Rise of the radio transient surveys

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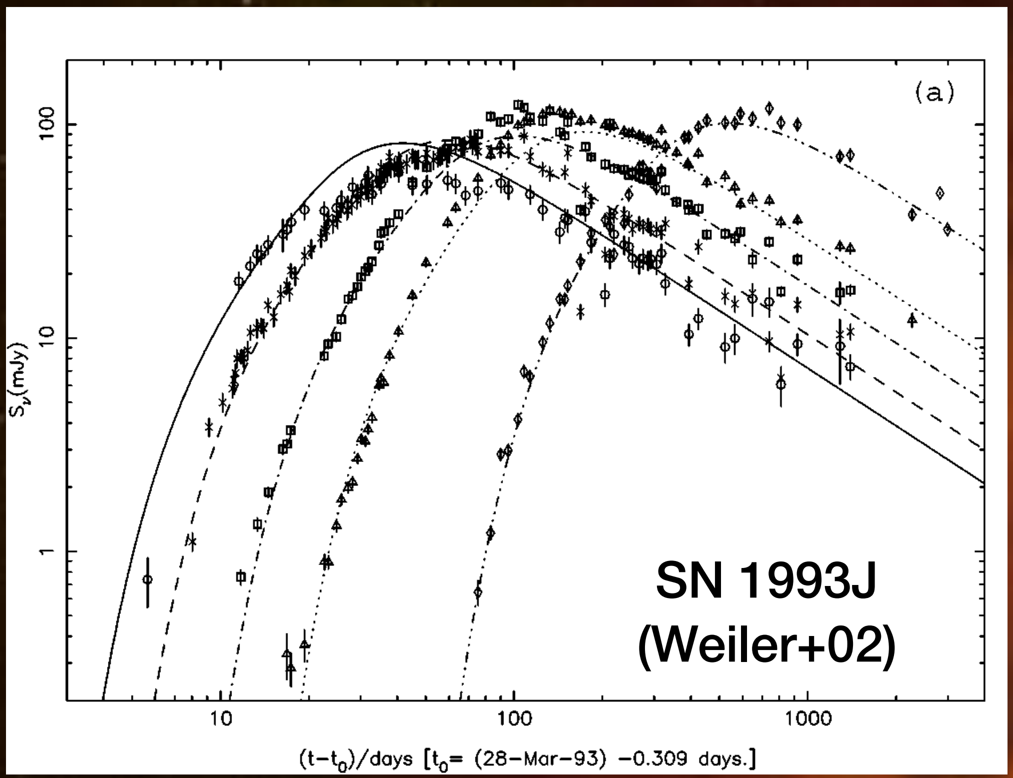
Thanks to K. P. Mooley, G. Hallinan, D. Z. Dong (Caltech), A. Horesh (Hebrew), A. Corsi (Texas M&A), D. Dobie, A. T. Deller (Swinburne U.), T. Murphy (U of Sydney), D. L. Kaplan (UWM) E. Nakar (Tel Aviv)

Outline

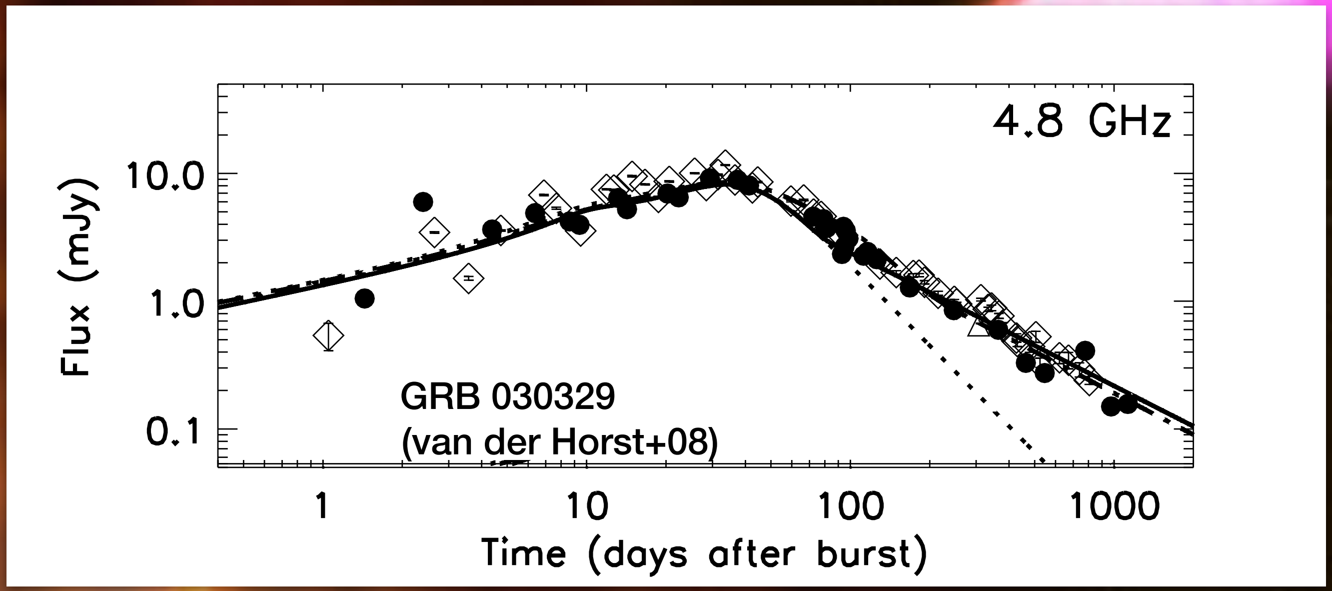
- Introduction
- Radio signal from compact binary merger
- Radio survey -A new type of transient?-

Extreme outflow and radio transient

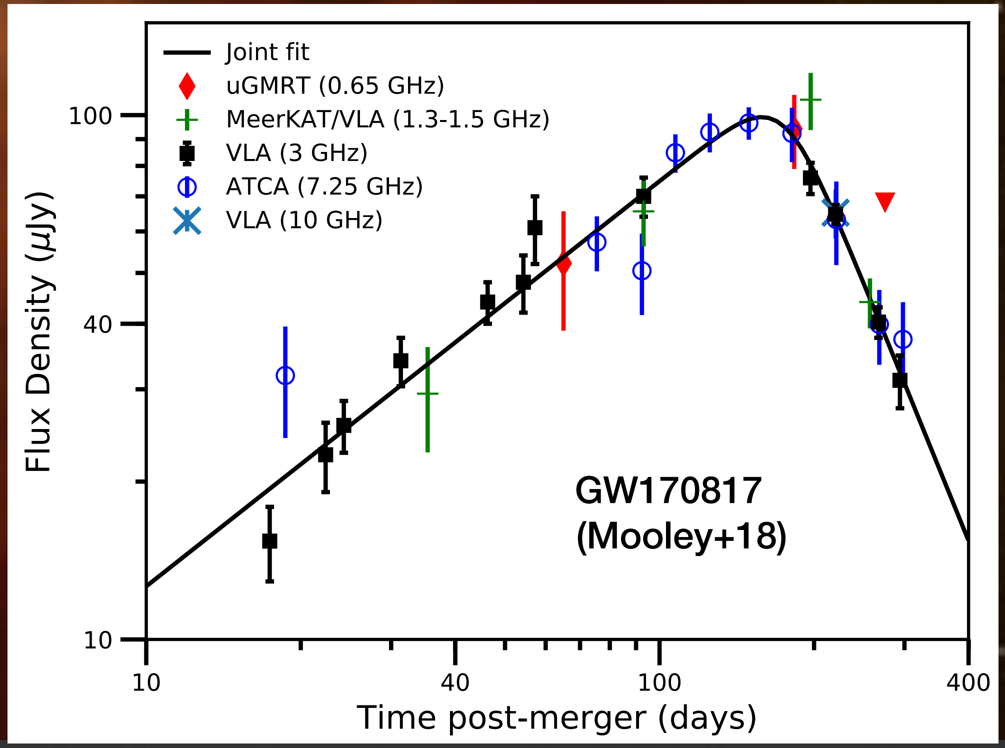
Supernova



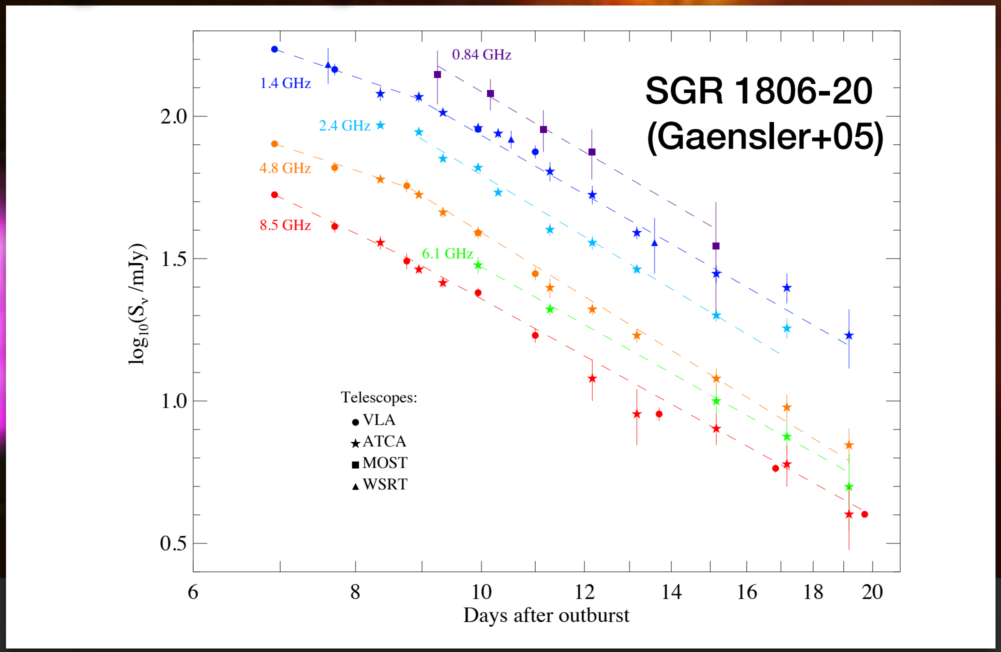
Long GRB



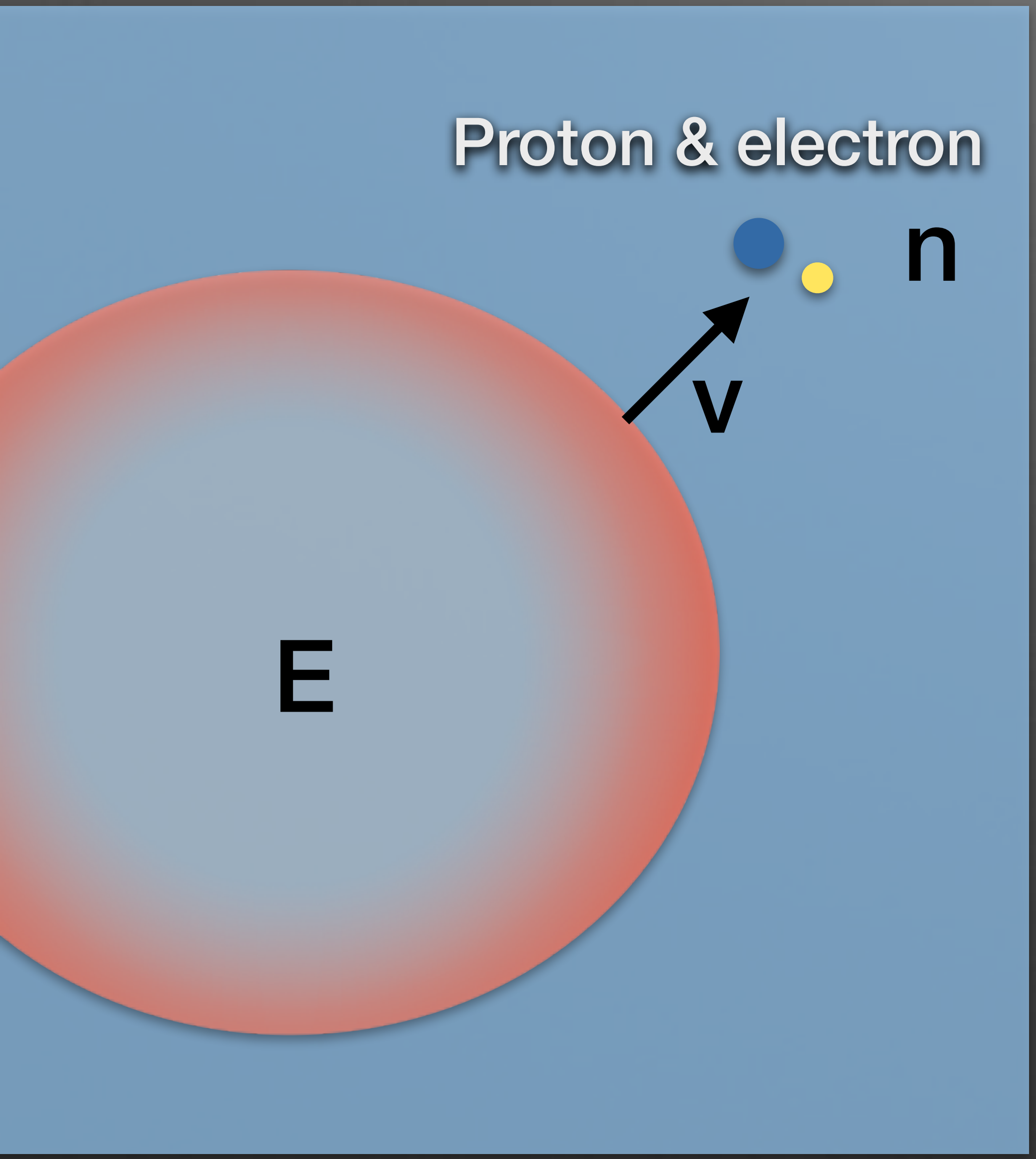
Neutron Star Merger



Magnetar giant flare



Introduction Radio transient 101



Energy per particle ~ $m_p v^2/2$
10% => electons' energy and magnetic energy

Electron Lorentz factor:

$\gamma \sim m_p v^2/m_e c^2 \sim 100\ (v/c)^2$
$B \sim 0.01G\ n^{1/2}\ (v/c)$

Synchrotron frequency:

$\nu_s = \gamma^2 eB/2\pi m_e c^2$
$\sim 1\ \mathrm{GHz}\ n^{1/2}\ (v/c)^5$

Relativistic outflow (v~c) in the typical ISM ($n \sim 1 cm^{-3}$) emits synchrotron radiation peaking at radio.

Time scale: the deceleration time of the outflow

$t_p \sim 80\ \mathrm{day}\ n^{-1/3}(E/10^{50} erg)^{1/3}\ (v/c)^{-5/3}$

Introduction

Extreme outflows produce a bright radio signal

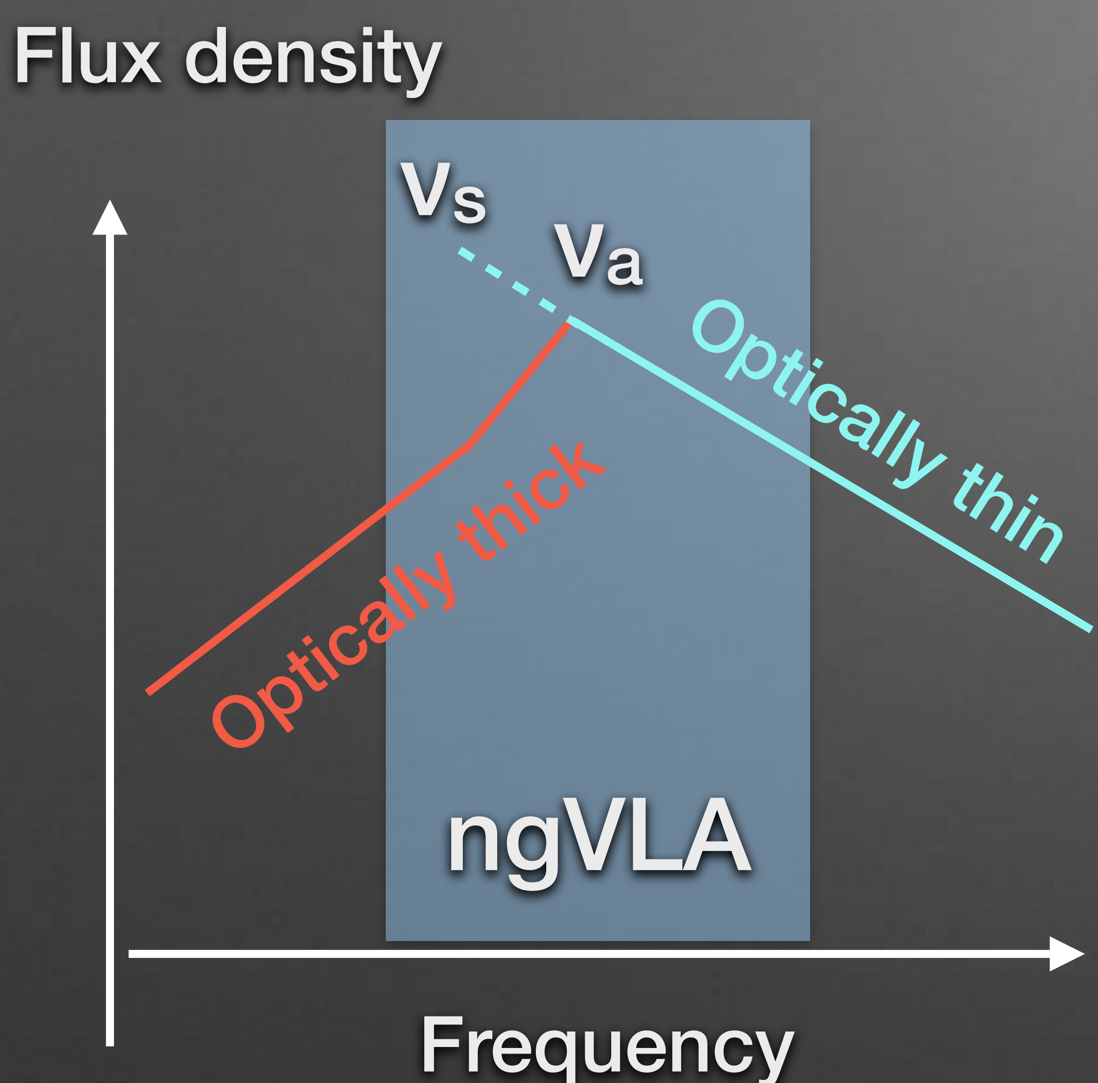
Table 2: Velocity dependence of radio fluxes in different regimes

	Flux	Full	Rela ($t < t_{\rm dec}$)	Non Rela ($t < t_{\rm dec}$)
Thin (i)	$F_\nu \propto R^3 B \Gamma \nu_m^{(p-1)/2}$	$\beta^3 \Gamma^{(3p+3)/4} (\Gamma-1)^{(5p-3)/4} / (1-\beta)^3$	Γ^{6+2p}	$\beta^{(5p+3)/2}$
Thin (ii)	$F_\nu \propto R^3 B \Gamma \nu_m^{-1/3}$	$\beta^3 \Gamma (\Gamma-1)^{-1/3} / (1-\beta)^3$	$\Gamma^{20/3}$	$\beta^{7/3}$
Thick (i)	$F_\nu \propto \theta^2 R^2 \gamma_m \Gamma$	$\beta^2 (\Gamma-1) / (1-\beta)^2 / \Gamma$	Γ^4	β^4
Thick (ii)	$F_\nu \propto \theta^2 R^2 \gamma_m \nu_m^{-1/2}$	$\beta^2 \Gamma^{-15/4} (\Gamma-1)^{-1/4} / (1-\beta)^3$	Γ^2	$\beta^{3/2}$

e.g., p = 2 ~ 3

The flux is extremely sensitive to the outflow's velocity.
=> Relativistic phenomena is bright !!

電波カロリメトリー



シンクロトロン放射では自己吸収によるピークがしばしば電波帯で観測される

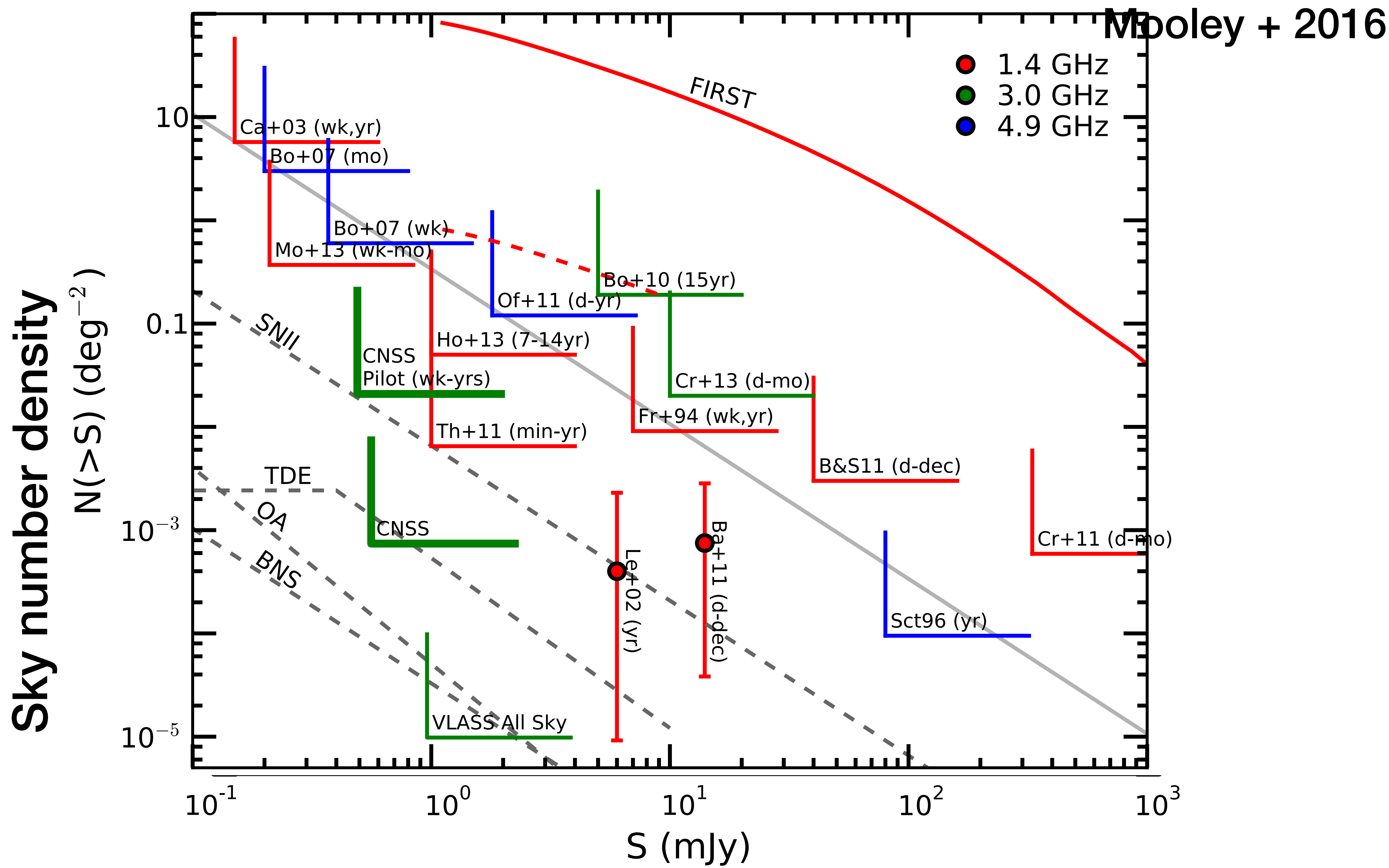
加速電子が持つ全エネルギー

$$E_e \approx 1.3 \cdot 10^{50}\,\mathrm{erg}\, f_B^{-8/19} \left(\frac{L_{\nu_a}}{3.3 \cdot 10^{29}\,\mathrm{erg/s/Hz}}\right)^{23/19} \left(\frac{\nu_a}{0.3\,\mathrm{GHz}}\right)^{-1}$$

See, .e.g. Chevalier 98

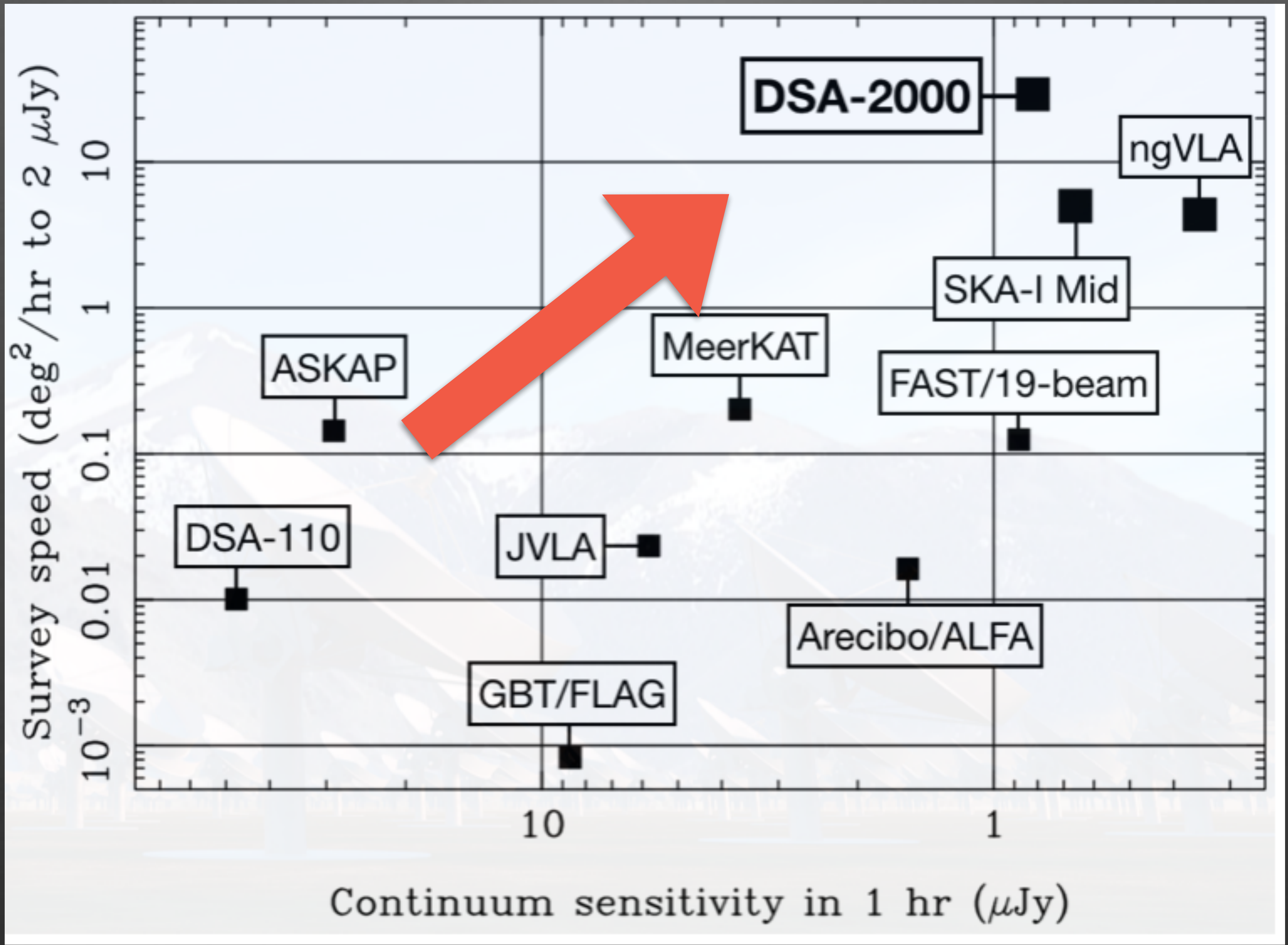
スペクトル => 爆発エネルギーの推定

Radio transient sky in 2016



$$N(>S) \approx 10^{-4}\,\mathrm{deg}^{-2}\left(\frac{S}{1\,\mathrm{mJy}}\right)^{-3/2}\left(\frac{L_\nu}{10^{29}}\right)^{3/2}\left(\frac{\dot{n}\Delta t}{50\,\mathrm{Gpc}^{-3}}\right)$$

Rise of the Radio Surveys



Radio transients

- Times scales are long (>year)
- They have been usually discovered by the follow-up of high energy transients
- Faster outflows are brighter
- A good measure of R, energy, and ISM density
- The size can be directly measured via VLBI
- The survey speed is significantly increasing

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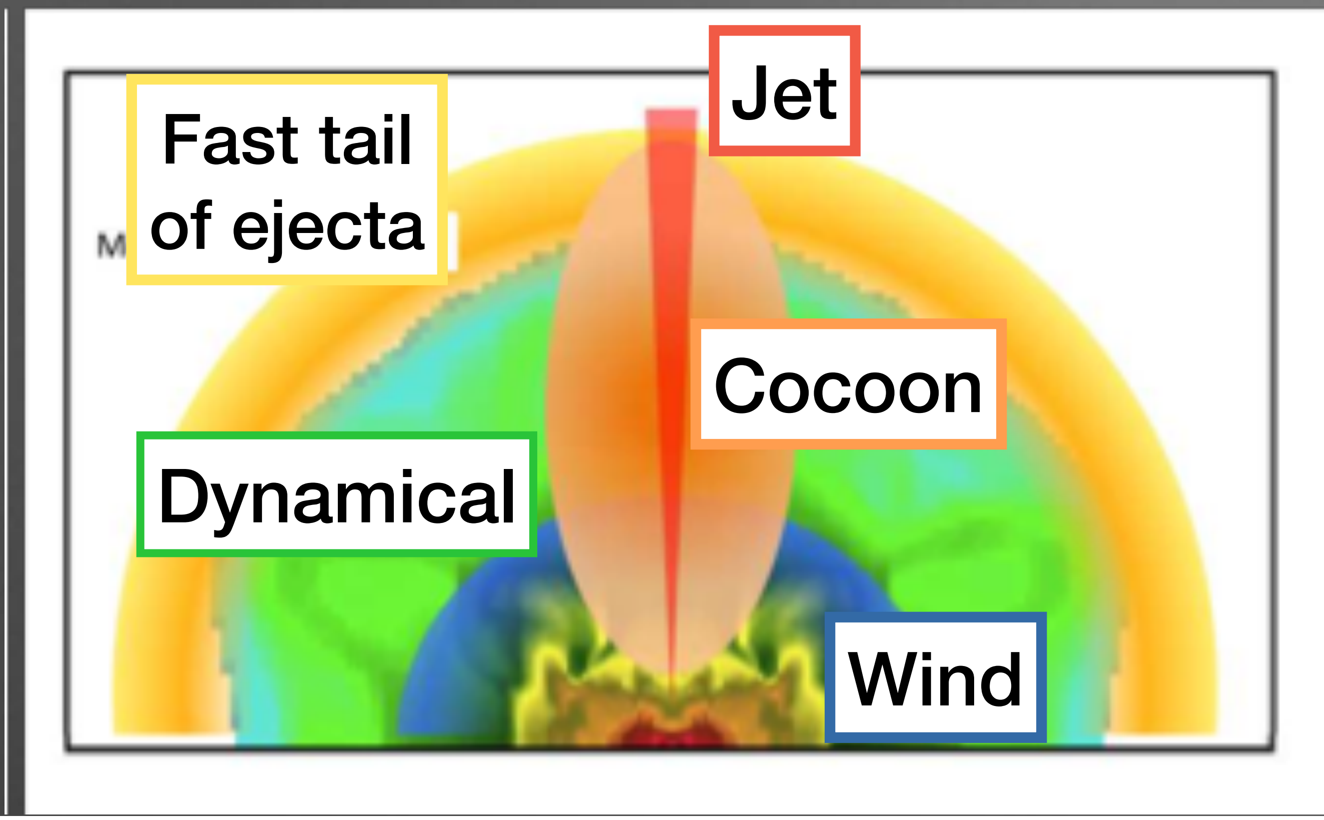
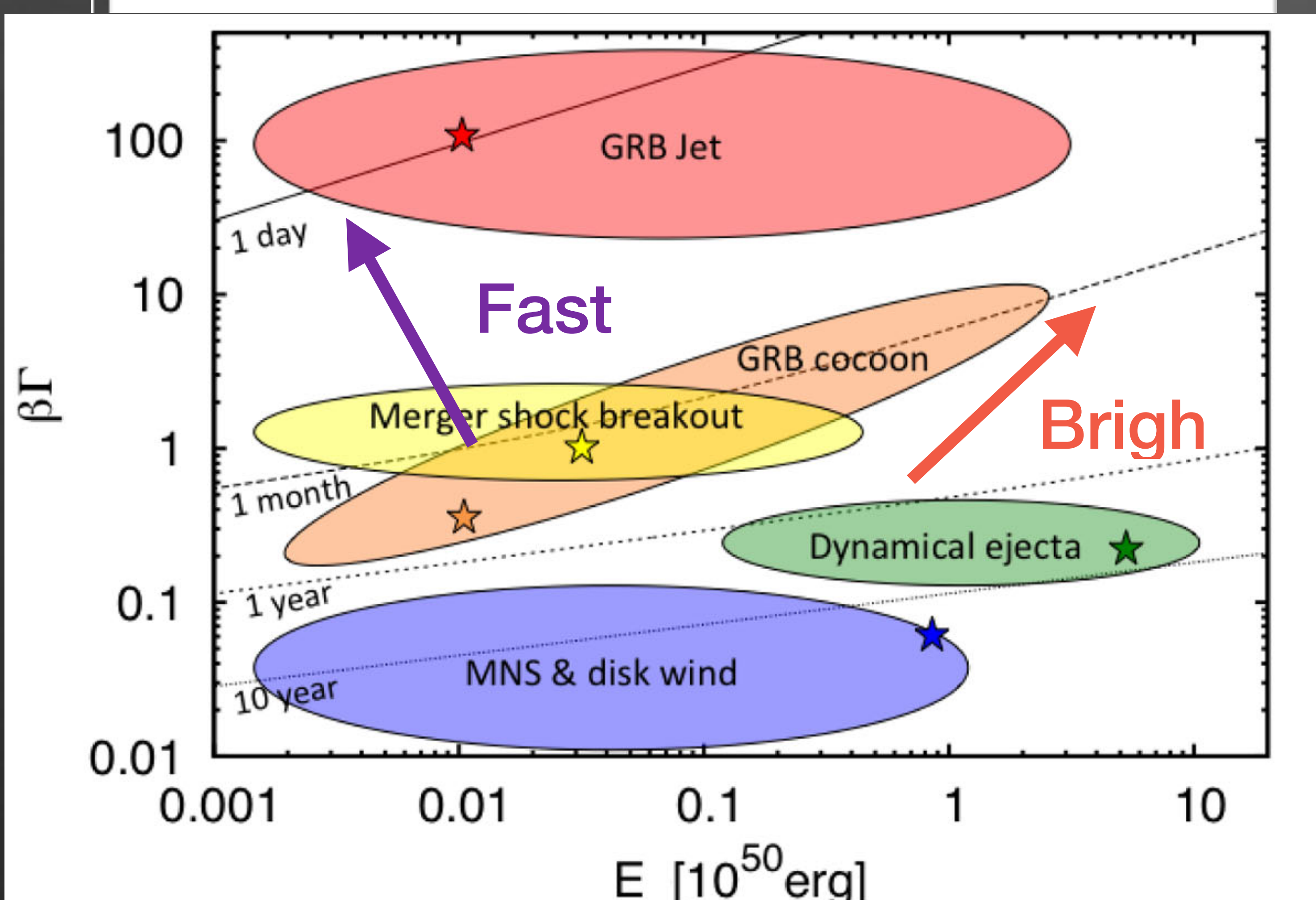
中性子星合体に付随する種々のアウトフロー





2015年の予想図 (KH & Piran 2015)
様々なアウトフローが中性子星合体に付随するはず。

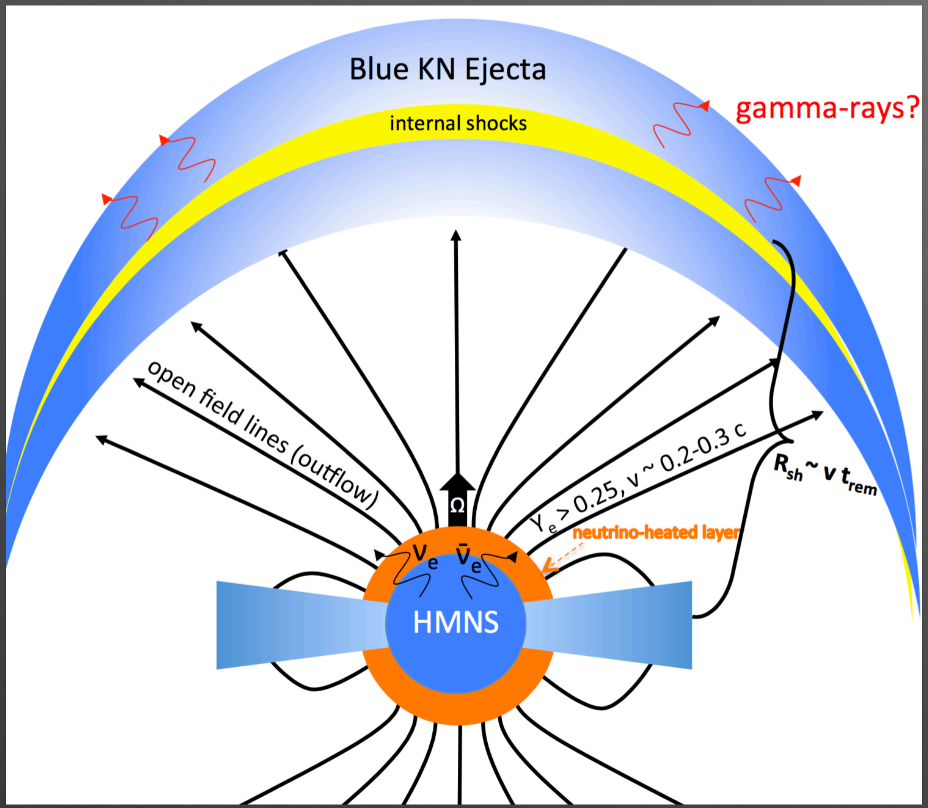
GW170817では、(おそらく)これら全てのアウトフローが見えた。

異なる質量の中性子星合体、ブラックホール中性星合体によって質的にも量的にも異なるはず。

Magnetar in merger

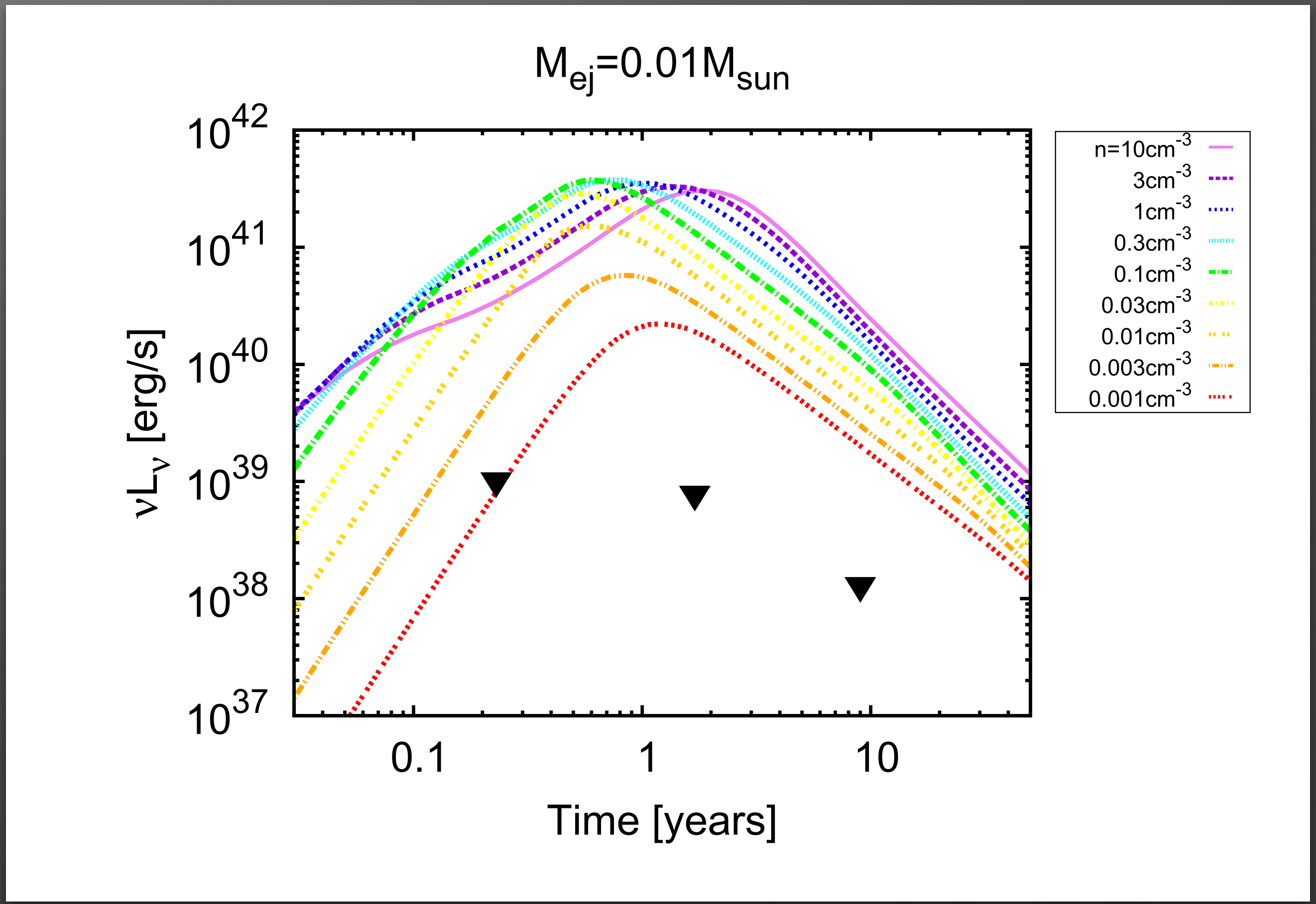
Metzger & Bower 14, Horesh, KH+15, Fong+16, Klose+19, Schroeder+21, Bruni+21

Metzger et al 18



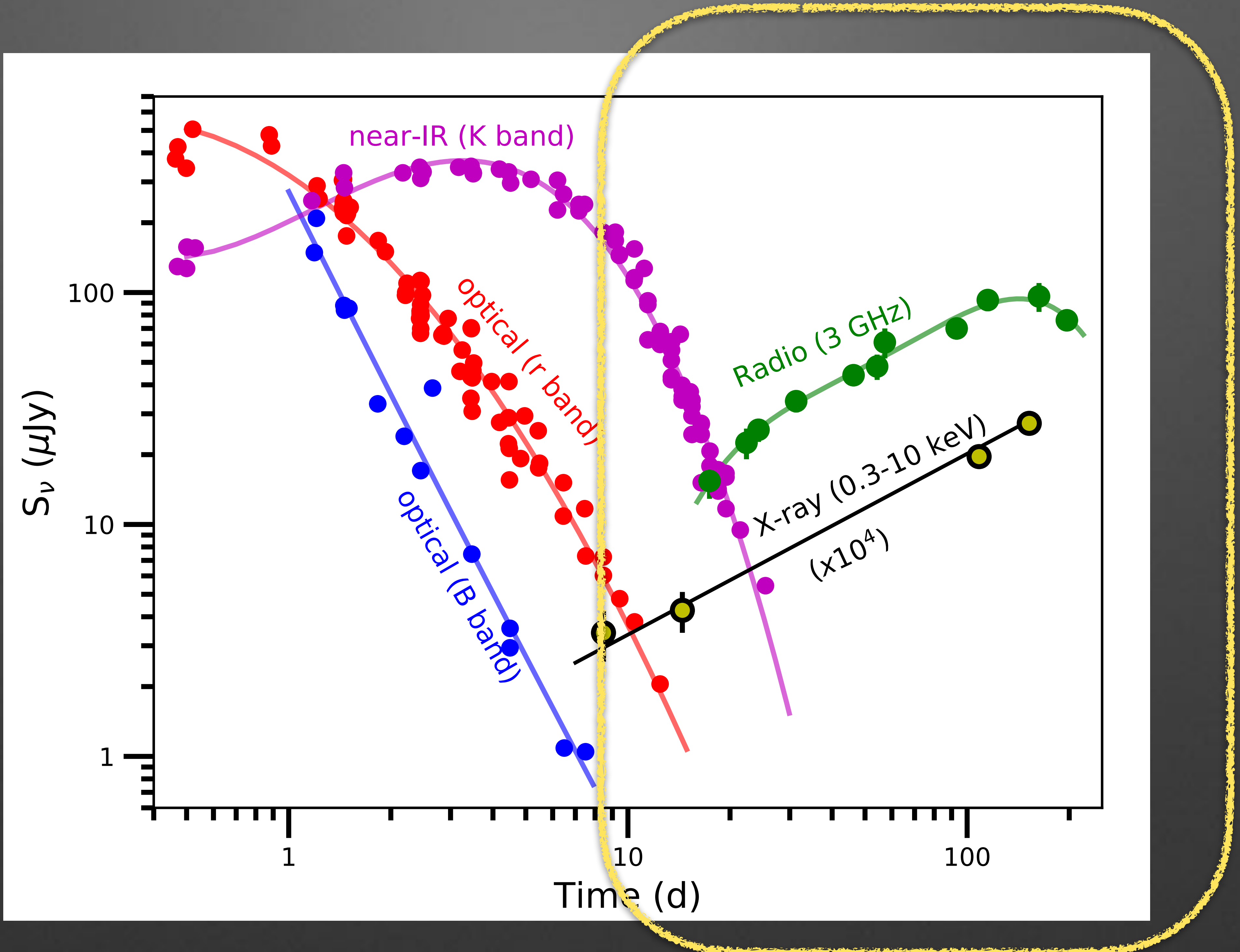
$$E_{rot} = \frac{I(2\pi)^2}{2P^2} \sim 10^{52}\ \mathrm{erg}$$

Horesh, KH+15



A merger-magnetar can be extremely bright in radio, like TDEs, LGRBs.
So far, we've never seen such phenomena after short GRBs.

キロノバ・残光　in GW170817



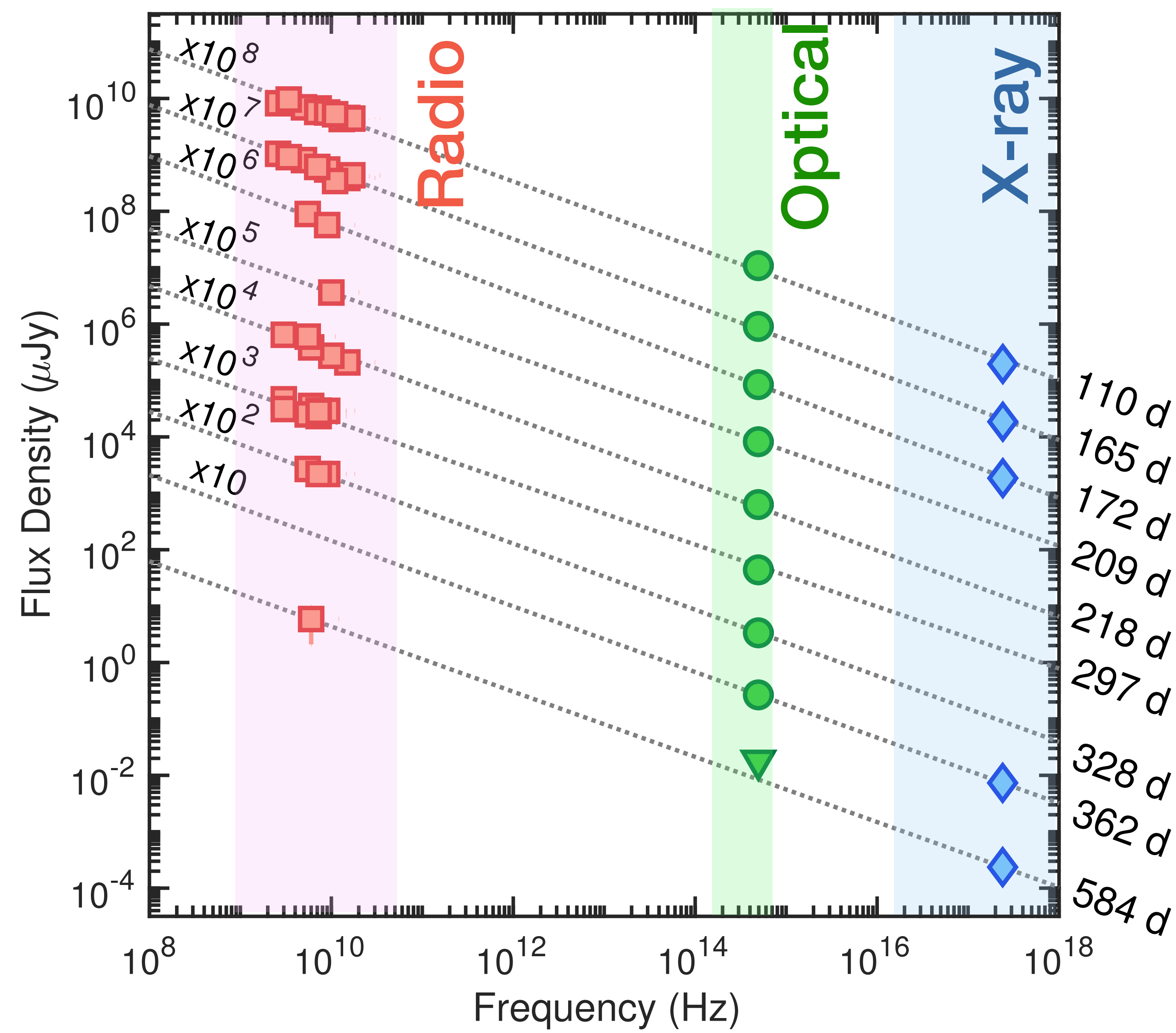
残光スペクトル　in GW170817

周波数およそ８桁にわたって単一ベキ則
=> シンクロトロン放射、標準的な残光モデルですごくよく説明できる。

加速電子は、４桁に渡って、
dN/dγ ~ γ^{-p}, where p ~ 2.16

相対論的な衝撃波加速がとてもうまく働いてるように見える.
(e.g. Sironi & Spitkovsky 2011)

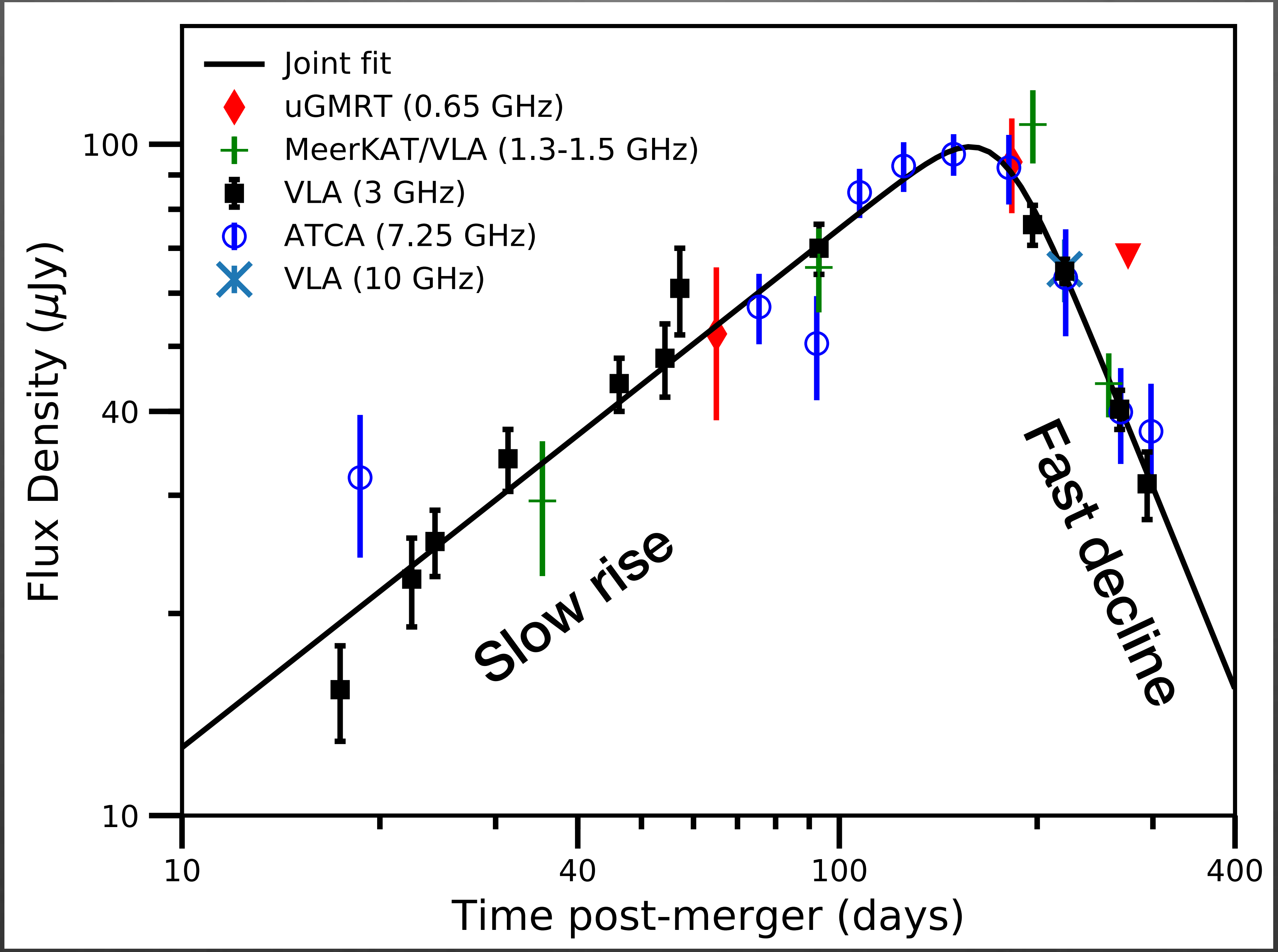
Fong+19, also Margutti+18



Hallinan+17, Margutti+17,18, Troja+17,19,
Haggard+17, Ruan+17,Lyman+18,Mooley+18

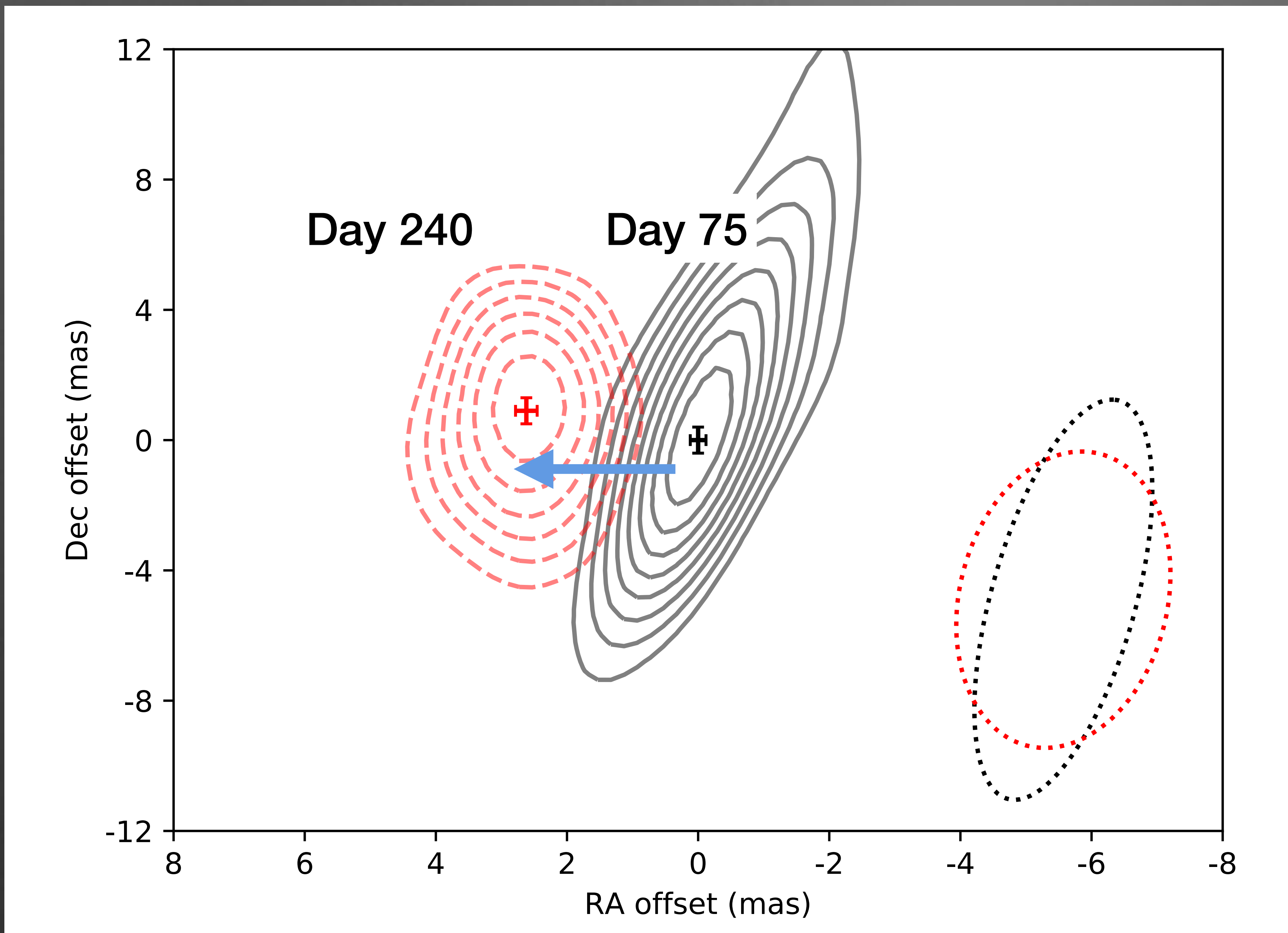
電波残光 in GW170817

Mooley et al 18



超光速度ジェット in GW170817

VLBI: Mooley...KH (2018)



1, 電波源が155日間に

2.7 mas　動いた！

=> 2.7 mas ~ 0.5 pc (at 40Mpc)

$$\beta_{\rm app} = 4.1 \pm 0.4$$

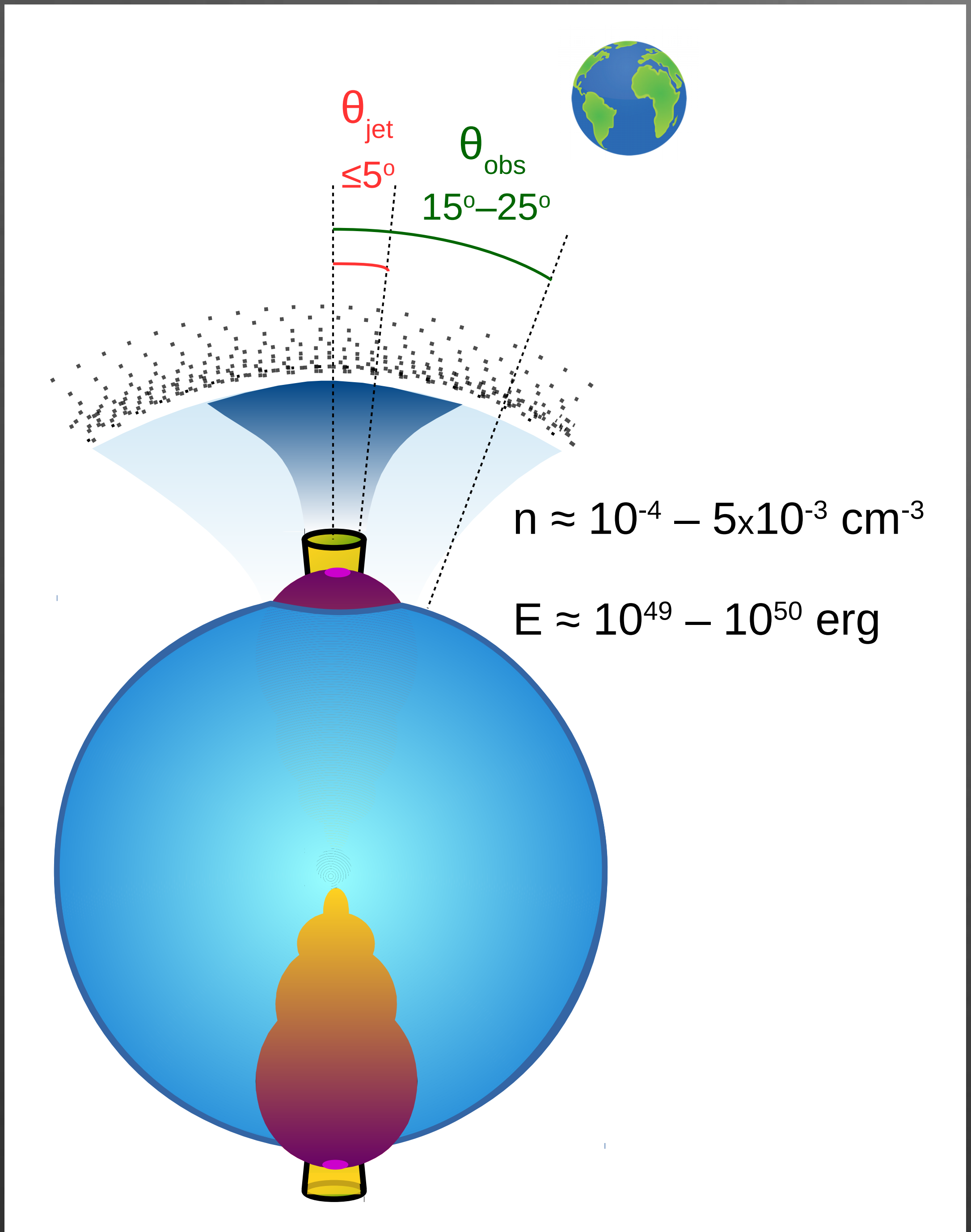
2, 電波源は点源と無矛盾

=>動きに比べて広がりが小さい

これは絞られた相対論的ジェットを斜めから観測したことを強く支持する

超光速度ジェット in GW170817

VLBI: Mooley…KH (2018)



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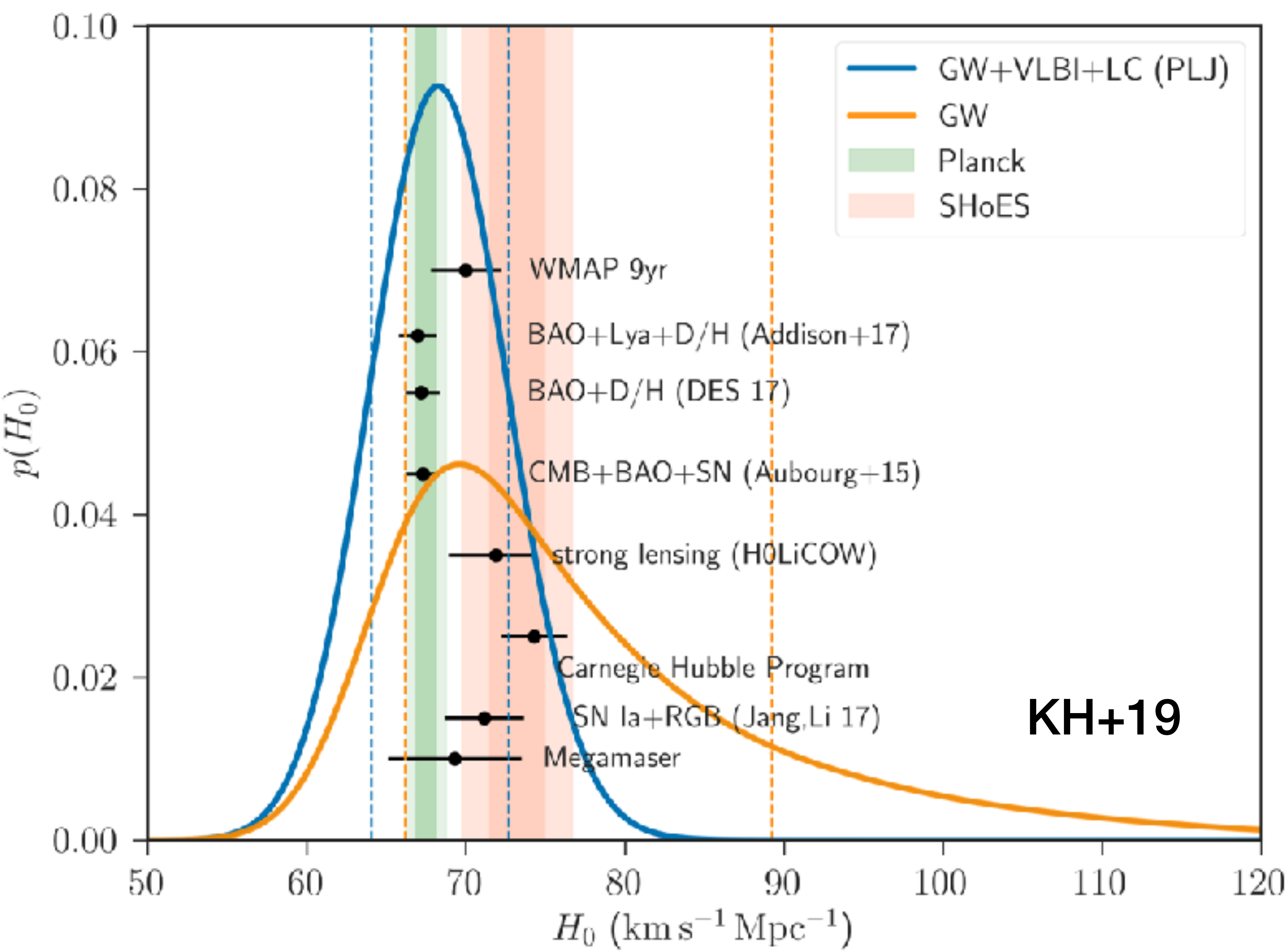
もしも、これを正面から見ていれば、強いshort GRBが見えたはず。

GW + light curve + VLBI => H0

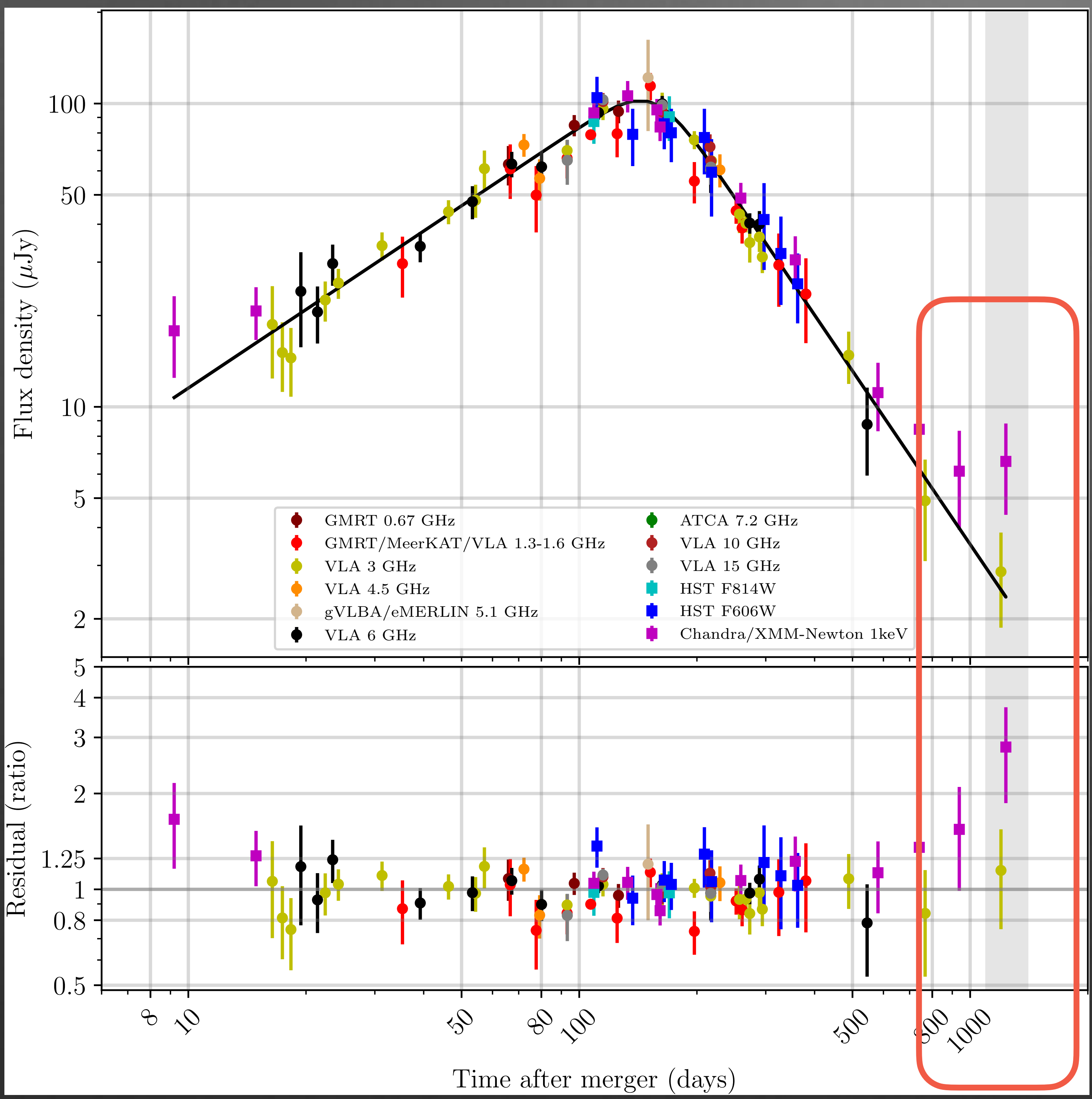


$68.1^{+4.5}_{-4.3}$ km/s/Mpc

3-4% of a systematic uncertainty due to jet modeling

残光、3.5年、X線超過

Balasubramanian, ...KH et al 21 and Hajela + 21



最新の観測 (たいへん)：

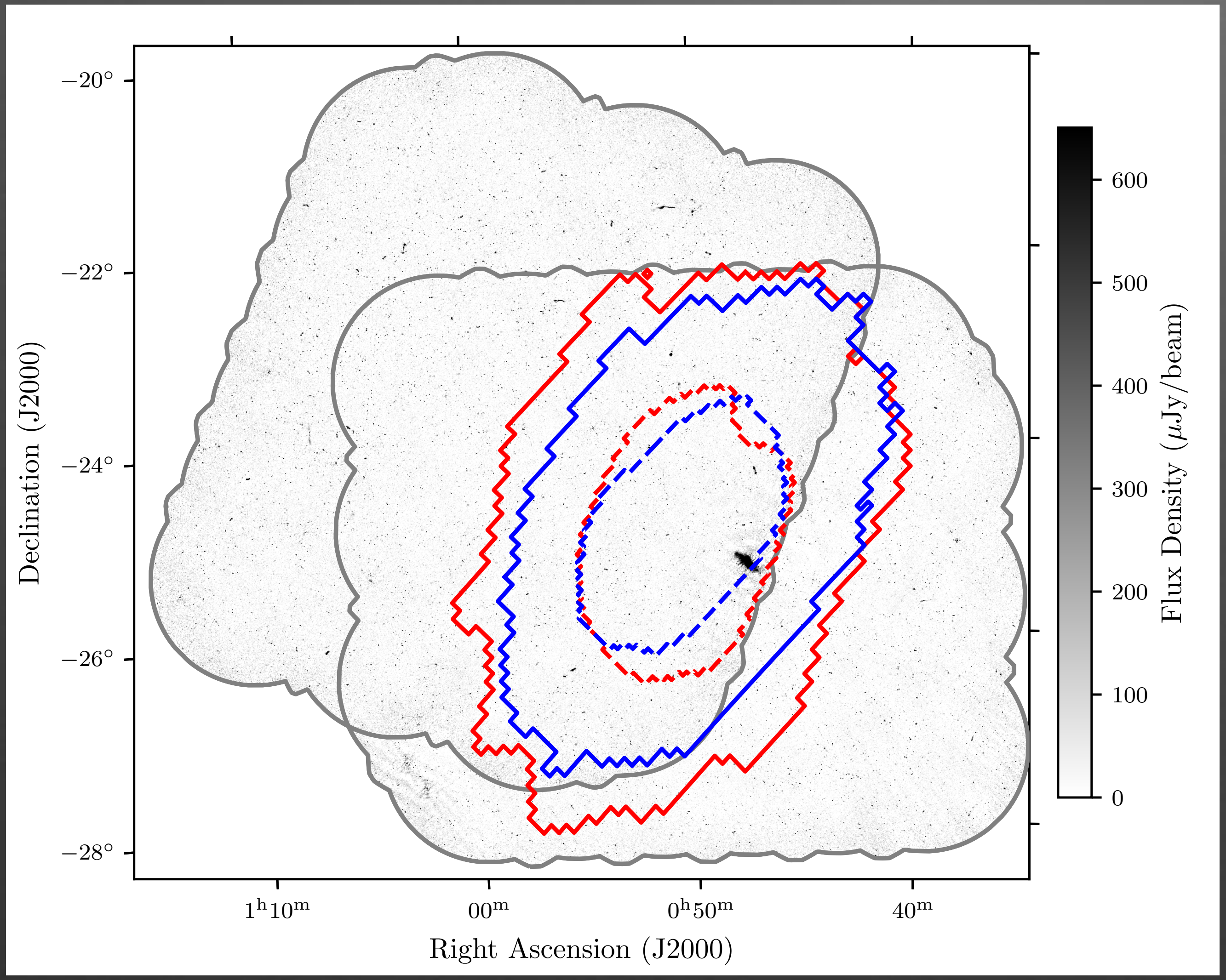
- X線が落ちなくなった (PI: Margutti, 190ks, rms~0.4e-15 erg/s/cm^2)
- 電波は減光 (PI: Corsi ~25hr, rms ~ 0.99 uJy)

(1) これまでのように、単一べキならp~2ジェットではなくキロノバエジェクタが見え始めたか？(e.g. KH, Kiuchi, Shibata+18) 非相対論フェルミ加速？そうであれば、今後、電波も増光。

(2) X線だけ残光に比べて増光したのか？Fall-back disk (Ishizaki + 21, Metzger & Fernandez 21)

ASKAP blind search for GW190814

Dobie…KH+ in prep.



~ 30 deg^2

0.9GHz

2-655 days

10 epochs

~ 40 uJy

Astrophysical variables found here are mostly AGNs.

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Unbiased radio surveys

Completed

- Caltech-NRAO Stripe 82 Survey (2013-2015, Mooley+16)

3GHz, 5 epochs, 270 deg^2 , 80μJy

- Variable And Slow Transients Survey pilot (2019-2020, Murphy+2021)

0.9 GHz, 5-13 epochs, 1646 deg^2 , 240 μJy

- GW190814 unbiased follow-up (2019-2021, Dobie + in prep)

0.9 GHz, 10 epochs, 30 deg^2 , 40μJy

On-going and the near future

- VLA All Sky Survey (Lacy + 2020, 2017 - 2024)

3GHz, 30000 deg^2 , 70μJy

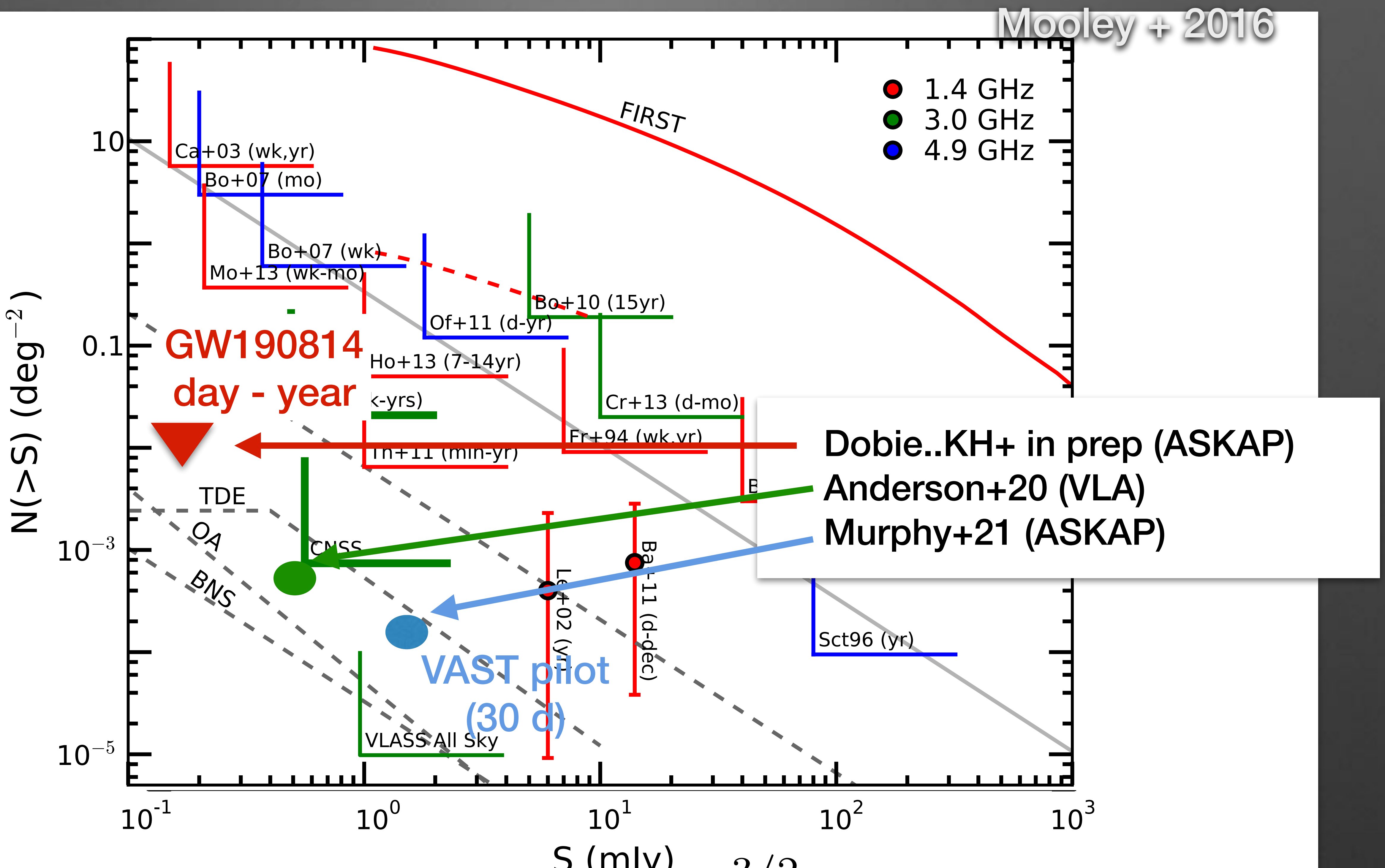
- ThunderKAT (Fender+2017)

1.4 GHz, South, 30 μJy

- VAST survey (Murphy+2013, 2022-)

0.9GHz, xx epochs, South, 60μJy

Radio transient sky in 2021



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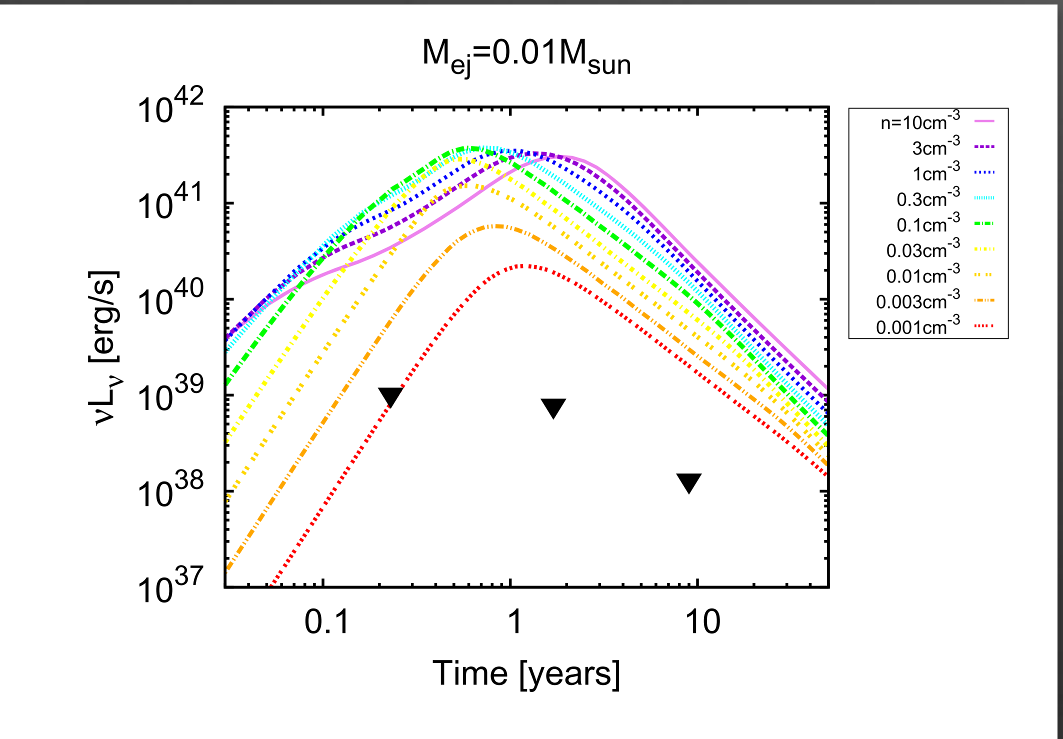
Implication to the magnetar formation in BNS merger

LIGO/Virgo BNS merger rate : $R_{GW} = 320^{+490}_{-240}$ Gpc^{-3} yr^{-1}

if some fraction of BNSs, f, form a magnetar, we expect



$$N(>S) \approx 0.02 f \,\mathrm{deg}^{-2} \left(\frac{S}{1\,\mathrm{mJy}}\right)^{-3/2} \left(\frac{L_\nu}{10^{30}}\right)^{3/2} \left(\frac{\dot{n}\Delta t}{300\,\mathrm{Gpc}^{-3}}\right)$$

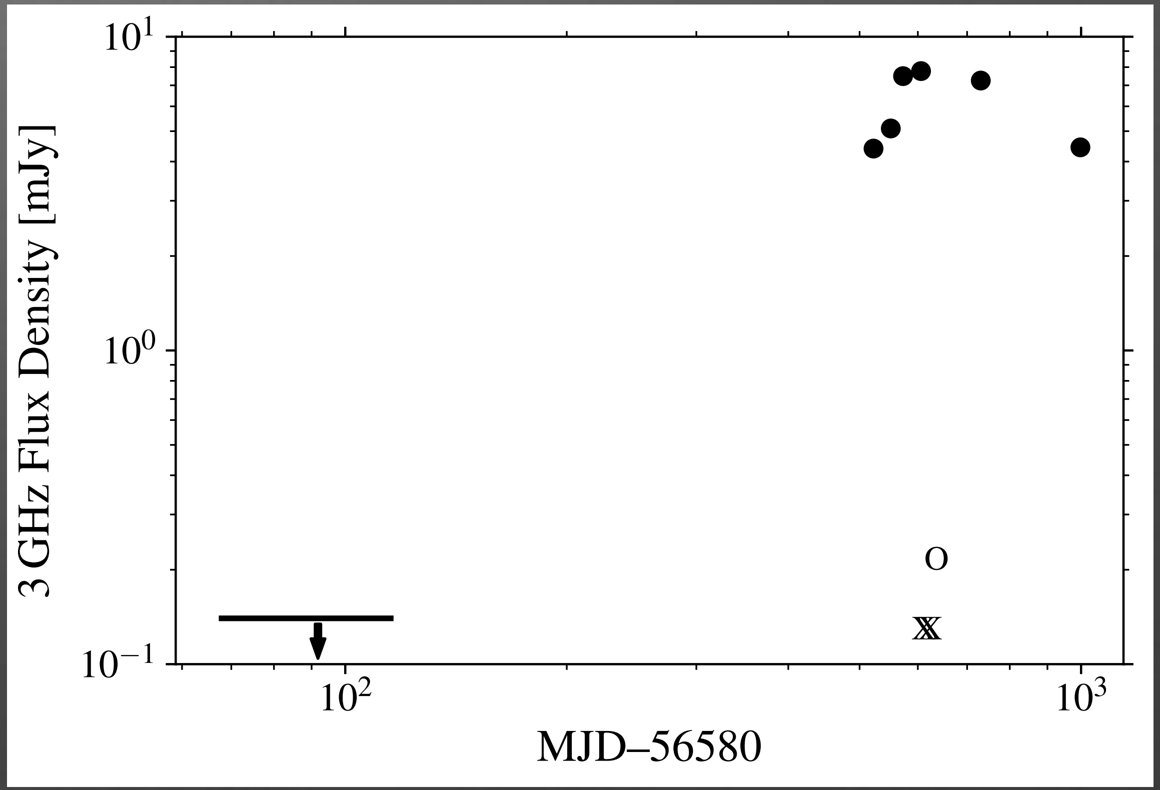
Now the observed density is ~ 0.0017 at 1 mJy, suggesting f < 0.1.

With full VLASS data, f will be limited down to 1.0e-3 or even stronger.

Caltech-NRAO Stripe 82 Survey

Discovery of a tidal disruption event in radio

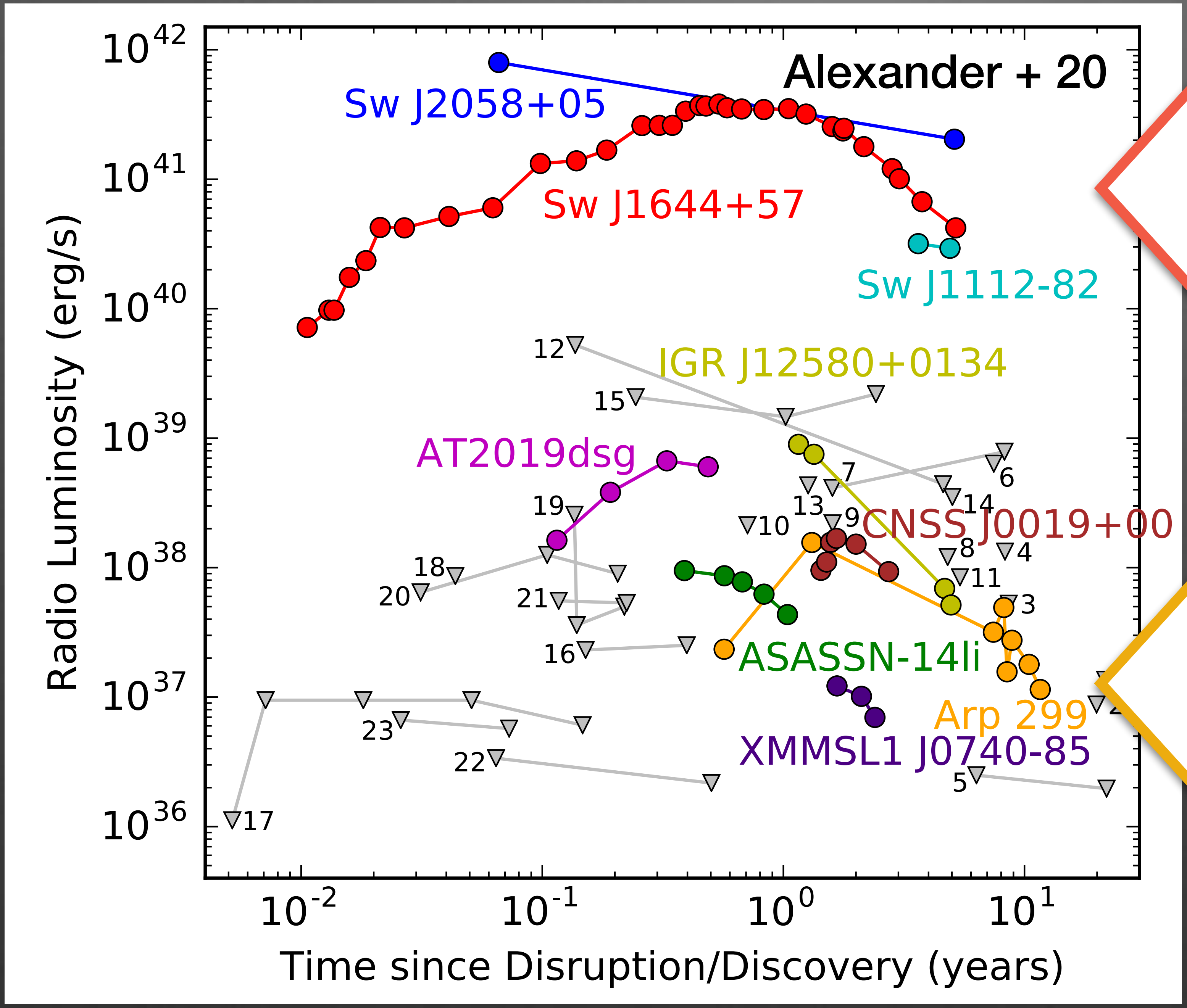
(Anderson + 20)



CNSS J0019+0035: a nucleus radio transient in a S0-Seyfert galaxy at 77 Mpc.

Caltech-NRAO Stripe 82 Survey

Discovery of a tidal disruption event in radio

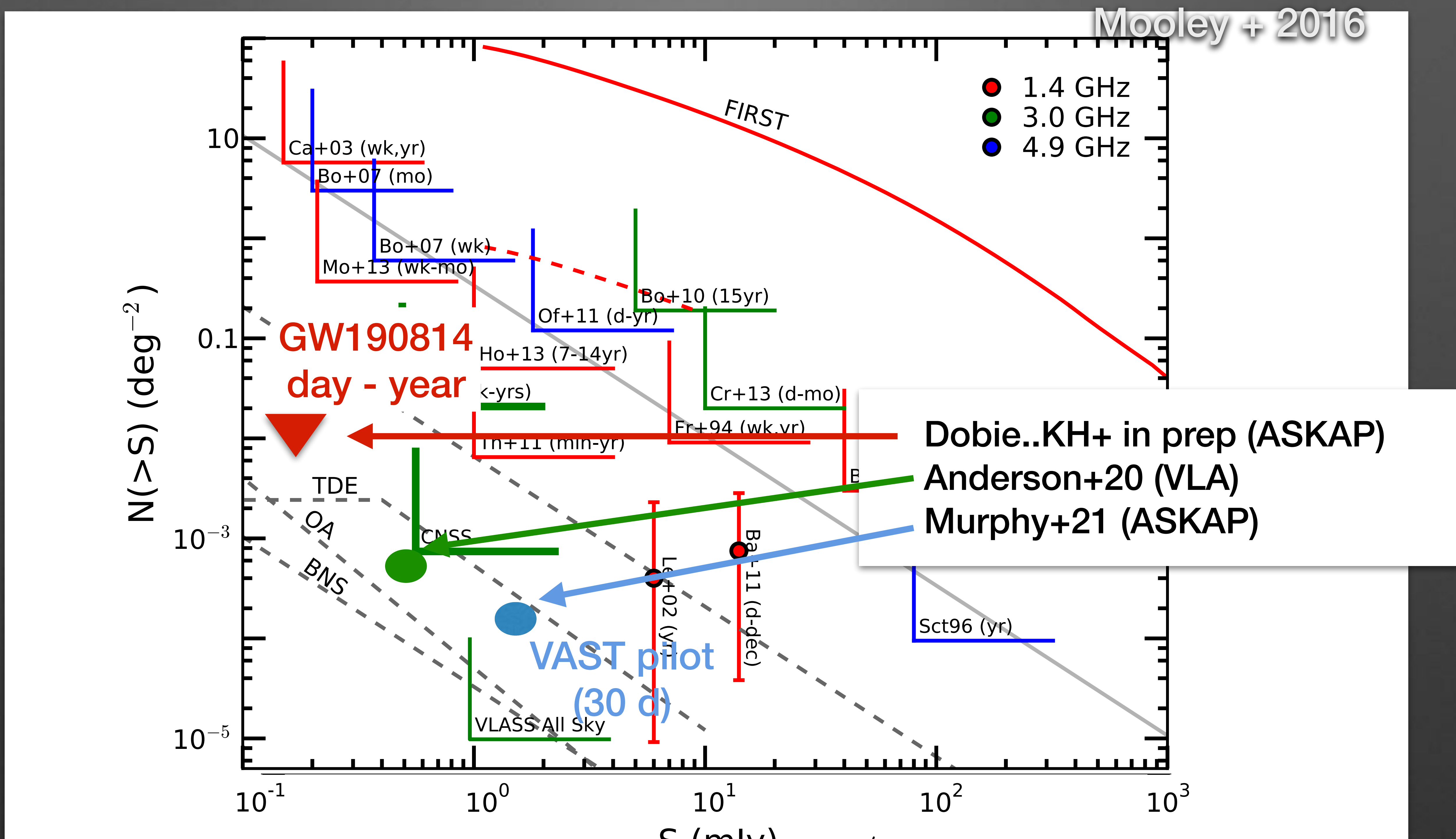


Jet TDEs

Thermal TDEs

Radio zoo of tidal disruption events.

Radio transient sky in 2021



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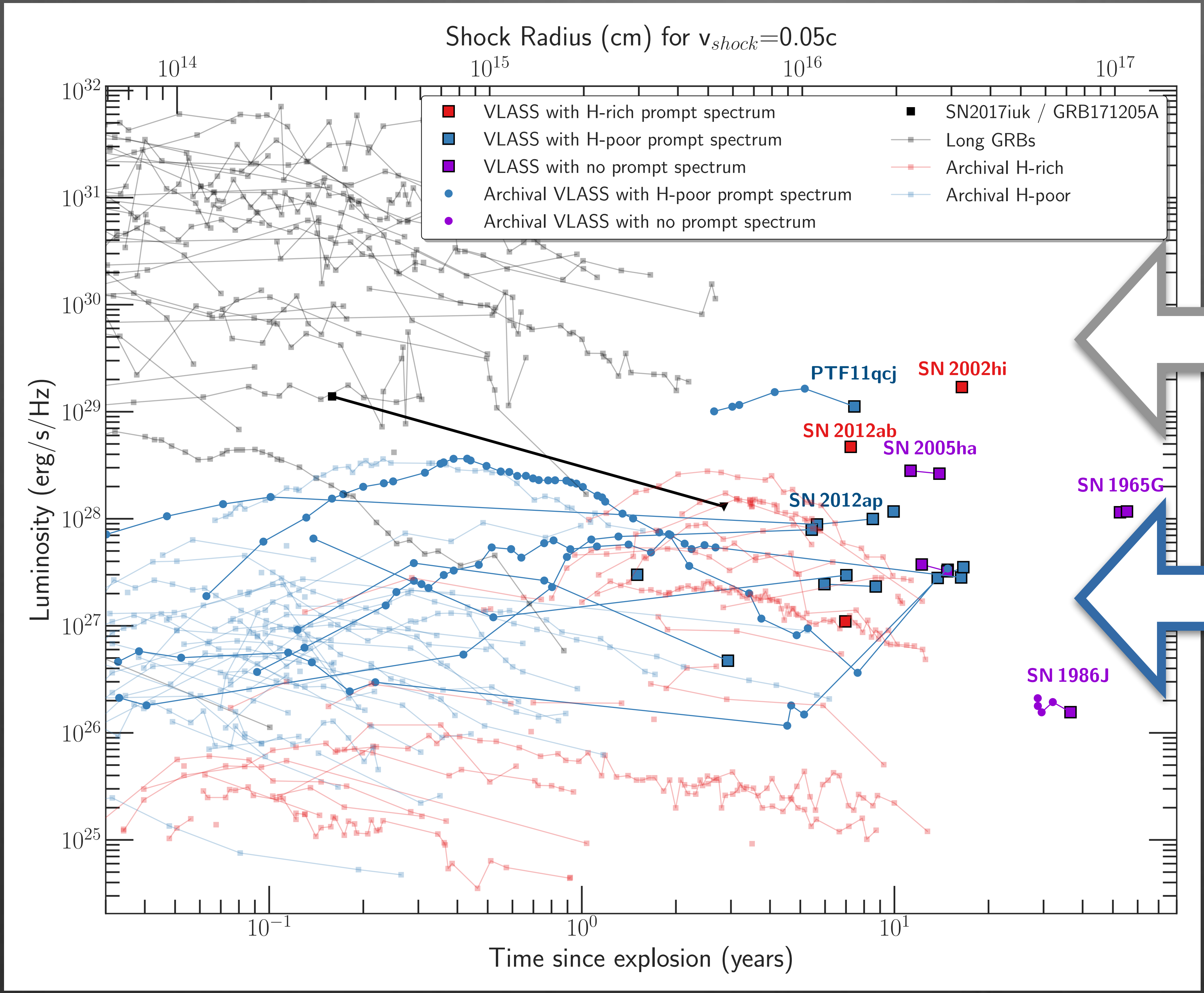
VLA-All Sky Survey (VLASS)

Radio transients for known SNe and GRBs

Stroh + 21



Quite powerful to see late time activities of known objects.