High-energy Transients and their non-thermal emission

- Collapse of Massive Stars (SNe + long GRBs)
- Neutron Star Mergers (short GRBs and GWs)
- Tidal Disruption Events
- [Thermonuclear Stellar Explosions (Ia)]

NORTHWESTERN UNIVERSITY

Raffaella Margutti[1]

CIFAR Global Scholar Fellow

High-energy emission from transients

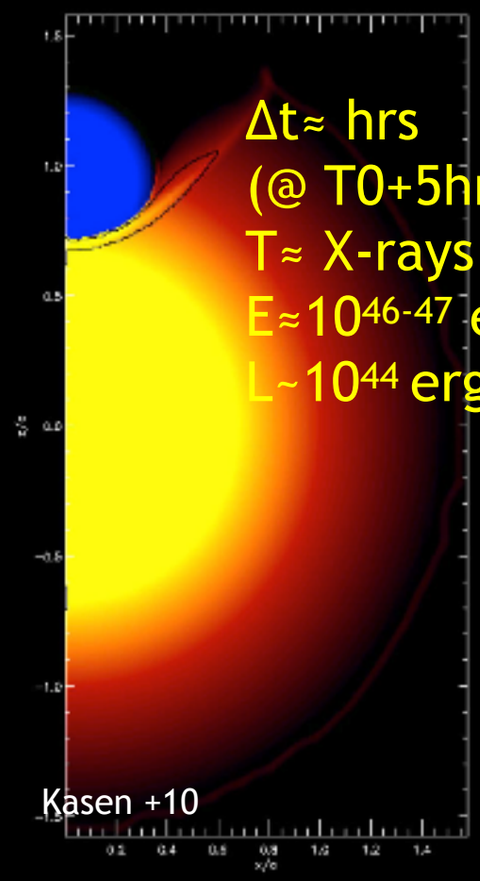
Log Lx

SHOCK BREAK OUT
(R exploding star or BNS ejecta)

Δt≈ 2ms
T≈250 keV
E≈10^{41} erg

PROGENITORS

SHOCK INTERACTION w. COMPANION
(R and distance of the companion

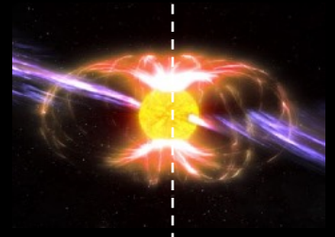


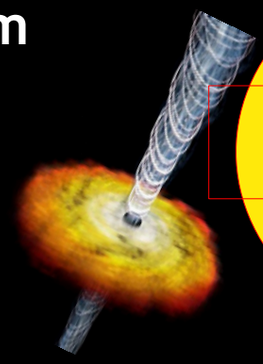
Δt≈ hrs
(@ T0+5hrs)
T≈ X-rays
E≈$10^{46\text{-}47}$ erg
L~10^{44} erg/s

SHOCK/JET INTERACTION w. the MEDIUM
(mass-loss of the progenit

MASS-LOSS

RADIATION from the REMNANT





REMNANT

< hr

< several hrs

> 10 years

Log Time

High-energy emission from transients

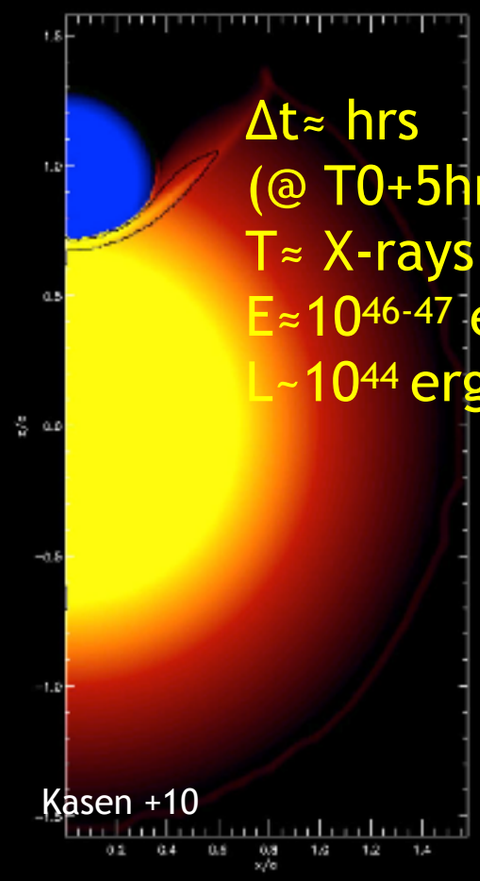
Log Lx

SHOCK BREAK OUT
(R exploding star or BNS ejecta)

Δt≈ 2ms
T≈250 keV
E≈10^{41} erg

PROGENITORS

SHOCK INTERACTION w. COMPANION
(R and distance of the companion

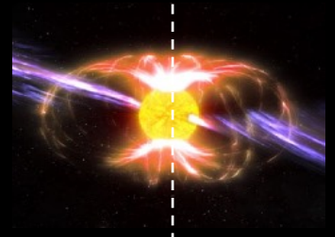


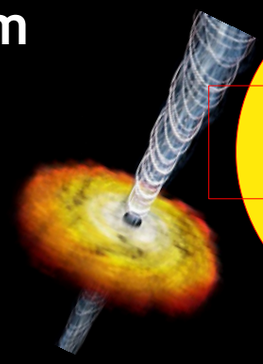
Δt≈ hrs
(@ T0+5hrs)
T≈ X-rays
E≈$10^{46\text{-}47}$ erg
L~10^{44} erg/s

SHOCK/JET INTERACTION w. the MEDIUM
(mass-loss of the progenit

MASS-LOSS

RADIATION from the REMNANT





REMNANT

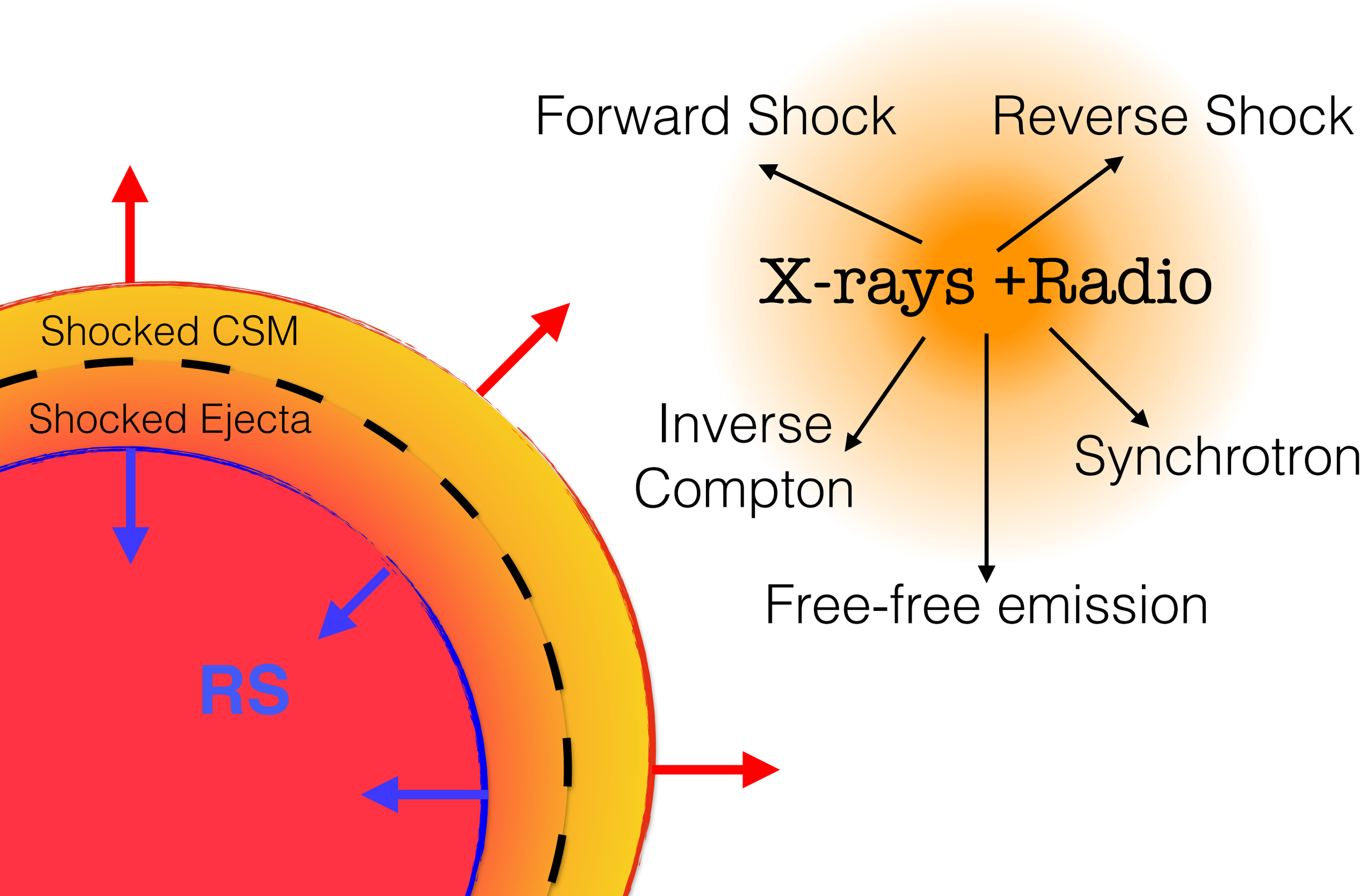
< hr

< several hrs

> 10 years

Log Time

A Tale of two Shocks



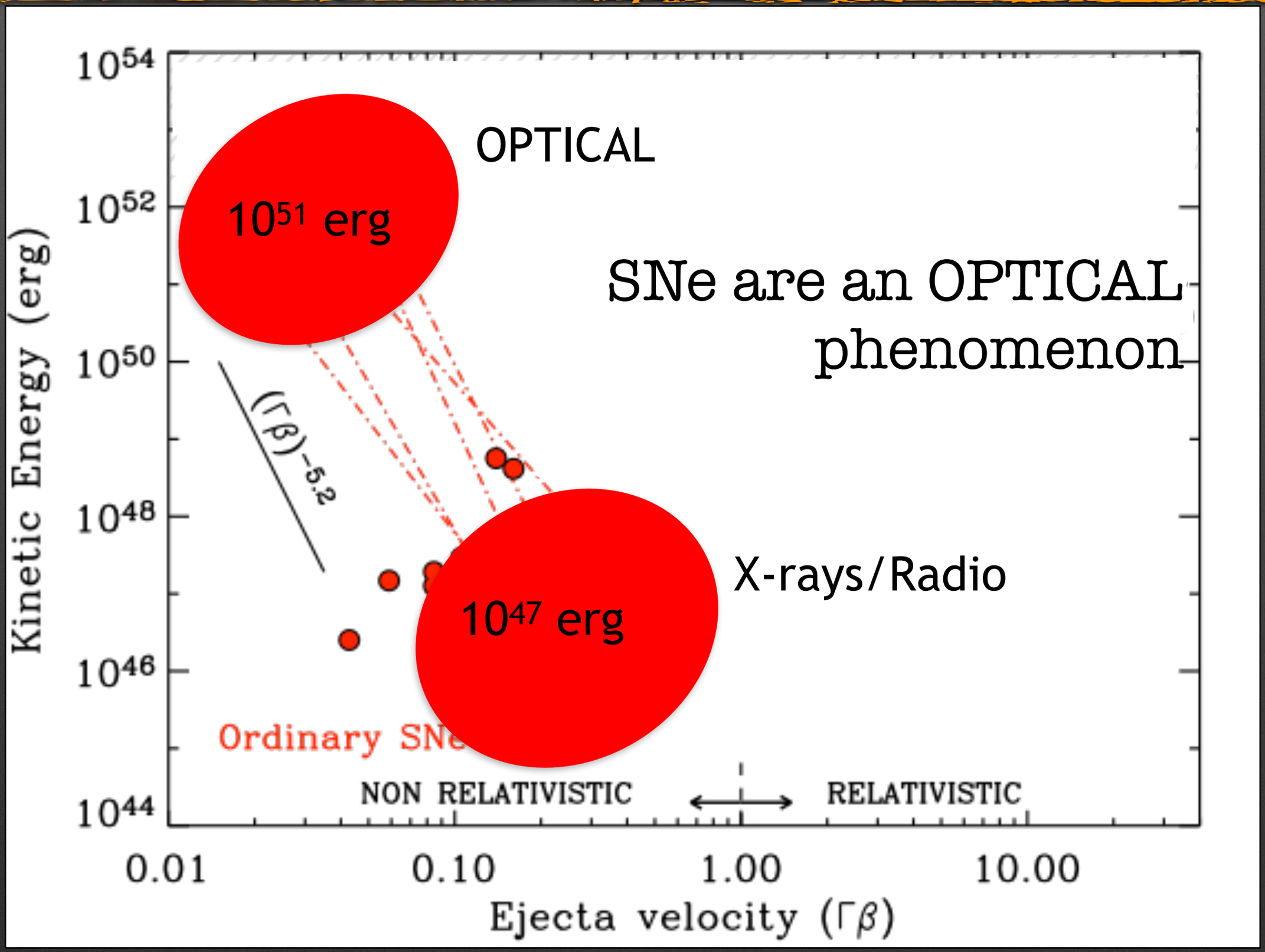
WHY?

Energy

Density of the medium

DECELERATION
of a shock into the environment

(1) Energy partitioning



(2) Mapping the local Environment

?

?

NS

BH

~ 1000 yr

The last thousands years

Direct Observations

Flash Spectroscopy

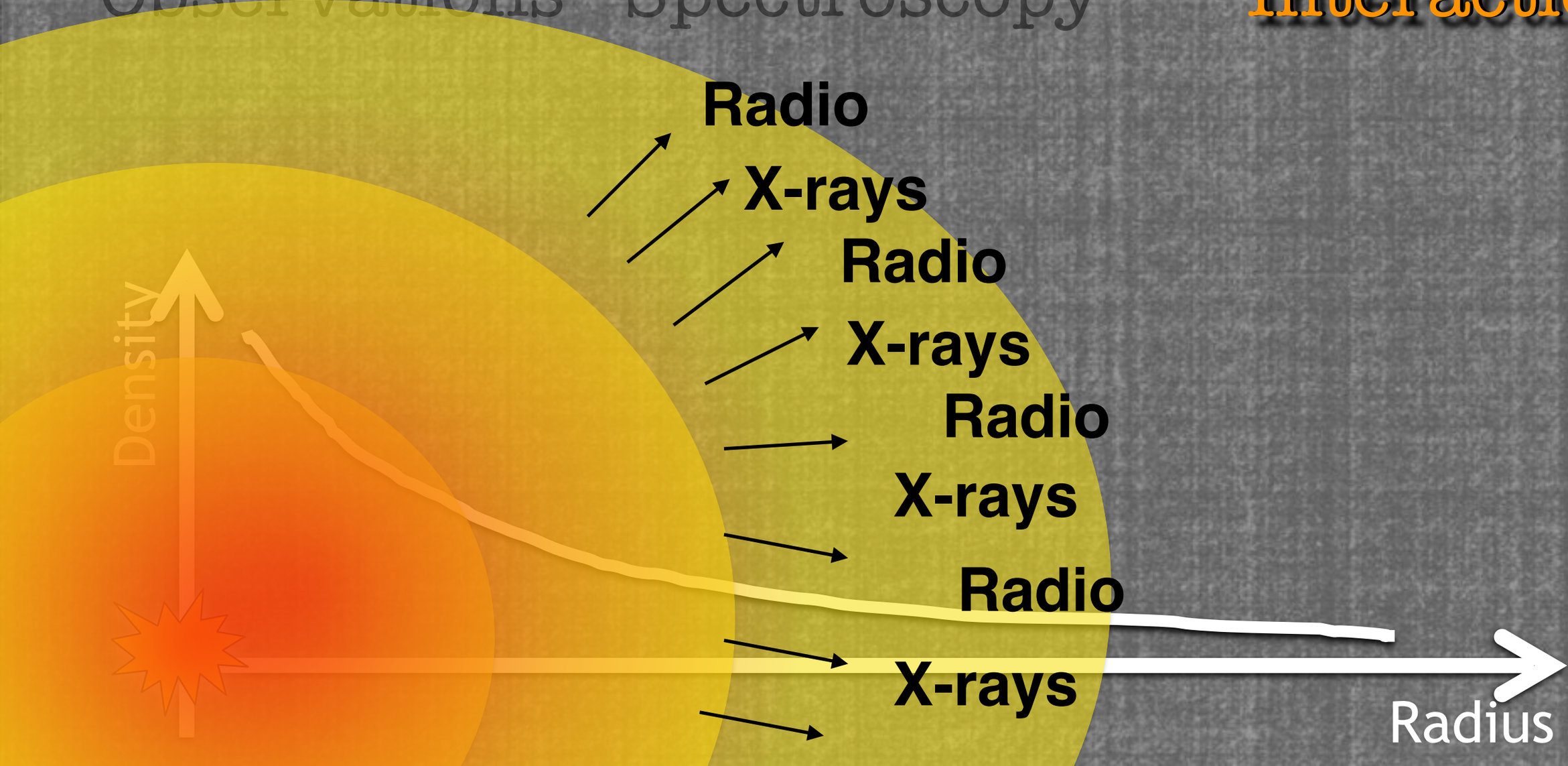
Shock Interaction

The last thousands years

Direct Observations

Flash Spectroscopy

Shock Interaction

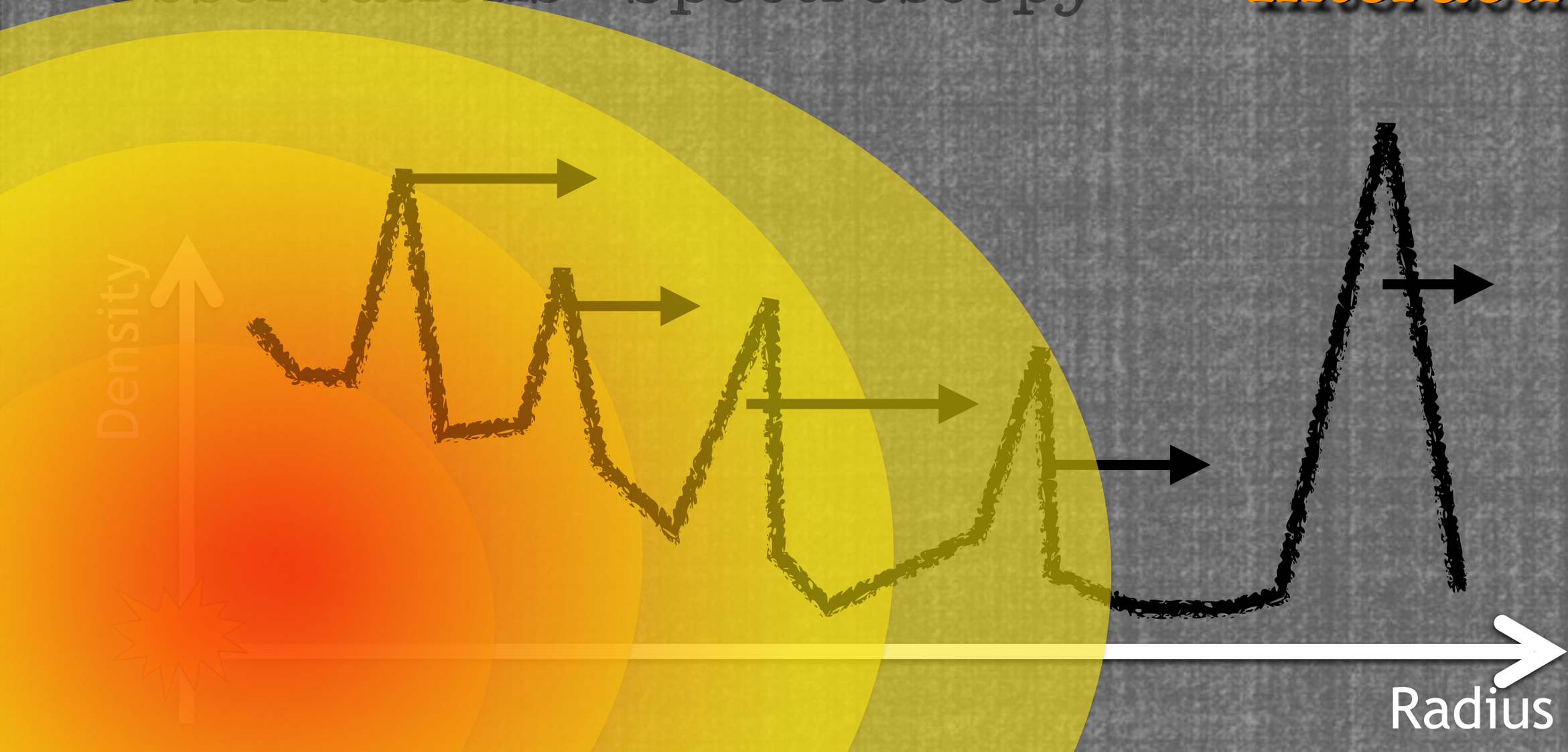


The last years before explosion

Direct Observations

Flash Spectroscopy

Shock Interaction



Vshock >> Vejection

(Vshock/Vejection) t

The last thousand years...

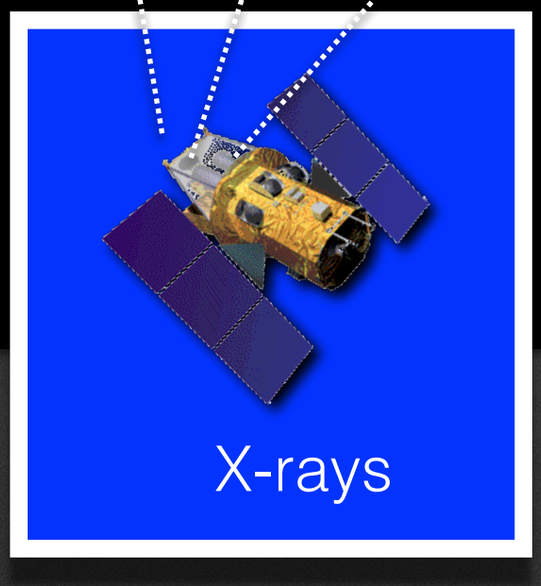
SN shock as a probe

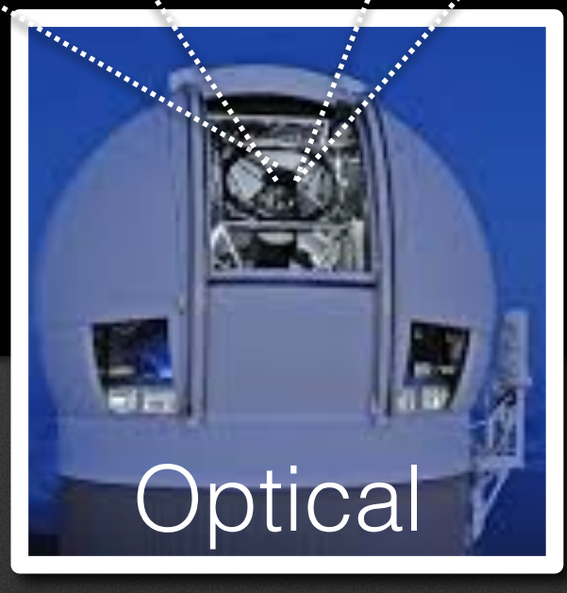
FLASH Spec

-1000 -100 -10 yrs

Time

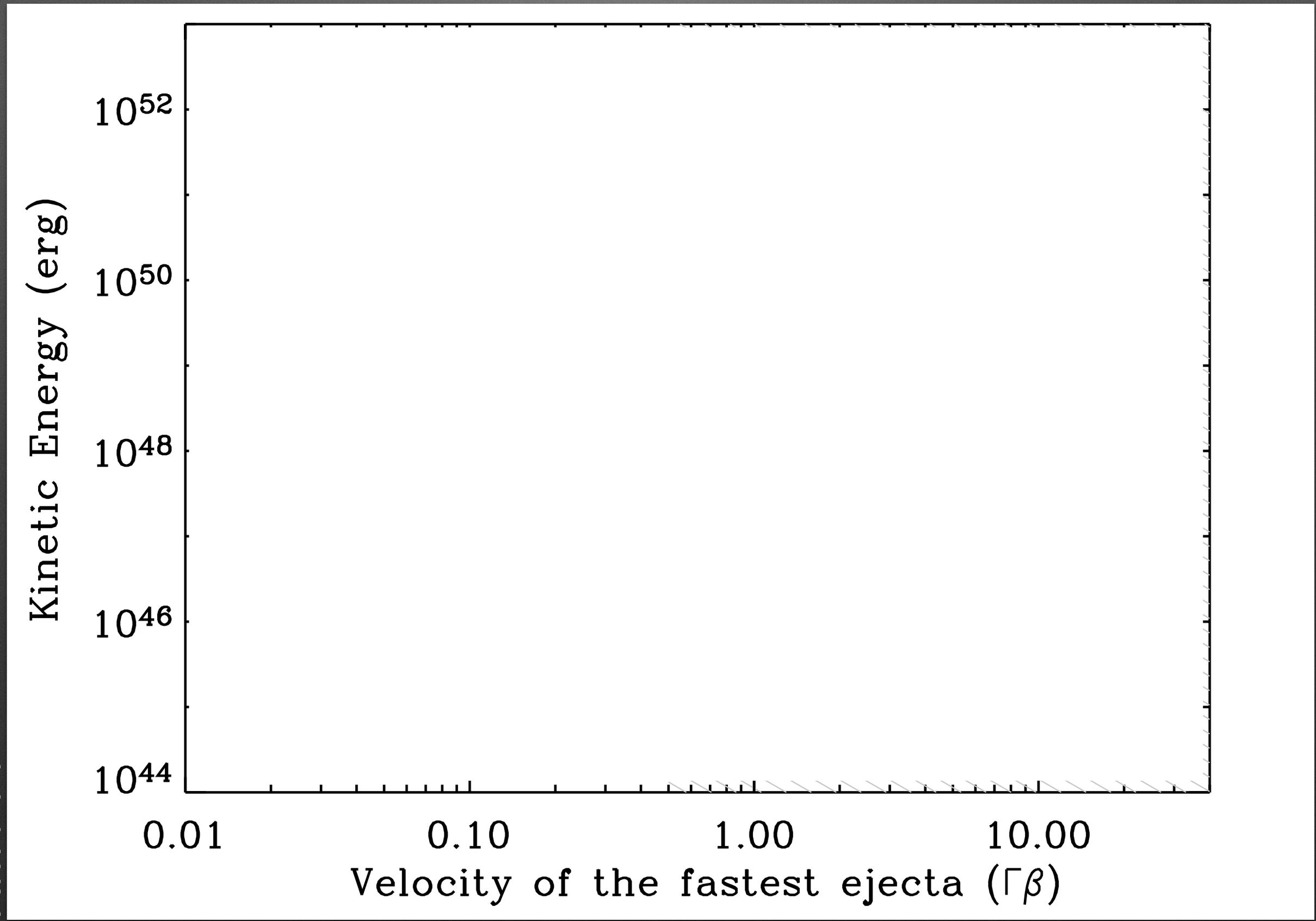
Nuclear Burning Sequence





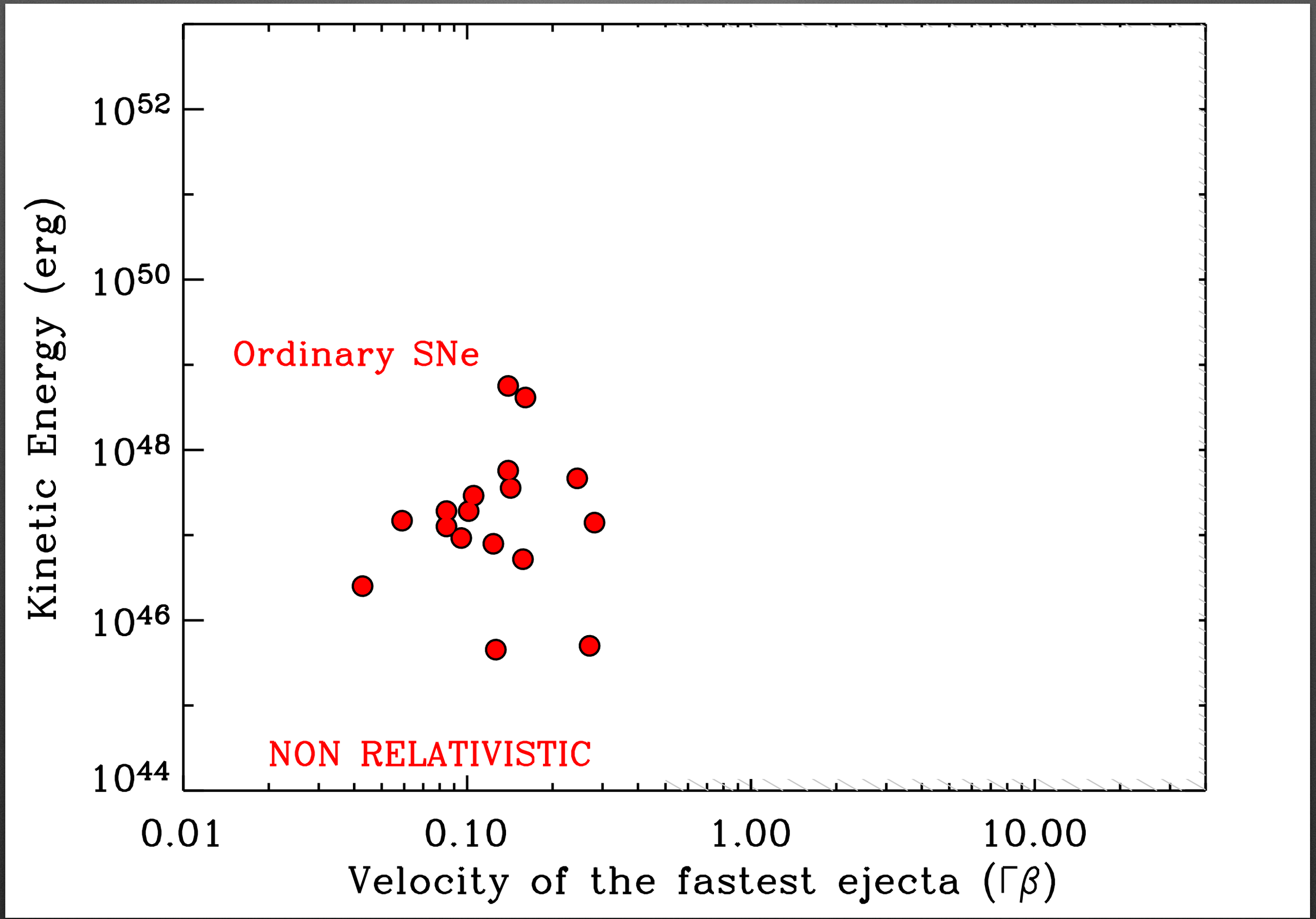
Direct Imaging

@1 day


Kinetic Energy (erg)
10^{52}
10^{50}
10^{48}
10^{46}
10^{44}
0.01
0.10
1.00
10.00
Velocity of the fastest ejecta ($\Gamma\beta$)

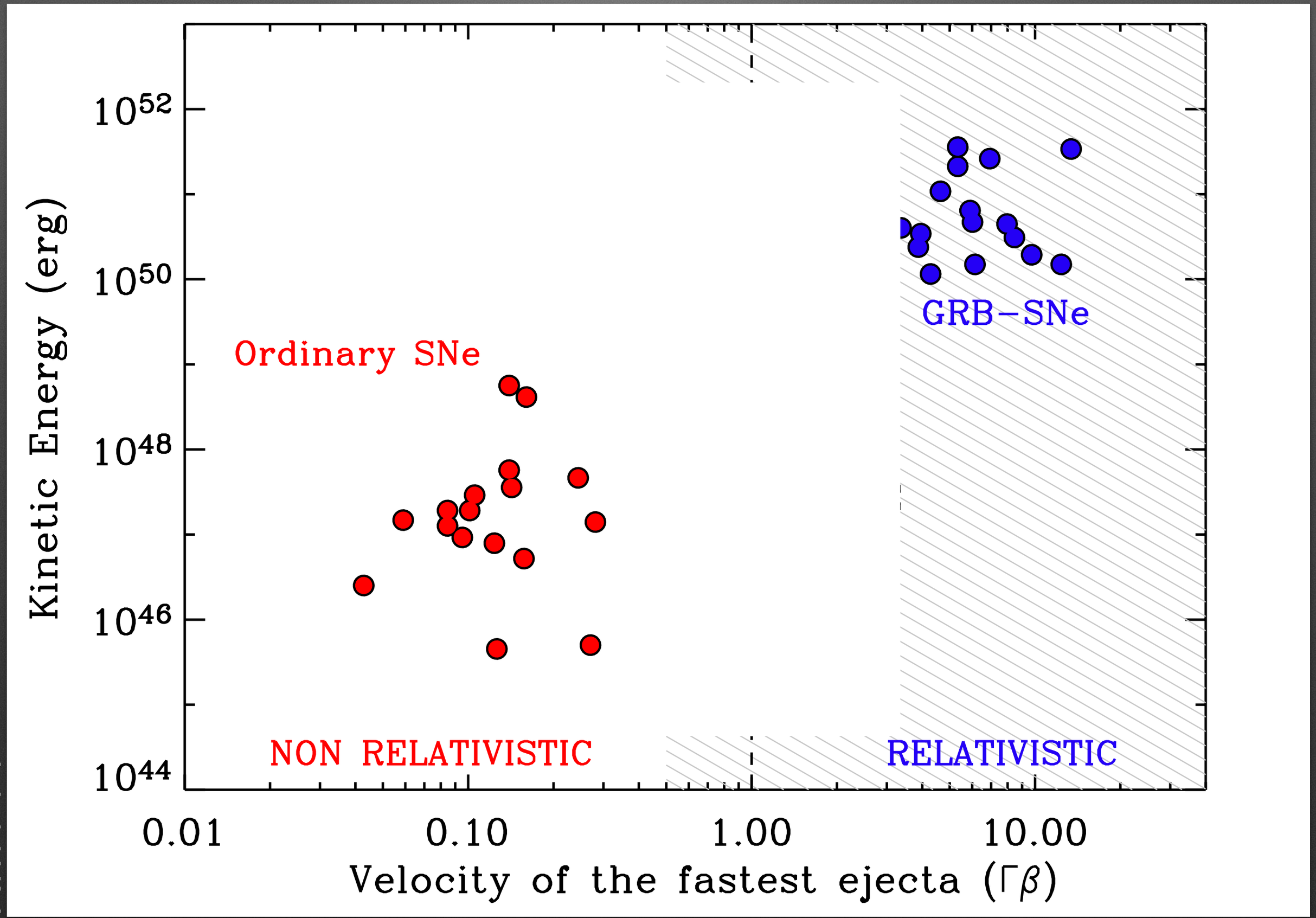
RM+14

@1 day


Kinetic Energy (erg)
10^{52}
10^{50}
10^{48}
10^{46}
10^{44}
Ordinary SNe
NON RELATIVISTIC
0.01
0.10
1.00
10.00
Velocity of the fastest ejecta ($\Gamma\beta$)

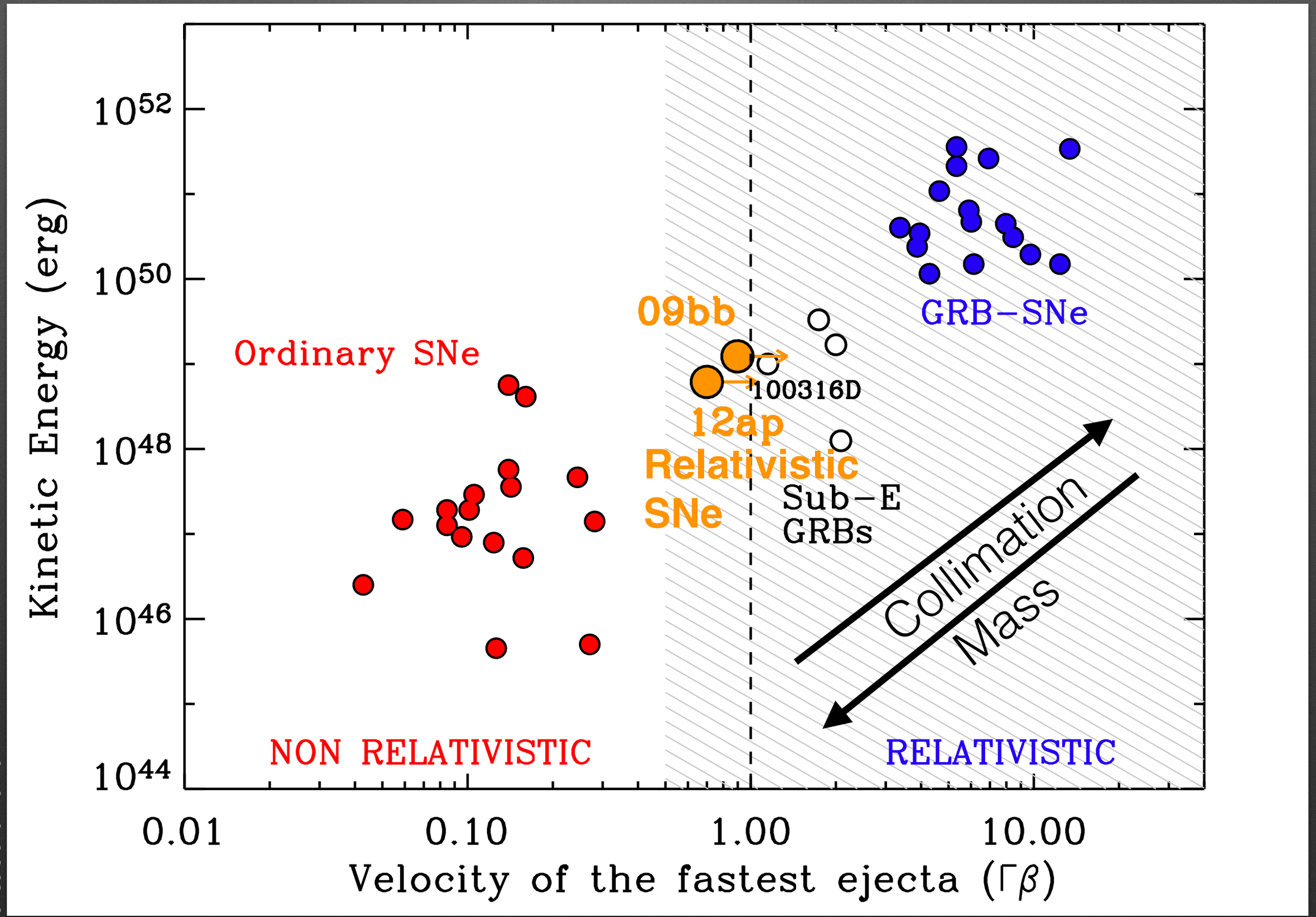
RM+14

@1 day


Kinetic Energy (erg)
10^{52}
10^{50}
10^{48}
10^{46}
10^{44}
Ordinary SNe
GRB−SNe
NON RELATIVISTIC
RELATIVISTIC
0.01
0.10
1.00
10.00
Velocity of the fastest ejecta ($\Gamma\beta$)

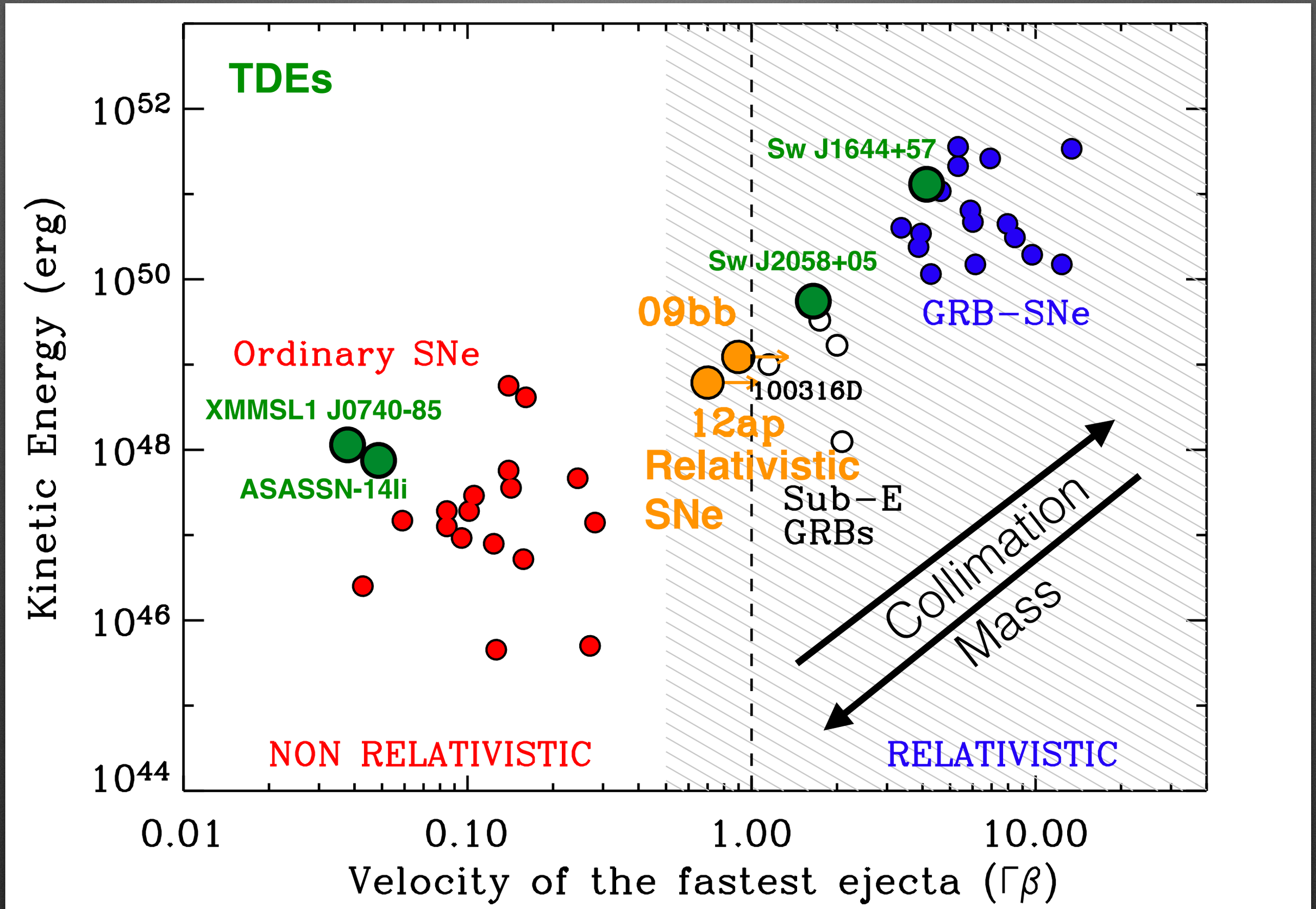
RM+14

@1 day


Kinetic Energy (erg)
10^{52}
10^{50}
10^{48}
10^{46}
10^{44}
Ordinary SNe
09bb
100316D
12ap
Relativistic
SNe
GRB−SNe
Sub−E
GRBs
Collimation
Mass
NON RELATIVISTIC
RELATIVISTIC
0.01
0.10
1.00
10.00
Velocity of the fastest ejecta (Γβ)

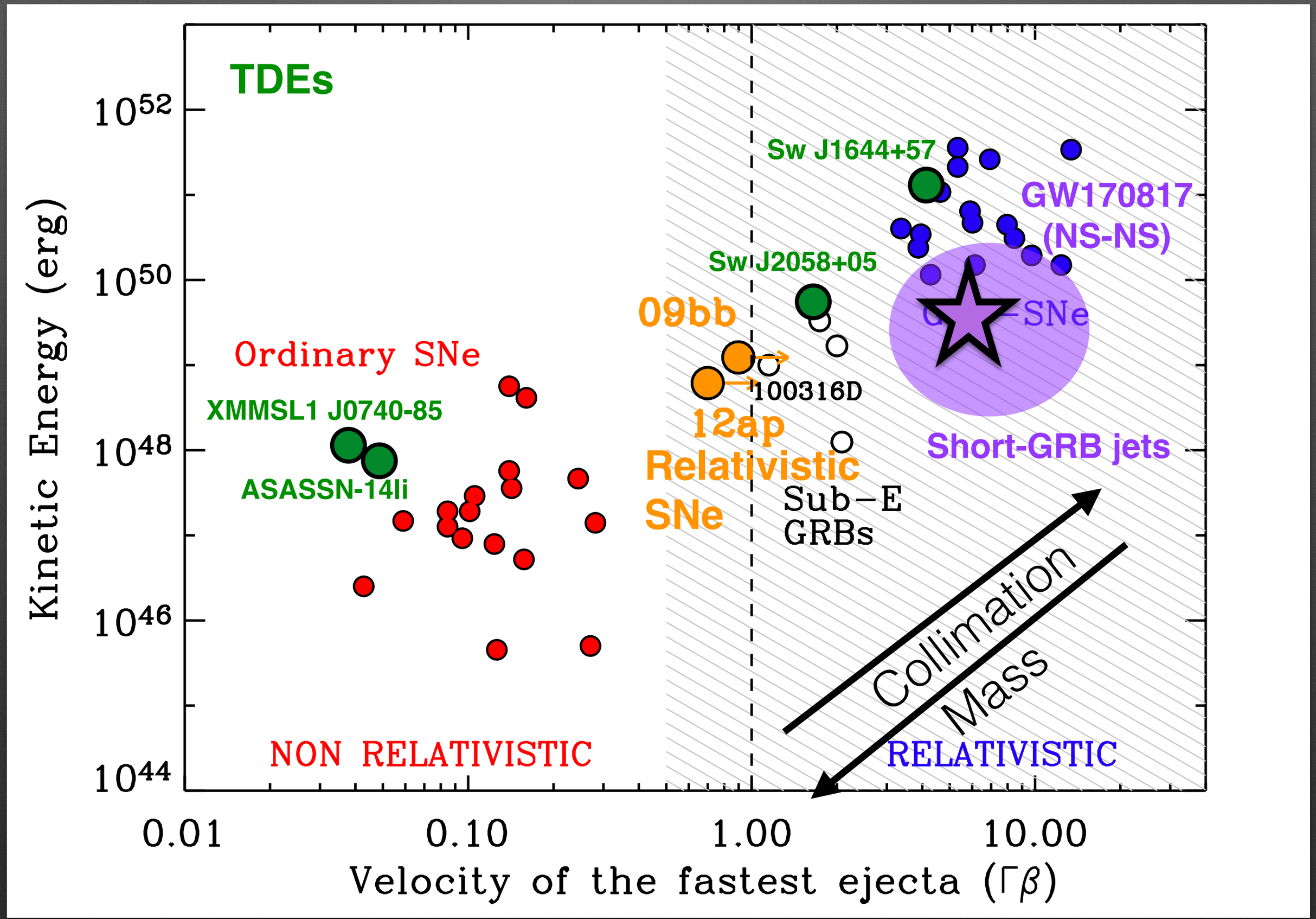
RM+14

@1 day

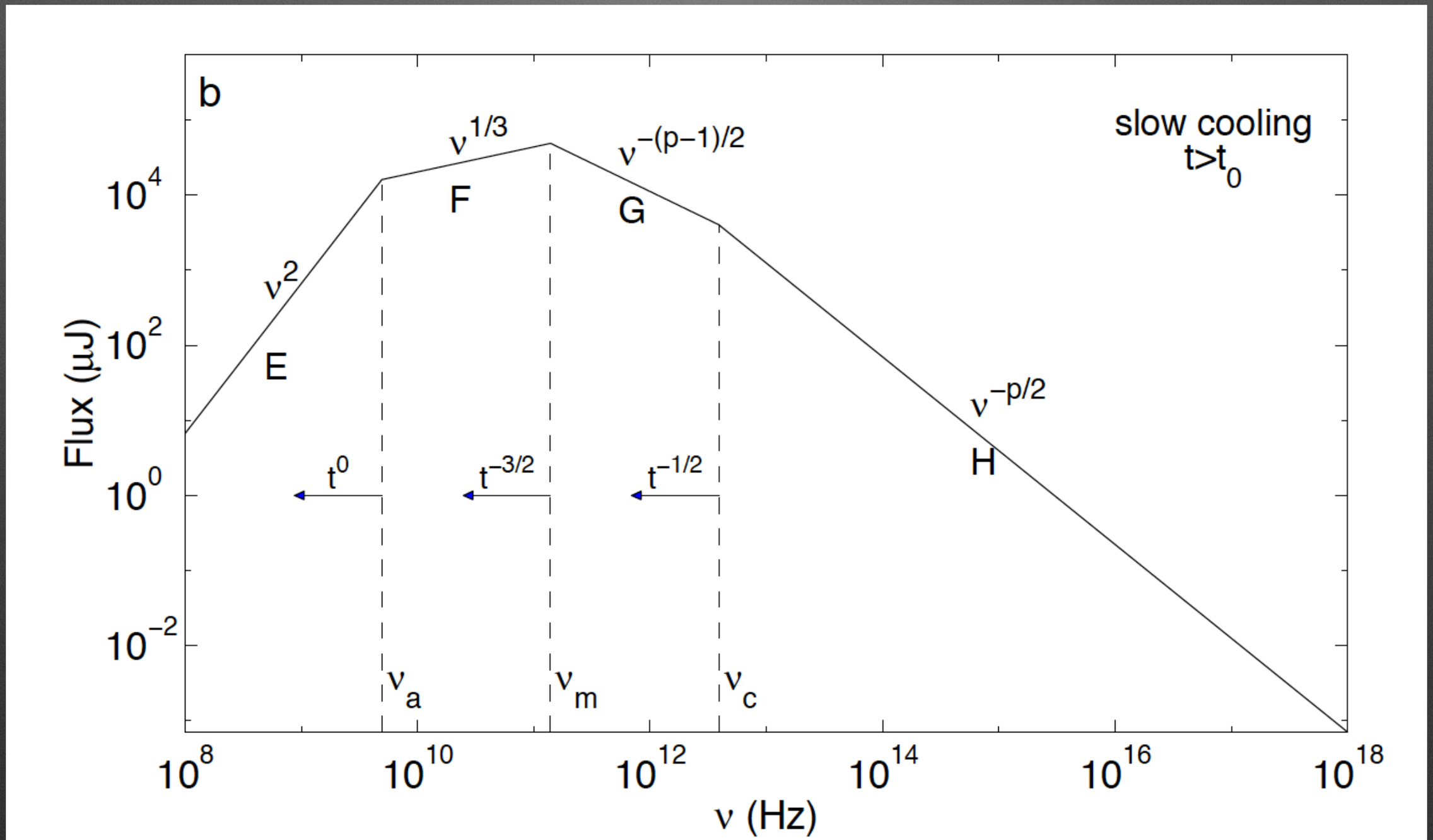


RM+14,Alexander+2014

@1 day

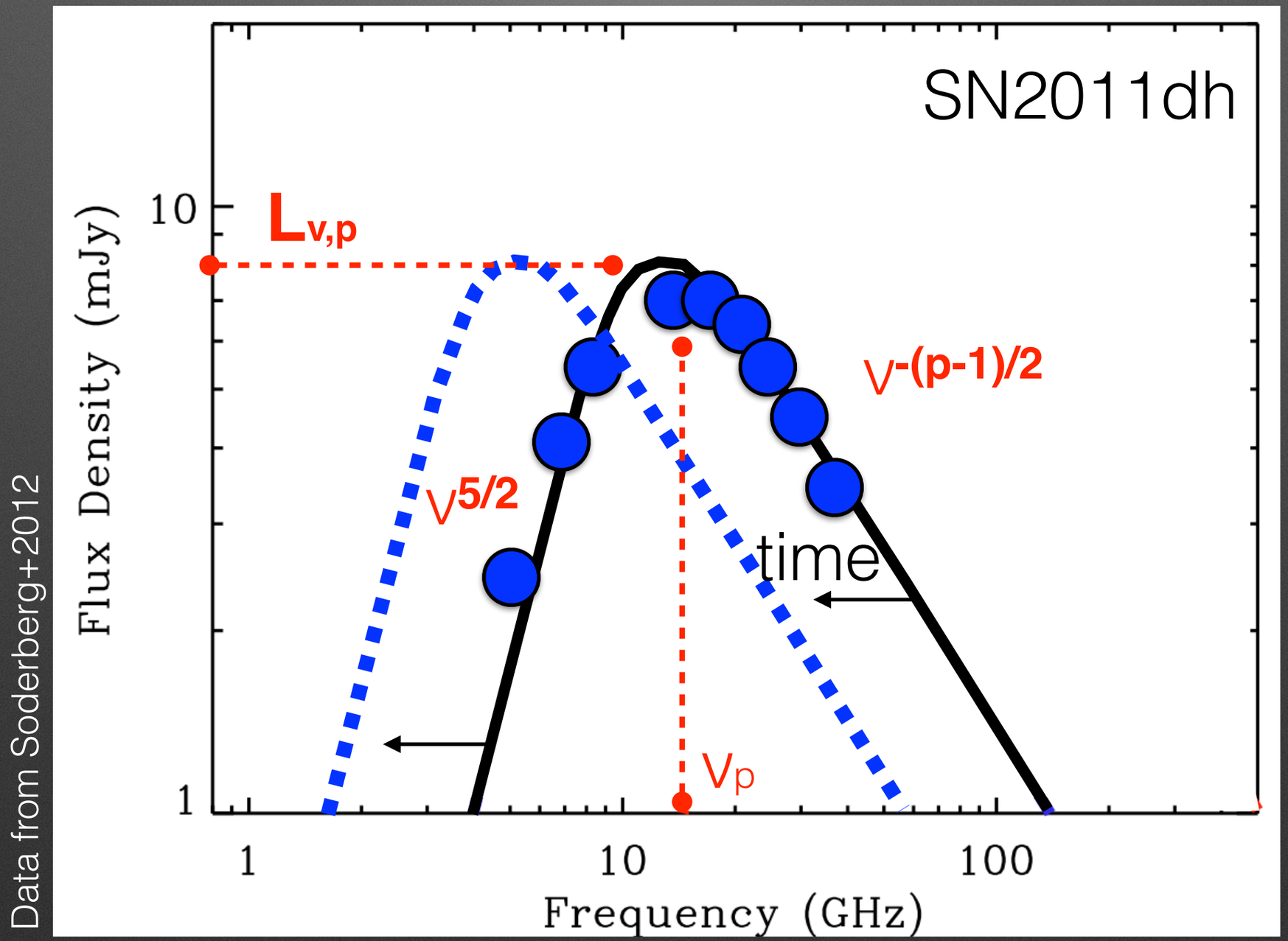

TDEs
Ordinary SNe
XMMSL1 J0740-85
ASASSN-14li
Sw J1644+57
GW170817
(NS-NS)
SwJ2058+05
09bb
100316D
12ap
Relativistic
SNe
Sub−E
GRBs
SNe
Short-GRB jets
Collimation
Mass
NON RELATIVISTIC
RELATIVISTIC
Kinetic Energy (erg)
Velocity of the fastest ejecta (Γβ)
10^52
10^50
10^48
10^46
10^44
0.01
0.10
1.00
10.00
RM+14,Alexander+2014, Fong+2015

Synchrotron Spectrum (of an expanding blastwave)



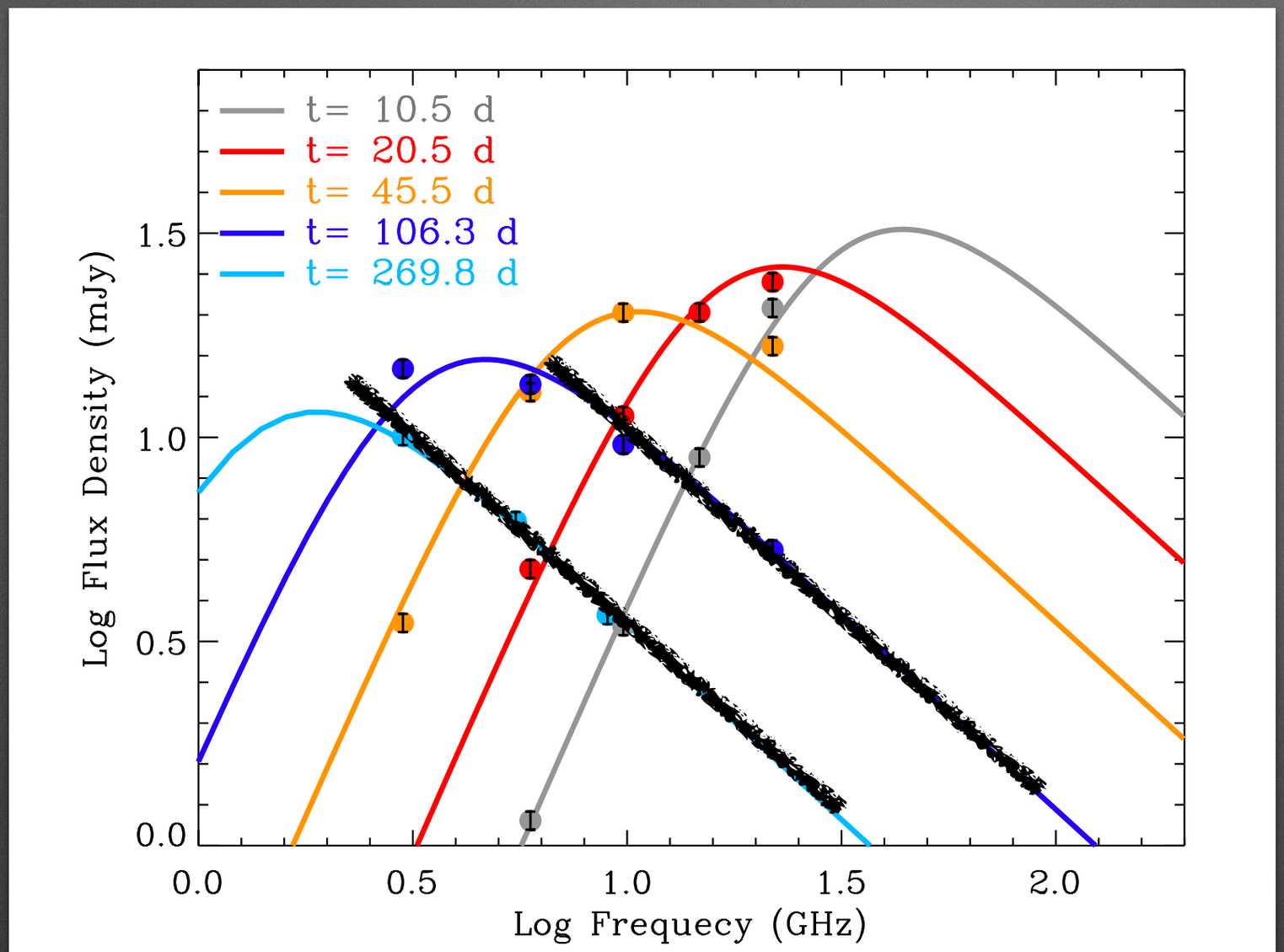
Parameters: Ek, p, n, ε_B, ε_e, [ζ_N] + distance + TIME

[1] Non-relativistic shocks (v≅0.1c)



Synchrotron Self-Absorption (SSA) spectrum (FS dominates)

Radio evolution of SN2016coi



Terreran+2019

Observed: ν^{-1}

$\nu^{-(p-1)/2}$ ==> **p~3**

where p is the index of the PL distribution of the electrons

N(γ)~ γ^{-p}

$$B(10.5\,\mathrm{d}) = (4.0 \pm 0.2)\left(\frac{\epsilon_e}{0.33}\right)^{-\frac{4}{19}}\left(\frac{\epsilon_B}{0.33}\right)^{+4/19}\,\mathrm{G},$$

$$R_{sh}(10.5\,\mathrm{d}) = (3.1 \pm 0.1) \times 10^{15}\left(\frac{\epsilon_e}{0.33}\right)^{-1/19}\left(\frac{\epsilon_B}{0.33}\right)^{+1/19}$$

⇦ Equipartition

…le dolenti note …
(Dante, Inferno, CantoV)

Radio evolution of SN2016coi

$$U(10.5\,\mathrm{d}) = (1.1 \pm 0.1) \times 10^{47} \left(\frac{\epsilon_e}{0.33}\right)^{-11/19} \left(\frac{\epsilon_B}{0.33}\right)^{-8/19} \mathrm{erg}.$$

→ Shock Internal Energy

$$\dot{M}_{eff}(10.5\,\mathrm{d}) = (3.6 \pm 0.3) \times 10^{-5} \left(\frac{\epsilon_e}{0.33}\right)^{-8/19} \left(\frac{\epsilon_B}{0.33}\right)^{-11/19} \mathrm{M_\odot yr^{-1}}$$

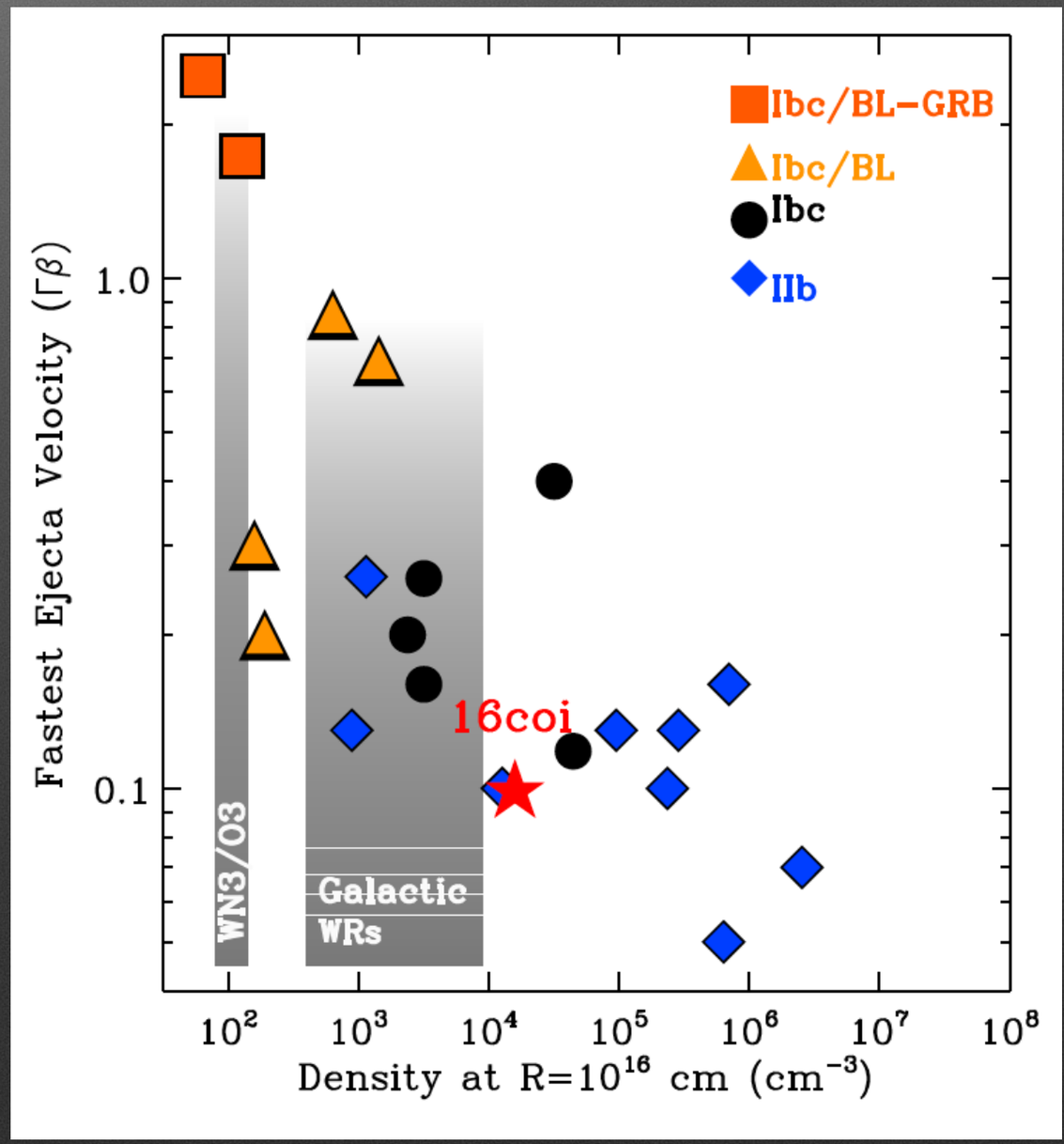
→ Mass-loss (i.e. density)

Problem:
$\varepsilon_e = 10^{-3}$
$\varepsilon_B = 10^{-3}$

U==> 330xU_{eq}
Mdot ==>330xMdot

Comparison to stellar mass-loss rates?
Absence of free-free absorption?

…le dolenti note …
(Dante, Inferno, CantoV)



What's new?

- NTE from Fast Blue Optical Transients
  Margutti+2018; Coppejans+2019 in prep.
- NTE from Super luminous SNe
  Jacobson-Galan+ in prep.
- NTE from Tidal Disruption Events
  Zauderer+2011; Alexander+2015

What are we missing?

- NTE from young Ia SNe

Discovery Phase Space of Astronomical Transients

Fast Blue Optical Transients (FBOTs)

Lum

FBOTs

Superluminous SNe

normal SN Lpeak

10^43 erg/s

pre-SN outbursts

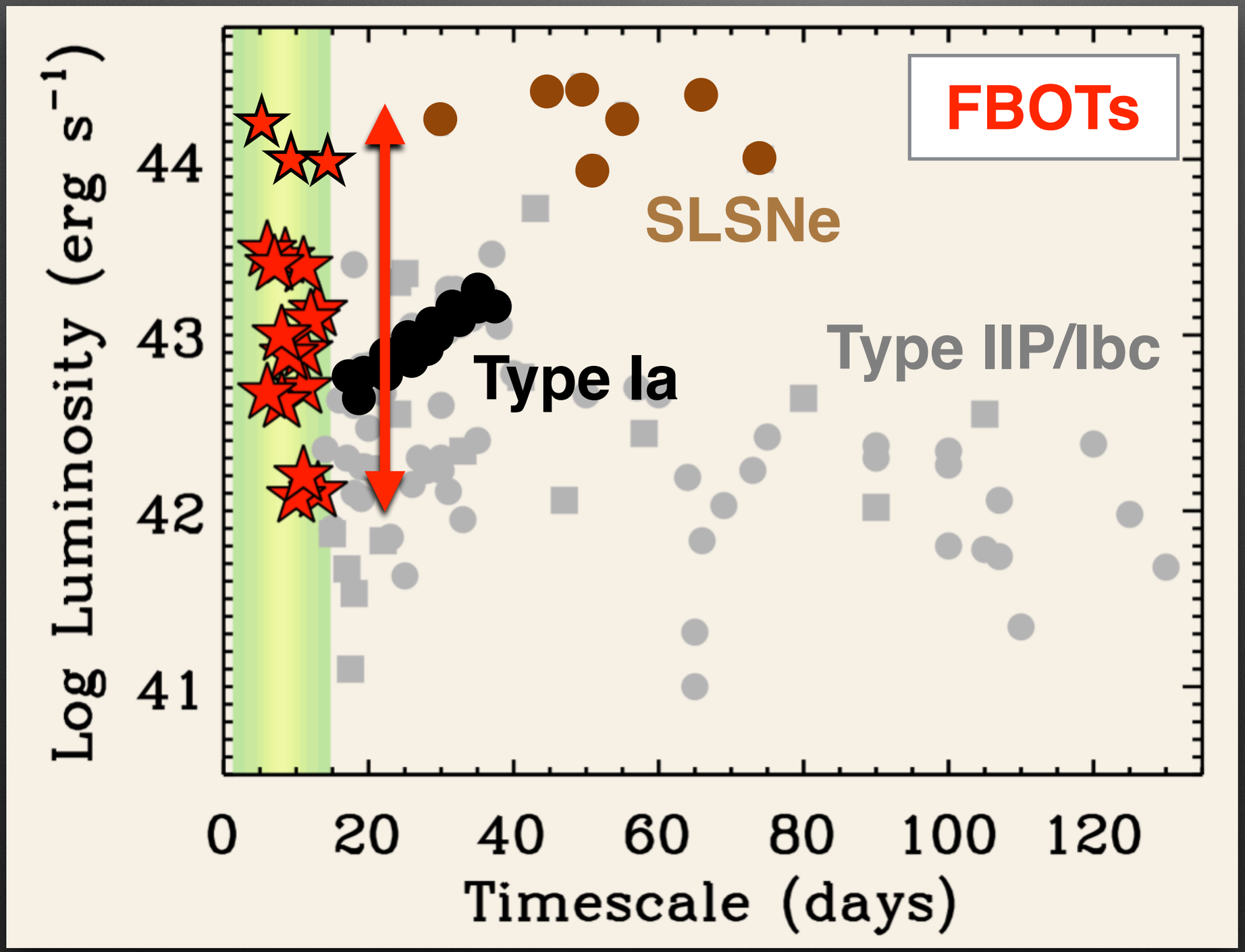
EM counterparts to GWs

Very late-time spectra

-100 yrs -10 yrs ~ few days +Years Time

Fast Blue Optical Transients

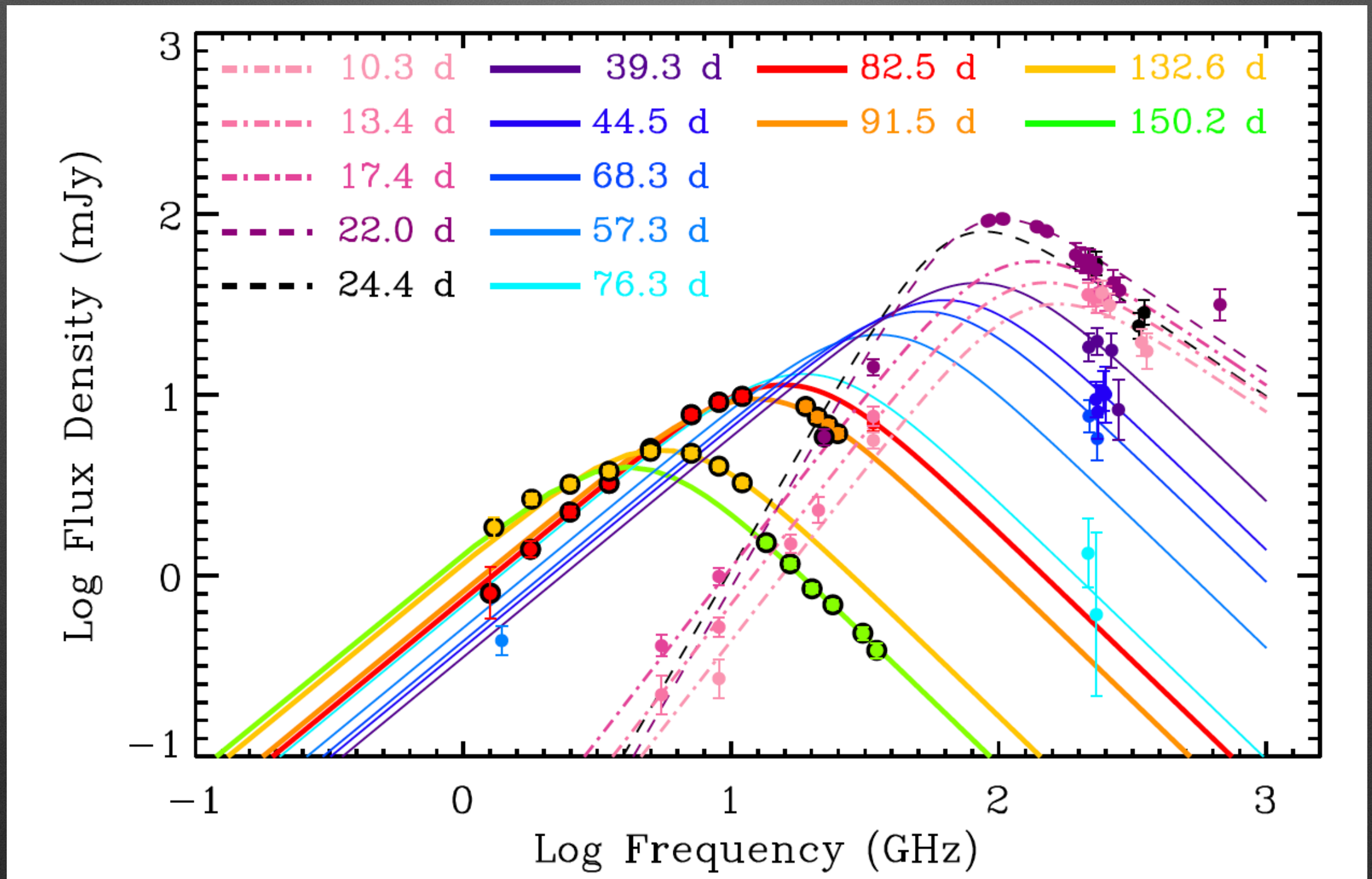
Sample studies: Drout+14 (PanSTARSS), Tanaka+16 (Subaru), Arcavi+16 (SNLS+PTF), Pursiainen+18 (DECam)



Modified from Drout+14

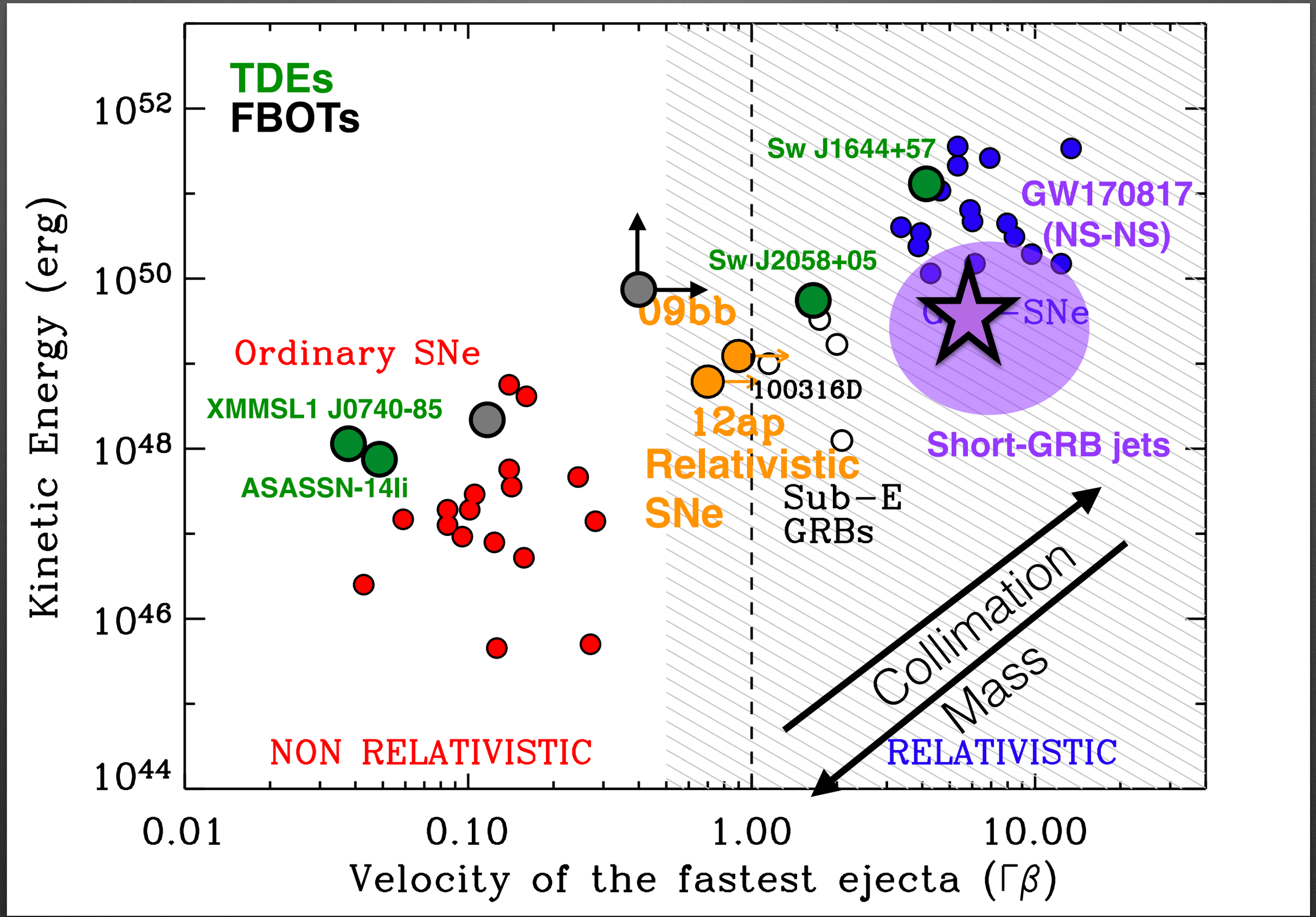
First radio SED(t) of an FBOT:

SN2018cow



RM+2019

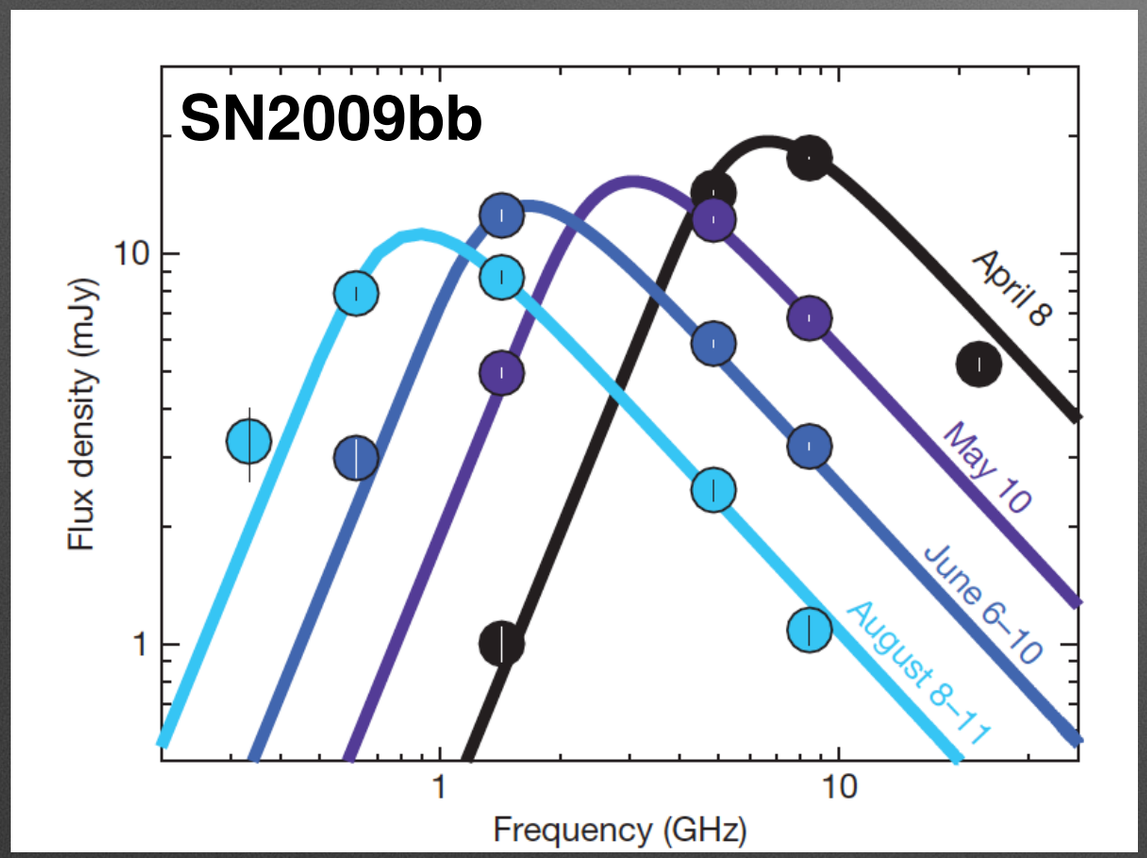
@1 day



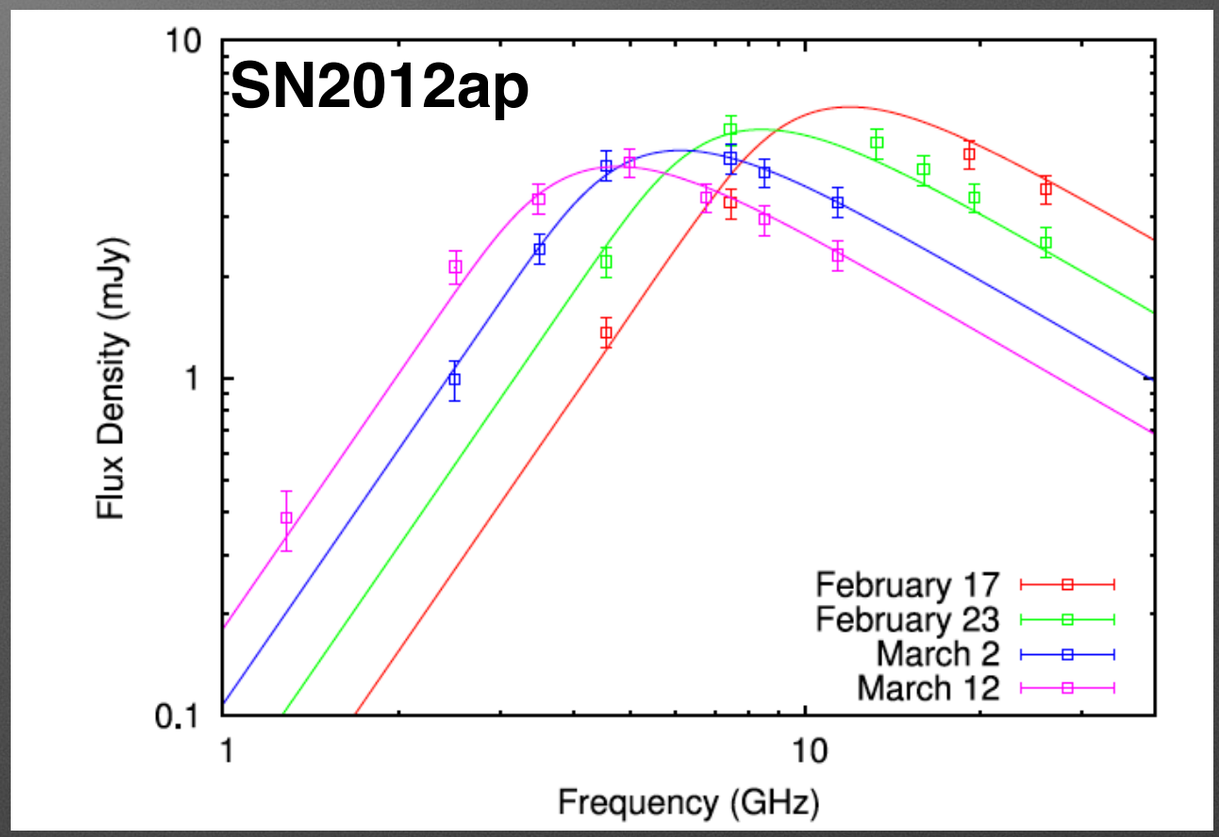
RM+14,Alexander+2014, Fong+2015

[2] Trans-relativistic shocks (v ≥0.6c)

We have N=2 relativistic SNe…



Soderberg+2010



Chakraborti+2015

v≅0.6-0.8c

p≅3

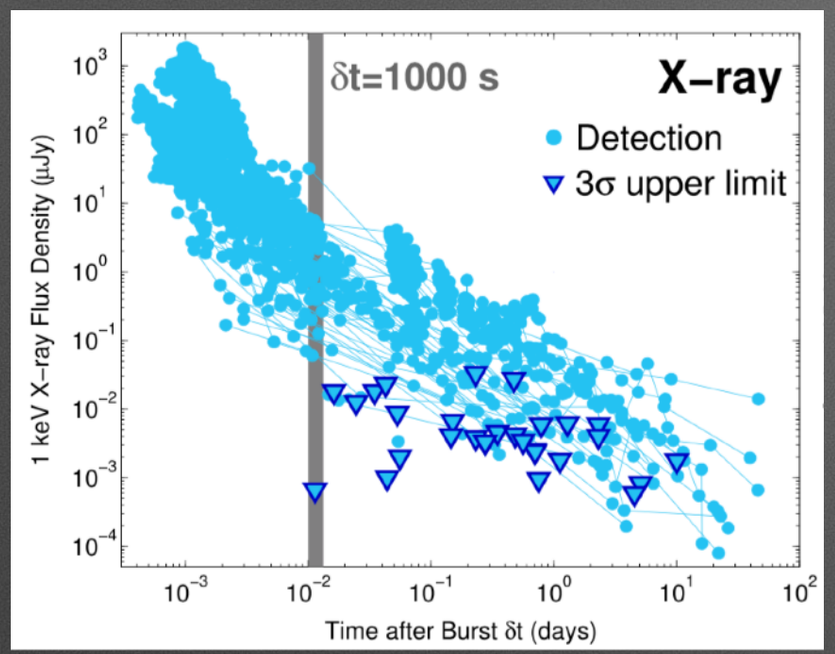
[3] Ultra-relativistic shocks ($\Gamma \cong 100$)

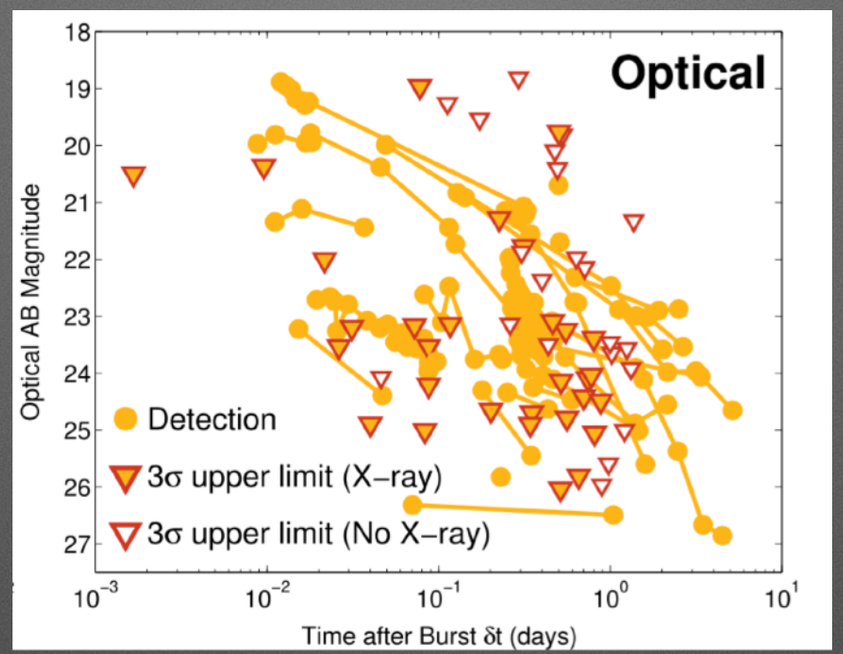
Short GRBs

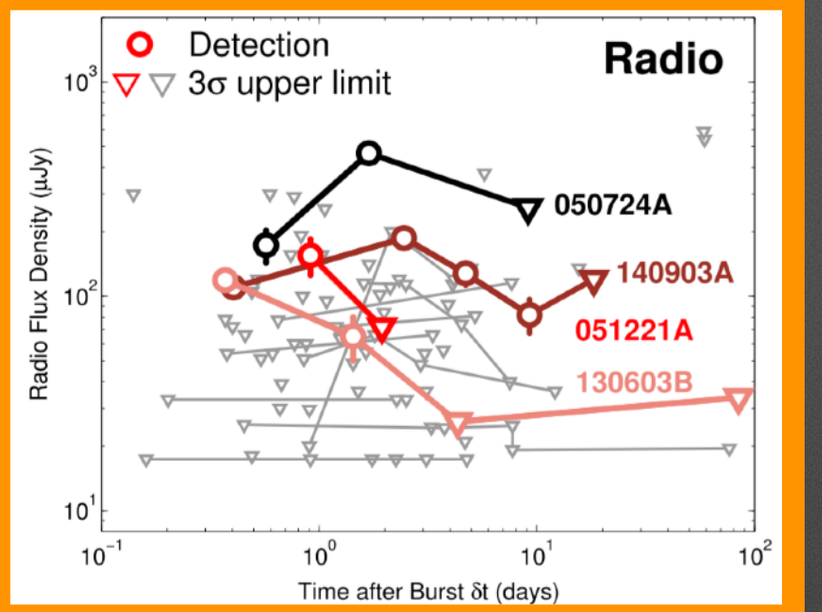
Long GRBs

Short GRB jets (15yrs of monitoring!)

Fong+15







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

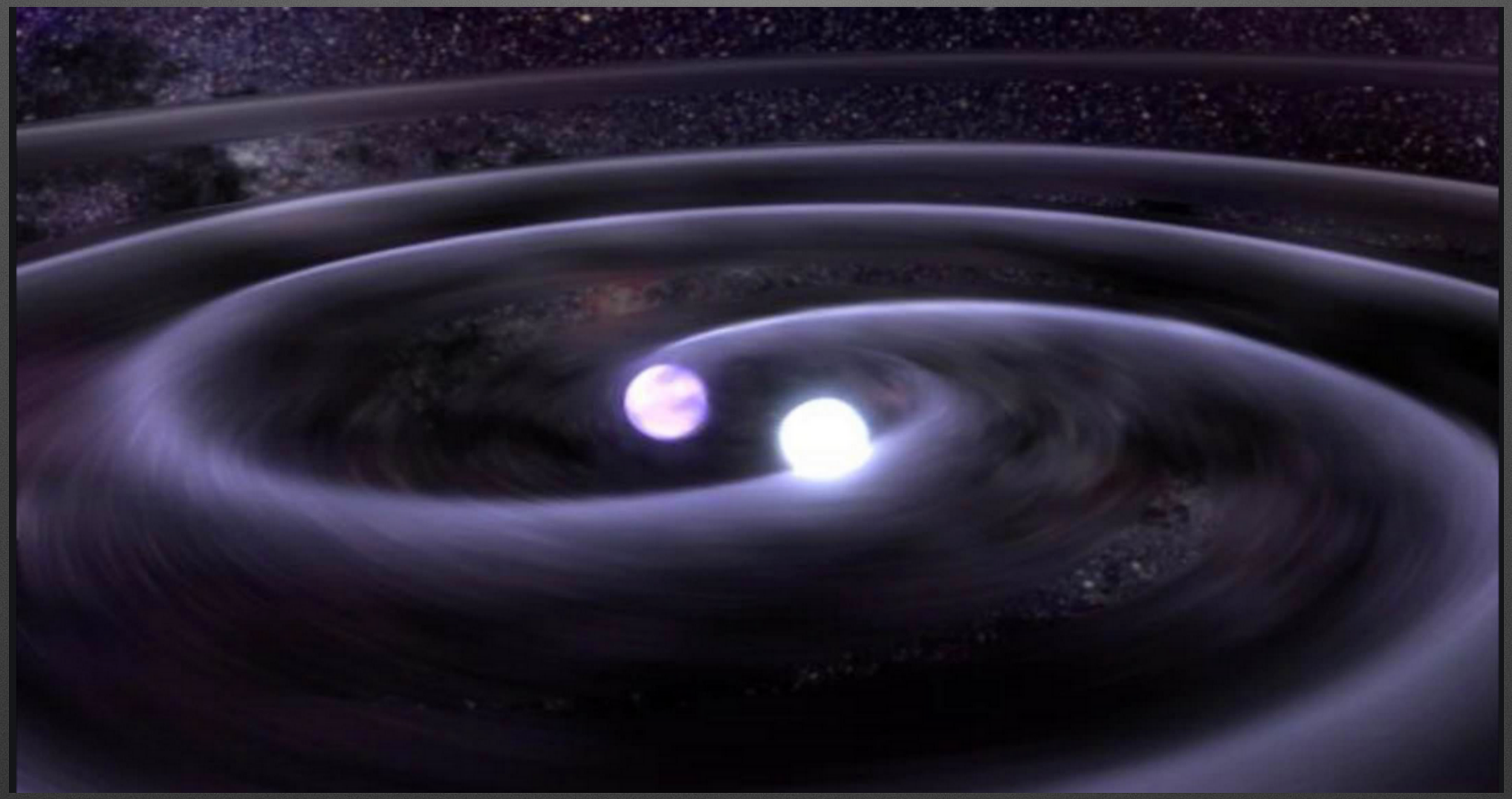
(= we do not solve for **ϵ**_e and **ϵ**_B)

==> location of **ν**sa, **ν**m, is typically a reasonable assumption, **ν**c is inferred for ~50% of the sample.

νm (**ν**sa)< Optical< **ν**c

Radio < **ν**m

The NS-NS merger GW170817

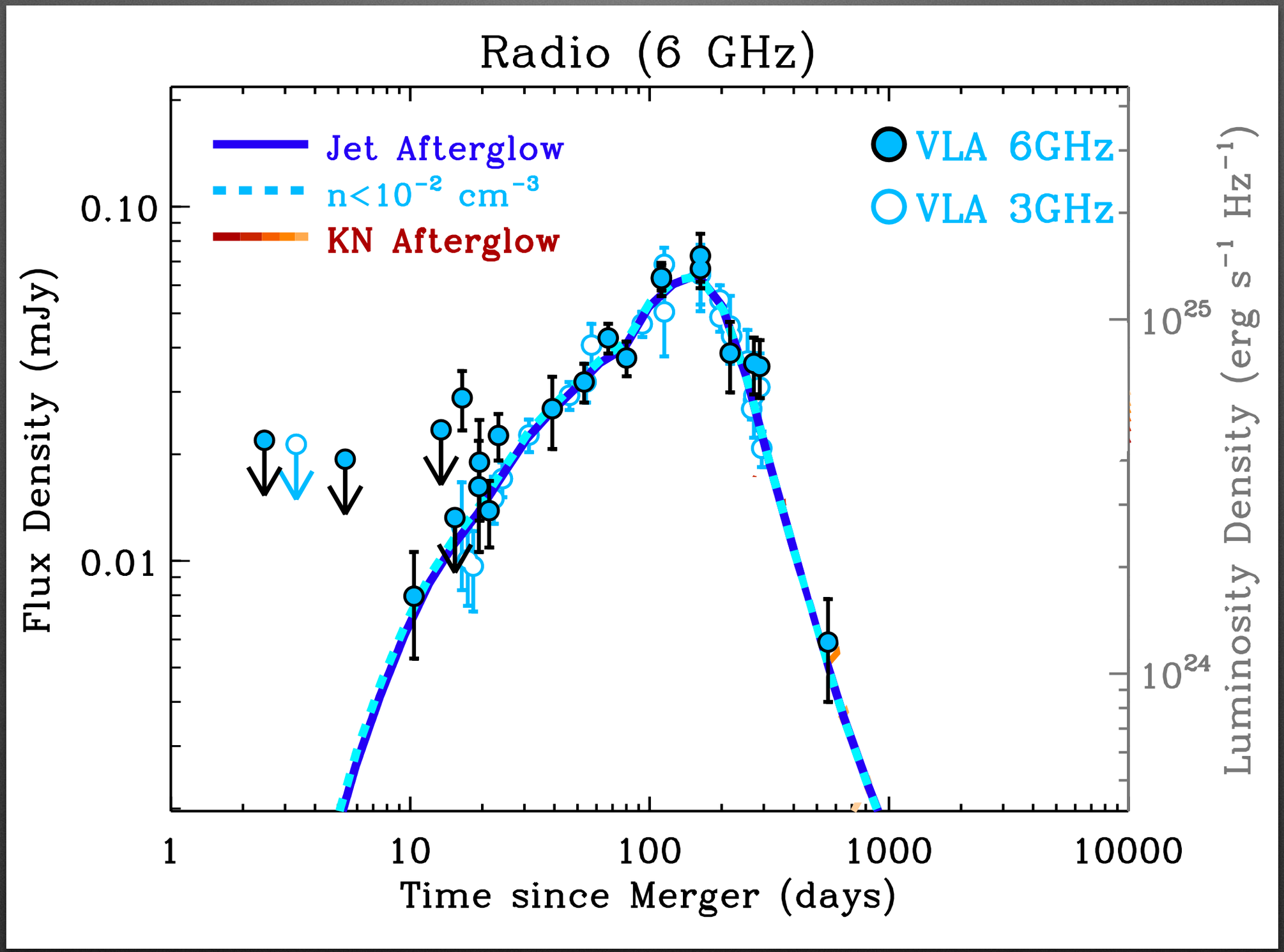


Outflows: Kilonova (spherical) + Jet

RM & Chornock ARA&A

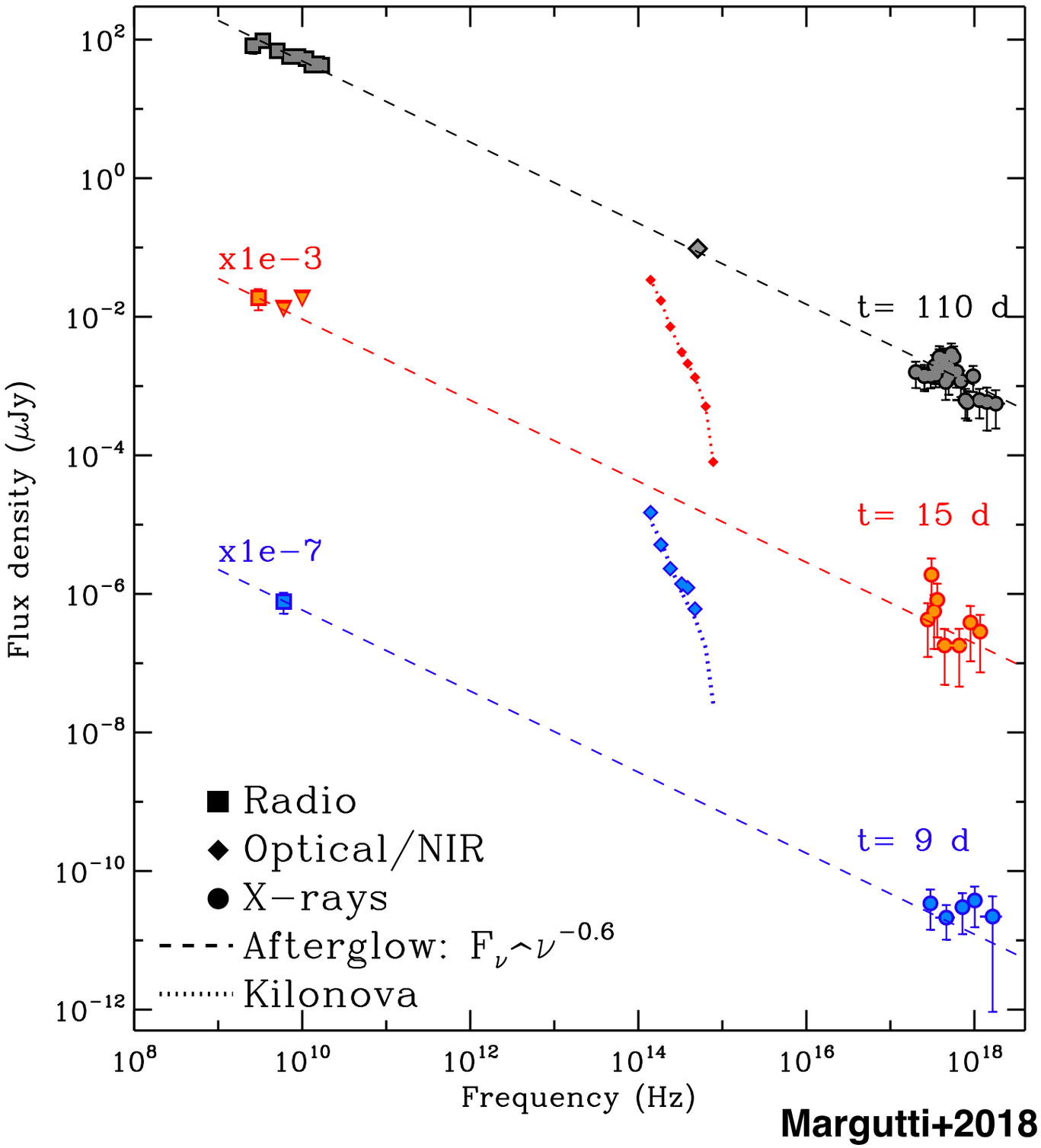
RM & Chornock ARA&A

2 yrs of non-thermal emission from GW170817



Hajela+2019

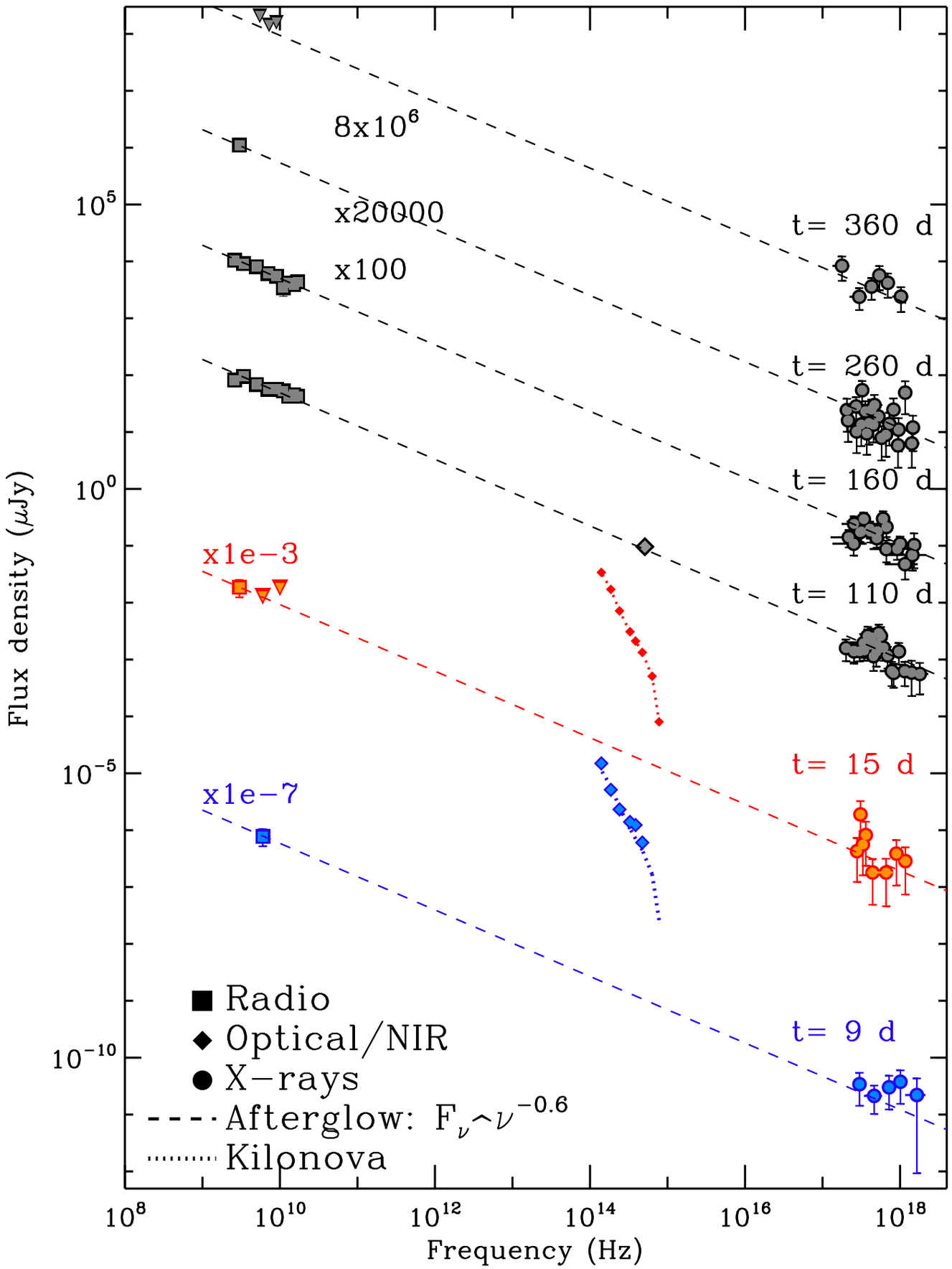
Non-thermal **synchrotron** emission across the spectrum: the show is still on



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 $\Gamma \sim 3$-10



RM & Chornock ARA&A in prep.

Simple power-law spectrum over 8 orders of magnitude in frequency

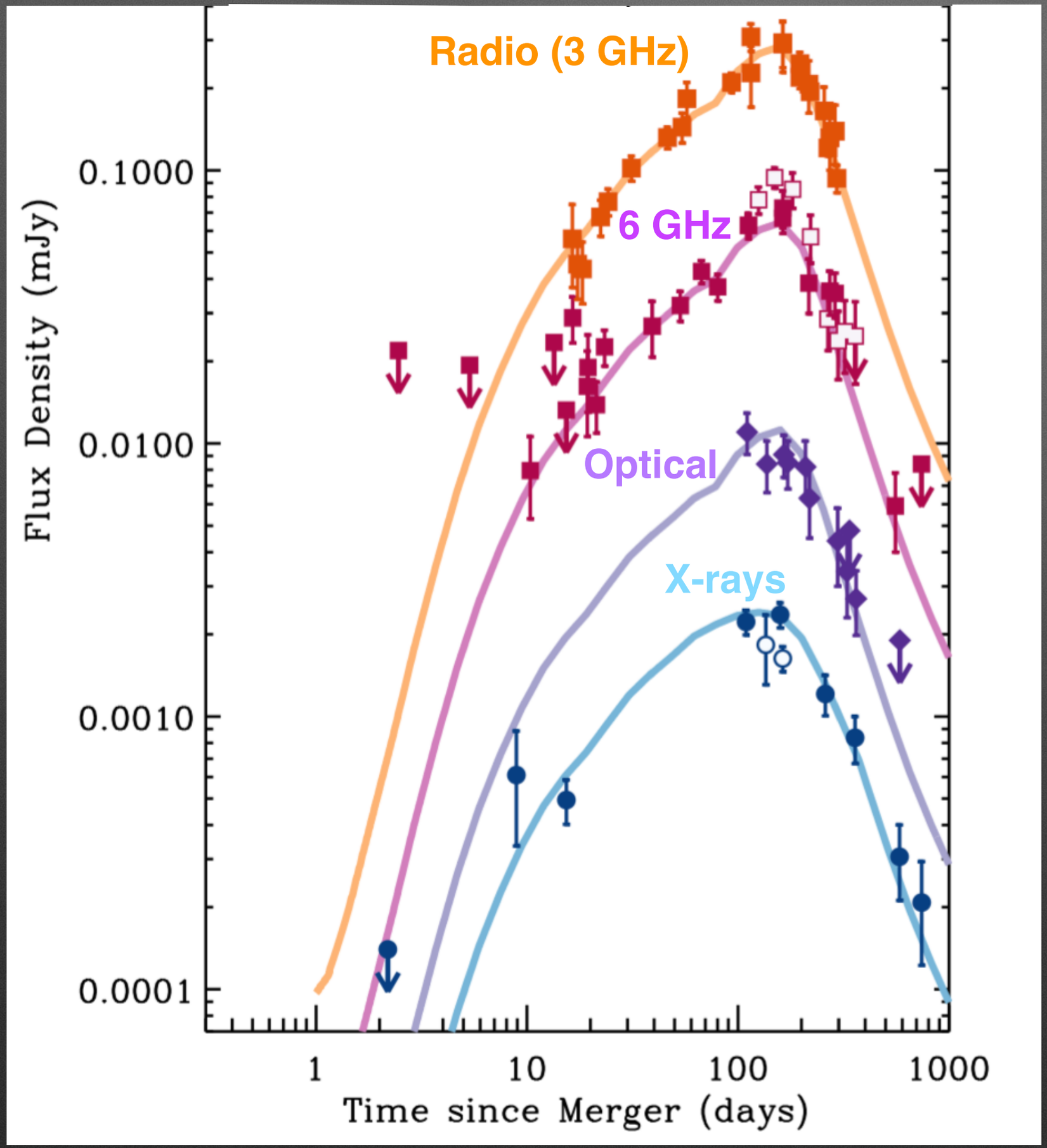
Observed:

$F_\nu \sim \nu^{-0.575 \pm 0.005}$

$F_\nu \sim \nu^{-(p-1)/2} \Longrightarrow$

p=2.15 +\-0.01

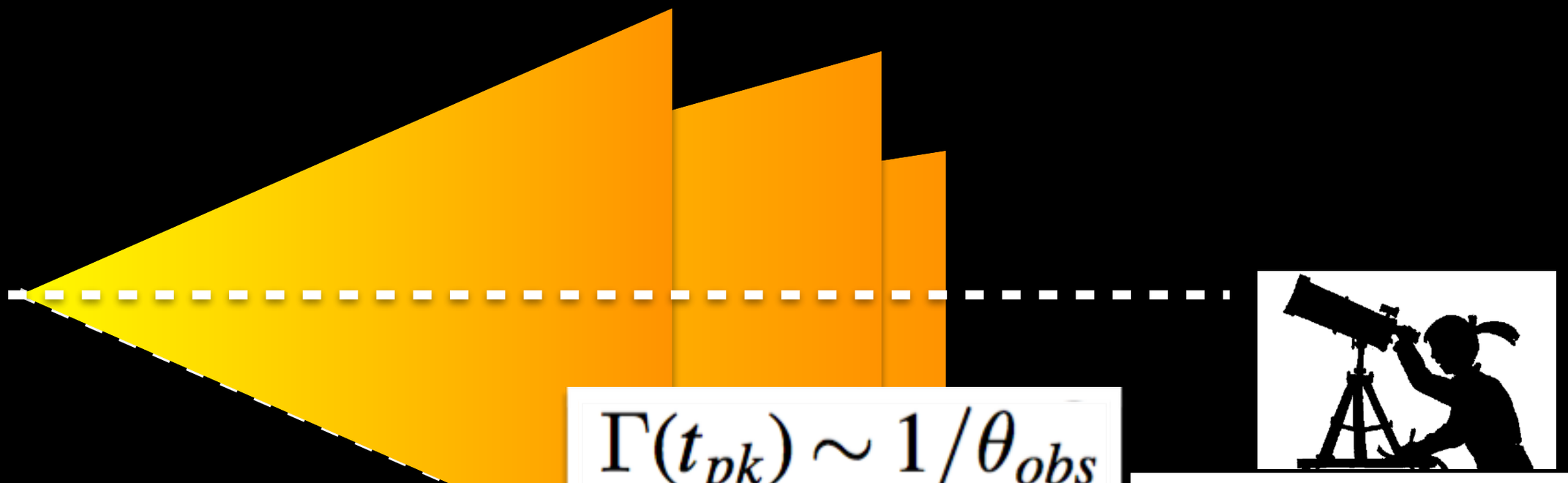
$[N(\gamma) \sim \gamma^{-p}]$



Non-thermal emission from GW170817 across the EM spectrum

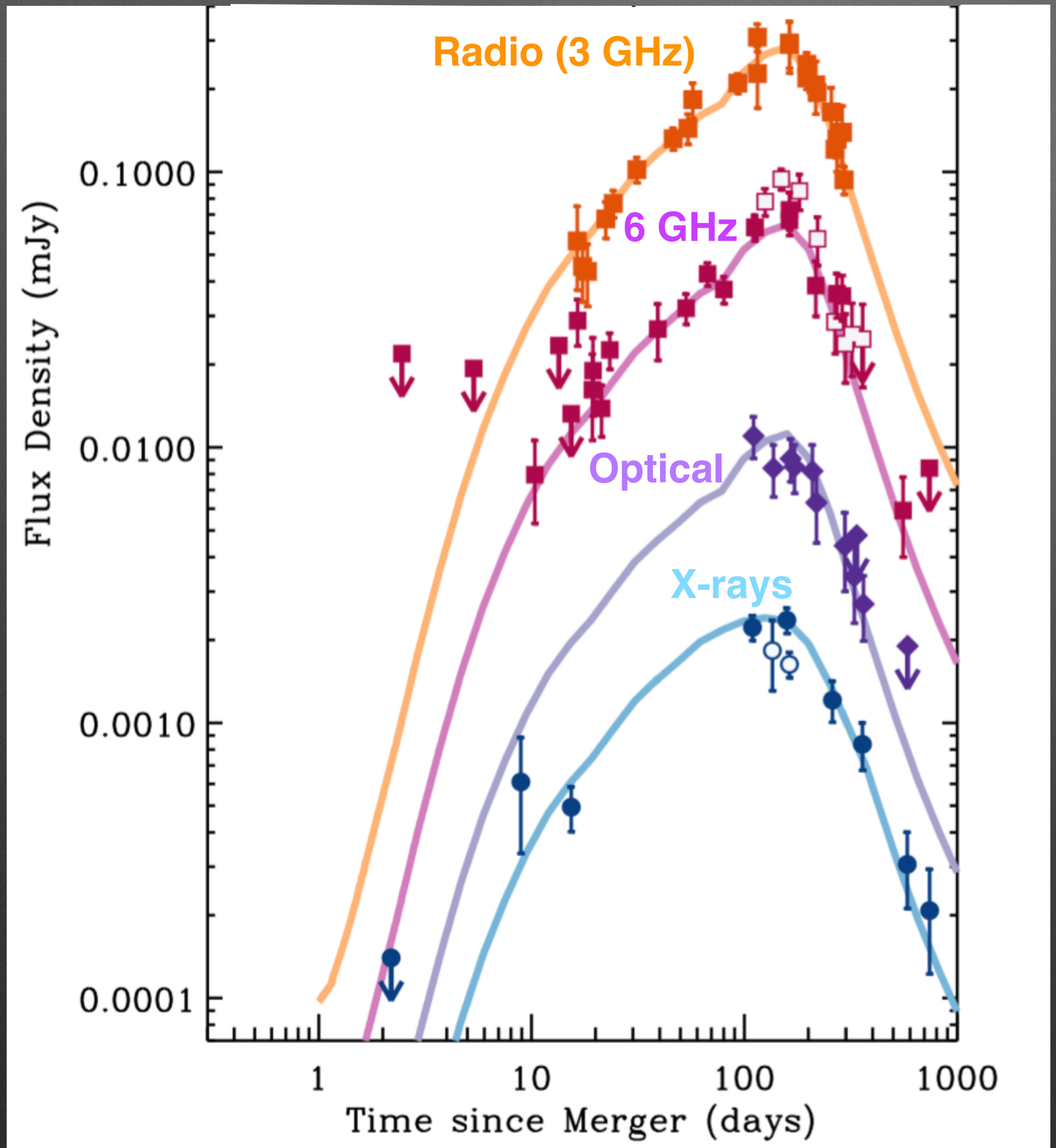
RM & Chornock ARA&A

Relativistically beamed emission:



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

DECELERATION

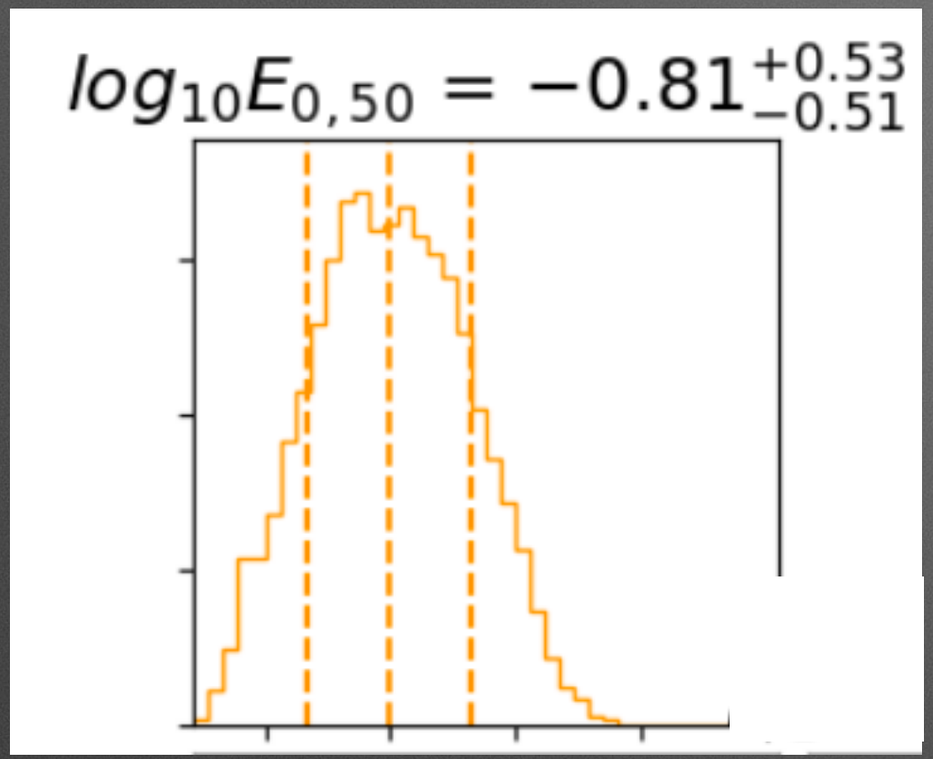


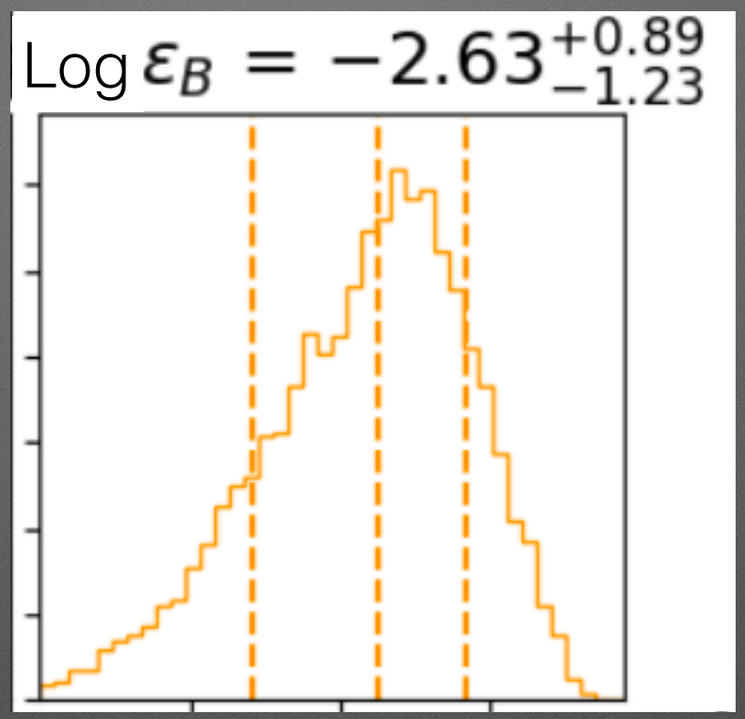
RM & Chornock ARA&A

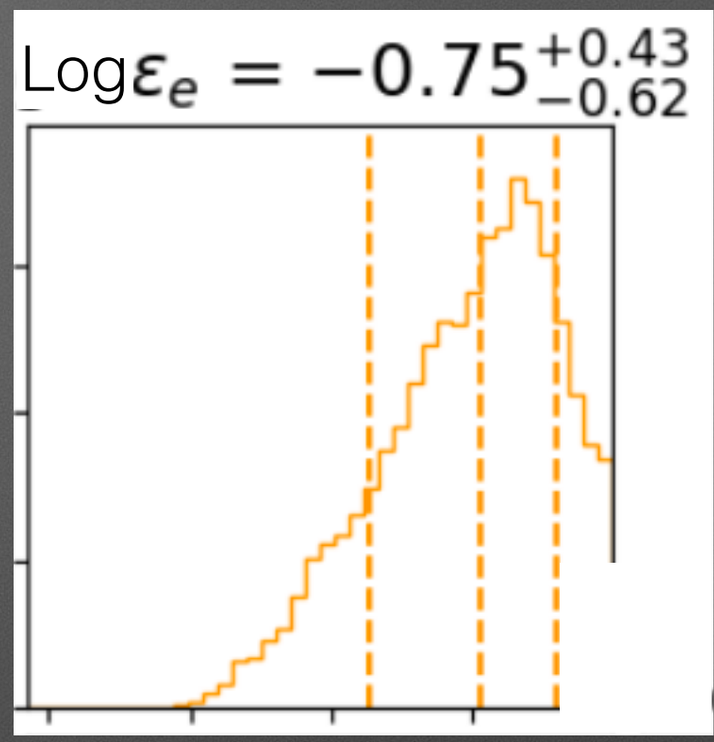
Non-thermal emission from GW170817 across the EM spectrum

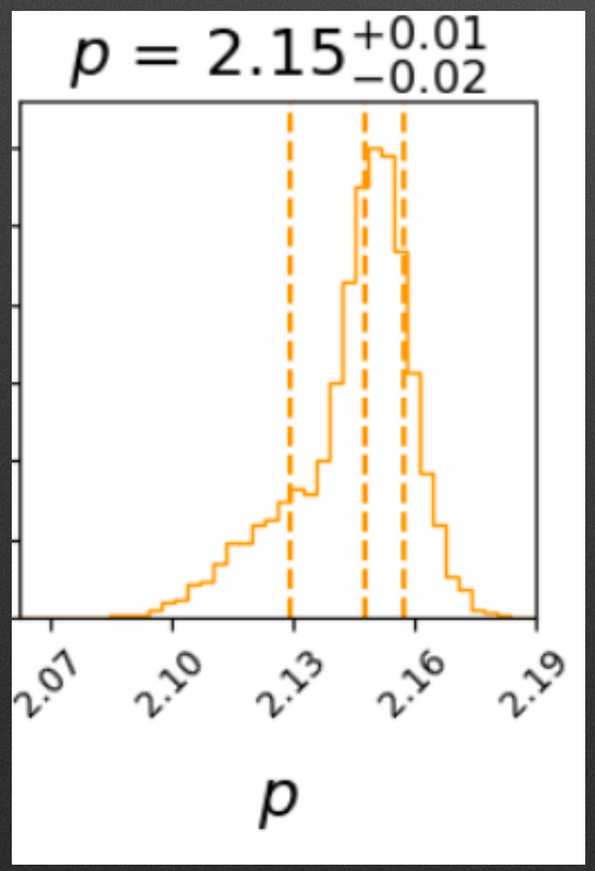
Modeling with the boosted fireball model by Wu & MacFadyen 2018/2019

Other relevant properties:





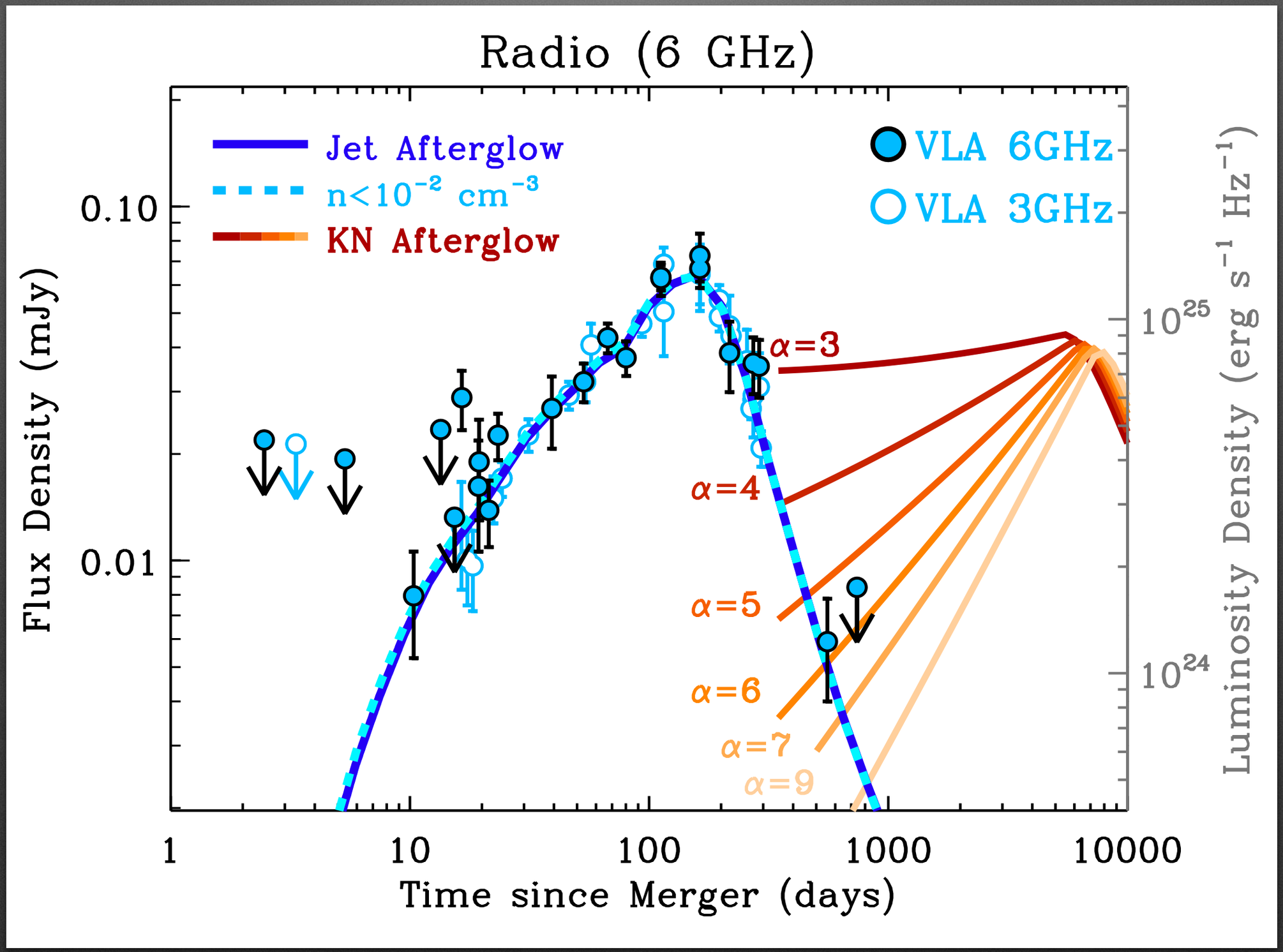




Hajela+2019

$\Gamma \cong 3$ shock

What's next? Kilonova Shock



Long GRBs

- FS+RS (and multiple emission components)
- Medium probed by the shock "disturbed" by the progenitor mass-loss history before death
- Emergence of the SN

Recent Progress:

Truly Multi-wave modeling E.g. Perley+, Laskar+

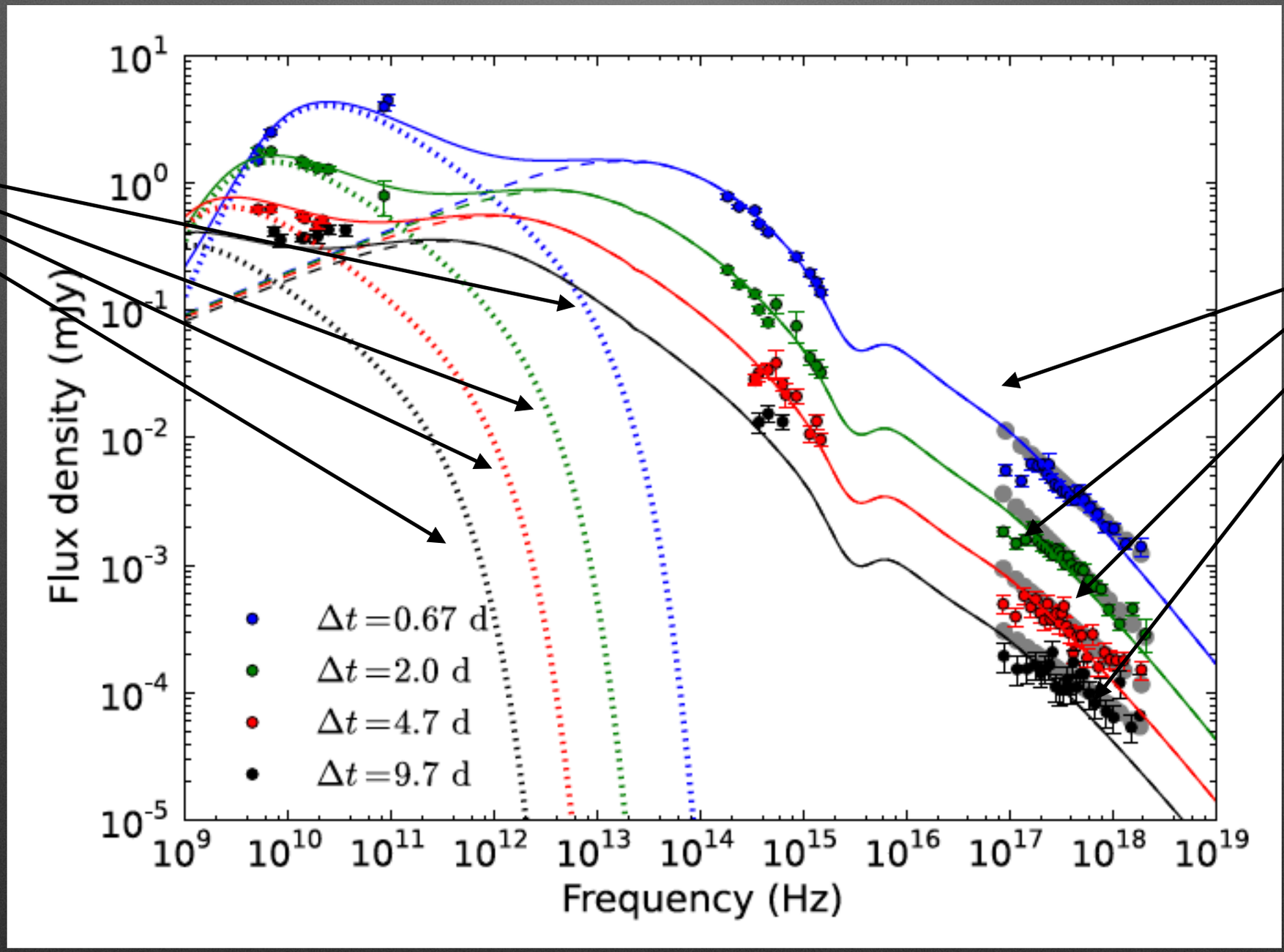
Early-time Radio Observations

Radio Polarization Laskar+2019

GRB130427A

RS

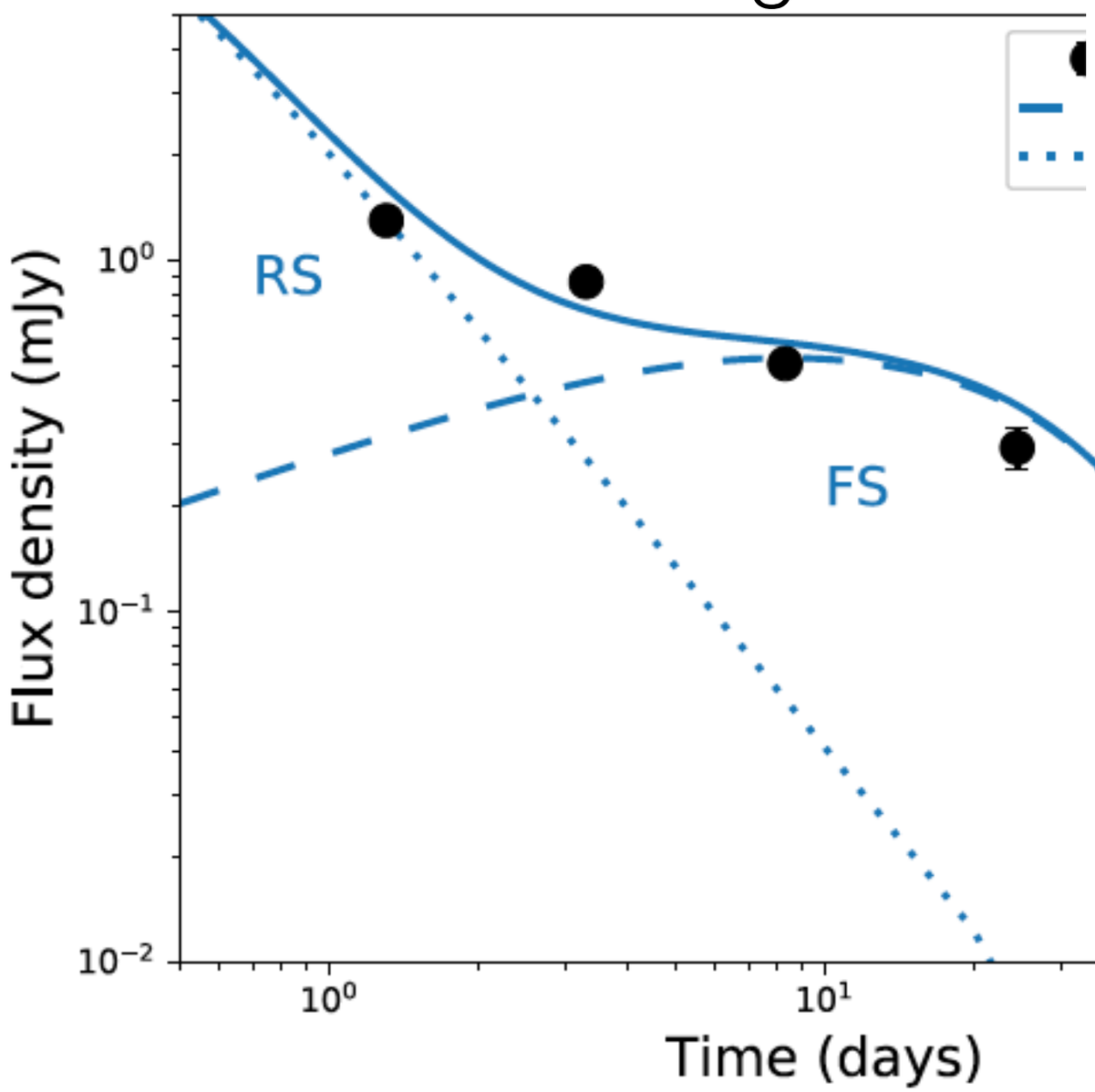
FS

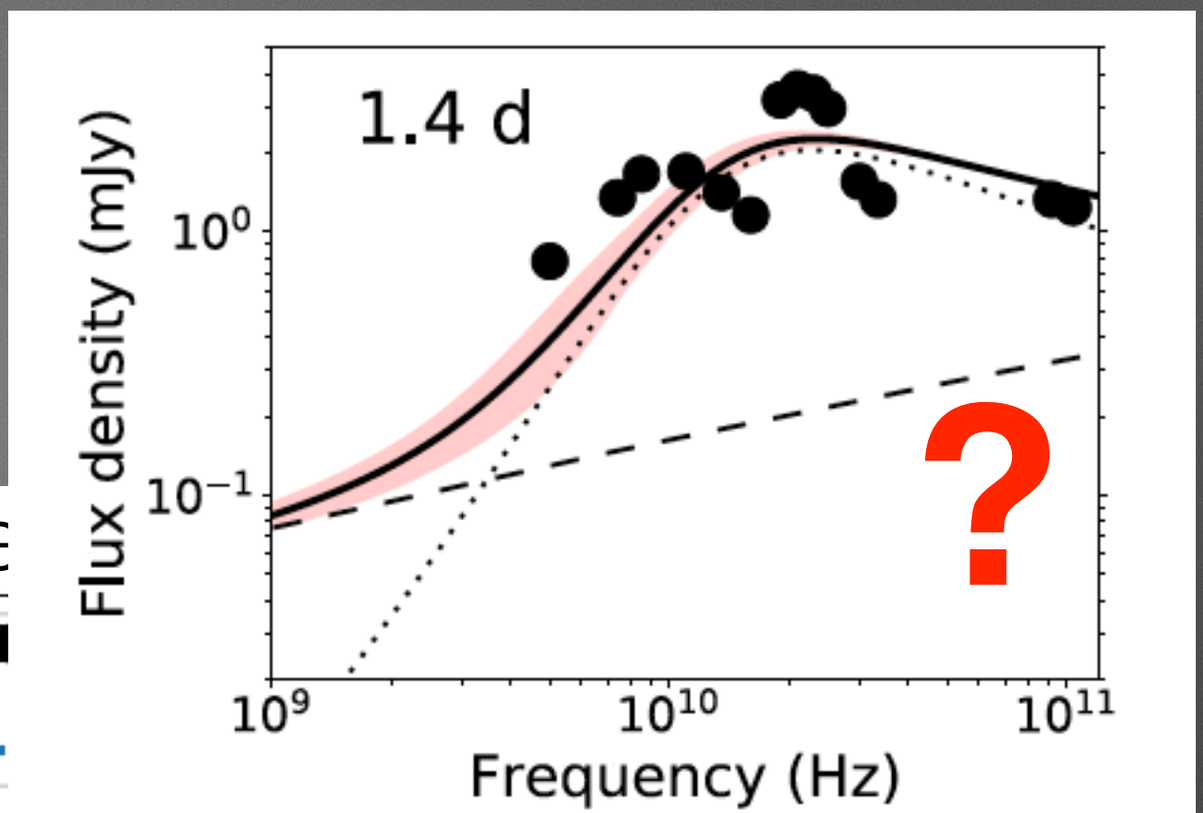


Perley+2013, Laskar+2013

GRB161219B

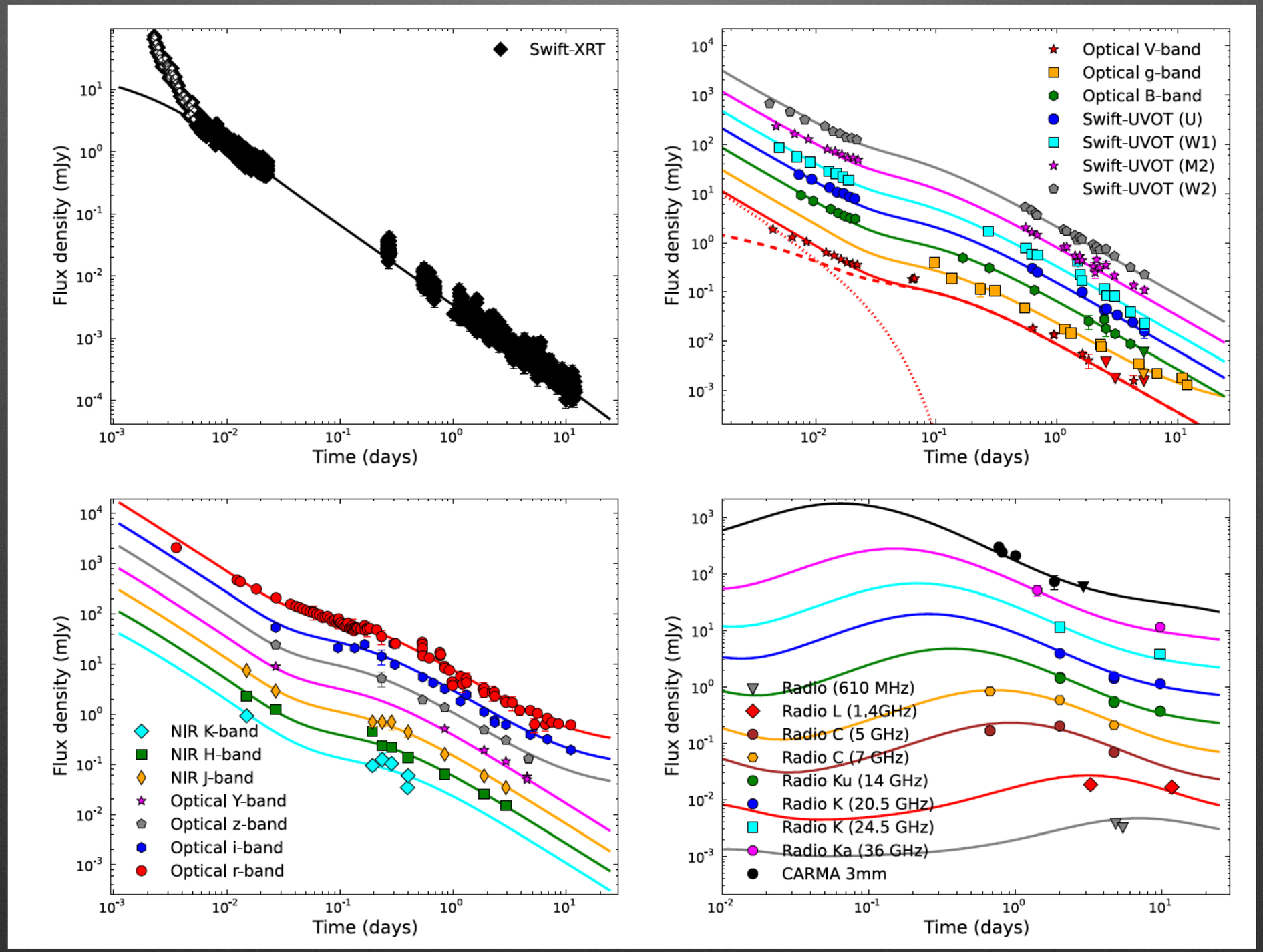
First ALMA light-curve





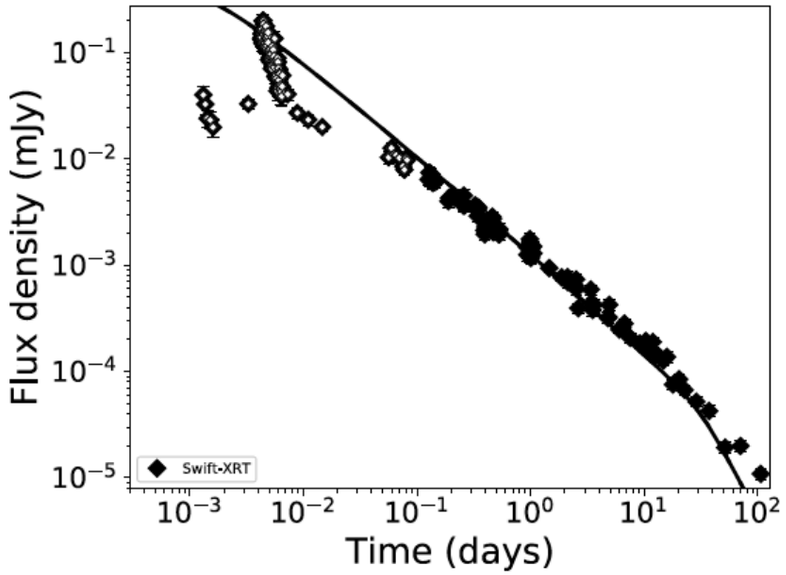
Laskar+2018

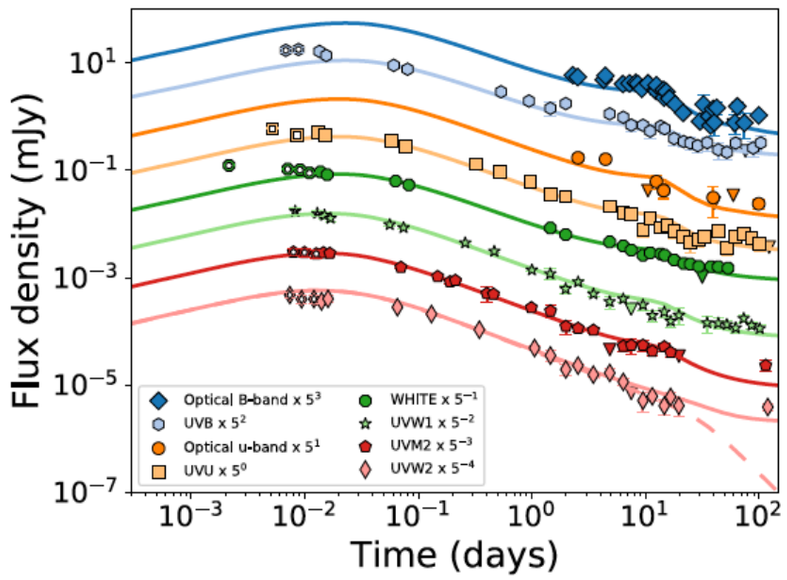
Truly Multi-wave modeling

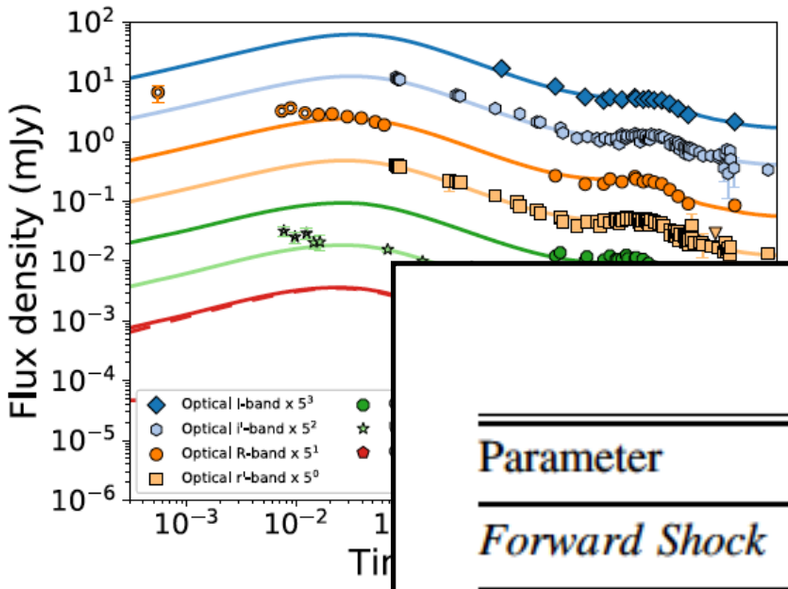


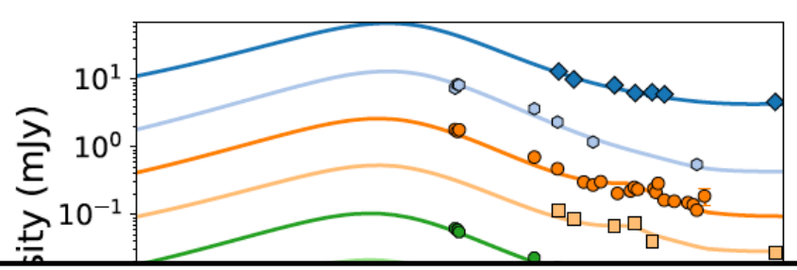
Perley+2013, Laskar+2013

GRB161219B









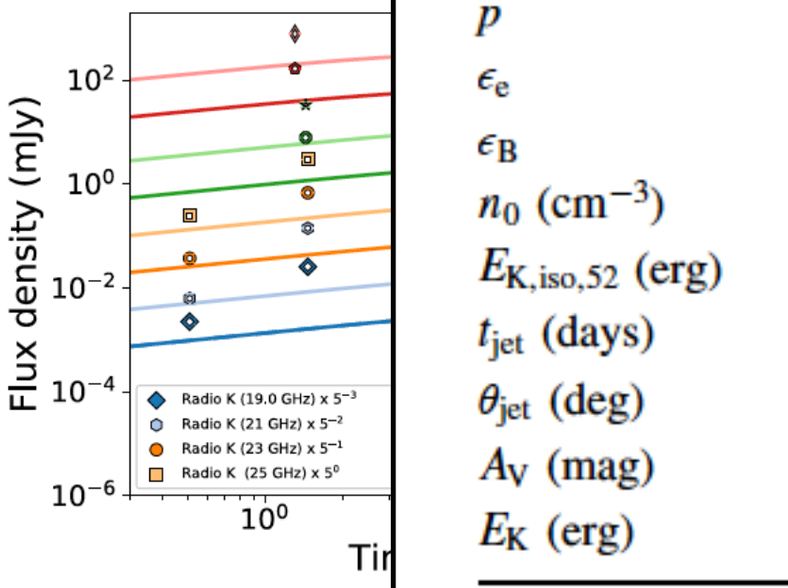
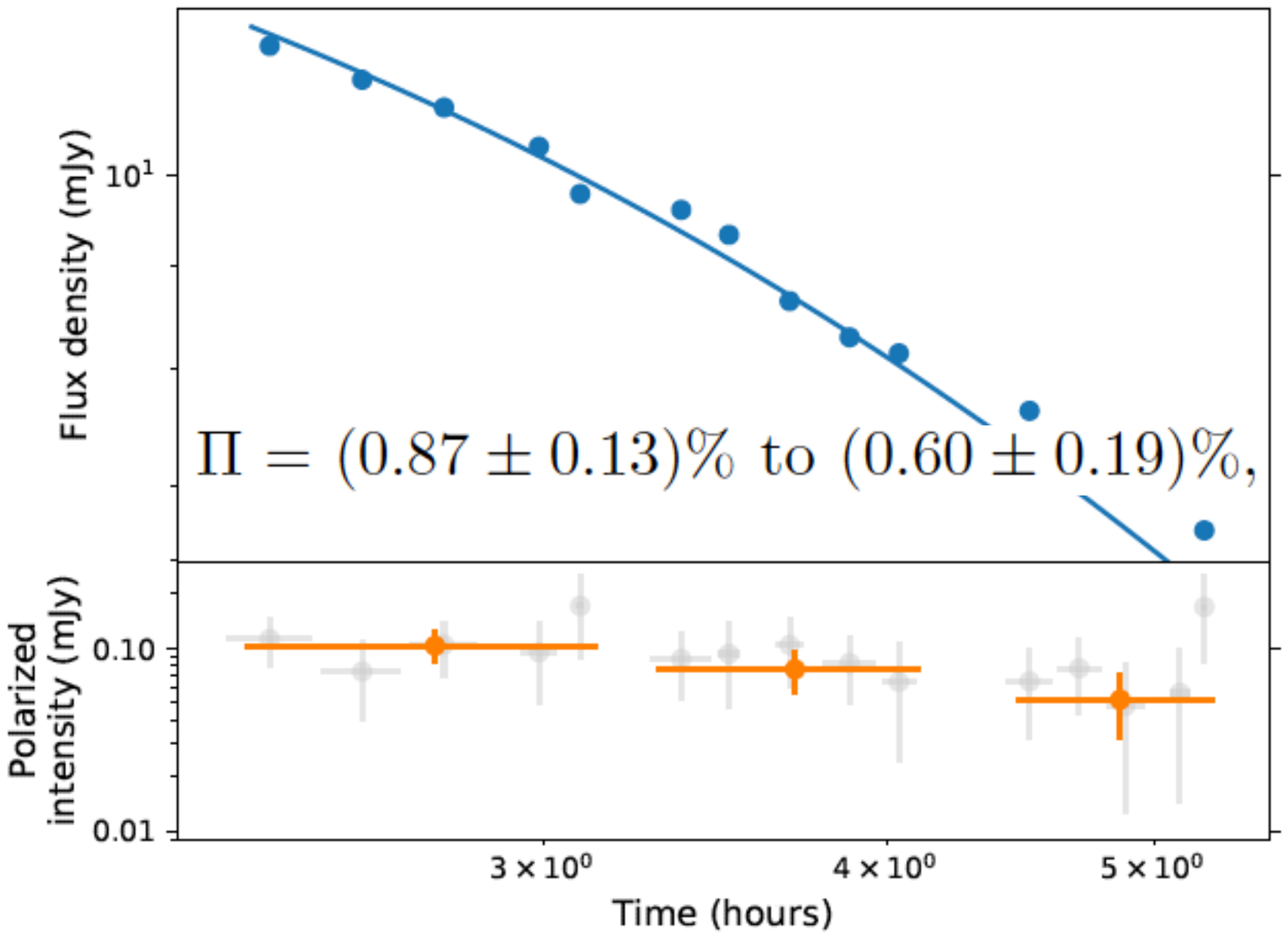


Table 8
Results of Multiwavelength Modeling

Parameter	Best Fit	MCMC
Forward Shock		
p	2.08	$2.079^{+0.009}_{-0.006}$
ϵ_e	0.93	$0.89^{+0.05}_{-0.07}$
ϵ_B	5.1×10^{-2}	$(5.8^{+5.4}_{-3.0}) \times 10^{-2}$
n_0 (cm^{-3})	3.6×10^{-4}	$(3.2^{+1.4}_{-1.2}) \times 10^{-4}$
$E_{K,iso,52}$ (erg)	0.47	$0.46^{+0.14}_{-0.09}$
t_{jet} (days)	31.5	$33.0^{+1.5}_{-1.4}$
θ_{jet} (deg)	13.5	13.44 ± 0.35
A_V (mag)	3.0×10^{-2}	$(2.1^{+2.0}_{-2.1}) \times 10^{-2}$
E_K (erg)	1.3×10^{50}	$(1.27^{+0.36}_{-0.25}) \times 10^{50}$

Laskar+2018

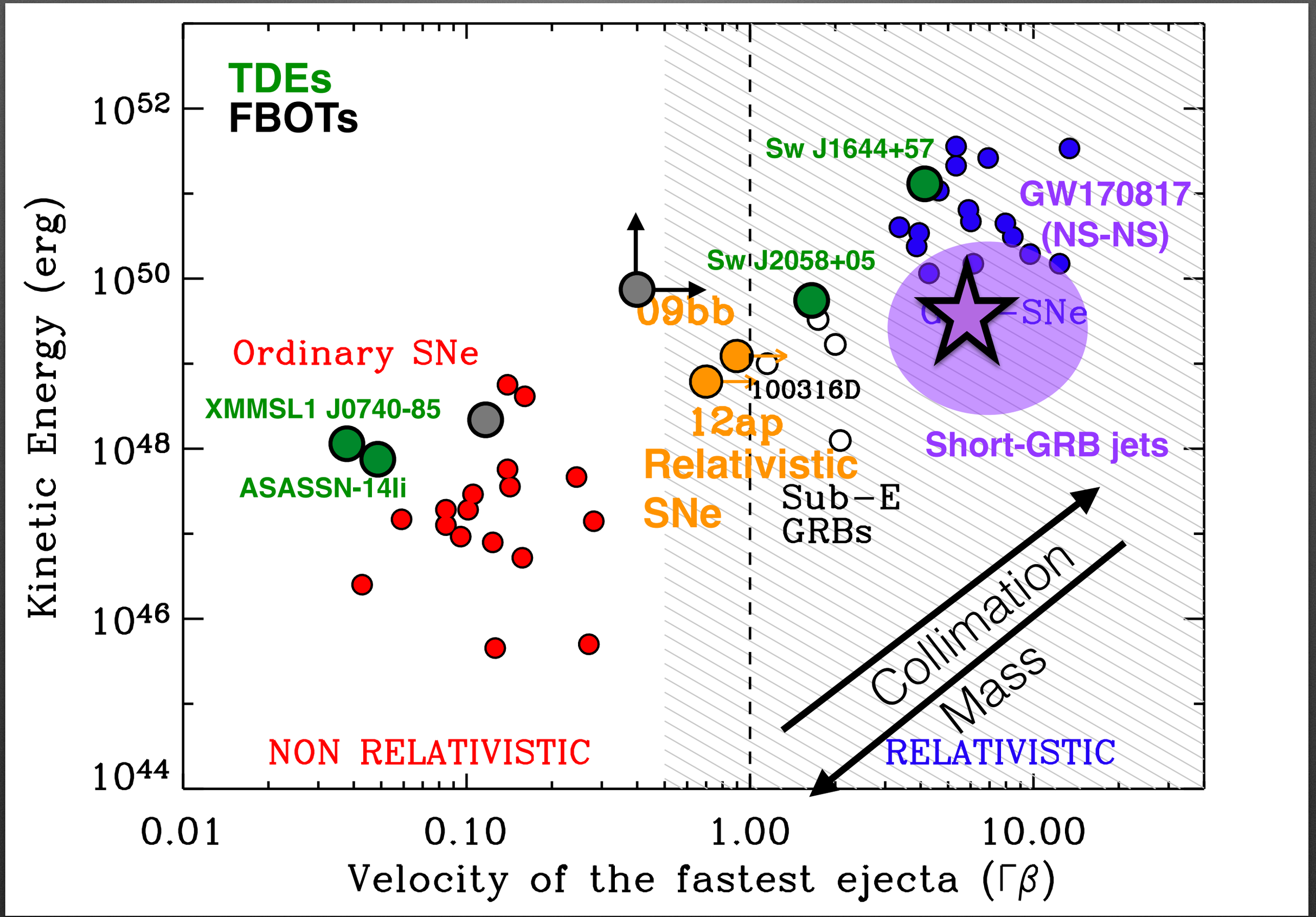
Radio Polarization: GRB190114C



Laskar+2019

The smooth variation in χ rules out models of axisymmetric, globally ordered magnetic fields in the GRB jet. If the emission arises from small patches of coherent magnetization, then the size of these regions is constrained to $\theta_B \approx 10^{-3}$ radian. Future work on GRB 190114C

Shocks in Astro Transients:



RM+14,Alexander+2014, Fong+2015