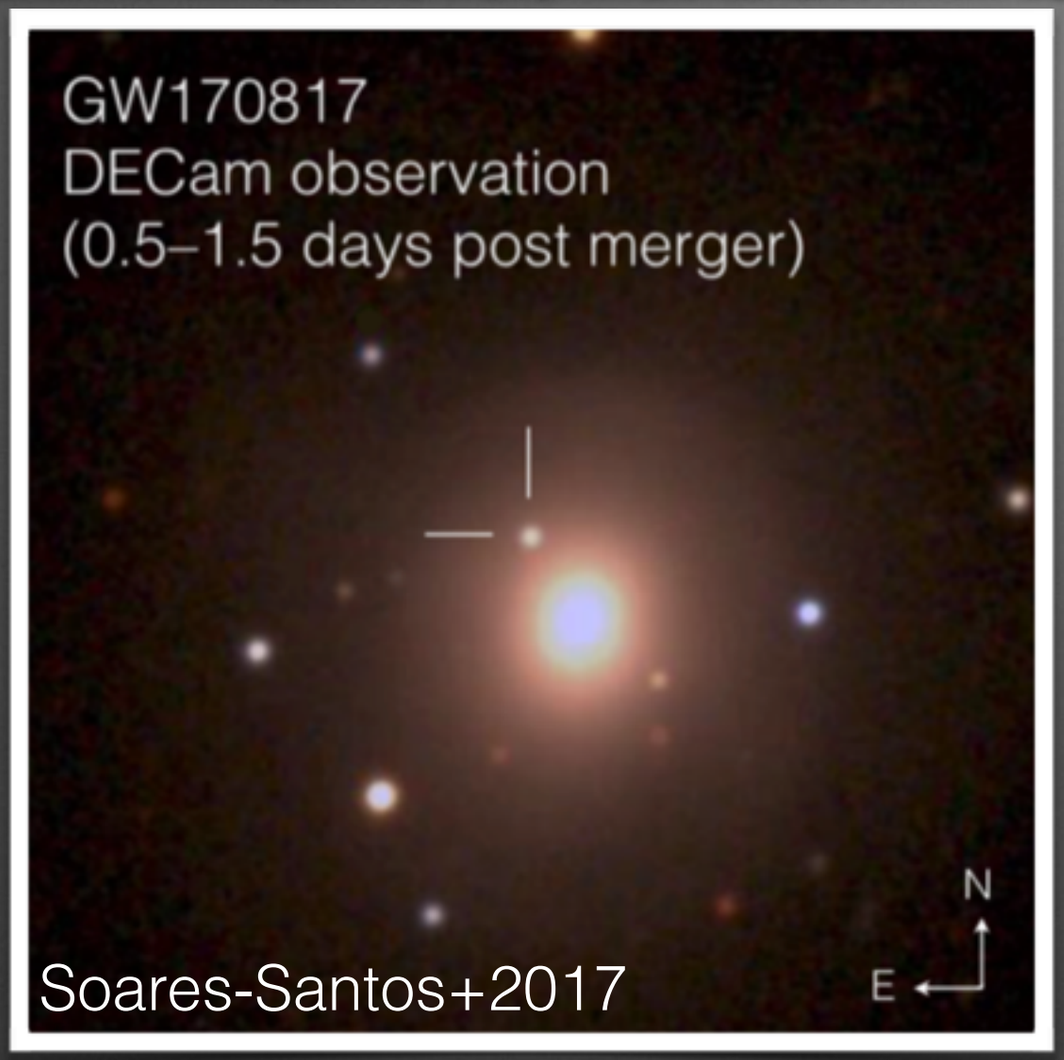
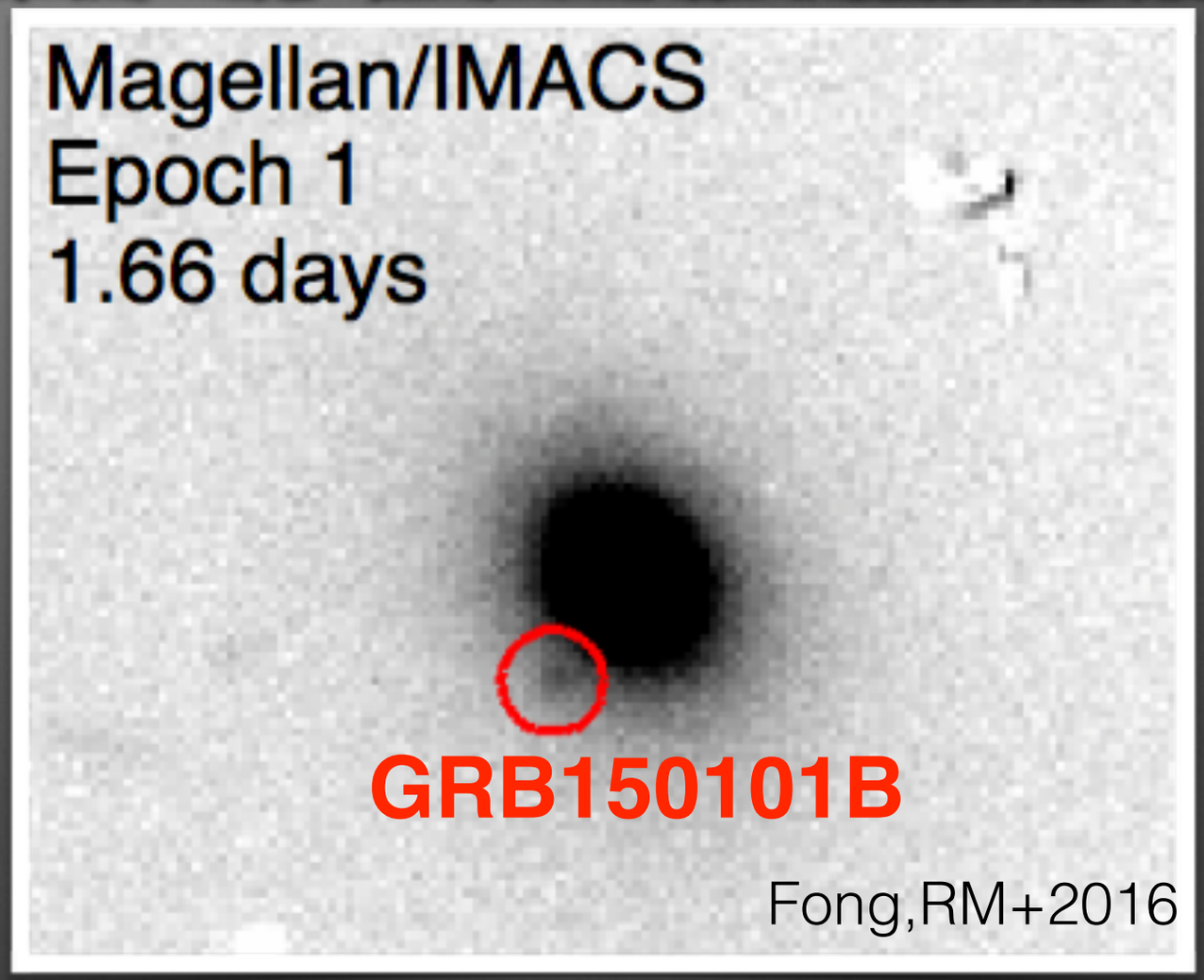
EM follow up of GWs: Updates, Open questions and Future observations





GW170817... 2yrs afterwards....

Raffaella Margutti

NORTHWESTERN UNIVERSITY

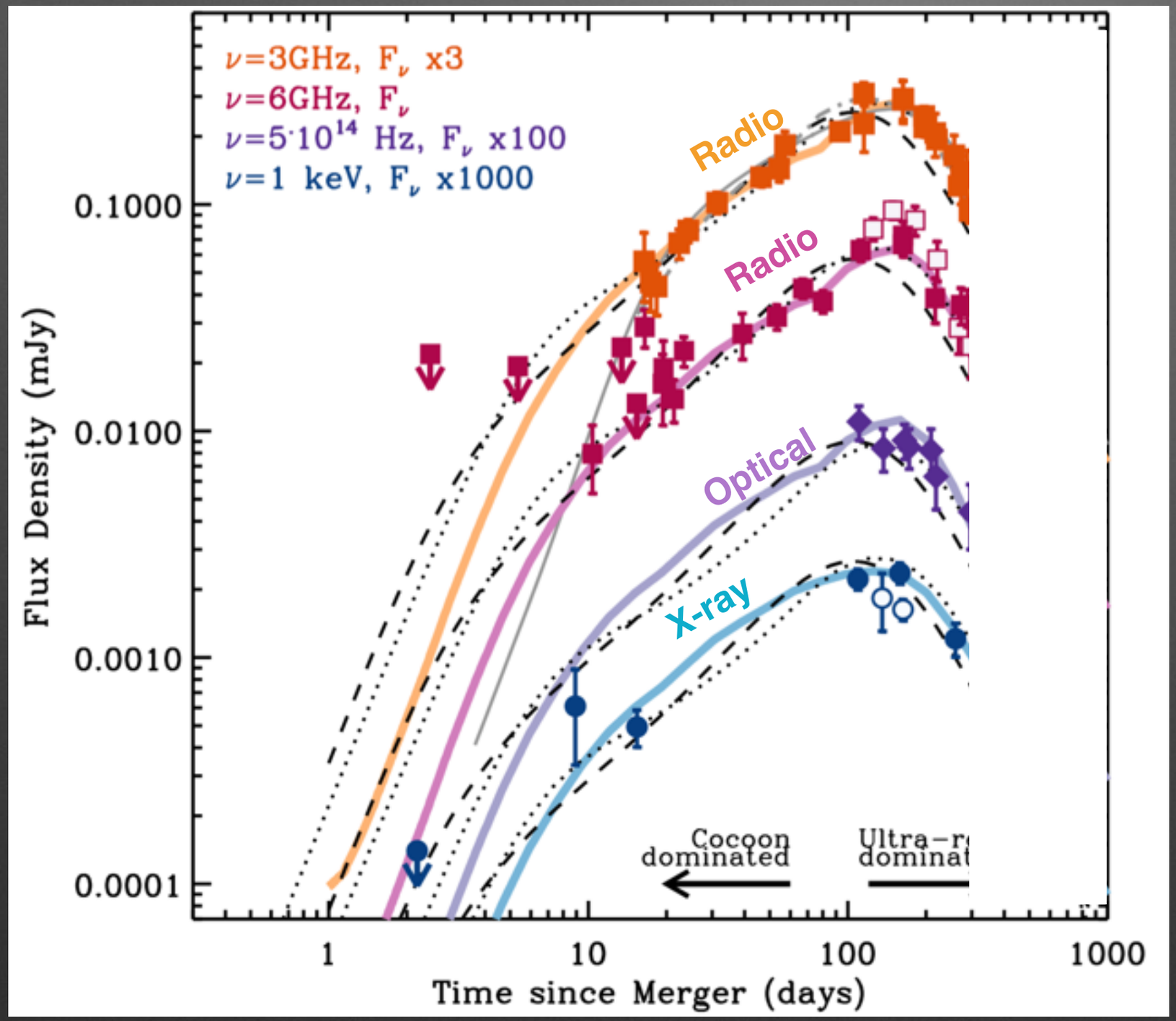
CIERA

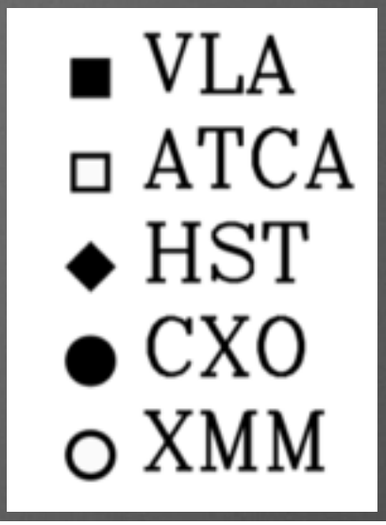
Update on EM follow up in O3:

No convincing EM counterpart to a GW event has been publicly announced during LIGO/O3

GW170817: 2yrs of non-thermal emission

Hajela+19

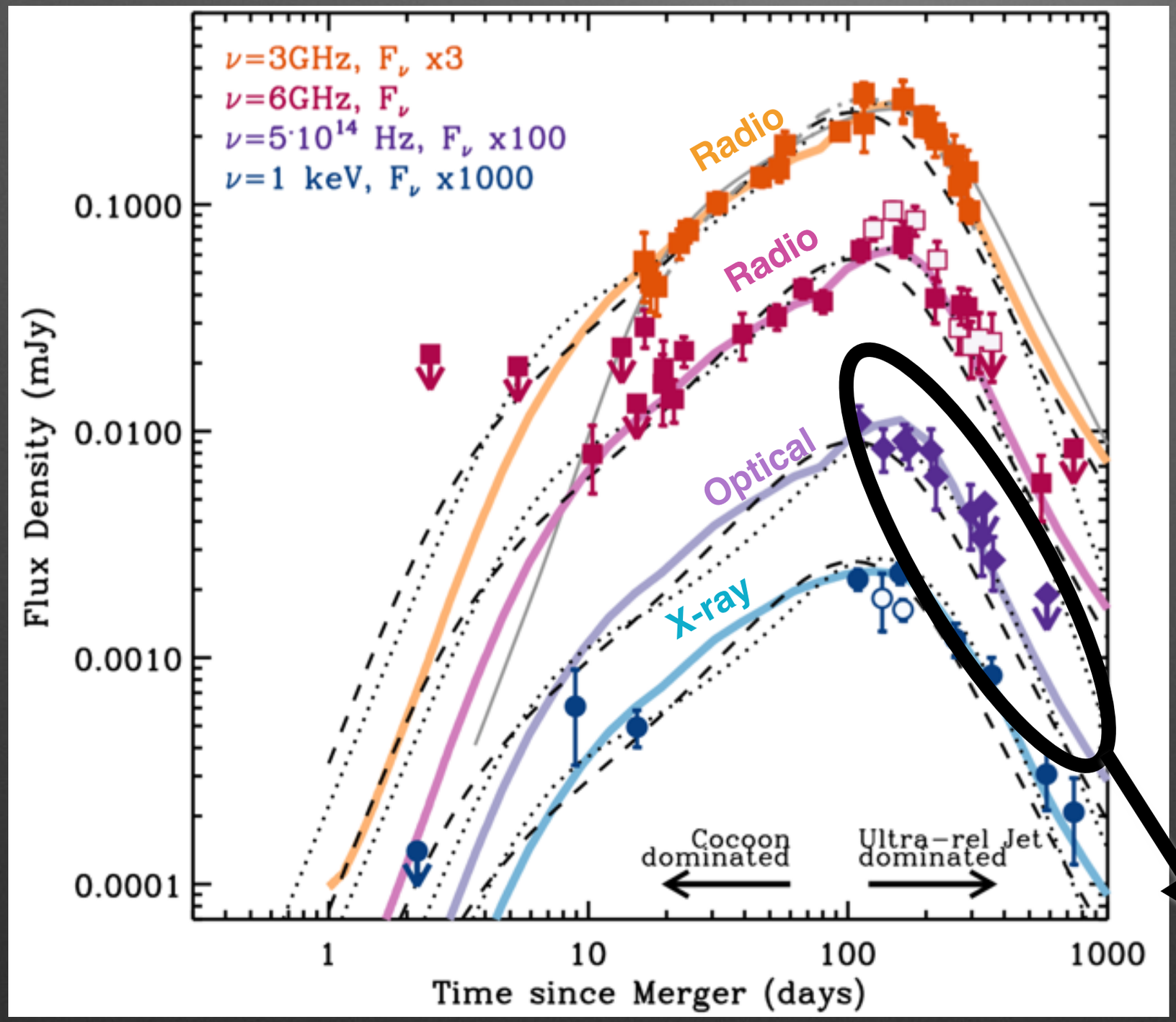




Margutti & Chornock in prep

GW170817: 2yrs of non-thermal emission

Hajela+19



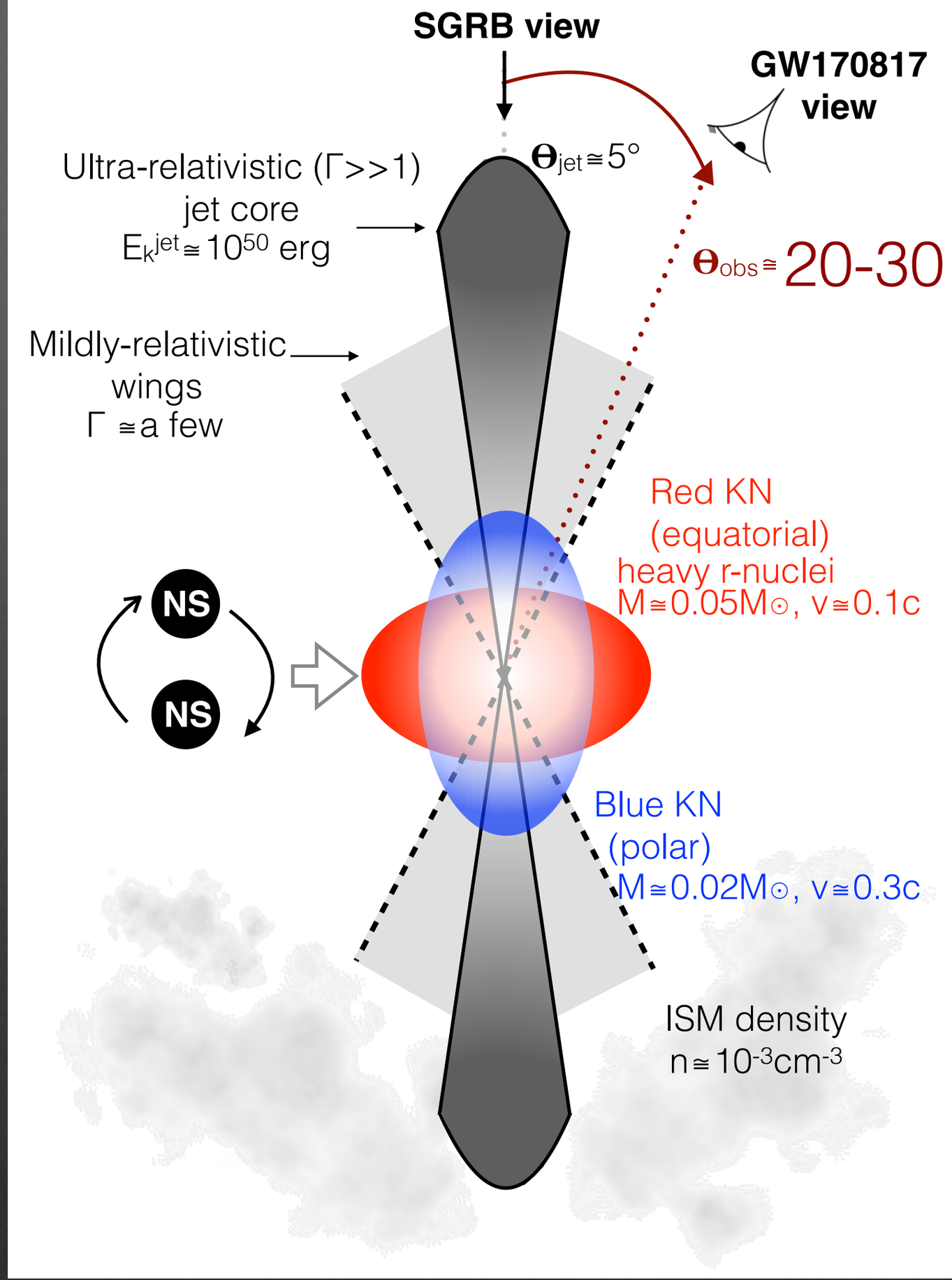
- VLA
- ATCA
- HST
- CXO
- XMM

- Hajela+19
- Ghirlanda+19
- Lazzati+19
- Kathirgamaraju+19
- Mooley/Gottlieb+19

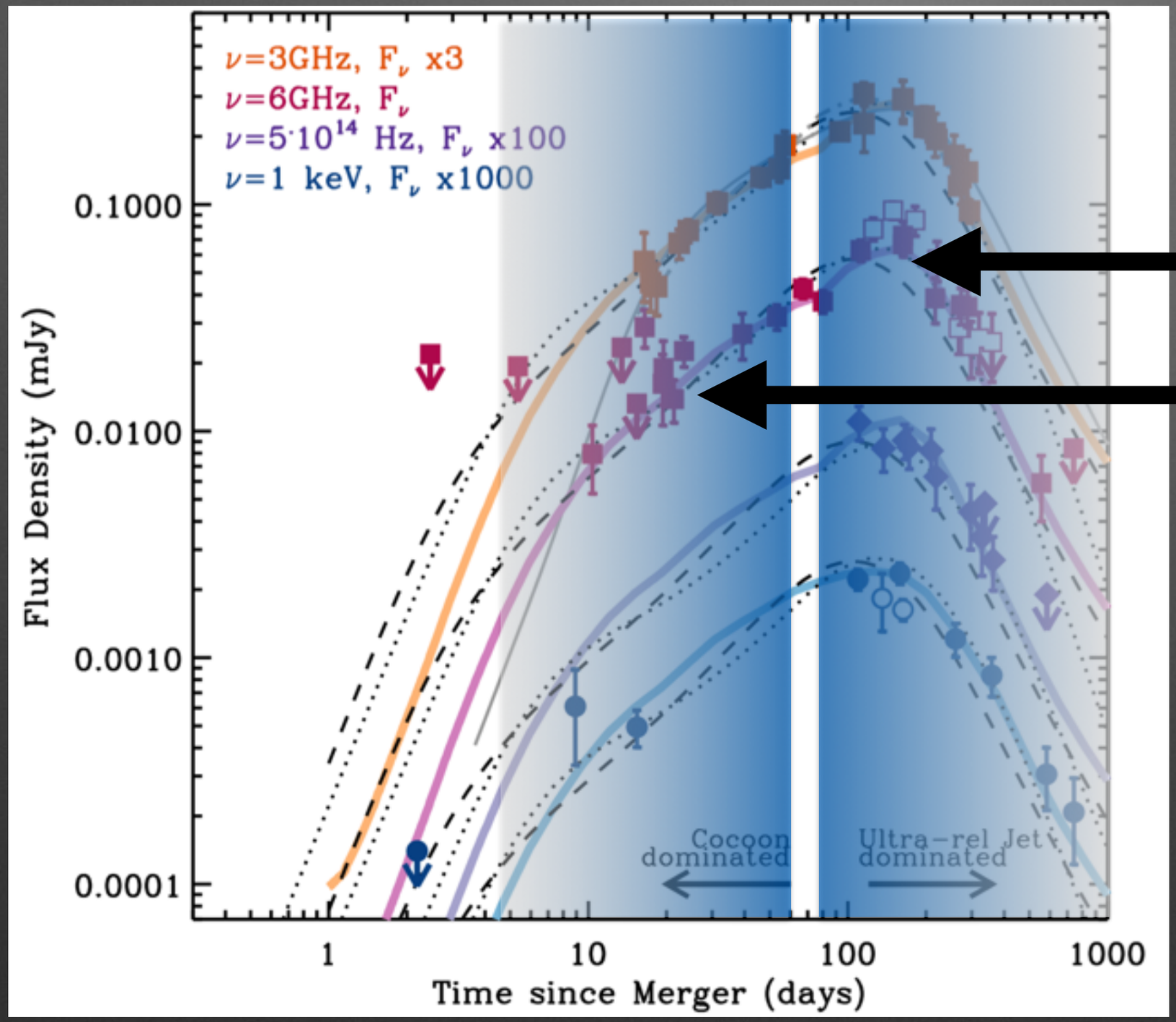
HST afterglow light-curve

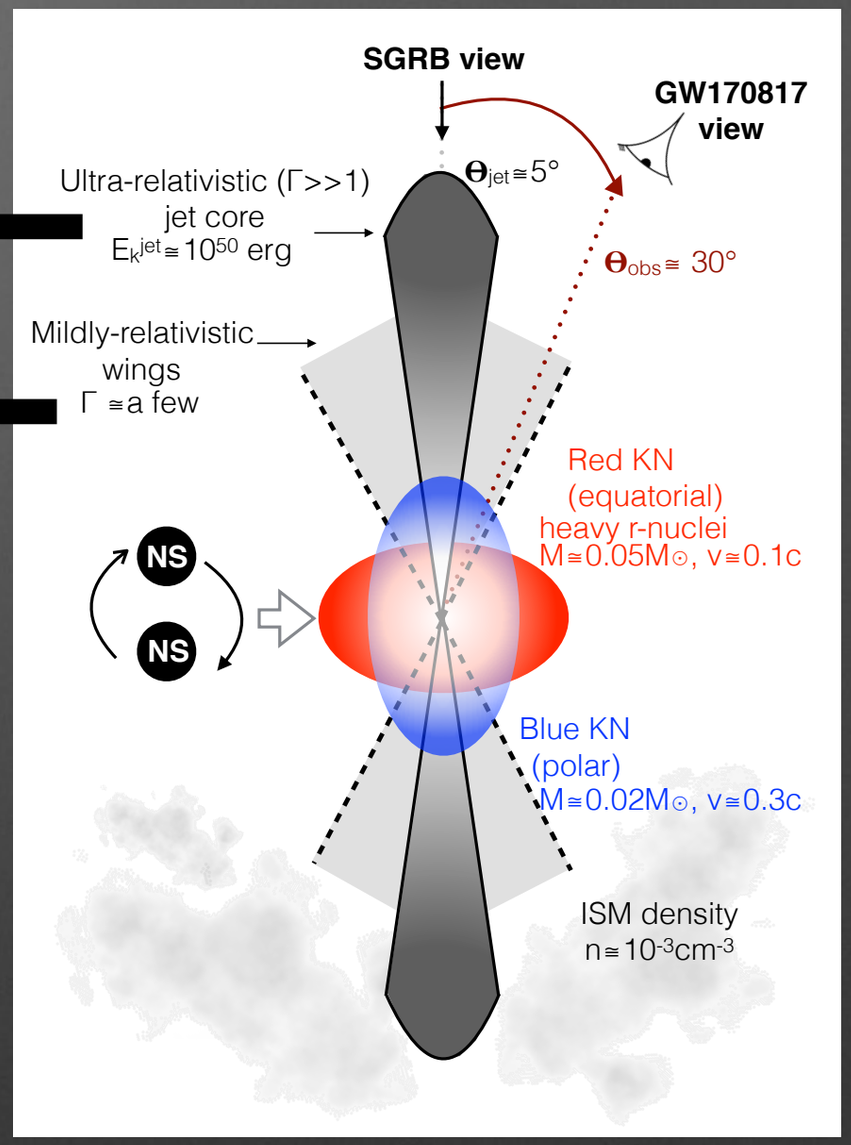
Lyman+19 Fong+19

Margutti & Chornock in prep

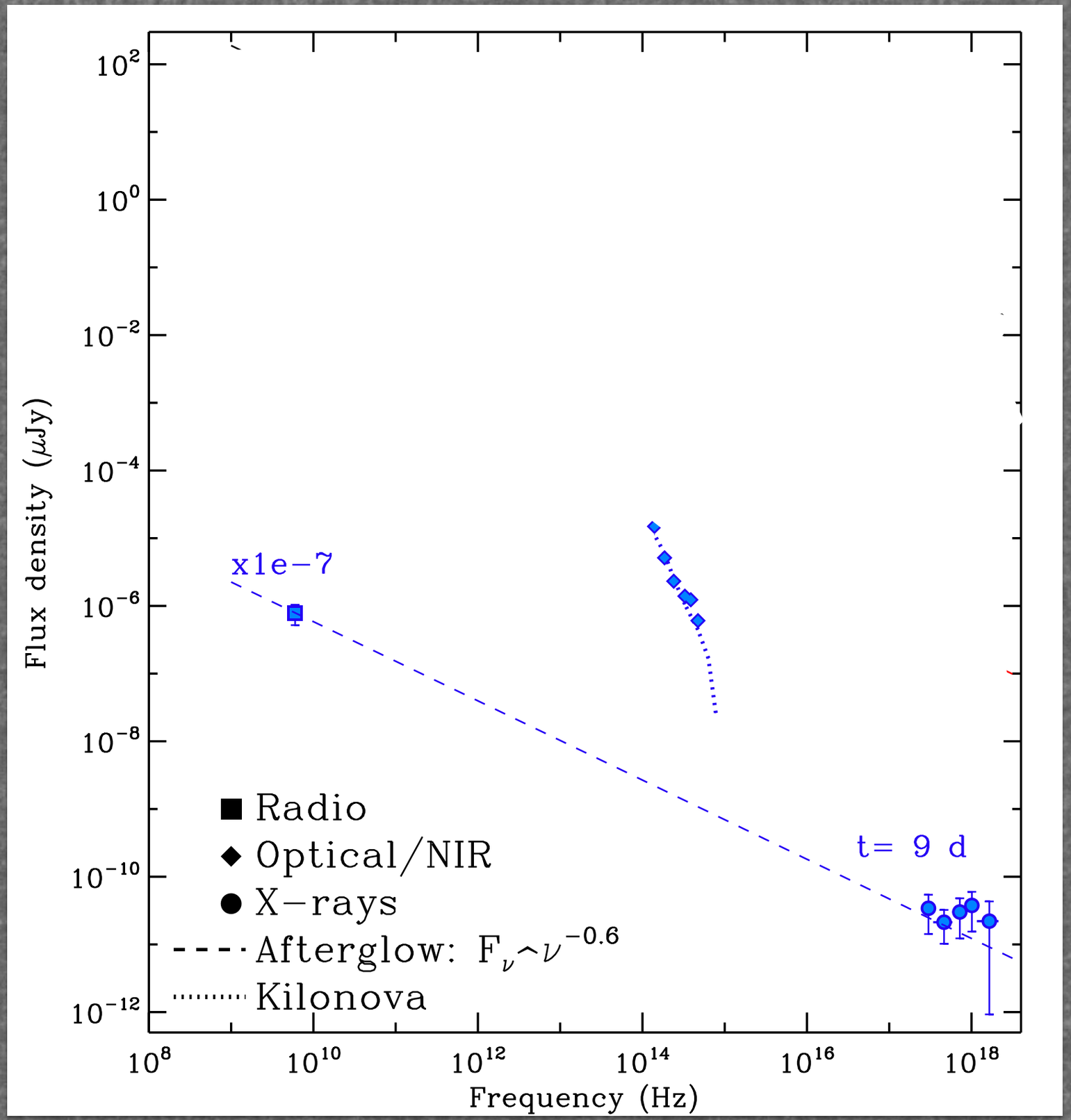


Margutti & Chornock in prep


ν=3GHz, F_ν x3
ν=6GHz, F_ν
ν=5·10^14 Hz, F_ν x100
ν=1 keV, F_ν x1000
0.1000
0.0100
0.0010
0.0001
Flux Density (mJy)
Cocoon dominated
Ultra-rel Jet dominated
1
10
100
1000
Time since Merger (days)

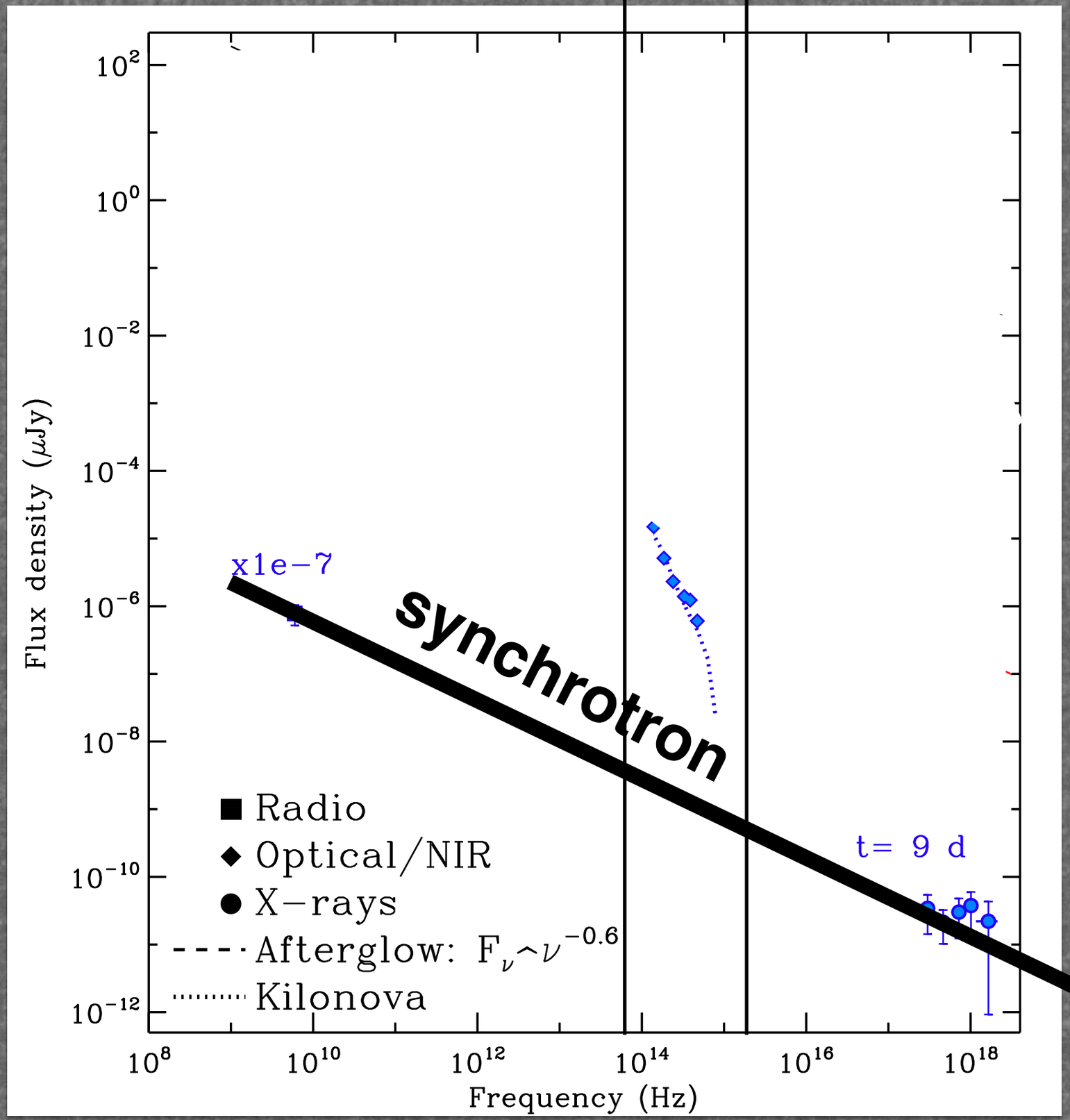

SGRB view
GW170817 view
Θjet≅5°
Ultra-relativistic (Γ>>1) jet core
Ek^jet≅10^50 erg
Θobs≅ 30°
Mildly-relativistic wings
Γ ≅a few
Red KN (equatorial)
heavy r-nuclei
M≅0.05M⊙, v≅0.1c
NS
NS
Blue KN (polar)
M≅0.02M⊙, v≅0.3c
ISM density
n≅10^-3cm^-3

Radio X-rays



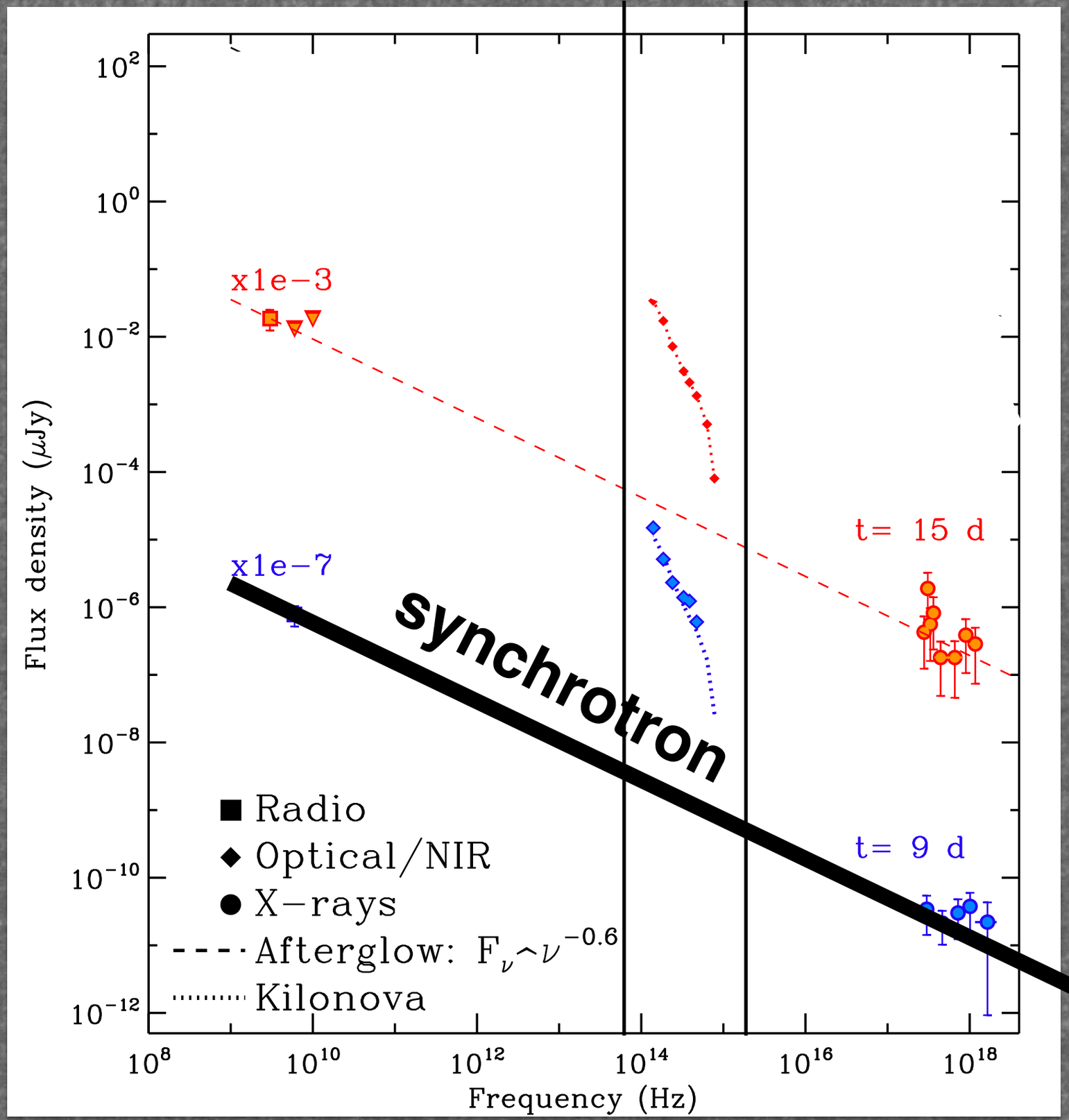
Margutti et al. 2018

Radio **Thermal KN** X-rays



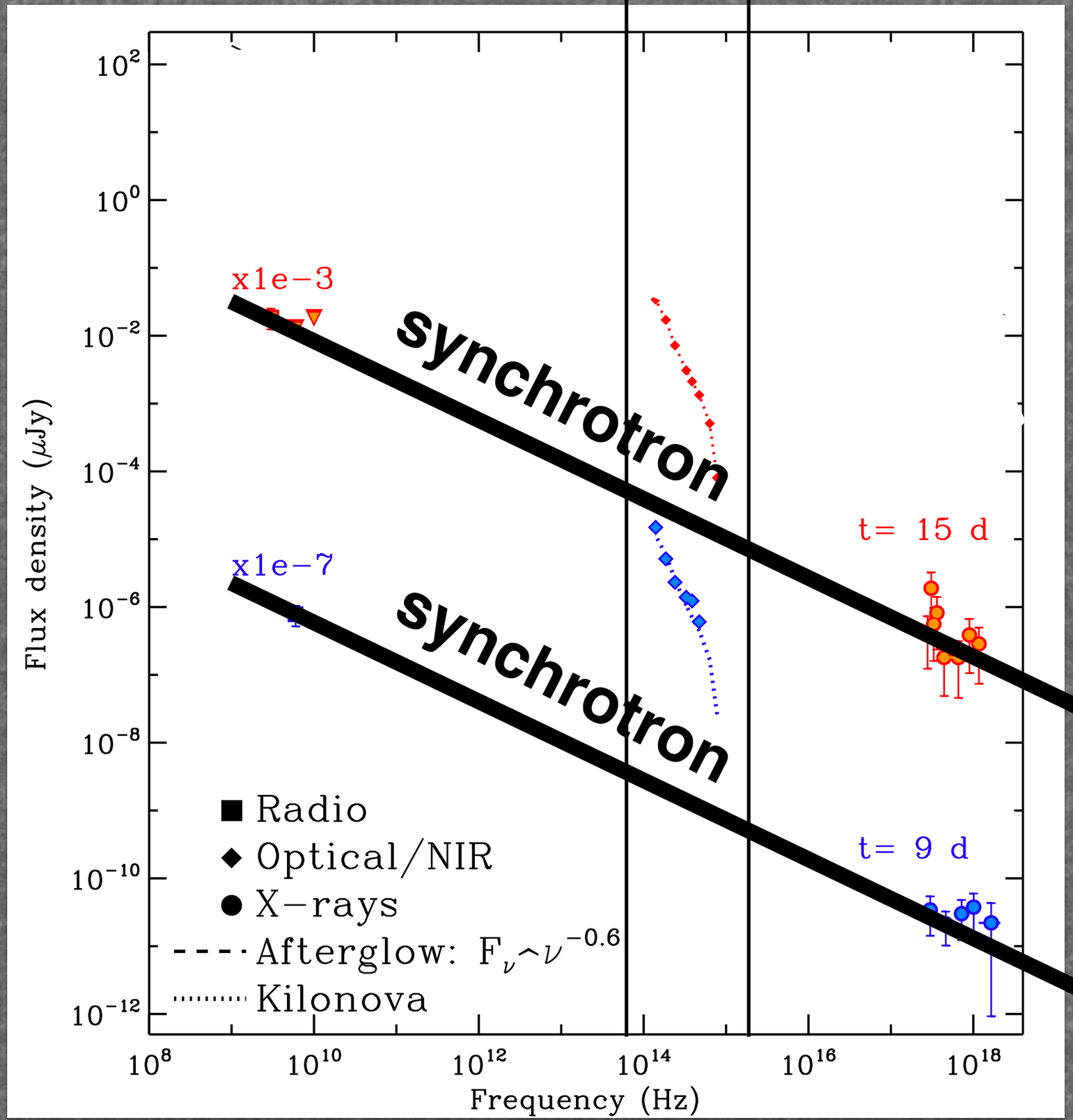
Margutti et al. 2018

Radio **Thermal KN** X-rays



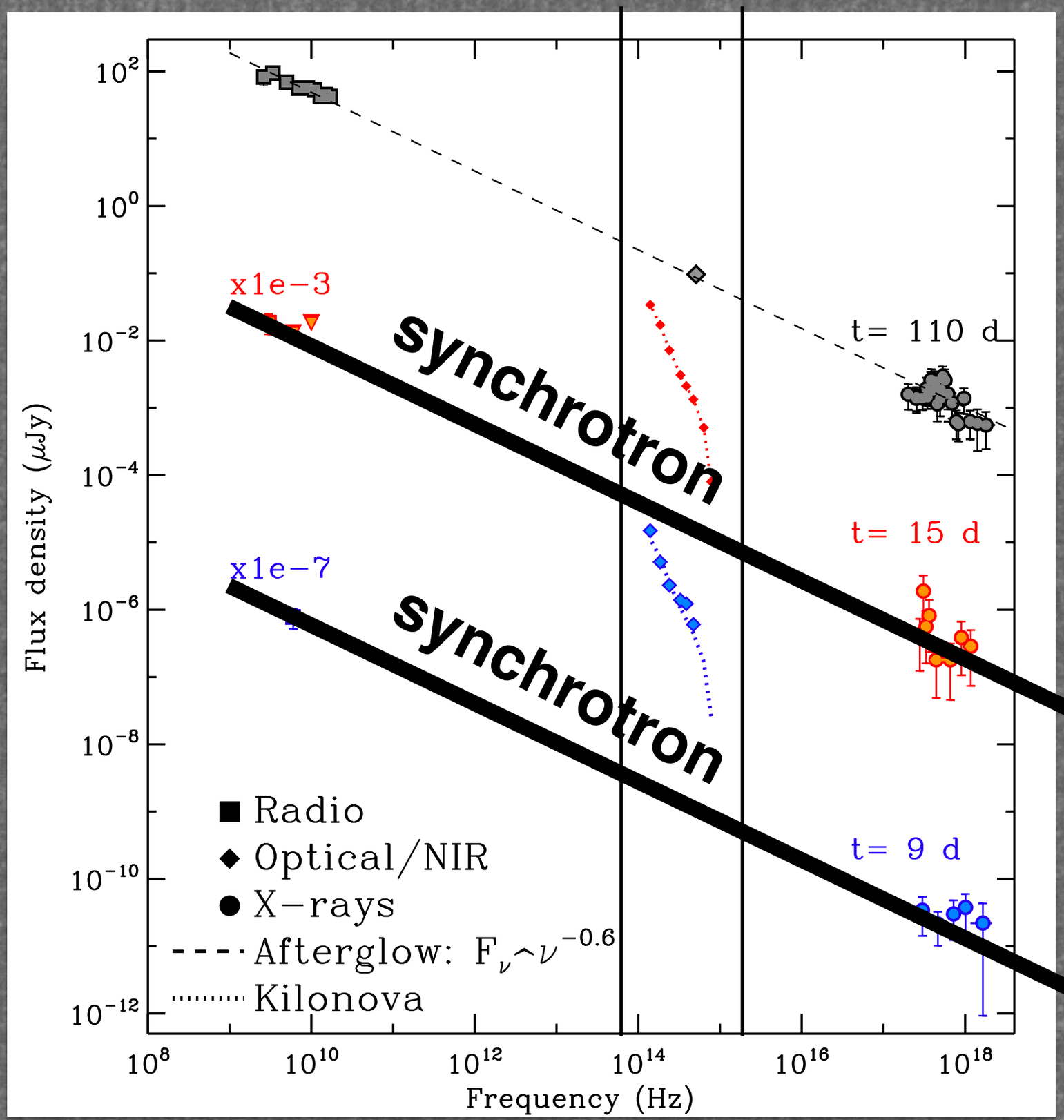
Margutti et al. 2018

Radio **Thermal KN** X-rays



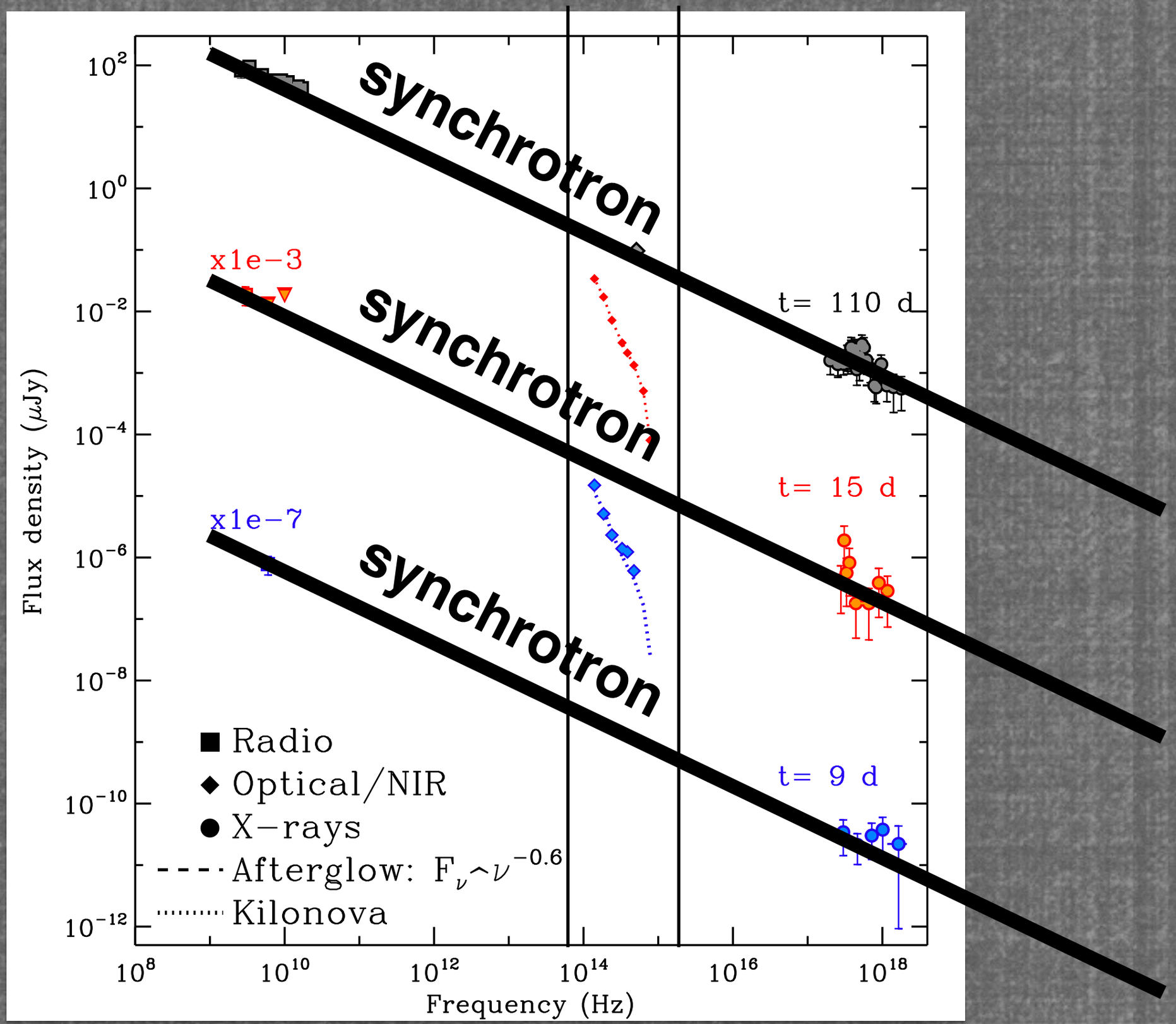
Margutti et al. 2018

A POWER-LAW in the Sky



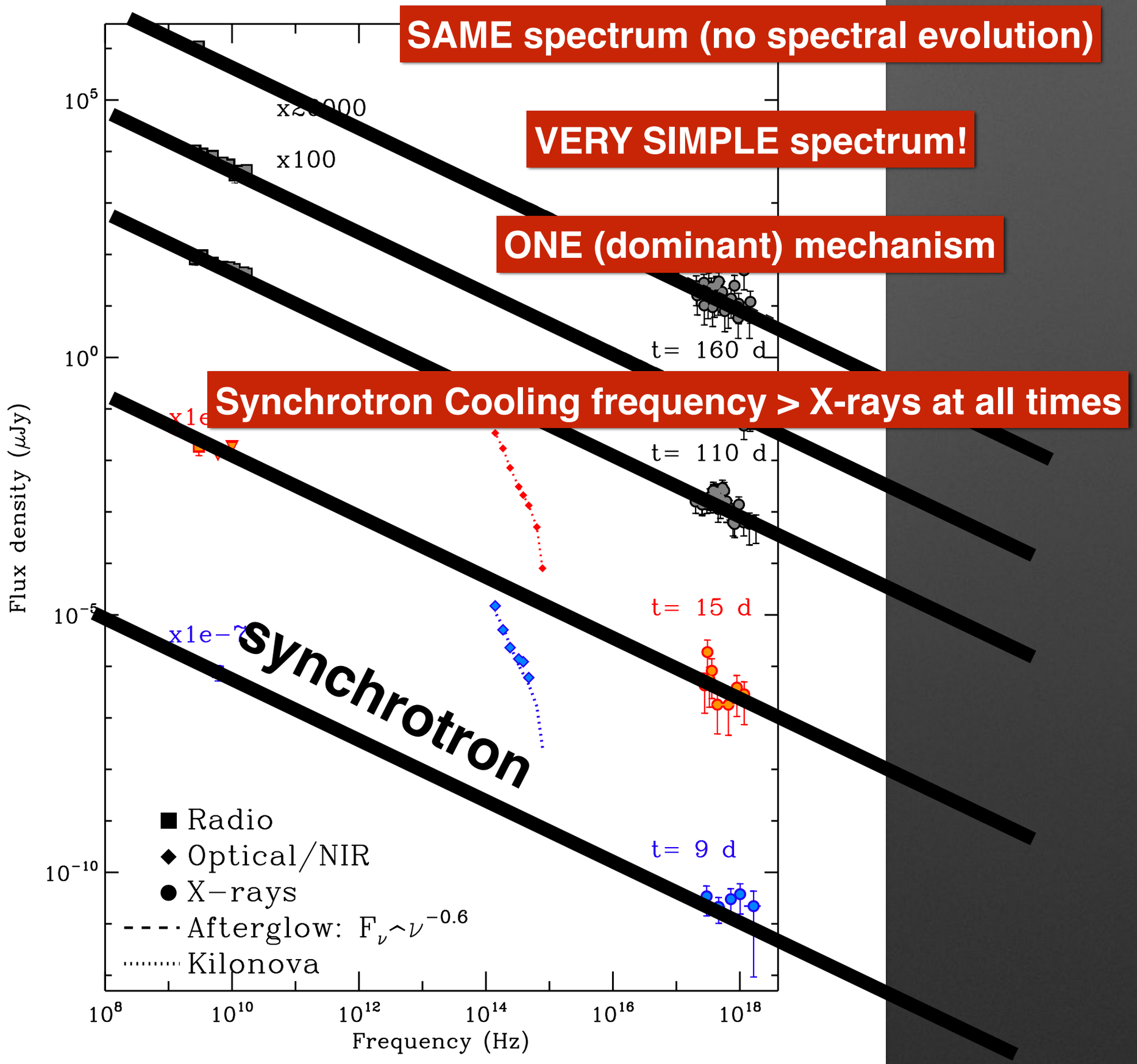
Margutti et al. 2018

A POWER-LAW in the Sky



Margutti et al. 2018

A power-law in the sky!



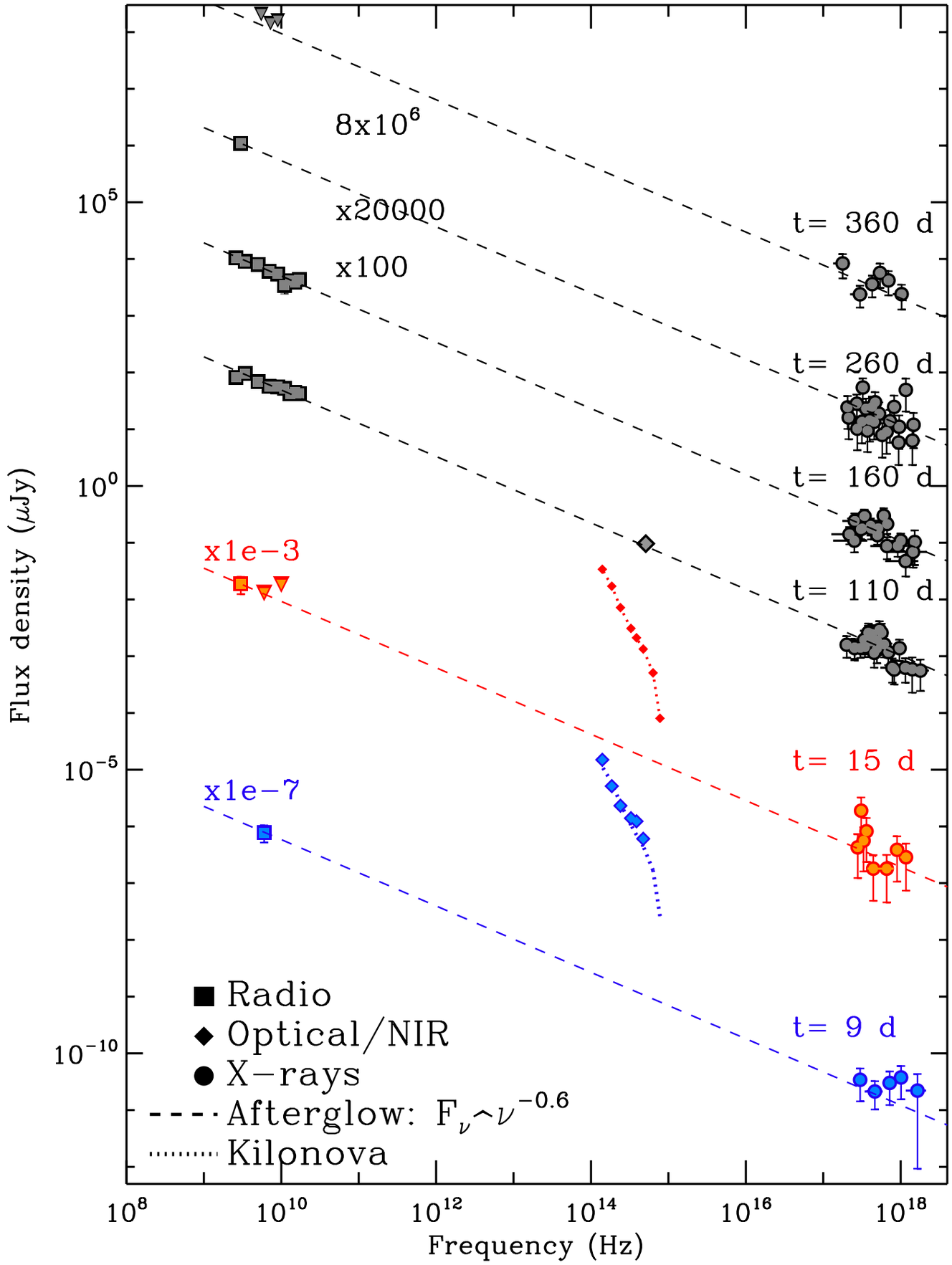
SAME spectrum (no spectral evolution)

VERY SIMPLE spectrum!

ONE (dominant) mechanism

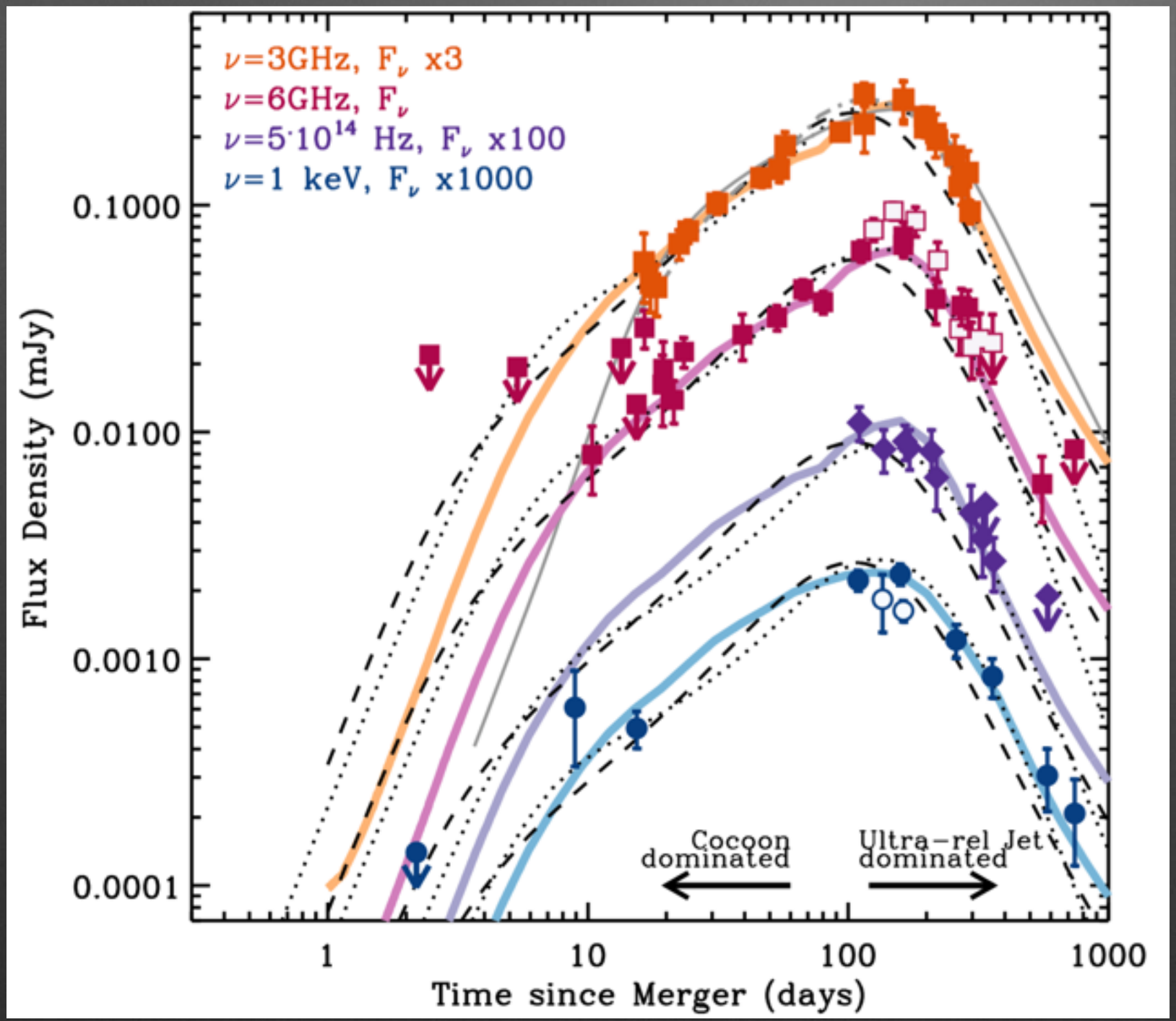
Synchrotron Cooling frequency > X-rays at all times

Margutti+2018 updated with new data from Alexander +2018


8x10^6
x20000
x100
t= 360 d
t= 260 d
t= 160 d
t= 110 d
x1e−3
t= 15 d
x1e−7
t= 9 d
Radio
Optical/NIR
X−rays
Afterglow: $F_\nu \sim \nu^{-0.6}$
Kilonova
Flux density (μJy)
Frequency (Hz)
10^5
10^0
10^−5
10^−10
10^8
10^10
10^12
10^14
10^16
10^18

Hajela+ 2019

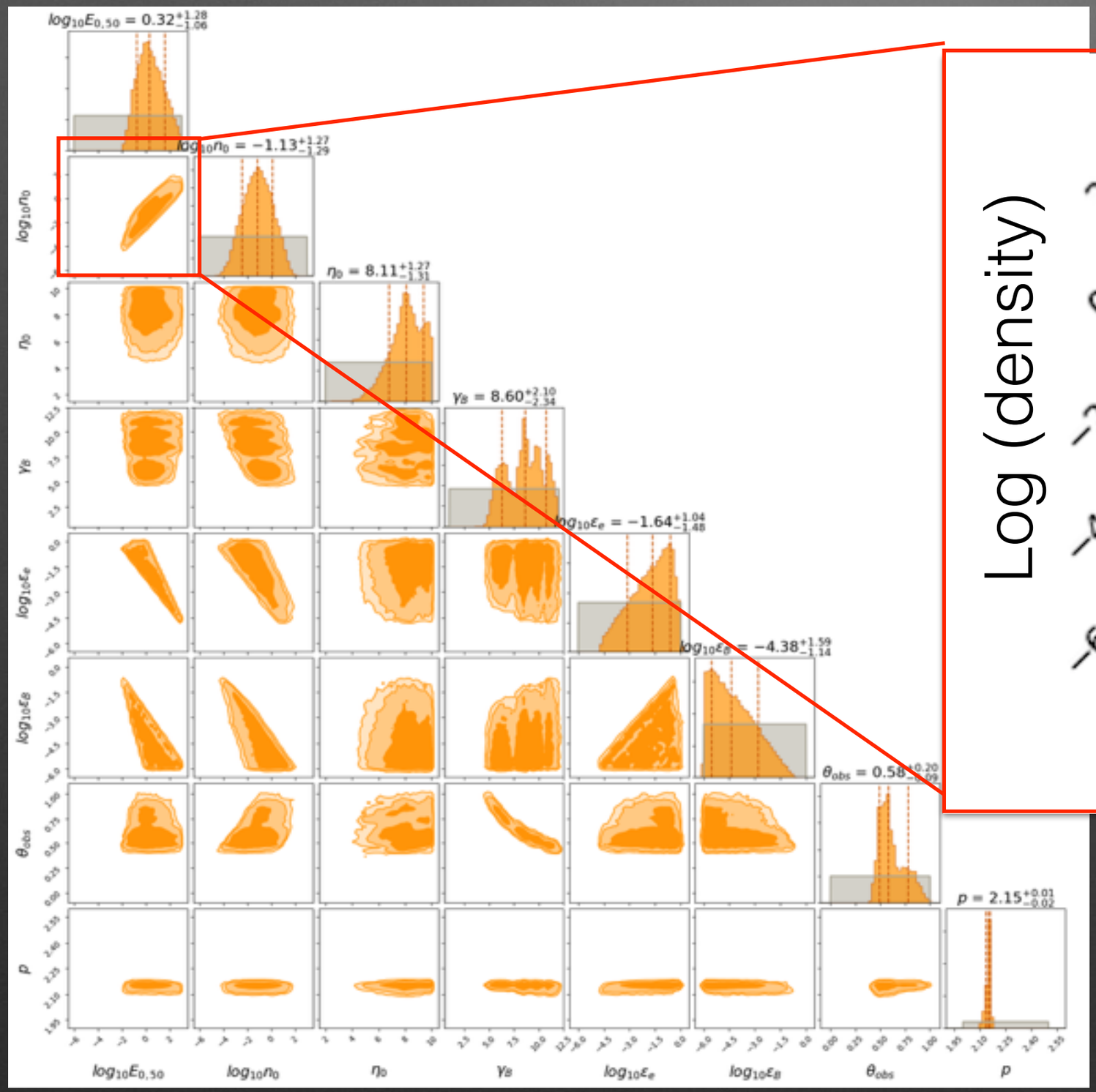
CONCORDANT PICTURE:
An off-axis jetted relativistic outflow with structure

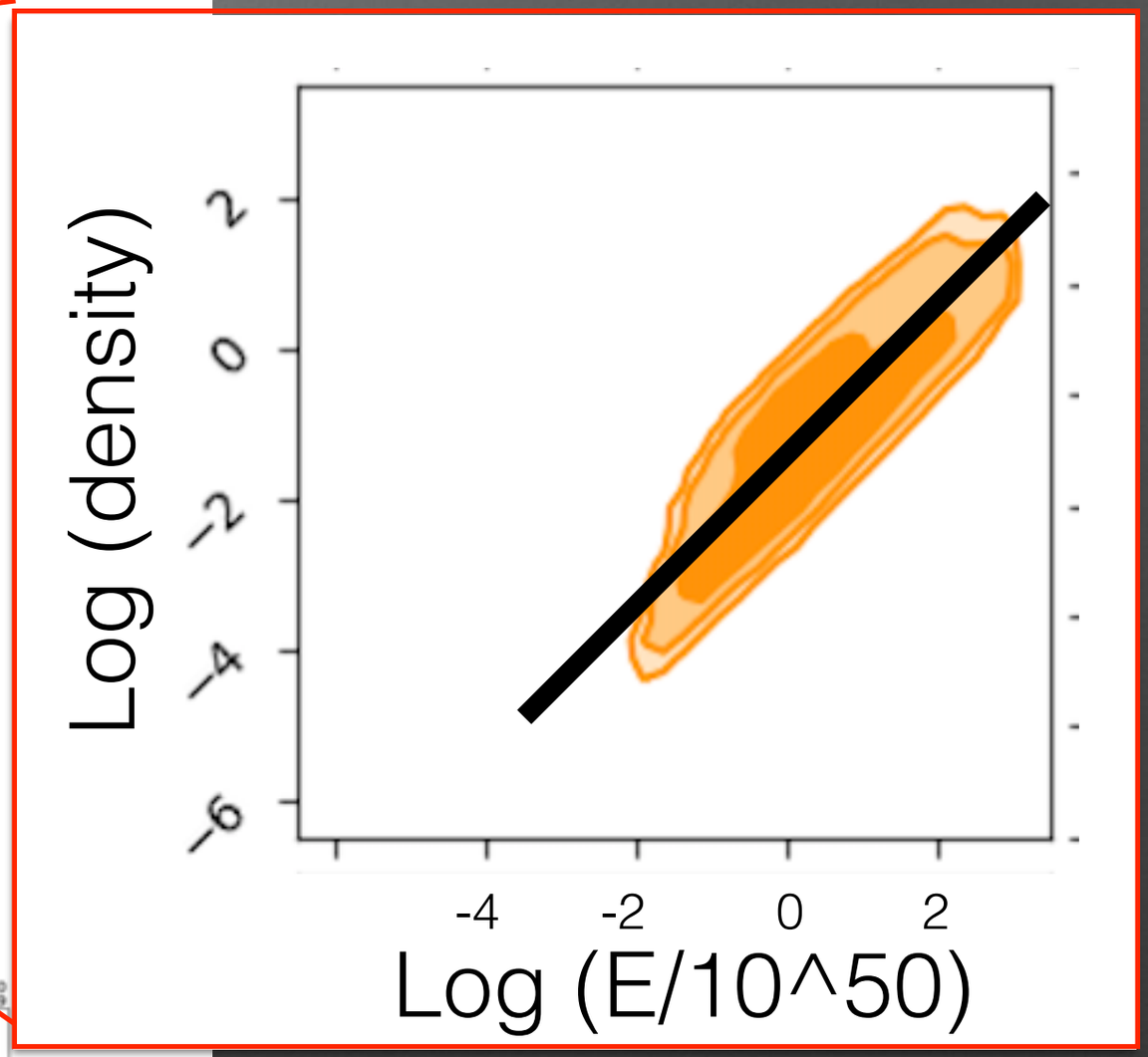


Hajela+19
Ghirlanda+19
Lazzati+19
Kathirgamaraju+19
Mooley/Gottlieb+19

Jet core~ 5 deg
Off-axis angle ~ 20-30 deg
Ejet~10^49-10^50 erg
n~ 0.001- 0.01 cm-3

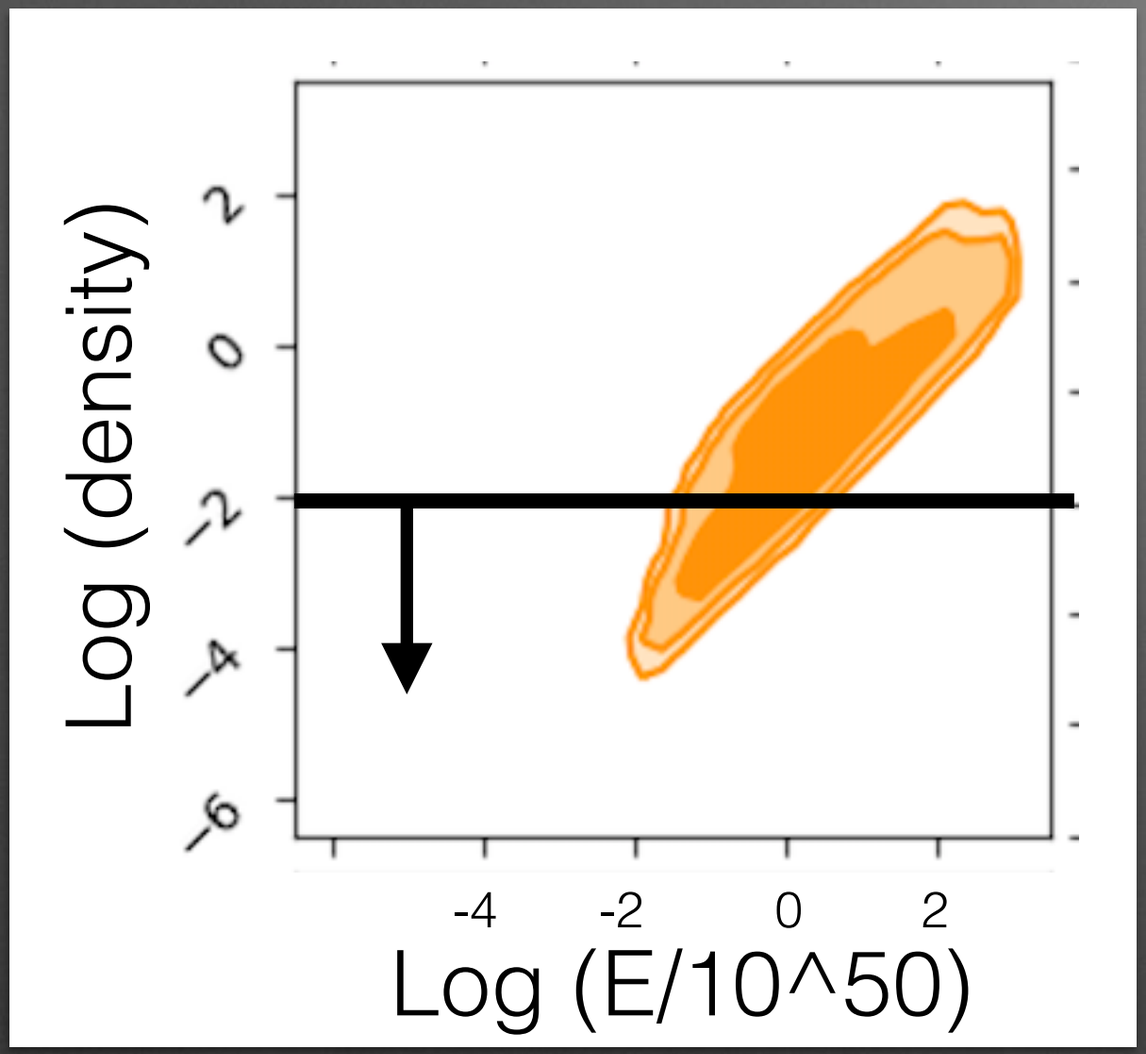
An off-axis jetted relativistic outflow with structure: Parameter Degeneracy

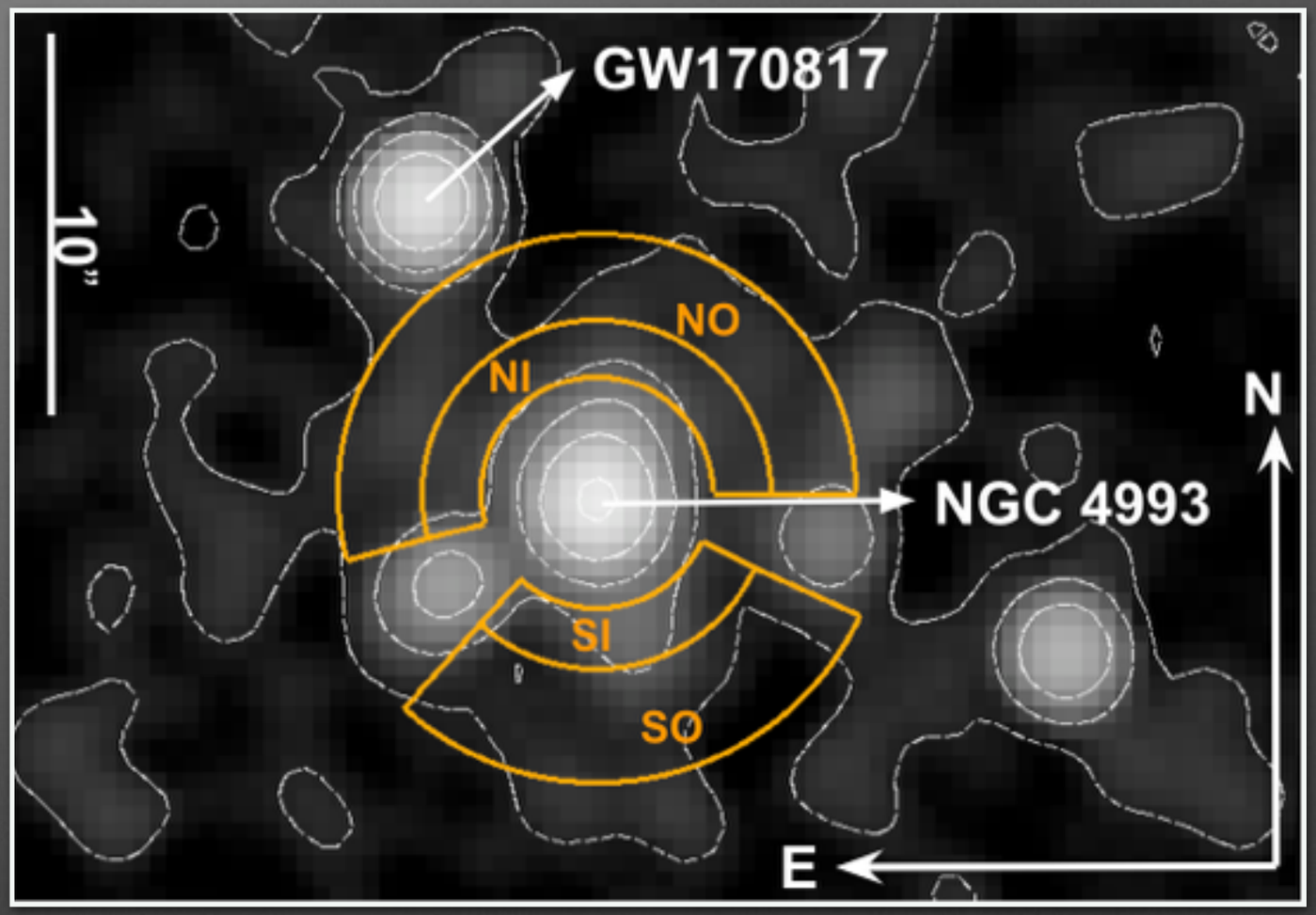




Hajela+2019

An off-axis jetted relativistic outflow with structure: Parameter Degeneracy





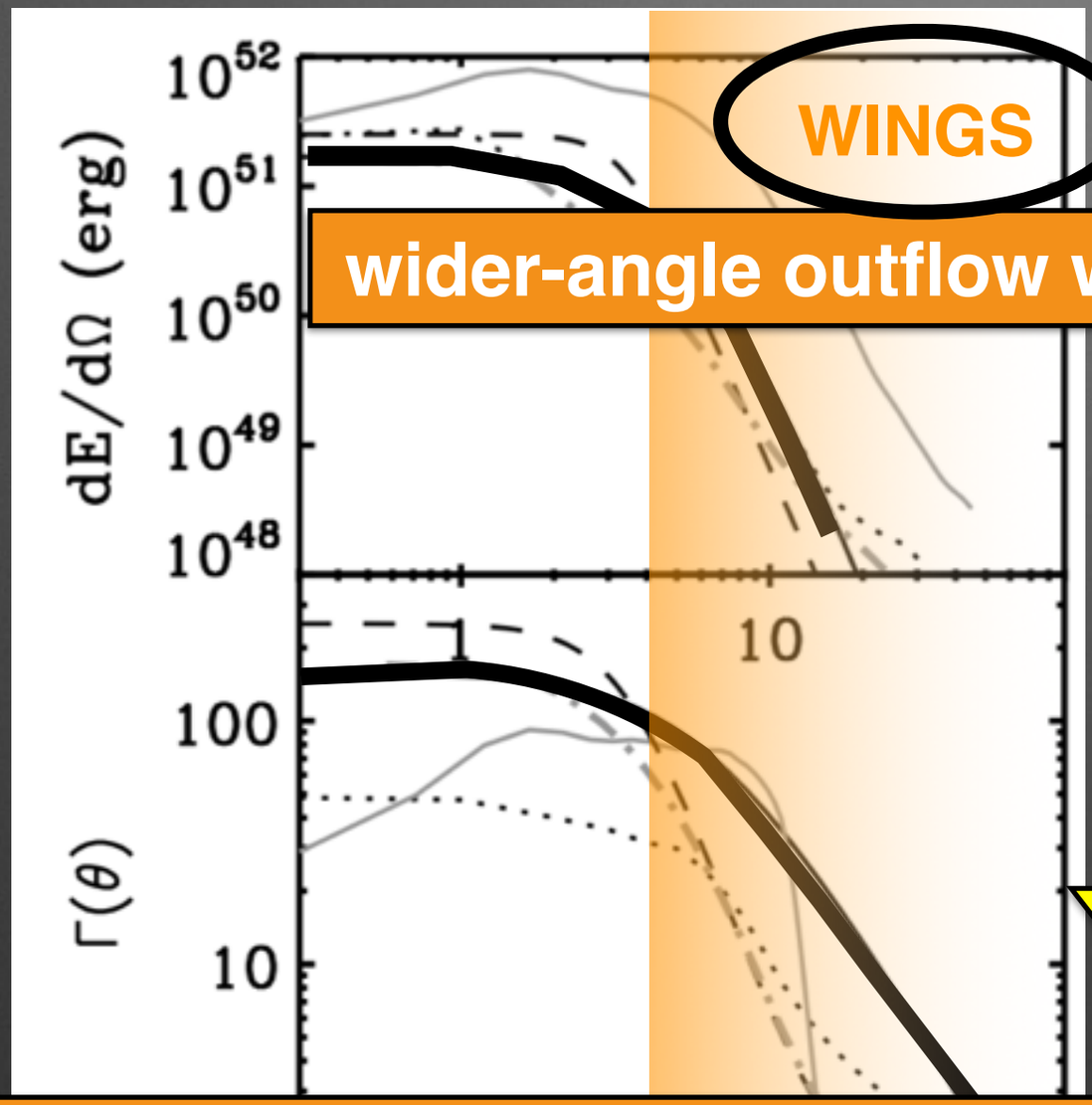
Hajela+2019

n<0.01 cm-3

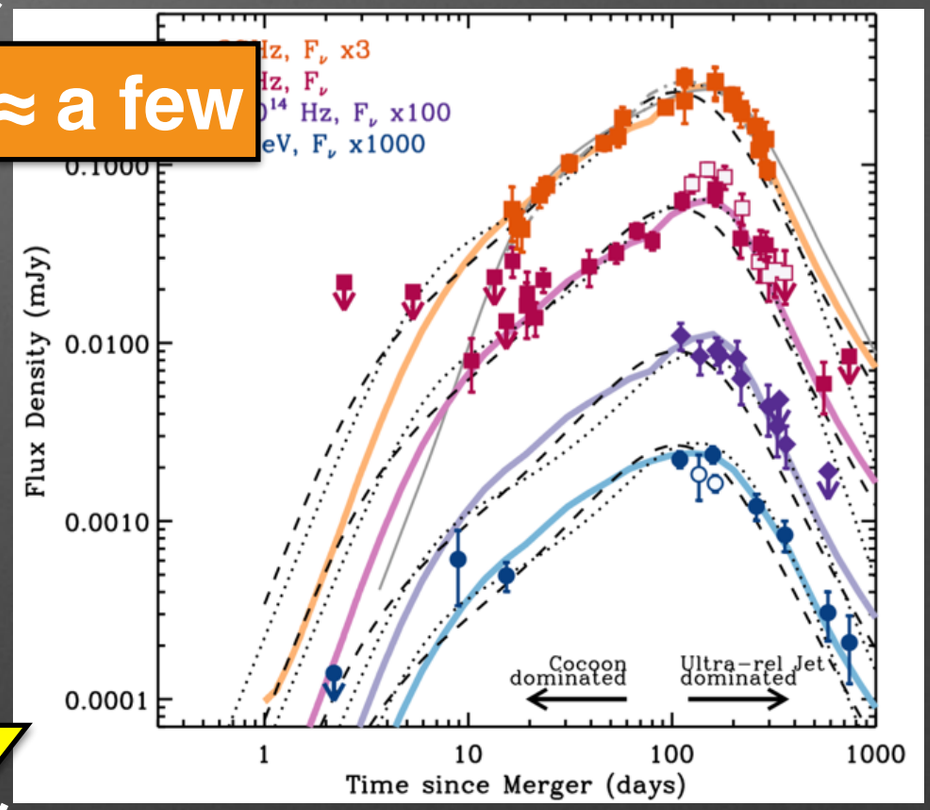
Ek~ 10^49 erg

The OUTFLOW STRUCTURE:

Hajela+19
Ghirlanda+19
Lazzati+19
Kathirgamaraju+19
Mooley/Gottlieb+19

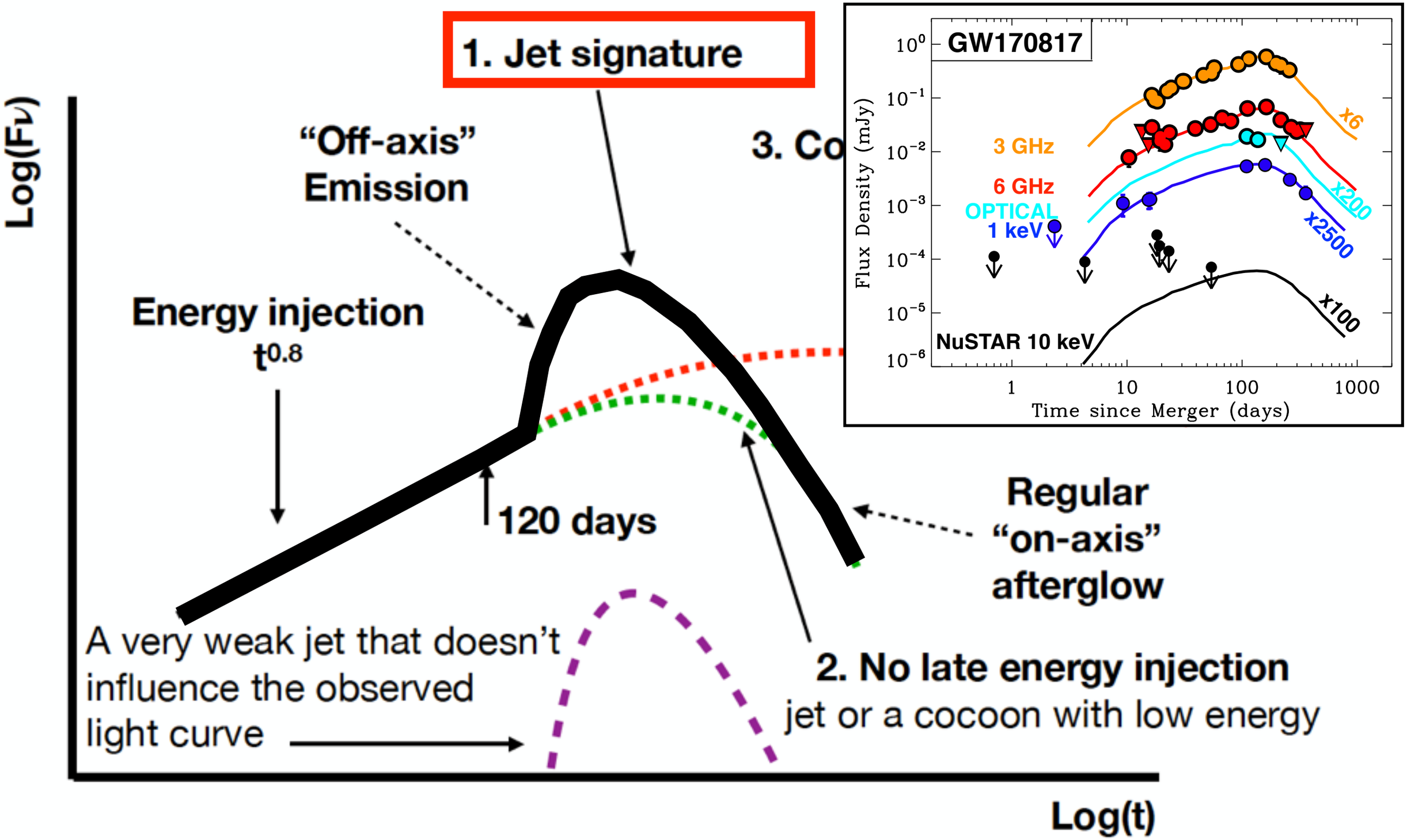


wider-angle outflow with Γ≈ a few



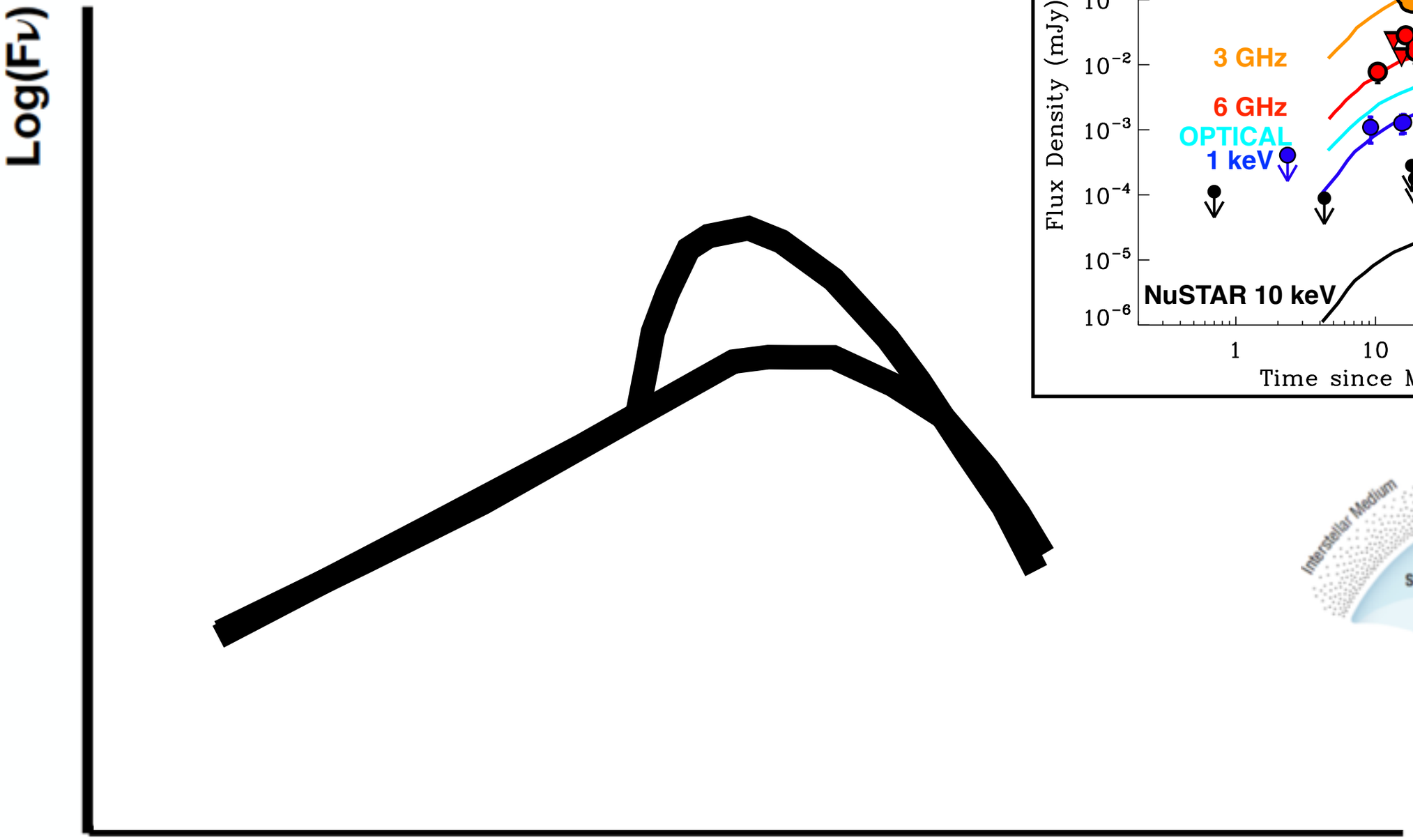
Physically,
they are likely to originate from a cocoon inflated by the jet as it propagates through the binary merger ejecta
(E.g. Lazzati+, Gottlieb+, Bromberg+)

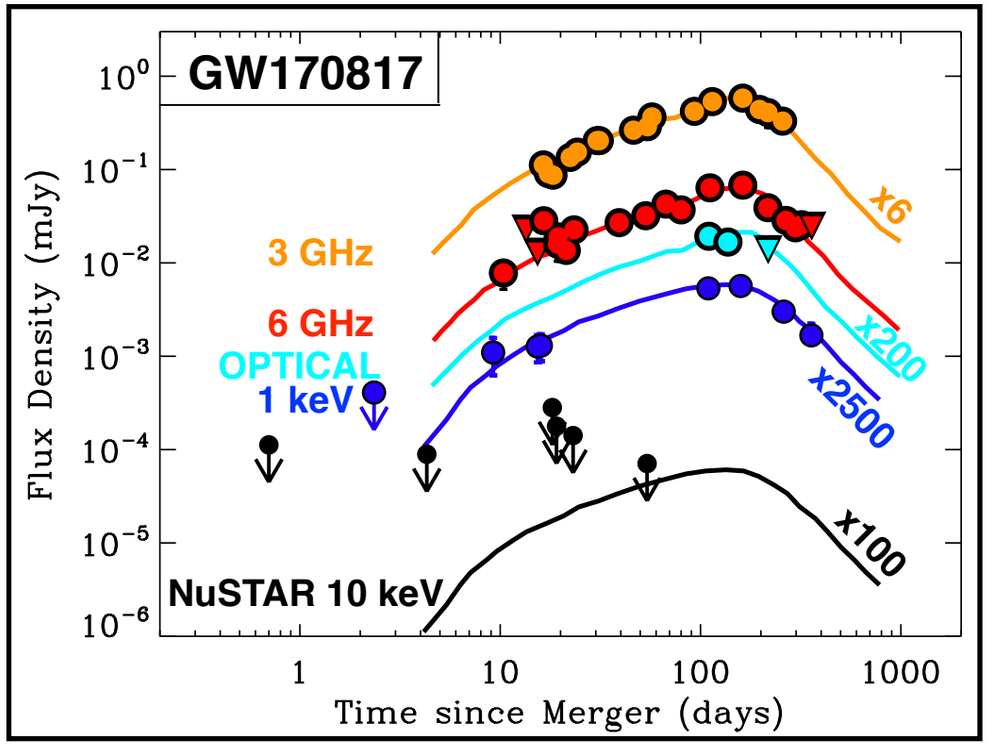
eg

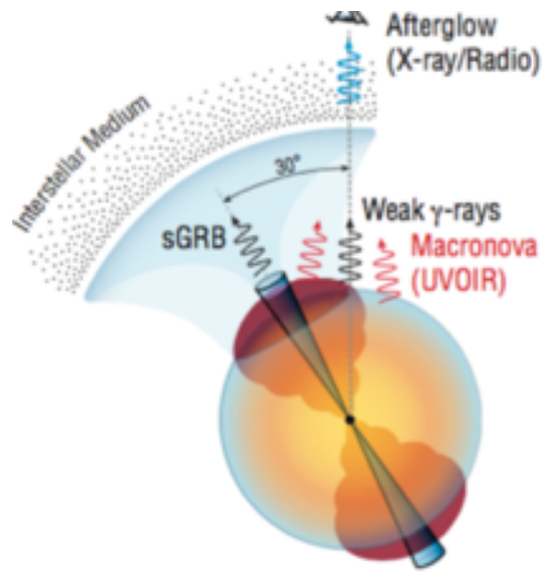

1. Jet signature
"Off-axis"
Emission
3. Co
Energy injection
$t^{0.8}$
120 days
Regular
"on-axis"
afterglow
A very weak jet that doesn't
influence the observed
light curve
2. No late energy injection
jet or a cocoon with low energy
Log(Fν)
Log(t)
GW170817
3 GHz
6 GHz
OPTICAL
1 keV
NuSTAR 10 keV
x6
x200
x2500
x100
Flux Density (mJy)
Time since Merger (days)

Nakar+2018

1. Jet signature



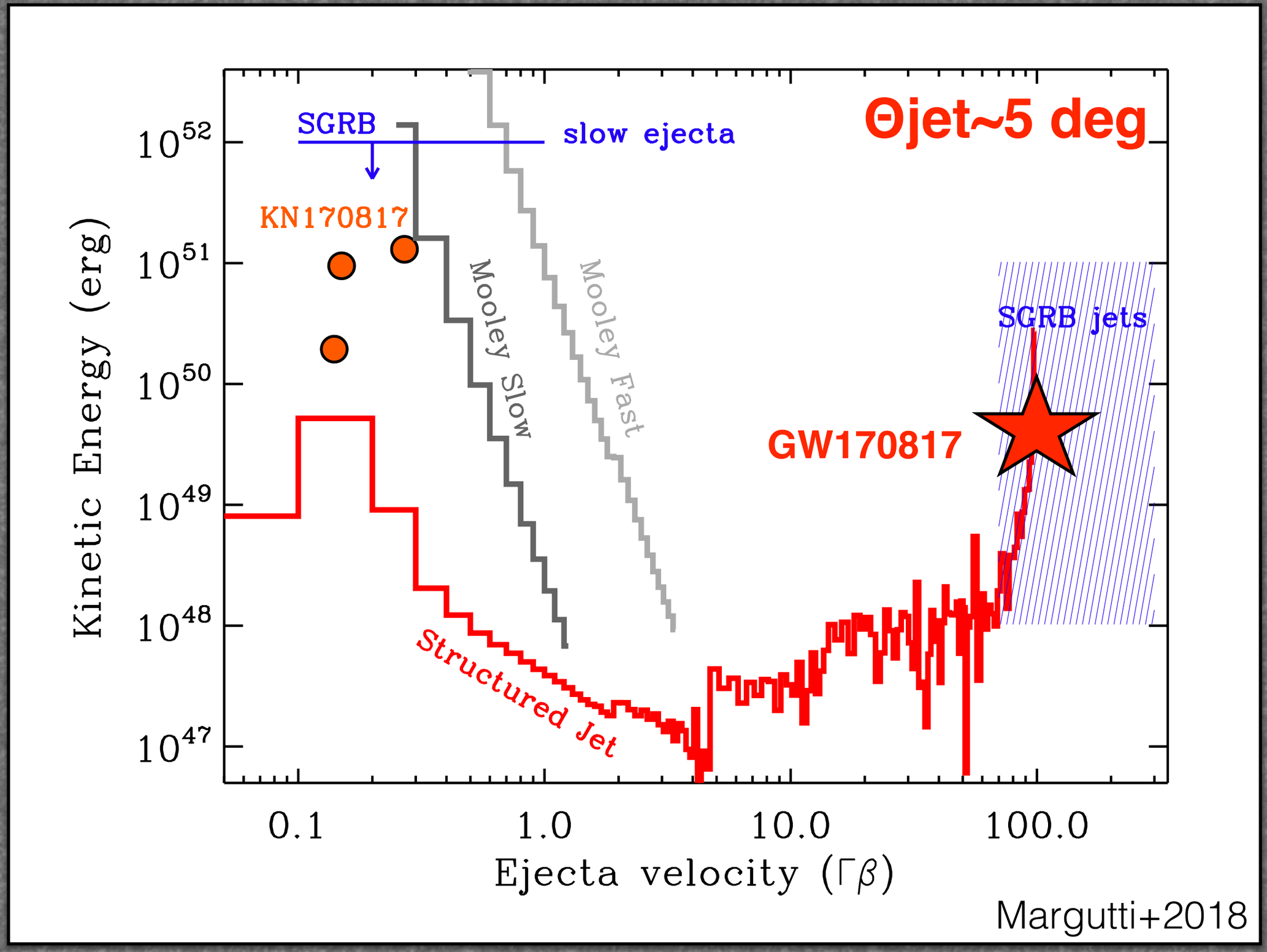




Kasliwal+2017

Nakar+2018

Energy Partitioning



Not unprecedented!

A structured ultra-relativistic outflow in a low density environment provides a natural explanation of what we are observing in GW170817

How to distinguish which model is correct?

Synch. Cooling Frequency

Temporal Decay

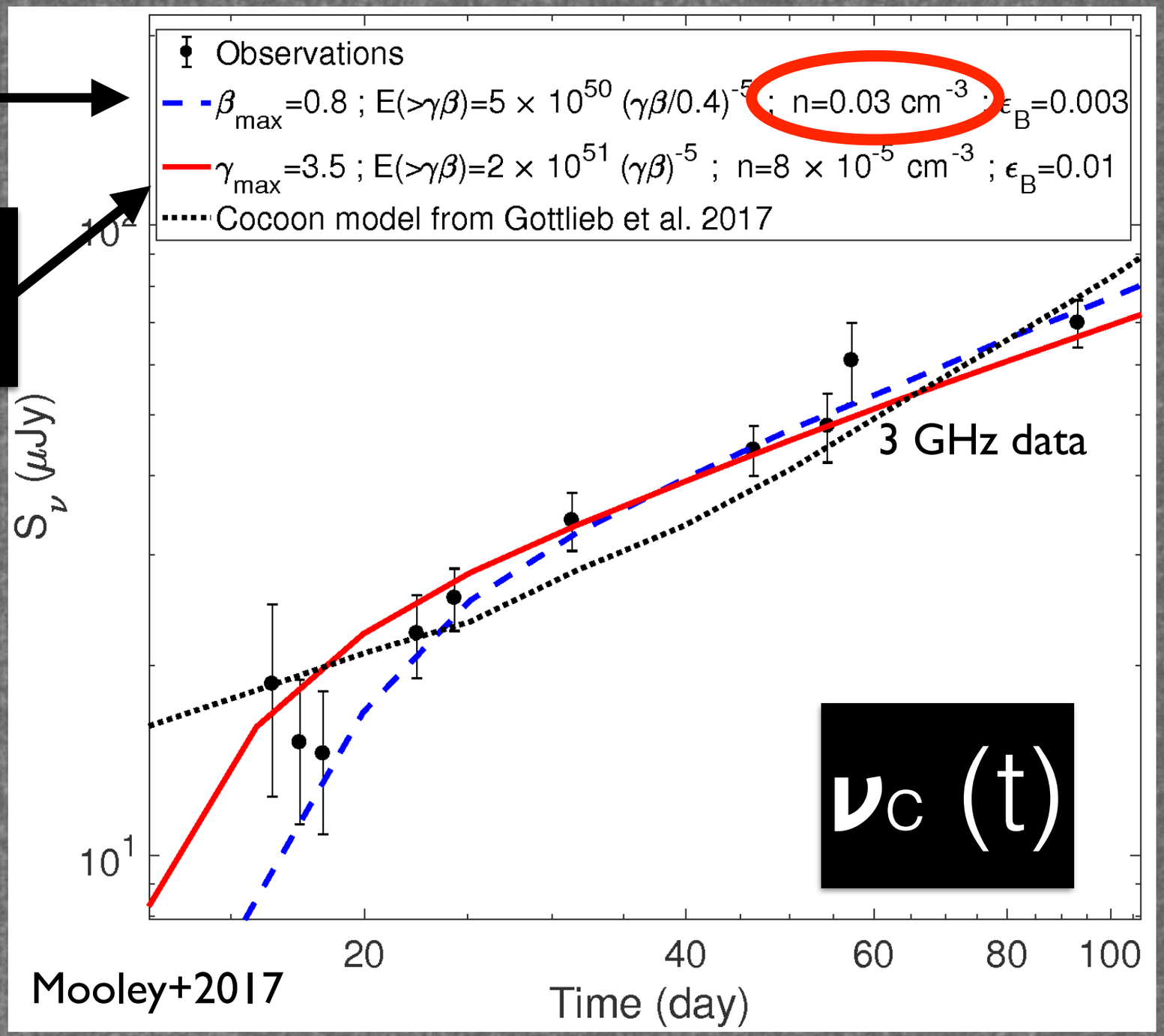
“Image” of the blast wave

Introduce STRUCTURE in the quasi-spherical ejecta

E(>GammaBeta)~(GammaBeta)^-alpha

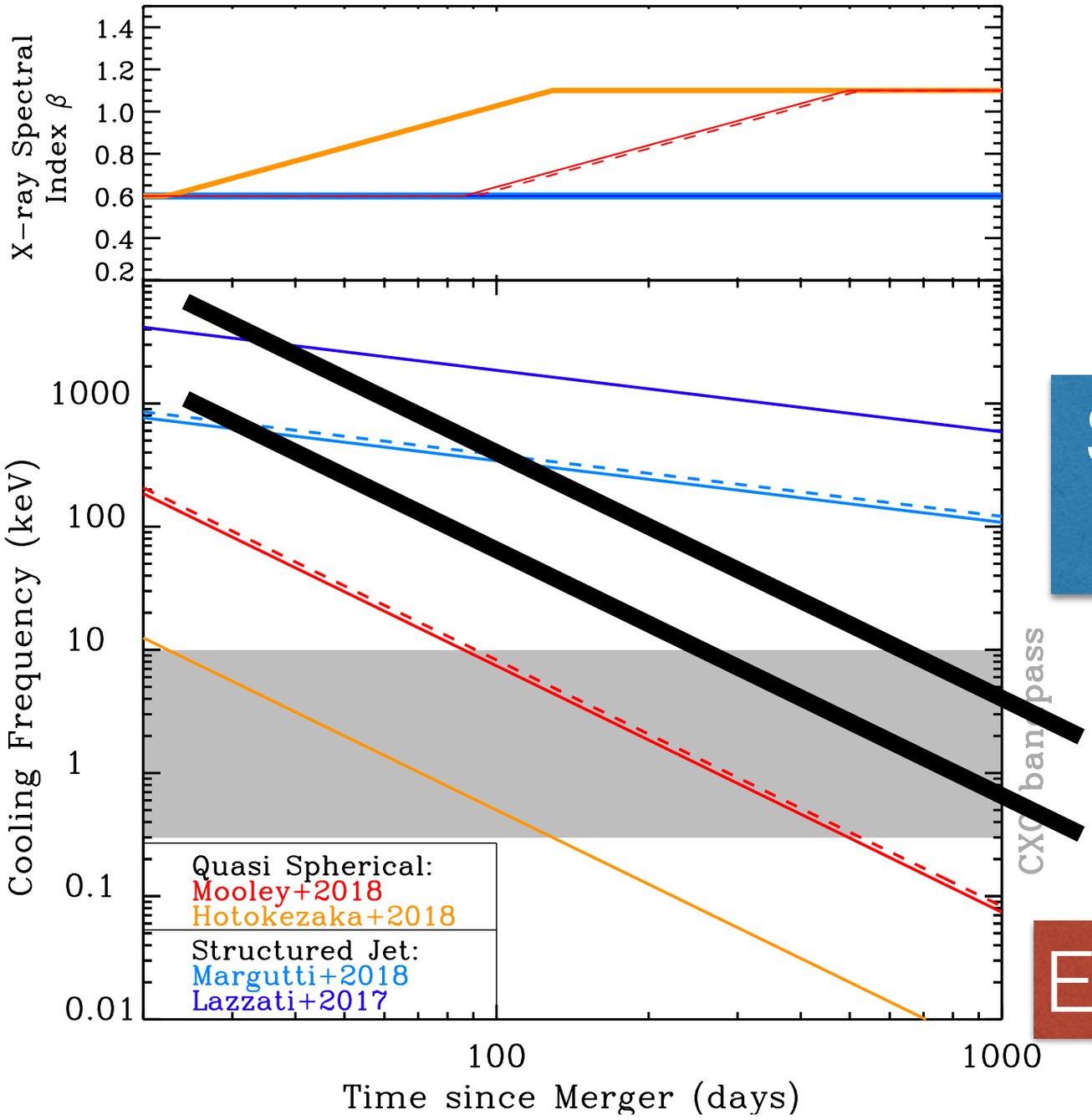
Tail of the merger ejecta

Cocoon driven by a wide angle chocked jet



Hallinan, Corsi +2017

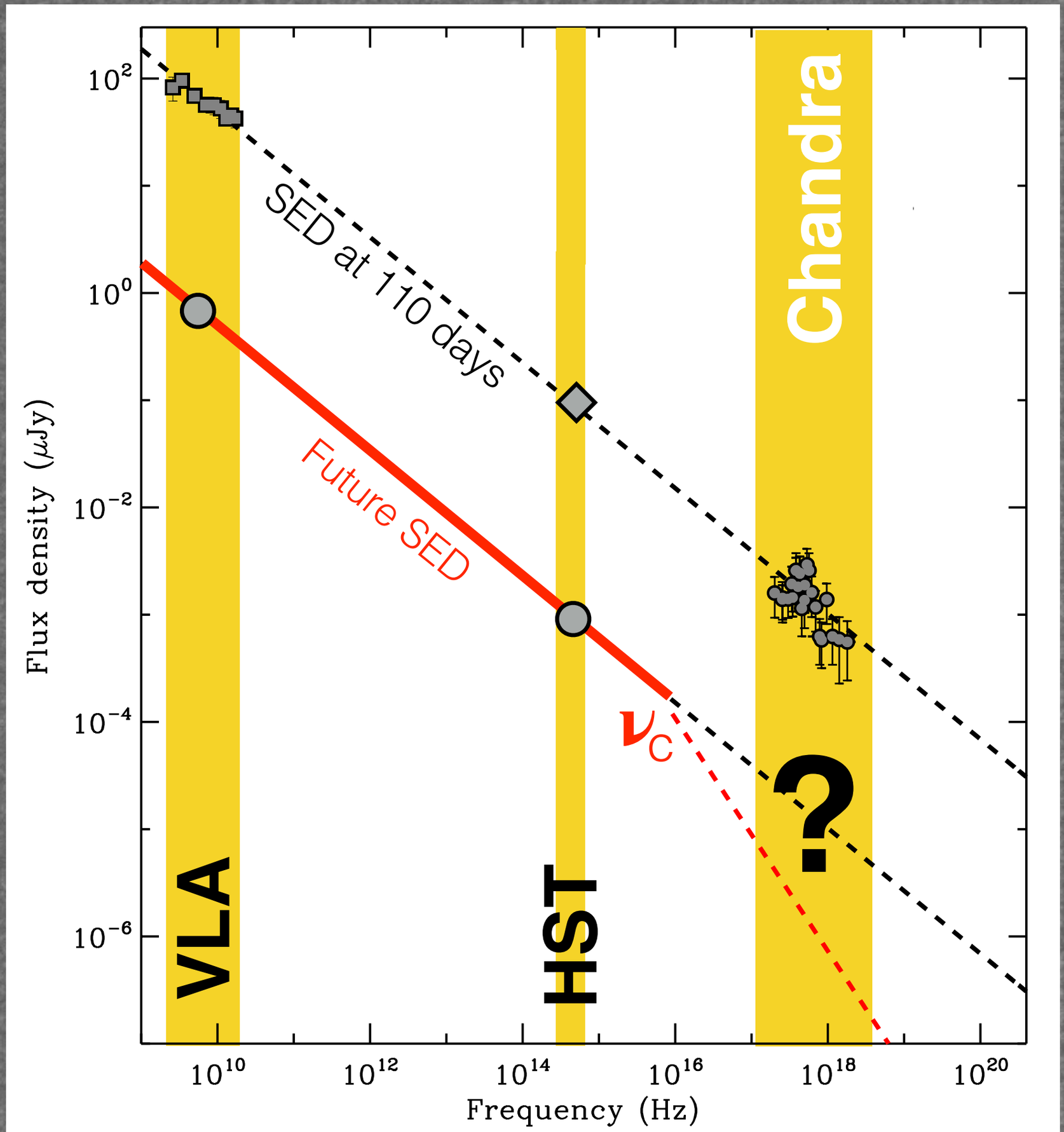
Synchrotron Cooling Frequency Evolution

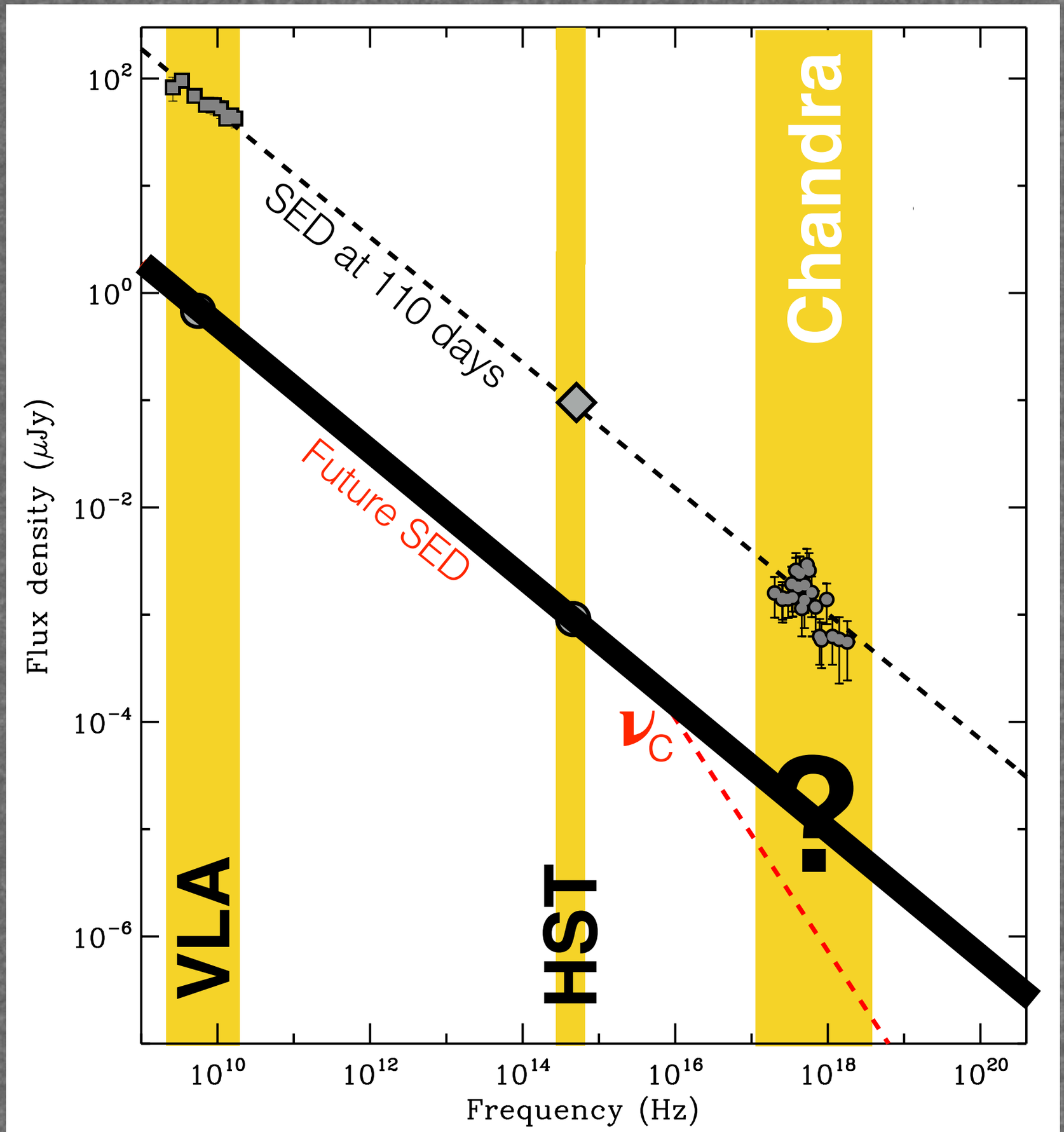


Structured collimated ultra-rel outflows

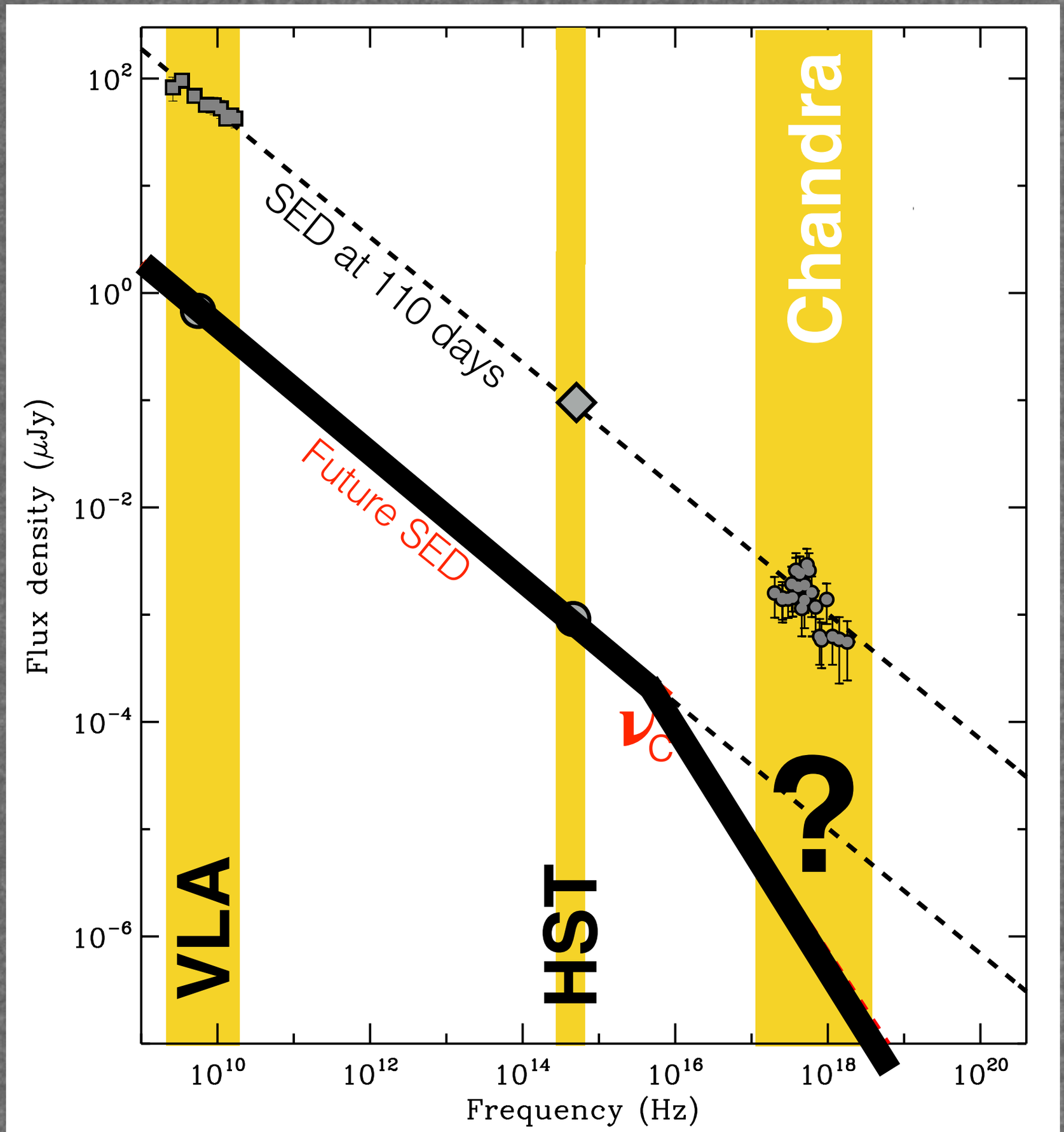
Cocoon Models

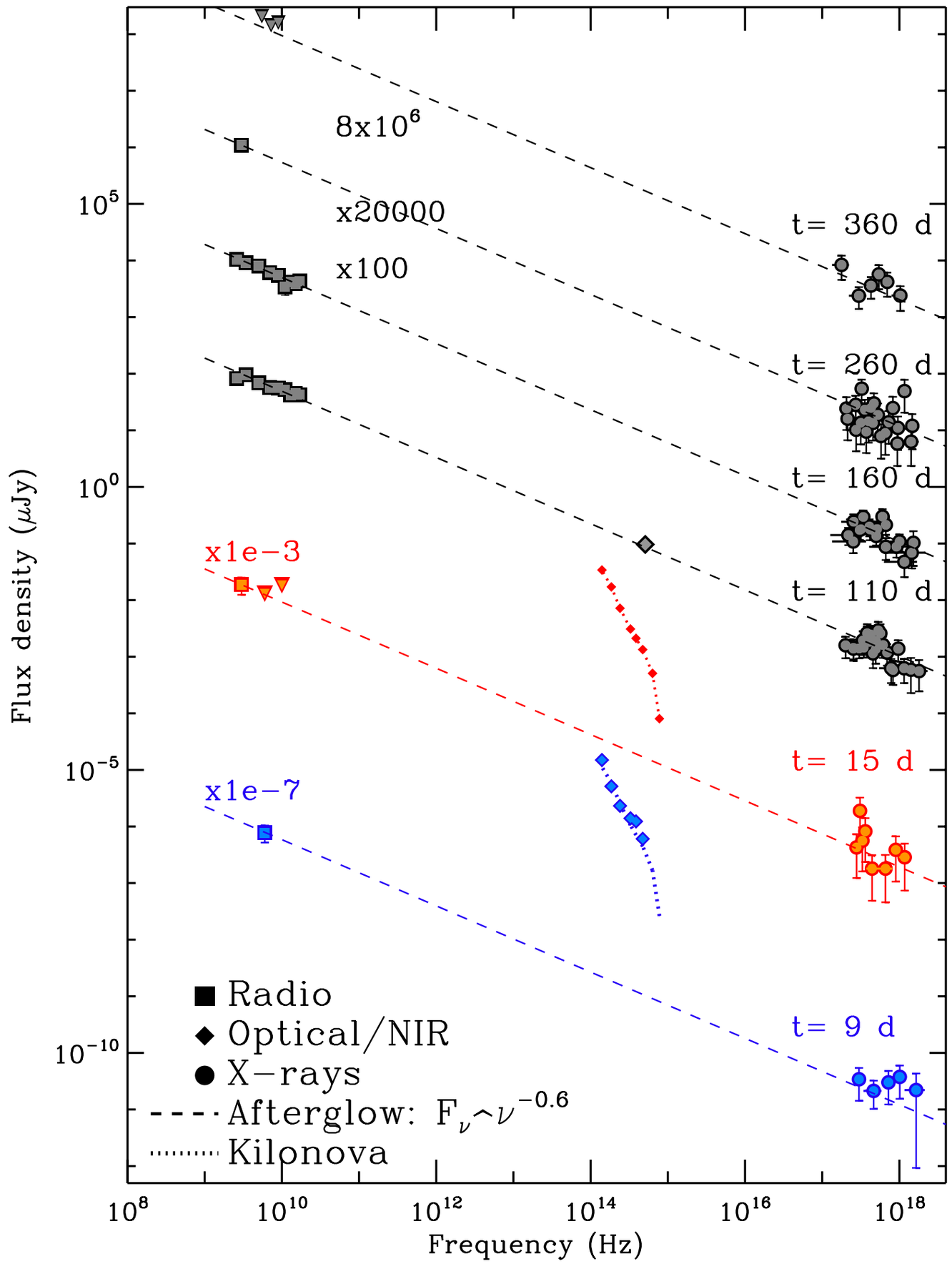
Ejecta Tidal Tail models


SED at 110 days
Future SED
ν_c
Chandra
VLA
HST
?
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Flux density (μJy)
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
Frequency (Hz)



Jetted models

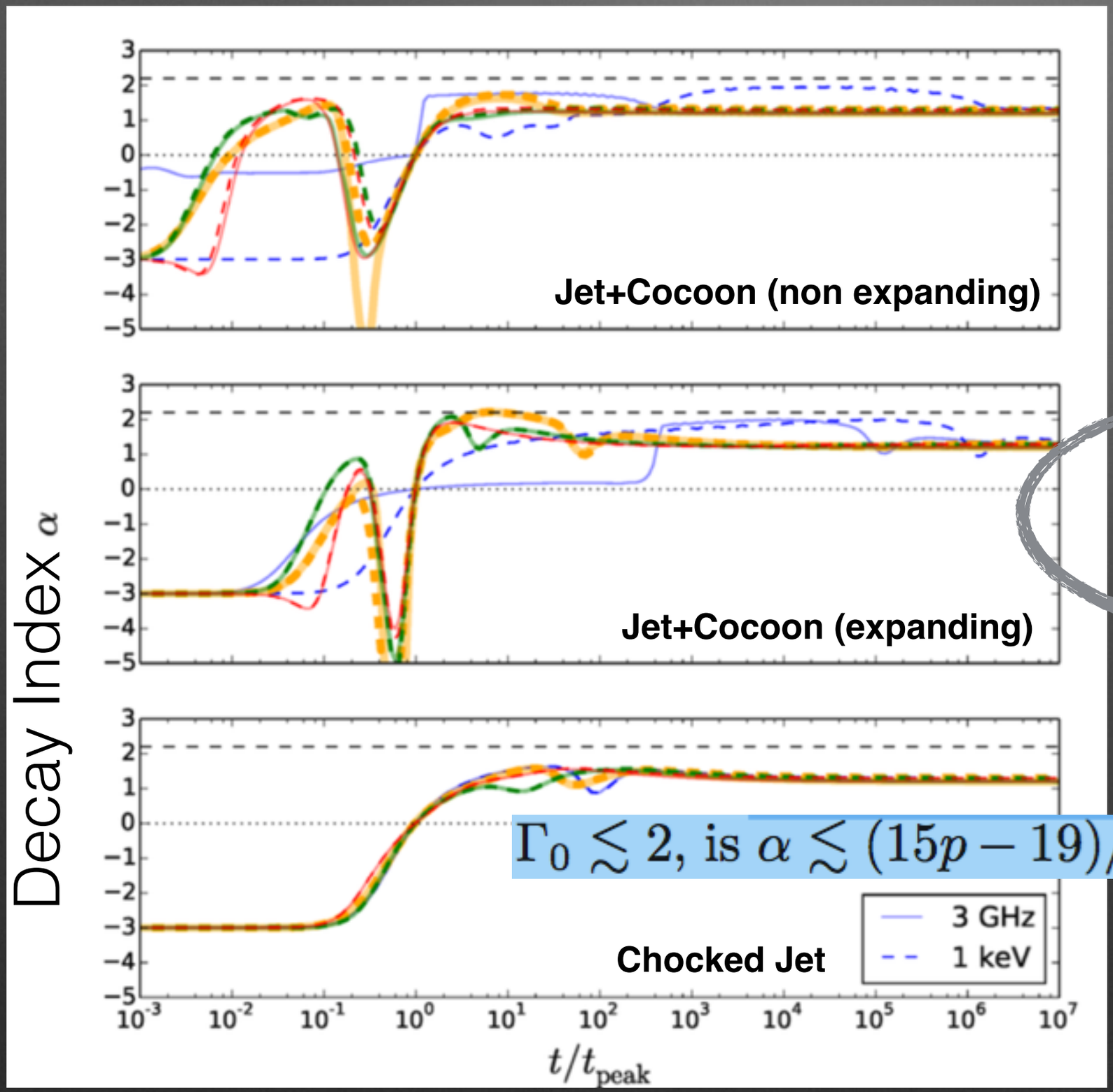

SED at 110 days
Future SED
ν_c
Chandra
VLA
HST
?
Flux density (μJy)
Frequency (Hz)
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}



Margutti in prep.

TEMPORAL DECAY

Measured at t>(5-6)x t_peak



for GW170817 p=2.17

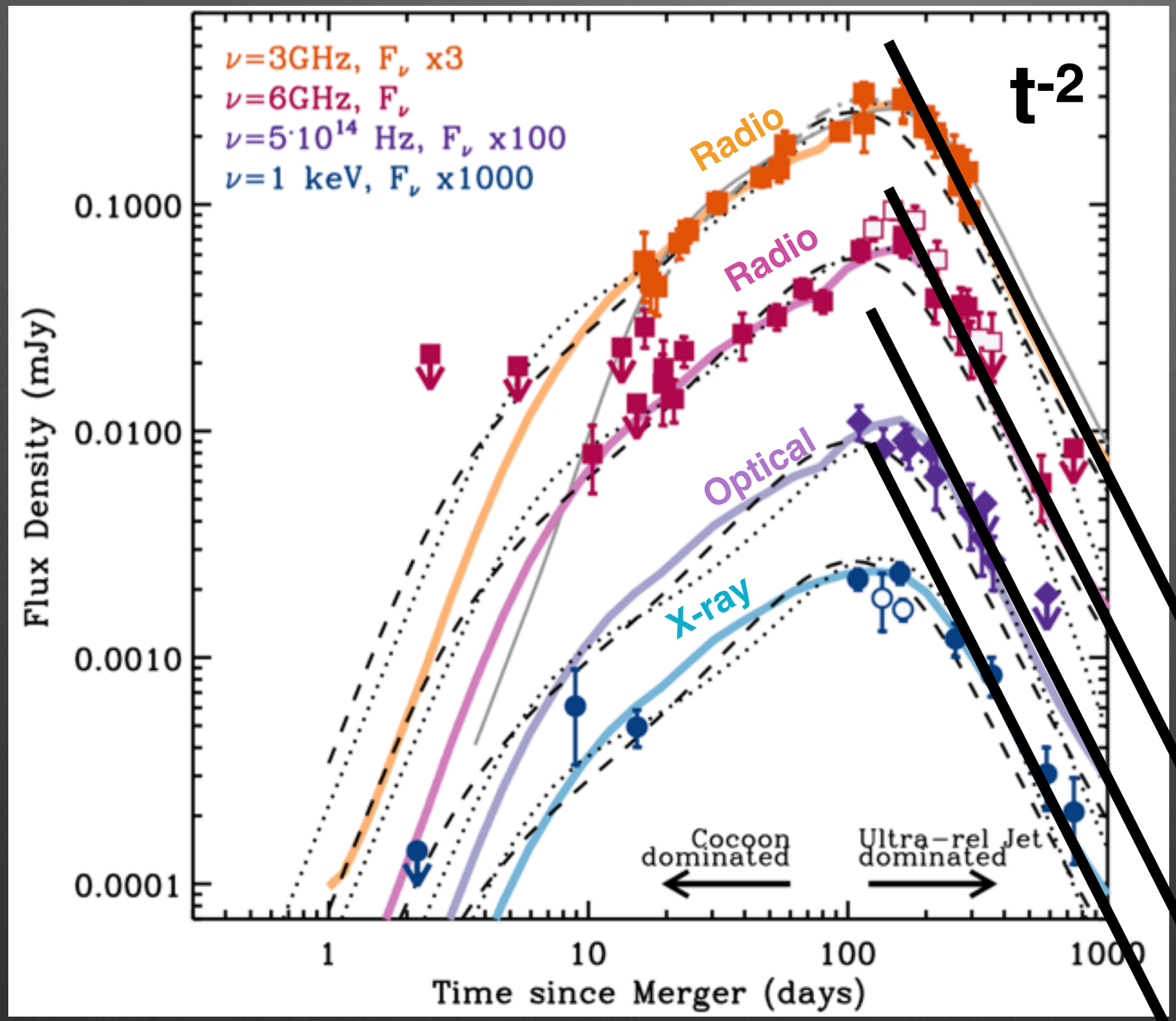
Below cooling
$\alpha <= 1.34$

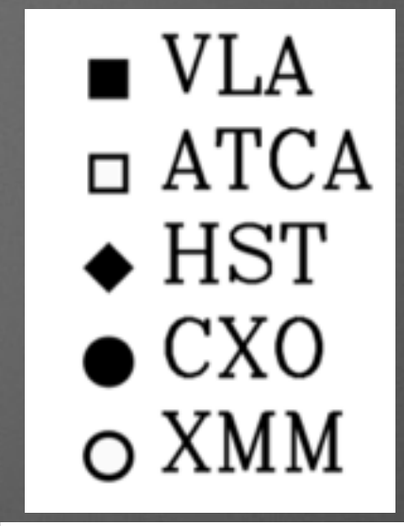
Above cooling
$\alpha <= 1.45$

$\Gamma_0 \lesssim 2$, is $\alpha \lesssim (15p-19)/10$ or $\alpha \lesssim (15p-18)/10$,

Cocoon
in free expansion

Lamb+2018

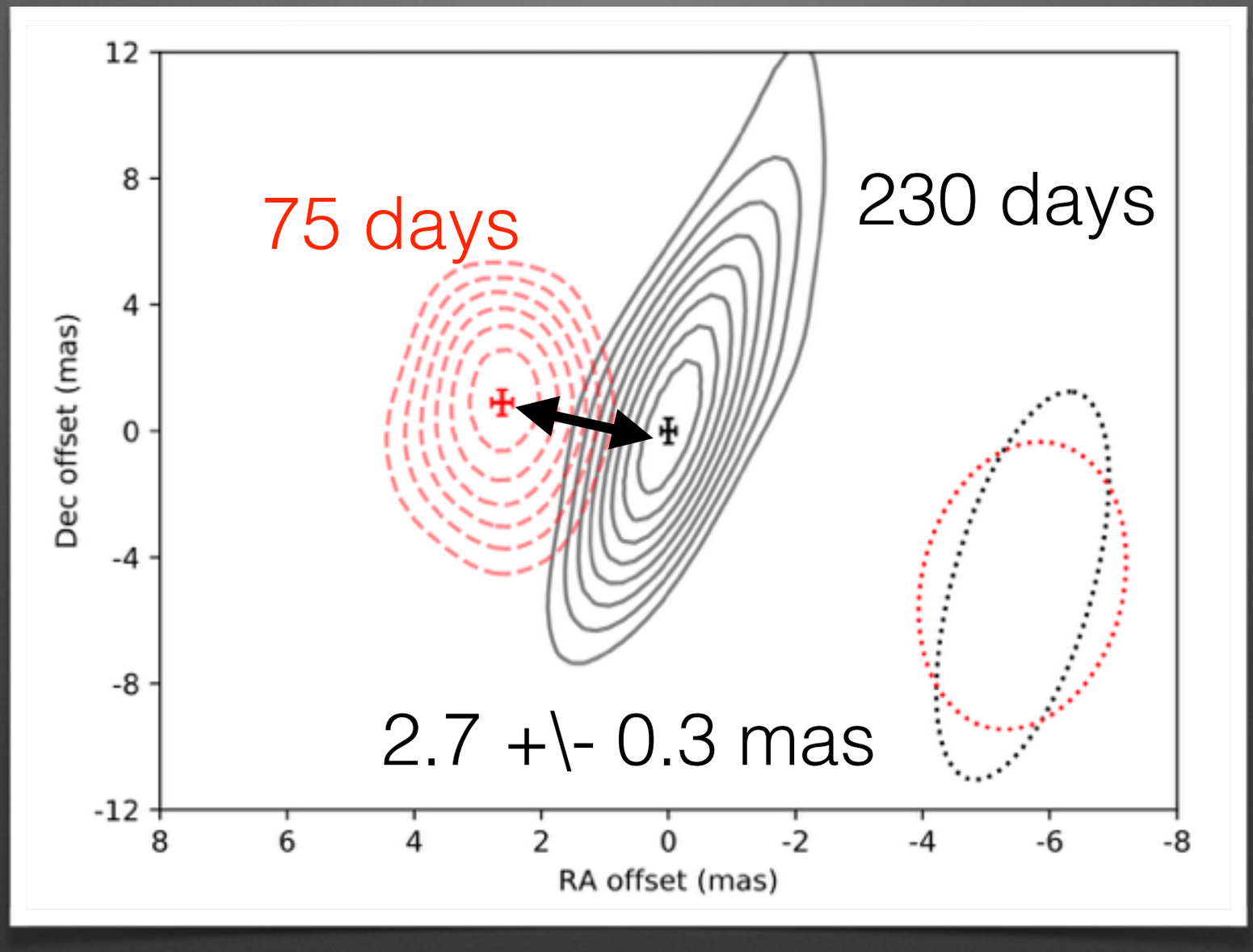




Margutti & Chornock in prep

VLBI images of GW170817

Mooley+2018; Ghirlanda+2019;

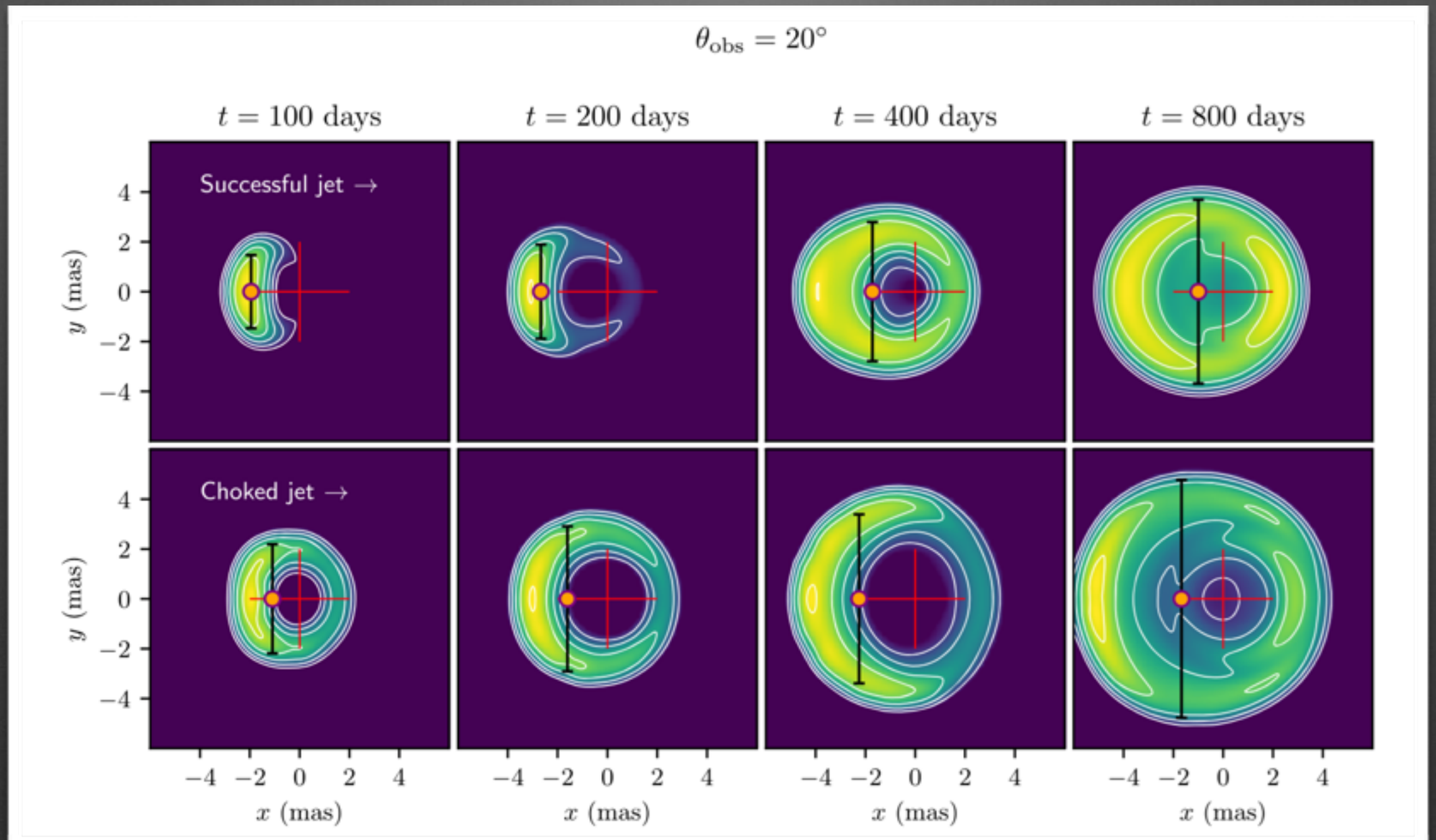


Unresolved + Superluminal motion of centroid

Rules out spherical explosions + axi-symmetric explosions

E.g. Zrake+2018, Mooley+2018, Ghirlanda+2019

Superluminal motion of centroid not enough by itself to distinguish between successful vs. chocked jet

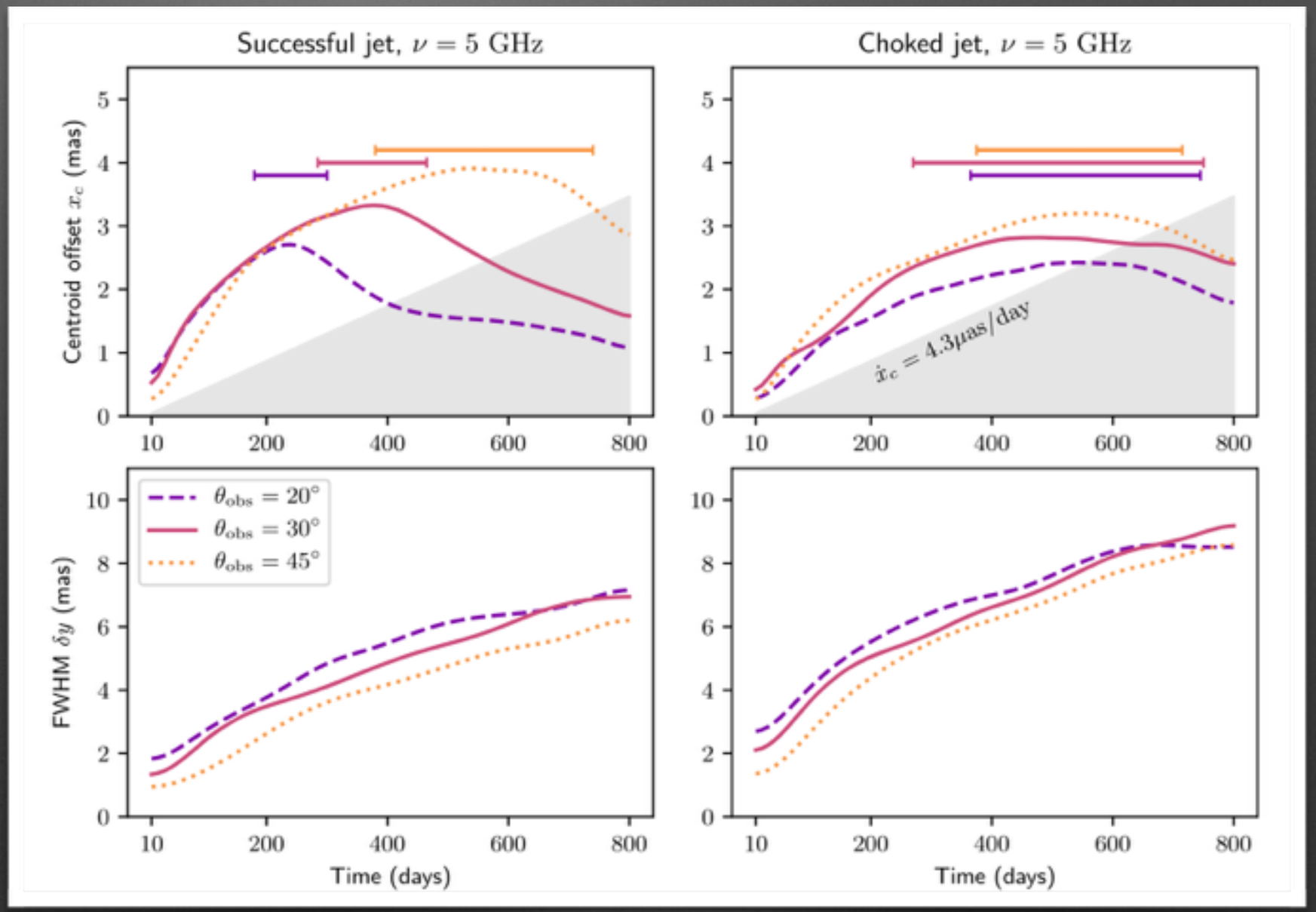


Zrake+2018

Centroid offset starts to decrease earlier in successful jets models, reaches larger offsets and images are smaller

Time when centroid reverses its motion

Image size when resolved



Zrake+2018

The emission is (still) non-thermal
and with the very same spectrum

It is decaying with time

Ejecta Tidal Tail models are disfavored

Pure cocoon models disfavored

GW170817 consistent with having harbored a SGRB-like outflow at ~30 deg off-axis, with a ~5 deg relativistic core, Ek~ some 10^49, n~10^-2 cm-3.

These properties are NOT UNPRECEDENTED

See Wu+2018, Wu+2019

GW170817 in the context of SGRBs: why GW170817 (and alike) is a unique opportunity

Constraining the physical parameters of BNS outflows

Nature of the remnant

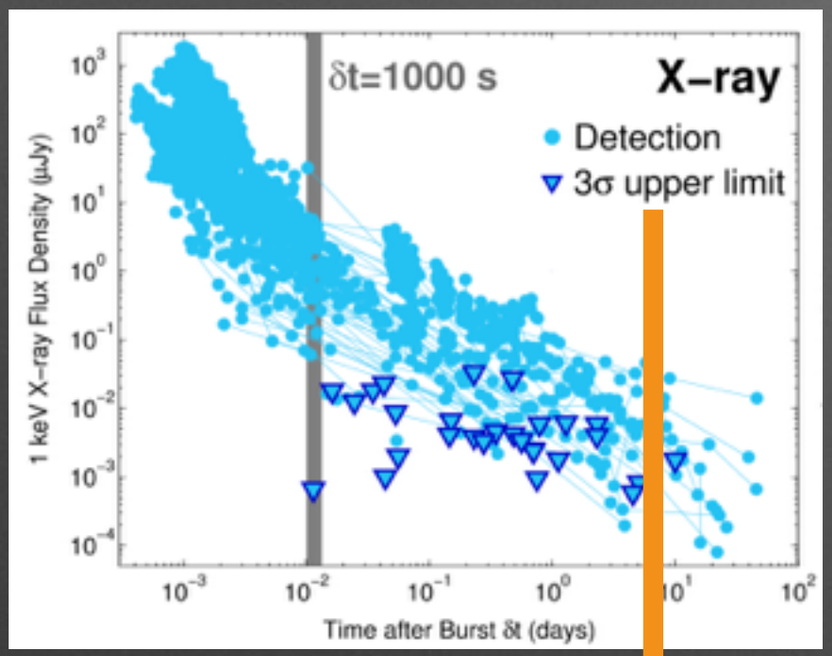
Discovery Frontiers

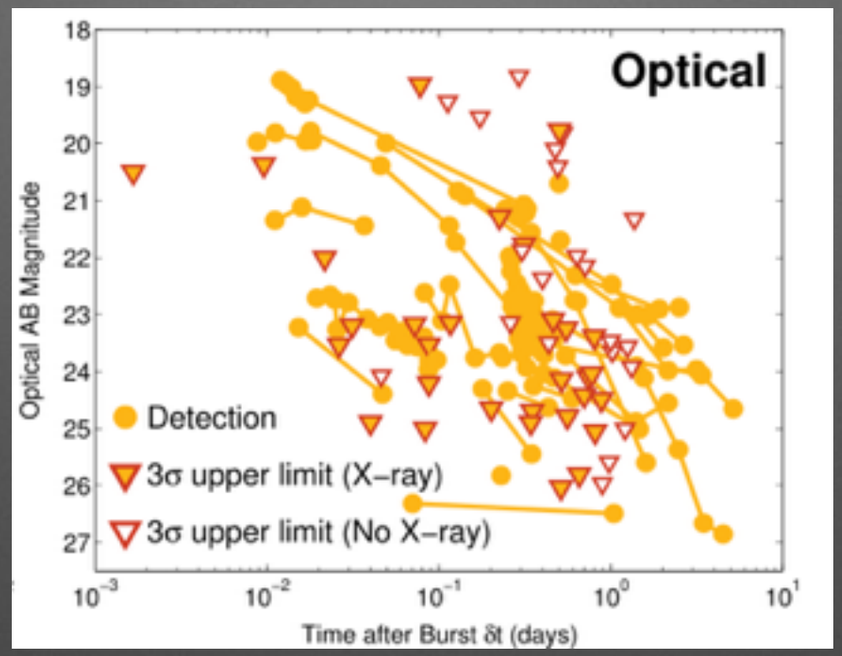
BH-NS mergers

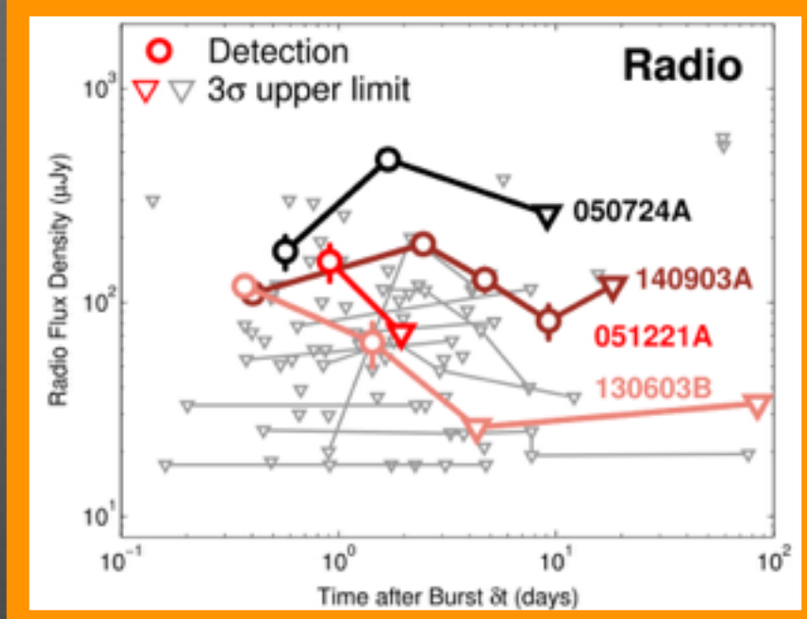
Population of BNS

Connection to Cosmology

ENERGETICS and SUB-PC ENVIRONMENTS of SGRBs







Fong+2015

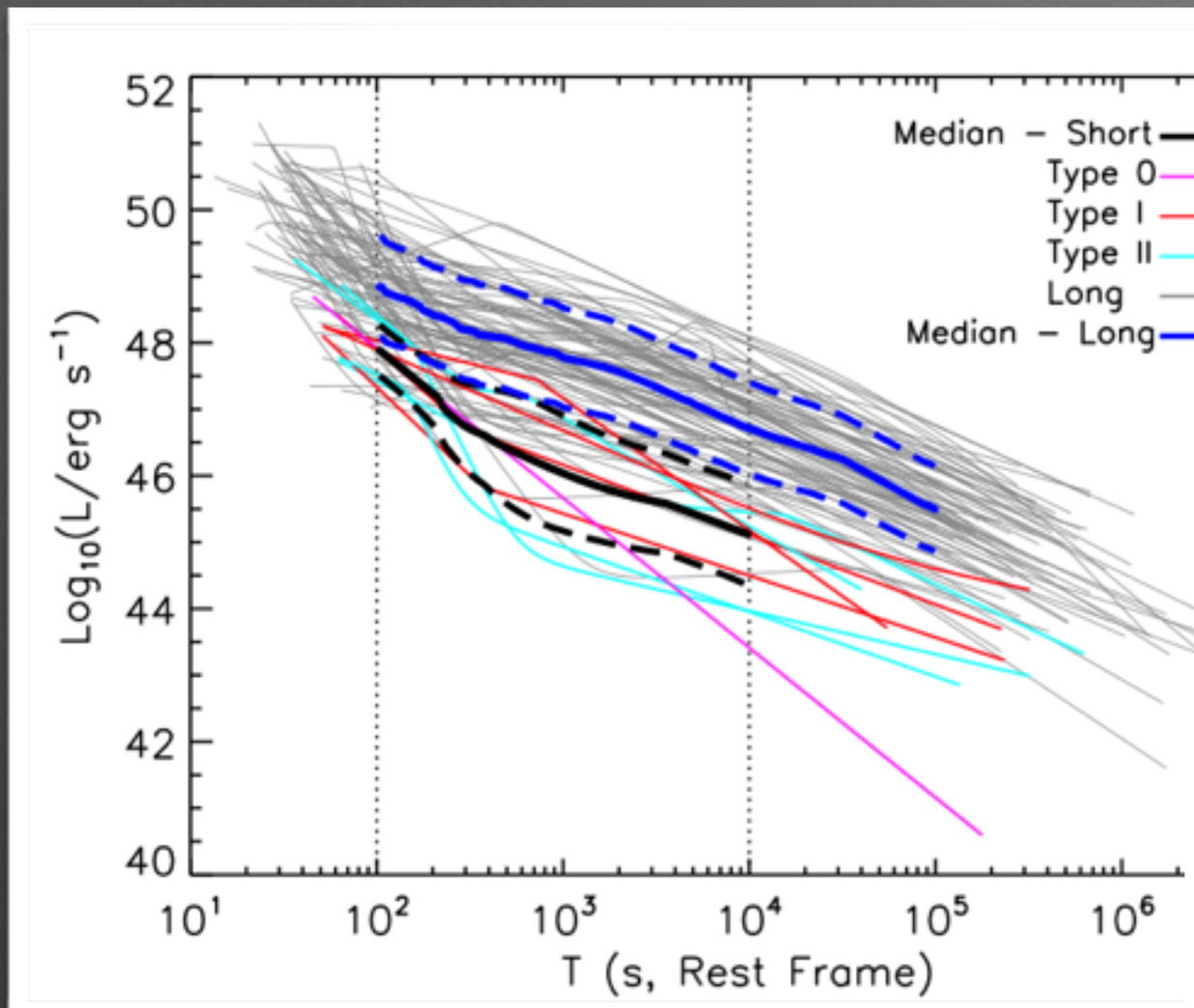
~10 days

Out of >100 SGRBs, 4 radio detections

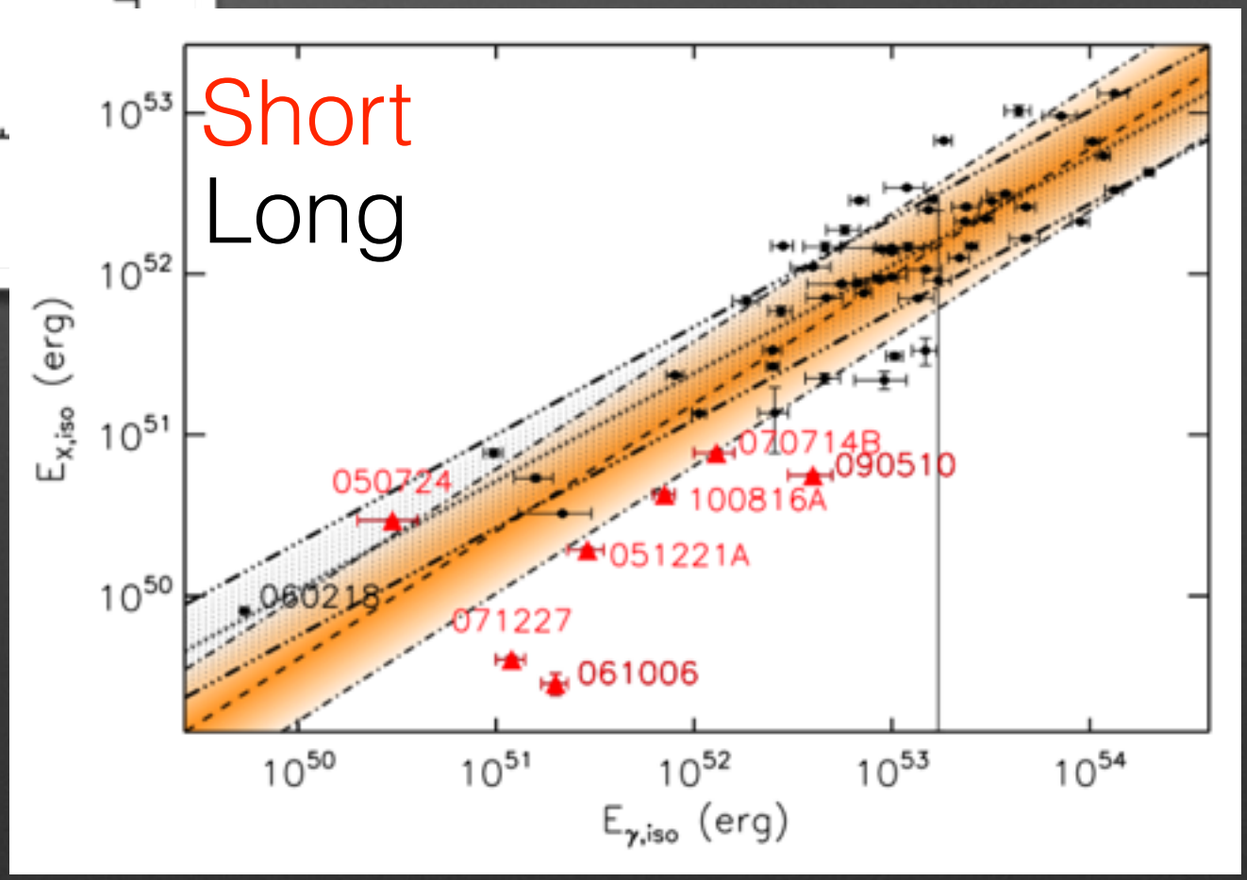
Impairs our ability to accurately constrain Ek, n, θ_{jet},

(+microphysics)

Lower X-ray Luminosity —-> Lower Energy, density

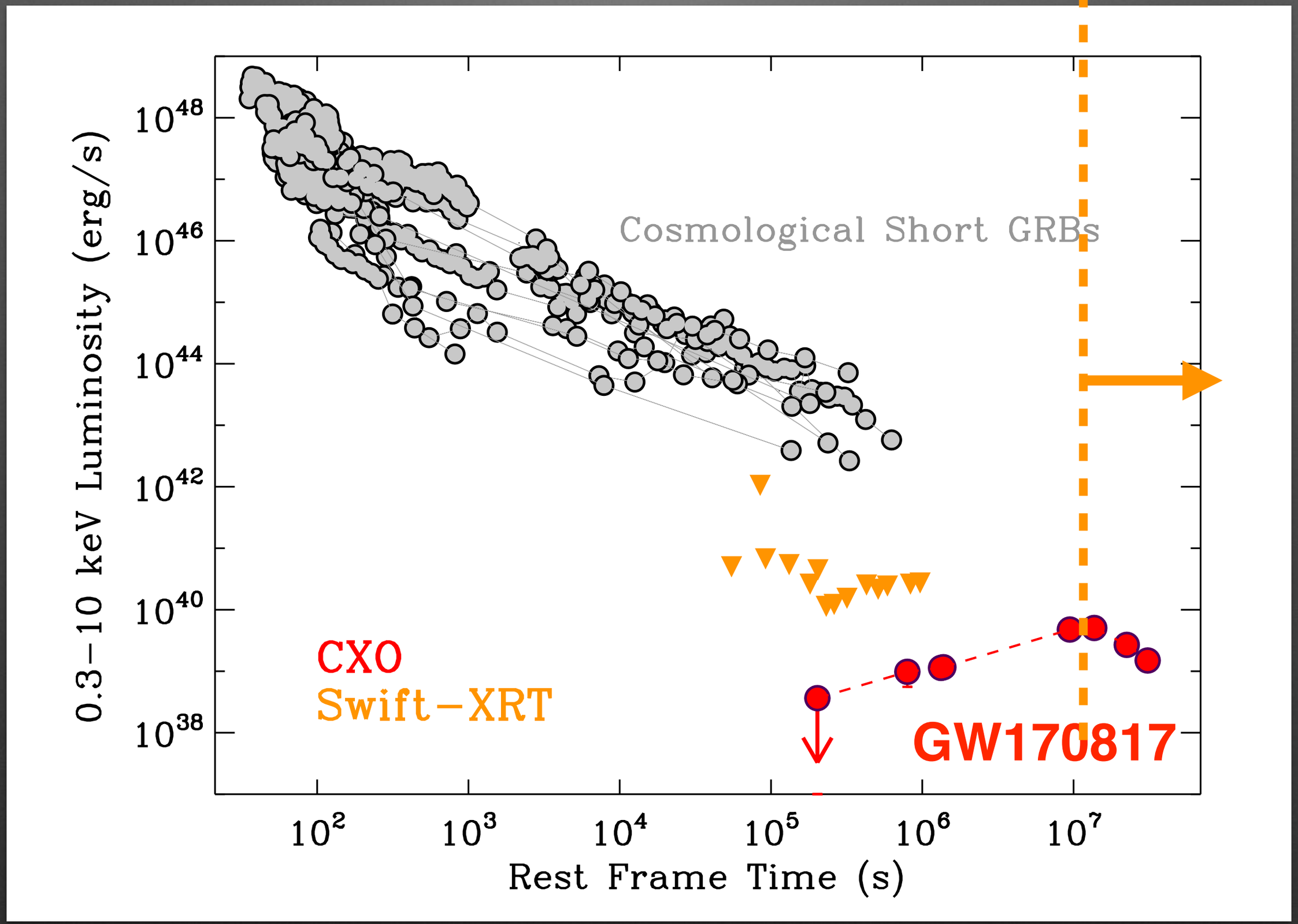


Margutti+2013

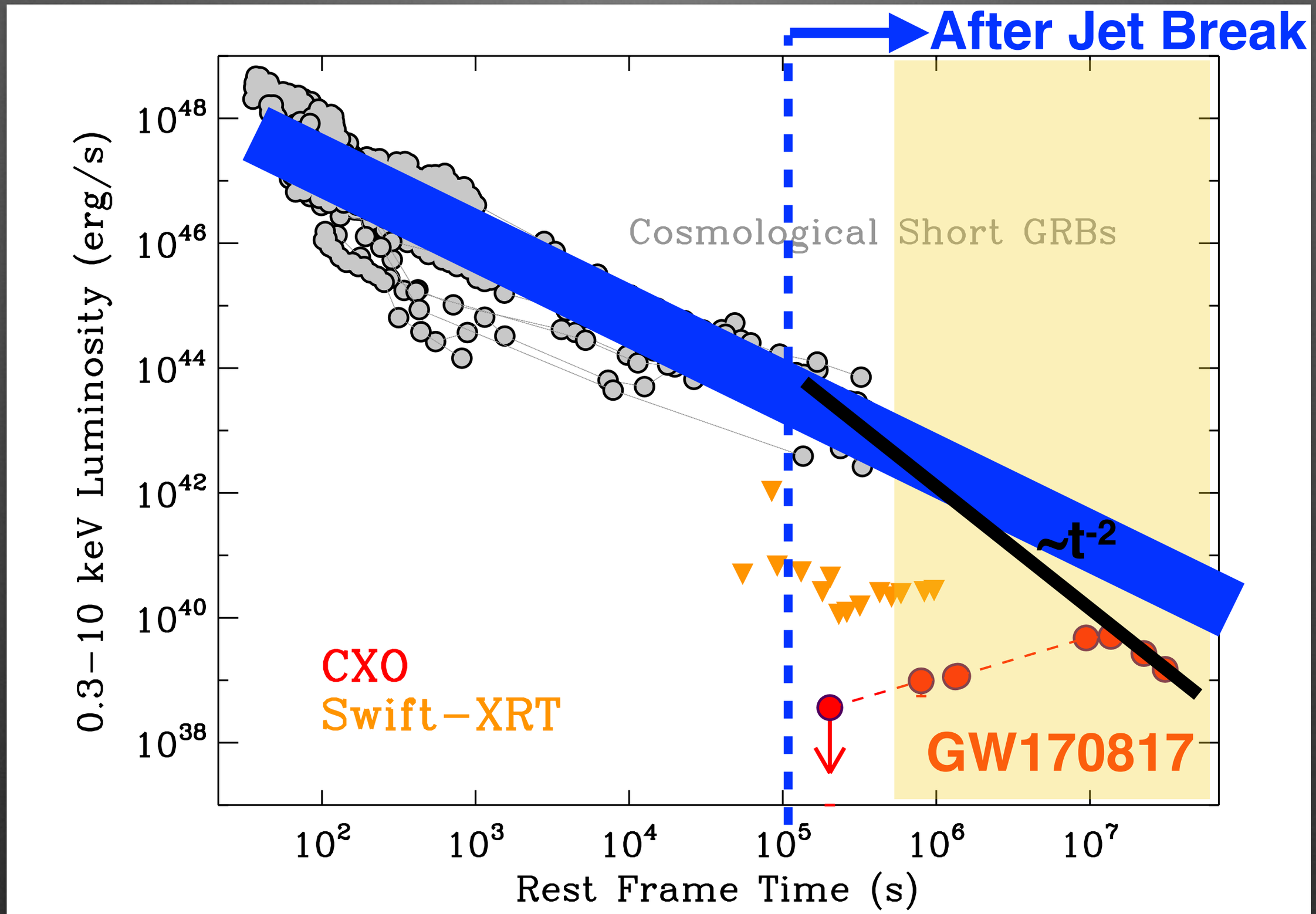


Margutti+2013

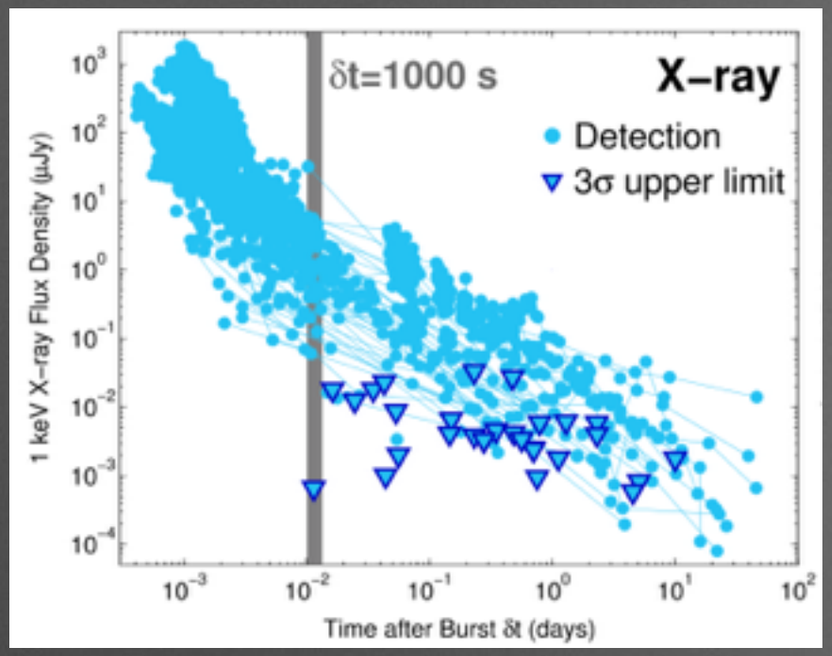
Jet comes into view

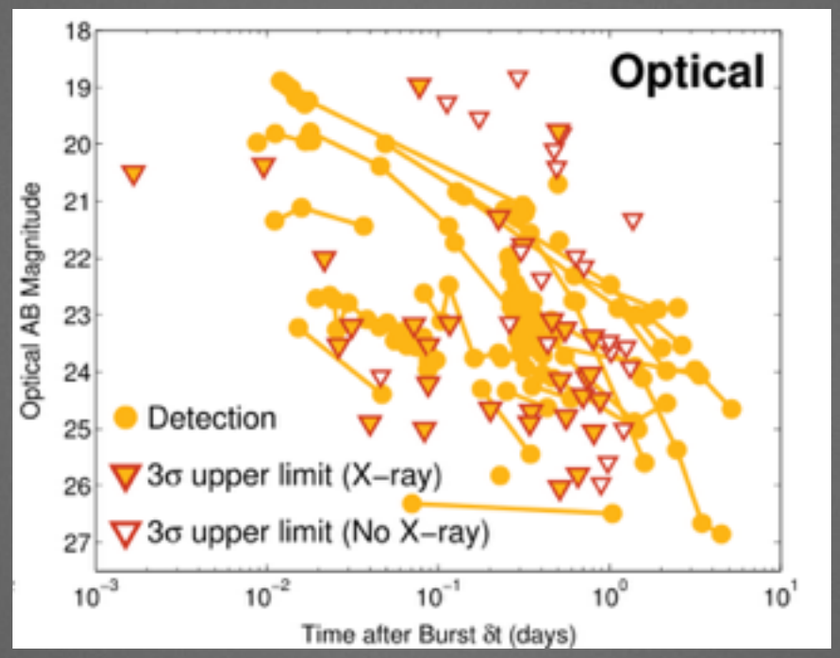


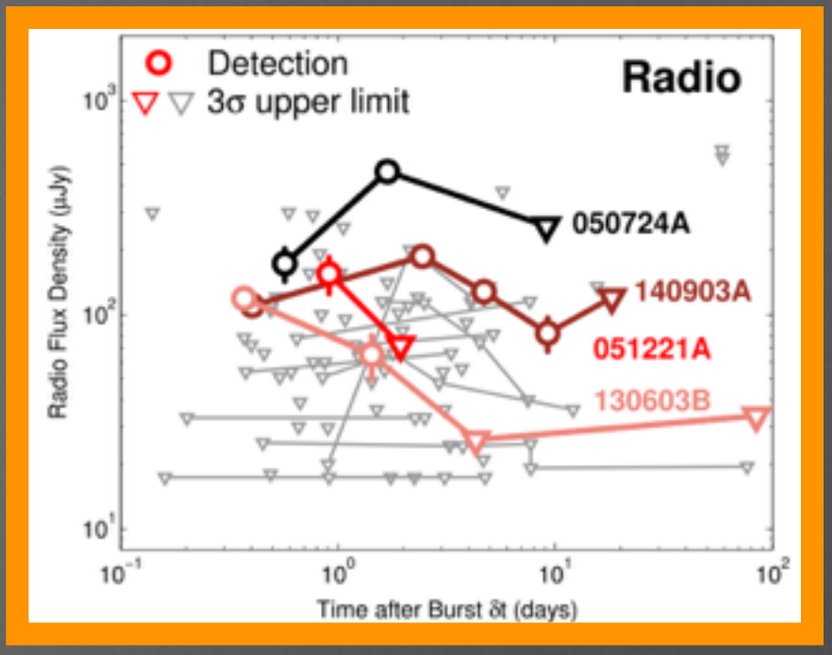
Hajela+2019


After Jet Break
Cosmological Short GRBs
0.3−10 keV Luminosity (erg/s)
10^{48}
10^{46}
10^{44}
10^{42}
10^{40}
10^{38}
~t^{-2}
CXO
Swift−XRT
GW170817
10^2
10^3
10^4
10^5
10^6
10^7
Rest Frame Time (s)

Hajela+2019







Observations are sparse, so we can't solve for all the model parameters, and typically we do not know **ν**sa, **ν**m, **ν**c

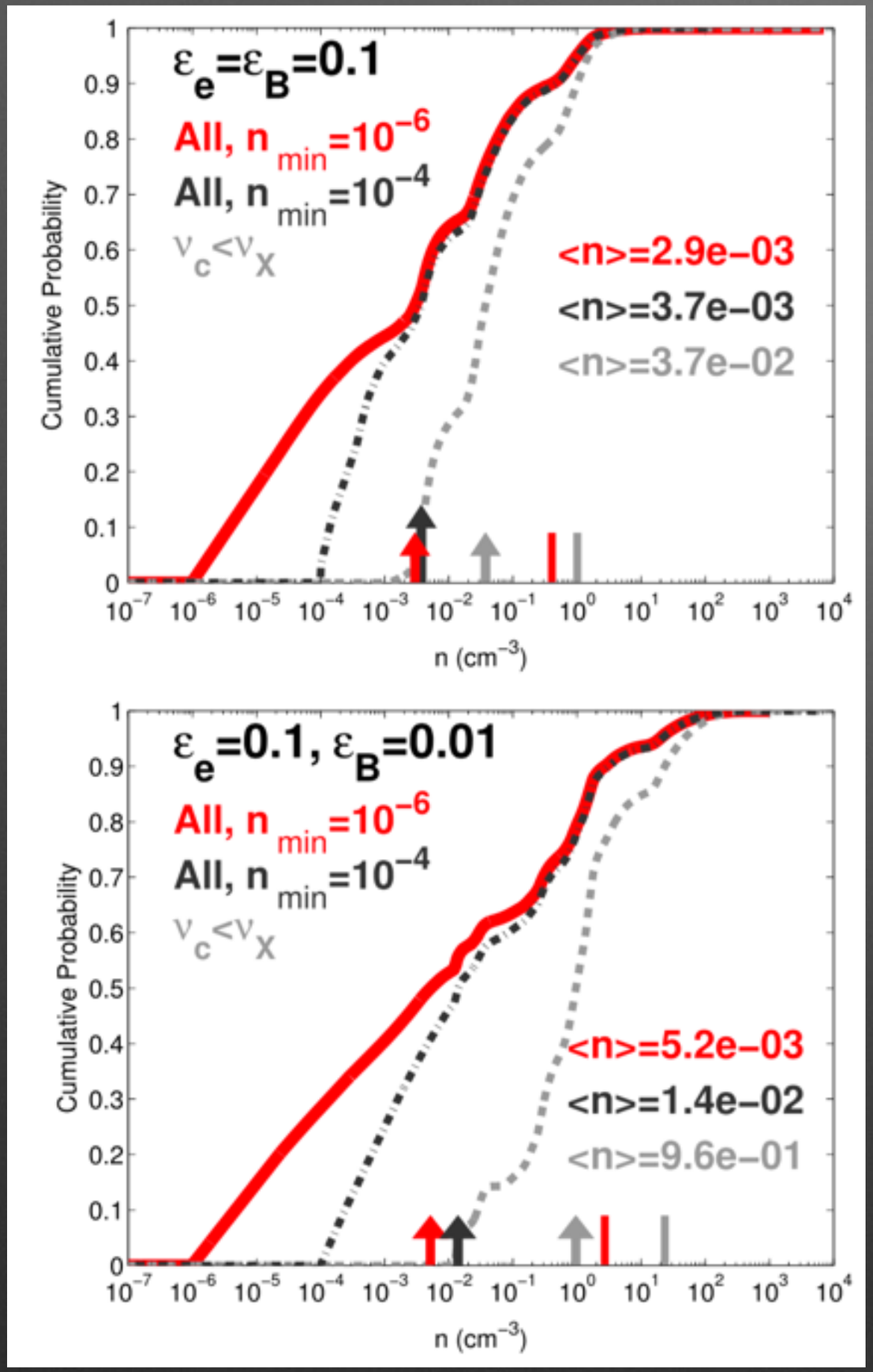
(= we do not solve for **ϵ**_e and **ϵ**_B)

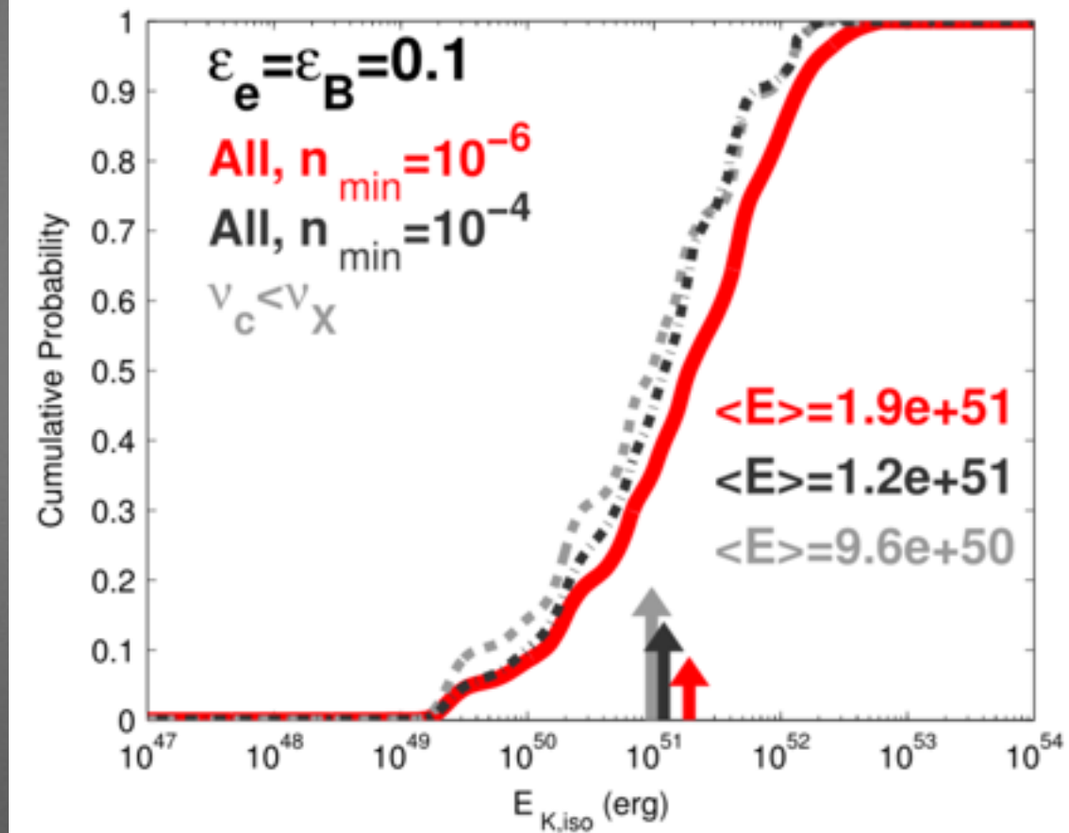
==> location of **ν**sa, **ν**m, is typically a reasonable assumption,

νc is inferred for ~50% of the sample.

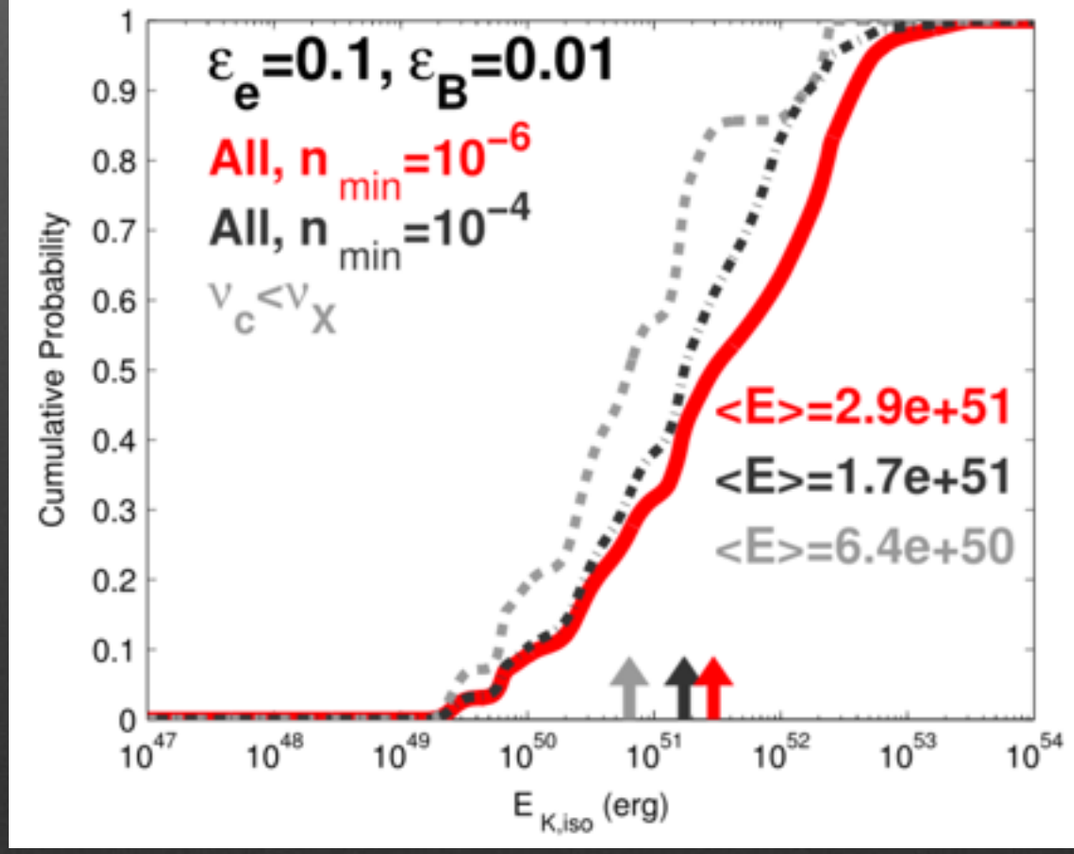
νm (**ν**sa)< Optical< **ν**c

Radio < **ν**m





Fong+2015

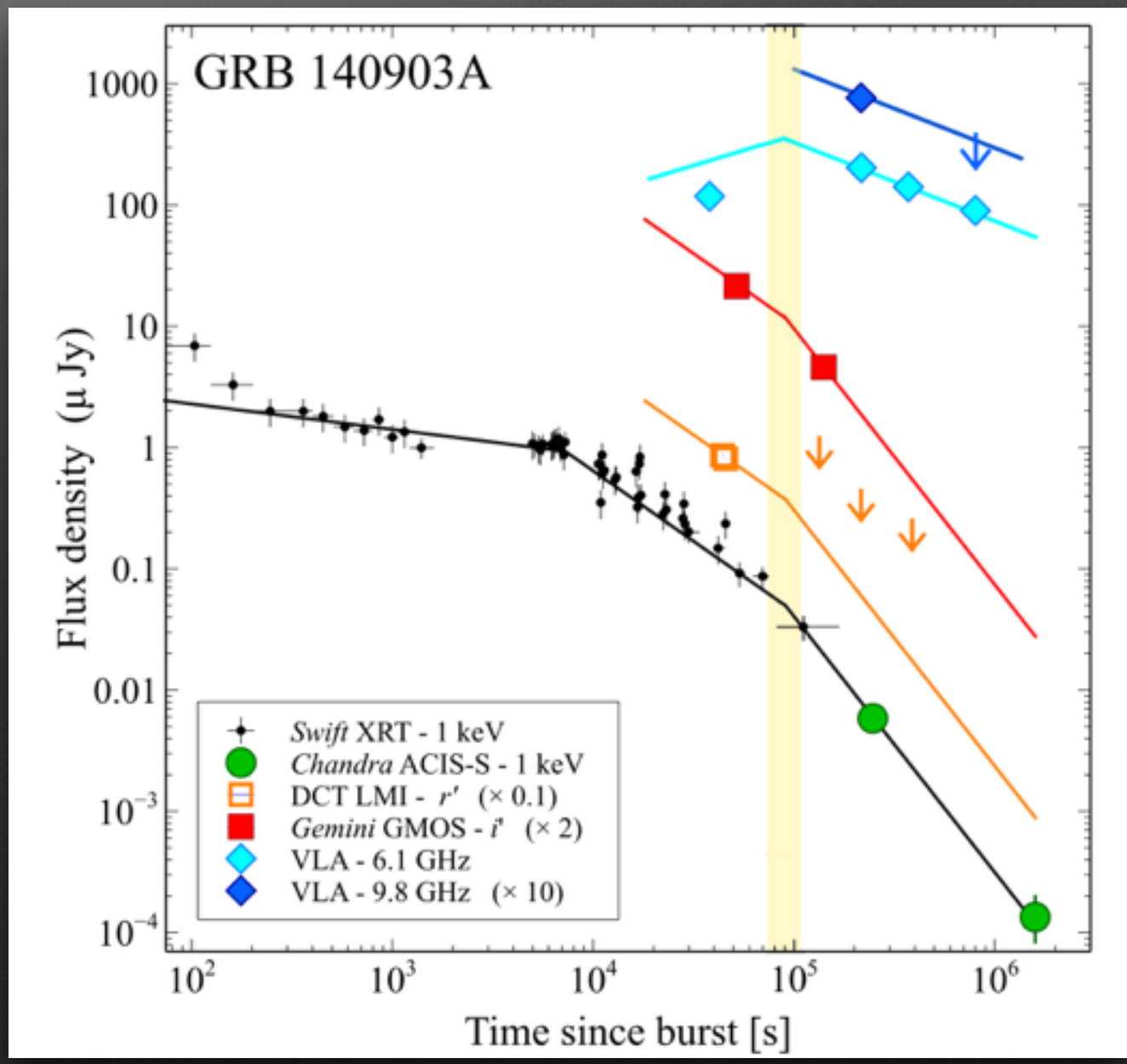


Fong+2015

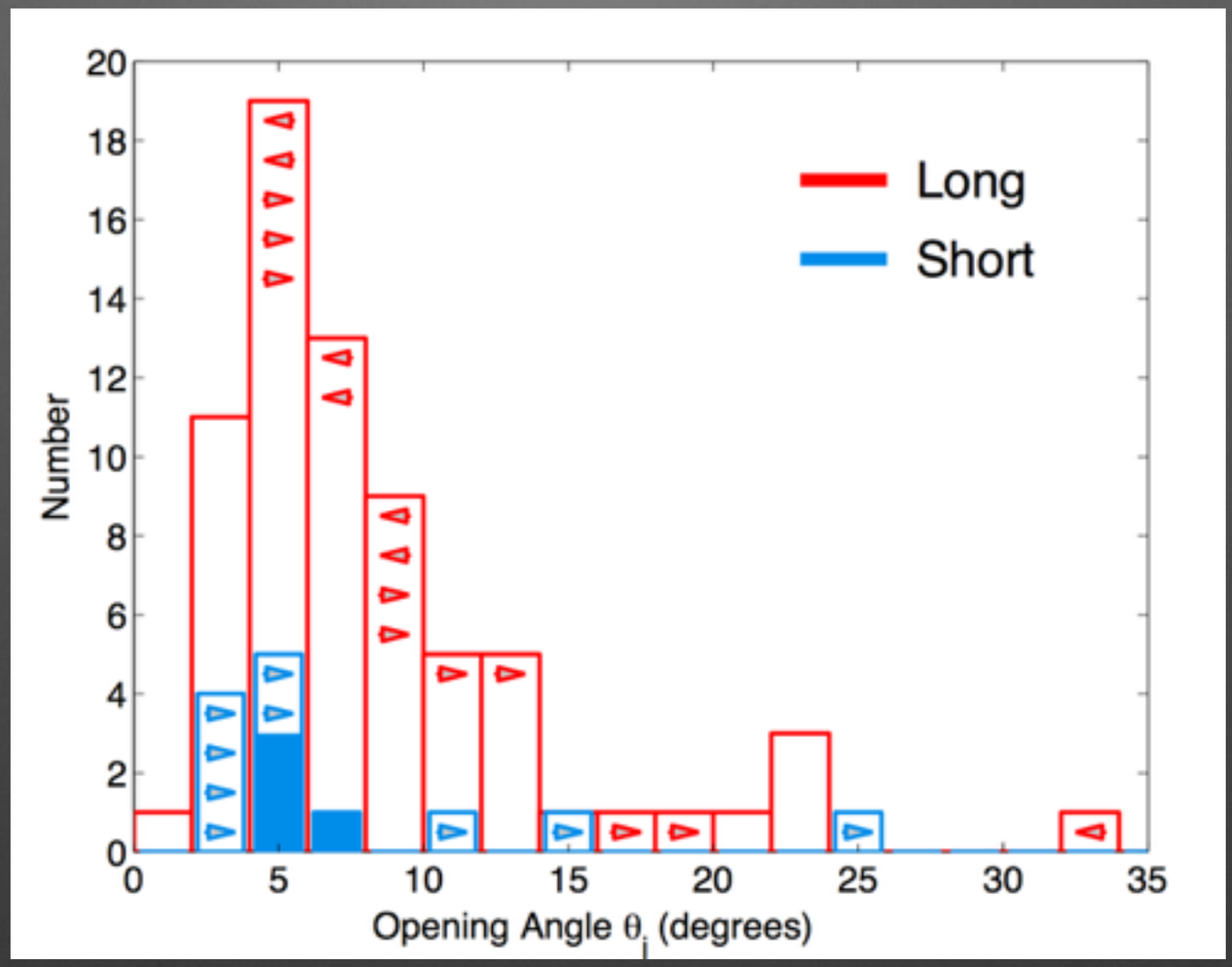
COLLIMATION of the FASTEST EJECTA

==> Jet Breaks

Best example:



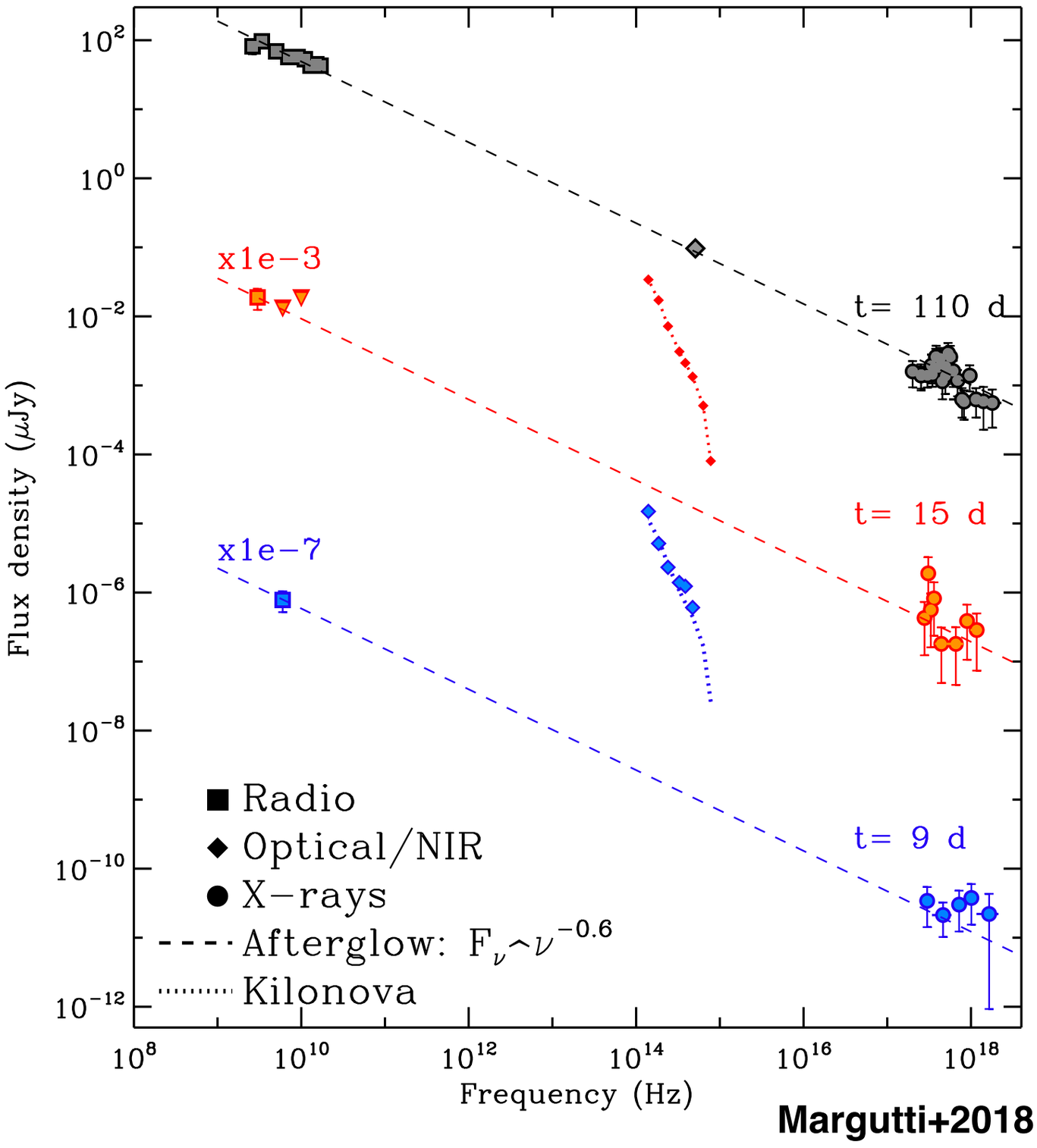
Collimation in SGRBs
==> Jet Breaks



Fong+2015

Very small statistics of few

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

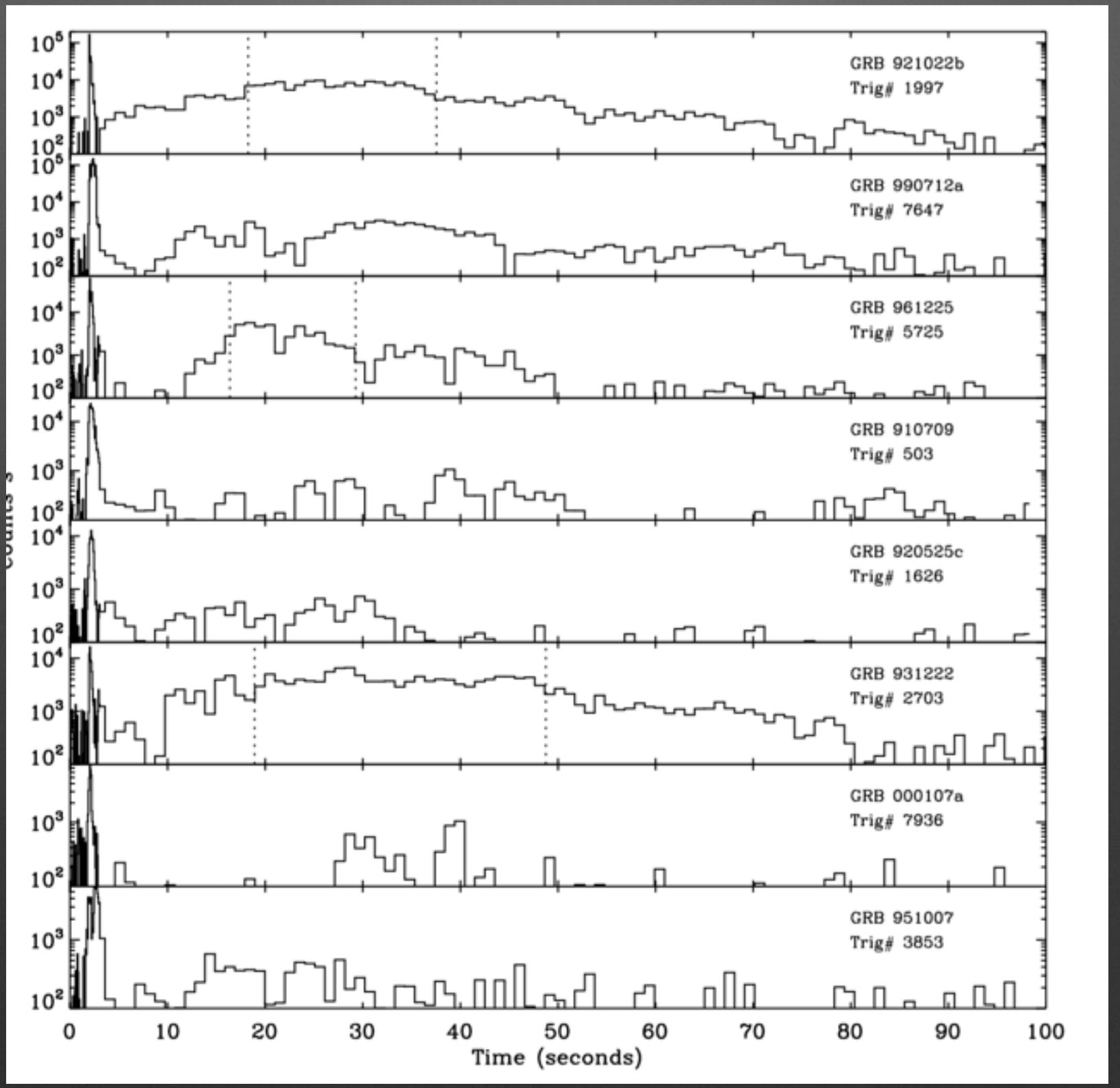
WHAT WE DO NOT UNDERSTAND?

(1) Extended Emission

(2) Temporal Variability

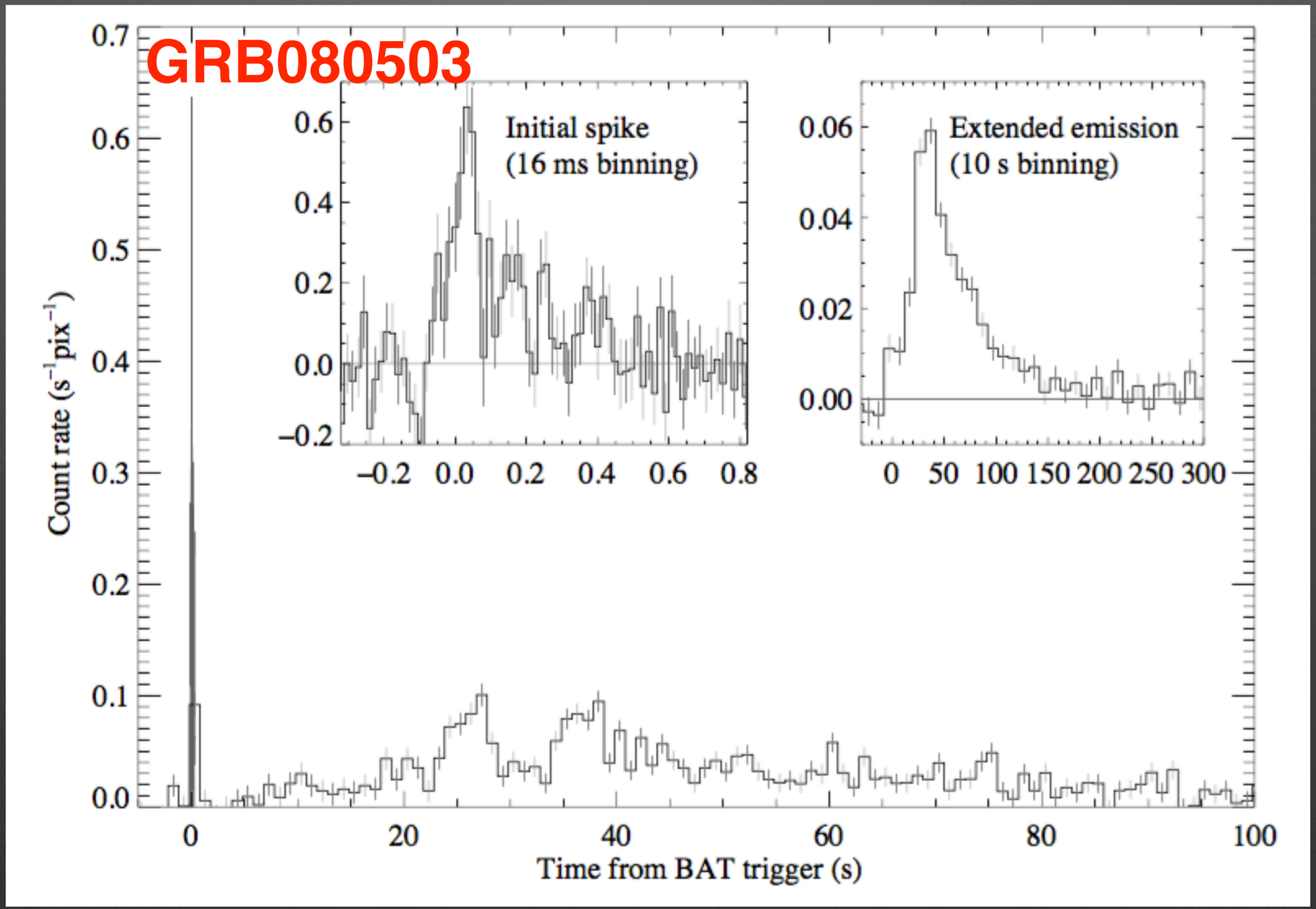
(3) GRB130603B - X-ray excess

Extended Emission



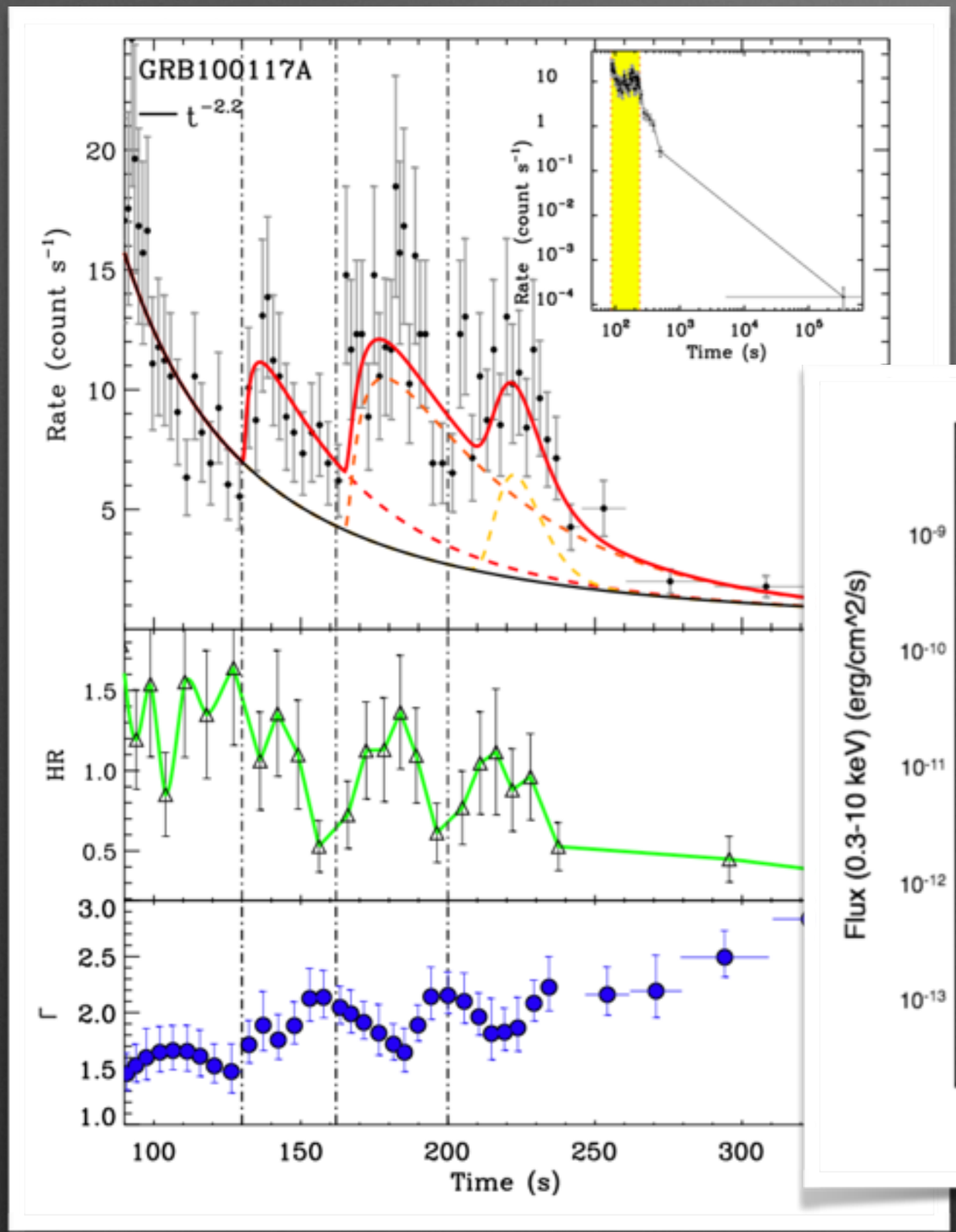
Norris & Bonnel 2006

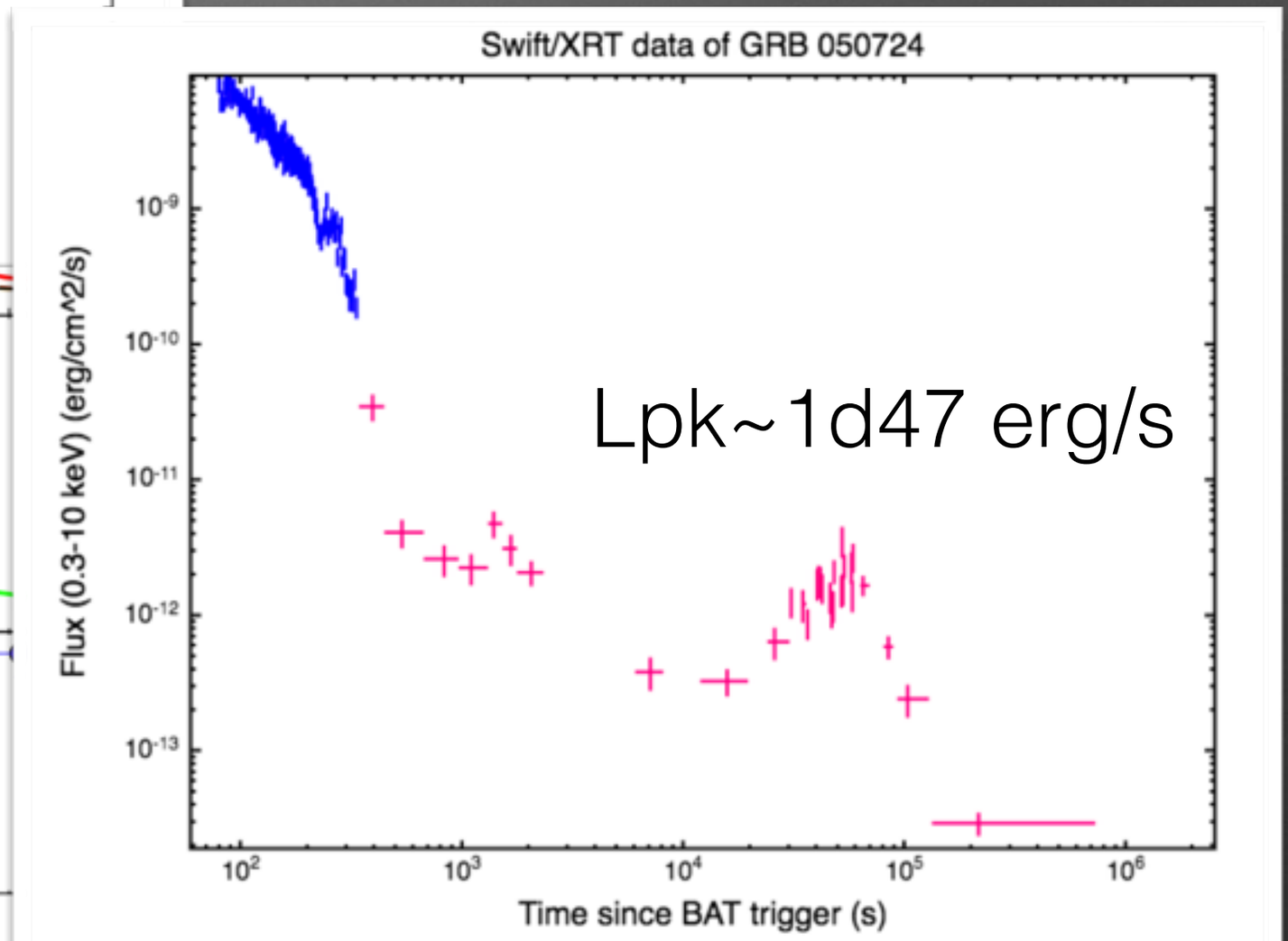
Extended Emission



Perley+2009

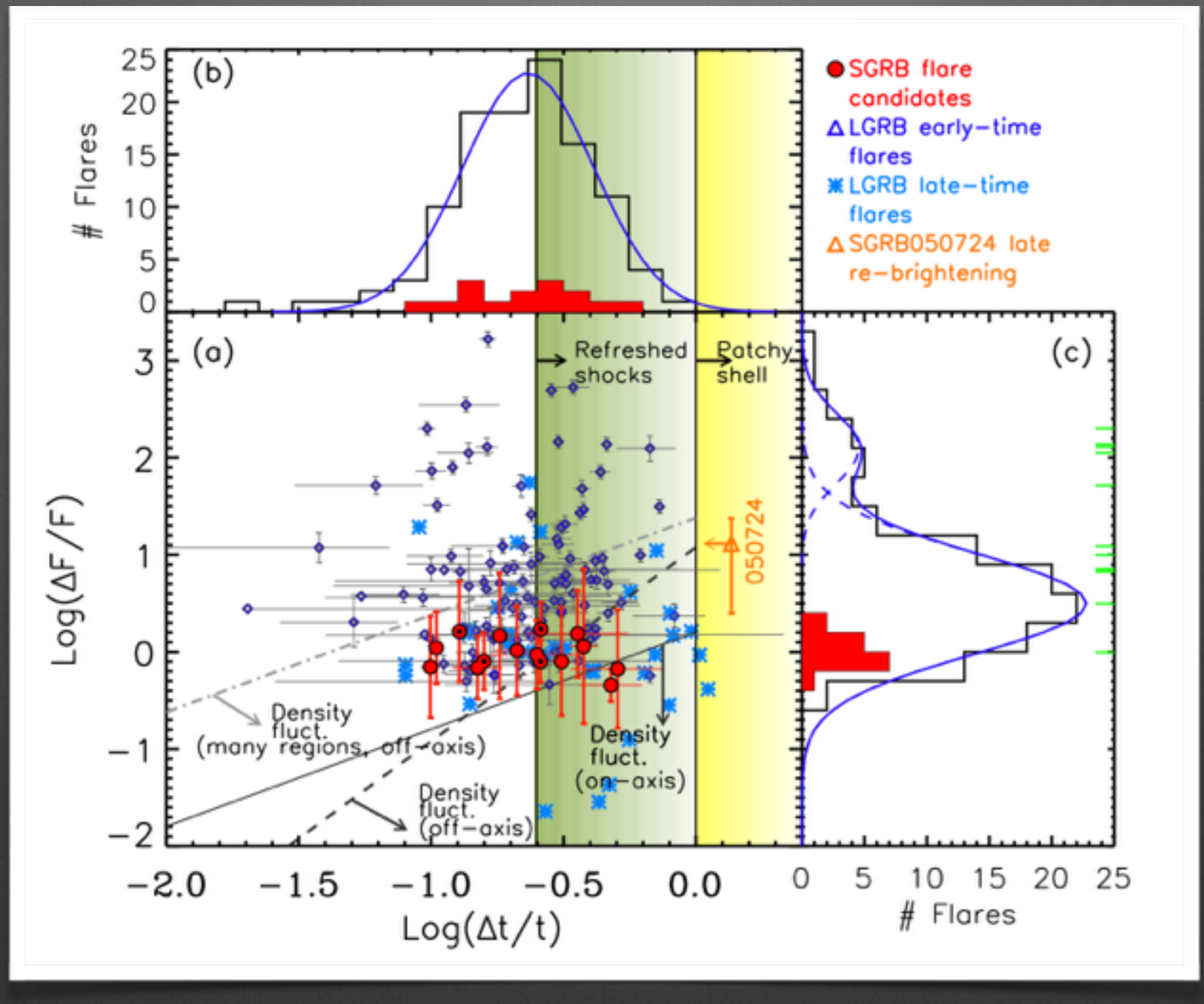
SGRB X-ray Variability





Margutti+12

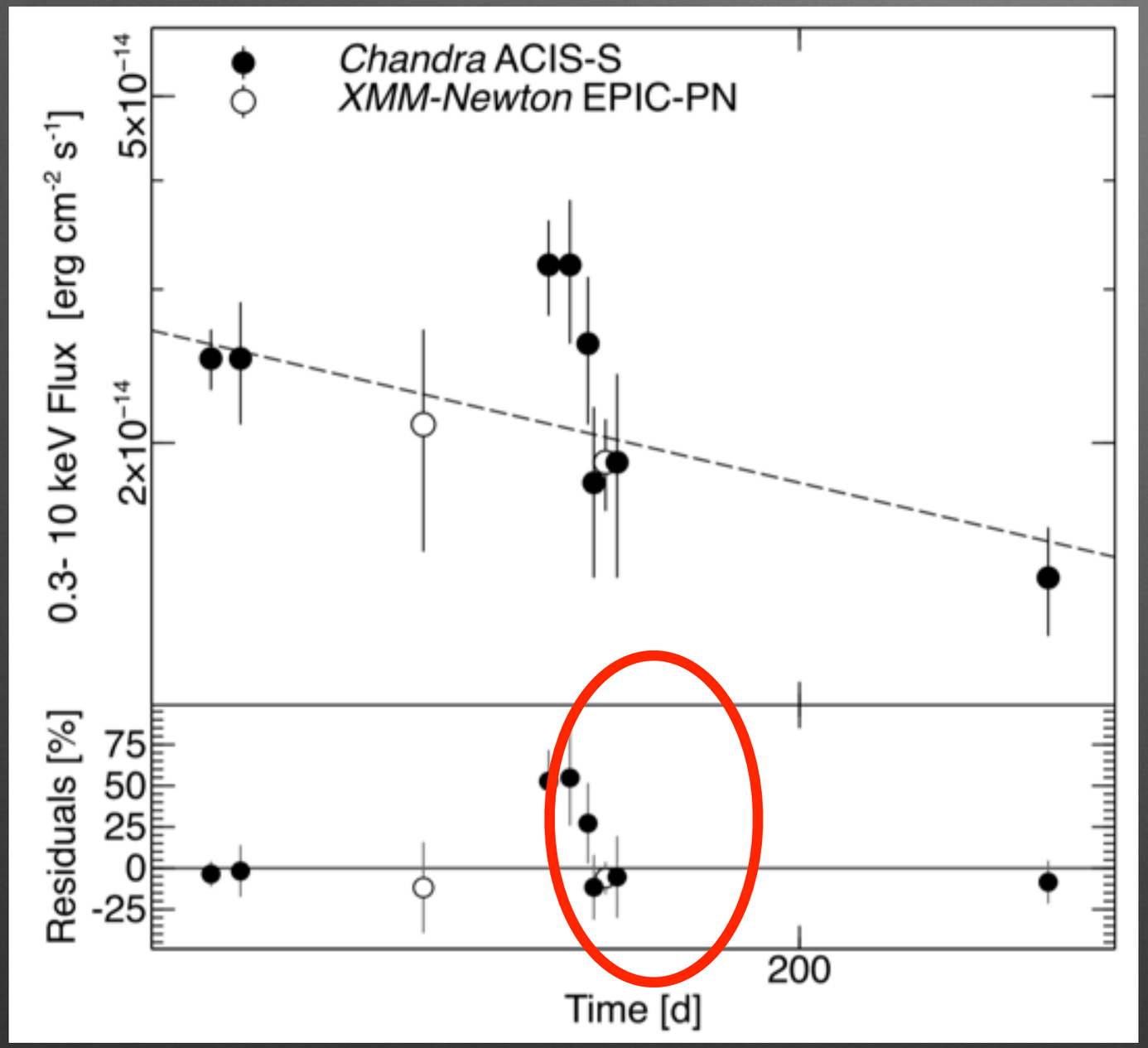
SGRB X-ray Variability



Margutti+2011

X-ray variability in GW170817?

X-ray variability in GW170817?

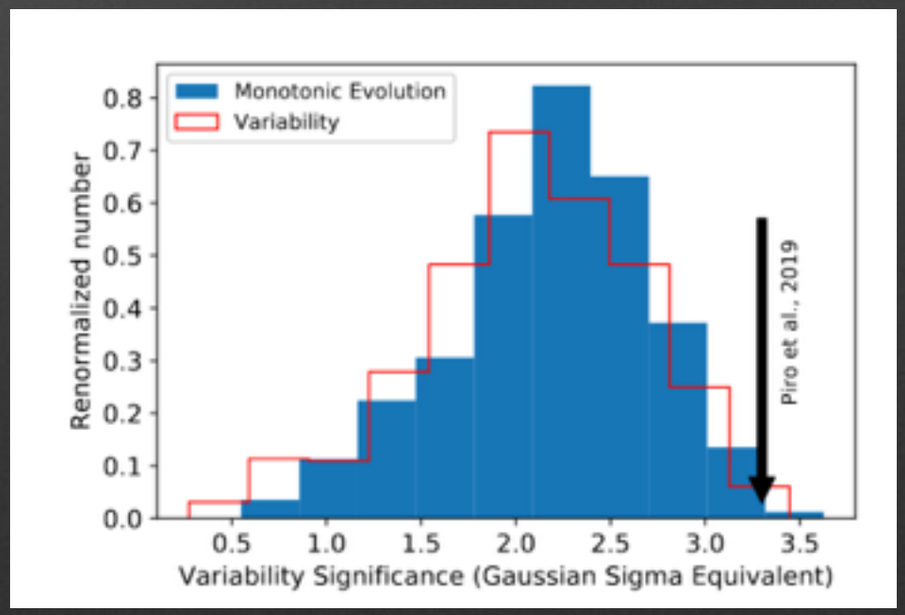


Piro+2018

Poissonian Probability = 3.3 σ (*not accounting for trials)

Piro+2018

Reduced statistical significance of 2.2 σ when the number of trials is properly accounted for



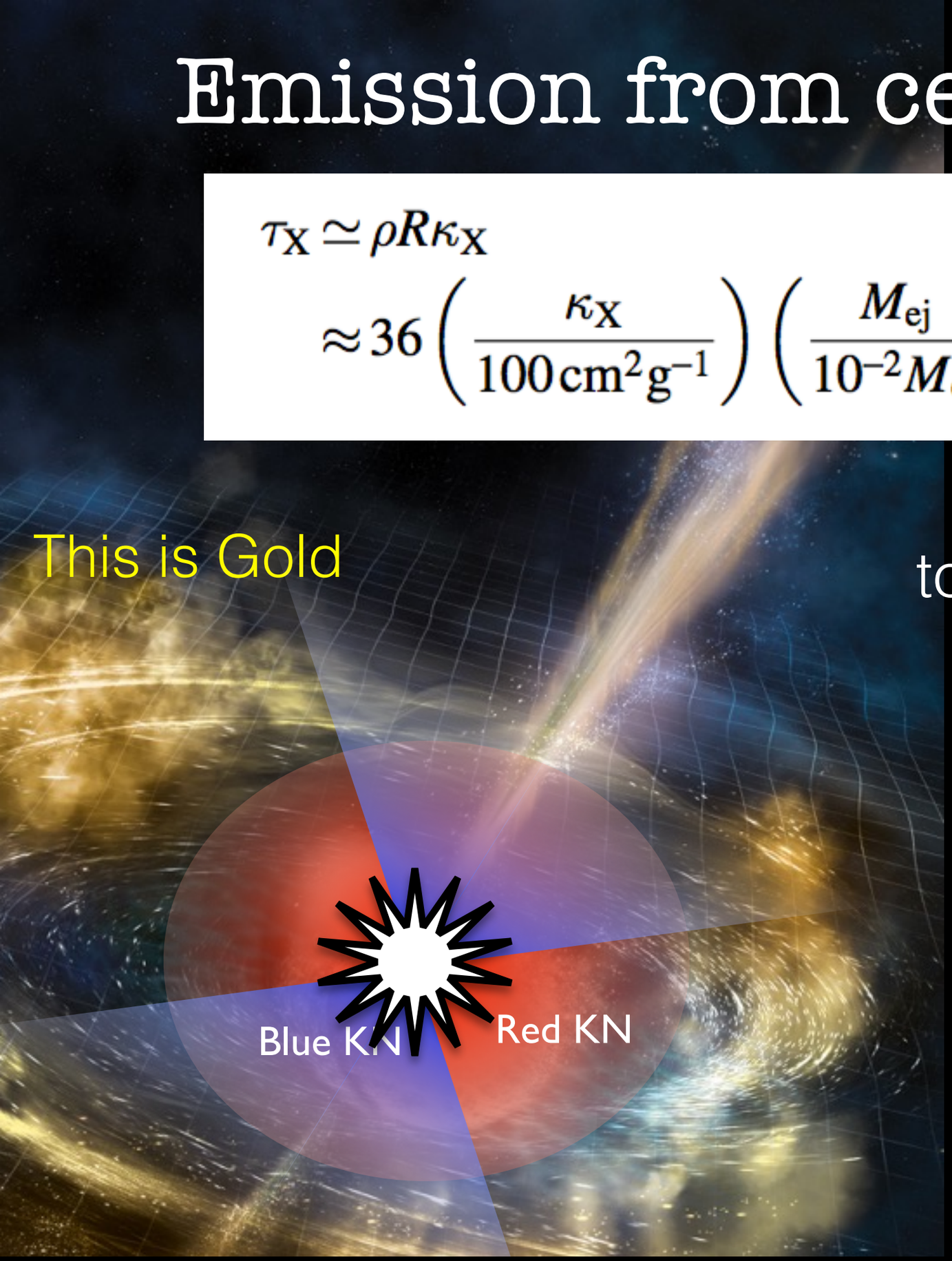
Hajela+2019

The nature of the remnant

Emission from central engine?

$$\tau_X \simeq \rho R \kappa_X$$
$$\approx 36 \left(\frac{\kappa_X}{100\,\mathrm{cm^2 g^{-1}}}\right)\left(\frac{M_{ej}}{10^{-2} M_\odot}\right)\left(\frac{v_{ej}}{0.2c}\right)^{-2}\left(\frac{t}{1\,\mathrm{week}}\right)^{-2} \quad (1)$$

This is Gold



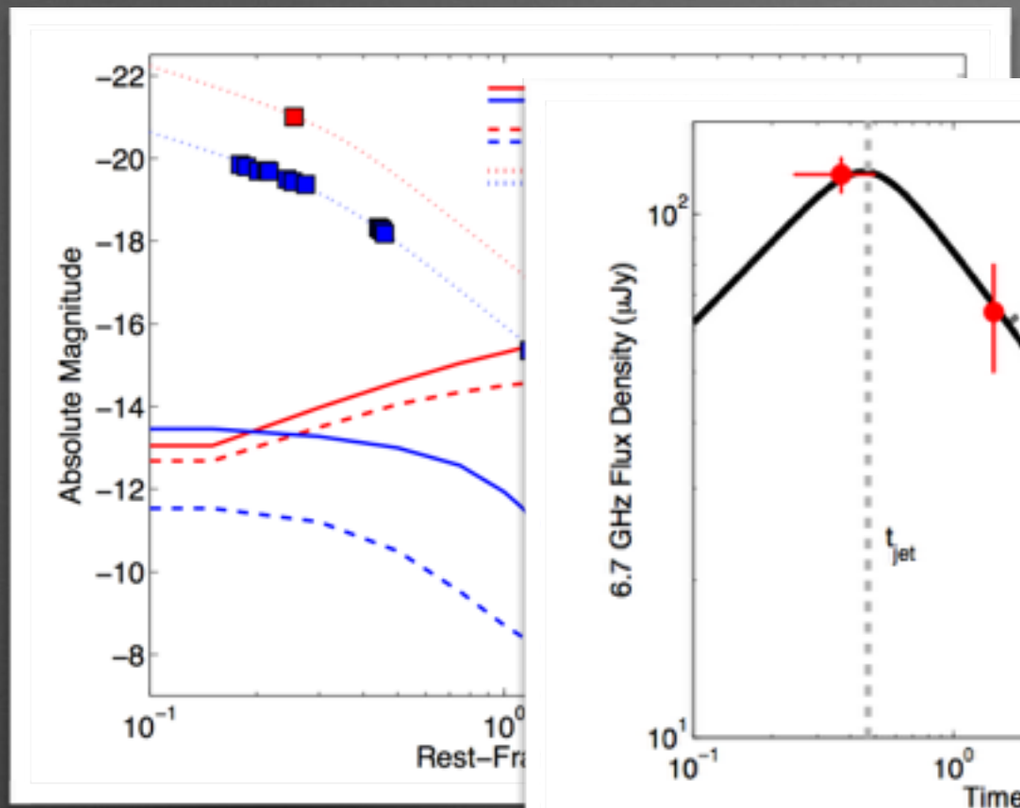
Unlikely to be able
to escape at early times
t<100 days

BUT:
photoionization of the
ejecta (for Lx>10^44 erg/s)

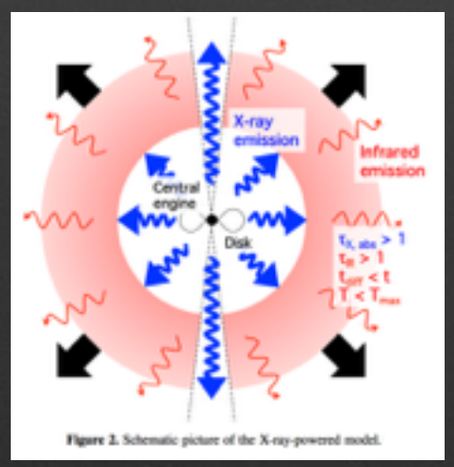
Funnel geometry

Nakar & Piran 2011; Metzger & Berger 2012; Metzger & Bower 2014; Hotokezaka & Piran 2015

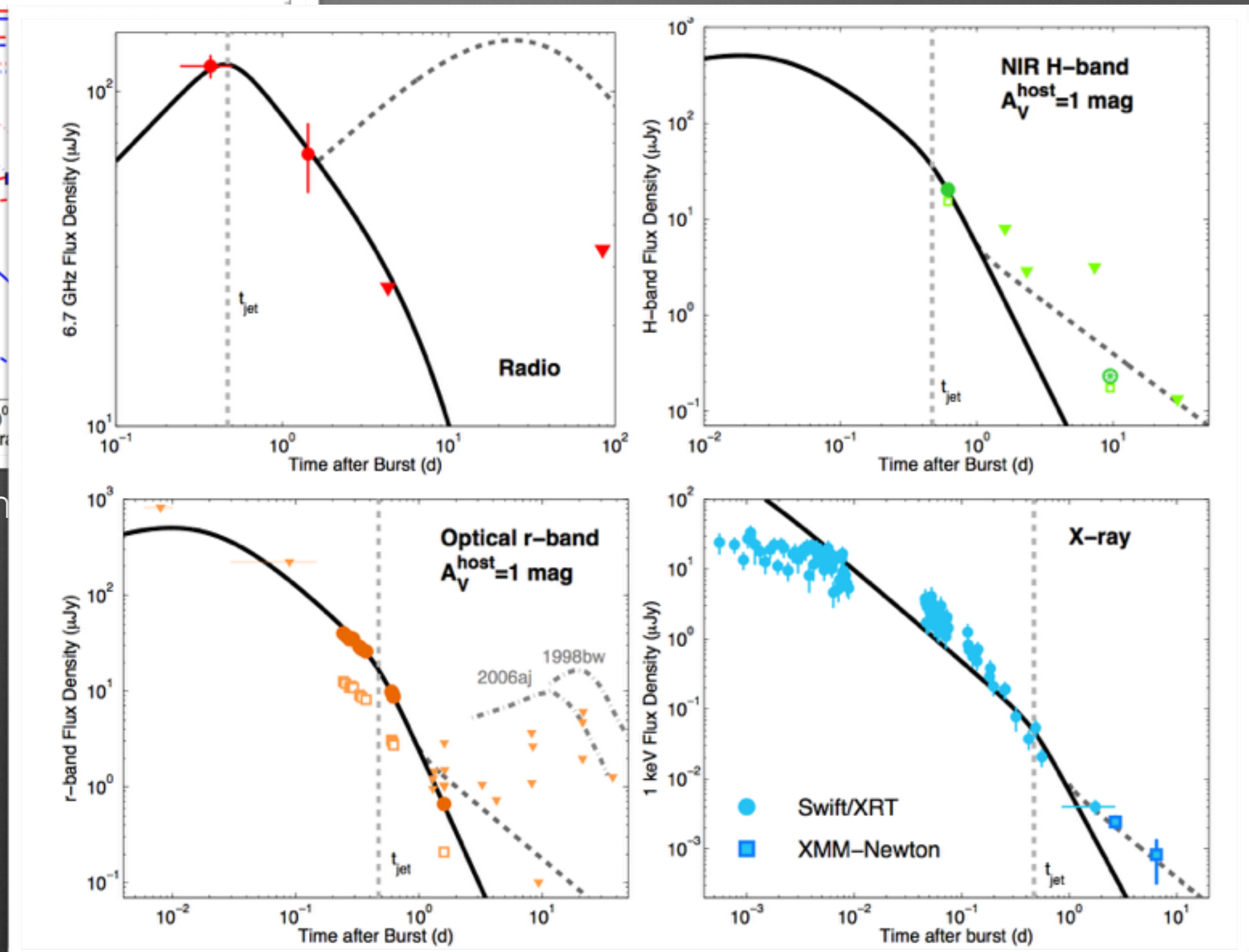
X-ray "excess" in GRB130603B



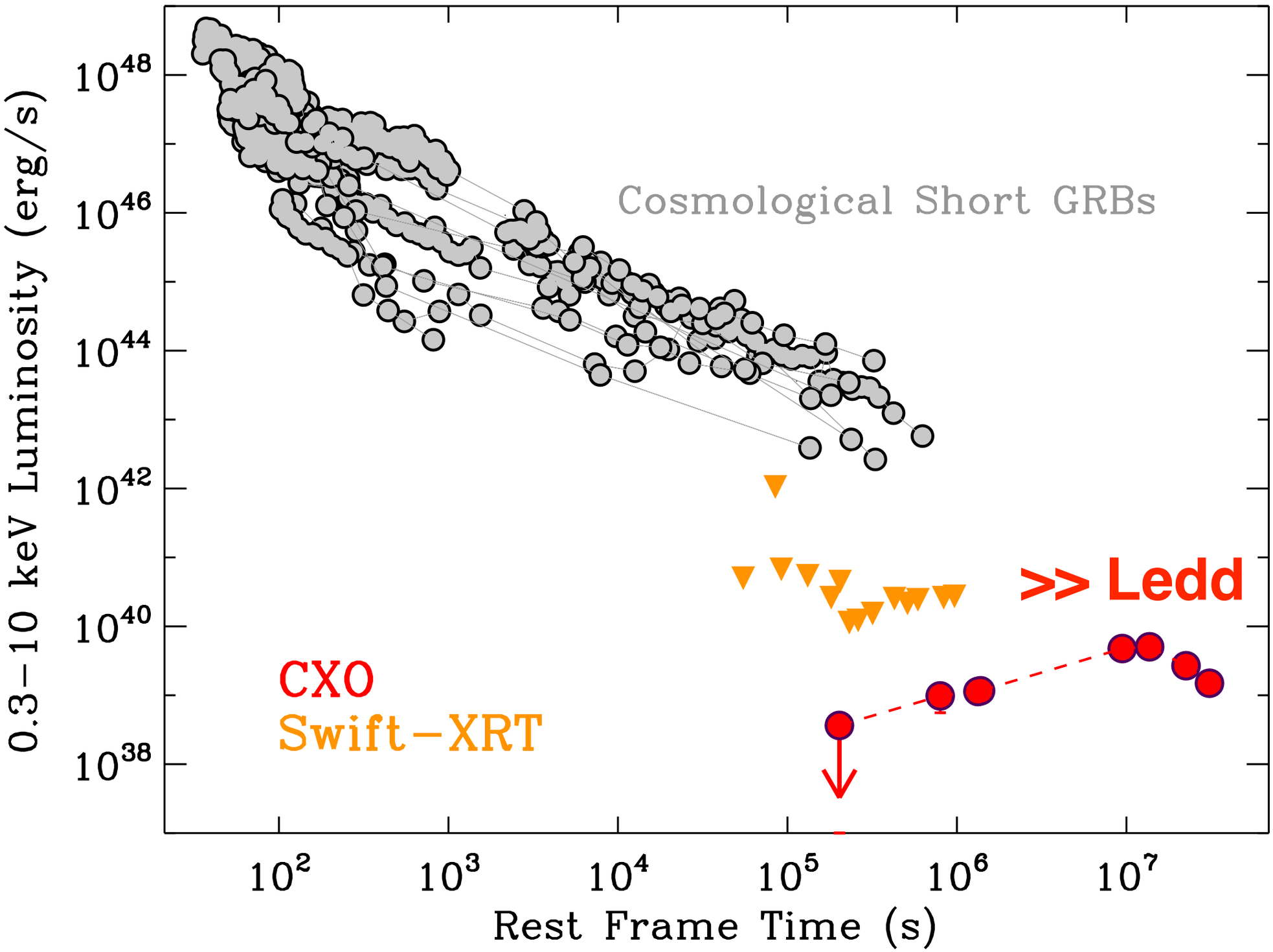
Berger+2013, Tan



Kisaka+2016



Fong+2014


Cosmological Short GRBs
>> Ledd
CXO
Swift−XRT
0.3−10 keV Luminosity (erg/s)
10^{48}
10^{46}
10^{44}
10^{42}
10^{40}
10^{38}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Rest Frame Time (s)

GW170817 in the context of SGRBs: why GW170817 (and alike) is a unique opportunity

Constraining the physical parameters of BNS outflows

Nature of the remnant

Discovery Frontiers

BH-NS mergers

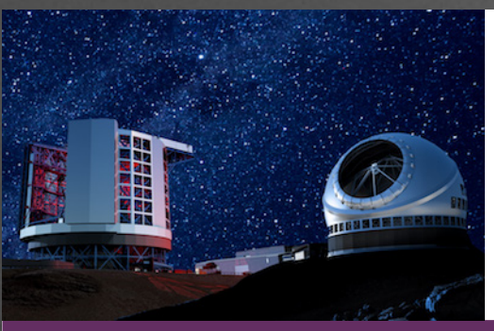
Population of BNS

Connection to Cosmology

Future obs of GW170817

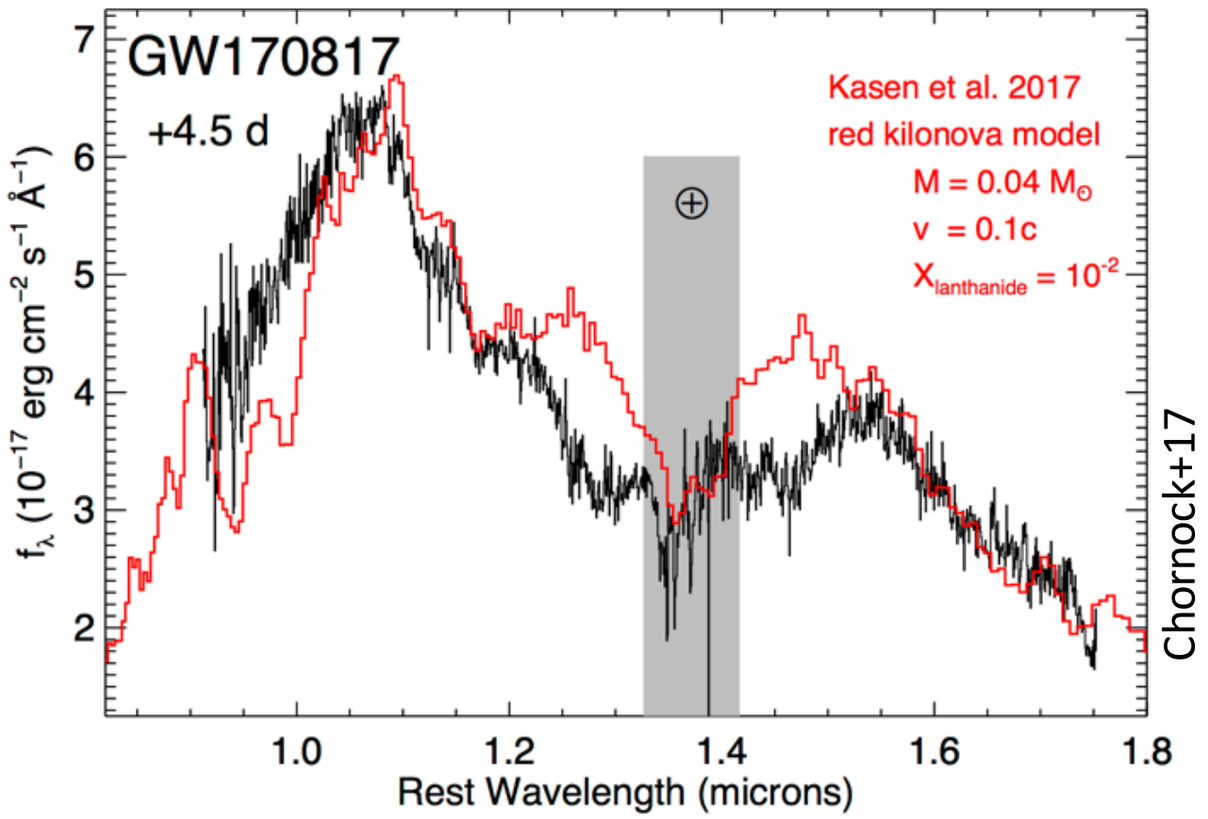
Spectroscopic characterization: the Extremely Large Telescopes (ELTs)

Conveners for Time Domain and MMA: D. Milisavljevic, R. Chornock
Representative on the US-ELT Advisory Committee: Margutti



Heavy elements production in the Universe

Chemical Enrichment of the Universe: **Production and Enrichment history** of the heaviest chemical elements

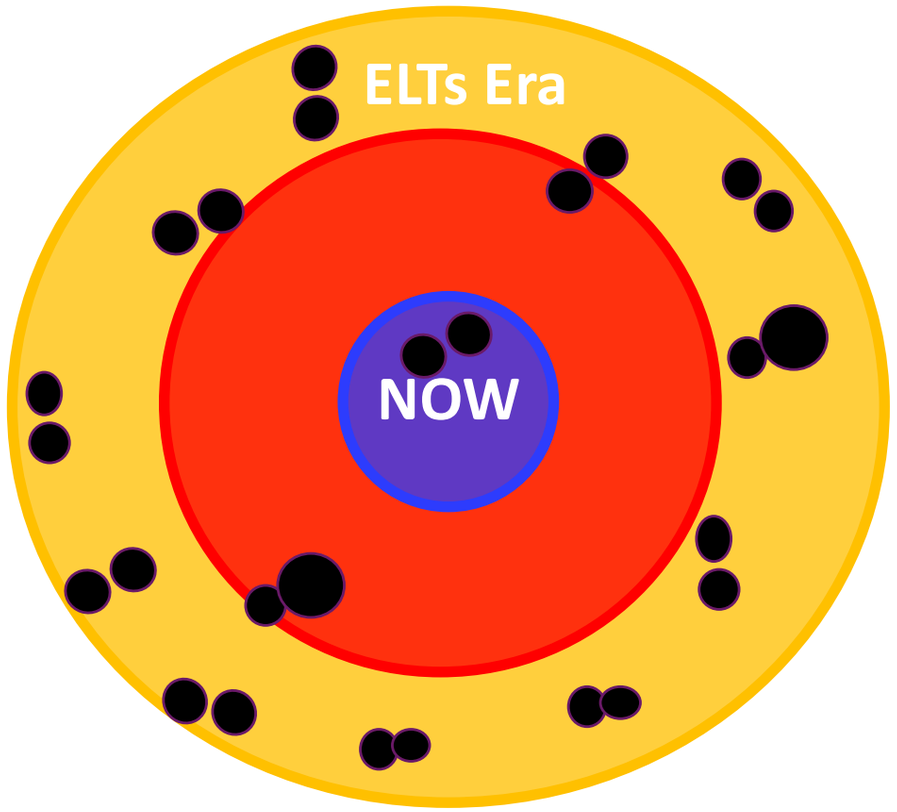


Why the ELTs?

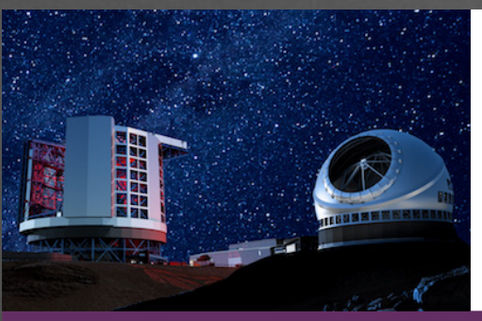
z=0.024

z=0.1

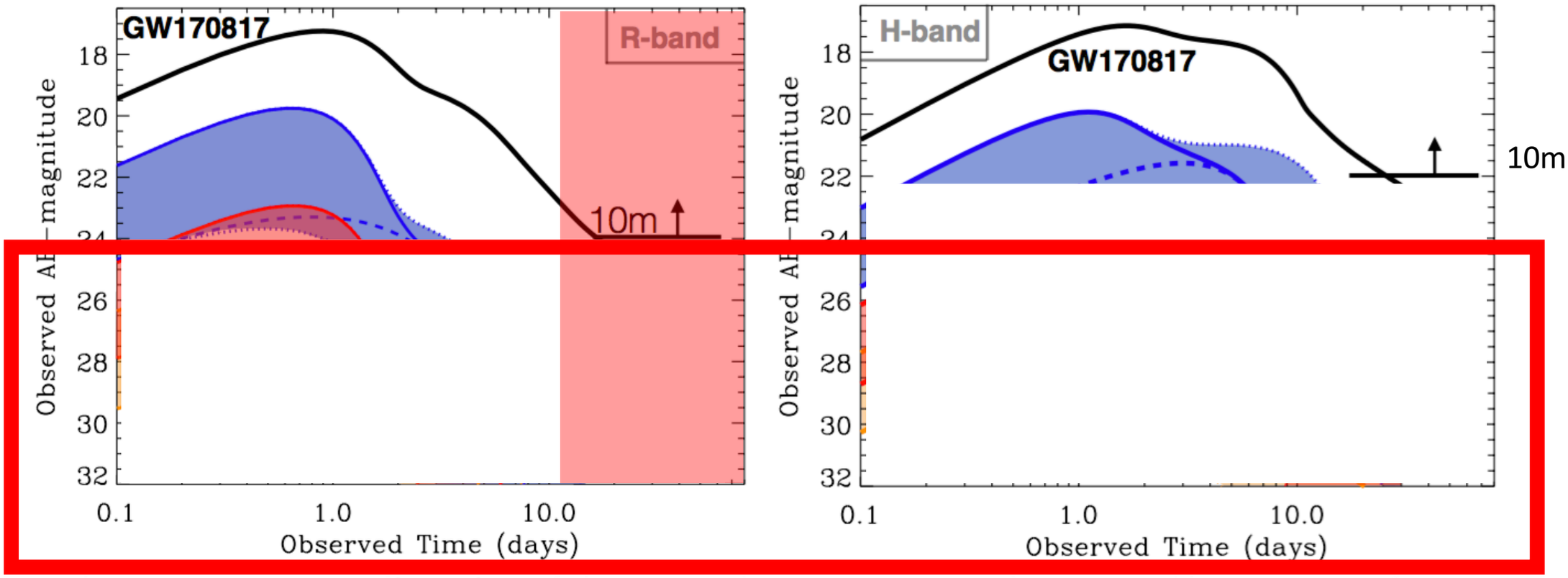
z=0.2



Mapping the spectroscopic **diversity** of the **most distant mergers** discovered by GW interferometers



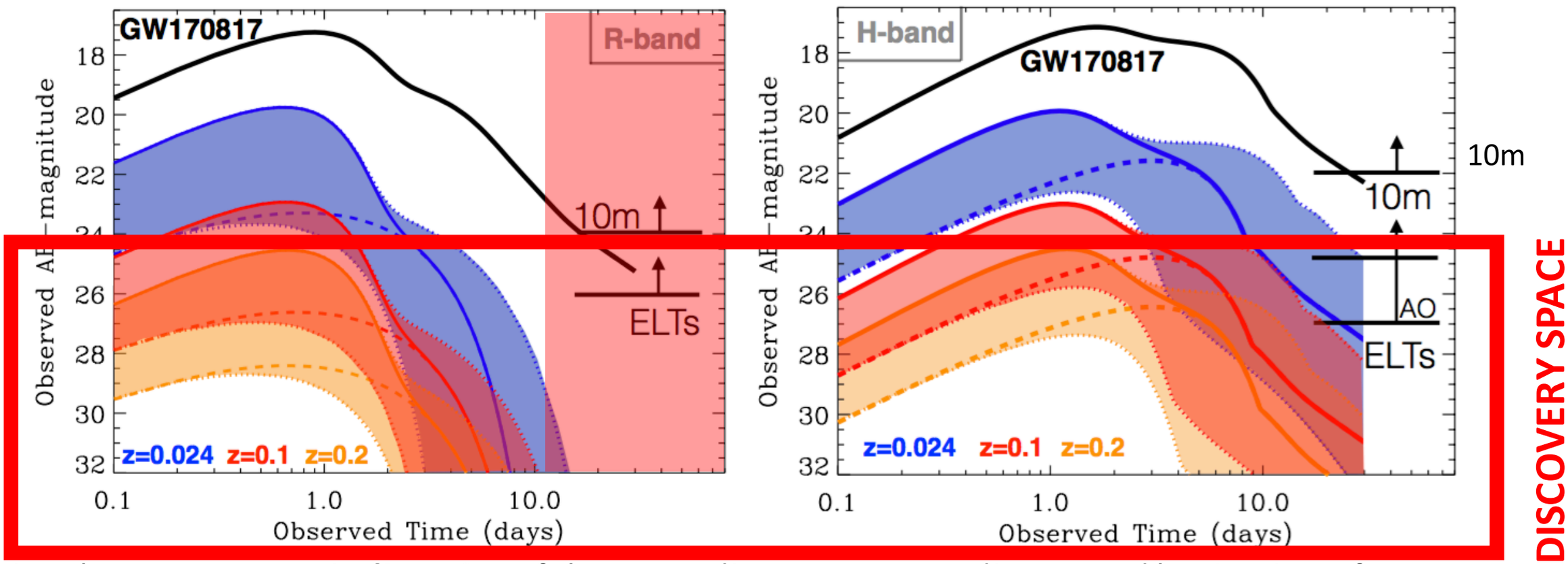
Why the ELTs?



Mapping the spectroscopic **diversity** of the most distant mergers discovered by GW interferometers

Why two ELTs?

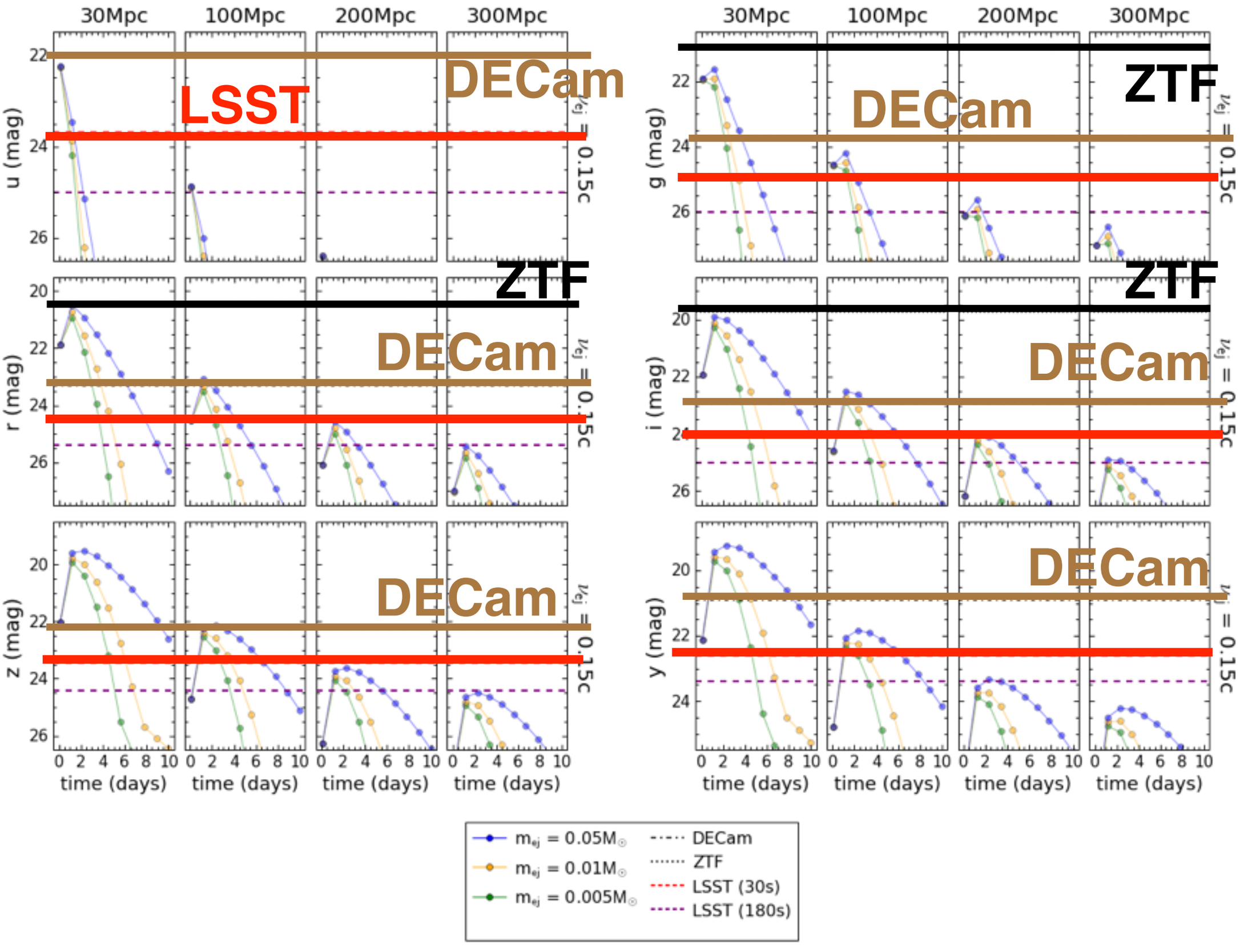
2-hemisphere system → all-sky coverage
Longitudinal separation of GMT & TMT
Complementary Instrumentation



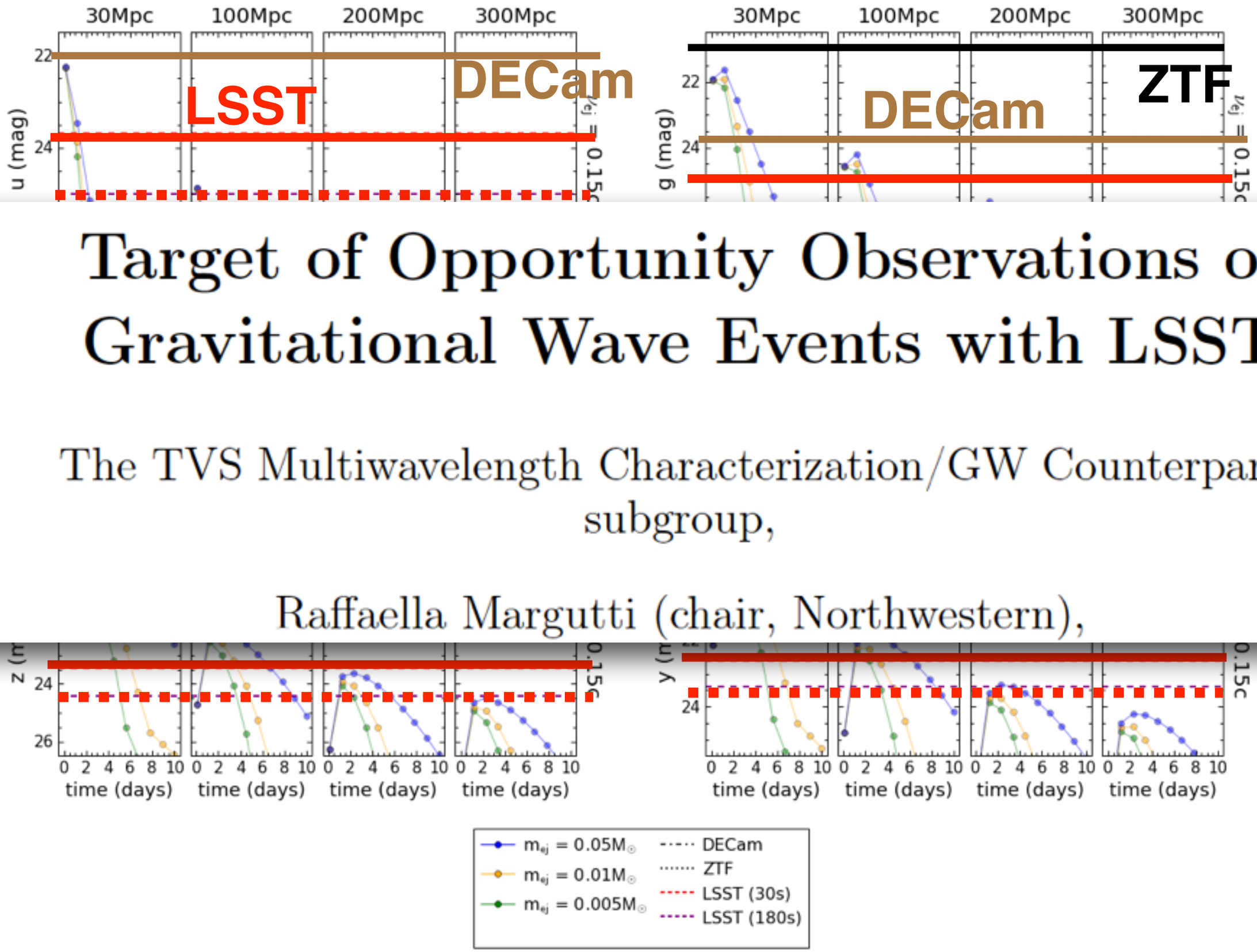
Mapping the spectroscopic **diversity** of the most distant mergers discovered by GW interferometers

"Multi-Messenger Astronomy with Extremely Large Telescopes"
Chornock et al., arXiv:1903.04629

LSST: ToOs to tile the field of GW sources



LSST: ToOs to tile the field of GW sources



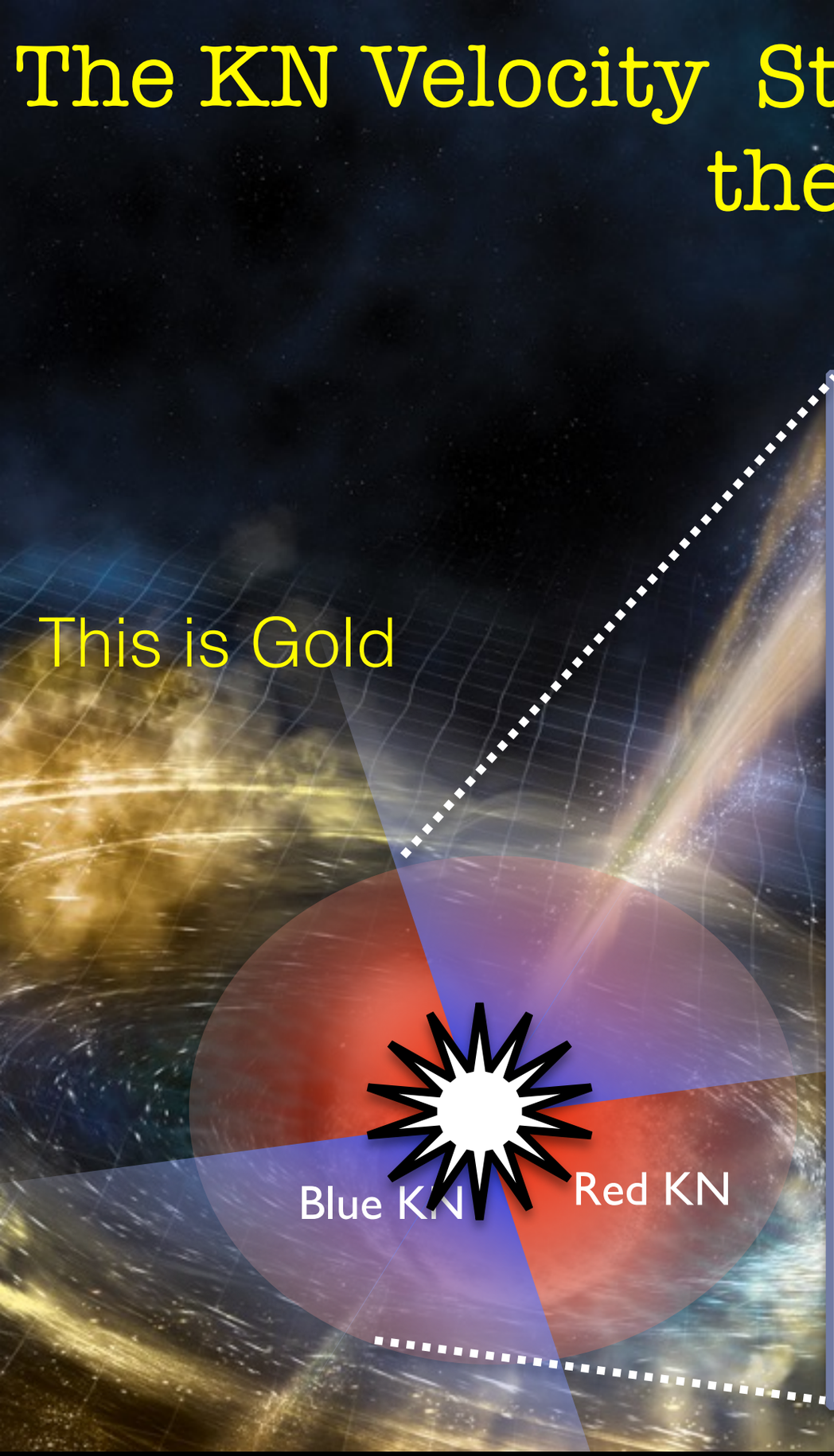
Target of Opportunity Observations of Gravitational Wave Events with LSST

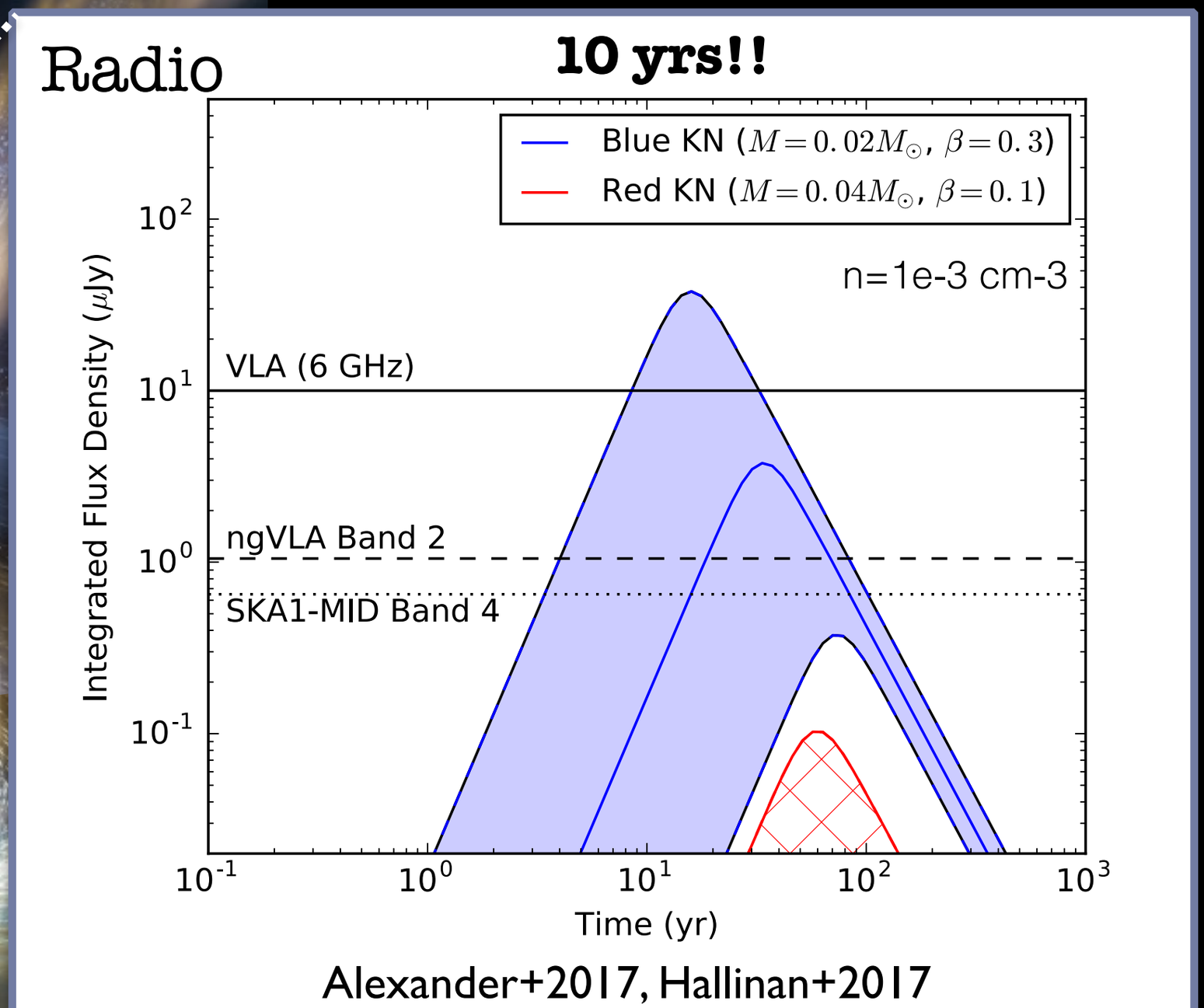
The TVS Multiwavelength Characterization/GW Counterparts subgroup,

Raffaella Margutti (chair, Northwestern),

The KN Velocity Structure (and the nature of the remnant)

This is Gold

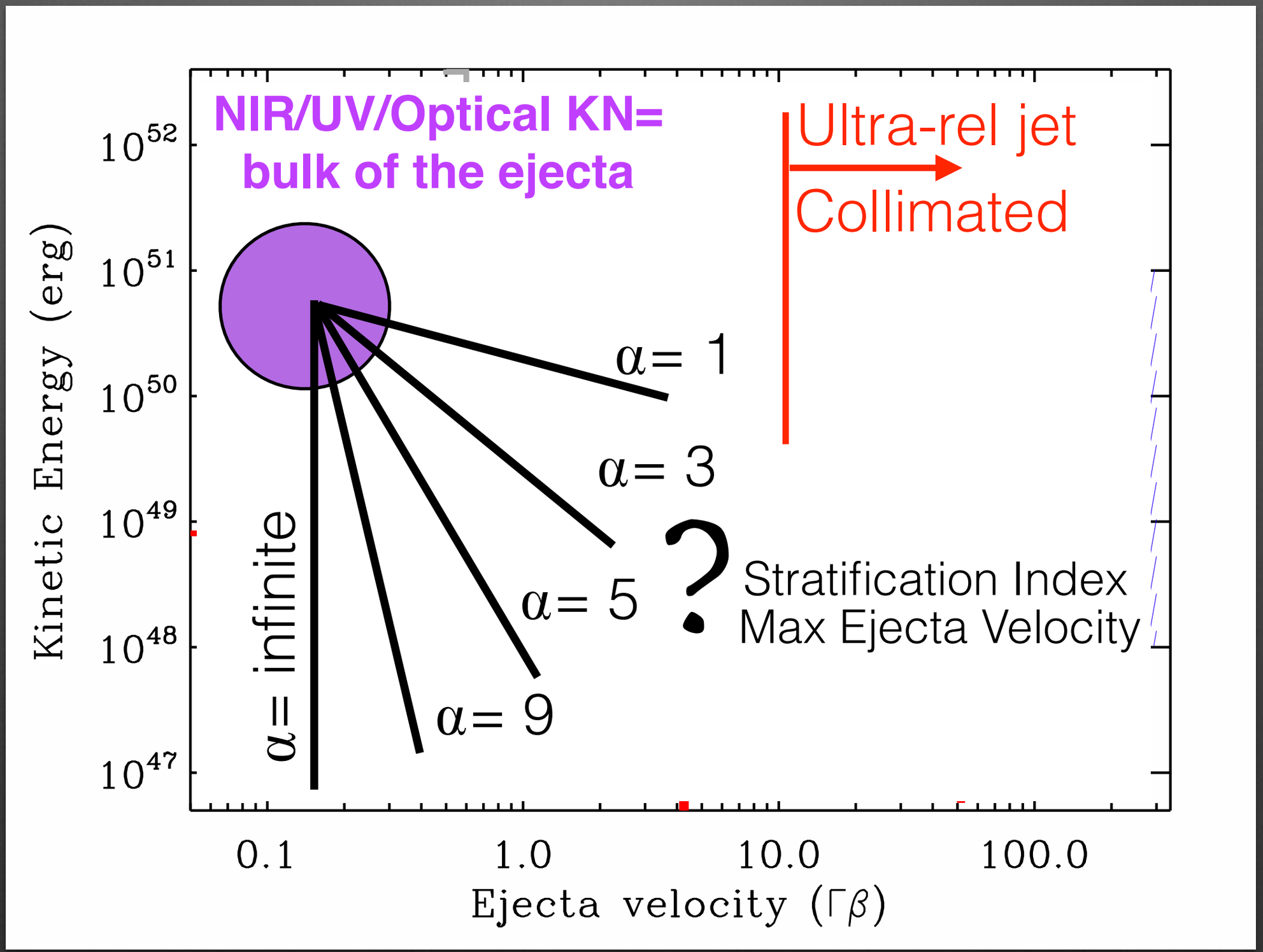




Alexander+2017, Hallinan+2017

Nakar & Piran 2011; Metzger & Berger 2012; Metzger & Bower 2014; Hotokezaka & Piran 2015

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

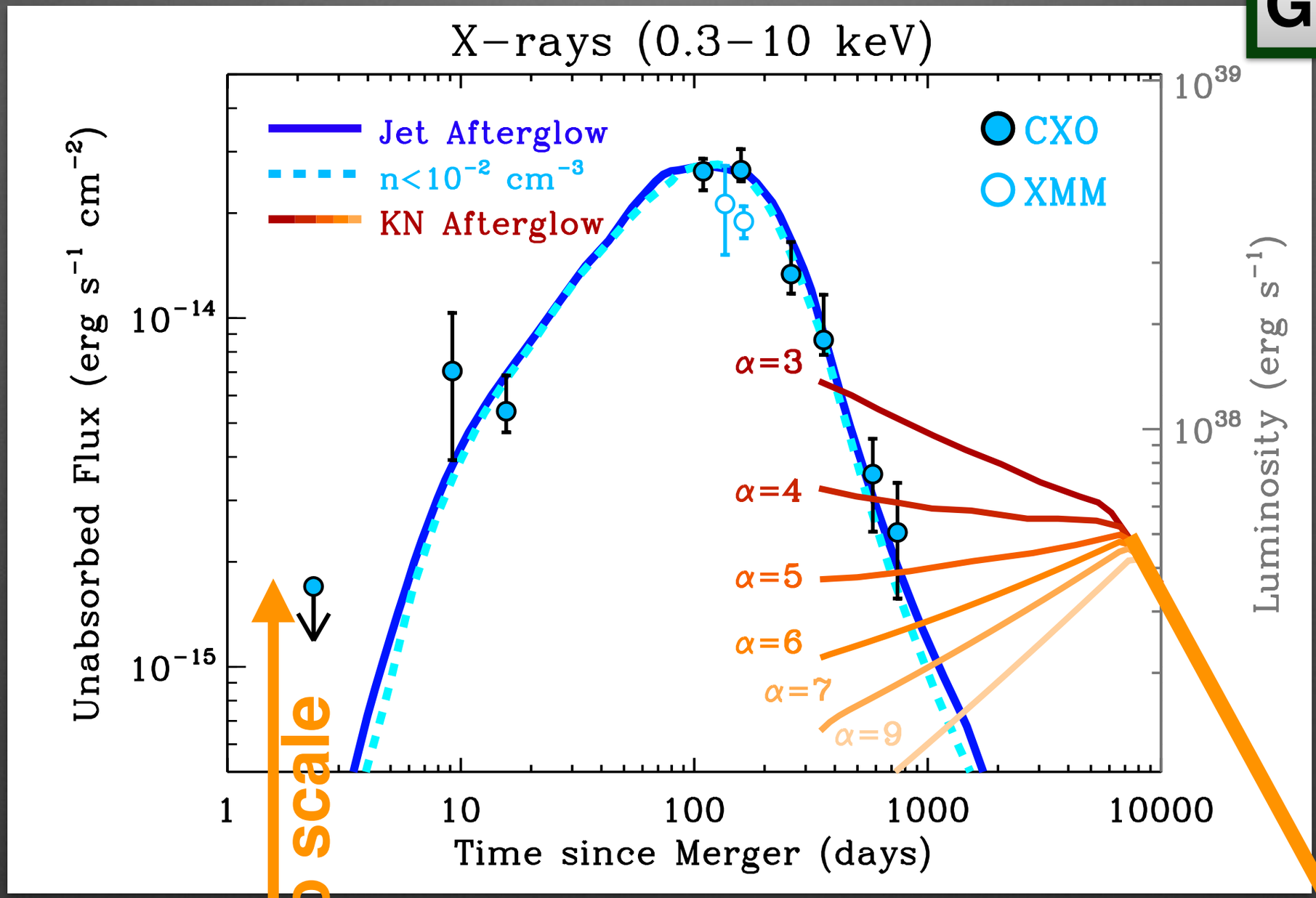


Connection to nature of the remnant

e.g., Radice+2018

The KN afterglow (X-rays):

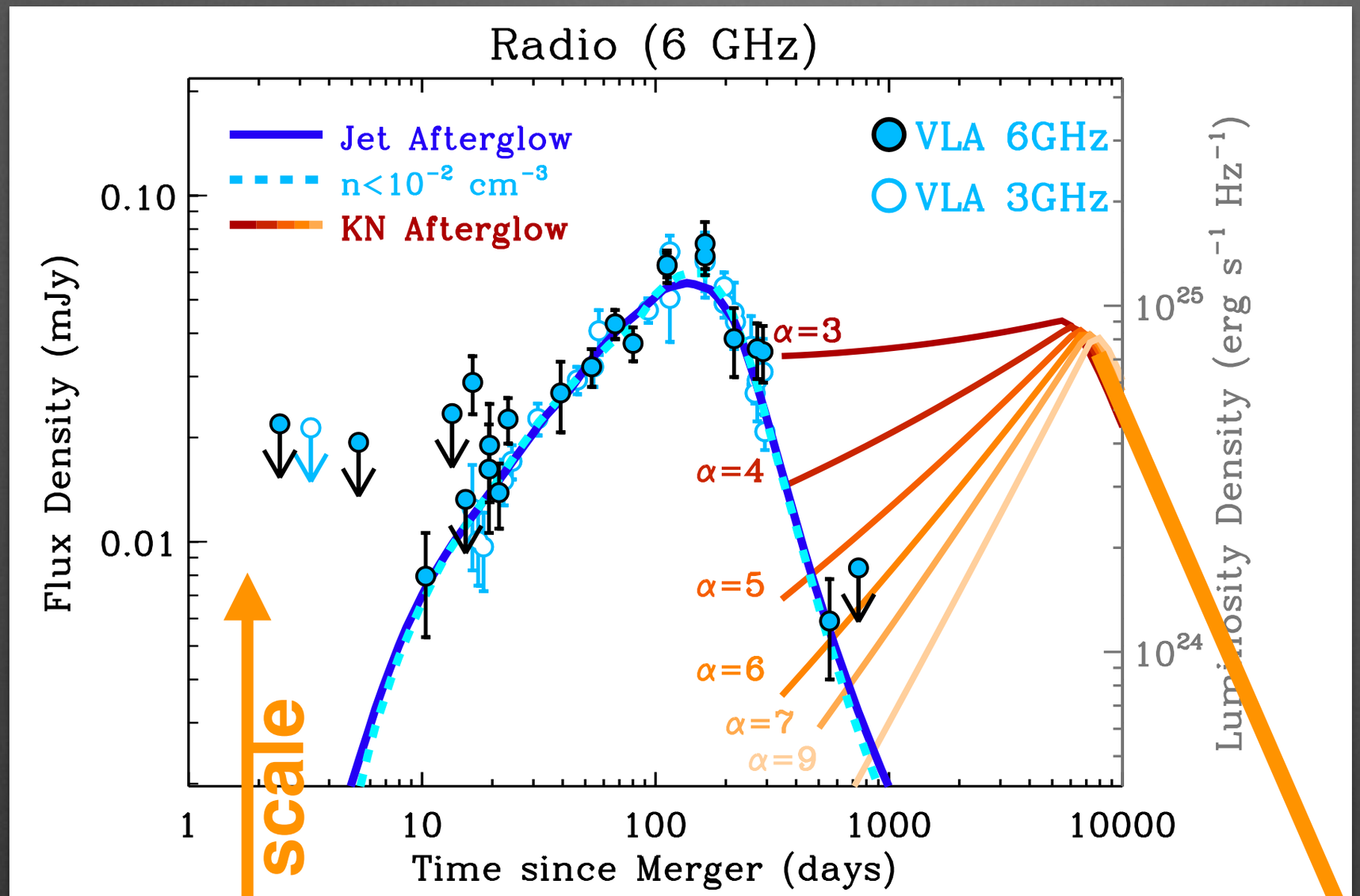
GW170817



Not to scale

6d-19 erg/s/cm2 100 ks Lynx

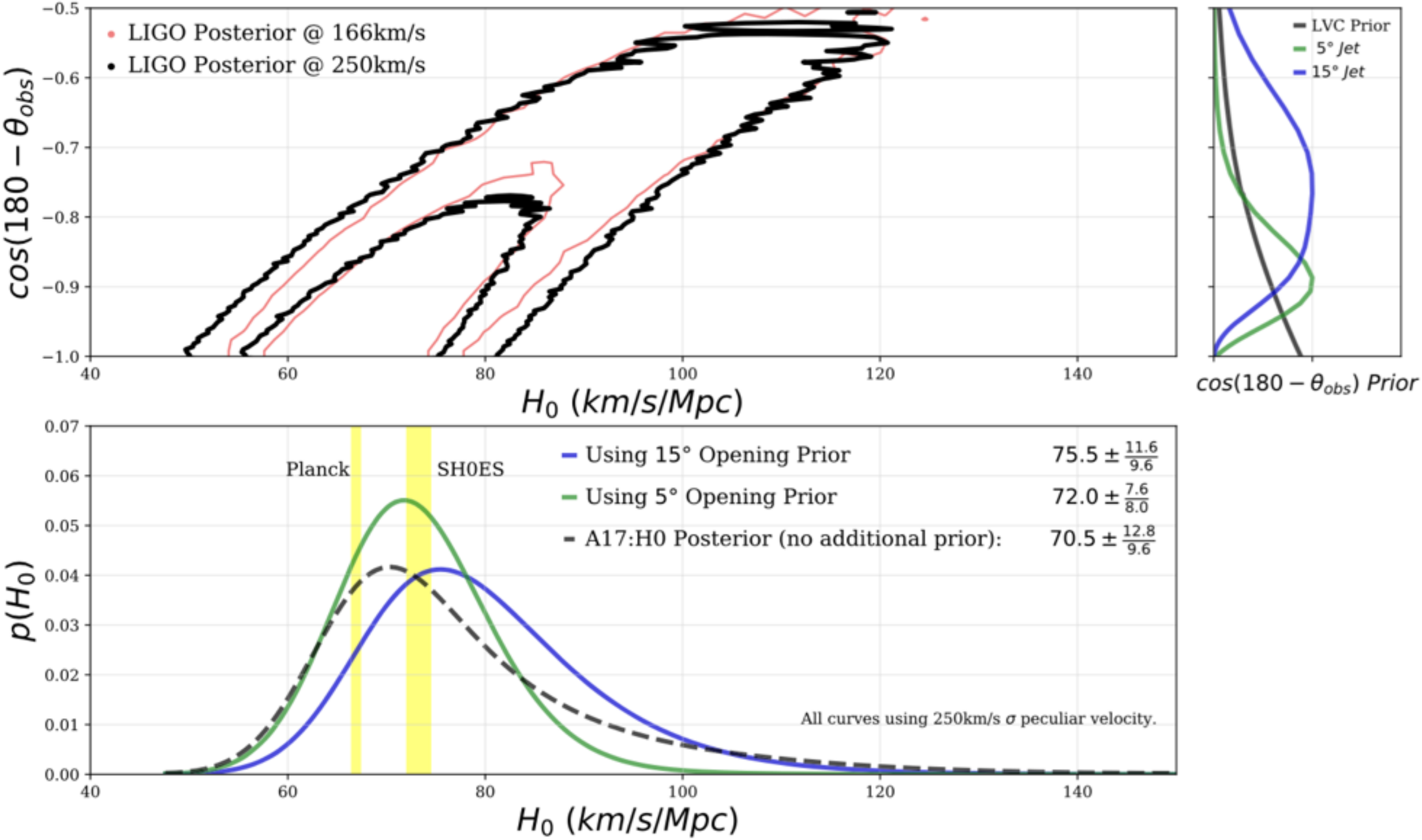
The KN afterglow (radio):



Not to scale

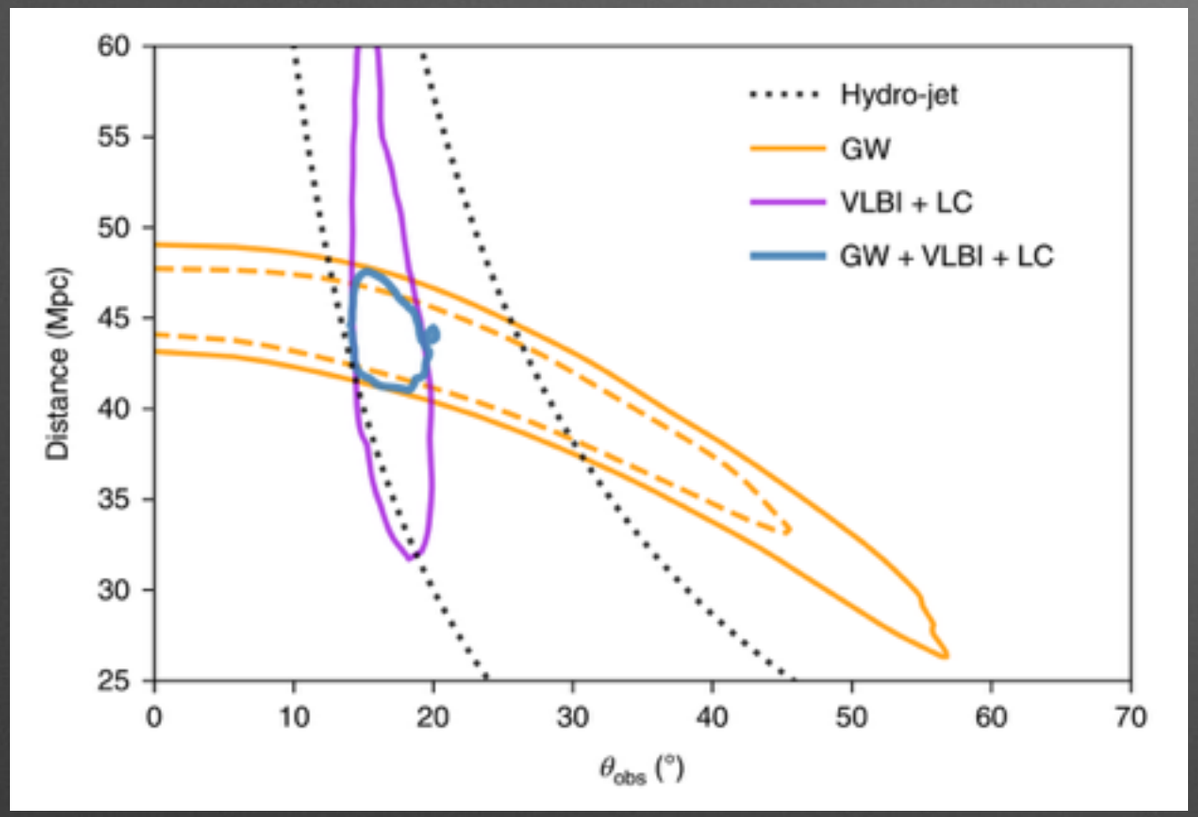
0.0002 mJy 1 hr ngVLA

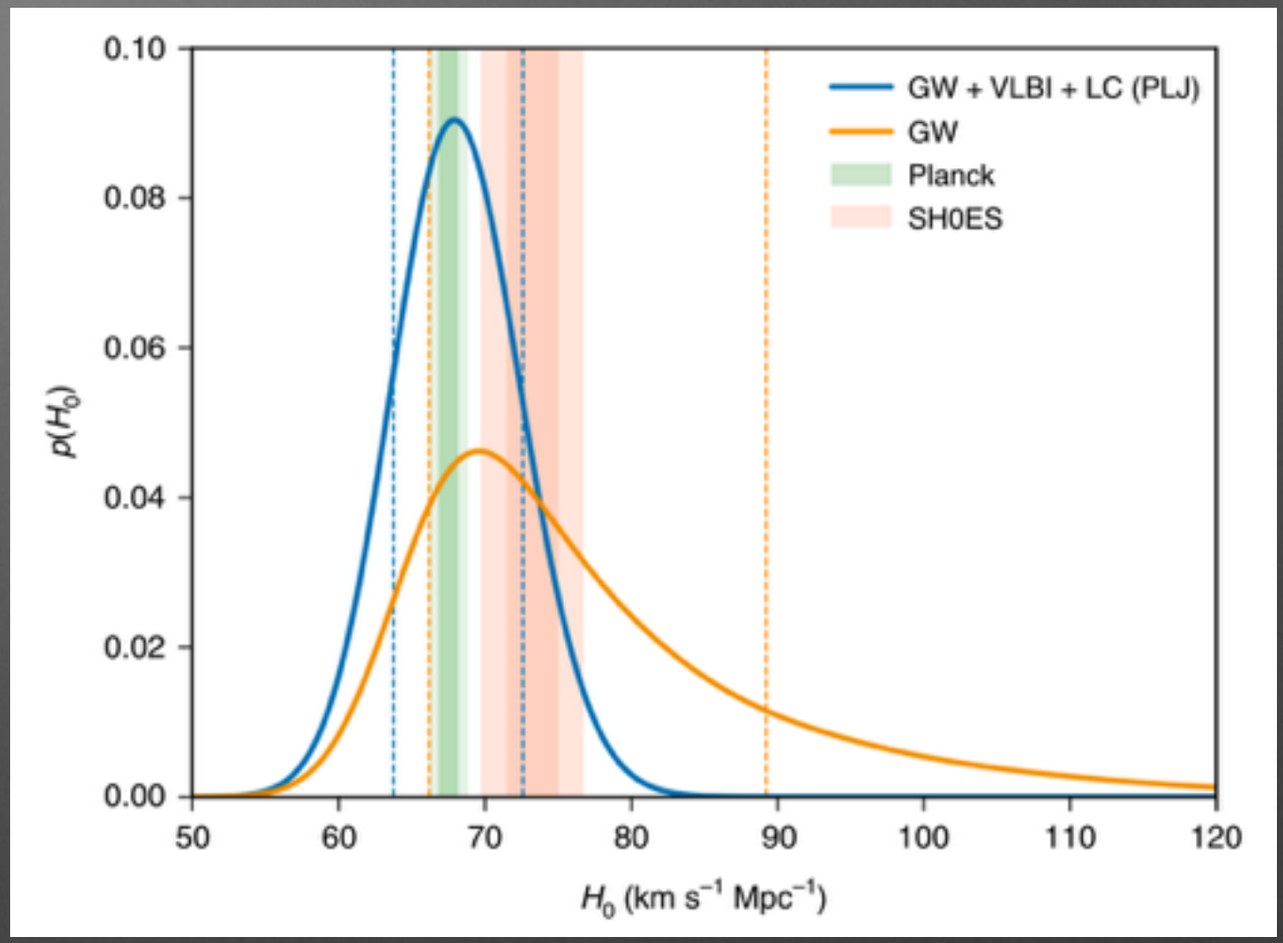
Cosmology:



Guidorzi+17

Cosmology:



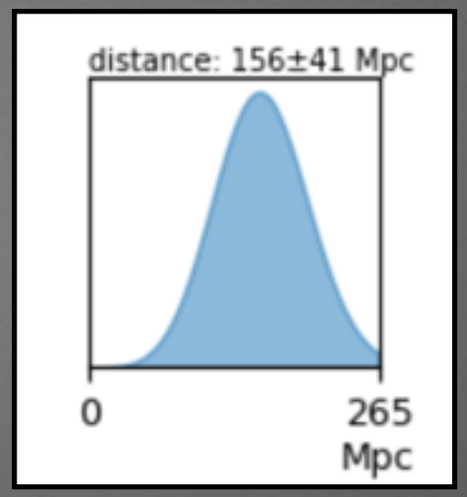


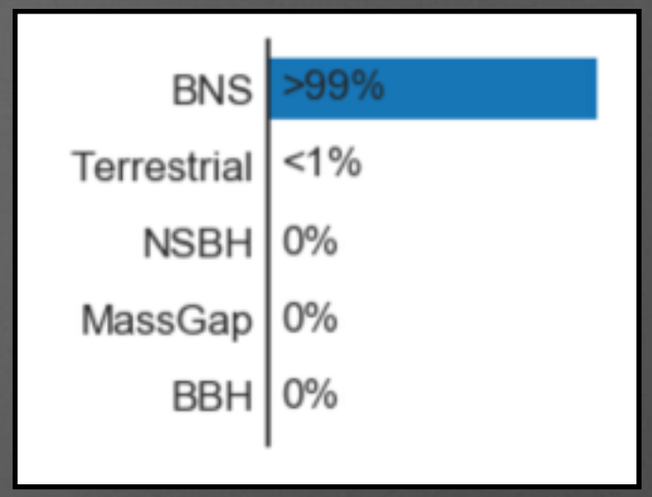
Hotokezaka+2019

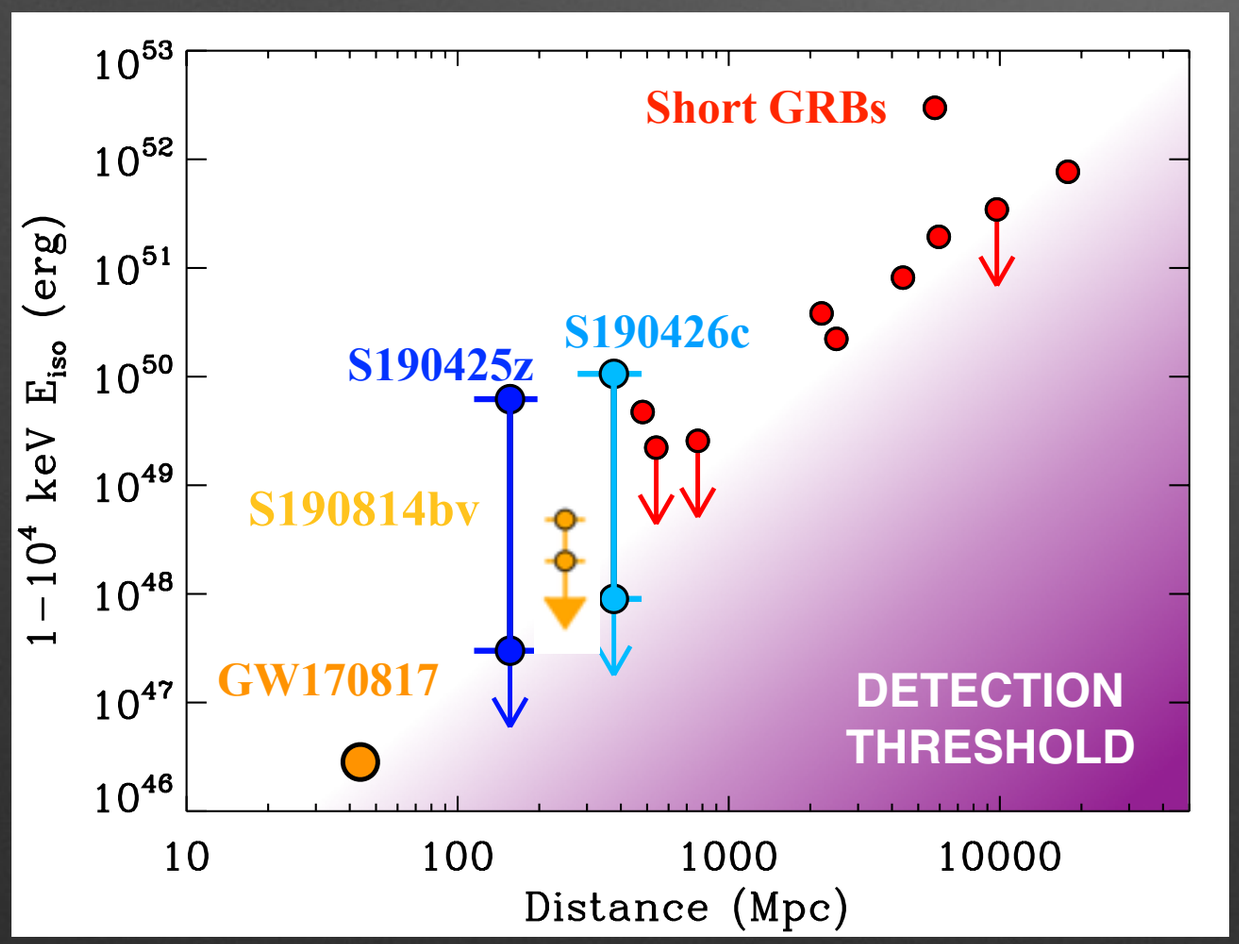
Update on results from EM follow up in O3:

S190425z (NS-NS)

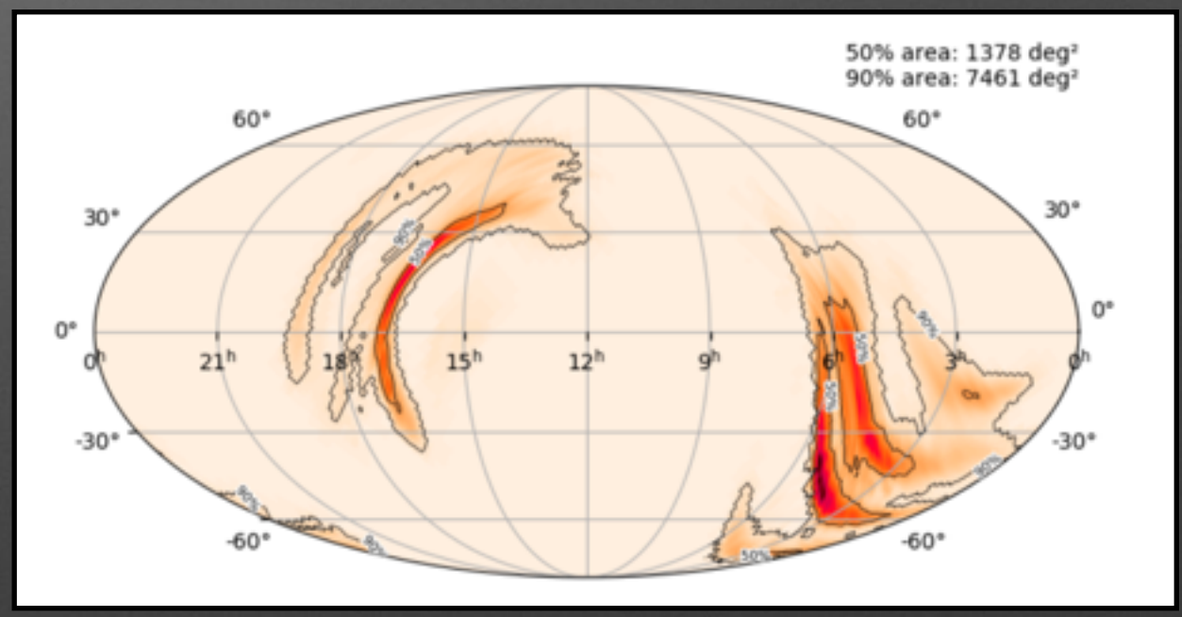
Hosseinzadeh+2019
Coughlin+2019







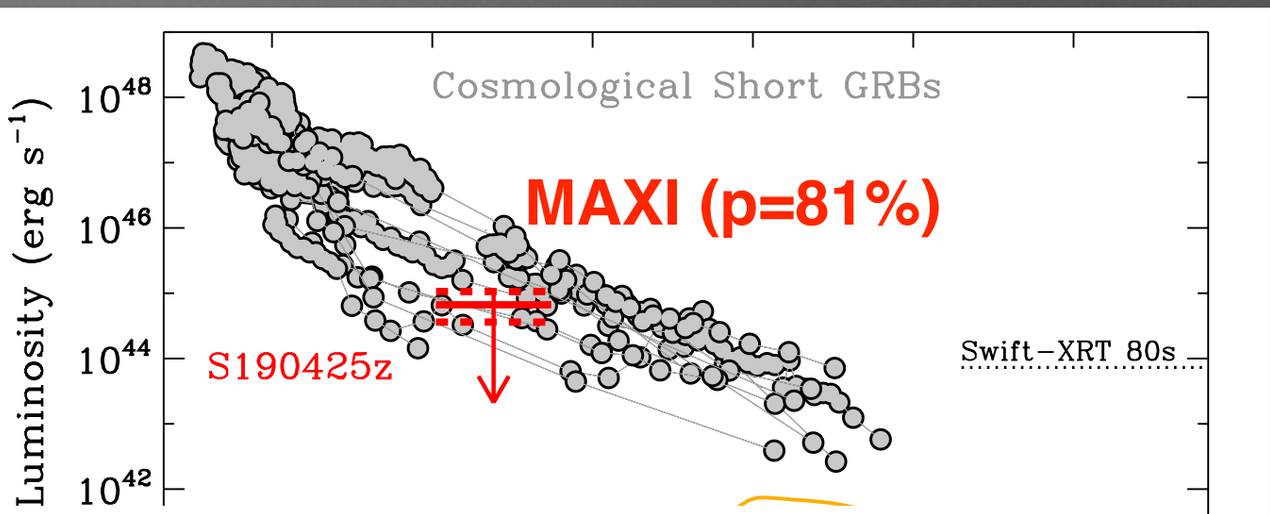
Hosseinzadeh+2019

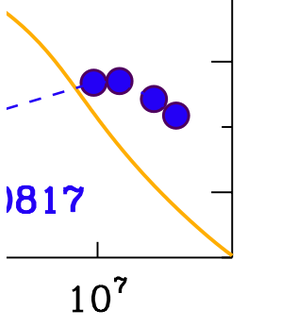


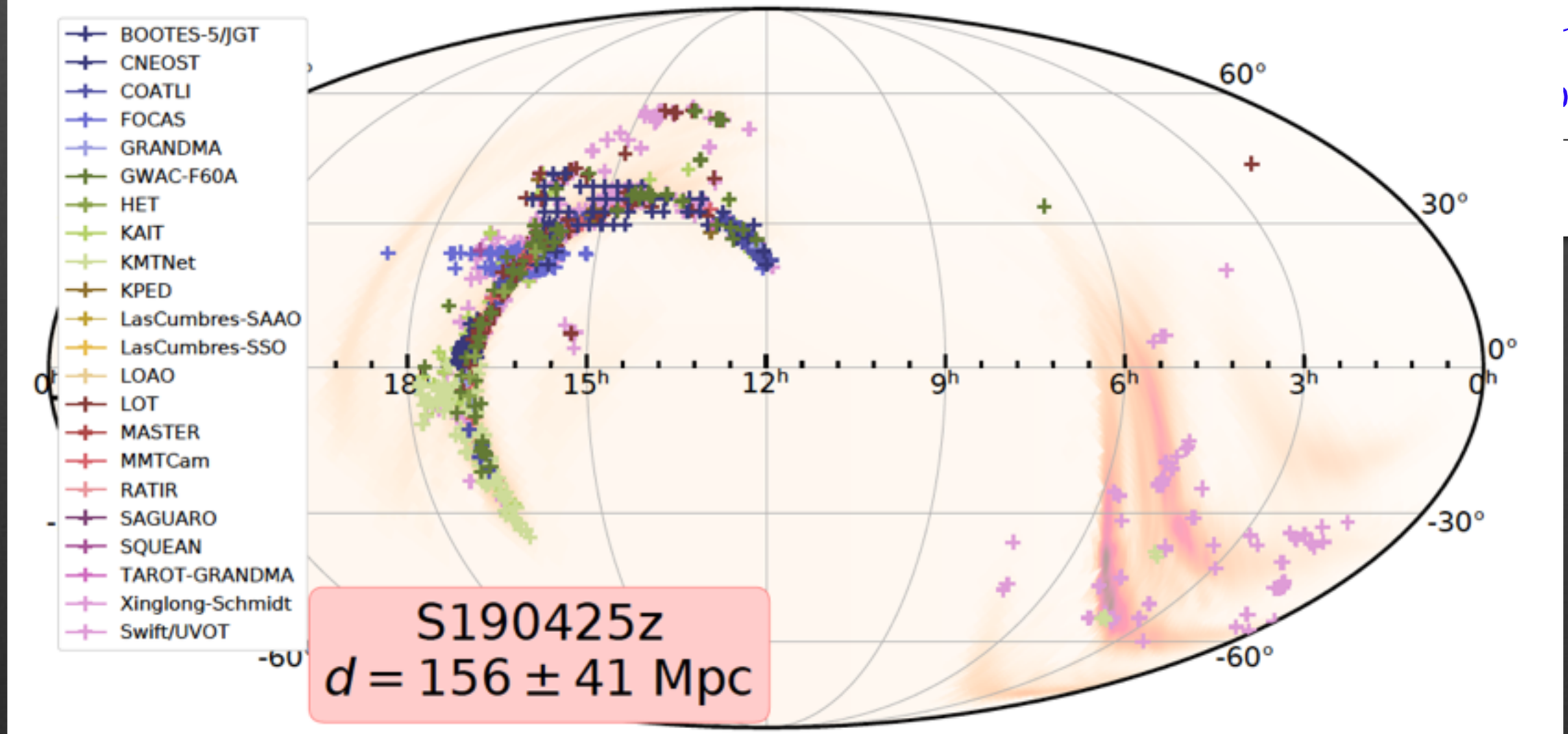
Update on results from EM follow up in O3:

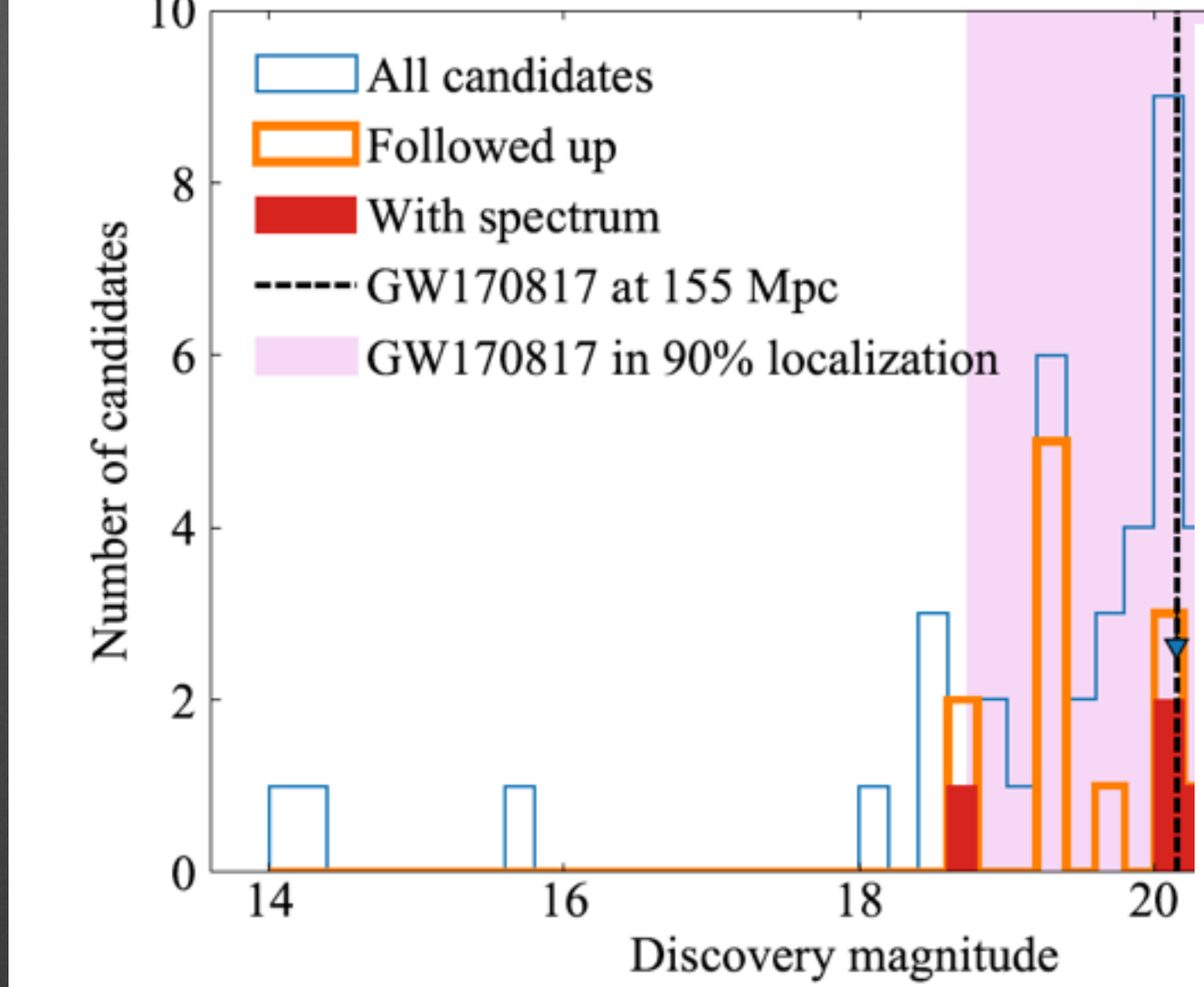
S190425z (NS-NS)

sseinzadeh+2019



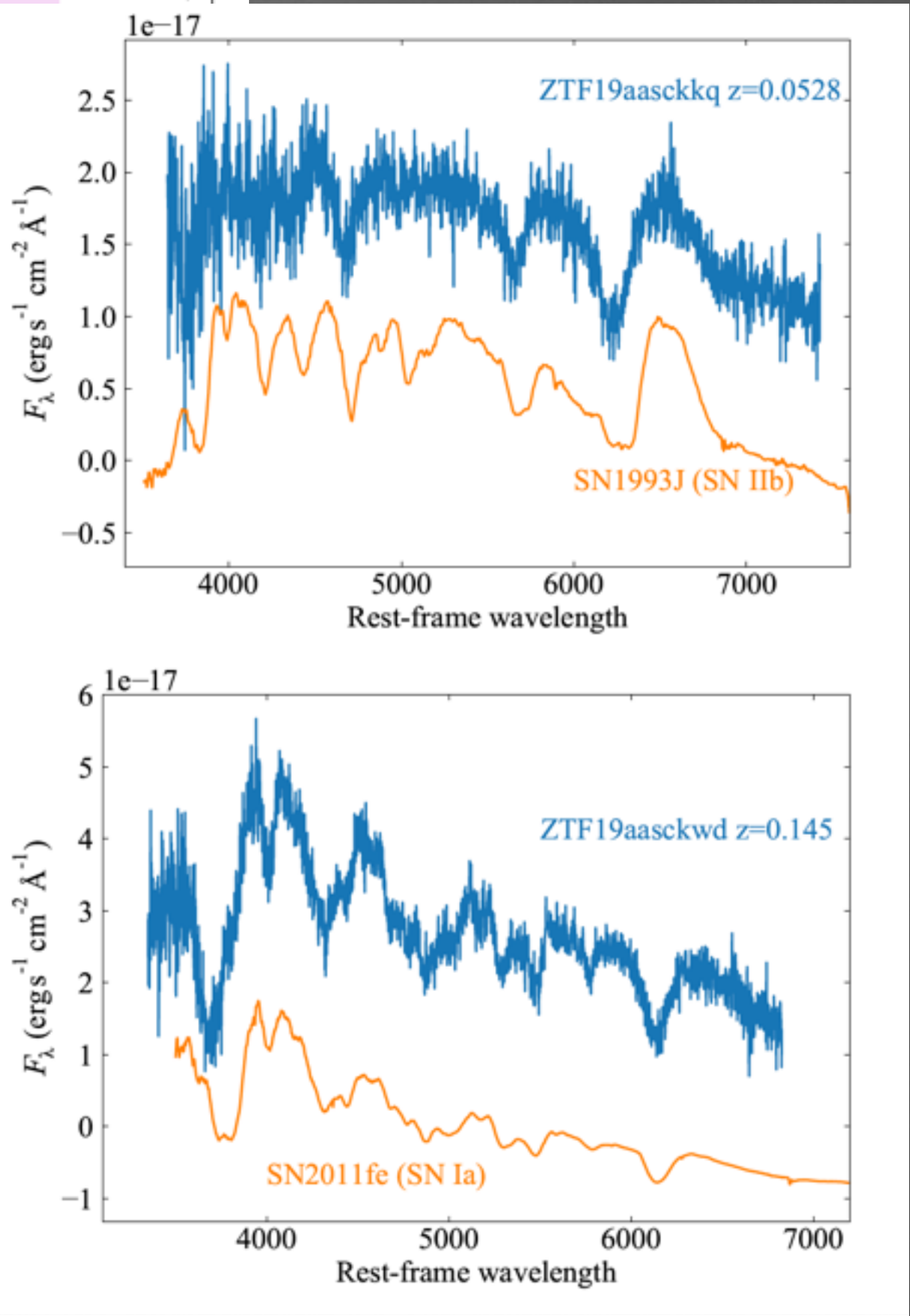






Hosseinzadeh+2019

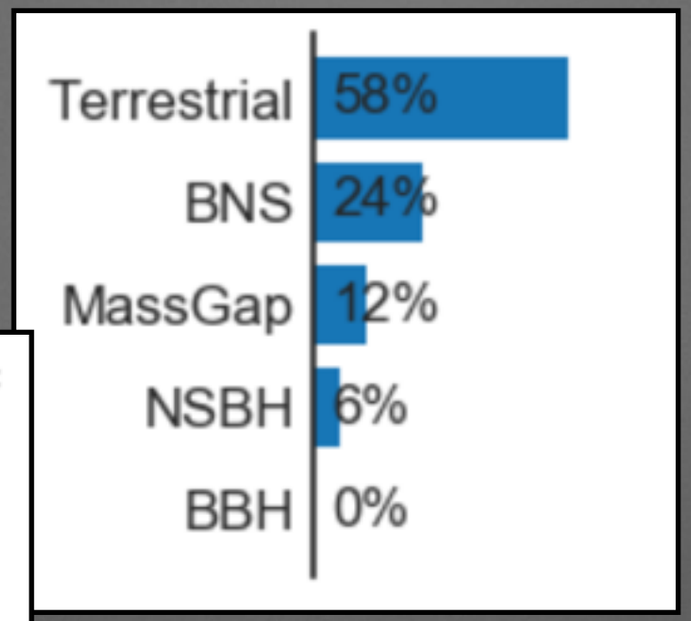
Fractional Volume Coverage ~40% by ZTF

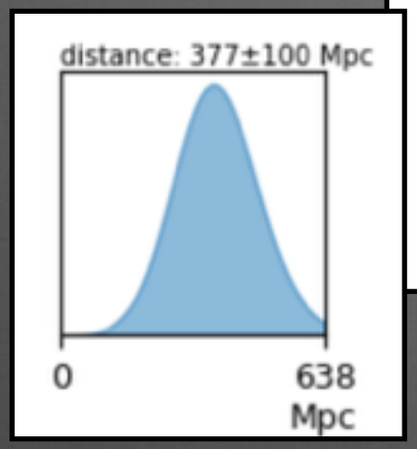


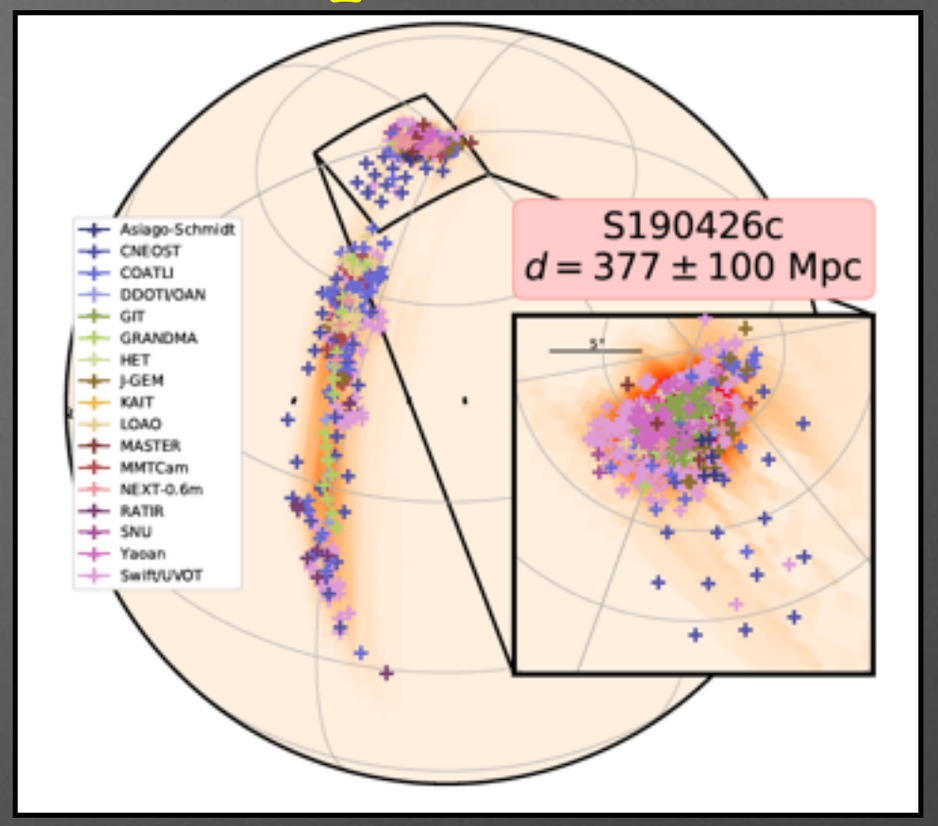
Update on results from EM follow up in O3:

(S190426c)

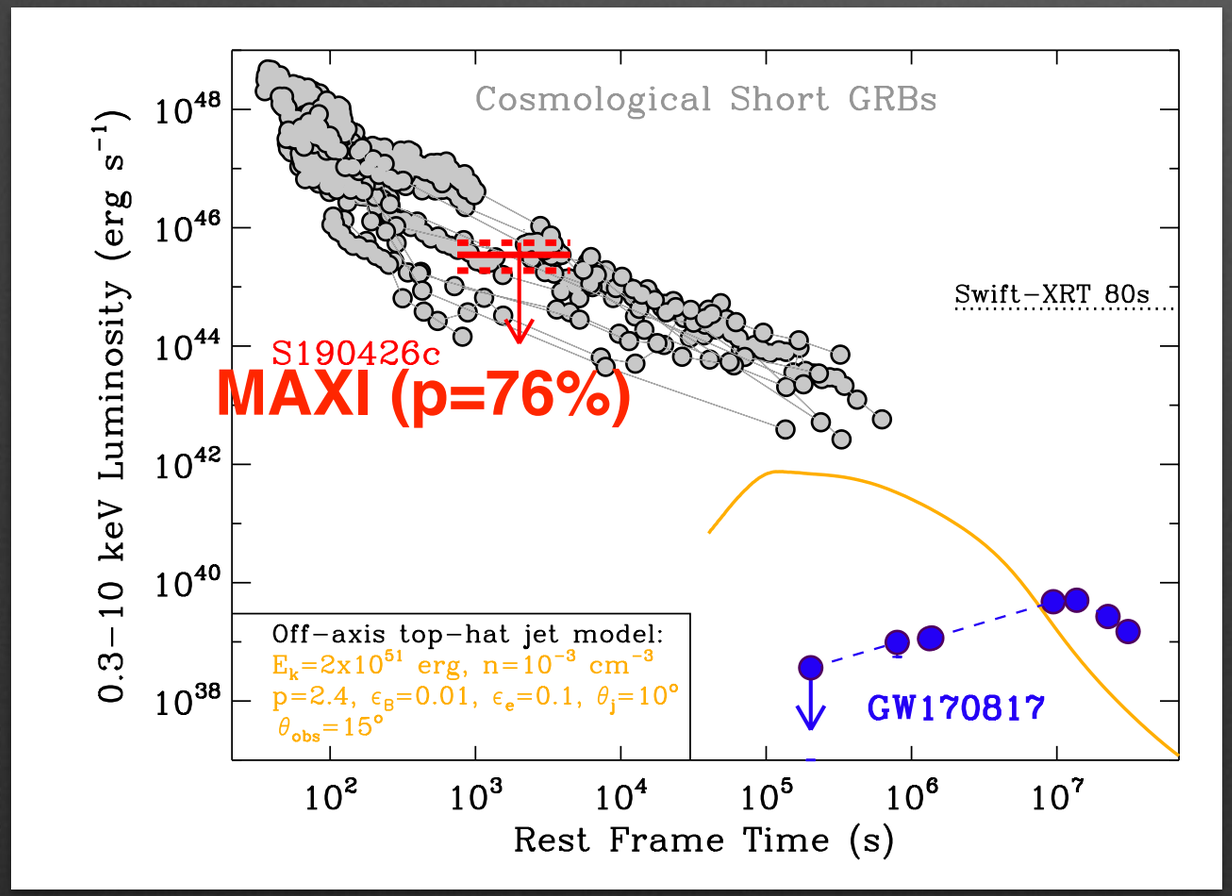
Hosseinzadeh+2019
Goldstein/Andreoni+2019

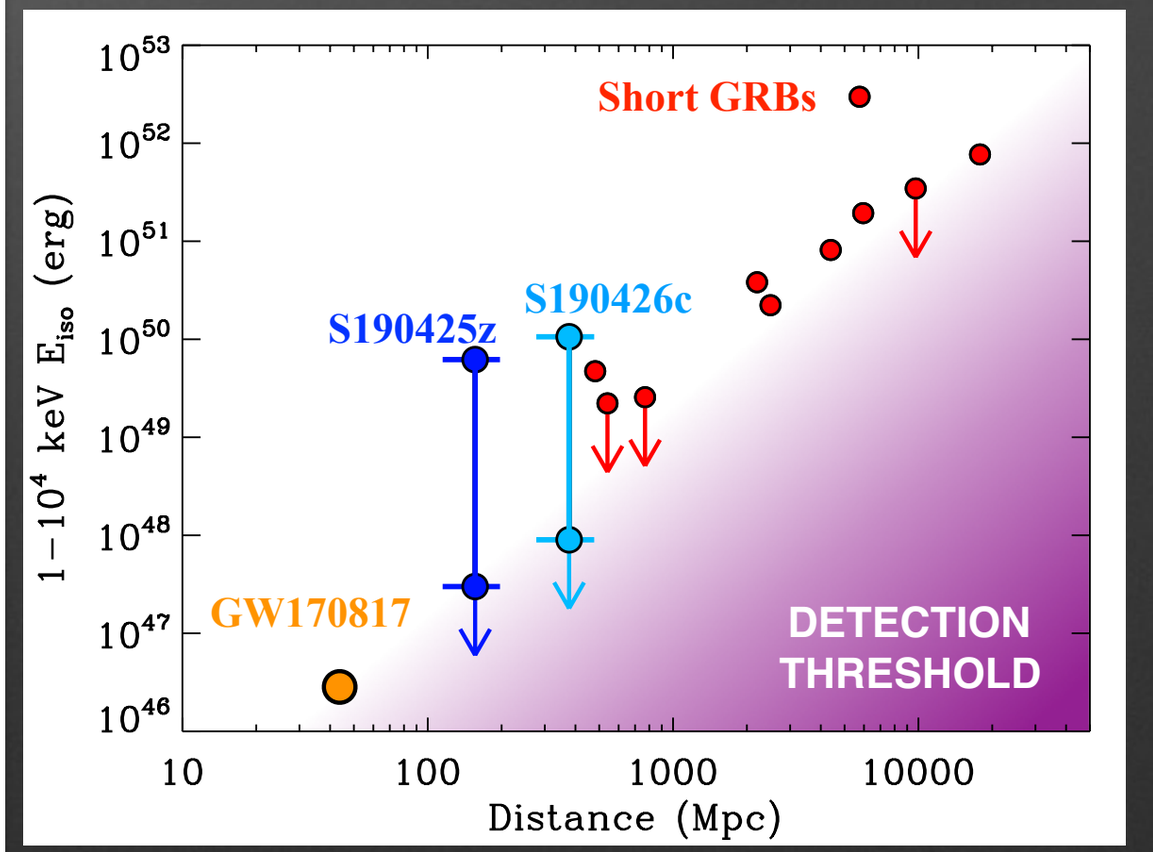






Hosseinzadeh+2019

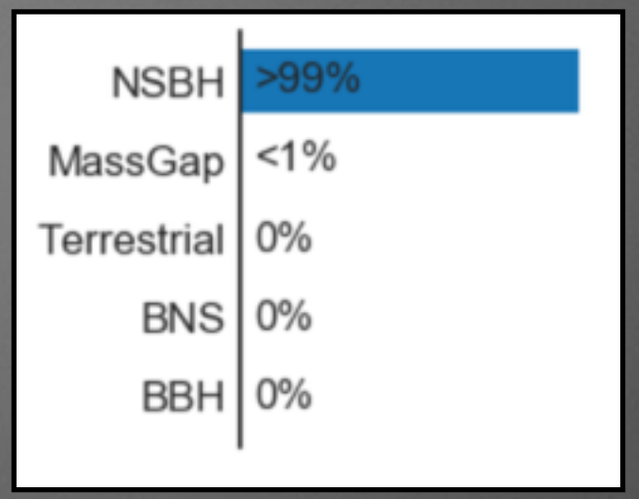


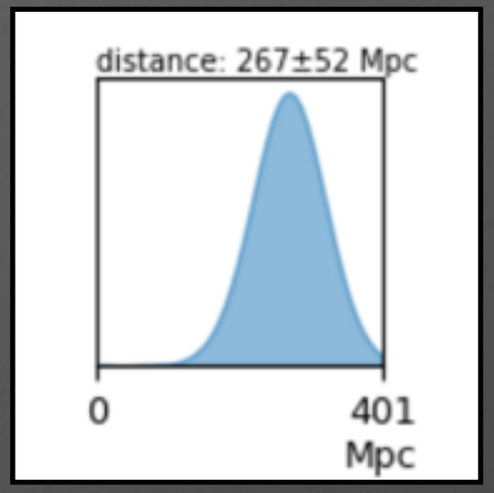


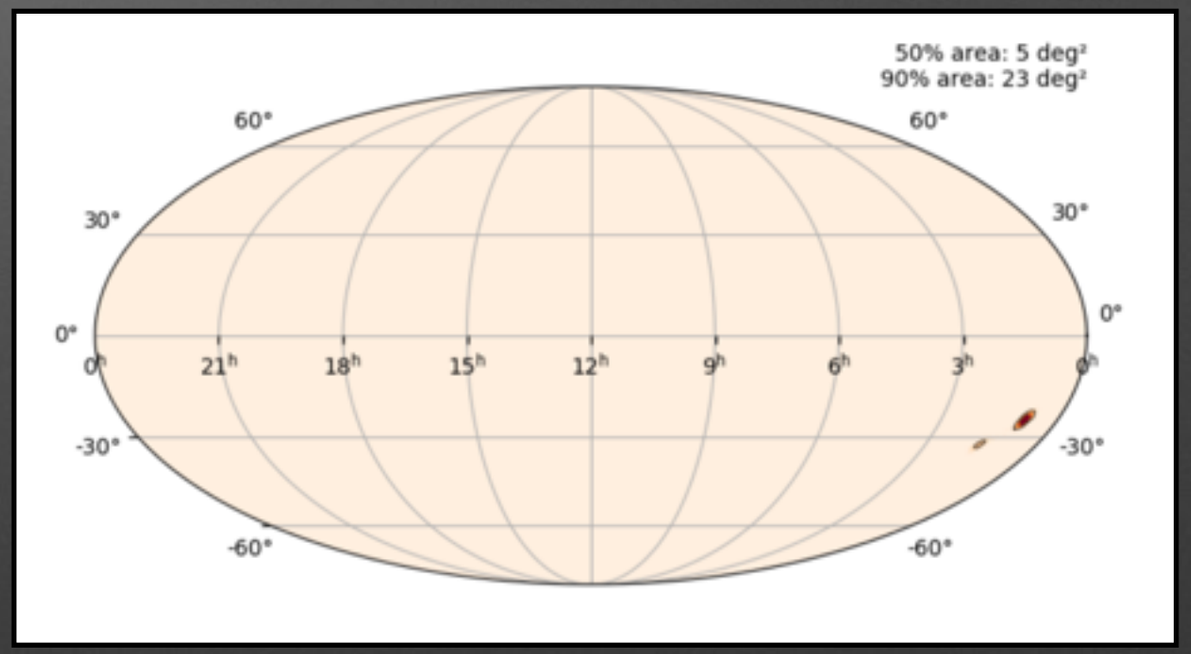
Update on results from EM follow up in O3:

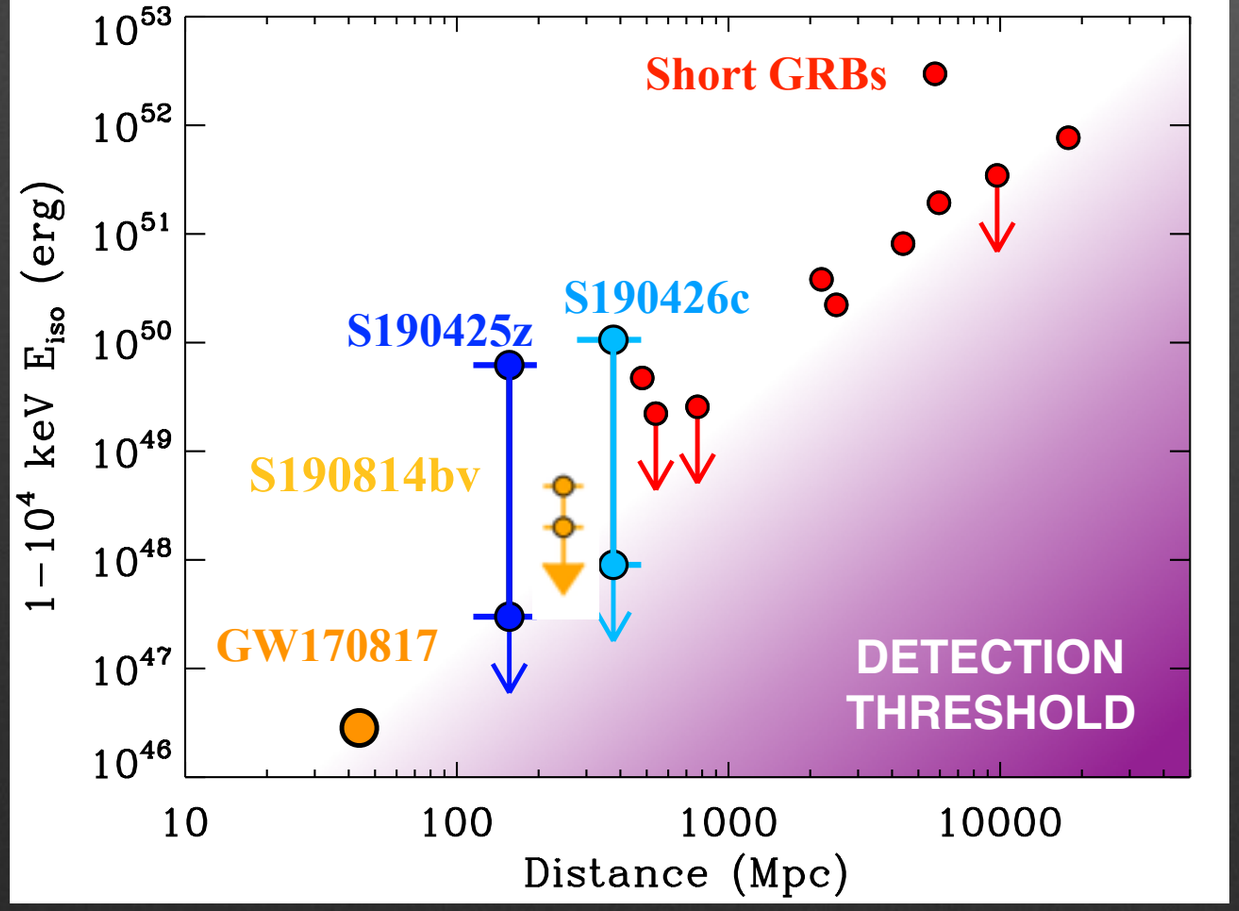
S190814bv (NS-BH)

(Gomez+2019)







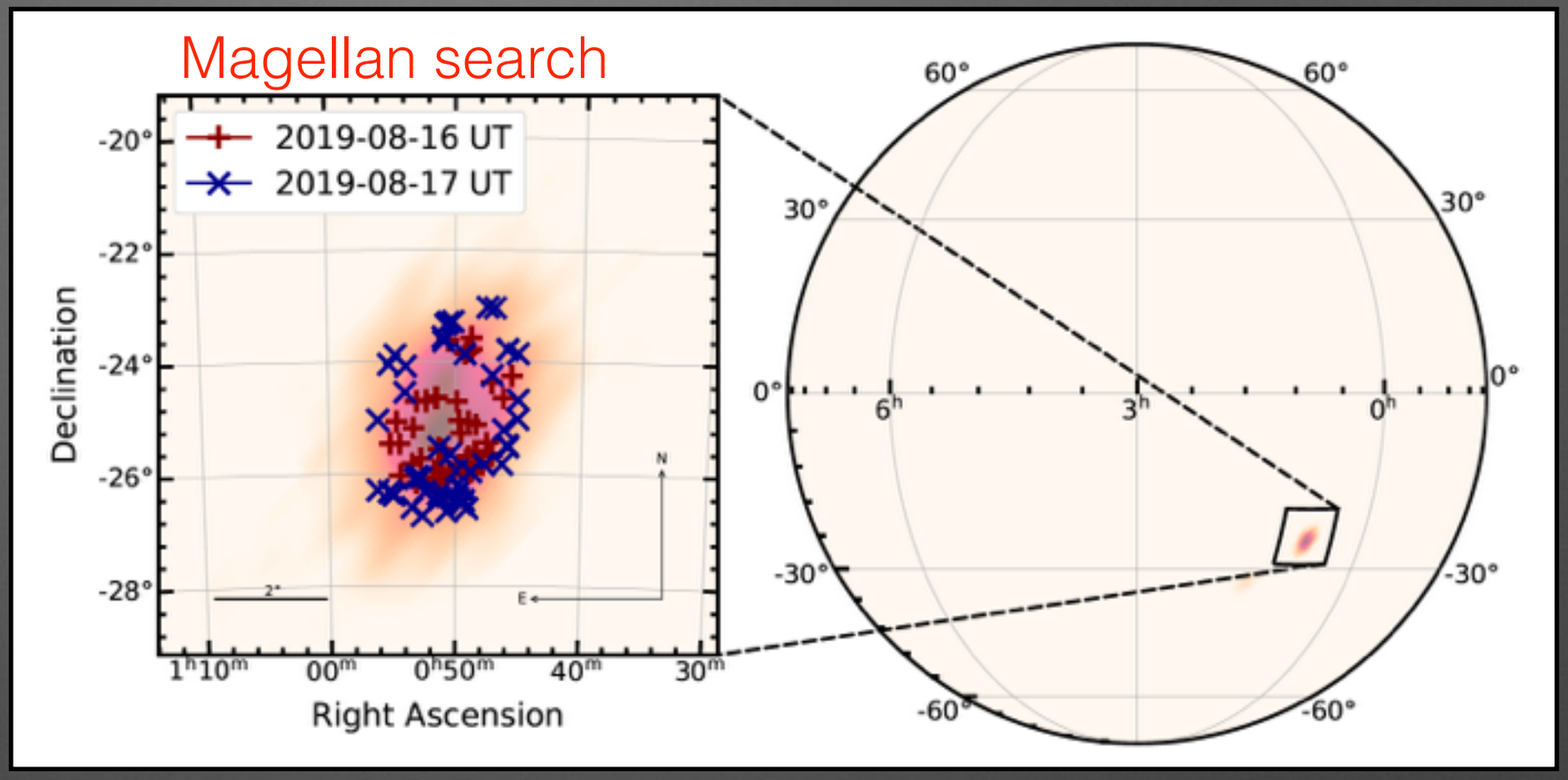


Matthews+2019

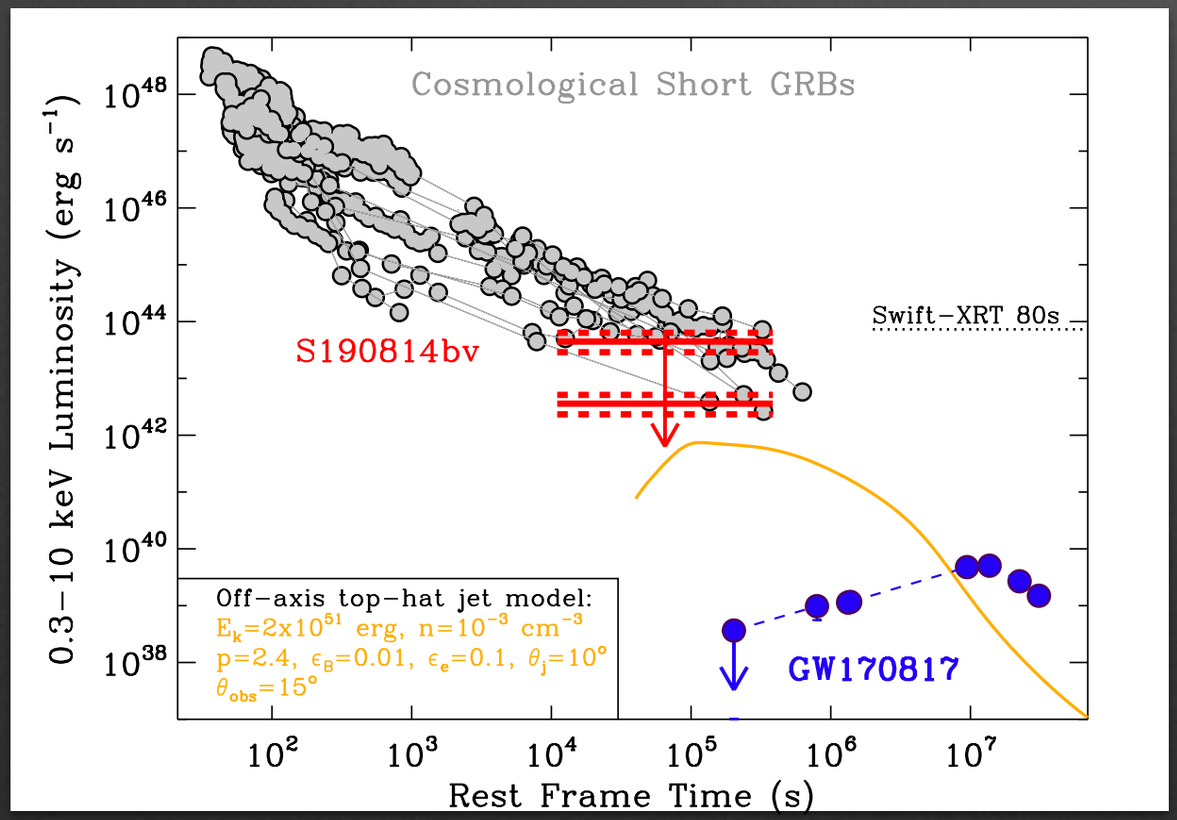
Update on results from EM follow up in O3:

S190814bv

100% coverage!!



Gomez+2019



Matthews+2019

Ongoing Galaxy Targeted Radio follow-up (K. Alexander+, K. Mooley+)

This is not

...The End...

yet