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

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

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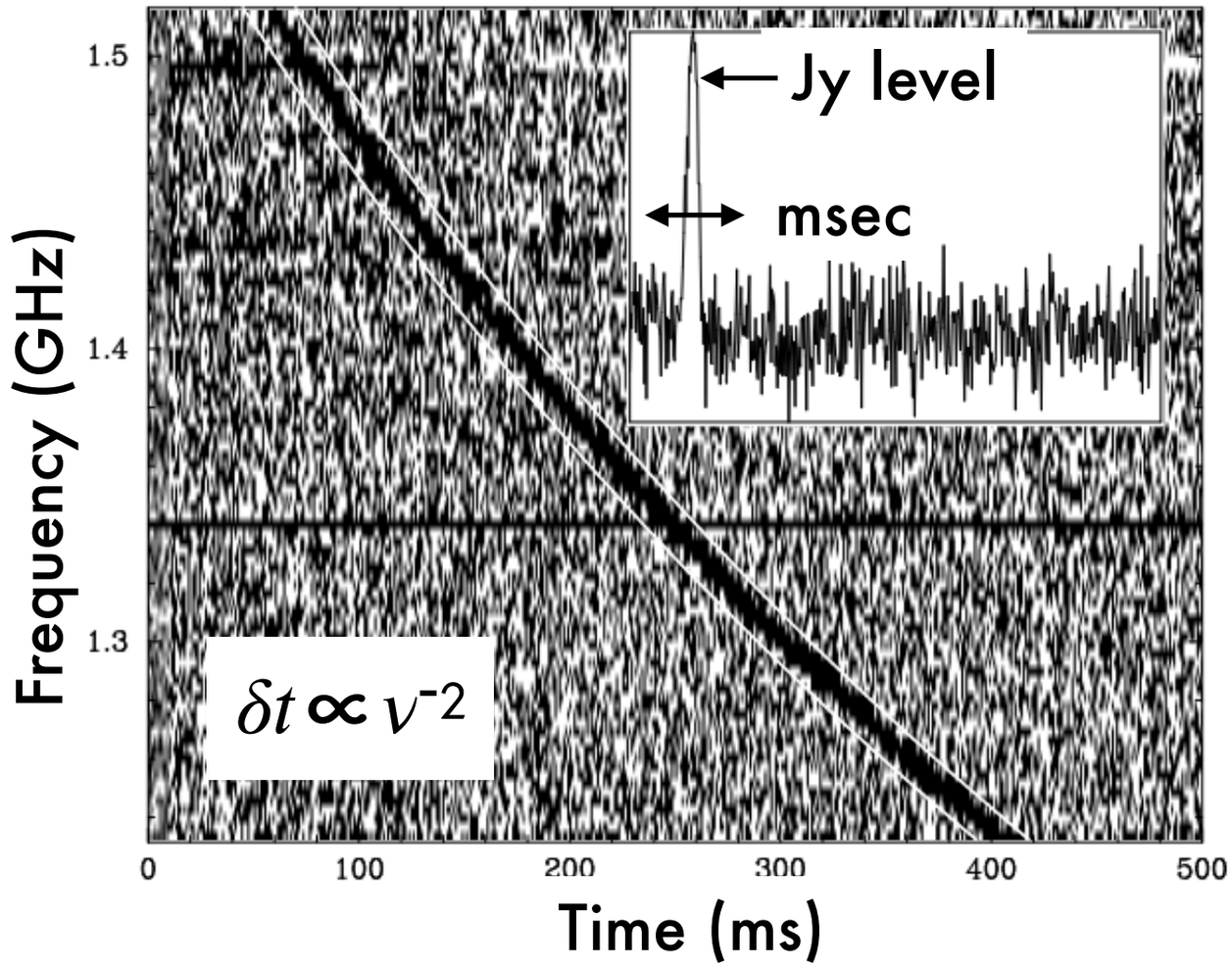
Introduction

Fast radio bursts (FRBs, 2007-)

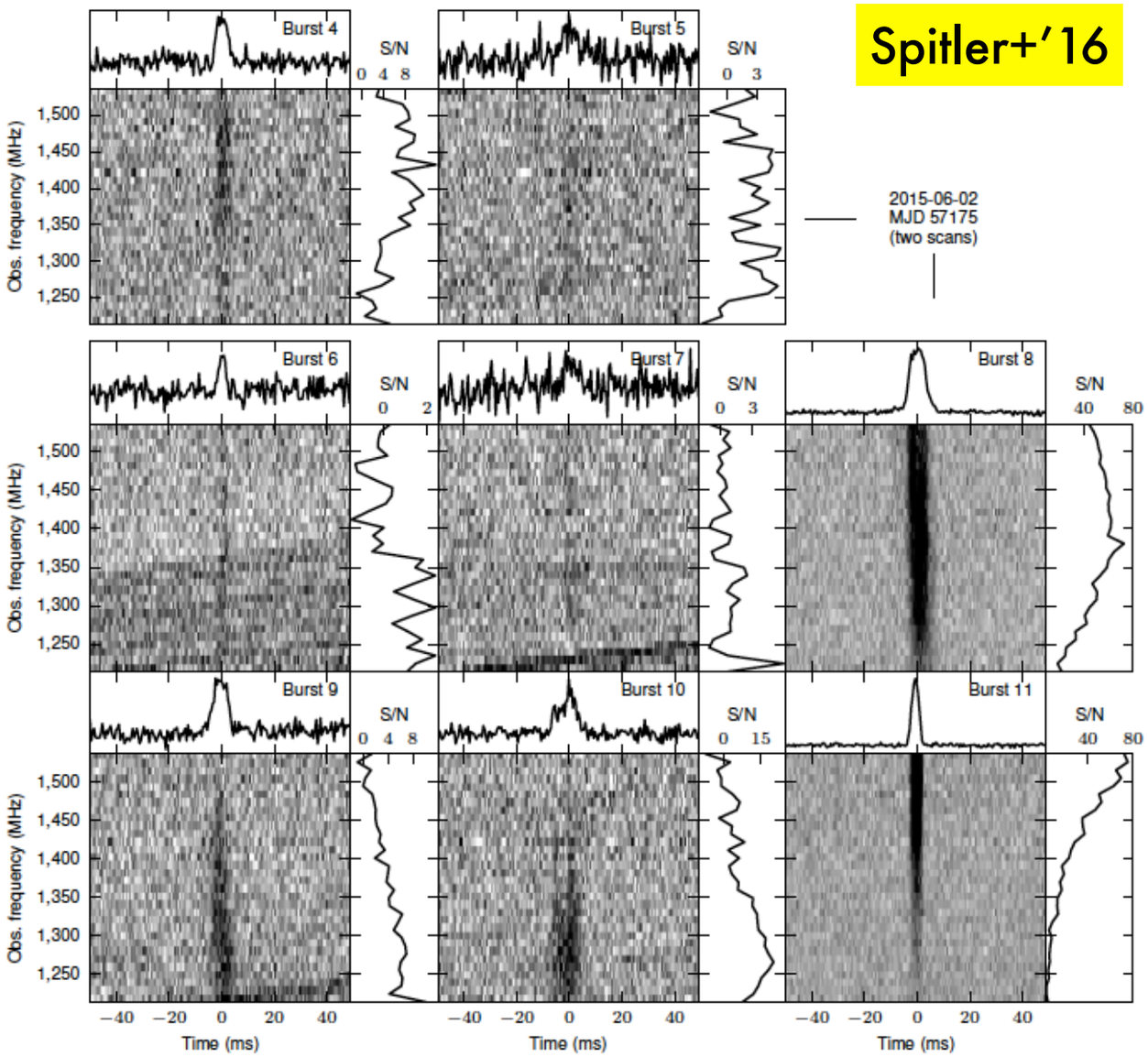
- Duration <~1-10 ms
- Flux = 0.1-1 Jy @GHz
- Unique frequency-dependent time delay due to IGM
- DM= $\int_0^D n_e d\ell$ = 300-2500 pc cm^{-3} (cosmological distances: z ~1)
- Rate : 10^3-10^4 sky^{-1} day^{-1}
- Energy : 10^{38}-10^{41} erg
- Most of FRBs do not show evidence for repetition



Dynamic spectra & light curve of FRB 010724 (Lorimer+'07, see also Petroff+'16)

Arecibo FRB 121102 repeats!

- Discovered by the high sensitivity search of Arecibo, while non-repeating FRBs are mostly found by Parkes
- DMs are constant around 560 pc cm^{-3}
- Lowest luminosity FRB (~0.1 Jy @ z=0.19)
- No apparent periodicity



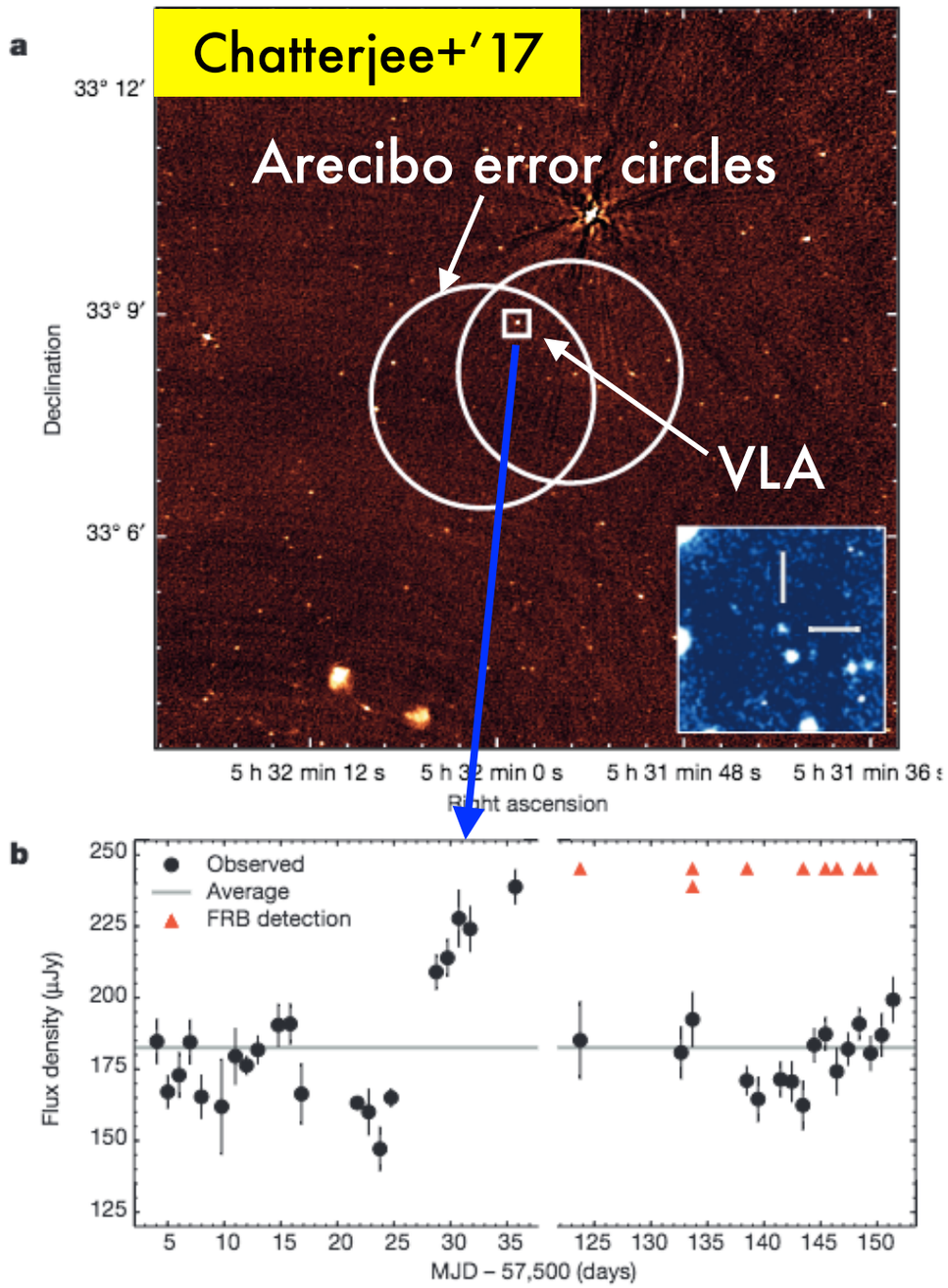
Host galaxy of FRB 121102 identified

- VLA detection and 0.1″ localization (Chatterjee+'17)

- Dwarf, star-forming host galaxy at z=0.19 (Tendulkar+'17)
  - SFR ~0.4 M_{sun}/yr, M_{star} ~ (4-7)e7 M_{sun}

- Radio counterpart
  - persistent radio source (10^{39} erg/s)
  - offset from host nucleus
  - size <~ 0.7 pc (Marcote+'17)

- The progenitor is most likely a young neutron star



Faraday rotation of FRBs

- Faraday rotation measure: $$RM = \frac{e^3}{2\pi m_e^2 c^4} \int n_e B_{\parallel} dl$$
  - Galactic nearby pulsar: RM <~ 100 rad m^{-2}
- FRB 121102 shows extremely large RMs (~10^5 rad m^{-2}) and fast variability
  - implying a dense, strongly magnetized environment (Michilli+'18)
- Some non-repeating FRBs show negligible host RMs (similar to Galactic RMs)
  - FRB 150807 (RM <~2 rad m^{-2}; Ravi+'17)
  - FRB 150215 (RM <25 rad m^{-2}; Petroff+'17).
- At least, some FRBs favor clean environment
  - non-repeating FRB population may originate from BNS mergers?

Non-Repeating FRBs from BNS mergers

(Non-repeating) FRBs from BNS mergers

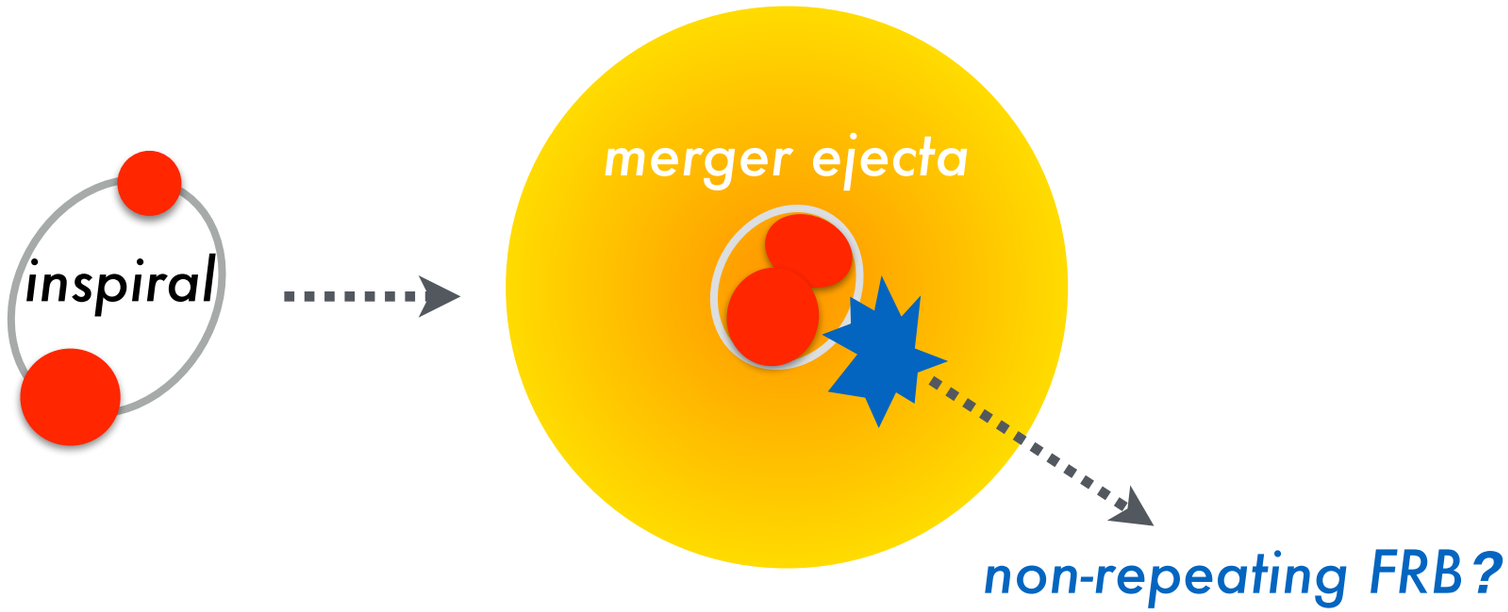
Totani 2013, PASJ, 65, L12

- FRB rate vs. NS-NS merger rate
  - FRB rate 10^3-10^4 /day/sky at z=1 is roughly 10^3-10^4 /Gpc^3/yr at z=0
  - high end of NS-NS merger rate estimate before GW 170817
  - now NS-NS rate 1540^{+3200}_{-1220} /Gpc^3/yr (LVC '17 PRL 119, 161101)
- predicted radio flux by dipole radiation is similar to FRBs, if
  - dipole with B ~ 10^{12} G and rotation period ~ msec
  - radio conversion efficiency similar to pulsars (~ 10^{-4})

$$\dot{E} = -6.2\times10^{45}\left(\frac{B}{10^{12.5}\,\mathrm{G}}\right)^2\left(\frac{R}{10\,\mathrm{km}}\right)^6 \times\left(\frac{P}{0.5\,\mathrm{ms}}\right)^{-4}\mathrm{erg\ s^{-1}}\,.$$

$$F_\nu = \frac{1}{\nu_{\rm obs}}\frac{\epsilon_{\rm r}|\dot{E}|}{4\pi D_{\rm lum}^2} = 0.02\left(\frac{\epsilon_{\rm r}}{10^{-4}}\right)\left(\frac{D_{\rm lum}}{4.6\,\mathrm{Gpc}}\right)^{-2} \times\left(\frac{B}{10^{12.5}\,\mathrm{G}}\right)^2\left(\frac{R}{10\,\mathrm{km}}\right)^6\left(\frac{P}{0.5\,\mathrm{ms}}\right)^{-4}\mathrm{Jy}\,.$$

A theoretical concern…

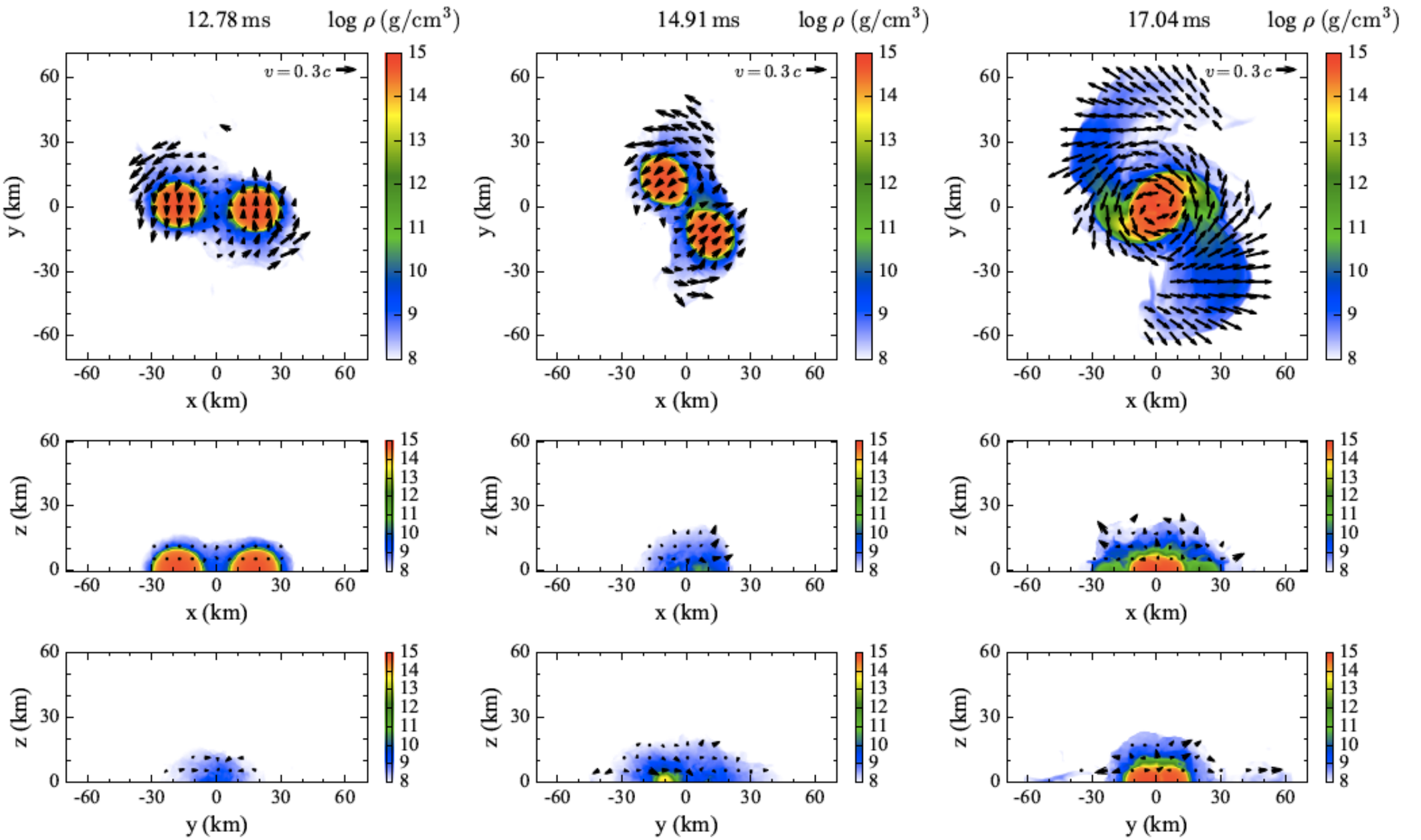


The merger environment could be polluted by dense dynamical ejecta, which would suppress radio emissions

Is there any chance of FRB transmission? → Simulation

BNS merger ejecta vs radio emission

BNS merger simulation by K. Kiuchi



BNS merger ejecta vs radio emission

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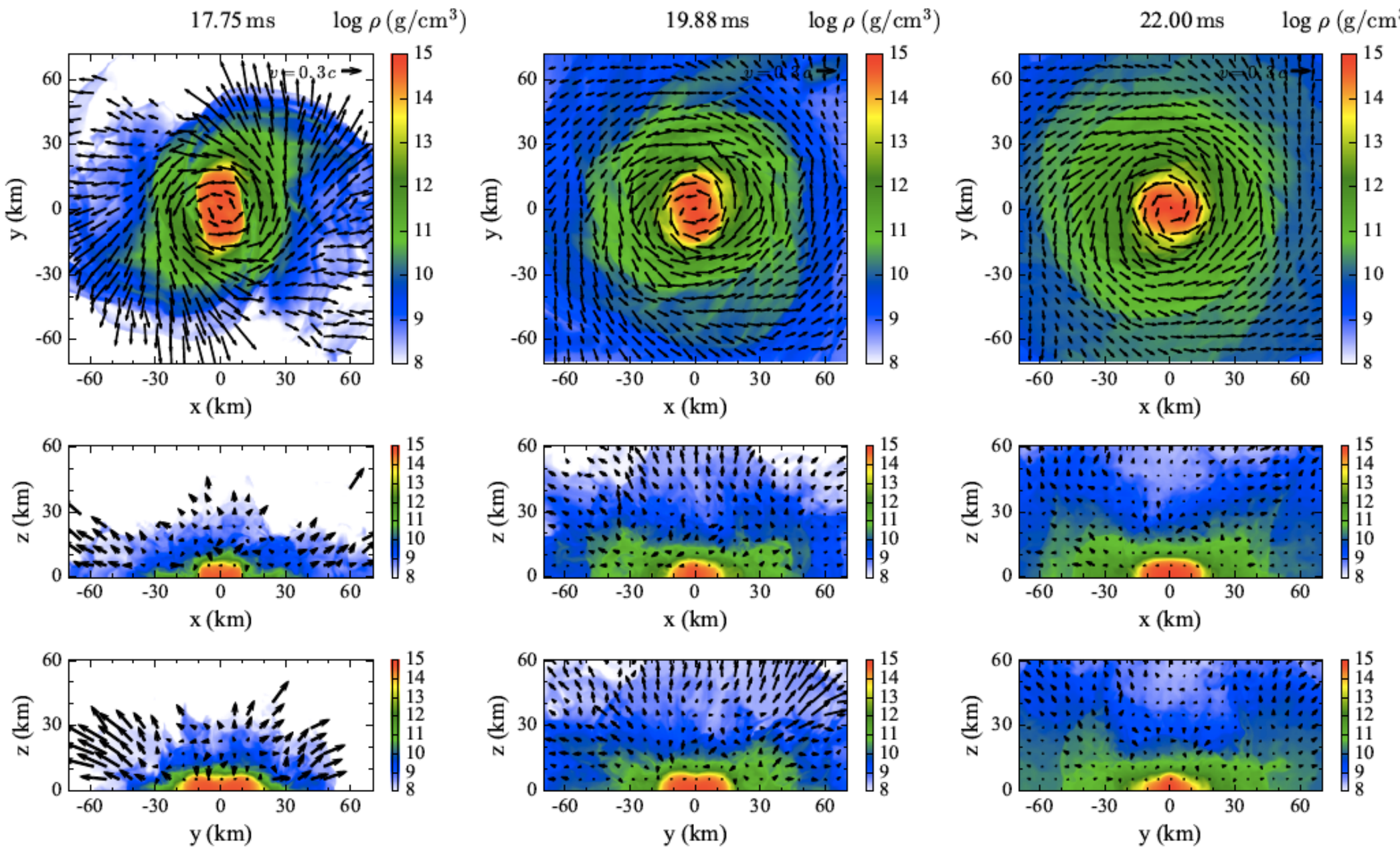
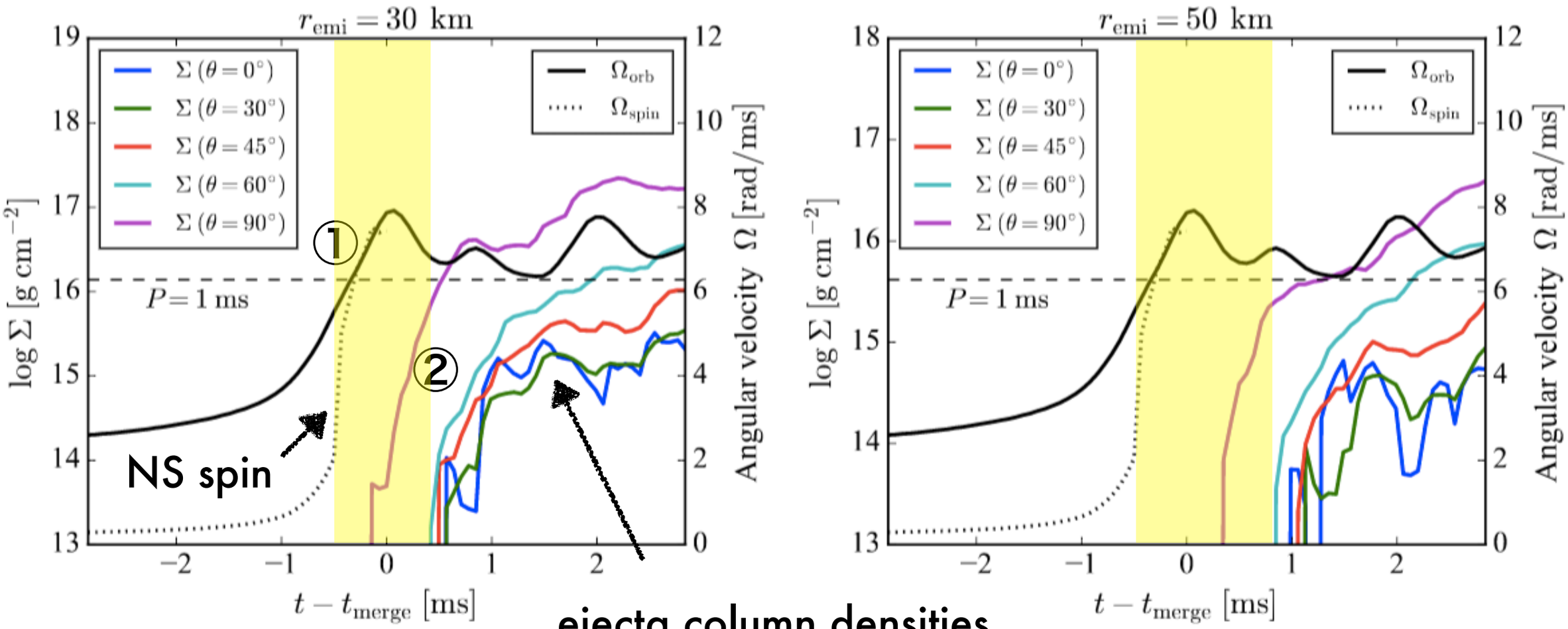


NS spin-up vs ejecta formation

SY, T. Totani & K. Kiuchi'18



ejecta column densities

- 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 msec
- "Non-repeatingness" may be explained by the screening of ejecta

Repeating FRBs from BNS mergers

Then, how to explain repeating FRBs?

- A favored model: a young NS from supernovae (Kashiyama & Murase'17; Metzger+'17)
  - Super-luminous supernovae (SLSNe) may be powered by magnetars
  - SLSN occurs preferentially in dwarf galaxies like FRB 121102

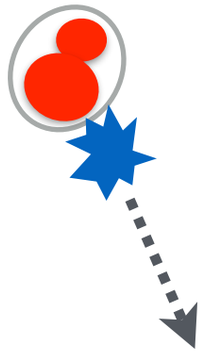
- Some fraction of BNS mergers may leave a long-lived massive NS
  - fraction depends on NS mass distribution and equation of state
  - rapidly rotating (~msec) compared with general NS from supernovae

- BNS merger rate is much higher (~100x) than SLSN rate (40 /Gpc^3/yr)

- Ejecta mass of BNS merger (0.01 M_{sun}) much smaller than supernovae
  - becomes transparent to radio signal earlier, i.e., younger NS

Double population model by BNS mergers

BNS merger
(Phase I)



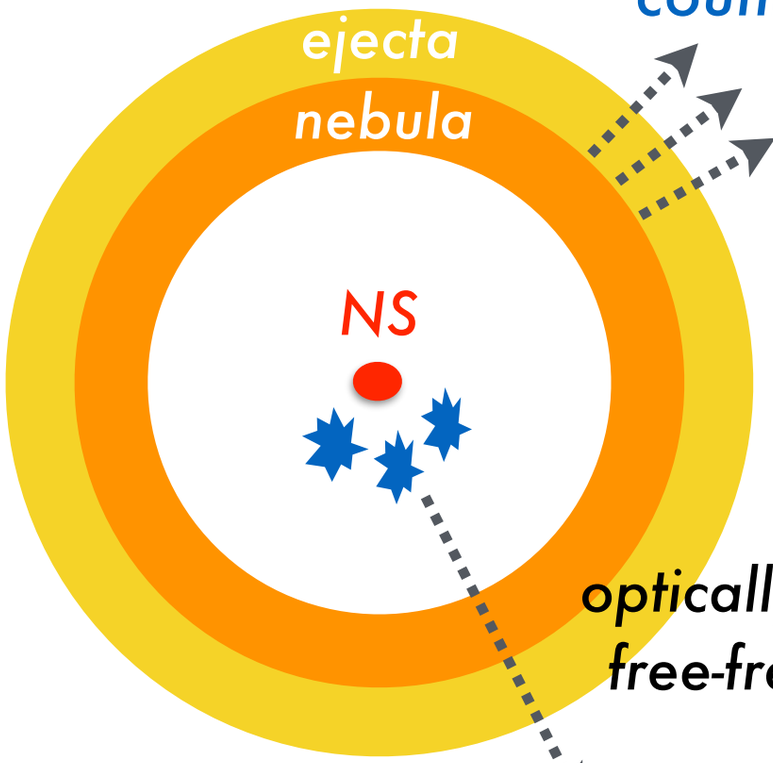
non-repeating FRB

remnant NS
(Phase II)

dense ejecta prohibit
radio emission to escape

PWN
(Phase III)

radio
counterpart



optically thin to
free-free abs.

repeating FRBs

Assuming a remnant NS with B~$10^{12.5}$ G inside ejecta (0.01 M_{sun} and 0.1 c), the allowed NS age is 1-10 yr

FRB rate evolution model

Double population model

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

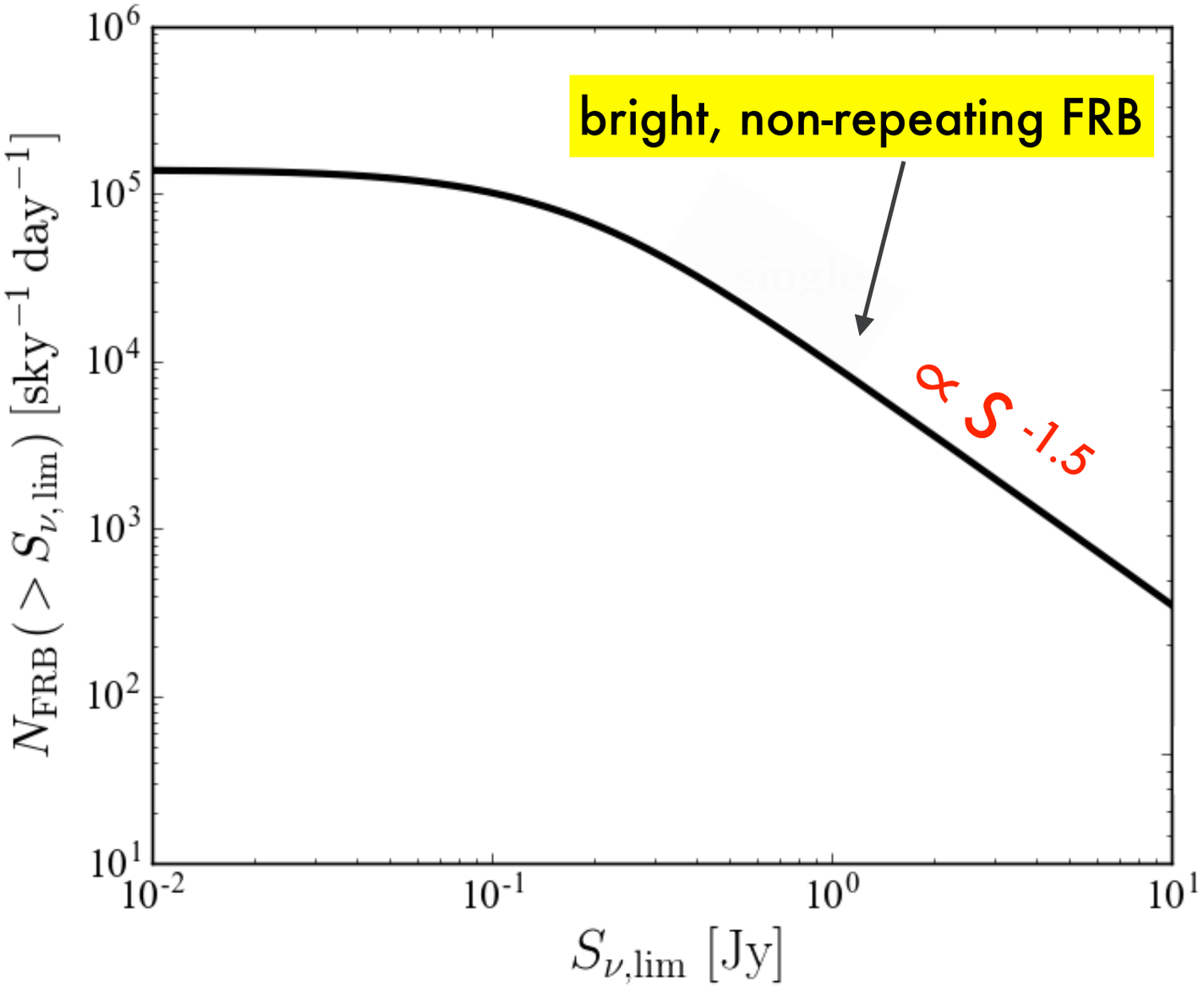
- Standard candle approximation:

  - 1.0Jy@z=1 (bright) for non-repeating 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:

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

Why the faintest FRB found as a repeater?



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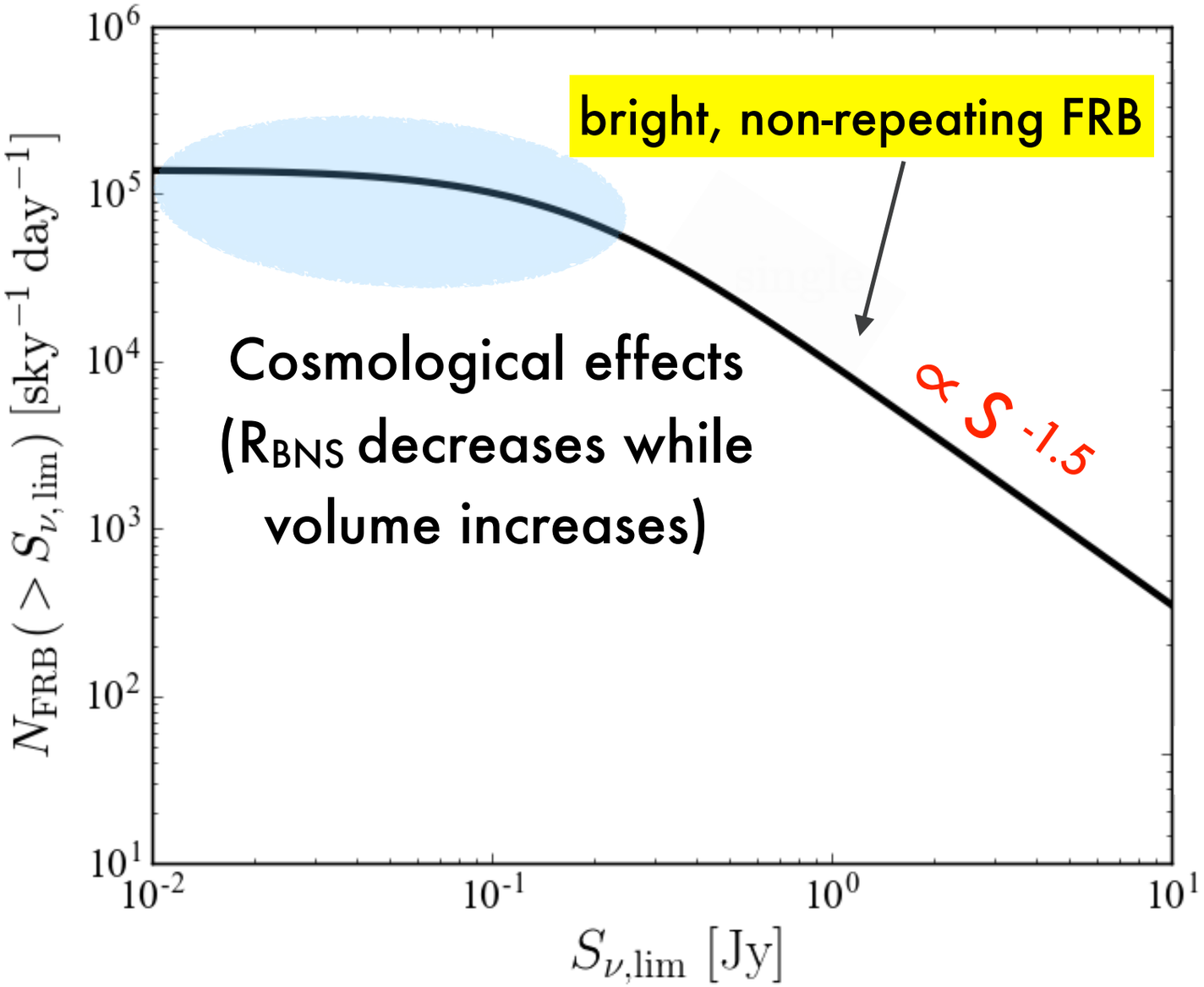

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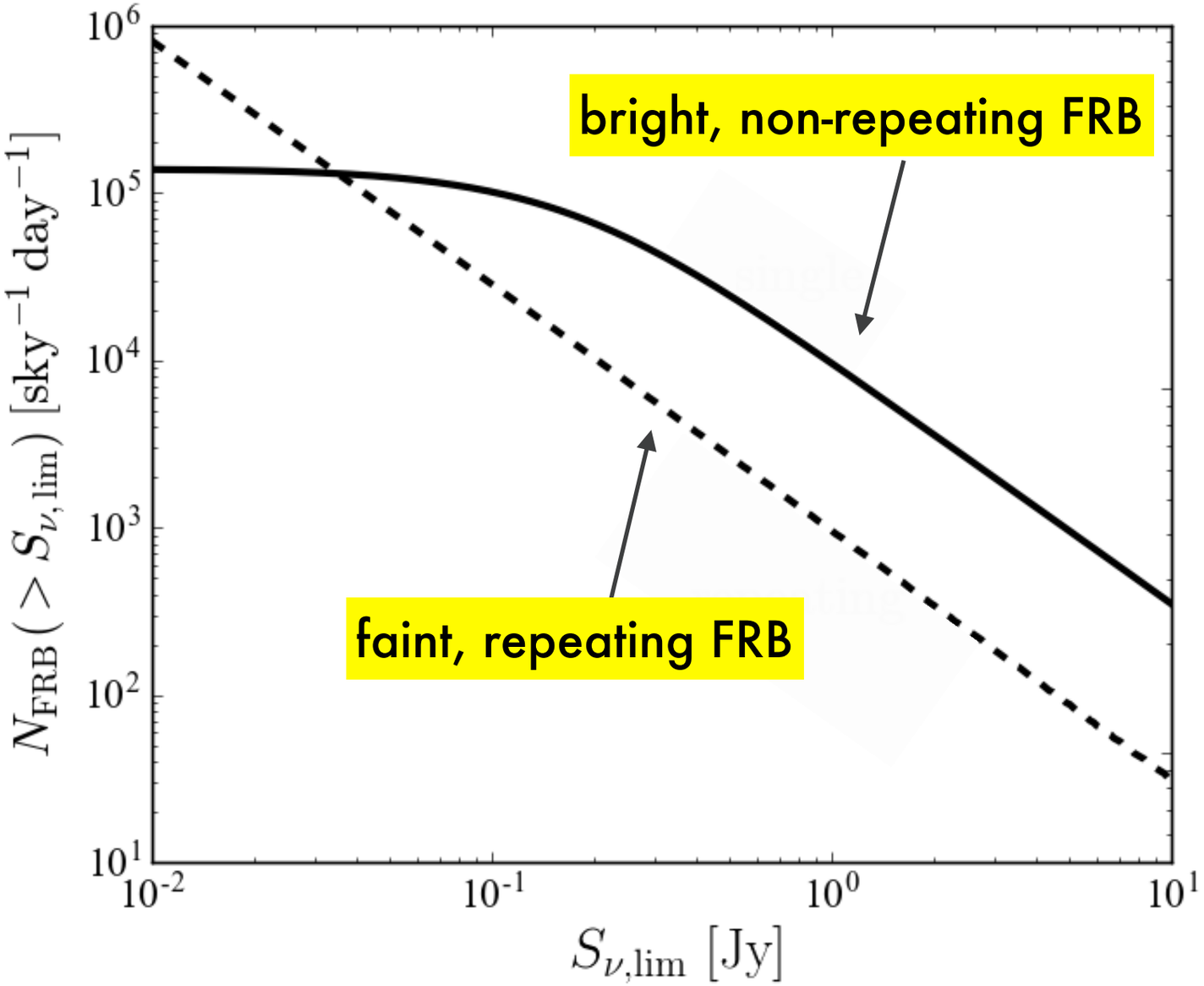

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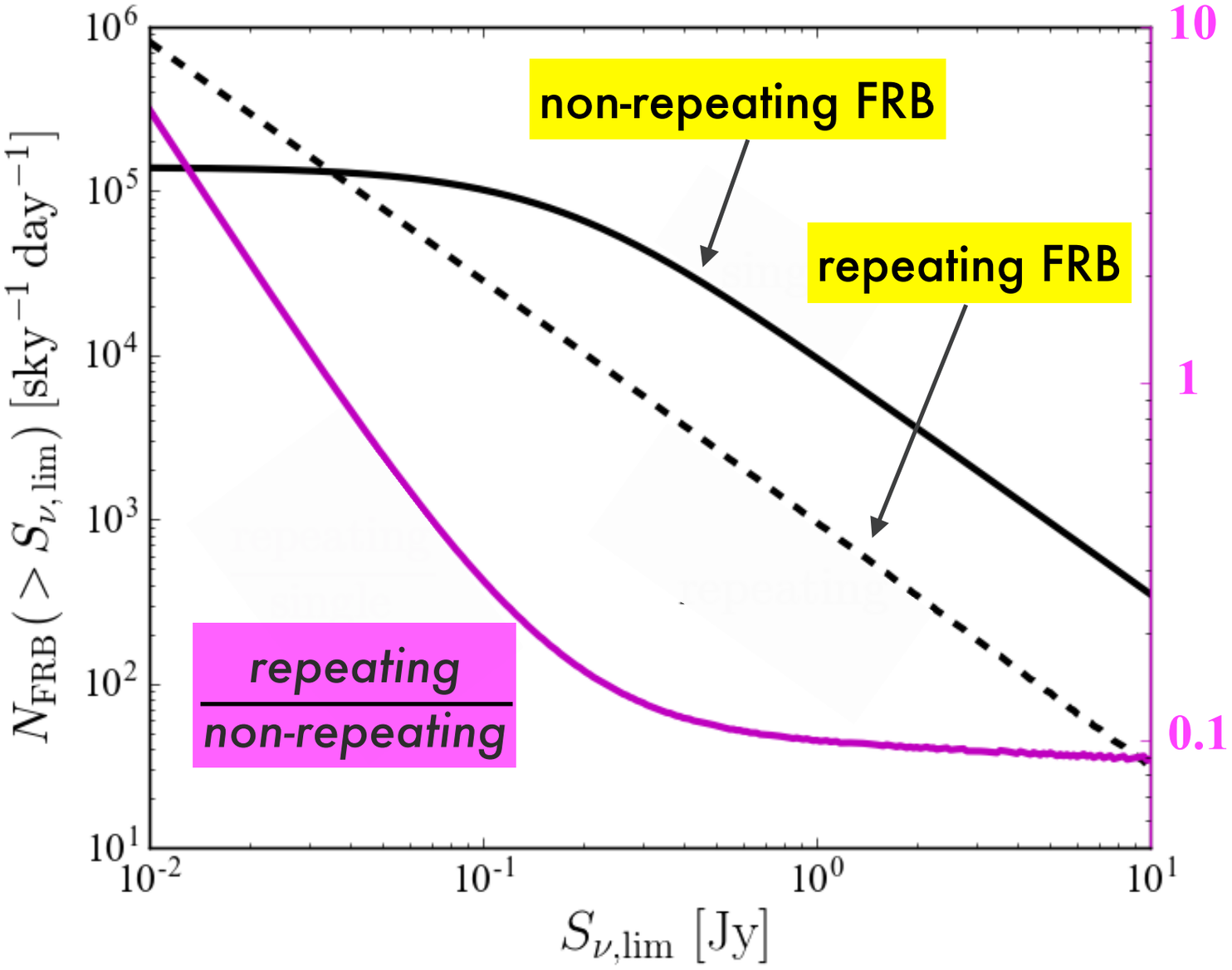
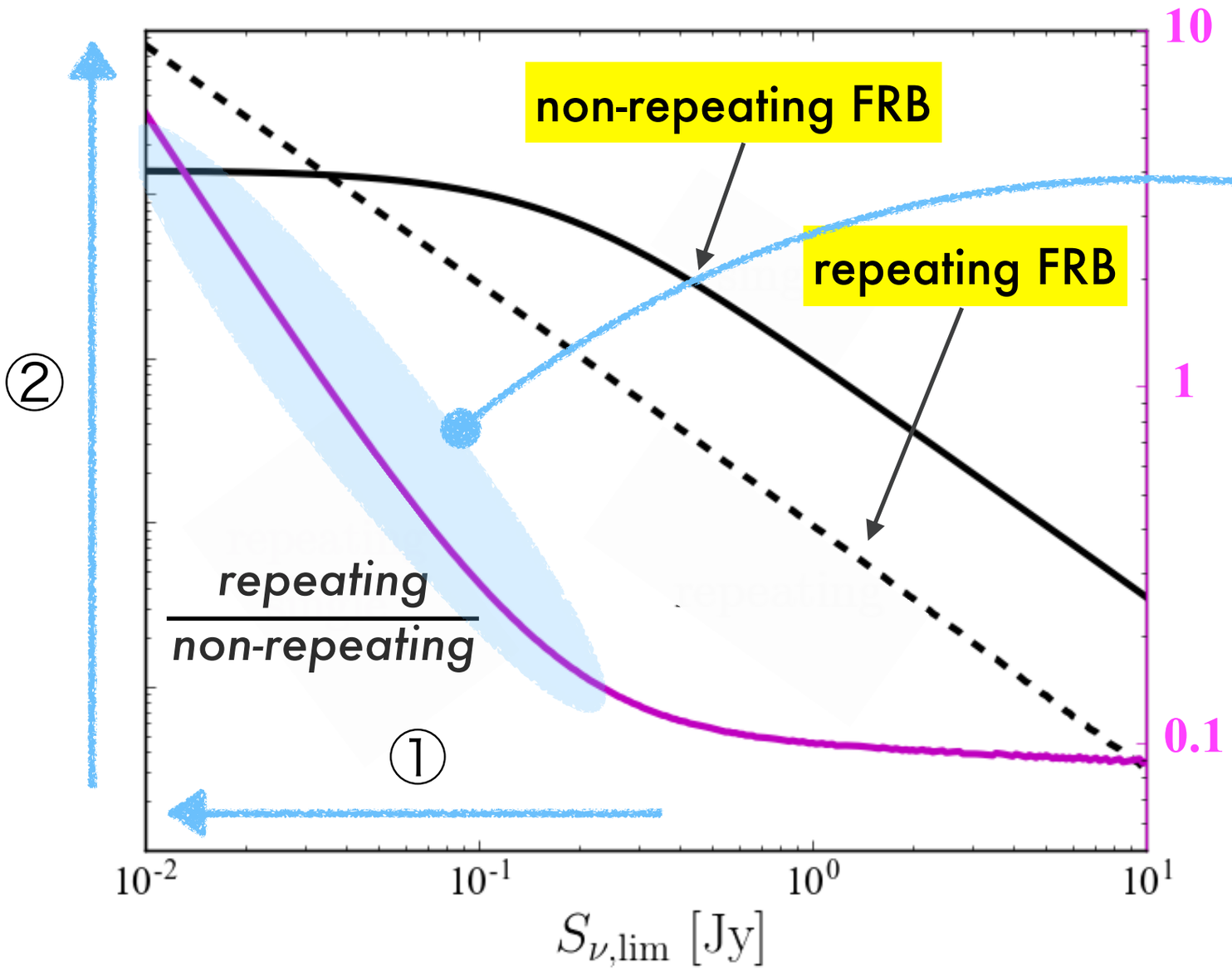


- Assuming *repeating to non-repeating ratio* <~ 0.1 at about 1Jy (@Parkes)

  → f <~ 400

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

Why the faintest FRB found as a repeater?



① With improving sensitivity,

② *repeater/non-repeater ratio* rapidly increases

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

Arecibo: Parkes = 10:1 (sensitivity)

Summary

- Faraday rotation observations imply at least some non-repeating FRBs are from clean environment (i.e., not star-forming) → NS-NS merger?

- Simulation suggests the ejecta appears only about 1 ms after the rotation speed of the merged NS becomes the maximum.
  - There is a possibility of non-repeating FRB production

- Repeating FRB might be explained by a long-lived BNS merger remnant NS
  - Appearance timescale and lifetime of FRB signals are 1-10 yr (earlier and shorter than in SN scenario)
  - Repeating FRBs should also arise from elliptical galaxies
  - There is a good chance to discover repeating FRBs in 1-10 yr after GW detection and EM counterpart localization of BNS mergers

- Double population model (bright non-repeaters and faint repeaters) can explain why the faintest FRB 121102 has been found as a repeater

Supplementary slides

Search for FRB121102-like Radio Source

Ofek '17

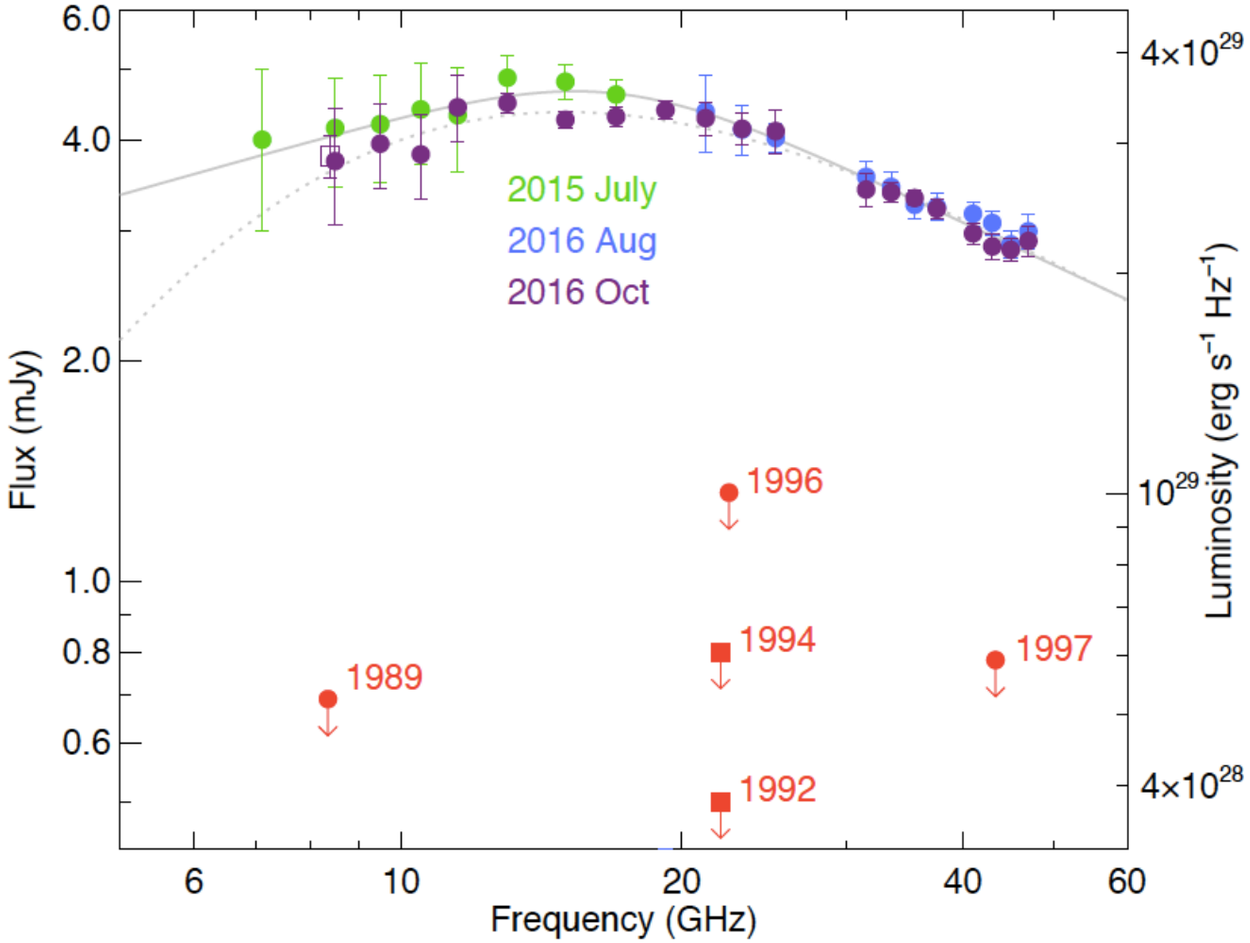
Table 1
Luminous Persistent Radio Source Candidates

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)

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.