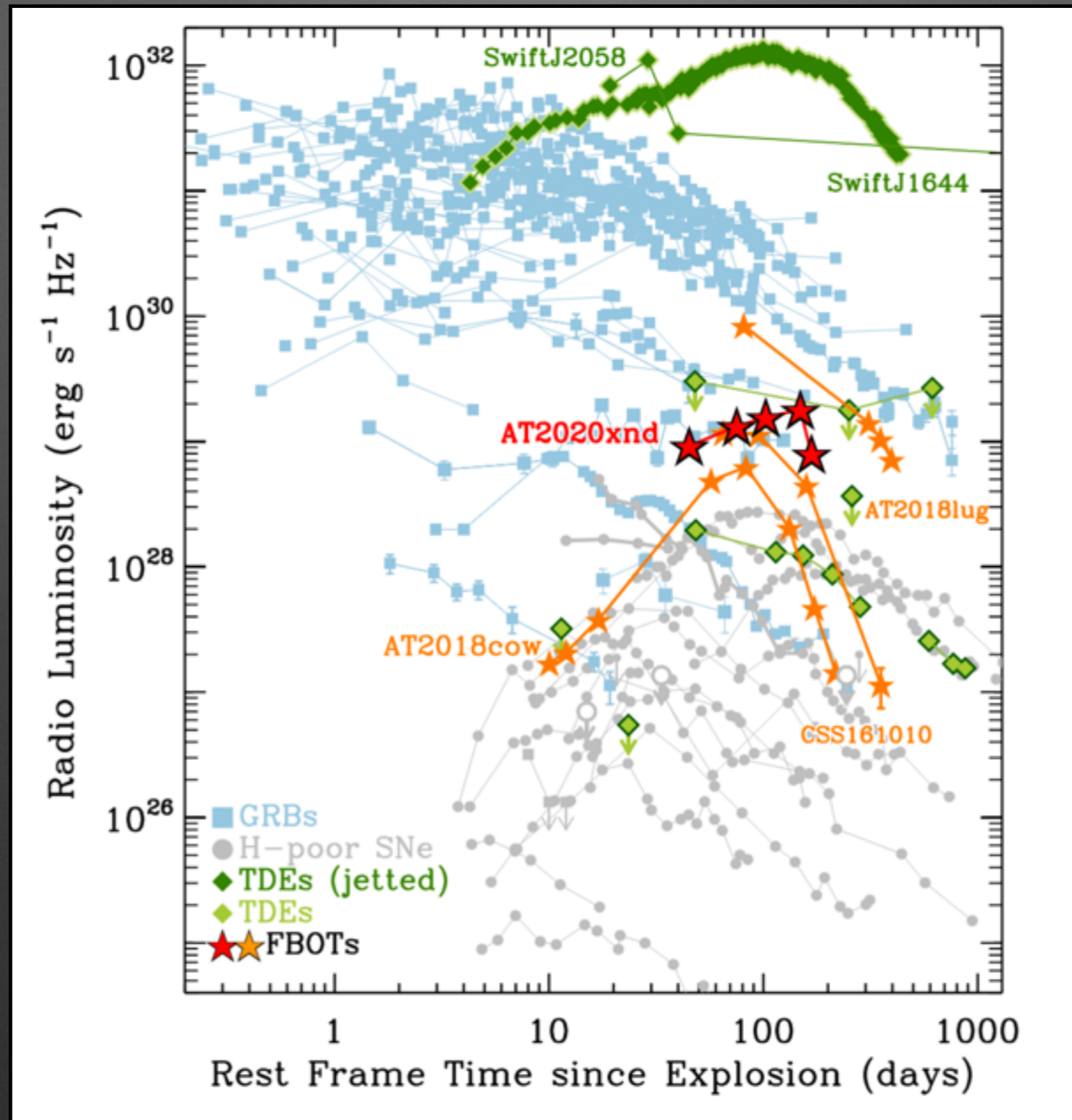
Is the COW alone?



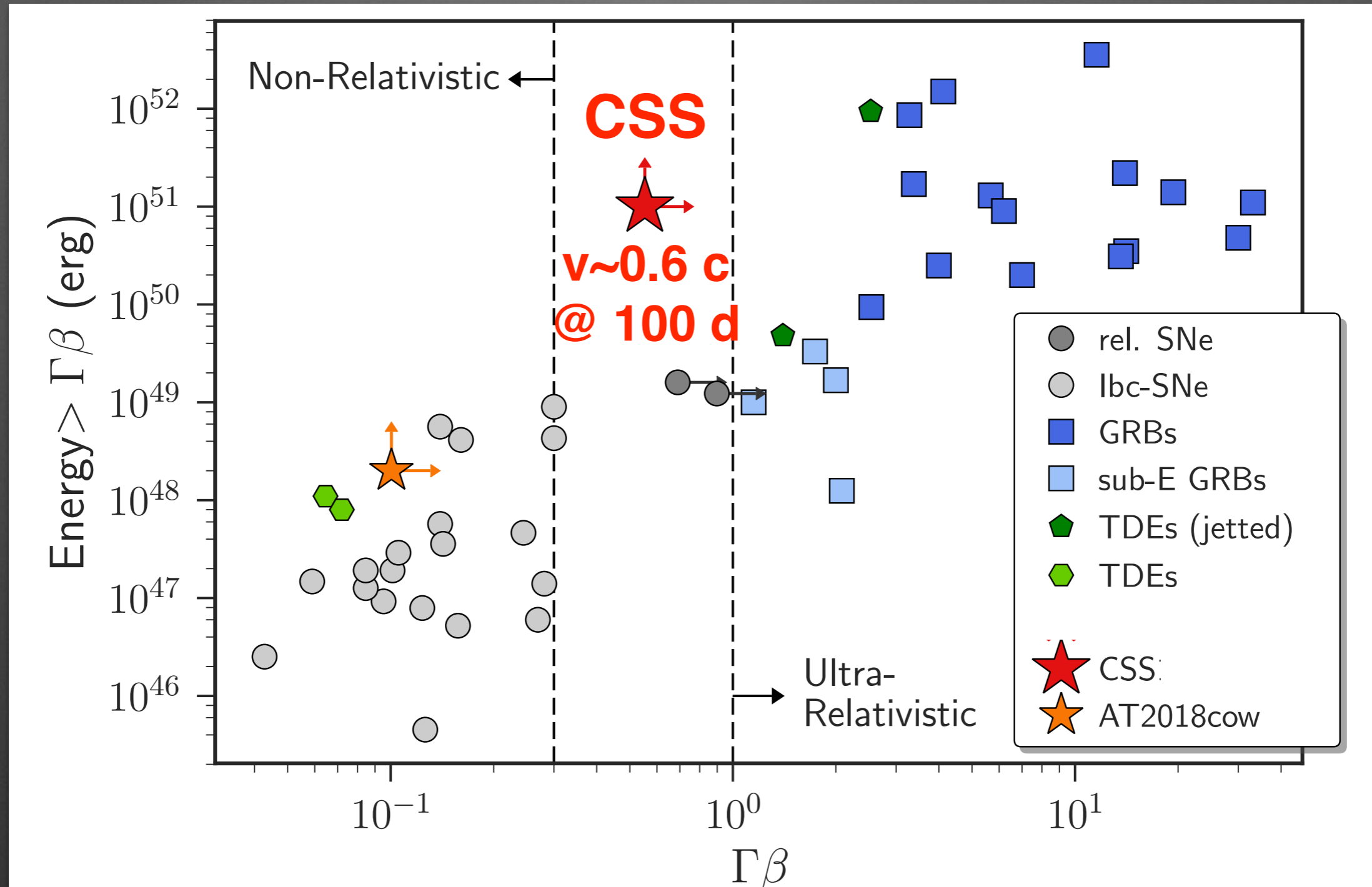
# X-ray FBOTs



# Radio FBOTs

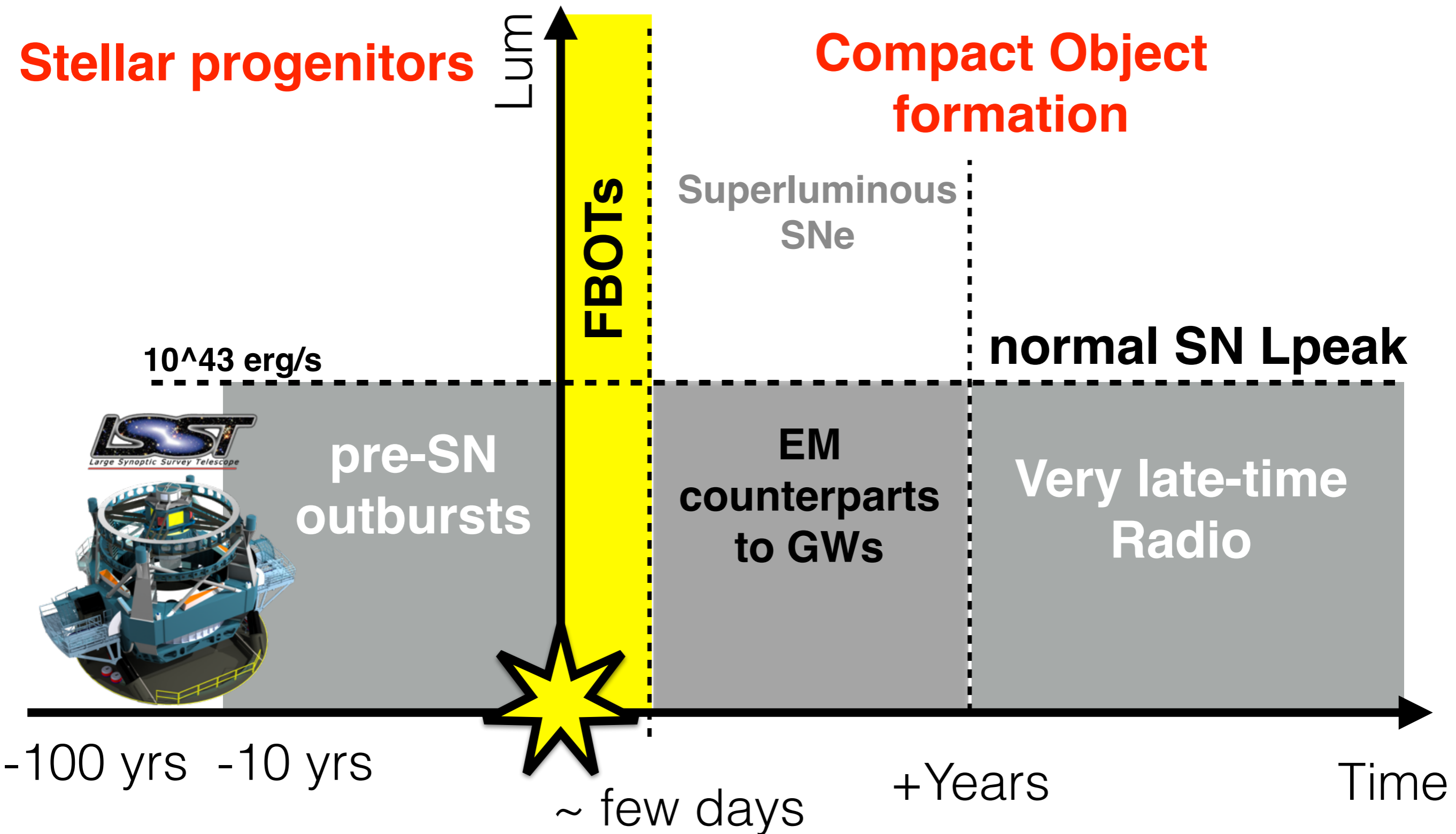






New class of transients with relativistic ejecta, distinct from GRBs, and with Hydrogen

# Discovery Frontiers:





# Future Directions



*(As far as we know, photo is public domain)*

Systematic exploration of NEW areas of the parameter space

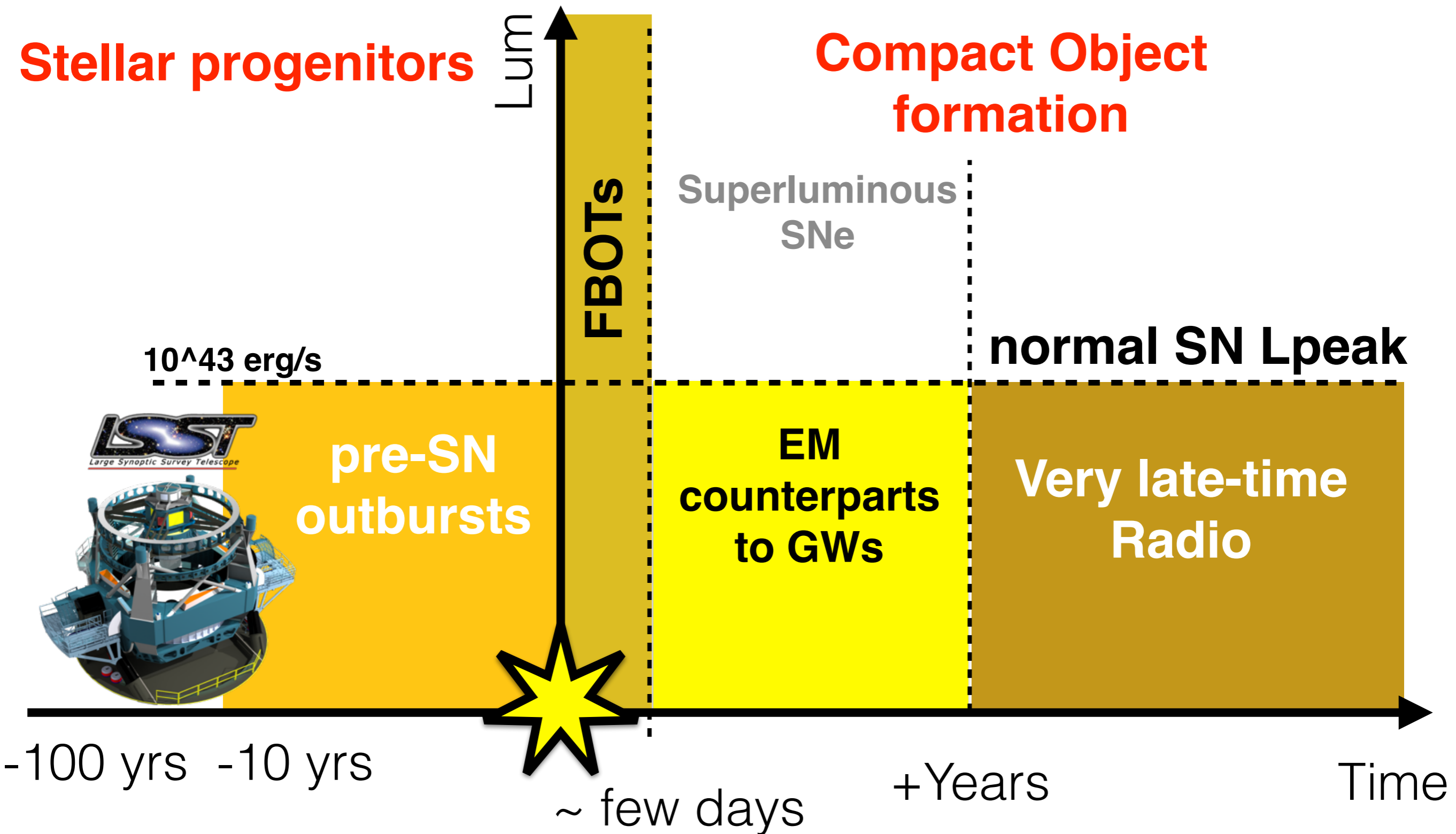
# Research Directions

- ✓ VLASS (mass-loss + PWN connection)
- ✓ FBOTs (manifestation of compact objects)
- ✓ Compact-object mergers → LSST prep. + multi-wave follow up (GW170817 included)
- ✓ Shock Physics

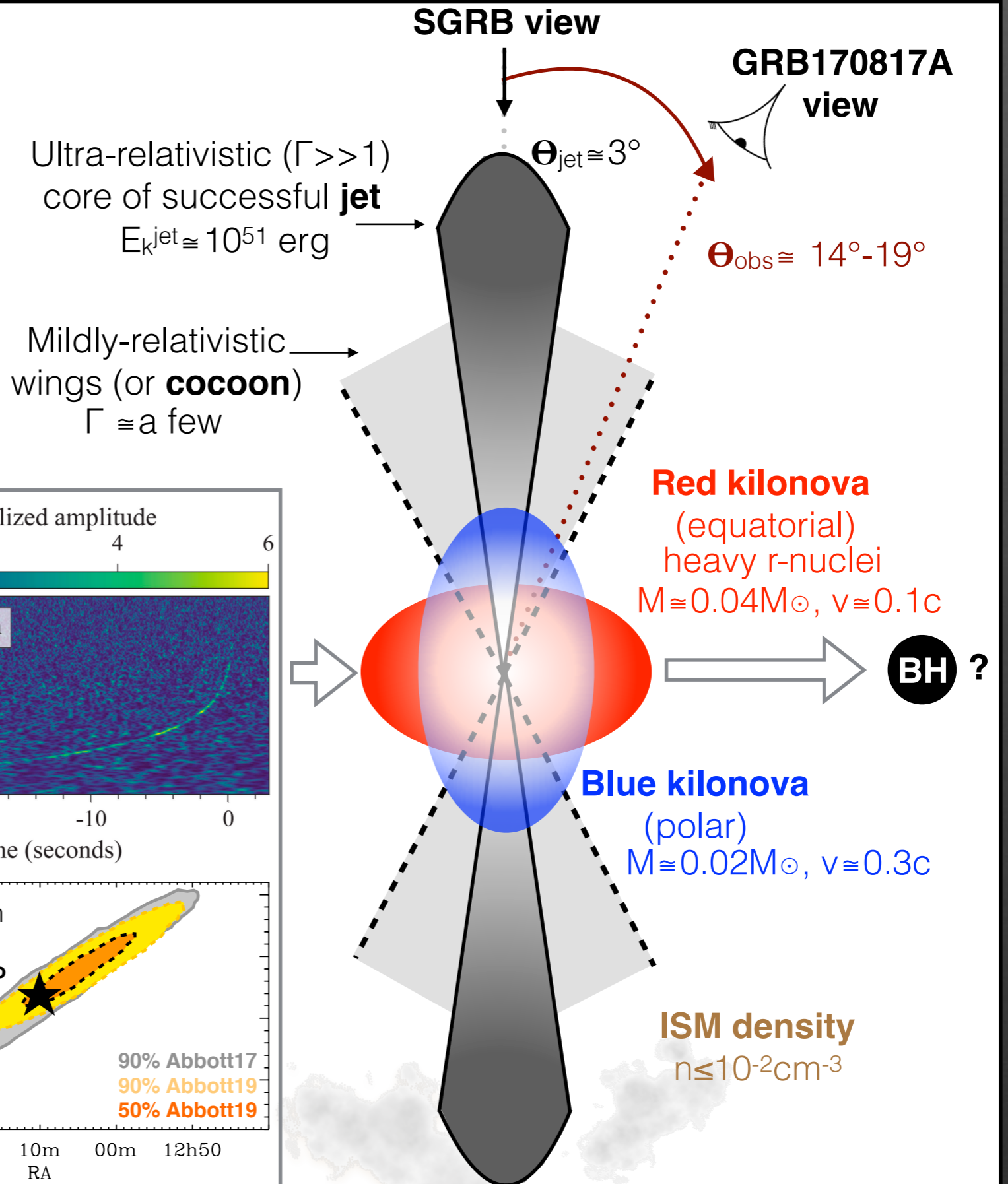
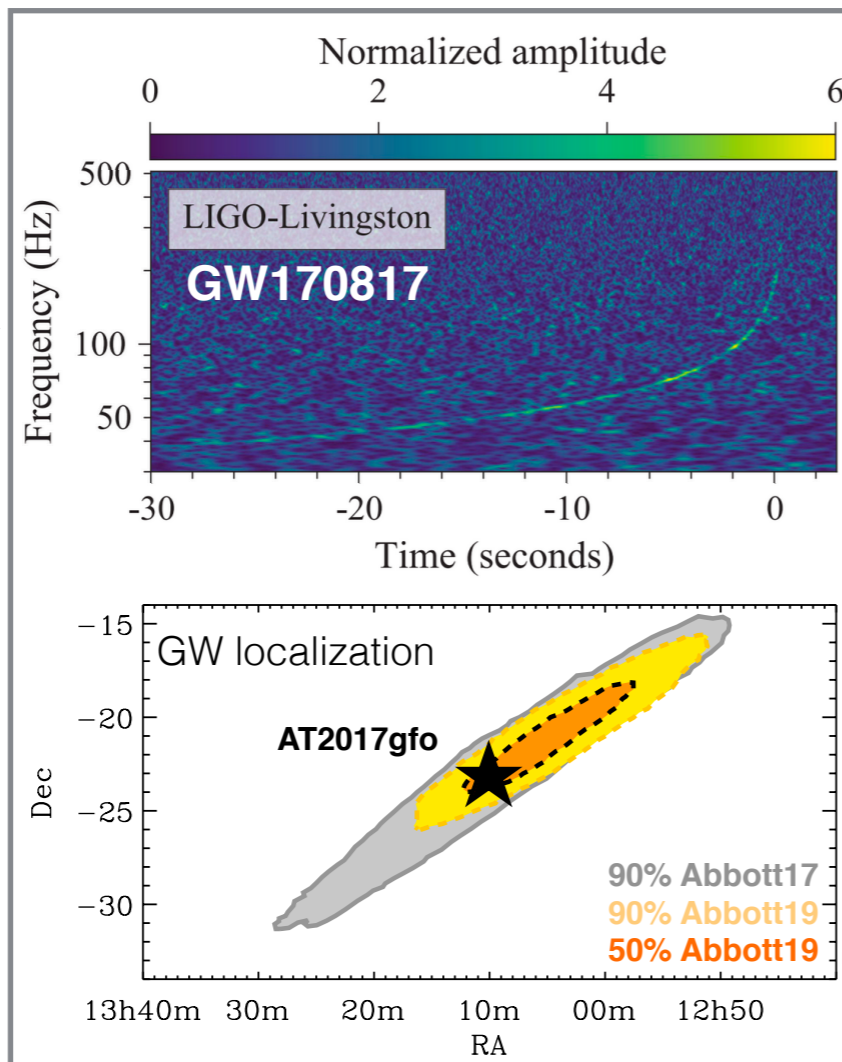
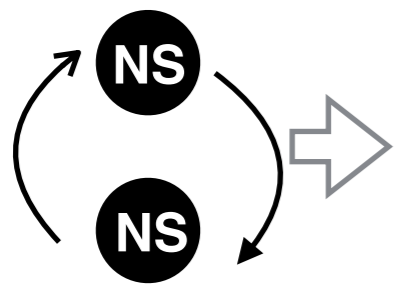
Systematic exploration of NEW areas of the parameter space



# Discovery Frontiers:



# GW170817 (GW+EM)





# Where do we go from here?



The kilonova afterglow or BH accretion of GW170817: Exploration of new areas in the parameter space of NS-NS mergers

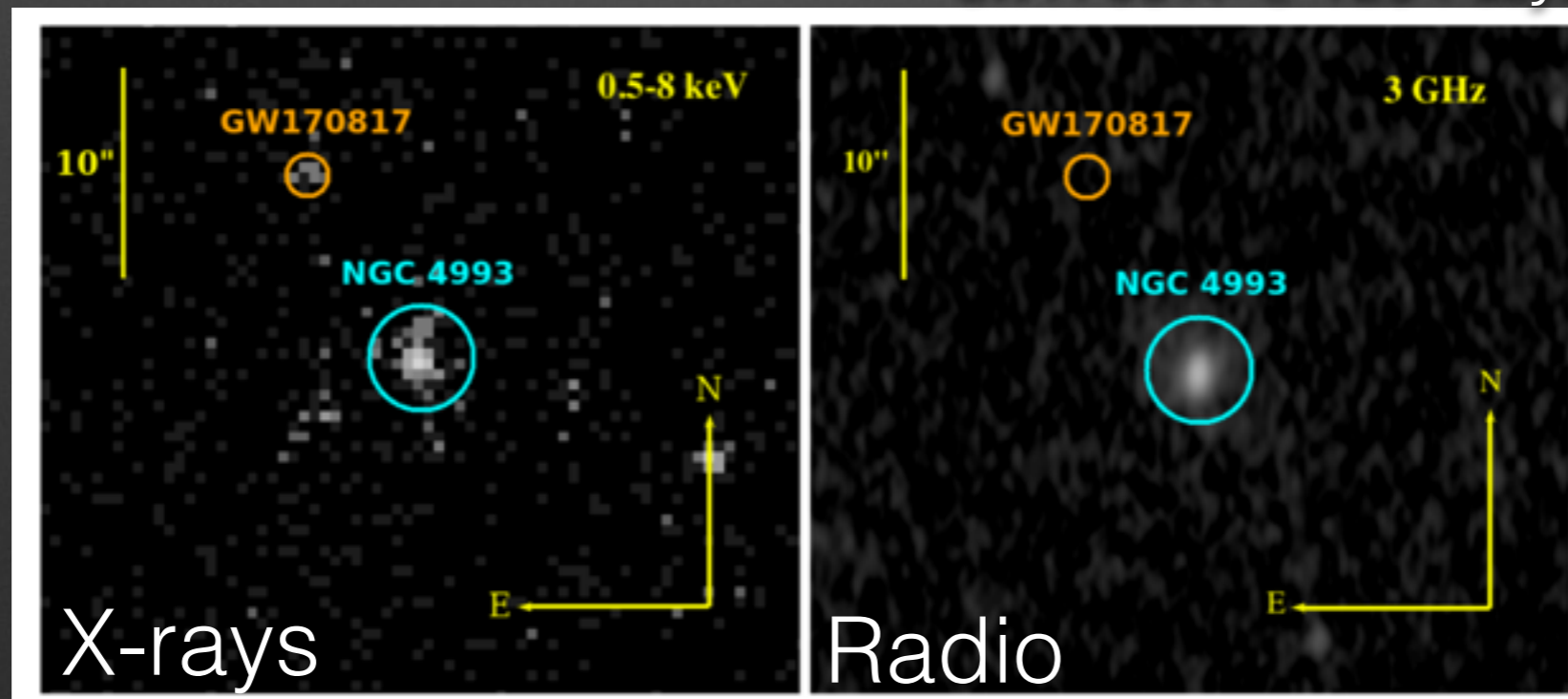


BNS mergers Population Studies

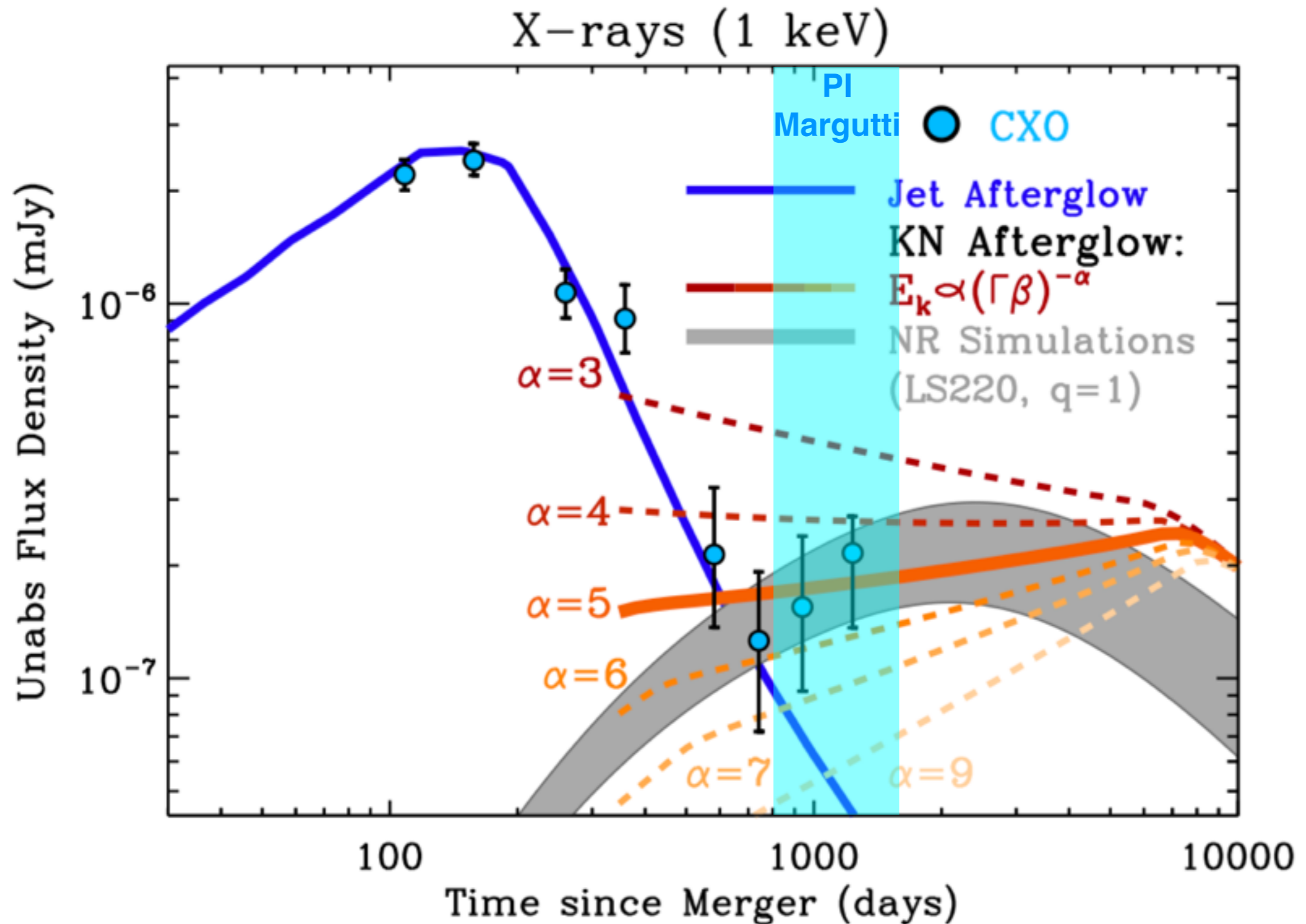
## The emergence of a new source of X-rays from the binary neutron star merger GW 170817

<sup>2</sup> A. HAJELA,<sup>1</sup> R. MARGUTTI,<sup>1</sup> J. S. BRIGHT,<sup>1</sup> K. D. ALEXANDER,<sup>1,\*</sup> B. D. METZGER,<sup>2,3</sup> V. NEDORA,<sup>4</sup> A. KATHIRGAMARAJU,<sup>5</sup>  
<sup>3</sup> B. MARGALIT,<sup>5</sup> D. RADICE,<sup>6,7,8</sup> E. BERGER,<sup>9</sup> A. MACFADYEN,<sup>10</sup> D. GIANNIOS,<sup>11</sup> R. CHORNOCK,<sup>1</sup> I. HEYWOOD,<sup>12,13,14</sup>  
<sup>4</sup> L. SIRONI,<sup>15</sup> O. GOTTLIEB,<sup>16</sup> D. COPPEJANS,<sup>1</sup> T. LASKAR,<sup>17</sup> Y. CENDES,<sup>9</sup> R. BARNIOL DURAN,<sup>18</sup> T. EFTEKHARI,<sup>9</sup> W. FONG,<sup>1</sup>  
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<sup>6</sup> G. TERRERAN,<sup>1</sup> V. A. VILLAR,<sup>22</sup> P. K. BLANCHARD,<sup>1</sup> S. GOMEZ,<sup>9</sup> G. HOSSEINZADEH,<sup>9</sup> D. J. MATTHEWS,<sup>1</sup> AND  
<sup>7</sup> J. C. RASTINEJAD<sup>1</sup>

GW170817 @ 1234 days



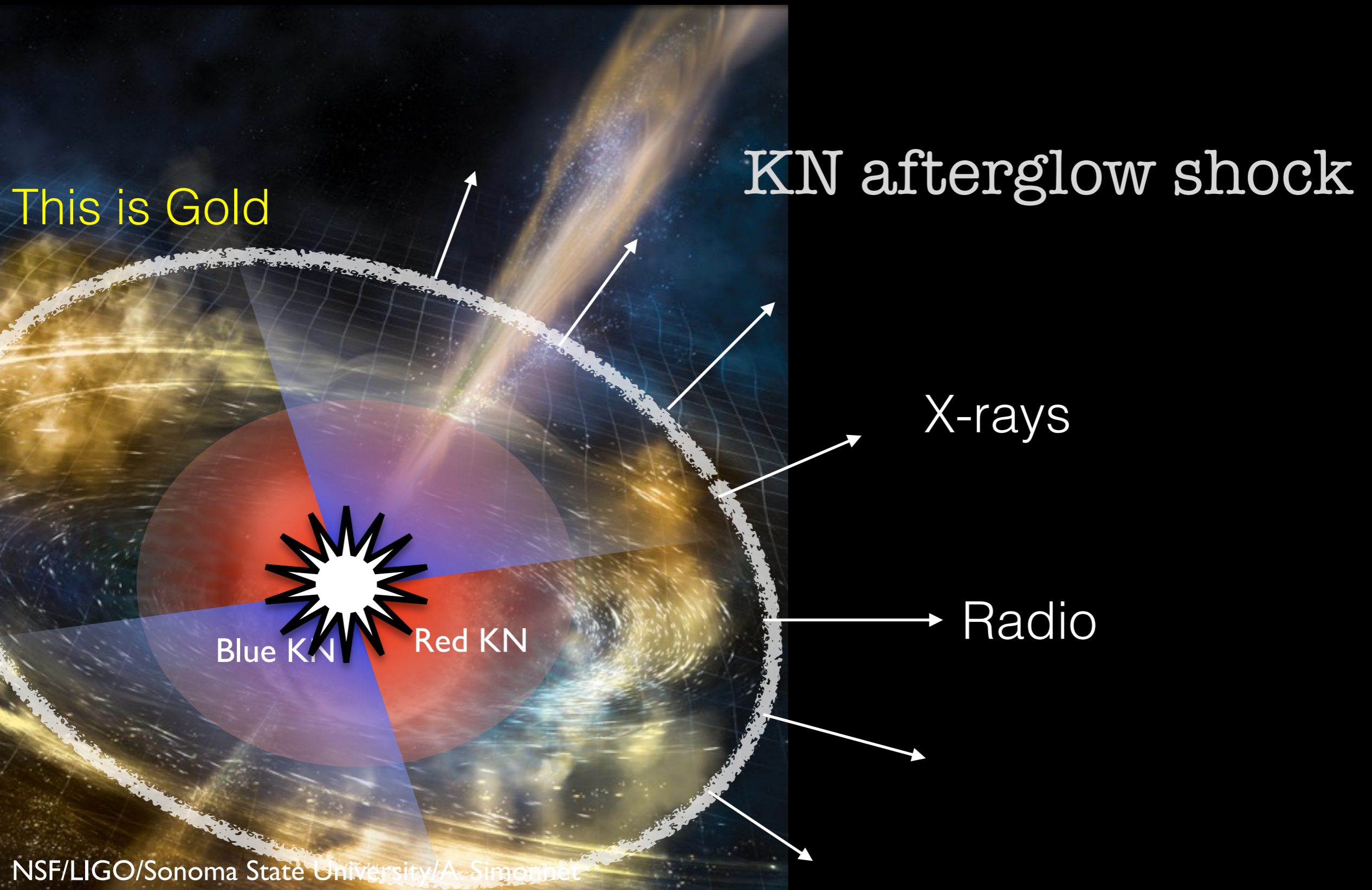
# The emergence of a **new X-ray component** of emission at 3.5 yrs since NS merger



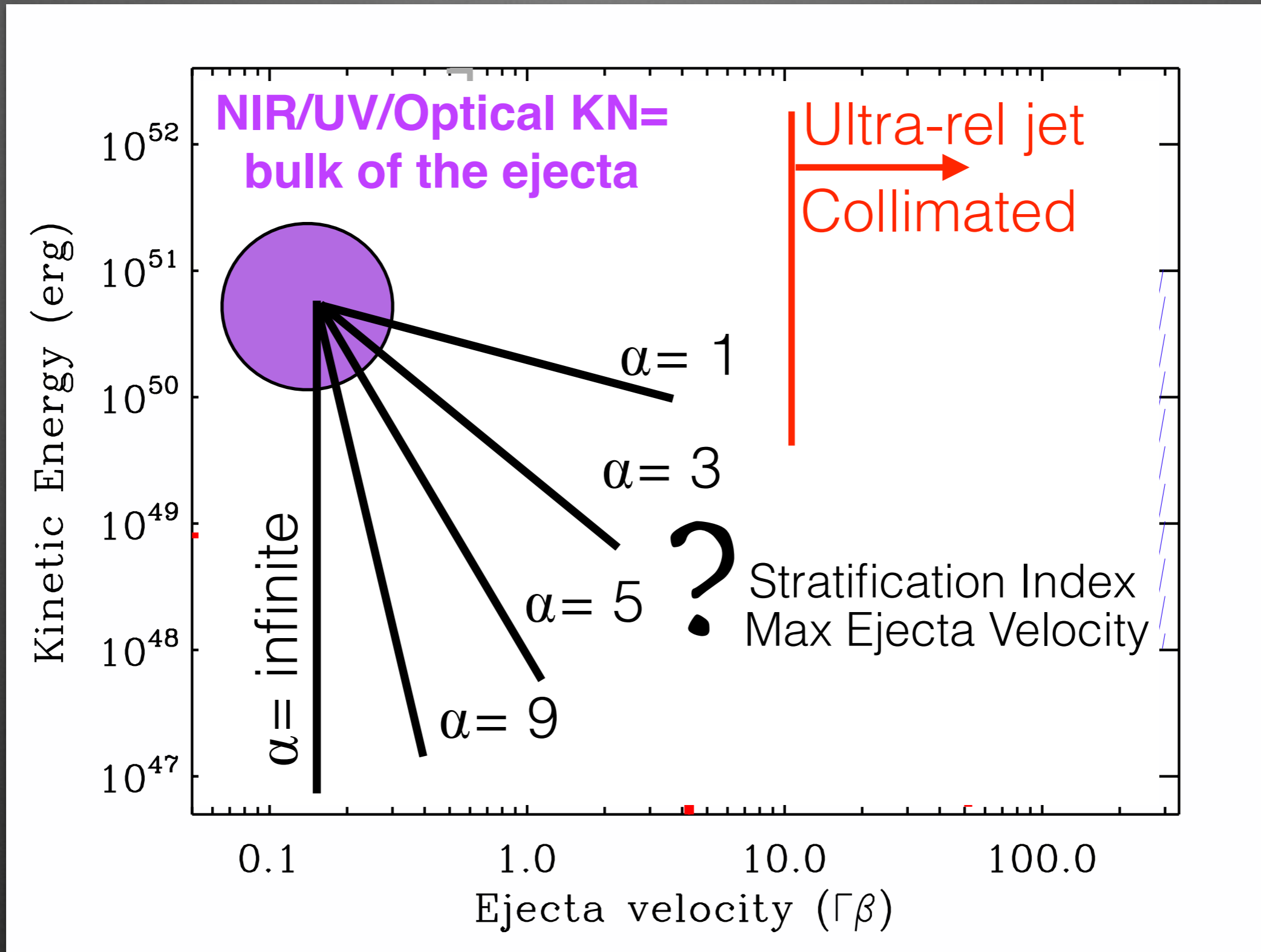


# The KN Velocity Structure and the nature of the remnant

Nakar & Piran 2011; Metzger & Berger 2012; Metzger & Bower 2014; Hotokezaka & Piran 2015, Kathirgamraju+2019



# Energy Partitioning $E(\Gamma\beta) \sim (\Gamma\beta)^{-\alpha}$

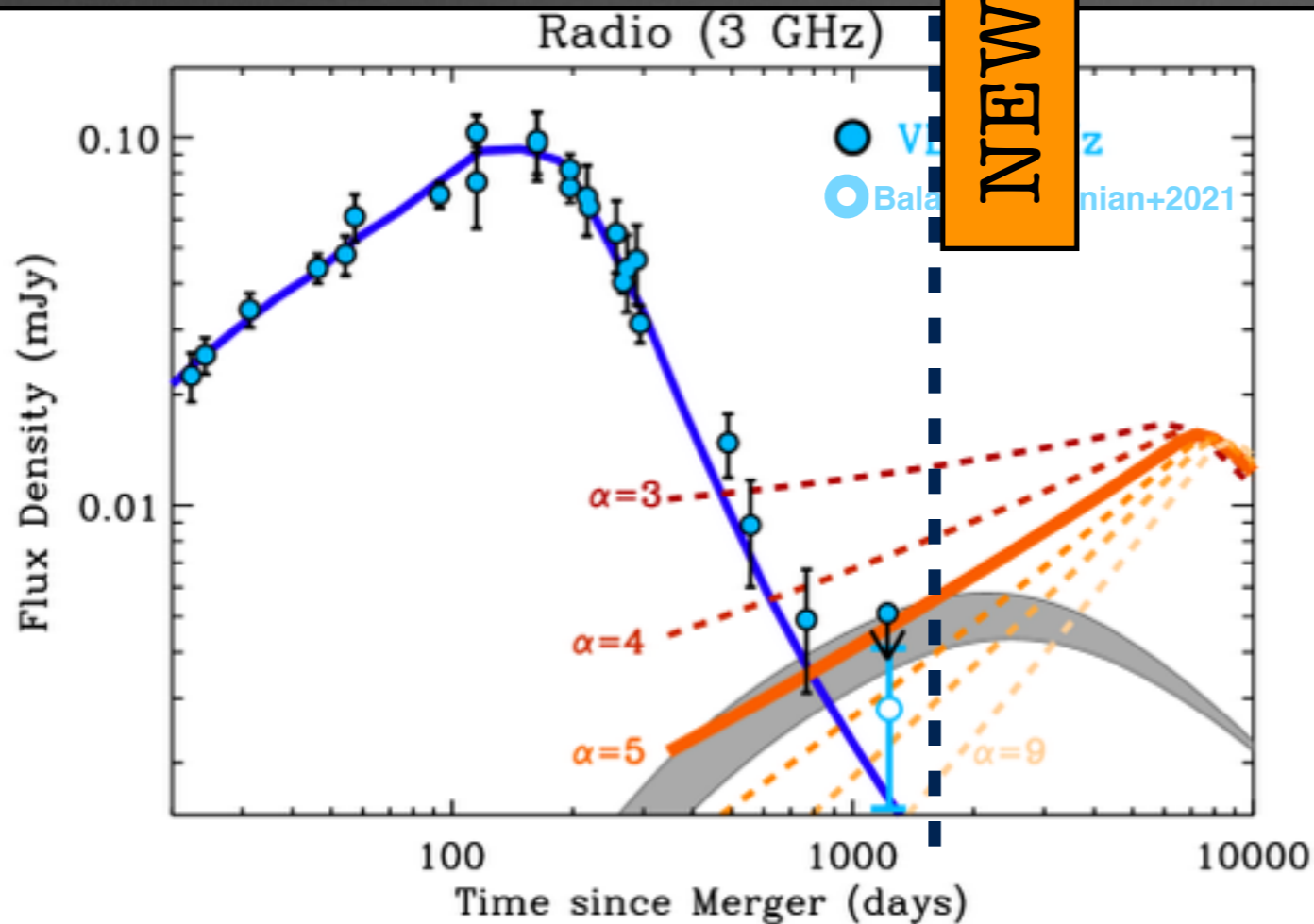
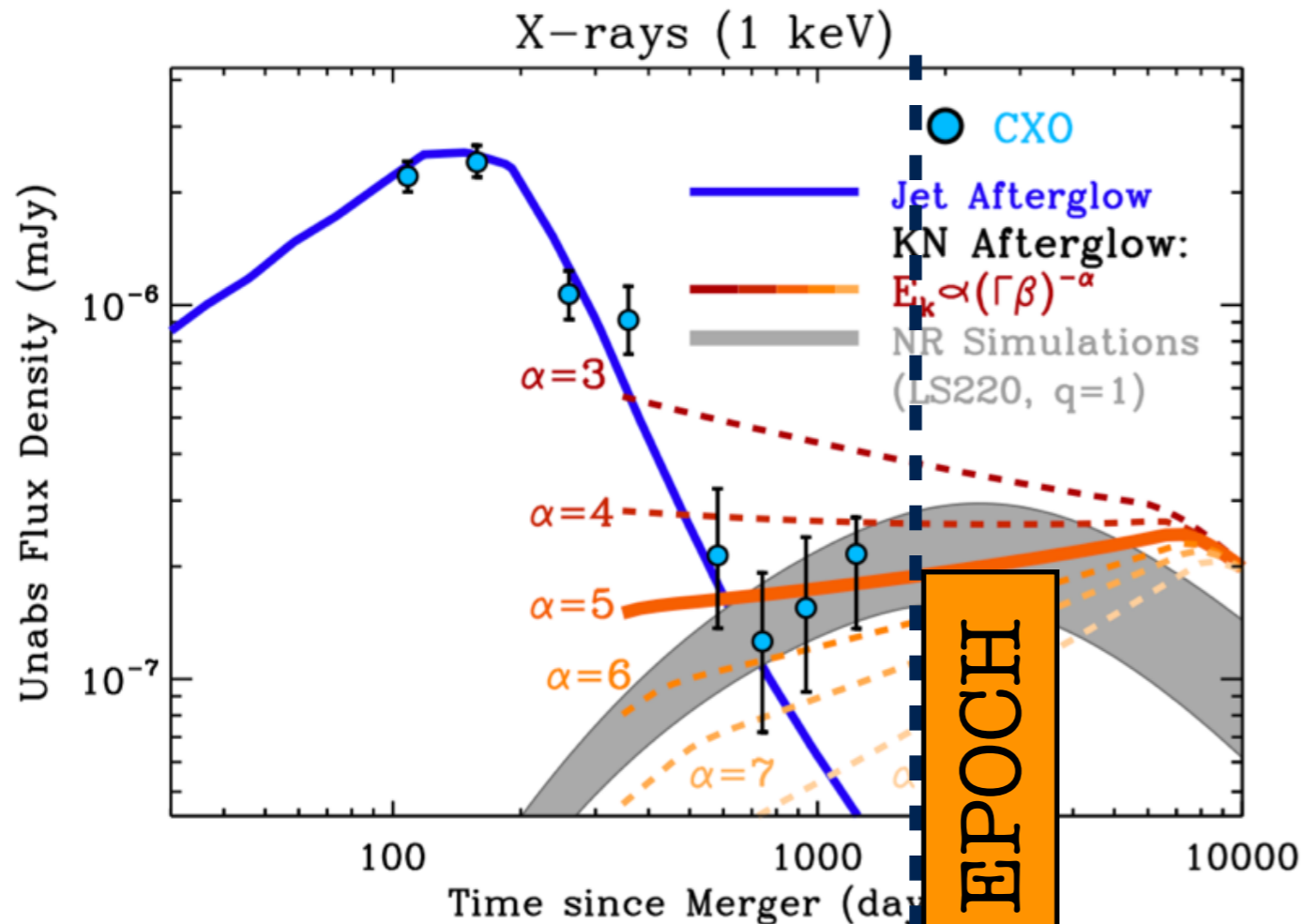


**Connection to nature of the remnant**

e.g., Radice+2018

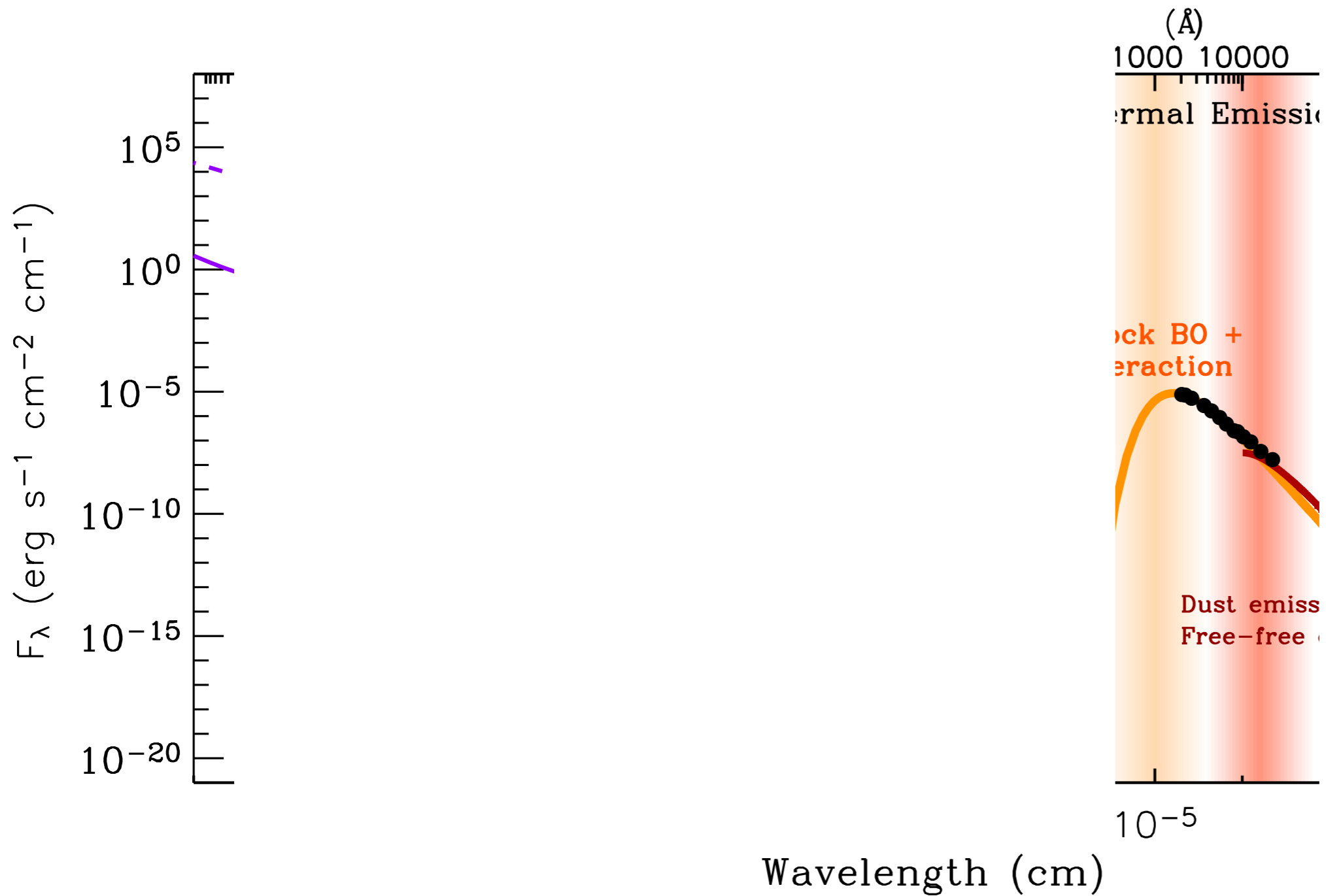


Where do we go from here?



New epoch of deep Chandra + VLA monitoring approved

# Gamma-ray to Radio SED of SN2009ip at peak



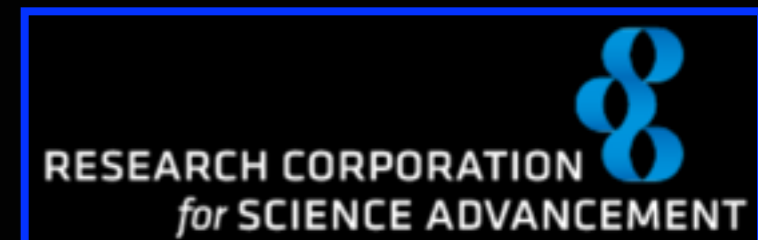


“...*The EMD*

*is where we start from...*”

*The Little Gidding by T. S. Eliot*

Thanks to NOAO, Chandra, XMM, Swift, NuSTAR, VLA, VLBI, CARMA, SMA, GMRT, Keck, SOAR, MMT, UKIRT, WIYN, Fermi for their generous support to our investigation



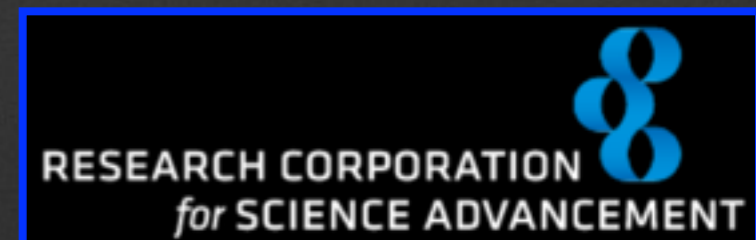
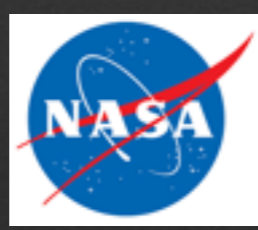
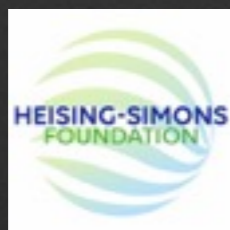
*(This is not)*

*.....The End....*

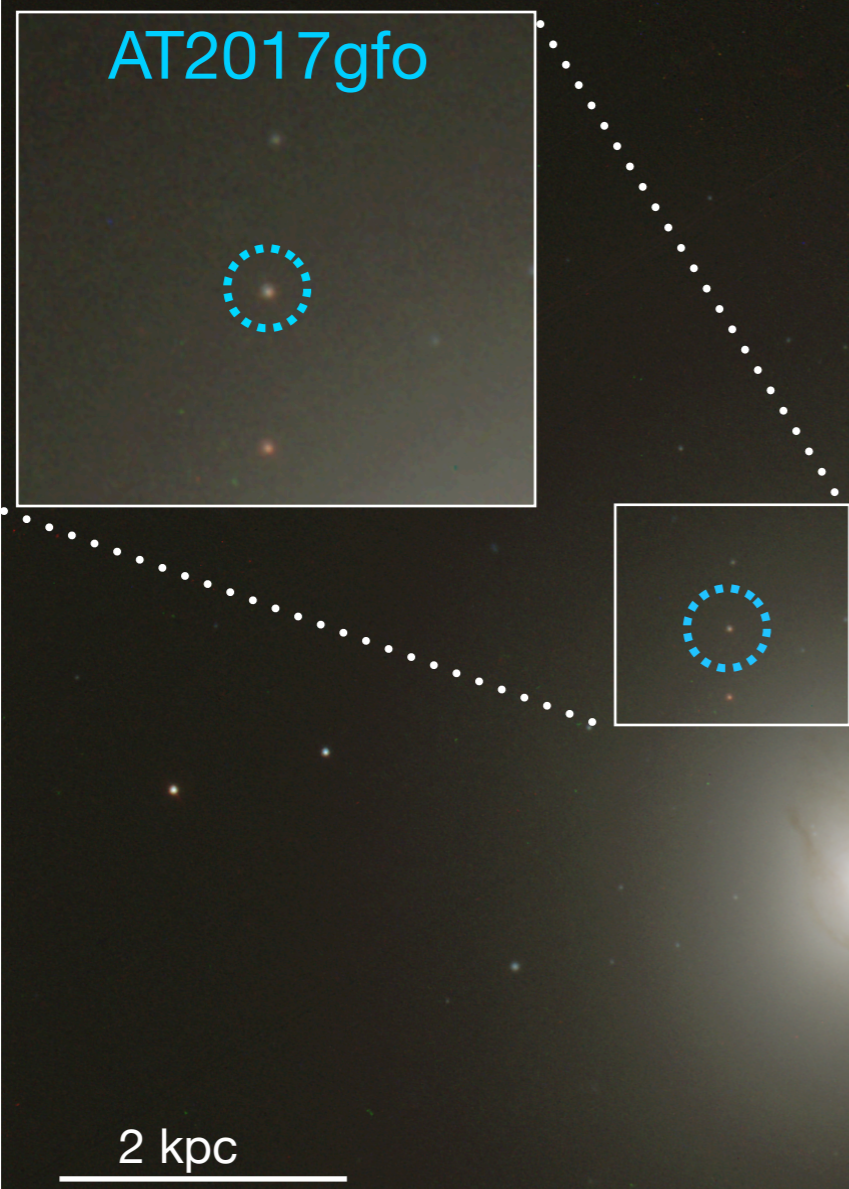
*“What we call the beginning is often the end.  
And to make an end is to make a beginning.*

*The end is where we start from.”*

*T. S. Eliot*





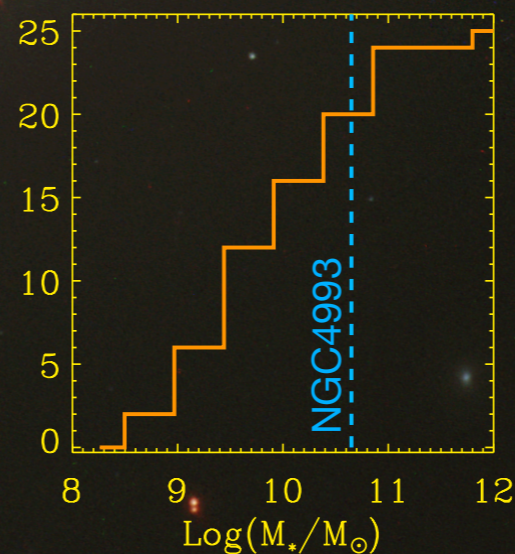
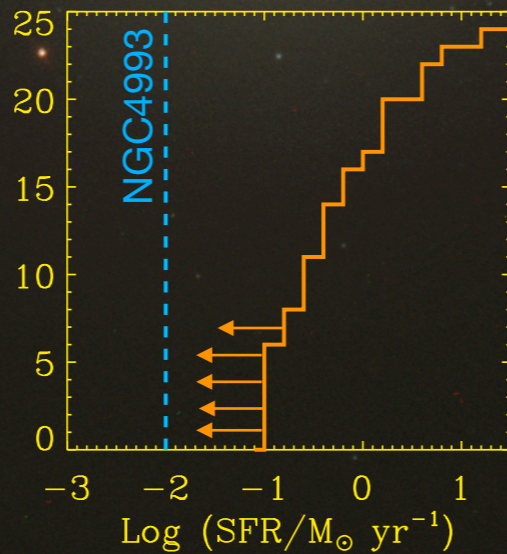
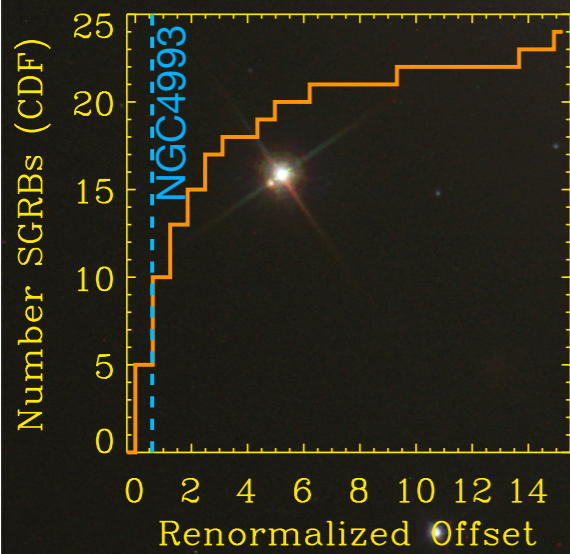
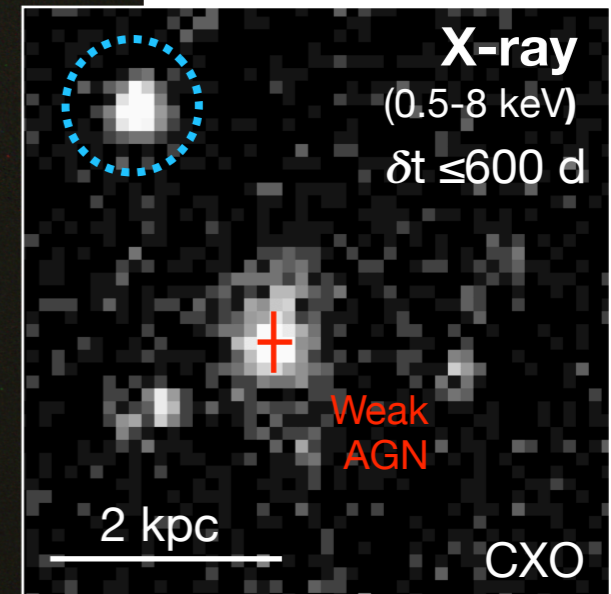
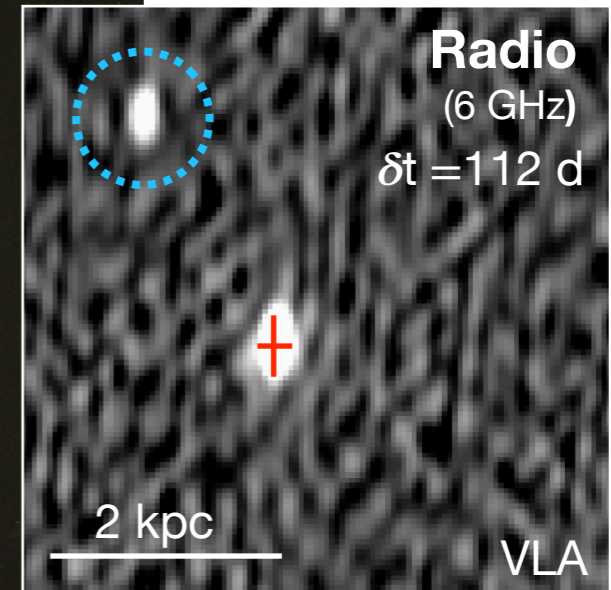
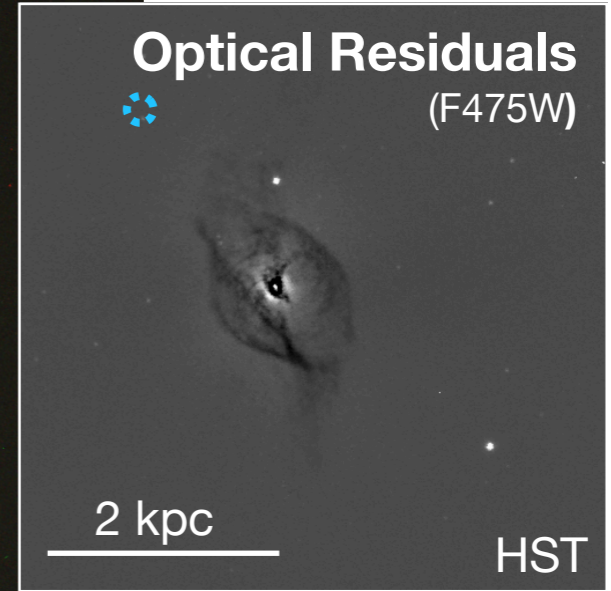


# NGC 4993

$d_L = 40.7$  Mpc

*HST/ACS*

$\delta t = 11$  d





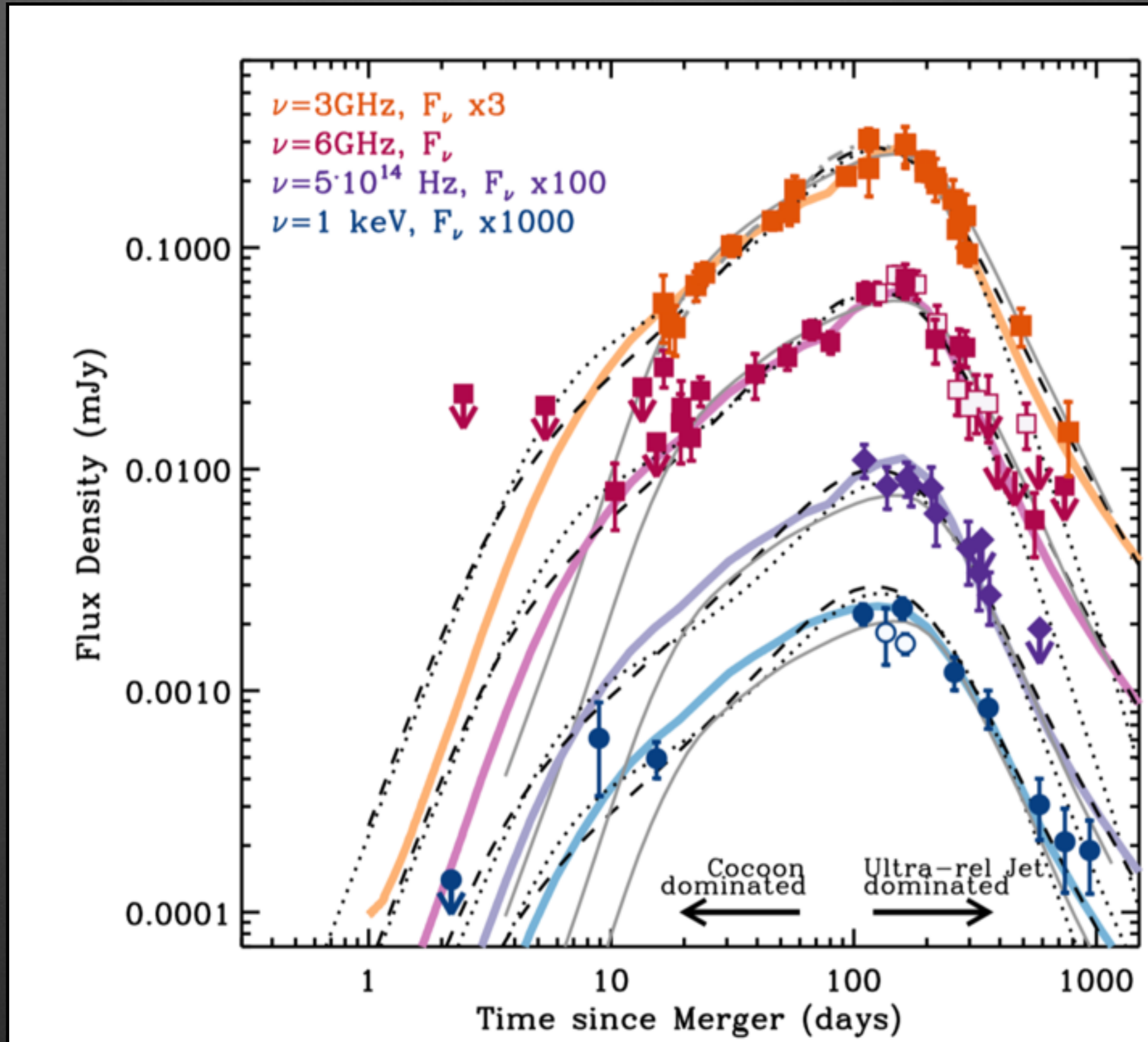
# Backup Slides





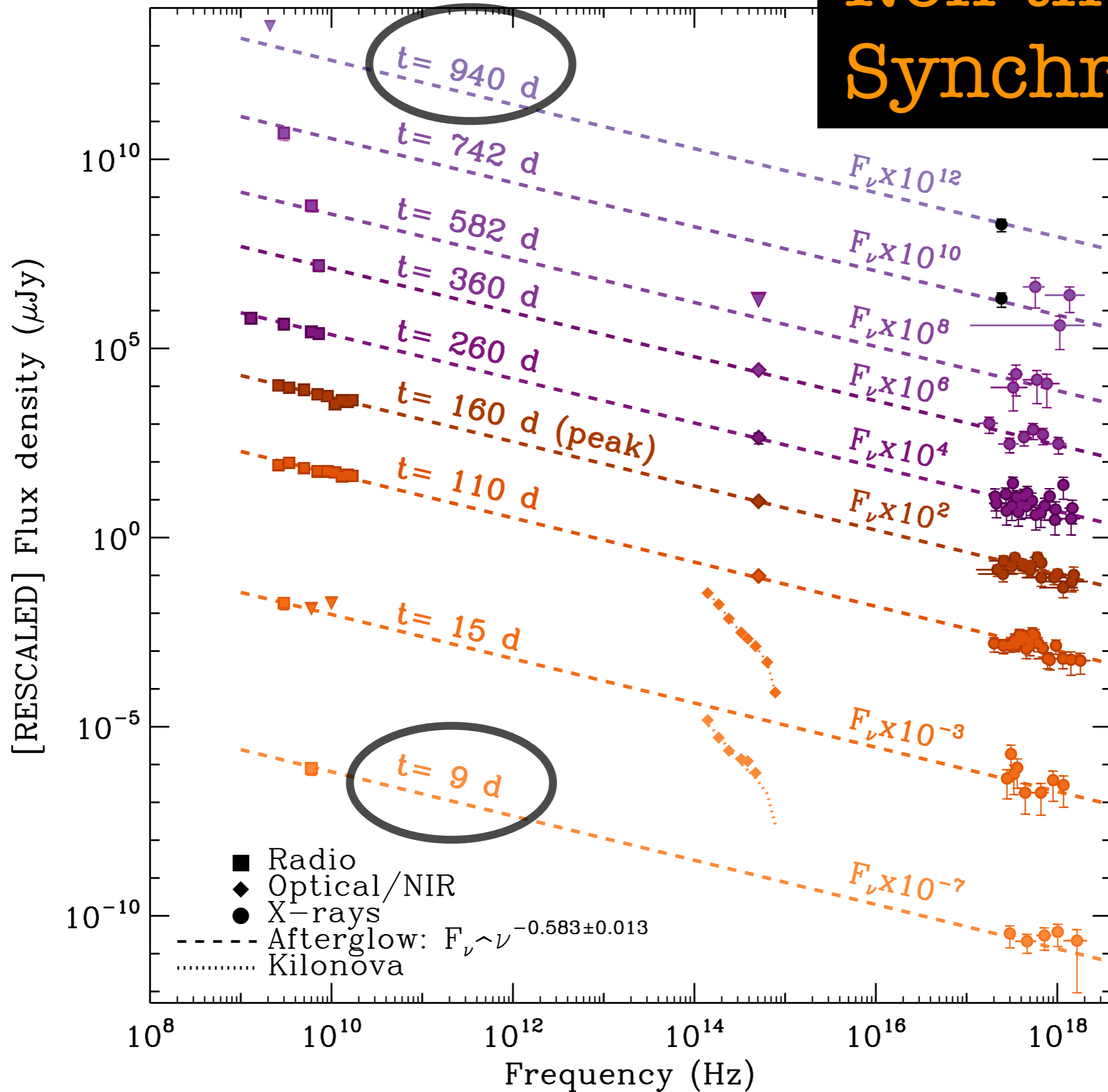
# GW170817 Jet Afterglow Emission:

Margutti & Chornock ARA&A 2021 in press, and references there in



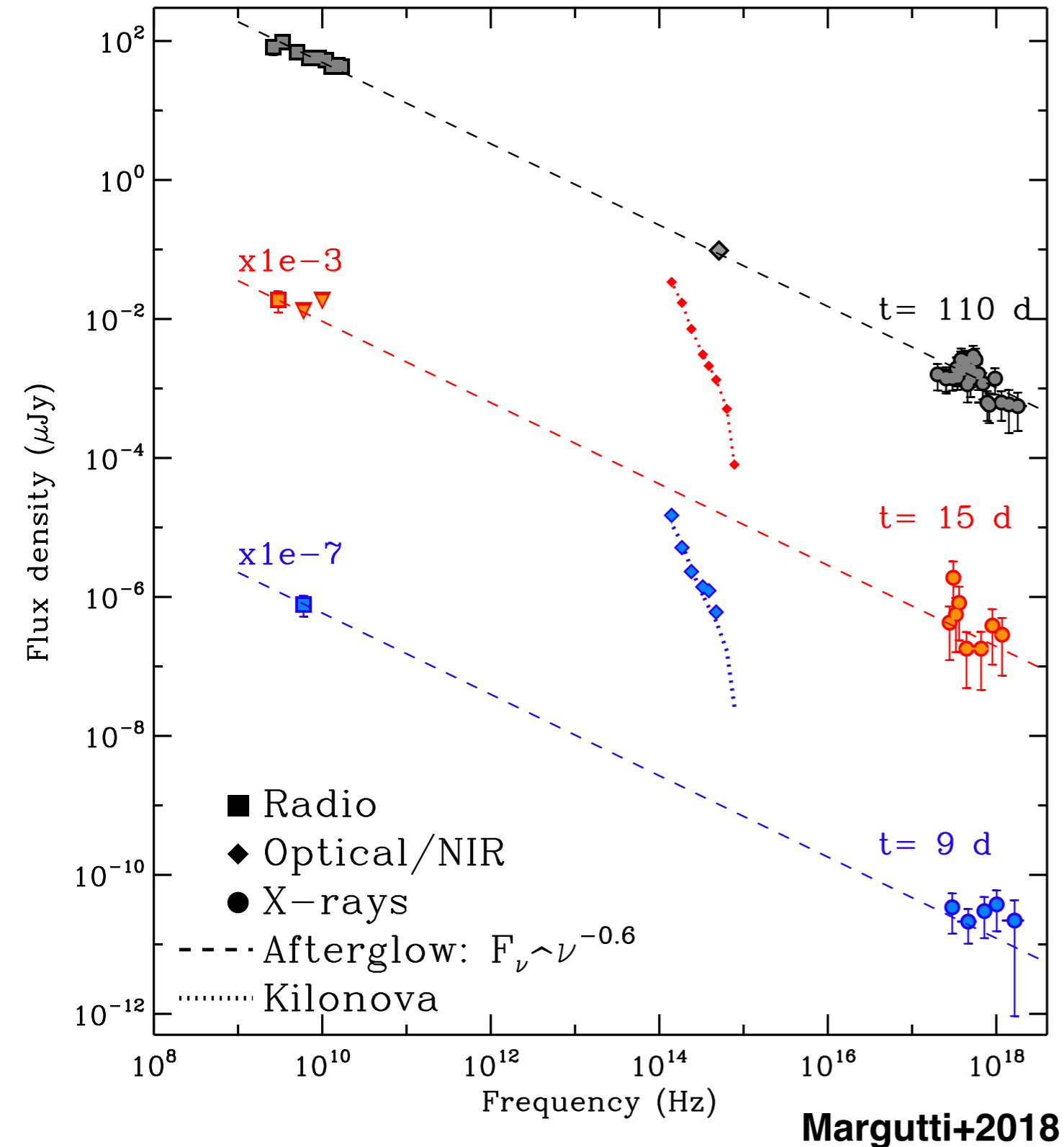
# Non-thermal Synchrotron

Margutti & Chornock ARA&A 2021 in press, and references there in





# Non-thermal **synchrotron** emission across the spectrum: the show is still on



Extremely **well-behaved** SPL spectrum over 8 orders of magnitude in frequency



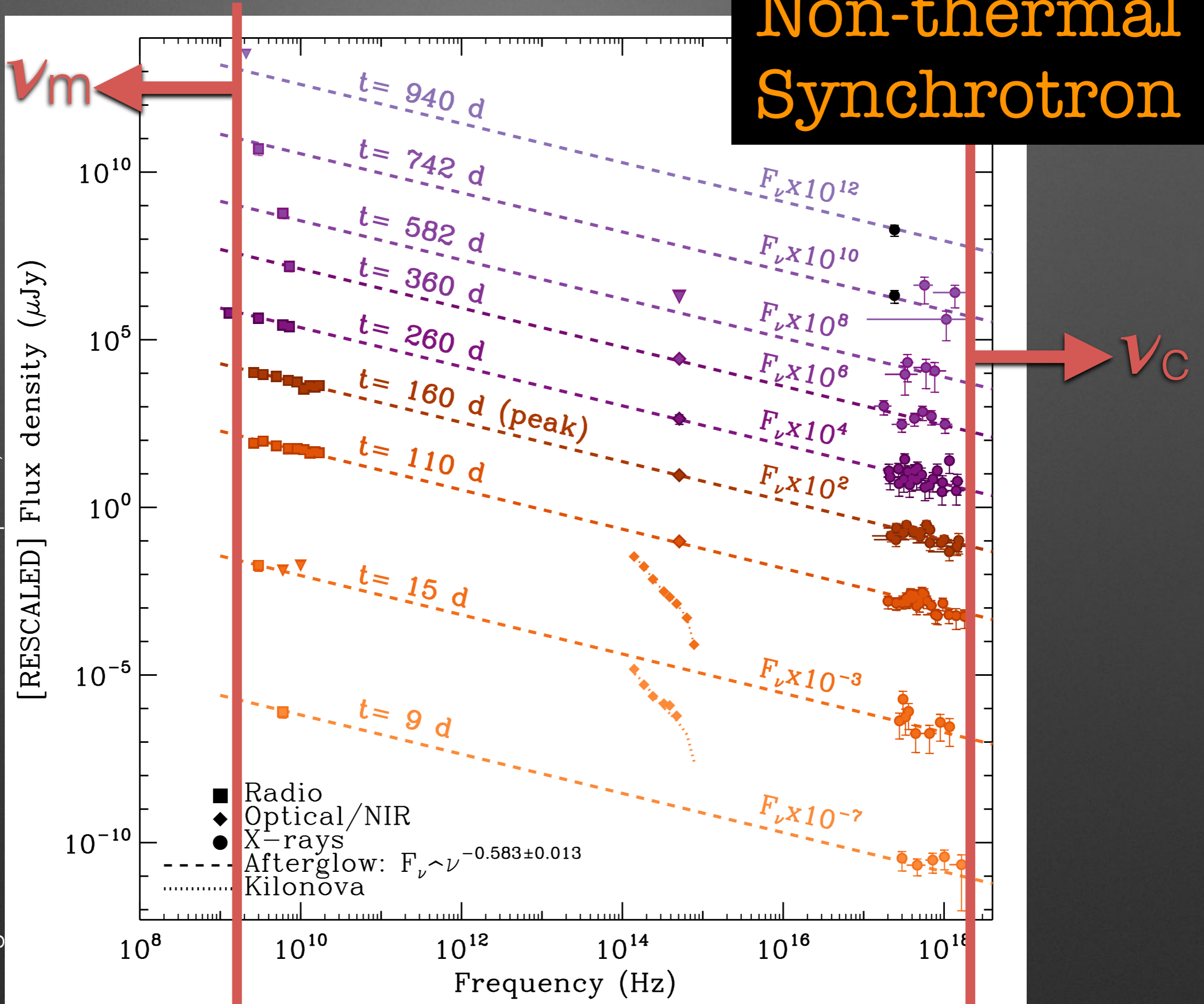
**Particle acceleration** by trans-relativistic shock in action!

Emitting material has

$$\Gamma \sim 3-10$$

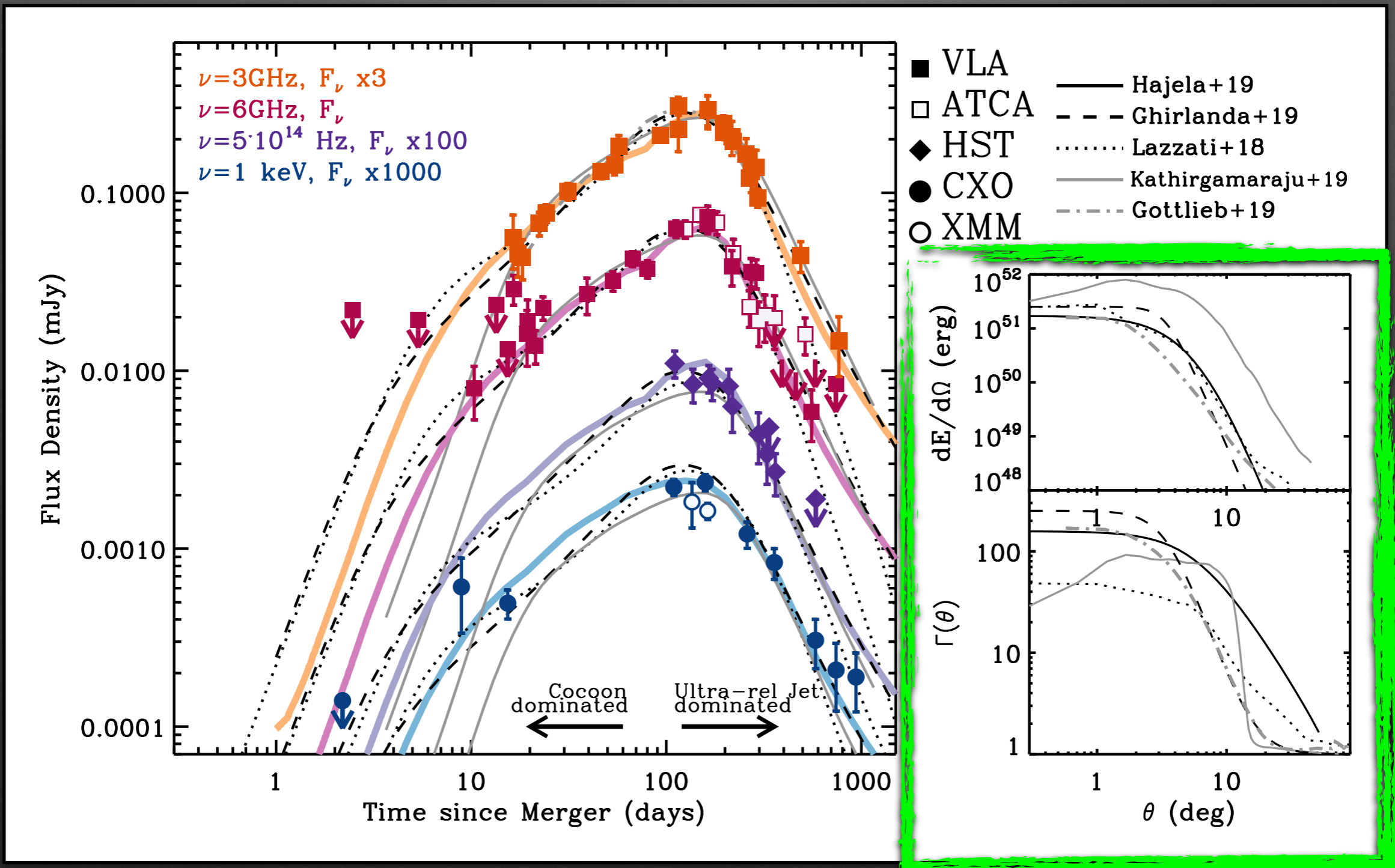
# Non-thermal Synchrotron

Margutti & Chornock ARA&A 2021 in press, and references there in





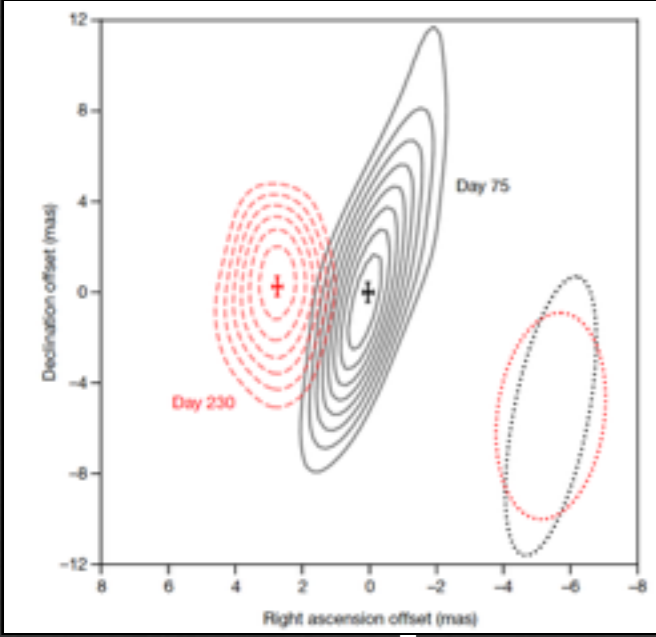
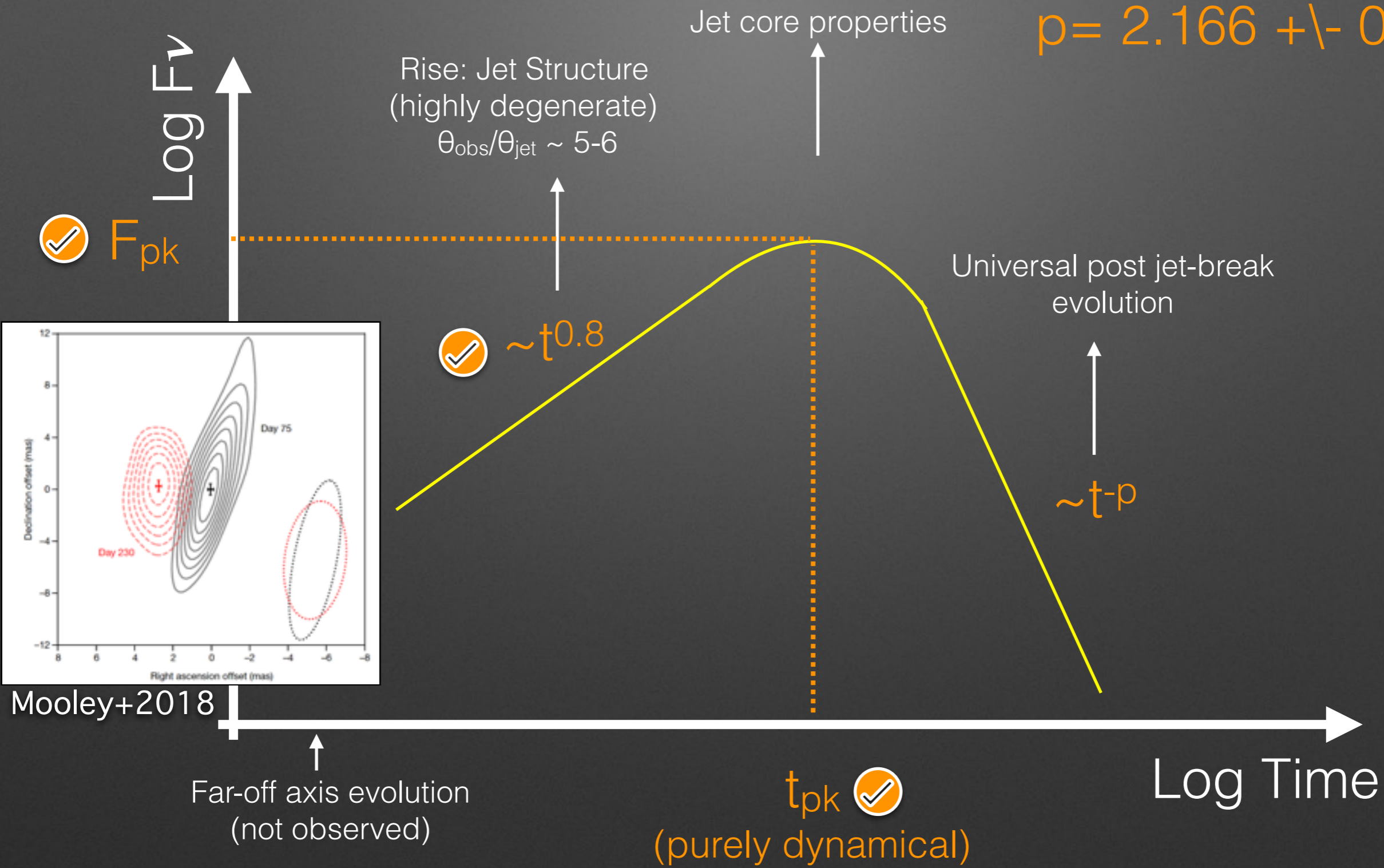
# Structure $E(\theta)$ and $\Gamma(\theta)$ of the jet launched by GW170817



Jet-core unknowns:  $\epsilon_B$ ,  $\epsilon_e$ ,  $\zeta_N$ ,  $p$ ,  $n$ ,  $E_k$ ,  $\theta_{\text{obs}}$ ,  $\theta_{\text{jet}}$

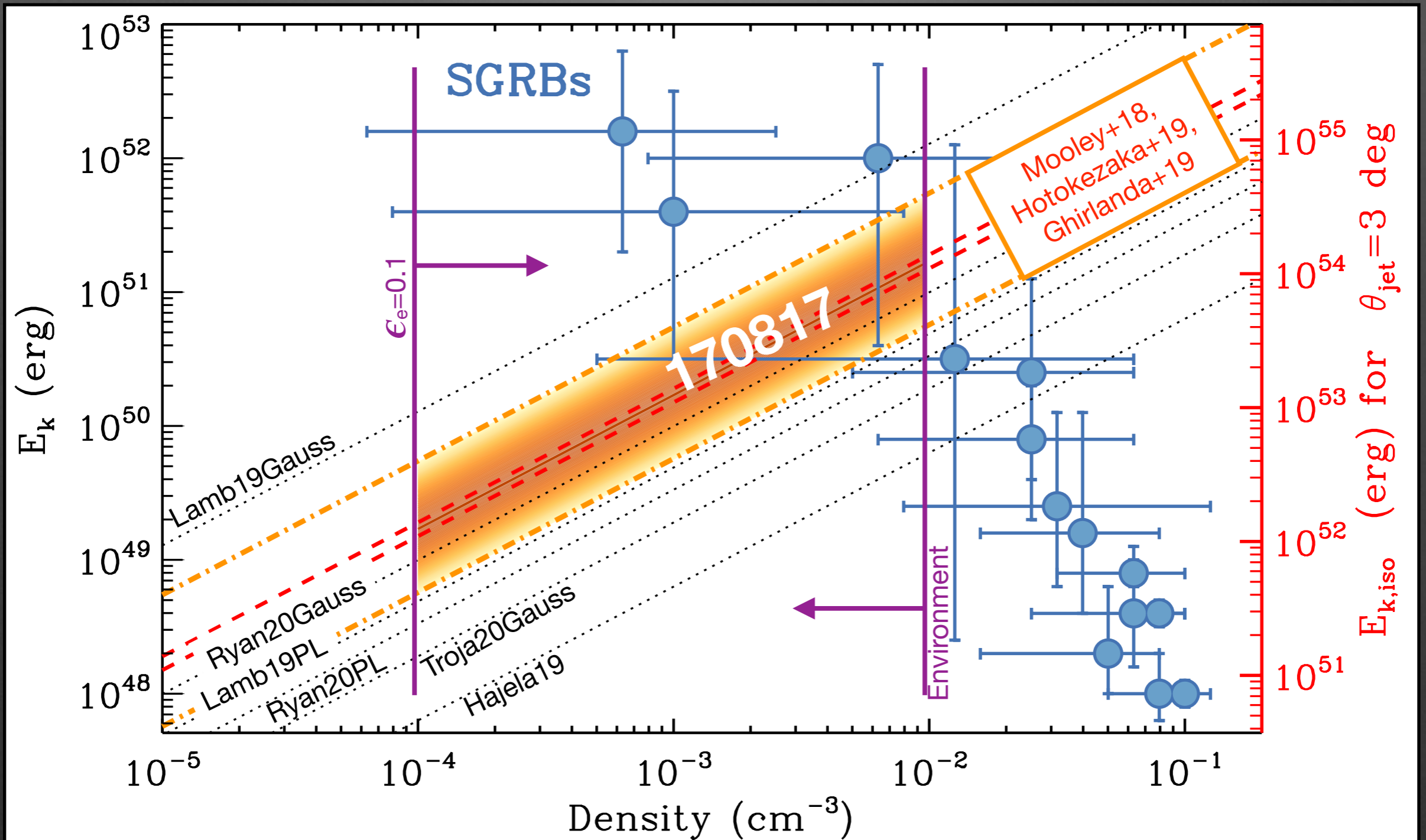
~~$\zeta_N$~~   
=1

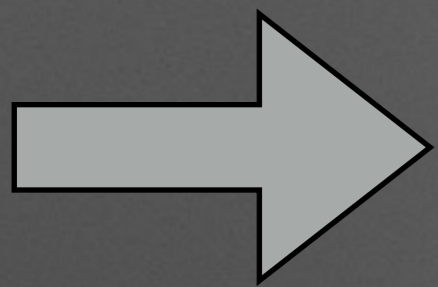
✓ Spectrum:  
 $p = 2.166 \pm 0.026$



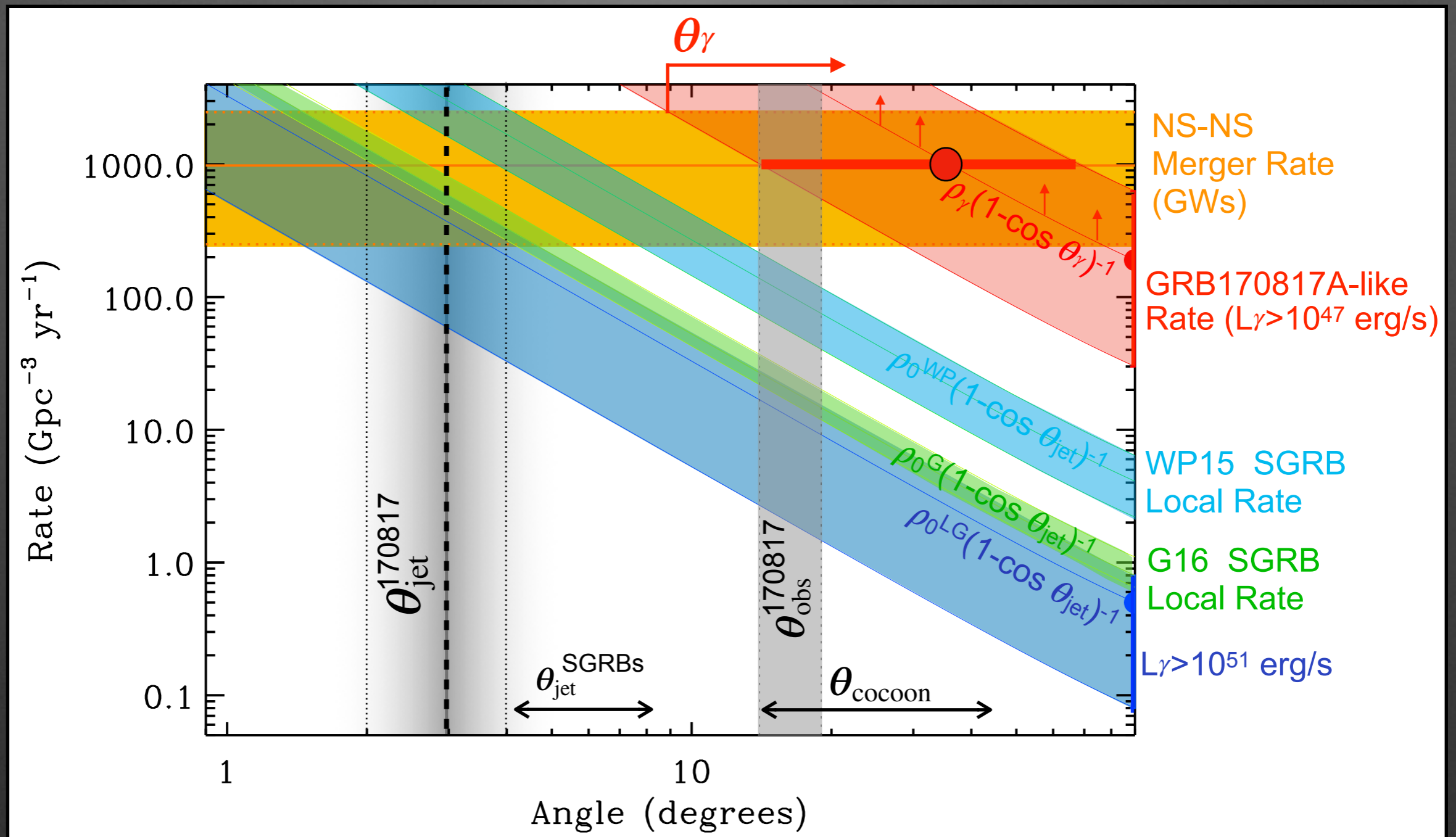


# Consequences: jet model parameters degeneracies





# Inferences on jets in NS-NS mergers





# Where do we go from here?



The kilonova afterglow or BH accretion of GW170817: Exploration of new areas in the parameter space of NS-NS mergers

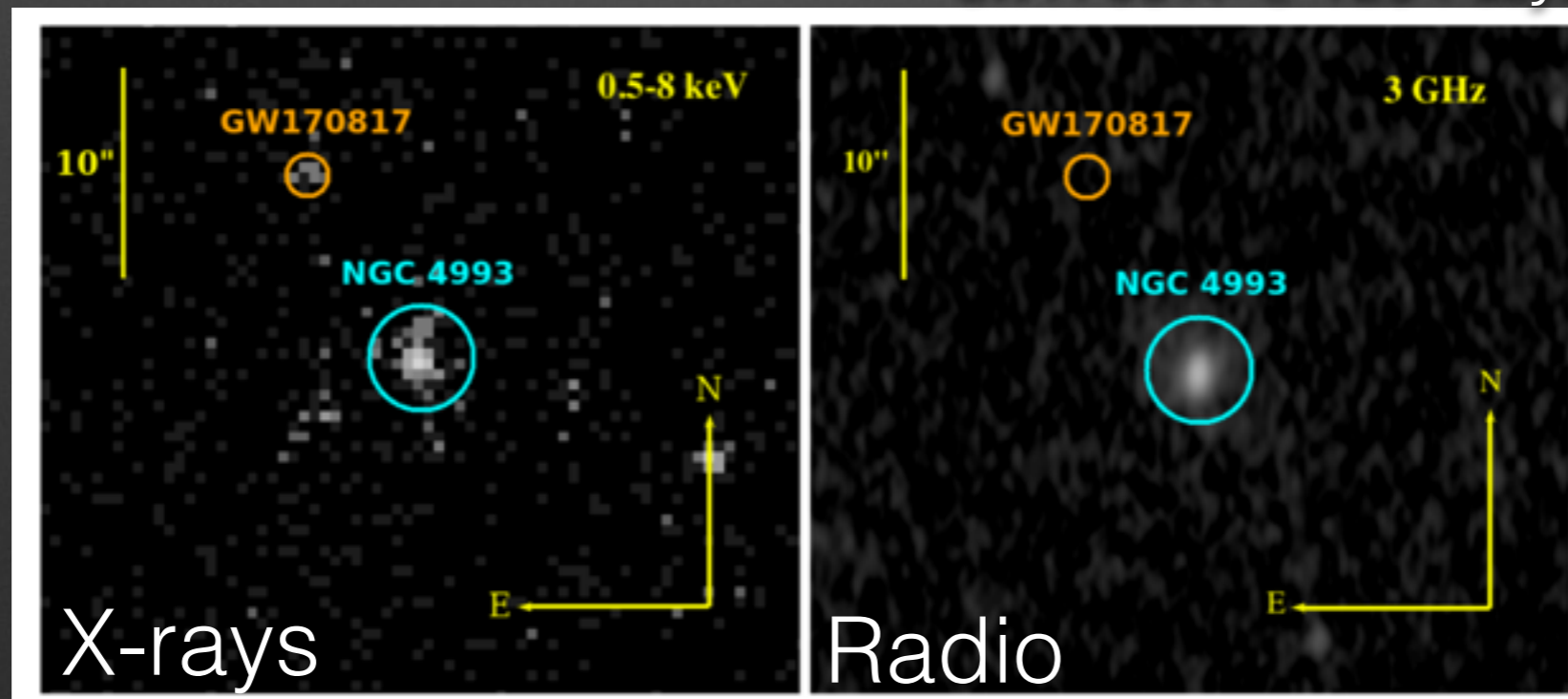


BNS mergers Population Studies

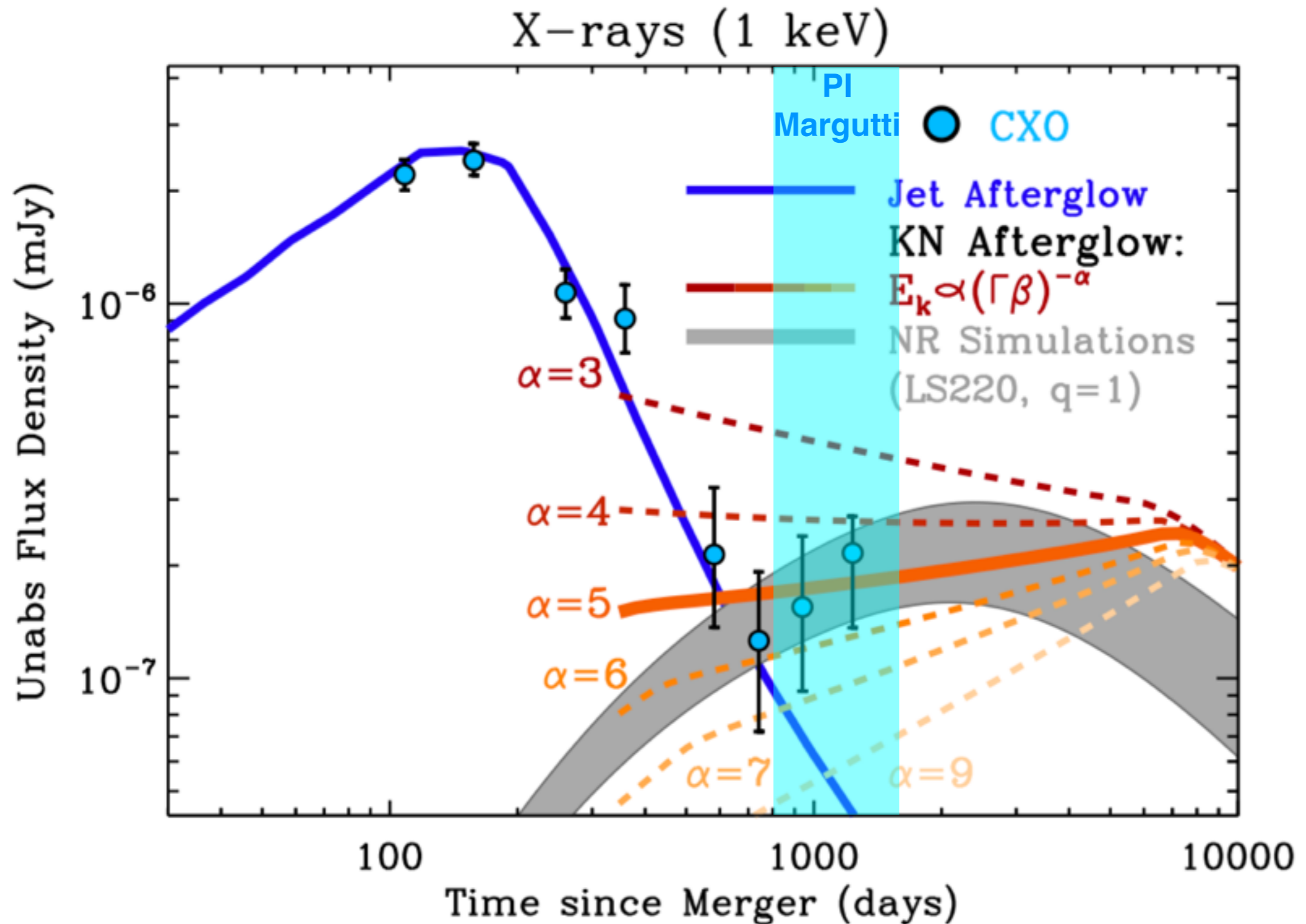
## The emergence of a new source of X-rays from the binary neutron star merger GW 170817

<sup>2</sup> A. HAJELA,<sup>1</sup> R. MARGUTTI,<sup>1</sup> J. S. BRIGHT,<sup>1</sup> K. D. ALEXANDER,<sup>1,\*</sup> B. D. METZGER,<sup>2,3</sup> V. NEDORA,<sup>4</sup> A. KATHIRGAMARAJU,<sup>5</sup>  
<sup>3</sup> B. MARGALIT,<sup>5</sup> D. RADICE,<sup>6,7,8</sup> E. BERGER,<sup>9</sup> A. MACFADYEN,<sup>10</sup> D. GIANNIOS,<sup>11</sup> R. CHORNOCK,<sup>1</sup> I. HEYWOOD,<sup>12,13,14</sup>  
<sup>4</sup> L. SIRONI,<sup>15</sup> O. GOTTLIEB,<sup>16</sup> D. COPPEJANS,<sup>1</sup> T. LASKAR,<sup>17</sup> Y. CENDES,<sup>9</sup> R. BARNIOL DURAN,<sup>18</sup> T. EFTEKHARI,<sup>9</sup> W. FONG,<sup>1</sup>  
<sup>5</sup> A. MCDOWELL,<sup>10</sup> M. NICHOLL,<sup>19</sup> X. XIE,<sup>20</sup> J. ZRAKE,<sup>21</sup> S. BERNUZZI,<sup>4</sup> F. S. BROEKGAARDEN,<sup>9</sup> C. D. KILPATRICK,<sup>1</sup>  
<sup>6</sup> G. TERRERAN,<sup>1</sup> V. A. VILLAR,<sup>22</sup> P. K. BLANCHARD,<sup>1</sup> S. GOMEZ,<sup>9</sup> G. HOSSEINZADEH,<sup>9</sup> D. J. MATTHEWS,<sup>1</sup> AND  
<sup>7</sup> J. C. RASTINEJAD<sup>1</sup>

GW170817 @ 1234 days

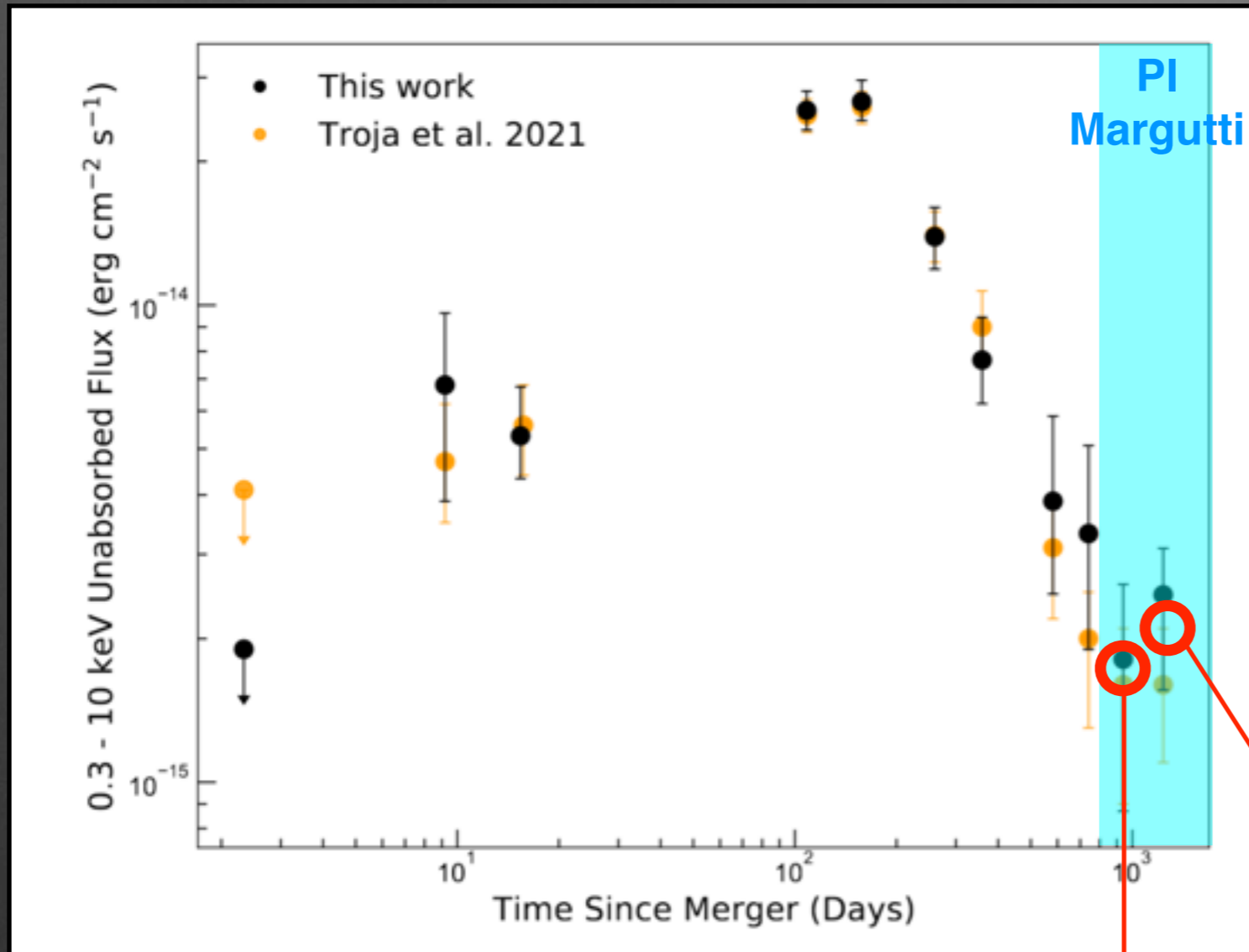


# The emergence of a **new X-ray component** of emission at 3.5 yrs since NS merger





# The emergence of a **new X-ray component** of emission at 3.5 yrs since NS merger



Hajela, Margutti, Bright et al., 2021

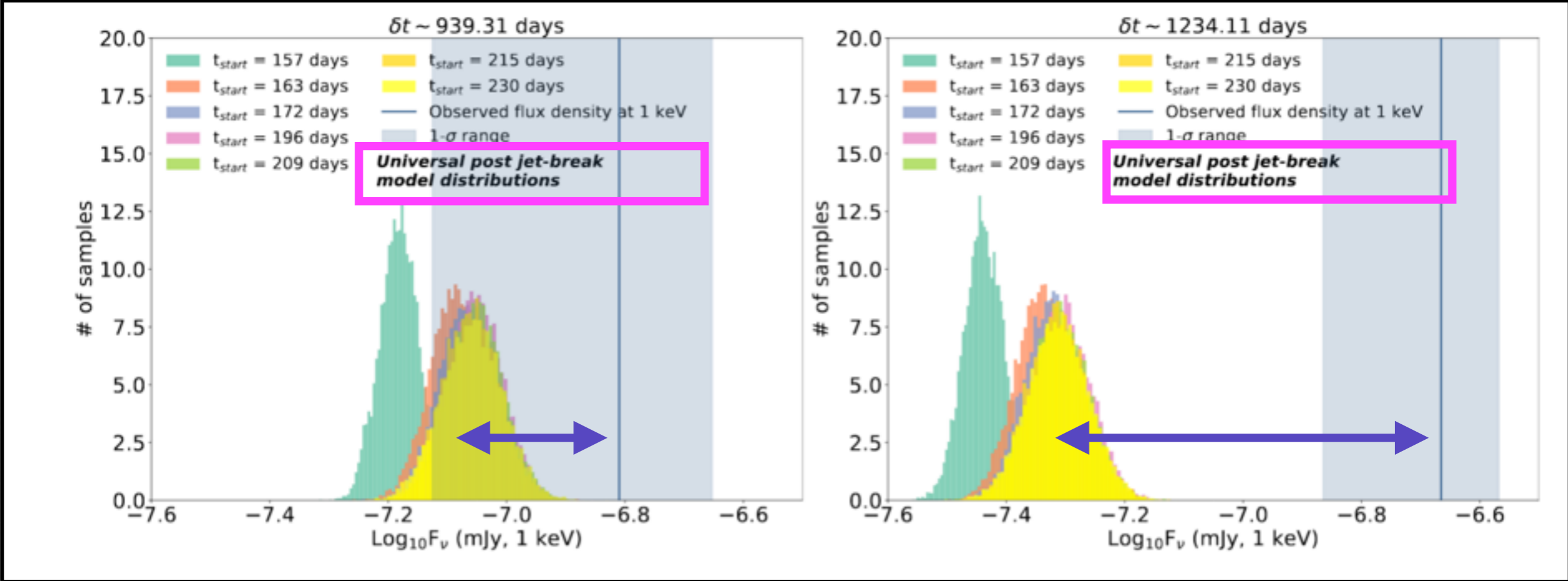
~100ks  
 (8 photons, 0.5-8 keV)

~200ks  
 (16 photons, 0.5-8 keV)

- ✓ Poisson nature of the process (for flux calibration and fitting!)
- ✓ Avoid using averaged instrumental responses
- ✓ Statistical tests carried out in the count phase space, self-consistently accounting for Poisson nature of sou+bk
- ✓ Test for the emergence of a new component at  $t > 900$  days vs. post jet break model
- ✓ Comparison model needs to be consistent with ALL existing observational constraints
- ✓ Test needs to be jet model INDEPENDENT

We do **NOT** claim re-brightening!

# Cumulative statistical significance of the excess of 3.5-4.3 $\sigma$ (Gaussian equivalent)



Hajela, Margutti, Bright et al., 2021

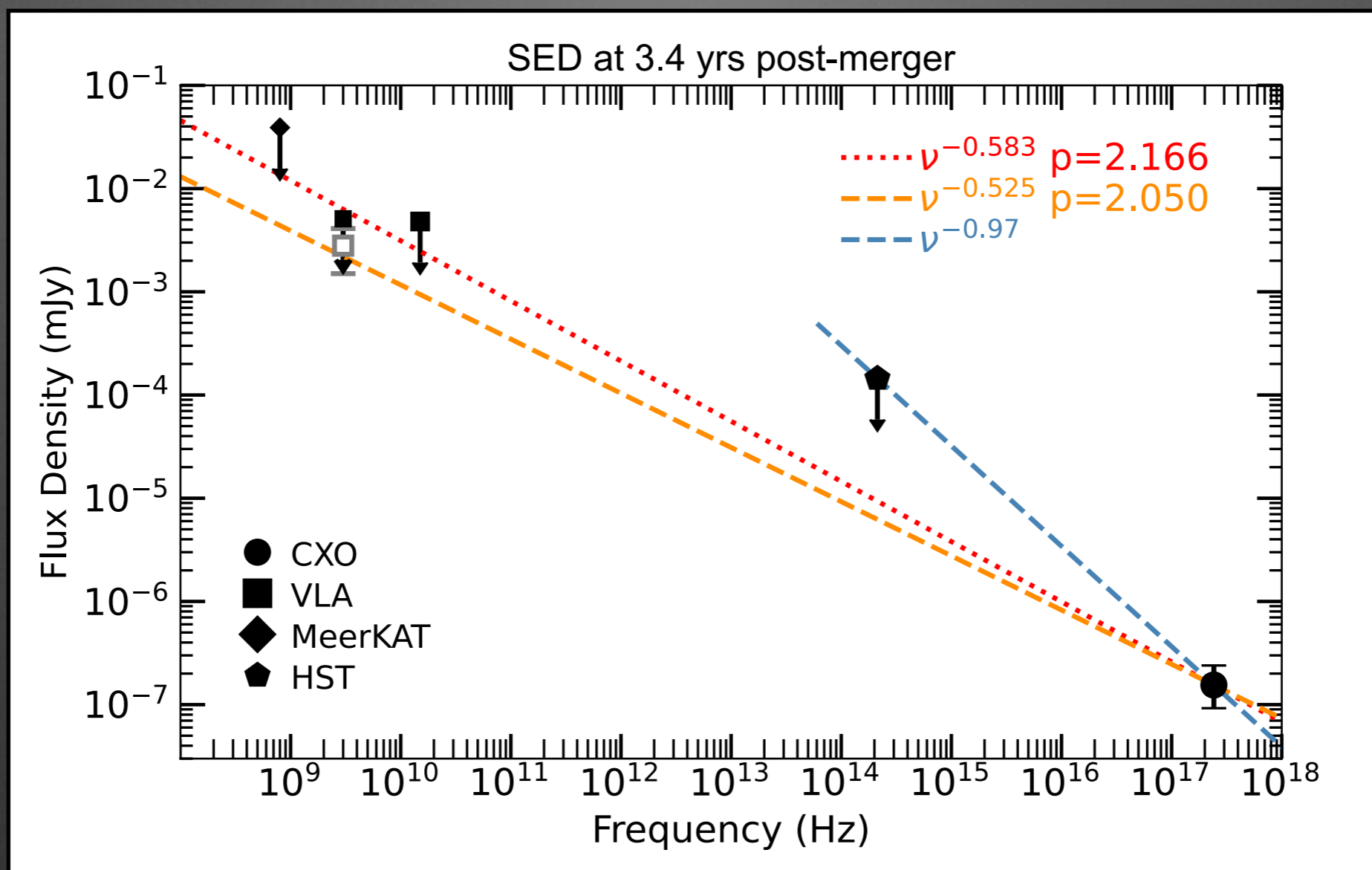
...in any case: **Time will tell**

Next Chandra+VLA epoch planned for Dec 2021 (PI Margutti)

our data are PUBLIC

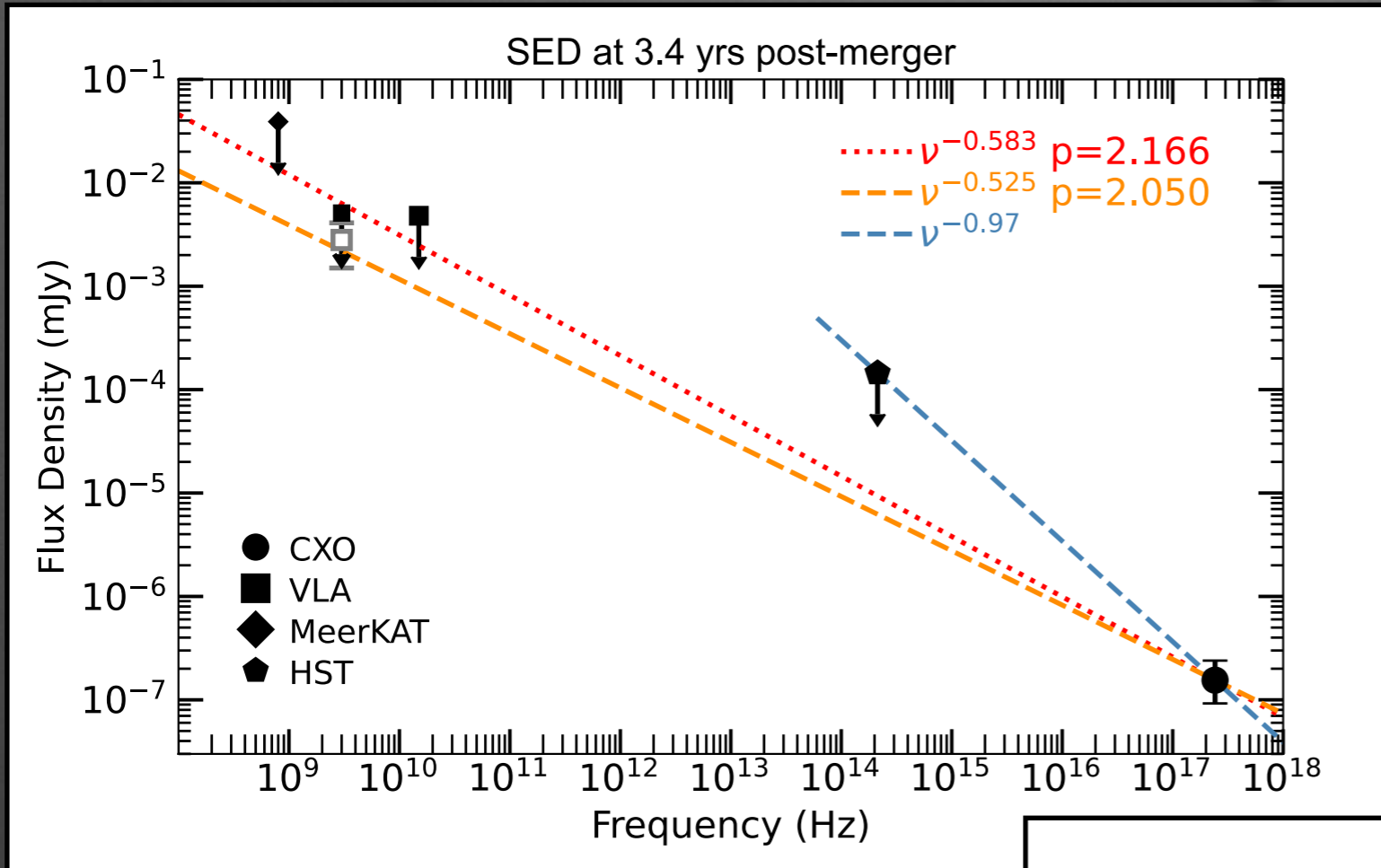


# Broad-band SED at 3.5 yrs since NS merger



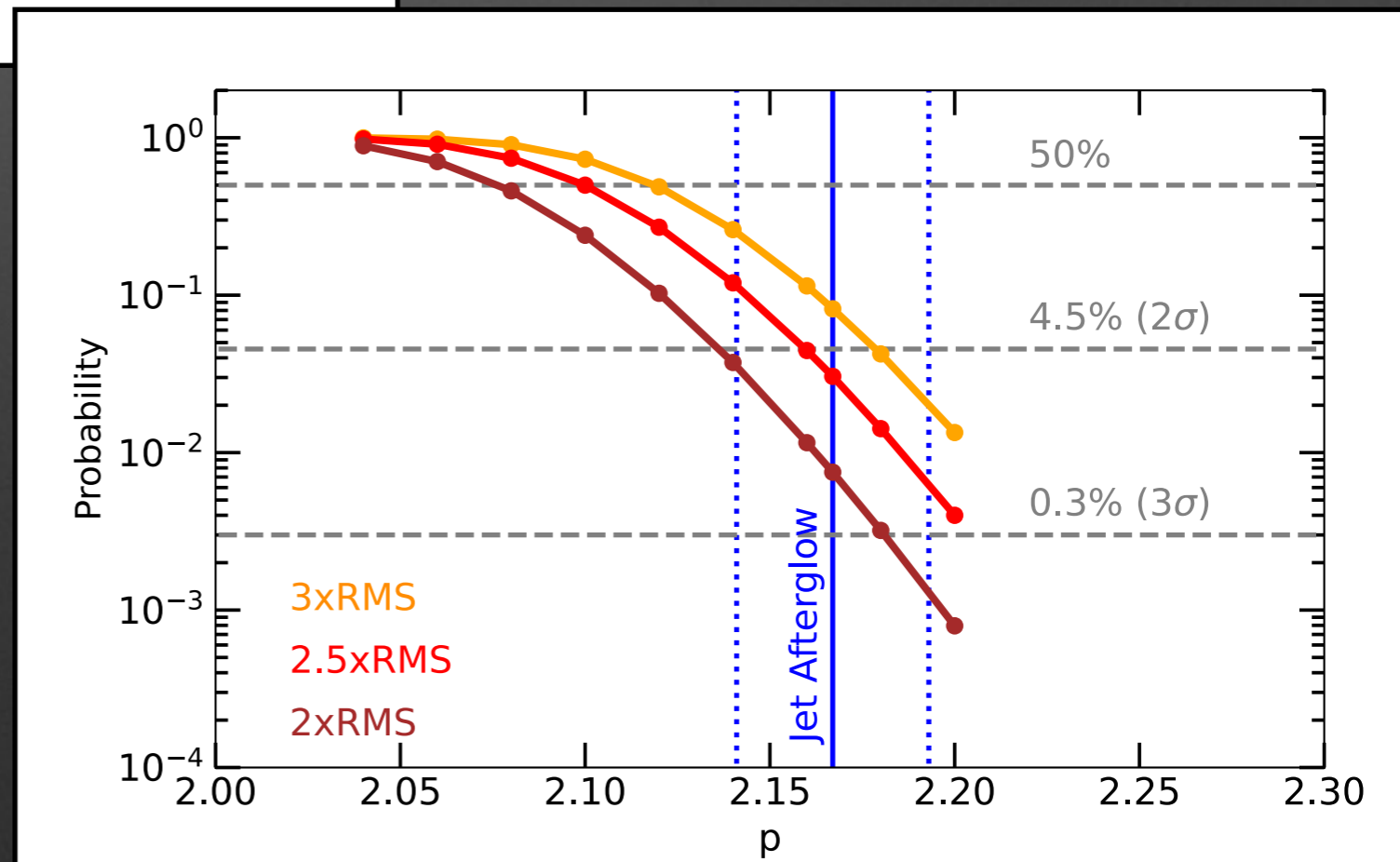
Hajela, Margutti, Bright et al., 2021

# Broad-band SED at 3.5 yrs since NS merger



Suggestive of Hardening of the spectrum at the level of  $>92\%$  c.i.

Hajela, Margutti, Bright et al., 2021





X-ray LC + broad-band spectrum=  
**New Component of emission**



Kilonova afterglow



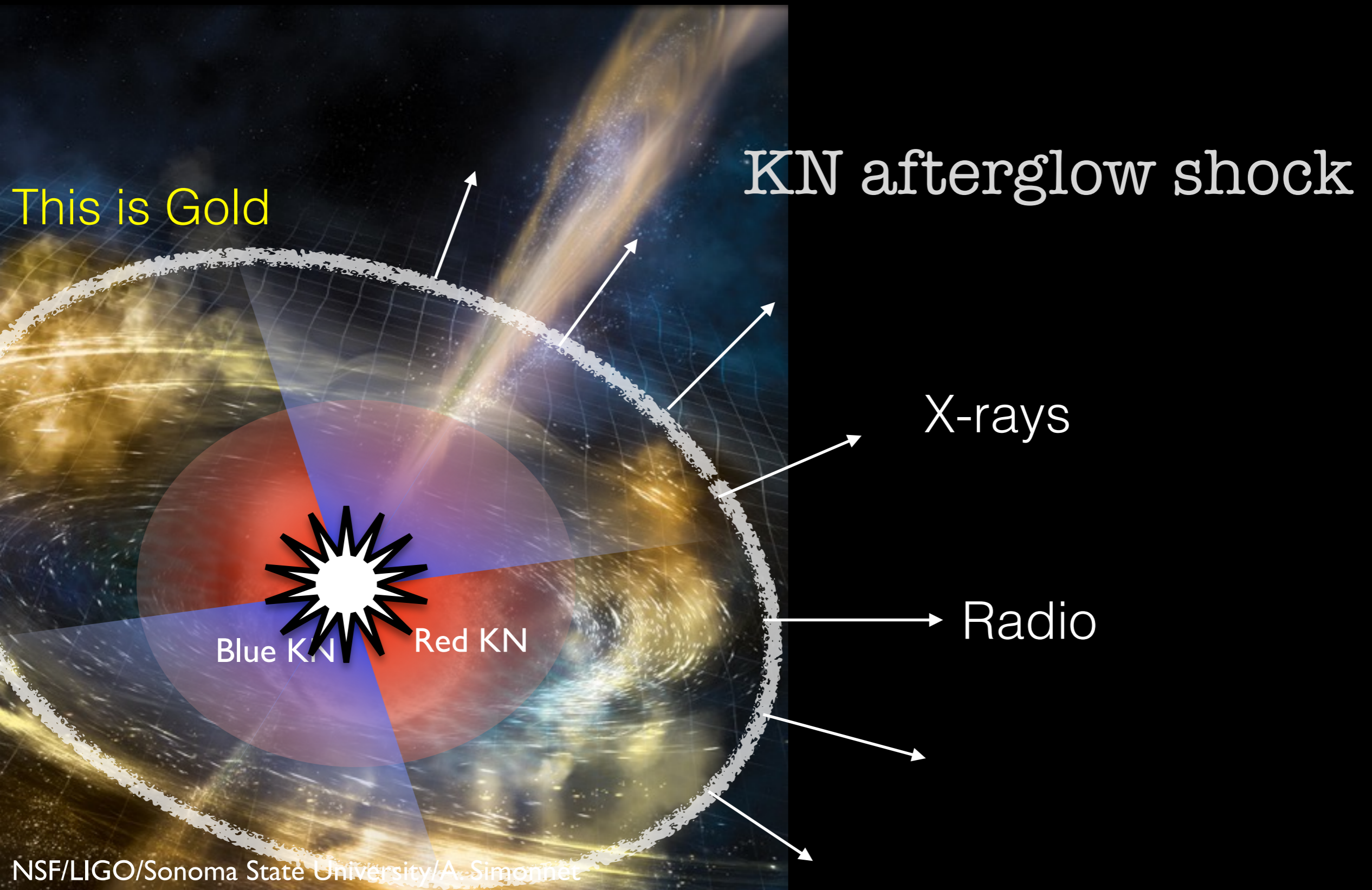
BH accretion

Jet afterglow evolution: over-density, transition to the non-rel regime, emergence of the counter jet, temporal variation of the shock microphysical parameters



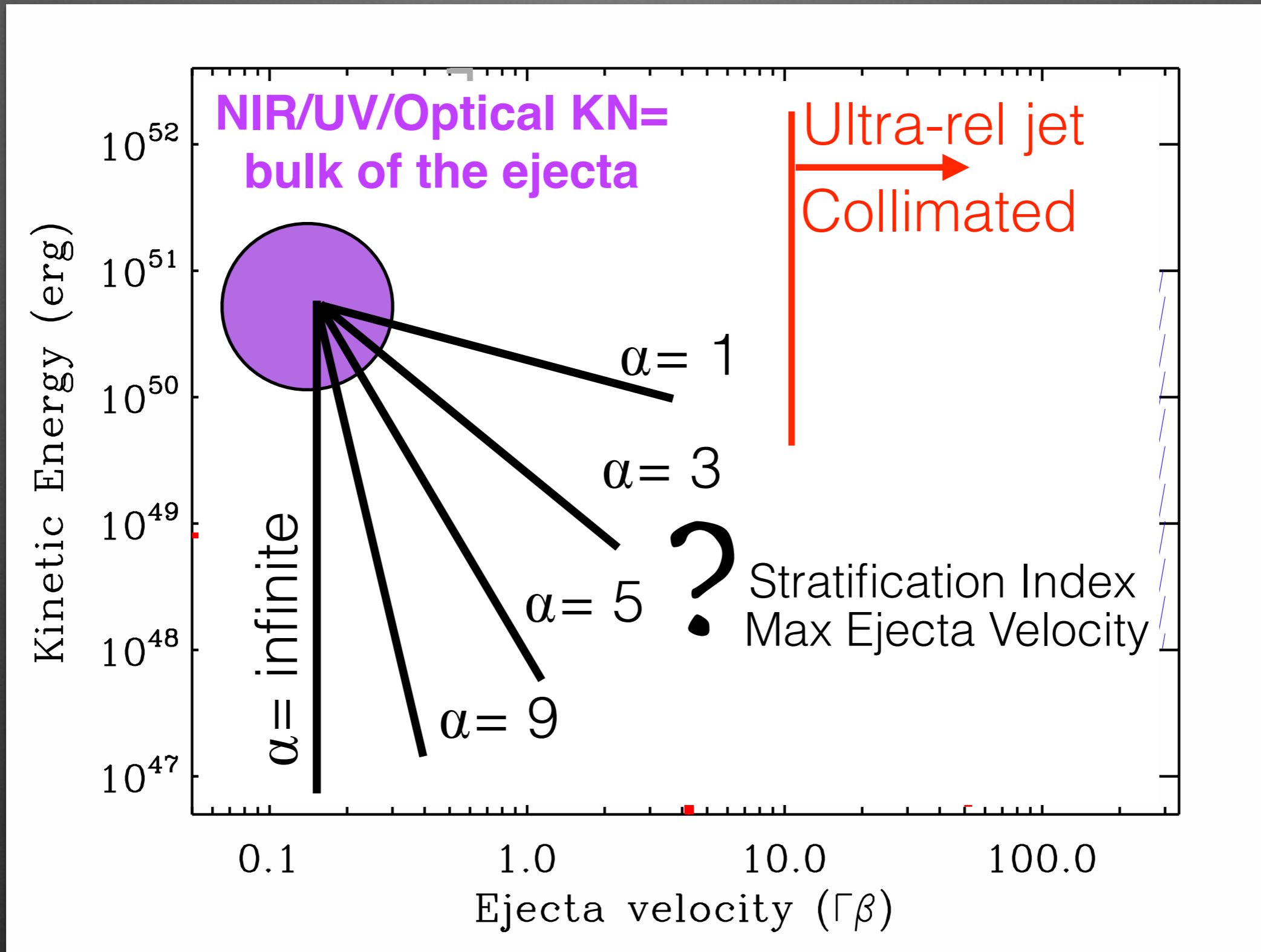
# The KN Velocity Structure and the nature of the remnant

Nakar & Piran 2011; Metzger & Berger 2012; Metzger & Bower 2014; Hotokezaka & Piran 2015, Kathirgamraju+2019





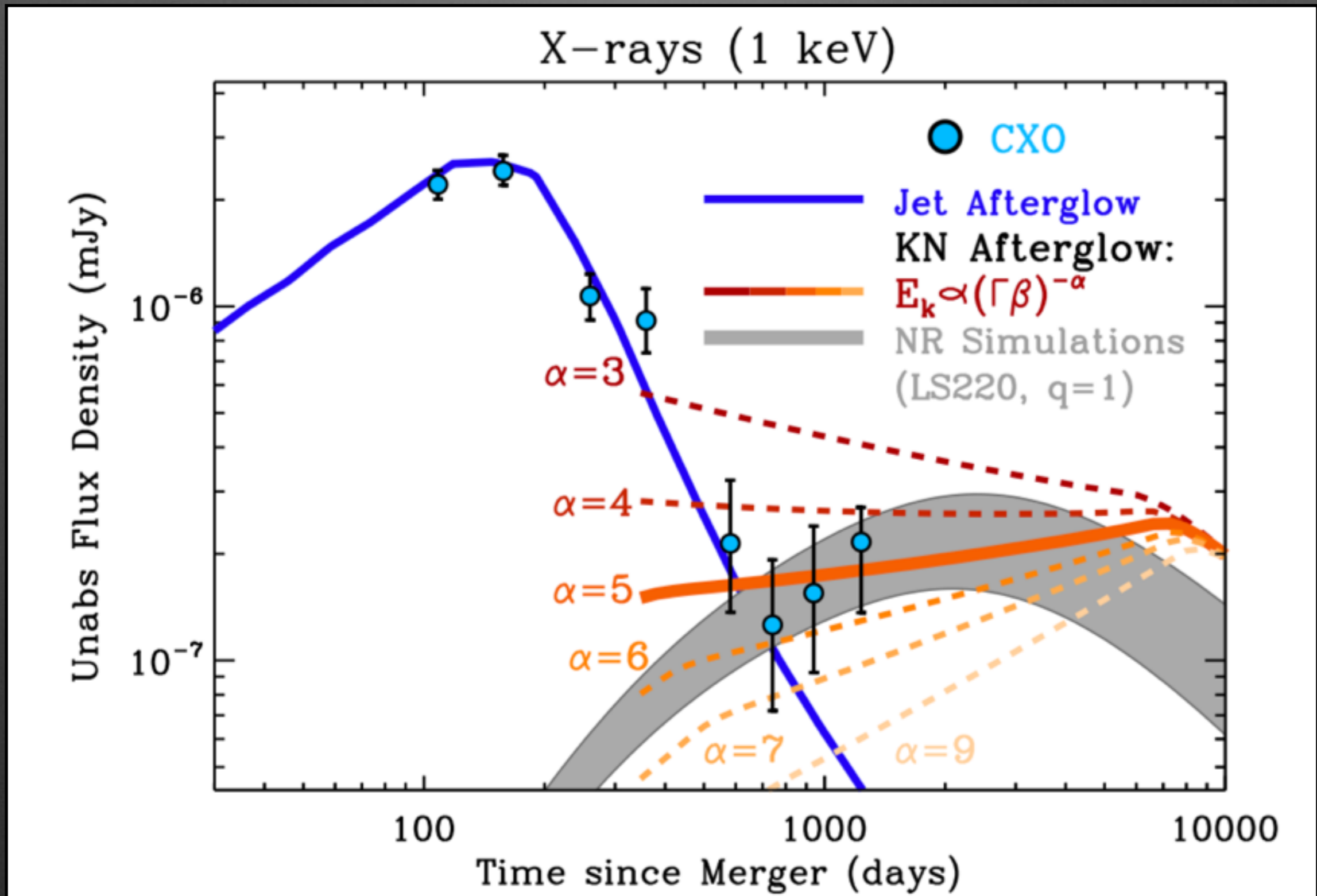
# Energy Partitioning $E(\Gamma\beta) \sim (\Gamma\beta)^{-\alpha}$



**Connection to nature of the remnant**

e.g., Radice+2018

# The emergence of a **new X-ray component** of emission at 3.5 yrs since NS merger



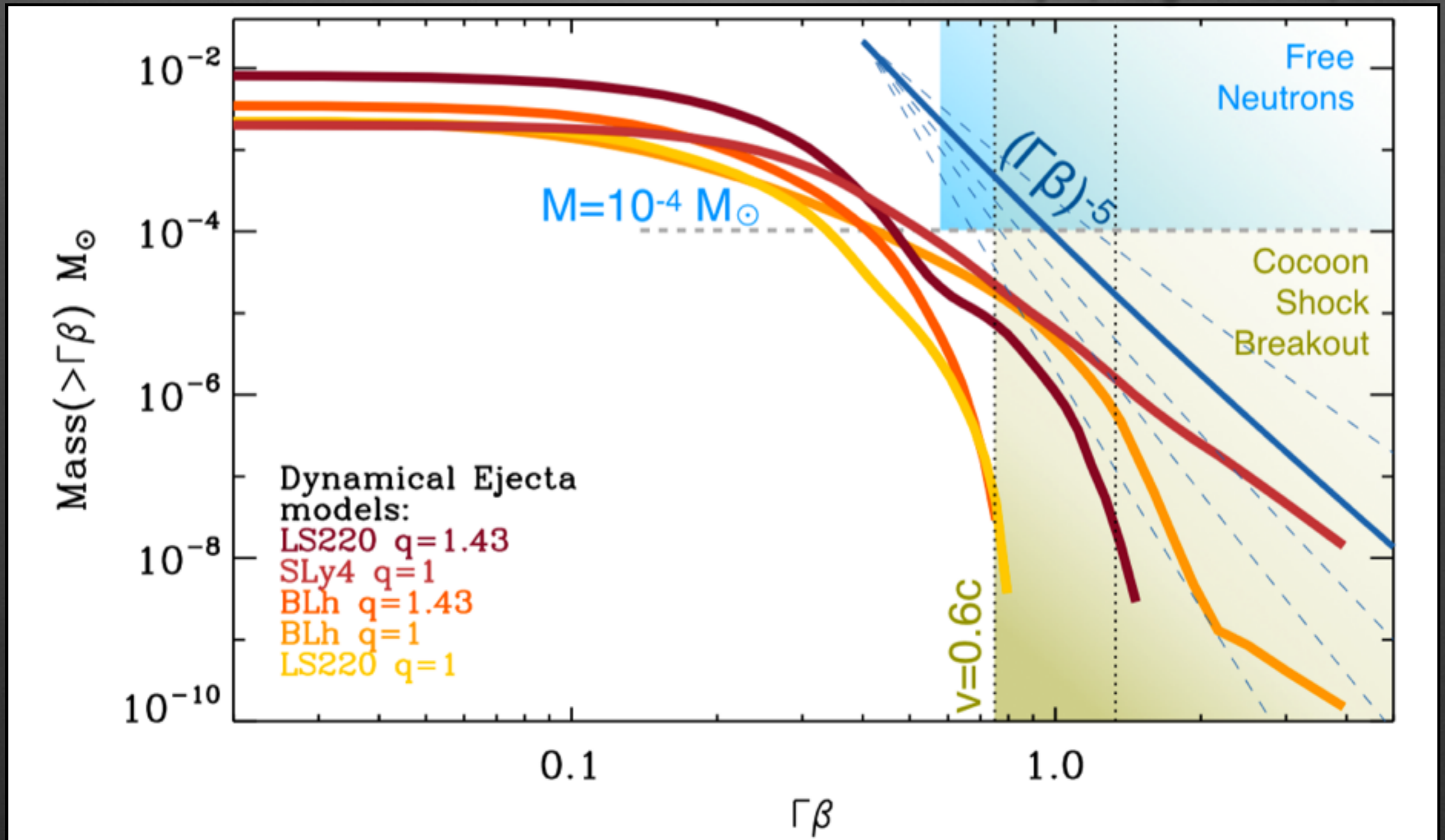
Hajela, Margutti, Bright et al., 2021

Models by: Kathirgamaraju+2019; Nedora+2021



# The emergence of a new X-ray component: broader implications

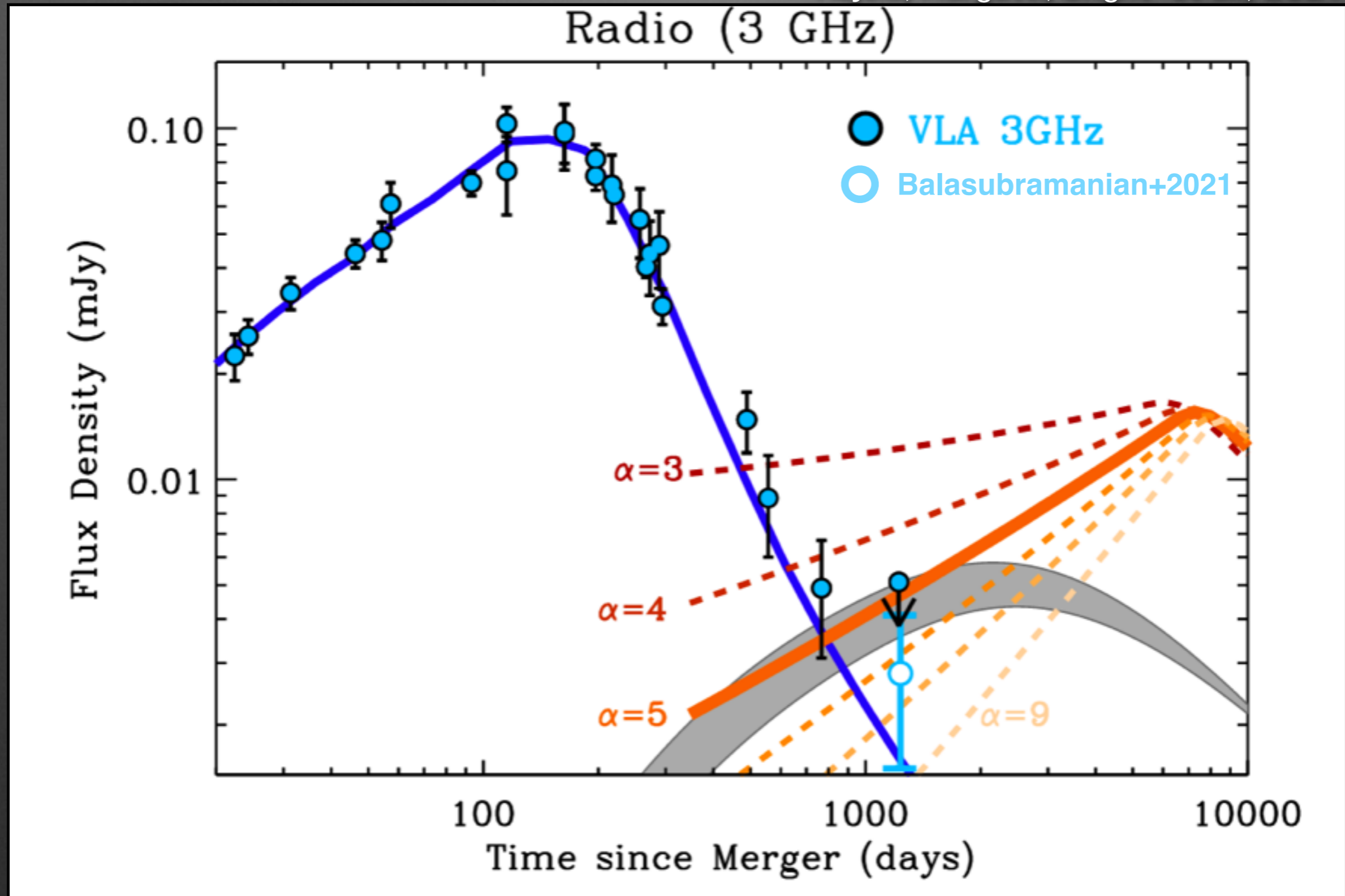
Hajela, Margutti et al., 2021



Cocoon Models by: Gottlieb+; Free Neutron models by: Brian Metzger

# The Radio KN afterglow

Hajela, Margutti, Bright et al., 2021



Models by: Kathirgamaraju+2019; Nedora+2021



X-ray LC + broad-band spectrum=  
**New Component of emission**



Kilonova afterglow



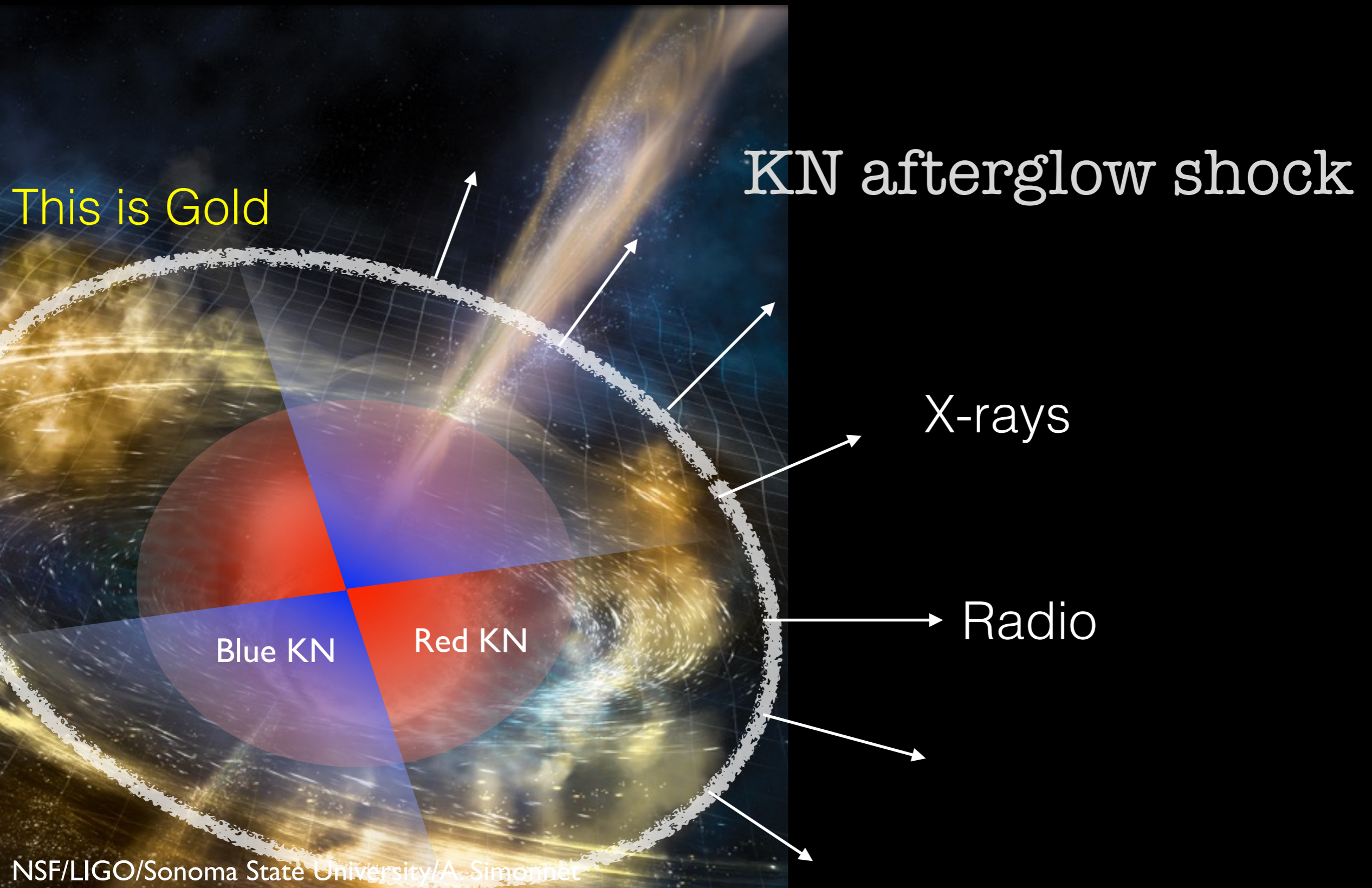
BH accretion

Jet afterglow evolution: over-density, transition to the non-rel regime, emergence of the counter jet, temporal variation of the shock microphysical parameters



# Accretion powered X-ray emission from the newly formed BH remnant

Nakar & Piran 2011; Metzger & Berger 2012; Metzger & Bower 2014; Hotokezaka & Piran 2015, Kathirgamraju+2019

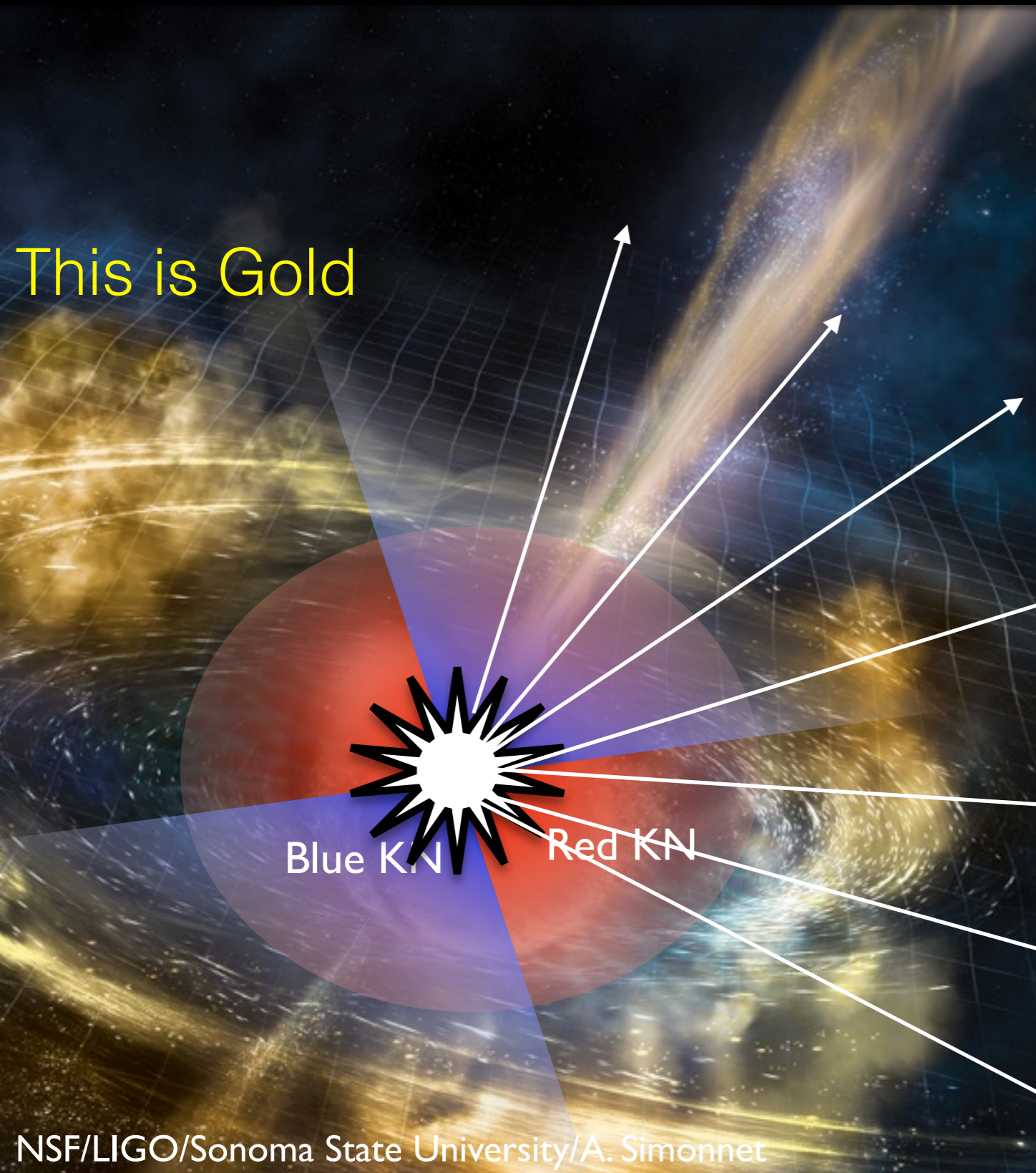




# Accretion powered X-ray emission from the newly formed BH remnant

Nakar & Piran 2011; Metzger & Berger 2012; Metzger & Bower 2014; Hotokezaka & Piran 2015, Kathirgamraju+2019

This is Gold



$$t_{\text{thin}} = \left( \frac{3M_{\text{ej}}\kappa_X}{4\pi v_{\text{ej}}^2} \right)^{1/2}$$
$$\approx 2000 \text{ days} \left( \frac{v_{\text{ej}}}{0.1c} \right)^{-1}$$
$$\times \left( \frac{\kappa_X}{10^4 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left( \frac{M_{\text{ej}}}{0.06M_{\odot}} \right)^{1/2},$$

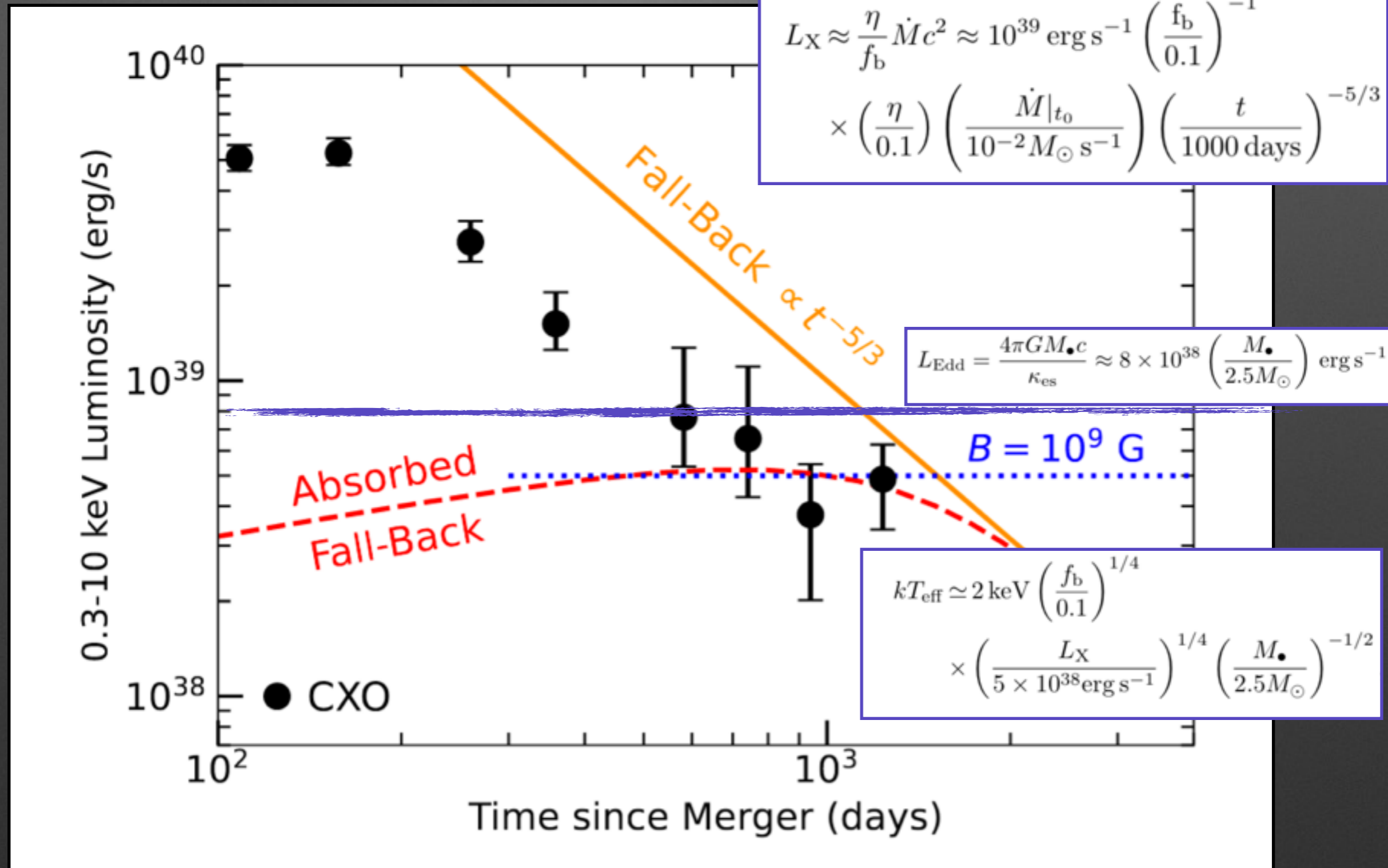
X-rays

Radio ?

# Alternative idea: accretion on the BH remnant

Fall-back from accretion disk outflows:

$$L_X \approx \frac{\eta}{f_b} \dot{M} c^2 \approx 10^{39} \text{ erg s}^{-1} \left( \frac{f_b}{0.1} \right)^{-1} \\ \times \left( \frac{\eta}{0.1} \right) \left( \frac{\dot{M}|_{t_0}}{10^{-2} M_\odot \text{ s}^{-1}} \right) \left( \frac{t}{1000 \text{ days}} \right)^{-5/3}$$



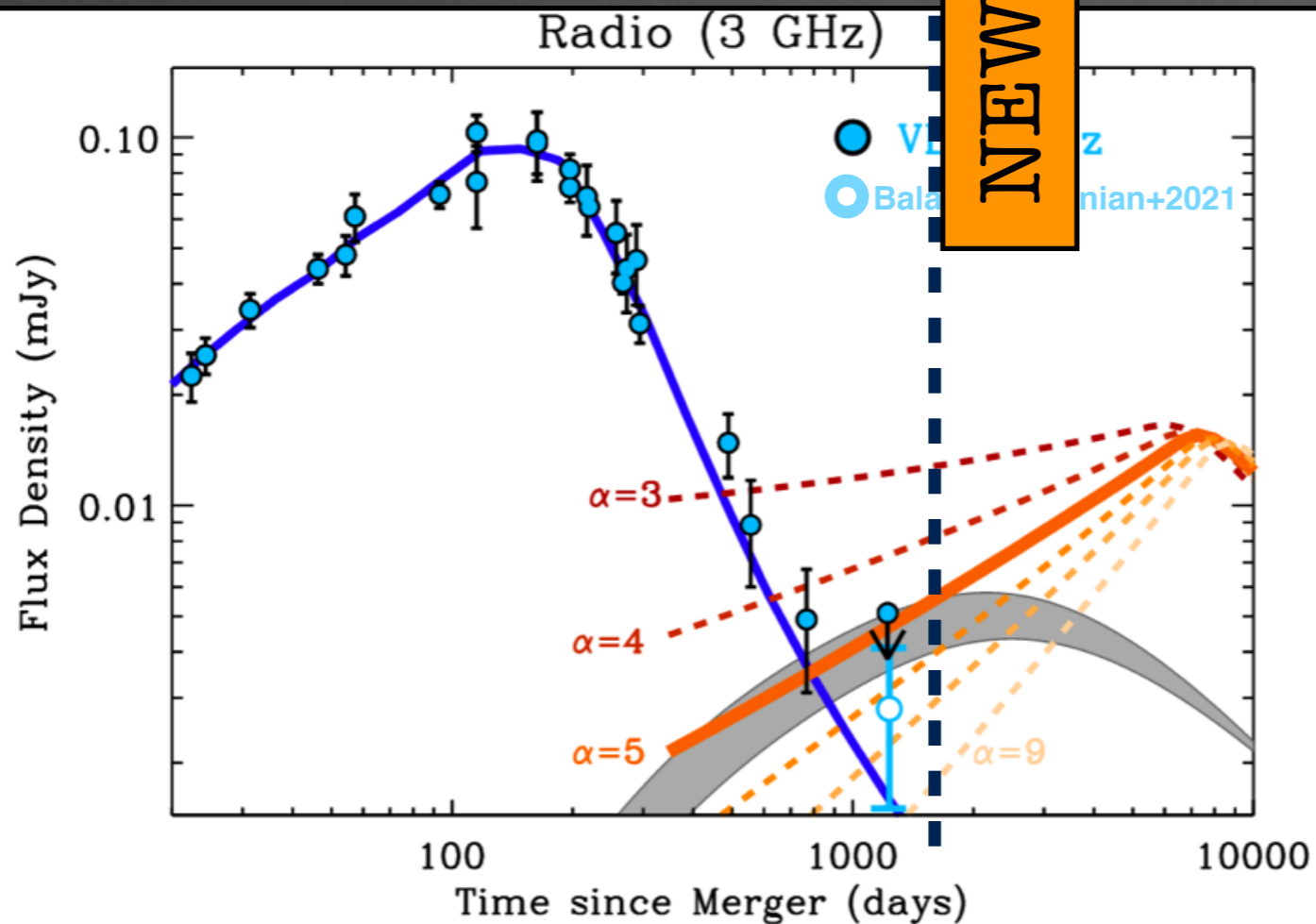
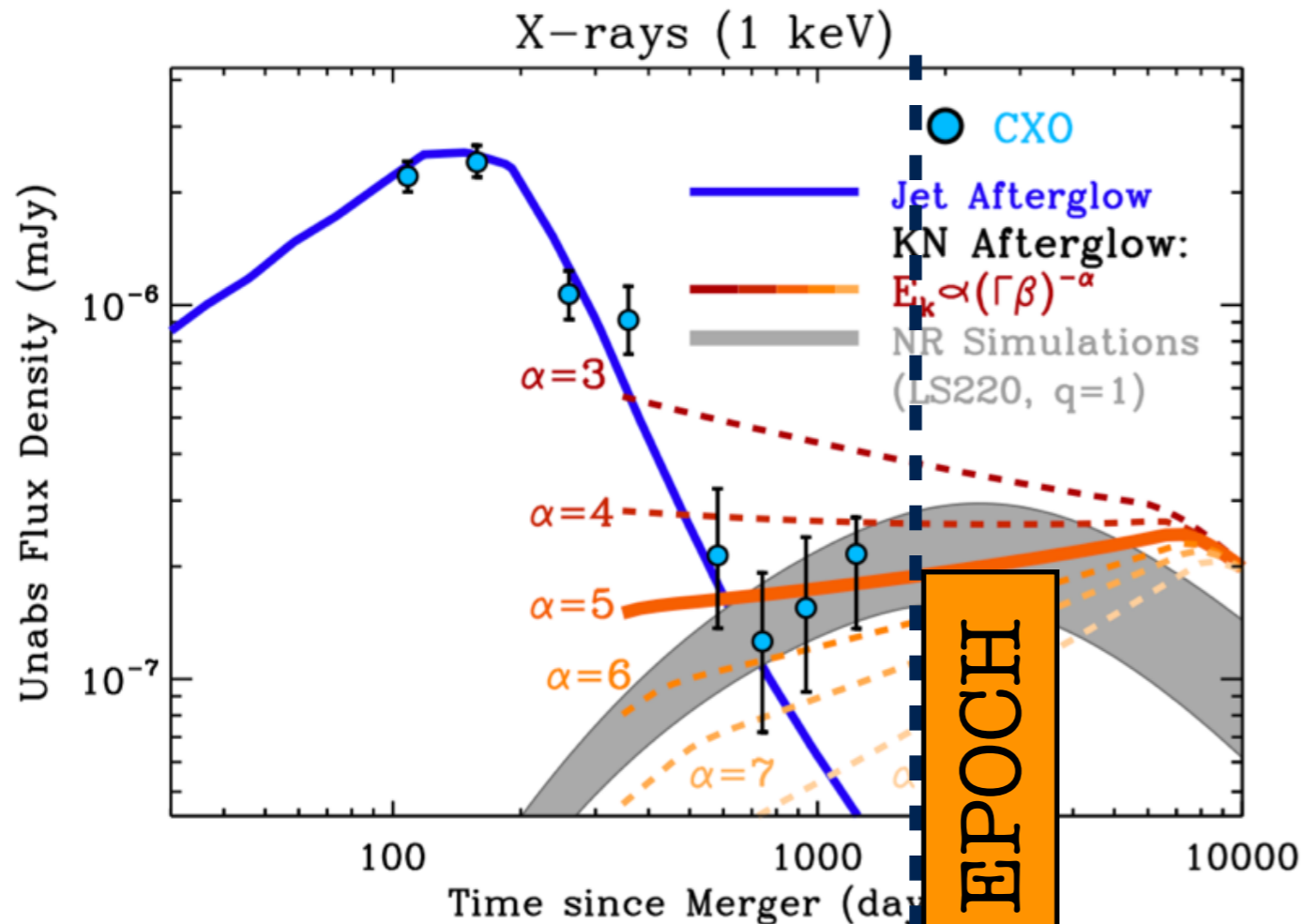
Idea credit: Brian Metzger

Hajela, Margutti, Bright et al., 2021

(see Metzger & Fernandez 2021, Ishizaki+2021)



Where do we go from here?



New epoch of  
deep  
Chandra + VLA  
monitoring  
approved

*(This is not)*

*....The End....*

*“What we call the beginning is often the end.  
And to make an end is to make a beginning.*

*The end is where we start from.”*

*T. S. Eliot*