VHE gamma-ray and neutrino emission from star forming galaxies / Some topics on neutron star mergers and fast radio bursts

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Outline

- gamma-rays & neutrinos from cosmic-rays in star-forming galaxies
  - modeling from galaxy physical quantities (M_{star}, M_{gas}, SFR, size, ...)
  - understanding gamma-ray luminosity of nearby galaxies
  - cosmic gamma-ray & neutrino background vs. IceCube

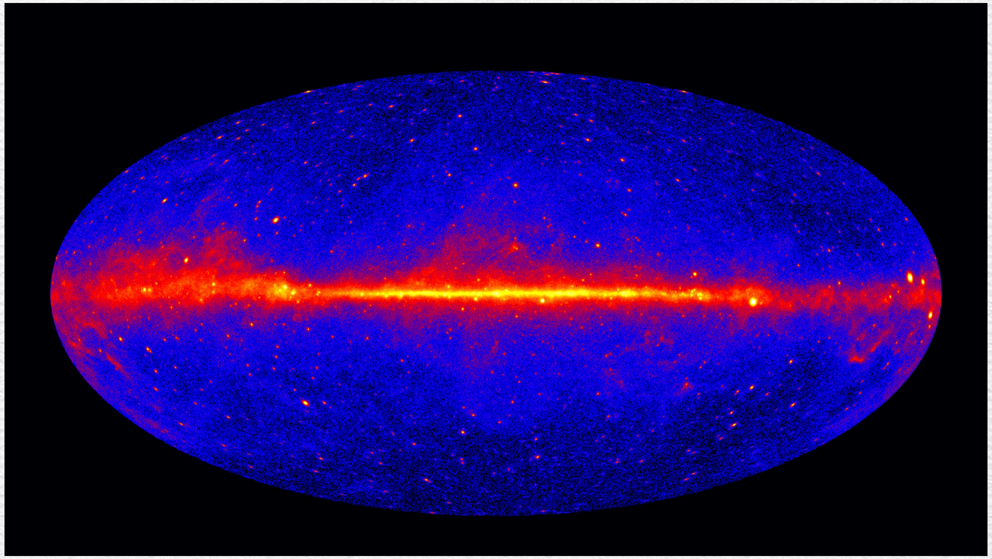
- non-thermal afterglow from GW 170817
  - a latest modeling with a natural electron energy distribution
  - possibility to detect a spectral break corresponding to the minimum electron energy?

- fast radio bursts (FRBs) and possible connection to neutron star mergers

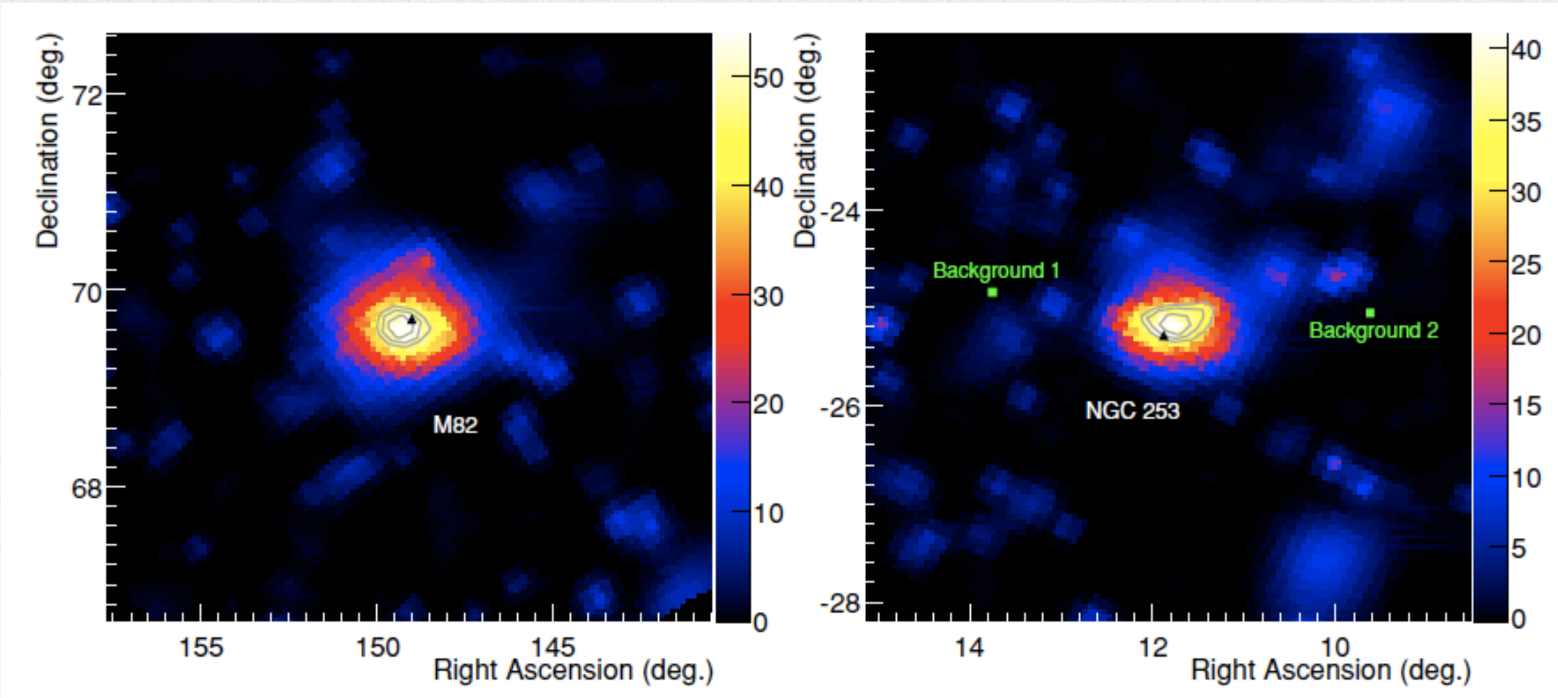
part I
gamma-rays and neutrinos from starforming galaxies

gamma-rays from star forming galaxies

- all star forming galaxies produces cosmic-rays from supernova remnants, and then gamma-ray and neutrinos from pion decays produced by CR interaction with interstellar medium

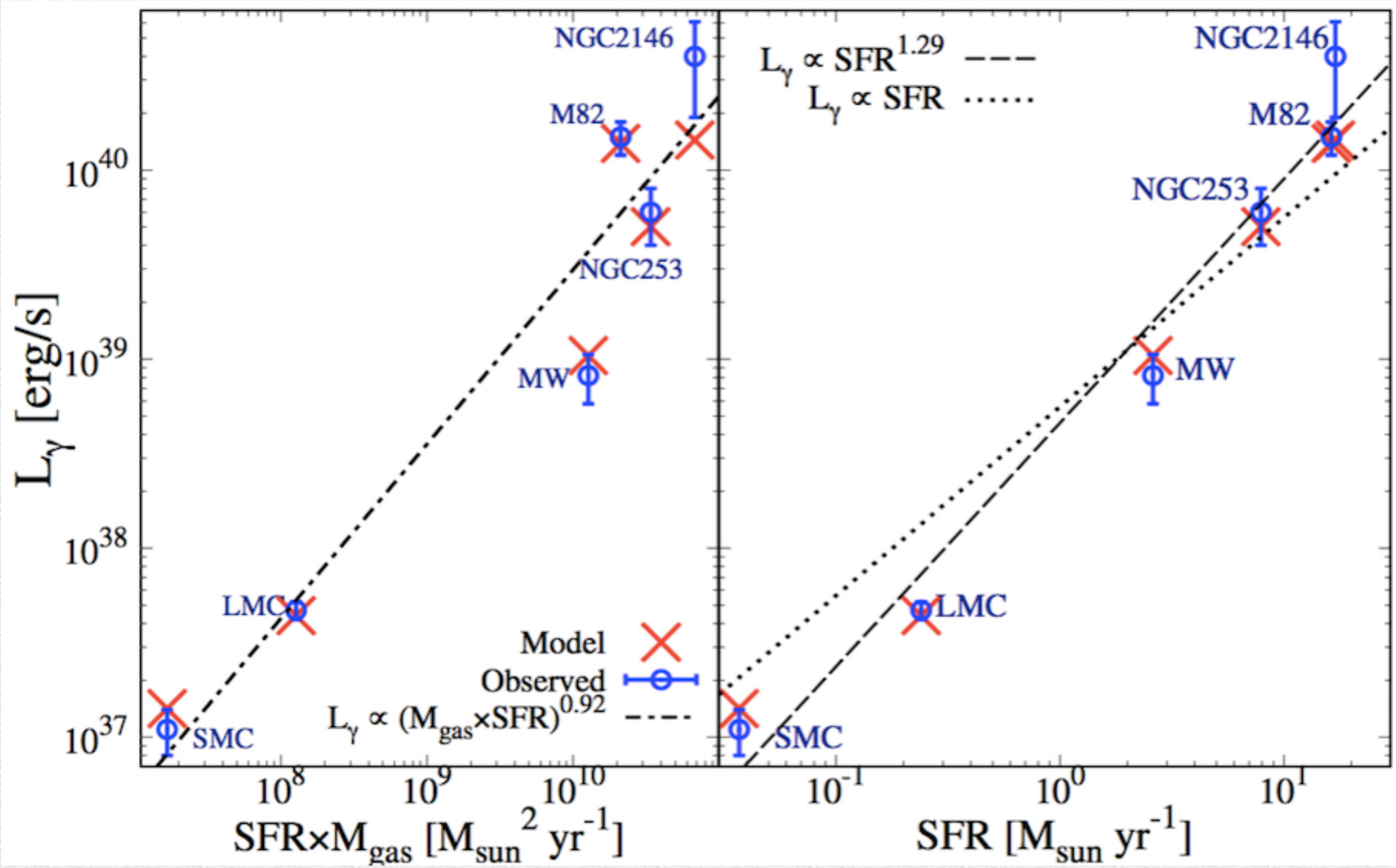


Fermi 5yr map of the Milky Way



Fermi views of starburst galaxies (M82 and HGC 253)

gamma-ray luminosities of nearby galaxies



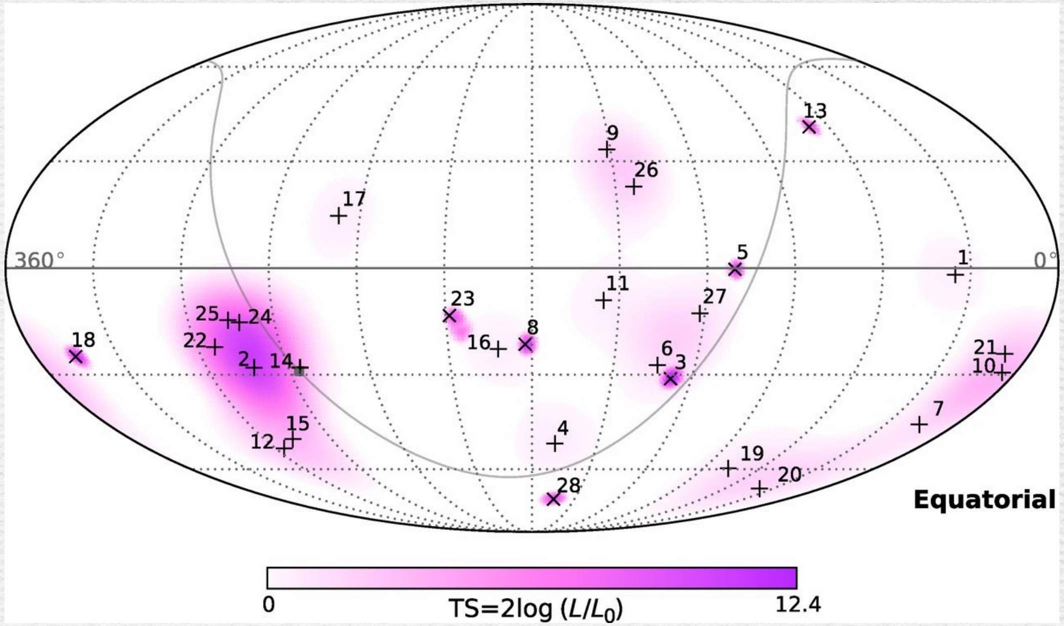
Sudoh, TT+ 2018

- correlation between L_{gamma} vs. SFR or SFR×M_{gas}

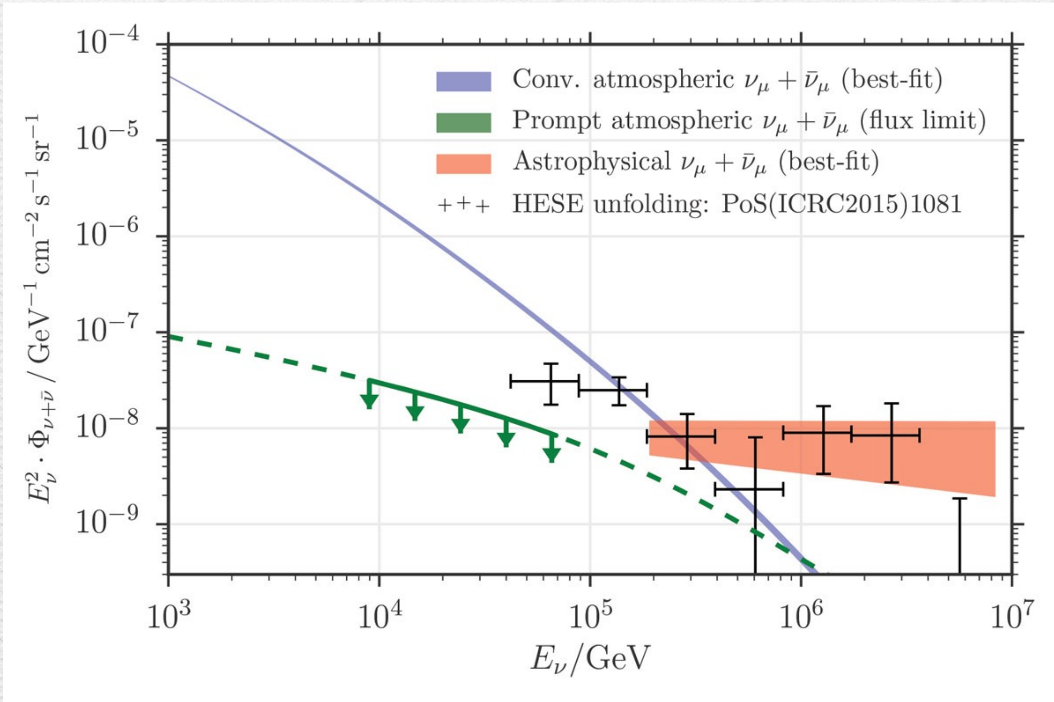
IceCube neutrinos?

- how much is the contribution from star-forming galaxies to the cosmic PeV ν background?
    - Loeb & Waxman 2006; Thompson et al. 2006; Stecker 2007; Lacki et al. 2011; Murase et al. 2013; He et al. 2013; Tamborra et al. 2014; Anchordoqui et al. 2014; Liu et al. 2014; Emig et al. 2015; Chang et al. 2015; Giacinti et al. 2015; Senno et al. 2015; Moharana & Razzaque 2016; Chakraborty & Izaguirre 2016; Xiao et al. 2016; Bechtol et al. 2017; Sudoh+2018, …

- somewhat controversial: many papers found a minor contribution, but some papers claim significant contribution



all sky map and spectrum by IceCube collab.



how to reliably predict ν flux from star forming galaxies?

- an important point, but missed by most previous studies: consistency with gamma-ray luminosity of nearby galaxies
  - pions produces inevitably gamma-rays with neutrinos, and nearby galaxy L_γ is a good calibrator of a theoretical model of neutrino emission

- connecting L_γ with physical quantities of galaxies
  - star formation rate (SFR) and gas mass (M_{gas}) are popularly considered, but are they enough?
  - there should be other important parameters (e.g., size, magnetic field, …)

- use a realistic model of cosmological galaxy formation. Predict neutrino luminosities based on the physical quantities of galaxies predicted by it.

- → Sudoh, TT, & Kawanaka 2018, PASJ 70, 49

温故知新

- 温故知新 from 論語(Analects) by 孔子(Confucius, 552BC-479BC)
    - meaning "visiting old, learn new"
- Careful modeling of nearby galaxies is crucial to know flux of cosmic background flux
    - 温近知遠, "visiting near, learn far"

modeling L_γ of nearby galaxies

Output

Table 1. Summary of properties of gamma-ray galaxies

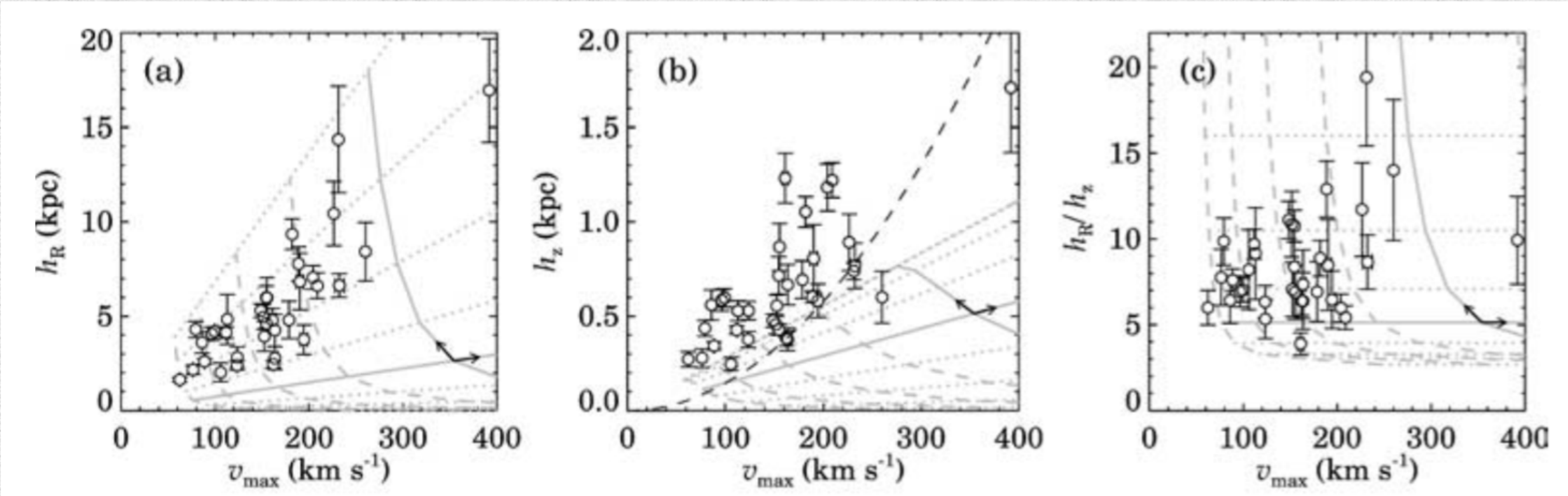
Objects	L_γ [(a)] 10^{39} erg/s	SFR $M_\odot$/yr	M_{gas} [(c)] $10^9 M_\odot$	M_* [(d)] $10^9 M_\odot$	R_{eff} [(e)] kpc
MW	0.82±0.24	2.6	4.9	50	6.0
LMC	0.047±0.005	0.24	0.53	1.5	2.2
SMC	0.011±0.003	0.037	0.45	0.46	0.7
NGC253	6±2	7.9	4.3	21	3.7
M82	15±3	16.3	1.3	-	1.2
NGC2146	40±21	17.5	4.1	20	1.8

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?

modeling γ/ν emission (1)

- CR production rate: ∝ SFR
- CR energy spectrum: power-law with index Γ
- target ISM gas density: from M_{gas}, R_{eff} assuming disk geometry
  - disk scale height $H \propto R_{eff}$
  - H(gas) = 150 pc, R_{eff} = 6 kpc for the MW galaxy
- velocity dispersion within the disk: dynamical equilibrium along the disk height
  - $G\,(M_{gas} + M_{star}) / R_{eff}^2 \sim \sigma^2 / H$
  - used to estimate
    - advection time scale of CRs
    - magnetic field strength



Kregel+'05

modeling γ/ν emission (2)

- magnetic field
  - (energy density injected by star formation in dynamical time H/σ) ~ $B^2/(8\pi)$

- diffusion and escape of a CR proton of energy E_p:
  - 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 30 pc from observations

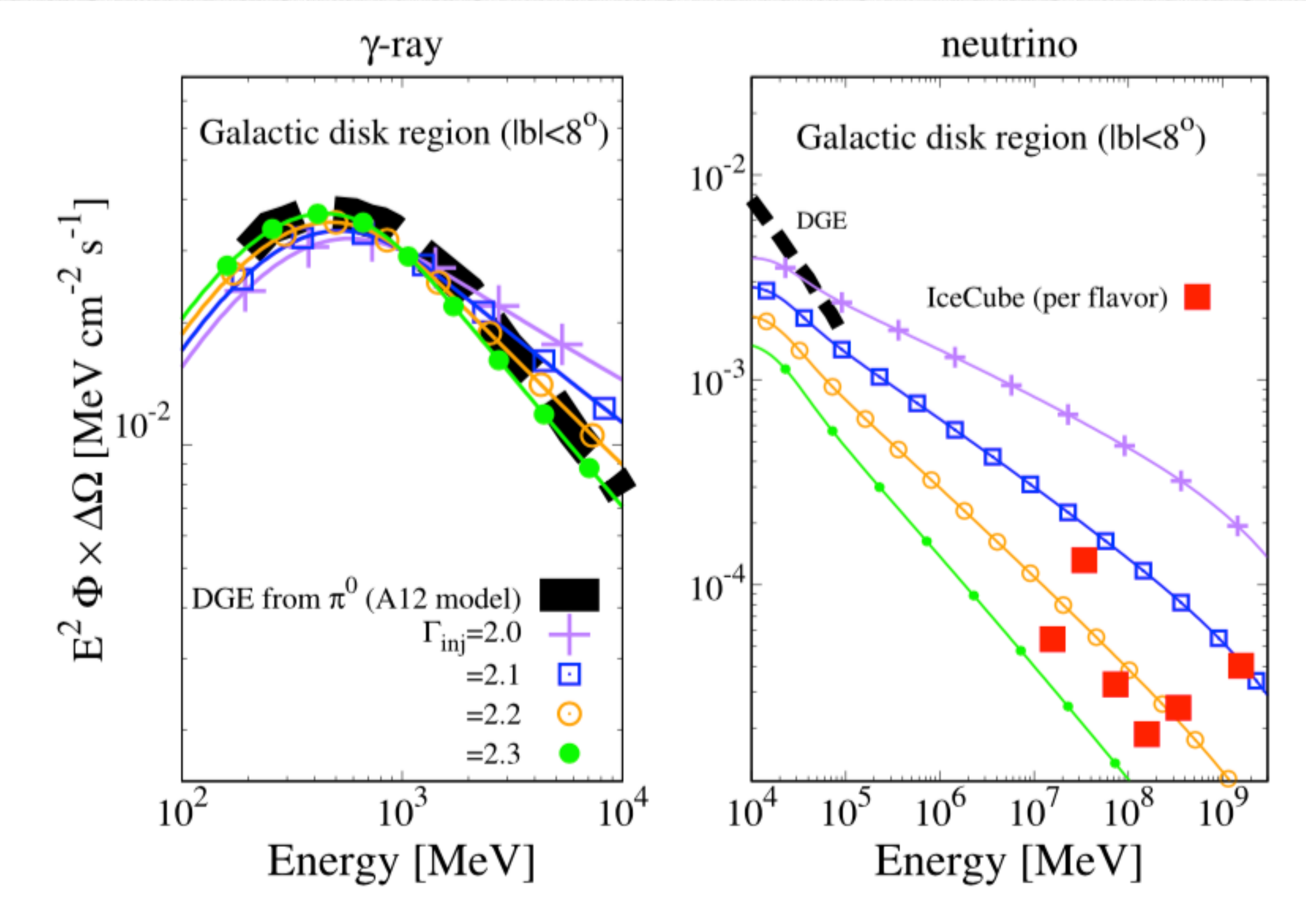
$$D(E_p) = \begin{cases} \frac{cl_0}{3}\left[\left(\frac{R_L}{l_0}\right)^{\frac{1}{3}} + \left(\frac{R_L}{l_0}\right)^2\right] & (R_L \leq \sqrt{Hl_0}) \\ \frac{cH}{3} & (R_L > \sqrt{Hl_0}) \end{cases}$$

- CR escape time: $t_{esc} = \min[t_{diff}, t_{adv}]$
  - diffusion time: $t_{diff} = H^2 / [2\, D(E_p)]$
  - advection time: $t_{adv} = H/\sigma$

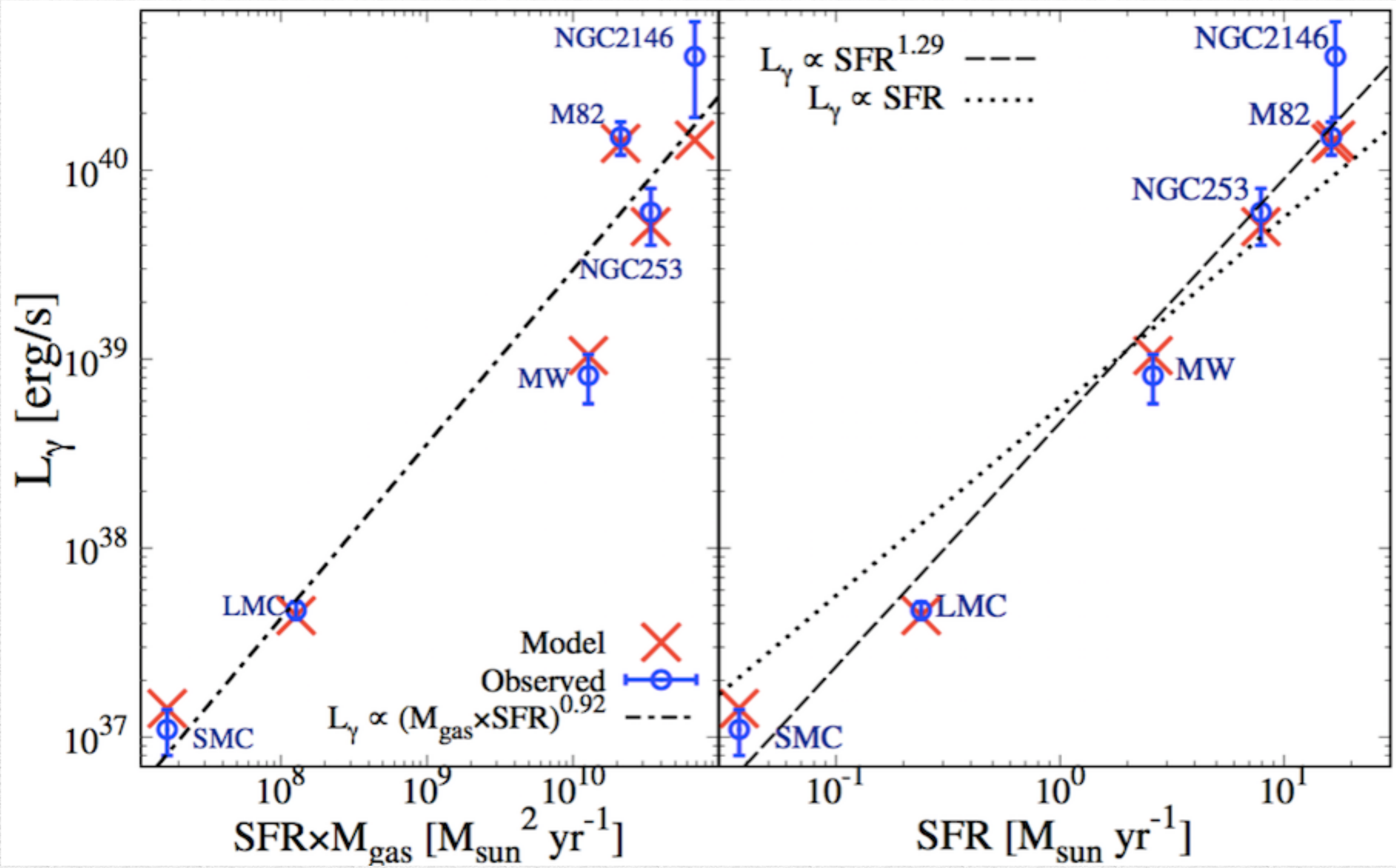
- → you can calculate CR amount at a given E_p remaining in the disk, and then luminosity and spectrum of gamma-ray and neutrinos by pion production in ISM

emission from the Galactic disk

- CR spectral index of Γ~2.3 consistent with the diffuse Galactic γ background spectrum
- predicted ν flux close to the IceCube isotropic component (per solid angle)
  - can we see an excess along the disk in the near future?
  - flatter index (Γ < 2.1) disfavored



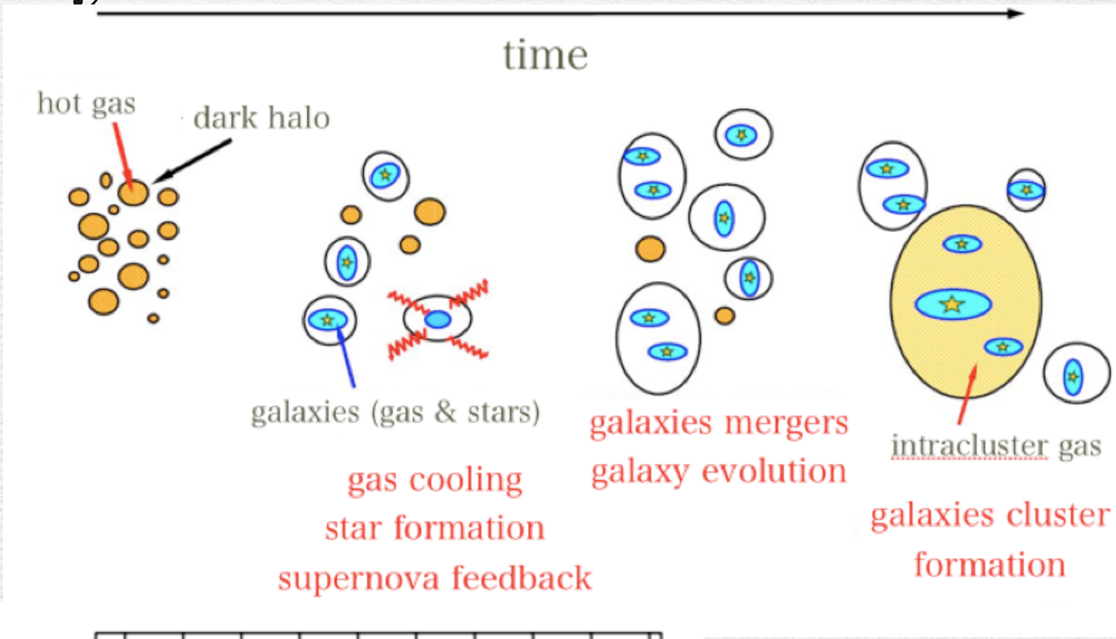
Comparison with nearby galaxies



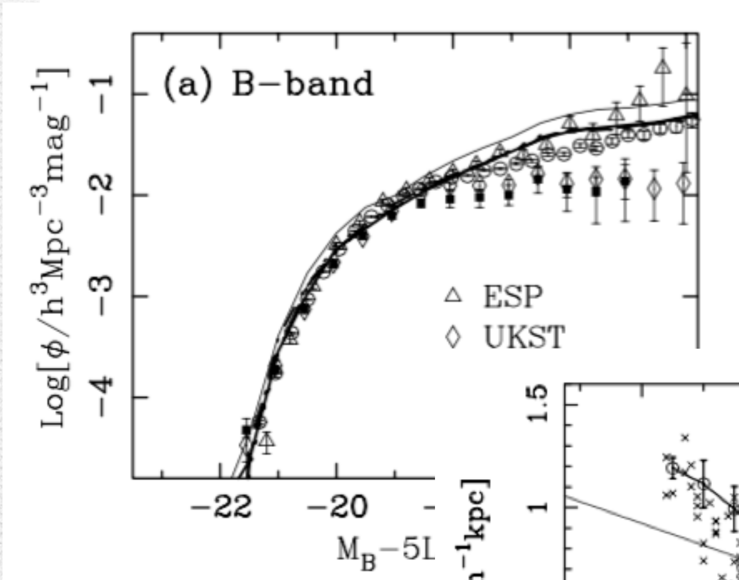
- our model reproduces gamma-ray luminosities fairly well
- quantitatively better than the simple $L_{gamma} \propto$ SFR or $L_{gamma} \propto$ SFR x M_{gas}

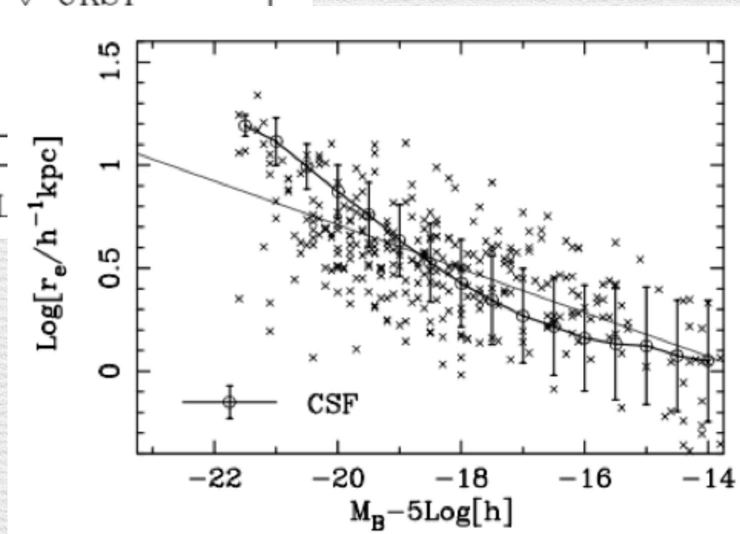
cosmological galaxy formation model

- 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.)



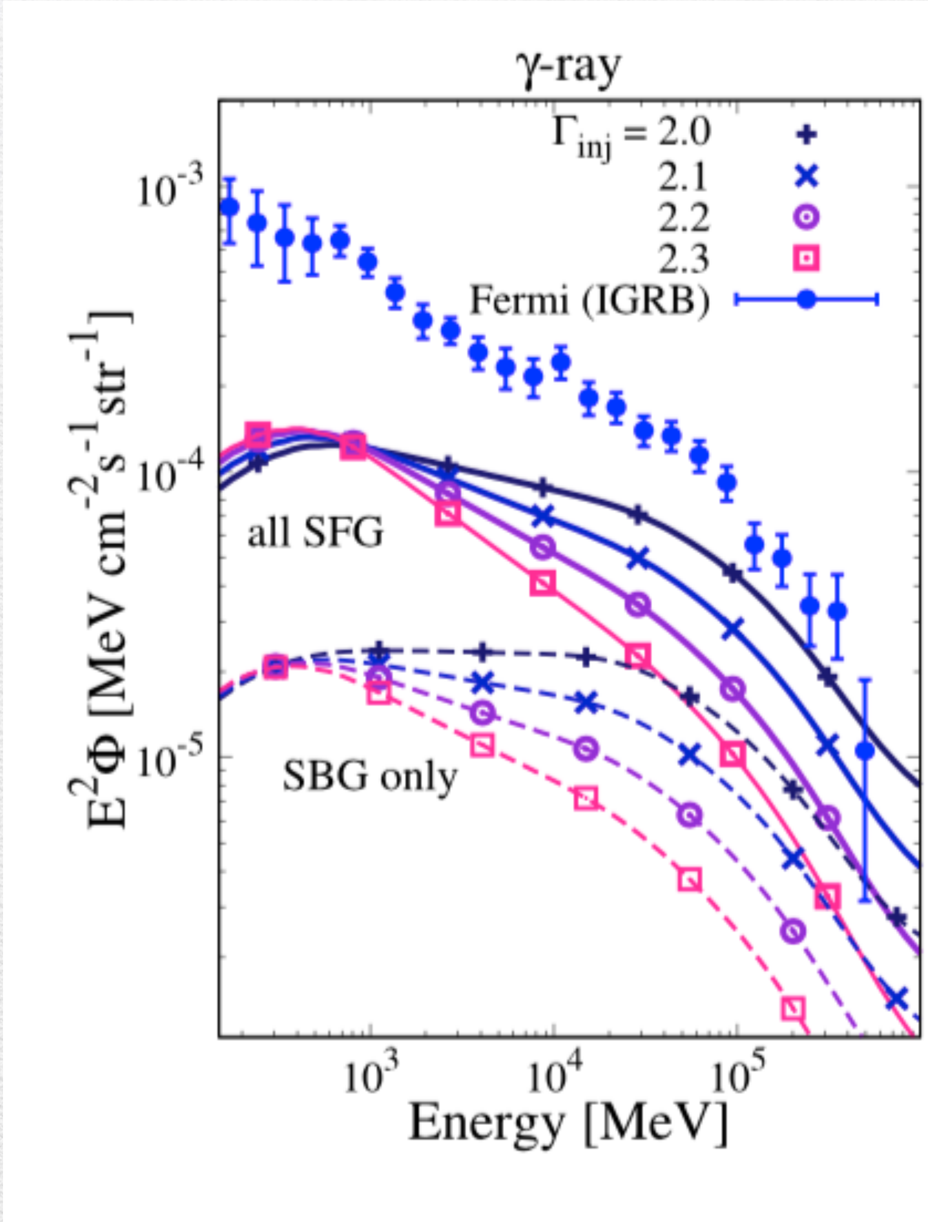


- tested against various high-z galaxy data set (e.g. Ly-break galaxies)

- major mergers produce starburst galaxies

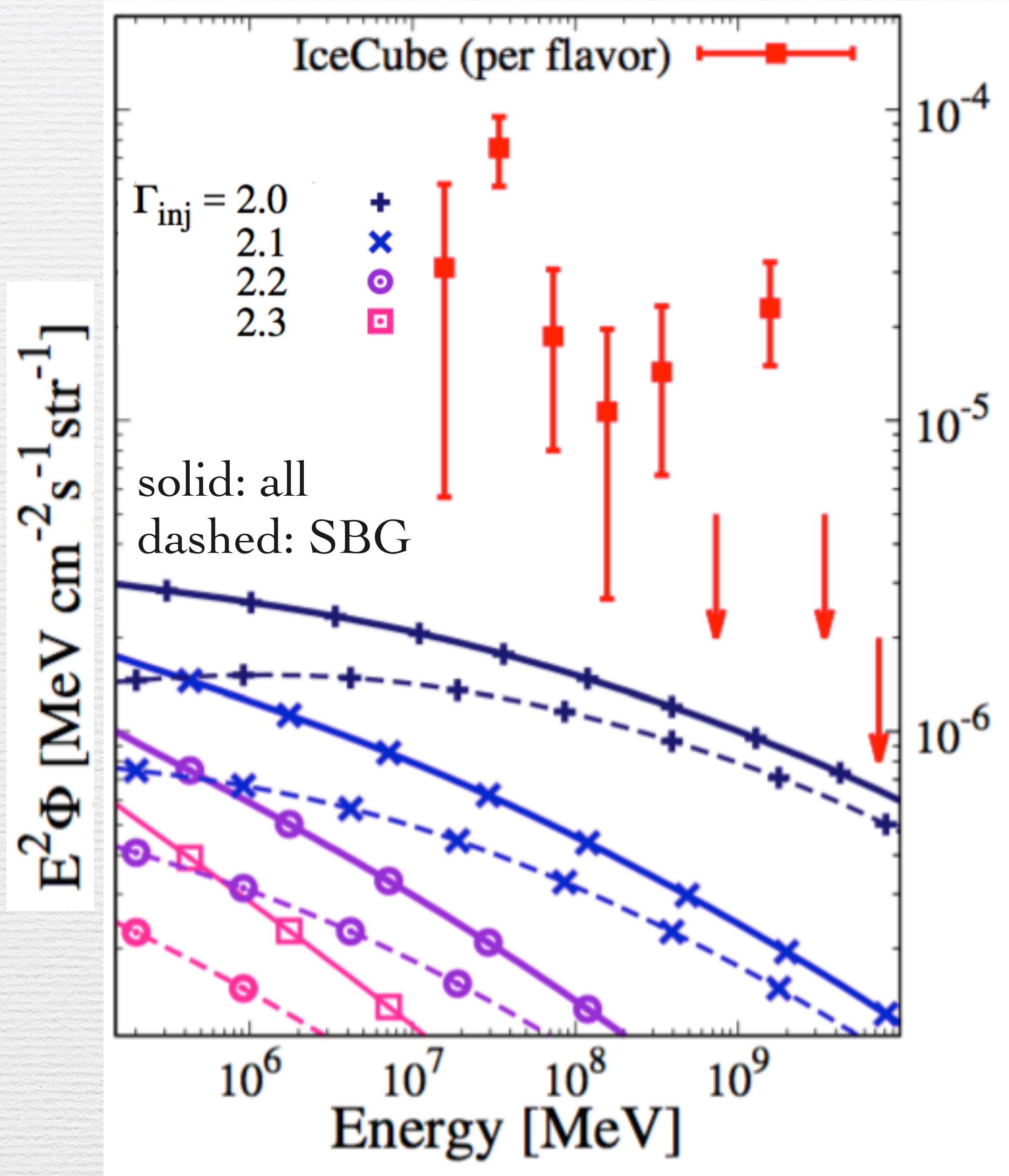
cosmic gamma-ray background

- about 10% contribution to the total cosmic gamma-ray background in GeV
- consistent with previous studies



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



Conclusions (part I)

- 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 can be further tested by future γ observation by CTA

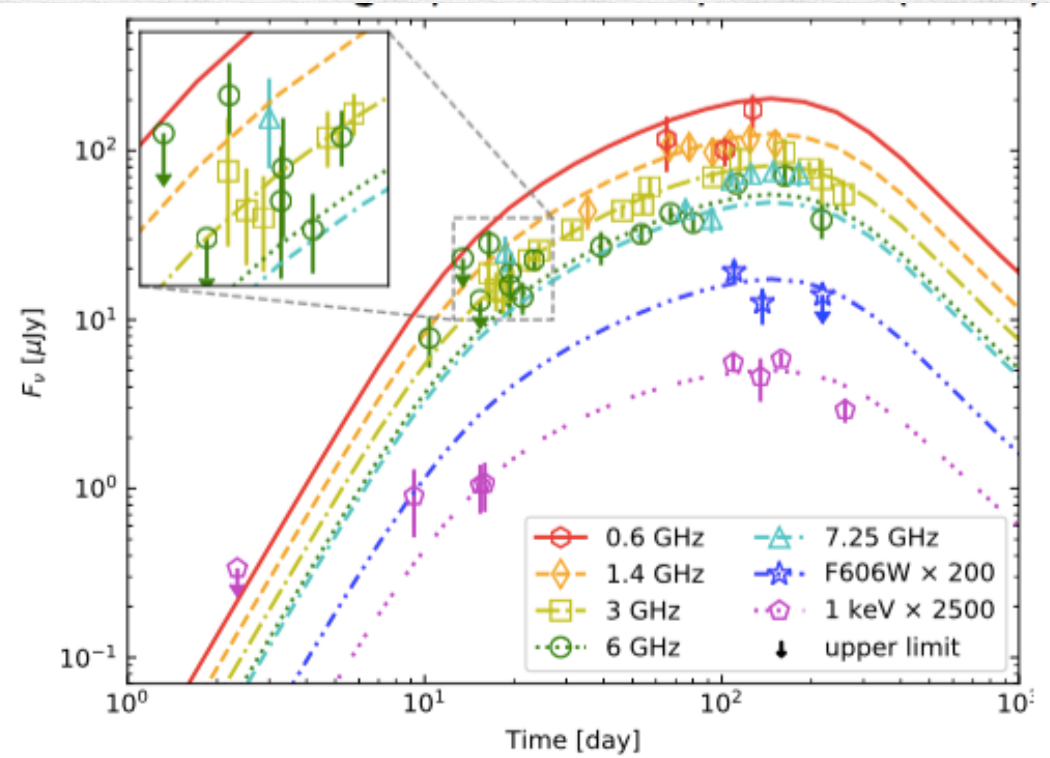
- This model is combined with a semi-analytical galaxy formation model in Lambda-CDM cosmology to predict neutrino background from star-forming galaxies

- It is extremely difficult to explain all the IceCube neutrinos by star-forming galaxies in the standard picture of galaxy formation.
  - accounts for 0.4% in our plausible model
  - 15% even if we make an extreme assumption of Γ=2.0 for all galaxies

Part II
non-thermal afterglow of GW 170817

nonthermal afterglow of GW170817

- non-thermal afterglow in radio, optical, and X-ray
- synchrotron emission from accelerated electrons in (mildly) relativistic shock
  - in between supernova remnants (non-relativistic) and GRB afterglows (ultra-relativistic)
  - a new experimental site of particle acceleration
- outflow geometry?
  - two popular models
    - radially stratified spherical shell
    - off-axis and angularly extended jet
  - simpler models do not fit the data
  - latest data favors the latter

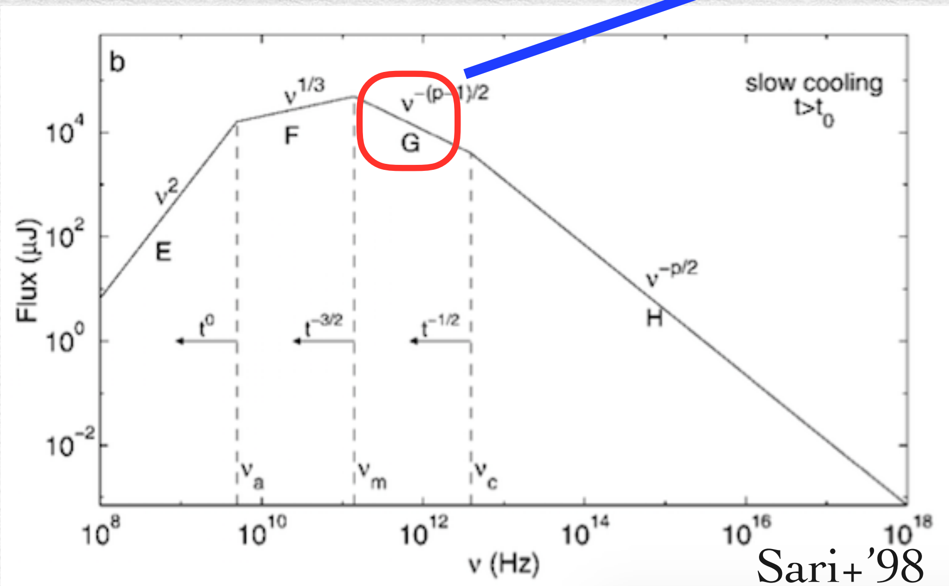


n=$10^{-2.5}$ cm^{-3}, ϵ_B=$10^{-2.3}$, ϵ_e=$10^{-1.5}$, p=2.13,
$E_{c,\rm iso}$=$10^{51.70}$ erg, Γ_c=229, θ_c=0.11, θ_v=0.58

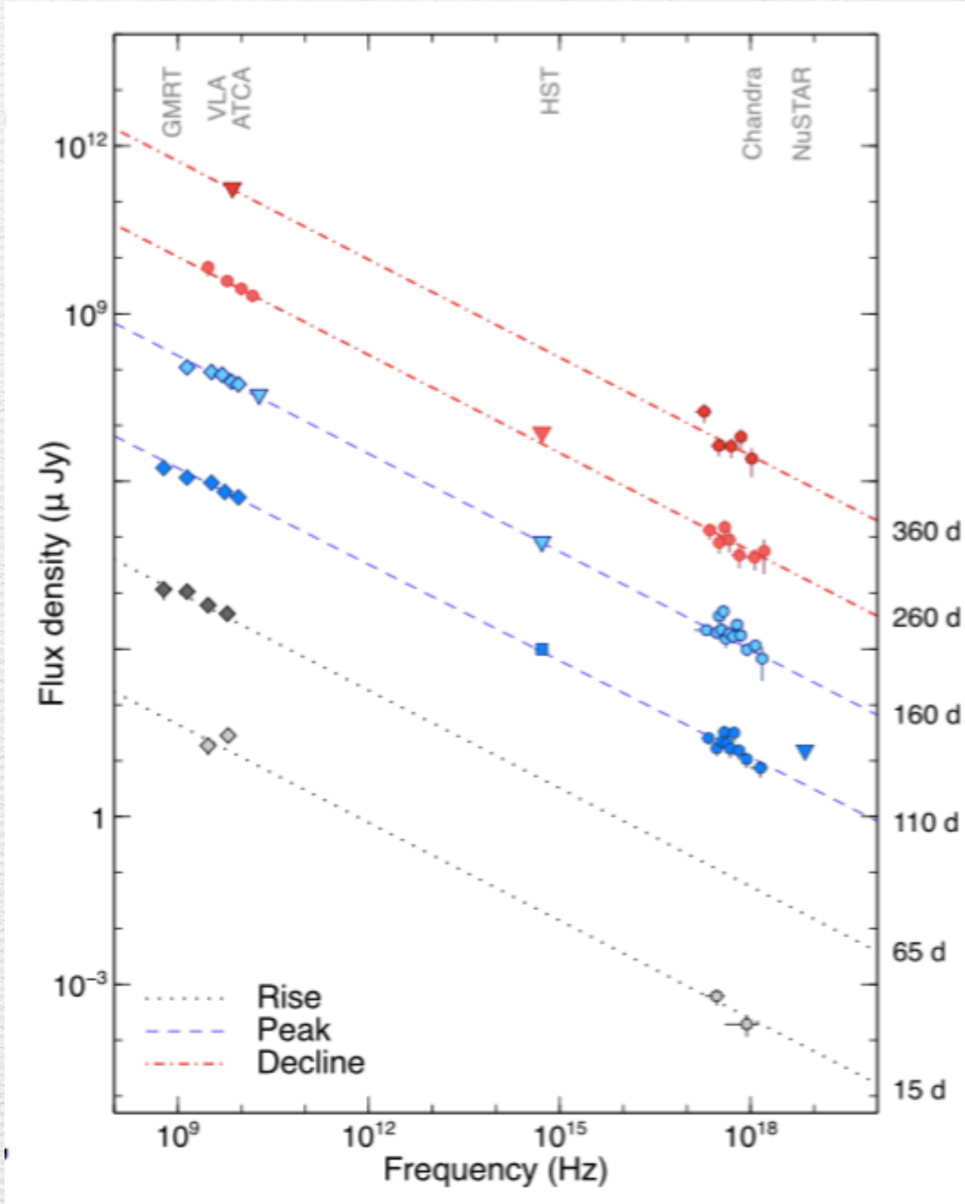
Lin+'18 $\chi^2_{\rm min} \sim 137$

spectral energy distribution

- single power-law from radio to X-rays in all time
- means all observed frequencies above ν_m (corresponding to the minimum electron energy)
- best-fit by previous studies predict $\nu_{radio} << \nu_m$
    - it is a pity! but…



Sari+'98



Afterglow SED of GW170817 (Troja+18)

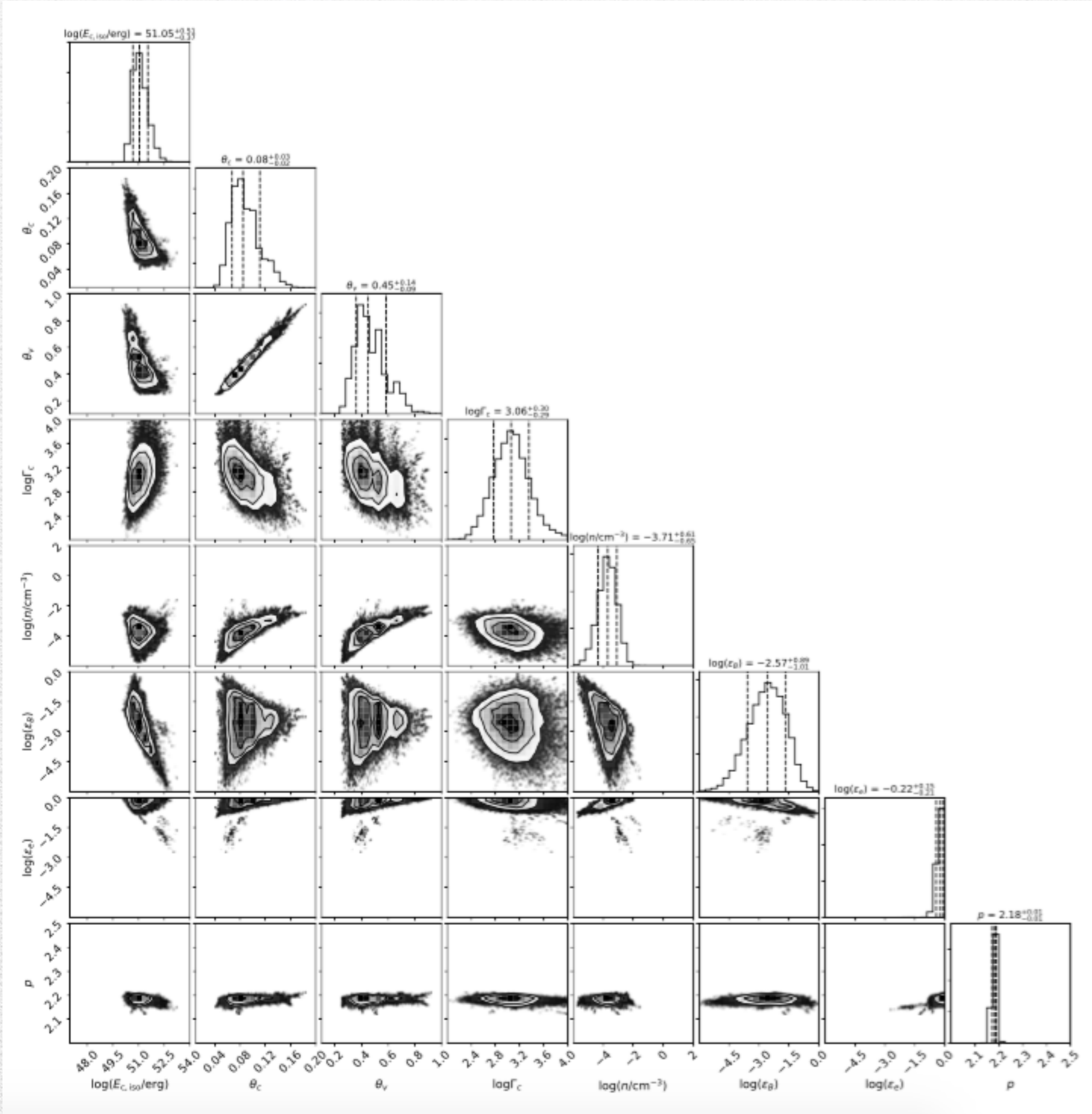
what about particle acceleration efficiency?

- 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 only by the minimum energy of the electron energy distribution
  - simple, but obviously too simple physically (c.f. supernova remnants)

- Lin, TT & Kiuchi (2019), MNRAS in press (arXiv:1810.02587)
  - add a new, but natural model parameter, so that both of
    - non-thermal electron energy fraction
    - minimum electron energy
      - are variable
  - allows to explore
    - particle acceleration efficiency
    - ion/electron equipartition

MCMC fits

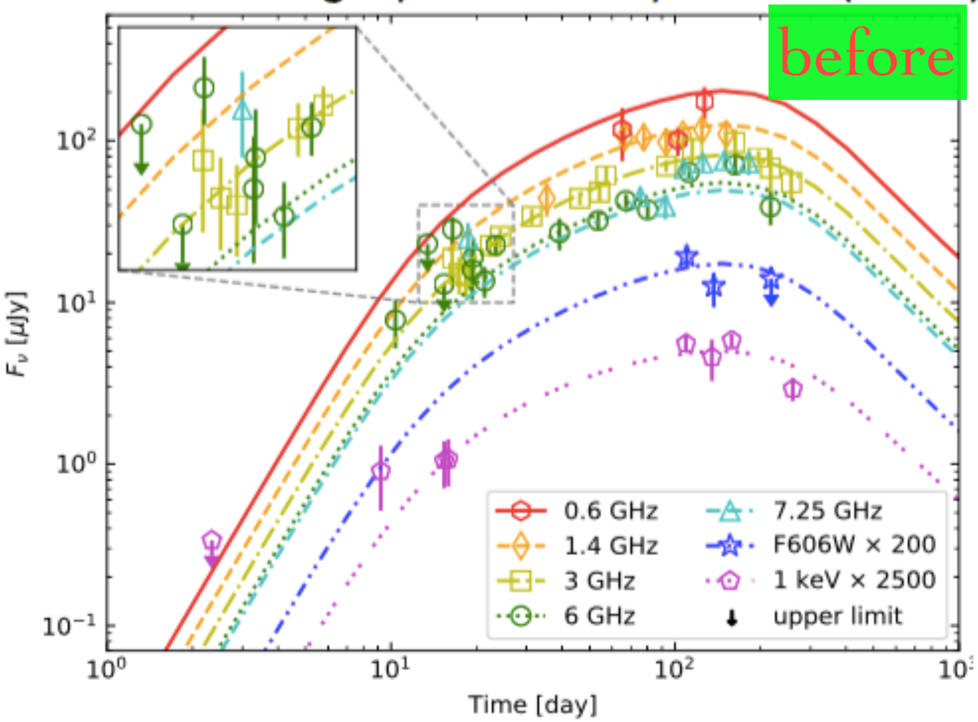
- with two standard geometrical models:
  - radially stratified spherical outflow
  - off-axis, angularly extended jet



ν_m is in radio band at earliest time!

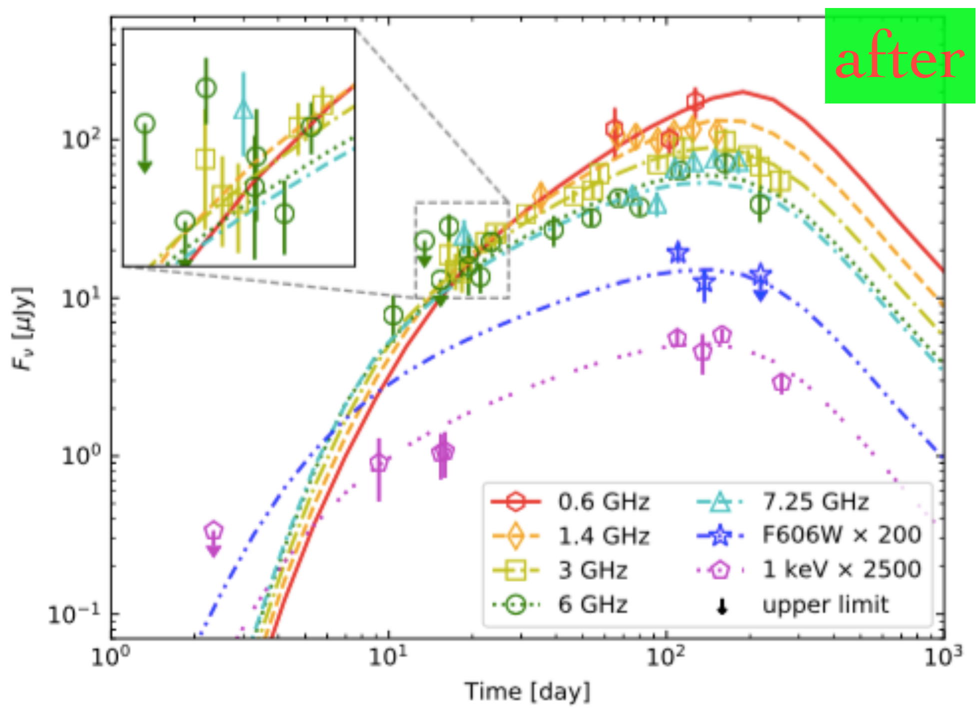
Best-fit model (Jet)

$f = 1$ 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,
$E_{c,\rm iso}$=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 ($\nu < \nu_m$)

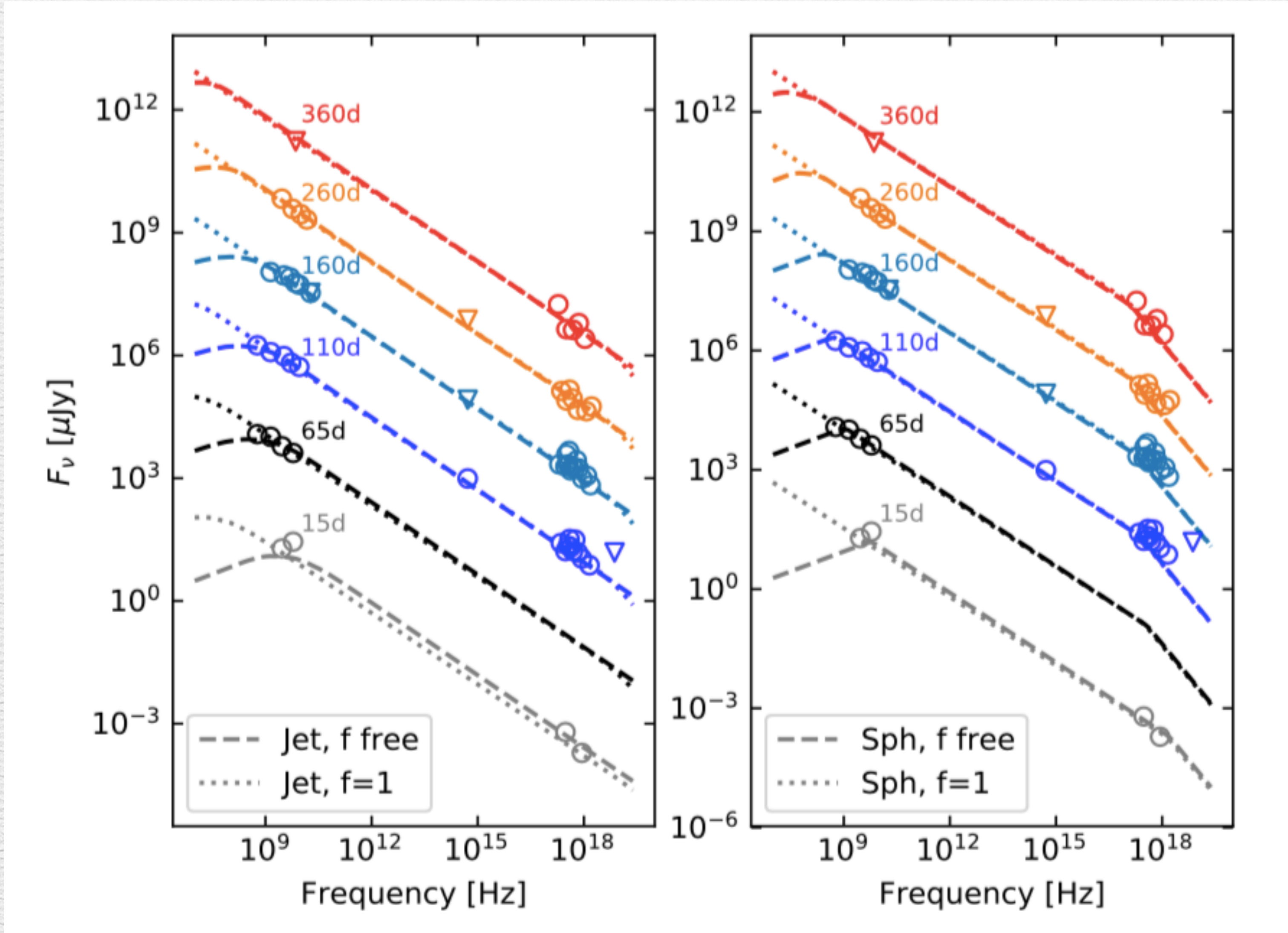


n=10$^{-2.5}$ cm^{-3}, ϵ_B=10$^{-4.7}$, ϵ_e=10$^{-1.2}$, p=2.18,
$E_{c,\rm iso}$=10$^{52.59}$ erg, Γ_c=242, θ_c=0.09, θ_v=0.45, η_e=0.14
$\chi^2_{\rm min} \sim 108$

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

ν_m in spectral energy distribution?

- our model is statistically more favored than conventional models, but the signature of ν_m in early radio data is marginal
- denser sampling of early radio data in future events would detect ν_m clearer



Conclusions of Part II

- a more natural electron energy distribution leads to the synchrotron tail in early radio bands!
  - confirming only a small energy fraction (1-10%) is accelerated to nonthermal
  - close to electron-ion equipartition (minimum electron energy close to kT)

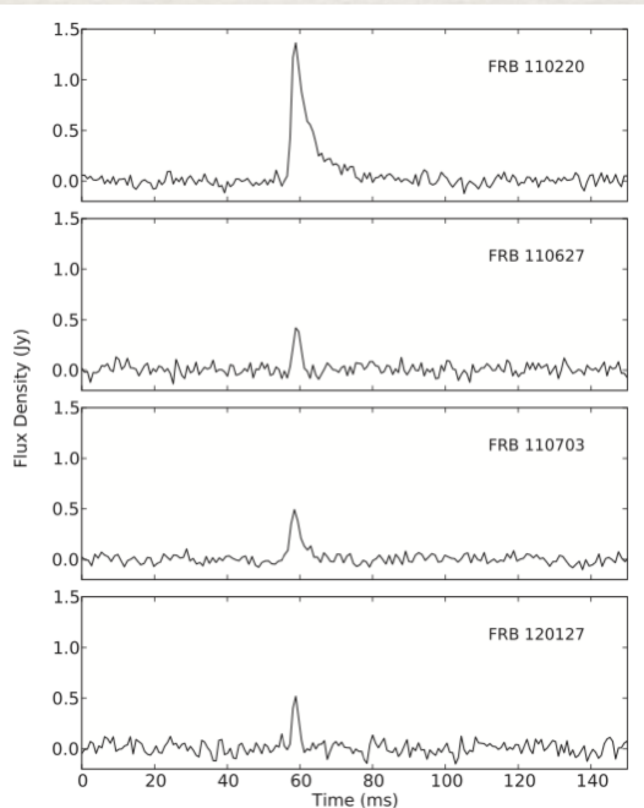
- low-frequency early radio observations highly encouraged in future events
  - would give important information for:
    - particle acceleration efficiency
    - electron-ion equipartition

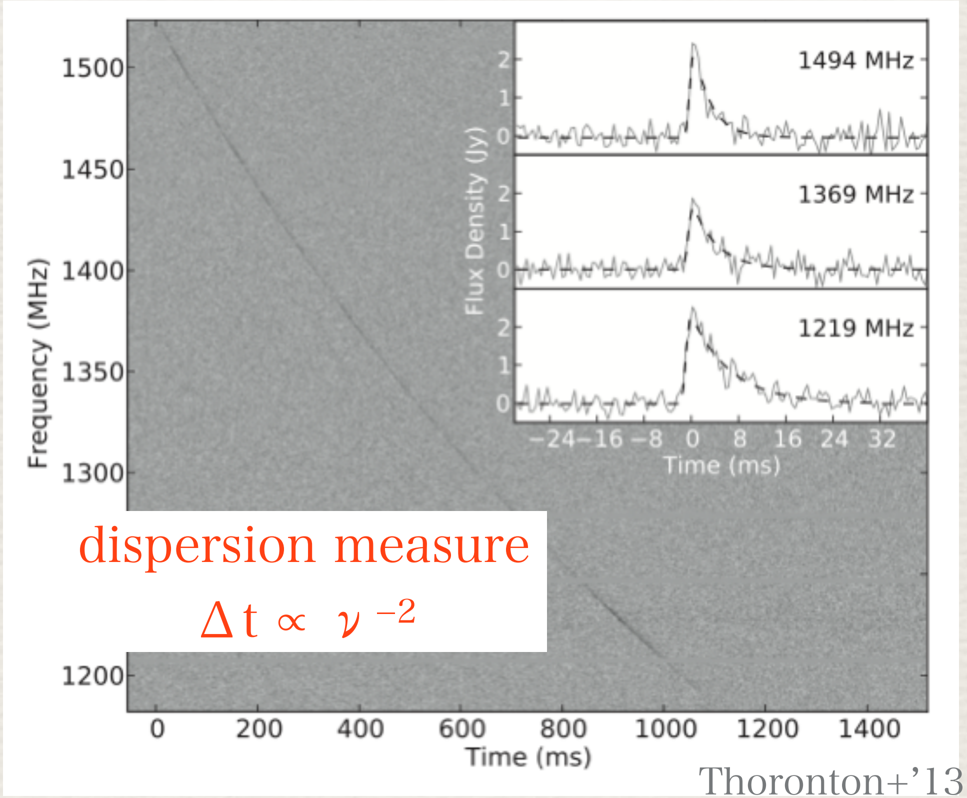
- change of other model parameters?
  - jet energy ~ 10^{52} erg (isotropic-equivalent to the jet direction), about 10 times larger than the conventional modeling
    - still consistent with the distribution of the short GRB energy distribution
  - ambient matter density n ~ 10^{-3}-10^{-2} cm^{-3}, about 10 times larger than the conventional modeling
    - consistent with the hot gas density in typical giant elliptical galaxies

Part III
fast radio bursts (FRBs) and binary neutron star mergers

Fast Radio Bursts: A New Transient Population at Cosmological Distances

- ~msec duration radio bursts at high galactic latitudes, ~Jy level peak flux
  - Lorimer et al. (2007); Thornton et al. (2013)
- event rate ~ $10^{3\text{-}4}$ /sky /day
- ~60 FRB detected so far,
- dispersion measure (DM) much larger than the maximum by ISM in the Galaxy





Thoronton+'13

large DMs! a cosmological origin?

- extragalactic DM in reionized universe
  - DM ~ 1000 cm^{-3} pc at z=1
- dispersion measure indicates z ~ 0.5-1
- ~ 10^4 /sky /day ~ 4×10^4 yr^{-1} Gpc^{-3} (z < 1, ⟨z⟩ =0.75)

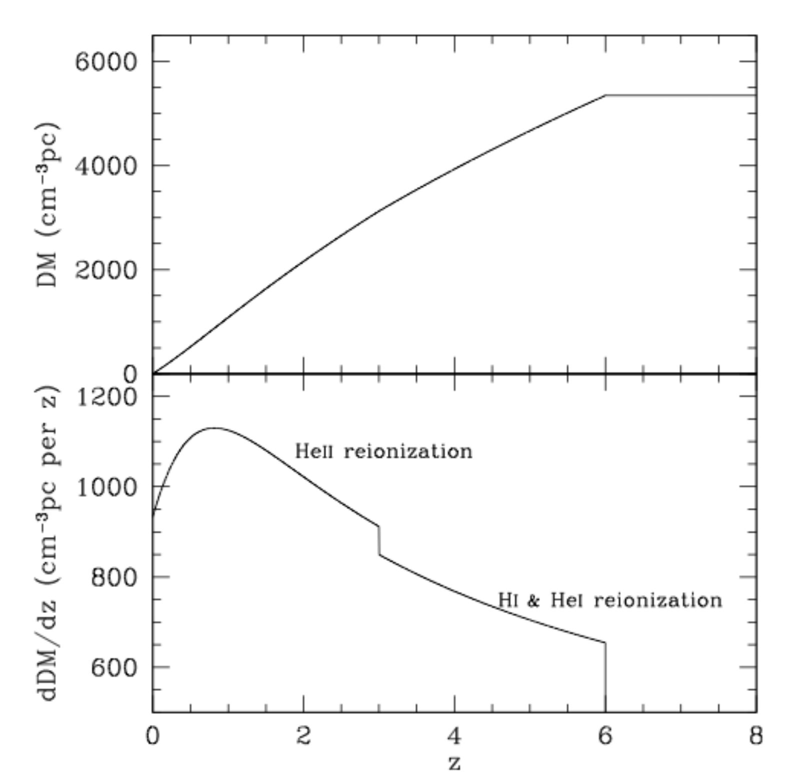
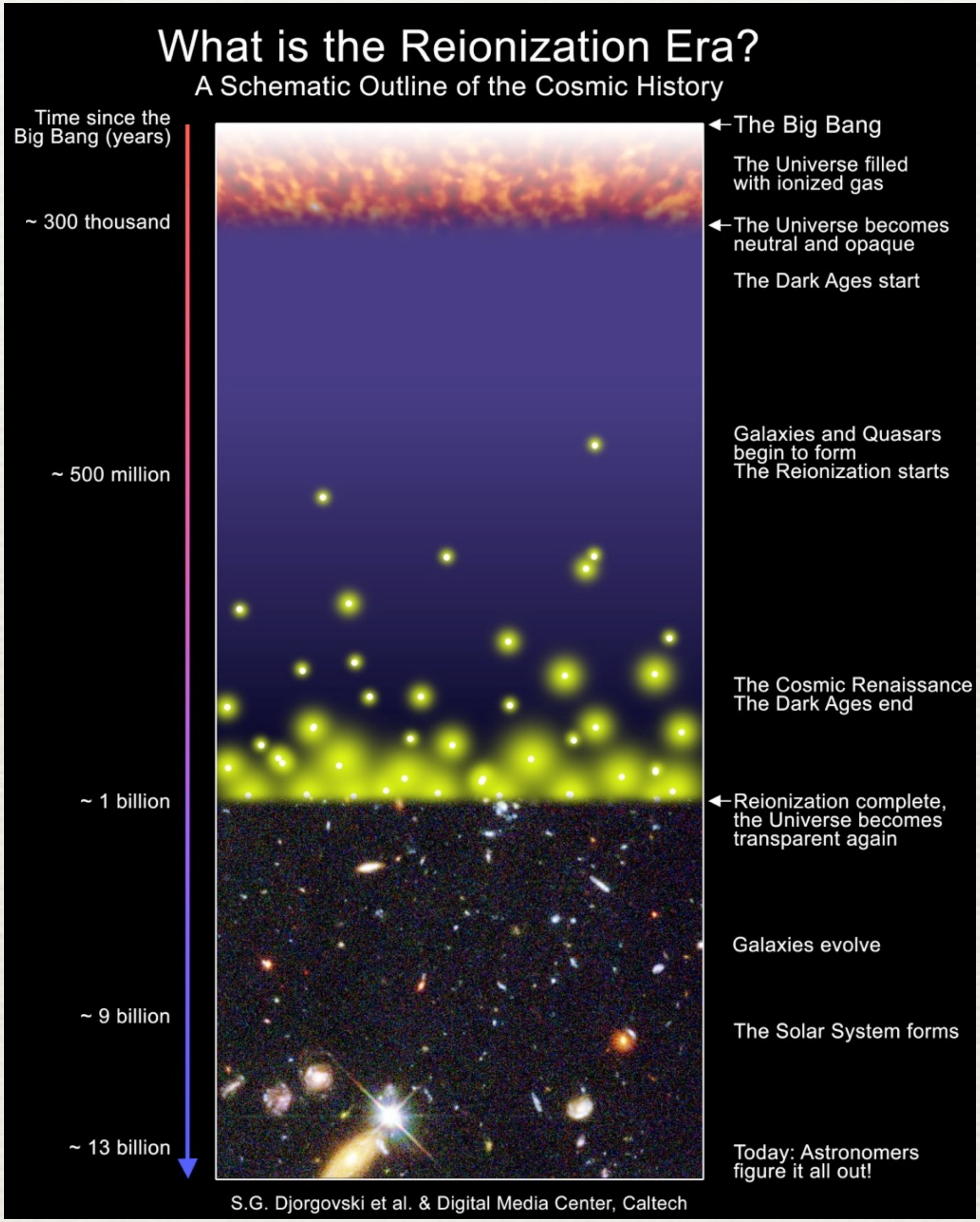


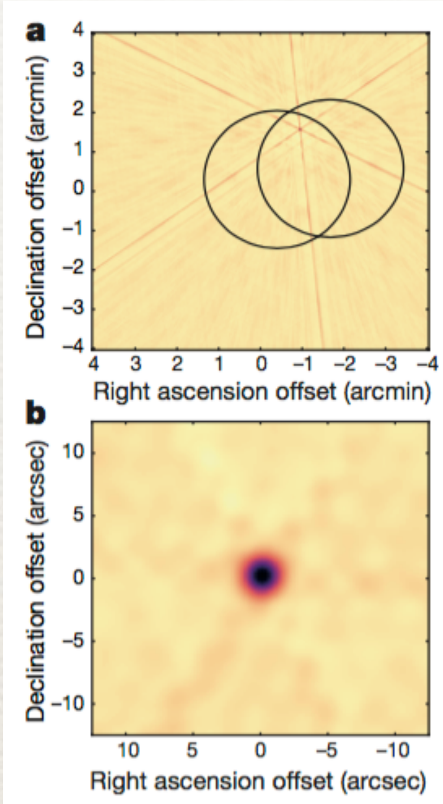
Figure 1. Illustration of using dispersion measure to probe the epoch of reionization of He II. Top and bottom panels show DM and its derivative as a function of redshift, respectively. A sharp H I and He I reionization at $z \sim 6$ and a sharp He II reionization at $z \sim 3$ are assumed.

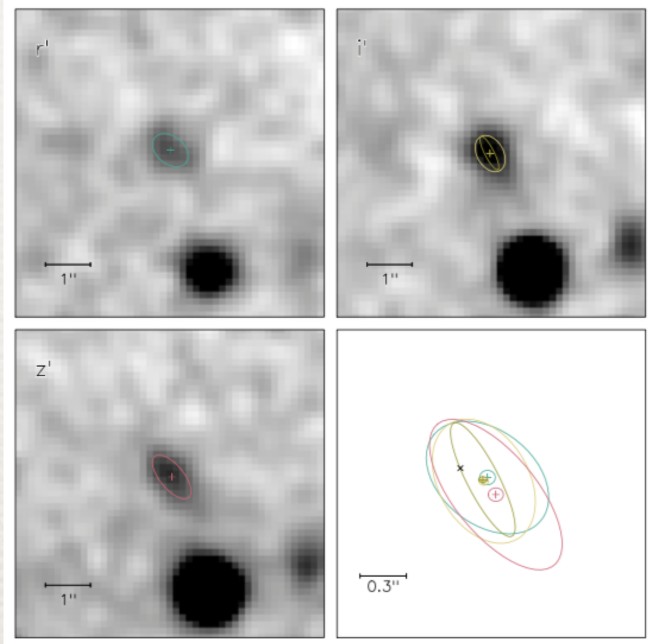
Zheng+'14

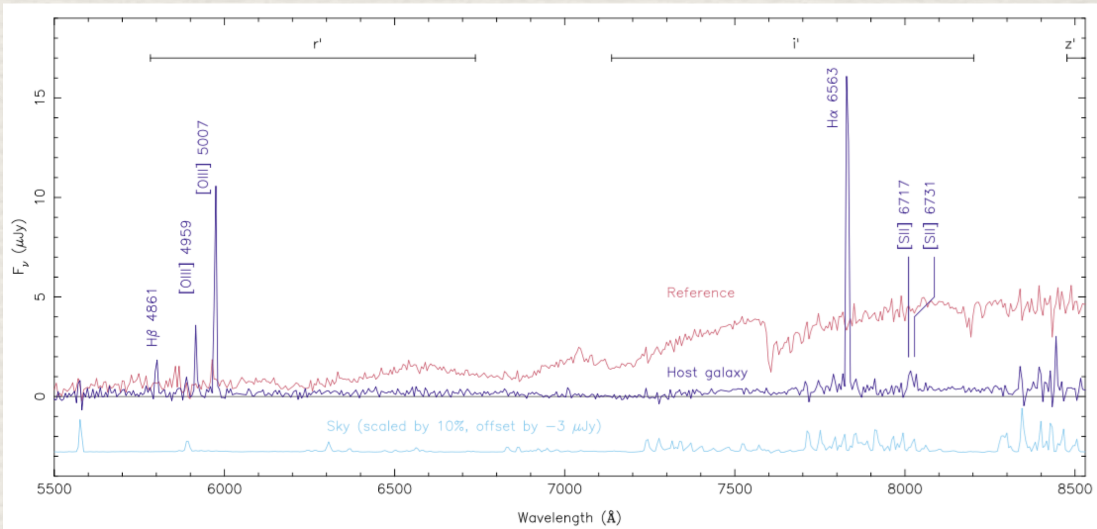


FRB 121102 is repeating!

- discovered by Arecibo
- DMs ~ 560 pc cm^{-3}
- 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}
- persistent radio source 180 uJy
  - offset from host nucleus
  - size < 0.7 pc (Marcote+’17)
- most likely a young neutron star
- the second repeating FRB 180814.J0422+73 discovered (CHIME collab. ’19)
- but repeating bursts are not found from other FRBs in spite of follow-up monitoring
  - more than one population?







Faraday rotation of FRBs

- FRB 110523 (Masui+'15)
  - RM = -186.1 +/-1.4 rad m^{-2}
  - much higher than expected from MW ISM
  - strong magnetization of circumburst environment
  - "favours models involving young stellar populations such as magnetars over models involving the mergers of older neutron stars"

- FRB 150807 (Ravi+'16)
  - RM = -12.0 +/- 0.7 rad m^{-2}
  - similar RM for nearby Galactic pulsar
  - → RM <~ 2 rad m^{-2} outside the Galaxy or circumburst environment
  - "FRB progenitor theories that propose emission from young neutron stars or other objects embedded in highly magnetized star forming regions or galaxy centers may be inconsistent with the low RM of FRB 150807"

- at least some FRBs from clean environment?
  - e.g., non-repeating FRB population from NS-NS mergers?

(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
    - FRB rate 2000^{+1100}_{-500} /Gpc^3/yr (Hassal+'13)
    - c.f. short GRBs ~1-10 /Gpc^3/yr
  - high end of NS-NS merger rate estimate before GW 170817
  - NS-NS rate 1540^{+3200}_{-1220} /Gpc^3/yr (LVC '17 PRL 119, 161101)

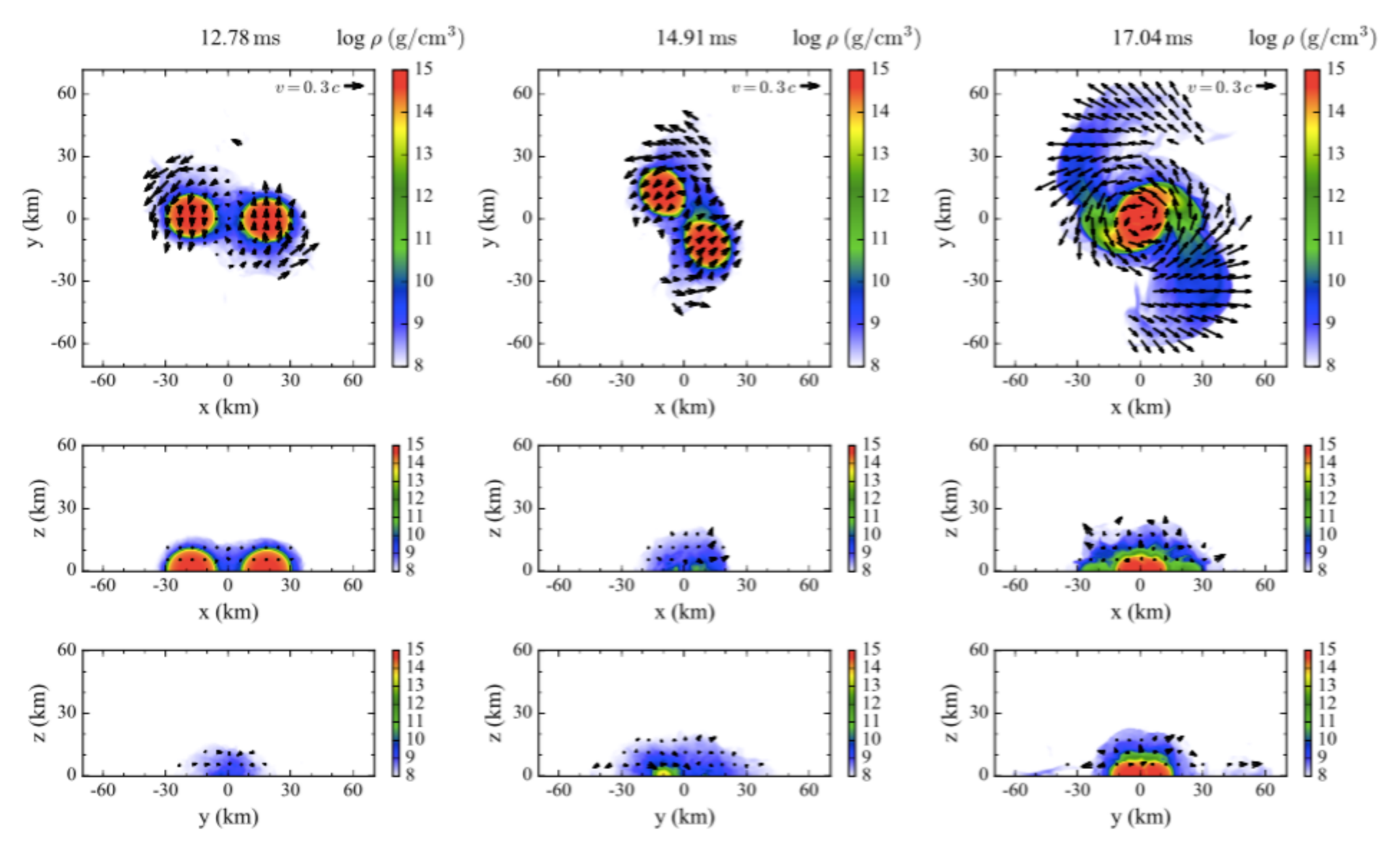
- predicted radio flux by dipole radiation is similar to FRBs, if
  - dipole with B ~ 10^{12} G and r ~ 10 km
  - rotation period ~ msec
  - radio conversion efficiency similar to pulsars (~10^{-4})

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

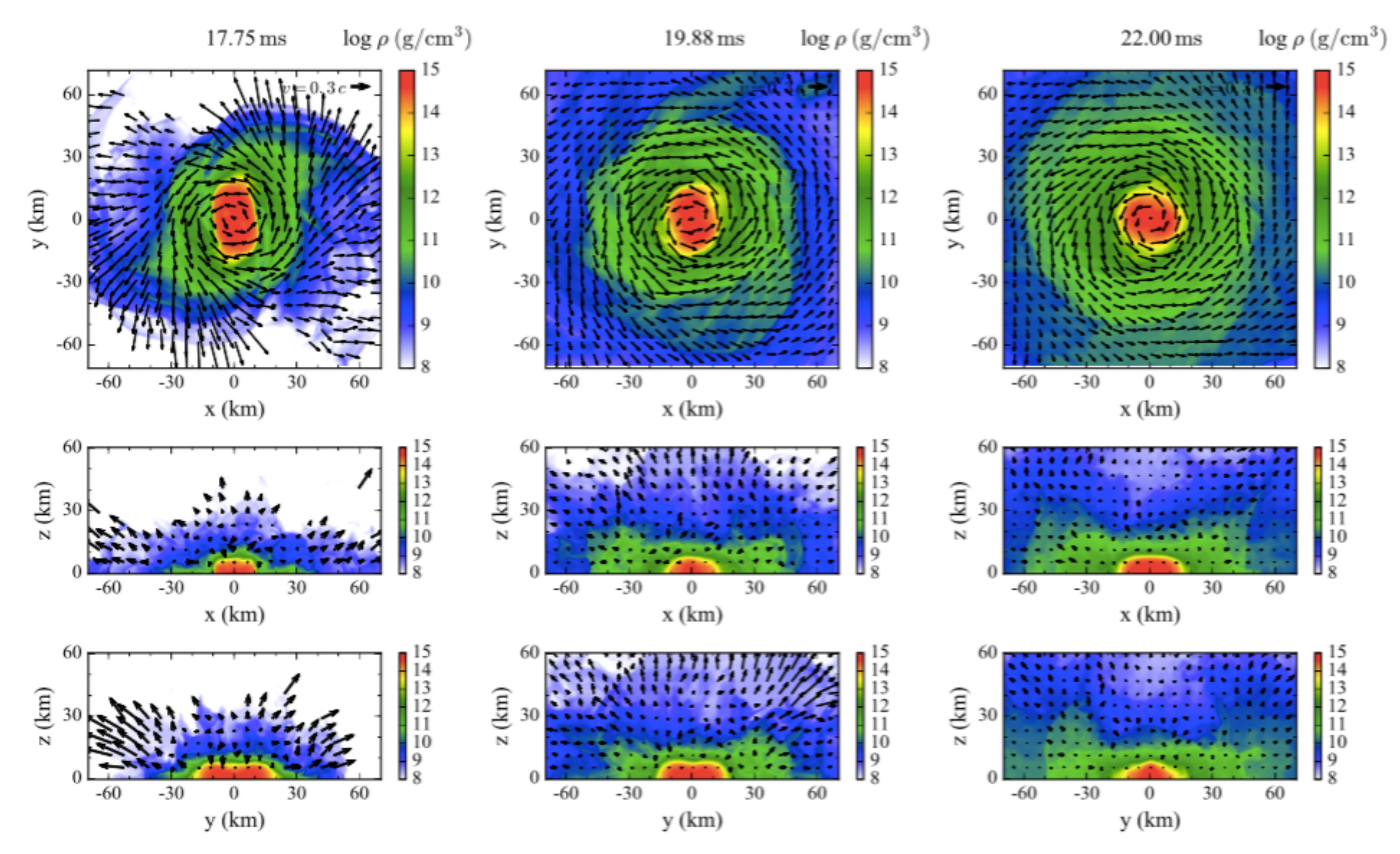
$$F_\nu = \frac{1}{\nu_{\rm obs}} \frac{\epsilon_{\rm r}|\dot{E}|}{4\pi D_{\rm lum}^2} = 0.02 \left(\frac{\epsilon_{\rm r}}{10^{-4}}\right) \left(\frac{D_{\rm lum}}{4.6\,\mathrm{Gpc}}\right)^{-2} \times \left(\frac{B}{10^{12.5}\,\mathrm{G}}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^6 \left(\frac{P}{0.5\,\mathrm{ms}}\right)^{-4}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

NS-NS merger ejecta vs. radio emission

- 10^{-3}~10^{-2} $M_\odot$ ejecta expected from merger
- no radio emission if they are absorbed by thick ejecta?



NS-NS merger simulation by K. Kiuchi

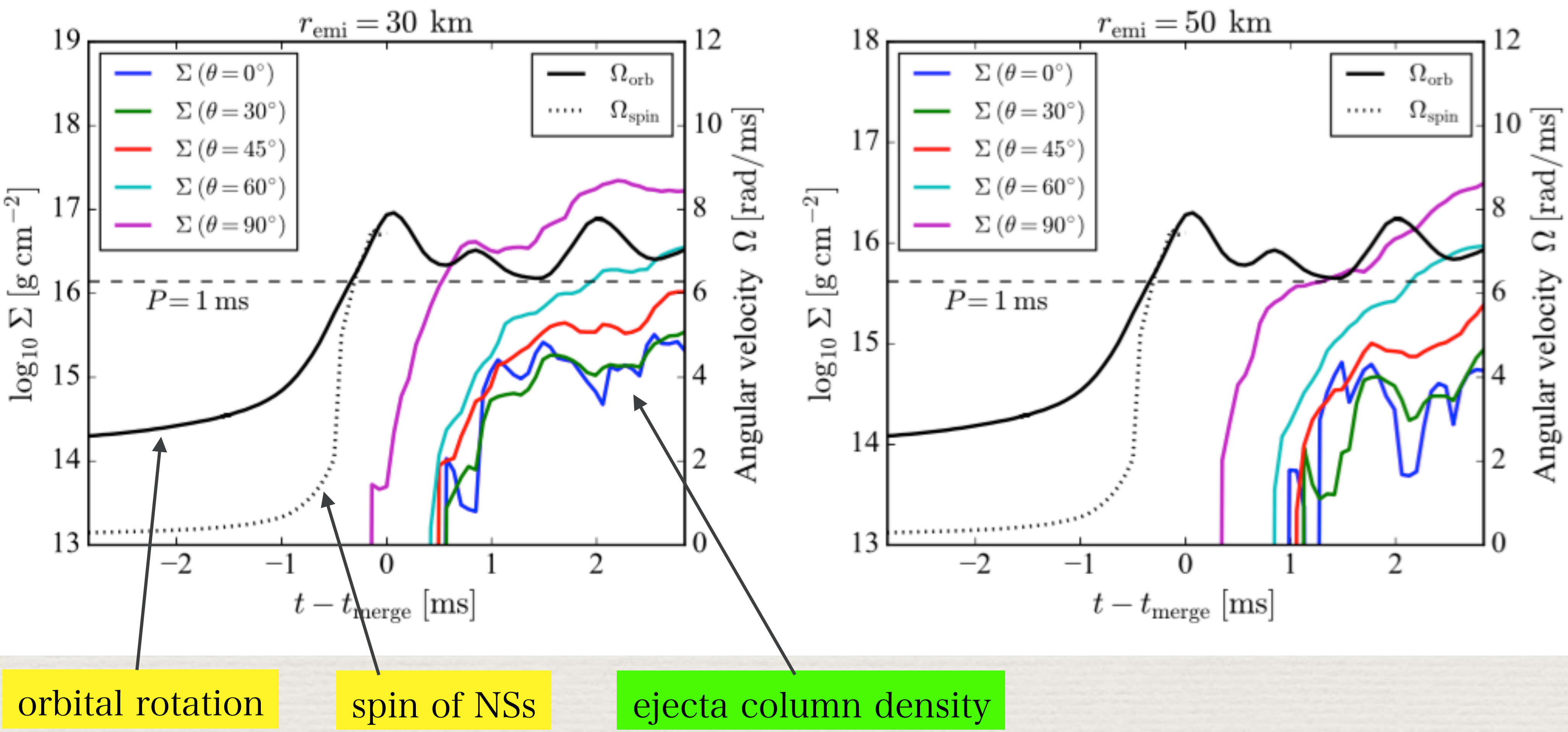


17.75 ms
log ρ (g/cm^3)
19.88 ms
log ρ (g/cm^3)
22.00 ms
log ρ (g/cm^3)
$v = 0.3c$
y (km)
x (km)
z (km)
x (km)
z (km)
y (km)

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 ’18



repeating FRB from NS-NS mergers?

Yamasaki, TT, & Kiuchi ’18

- a long-lived massive NS may be left after a fraction of NS-NS mergers, depending on EOS
- merger ejecta becomes transparent in 1-10 yrs to radio signals
  - the opportunity to see the most extreme neutron star!
  - c.f. ~10-100 yrs for supernova scenario
- repeating burst detection rate broadly consistent with NS-NS merger rate if, e.g., the repeater life time is ~10 yrs and 1% of BNS mergers leave repeating FRBs
- 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

Conclusions (Part III)

- Observations imply that a fraction of FRBs are non-repeating and occurring in clean (low density) regions
  - making BNS mergers a good candidate
- Rate and expected radio flux from BNS mergers roughly consistent with FRBs
- ejecta from BNS mergers would prohibit radio signal transmission, but there is a time window of a few msec from the merger to significant matter ejection
- a fraction of BNS merger would leave a massive, rapidly rotating neutron star, which may become a repeating FRB
  - ~10 yr time scale of appearance after the merger
  - repeating FRBs in elliptical galaxies