

The Dawn of Multi-Messenger Astrophysics with Gravitational Waves: the first joint detection of GWs and Light

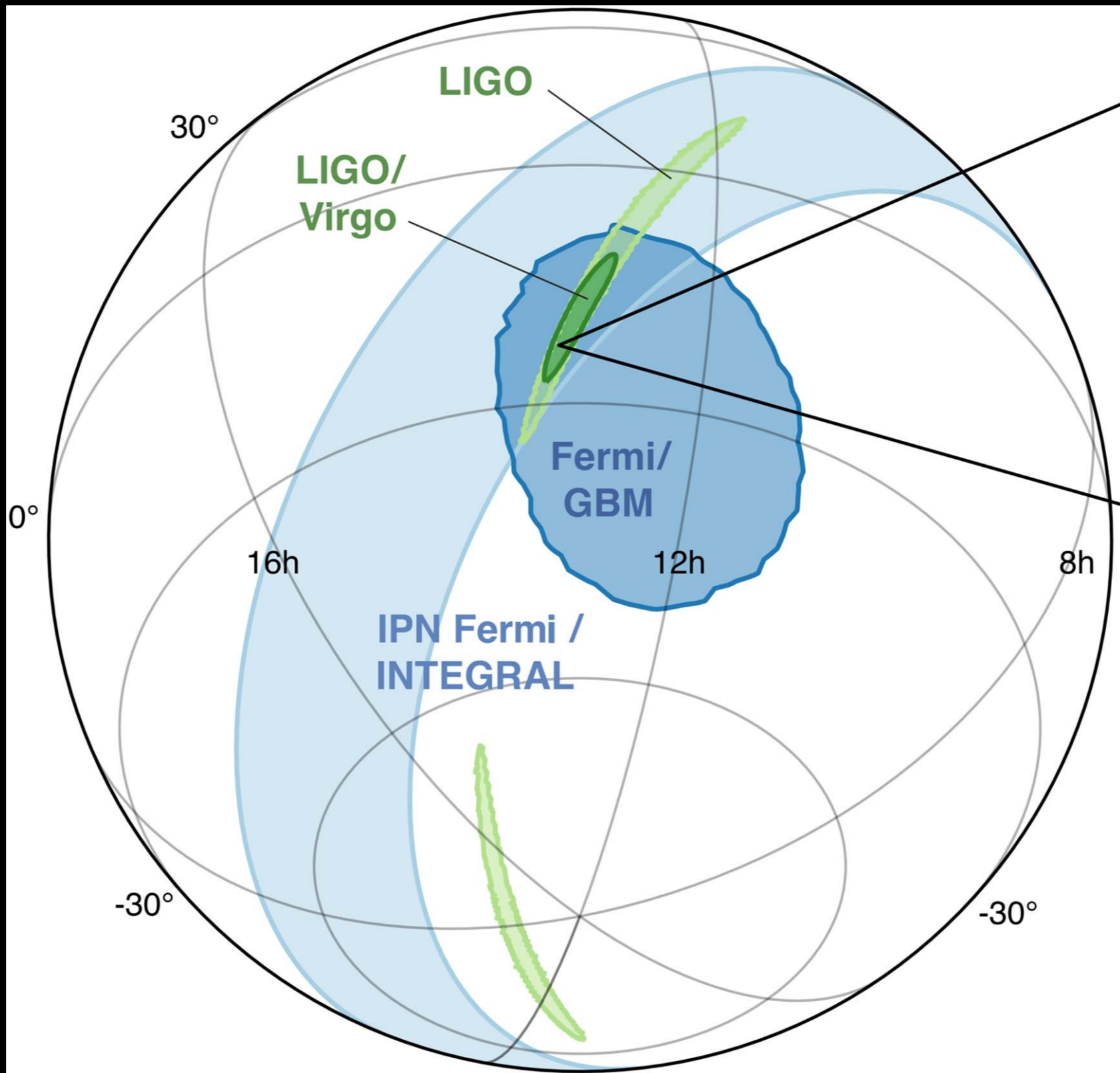
LIGO-Virgo/Nick Gertsonson - Daniel Schwen/Northwestern



NORTHWESTERN
UNIVERSITY

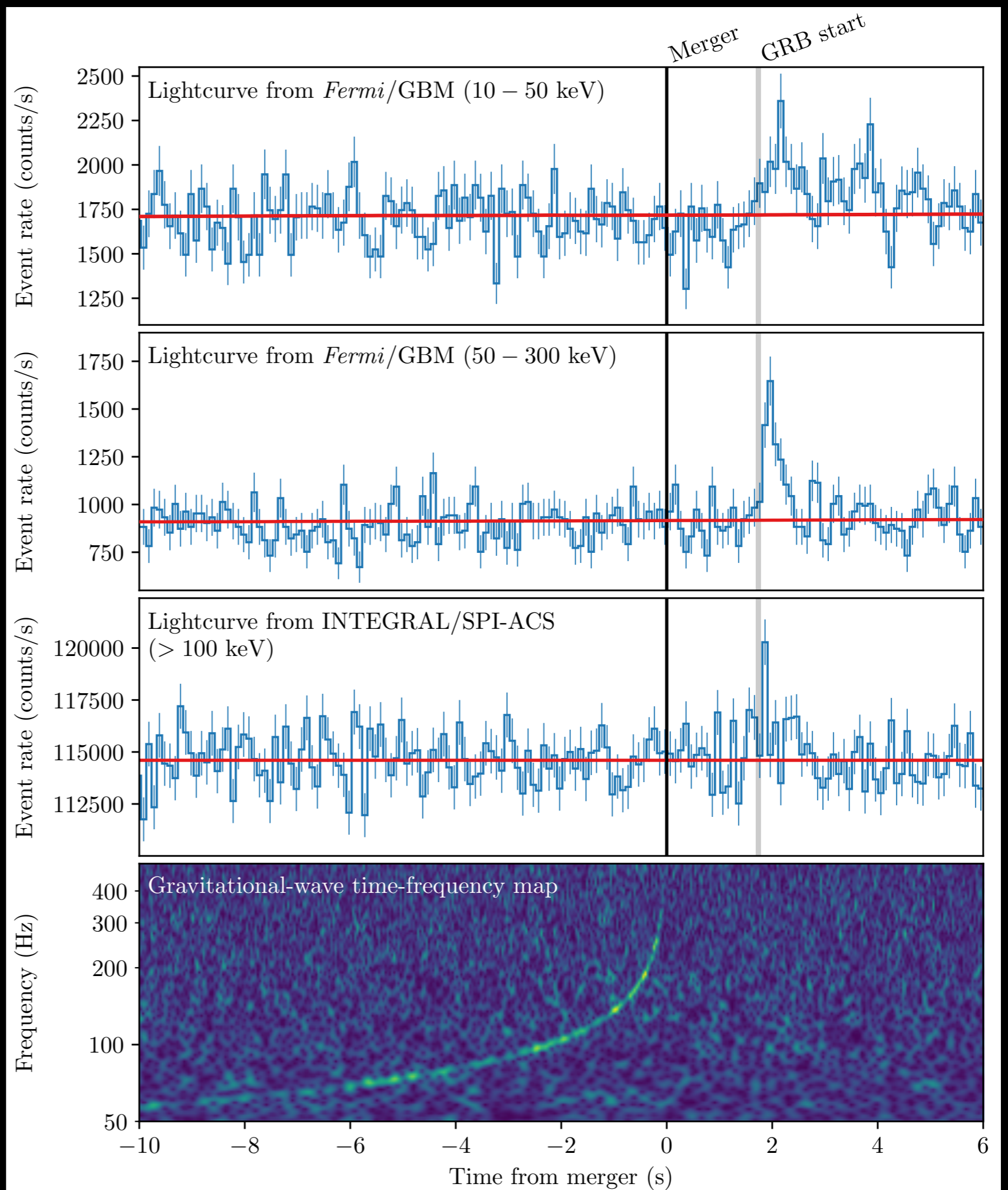
Raffaella Margutti



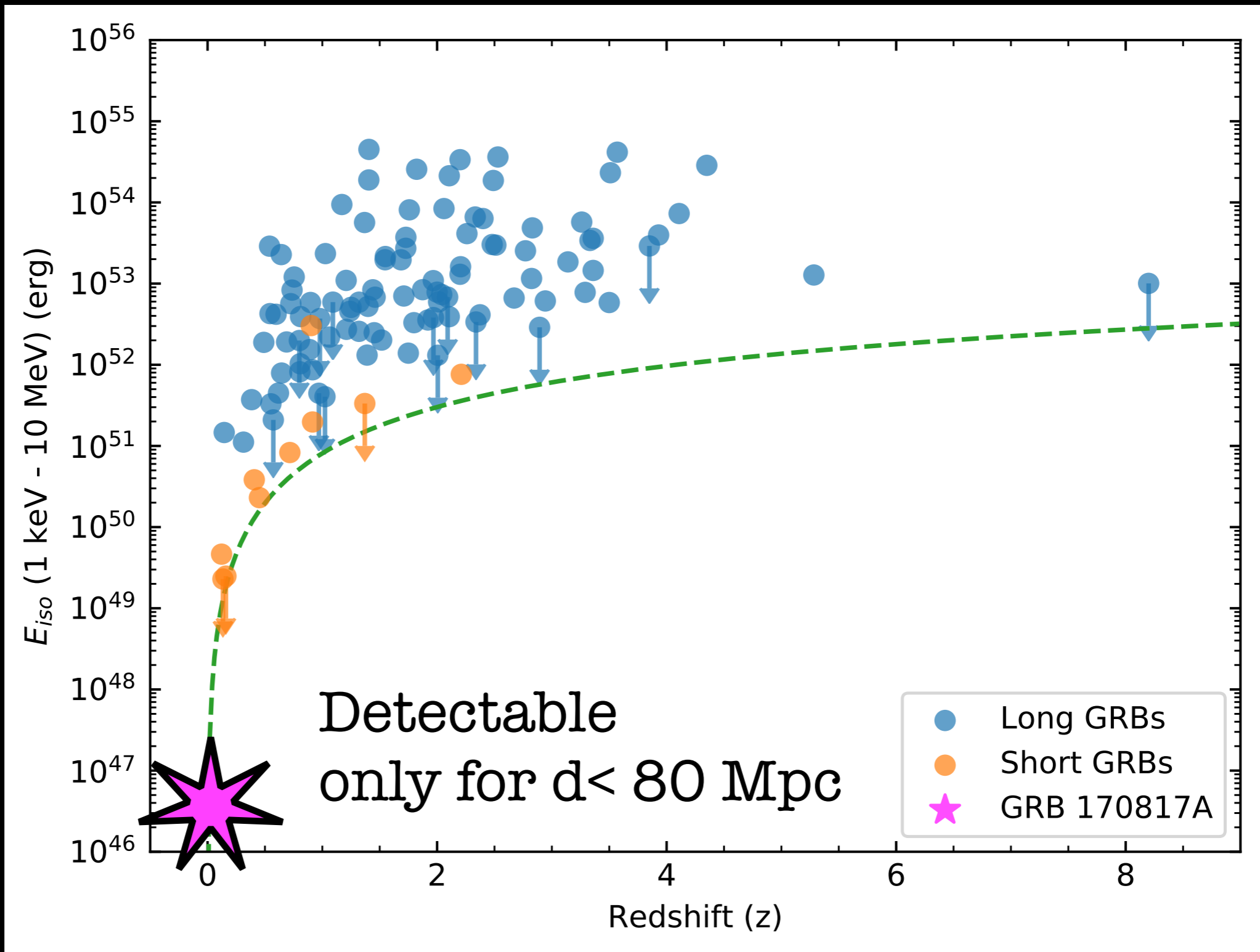


GW paper, the LVC, PRL, 2017

GW+GRB paper,
LVC+Fermi+INTEGRAL teams,
ApJ Letters, 2017



Very Low Energy in the Gamma-rays



Follow-up of GW170817 from Earth and Space

Earth

Space



GW170817: EM follow-up the spectrum



X-ray

UV/Optical

Near-IR

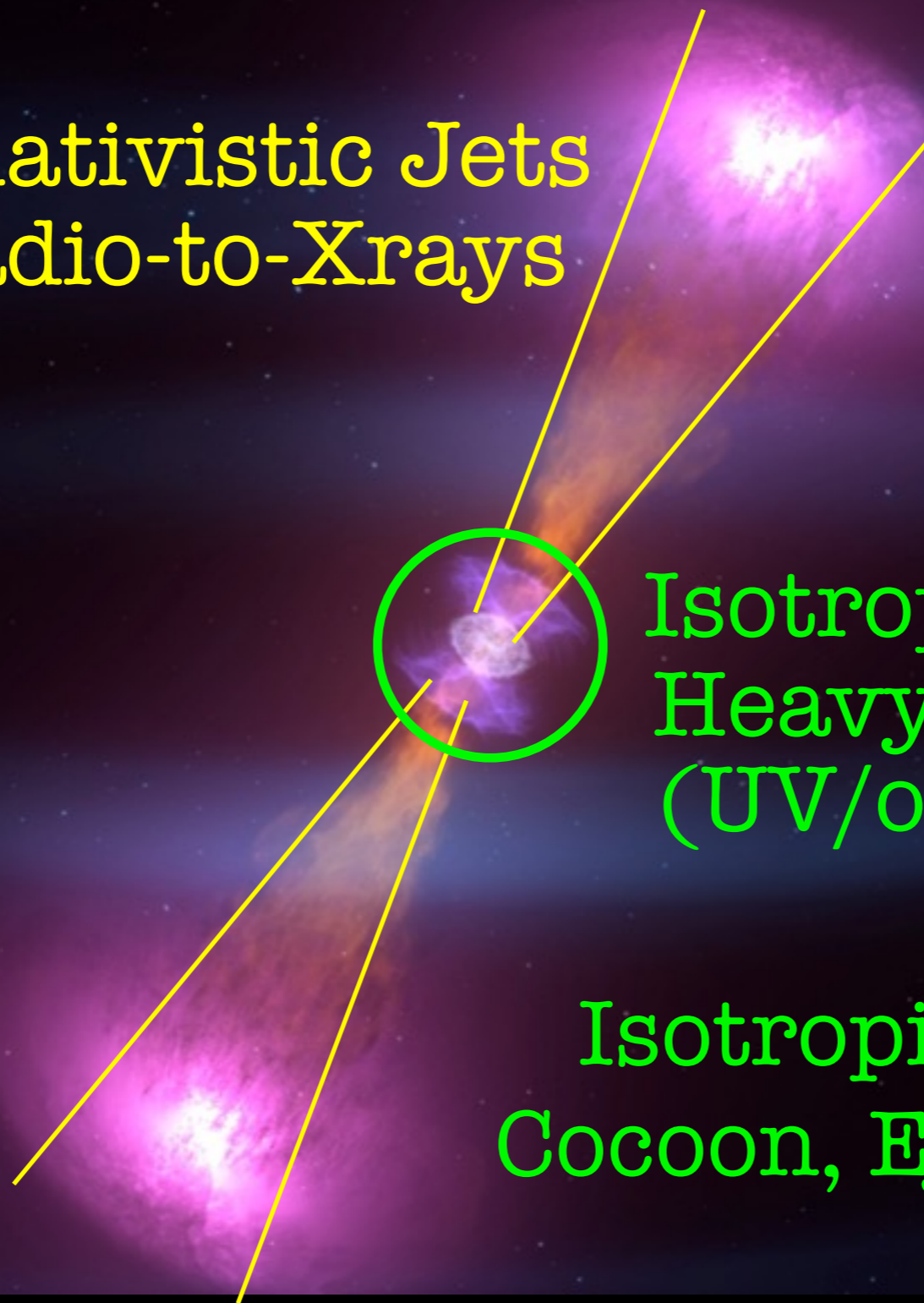
Radio

Picture to keep in mind:

Relativistic Jets
Radio-to-Xrays

Isotropic Component:
Heavy Elements
(UV/optical/IR)

Isotropic Component:
Cocoon, Ejecta Tidal tail

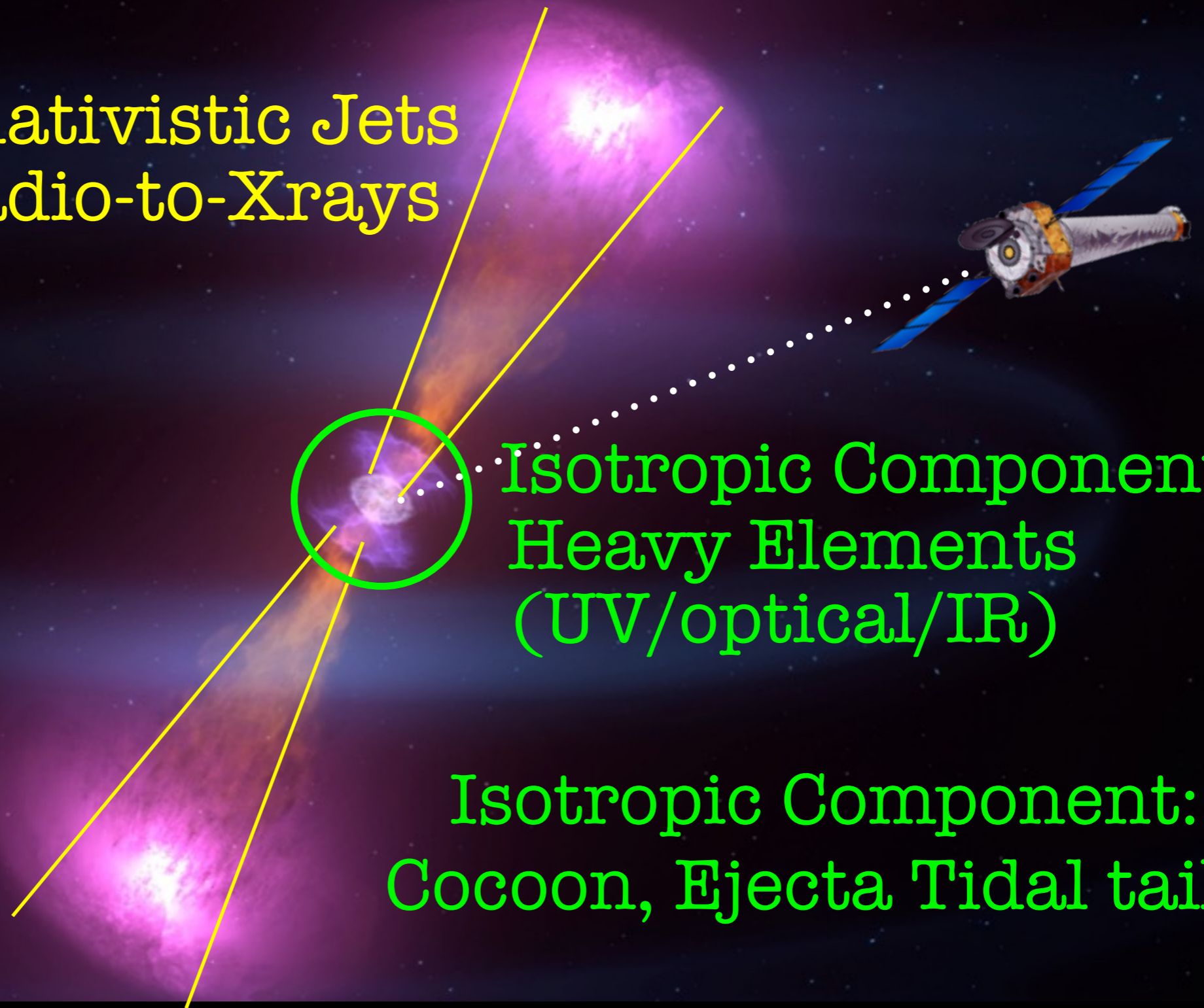


Picture to keep in mind:

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DECam team set-up for this event



Advanced LIGO-VIRGO network detects a source (30deg²)



DECam identifies candidate counterparts. (PI: Berger)

Arcsec Localization



Gemini provides spectroscopic confirmation.



VLA detects off-axis radio afterglow emission.



Chandra detects off-axis X-ray afterglow emission.

**+ 70 other
+ teams!!**



All Eyes! G298048. Images will be downloadable here

Ryan Chornock <chornock@ohio.edu>

Thu, Aug 17, 2017 at 7:42 PM

Reply-To: chornock@ohio.edu

To: Sahar Allam <sallam@fnal.gov>, "Berger, Edo" <eberger@cfa.harvard.edu>, Douglas L Tucker <dtucker@fnal.gov>

Cc: "Philip S. Cowperthwaite" <pcowperthwaite@cfa.harvard.edu>, Dillon Brout <dbrout@physics.upenn.edu>, Marcelle Soares Santos <marcelle@fnal.gov>, Dan Scolnic <dscolnic@kicp.uchicago.edu>, des-gw <des-gw@fnal.gov>

cow

Holy 

Check out NGC 4993 in DECam_00668440.fits.fz[N5]

Attached is tonight's image + ps1-3pi.

Galaxy is at 40 Mpc.

-R



All Eyes! G298048. Images will be downloadable here


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^{cow}
Holy 

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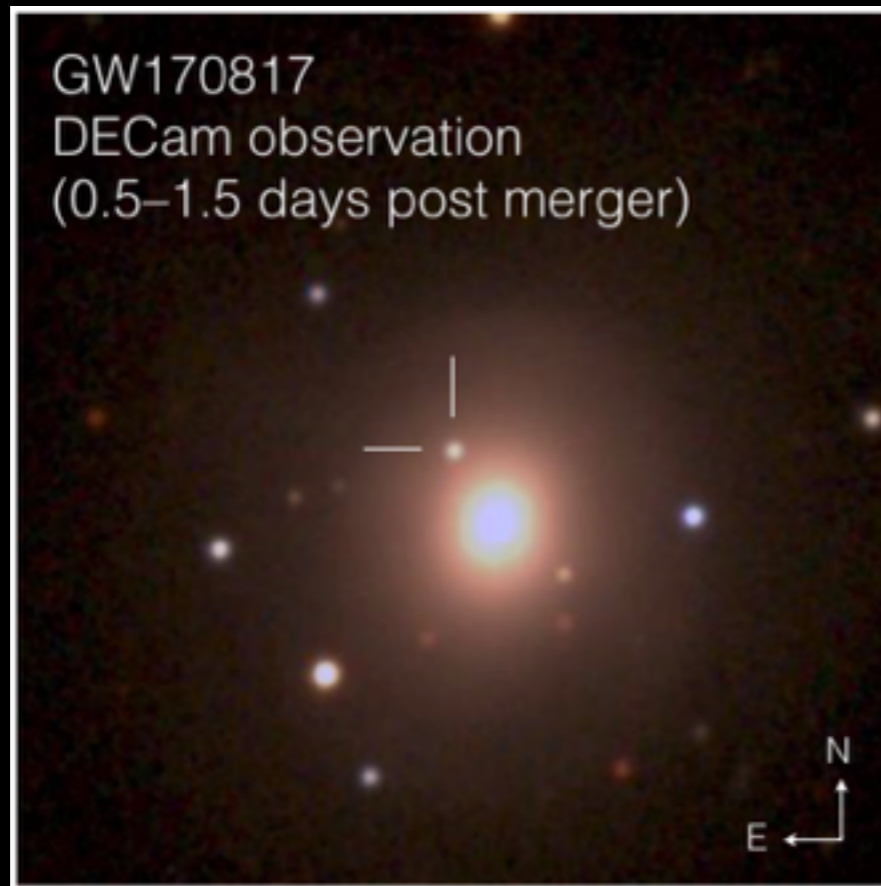
Galaxy is at 40 Mpc.

-R


100+
people

Discovery of visible light from the GW source GW170817

What had caused Ryan C. to curse?



Soares-Santos... Fong, Margutti et al. 2017

**Galaxy
@
40 Mpc
NEARBY!**



DECAM Cerro-Tololo (Chile)

Discovery of visible light from the GW source GW170817

What had caused Ryan C. to curse?

GW170817
DECam observation
(0.5–1.5 days post merger)

NGC 4933

1st announcements
taken from data
@ approx. 12 hr:

Swope

DECam

DLT40

VISTA

MASTER

Las Cumbres

(Coulter et al., Soares-Santos et al., Valenti et al.,
Tanvir et al., Lipunov et al., Arcavi et al. 2017)
c.f. LIGO Scientific & Virgo Collaboration et al. 2017;
ApJL, 848, L12

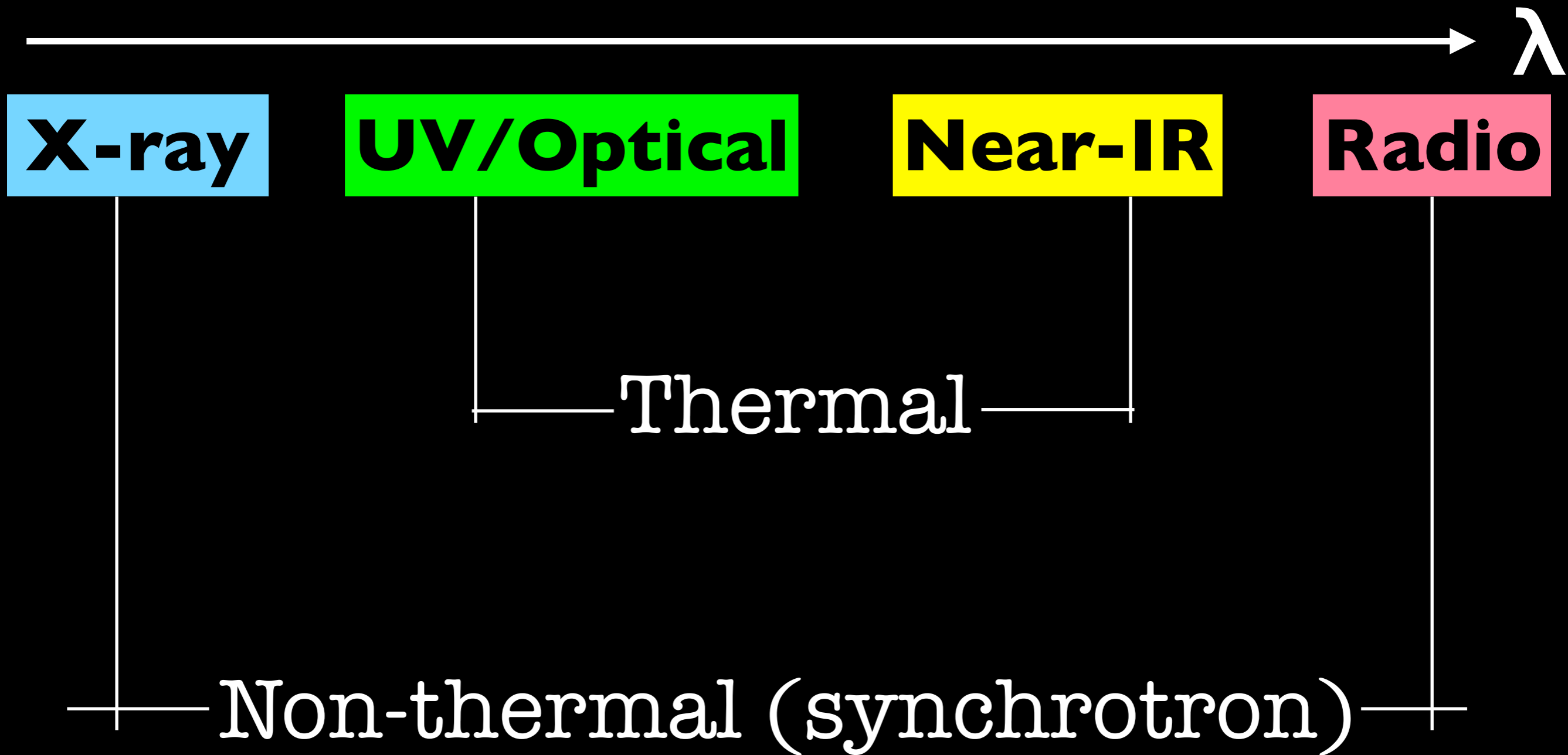
ng, Margutti et al. 2017

Galaxy
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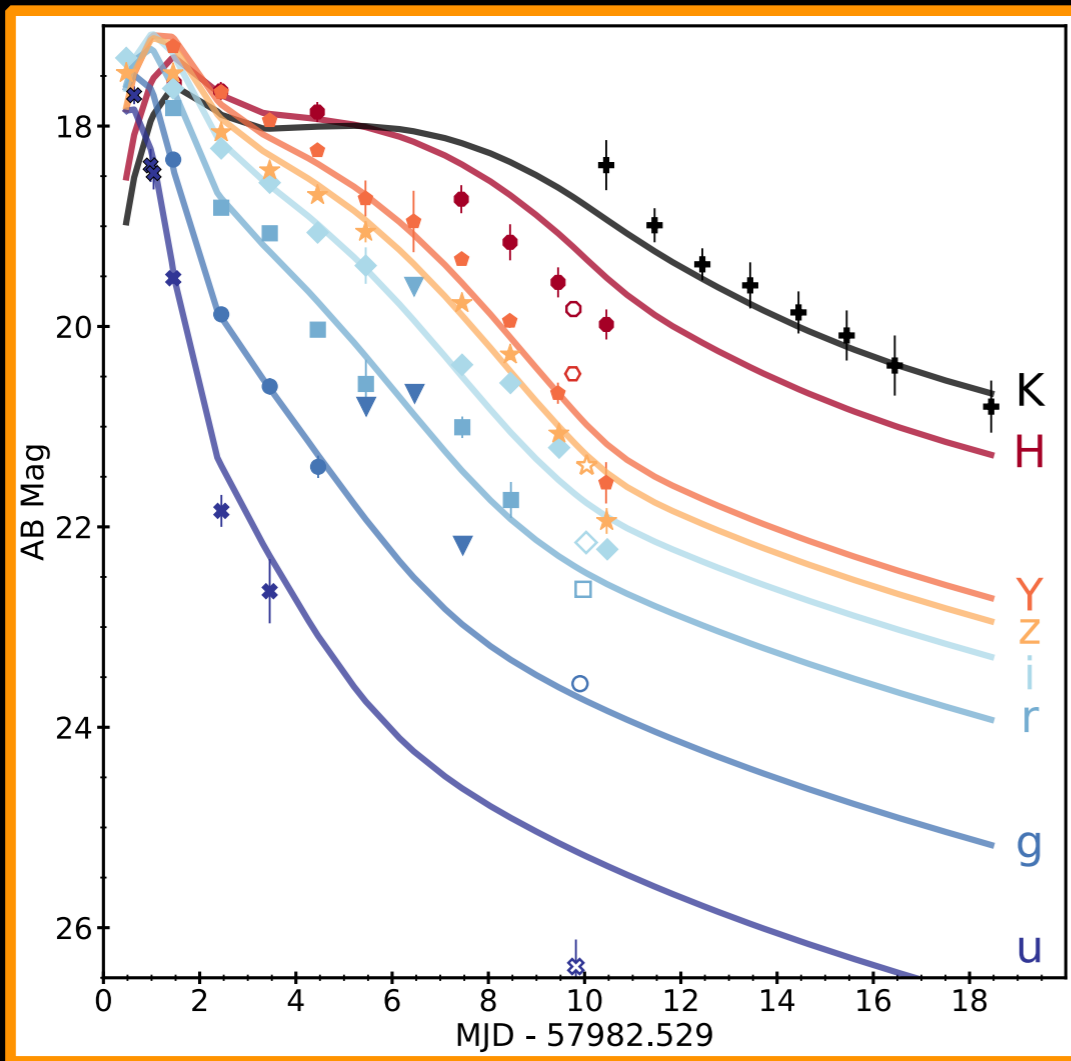
DECam Cerro-Tololo (Chile)

GW170817: EM follow-up across the spectrum



The Kilonova Red+Blue emission

The first two weeks



Cowperthwaite, .. Margutti et al. 2017

Near-infrared observations, together with information from visible light, the observations require two components!

i) **Blue, fast:** $M_{ej} = 0.01 M_{sol}$
 $v_{ej} = 0.3c$

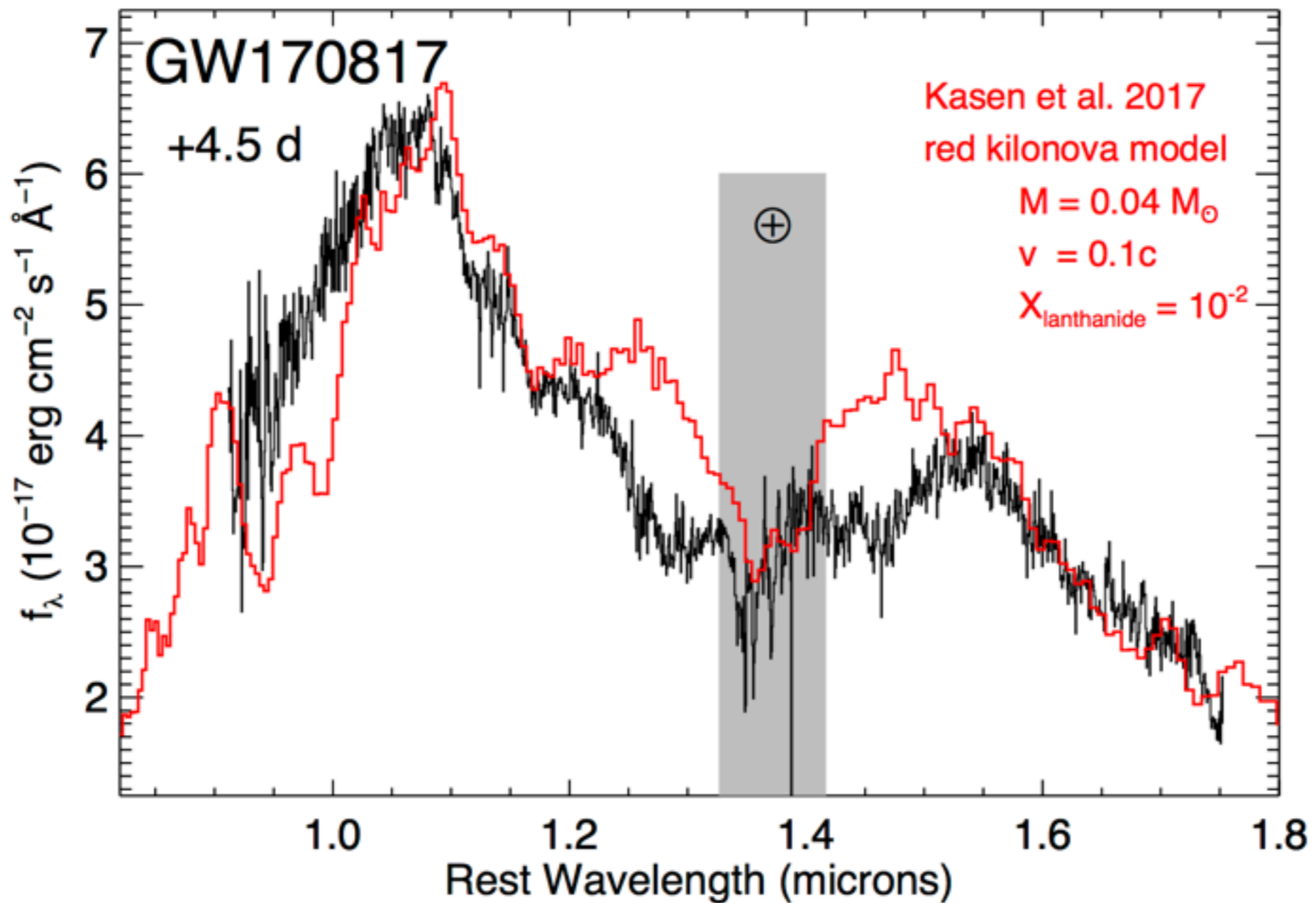
ii) **Red, slow:** $M_{ej} = 0.04 M_{sol}$
 $v_{ej} = 0.1c$

(Cowperthwaite et al. 2017; Nicholl et al. 2017, Smartt et al. 2017, Kasliwal et al. 2017 AND MORE)

“Time after Merger”

...faded away after ~ 2 weeks

Amazing Agreement!



Chornock et al. 2017

Neutron star mergers as an origin of heavy elements?

1 H																	2 He	
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		89 Ac	90 Th	91 Pa	92 U													

Merging Neutron Stars
Dying Low Mass Stars

Exploding Massive Stars
Exploding White Dwarfs

Big Bang
Cosmic Ray Fission

Based on graphic created by Jennifer Johnson

Evidence for *r*-process

1. That there was anything at all to see in the optical/NIR!
2. SED peaks near ~ 1 micron are a consequence of lanthanide opacity

Did we see GOLD? No!!!

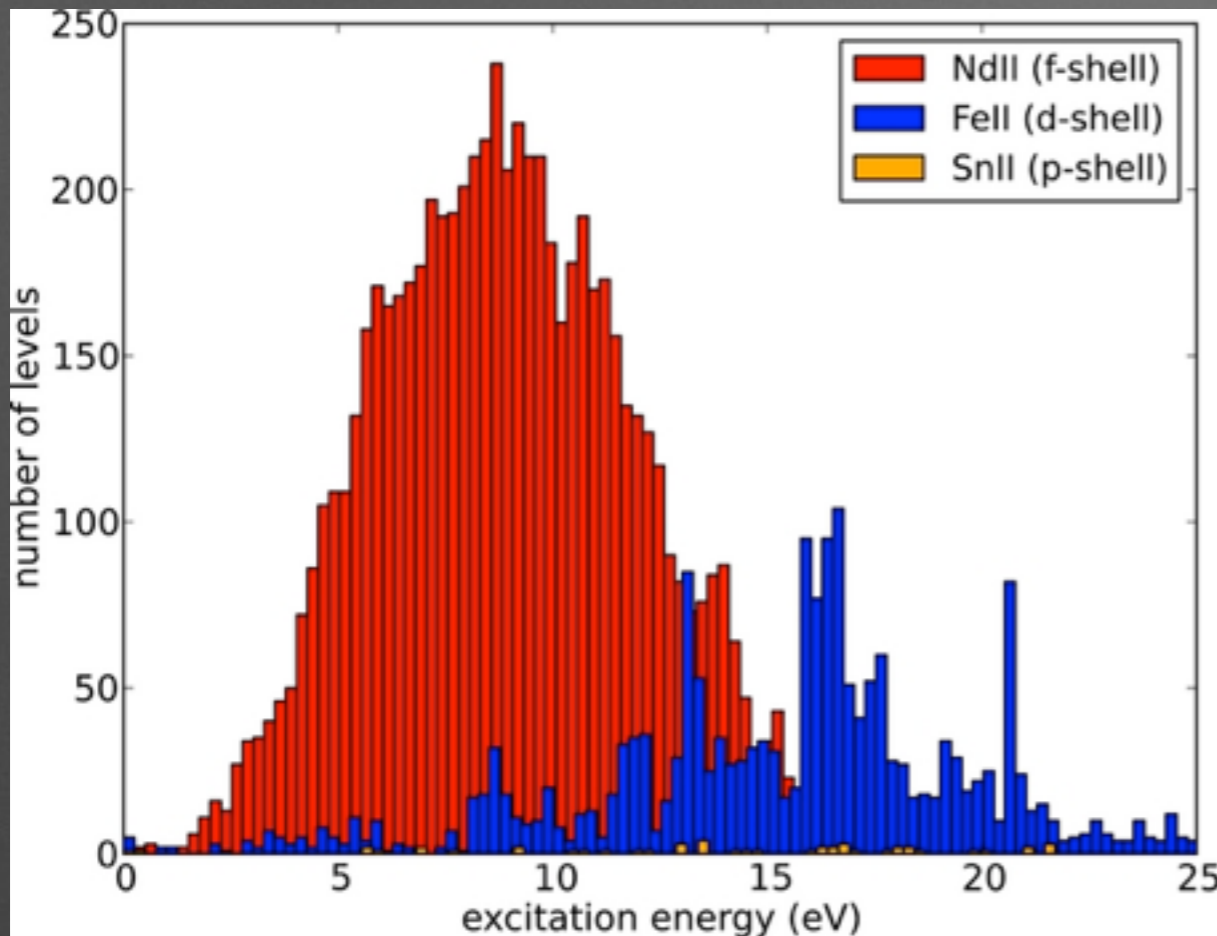
1 H																	2 He	
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37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba			72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																	
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			89 Ac	90 Th	91 Pa	92 U												

Merging Neutron Stars
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- Atoms/ions with open *f*-shells have many more available states compared to iron-peak elements

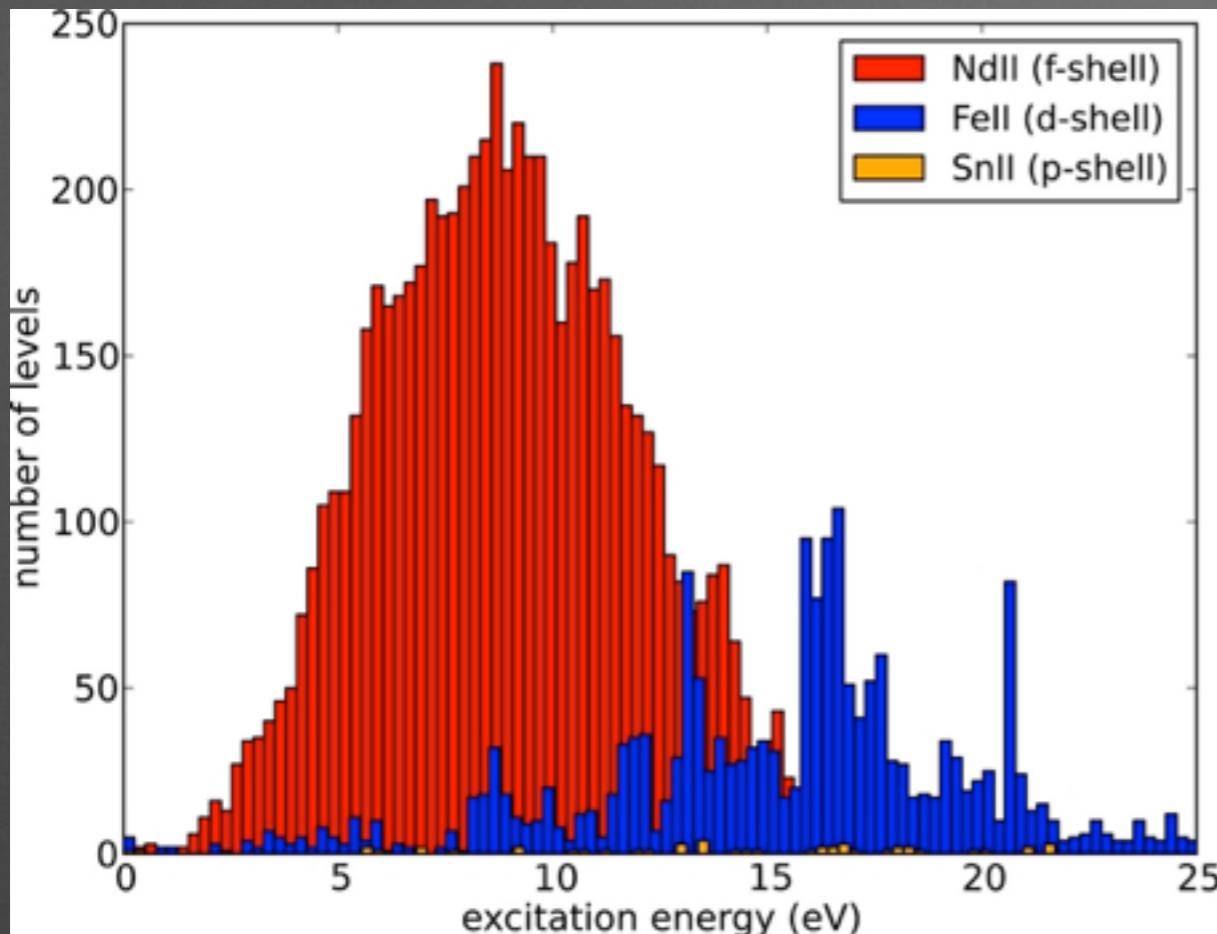
Kasen et al. 2013

Ion	Configurations	Number of levels	Number of lines
Nd I	$4f^4 6s^2$, $4f^4 6s(5d, 6p, 7s)$, $4f^4 5d^2$, $4f^4 5d6p$, $4f^3 5d6s^2$, $4f^3 5d^2(6s, 6p)$, $4f^3 5d6s6p$	31,358	70,366,259

Tanaka et al. 2017

This matters for the opacity

→ NIR



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Kasen et al. 2013

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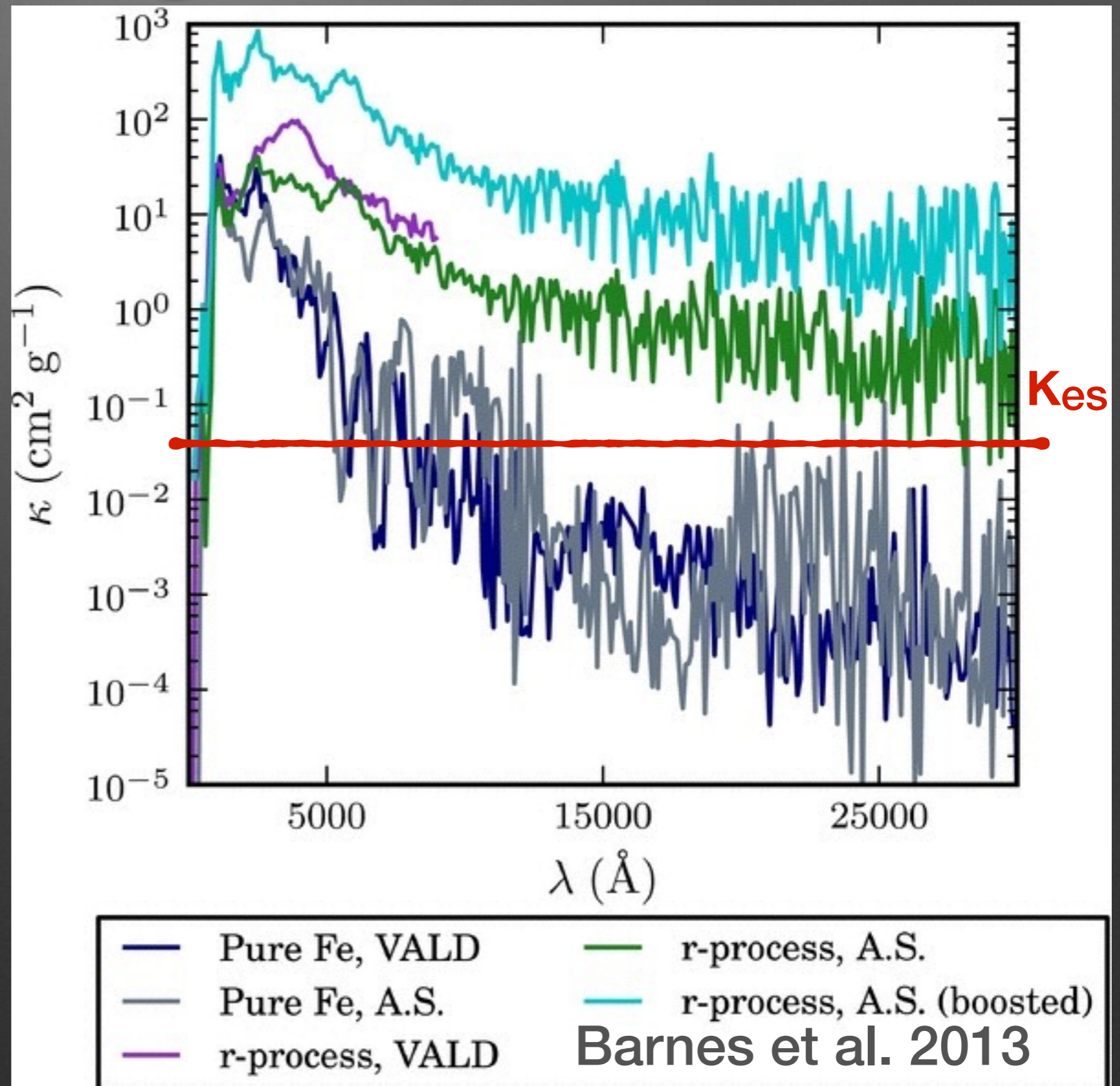
Tanaka et al. 2017

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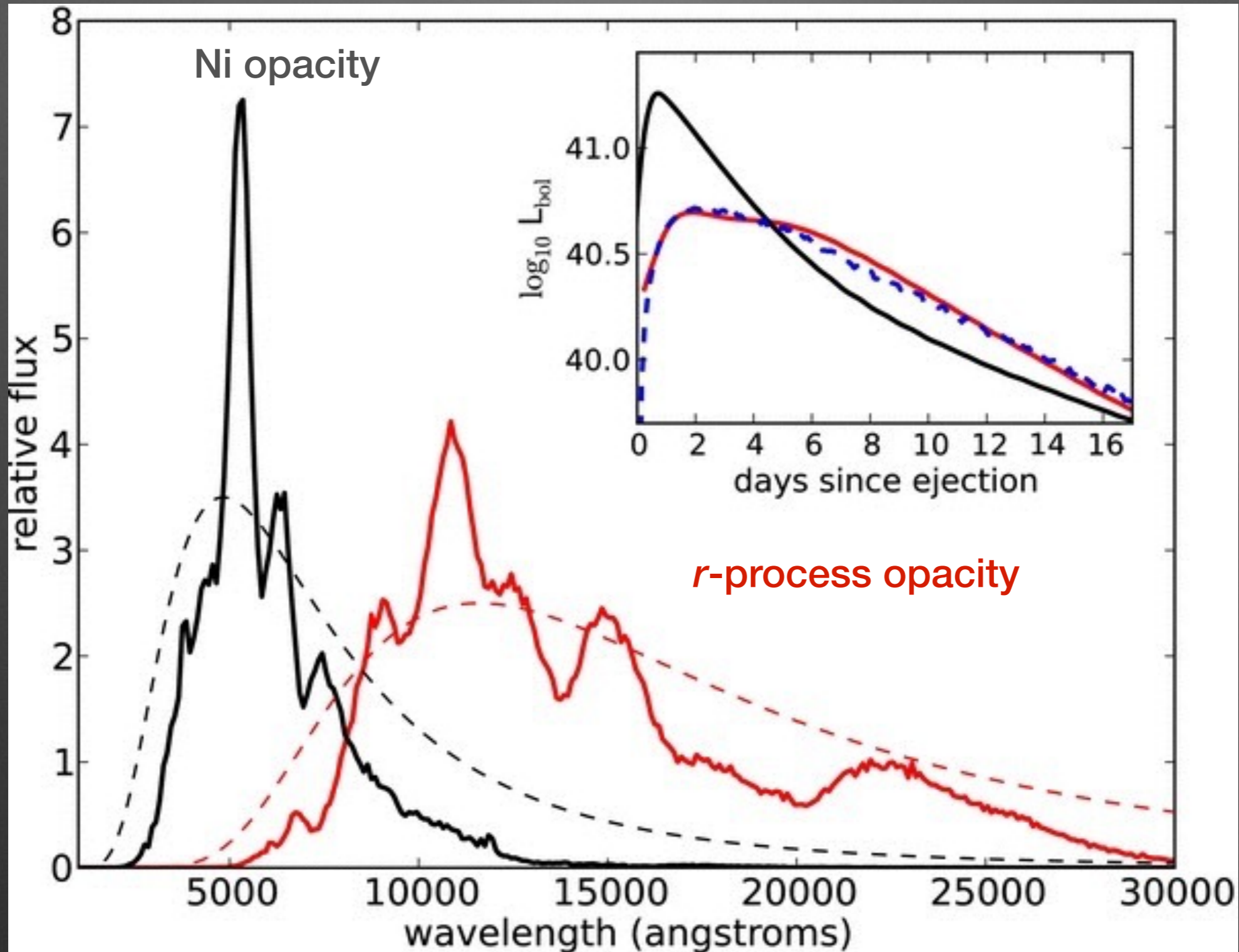
→ NIR

Ingredient #2: Expansion= everything is blended

- The effects of weak lines are greatly enhanced in material with strong velocity gradients

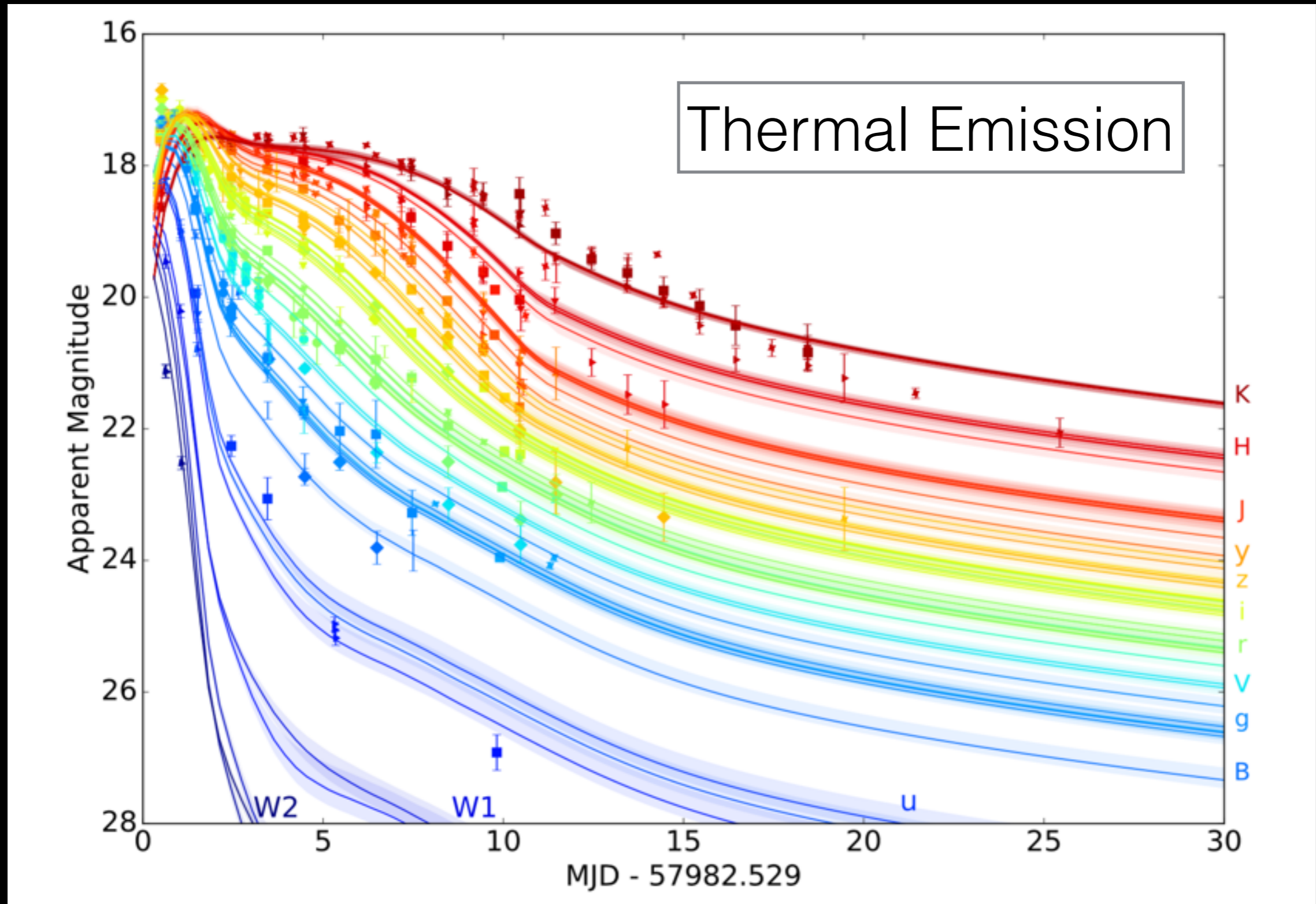


r-process \rightarrow NIR



Kasen, Badnell, & Barnes 2013

Comprehensive kilonova photometry



Villar,...RM et al., 2017

Schematics of the EM emission from the BNS

*Image credit:
NSF
LIGO
Sonoma State University
A. Simonnet*

This is Gold

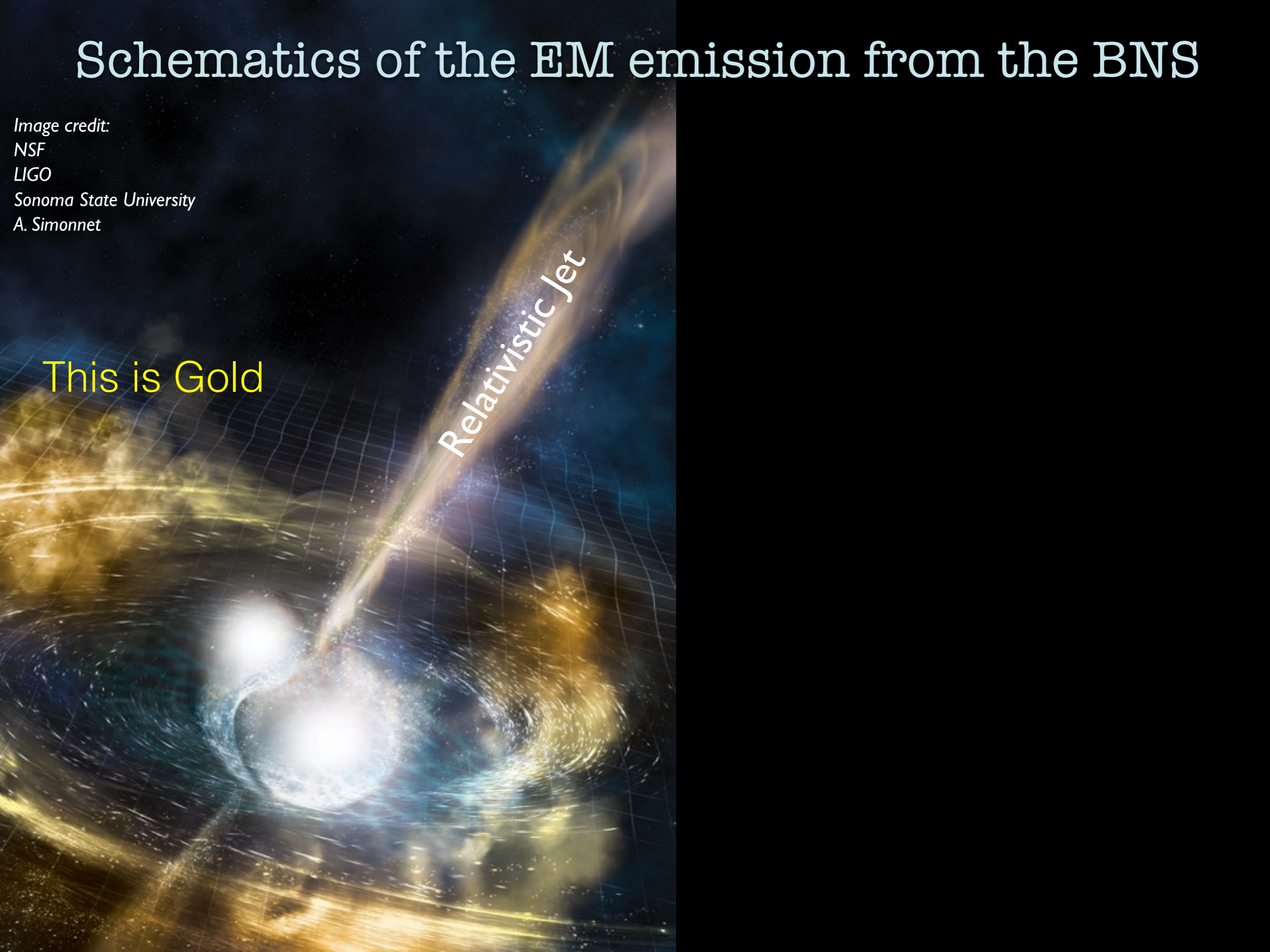
A detailed schematic illustration of the electromagnetic emission from a binary neutron star (BNS) merger. The scene is set against a dark, star-filled background. Two bright, glowing neutron stars are shown in the process of merging, their surfaces depicted with a grid-like texture. A powerful, narrow jet of high-energy radiation, primarily in the gamma-ray and X-ray bands, is emitted from the point of impact, extending upwards and to the right. This jet is surrounded by a complex, multi-colored structure of electromagnetic emission, including a broad, glowing disk of light in the blue and purple hues. The overall appearance is that of a highly energetic and complex astrophysical event.

Schematics of the EM emission from the BNS

Image credit:
NSF
LIGO
Sonoma State University
A. Simonnet

This is Gold

Relativistic Jet

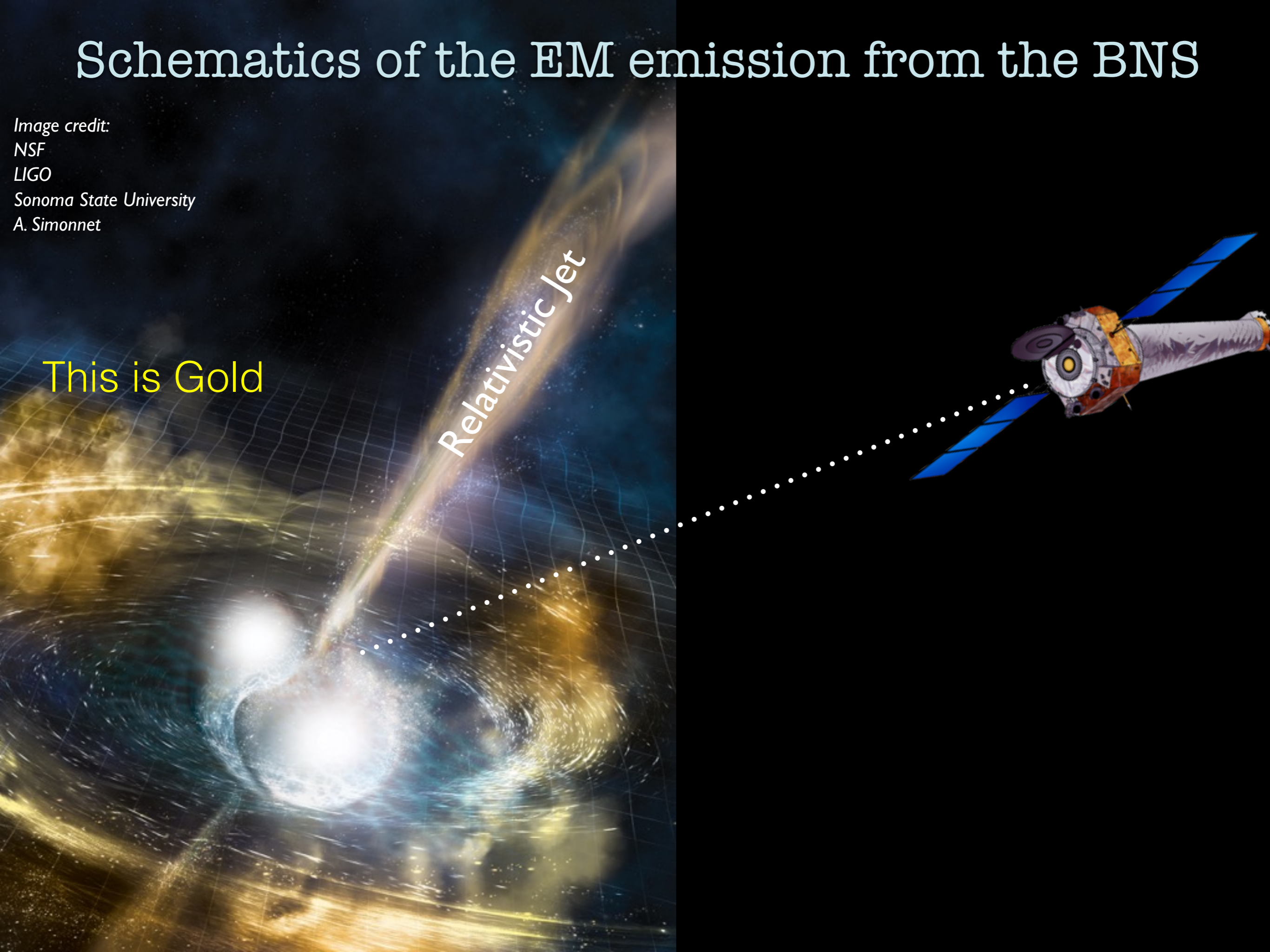


Schematics of the EM emission from the BNS

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Relativistic Jet



Schematics of the EM emission from the BNS

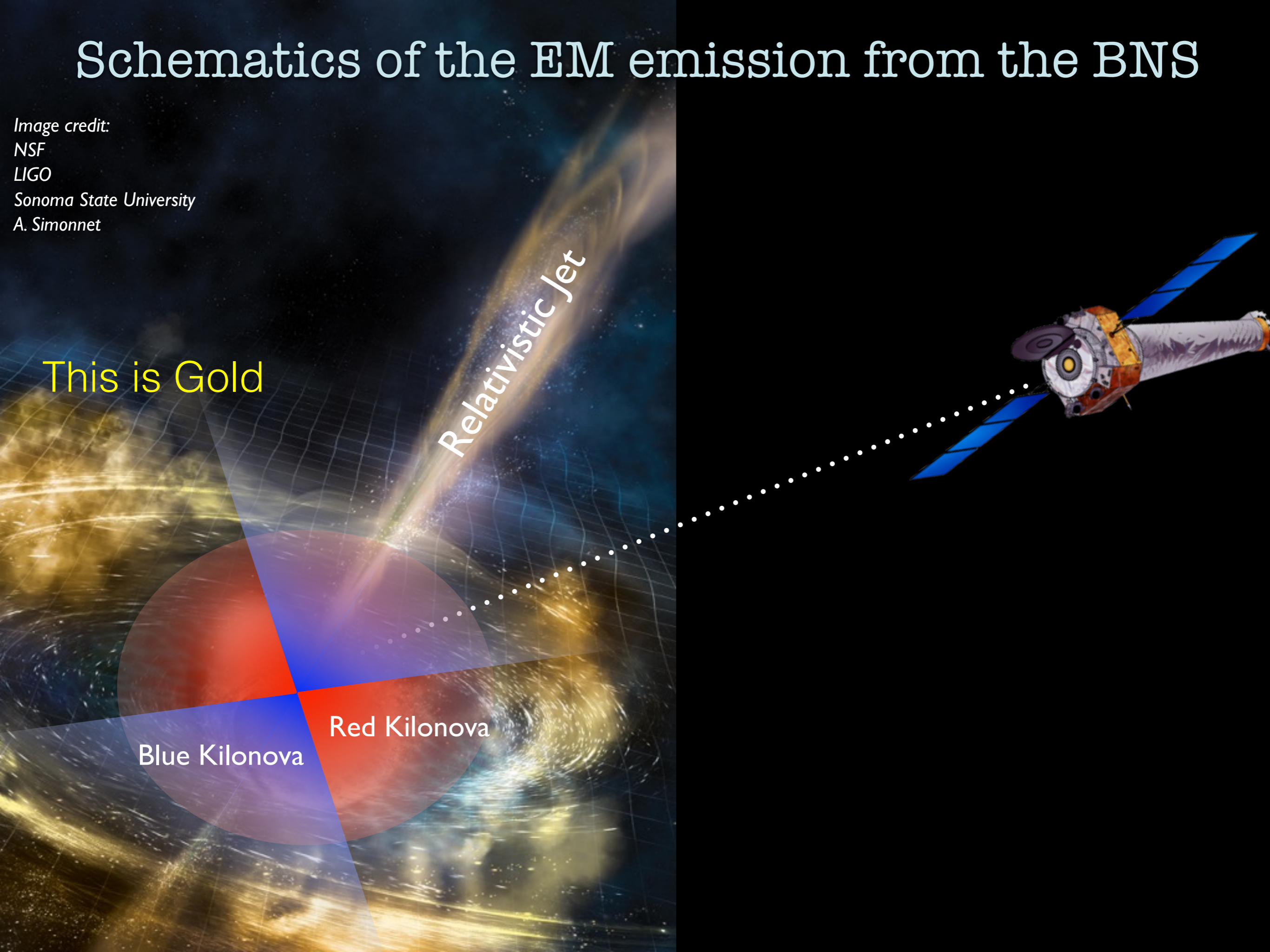
Image credit:
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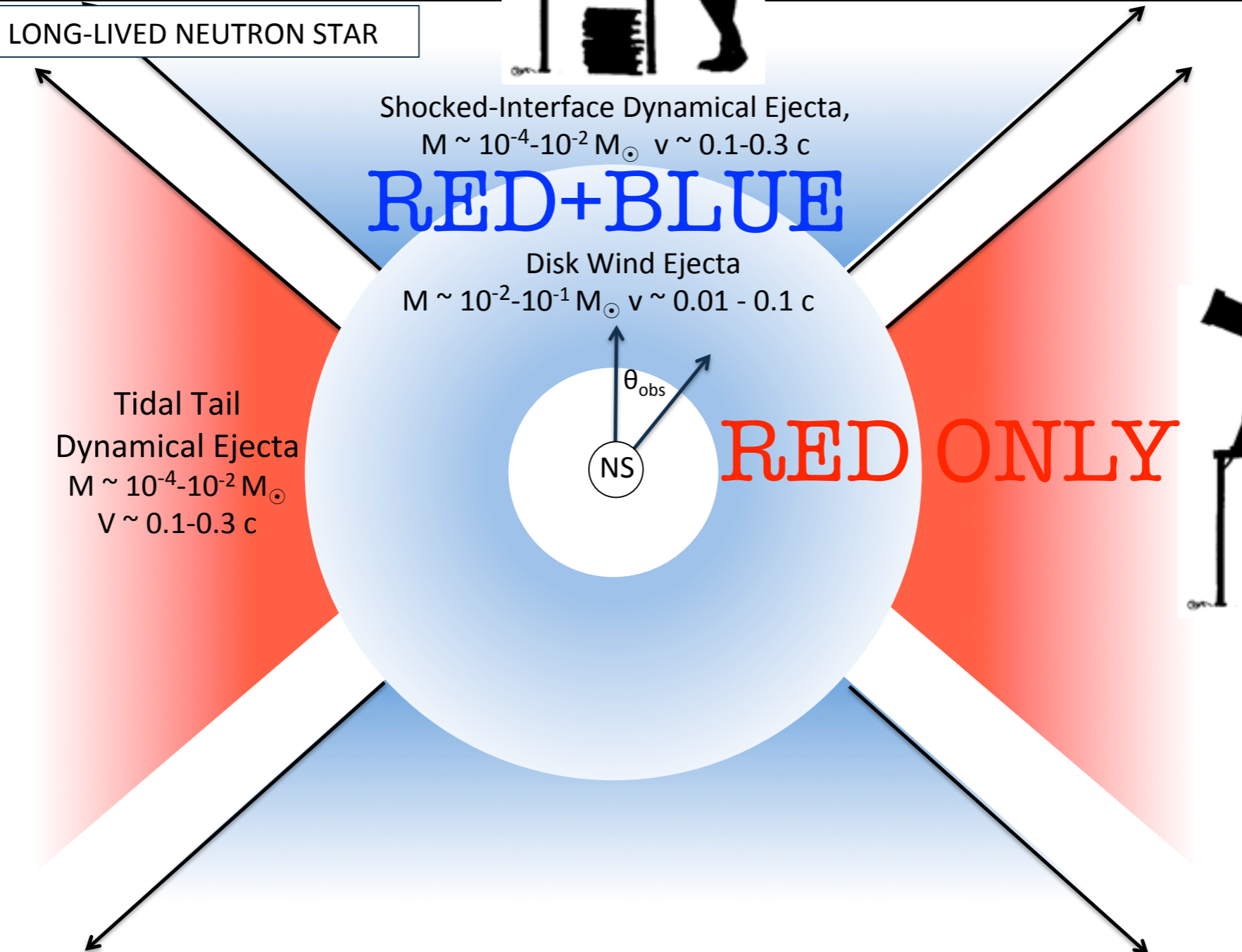
Relativistic Jet

Blue Kilonova

Red Kilonova



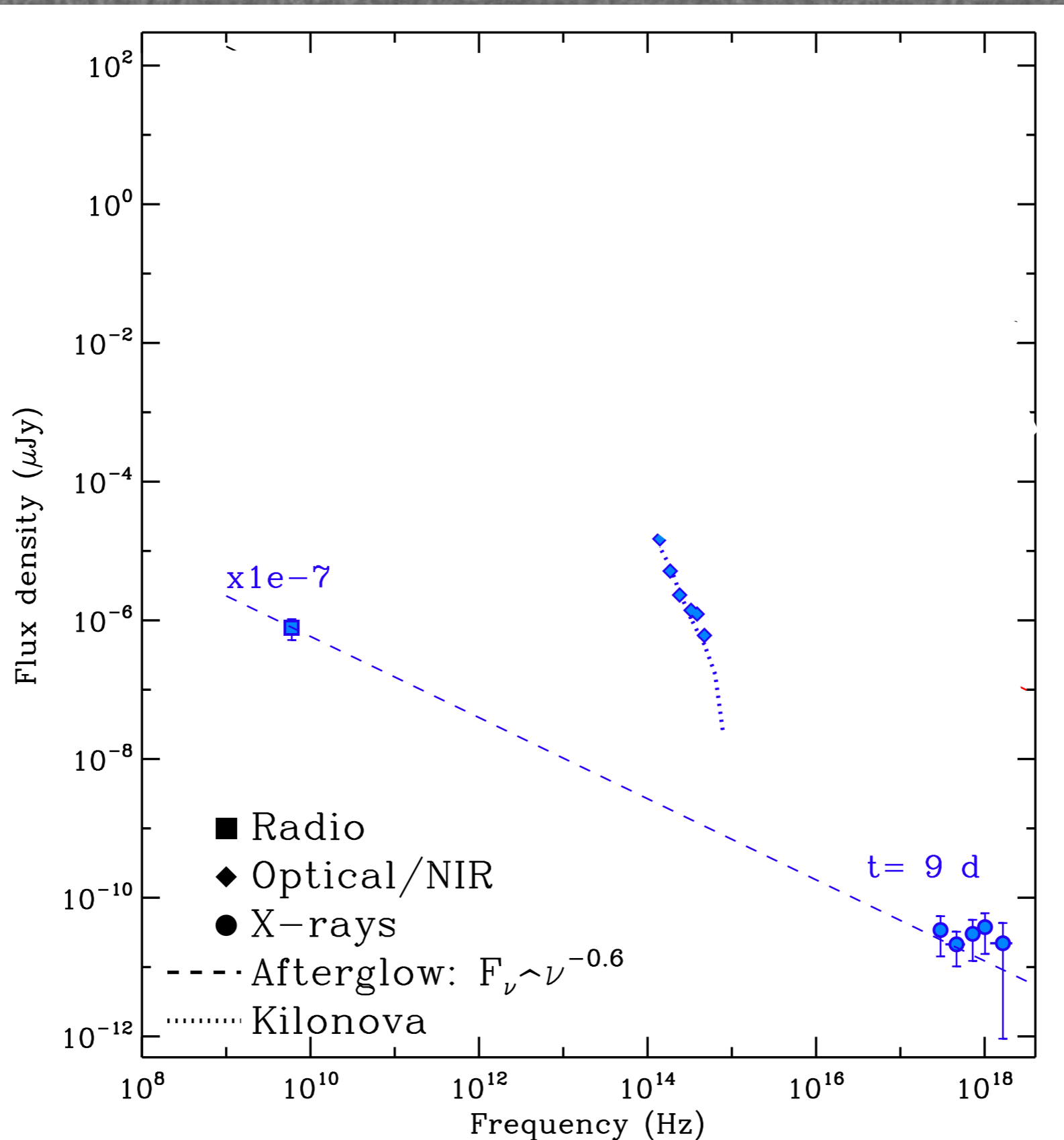
Kilonova Colors



The broad-band Radio-to-Xray spectrum
NON-THERMAL EMISSION

Radio

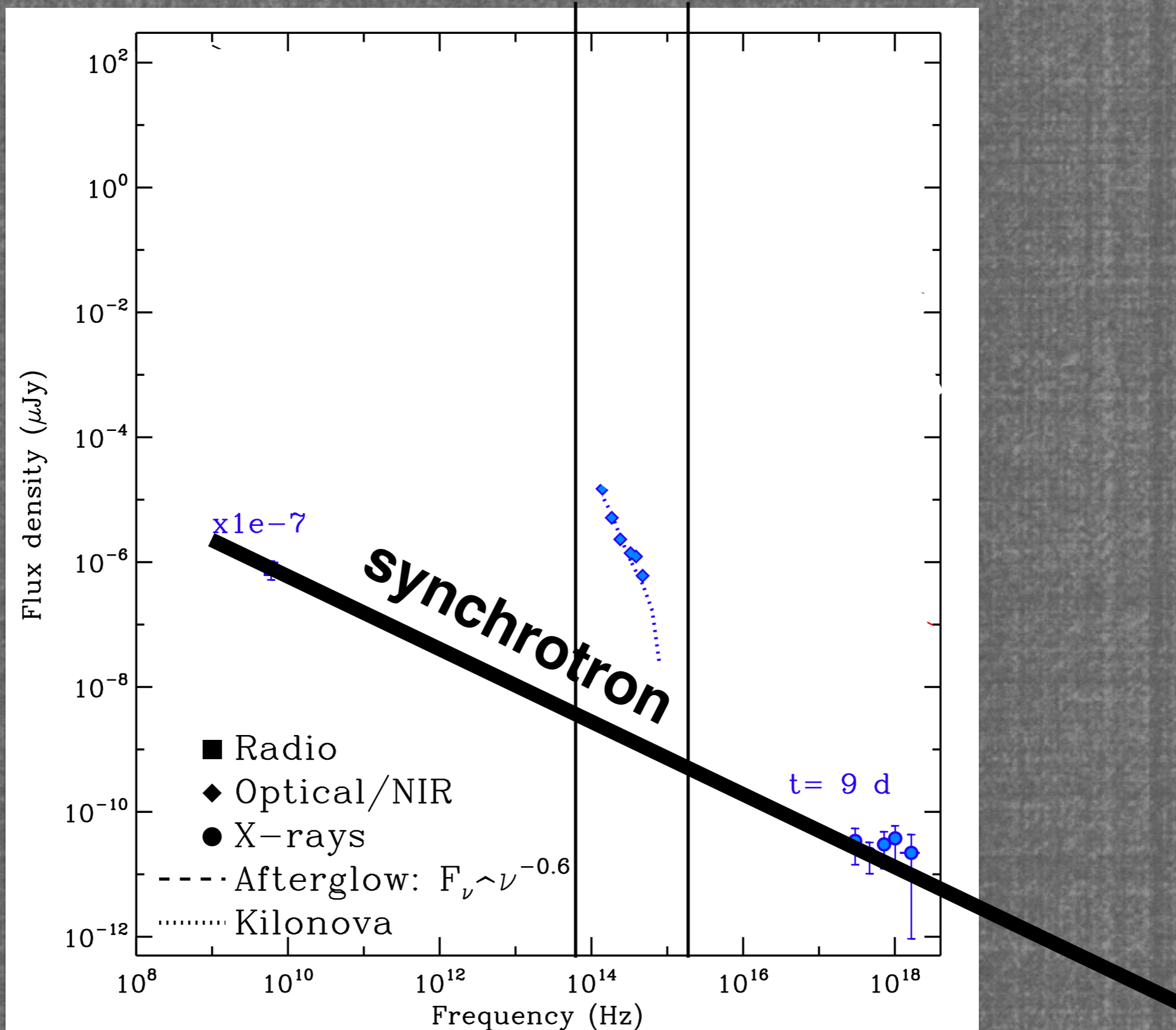
X-rays



Radio

Thermal KN

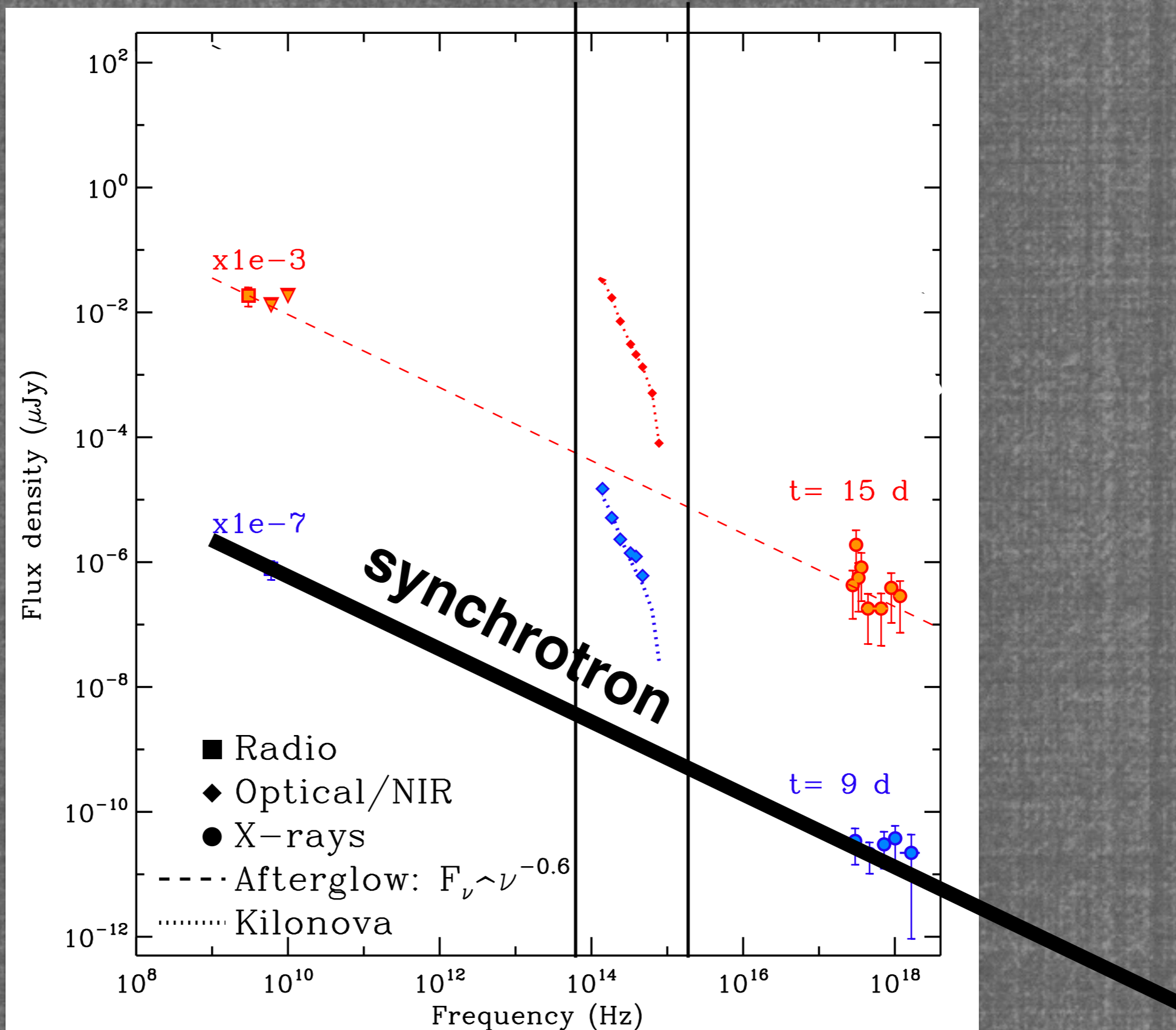
X-rays



Radio

Thermal KN

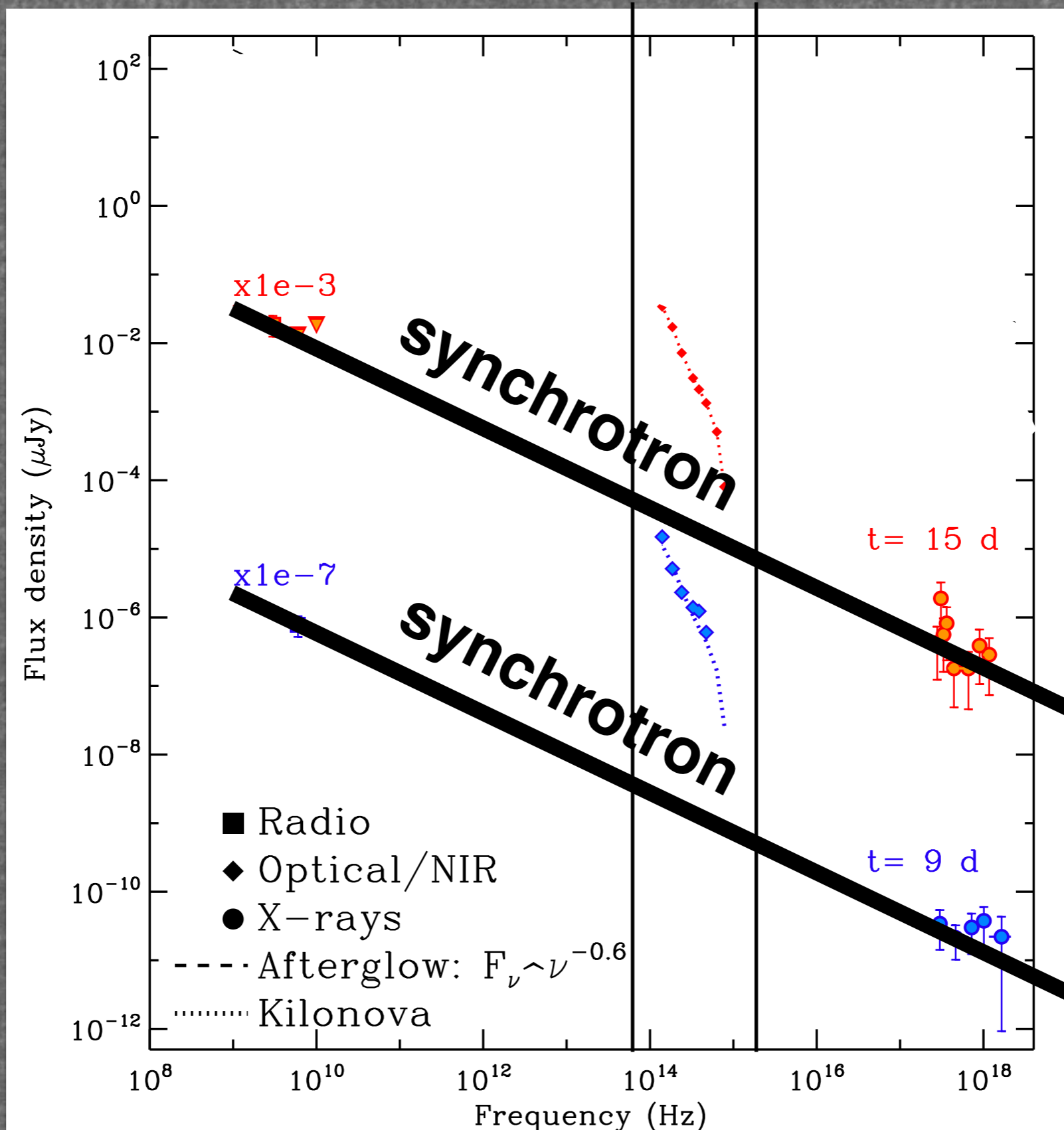
X-rays



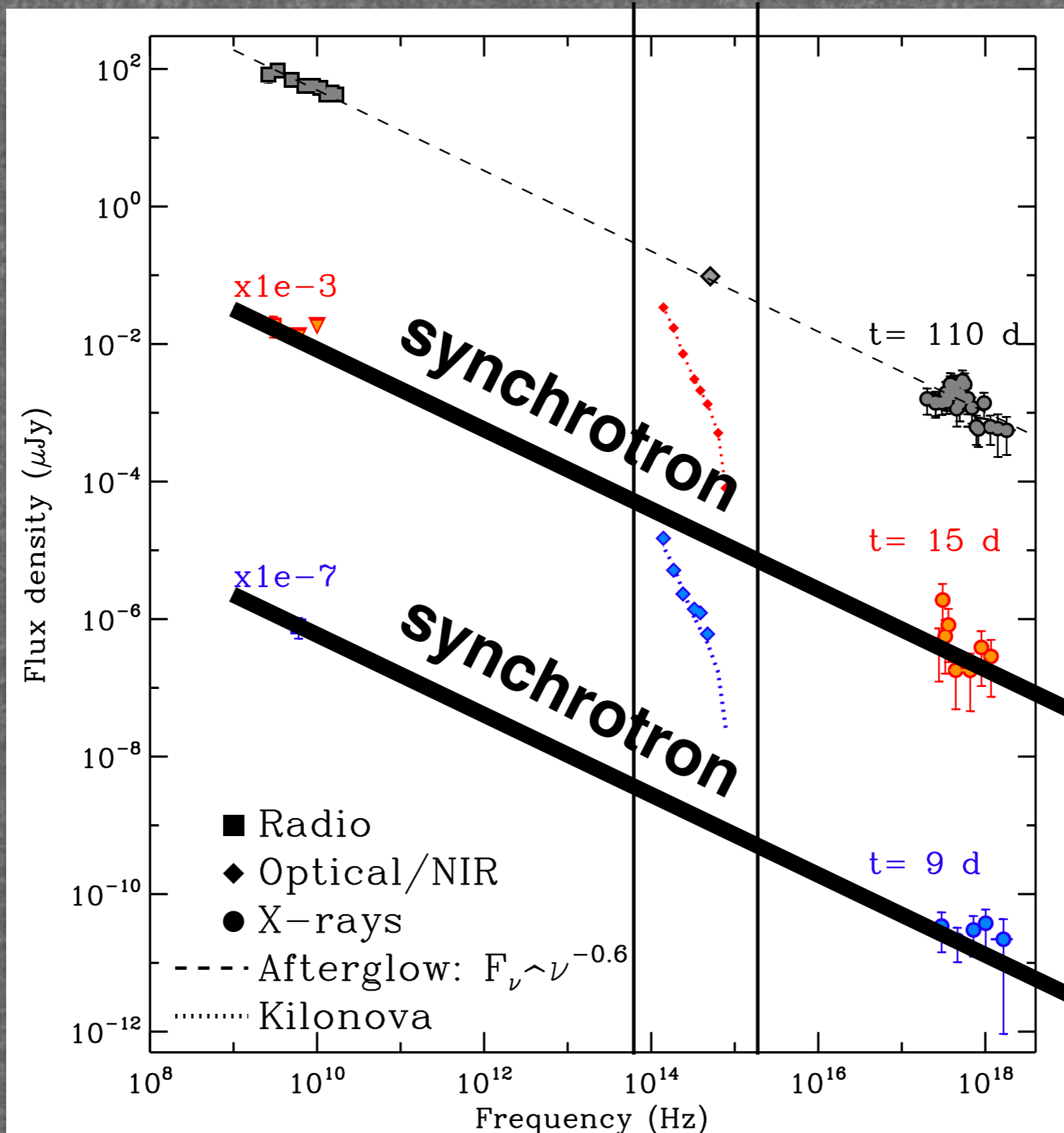
Radio

Thermal KN

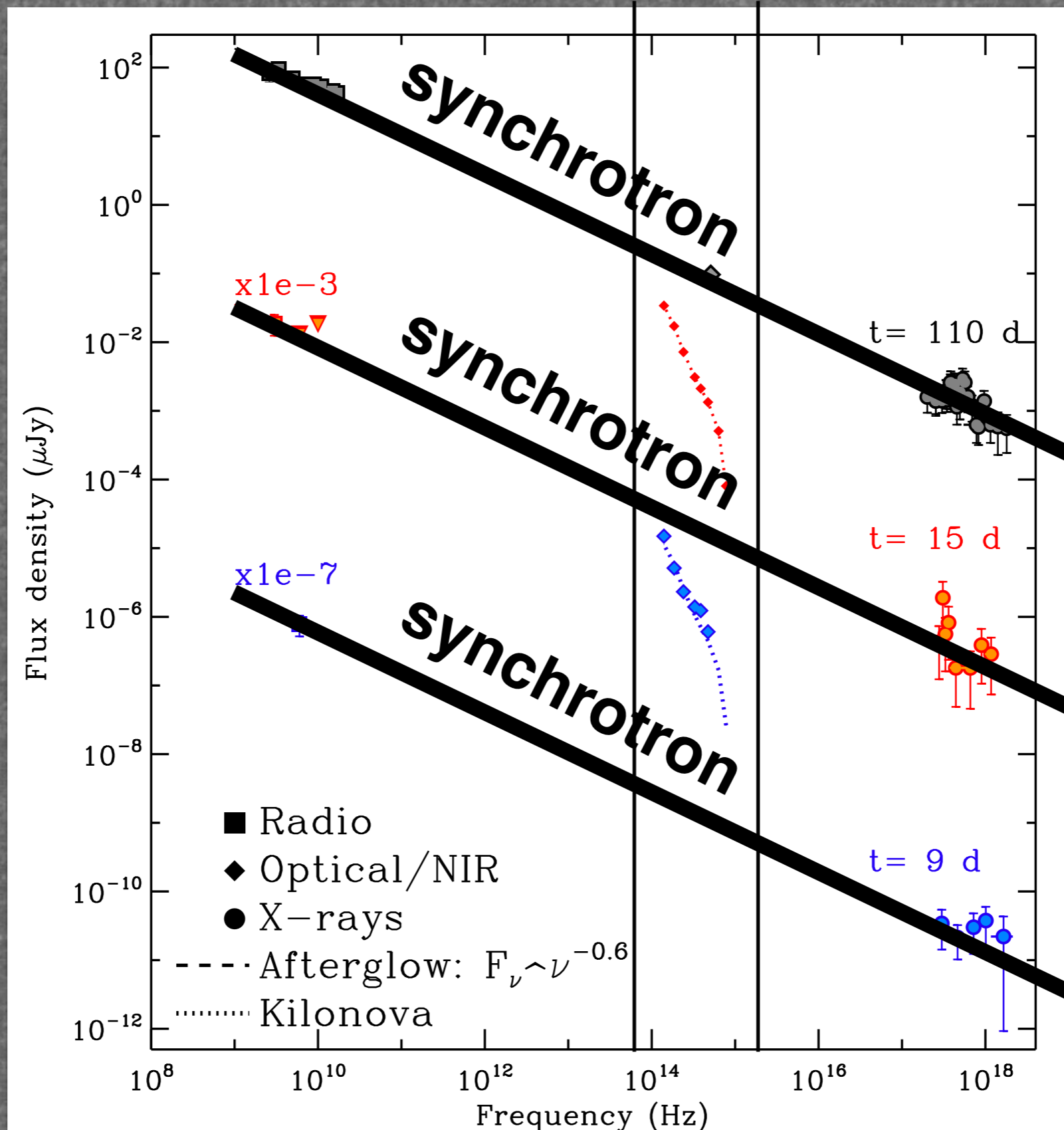
X-rays



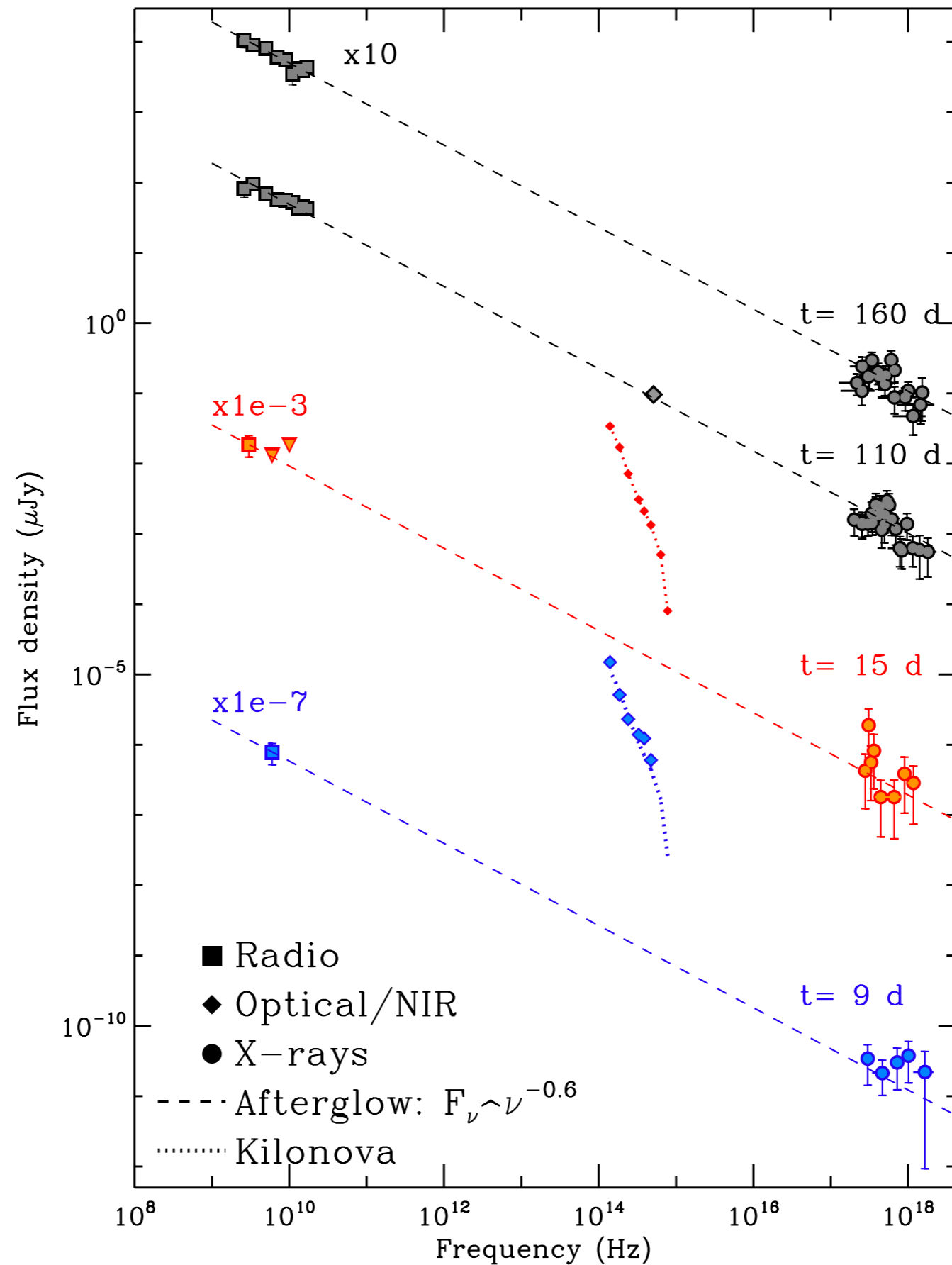
A POWER-LAW in the Sky



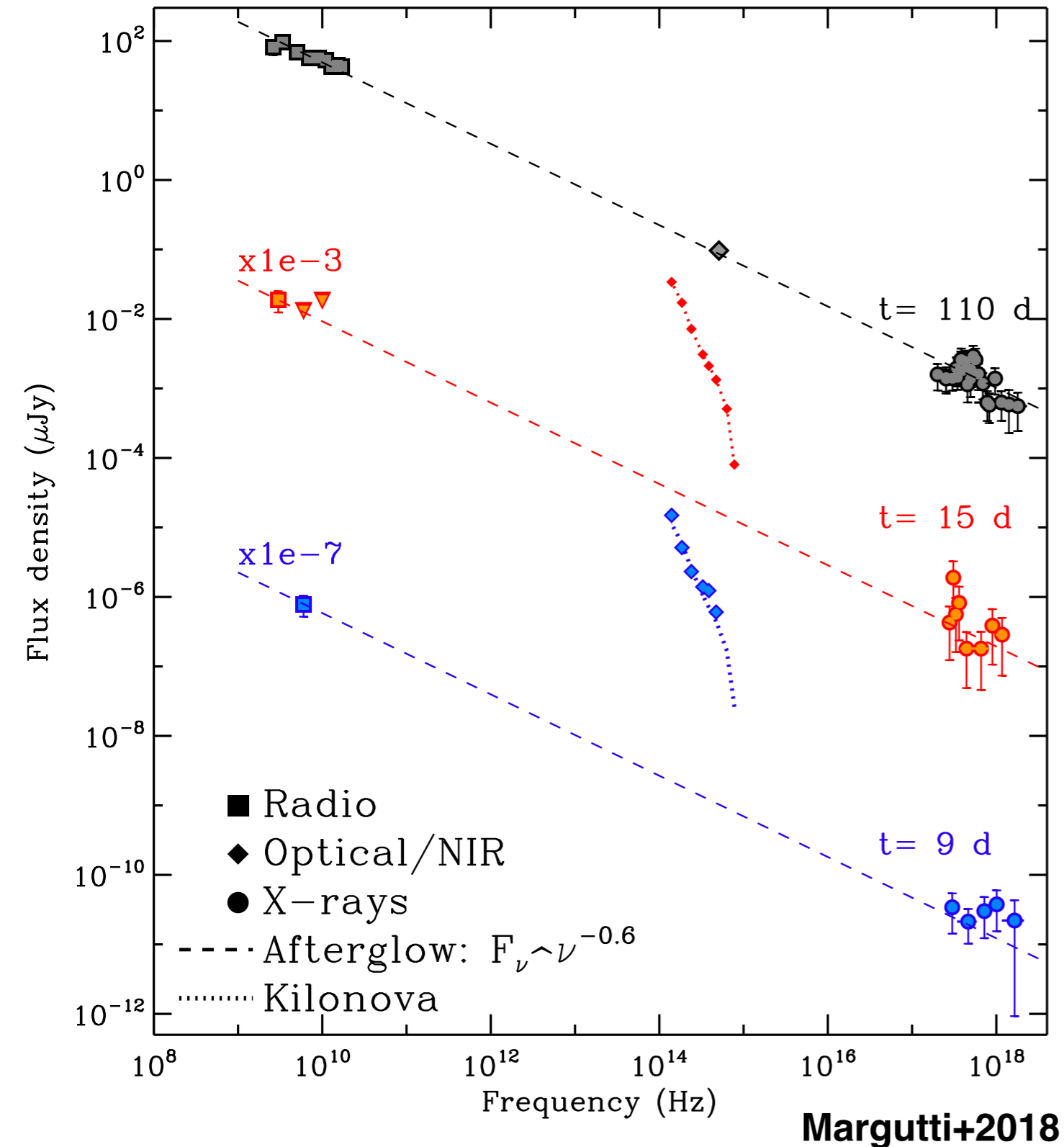
A POWER-LAW in the Sky



A power-law in the sky!



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



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

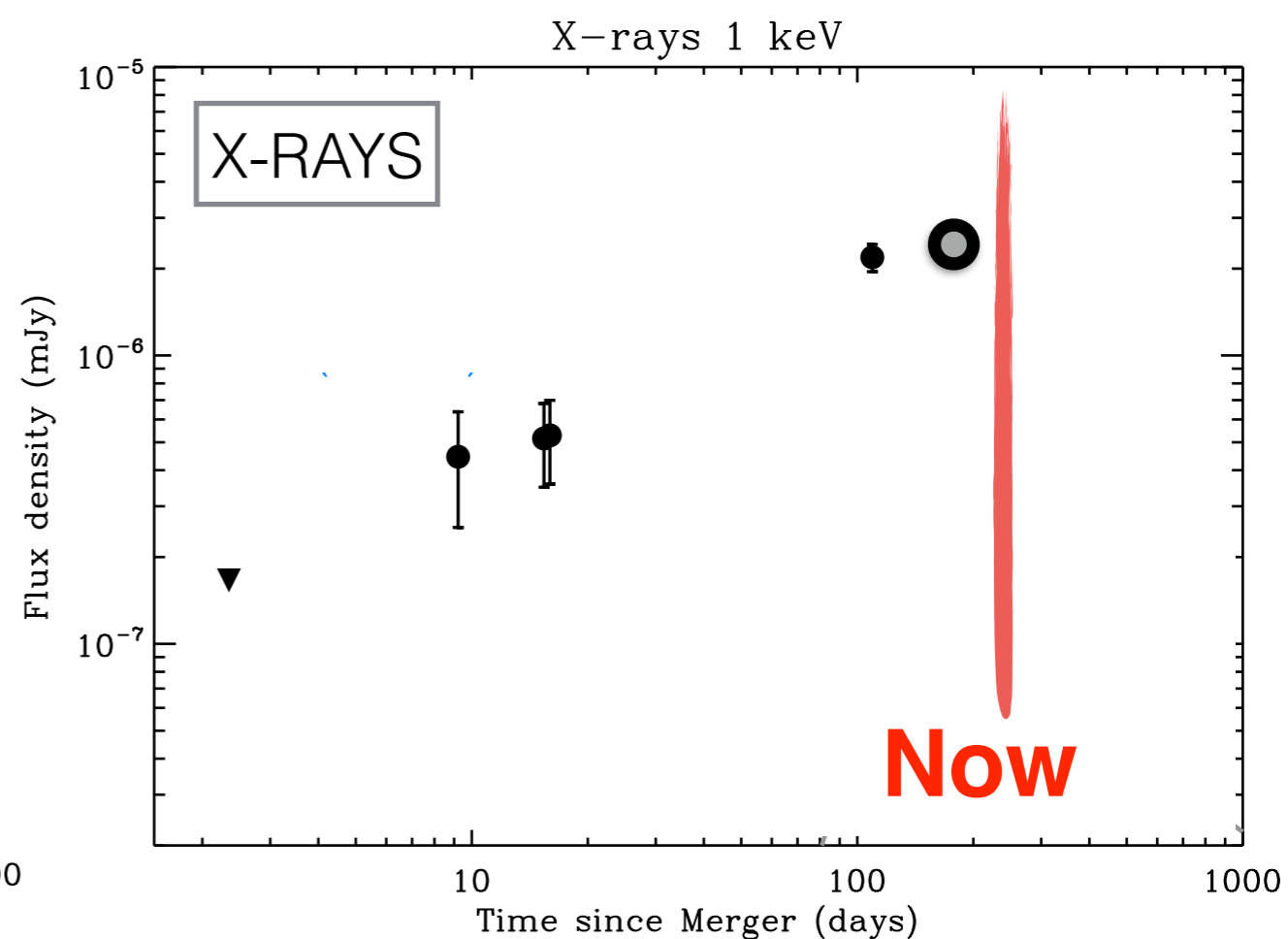
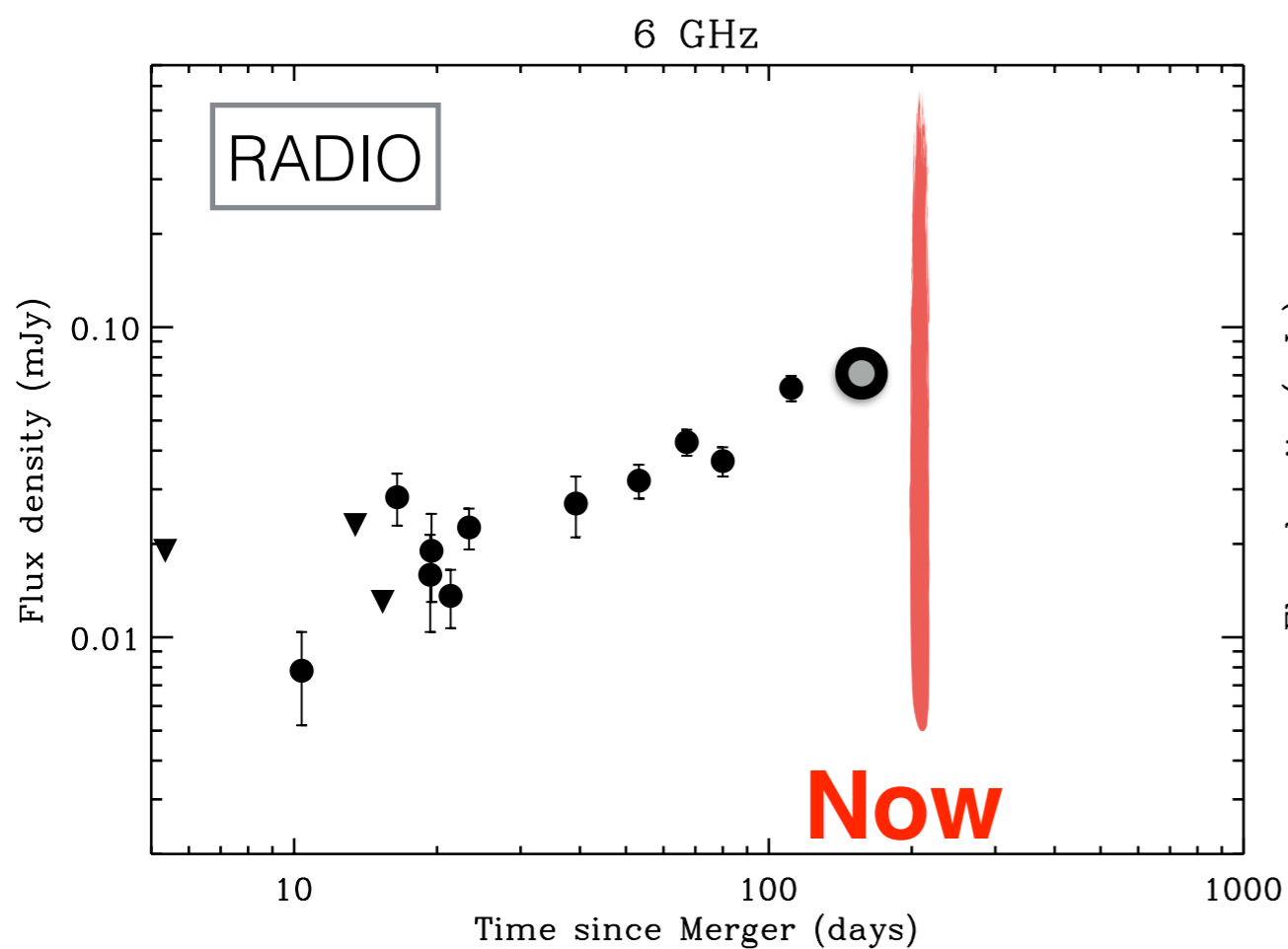


Particle acceleration by trans-relativistic shock in action!
Emitting material has $\Gamma \sim 3-10$

ALL GOOD BUT...

GW170817

Non-thermal emission is RISING!

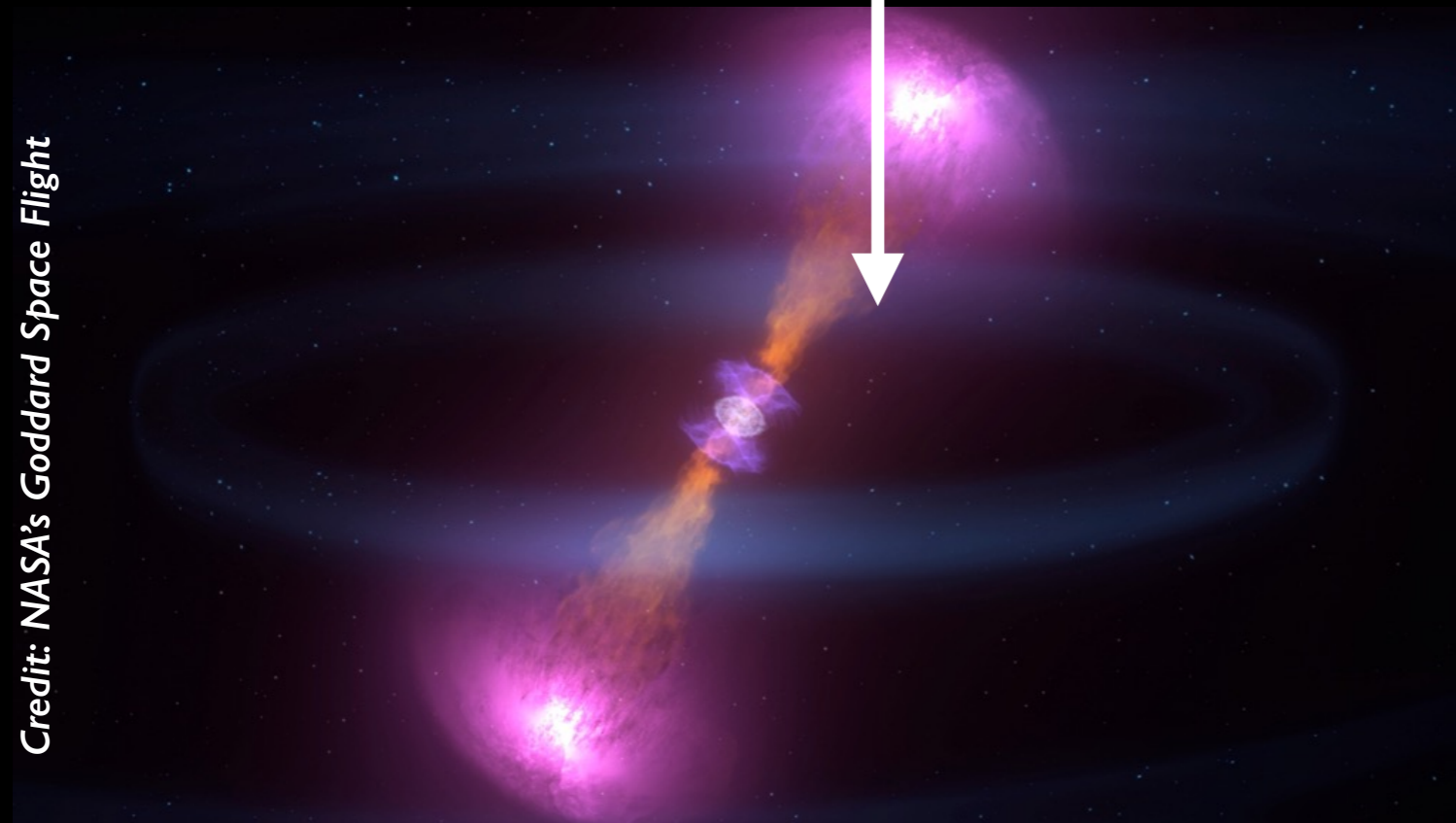


Observer **sees** more Energy(t)

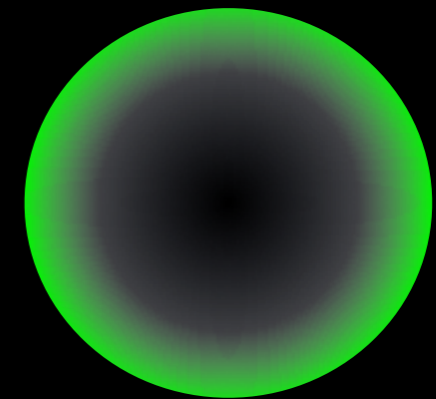
REAL

“FAKE”

What's the nature of the mildly relativistic ejecta?
(What is the **INTRINSIC** nature of **GW170817**)

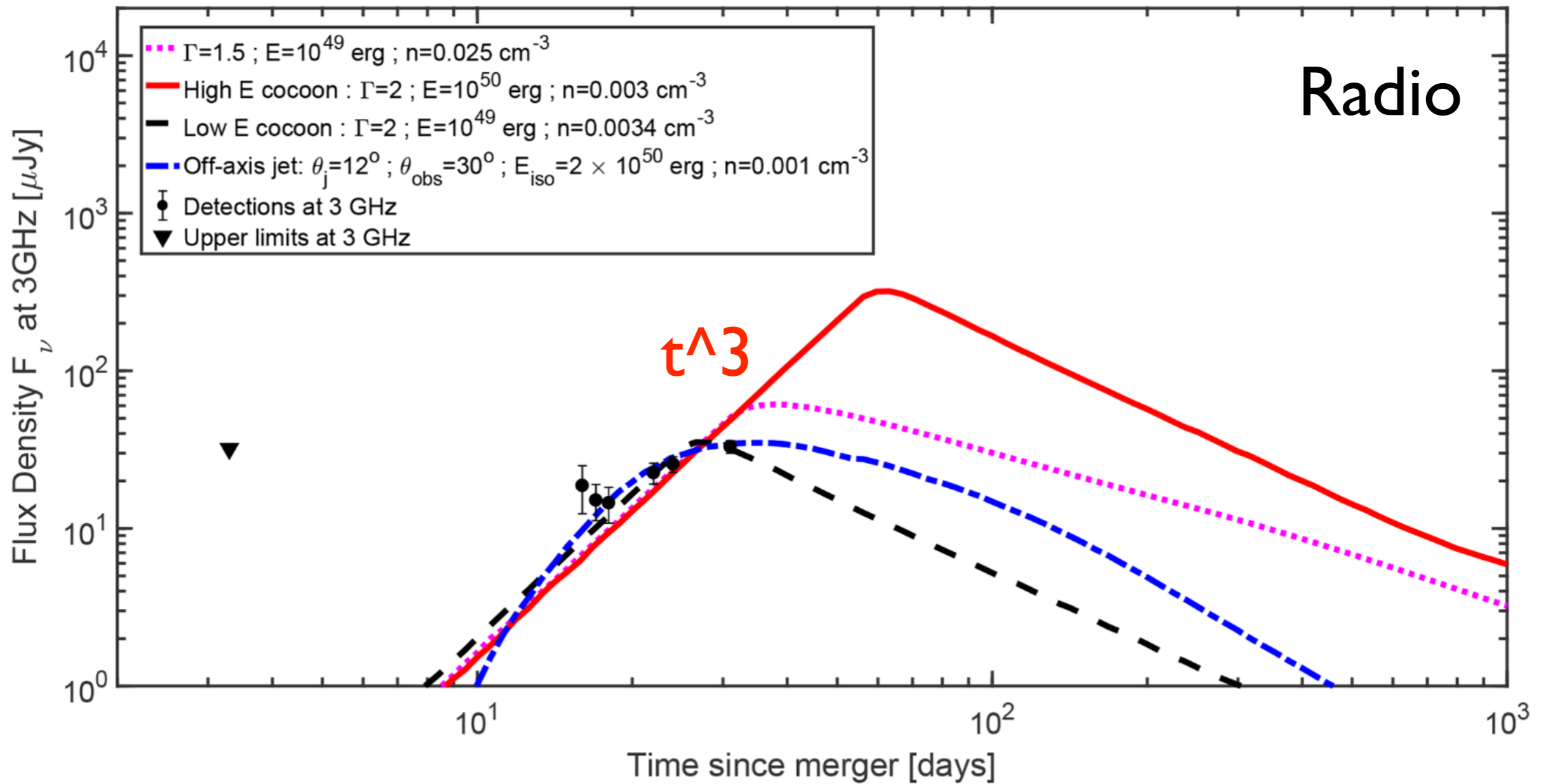
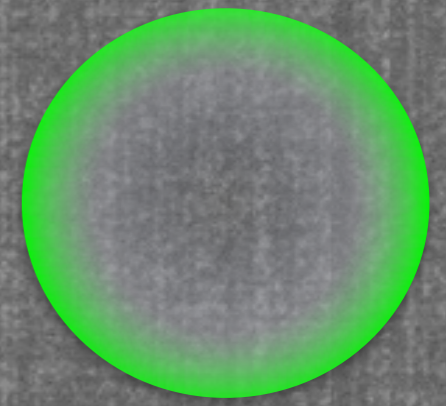


Classical Short GRB viewed
from the side

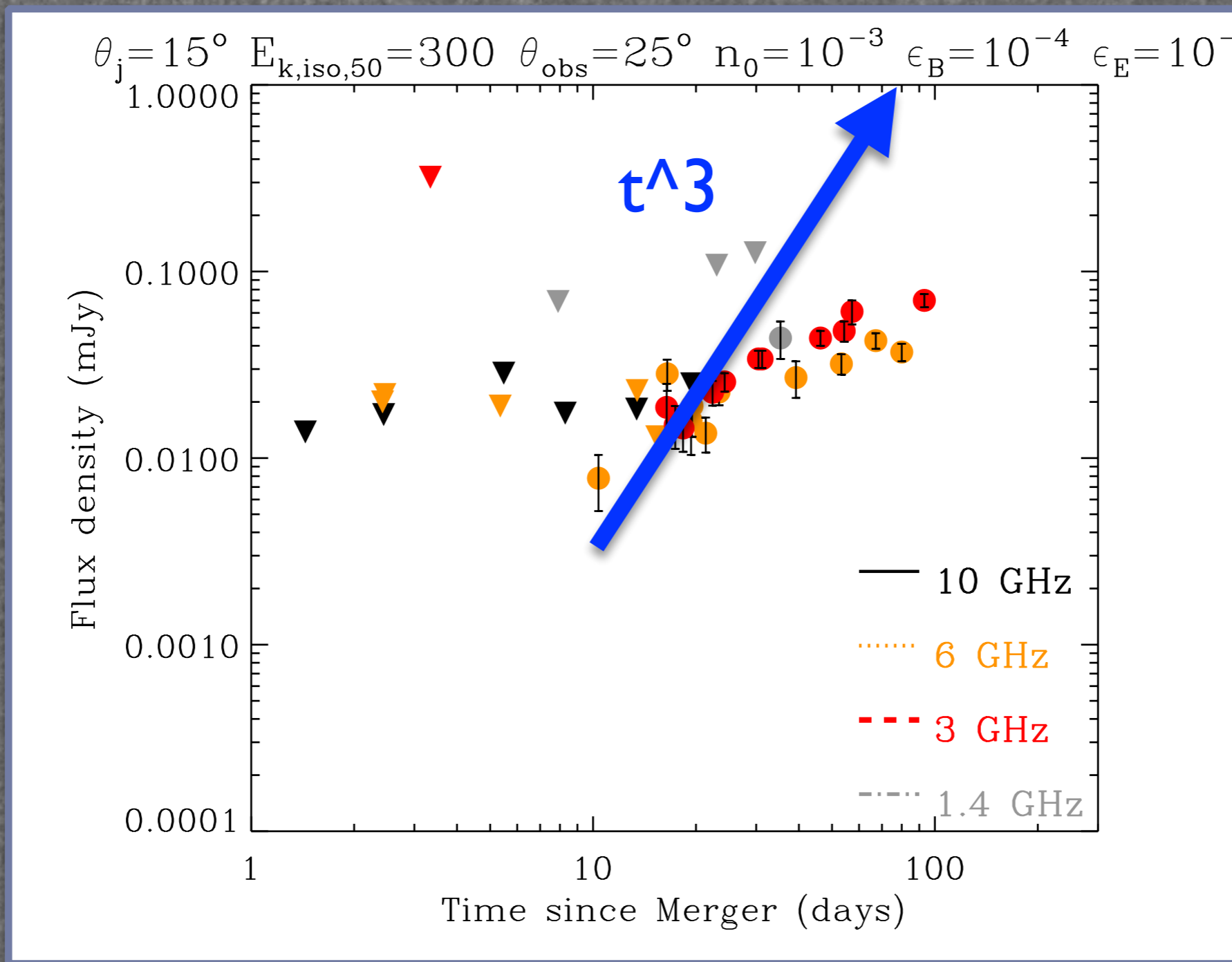


New class of transients
powered by NS-NS mergers

Onset of the afterglow (on-axis / spherical)



With NEW DATA does not work



Single Gamma fireball does NOT work

REAL energy injection

Kasliwal+2017; Mooley+2017; Gottlieb+2017;
Hotokezaka +2018



Failed Jet

Ejecta kinetic energy
profile

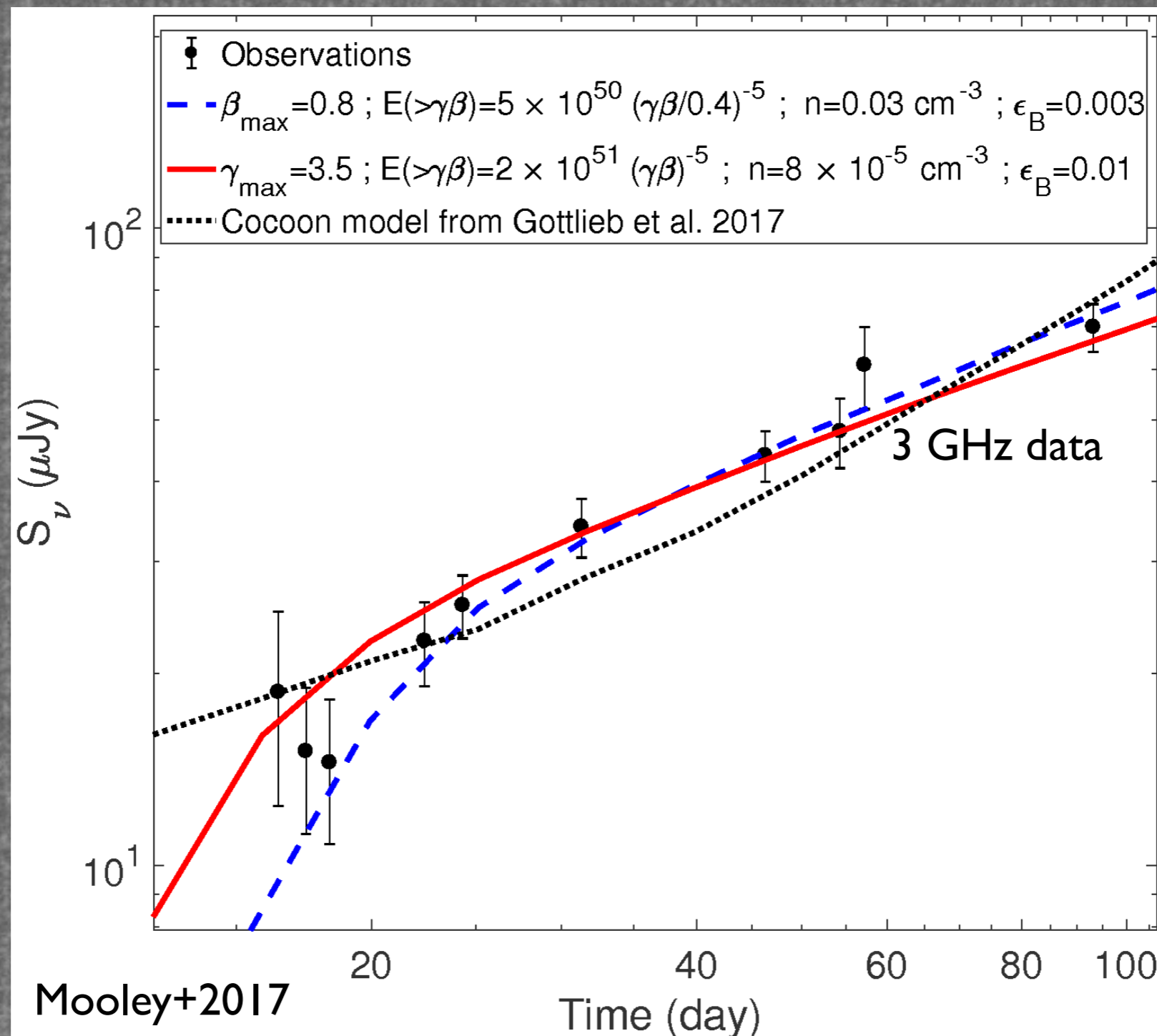
E_k

$(\Gamma\beta)^{-5}$

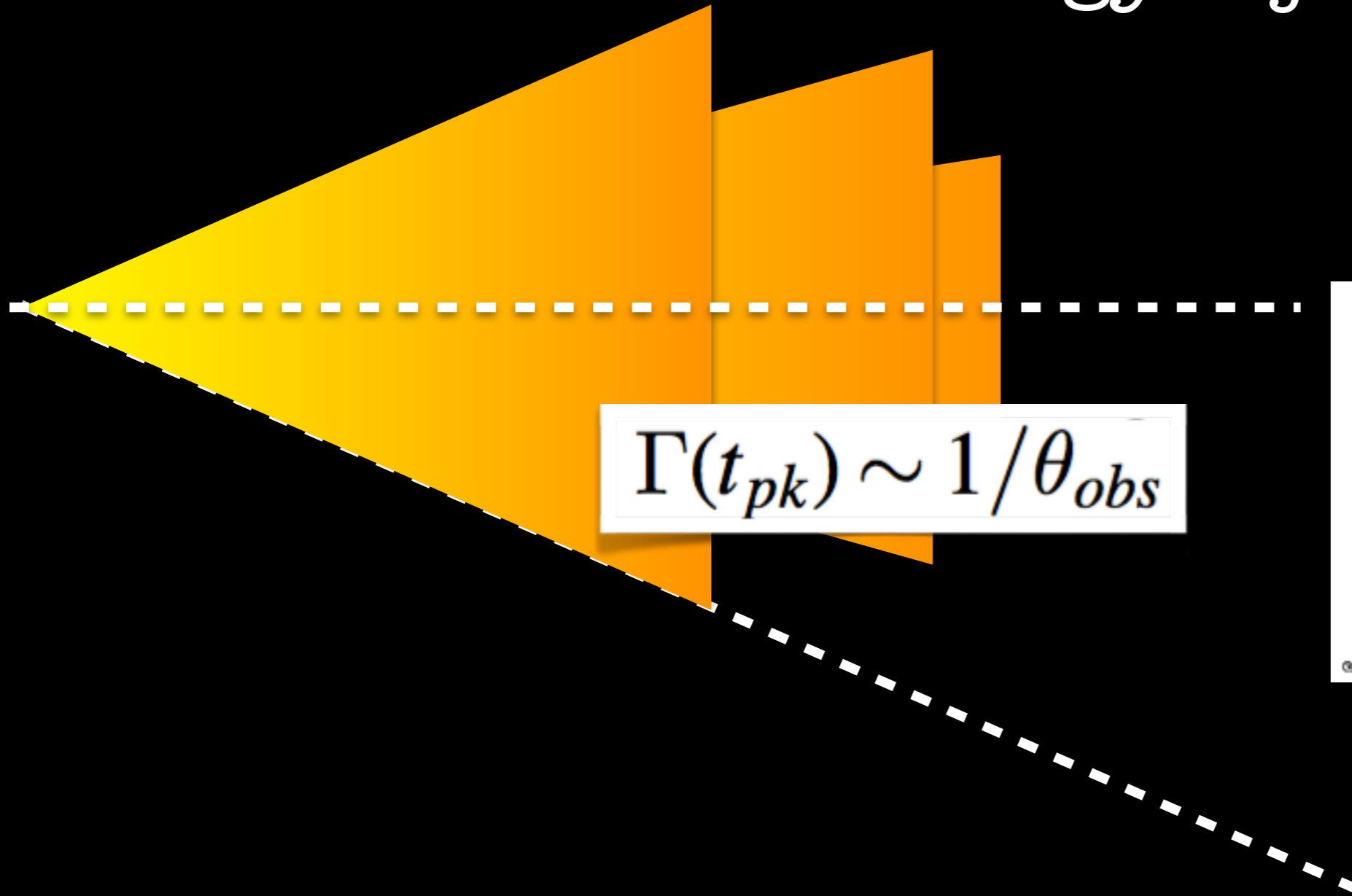
$\Gamma\beta$

Introduce STRUCTURE in the quasi-spherical ejecta

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



Off-Axis Jet [w. structure] APPARENT energy injection

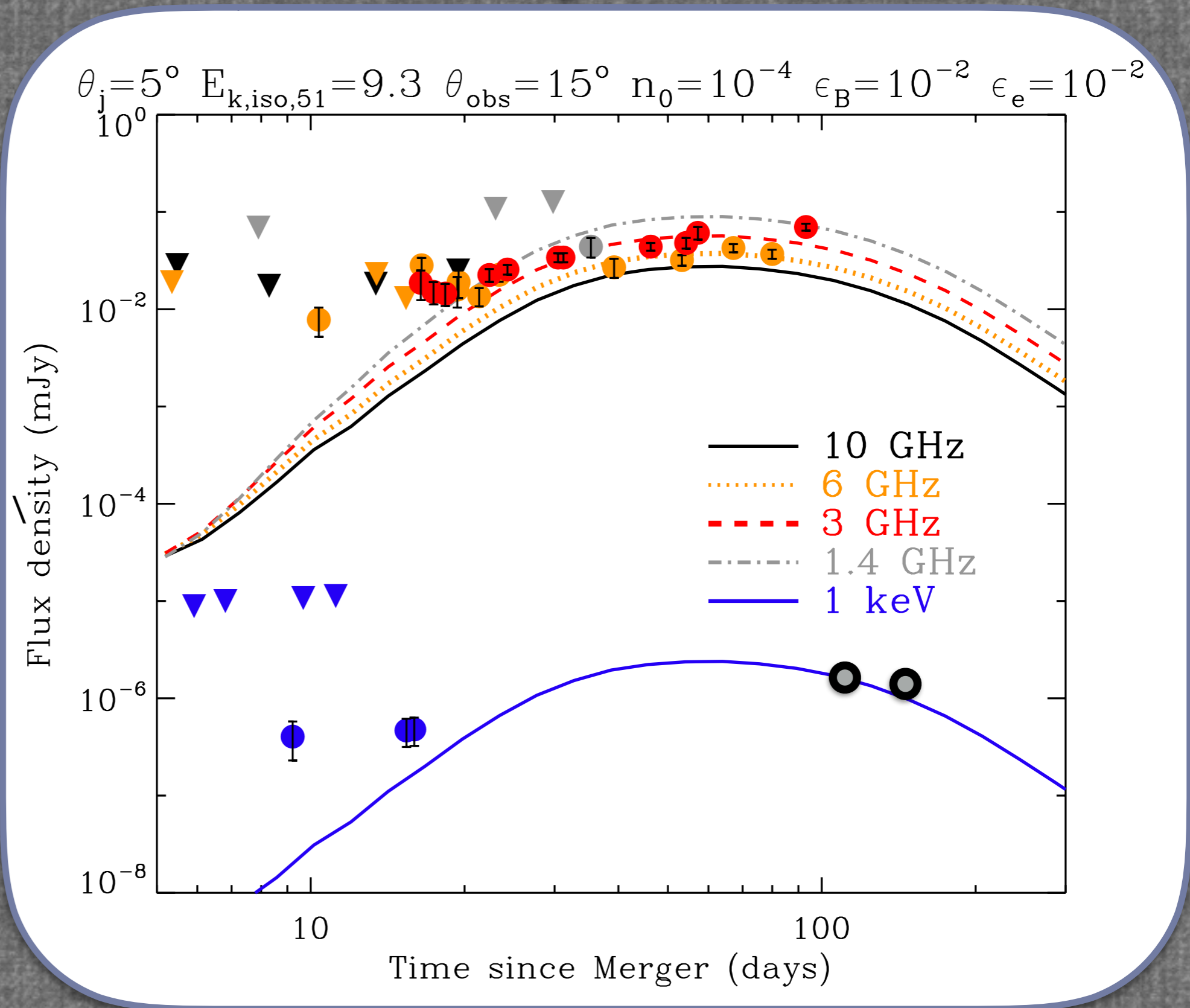


$$\Gamma(t_{pk}) \sim 1/\theta_{obs}$$

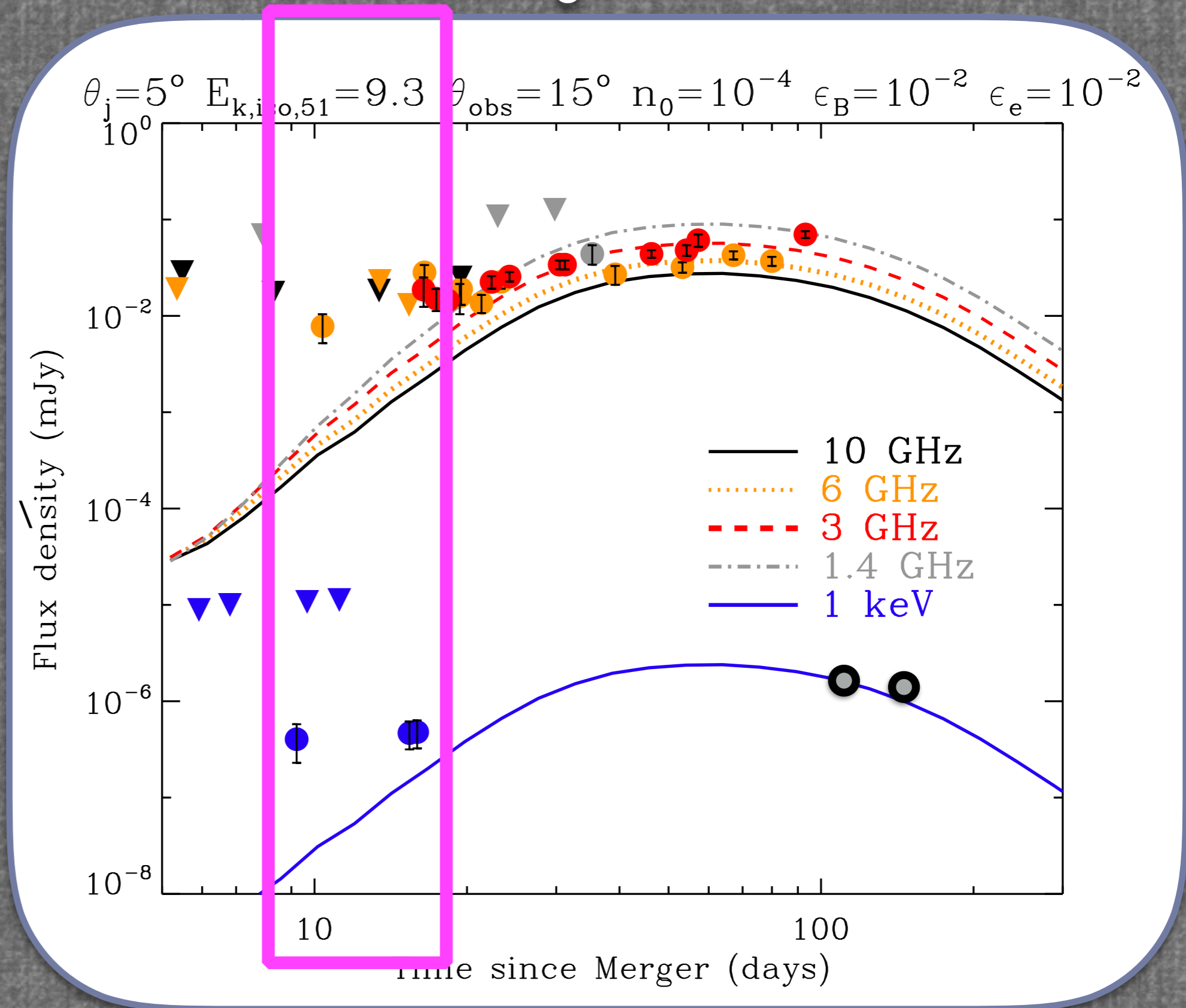


DECELERATION

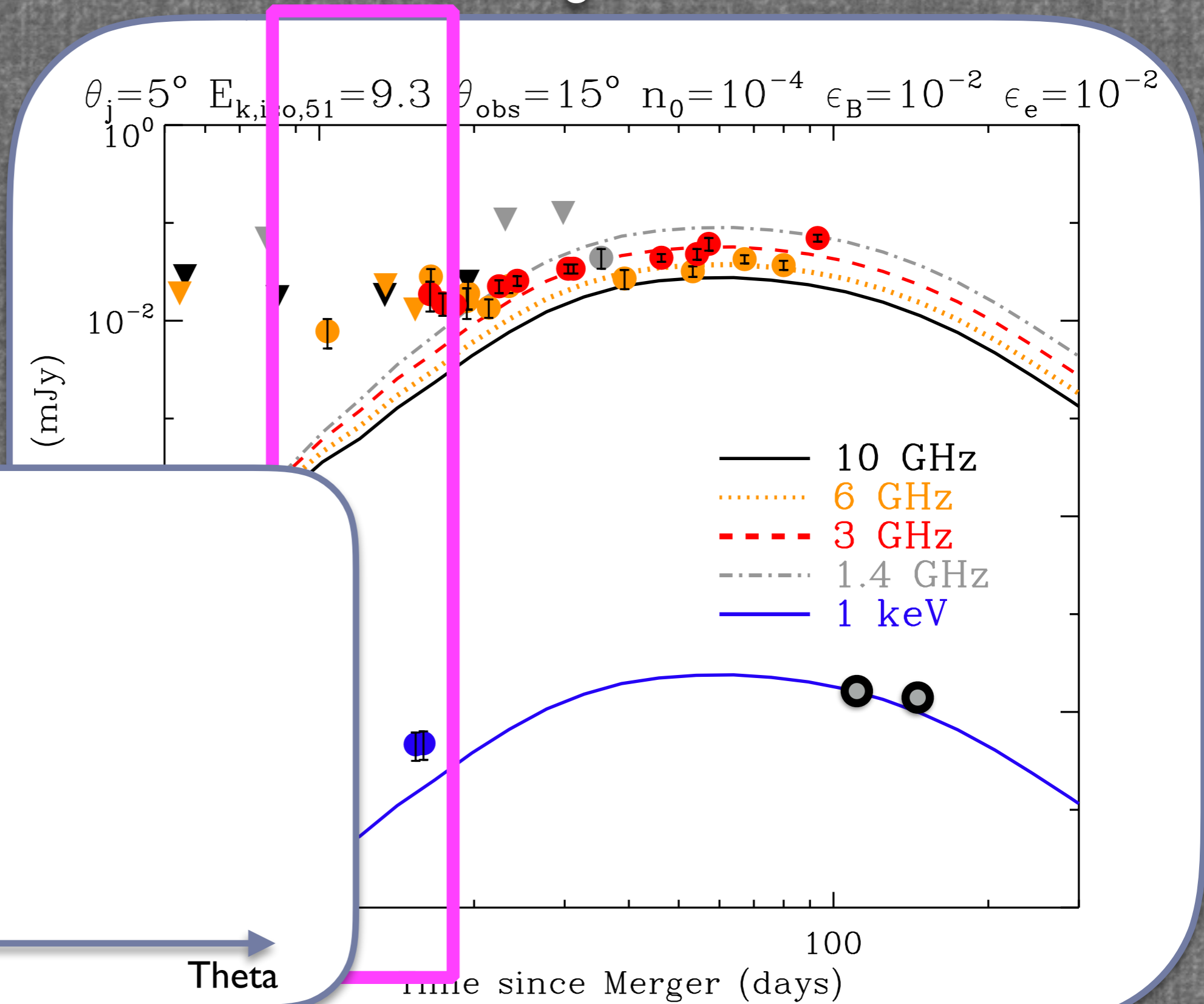
This is the **SIMPLEST** version of a relativistic jet



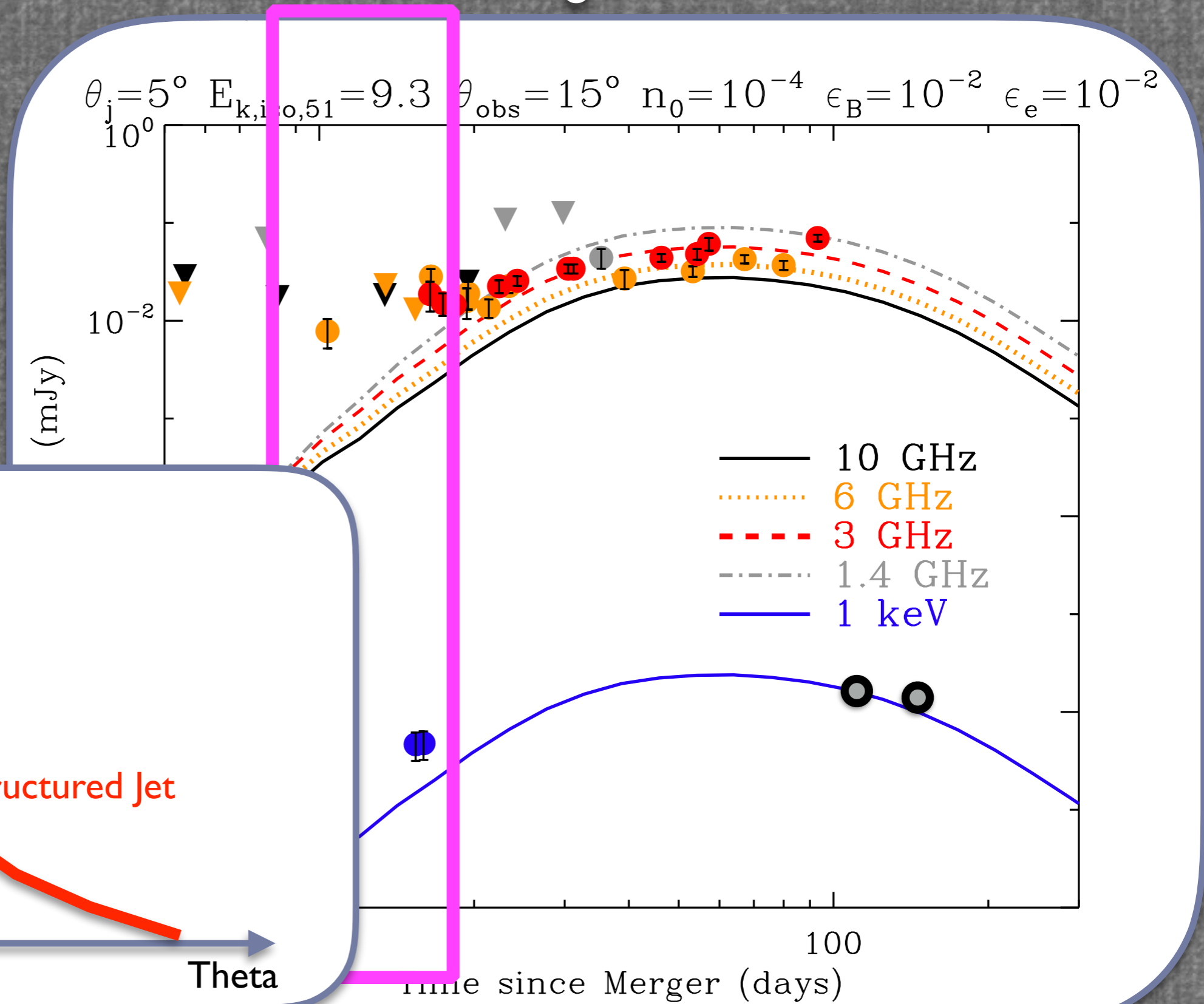
This is the **SIMPLEST** version of a relativistic jet



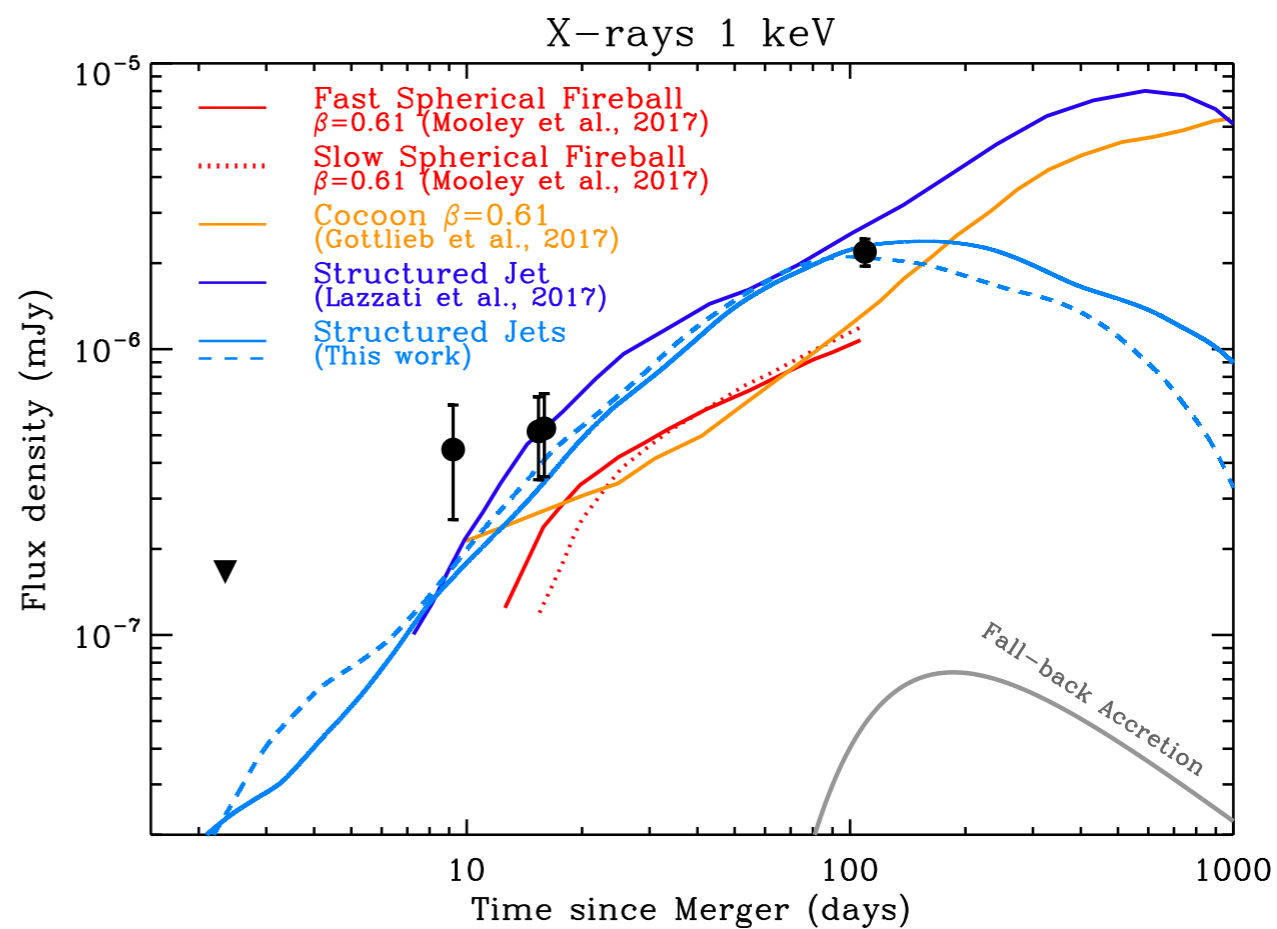
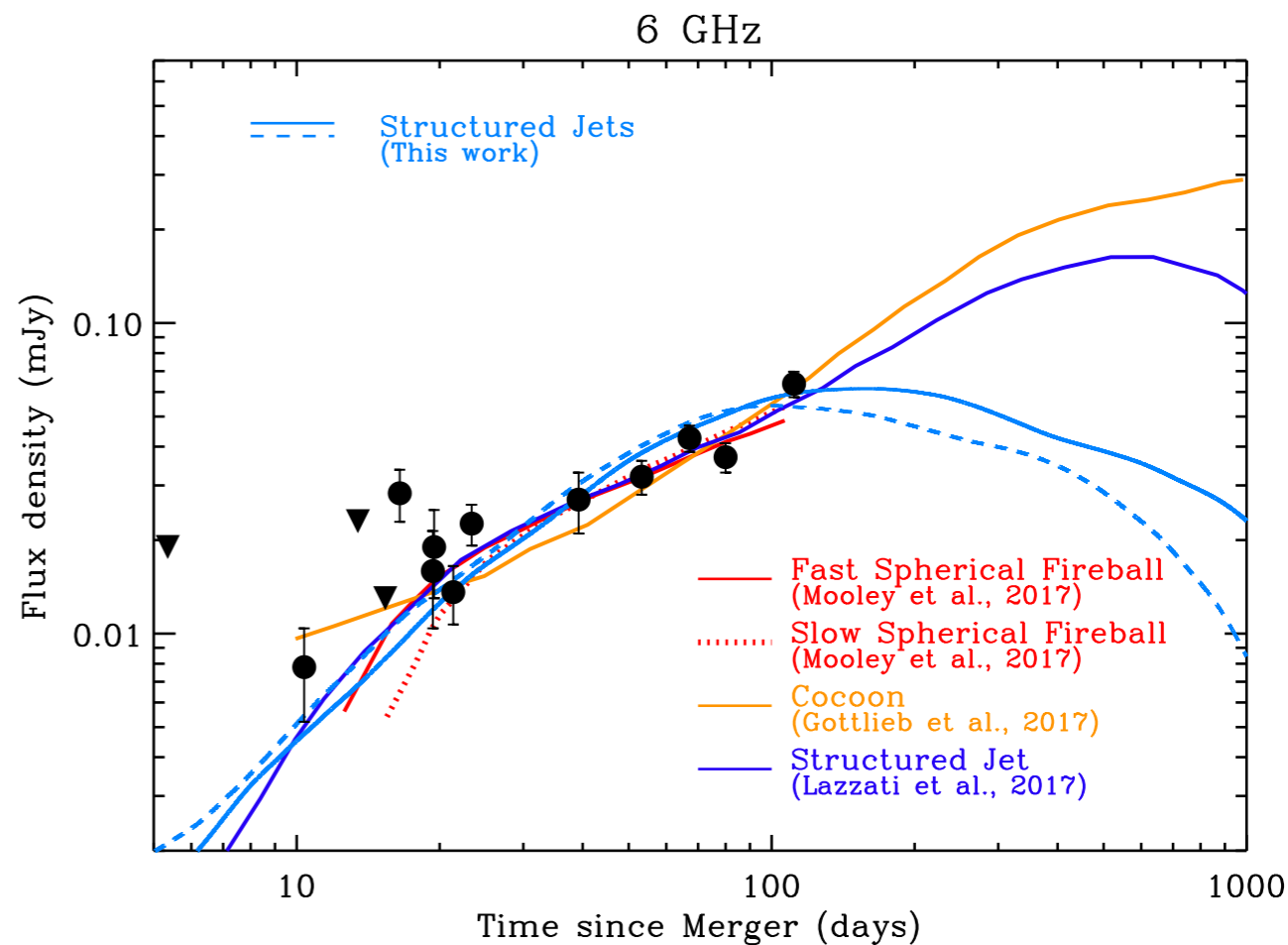
This is the **SIMPLEST** version of a relativistic jet



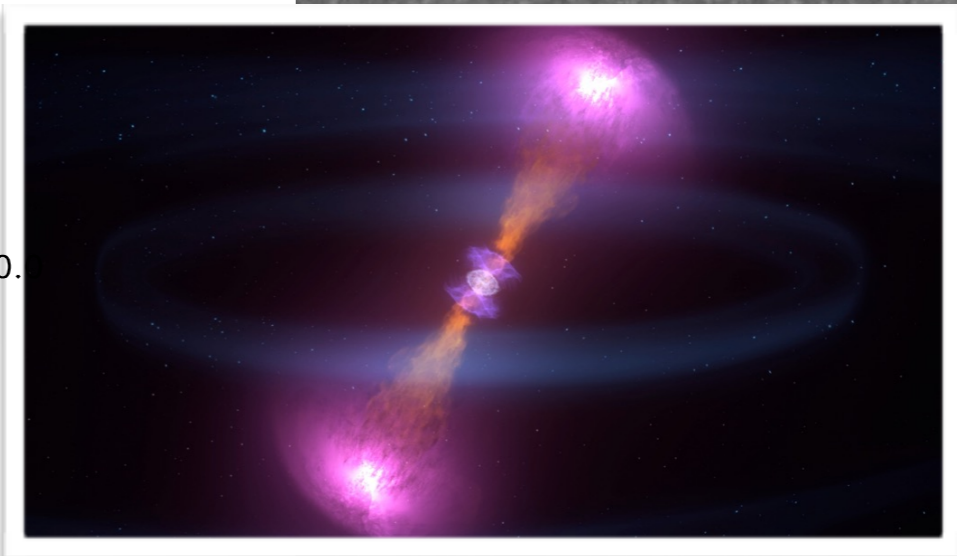
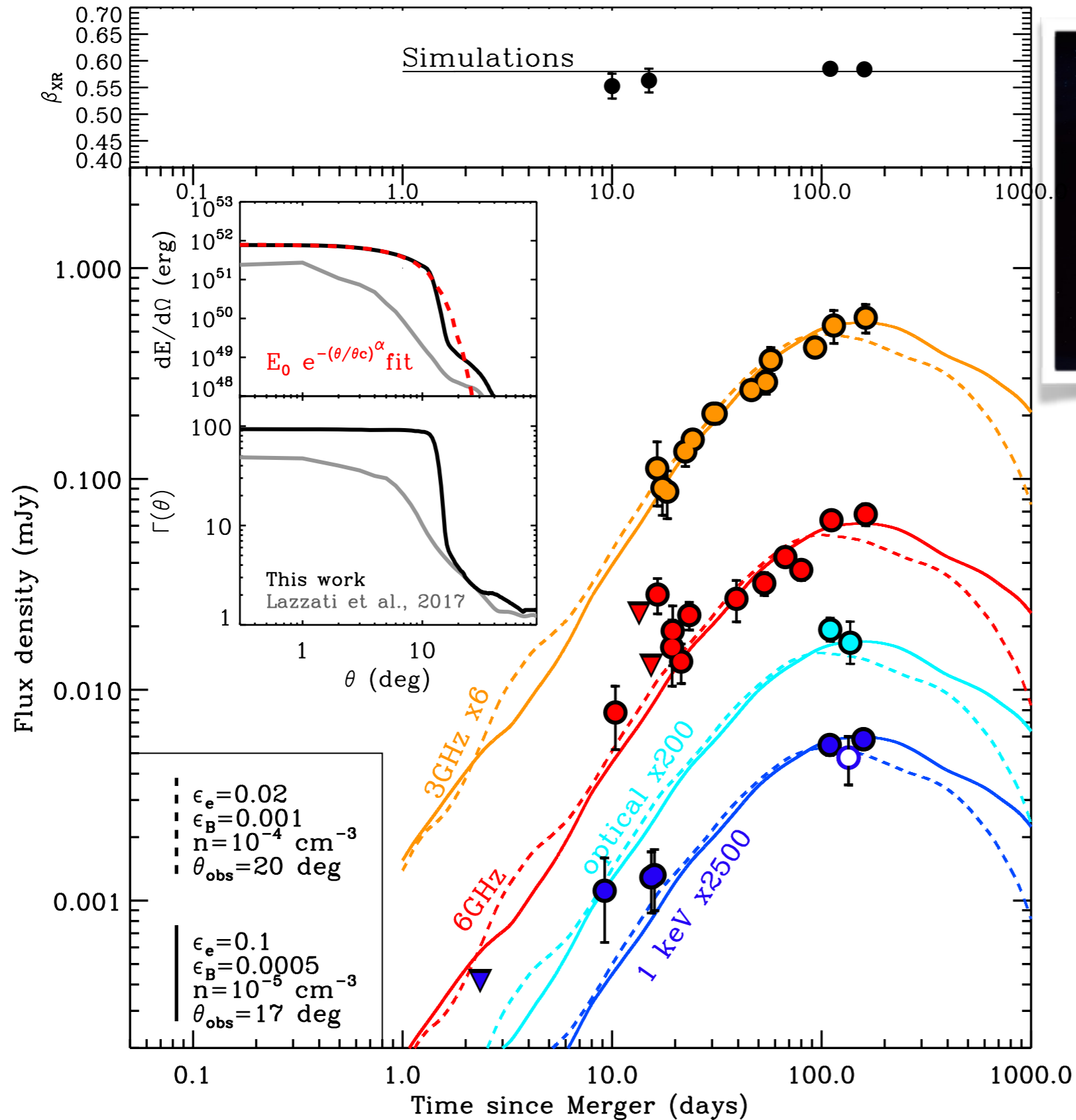
This is the **SIMPLEST** version of a relativistic jet



REAL OR APPARENT

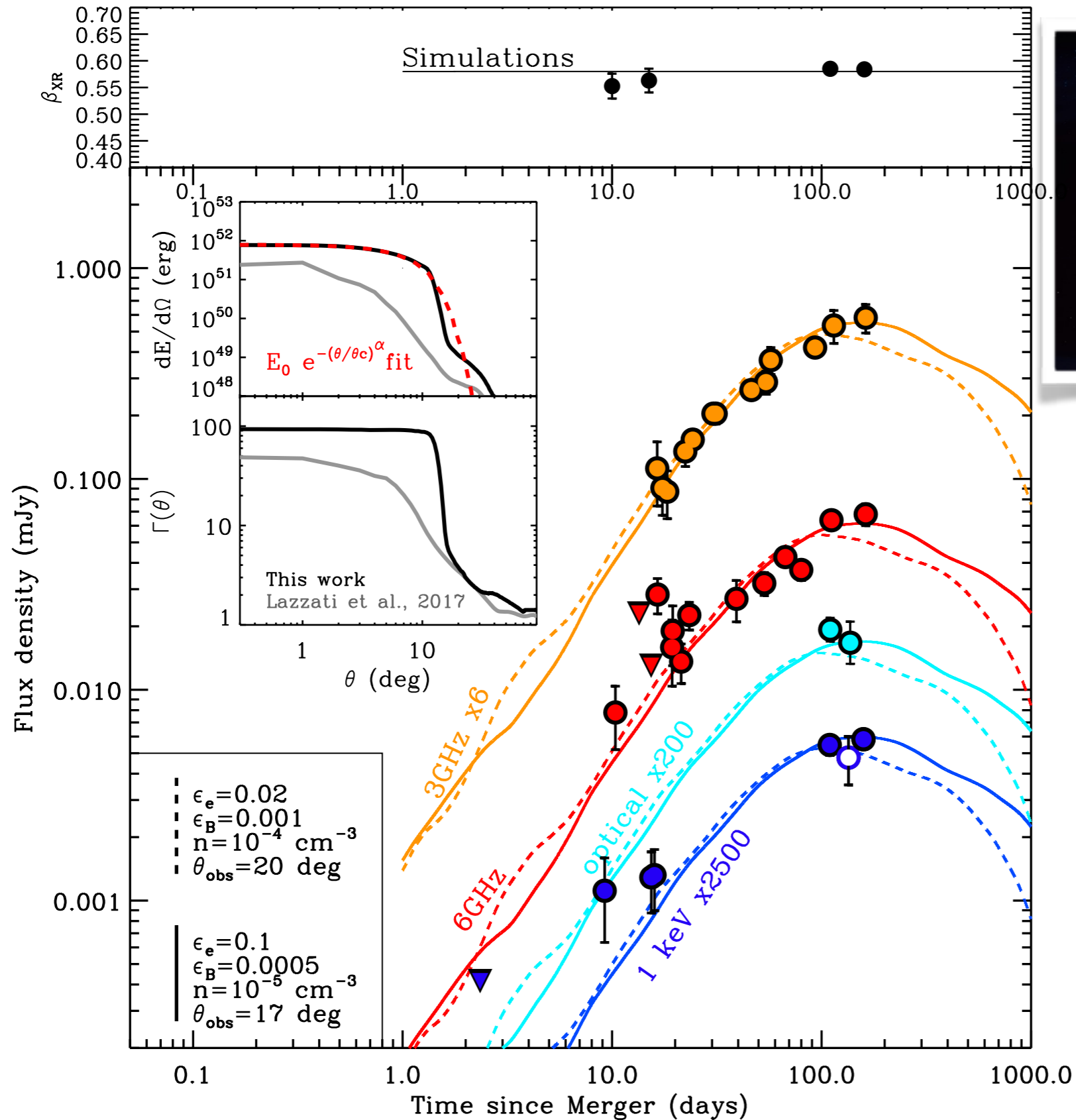


Structured Jet Simulations for GW170817

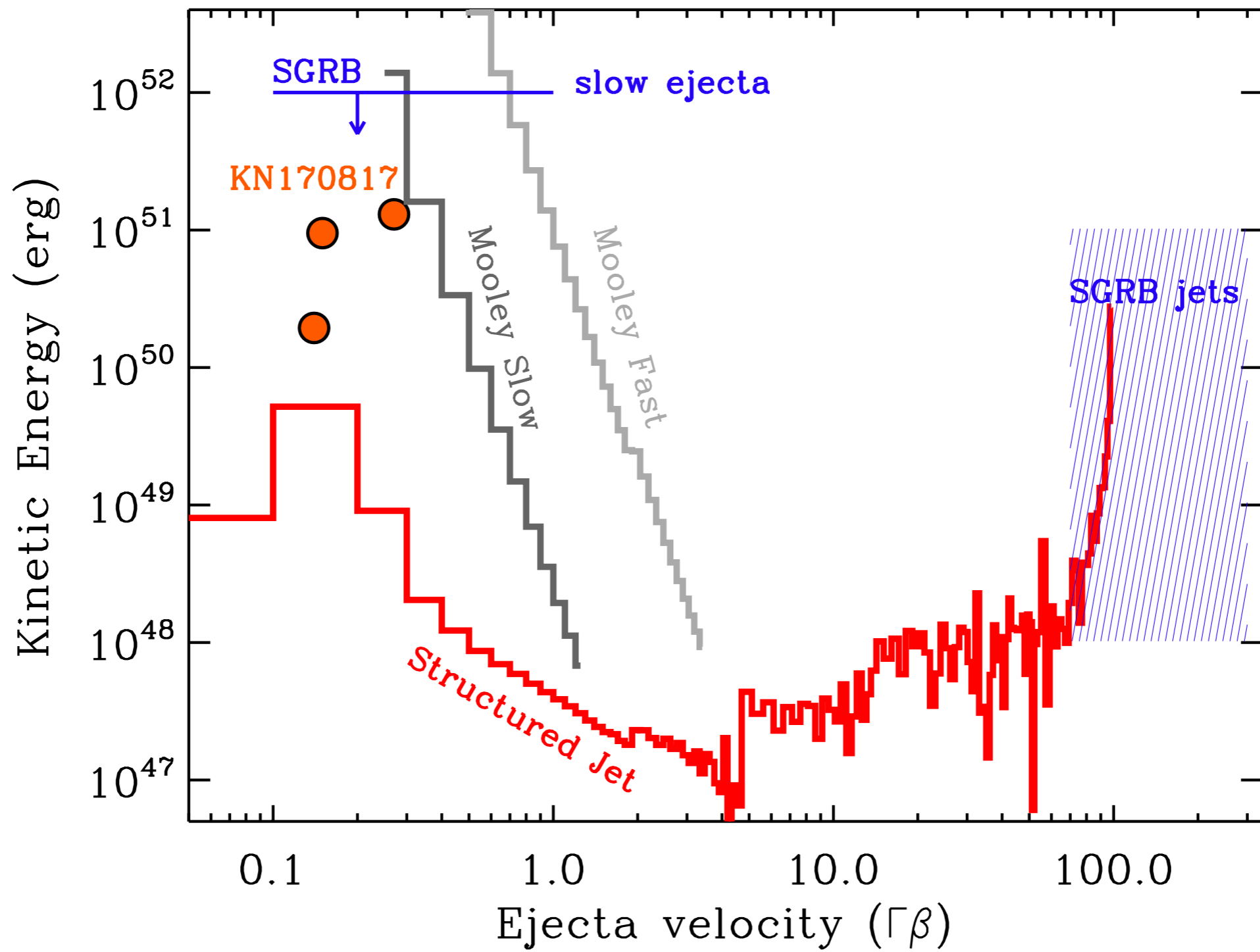


Ultra-relativistic jet viewed from the side

Structured Jet Simulations for GW170817



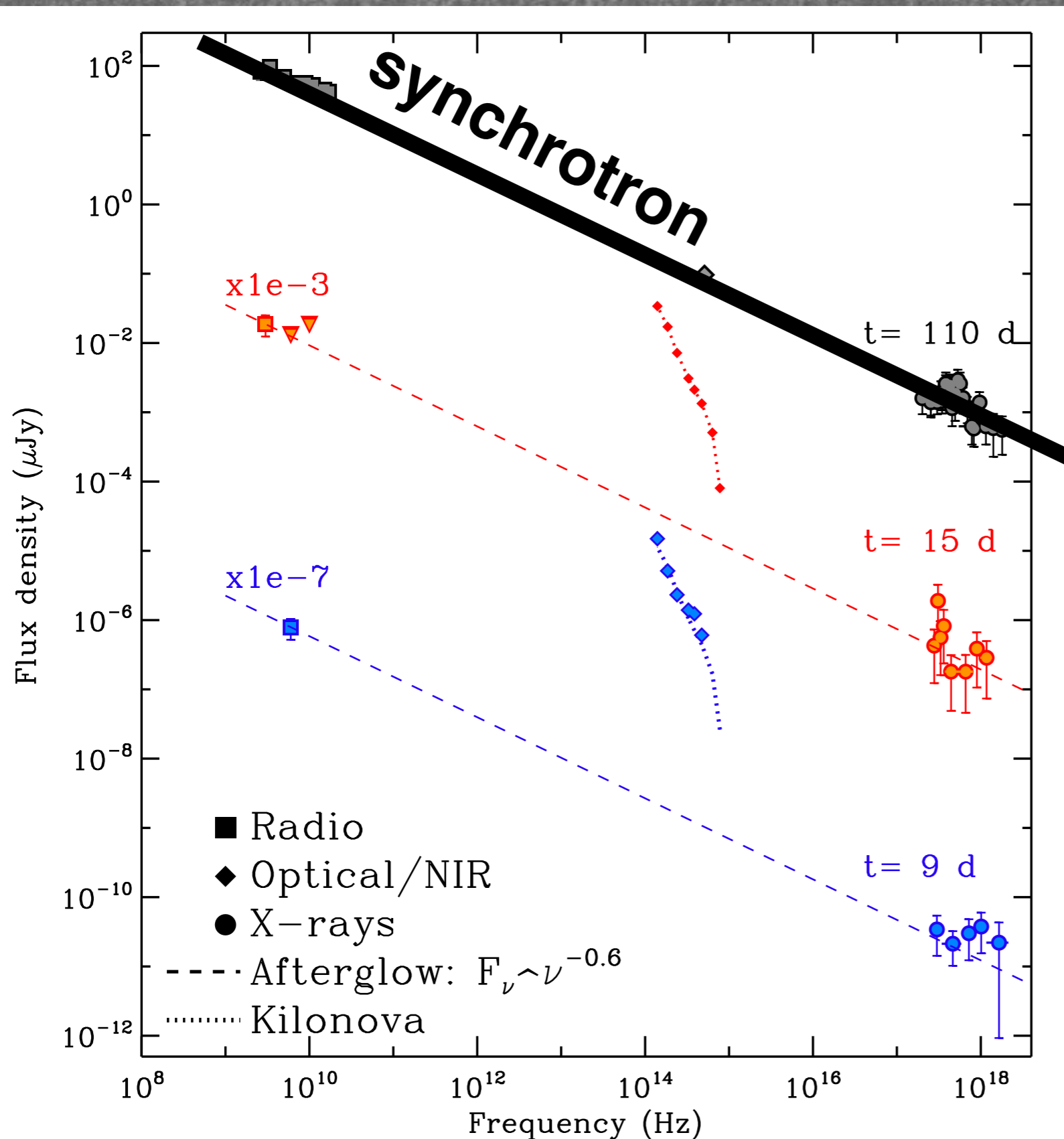
Ultra-relativistic jet viewed from the side



Margutti+2018

POINT #1

A POWER-LAW in the Sky

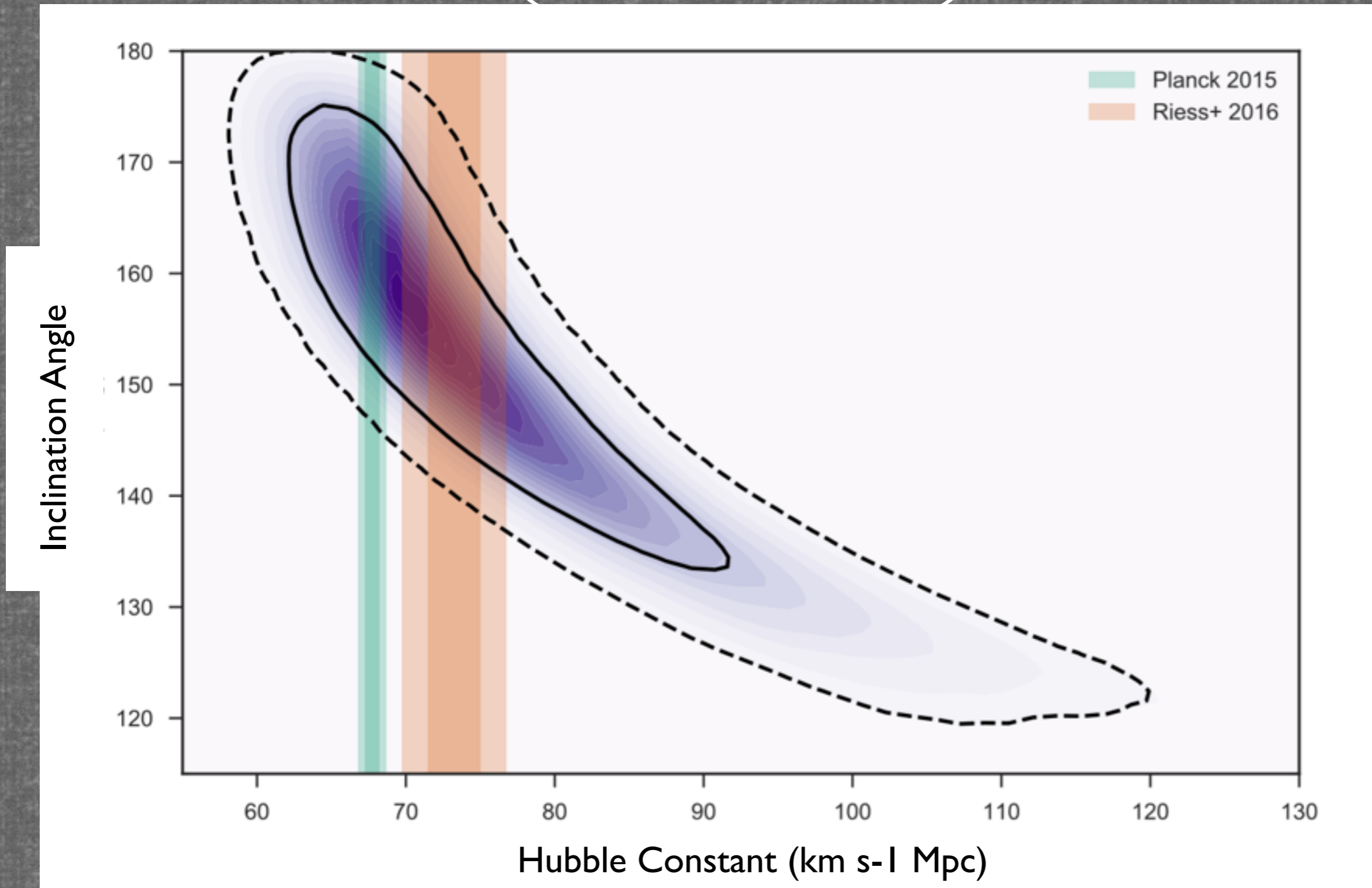


Particle acceleration by
a transrelativistic
jet in action

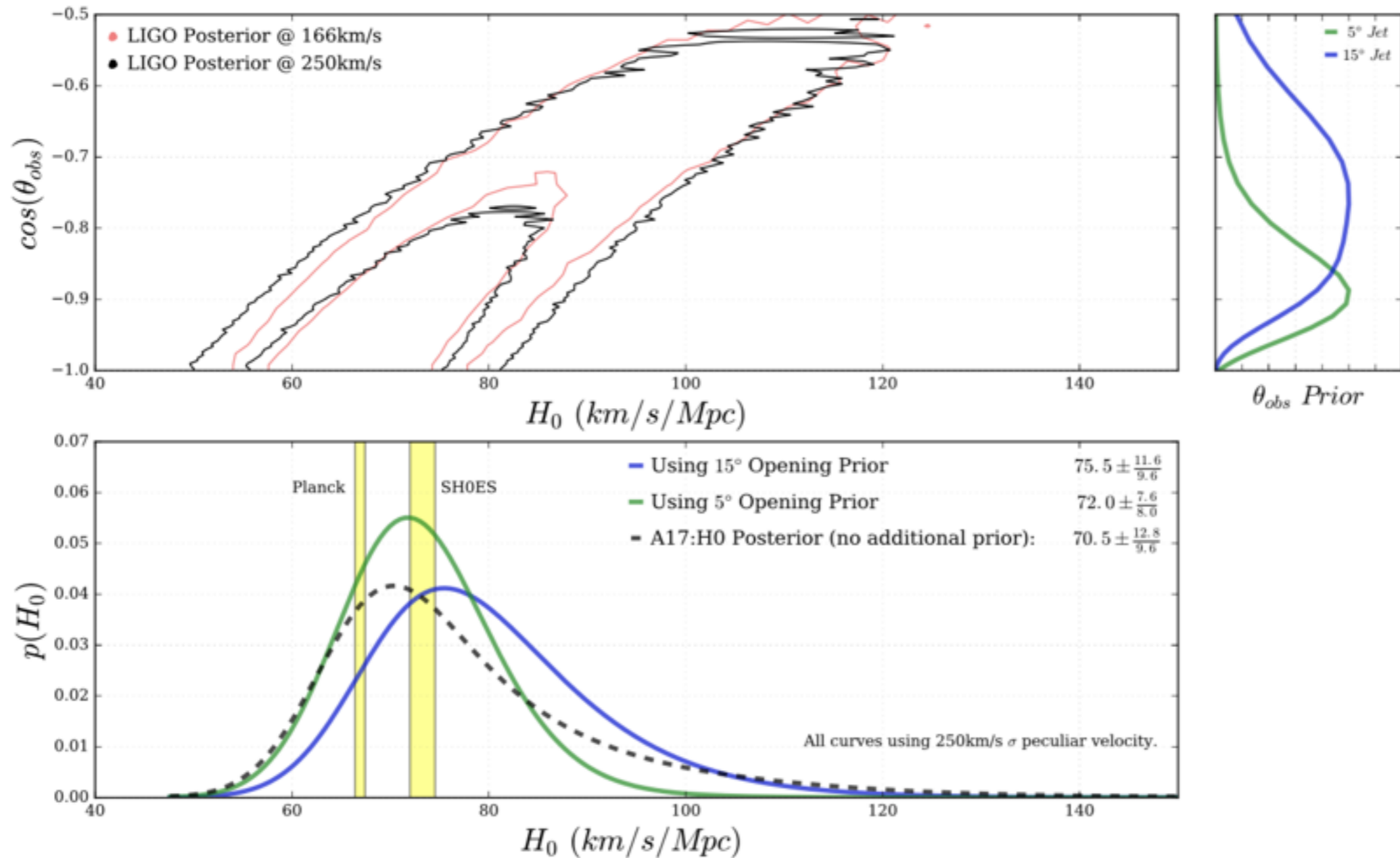
$$\Gamma \sim (3=10)$$

POINT #2

New Method for Hubble Constant Measurement (Schutz 1986)

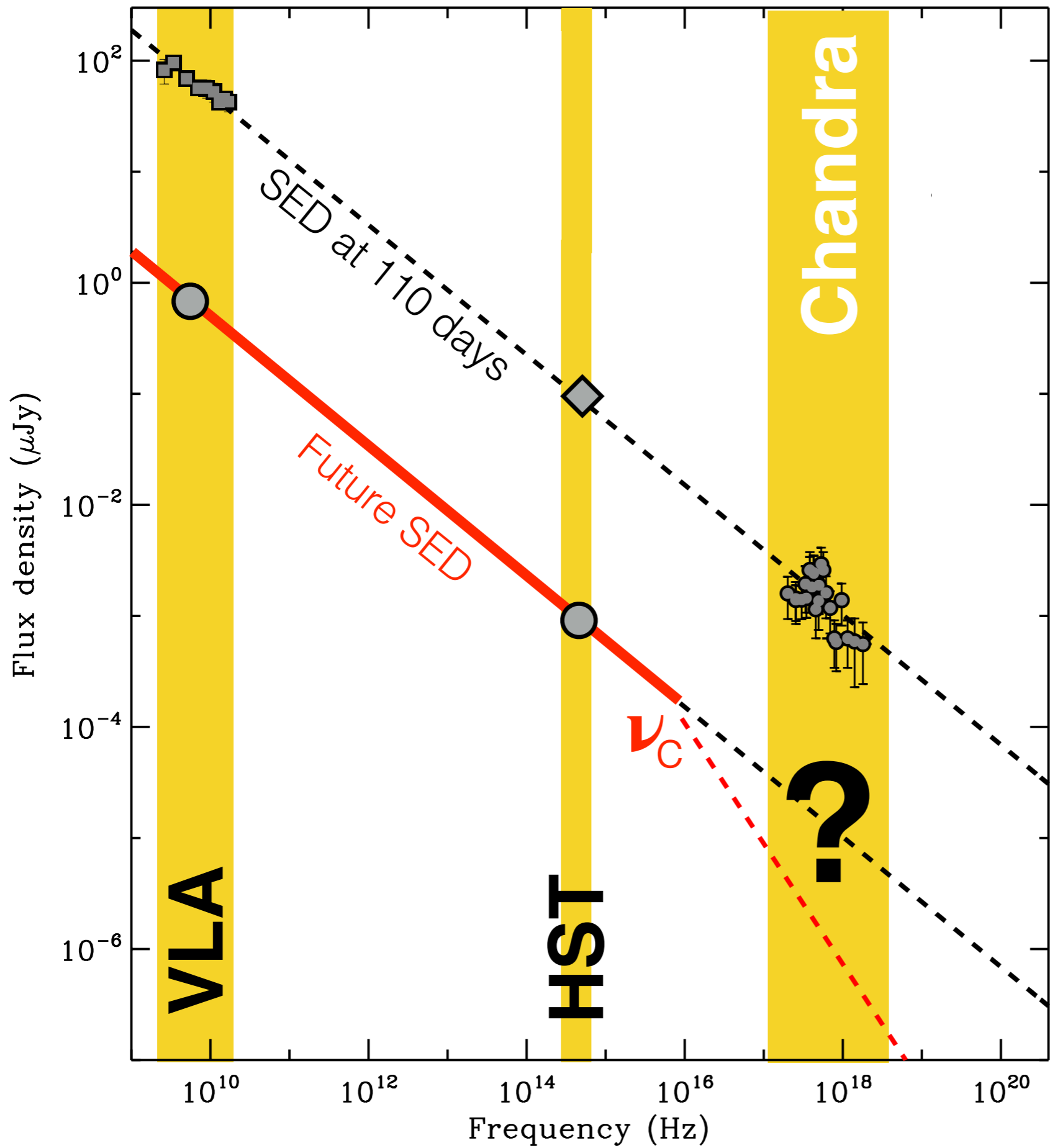


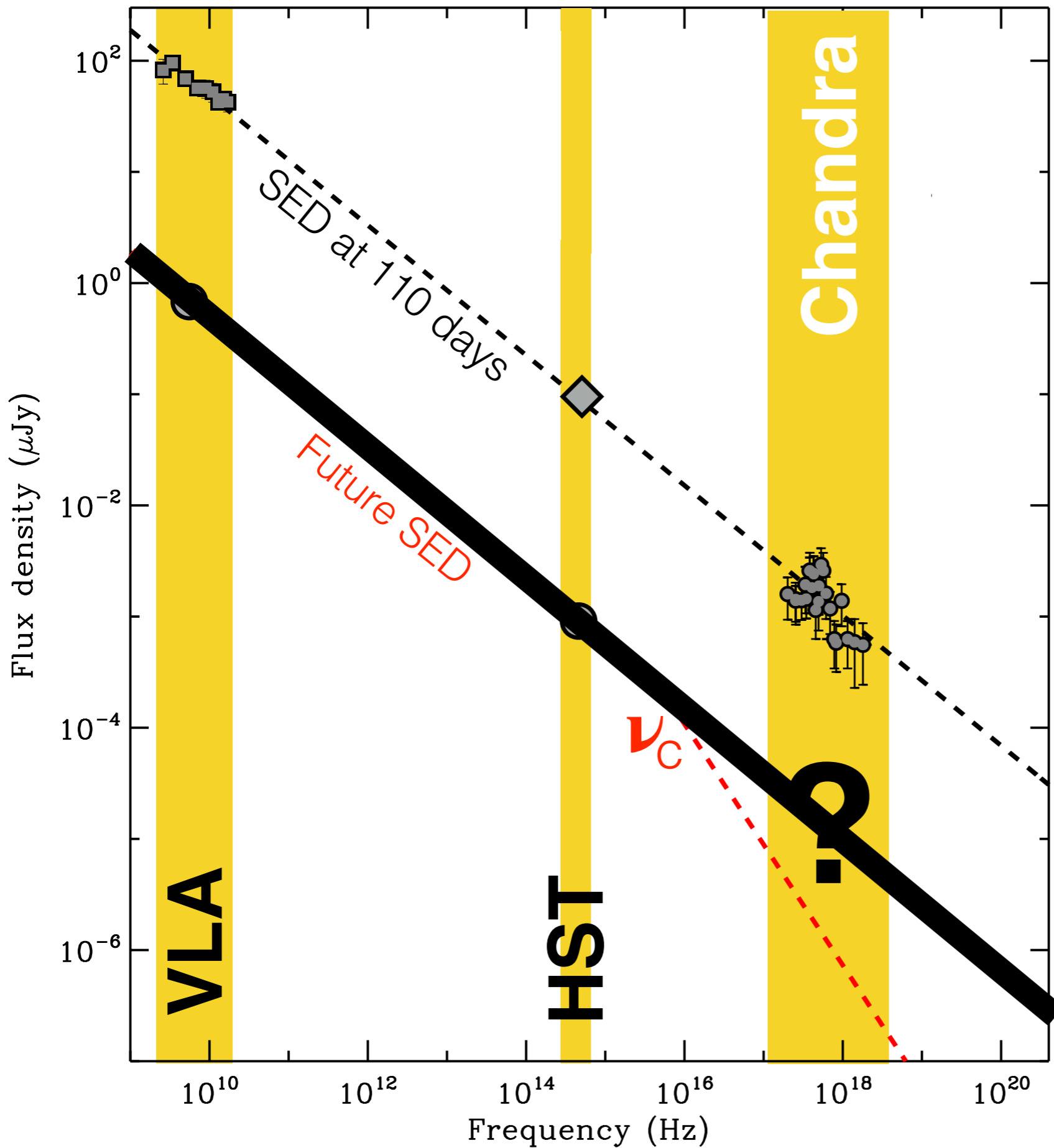
Improving the constraints on H_0 with GW + EM



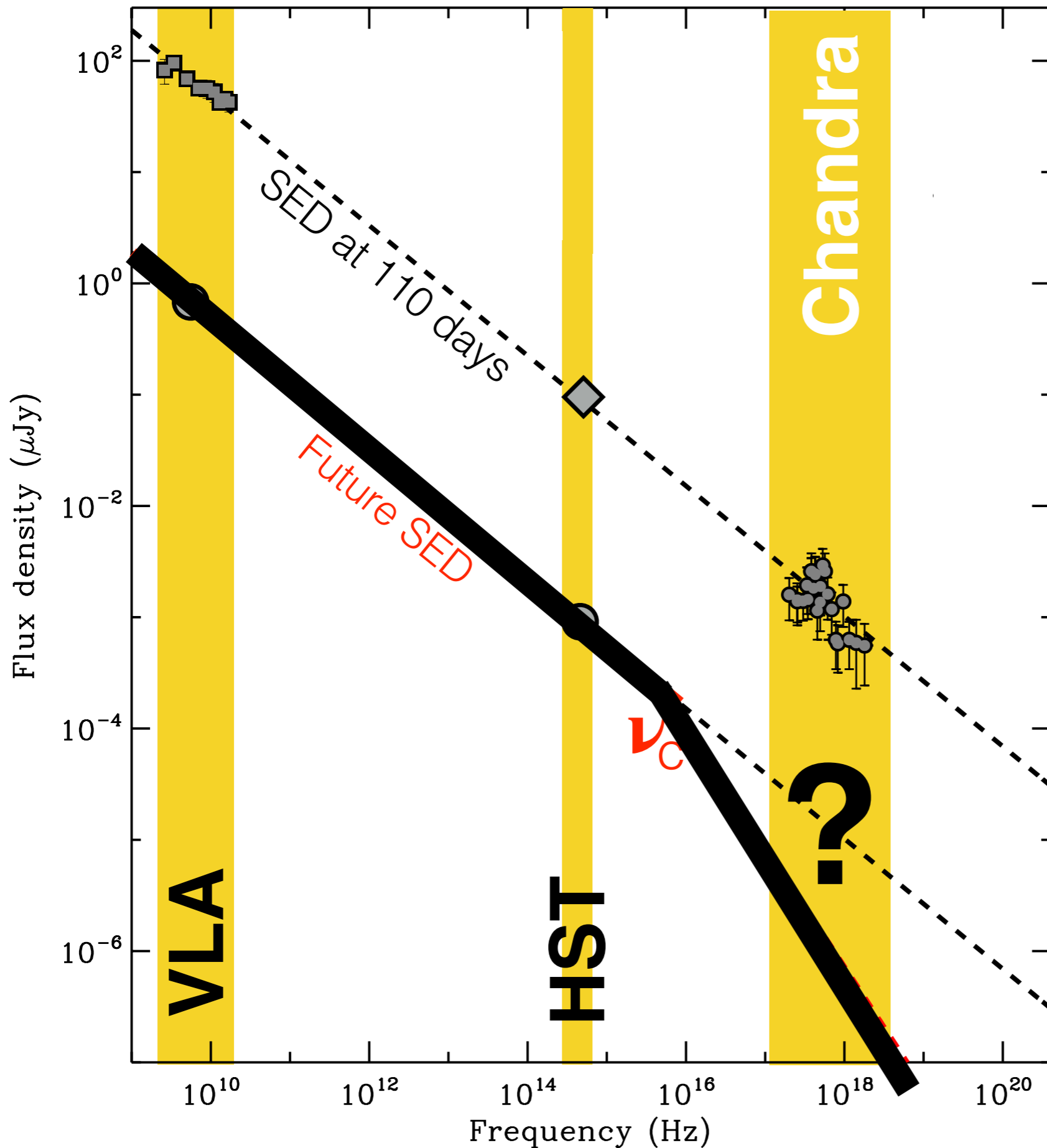
An ultra-relativistic outflow in
GW170817 is NOT ruled out

POINT #3: how to distinguish
between quasi-spherical models
and structured-jet models?





Jetted
models
Quasi-
spherical



Jetted
models
Quasi-
spherical