Discovery Frontiers

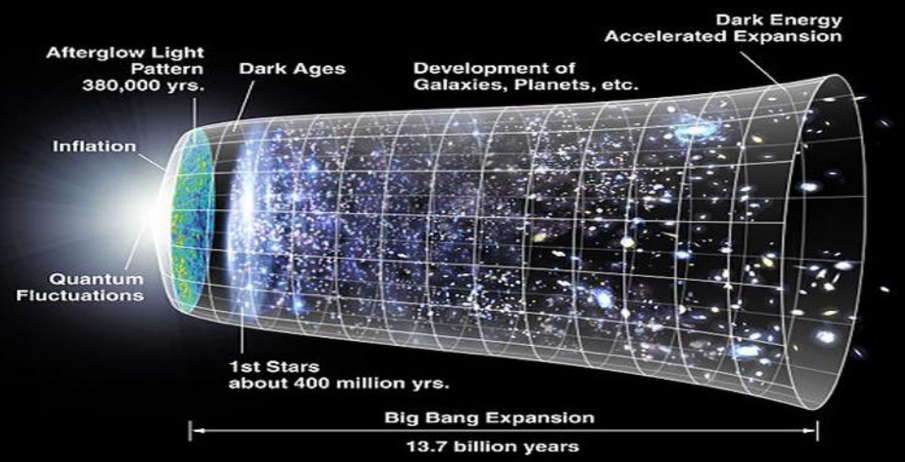
in the New Era of Observations with Gravitational Waves and Light

Credit: G. Chincarini

Raffaella Margutti
UC Berkeley

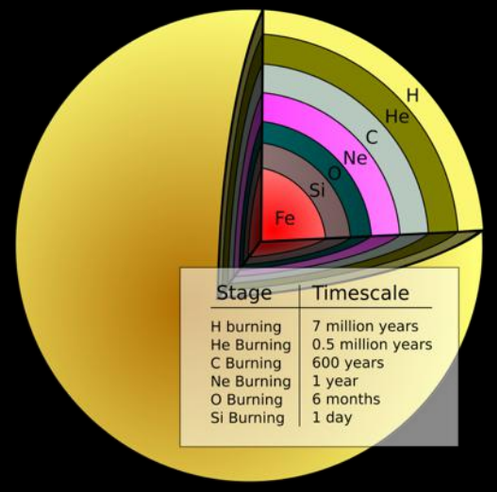
"We always find something, eh Didi,
to give us the impression we exist?"

Cosmology: Distance Ladders



First sources of ionizing photons

Chemical Enrichment

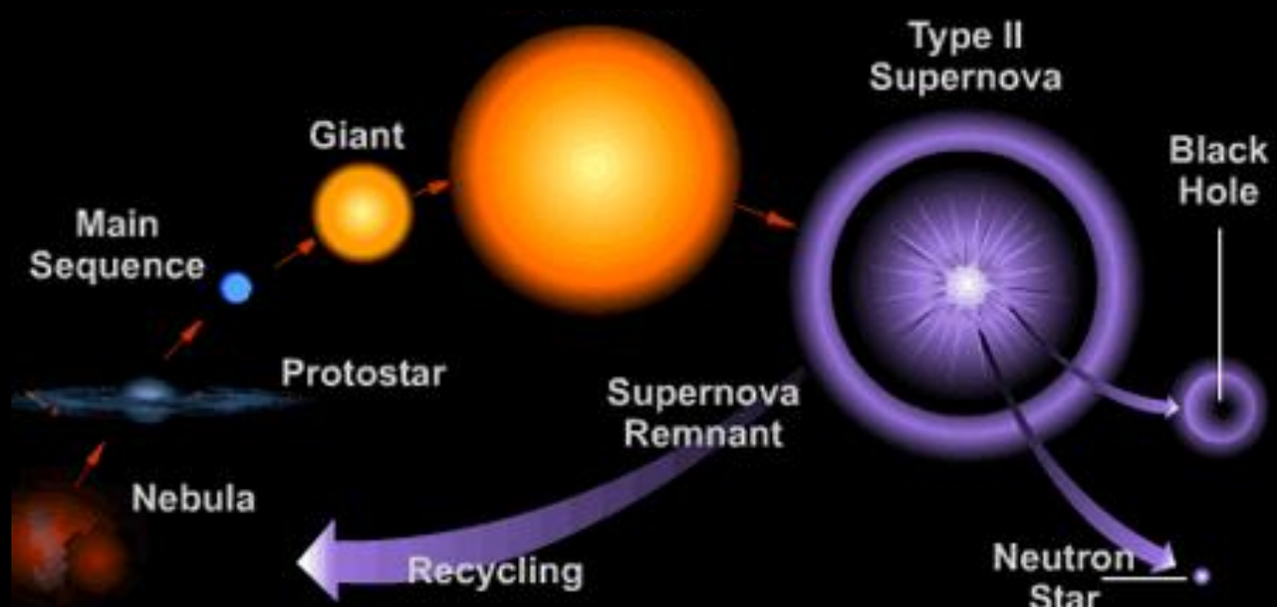


Galaxy Feedback

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?

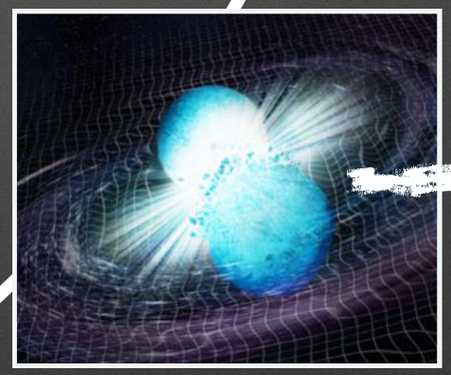
What powers stellar explosions?

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

SN1987A

BH

NS



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What are the progenitors?

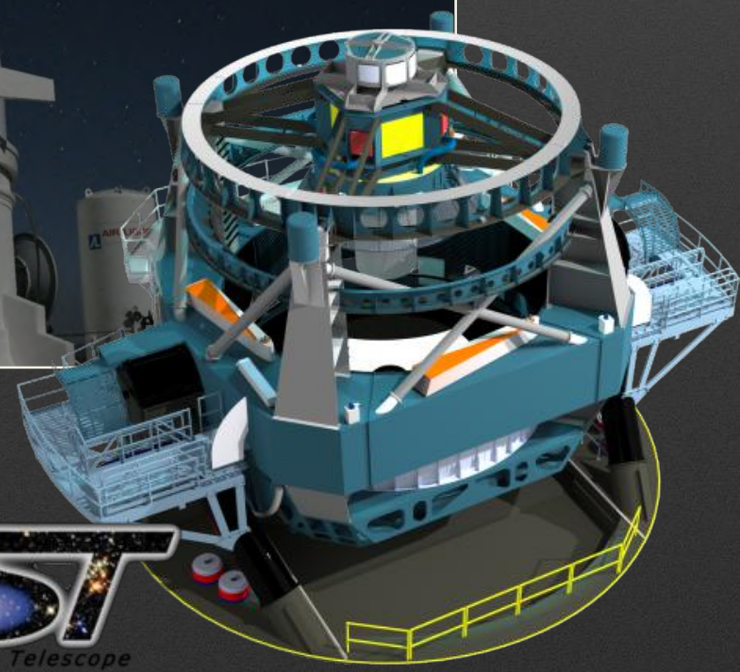
Gravitational Waves
+ Light

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

Why NOW?

1. Technological Revolution ==> Time Domain Astrophysics

+ many others!

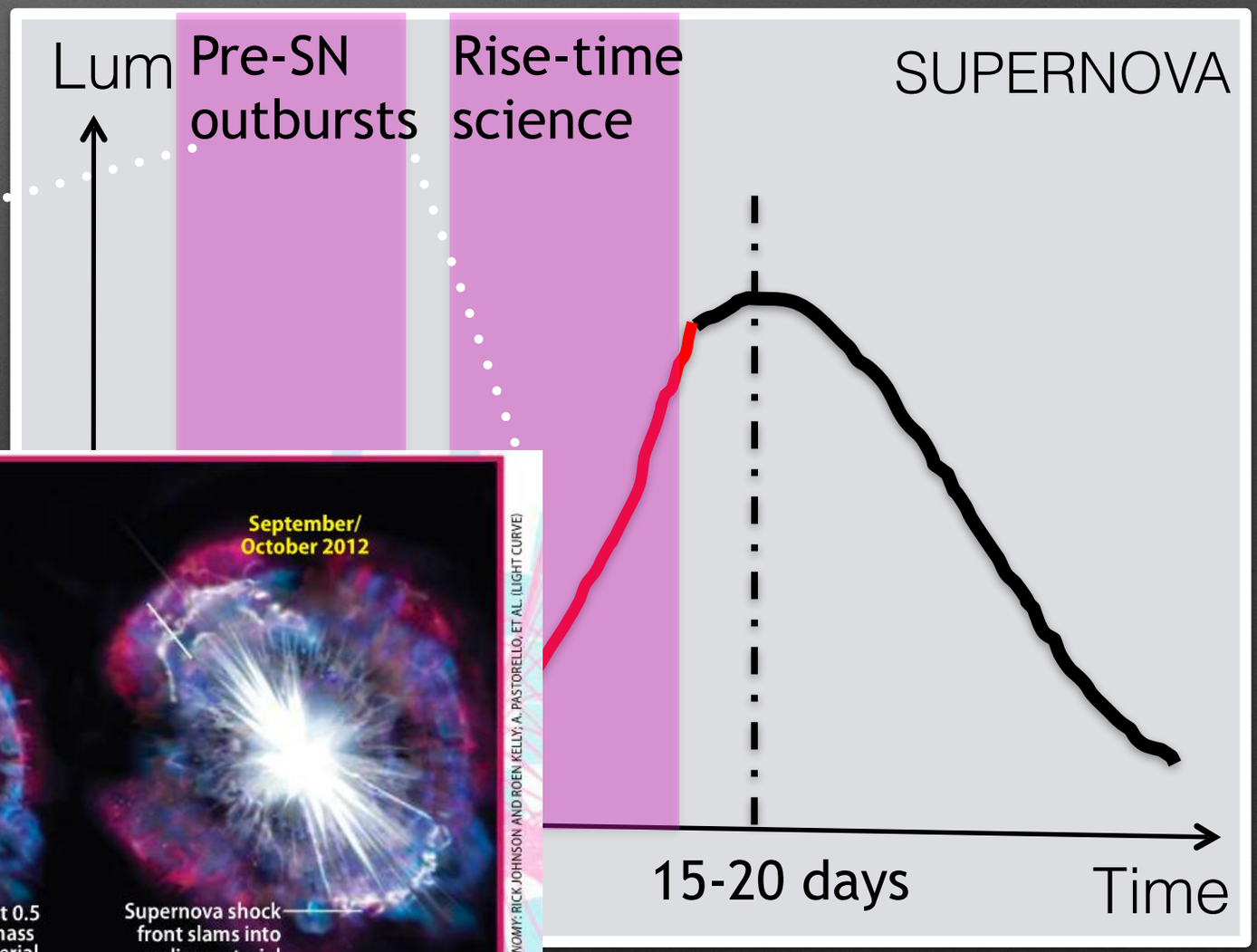


Where do we stand?

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)



Margutti Astronomy Magazine 2014

Where do we stand?

Where do we go?

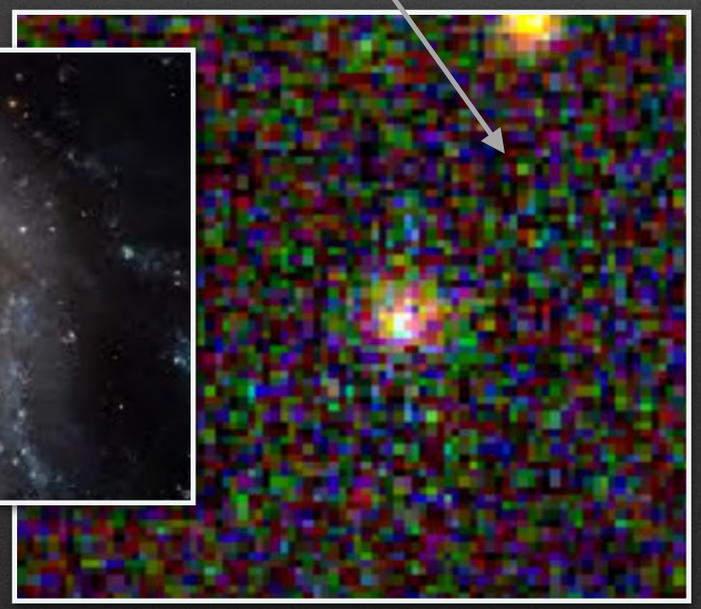
1. Technological Revolution ==> Time Domain Astrophysics

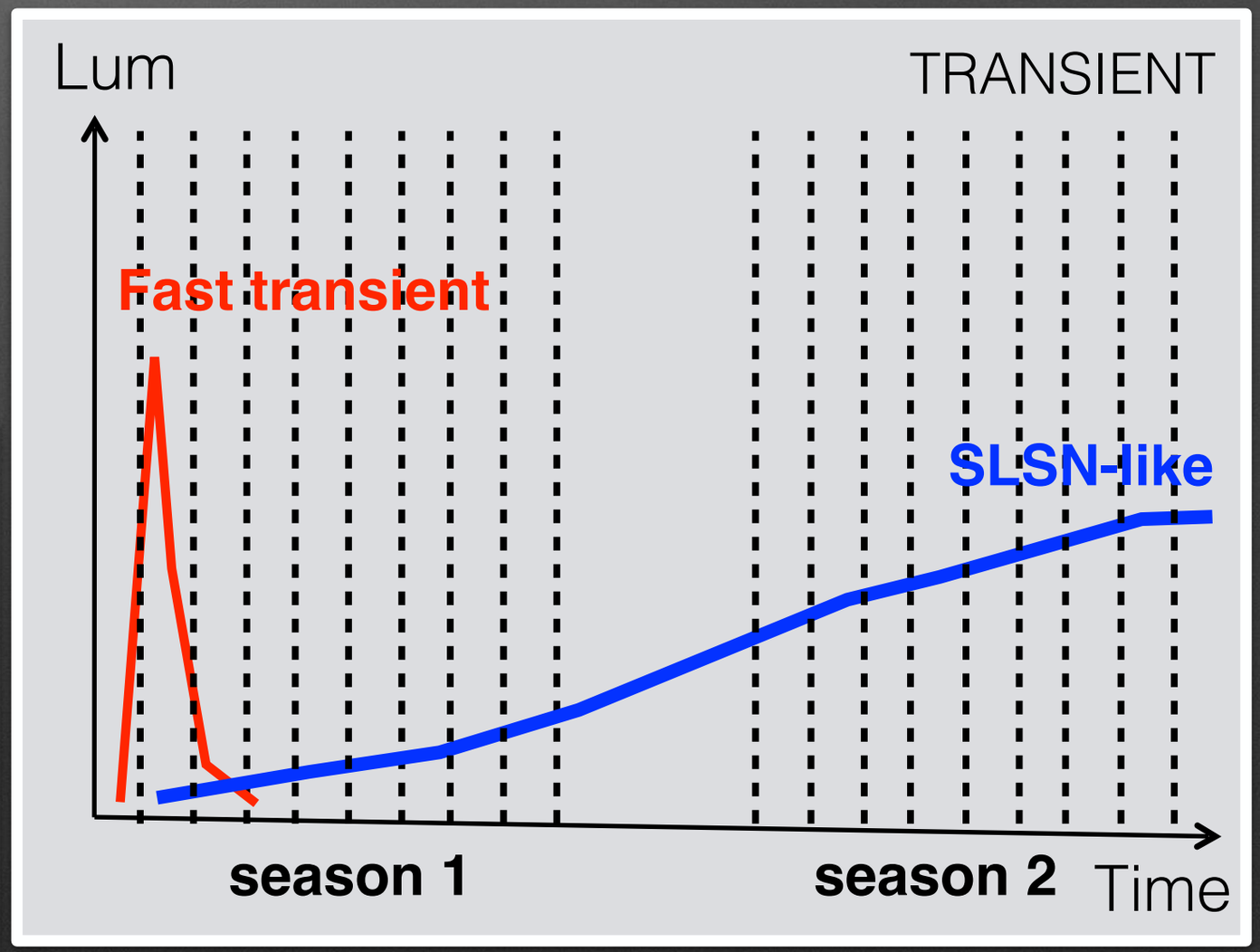
Explore a new parameter space in already known transients
(Rise-time science; pre-SN science; shock break out science)

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

Time scales

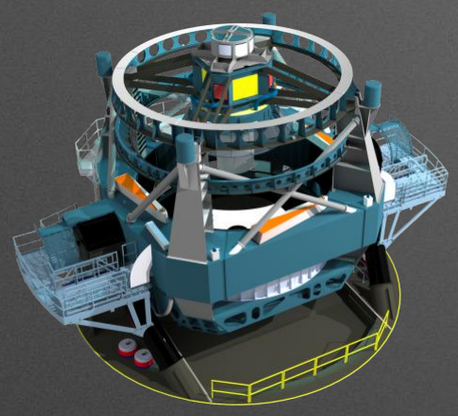
Untargeted search





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?

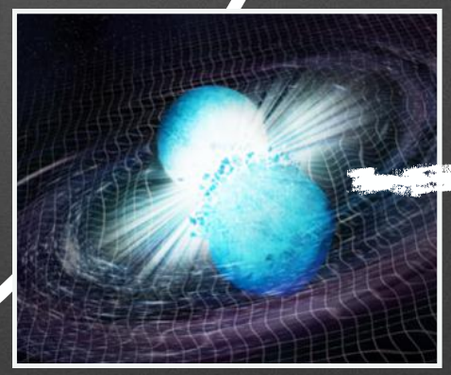
What powers stellar explosions?

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

SN1987A

BH

NS



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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

VLBA

VLA

MMT

UKIRT

Magellan

18cow

Keck Telescopes

CTIO

SOAR

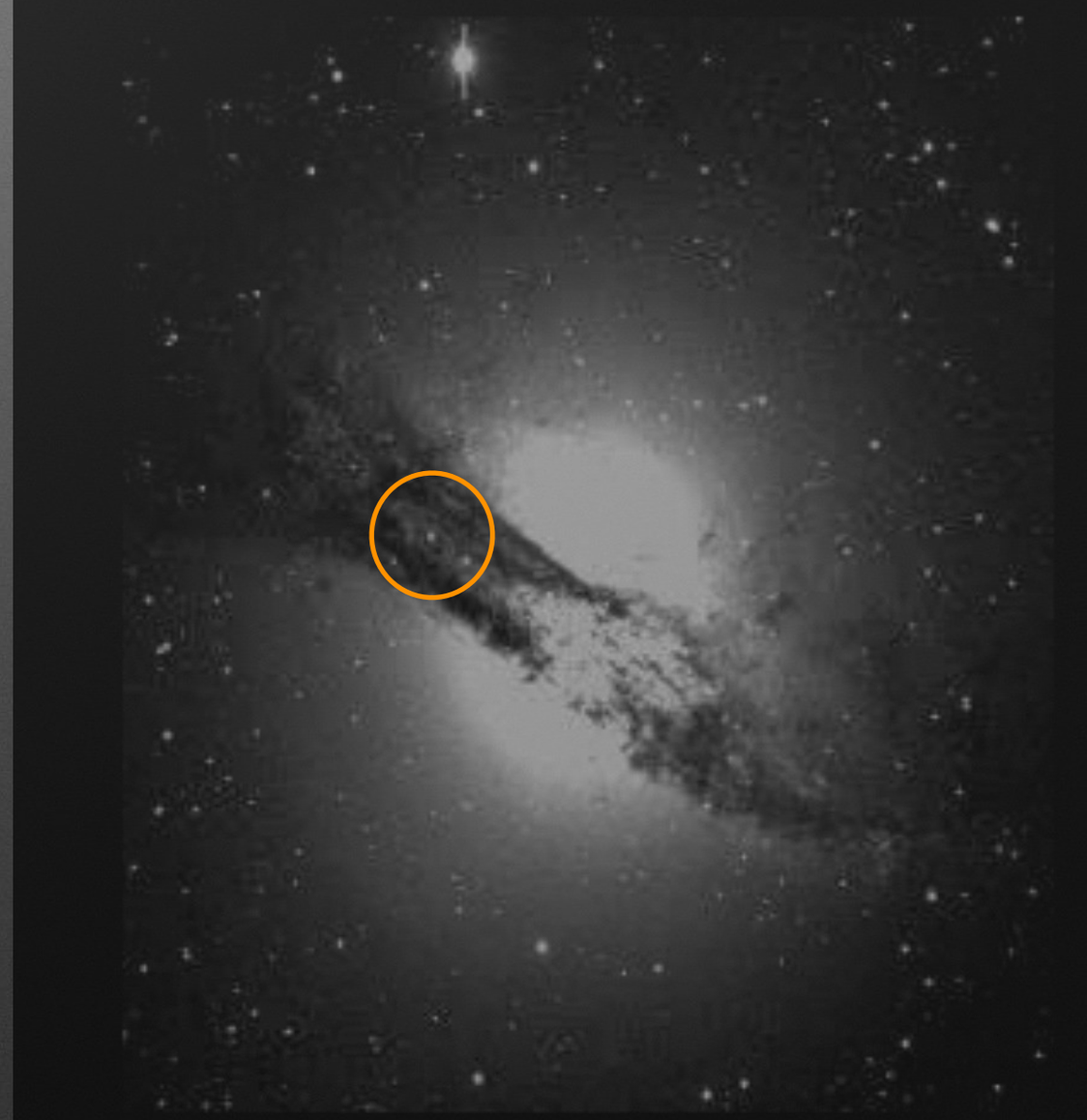
γ-rays X-rays UV/Optical/NIR Radio

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

FOLLOW UP TEAM

Trigger Feed

DISCOVERY ENGINE



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

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

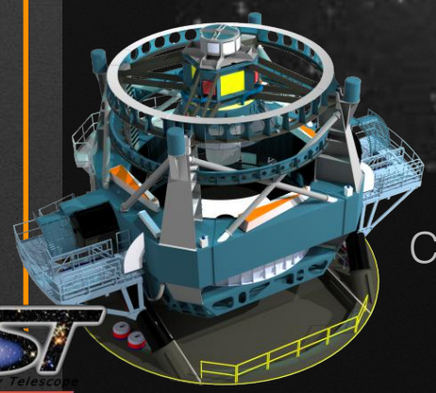
DISCOVERY ENGINE

YSE (PS1-2: depth)
ZTF (rate)
+
ARTIFICIAL INTELLIGENCE
(HS supported, new approach)

HEISING-SIMONS FOUNDATION

FOLLOW UP TEAM

Trigger Feed



LSST Large Synoptic Survey Telescope

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

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

DISCOVERY ENGINE

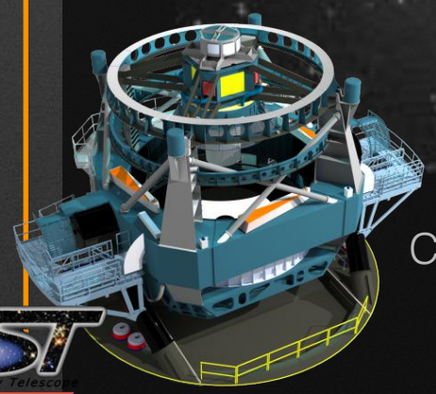
YSE (PS1-2: depth)
ZTF (rate)
+
ARTIFICIAL INTELLIGENCE
(HS supported, new approach)

+

LIGO (GW sources)

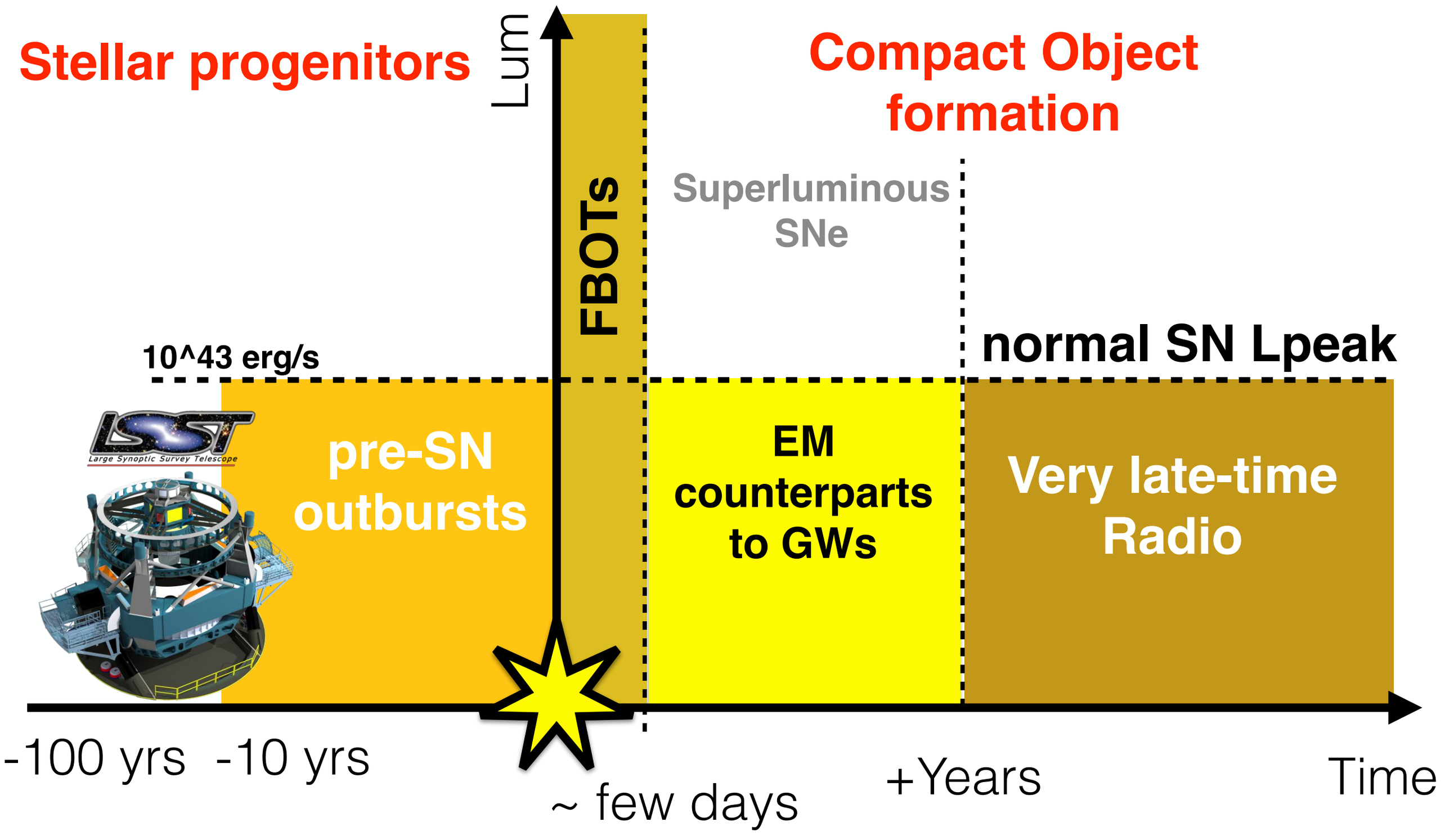
Trigger Feed

FOLLOW UP TEAM

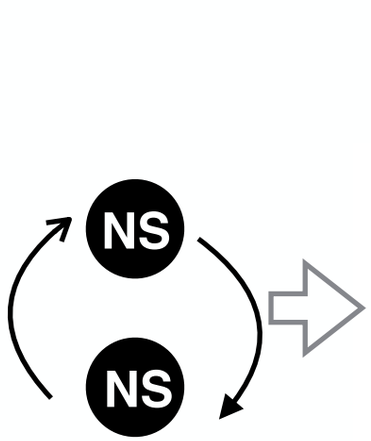


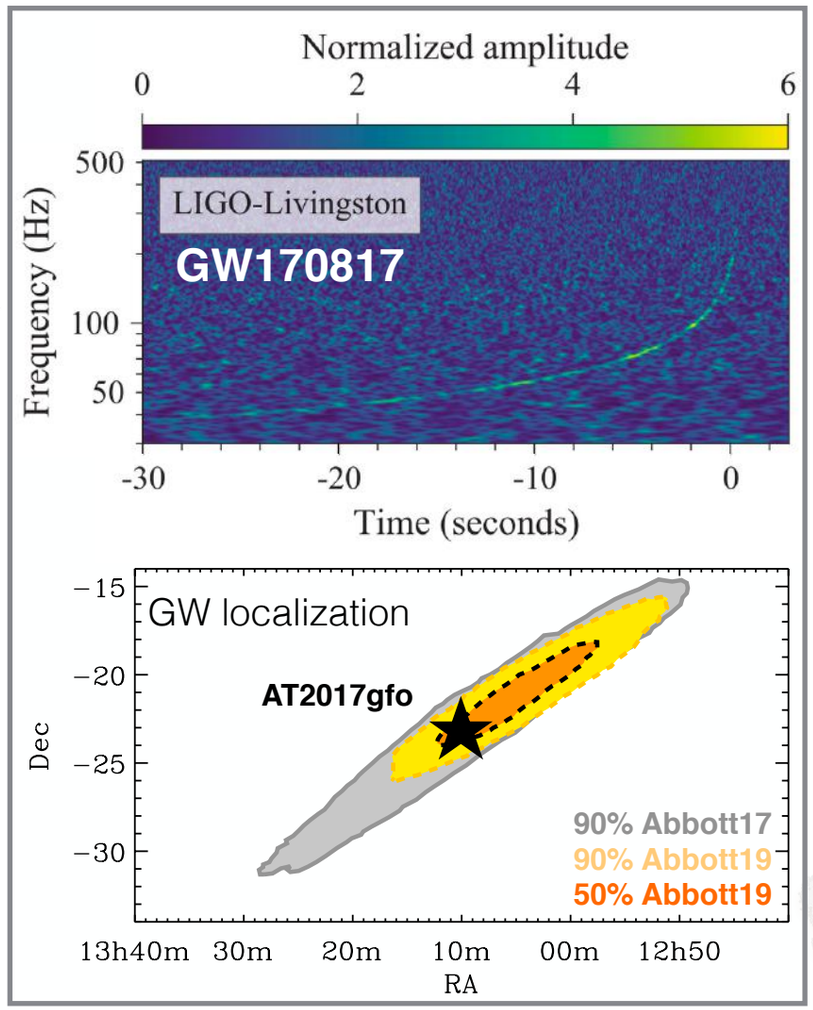
Credit: SSP/Lawrence Berkeley National Laboratory's Computer Visualization Laboratory

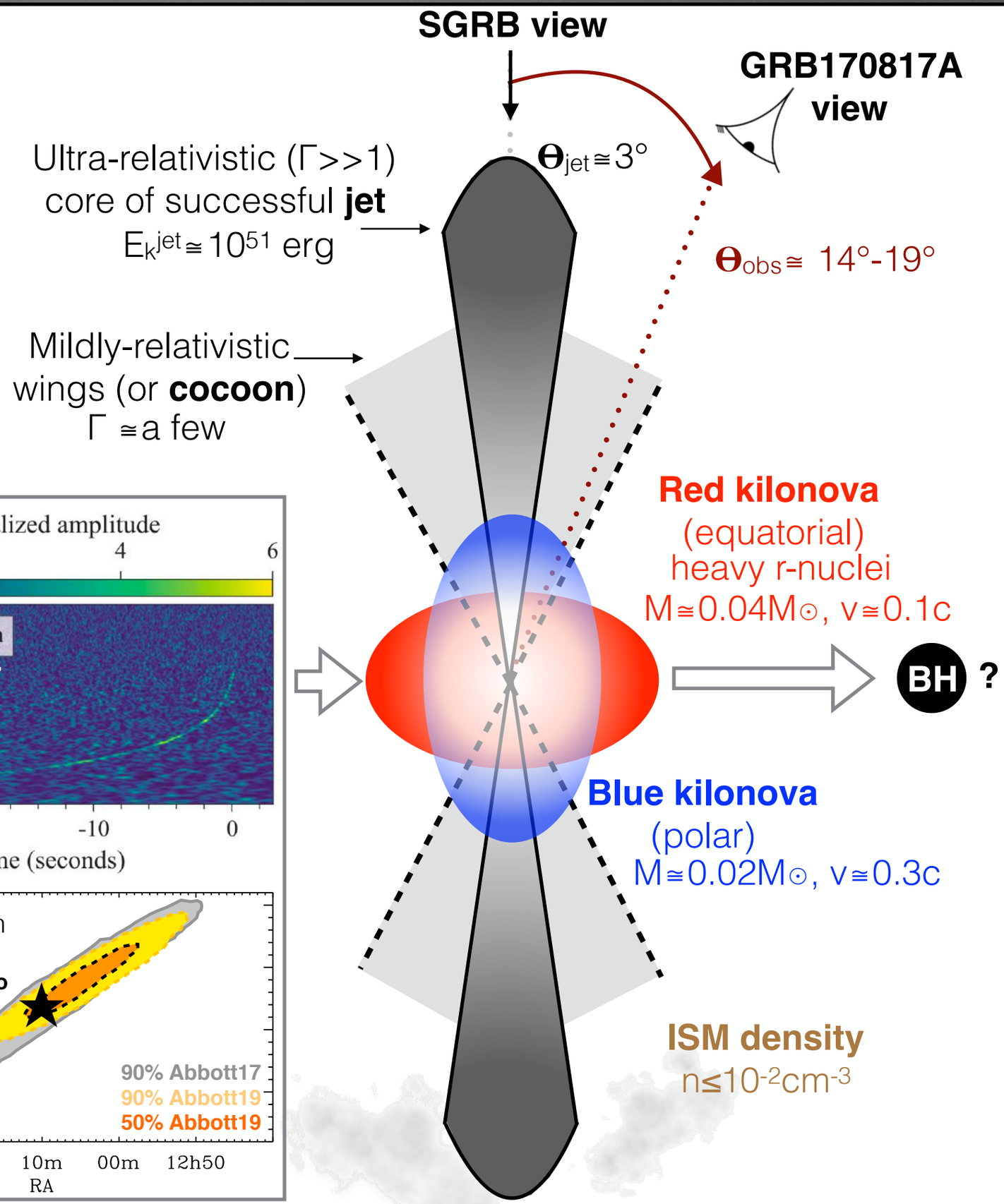
Discovery Frontiers:



GW170817 (GW+ EM)

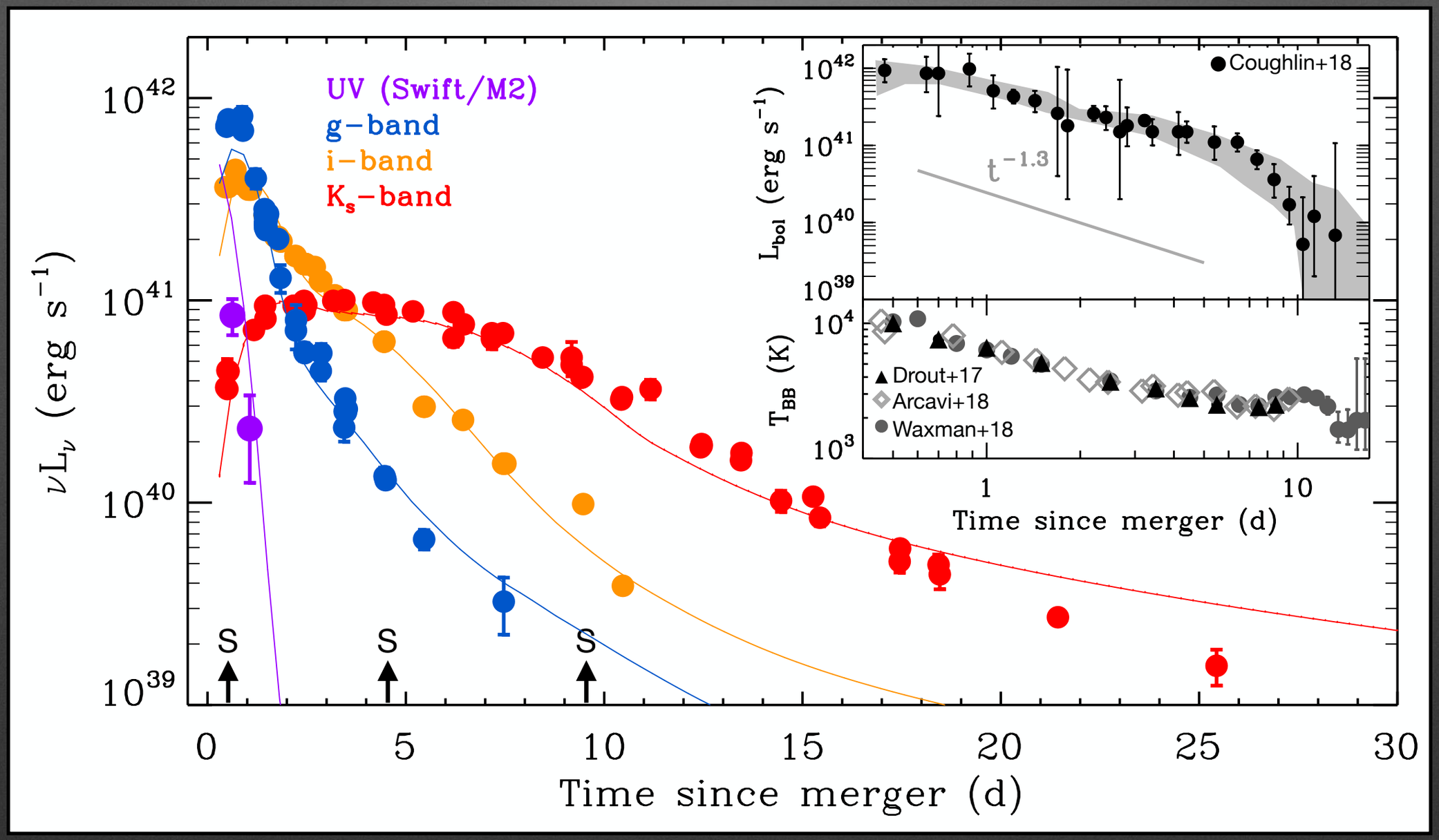






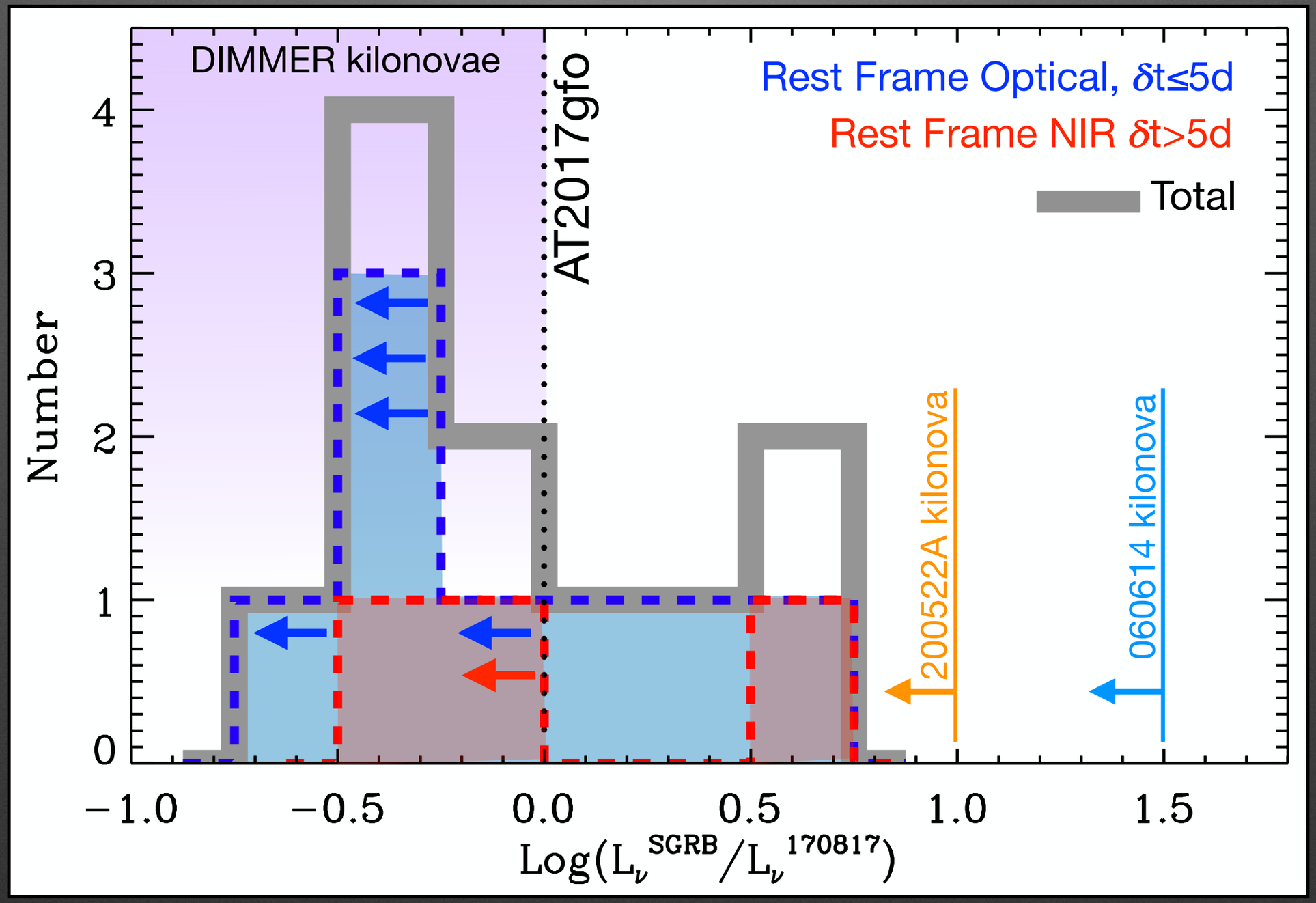
Margutti & Chornock ARA&A 2021 in press, and references therein

UV/optical/IR kilonova emission associated with GW170817



Margutti & Chornock, ARA&A 2021 and references therein

Diversity of KN emission in SGRBs



Margutti & Chornock, ARA&A 2021 and references therein

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

AT2017gfo

NGC 4993
d_L=40.7 Mpc
HST/ACS
δt =11 d

2 kpc

N

E

Optical Residuals
(F475W)

2 kpc

HST

Radio
(6 GHz)
δt =112 d

2 kpc

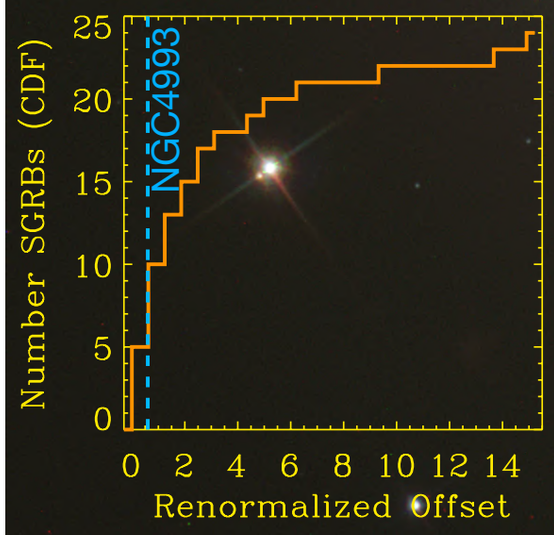
VLA

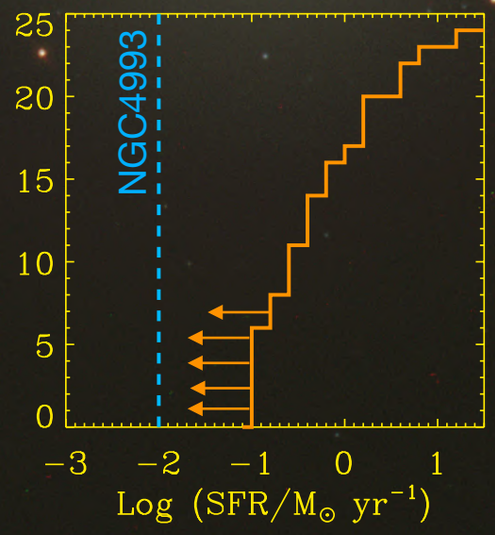
X-ray
(0.5-8 keV)
δt ≤600 d

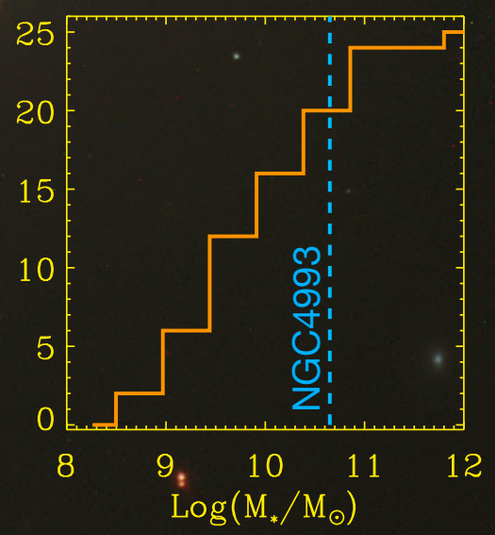
Weak
AGN

2 kpc

CXO





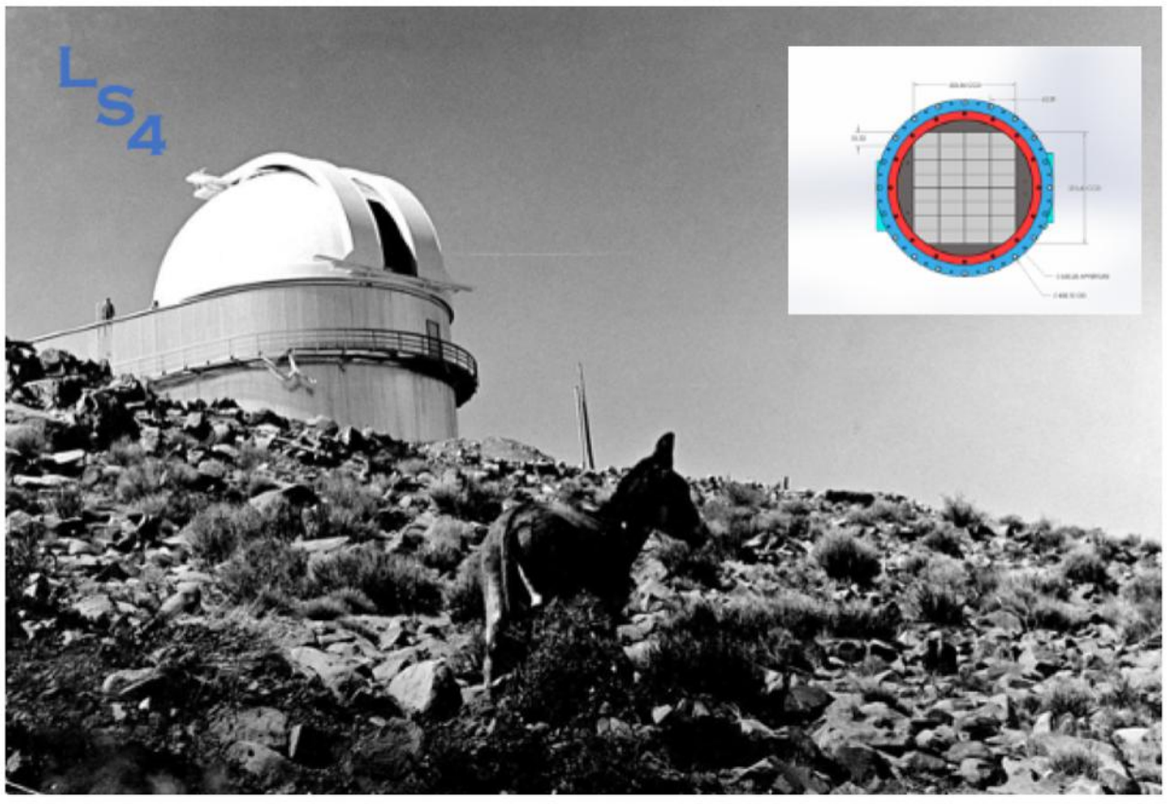


The La Silla Schmidt Southern Survey (LS4)

PI Peter Nugent

A shallow, southern, high-cadence, PUBLIC optical survey to compliment the Rubin Observatory.

LS4 Quick Facts Summary



Quick facts:

- **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% MMA ToO's**
- **Real-time public data**

Slide courtesy P. Nugent

....Fast Transients.....

How a SN-Ia would look:

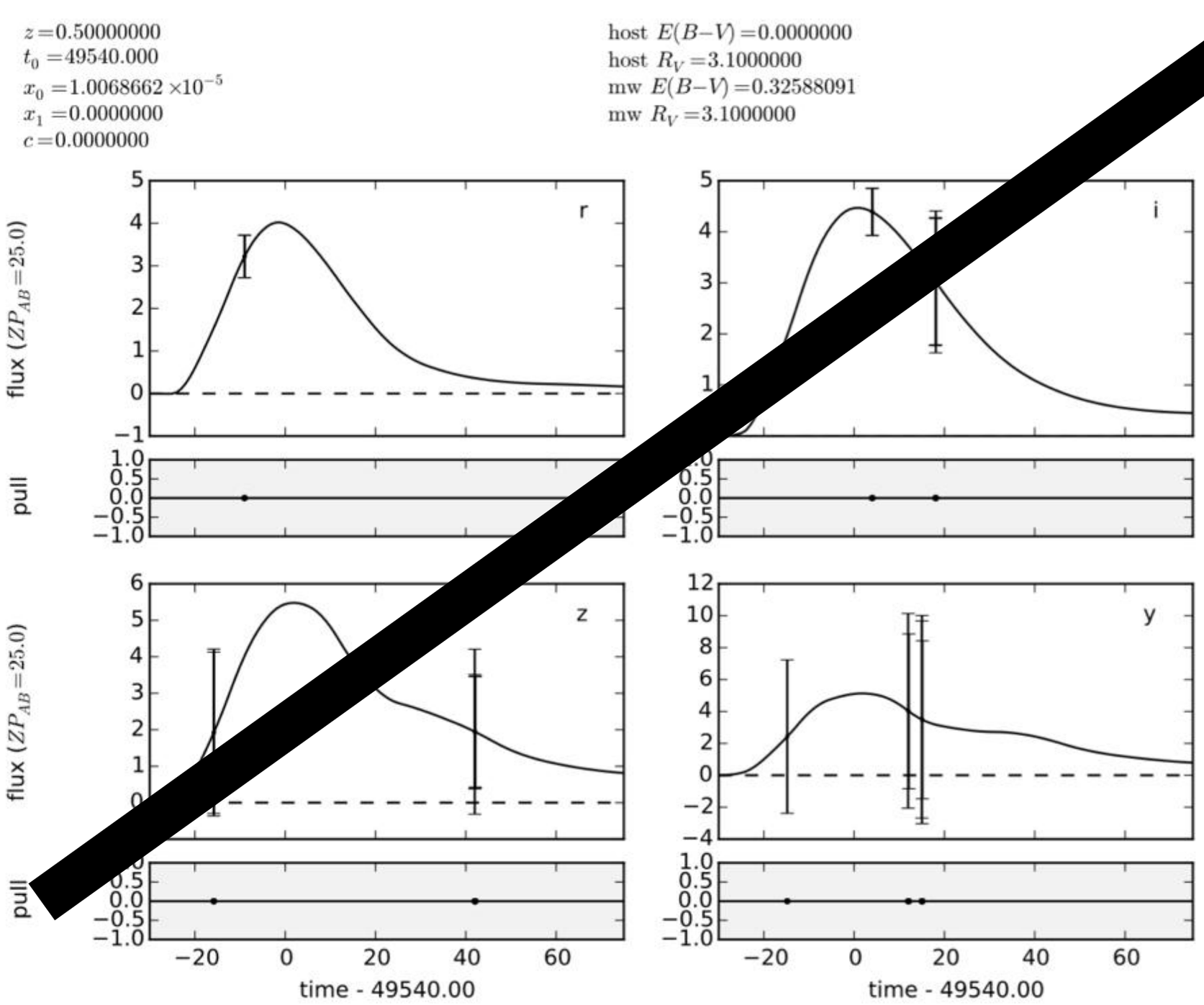


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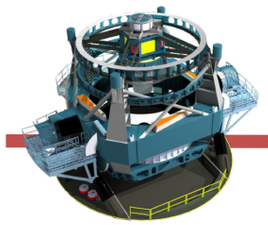
Figure 9.13: An example of a light curve, where only four filter bands are available, of a SN Ia from the WFD survey in **enigma_1189**.

Wide Deep Fast



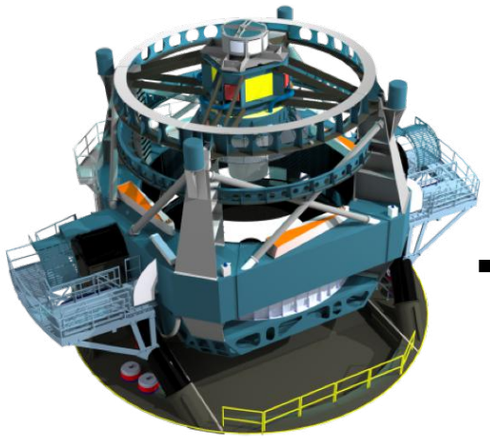
Where is the frontier after GW170817:

1. POPULATION studies: Mapping the DIVERSITY of BNS merger outcomes
2. Blue component + Discovery of NEW EM emission components
3. Discovery of the EM counterpart of a BH-NS merger
4. EM counterparts to BH-BH mergers??
5. EM counterparts to unidentified GW sources

DEEP (over the entire LIGO localization region)

Get on target **PROMPTLY**

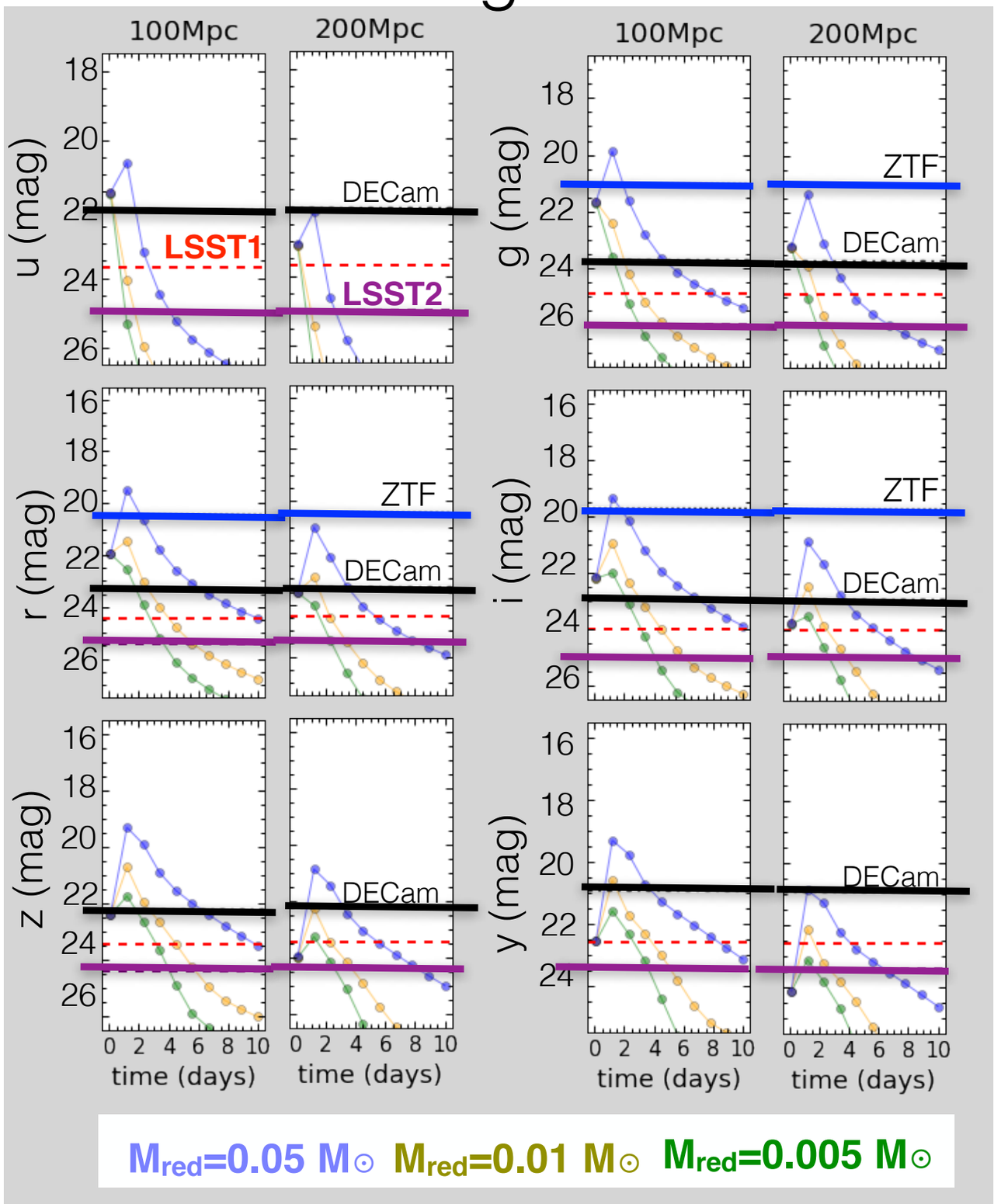
Why Rubin:



+ToOs

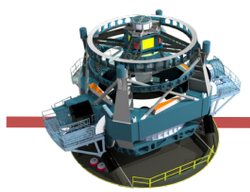
LSST1= 30s exposure
LSST2= 180s exposure

kilonova light-curves:



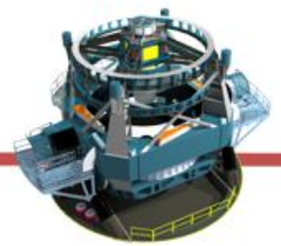
Mortensen, RM+2018

Why LSST+ Target of Opportunity (ToOs):



Luck is not a good idea

LSST Observing Strategy white paper (Summer 2016):



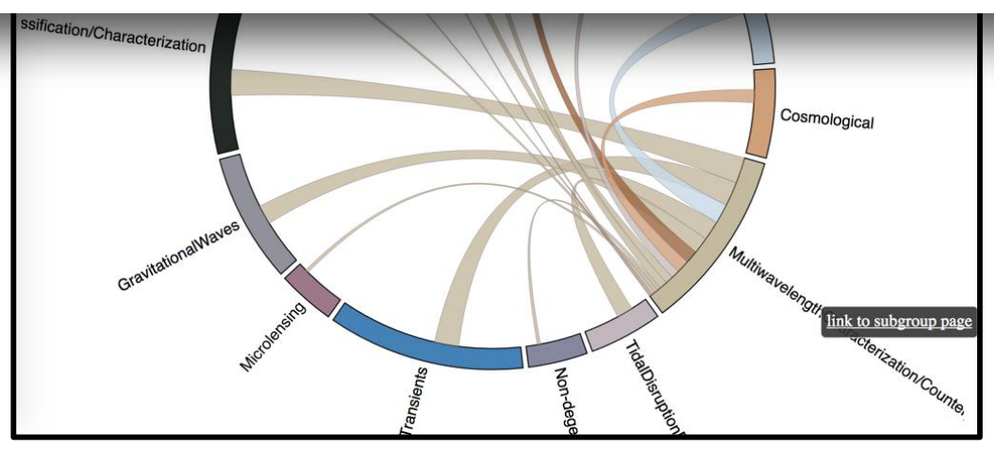
Luck is not a good idea

A~3000 deg2 (7% of the sky) with Delta_t<7 days

IMPORTANT:

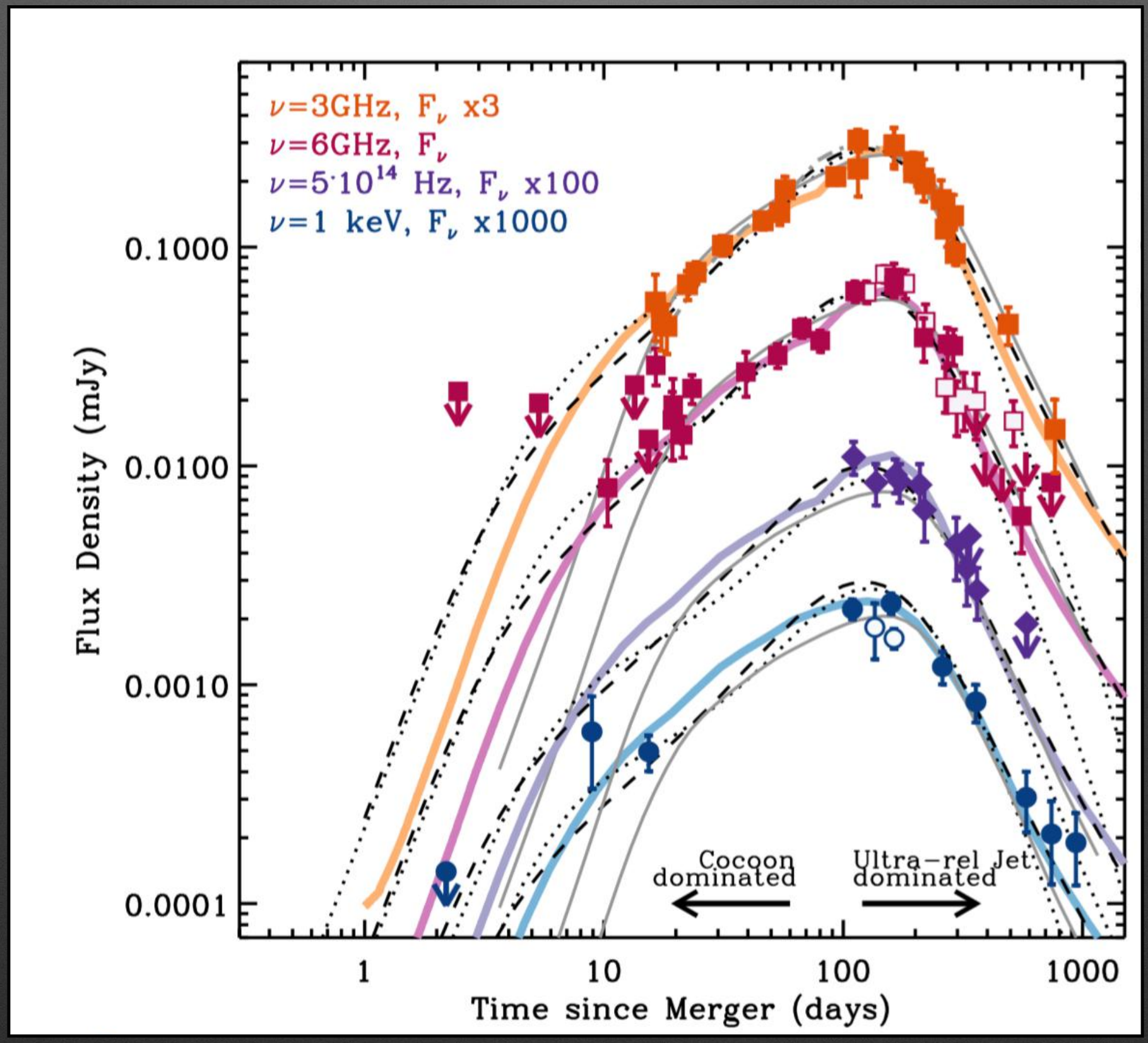
Limited Color Info + Coverage of total GW Area + Observing conditions

curate masses and spins of neutron stars and black holes, tests of General Relativity and an accurate census of the neutron star (NS) and black hole (BH) populations that might challenge our current understanding of massive stellar evolution. However, GW events are poorly localized (10-100 deg^2 at the time of LSST operations). The identification of EM counterparts would provide precise localization and distance measurements, in addition to the necessary astrophysical context (e.g. host galaxy properties, connection to specific stellar populations) to fully exploit the revolutionary power of this new GW era.



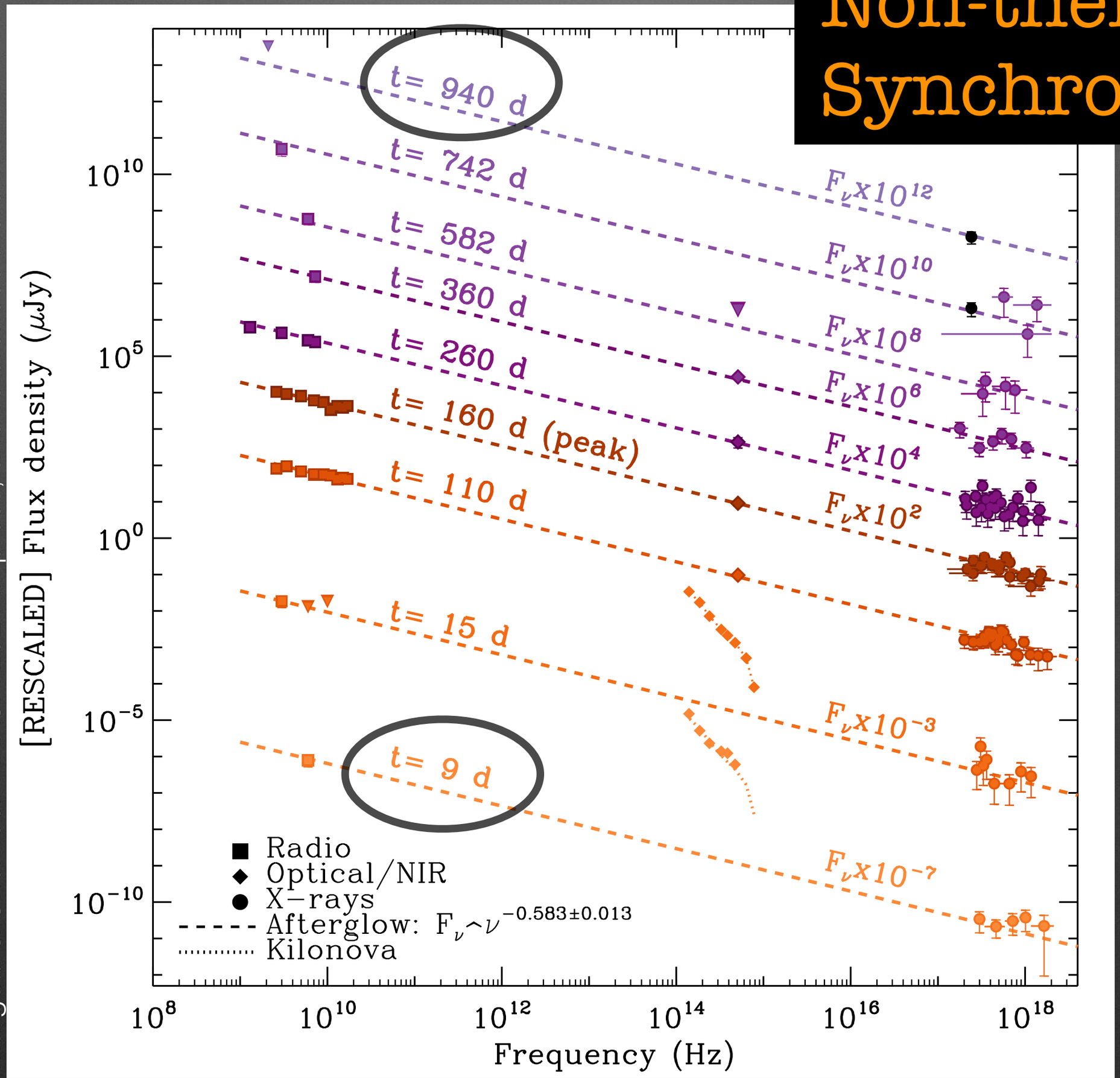
https://github.com/LSSTScienceCollaborations/ObservingStrategy/blob/pdf/whitepaper/LSST_Observing_Strategy_White_Paper.pdf

GW170817 Jet Afterglow Emission:



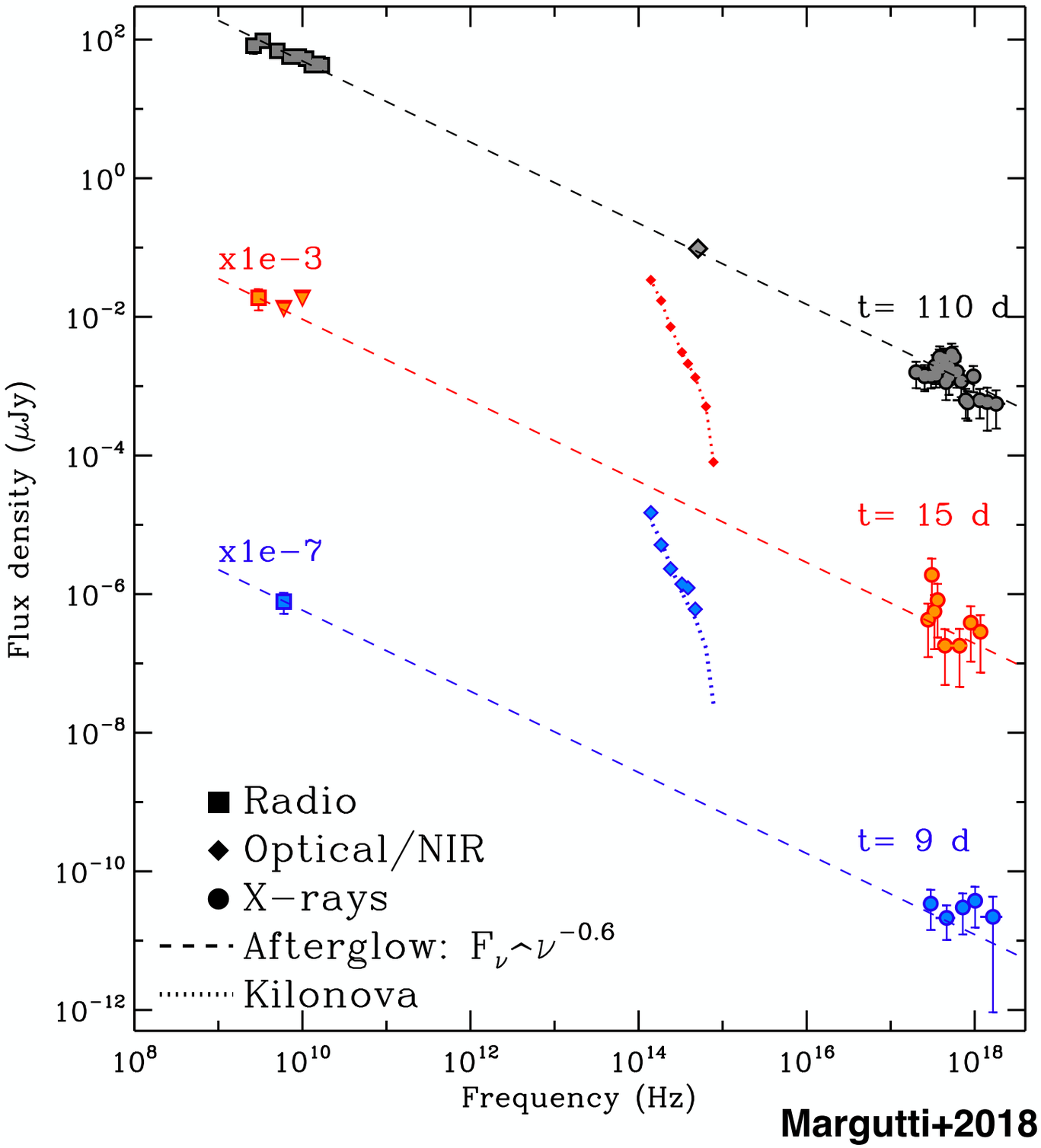
Margutti & Chornock ARA&A 2021 in press, and references there in

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



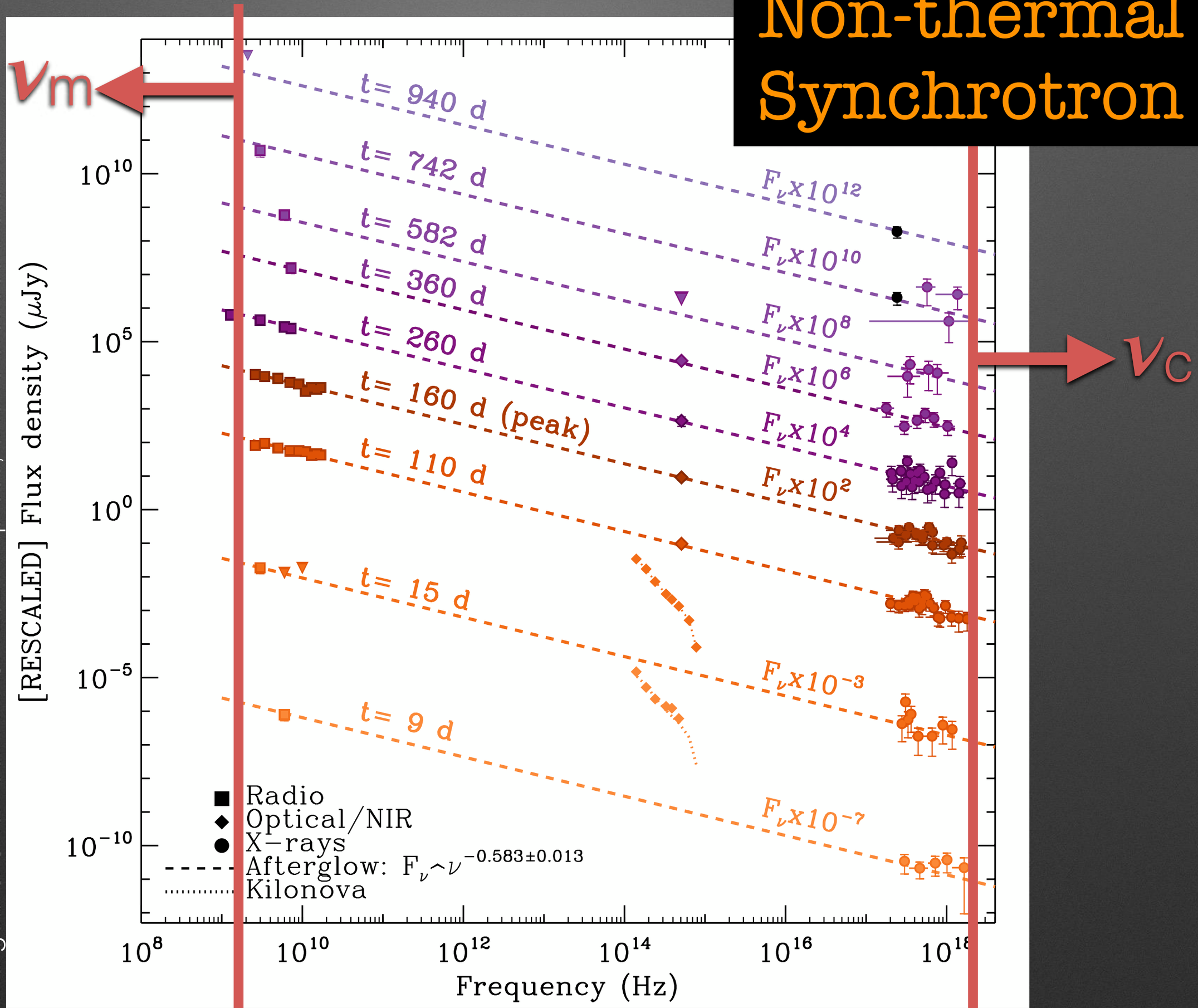
Margutti+2018

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

Particle acceleration by trans-relativistic shock in action!
Emitting material has

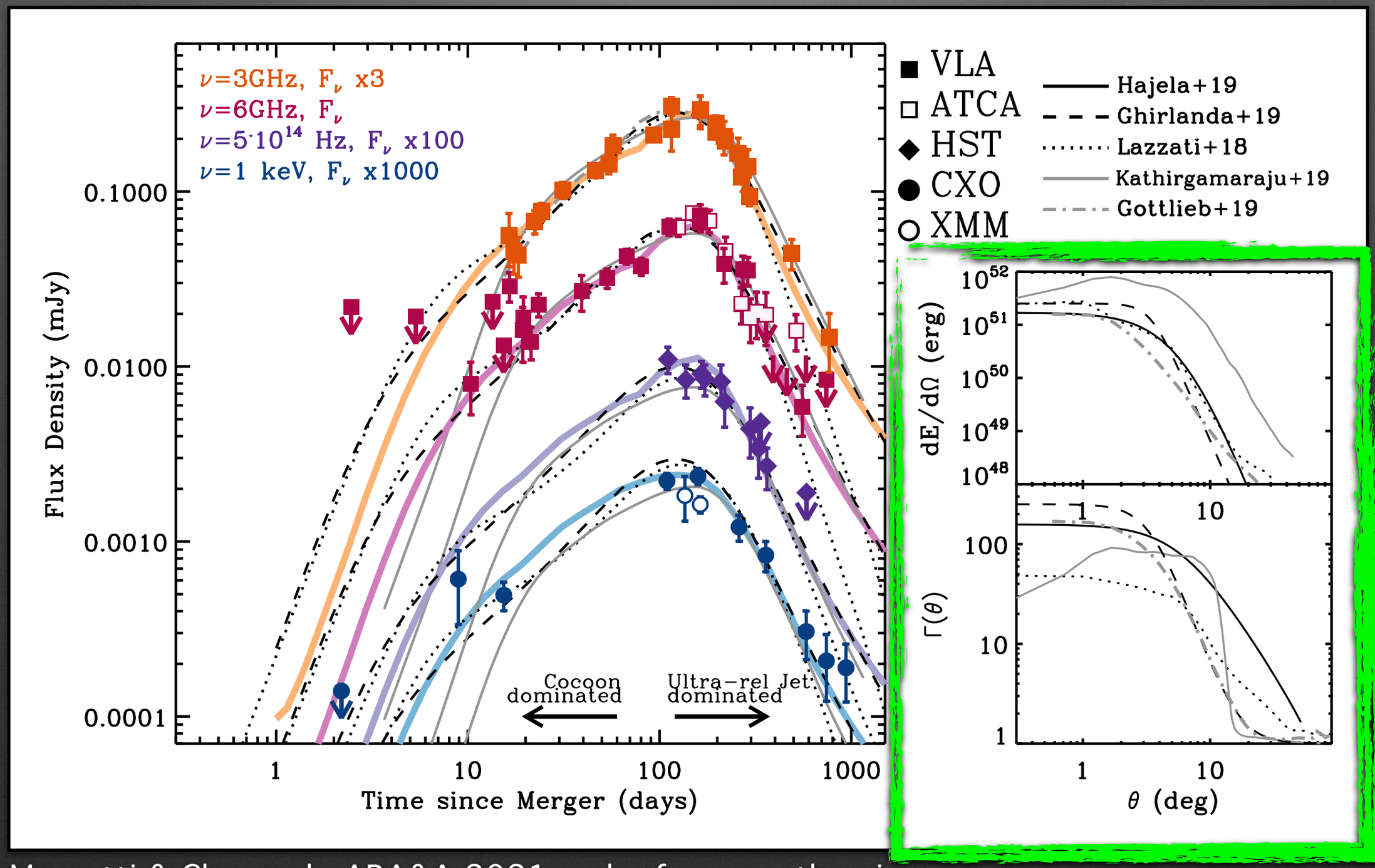
Γ~3-10

Non-thermal Synchrotron



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

Structure E(θ) and Γ(θ)
of the jet launched by GW170817



Margutti & Chornock, ARA&A 2021 and references therein

Jet-core unknowns: ε_B, ε_e, ~~ζ_N~~ =1, p, n, E_k, θ_{obs}, θ_{jet}

✓ Spectrum: p= 2.166 +\- 0.026

Jet core properties

Rise: Jet Structure (highly degenerate) $\theta_{obs}/\theta_{jet}$ ~ 5-6

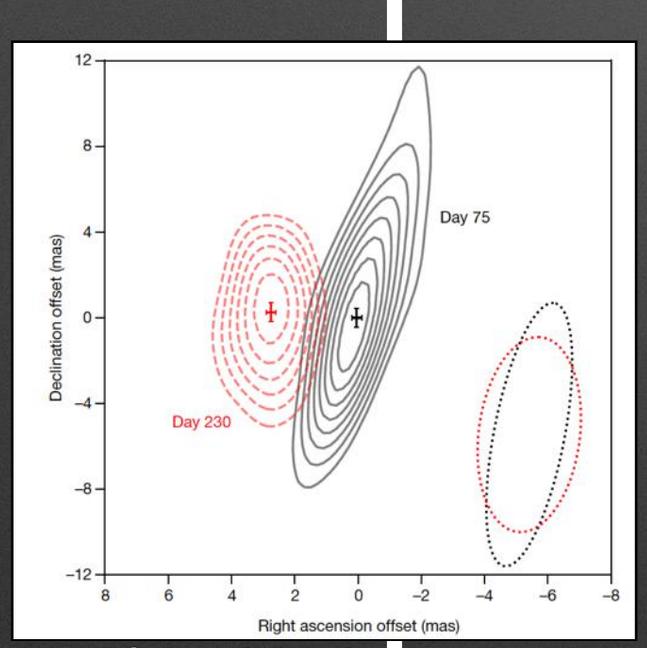
Log F_ν

✓ F_{pk}

✓ $\sim t^{0.8}$

Universal post jet-break evolution

$\sim t^{-p}$



Mooley+2018

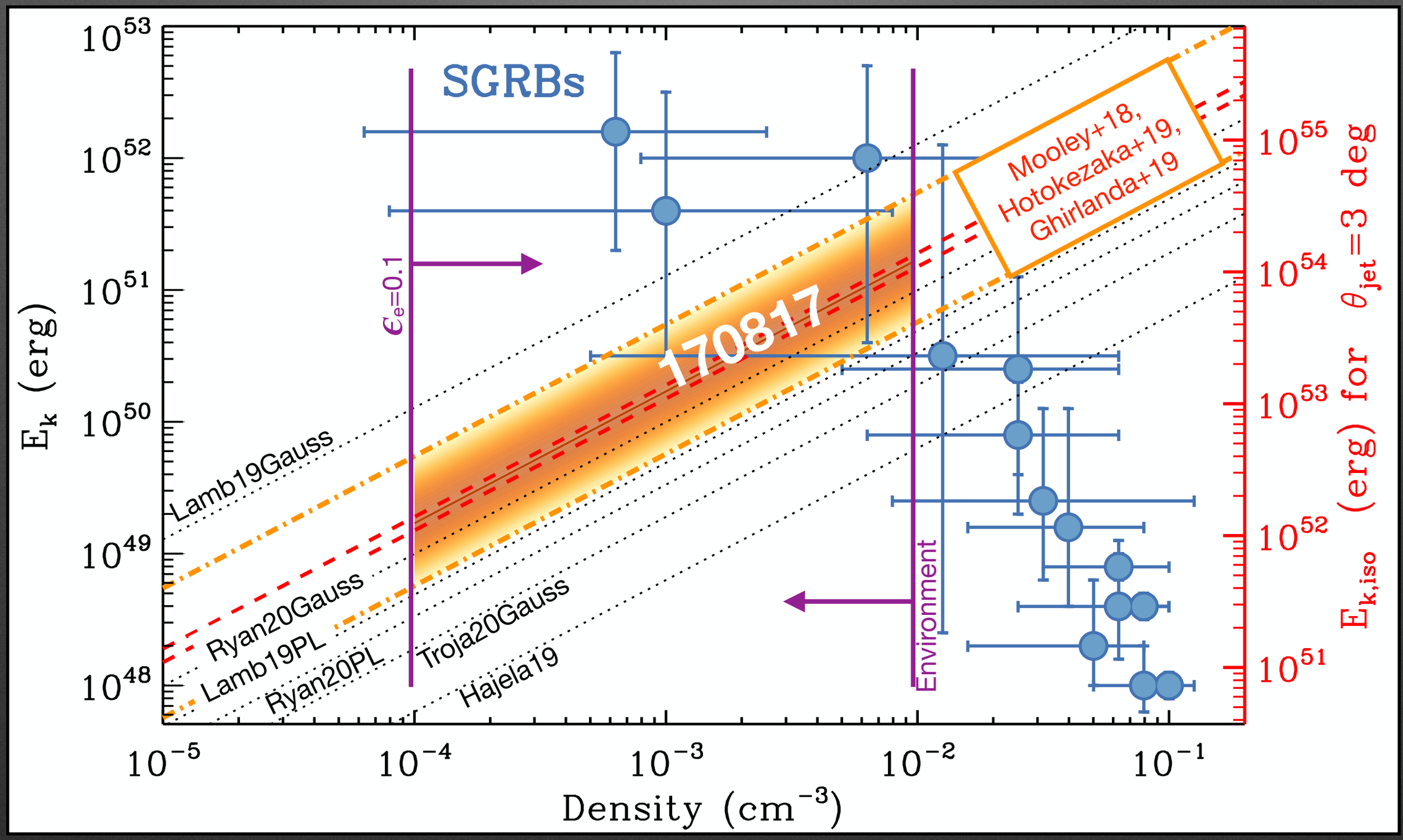
Far-off axis evolution (not observed)

t_{pk} ✓ (purely dynamical)

Log Time

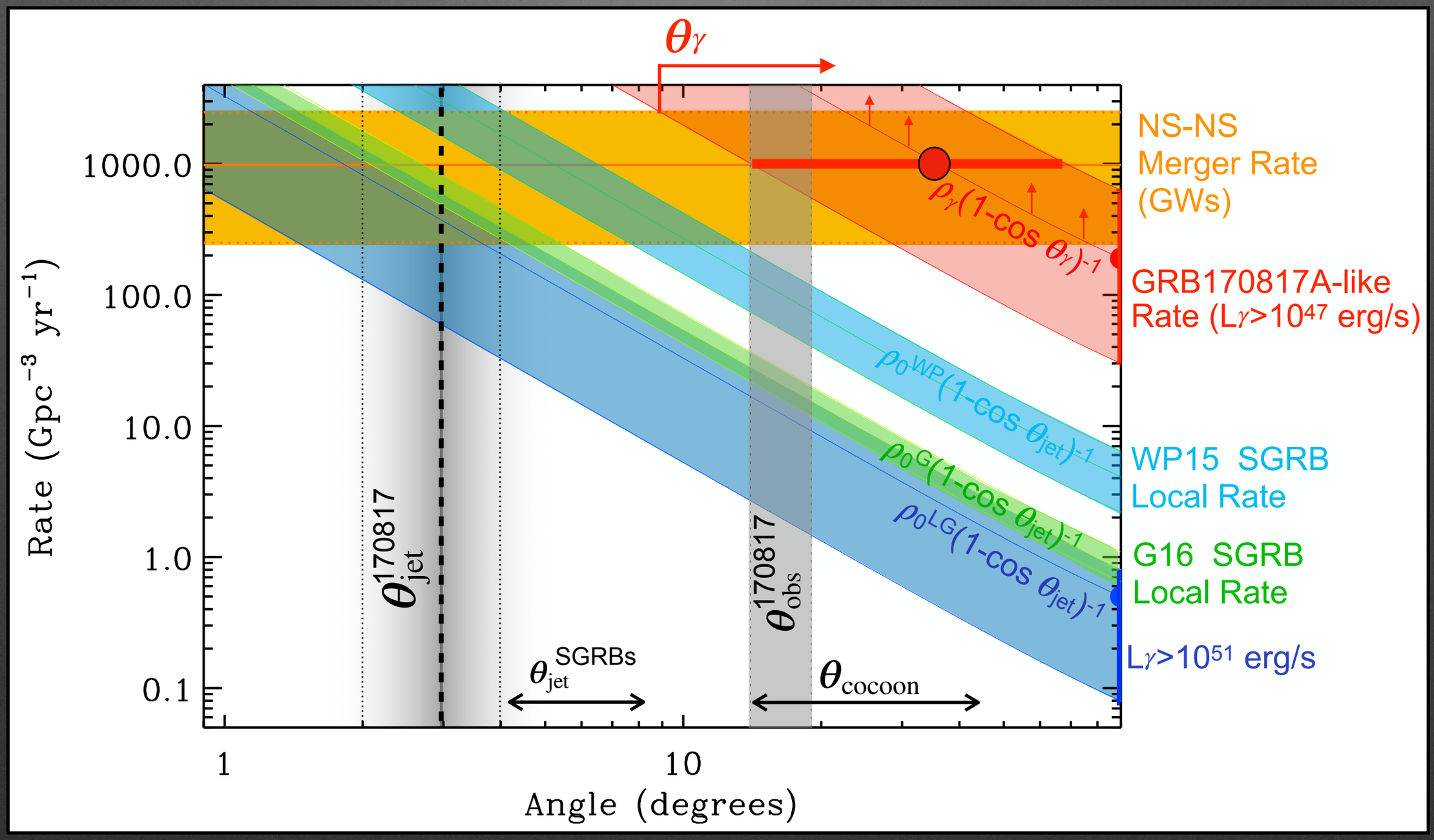
See literature by Nakar+; Granot+; Ryan+

Consequences:
jet model parameters degeneracies



Margutti & Chornock ARA&A 2021 in press

Inferences on jets in NS-NS mergers



Margutti & Chornock ARA&A 2021 in press

See literature by Beniamini+

Where do we go from here?

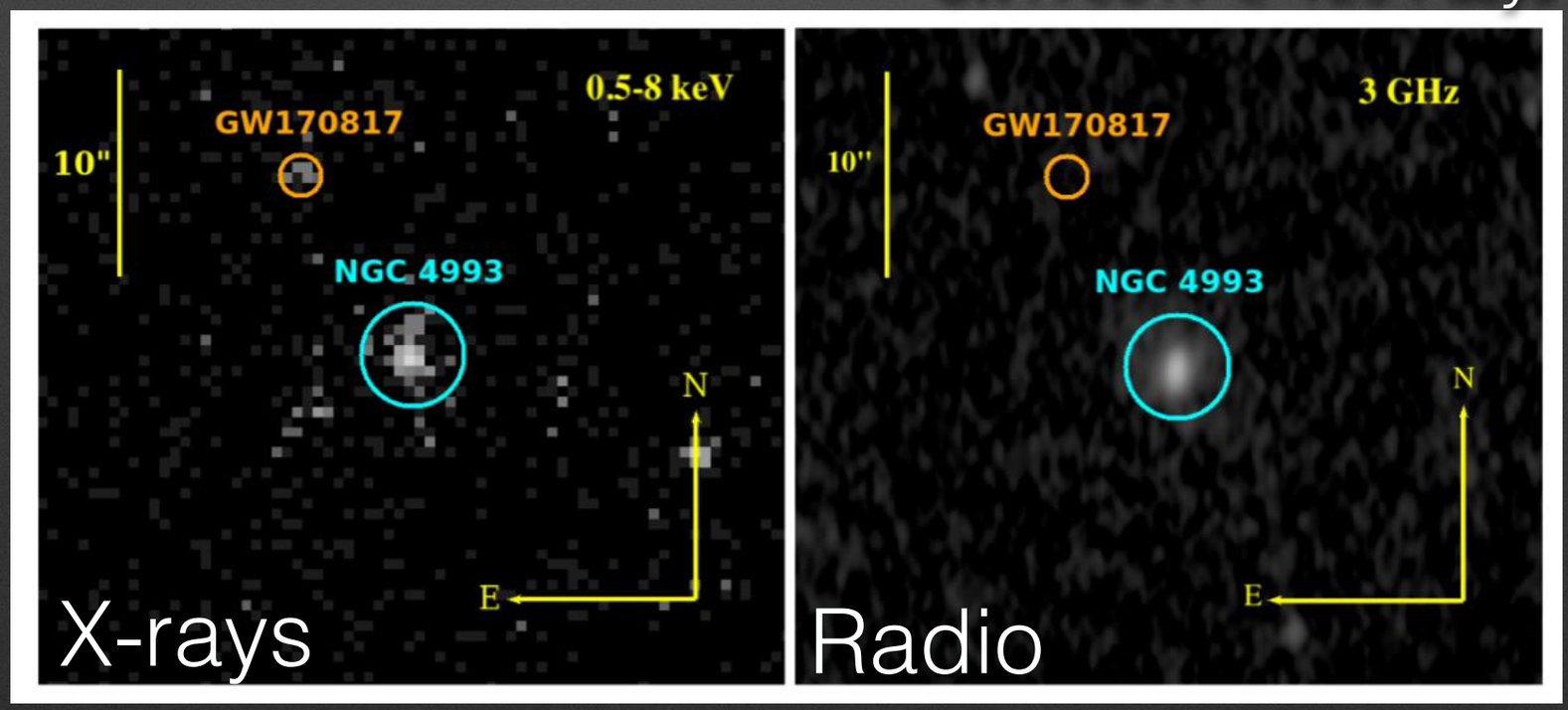
- The kilonova afterglow or BH accretion of GW170817: Exploration of new areas in the parameter space of NS-NS mergers

- BNS mergers Population Studies

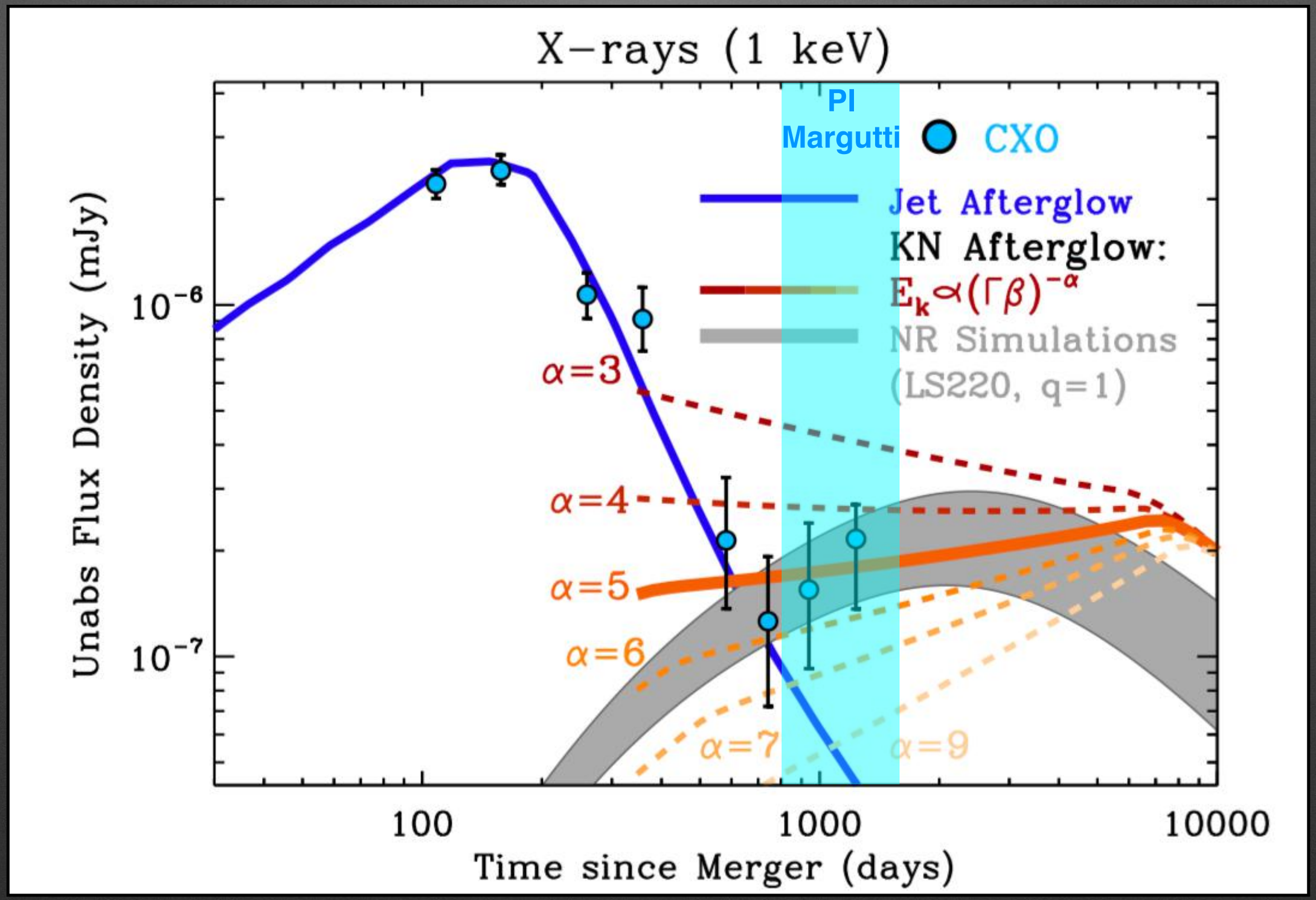
The emergence of a new source of X-rays from the binary neutron star merger GW 170817

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

GW170817 @ 1234 days

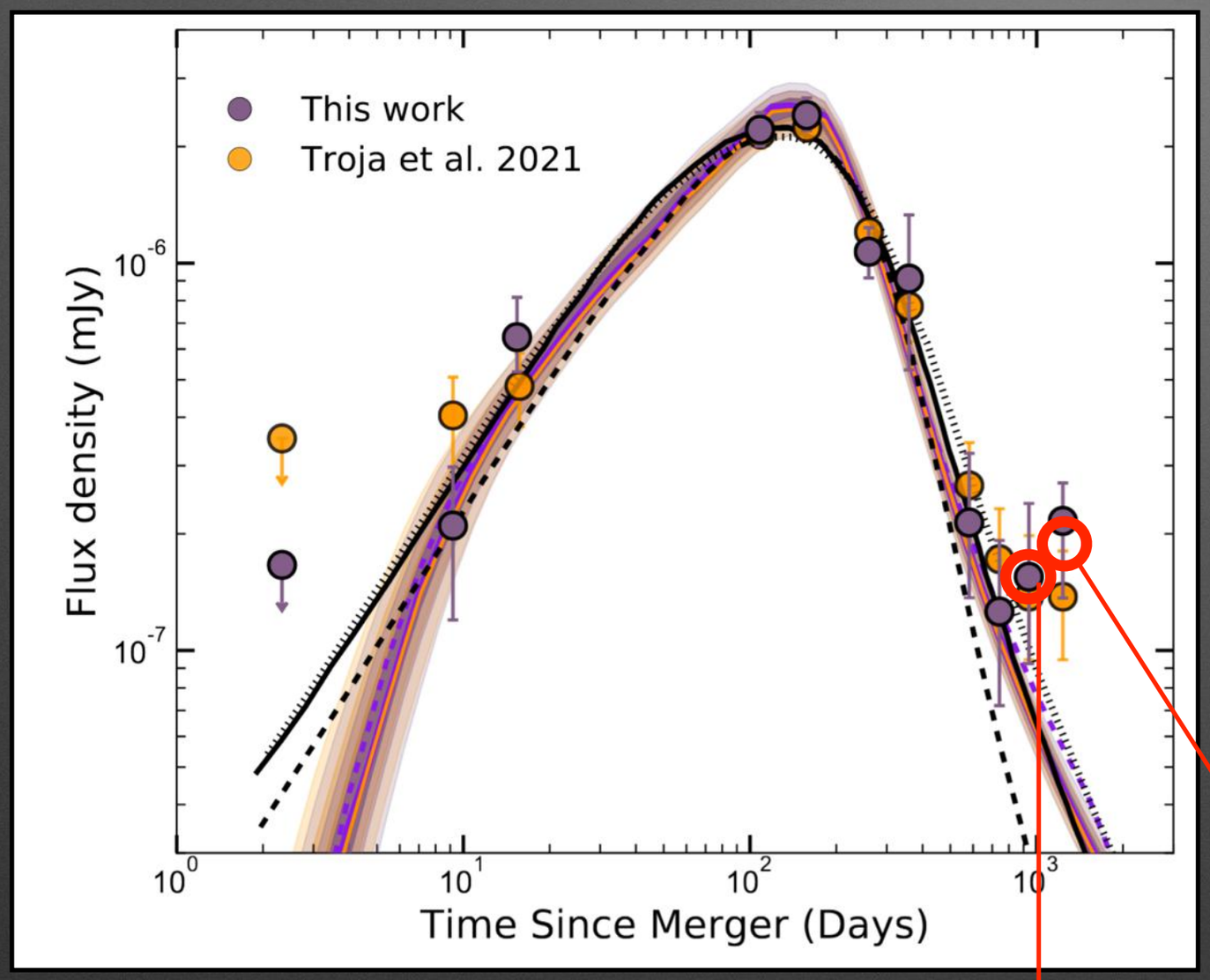


The emergence of a new X-ray component of emission at 3.5 yrs since NS merger



Hajela, Margutti, Bright et al., 2021

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



Hajela, Margutti, Bright et al., 2021

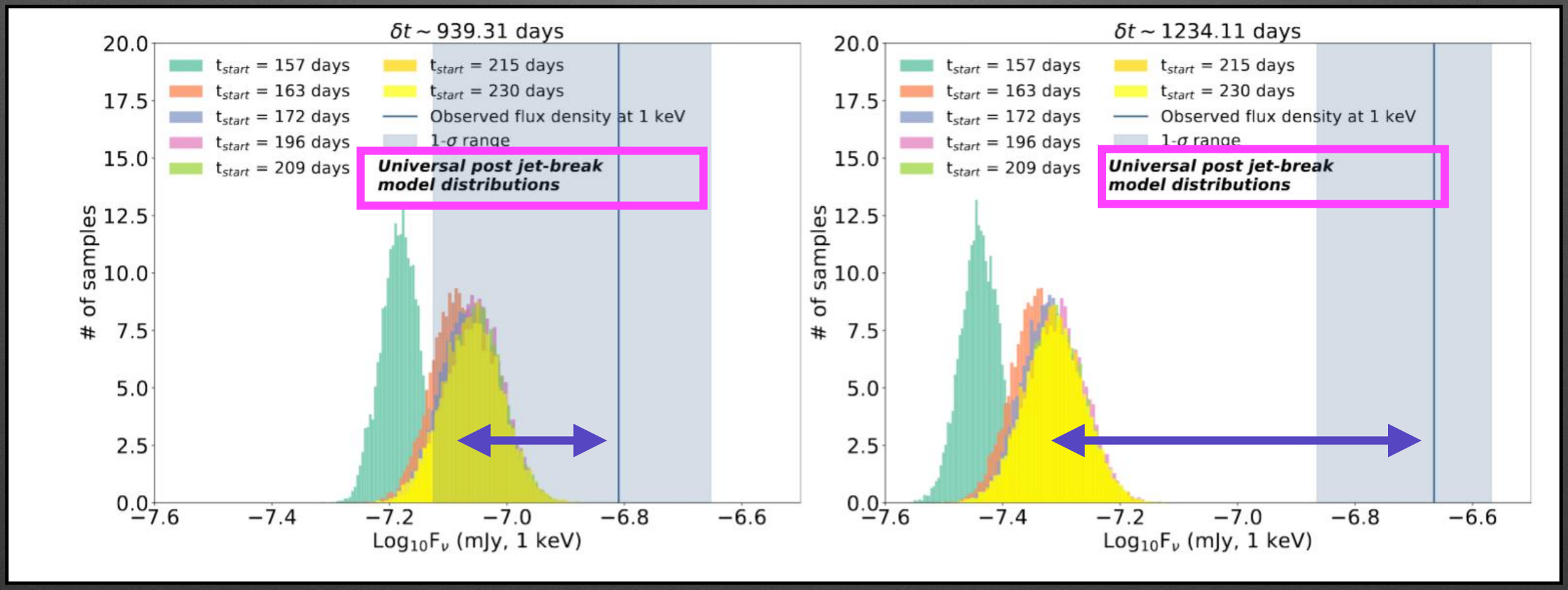
- Poisson nature of the process (for flux calibration and fitting!)
- Avoid using averaged instrumental responses
- Statistical tests carried out in the count phase space, self-consistently accounting for Poisson nature of sou+bk
- Test for the emergence of a new component at t> 900 days vs. post jet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

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

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

We do NOT claim re-brightening!

Cumulative statistical significance of the excess of 3.5-4.3σ (Gaussian equivalent)



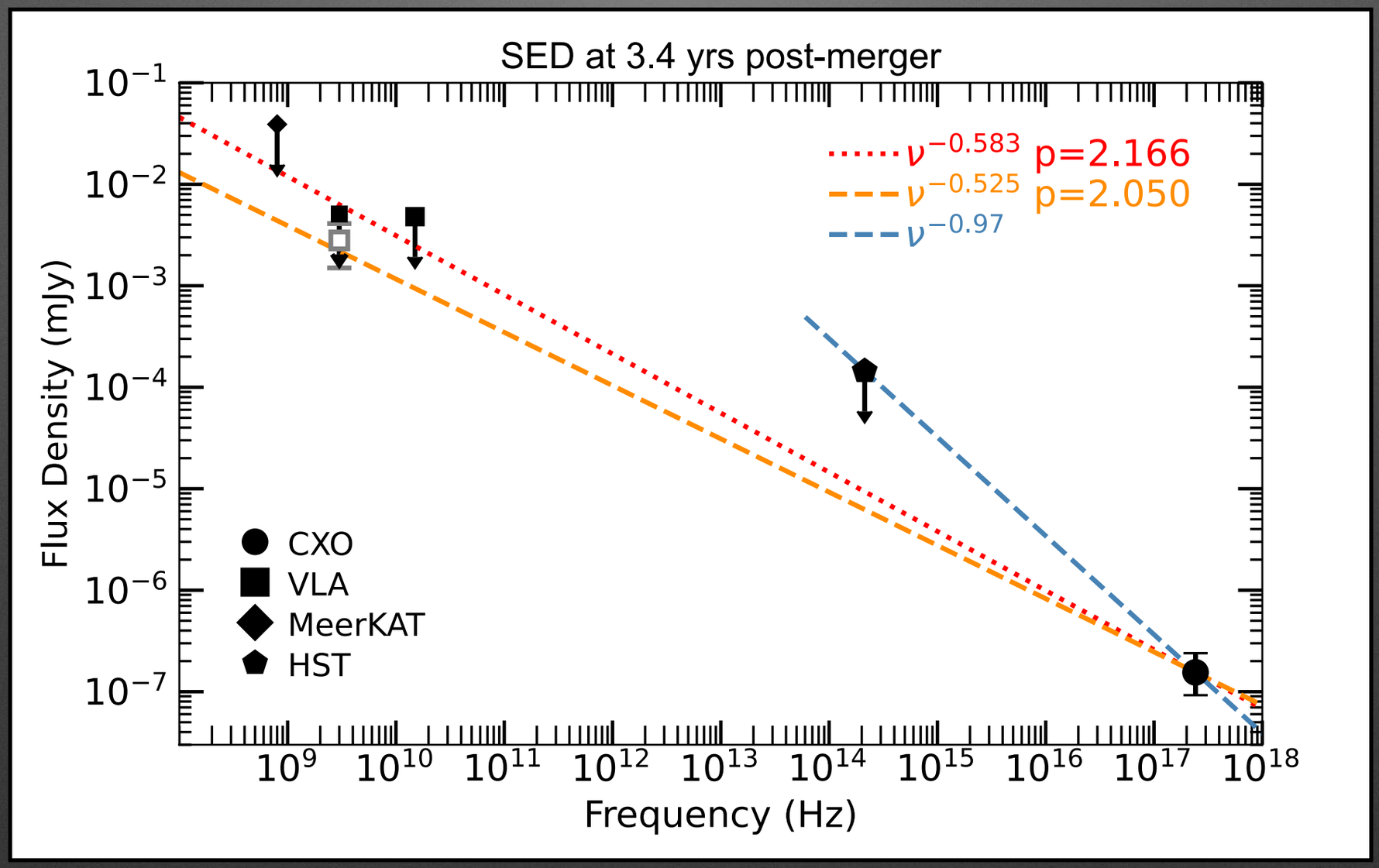
Hajela, Margutti, Bright et al., 2021

...in any case: Time will tell

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

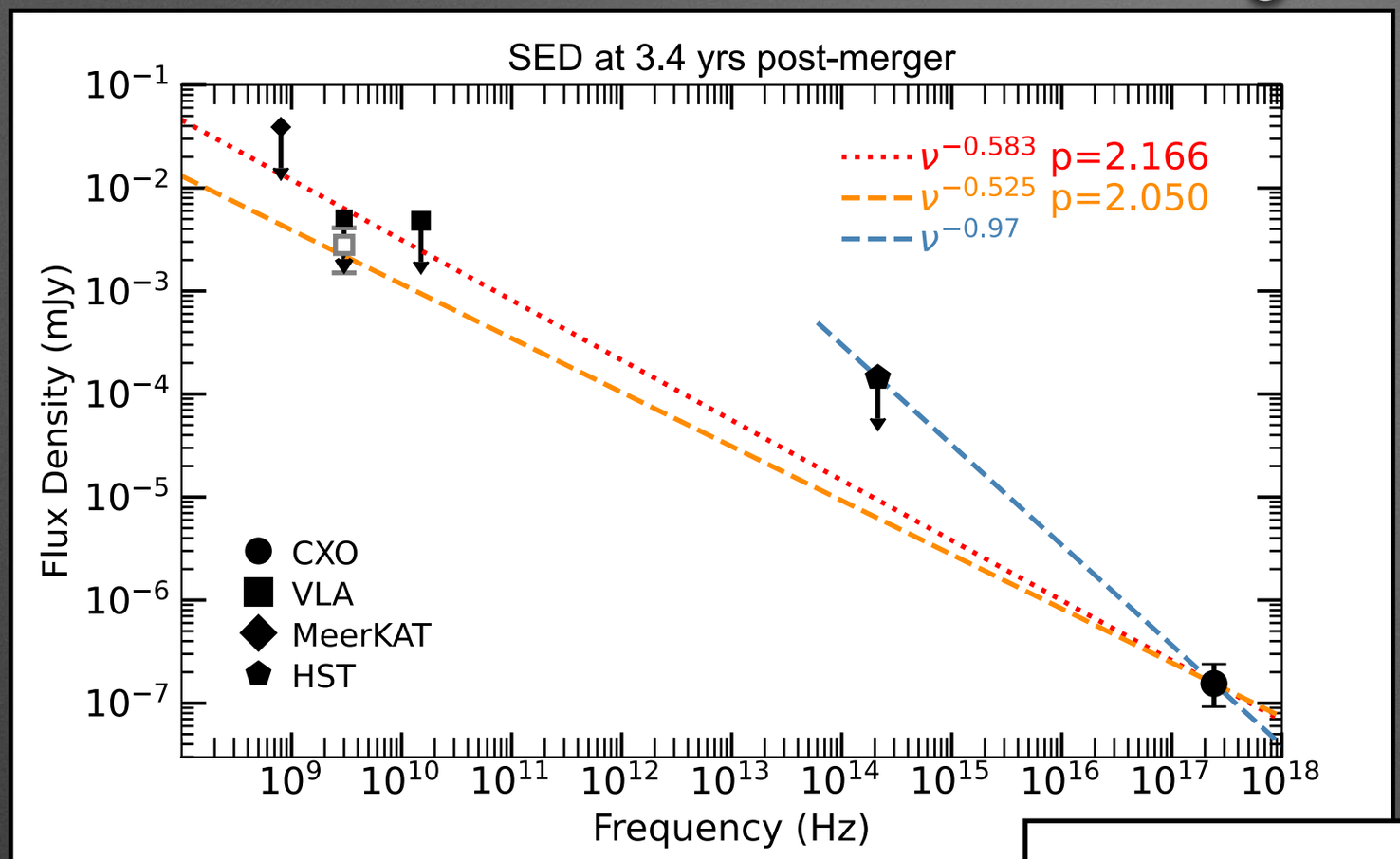
our data are PUBLIC

Broad-band SED at 3.5 yrs since NS merger



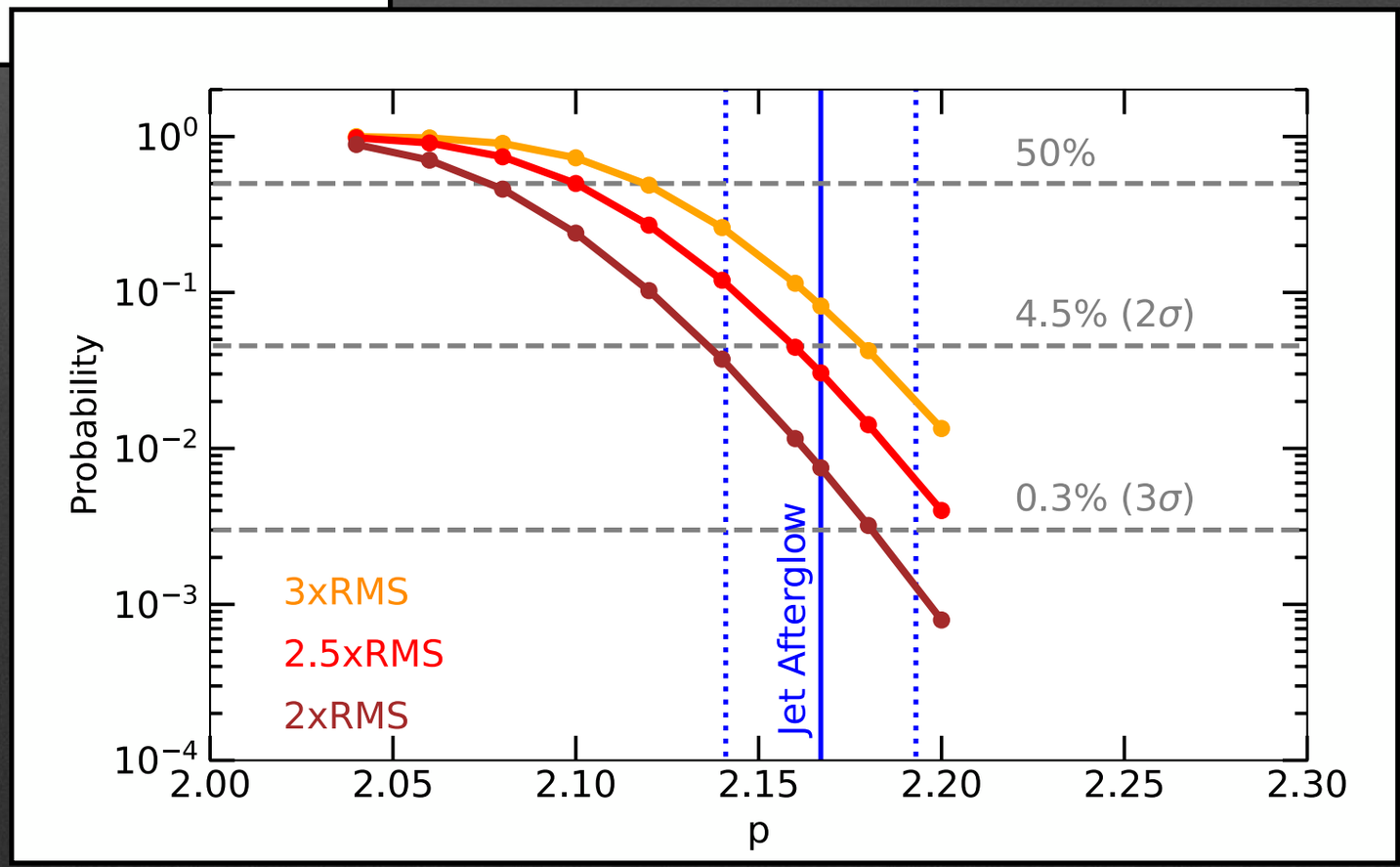
Hajela, Margutti, Bright et al., 2021

Broad-band SED at 3.5 yrs since NS merger



Hajela, Margutti, Bright et al., 2021

Suggestive of Hardening of the spectrum at the level of >92% c.l.



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

This is Gold

KN afterglow shock

X-rays

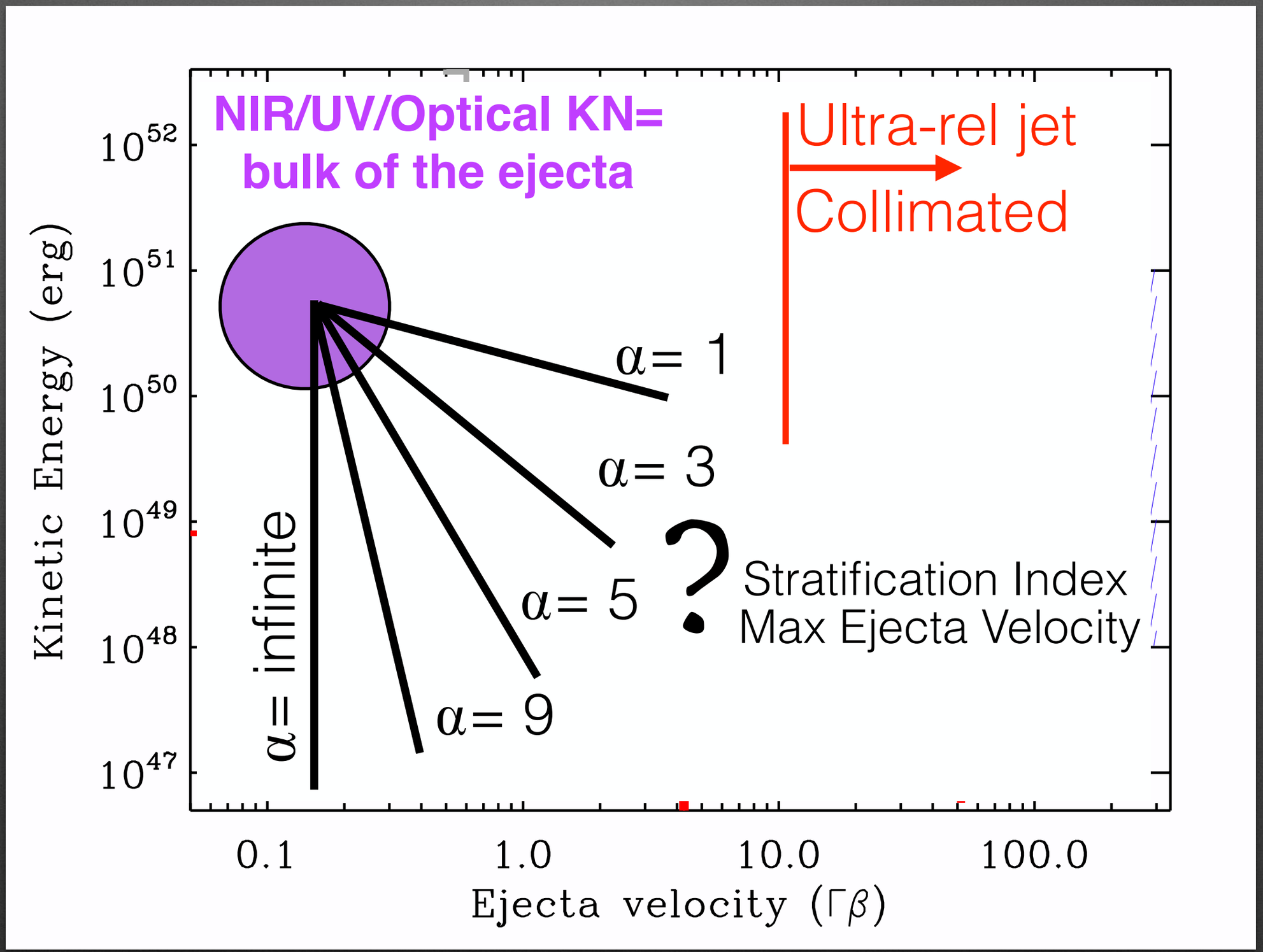
Radio

Blue KN

Red KN

NSF/LIGO/Sonoma State University/A. Simonnet

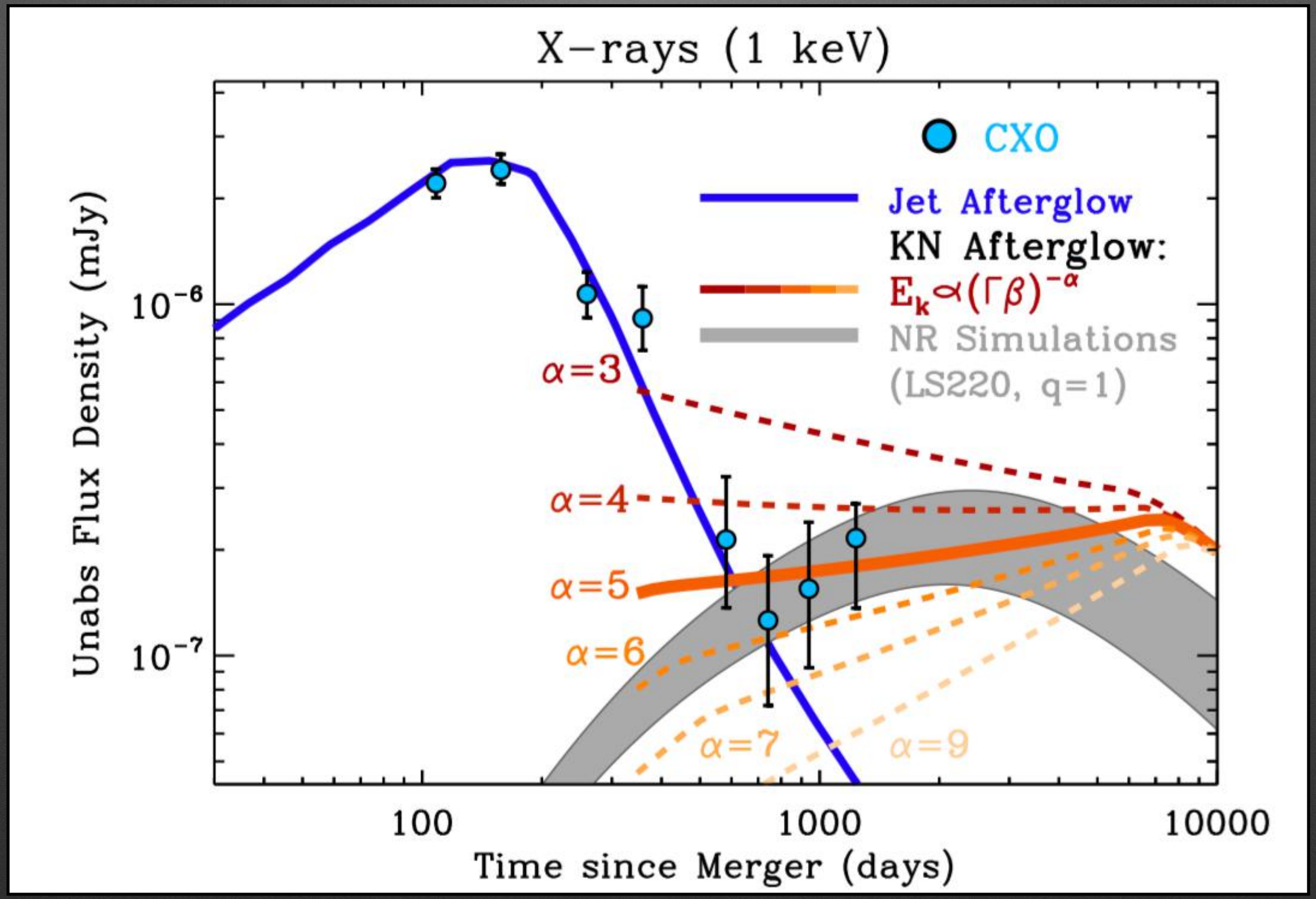
Energy Partitioning $E(\Gamma\beta)\sim(\Gamma\beta)^{-\alpha}$



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

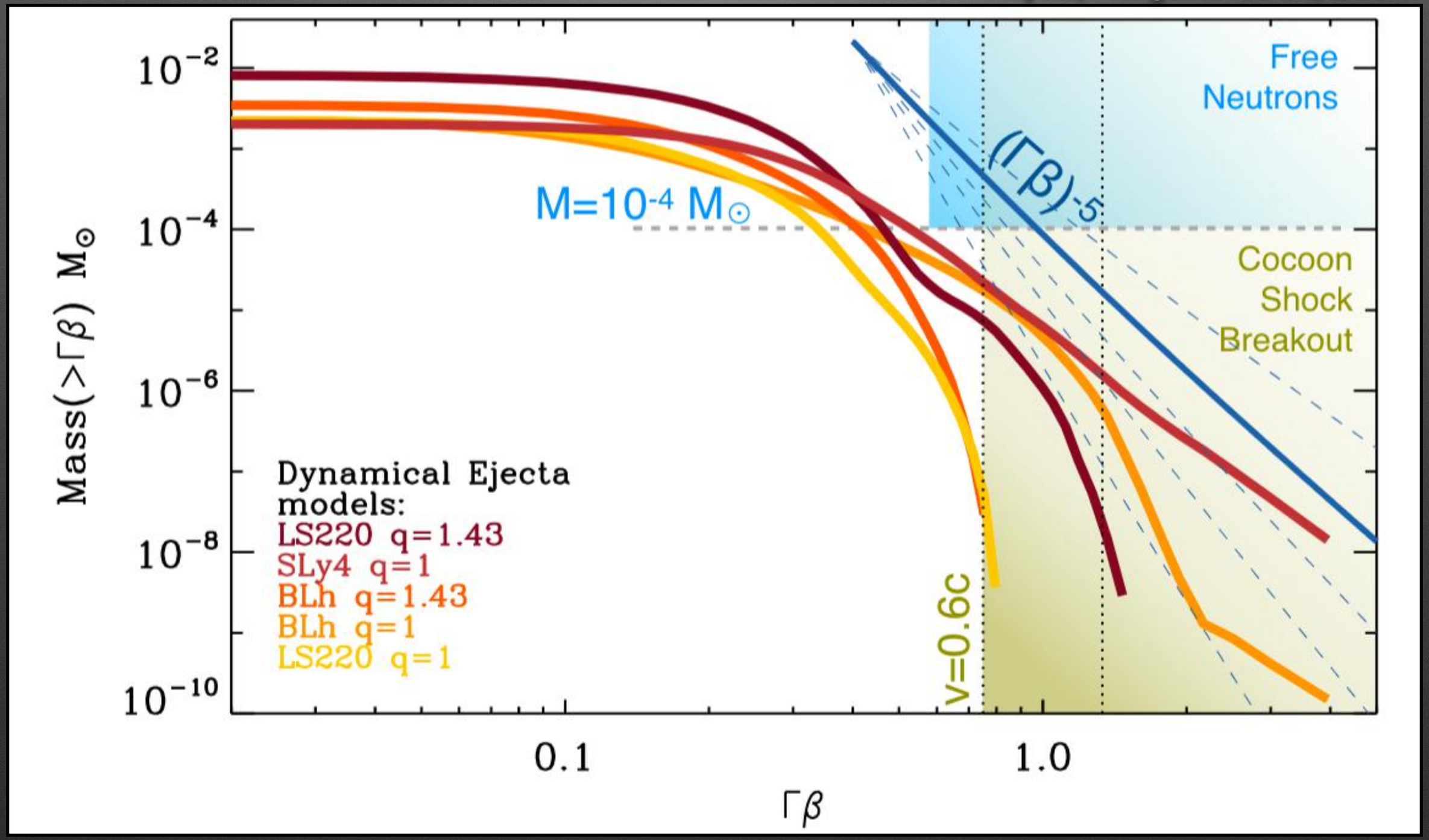


Hajela, Margutti, Bright et al., 2021

Models by: Kathirgamaraju+2019; Nedora+2021

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

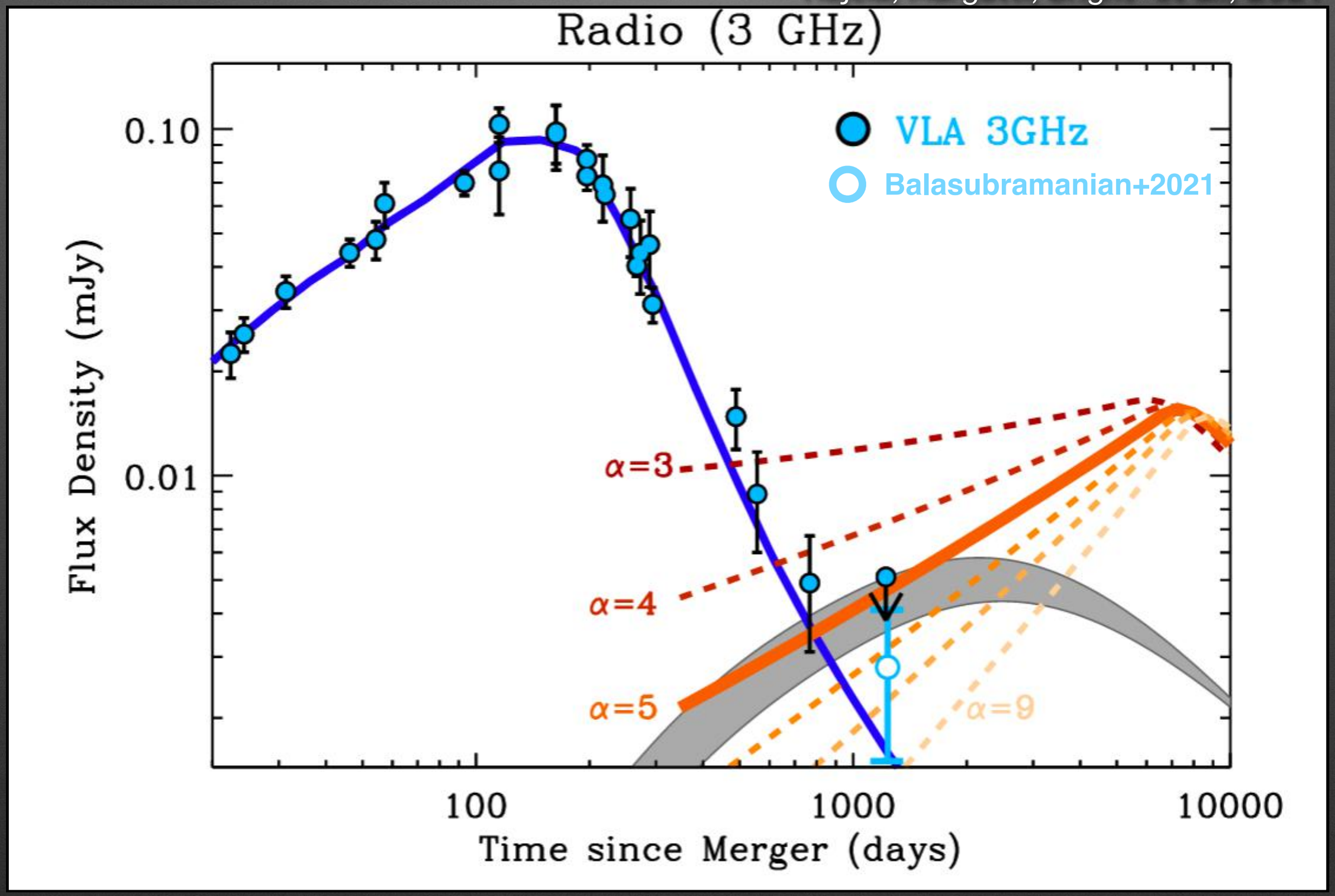
Hajela, Margutti et al., 2021



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

This is Gold

KN afterglow shock

X-rays

Radio

Blue KN

Red KN

NSF/LIGO/Sonoma State University/A. Simonnet

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

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

X-rays

Radio ?

Blue KN

Red KN

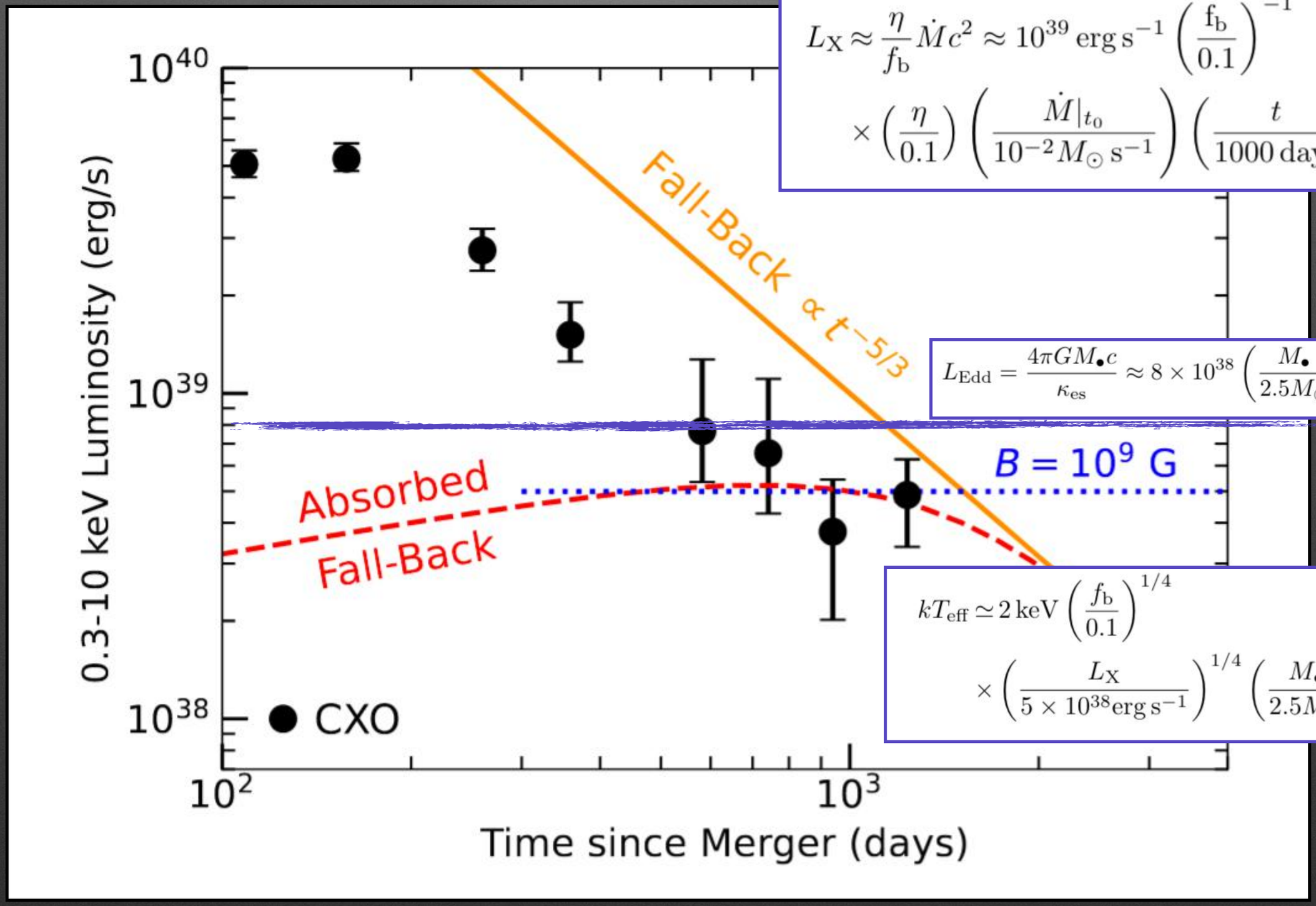
NSF/LIGO/Sonoma State University/A. Simonnet

Alternative idea: accretion on the BH remnant

Fall-back from accretion disk outflows:

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

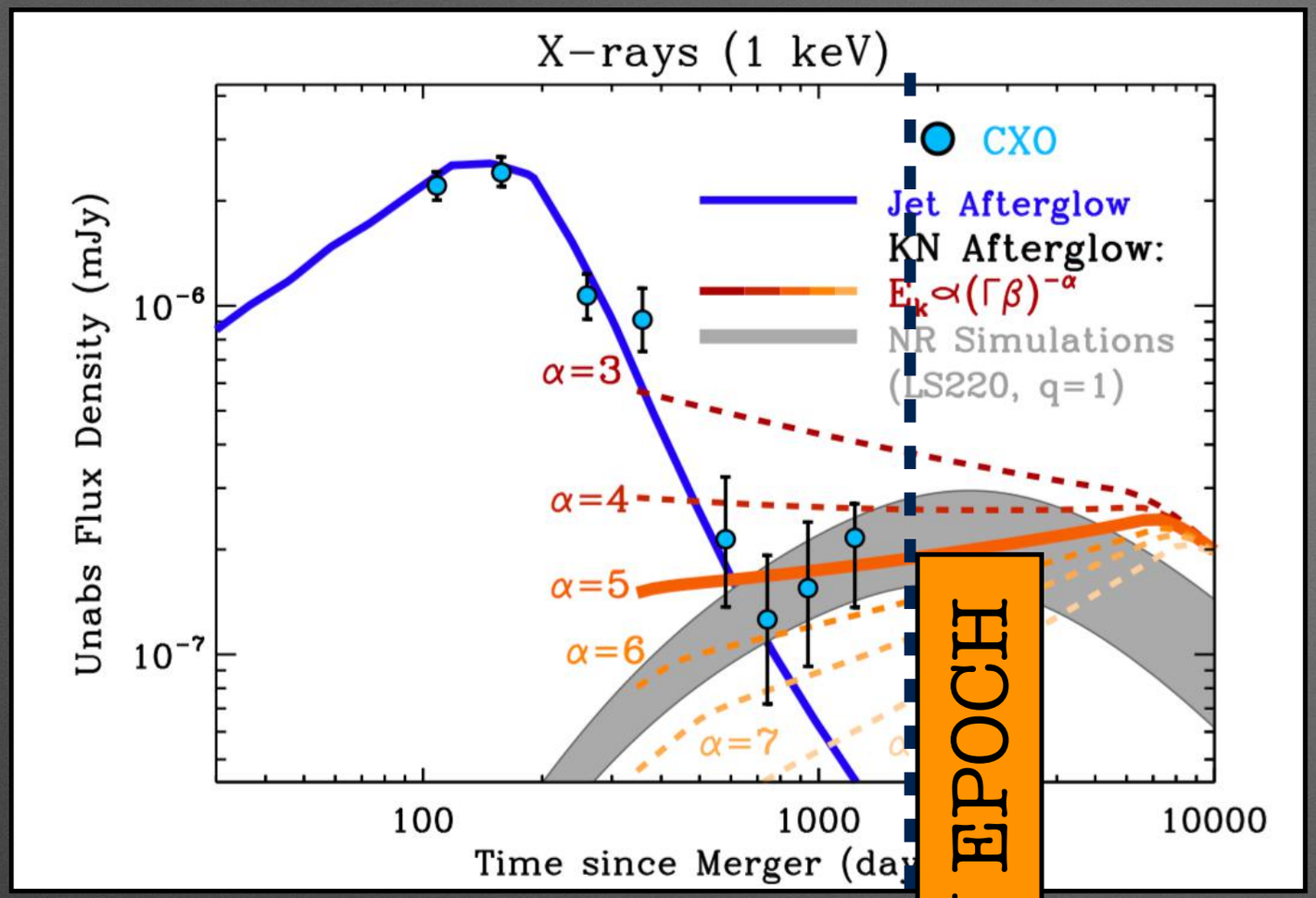
$$L_{\rm Edd} = \frac{4\pi G M_\bullet c}{\kappa_{\rm es}} \approx 8 \times 10^{38} \left(\frac{M_\bullet}{2.5 M_\odot}\right) {\rm erg\,s^{-1}}$$



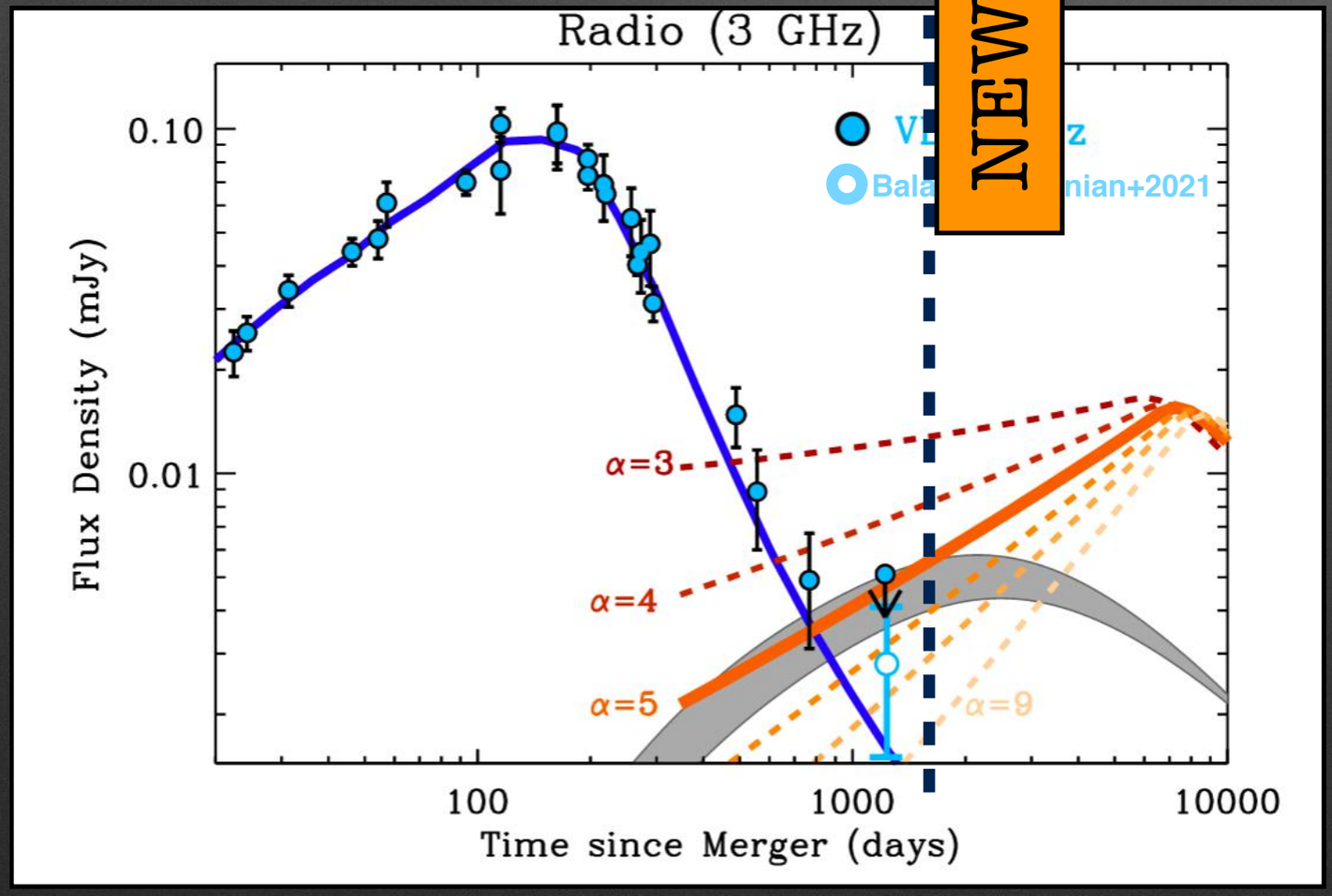
$$kT_{\rm eff} \simeq 2\,{\rm keV} \left(\frac{f_{\rm b}}{0.1}\right)^{1/4} \times \left(\frac{L_{\rm X}}{5 \times 10^{38} {\rm erg\,s^{-1}}}\right)^{1/4} \left(\frac{M_\bullet}{2.5 M_\odot}\right)^{-1/2}$$

Idea credit: Brian Metzger
(see Metzger & Fernandez 2021, Ishizaki+2021)

Hajela, Margutti, Bright et al., 2021



NEW EPOCH



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

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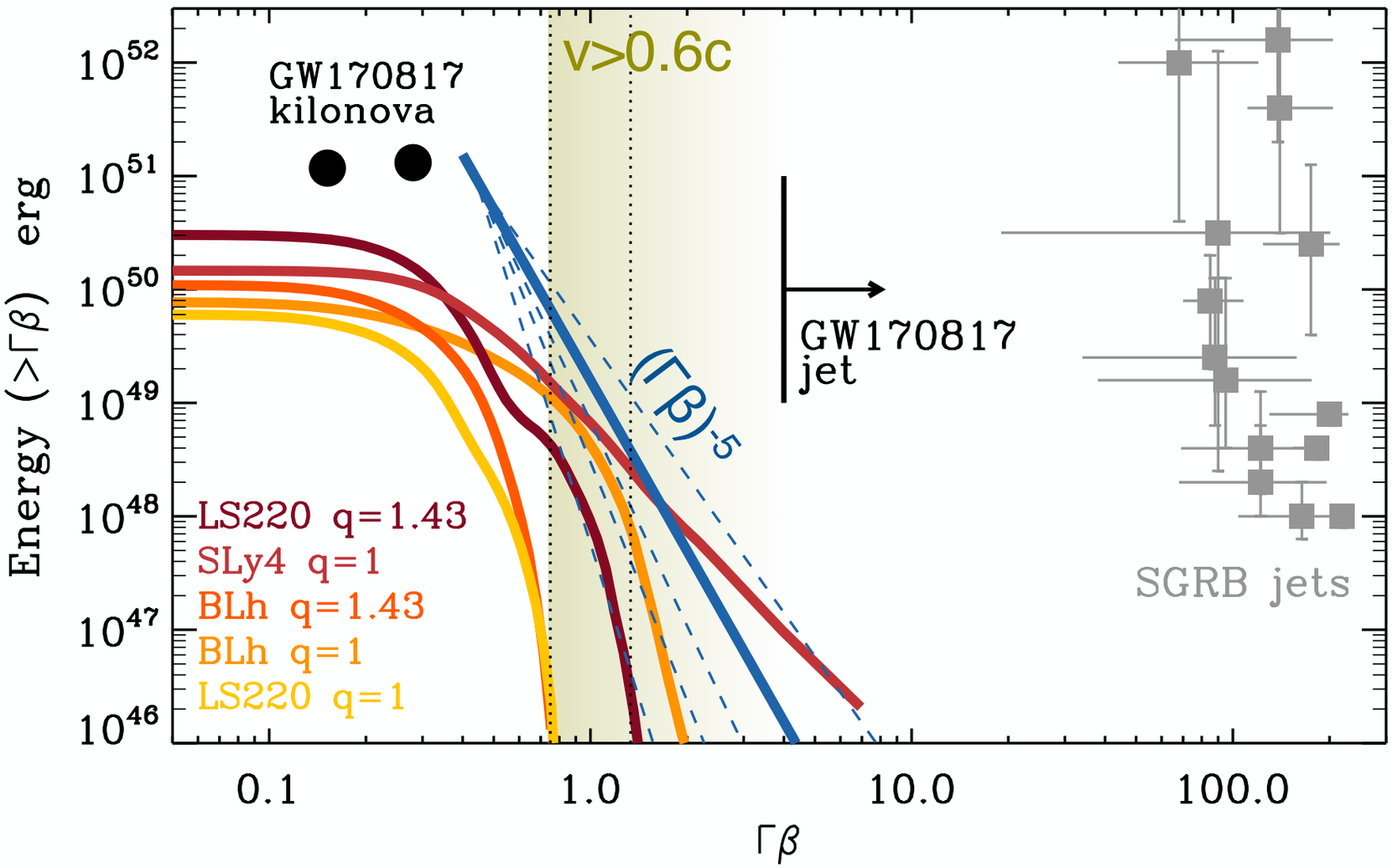
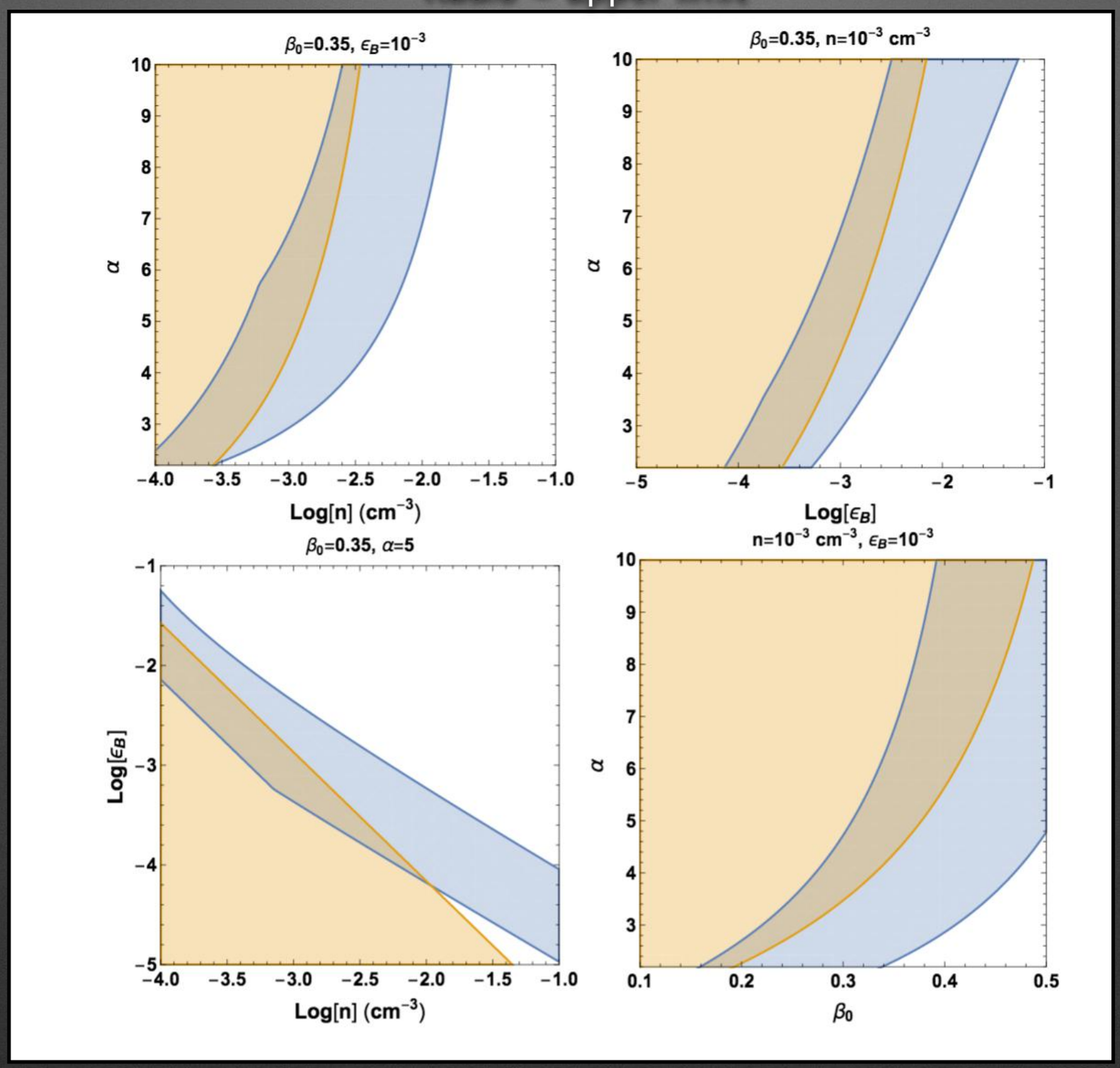

GW170817
kilonova
v>0.6c
GW170817
jet
SGRB jets
LS220 q=1.43
SLy4 q=1
BLh q=1.43
BLh q=1
LS220 q=1
(Γβ)-5
Energy (>Γβ) erg
Γβ
10^52
10^51
10^50
10^49
10^48
10^47
10^46
0.1
1.0
10.0
100.0

Radio = upper limit



Hajela, Margutti, Bright et al., 2021

Radio = measurement

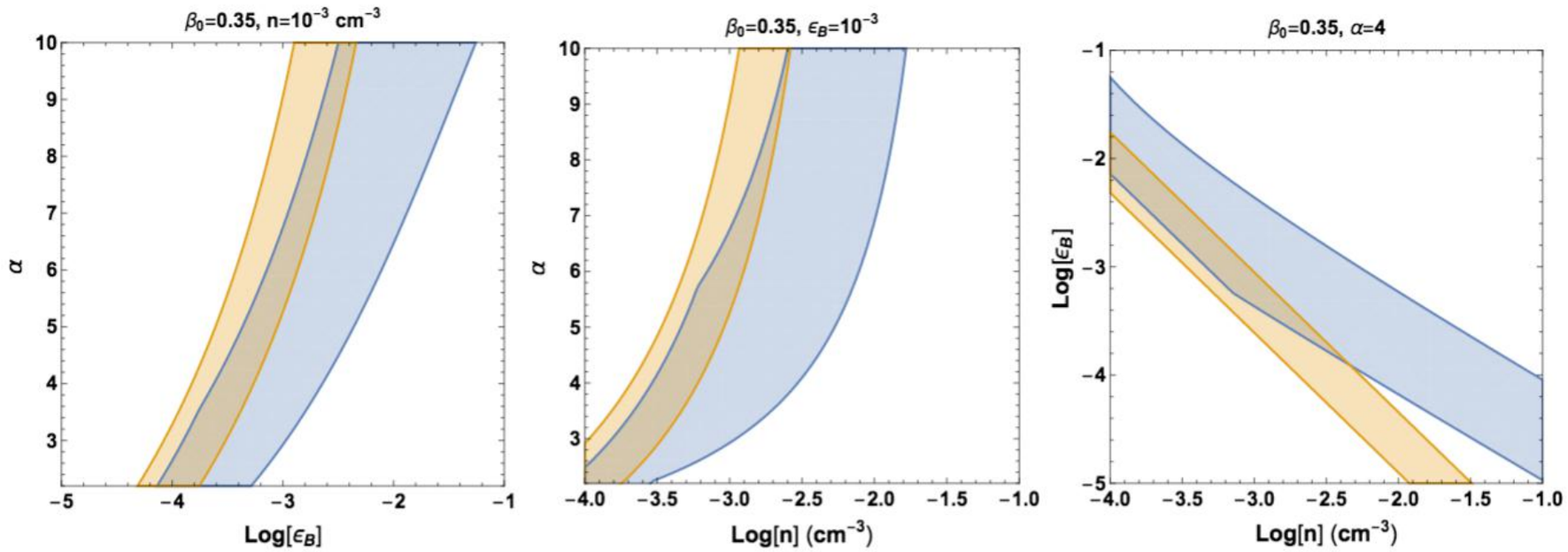


Figure 8. Kilonova afterglow parameter space with the same color scheme as Figure 7 where we used the peak pixel flux within one synthesized beam at 3 GHz from Balasubramanian et al. 2021 ($F_\nu = 2.8 \pm 1.3\,\mu$Jy) as a constraint on the radio emission from the kilonova. **As in Figure 7, we assume** $E_{\rm KN} = 10^{51}$ **erg,** $\epsilon_{\rm e} = 0.1$**, and** $p = 2.05$**.** Our conclusions remain unchanged.

Hajela, Margutti, Bright et al., 2021

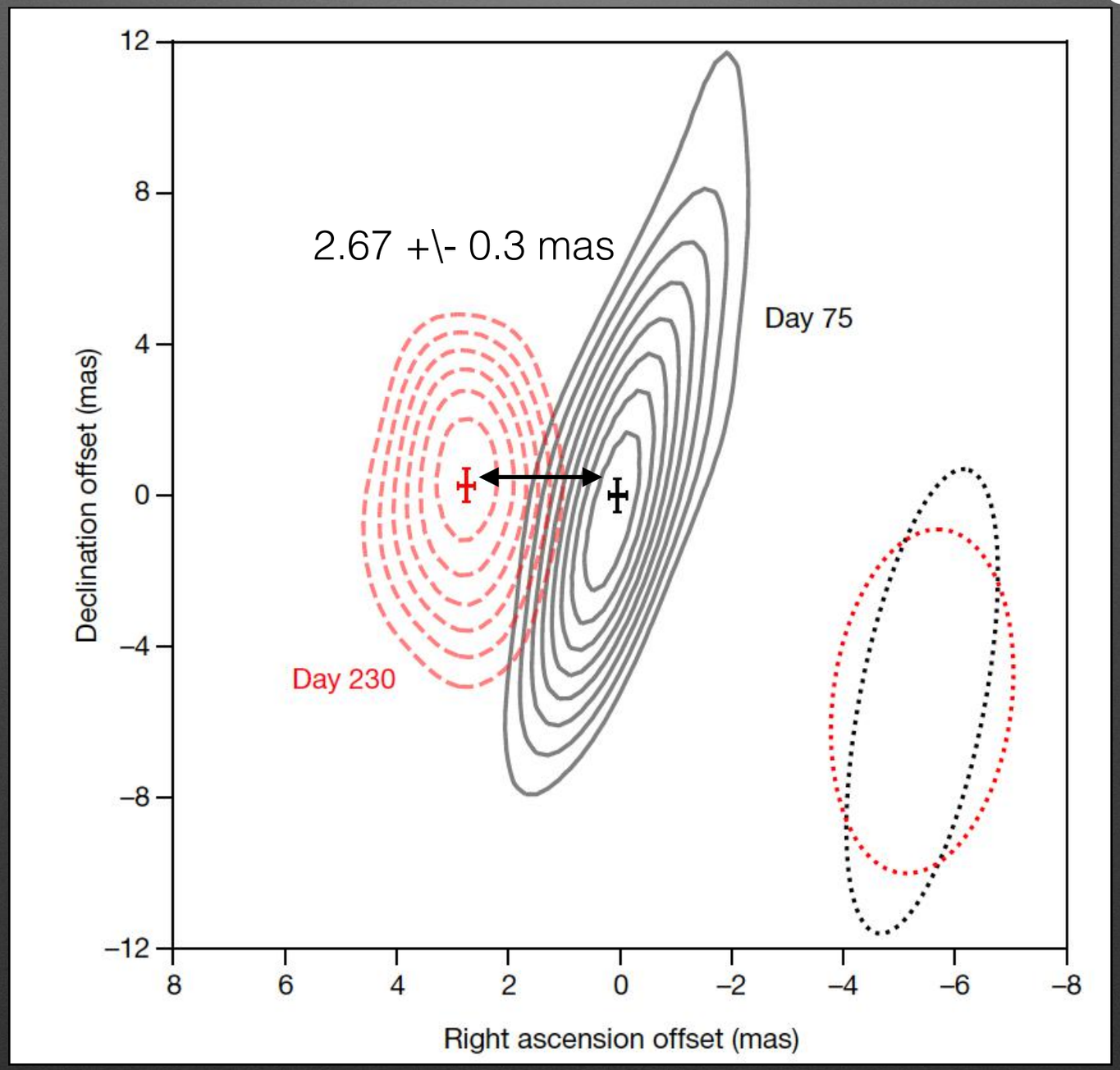
Displacement:

- $(\theta_{obs} - \theta_{jet}) \approx 1/\Gamma \approx 0.25$

Γ(@peak)≈4

Γ_0>4

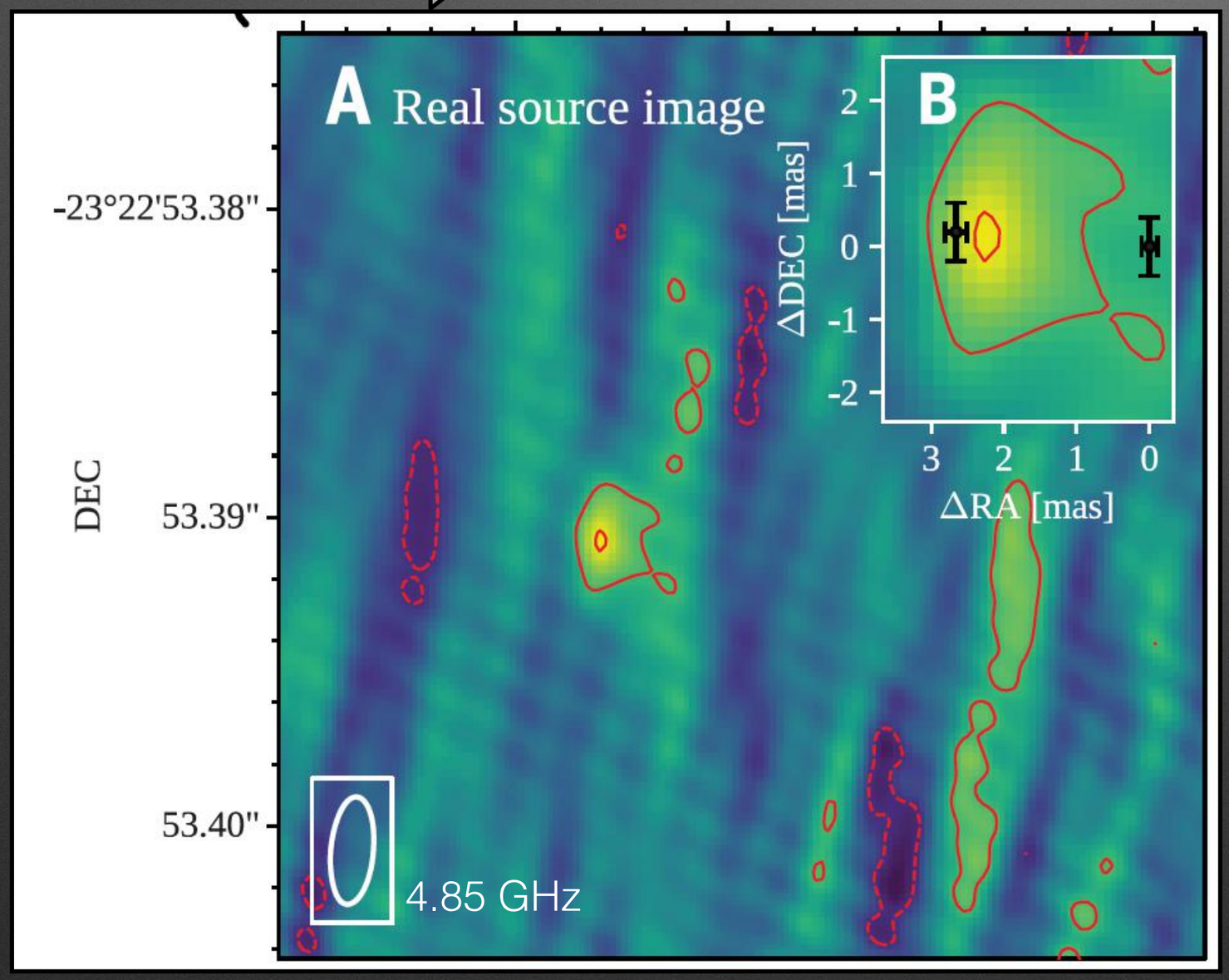
geometry



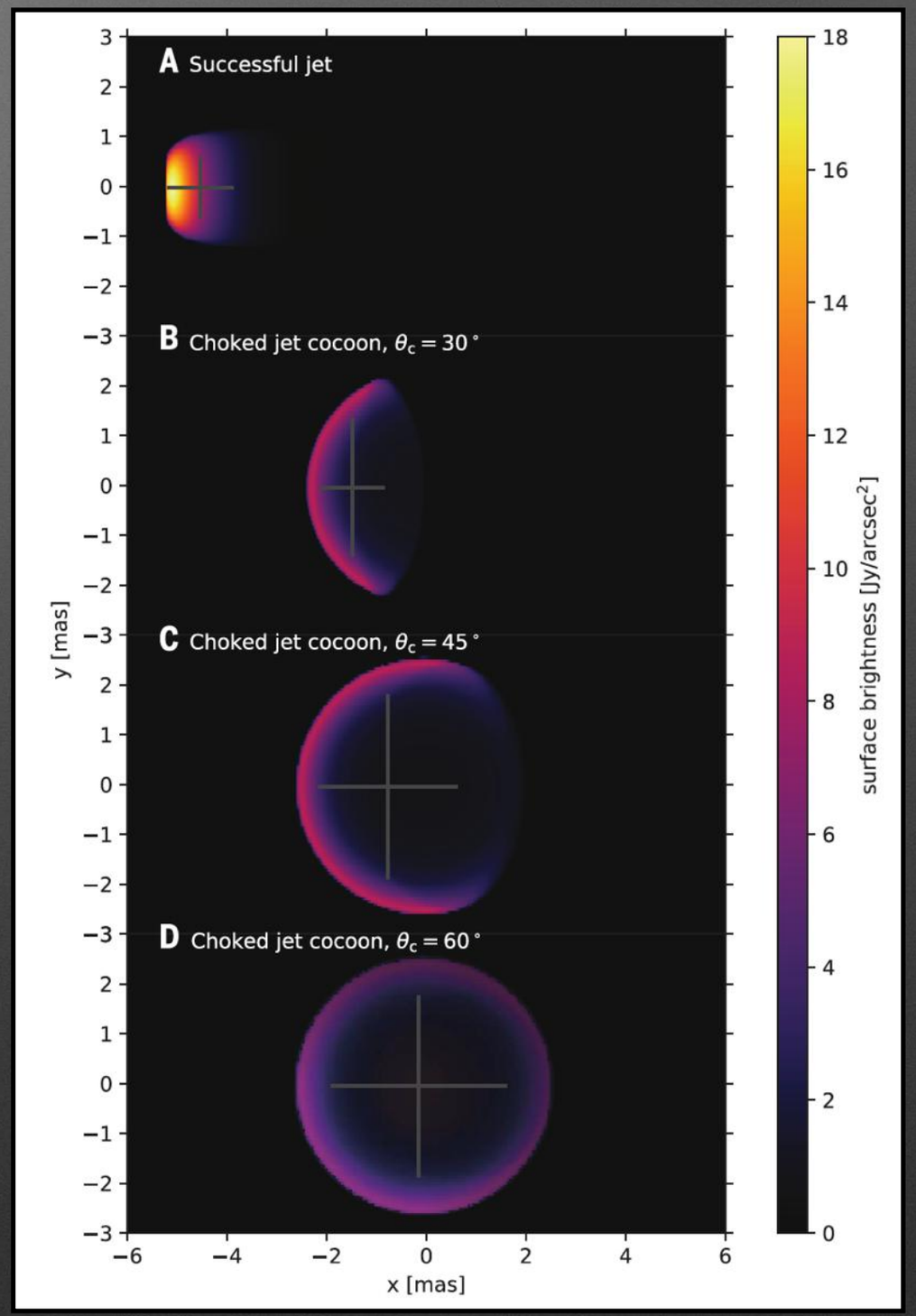
Mooley+2018

Apparent Source Size < 2.5 mas
@t=207 days

geometry



Ghirlanda+2019



Ghirlanda+2019