Repeating & Non-repeating Fast Radio Bursts from Binary Neutron Star Mergers

(Yamasaki et al. 2017, arXiv:1710.02302, submitted to PASJ)

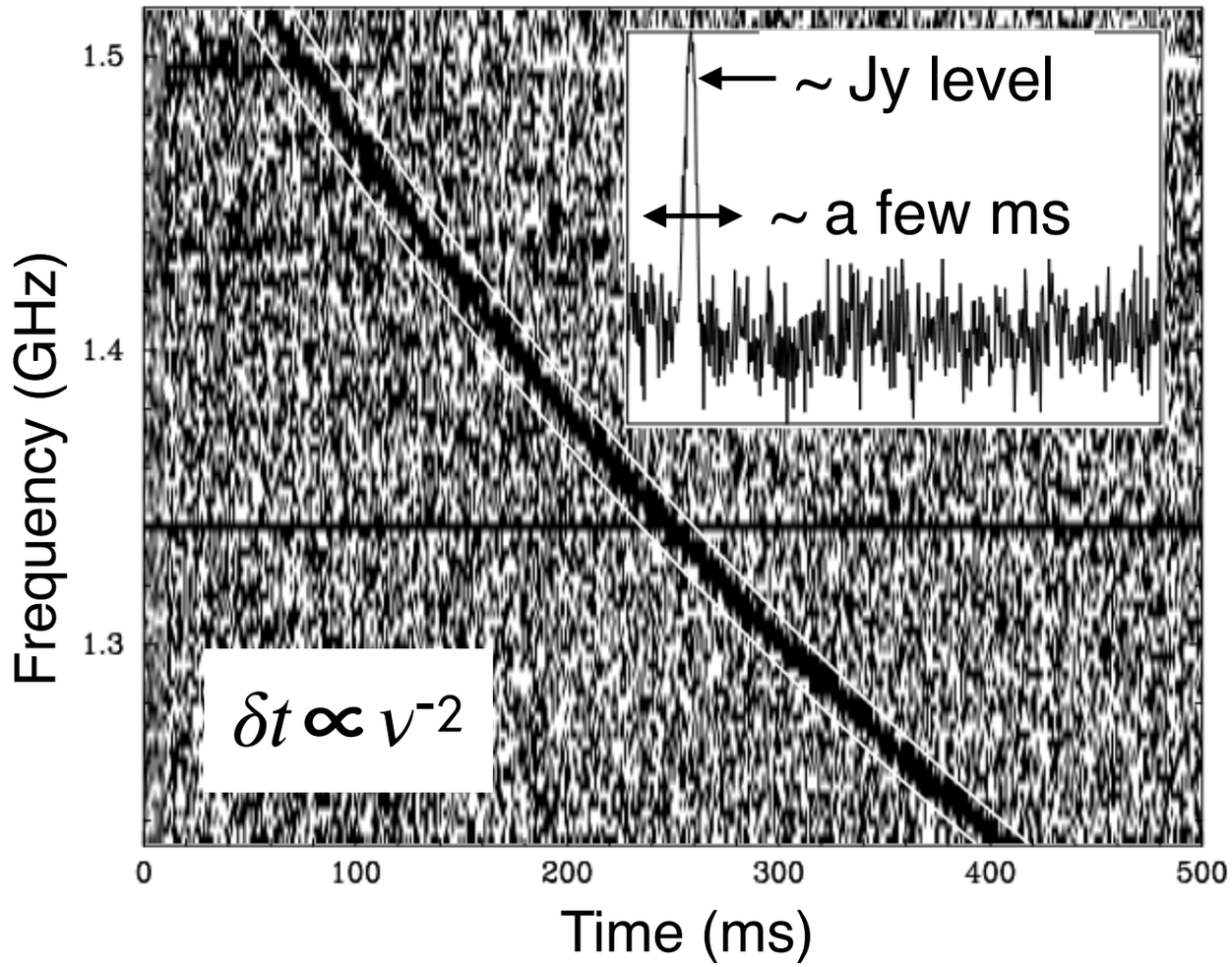
Shotaro Yamasaki (U-Tokyo)

+ Tomonori Totani (U-Tokyo) & Kenta Kiuchi (Kyoto-U)

Introduction

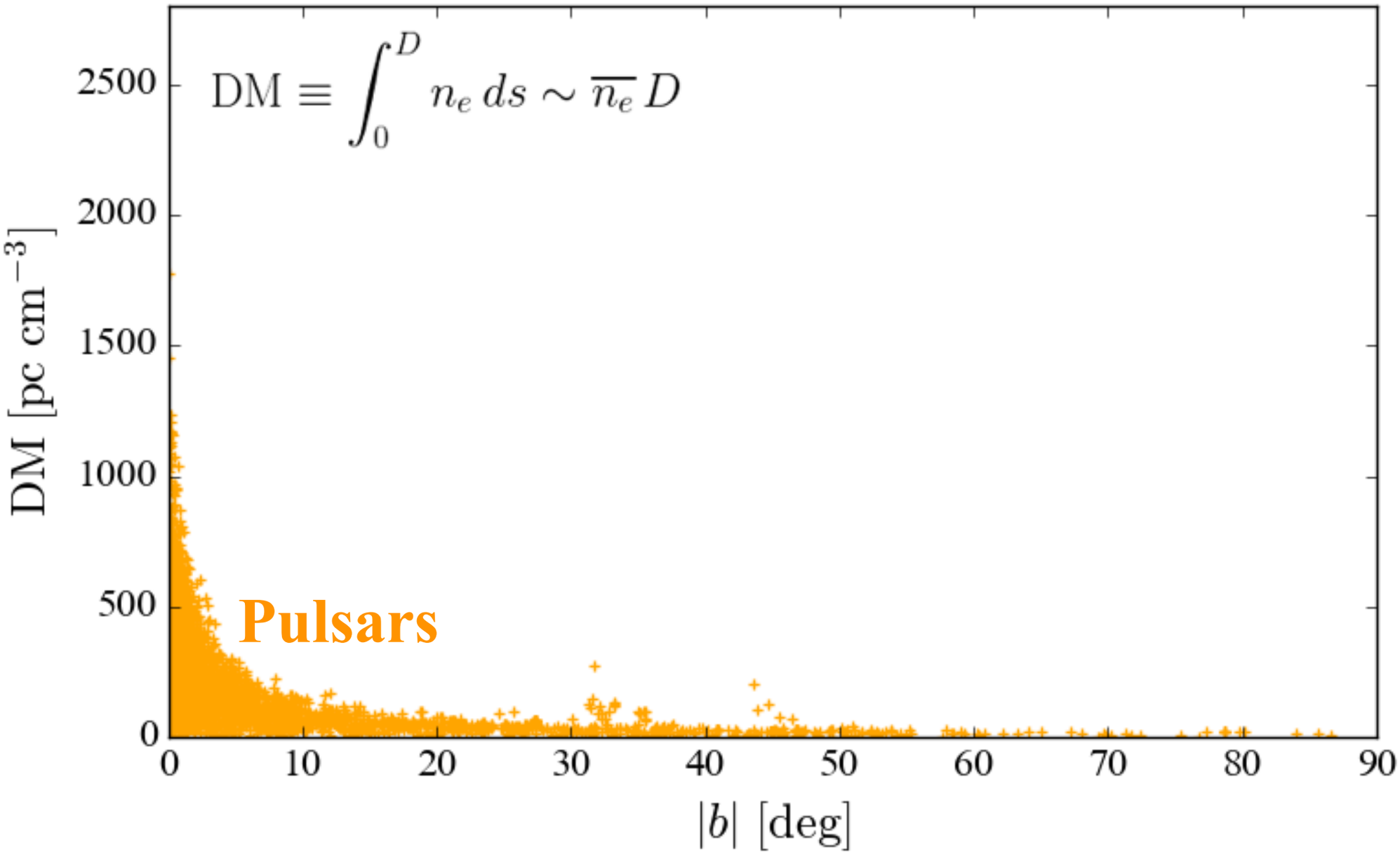
Fast Radio Bursts (FRBs, 2007-)

- Duration =1-10 ms
- Flux = 0.1-1 Jy @GHz
- Unique frequency-dependent time delay($\propto \nu^{-2}$)
- DM= $\int_0^D n_e d\ell$ = **300-2500 pc cm^{-3} (cosmological distance)**
- **Rate ~ 10^3-10^4 sky^{-1} day^{-1}**
- Energy ~ 10^{38}-10^{40} erg
- **Most of FRBs do not show evidence for repetition (30/31)**

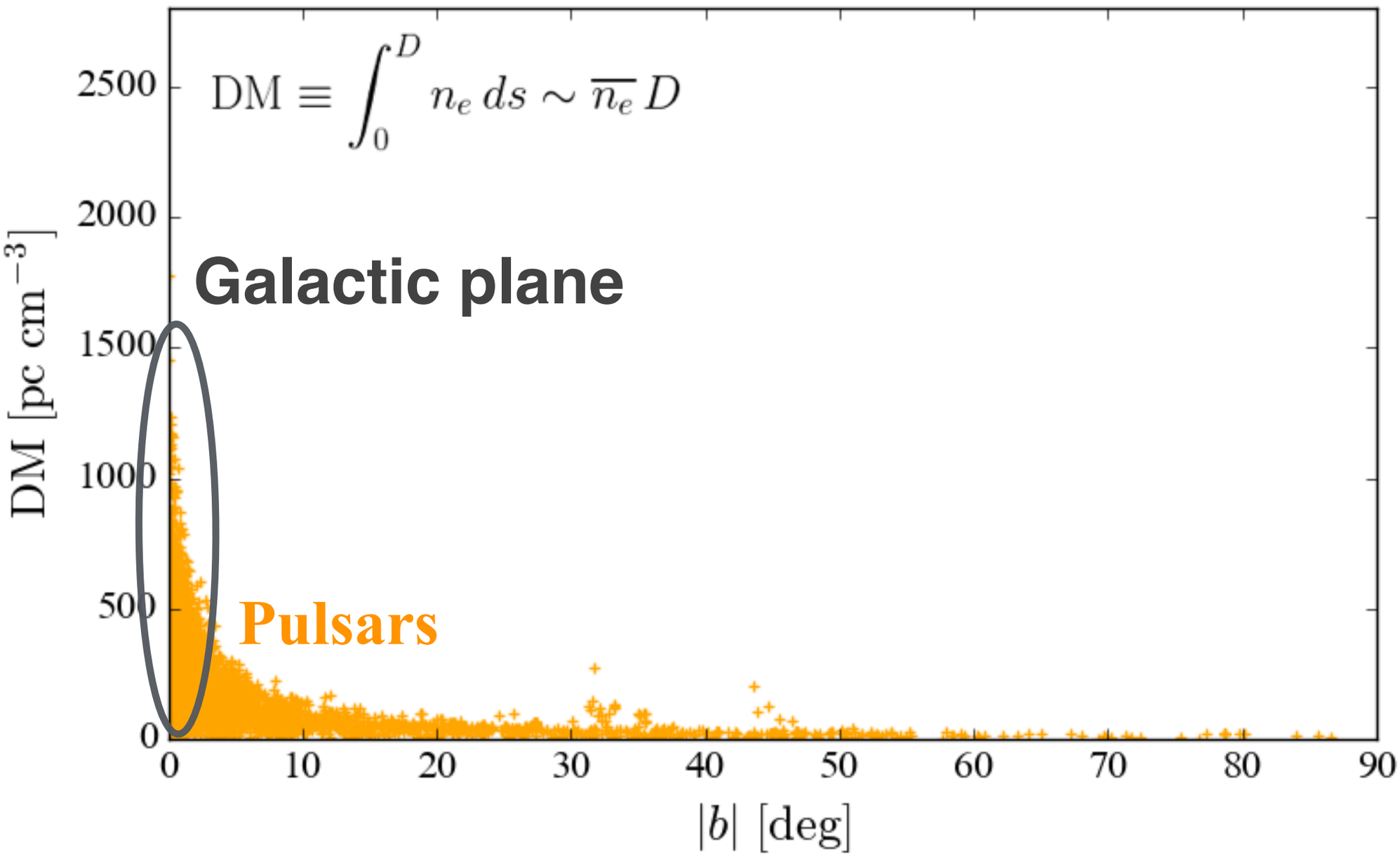


f-t plane & light curve of FRB 010724
(Lorimer+'07, see also Petroff+'16)

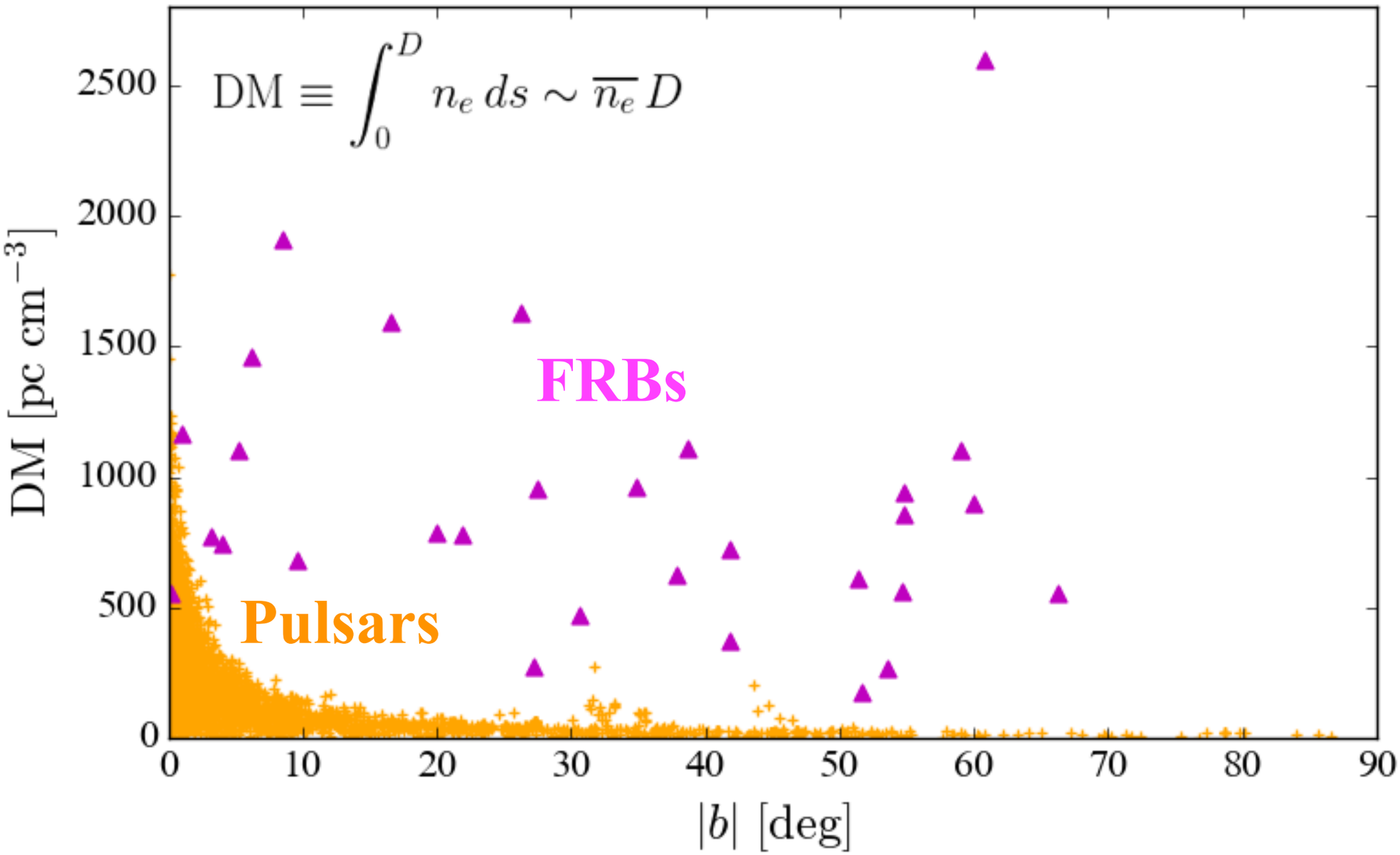
Anomalously Large DM



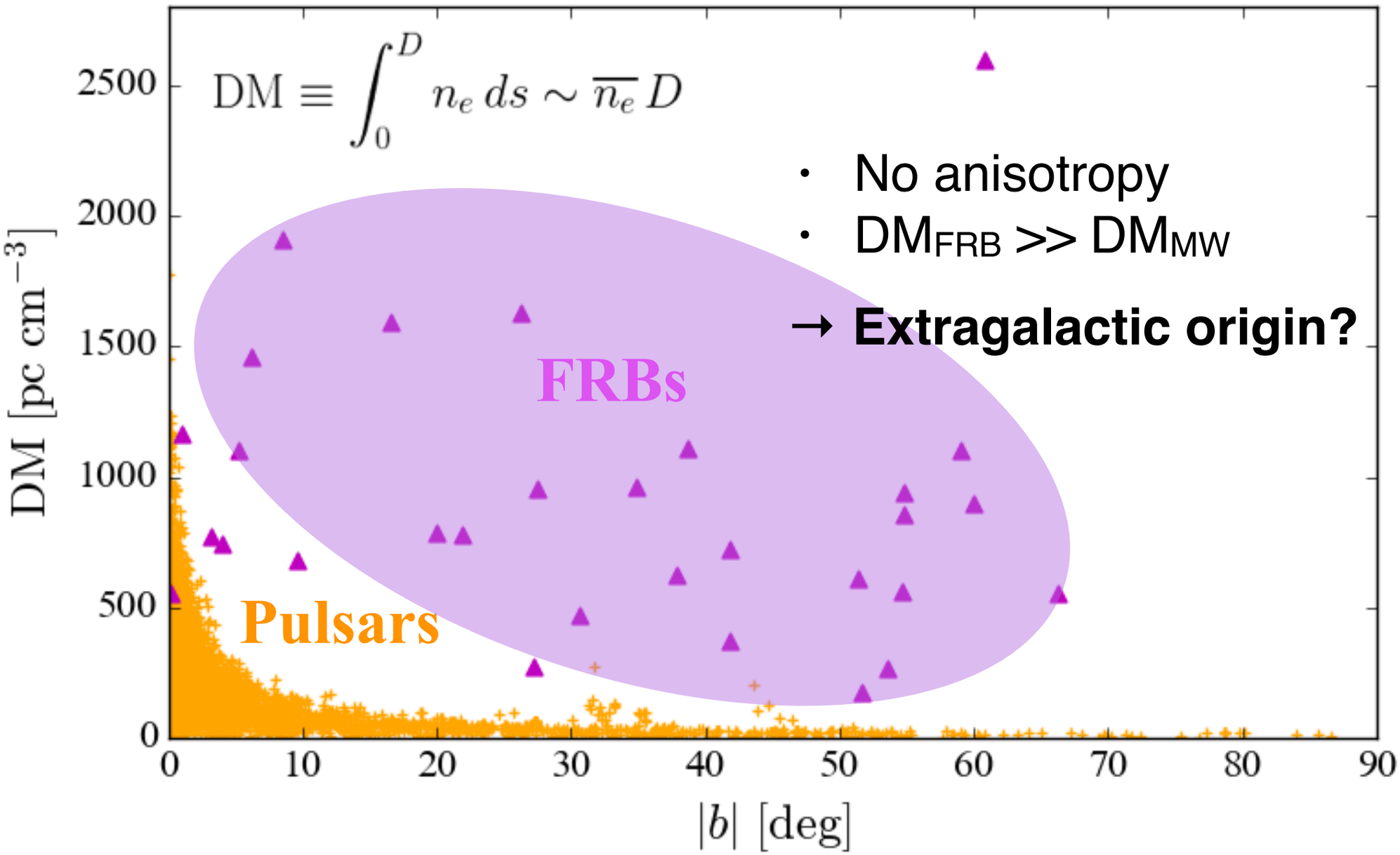
Anomalously Large DM



Anomalously Large DM

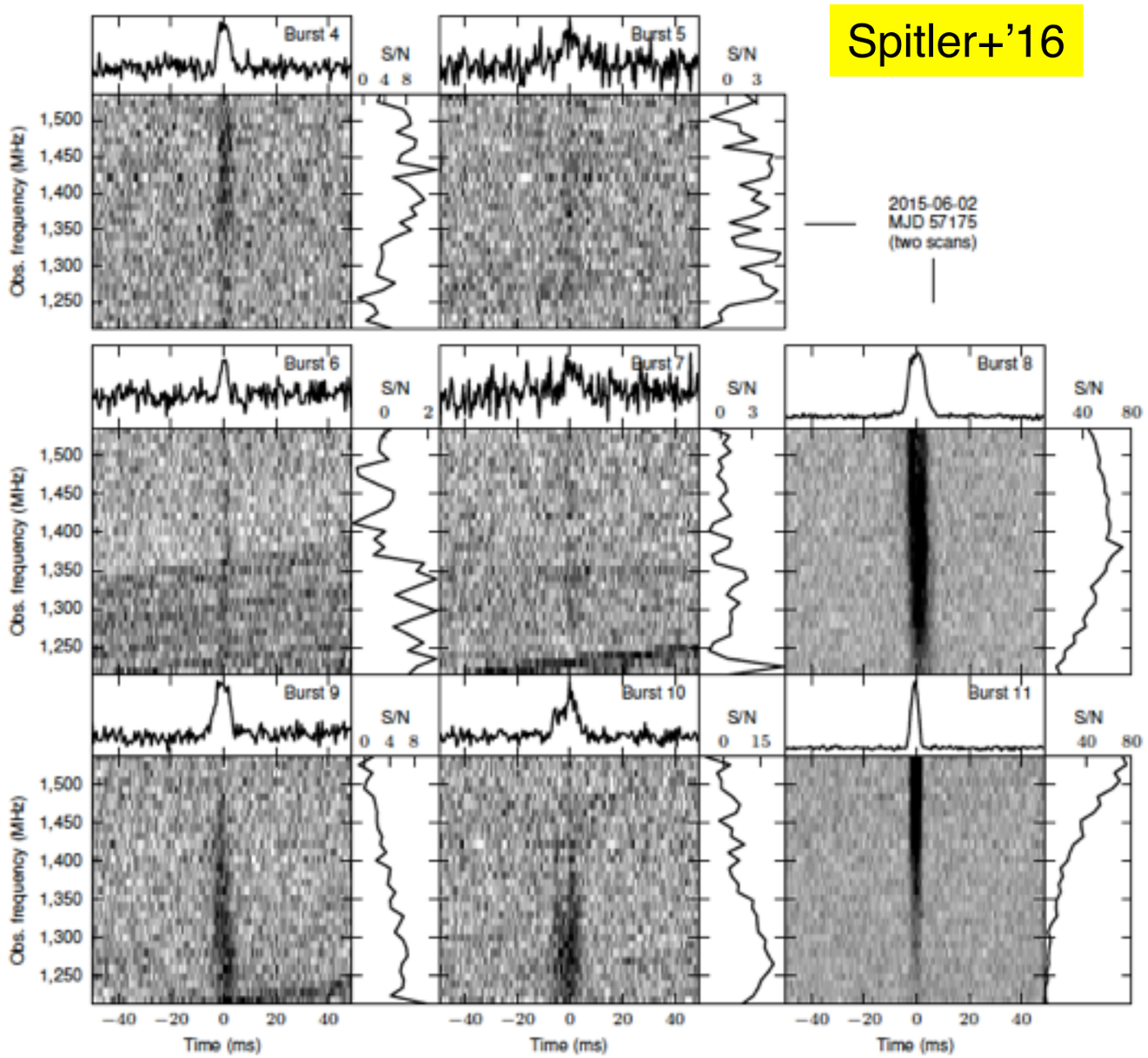


Anomalously Large DM



FRB 121102: It repeats!

- **Discovered by the high sensitivity search of Arecibo radio telescope (while non-repeating FRBs are mostly seen by Parkes radio telescope)**
- **Constant DM~560 pc cm^{-3}**
- **11 bursts in 22 hrs!**
- **No apparent periodicity**



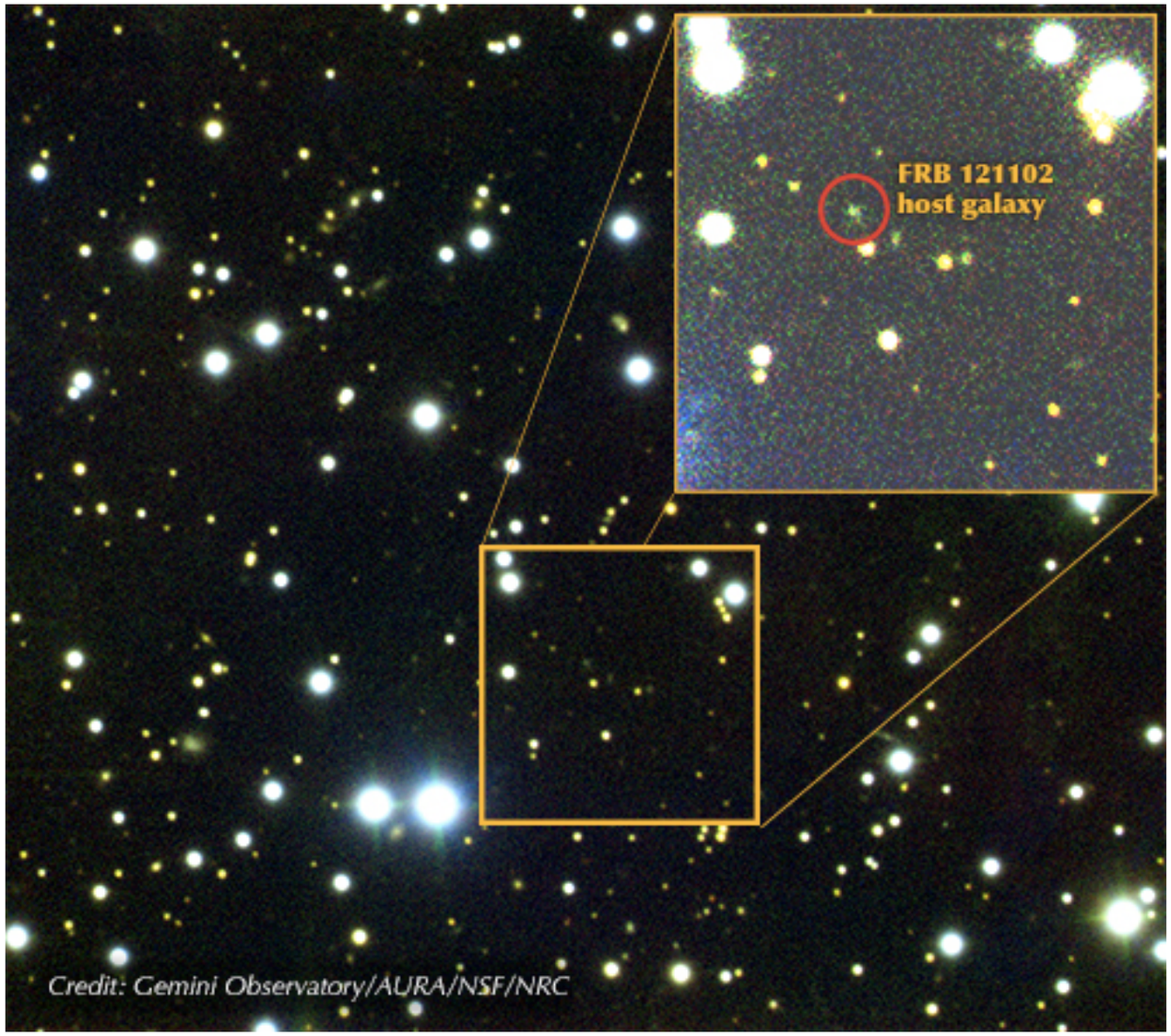
Optical counterpart

Direct localization by VLA allowed deep imaging with Gemini:

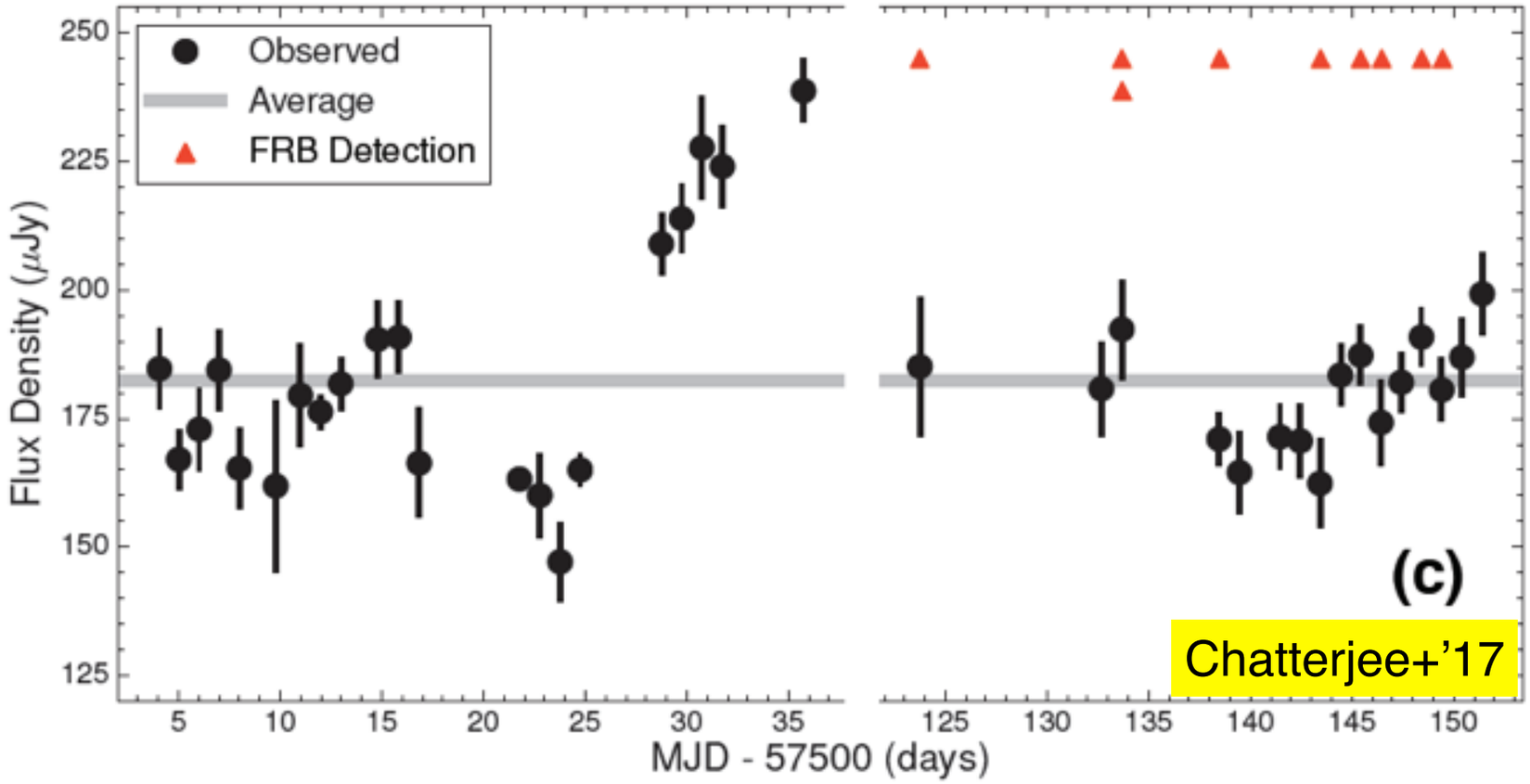
→ Dwarf galaxy

→ z = 0.193;

host is ~1 Gpc away



Radio counterpart



- **Quasi-steady radio source (~10^{39} erg s^{-1})**
- **Source size <~ 0.7 pc**
- **Non-thermal spectrum with broken power-law**

→ Progenitor is most likely a young neutron star (NS)!

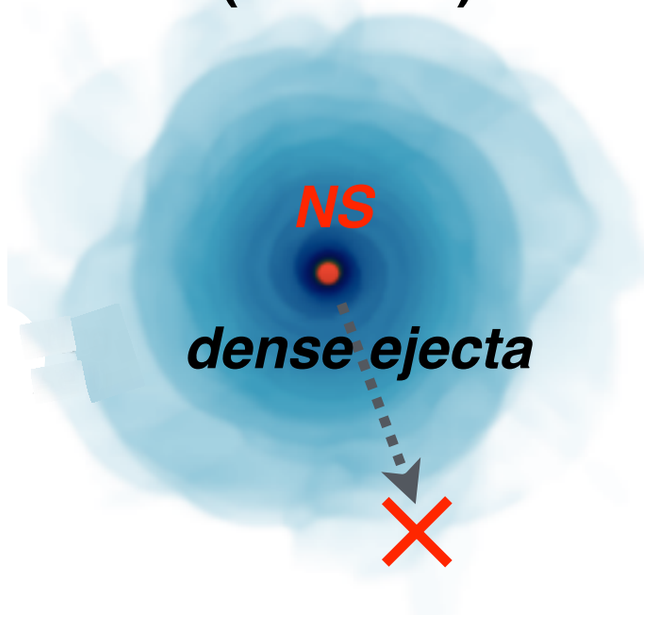
A favored model

Supernova scenario

super-luminous SN
(Phase I)

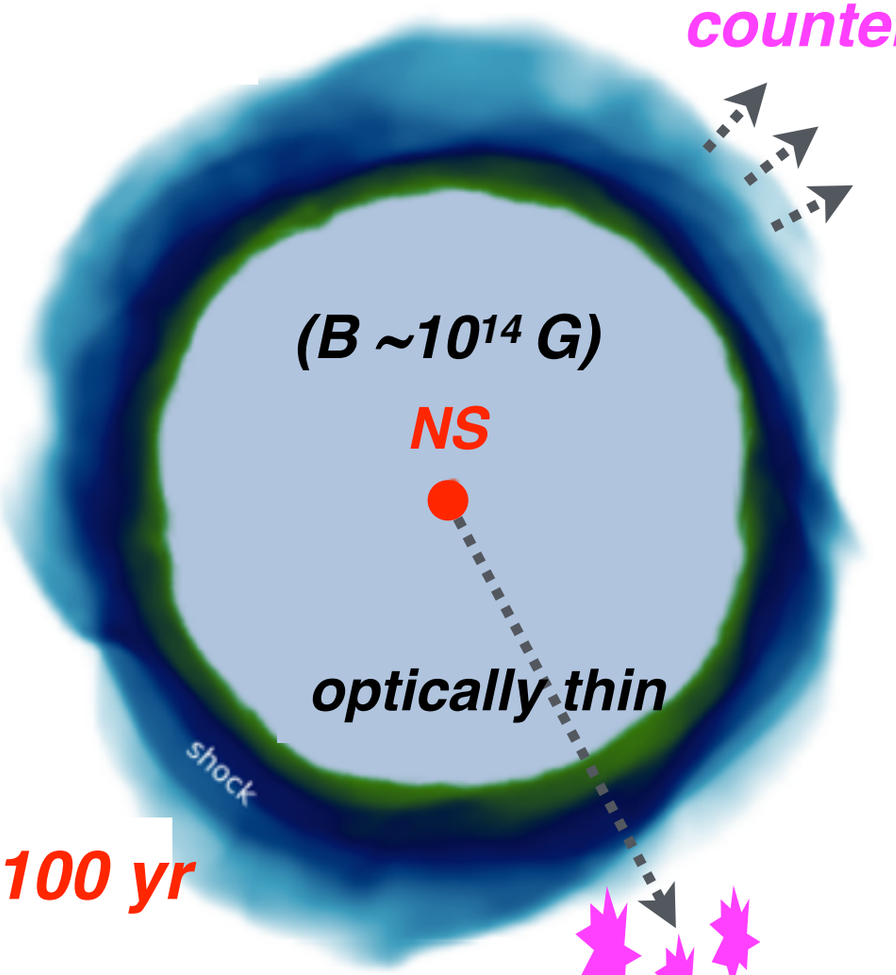
(preferentially occurs in dwarf galaxies)

remnant NS
(Phase II)



PWN
(Phase III)

radio counterpart



repeating FRBs

$M_{ejecta} \sim 10\ M_{sun}$
$V_{ejecta} \sim 0.03\ c$

→ ***allowed age: t_{age} = 10-100 yr***

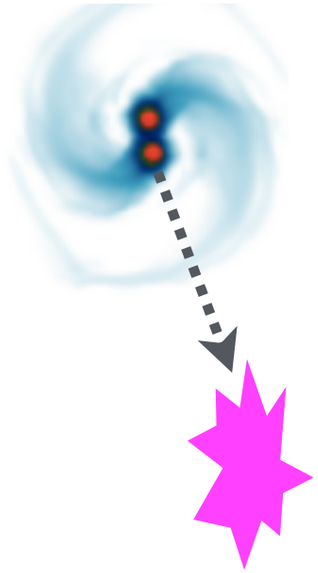
Metzger+'17; Nicholl+'17
Kashiyama & Murase '17

Non-Repeating FRBs from BNS mergers

Non-repeating FRBs from BNS mergers

Totani'13

BNS merger
(Phase I)



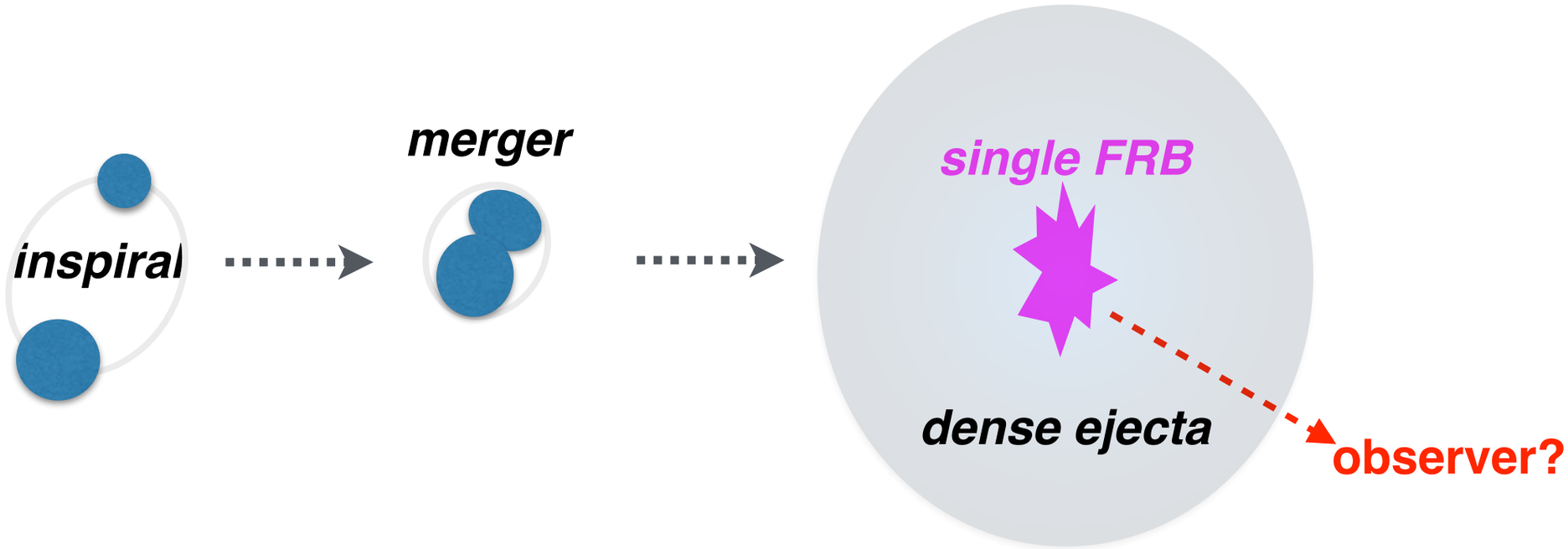
prompt or delayed collapse to BH
(Phase II)

BH

single FRB
(i.e., non-repeating FRB)

- A model for non-repeating FRBs
- Pulsar-like radio emission at the time of merger (rotation-powered)
- Dynamical timescale of merger may explain FRB duration **~msec**
- Association with GW, short gamma-ray burst & m/k-nova
- **$R_{FRB} \sim R_{BNS} = 10^{3}$-$10^{4}$ Gpc^{-3} yr^{-1}**

A theoretical concern...



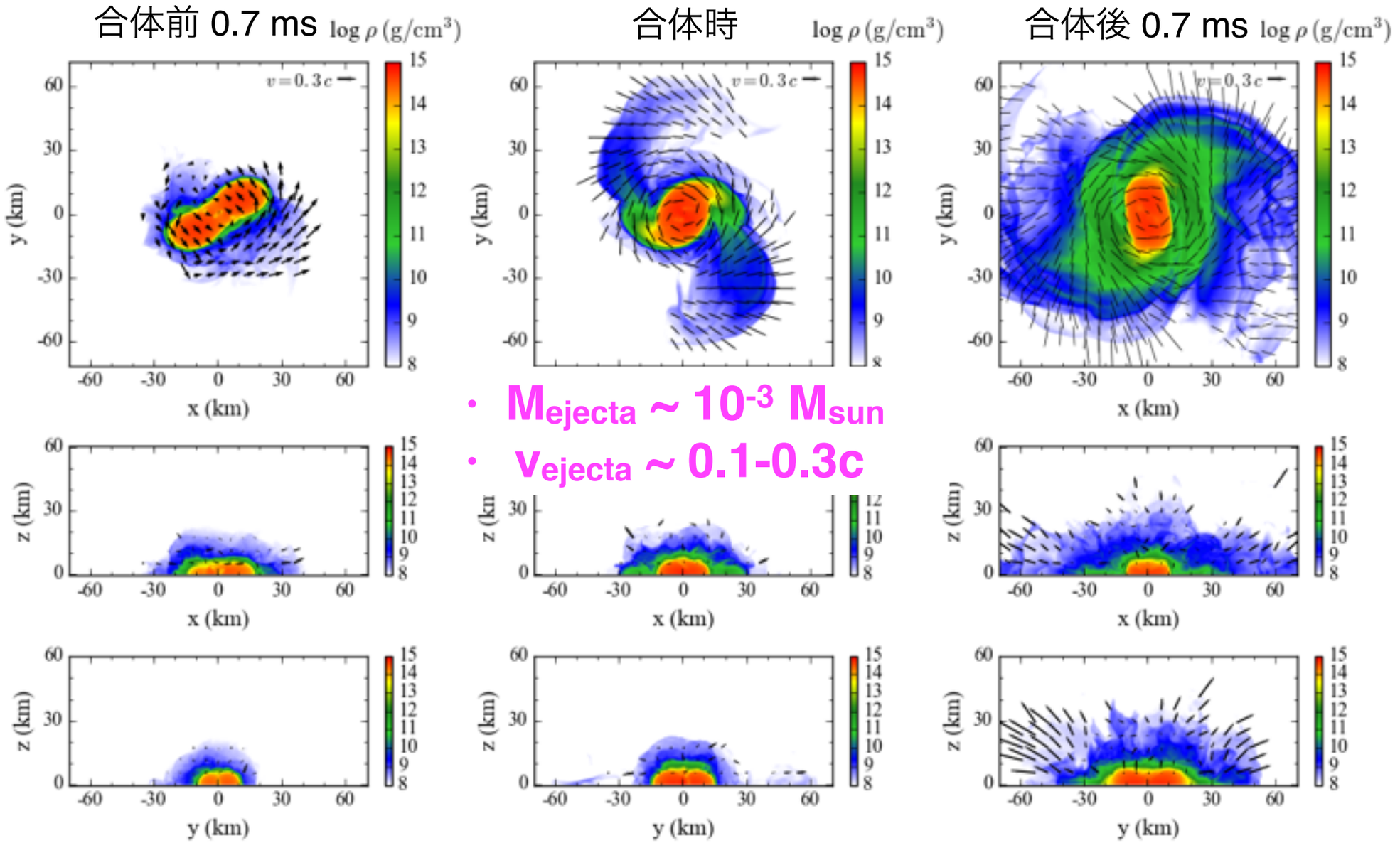
The merger environment could be polluted by dense dynamical ejecta, which would suppress radio emissions

Is there any chance of FRB transmission? -> Simulation

BNS merger simulation

(H4 EoS / 1.35M_{sun}-1.35 M_{sun} / No B-field)

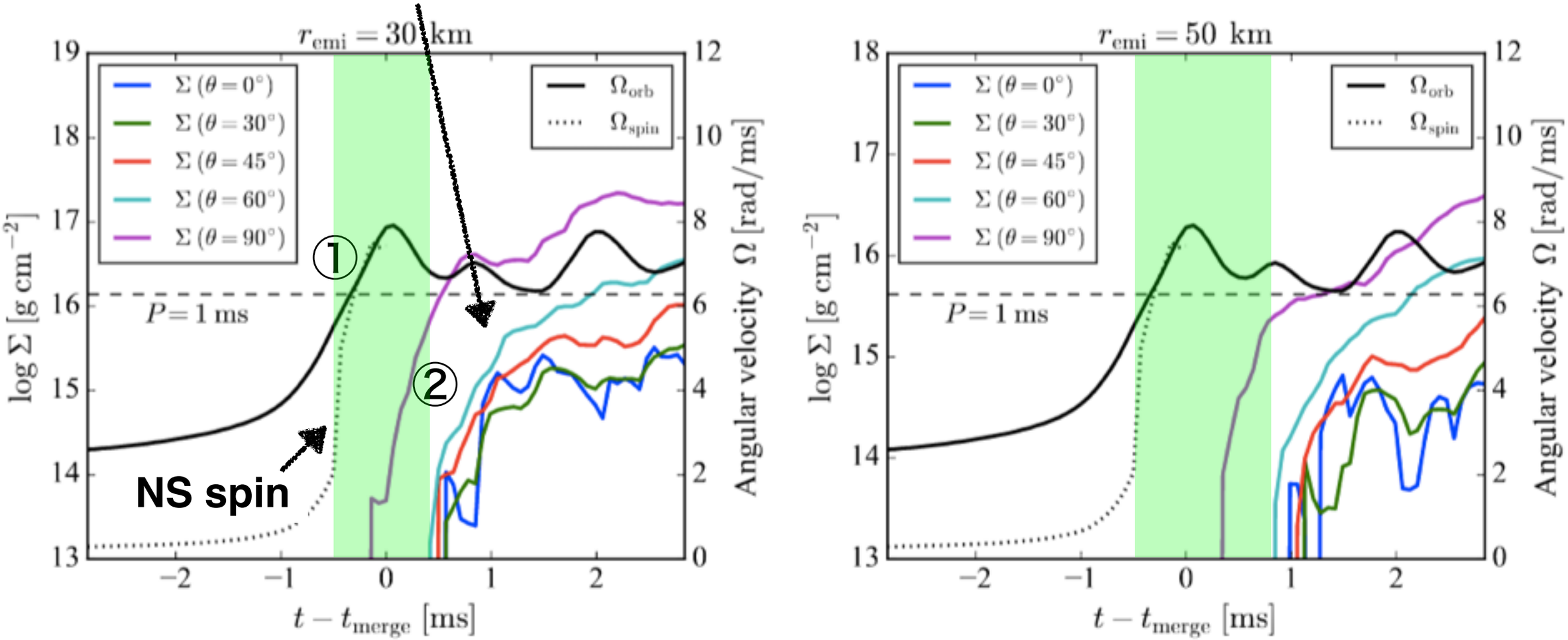
K. Kiuchi



- $M_{ejecta} \sim 10^{-3}\ M_{sun}$
- $v_{ejecta} \sim 0.1\text{-}0.3c$

Spin-up v.s. ejecta formation

Column density of ejecta (colored)

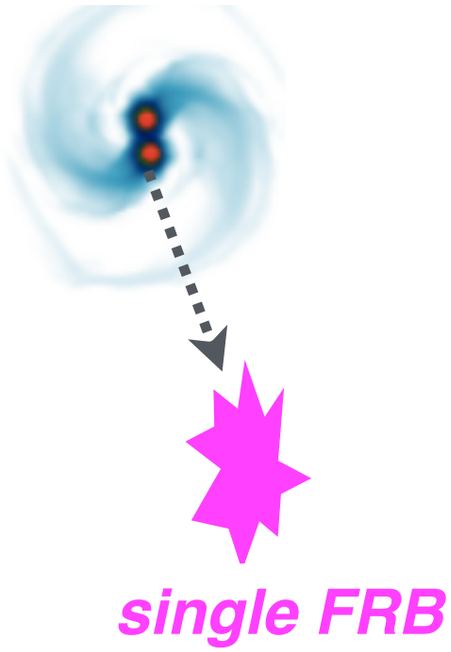


- ① NS Spins-up (FRB possibility increases) → ② Ejecta formation
- **An FRB signal can possibly escape during ($t - t_{\rm merge}$) = -0.5 to 0.5 ms**

Repeating FRBs from BNS mergers

Then, how to explain repeating FRBs?

BNS merger
(Phase I)



single FRB

prompt or delayed collapse to BH
(Phase II)

●

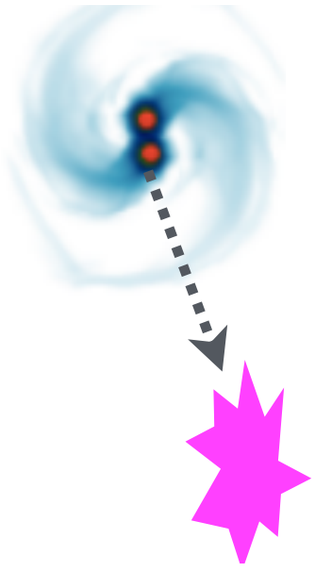
BH

←It is often assumed, but not that trivial…

Then, how to explain repeating FRBs?

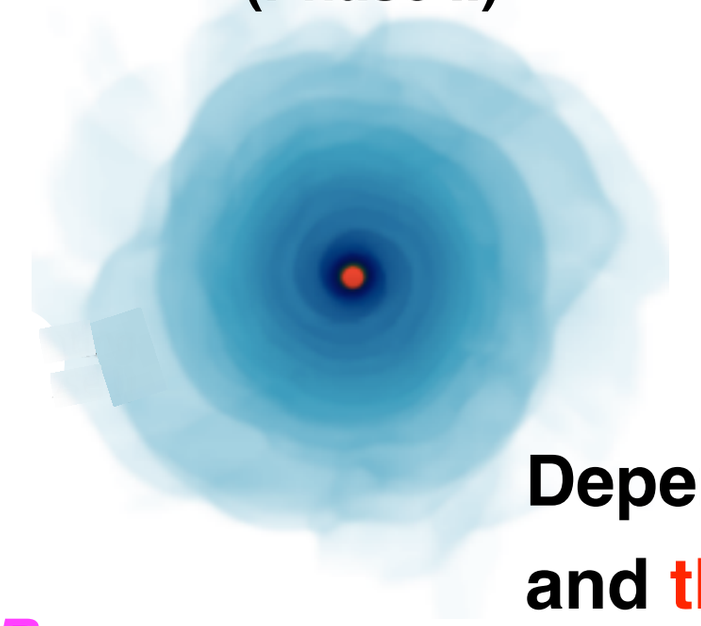
This work

BNS merger
(Phase I)



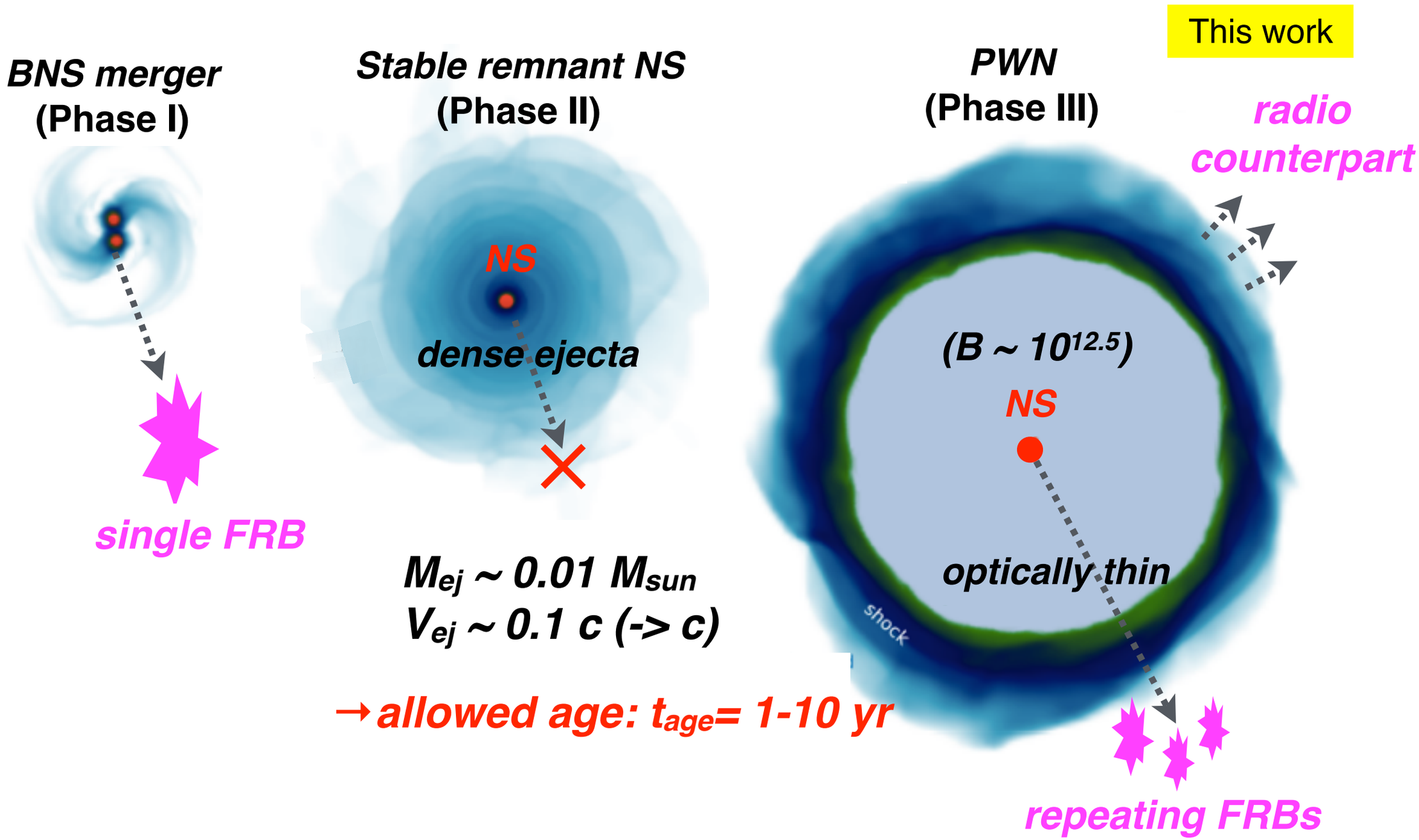
single FRB

Stable remnant NS
(Phase II)



Depending on the mass of NS-NS and the high-density equation of state, some fraction of BNS merger might leave a stable NS remnant!

Repeating FRBs from BNS mergers



Comparison with SN models

- **Consistent with DM, source size and source energetics**

- Compared to SN scenarios,
  - appearance timescale of FRBs = **shorter**
  - DM, RM = **smaller**
  - persistent radio source (nebula) size = **larger**

Rotation Measure (RM)

$$\mathrm{RM} \propto n_{\mathrm{e}} B_{\parallel} R_{\mathrm{ej}}$$

- **Large RMs expected in SN scenario [RM~10^{11} (t/yr)$^{-4}$ rad m^{-2}] cannot explain some FRBs with extremely small host RMs like**
  - FRB 150807 (RM **<~2 rad m^{-2}**; Ravi+'17)
  - FRB 150215 (RM **<25 rad m^{-2}**; Petroff+'17).

- **The BNS merger scenario can naturally explain the small RMs**

FRB rate evolution model

sensitivity:

Arecibo = 10

Parkes = 1

305m Arecibo Telescope

64m Parkes Telescope

Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

Caleb '17

~ 0.1Jy@z=0.2 (faint)

~ 1.0Jy@z=1 (bright)

Parameter	**Repeater (FRB 121102)**	**Non-repeating FRBs**
Discovery telescope	Arecibo	Parkes, GBT, UTMOST, ASKAP
Detection telescope	GBT, VLA, Effelsberg	–
Frequencies (GHz)	$1.4, 2, 4-8$	1.4, 0.8, 0.843
Spectral index	-10 to $+15$	$\gtrsim -3.0$ for FRB150418
Localisation	Dwarf galaxy at $z \sim 0.19273(8)$	No localisation yet
Polarisation	No detectable polarisation	Varied polarisation with no trend
Widths	$3-9$ ms	$\lesssim 0.4-26$ ms
Scattering	No	Measured for some FRBs
Frequency structure	Yes	Visible in some FRBs
Periodicity	No underlying periodicity	Singular events
DM variation	Consistent to within uncertainties	–

FRB rate evolution model

- Typical cosmic BNS merger rate evolution [$R_{BNS}(z)$]

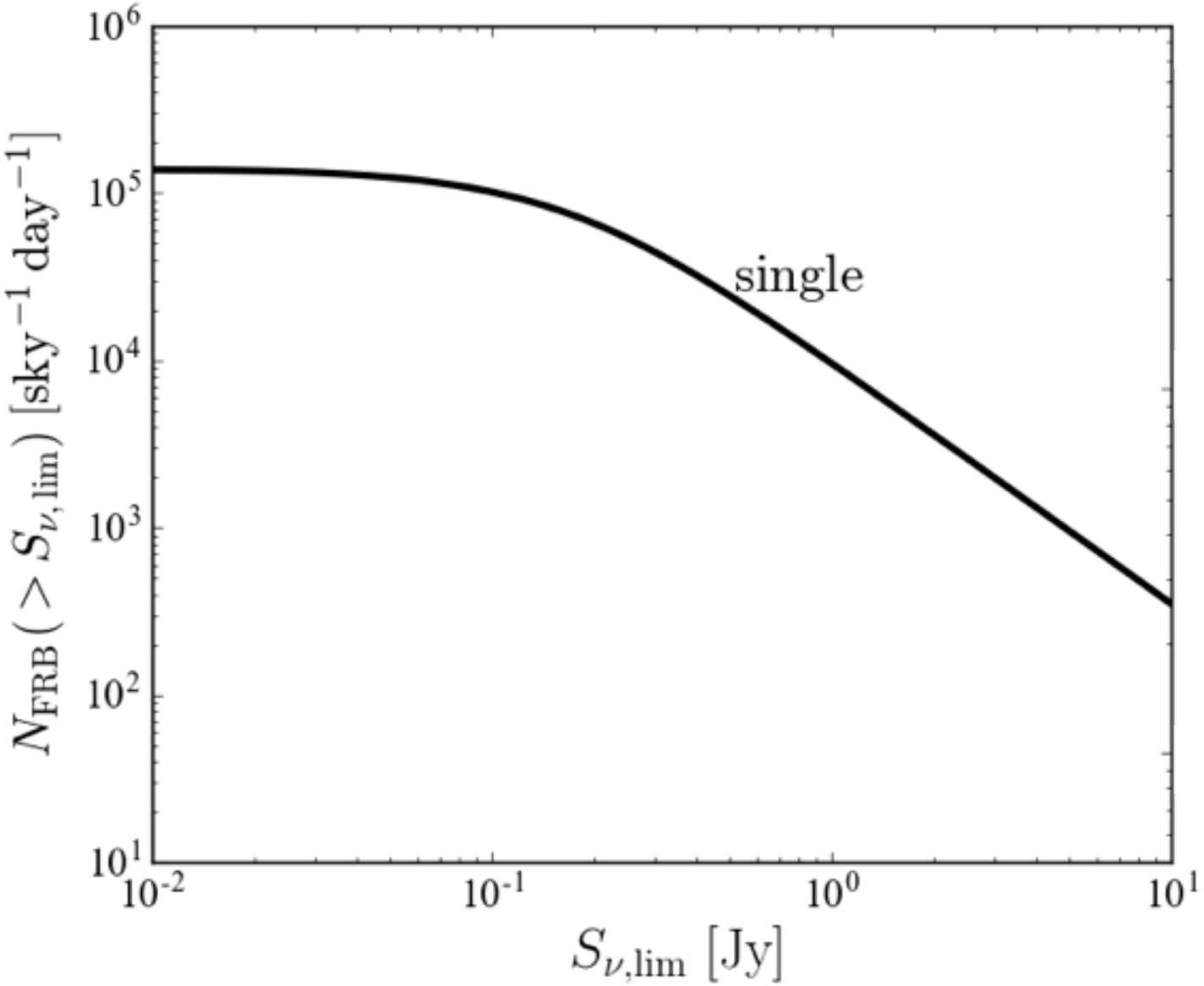
- Standard candle approximation:

  - **1.0Jy@z=1 (bright) for single FRBs** (based on Parkes FRBs)
  - **0.1Jy@z=0.19 (faint) for repeating FRBs** (based on FRB 121102)

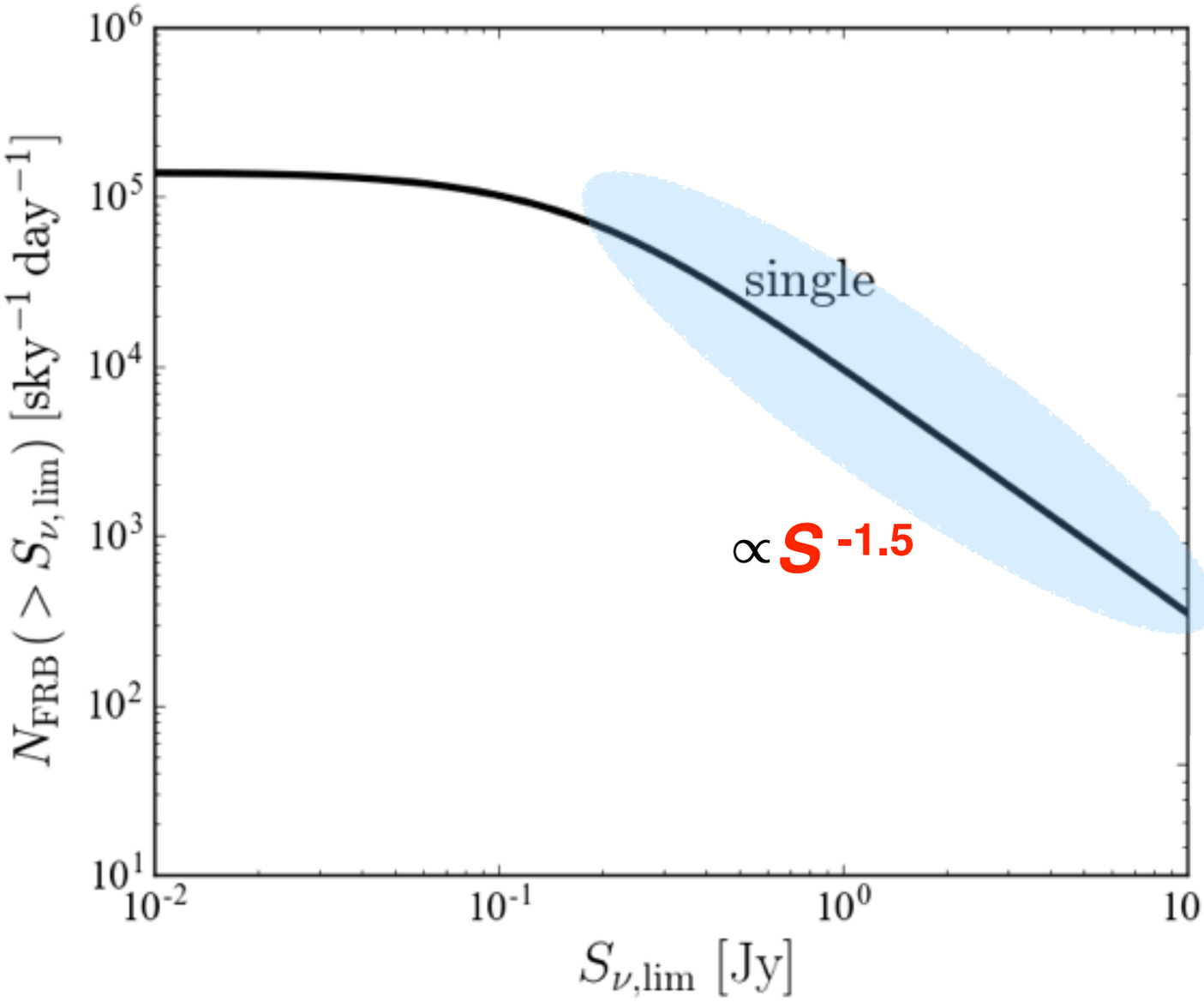
- All-sky rates **$N(>S_{lim})$** is calculated:

  - **$R_{singleFRB}(z) = R_{BNS}(z)$**: all BNS mergers produce a non-repeating FRB
  - **$R_{repeatingFRB}(z) = f\ R_{BNS}(z)$**(**f** : repeater-formation rate, depending on mass of NSs, equation of state and spin-down timescale)

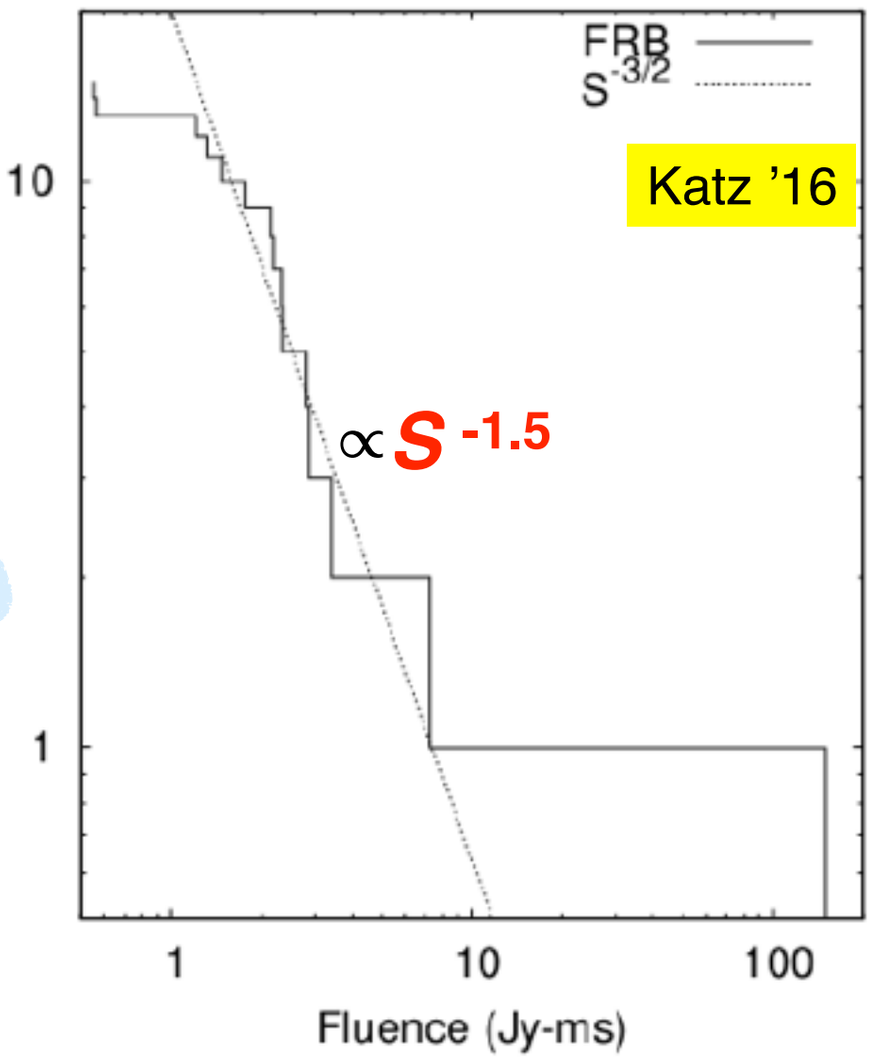
LogN-LogS Plot for FRBs



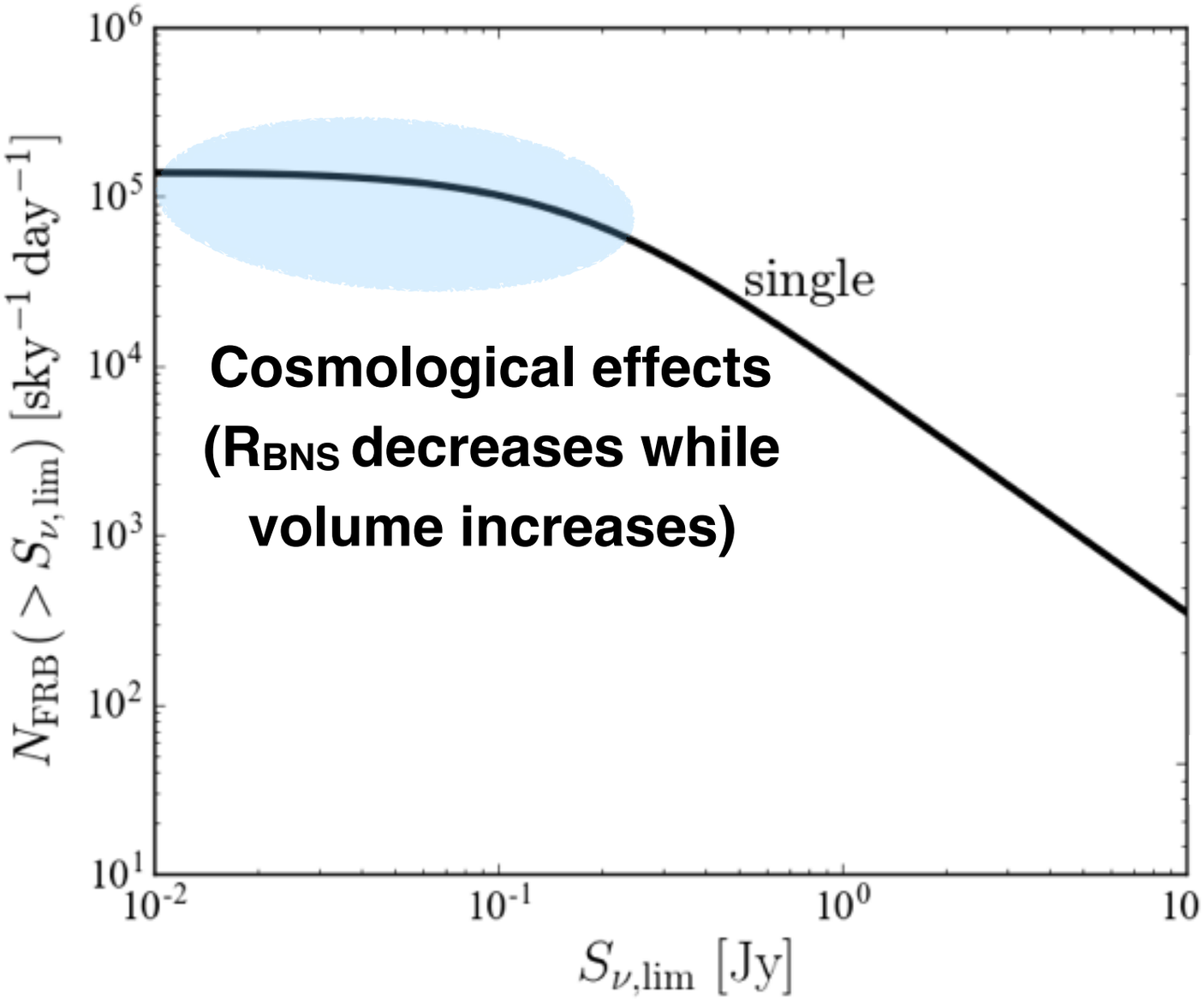
LogN-LogS Plot for FRBs



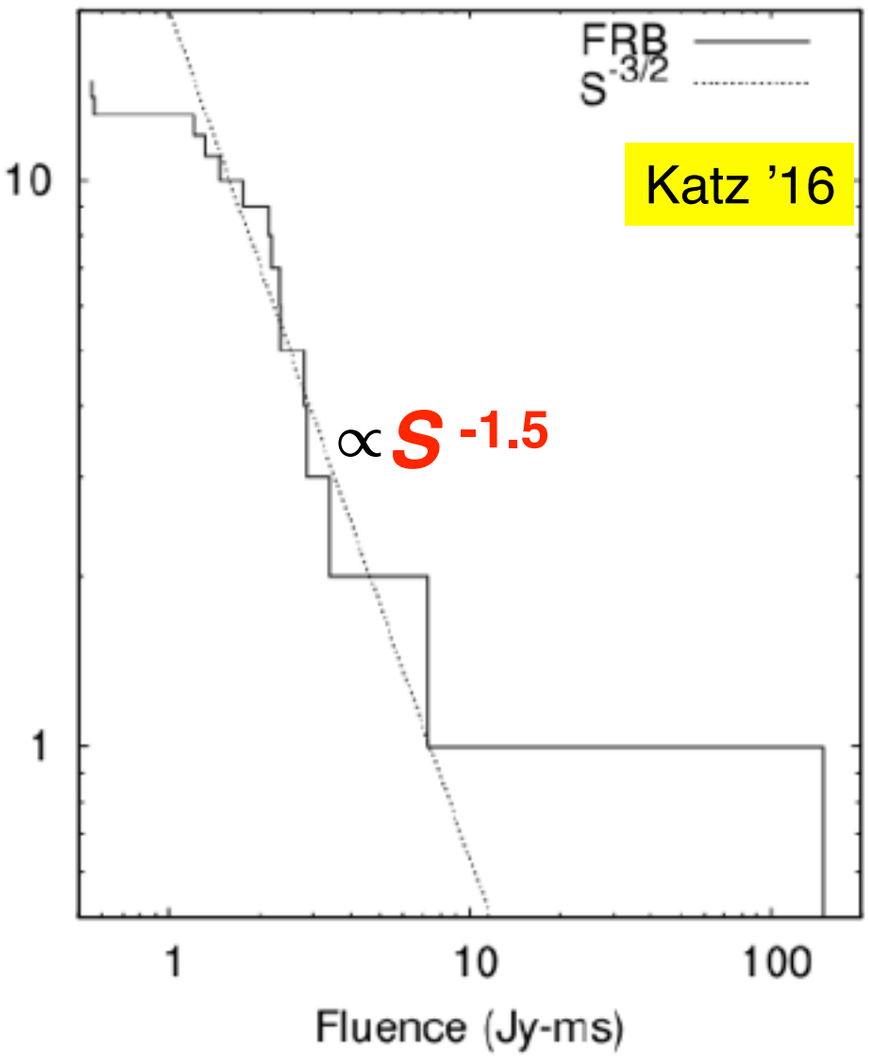
15 Parkes (single) FRBs



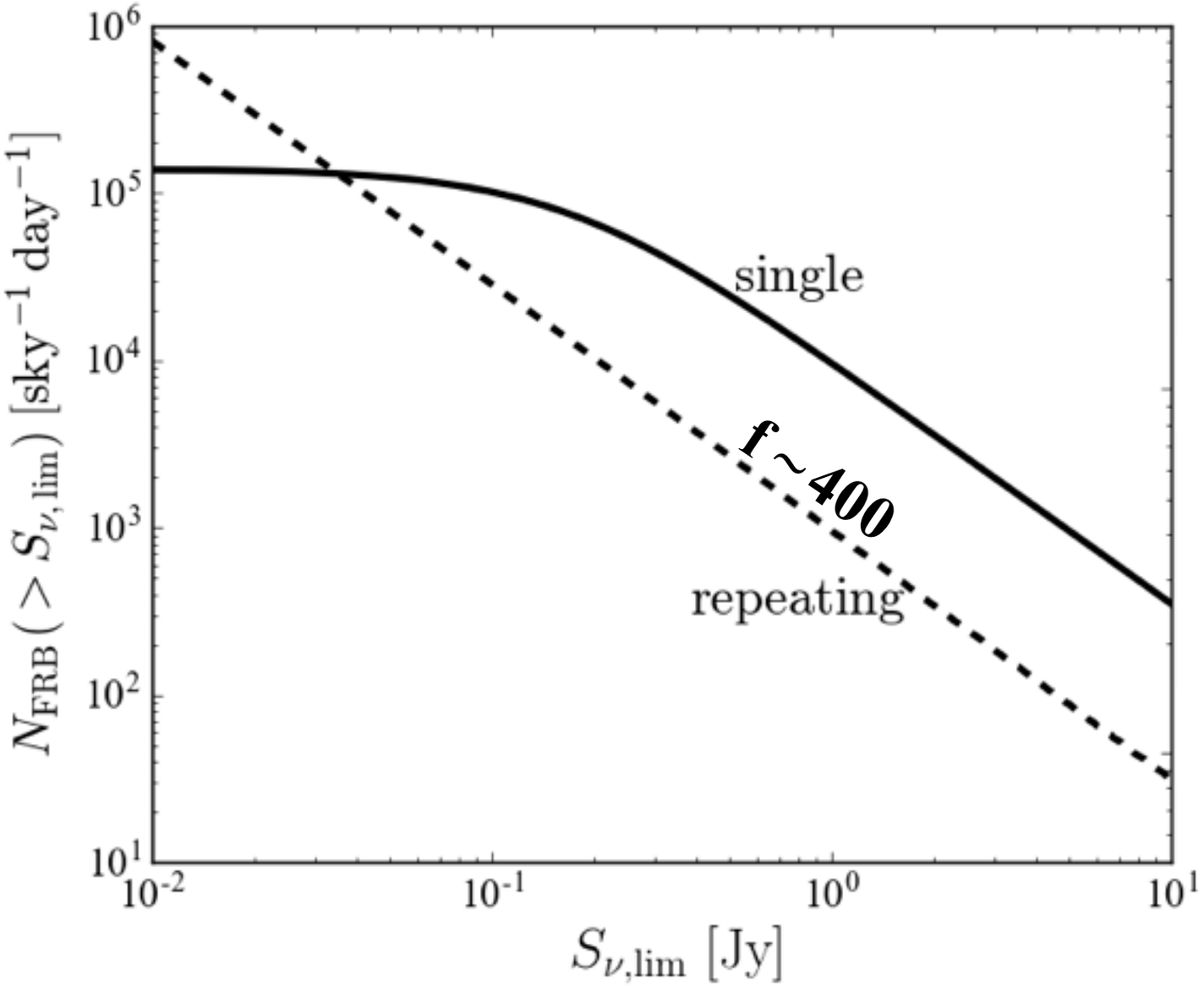
LogN-LogS Plot for FRBs



15 Parkes (single) FRBs



LogN-LogS Plot for FRBs

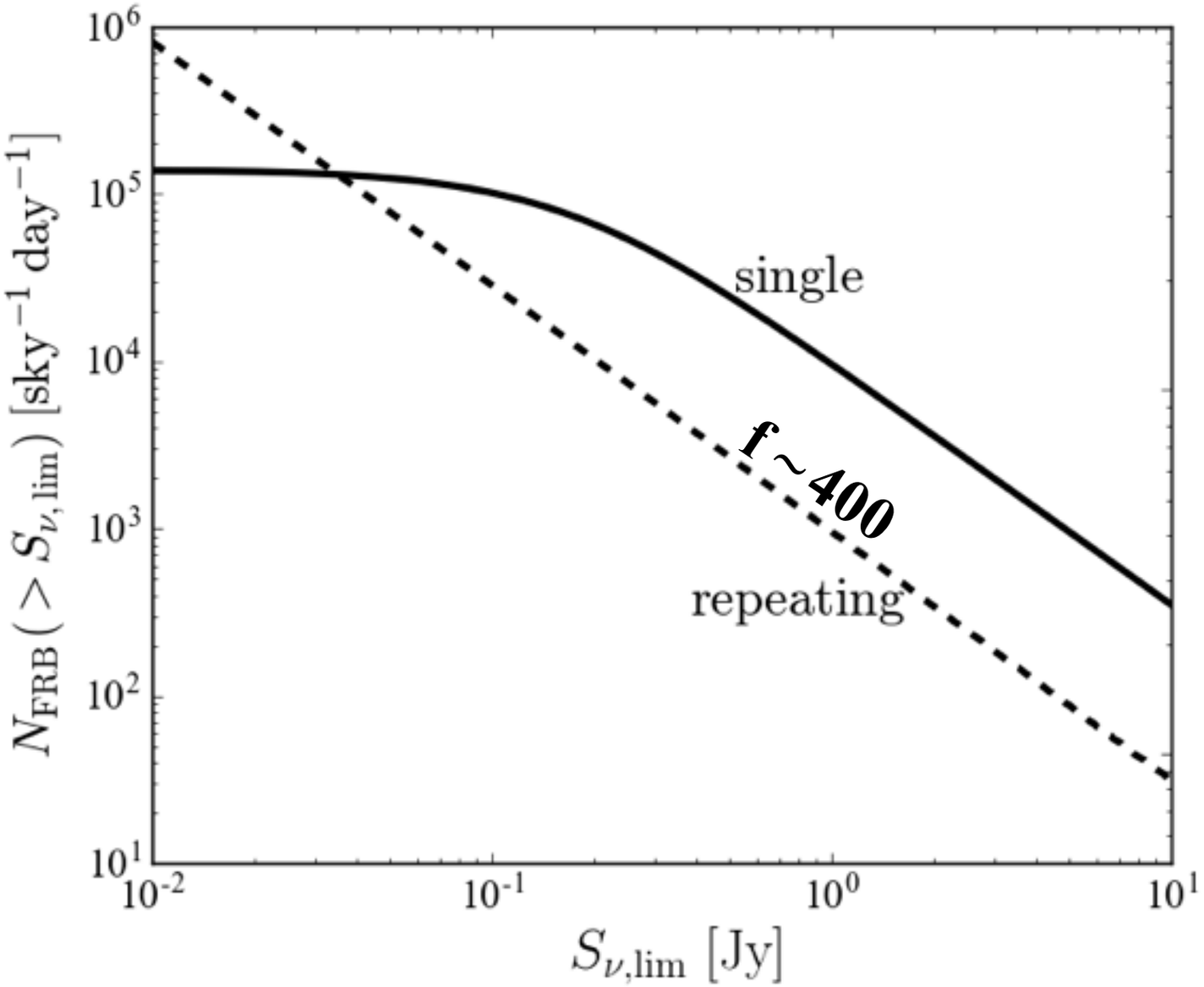


repeating/single <~ 0.1

@1Jy (Parkes)

→ f <~ 400

LogN-LogS Plot for FRBs



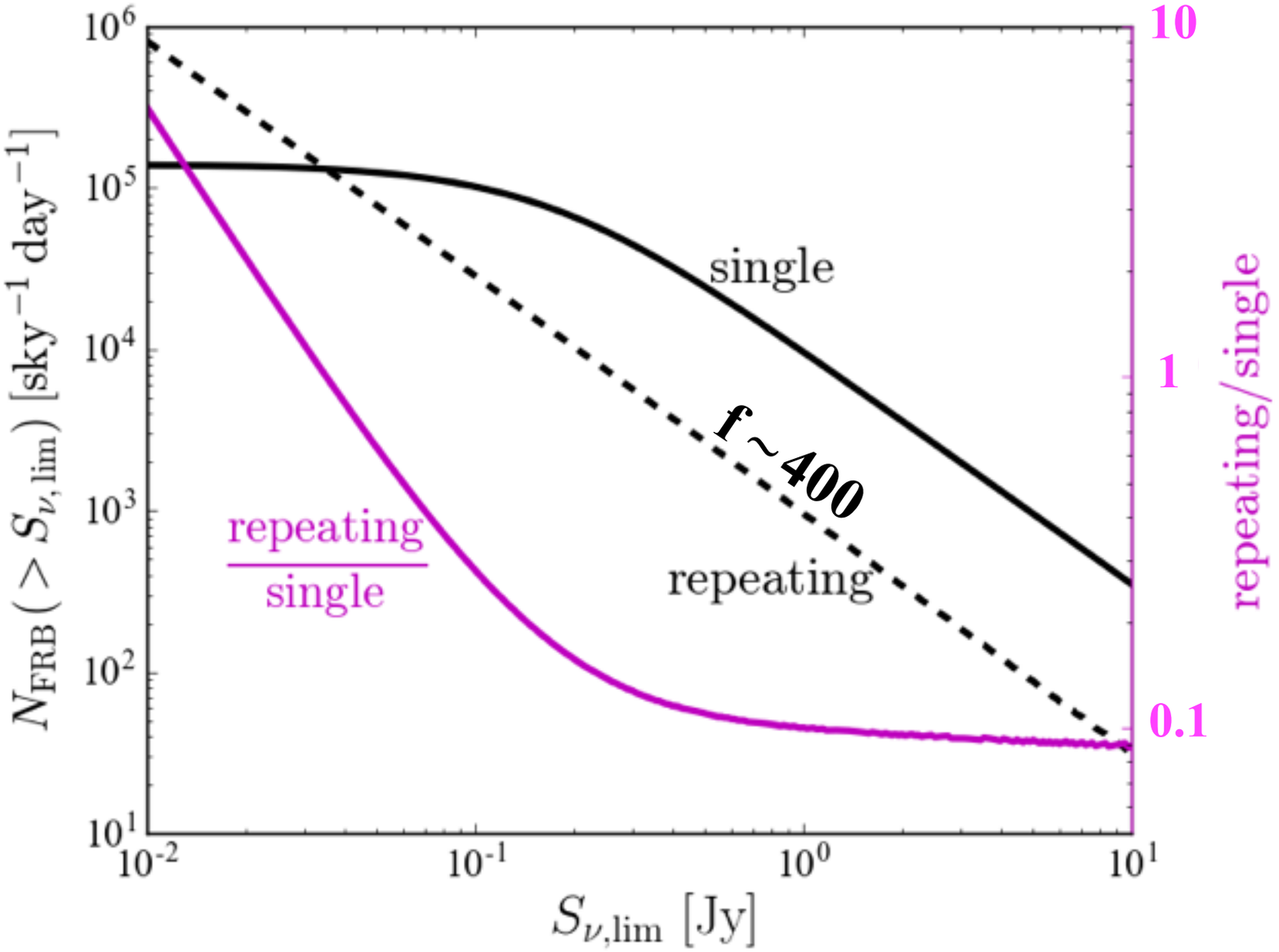
repeating/single <~ 0.1

@1Jy (Parkes)

→ f <~ 400

The lifetime of a repeating source ~10yr suggests <~10% of BNS mergers form an FRB-producing remnant NS!

LogN-LogS Plot for FRBs



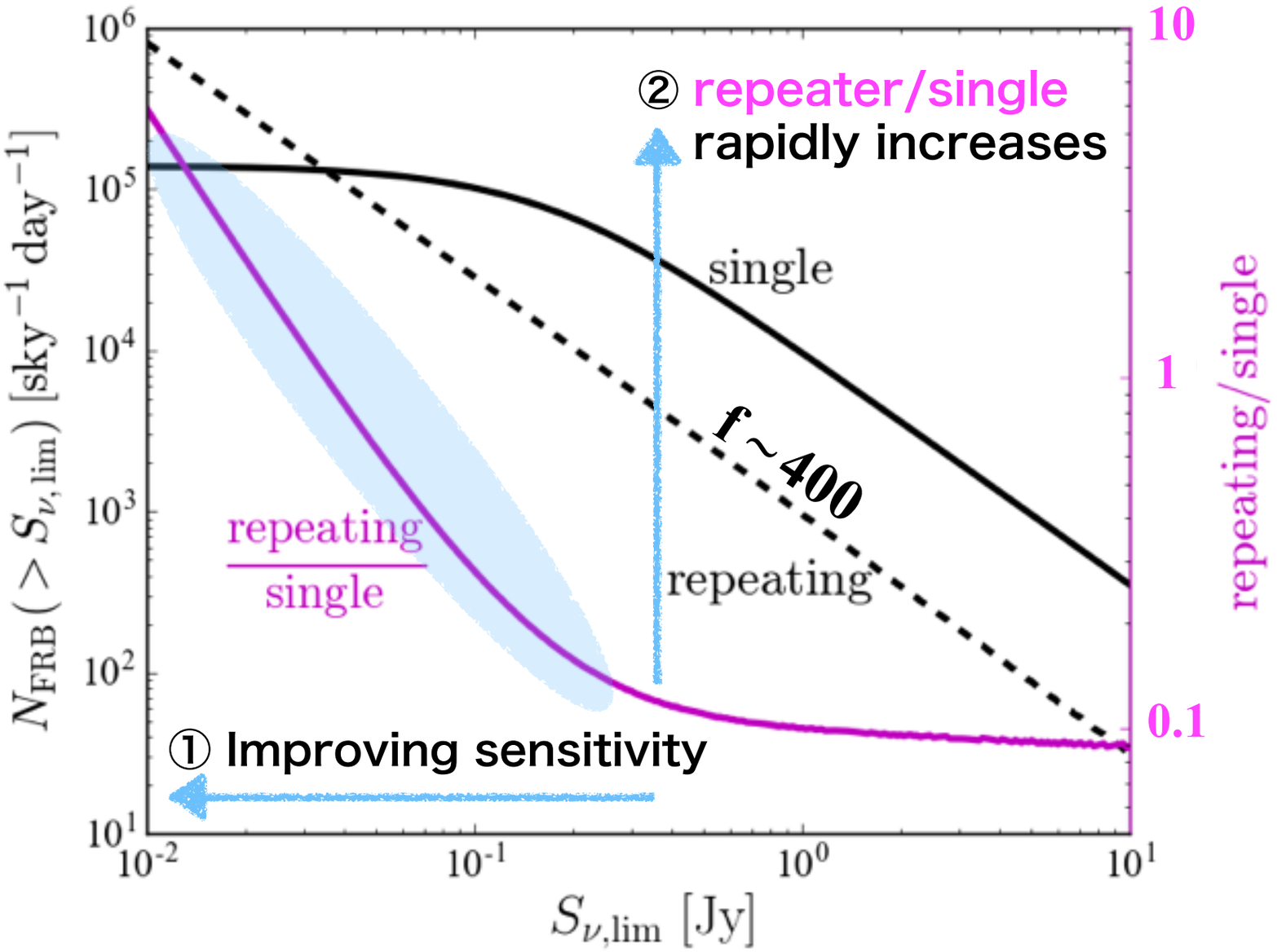
repeating/single <~ 0.1

@1Jy (Parkes)

→ f <~ 400

The lifetime of a repeating source ~10yr suggests <~10% of BNS mergers form an FRB-producing remnant NS!

LogN-LogS Plot for FRBs



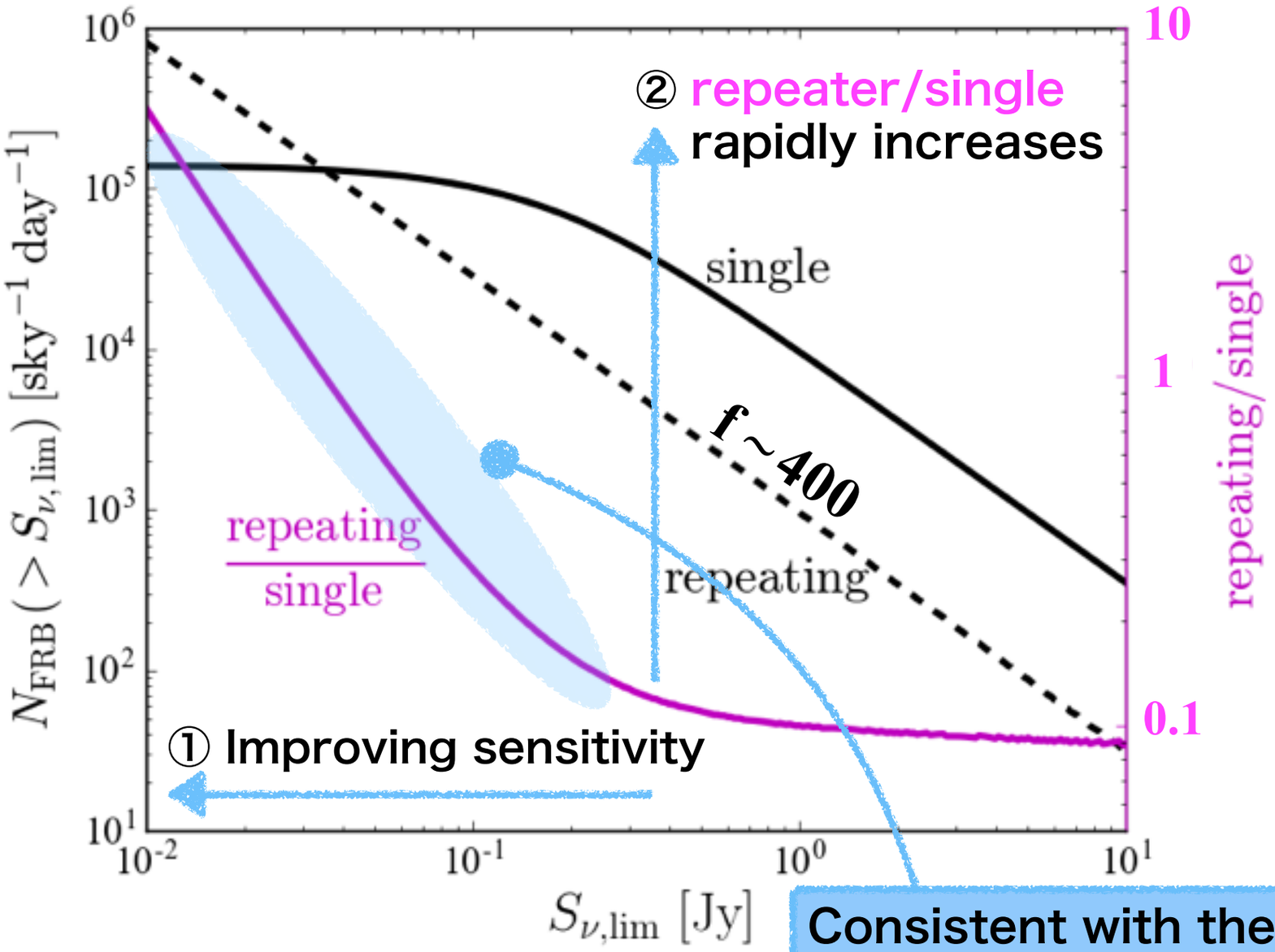
repeating/single <~ 0.1

@1Jy (Parkes)

→ f <~ 400

The lifetime of a repeating source ~10yr suggests <~10% of BNS mergers form an FRB-producing remnant NS!

LogN-LogS Plot for FRBs



repeating/single <~ 0.1

@1Jy (Parkes)

→ f <~ 400

The lifetime of a repeating source ~10yr suggests <~10% of BNS mergers form an FRB-producing remnant NS!

Consistent with the fact that the only repeating FRB was discovered by Arecibo survey

Conclusion & Prediction

- The Double population model by BNS mergers is broadly consistent with observational properties of FRB 121102

- Repeating FRBs should also arise from **old galaxies (e.g., elliptical)**

- If a BNS merger detected by GW is localized by EM counterparts (e.g., kilonova), **there is a good chance to discover repeating FRBs in 1-10 yr**

- **The repeater/non-repeater detection ratio rapidly increases with improving detector sensitivity.** This may explain that the only repeating FRB 121102 was discovered by the most sensitive FRB search with Arecibo

Search for FRB121102-like Radio Source

Ofek '17

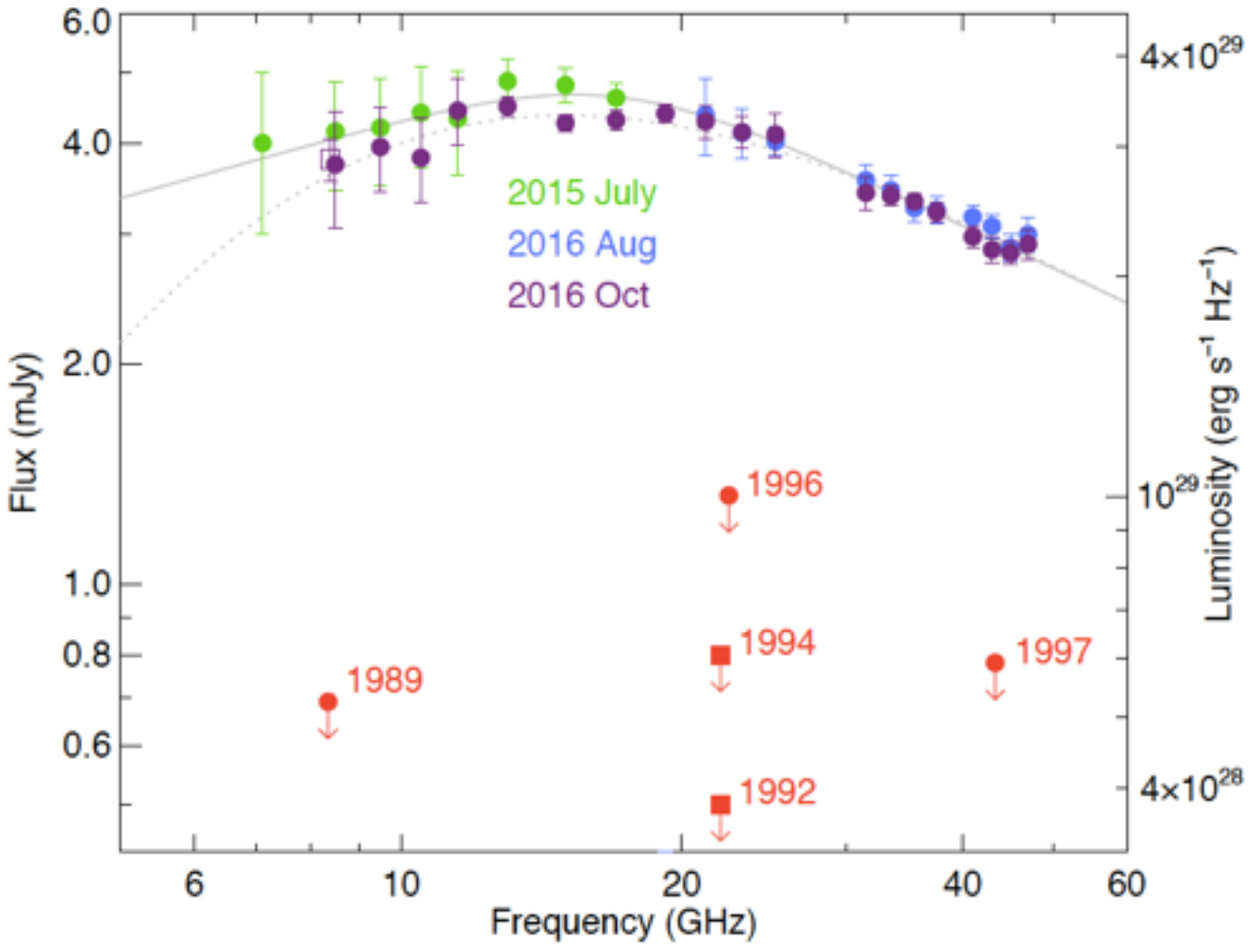
Table 1
Luminous Persistent Radio Source Candidates

f_p (mJy)	Δf_p (mJy)	L/L_{pers}	z	Comment
2.1	0.14	0.14	0.023	Spiral arm + IR source
2.9	0.14	0.13	0.019	Off galaxy center; passive galaxy
4.2	0.13	0.16	0.018	Near spiral arm; near red+IR source
3.2	0.15	0.21	0.023	Edge of spiral disk; red faint source?
2.8	0.13	0.11	0.018	Spiral arm
2.3	0.15	0.12	0.021	Spiral arm
2.2	0.14	0.14	0.023	Edge of spiral galaxy; IR source
2.0	0.15	0.11	0.022	Small blue galaxy; near center
1.5	0.15	0.11	0.025	Elliptical galaxy halo; no vis/IR source
3.5	0.20	0.26	0.025	Edge of galaxy; No optical or IR source
21.1	0.15	0.95	0.020	Compact blue star-forming galaxy

- 11 luminous radio sources in nearby (<108 Mpc) galaxies with offsets from the nucleus, whose *L* are similar to the persistent radio source associated with FRB 121102.
- Number density of these is **~ 5×10^{-5} Mpc^{-3}**
- Given the typical age **~10 yr** in our scenario, this translates **~ 5×10^{3} yr^{-1} Gpc^{-3},** which is interestingly similar to R_{BNS}
- **2 of the 11 sources are in old galaxies (passive & elliptical),** which cannot be explained by SN scenario (Nicholl+'17)

Cygnus A-2 as a Repeating FRB Source?

Perley +'17



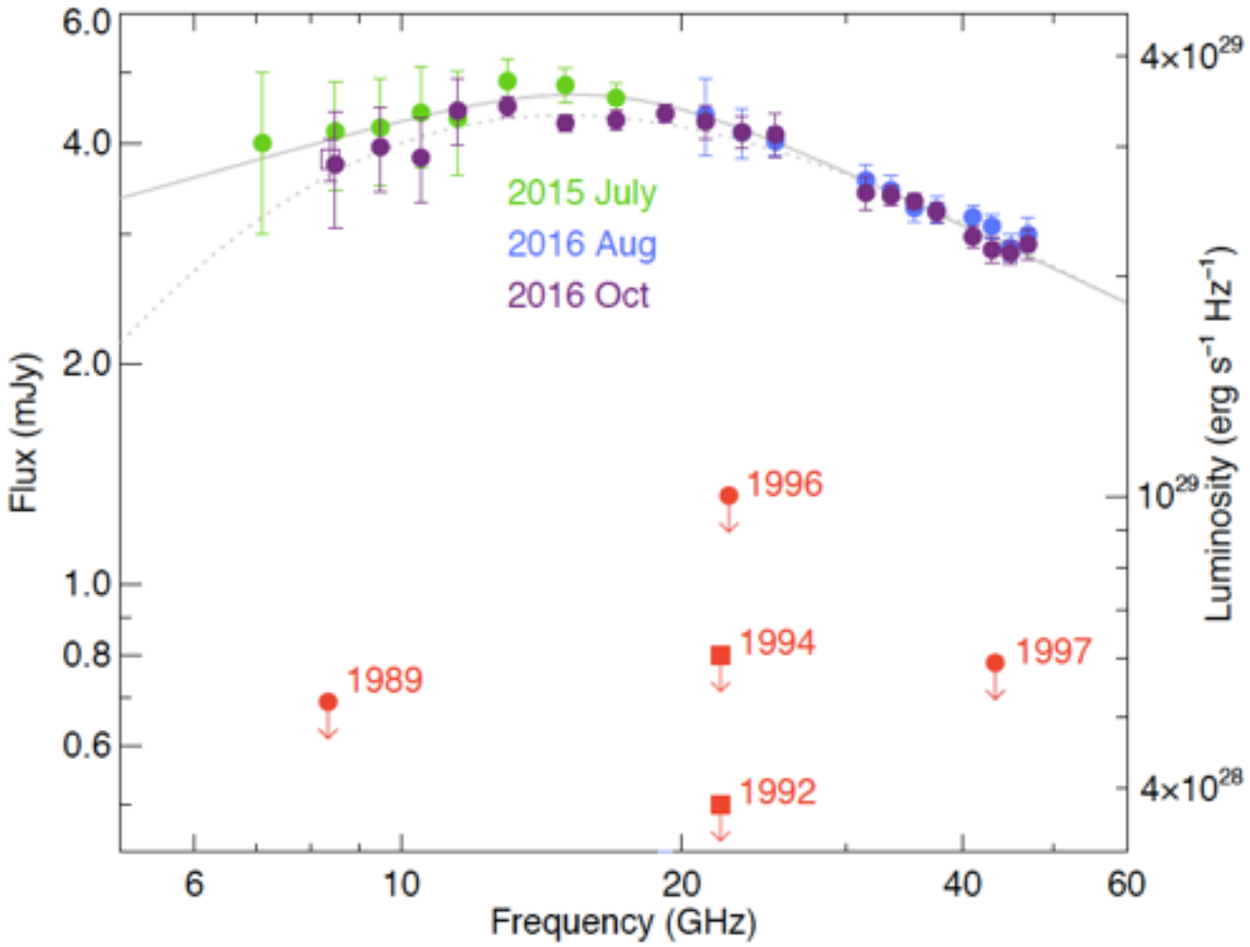
- A new radio source detected in 2015 but was not present until 1997 (appearance timescale **<~ 10 yr ?**).

- Unusually bright radio luminosity as a supernova, **$\nu L_\nu \approx 6\times10^{39}$ erg s^{-1}**, is very similar to the FRB 121102 radio source

- Projected offsets of 460 pc from the nucleus of Cygnus A (**z= 0.056**): much closer than FRB 121102 (z~0.2)

Cygnus A-2 as a Repeating FRB Source?

Perley +'17



- A new radio source detected in 2015 but was not present until 1997 (appearance timescale **<~ 10 yr ?**).
- Unusually bright radio luminosity as a supernova, **$\nu L_\nu \approx 6\times10^{39}$ erg s^{-1}**, is very similar to the FRB 121102 radio source
- Projected offsets of 460 pc from the nucleus of Cygnus A (**z= 0.056**): much closer than FRB 121102 (z~0.2)

If Cygnus A-2 is powered by a BNS merger remnant, a radio monitoring of this may lead to a discovery of another repeating FRB source.

Summary

- The apparent two populations (repeating and non-repeating) could be interpreted as events from a single progenitor (BNS)
  - **Single FRBs : produced by the merger process (t - t_{merge} =-0.5 to 0.5ms)**
  - **Repeating FRBs : produced by a remnant NS activity (age ~ 1-10yr)**
- The detection rate for repeating/non-repeating bursts
  - **Detection number ratio rapidly increases with improving sensitivity.**
- If a BNS merger detected by GW is localized by EM counterparts (e.g., kilonova), **there is a good chance to discover repeating FRBs in 1-10 yr.**