Fast Radio Burst and Non-thermal Afterglow from Binary Neutron Star Mergers

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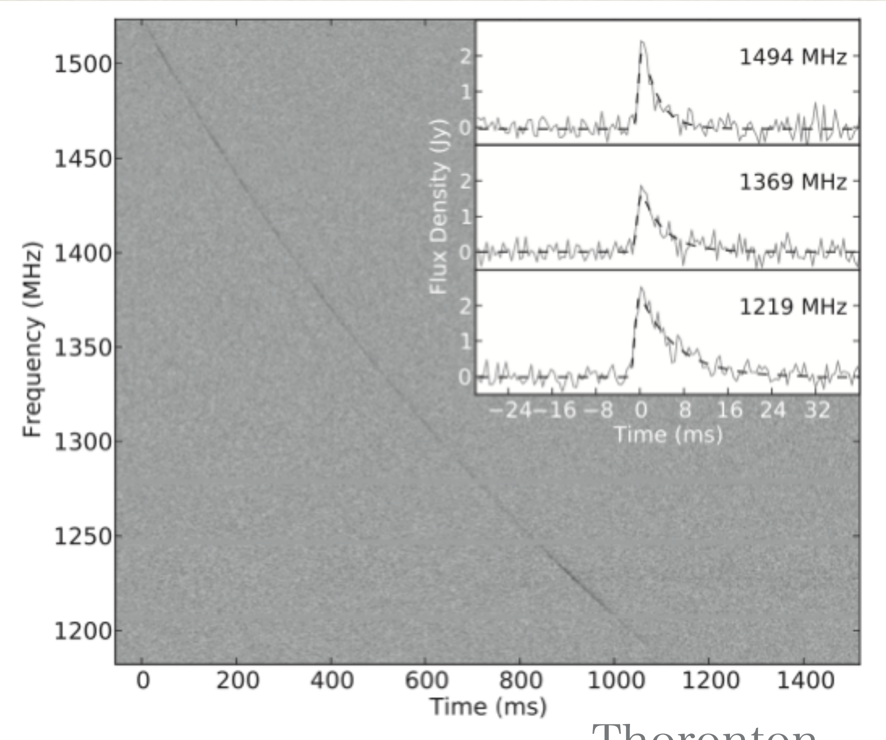
Outline

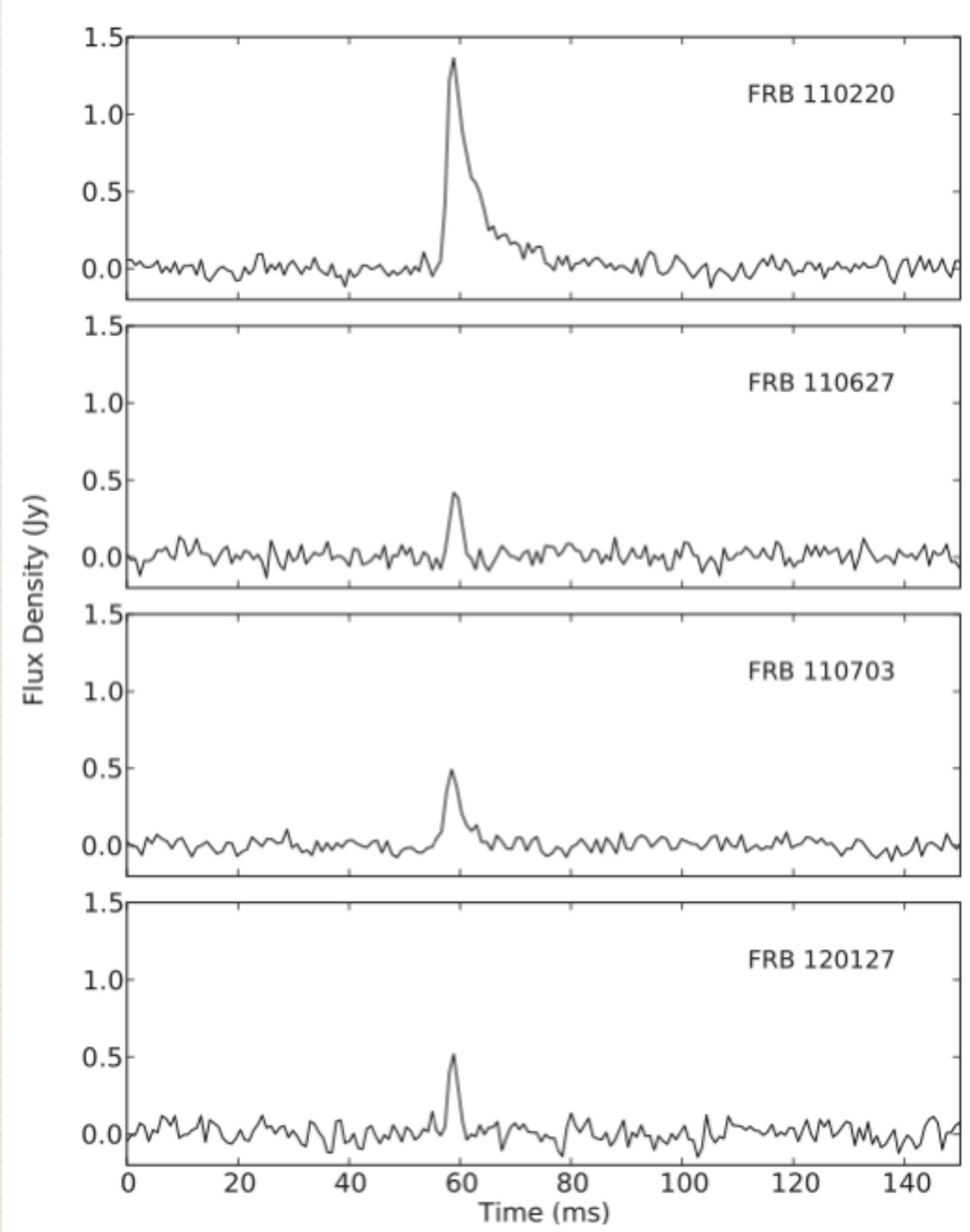
- Three recent papers by my students:
  - repeating and non-repeating FRBs from binary neutron star mergers
    - Yamasaki, TT, & Kiuchi '18, PASJ, 70, 39
  - A new, more natural modeling of electron energy distribution for the non-thermal afterglow of GW 170817
    - Lin, TT, & Kiuchi '18, arXiv:1810.02587
  - IceCube neutrinos from cosmic-rays in star-forming galaxies: a latest calculation by cosmological galaxy formation model
    - Sudoh, TT, & Kawanaka '18, PASJ, 70, 49

- repeating and non-repeating FRBs from binary neutron star mergers
  - Shotaro Yamasaki, TT, & Kiuchi '18, PASJ, 70, 39

Fast Radio Bursts: A New Transient Population at Cosmological Distances

- intrinsic pulse width <~ 1 msec (observed width broadened by scattering)
- event rate ~ $10^{3\text{-}4}$ /sky /day
- large dispersion measure implies z ~ 1





Thoronton

What’s the origin of FRBs?

- FRB 121102 is a repeater!
  - most likely a young neutron star
  - only one FRB detected by Arecibo (the faintest flux)
  - dwarf, star-forming host galaxy identified at z = 0.19
  - strong persistent radio flux detected (180 uJy, size < 0.7 pc)
  - only one case of confirmed repeating FRB: a different population from others?

- some FRBs show low rotation measure (e.g., FRB 150807, Ravi+’16)
  - highly magnetized environment like young supernova remnants or dense star forming regions not favored
  - clean environment such as neutron-star merger?

- FRB 171020 does not have any persistent radio counterpart similar to FRB 121102 (Mahony+’18)

(non-repeating) FRBs from NS-NS mergers

TT 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
    - c.f. short GRBs ~1-10 /Gpc^3/yr
  - 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)

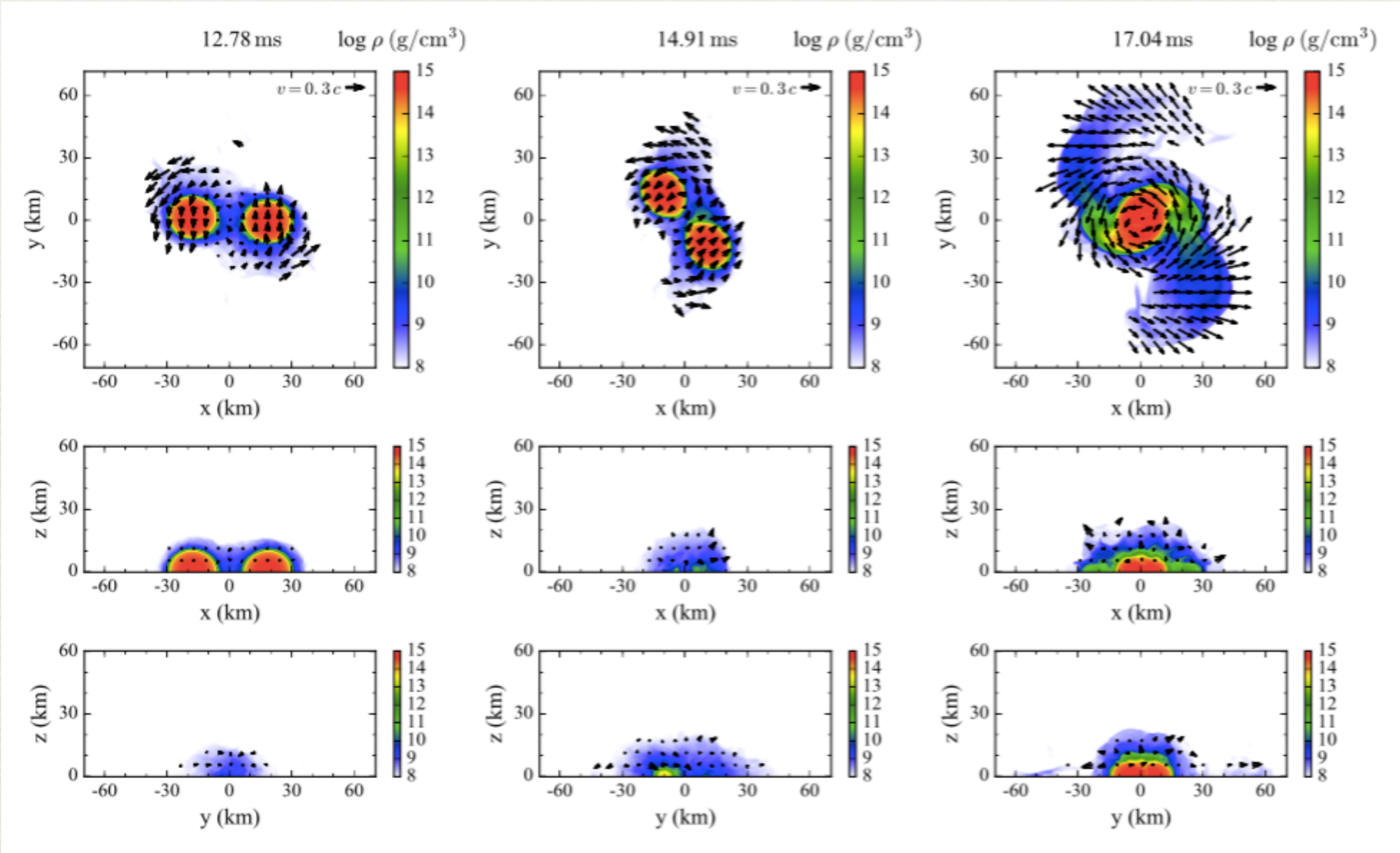
- predicted radio flux by dipole radiation is similar to FRBs, if
  - dipole with B ~ 10^{12} G and r ~ 10 km
  - rotation period ~ msec
  - radio conversion efficiency similar to pulsars (~10^{-4})

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

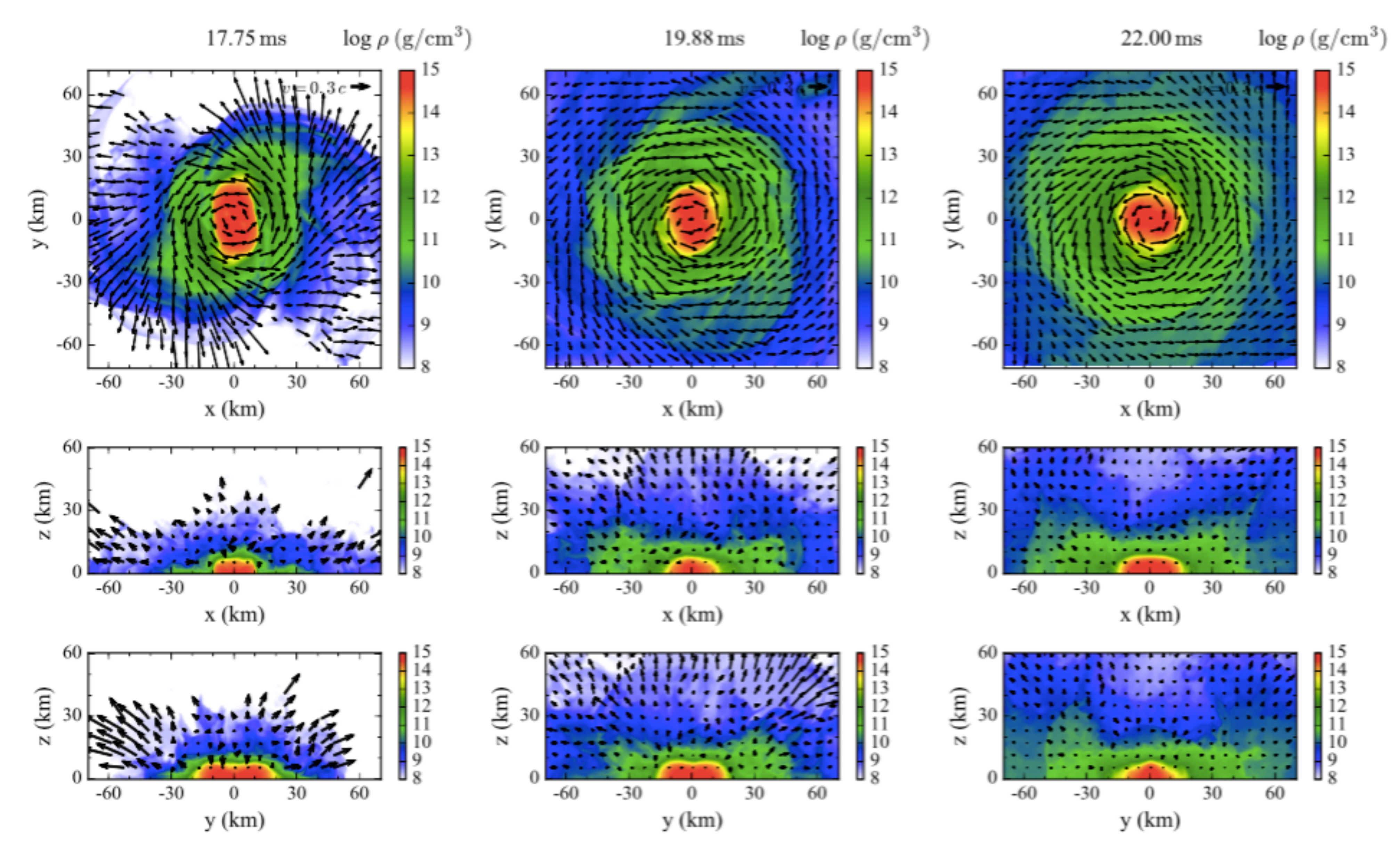
$$F_\nu = \frac{1}{\nu_{\rm obs}} \frac{\epsilon_{\rm r}|\dot{E}|}{4\pi D_{\rm lum}^2} = 0.02 \left(\frac{\epsilon_{\rm r}}{10^{-4}}\right) \left(\frac{D_{\rm lum}}{4.6\,\mathrm{Gpc}}\right)^{-2} \times \left(\frac{B}{10^{12.5}\,\mathrm{G}}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^6 \left(\frac{P}{0.5\,\mathrm{ms}}\right)^{-4}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

NS-NS merger ejecta vs. radio emission

- 10^{-3}~10^{-2} M◉ ejecta expected from merger
- no radio emission if they are absorbed by thick ejecta?



NS-NS merger simulation by K. Kiuchi

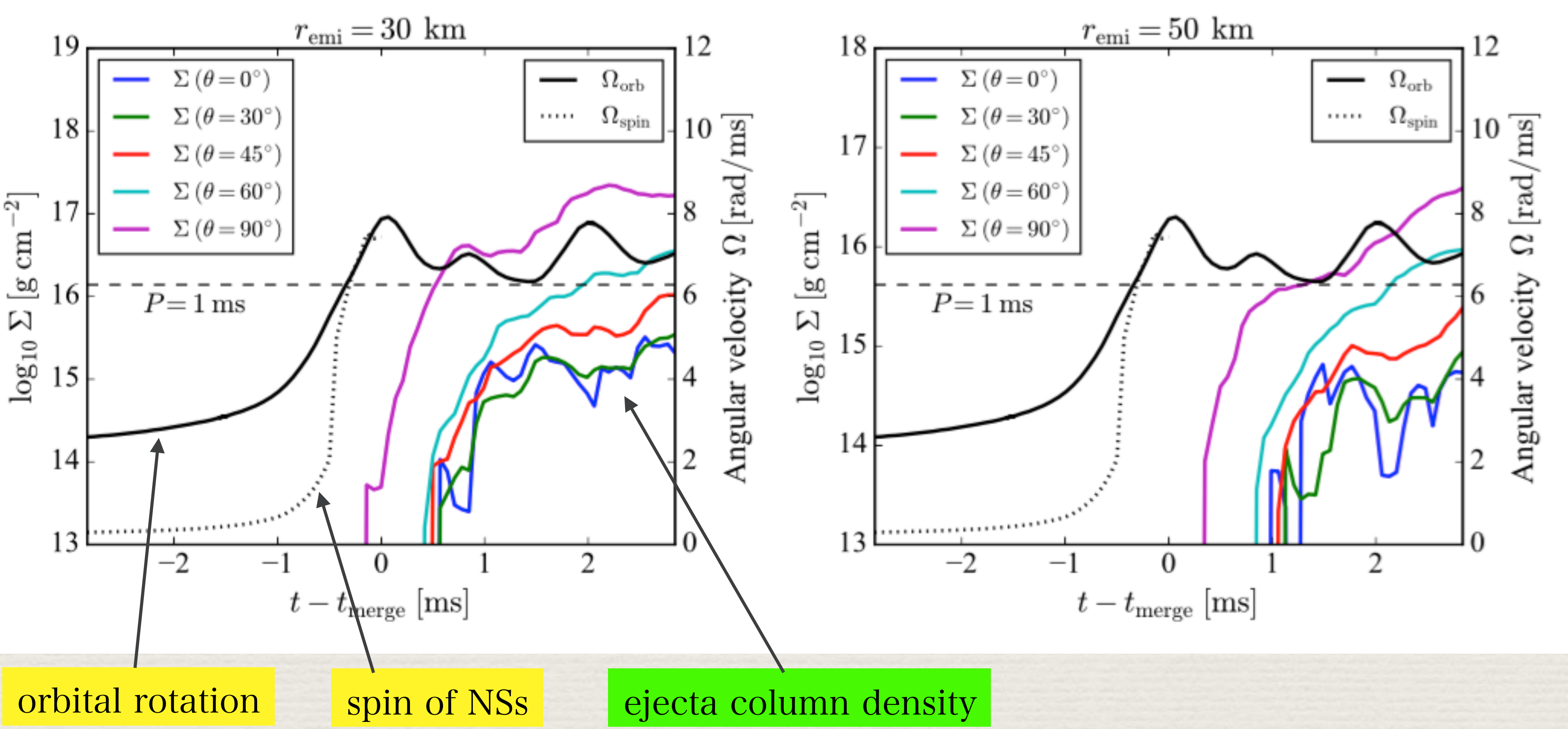


17.75 ms
19.88 ms
22.00 ms
log ρ (g/cm³)
v = 0.3c
x (km)
y (km)
z (km)

ejecta profile in merger simulation

- ejecta appears at r > 30 km only ~ 1 msec after the spin of merged star becomes maximum
- There is a time window (1-2 msec) to produce a FRB before hidden by ejecta
- ejecta formation gives a possible explanation for no repeating bursts for many FRBs

Yamasaki, TT, & Kiuchi '17



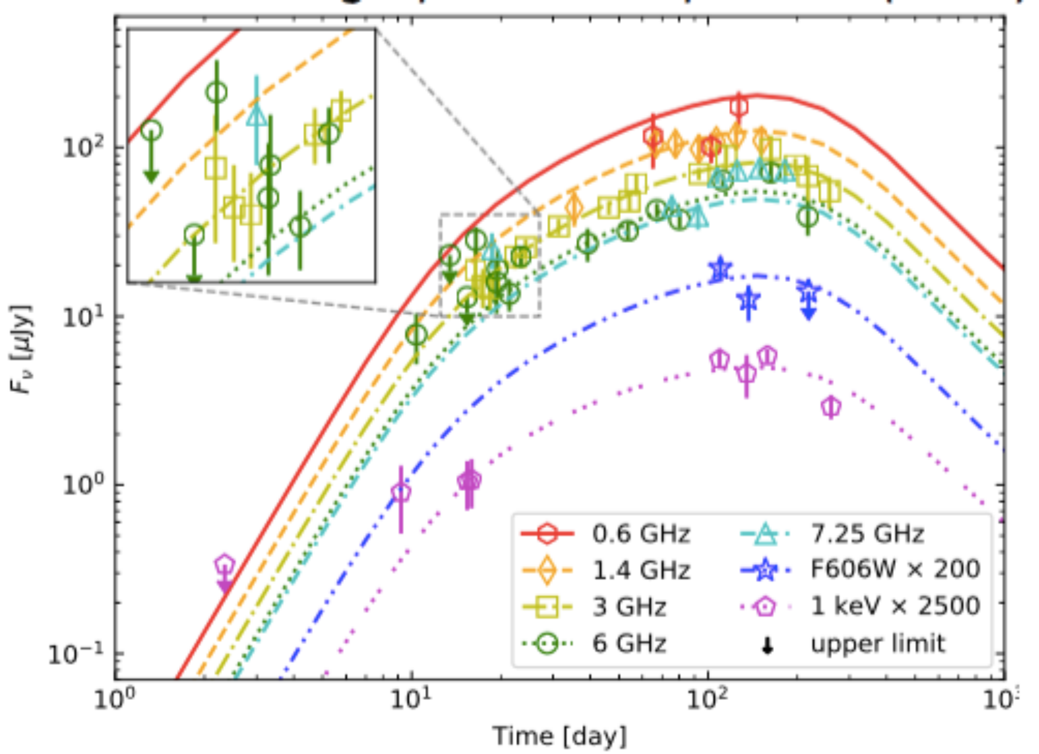
repeating FRB from NS-NS mergers

Yamasaki, TT, & Kiuchi '17

- a long-lived massive NS may be left after a fraction of NS-NS mergers, depending on EOS
- event rate of NS-NS mergers much (~100x) higher than SLSN rate (40 /Gpc^3/yr)
- merger ejecta becomes transparent in 1-10 yrs to radio signals
  - c.f. ~10-100 yrs for supernova scenario
- repeating burst rate of FRB 121102 broadly consistent with NS-NS merger rate if the repeater life time is ~10 yrs
- persistent radio emission from pulsar wind nebular interacting with merger ejecta
- prediction:
  - ejecta much faster than supernova —> source size evolution may be seen for FRB 121102 in the future
  - repeating FRBs also from elliptical/passive galaxies
  - a repeating FRB appears ~10 yrs following a fraction of NS-NS mergers detected by GW

- A new, more natural modeling of electron energy distribution for the non-thermal afterglow of GW 170817
    - Haoxiang Lin, TT, & Kiuchi '18, arXiv:1810.02587

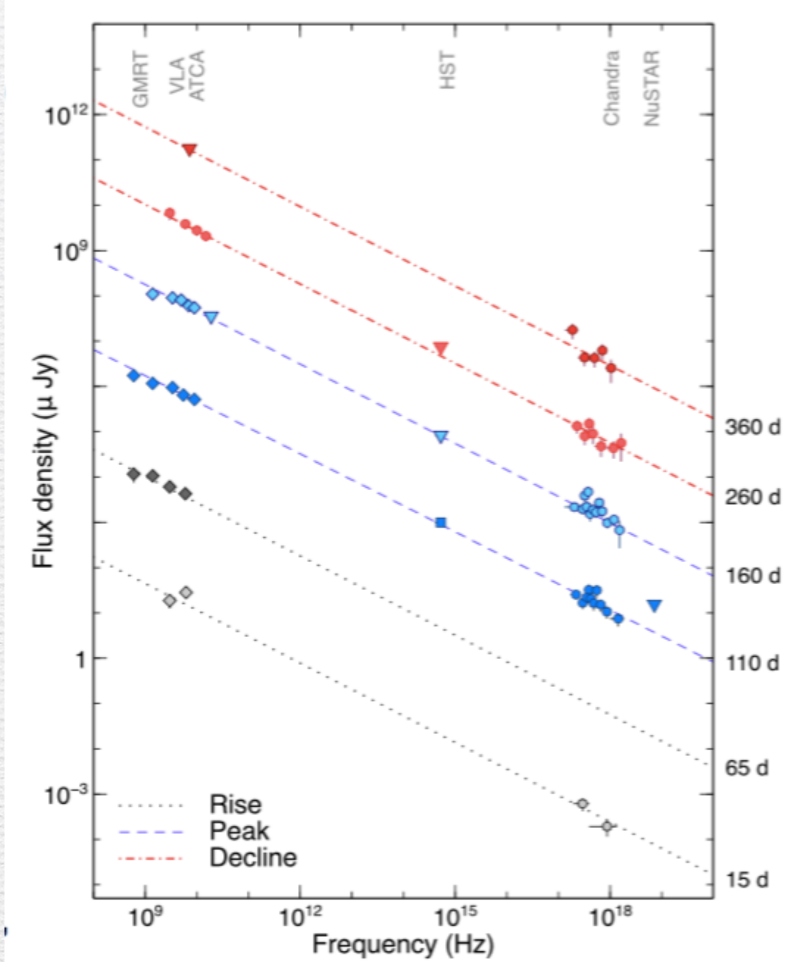
nonthermal afterglow of GW170817



$n=10^{-2.5}$ cm^{-3}, $\epsilon_B=10^{-2.3}$, $\epsilon_e=10^{-1.5}$, $p=2.13$,
$E_{c,\rm iso}=10^{51.70}$ erg, $\Gamma_c=229$, $\theta_c=0.11$, $\theta_v=0.58$

$\chi^2_{\rm min} \sim 137$

Lin+'18

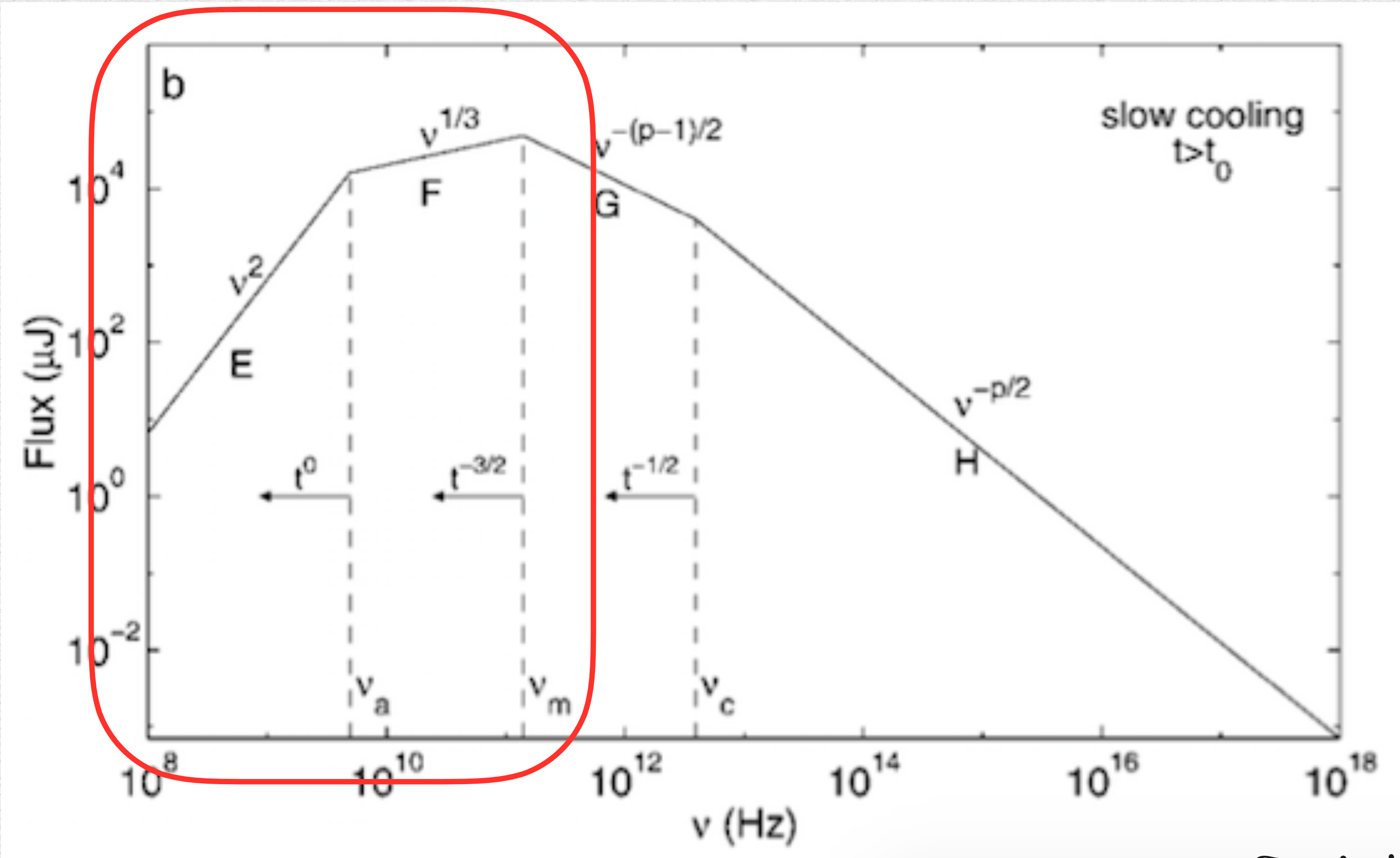


Afterglow SED of GW170817 (Troja+18)

- synchrotron emission from accelerated electrons in (mildly) relativistic shock, like GRB afterglow
- radially stratified spherical shell or off-axis and angularly extended jet
- best-fit by previous studies is single-power-law from radio to X-rays in all time
- means all observed frequencies above ν_m (corresponding to the minimum electron energy)

synchrotron tail?

- observed data of GW170817 do not show clear evidence of the synchrotron tail ($\nu < \nu_m$)



Sari+'98

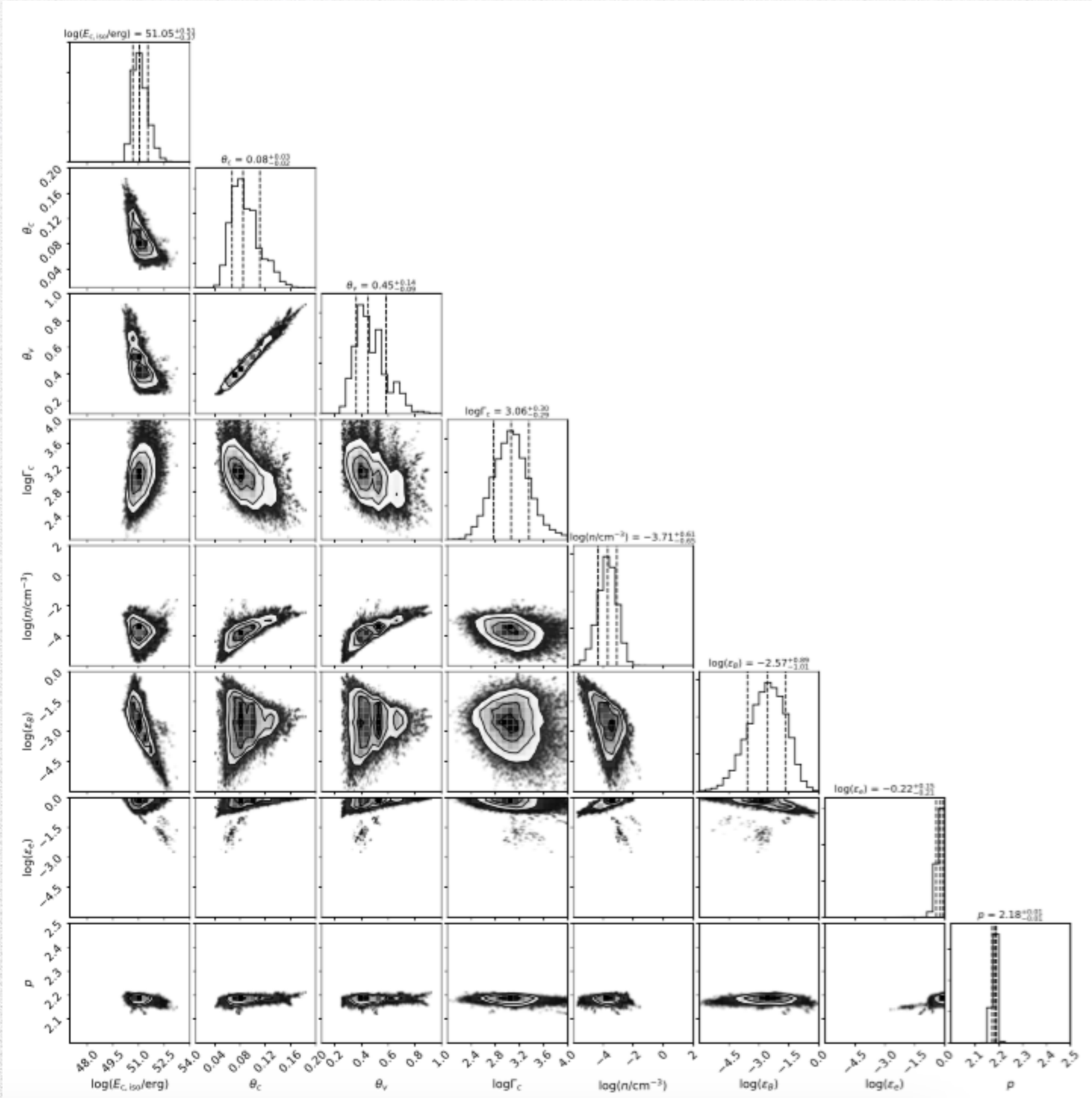
previous models, and our work

- previous studies all assumed that all electrons in the shock are accelerated as non-thermal particles!
  - following standard GRB afterglow modelings (e.g. Sari+'98)
  - energy fraction of accelerated electrons is controlled by the minimum energy of the electron energy distribution
  - simple, but obviously unphysical (c.f. supernova remnants)

- This work:
  - add a new, but natural model parameter, so that nonthermal electron energy fraction is variable
    - total number of nonthermal electrons: corresponds to the acceleration efficiency
    - the minimum electron energy: corresponds to the electron-ion equipartition

MCMC fits

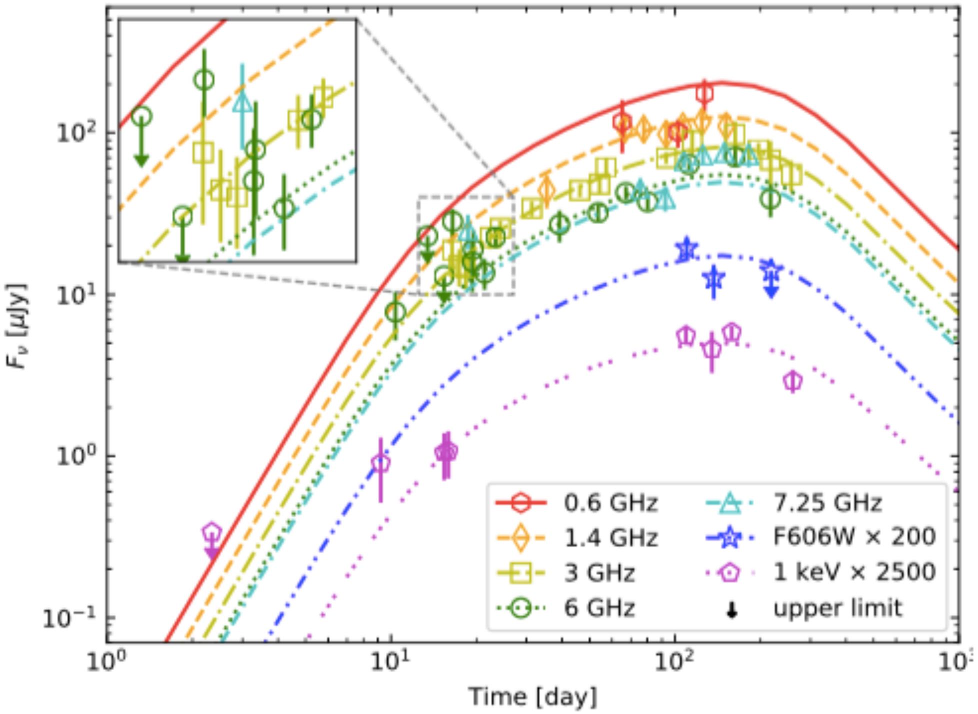
- with two standard geometrical models:
    - radially stratified spherical outflow
    - off-axis, angularly extended jet



New solution in synchrotron tail!

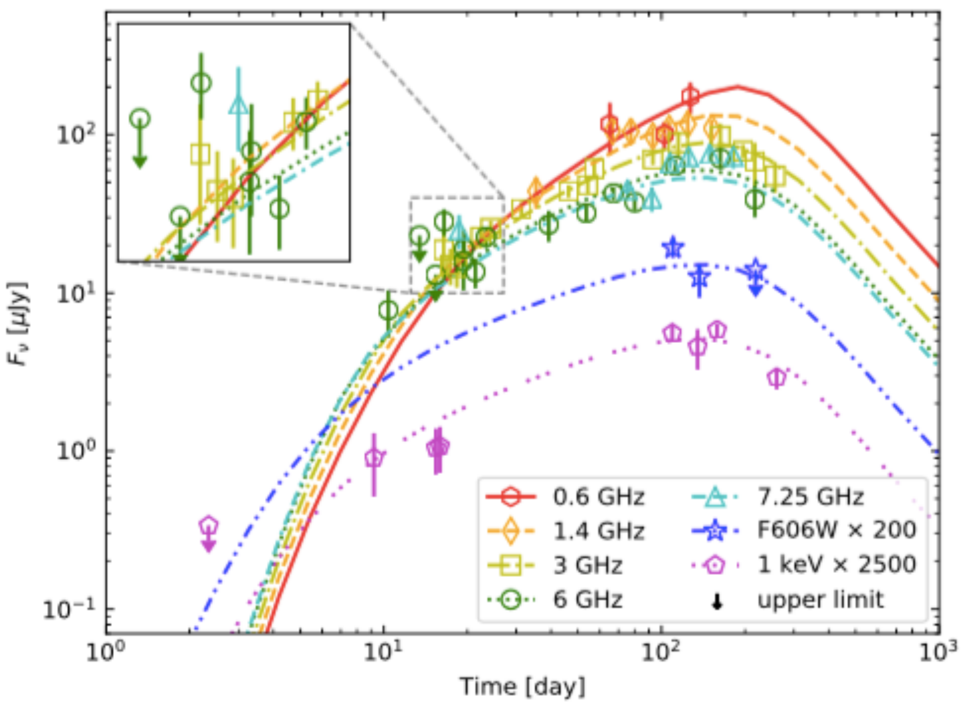
Best-fit model (Jet)

$f = 1$ with similar parameters of previous fits
Constant single power-law spectrum ($\nu > \nu_m$)



n=$10^{-2.5}$ cm^{-3}, ϵ_B=$10^{-2.3}$, ϵ_e=$10^{-1.5}$, p=2.13,
$E_{c,\mathrm{iso}}$=$10^{51.70}$ erg, Γ_c=229, θ_c=0.11, θ_v=0.58
$\chi^2_{\rm min} \sim 137$

Best-fit free f model by MCMC
New fit with radio in synchrotron tail ($\nu < \nu_m$)



n=$10^{-2.5}$ cm^{-3}, ϵ_B=$10^{-4.7}$, ϵ_e=$10^{-1.2}$, p=2.18,
$E_{c,\mathrm{iso}}$=$10^{52.59}$ erg, Γ_c=242, θ_c=0.09, θ_v=0.45, η_e=0.14
$\chi^2_{\rm min} \sim 108$

$N_{\rm data} = 54$ $\Delta\chi^2_{\rm min} \sim 29$! with 1 more model parameter

Main Results

- a more natural electron energy distribution leads to the synchrotron tail in early radio bands!
  - confirming only a small fraction is accelerated to nonthermal
  - close to electron-ion equipartition

- low-frequency early radio observations highly encouraged in future events
  - would give important information for:
    - particle acceleration efficiency
    - electron-ion equipartition

- jet energy ~ 10^{52} erg (isotropic-equivalent to the jet direction), about 10 times larger than the conventional modeling
  - still consistent with the distribution of the short GRB energy distribution

- ambient matter density n ~ 10^{-3}-10^{-2} cm^{-3}, about 10 times larger than the conventional modeling
  - consistent with the hot gas density in typical giant elliptical galaxies

- IceCube neutrinos from cosmic-rays in star-forming galaxies: a latest calculation by cosmological galaxy formation model
    - Takahiro Sudoh, TT, & Kawanaka '18, PASJ, 70, 49

Main Points of This Work

- Neutrinos produced by cosmic-ray interaction in star-forming galaxies should have some contribution to IceCube neutrinos, but its fraction is controversial

- We present a new model of gamma-ray and neutrino emission from a star-forming galaxy, from the quantities of (1) stellar mass, (2) gas mass, (3) star formation rate, and (4) disk radius.

- This model nicely reproduces gamma-ray luminosities of nearby galaxies detected by Fermi, from dwarfs to starbursts.
  - → good calibration for the prediction of neutrino flux

- This model is combined with a semi-analytical galaxy formation model in Lambda-CDM cosmology to predict neutrino background from star-forming galaxies

- It is extremely difficult to explain the IceCube neutrinos by star-forming galaxies in the standard picture of galaxy formation.

modeling gamma-ray and neutrino emission

- CR production rate: $\propto$ SFR
- CR energy spectrum: power-law with index Γ

- target ISM gas density: from M_{gas}, R_{eff}, and disk scale height $H \propto R_{eff}$

- velocity scale in the disk: virial equilibrium along the disk height
  - $G (M_{gas} + M_{star}) / R_{eff}^2 \sim \sigma^2 / H$

- CR diffusion and escape
  - energy-dependent diffusion coefficient:
    - $R_L < l_0 \rightarrow$ Kolomogorov turbulence
    - $R_L > l_0 \rightarrow$ small angle scattering
    - $R_L > (H\, l_0)^{1/2} \rightarrow$ free streaming
  - l_0: coherent length of turbulence, assumed to be 10 pc from observations

$$D(E_p) = \begin{cases} \frac{c l_0}{3}\left[\left(\frac{R_L}{l_0}\right)^{\frac{1}{3}} + \left(\frac{R_L}{l_0}\right)^2\right] & (R_L \leq \sqrt{H l_0}) \\ \frac{cH}{3} & (R_L > \sqrt{H l_0}) \end{cases}$$

- magnetic field
  - equilibrium with the energy density injected by star formation within the dynamical time scale H/σ

- $\rightarrow$ you can calculate luminosity and spectrum of gamma-ray and neutrinos via pion production in ISM

Calibration by gamma-rays from Nearby galaxies

Output

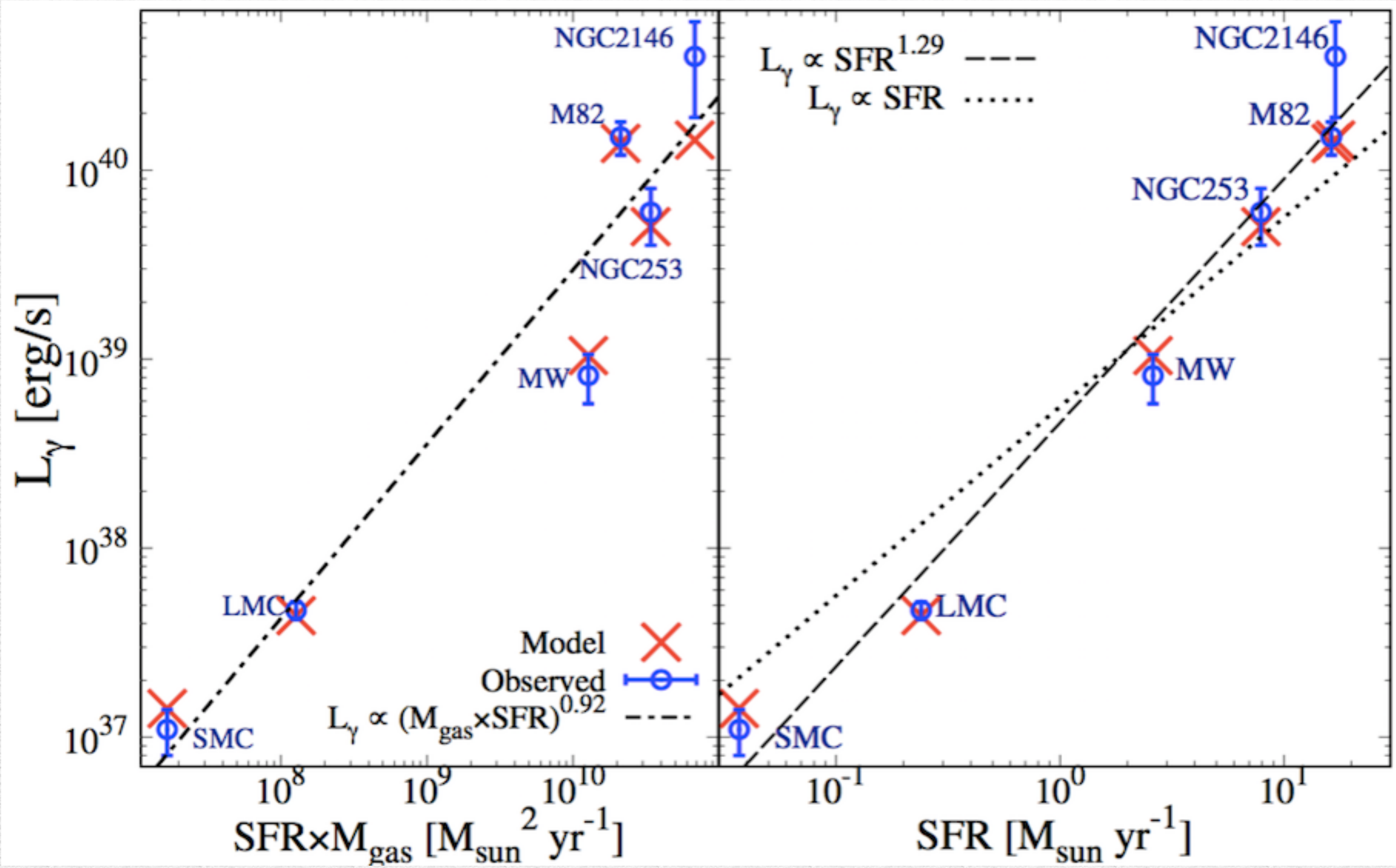
Table 1. Summary of properties of gamma-ray galaxies

Objects	L_γ [a] 10^{39} erg/s	SFR $M_\odot$/yr	M_{gas} [c] $10^9 M_\odot$	M_* [d] $10^9 M_\odot$	R_{eff} [e] kpc
MW	0.82±0.24	2.6	4.9	50	6.0
LMC	0.047±0.005	0.24	0.53	1.5	2.2
SMC	0.011±0.003	0.037	0.45	0.46	0.7
NGC253	6±2	7.9	4.3	21	3.7
M82	15±3	16.3	1.3	-	1.2
NGC2146	40±21	17.5	4.1	20	1.8

Input

- 6 nearby galaxies with good measurements of gamma-ray luminosity from CR interactions
- including various types (dwarfs to starbursts)
- good measurements of galaxy properties: star formation rate (SFR), gas mass (M_{gas}), stellar mass (M_{star}), disk effective radius (R_{eff})
- Can we make a physical model to predict gamma-ray luminosity from galaxy properties for these galaxies?

Comparison with nearby galaxies



- our model reproduces gamma-ray luminosities fairly well!
- better than the simple $L_{gamma} \propto SFR$ or $L_{gamma} \propto SFR \times M_{gas}$

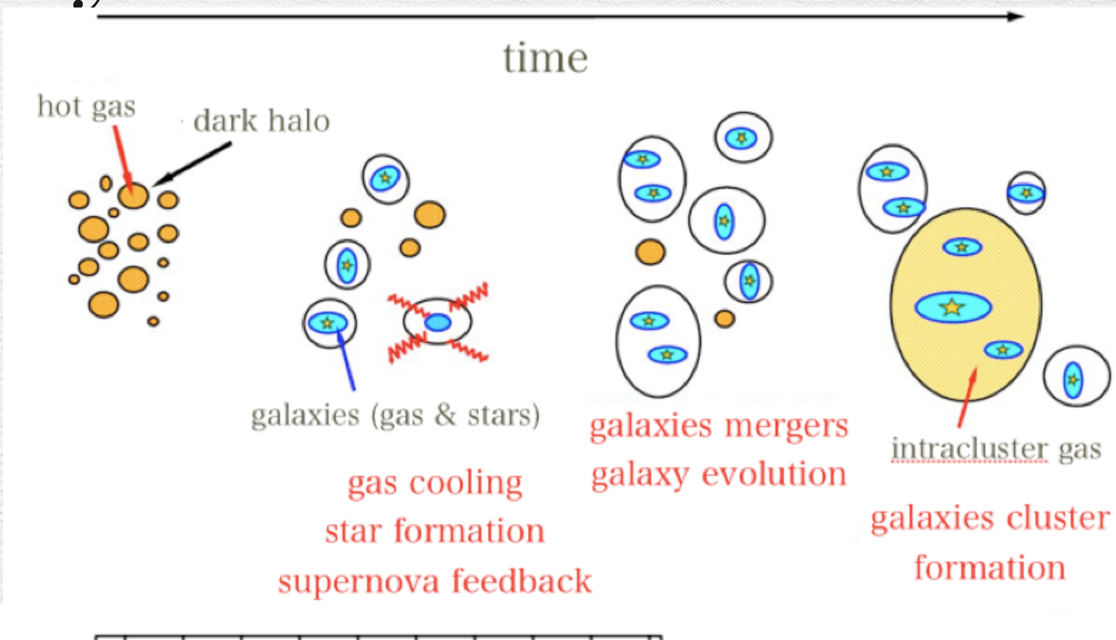
cosmological galaxy formation model

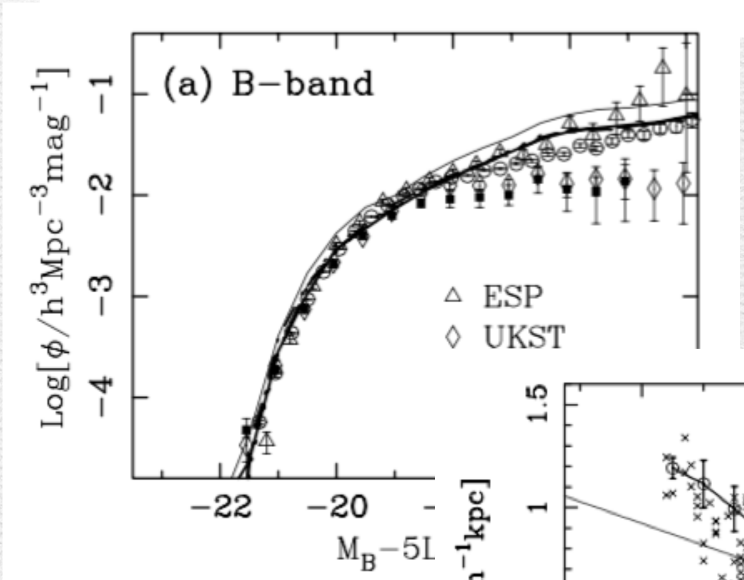
- use a semi-analytic model of hierarchical galaxy formation in the CDM framework
  - Nagashima & Yoshii '04
  - gives necessary inputs (SFR, M_{star}, M_{gas}, size)

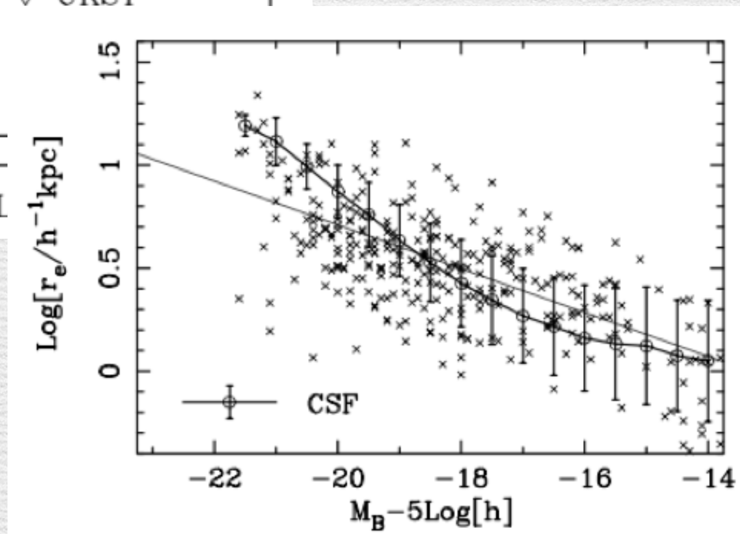
- reproduces local galaxy statistics (luminosity function, luminosity-size relation, etc.)

- tested against various high-z galaxy data set (e.g. Ly-break galaxies)

- major mergers produce starburst galaxies







neutrino background

- accounts for only 0.4% of IceCube neutrinos with the plausible Γ_{inj}~2.3!
- 15% even if we take an extreme value of Γ_{inj}=2 for all galaxies