Shock Acceleration of Electrons and Synchrotron Emission from the Dynamical Ejecta of Neutron Star Mergers

Herman S.-H. Lee, Kei-ichi Maeda, Norita Kawanaka (Kyoto U)

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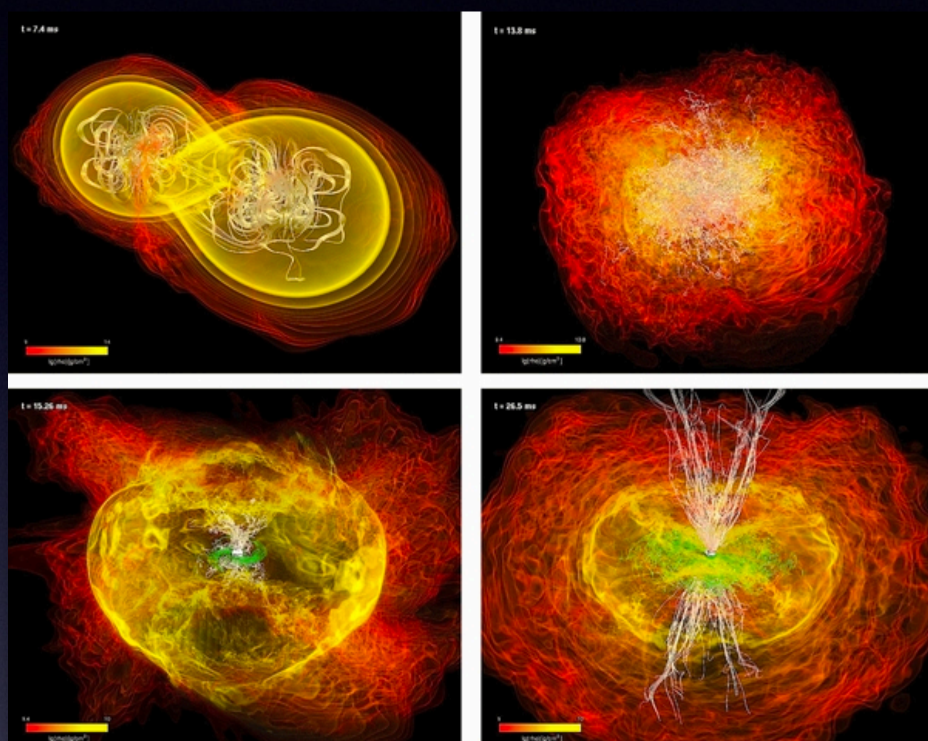
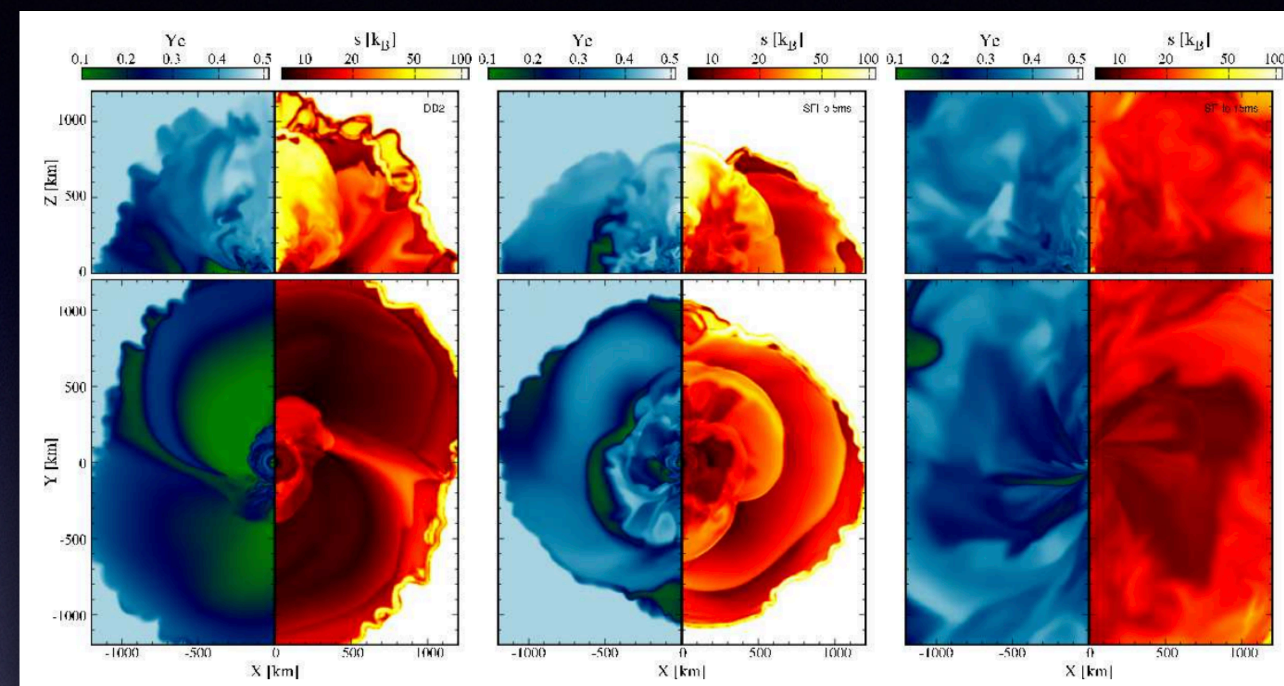
Jet and Shock Breakouts in Cosmic Transients, YITP, 14 - 18 May 2018

NS Merger Remnant



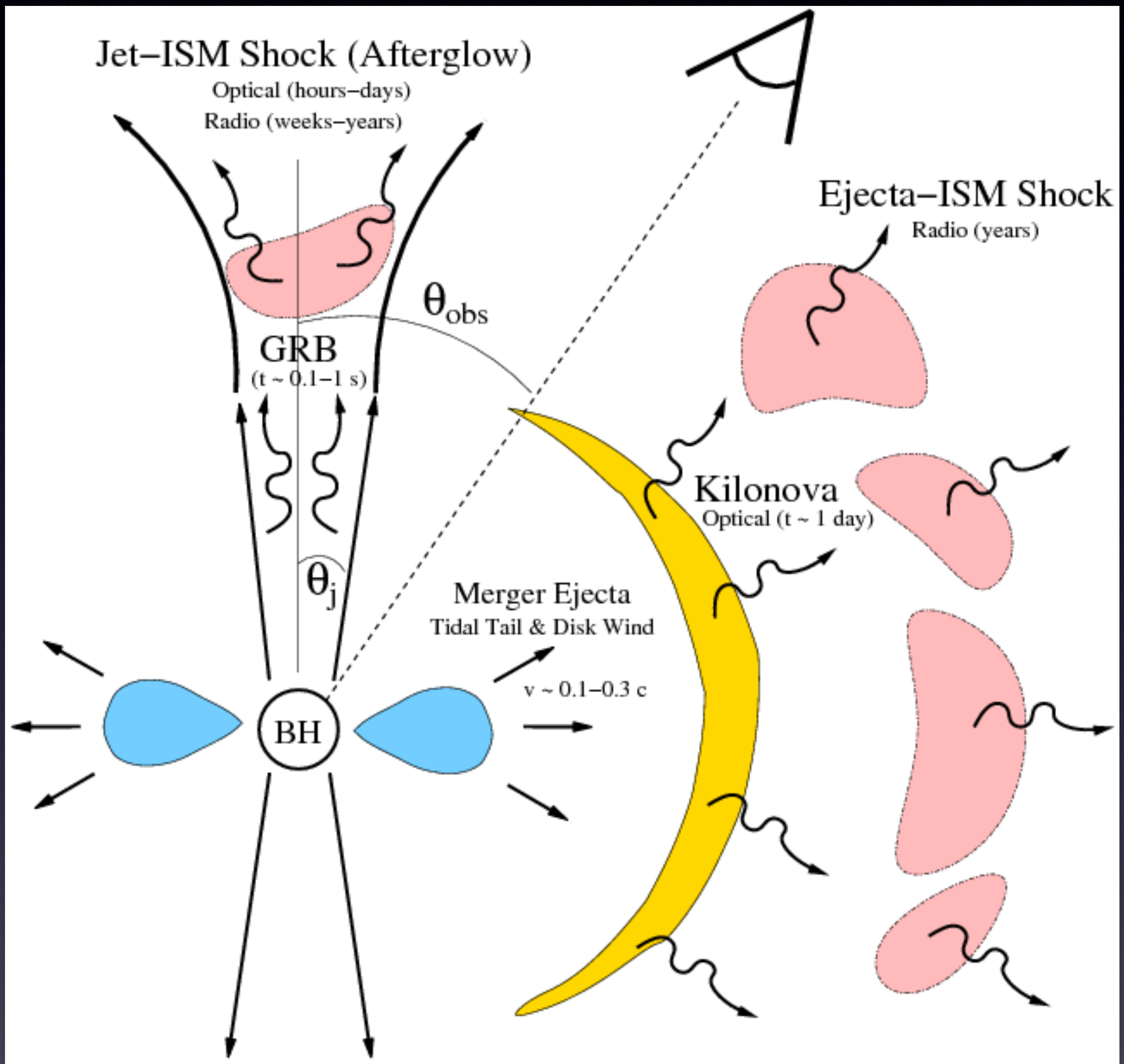
Rezzolla+ 11



Sekiguchi+ 15

- NSMs accompanied by **high-speed mass ejection (dynamical ejecta)**
- Ejecta interacts with **circumbinary medium (CBM)** and creates a **sub-relativistic shock**
- Shock **accelerates particles** and emits **EM signals**
- Possible additional EM signal following sGRB component

Our picture



Metzger+

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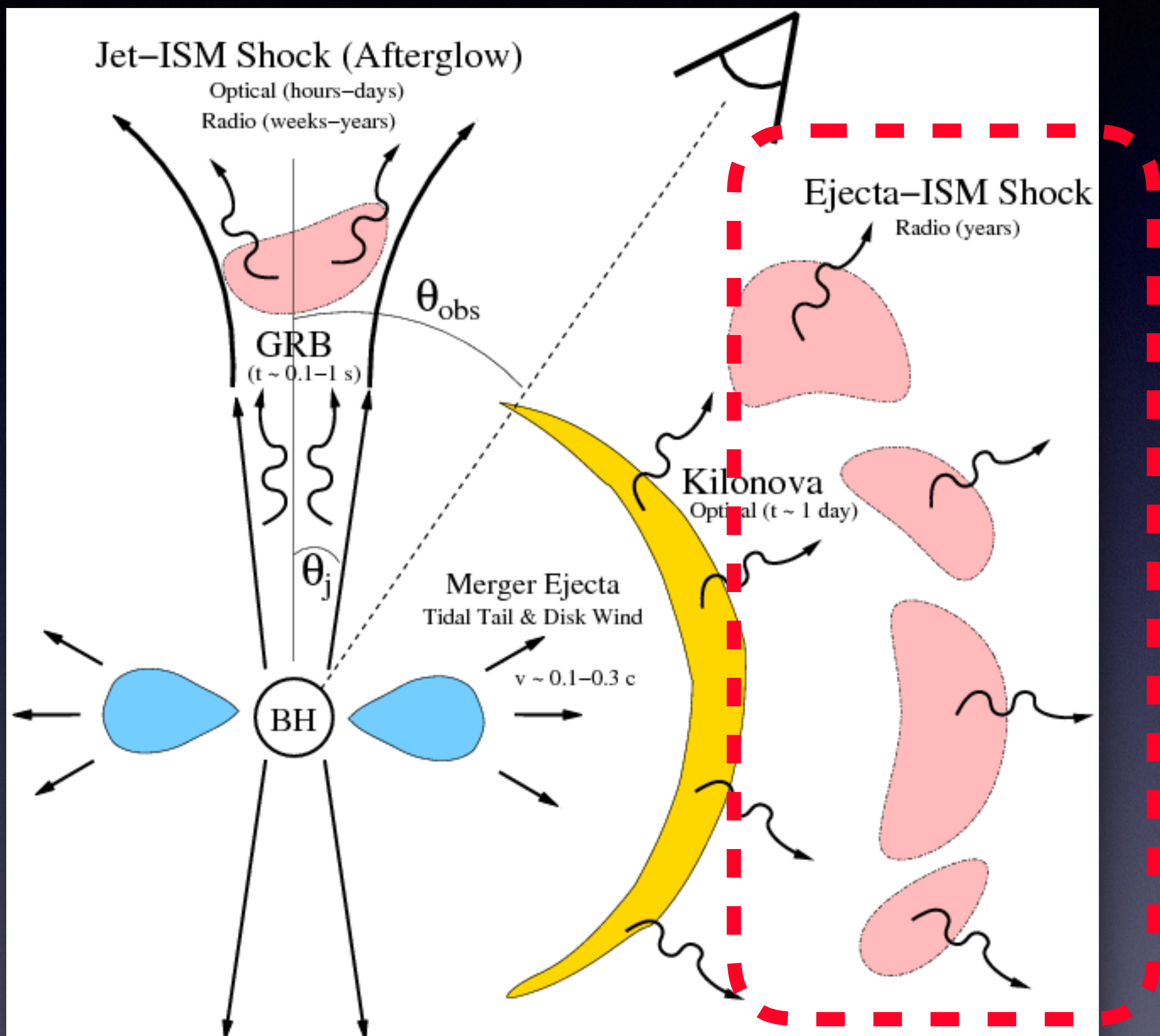

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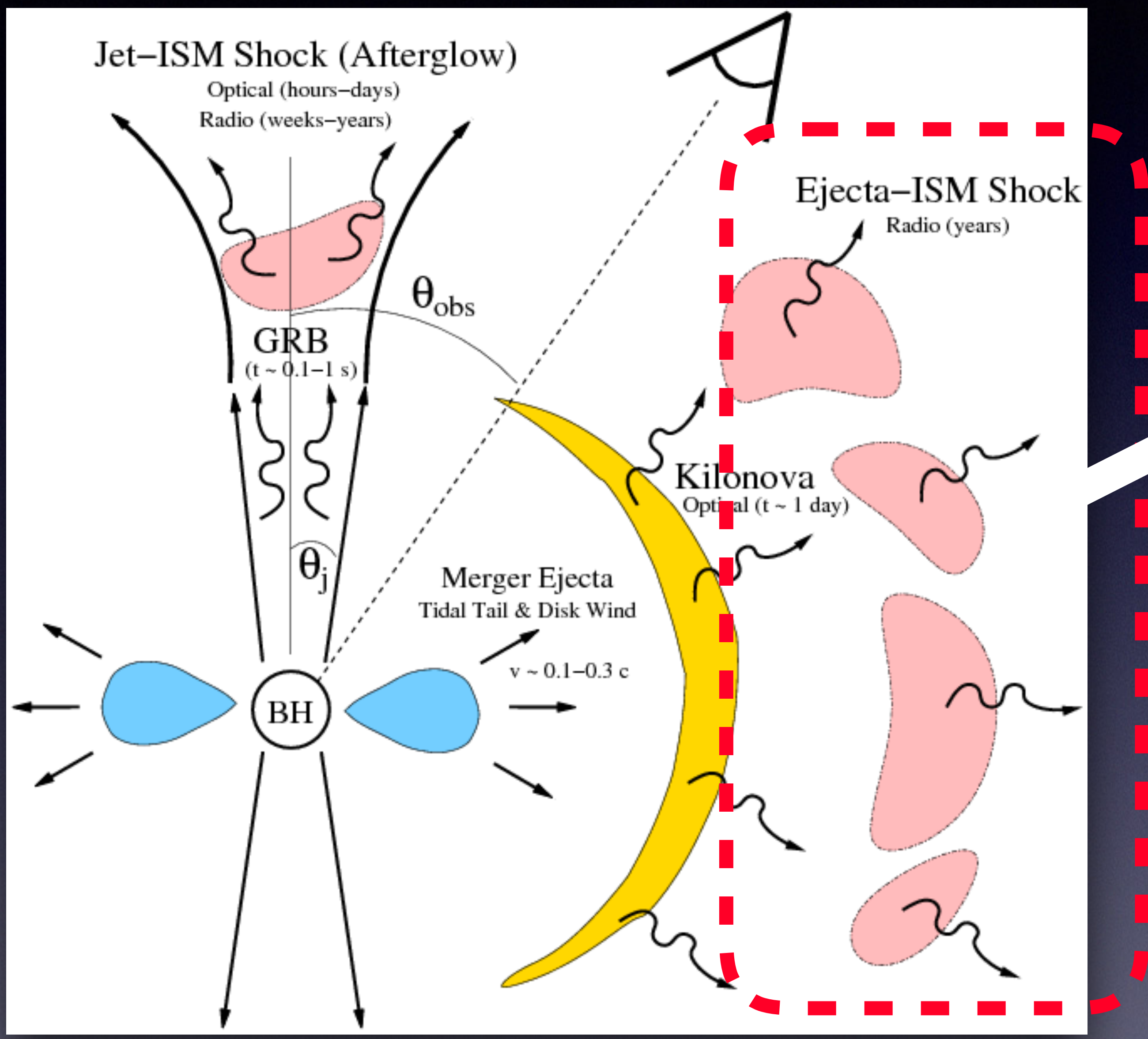
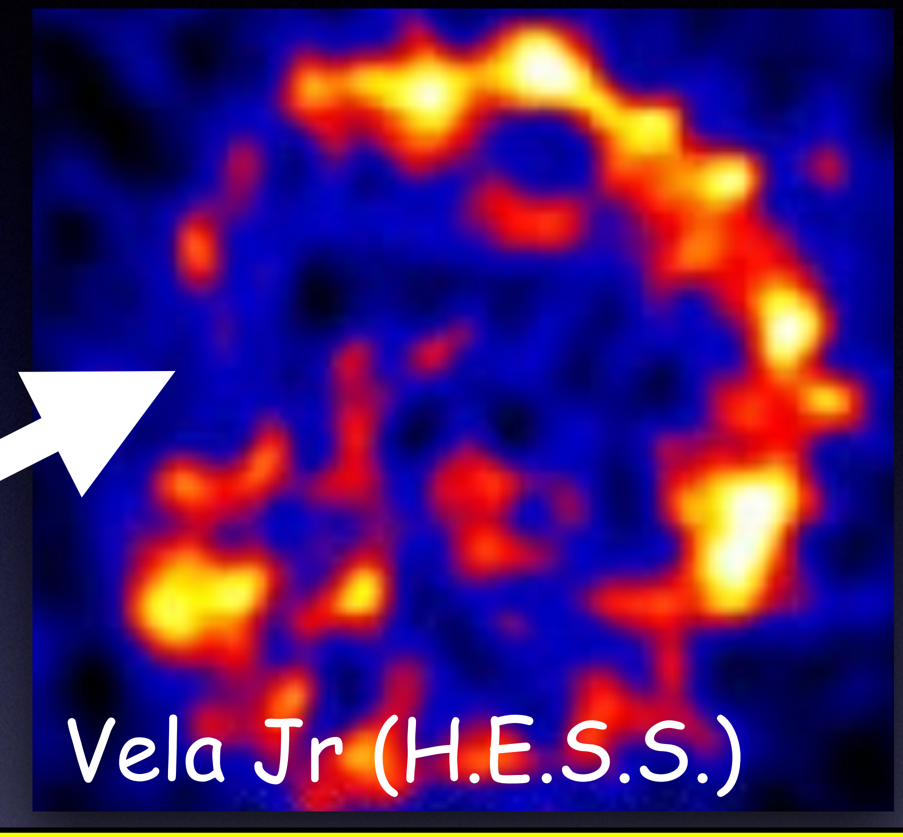


Metzger+



NSM ejecta-CBM interaction as a "miniature" SNR?

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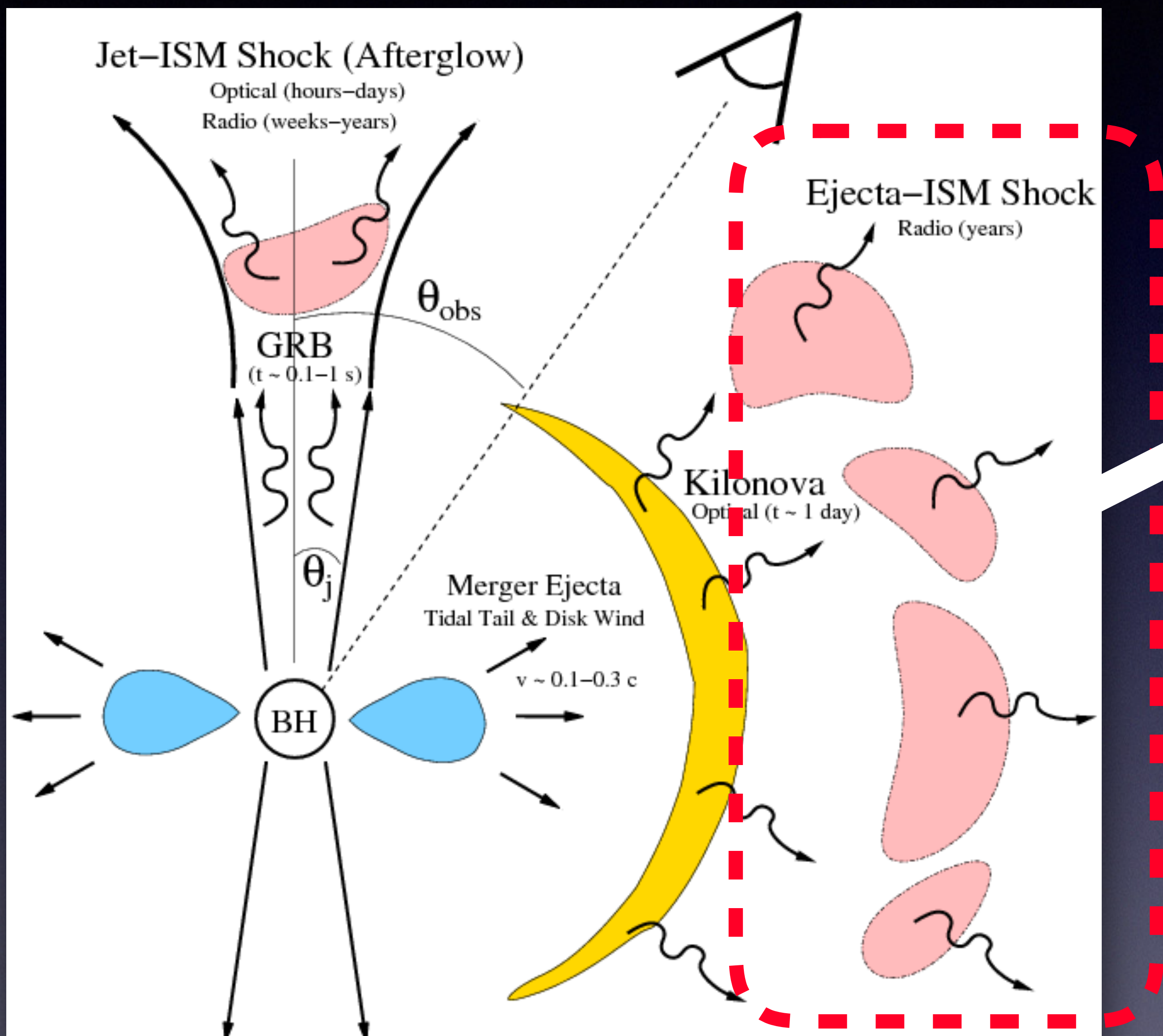

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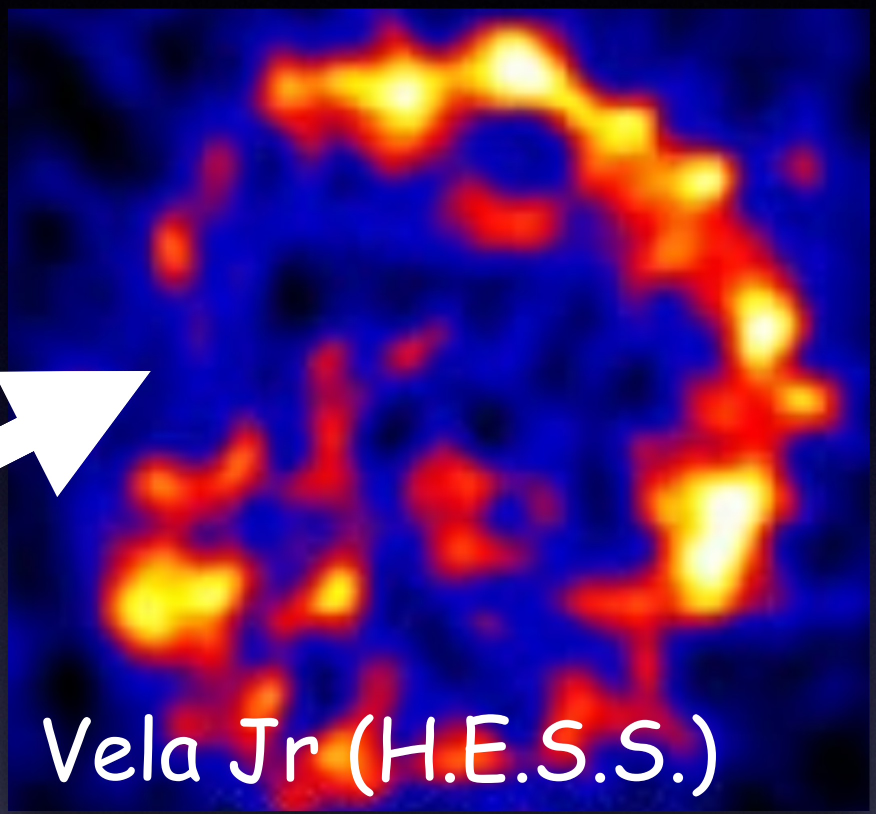

NSM ejecta-CBM interaction as a "miniature" SNR?

M_{ej} ~ 0.05 M_{sun} vs a few M_{sun}

E_{ej} ~ 10^{50} erg vs 10^{51} erg

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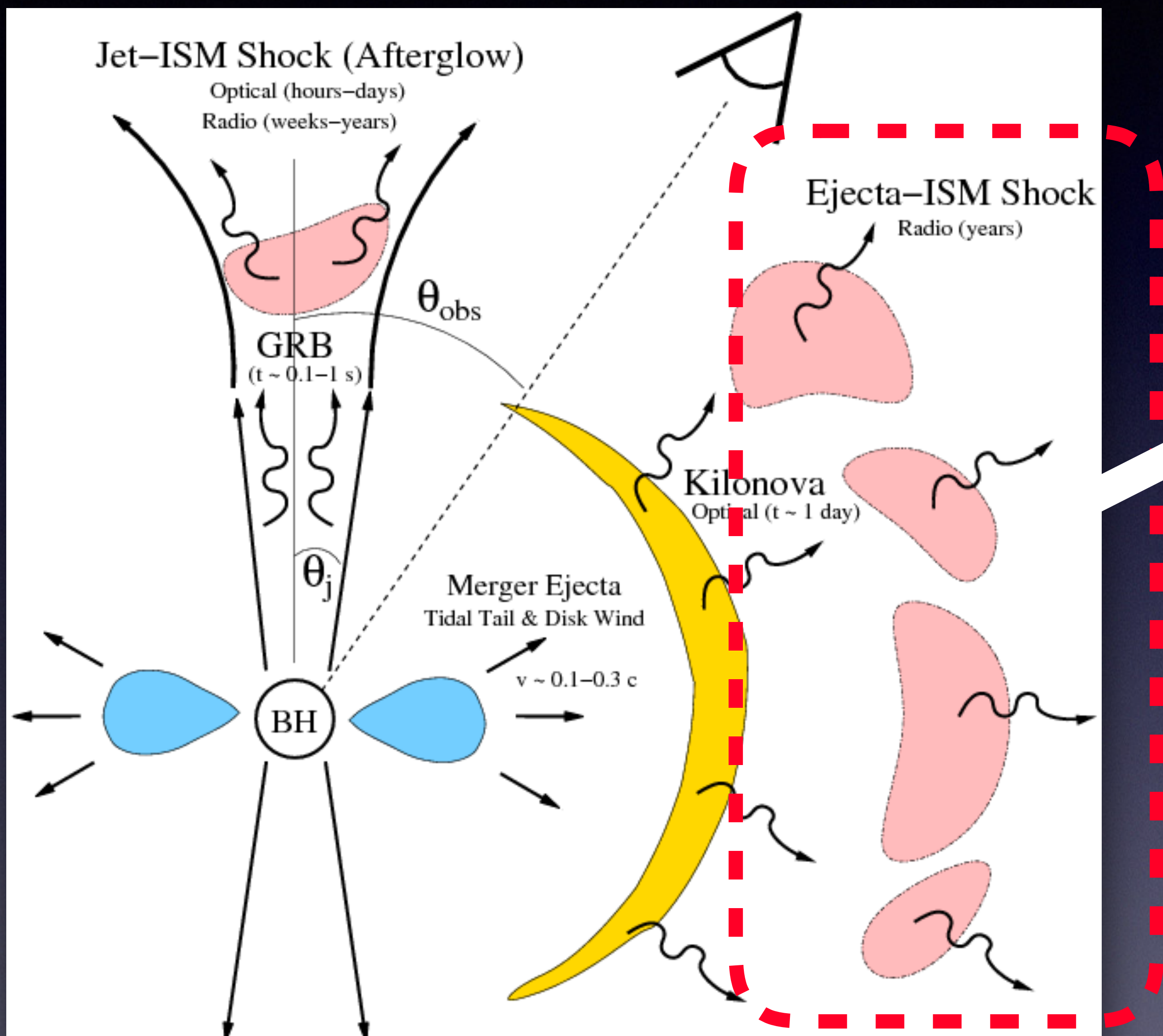

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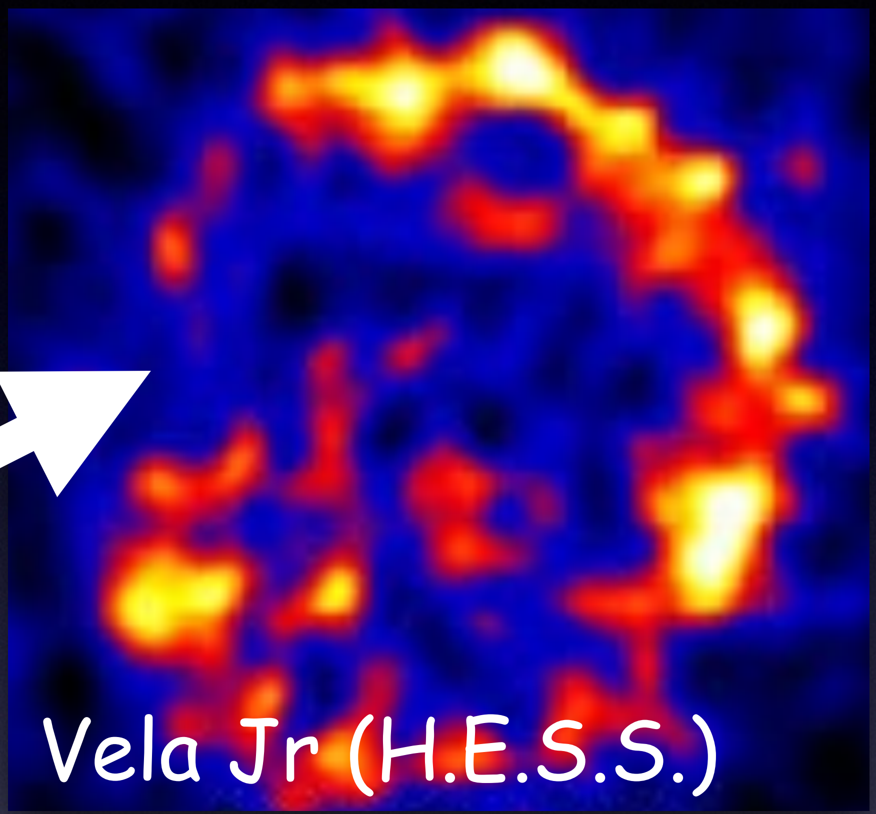

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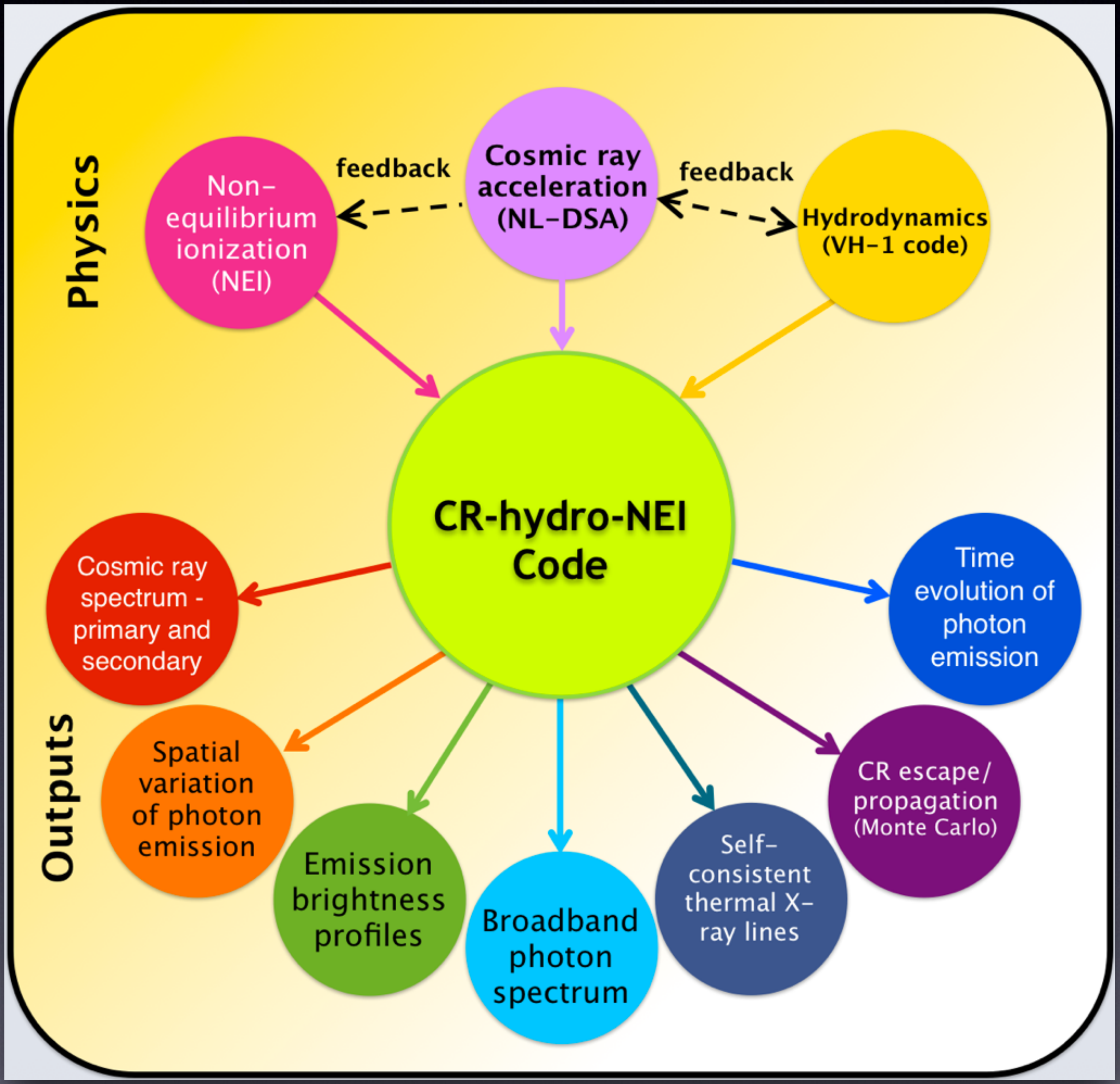
See also: Asano & To (2018), Hotokezaka+ (2018), Alexander+ (2017), etc

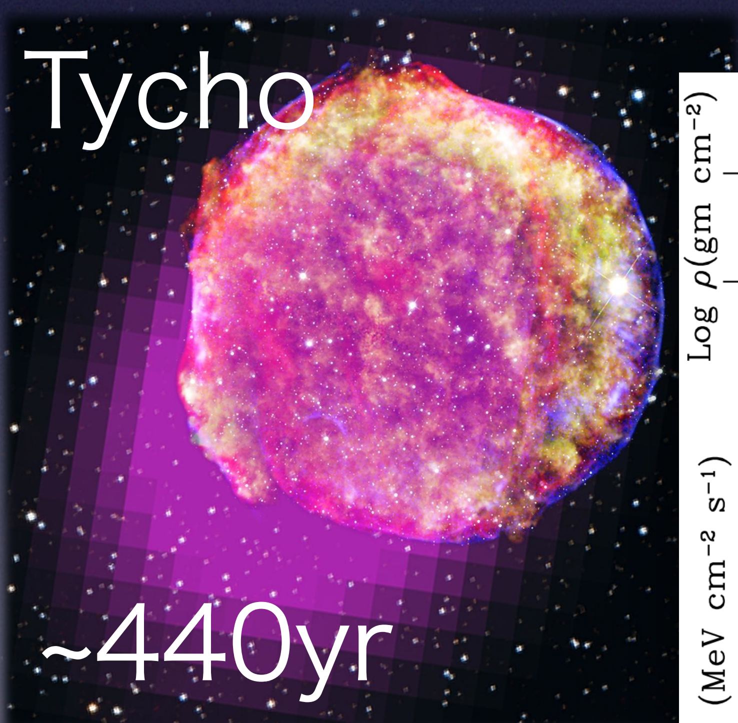
The code

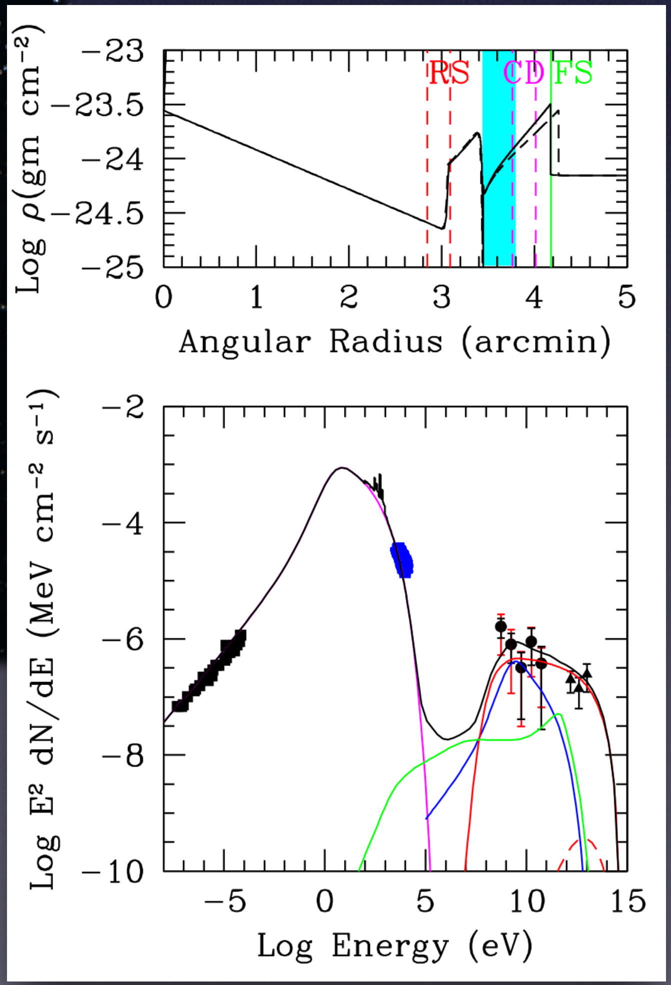


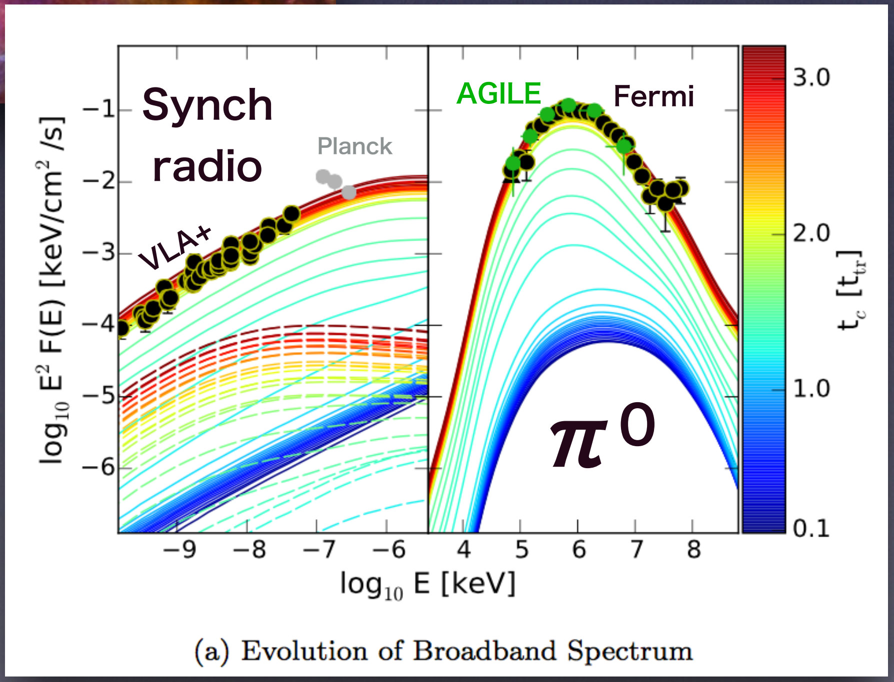
- 1-D Lagrangian hydro
- Non-linear diffusive shock acceleration
- CR-driven magnetic field amplification
- Spacetime-dependent broadband emission spectral calculation

Applications to SNRs

- Applied successfully to non-thermal young and evolved SNRs (e.g., Lee+ 2012-2015; Castro+ 2012; Slane, Lee+ 2014)







Source of seed e^-

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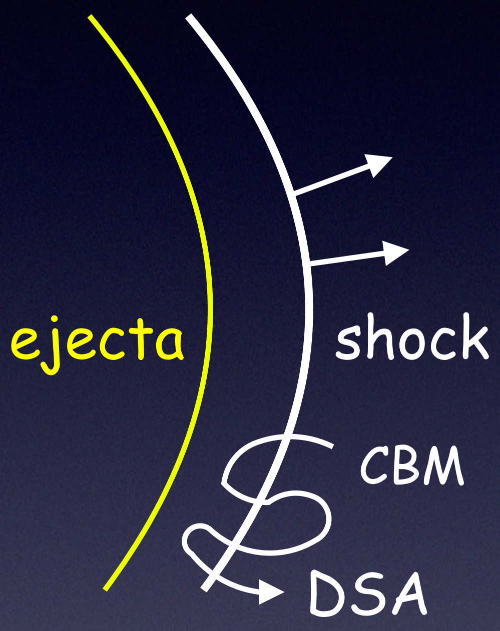
- 1) Shock-heated e^- from CBM
  - Same story as young SNR shocks
  - Typical DSA proton injection fraction $\eta_{inj,th} \sim 10^{-5}$ to 10^{-4}
  - e^- proportional to free parameter K_{ep} ("e-to-p ratio")
  - Typical K_{ep} = 0.003 - 0.01 from young SNR models



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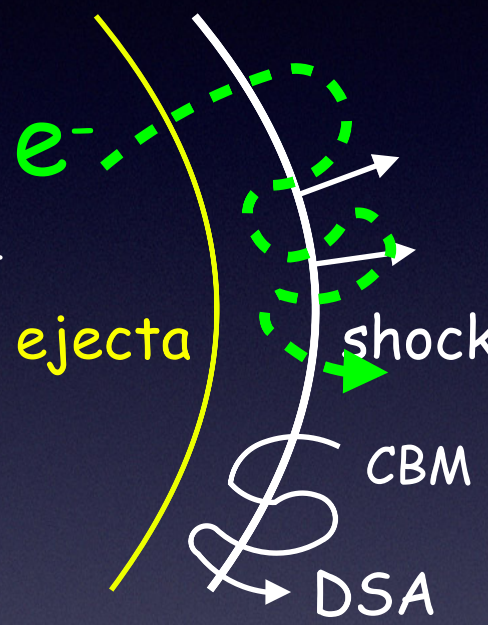

- 2) Escaped β-decay e^- from NSM dynamical ejecta
  - Emitted by decay of radioactive r-process stuff
  - Escape from ejecta —> catch up with forward shock —> DSA

$$t = t' + \left(\frac{R_{\rm sk} - R_{\rm esc}}{\widetilde{v_e} - v_{\rm sk}}\right)\left(1 - \frac{\widetilde{v_e} v_{\rm sk}}{c^2}\right),$$

escape-injection time delay

Luminosity of β-decay e^-

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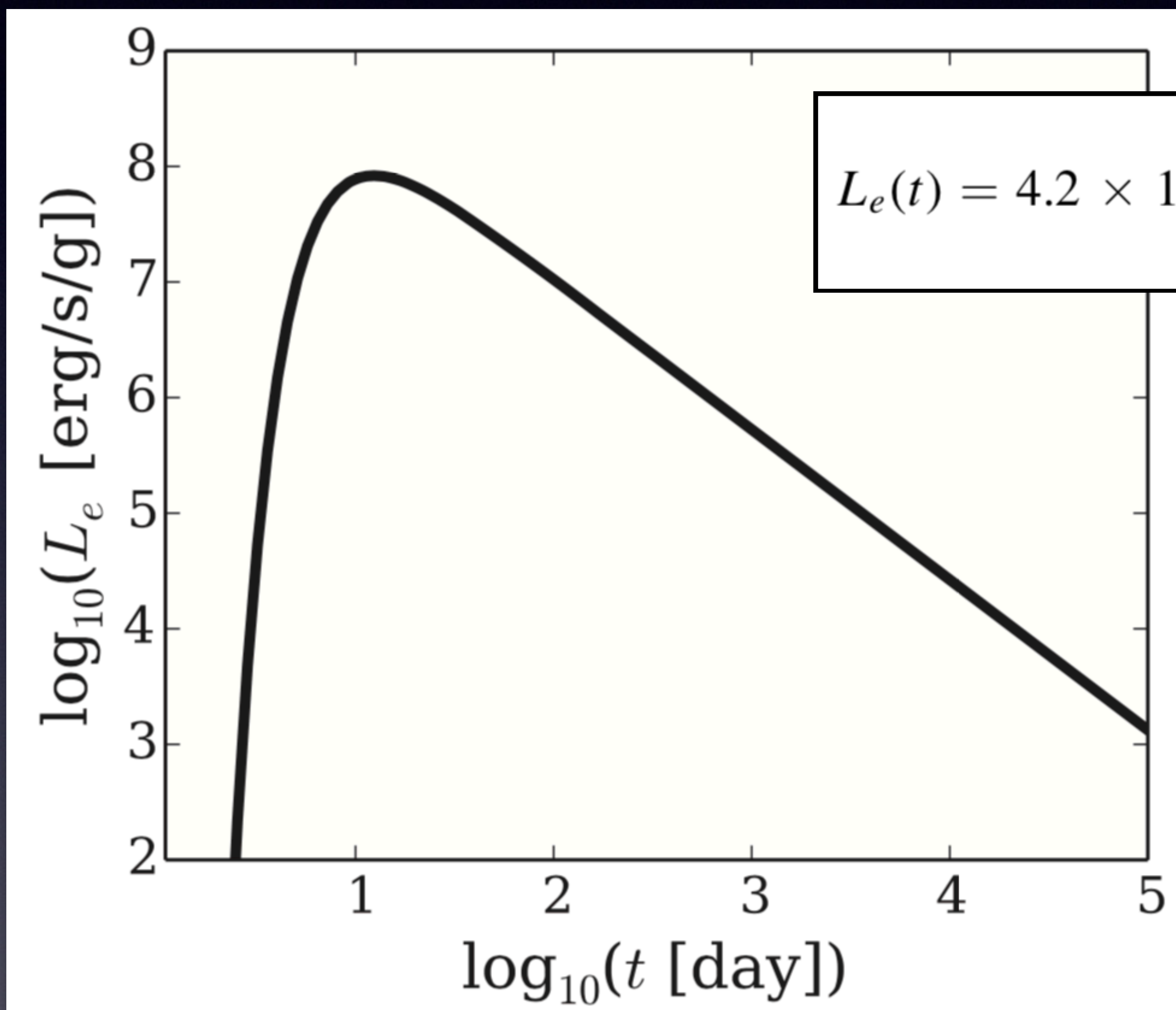
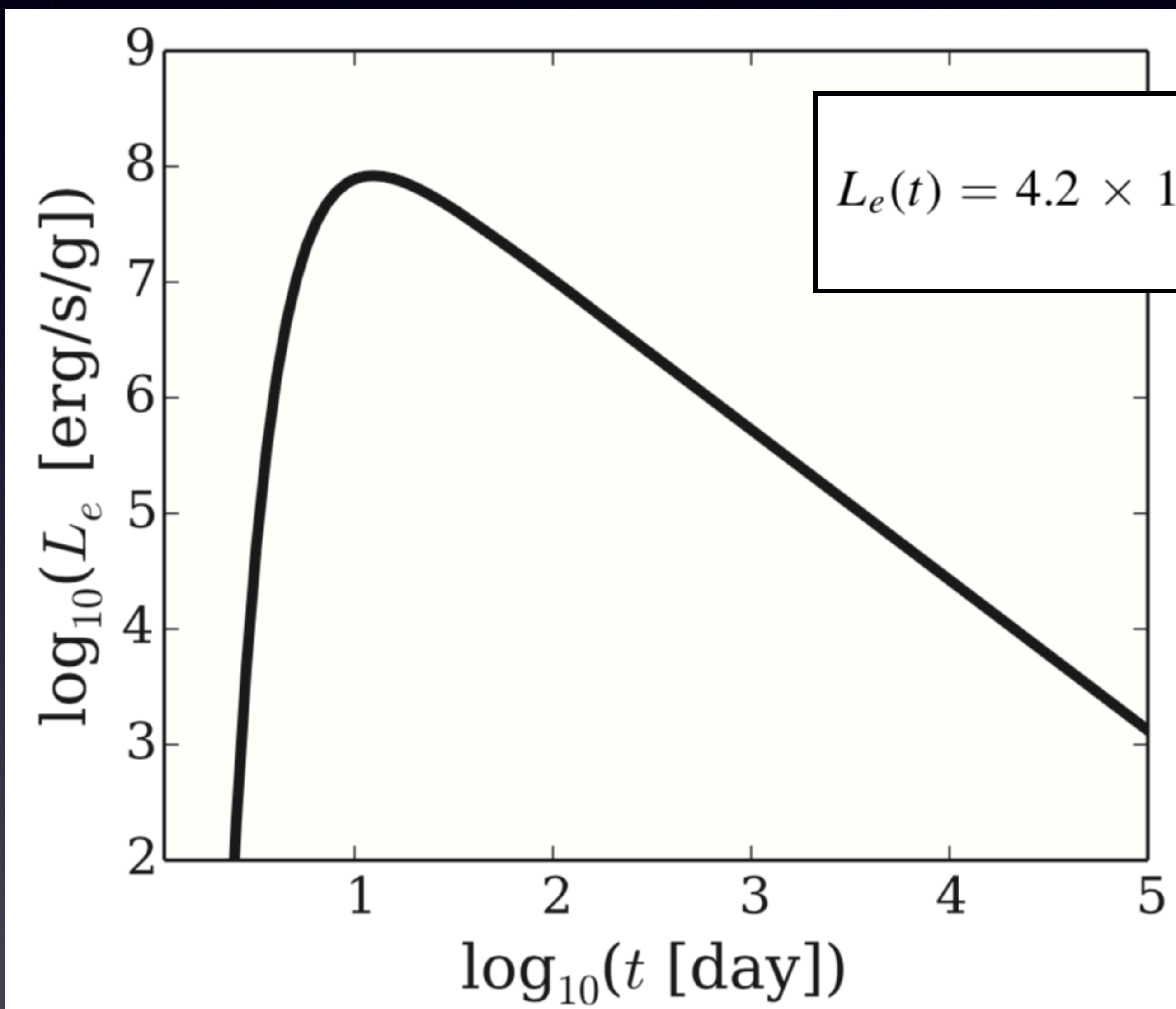


$$L_e(t) = 4.2 \times 10^9 \left(\frac{t}{\mathrm{day}}\right)^{-1.3} \exp\left[-\left(\frac{t}{t_{\mathrm{esc}}}\right)^{-2}\right] \mathrm{erg\ s^{-1}\ g^{-1}},$$

Specific luminosity of escaped e^-

- Inspired by Hotokezaka+ (2016)
- t_{esc} ~ 10 d (Barnes+ 2016) w/ uncertainty

Luminosity of β-decay e⁻



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$$n_{e,\text{decay}}(t) = \frac{L_e(t')M_{\text{ej}}}{4\pi R_{\text{sk}}^2 \widetilde{v_e E_e}},$$

β-decay e^- density at shock

Assume typical $\langle E_e \rangle$ ~ 1 MeV

(~0.1 MeV e^- cannot catch up with shock)

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$$N_{\rm e,sup-th}(t) \sim 4 \times 10^{40} \left(\frac{\eta_{\rm inj,th}}{10^{-4}}\right)\left(\frac{K_{\rm ep}}{0.01}\right)\left(\frac{t}{1000\ \rm days}\right)^2\ {\rm s}^{-1}.$$

(Number of accelerated shock-heated CBM e^-)

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- Actually, there are too many β-decay e^- in early phase
- Limited by shock energy budget, only a fraction can be accelerated
- We assume $F_e \le 0.1\ F_{shock}$ for β-decay e^- (note: $F_{shock} = \rho_{CBM} v_{shock}(t)^3/2$)

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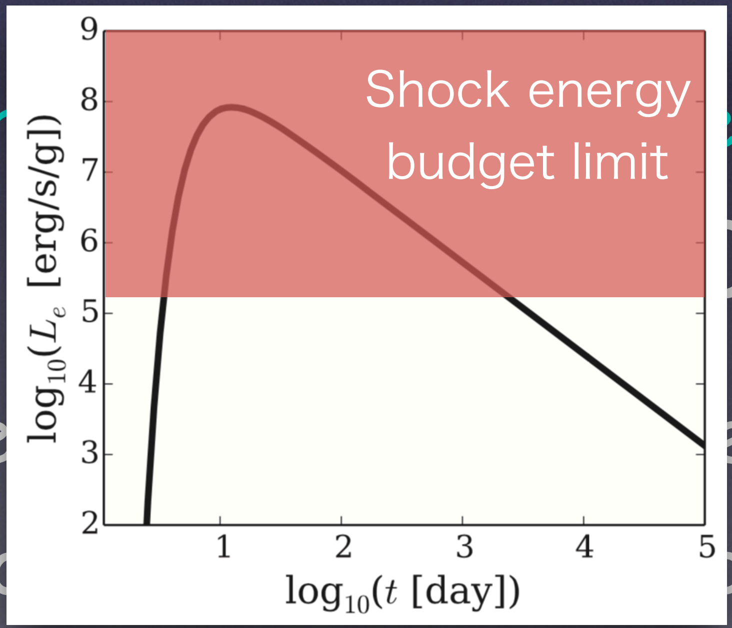
(Number ... cay e^-)

i.e., $N_{e,decay} \gg N_{e,th}$ ... 0 d



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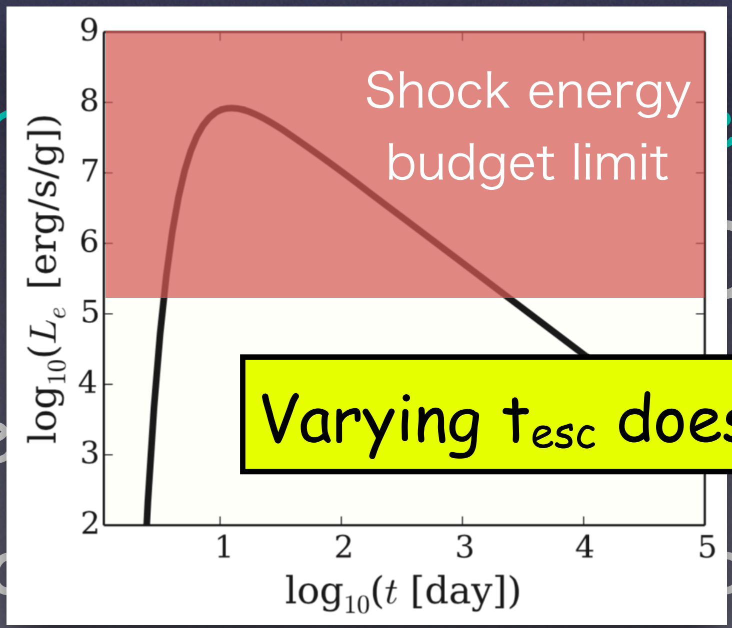

Varying t_{esc} does not affect result

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- We assume F_e <= 0.1 F_{shock} for β-decay e^- (note: $F_{shock} = \rho_{CBM} v_{shock}(t)^3/2$)

Parameters for NSMRs

Model Summary

Model	n_{CBM} (cm^{-3})	M_{ej} ($M_\odot$)	E_{ej} (10^{50} erg)	$\eta_{inj,th}$	β-decay e^-
1a	0.03	0.04	5.0	3.3×10^{-5}	No
1b	0.3	0.04	5.0	3.3×10^{-5}	No
1c	0.03	0.01	1.25	3.3×10^{-5}	No
1d	0.03	0.04	5.0	4.2×10^{-4}	No
2a	0.03	0.04	5.0	3.3×10^{-5}	Yes
2b	0.3	0.04	5.0	3.3×10^{-5}	Yes
2c	0.03	0.01	1.25	3.3×10^{-5}	Yes
2d	0.03	0.04	5.0	4.2×10^{-4}	Yes

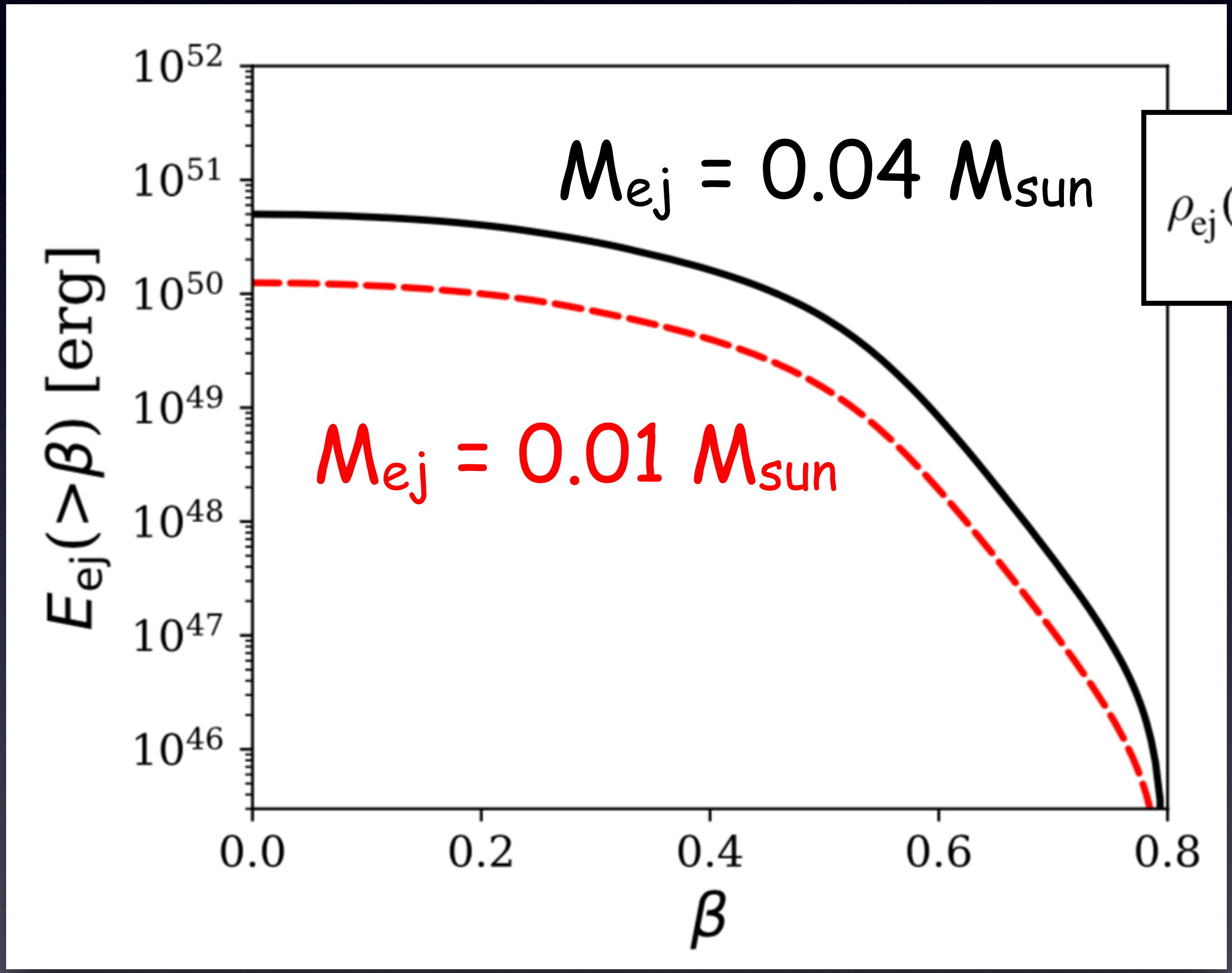
Parameter space (yellow: fiducial)

d_{NSM} = 40 Mpc

$B_{CBM} = 3 \times 10^{-6}$ G

- **Circumbinary medium**: uniform: n_{CBM} = 0.03 - 0.3 cm^{-3} (model b)
- **Ejecta mass**: M_{ej} = 0.01 - 0.04 M_{sun} (model c)
  - **Ejecta K.E.**: E_{ej} = 1.25 - 5.0×10^{50} erg
- **DSA injection fraction** (supra-thermal): $\eta_{inj,th}$ = 3.3×10^{-5} - 4.2×10^{-4} (model d)

NSM ejecta profile

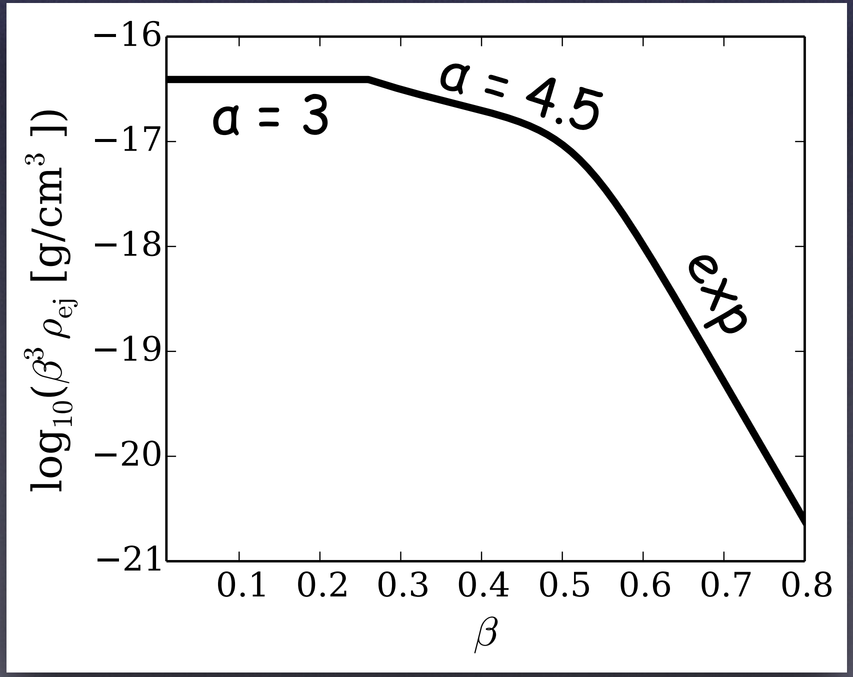


Cumulative E_{ej} profile

$$\rho_{ej}(\beta) = \frac{\rho_0(\beta/\beta_0)^{-\alpha}}{1 + \exp[(\beta - 2\beta_0)/\sigma]},$$

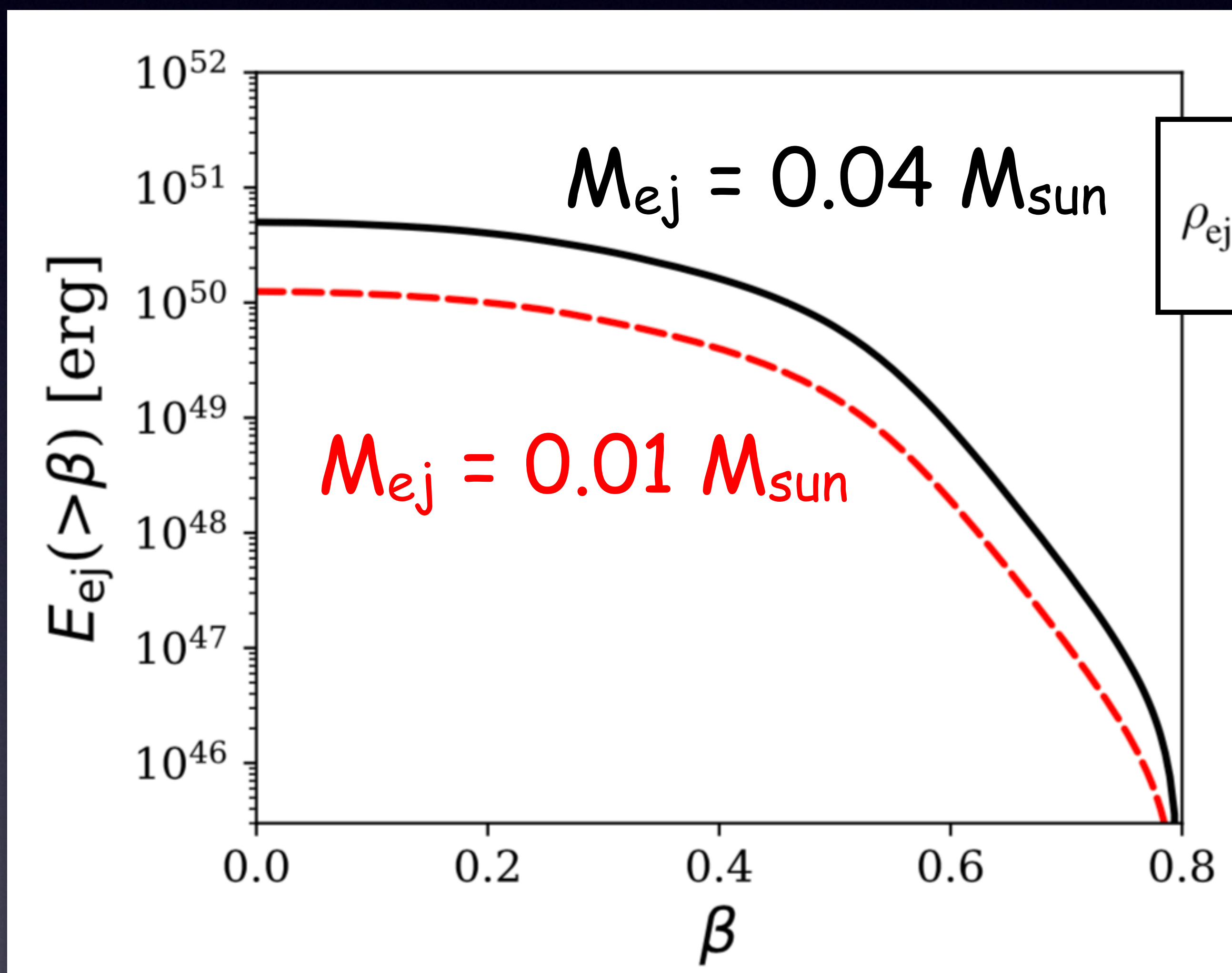
from Hotokezaka+ (2016)

We impose initial $\beta_{ej} < 0.8$



ρ_{ej} profile

NSM ejecta profile



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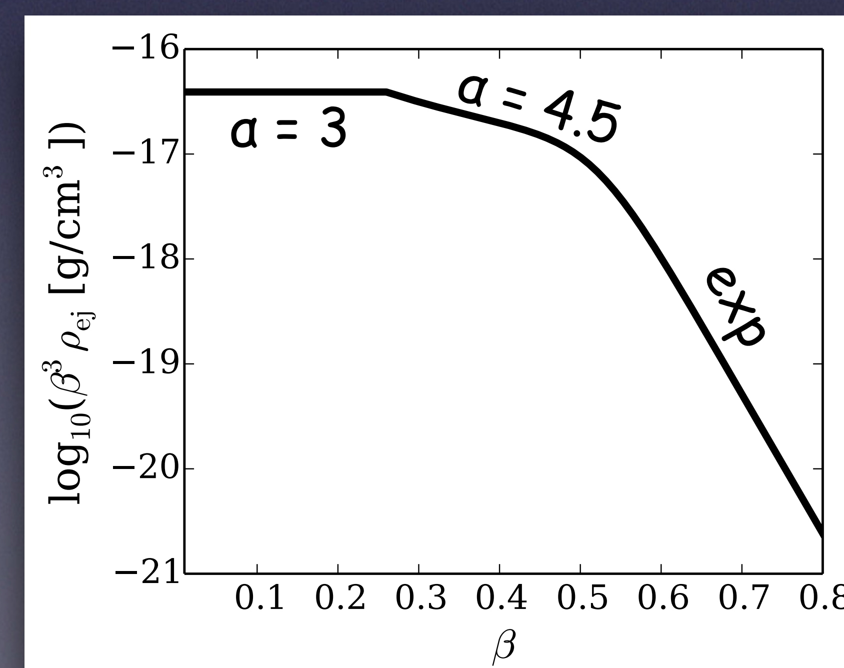
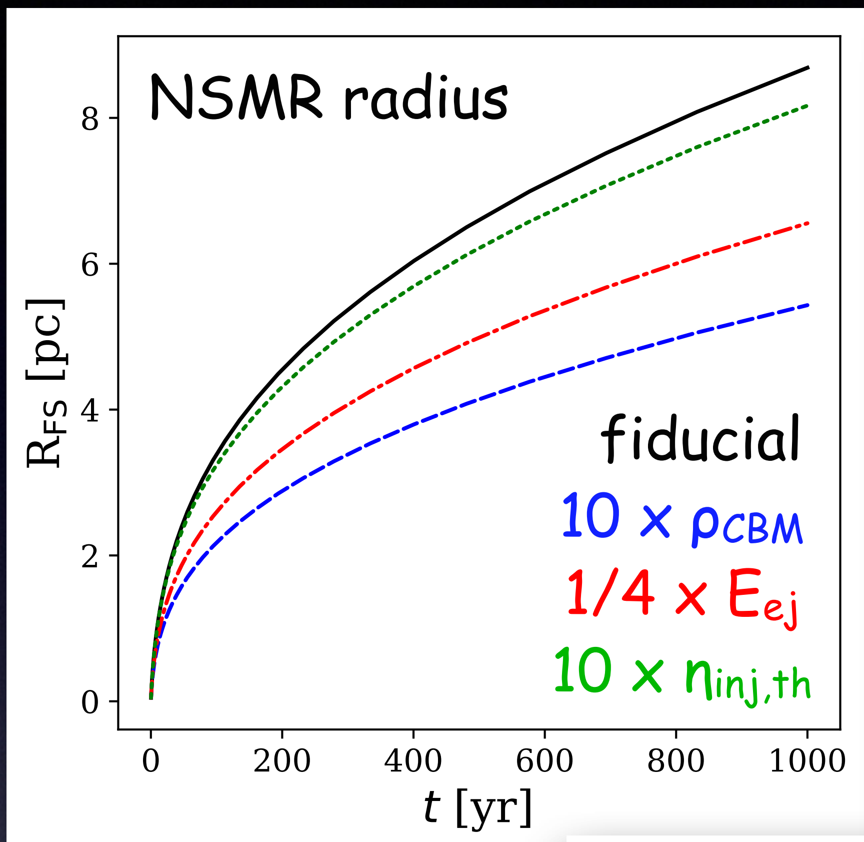
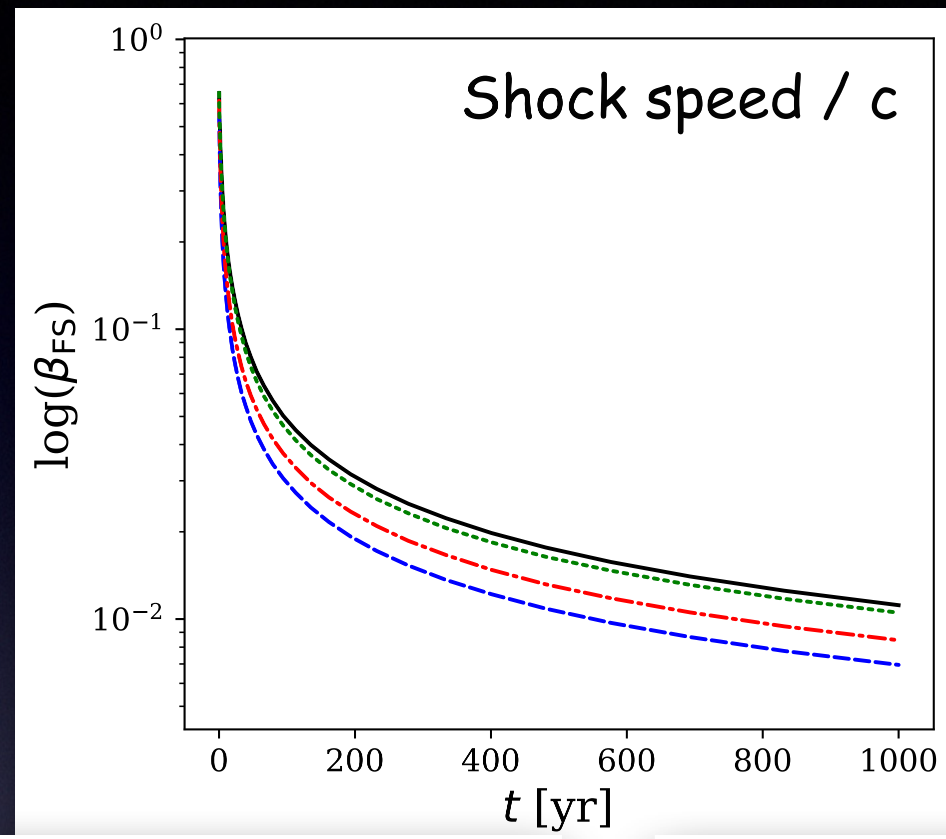


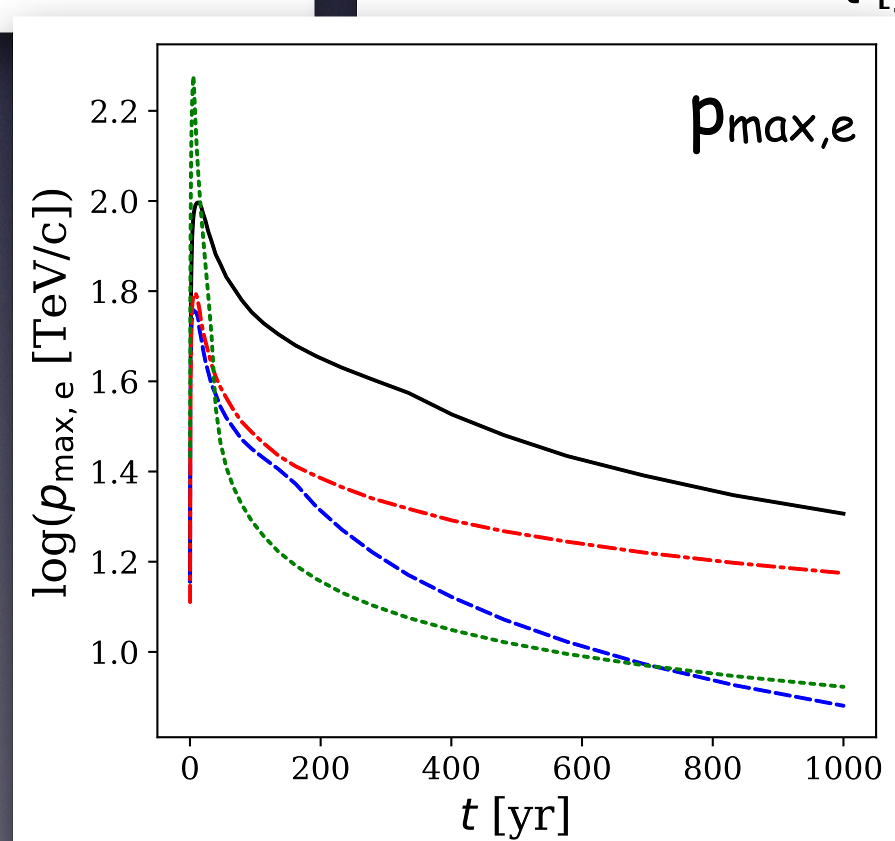
ρ_{ej} profile

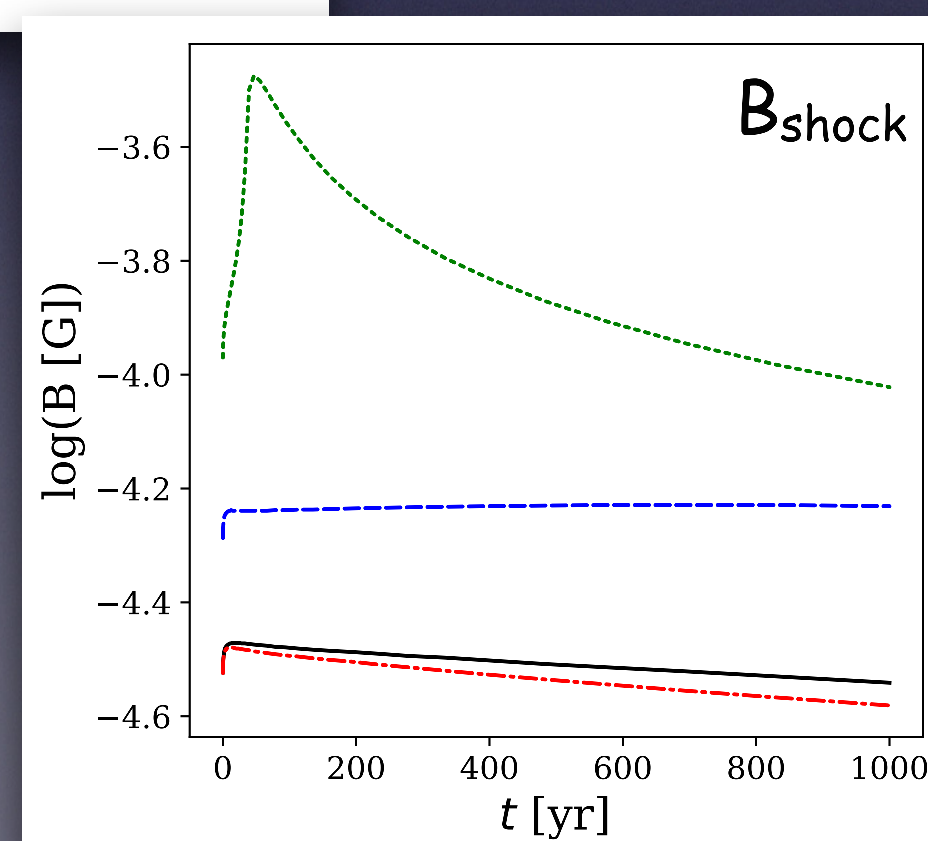
Possibility of high-speed tail (Hotokezaka+ 2018)?

Hydrodynamic evolution



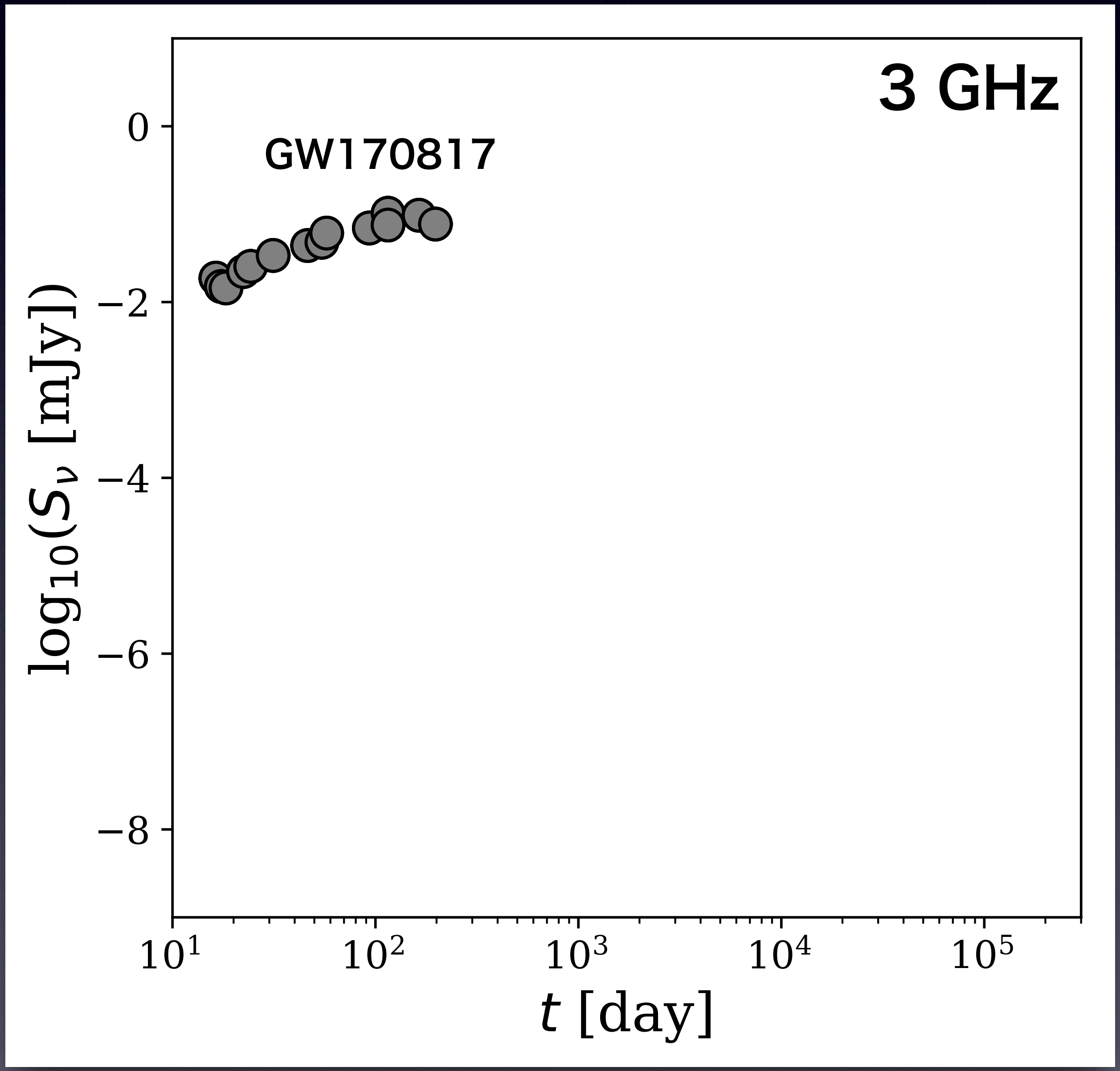






Radio lightcurve
Case without β-decay e^-

ATCA, VLA



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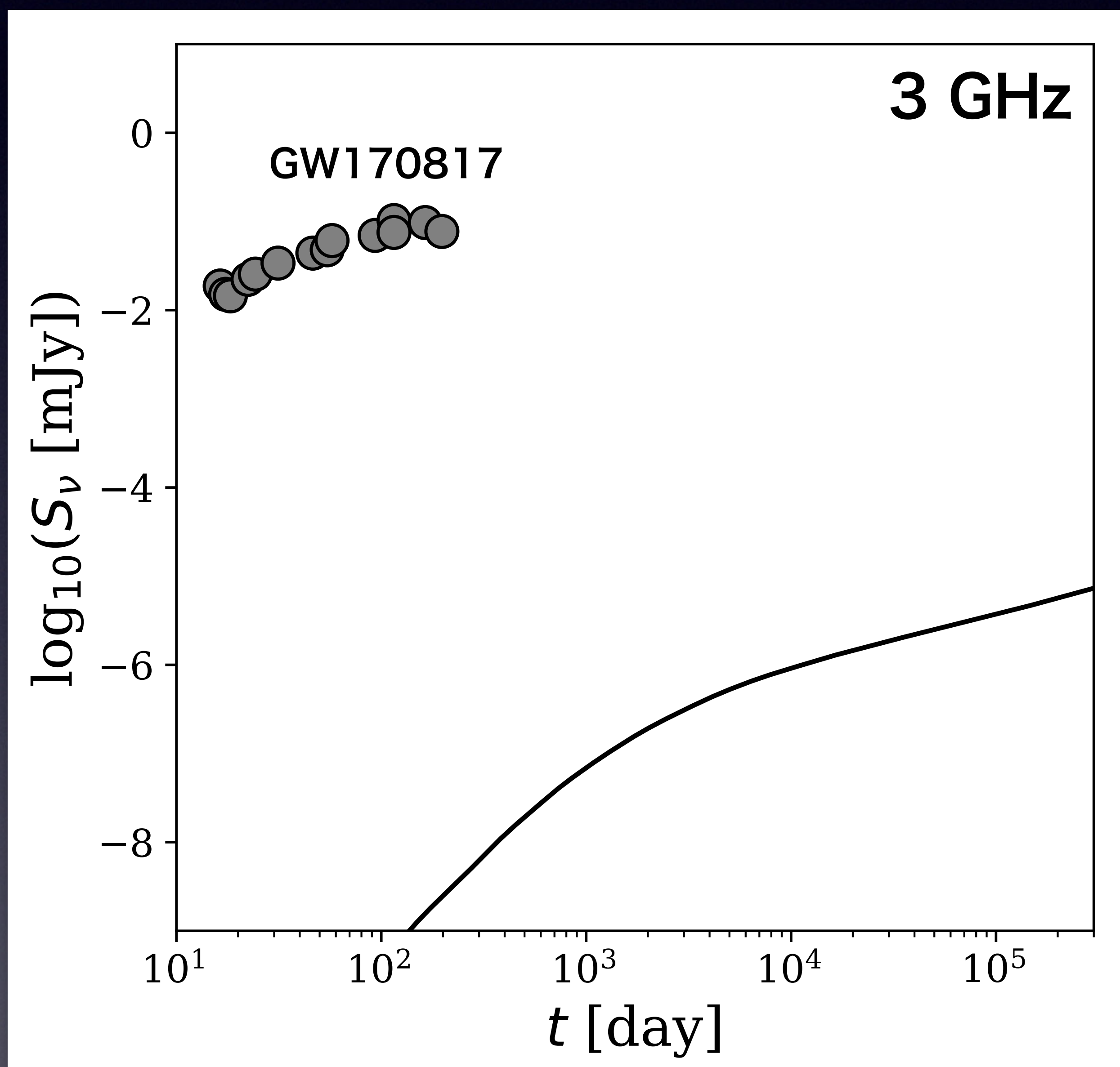

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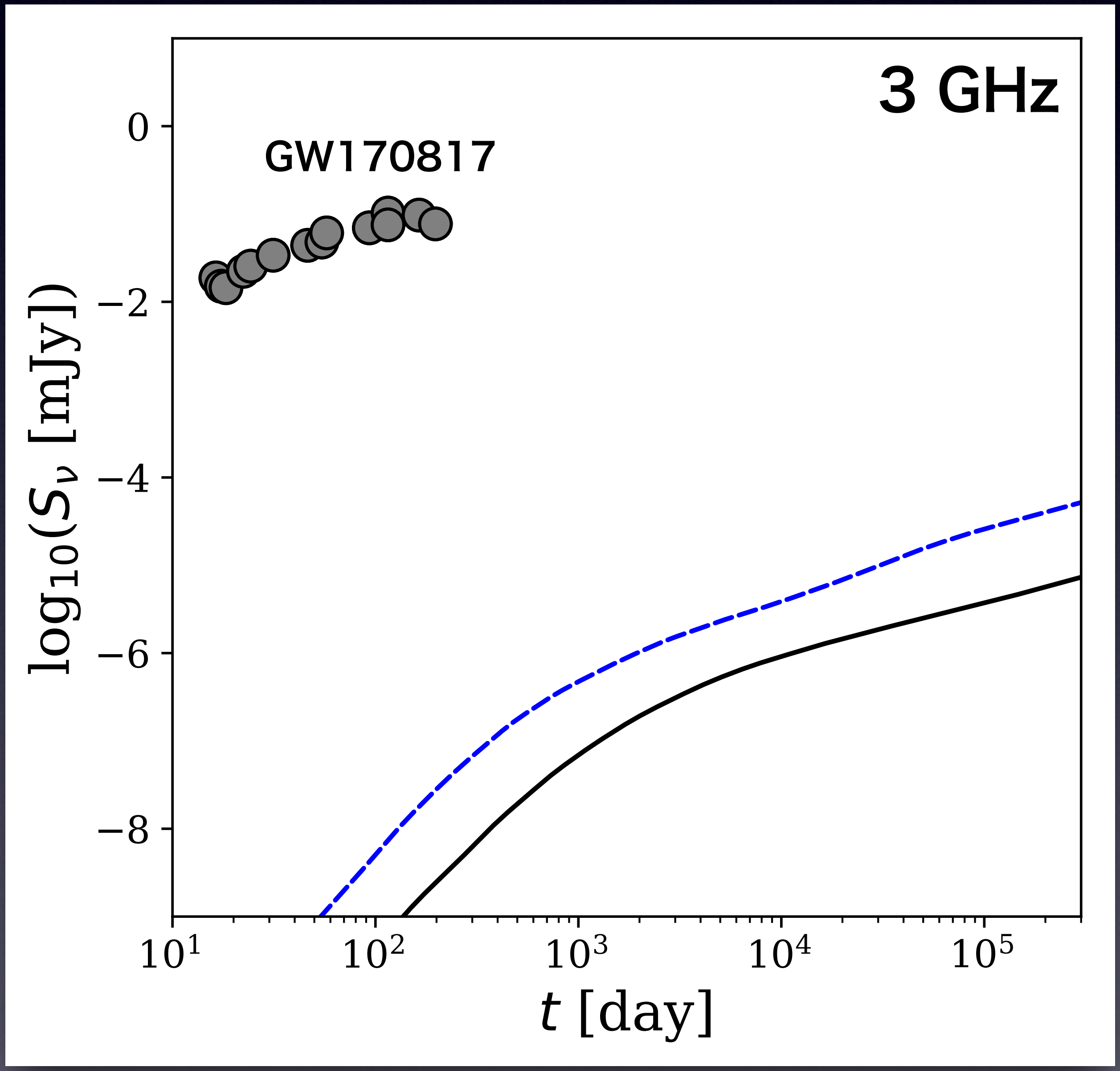

- Tenuous ISM
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- 10x denser CBM $K_{\rm ep}\eta_{\rm inj,th} \quad n_{\rm CBM}BV$
  - Faster dissipation of E_{shock} (smaller V)
  - More efficient DSA
  - Higher amplified B-field

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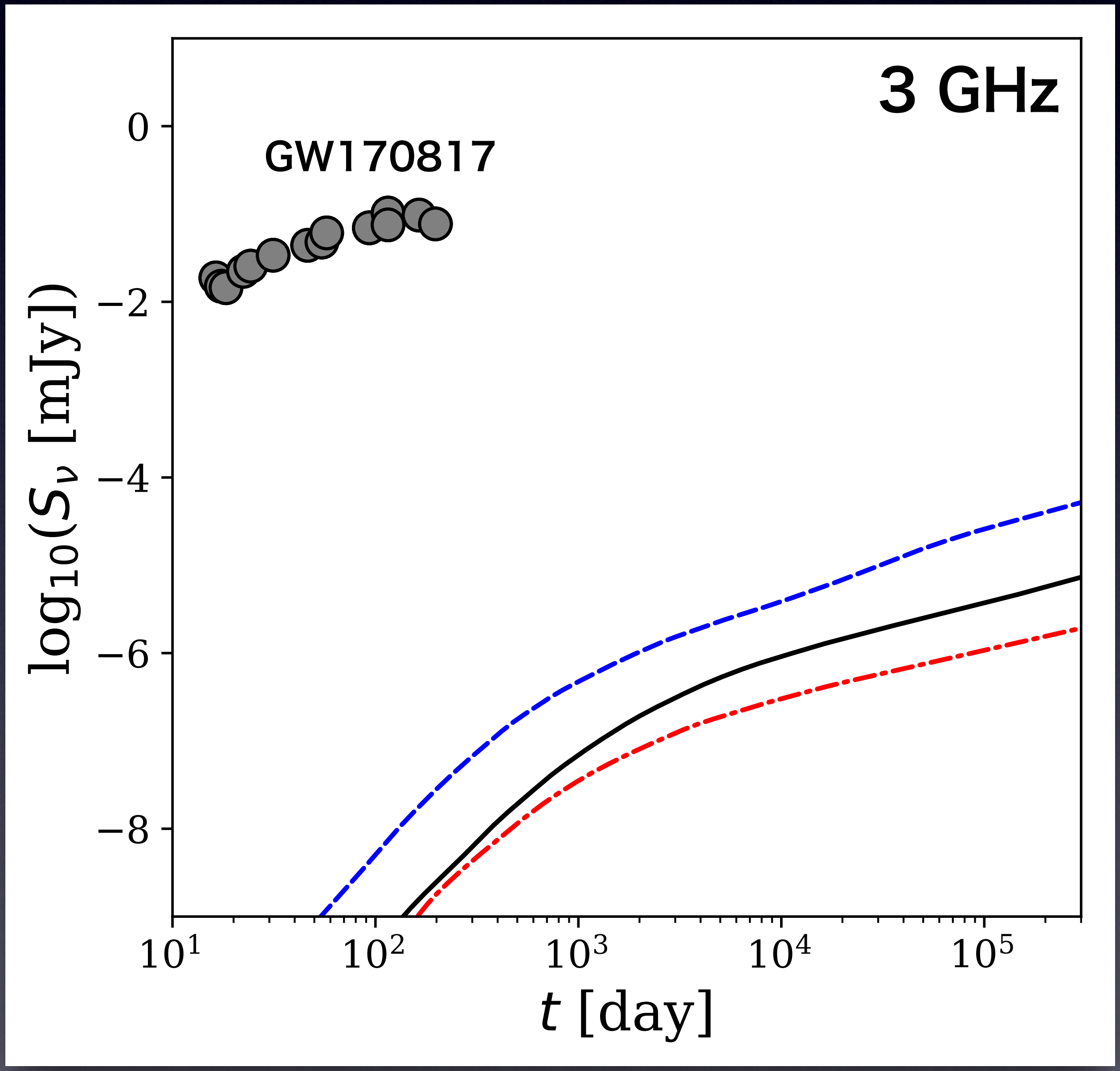

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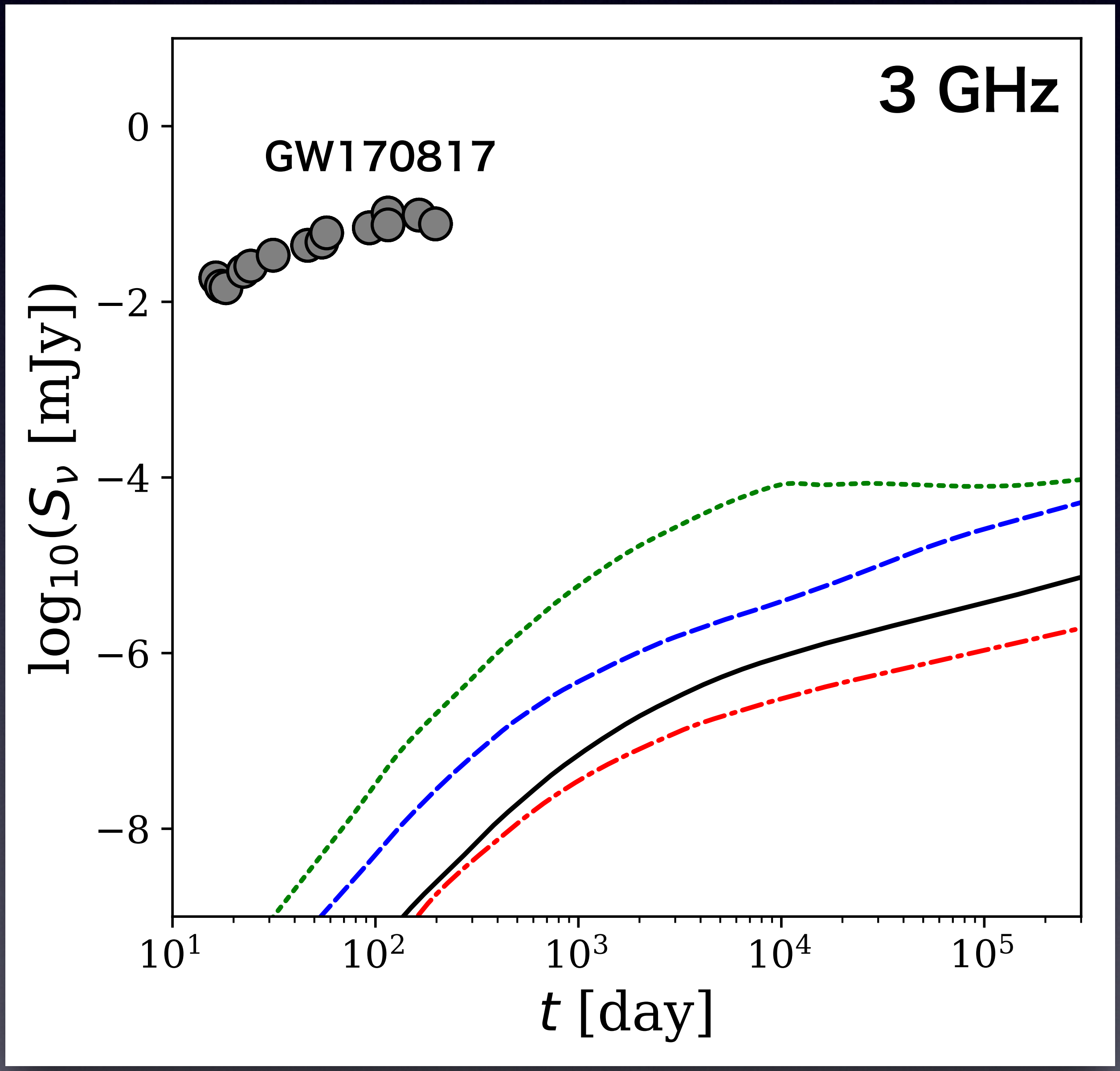

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- ~10x faster p & e^- injection
  - Very efficient DSA and MFA

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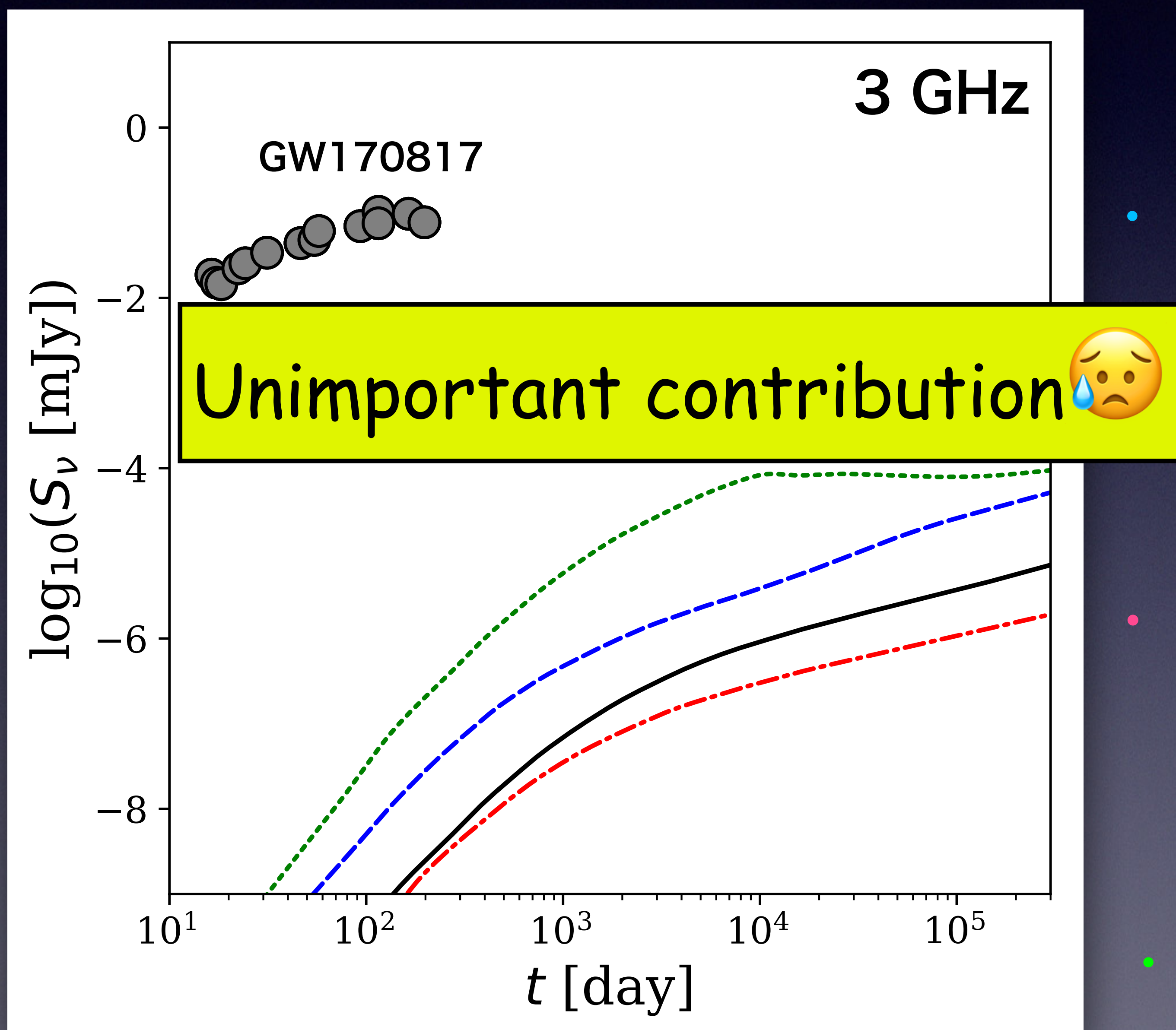

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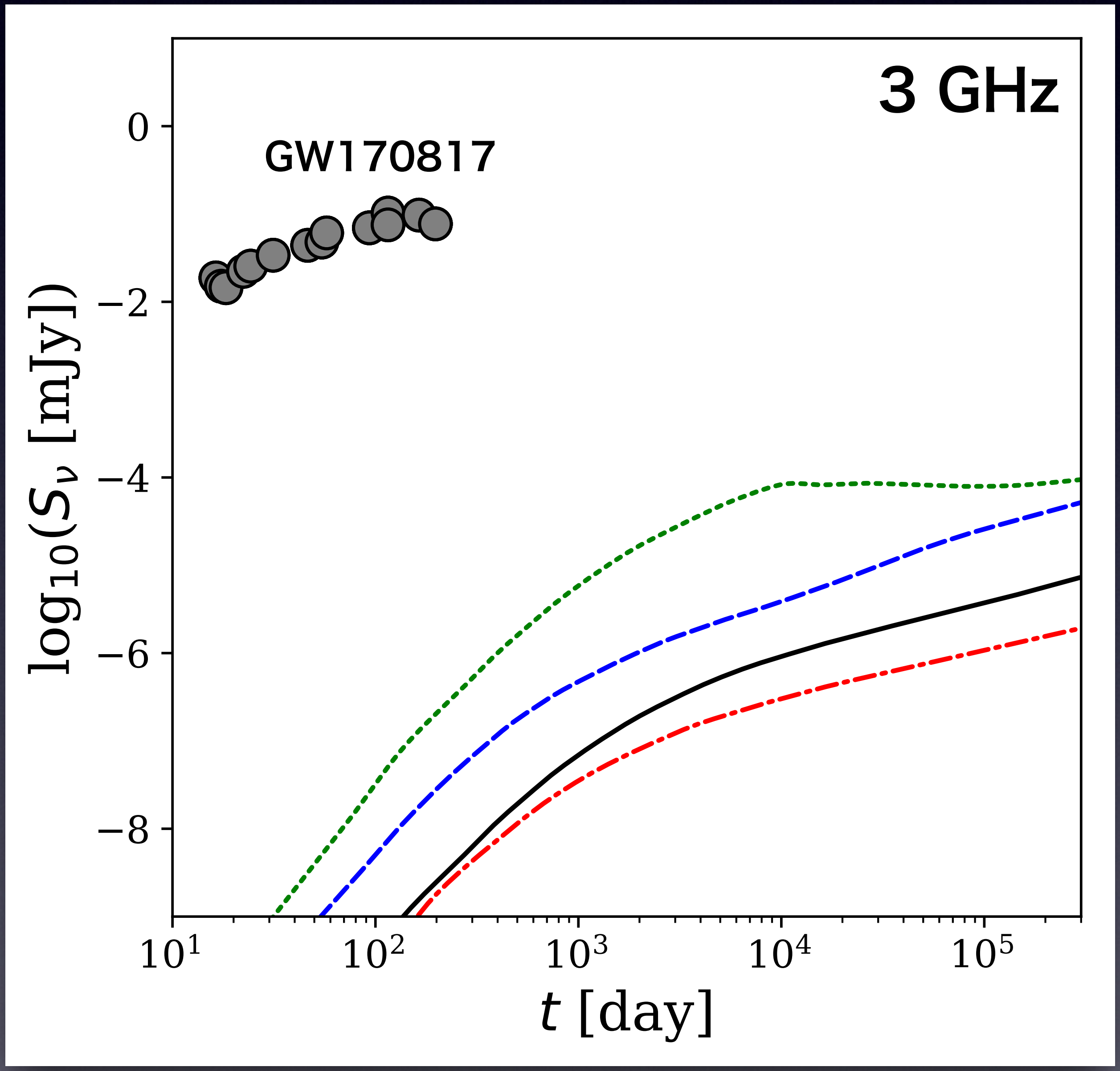

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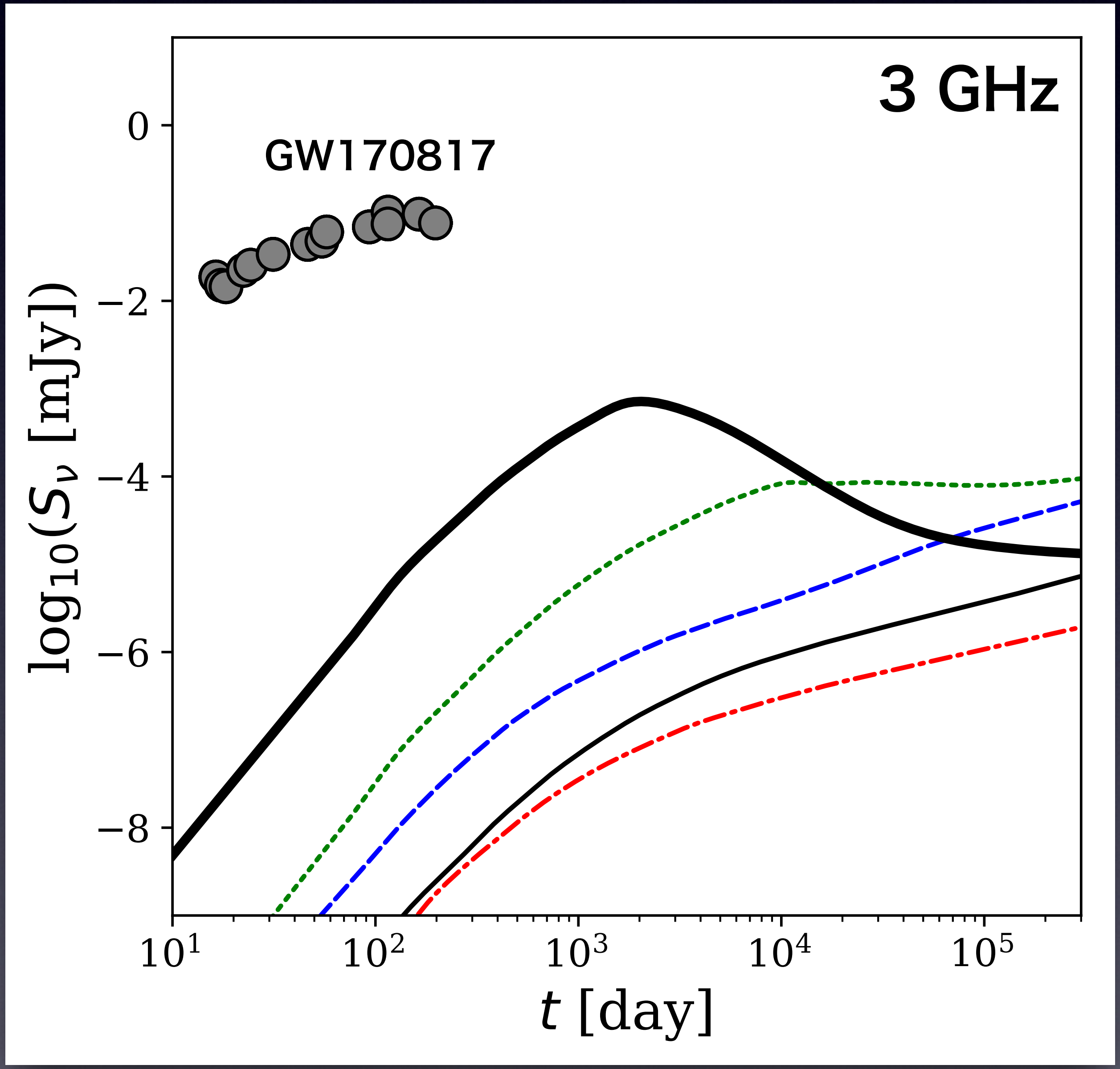

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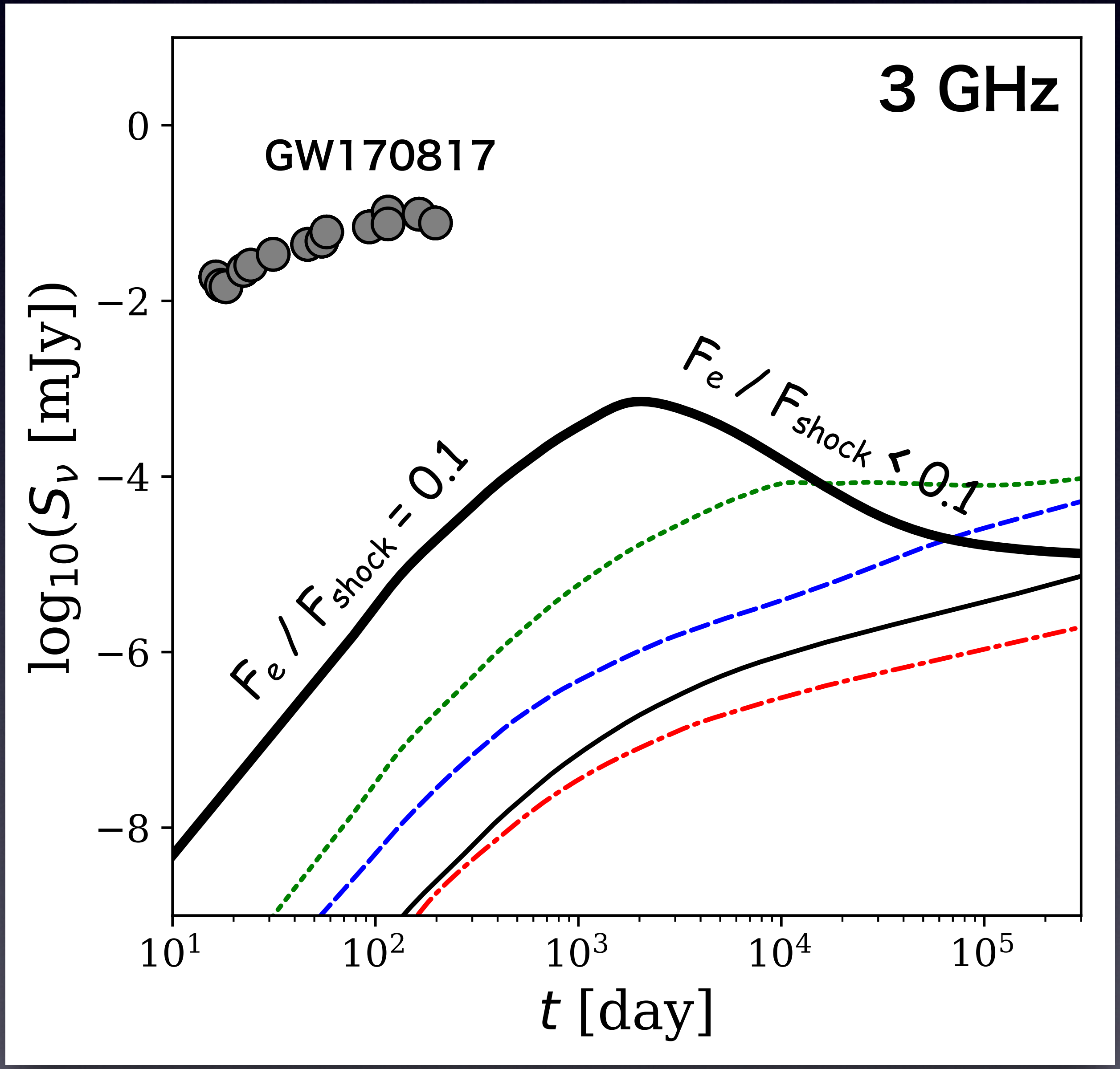

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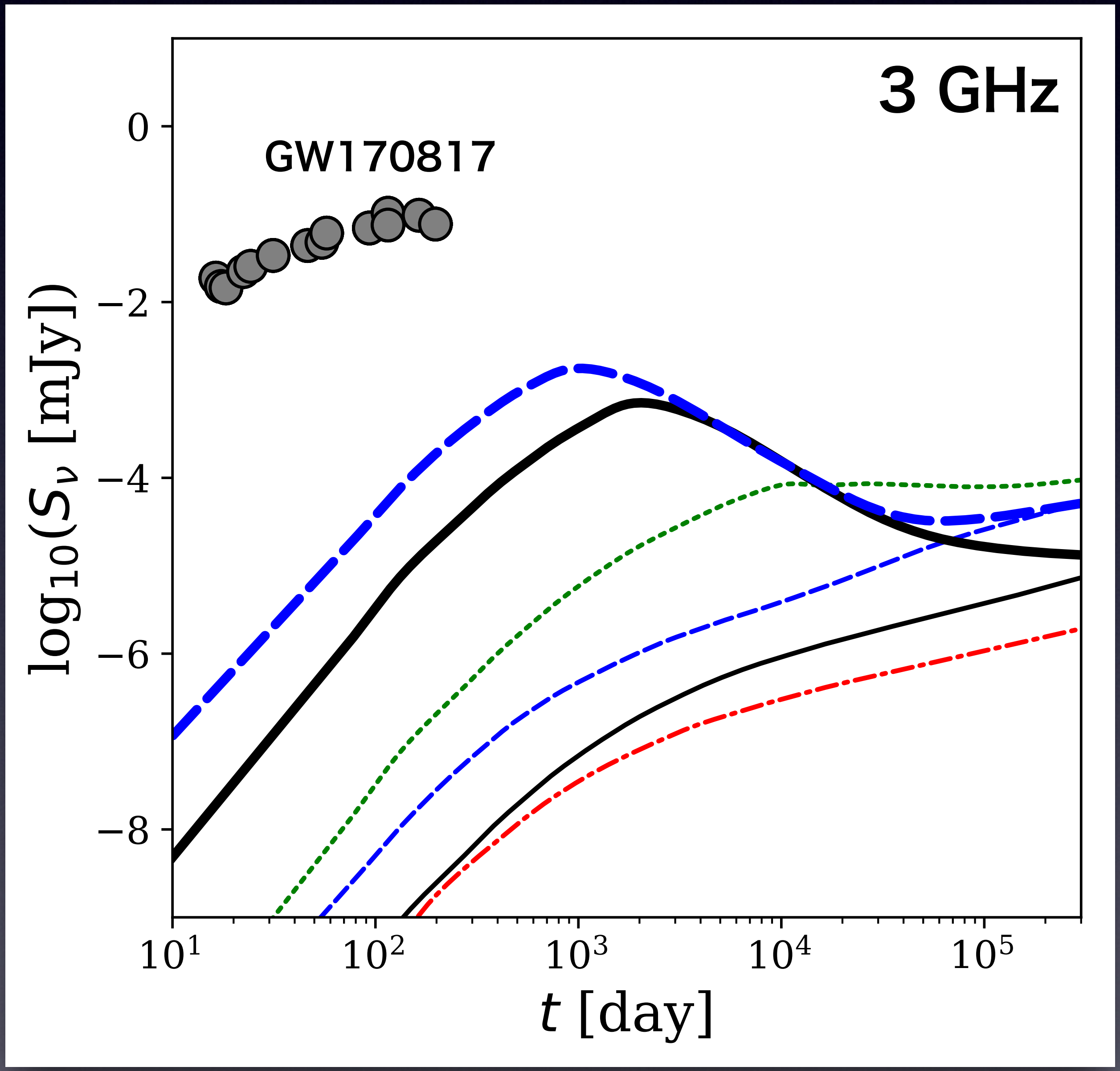
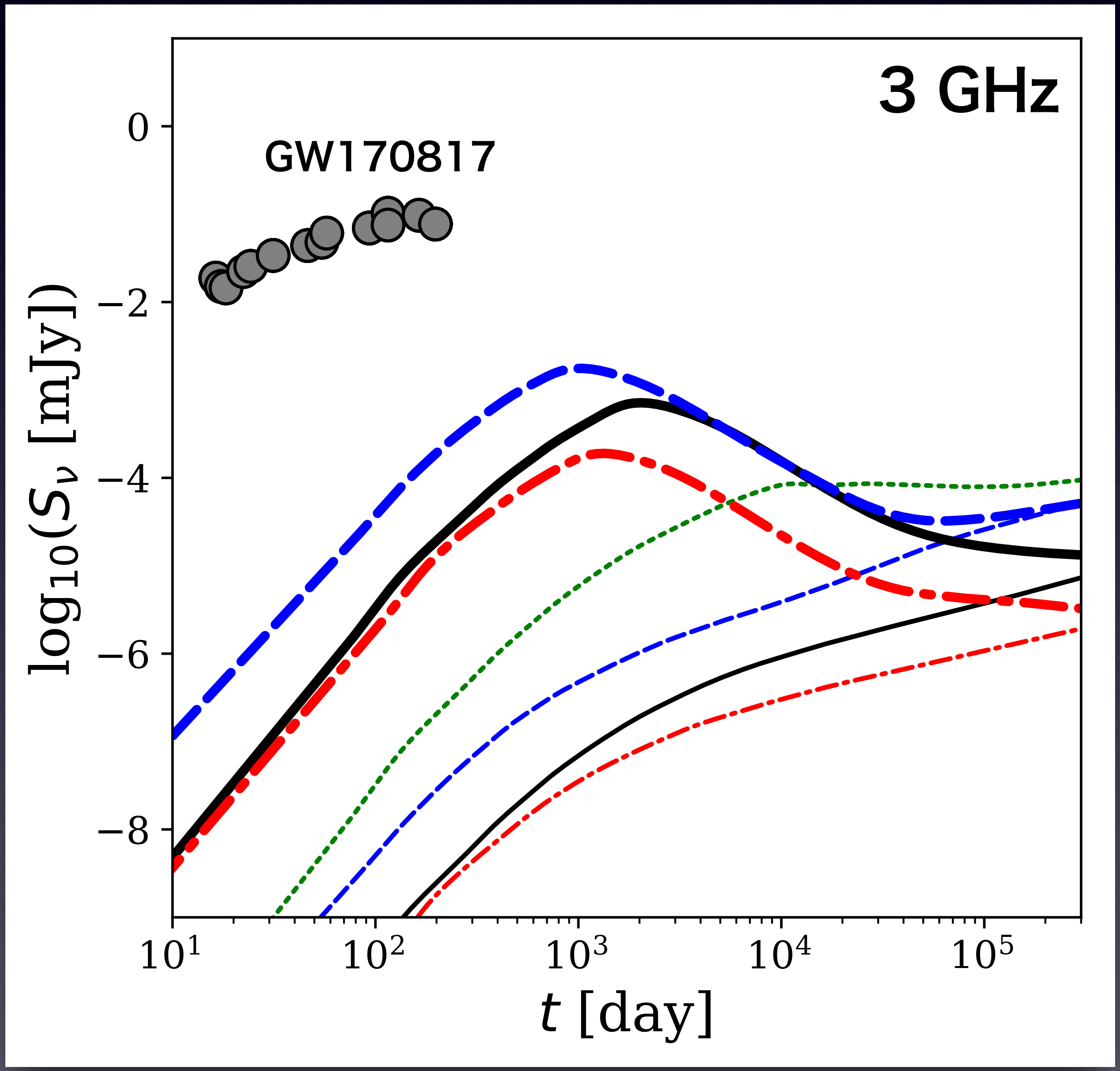


- Including β-decay e^-
  - Very efficient injection from early phase (t_{peak} ~ 10 d)
  - Acceleration of e^- limited by input energy flux at shock F_{shock}
- 10x denser ISM
  - No effect on β-decay e^- injection
  - But an **increased F_{shock}** ~ ρ_{CBM}
  - More accelerated β-decay e^-
  - (Note: F_e / F_{shock} ≦ 0.1 is an assumption)

Radio lightcurve
Case with β-decay e^-



- Including β-decay e^-
  - Very efficient injection from early phase (t_{peak} ~ 10 d)
  - Acceleration of e^- limited by input energy flux at shock F_{shock}
- 10x denser ISM
  - No effect on β-decay e^- injection
  - But an **increased F_{shock}** ~ ρ_{CBM}
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- 4x less energetic ejecta
  - Early phase limited by F_{shock}
  - Later phase L_e ~ M_{ej}

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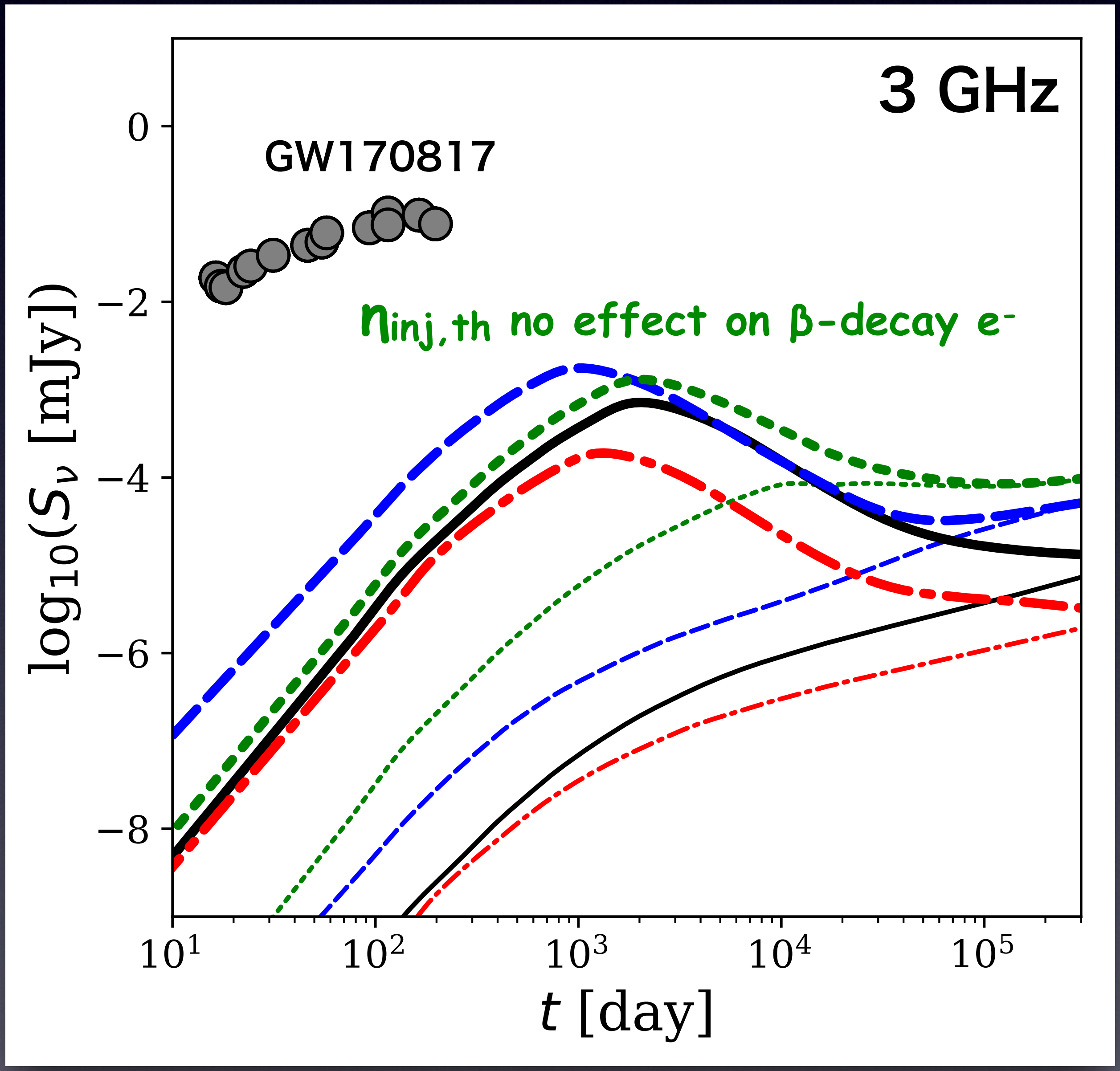

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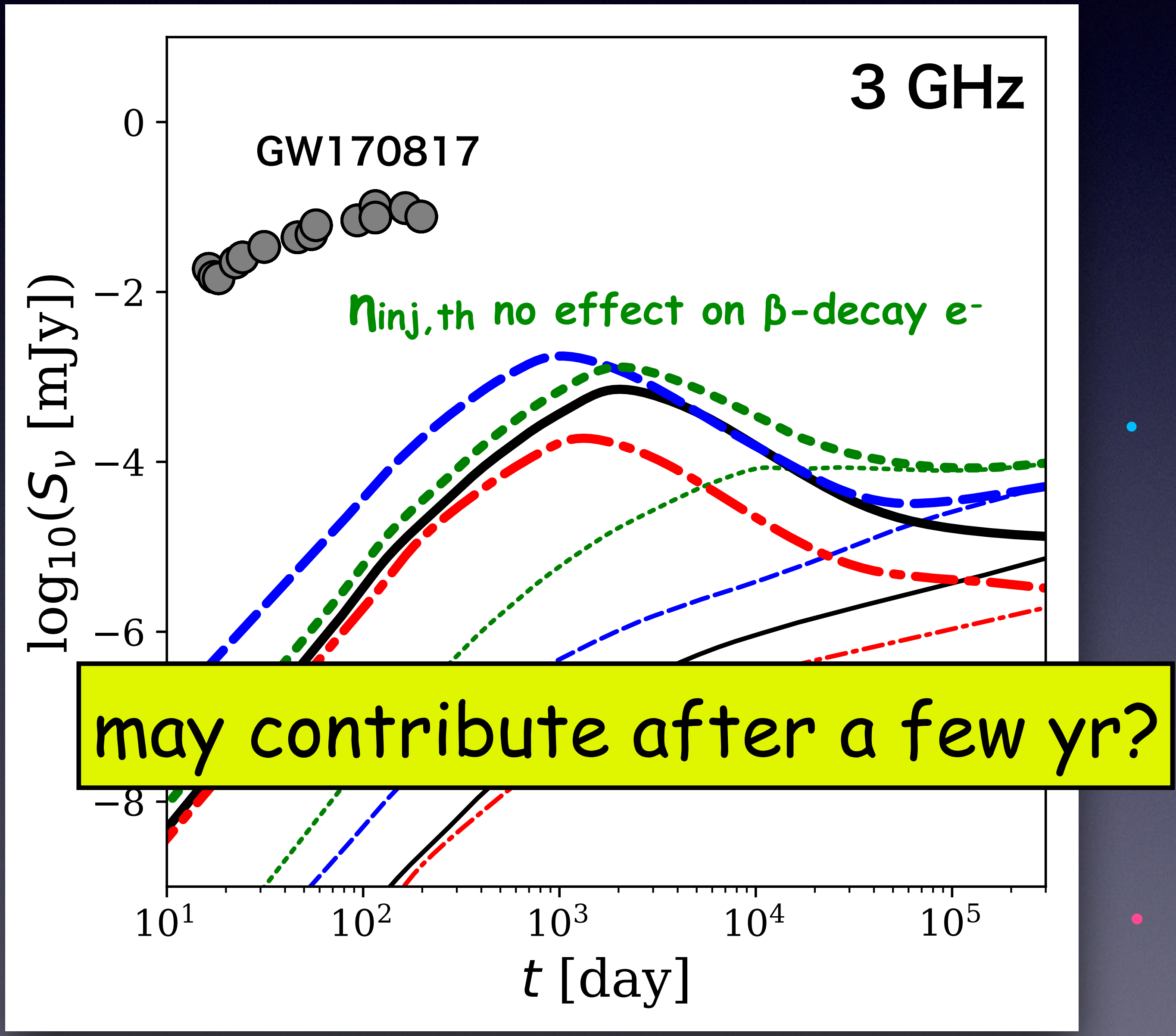

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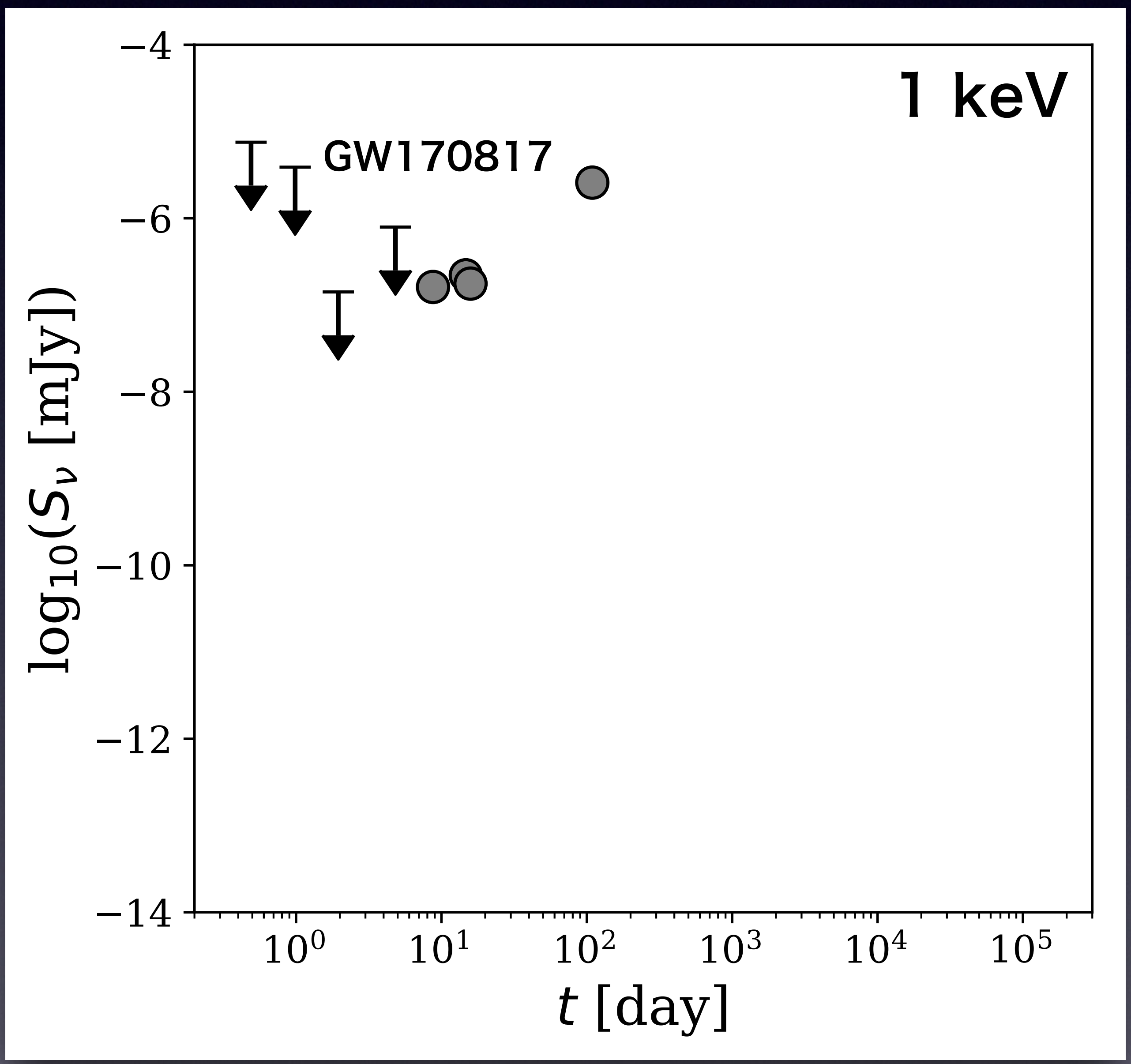
X-ray lightcurve
Case without β-decay e^-

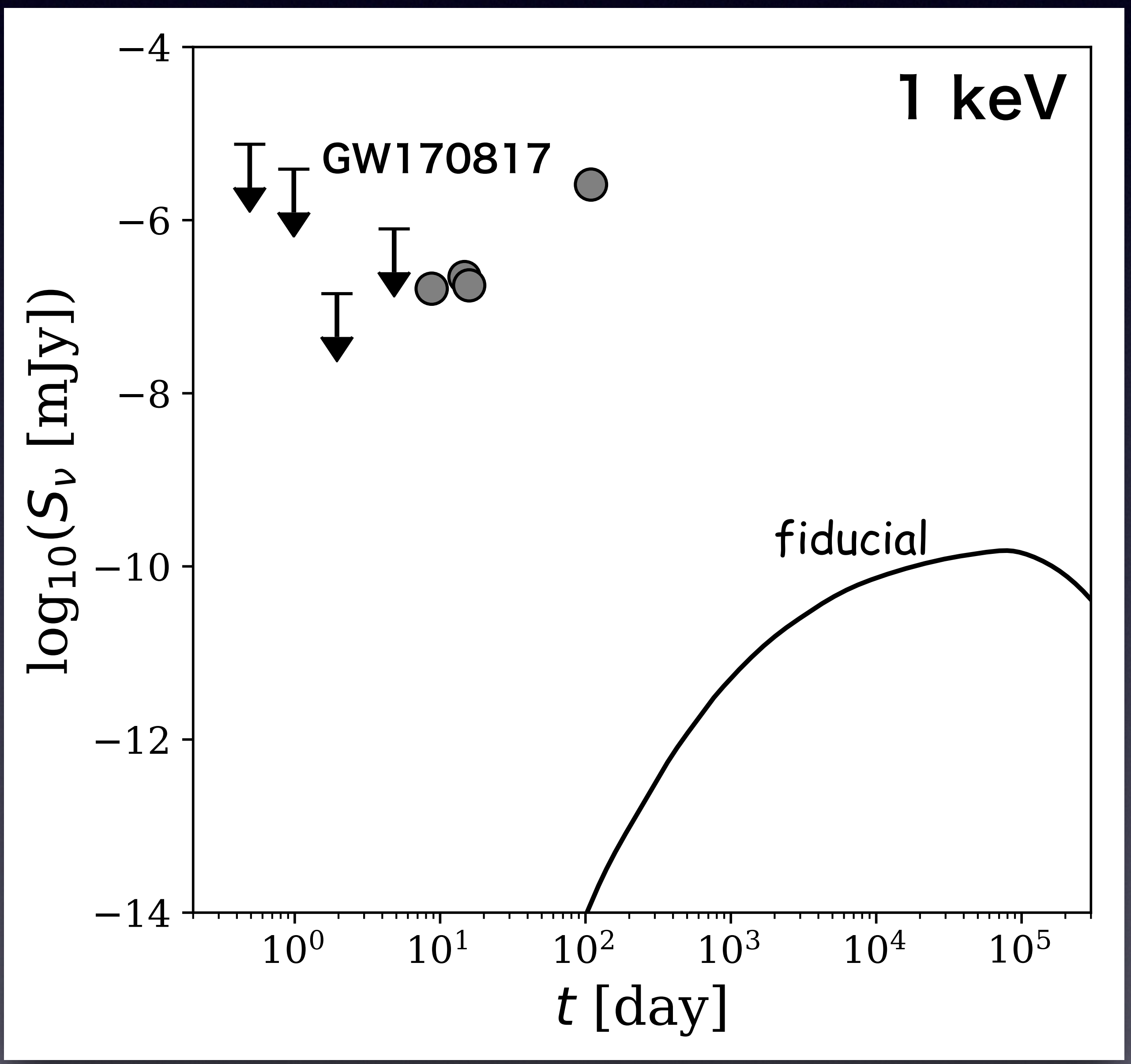
X-ray lightcurve
Case without β-decay e^-

Chandra



X-ray lightcurve
Case without β-decay e^-

Chandra



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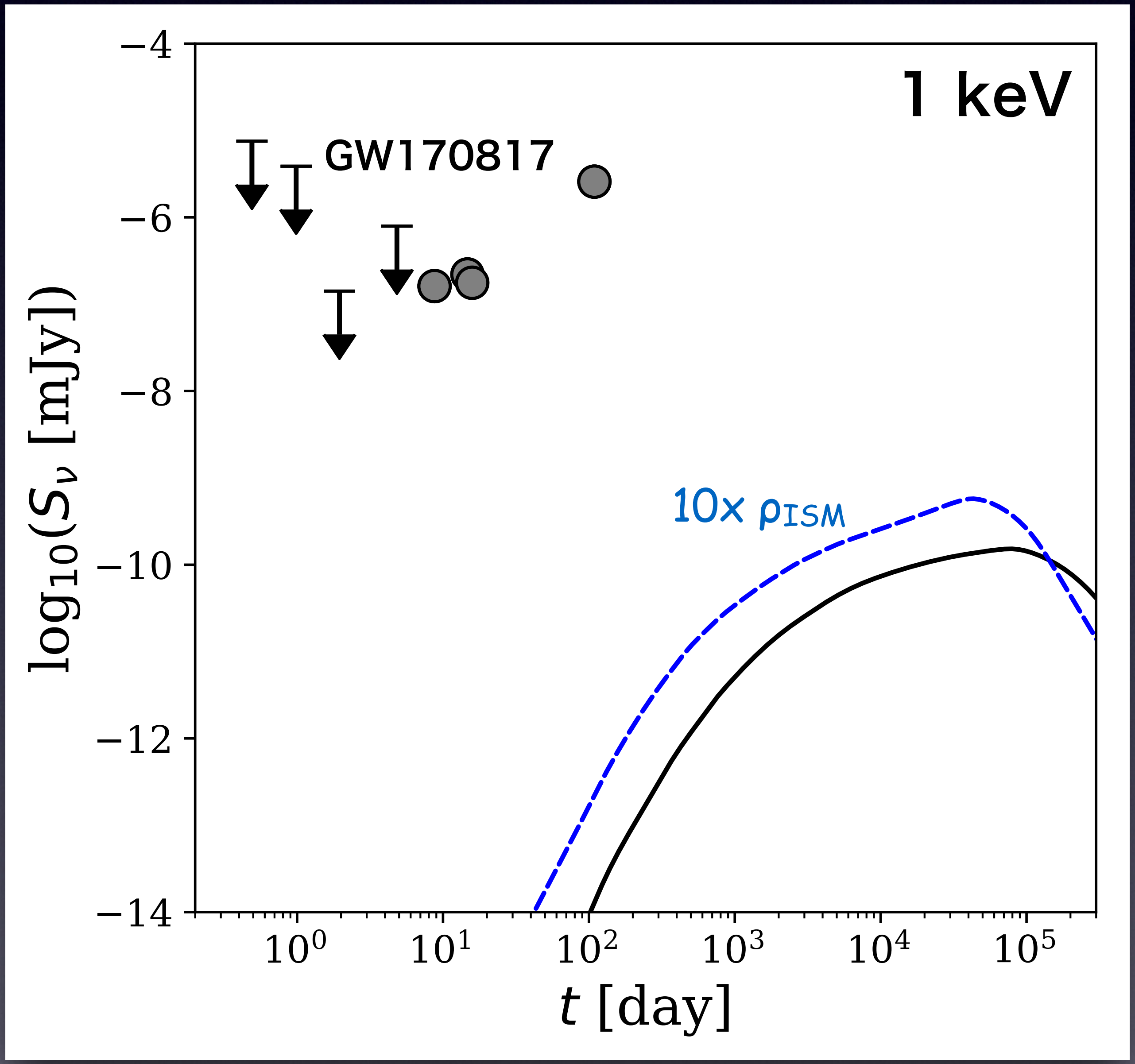

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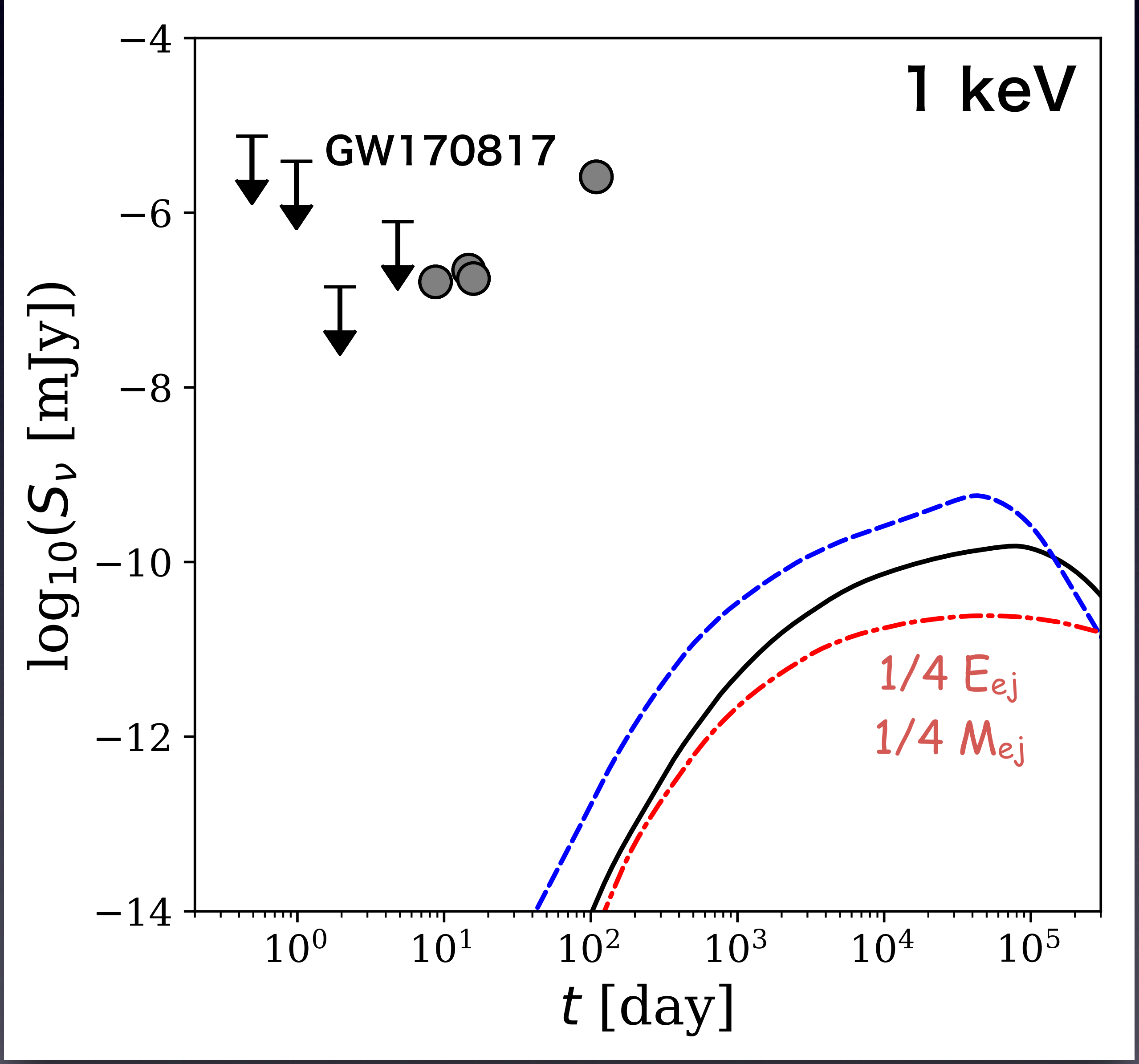

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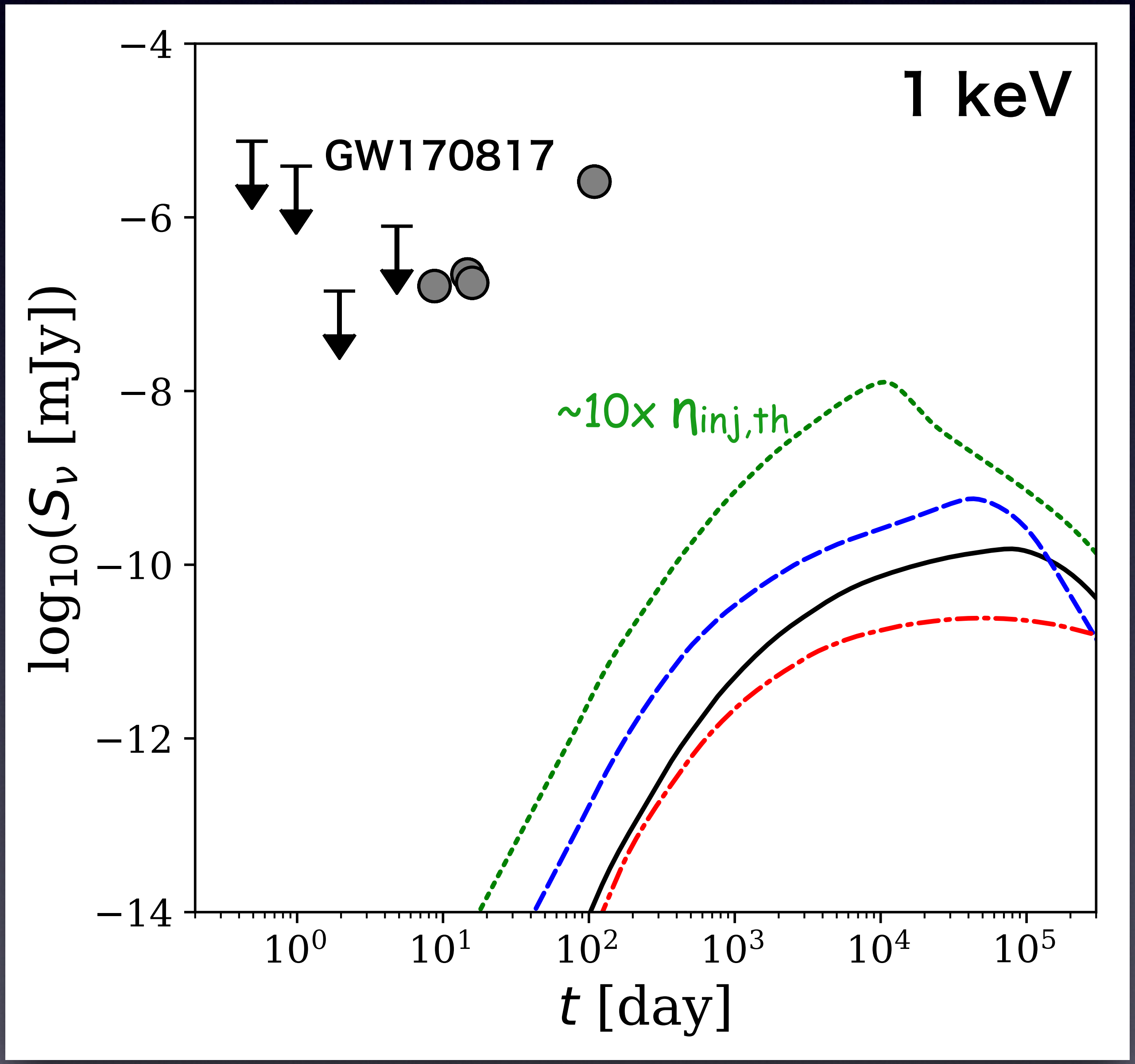
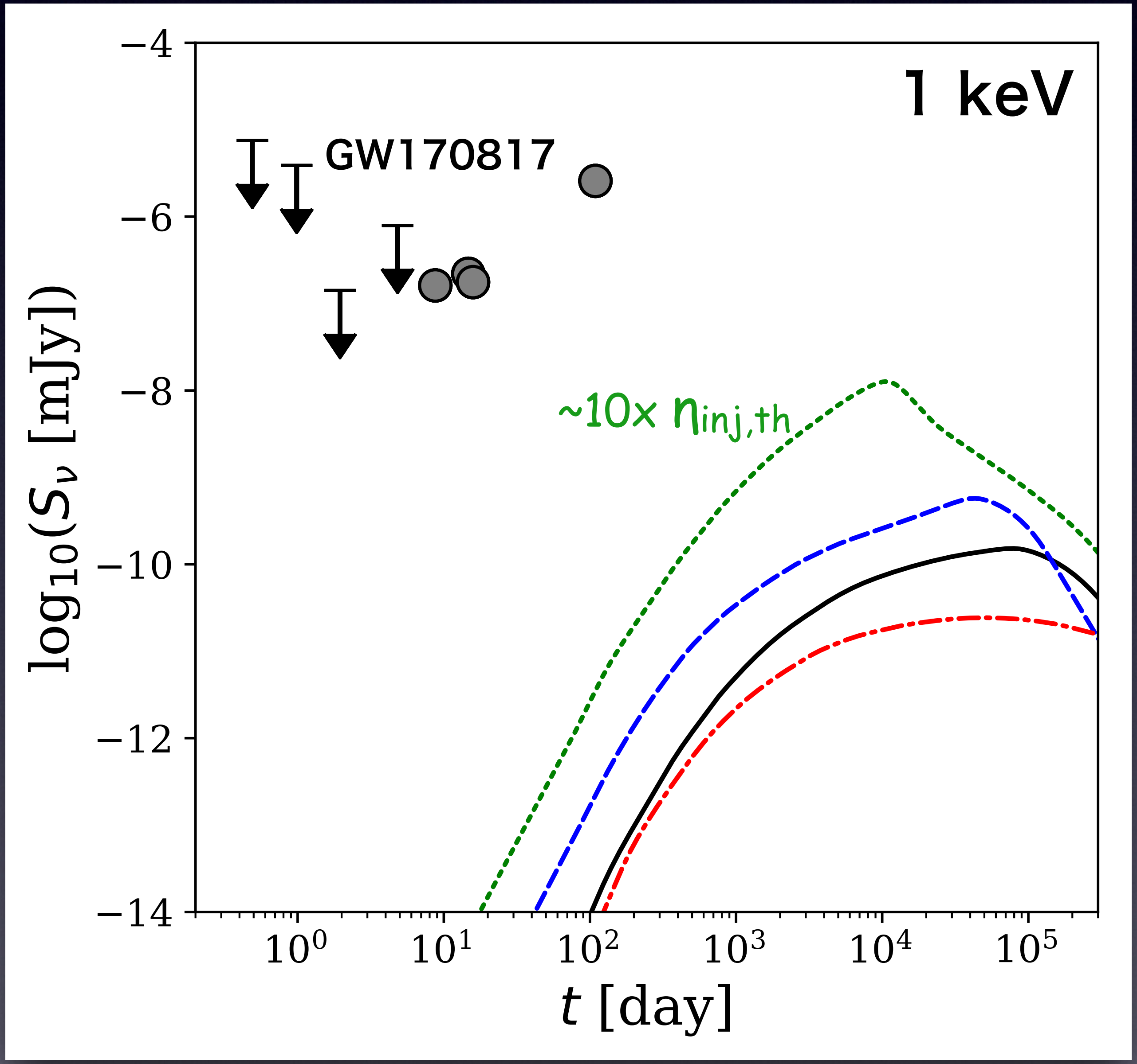
Chandra



- Model dependence of lightcurve similar to radio

X-ray lightcurve
Case <u>without</u> β-decay e^-

Chandra

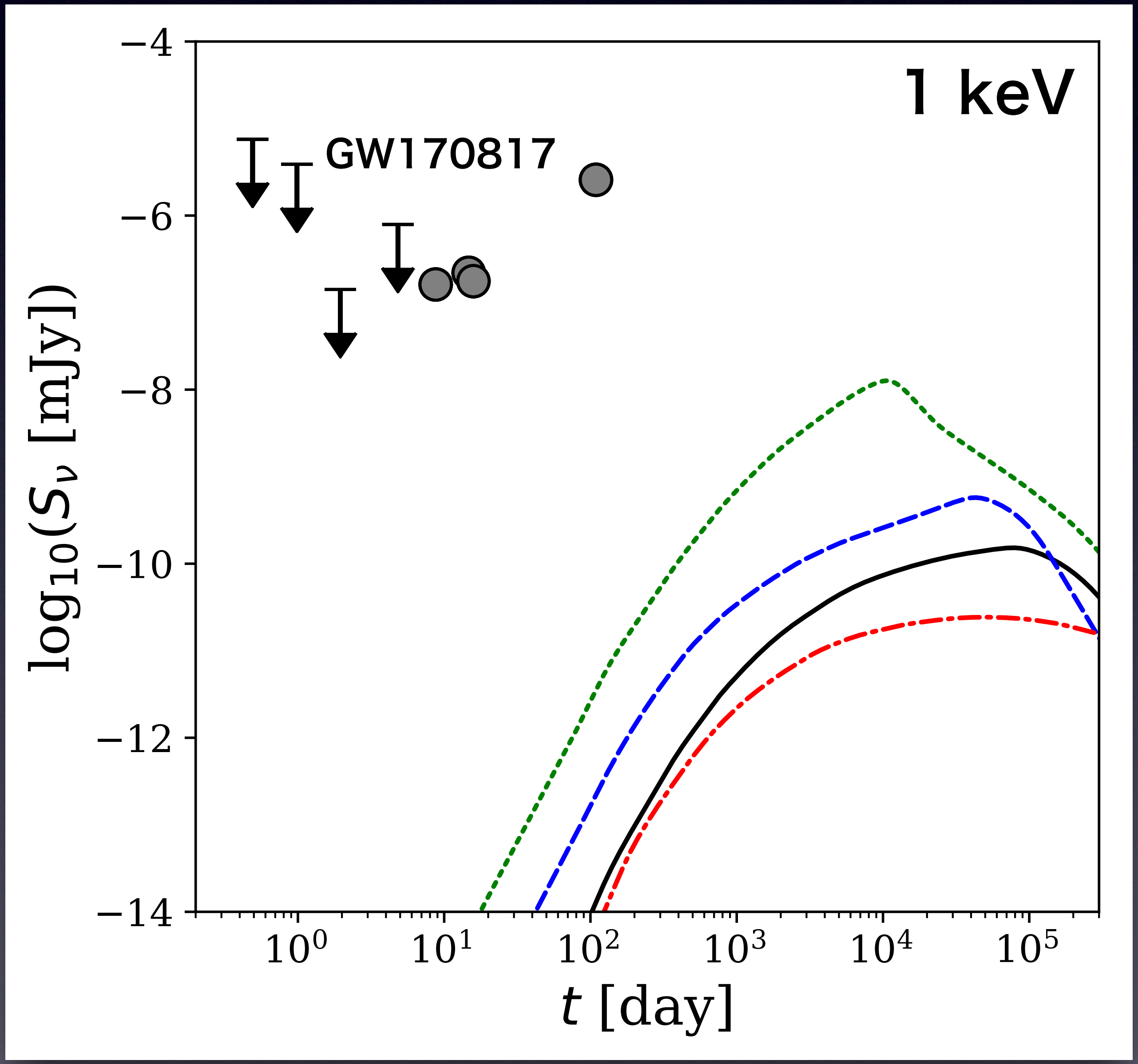


- Model dependence of lightcurve similar to radio
- Major difference: rolloff
  - Synch X-ray ν_{cut} sensitive to $E_{max,e}$
  - E_{max} of e^- determined by t_{acc} and t_{loss} (synch)
  - Model with larger ρ_{CBM} and $\eta_{inj,th}$ —> more efficient DSA —> larger B-field
  - Higher $E_{max,e}$ in early phase
  - $h\nu_{cut}$ drops below 1 keV faster

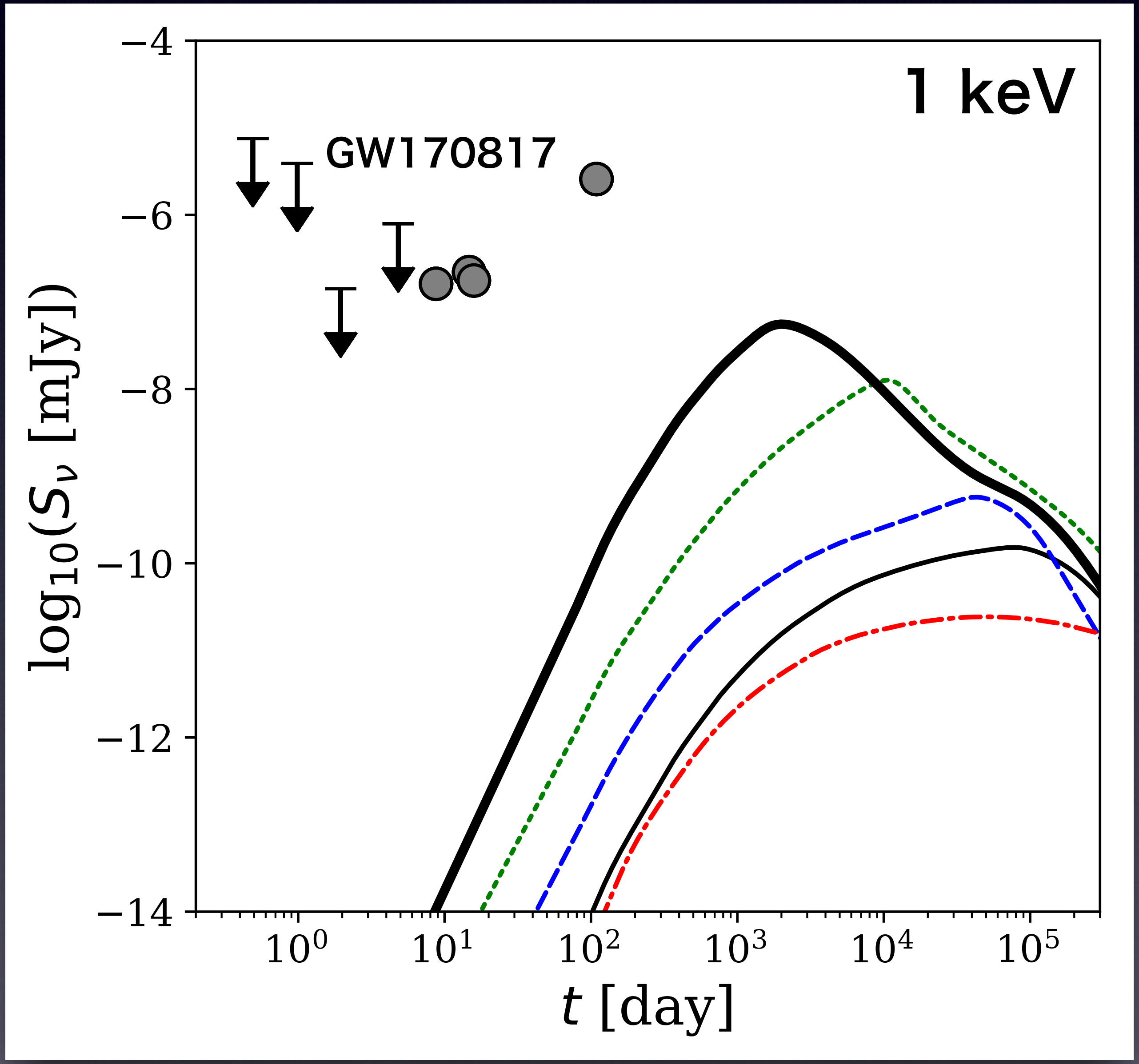
X-ray lightcurve

Case <u>with</u> β-decay e^-

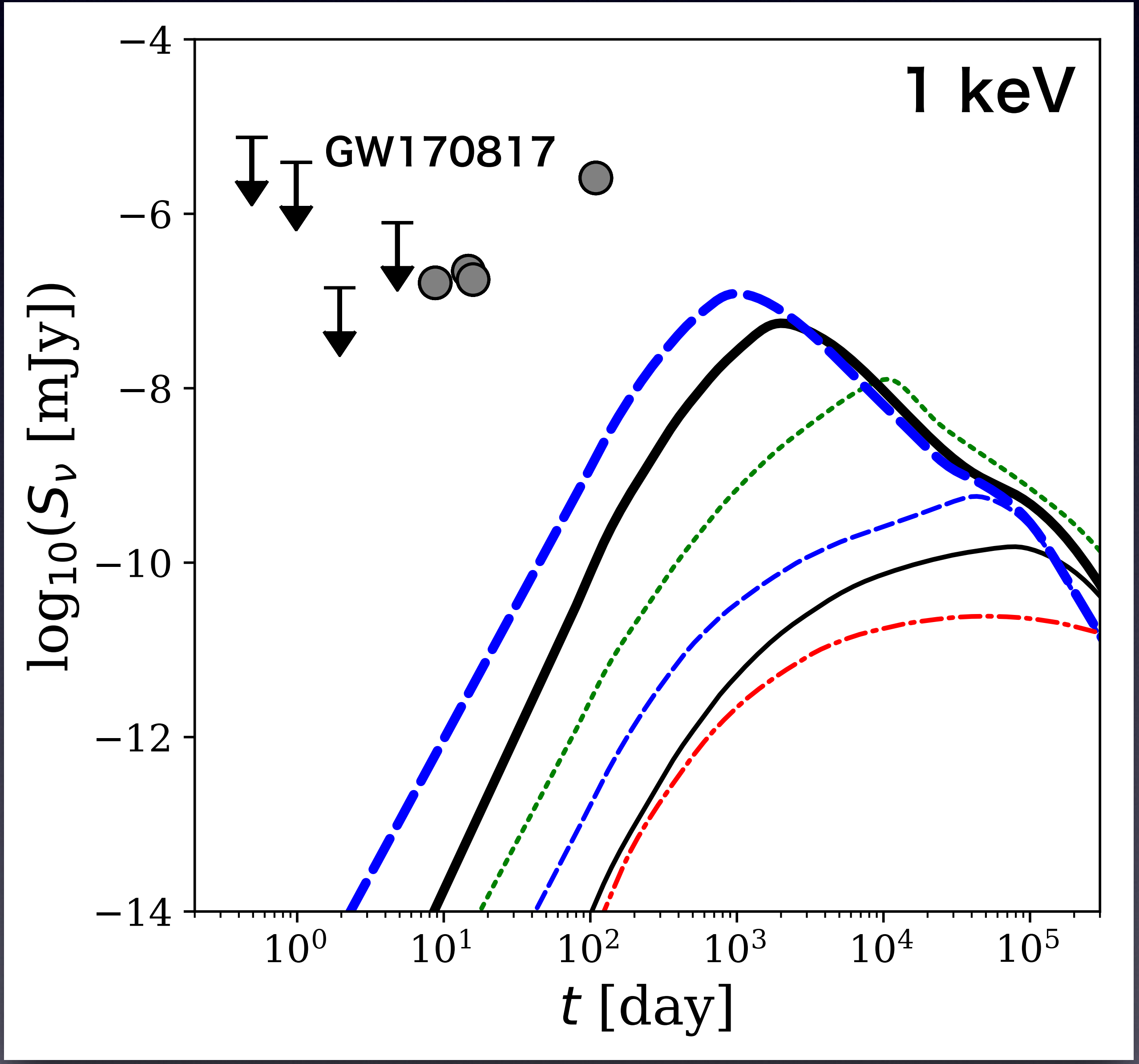
X-ray lightcurve
Case with β-decay e^-



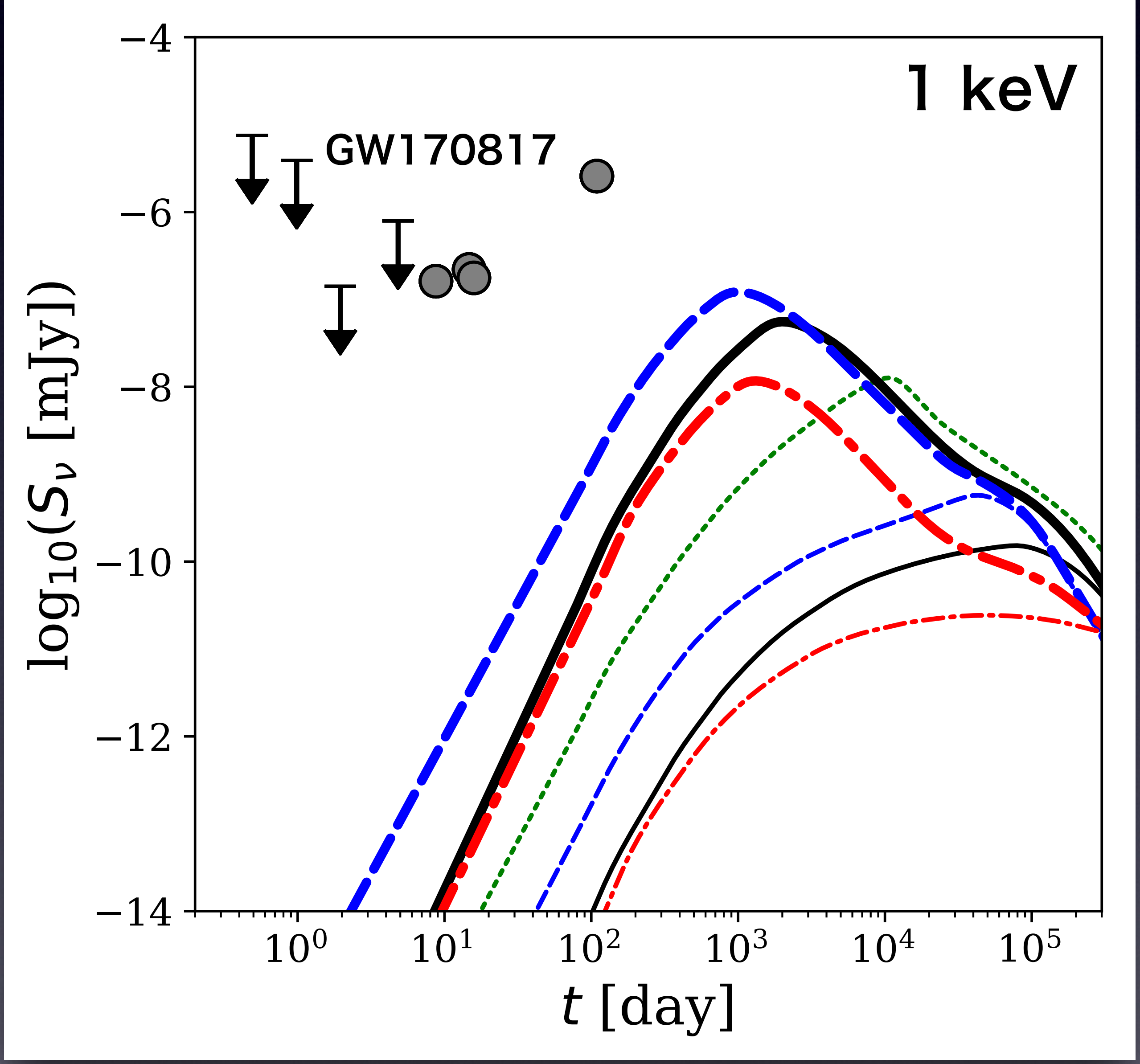
X-ray lightcurve
Case with β-decay e^-



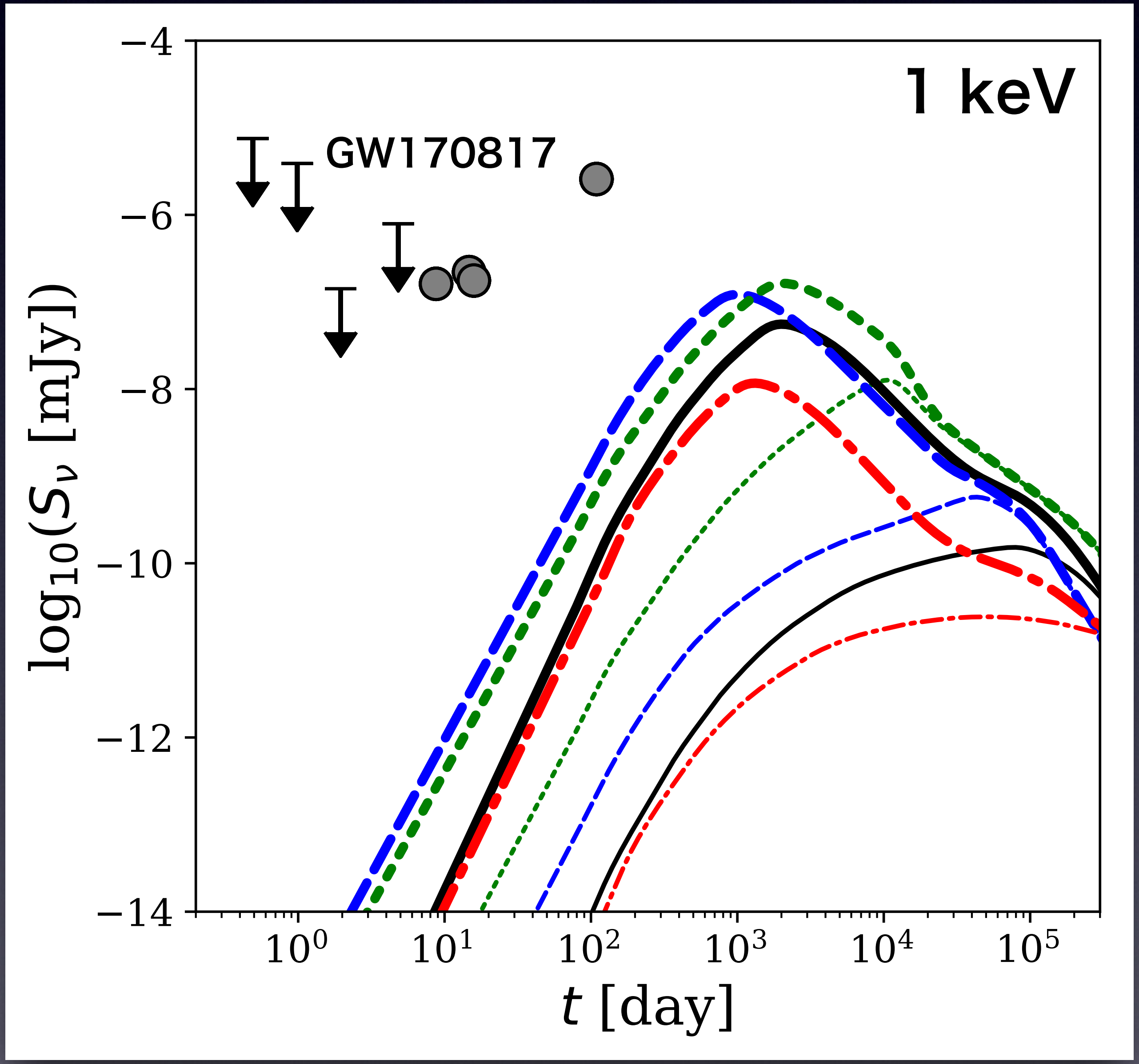
X-ray lightcurve
Case with β-decay e^-



X-ray lightcurve
Case with β-decay e^-

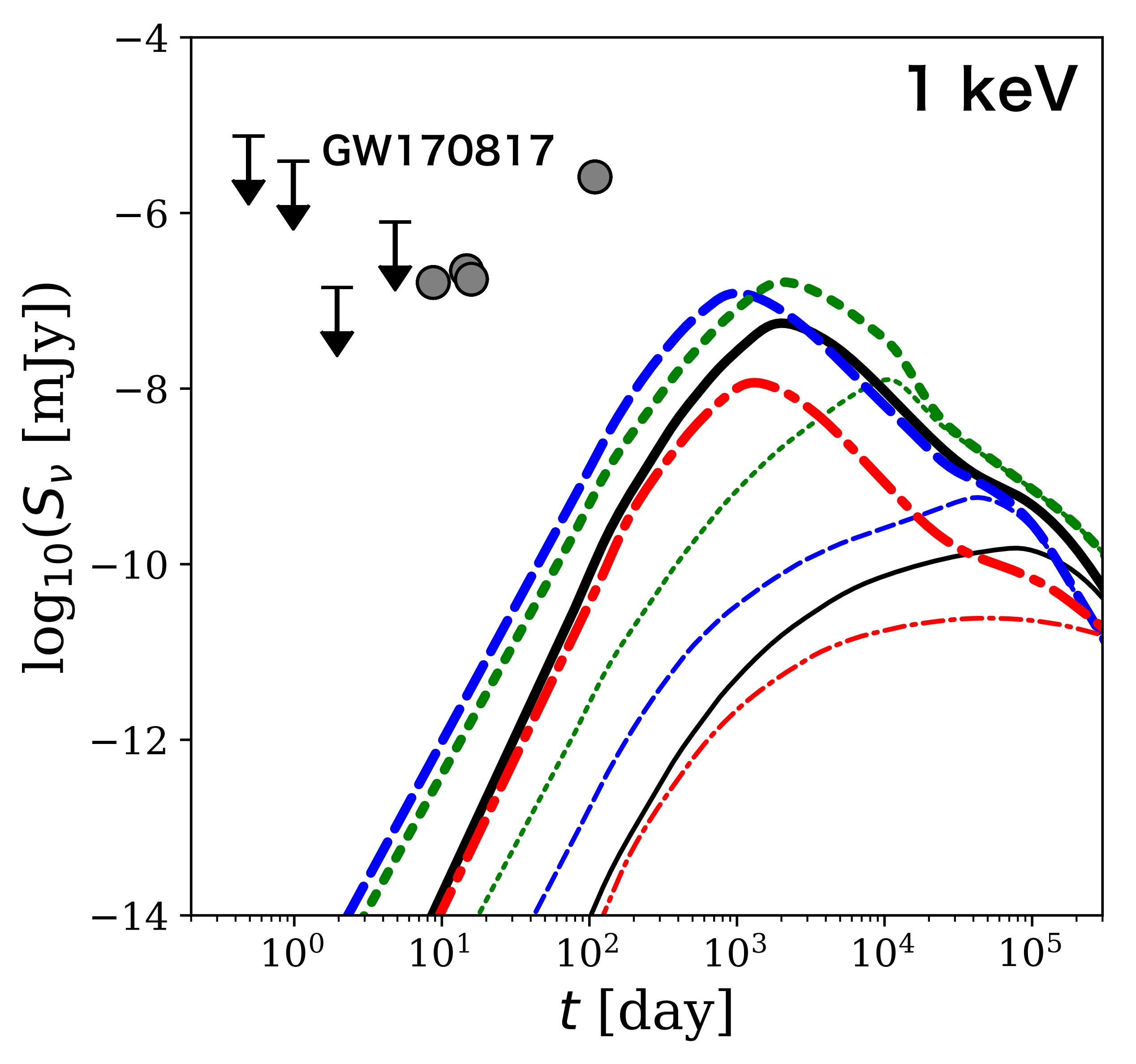


X-ray lightcurve
Case with β-decay e⁻



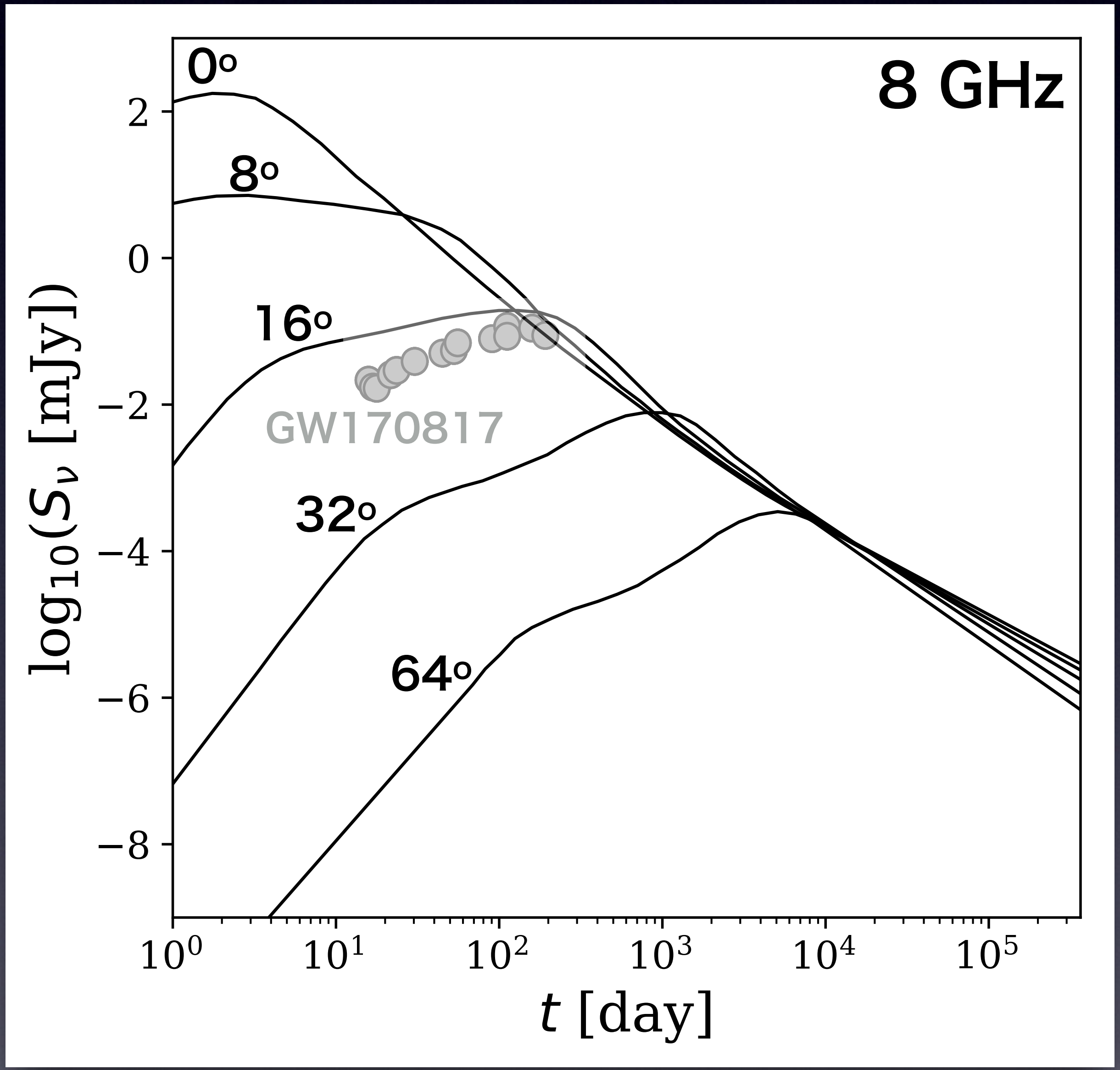
- Peak X-ray flux can sustain for ~ a few 1000d

X-ray lightcurve
Case with β-decay e^-



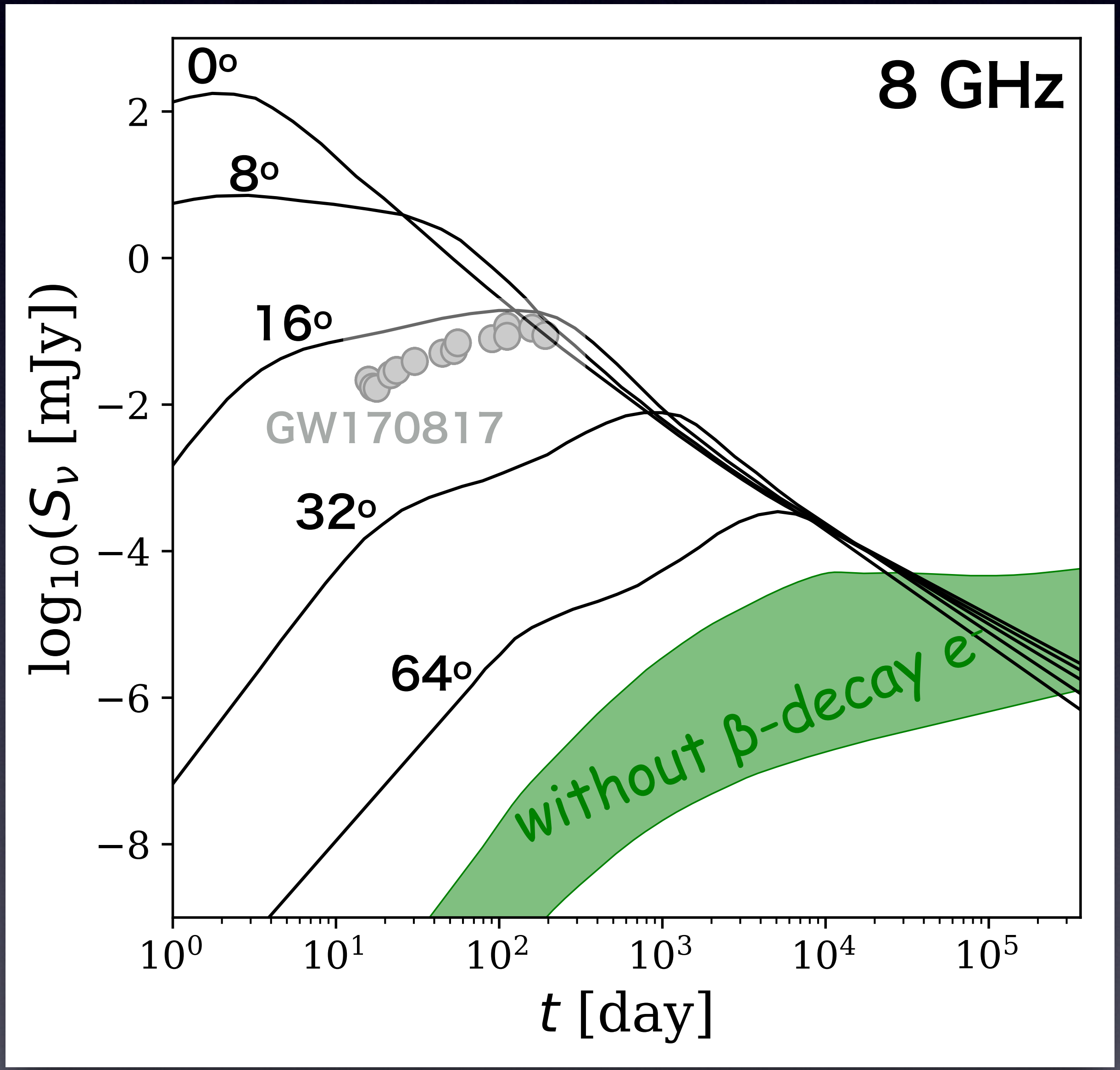
- Peak X-ray flux can sustain for ~ a few 1000d
- Q: optimistically, can this dynamical ejecta component become observable some time after merger?
  1. Dominance of "main" component (jet? cocoon?)
  2. Detectability by instruments

Comparison with Jet Component Radio case



Off-axis jet model (Lazzati+ 2017)

Comparison with Jet Component Radio case



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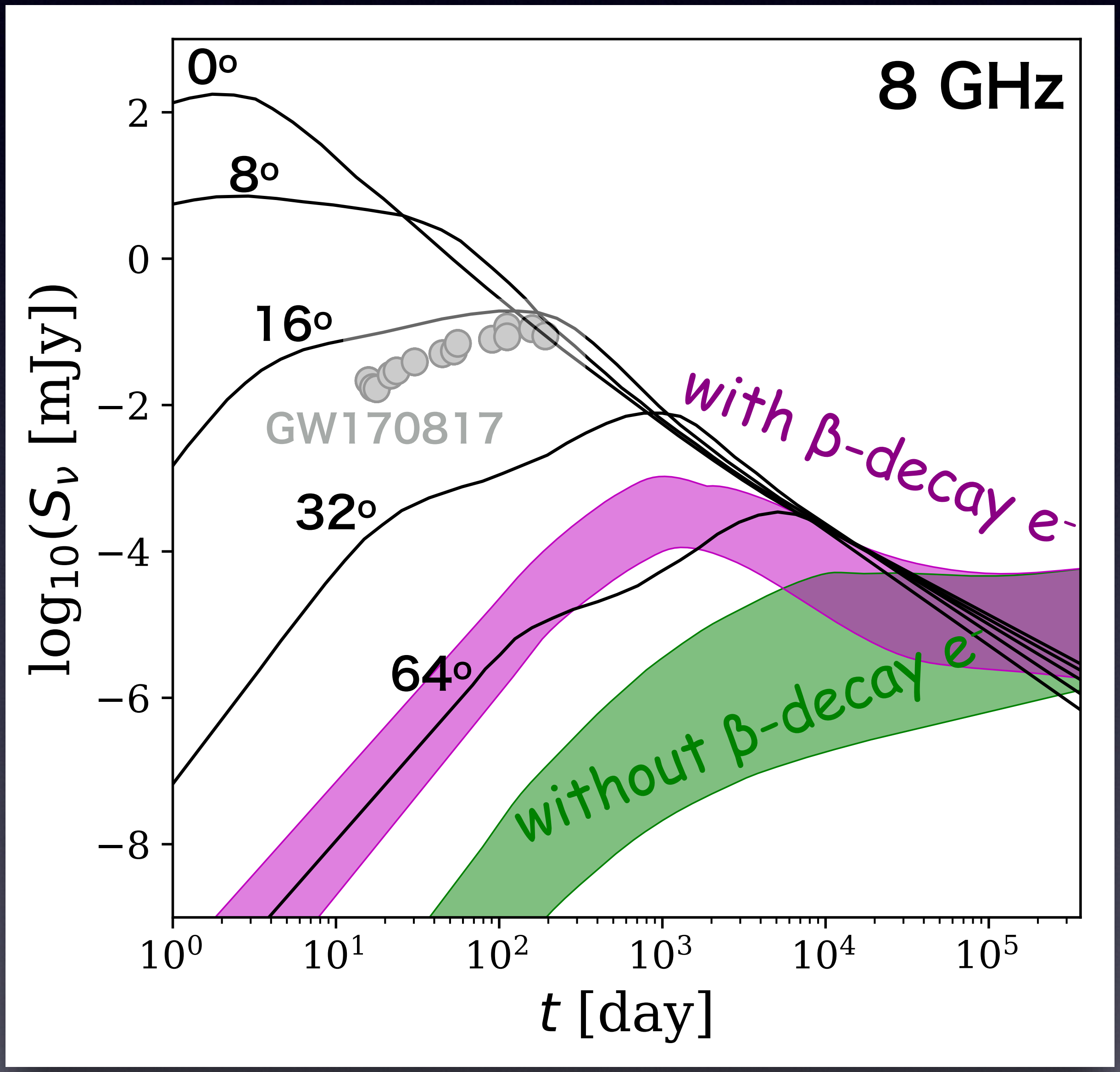
Comparison with Jet Component
Radio case



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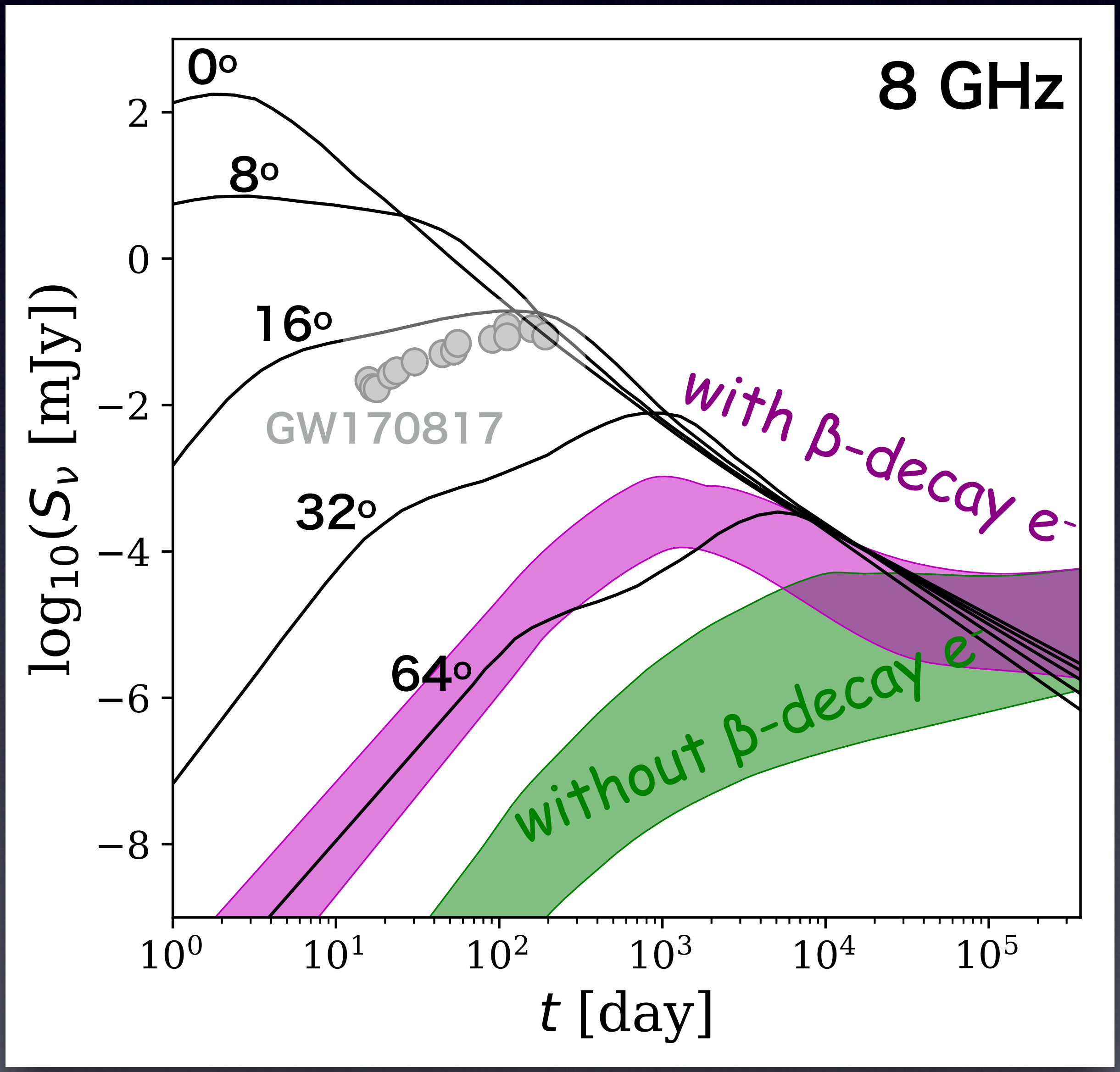
Comparison with Jet Component
Radio case

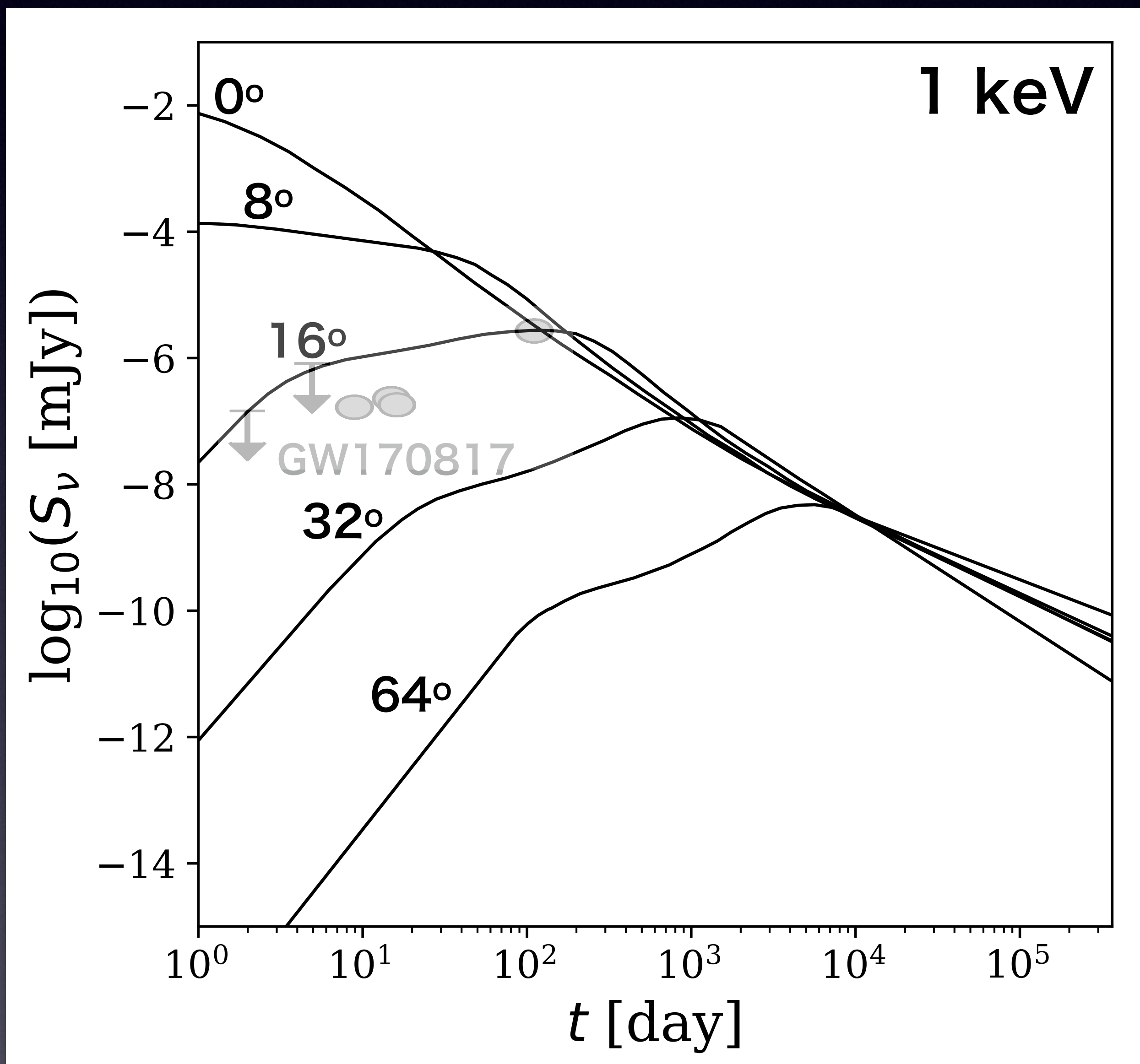


Off-axis jet model (Lazzati+ 2017)

In context of an off-axis jet model, NSM ejecta component can be comparable or even dominant if:

1. acceleration of β-decay e^- is efficient
2. jet-observer offset angle > ~50°

Comparison with Jet Component
X-ray case



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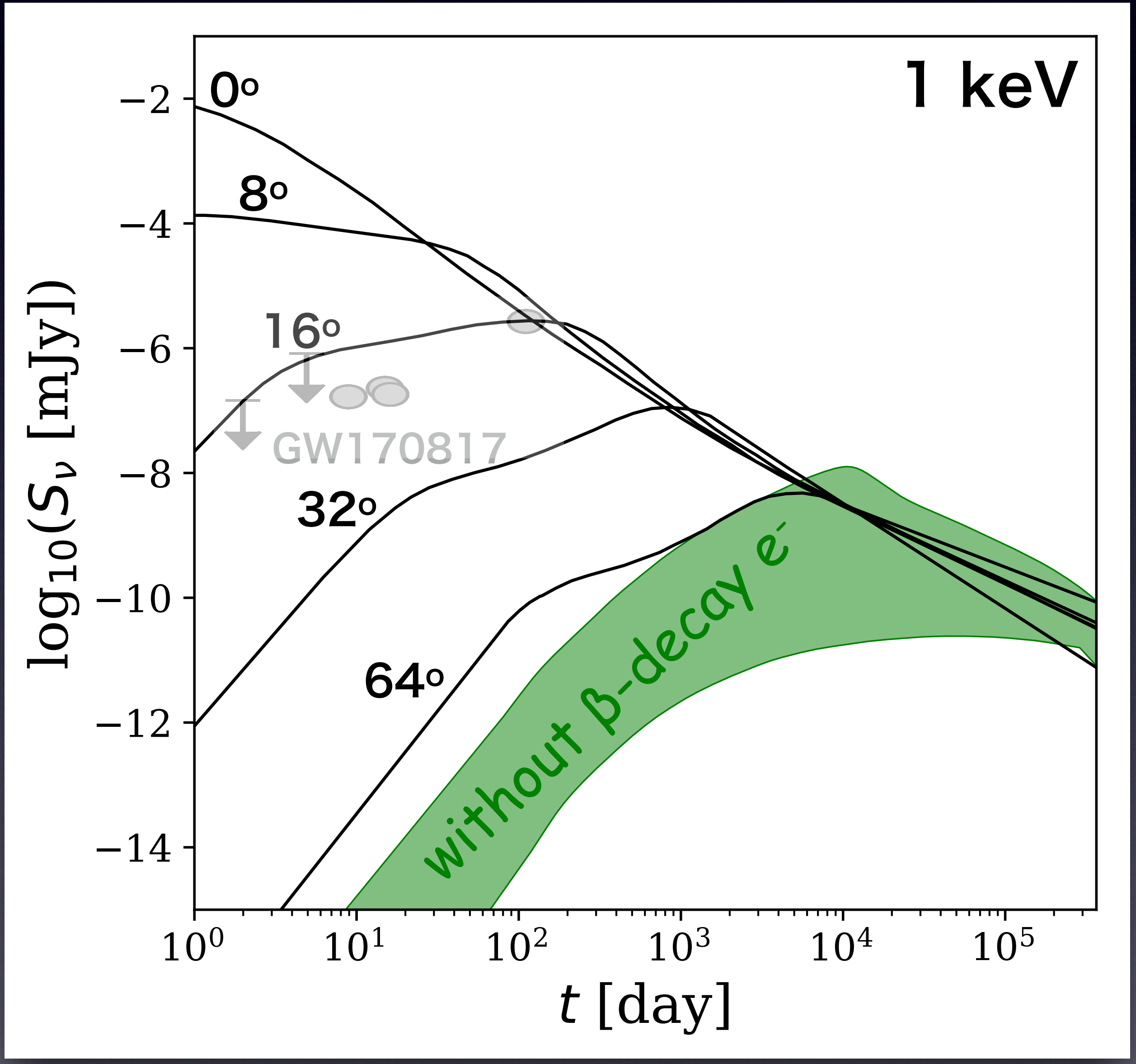
X-ray case



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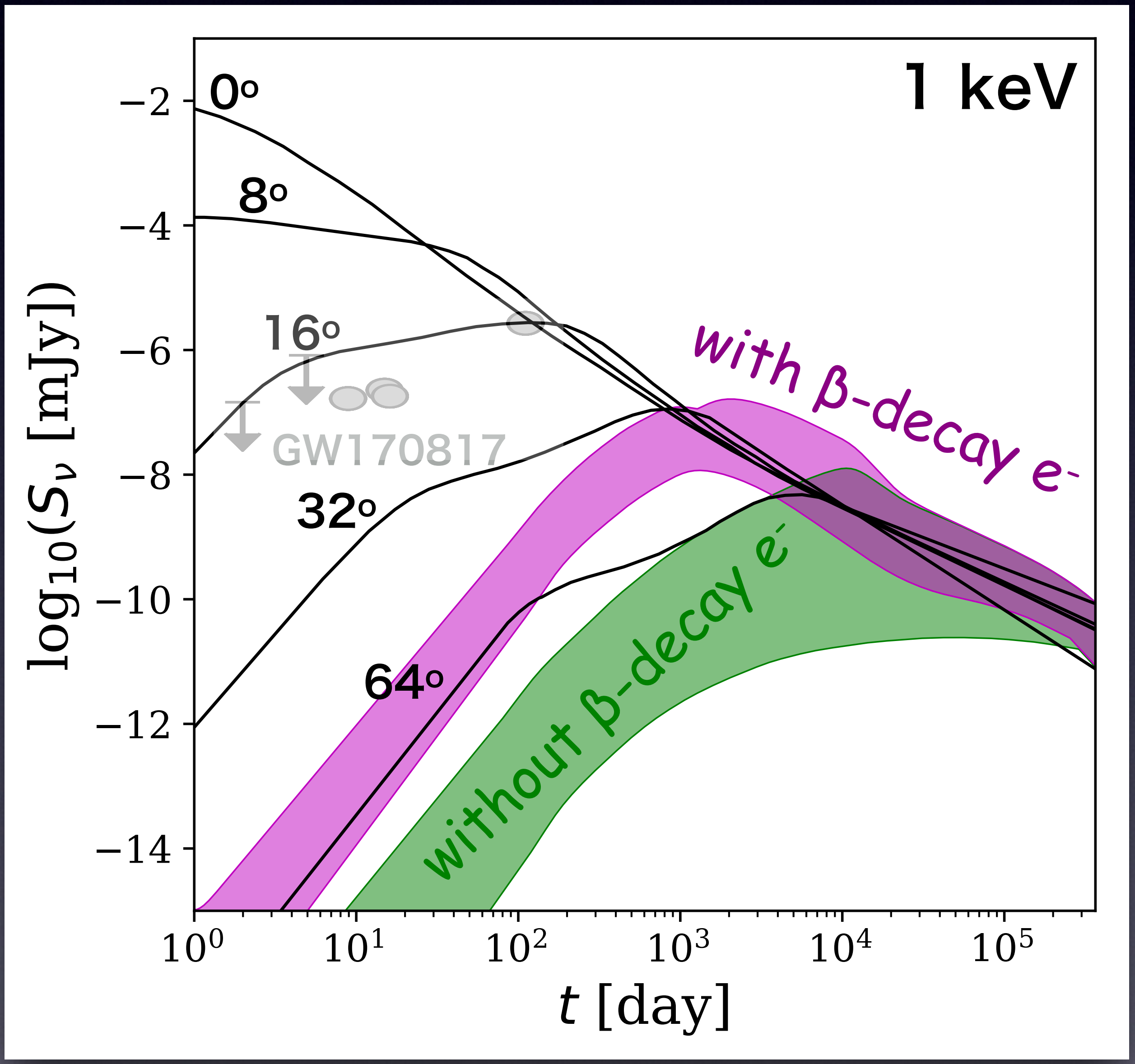

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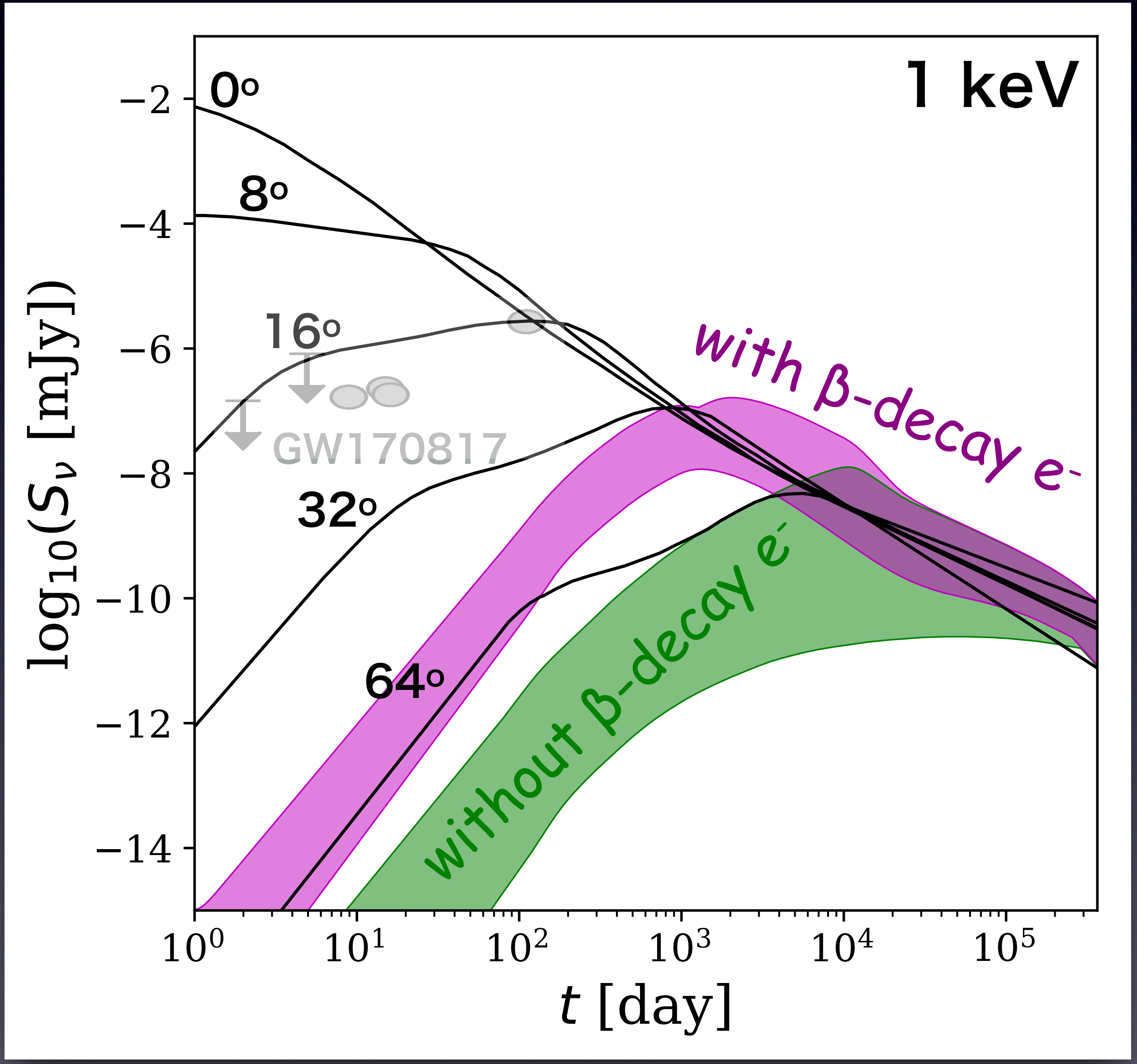
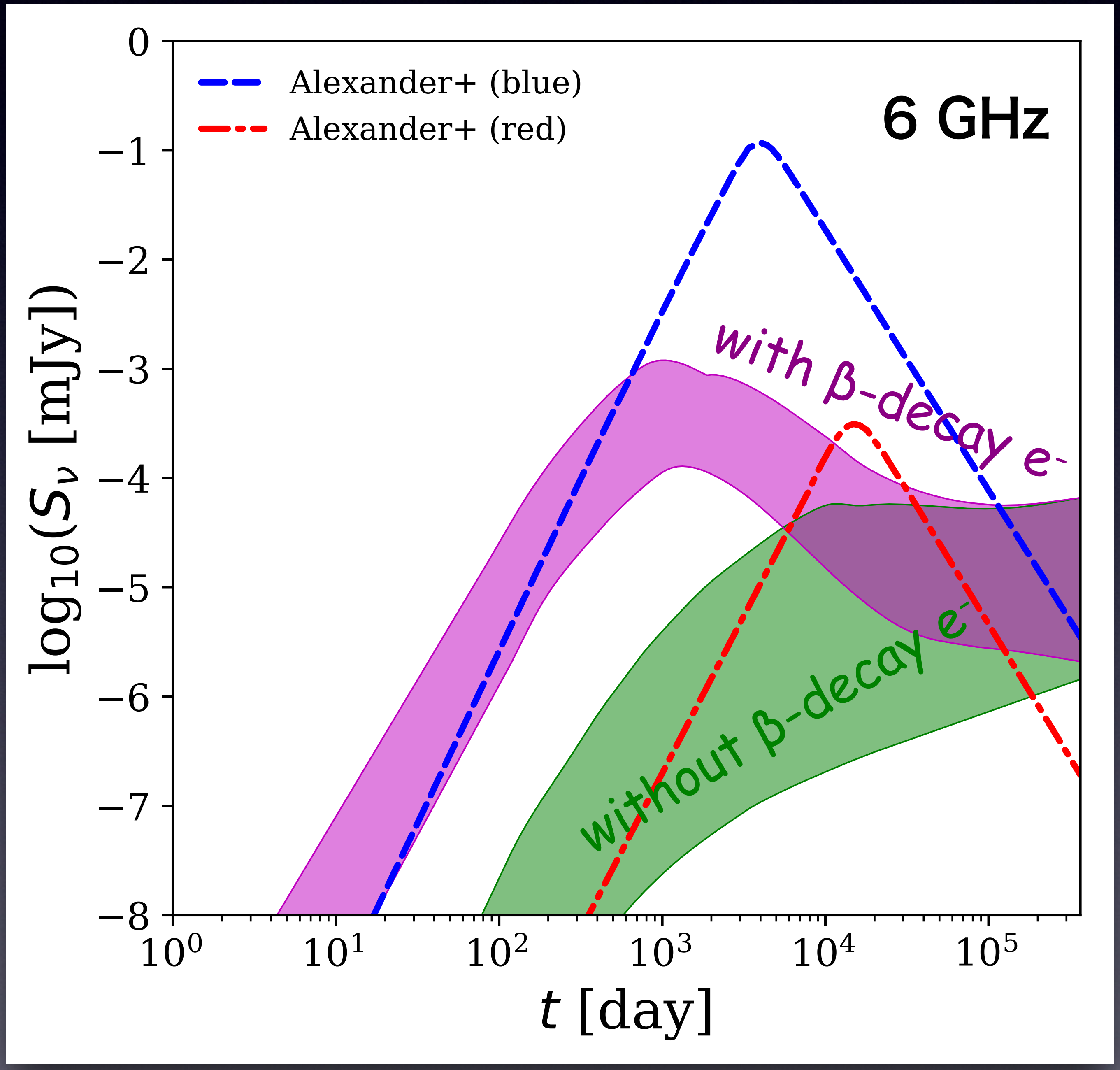


Off-axis jet model (Lazzati+ 2017)

Under same conditions, NSM dynamical ejecta component can dominate ~ 100d after merger

Comparison with 'conventional' models
Equipartition vs SNR-calibrated result



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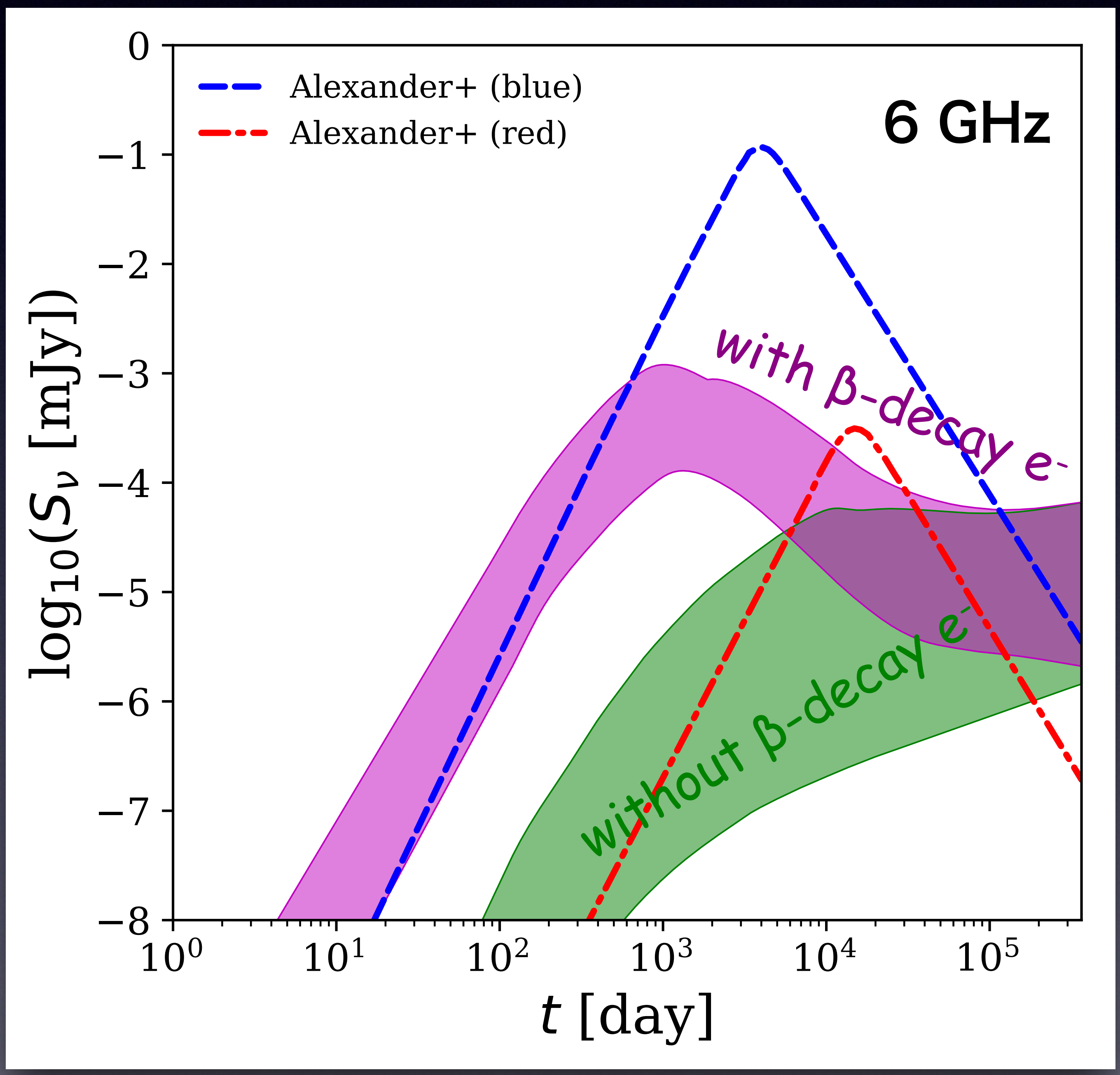

- Case without β-decay e^-
  - Parameters calibrated by SNR observations
  - Typical $\varepsilon_e(t)$, $\varepsilon_B(t)$ far lower than equipartition

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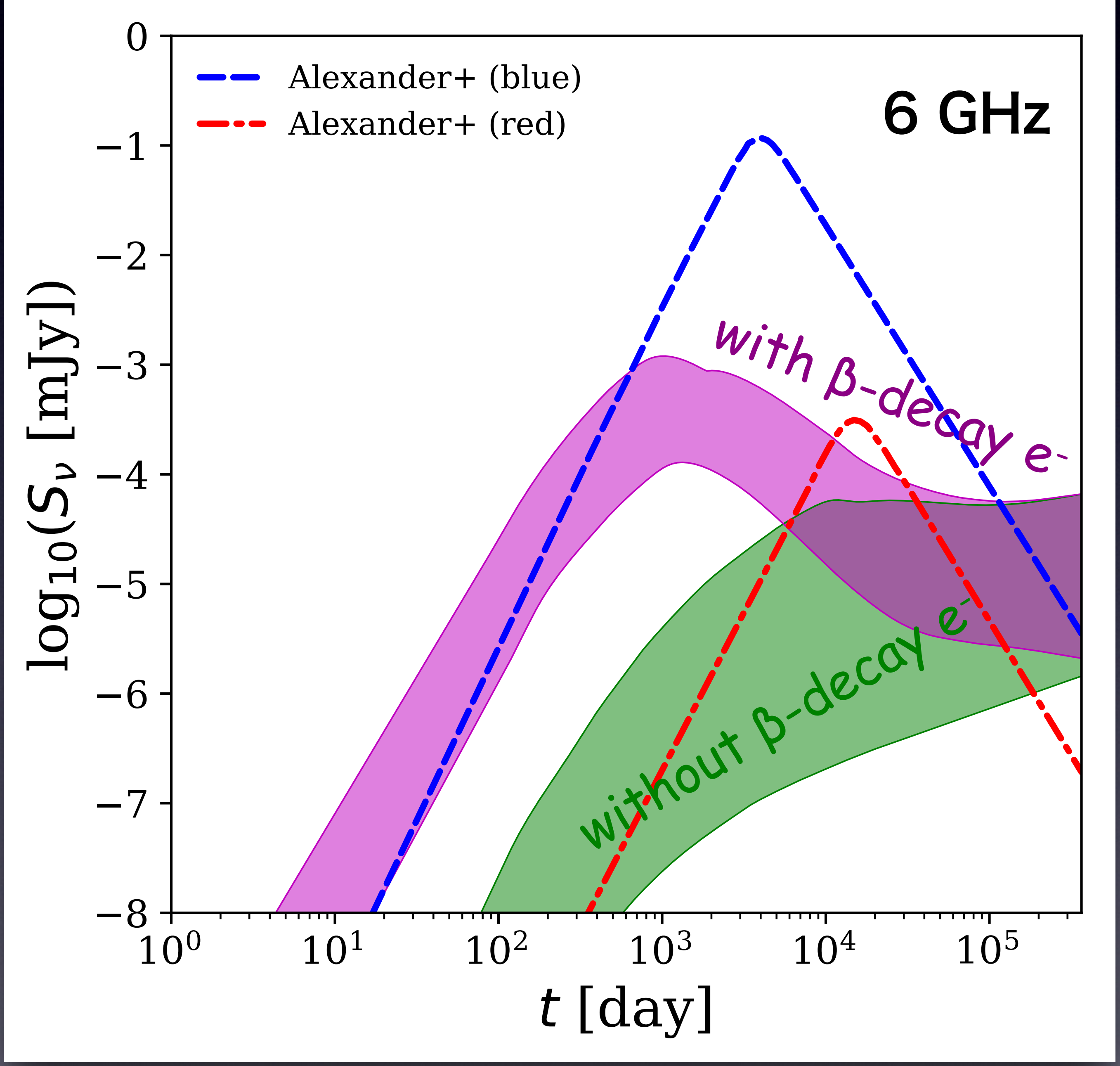
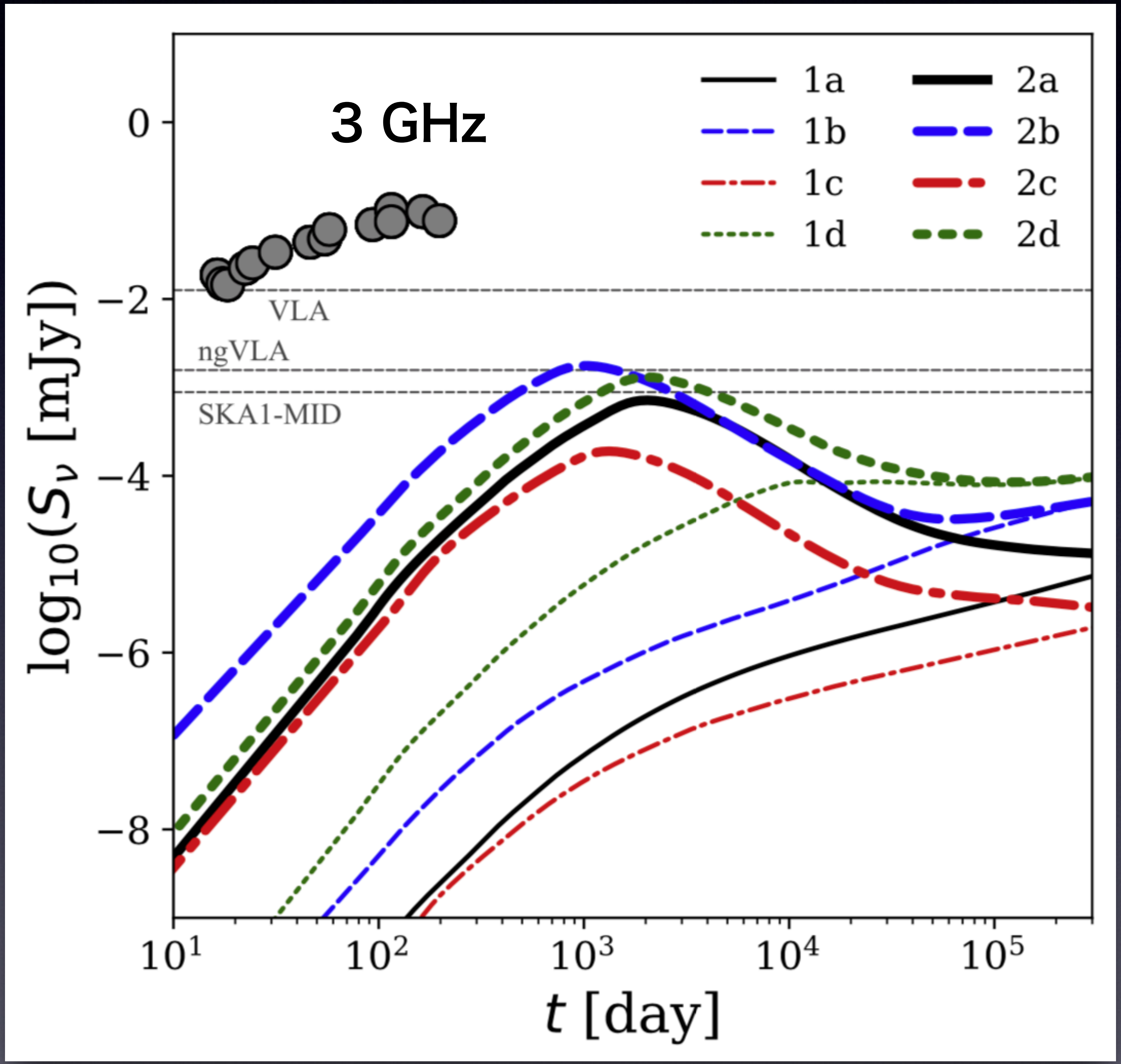
Equipartition vs SNR-calibrated result

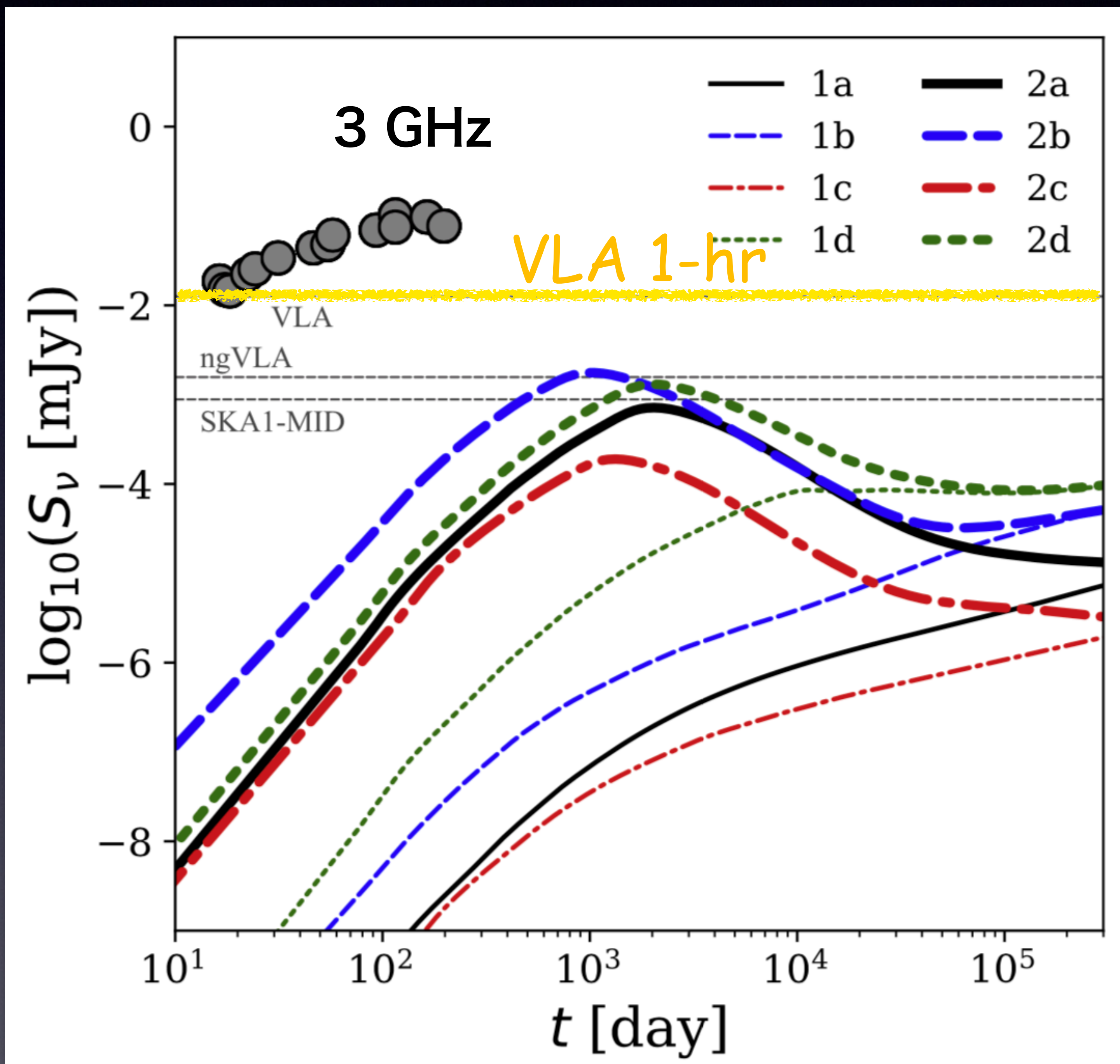


- Case without β-decay e^-
  - Parameters calibrated by SNR observations
  - Typical $\varepsilon_e(t)$, $\varepsilon_B(t)$ far lower than equipartition
- Case with β-decay e^-
  - ε_e limited to 0.1 at early phase
  - Lightcurve similar to conventional models
  - Start to deviate from ~1000d as ε_e limited by dropping $L_e(t)$

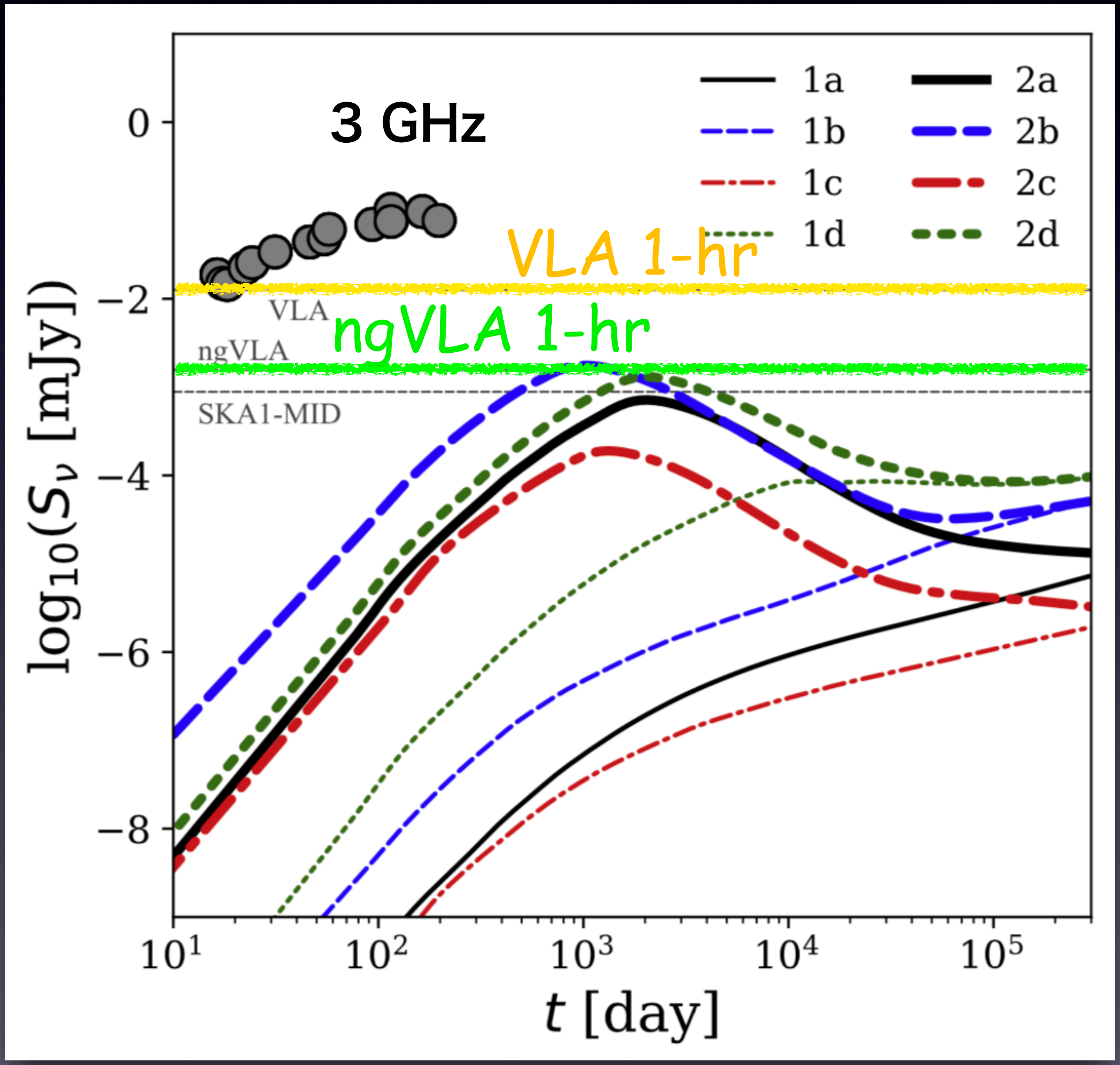
Detectability - radio



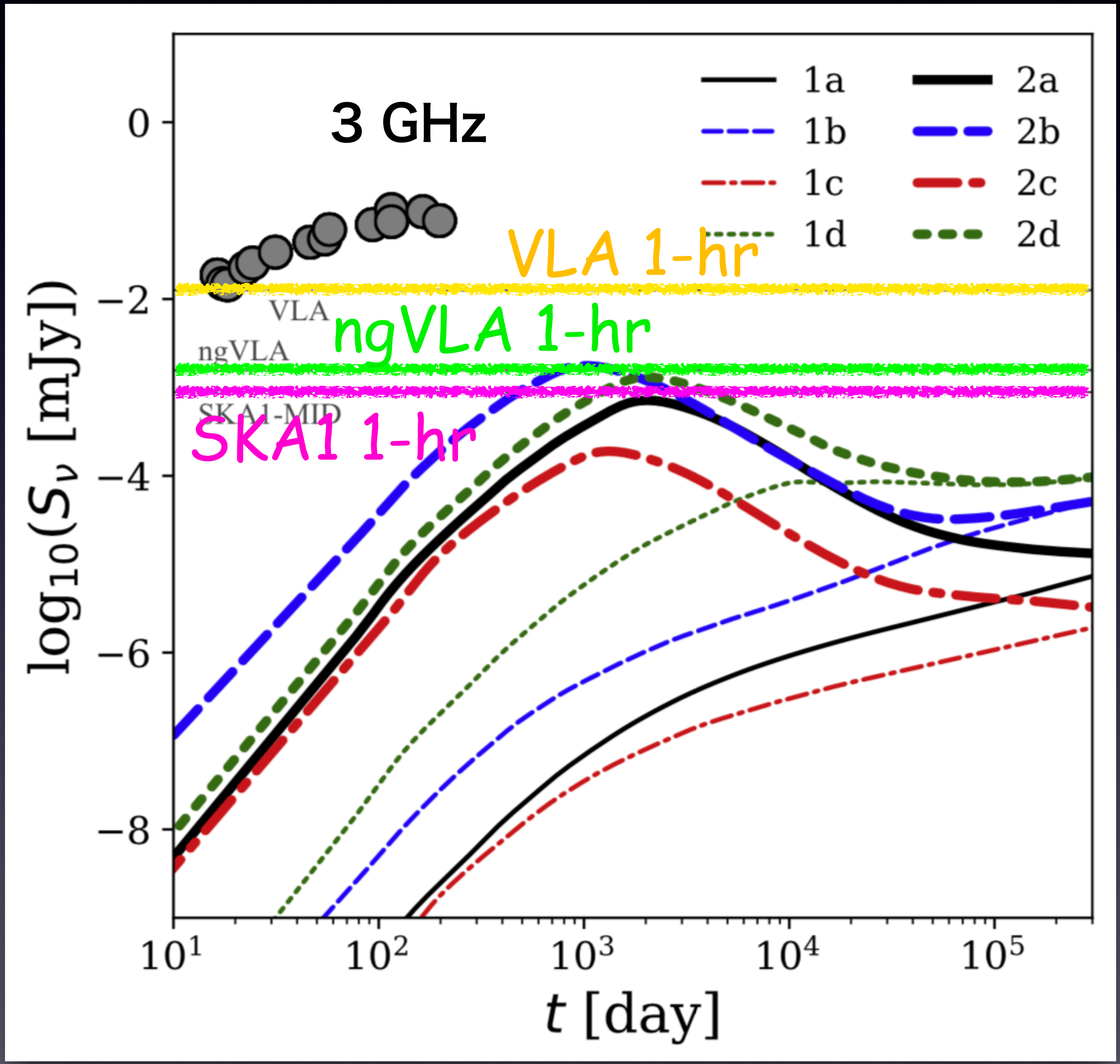
Detectability - radio



Detectability - radio



Detectability - radio



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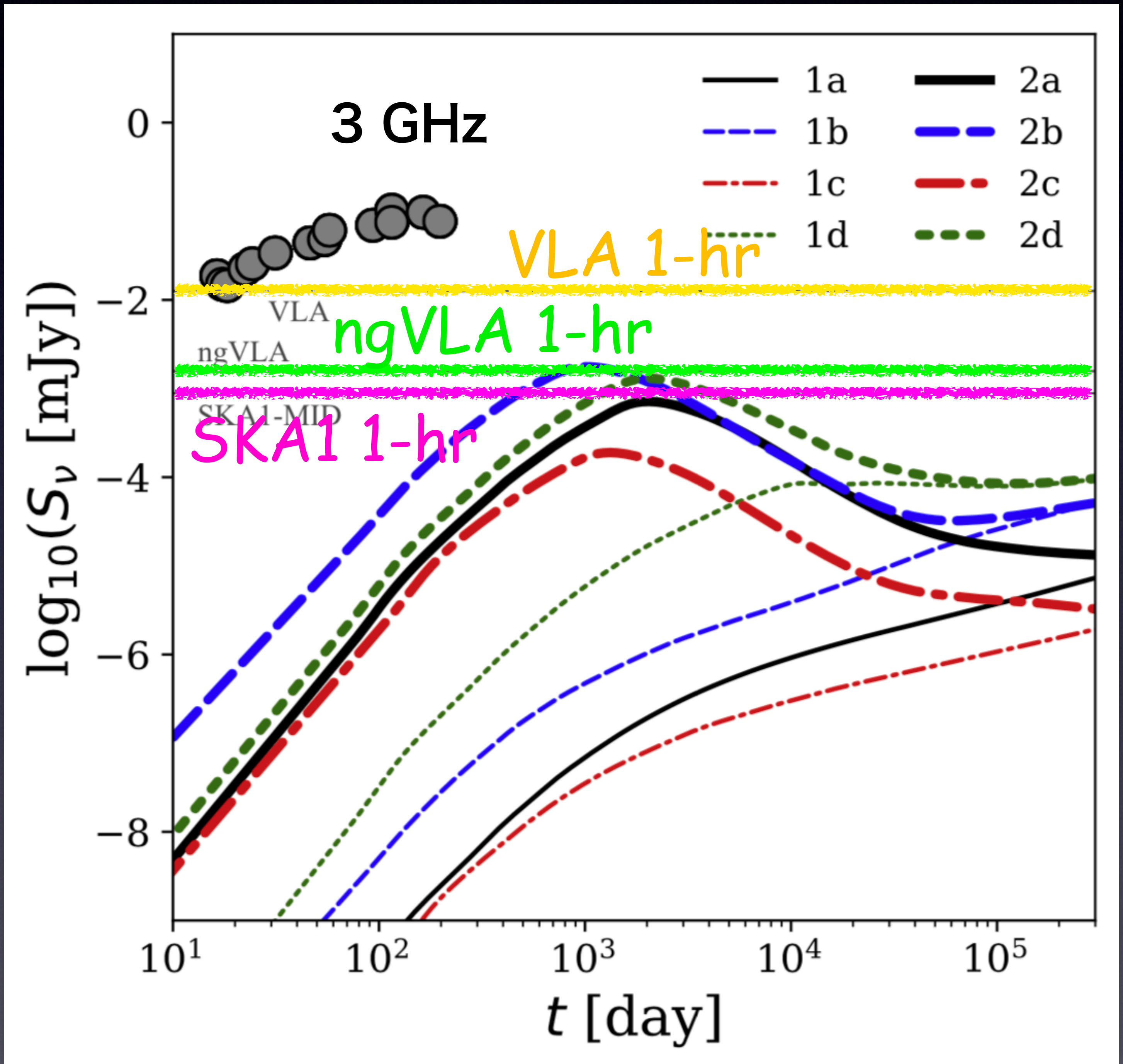
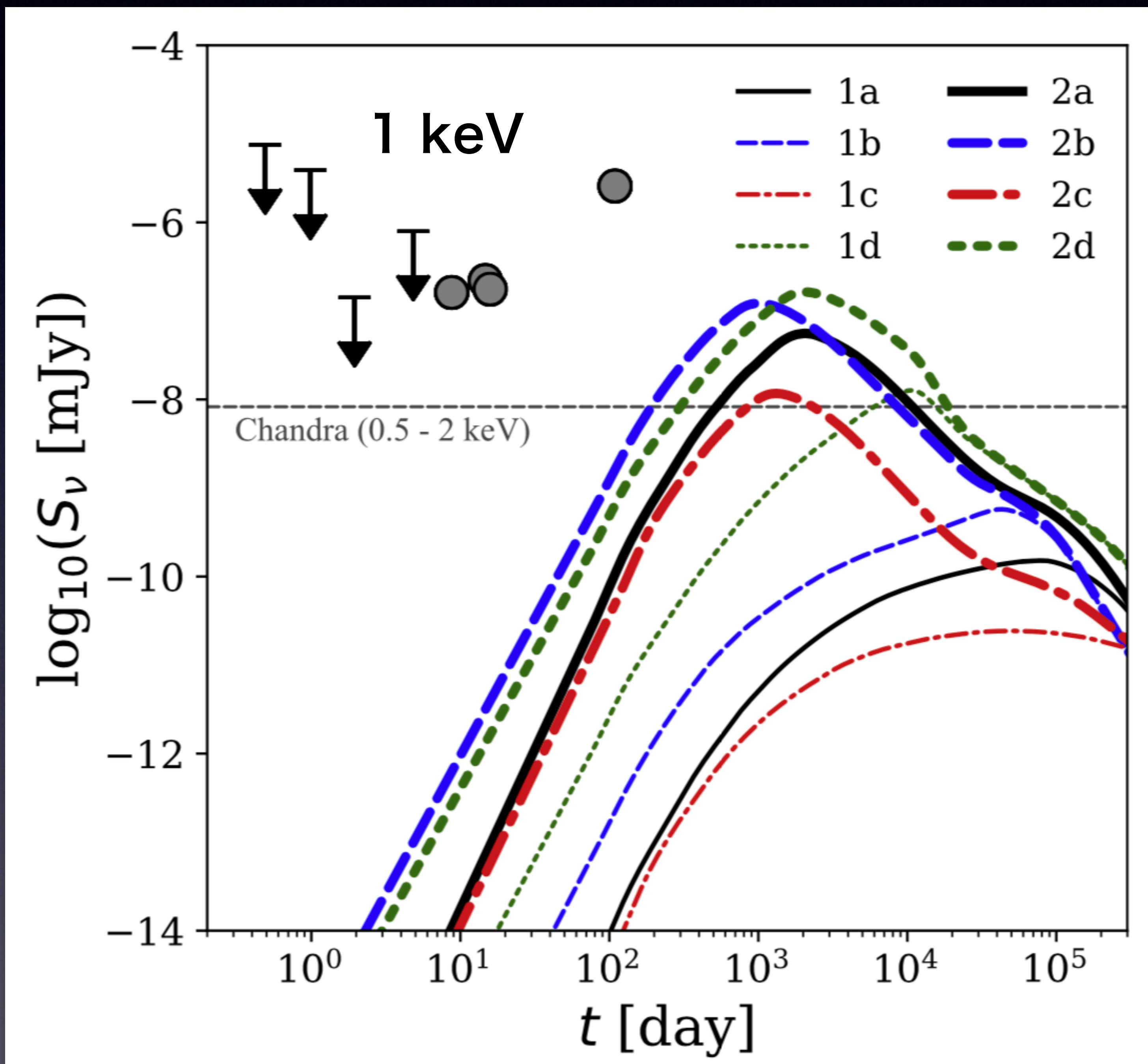


Peak fluxes predicted by our optimistic cases occur at ~1000d

Comparable to 1-hr sensitivities of near-future instruments for d = 40 Mpc

Detectability - X-ray



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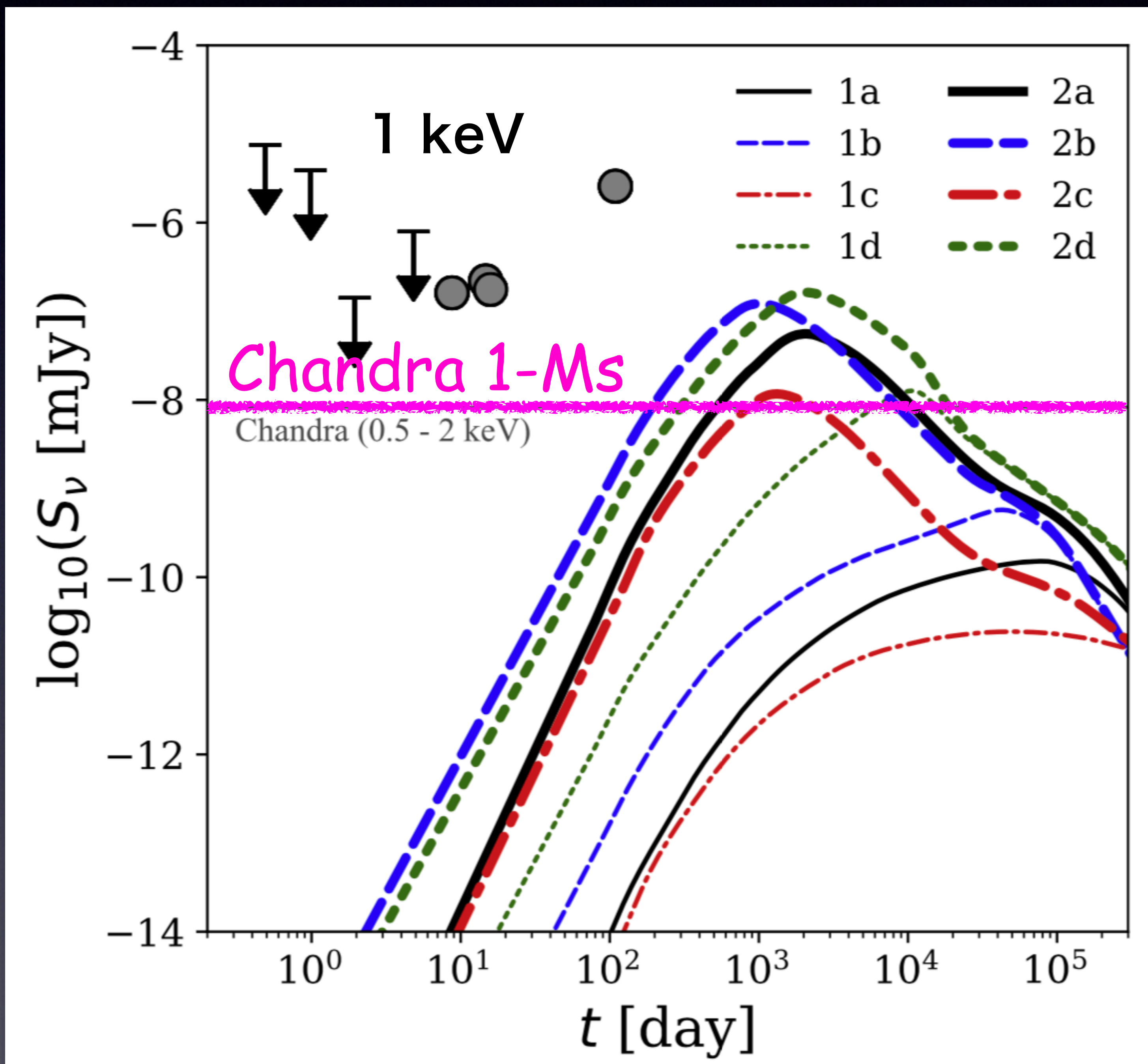

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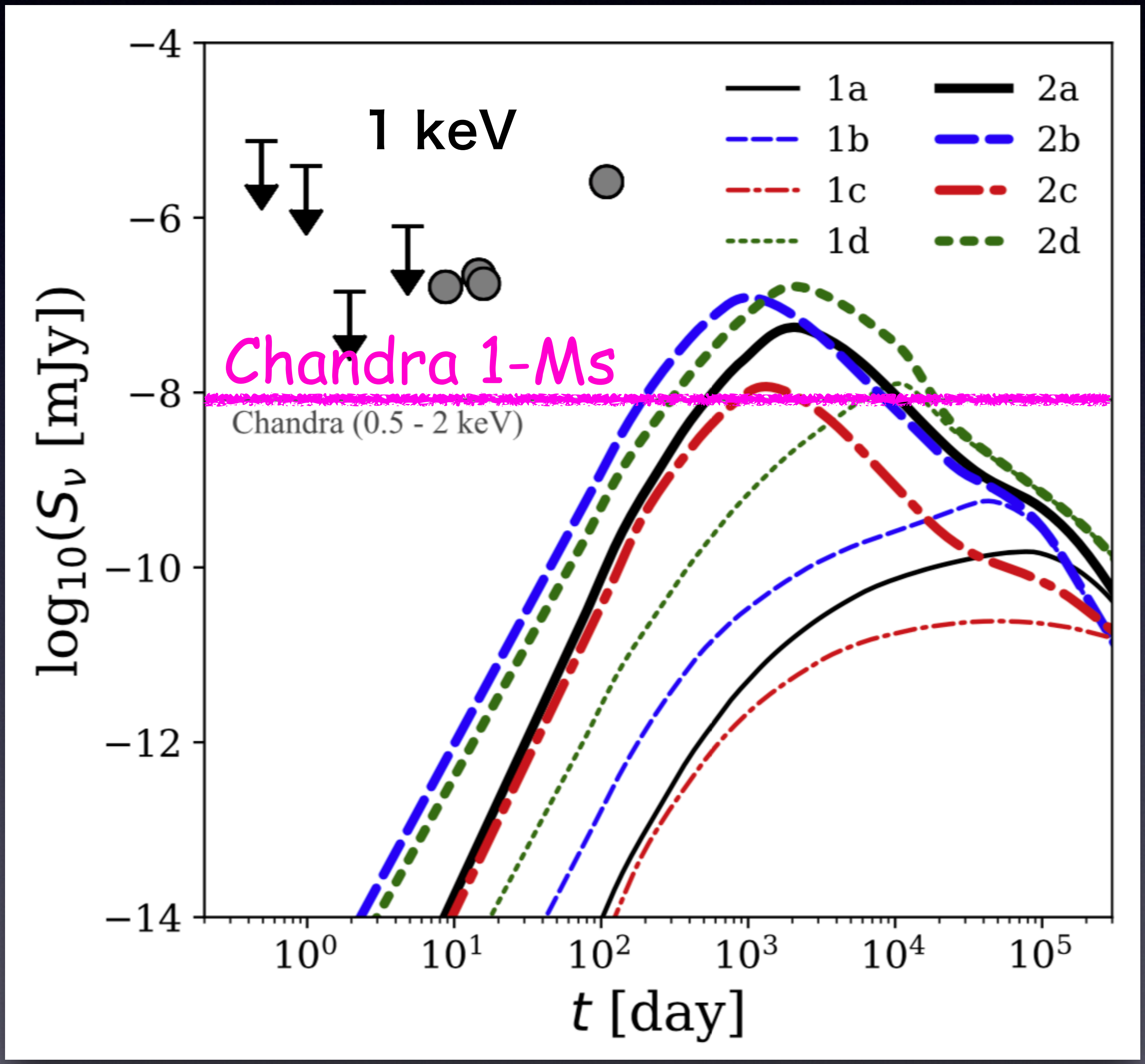
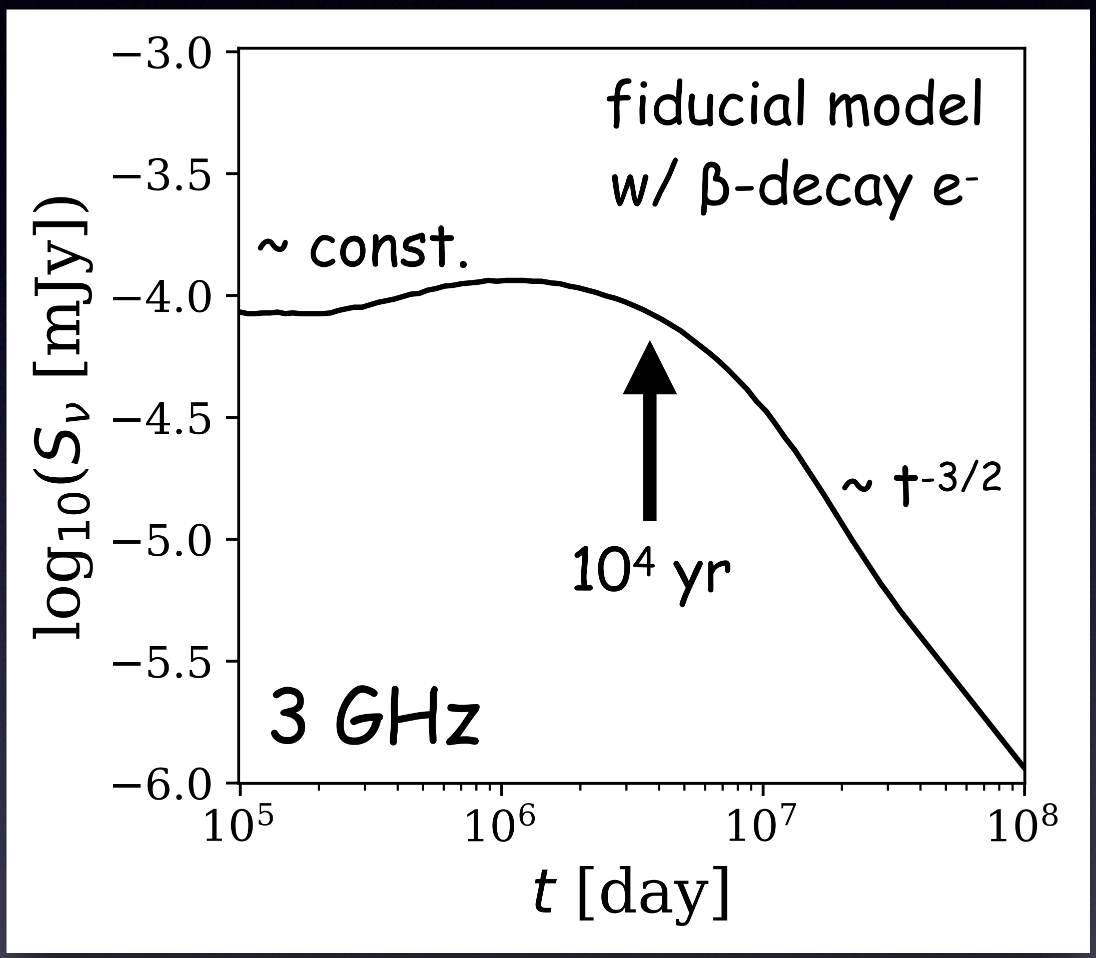


~Ms exposure by Chandra would detect the broad peak at ~ a few 1000d for d = 40 Mpc

'UnID' sources in radio surveys?



Long-term radio lightcurve predicted by our model

- Prediction: a roughly constant radio flux ~10^{-4} mJy at d = 40 Mpc up to ~10^4 yr after merger

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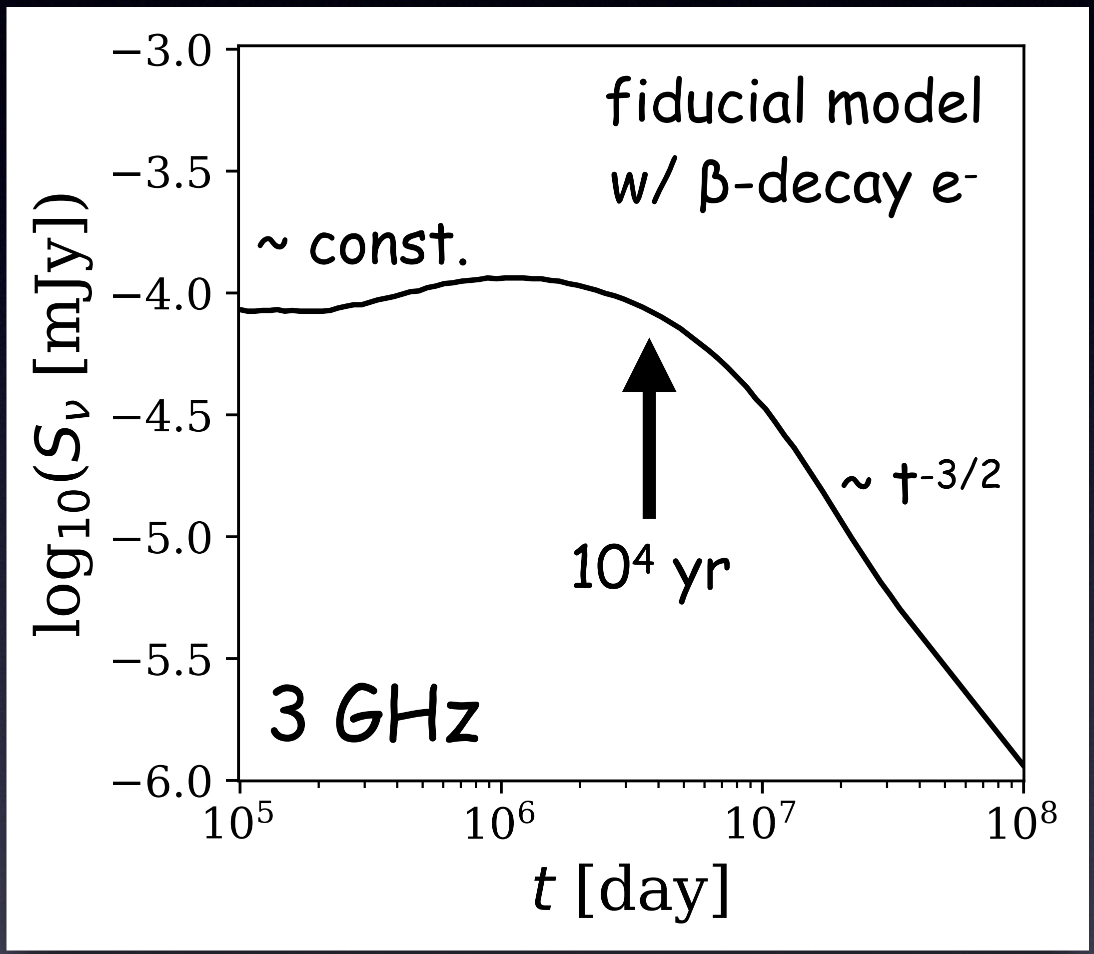

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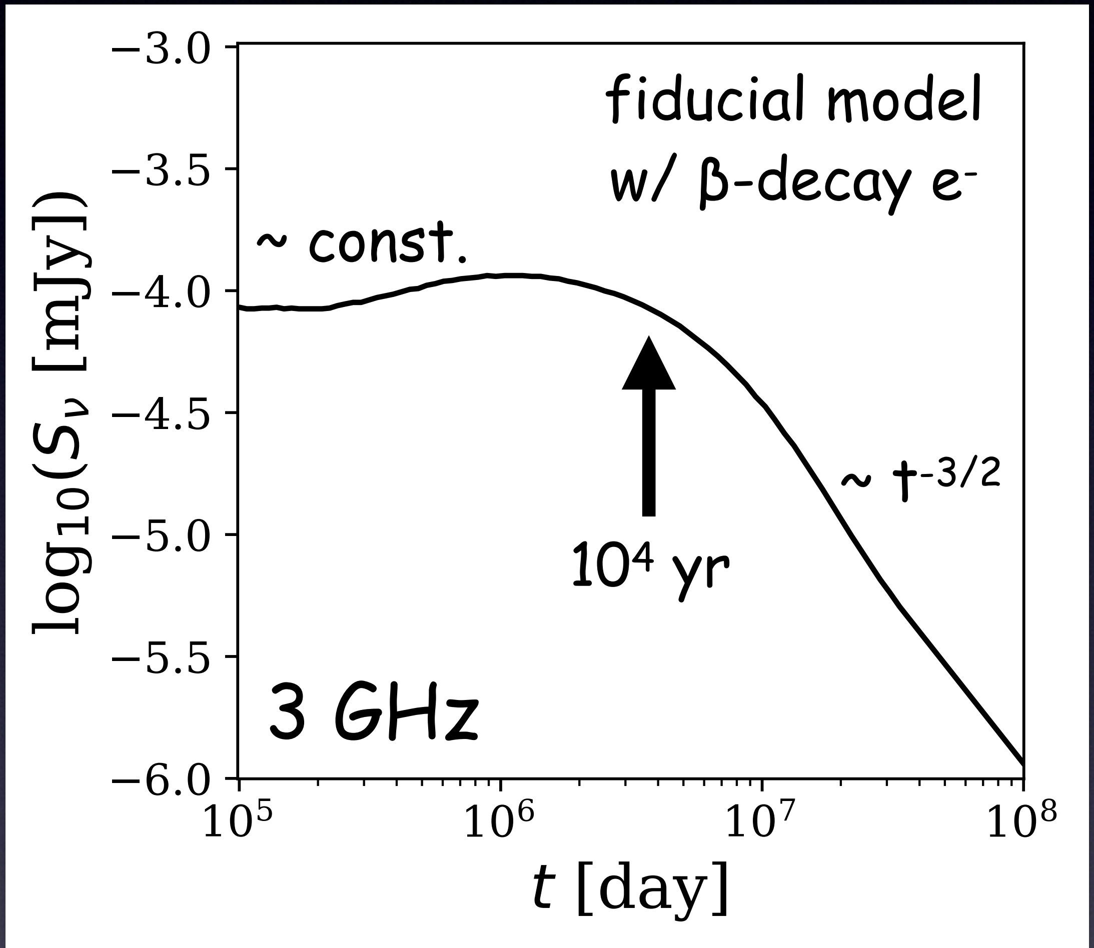

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- Assume NSM rate density in nearby galaxies r ~ 1540^{+3200}_{-1220} Gpc^{-3} yr^{-1} (Abbott+ 17),
  - detectable sources by 3-yr VLA survey, N_{NSMR} ~ 0.05-0.7
  - Case of ngVLA or SKA (with 10x better sensitivity), N_{NSMR} ~ 1.6-22

Summary

- We investigated radio and X-ray emission from NSM ejecta-CBM interaction using a self-consistent CR-hydro model calibrated by young SNR observations
- We suggested for the 1st time the importance of acceleration of β-decay e^- for NSMs, a unique feature not found anywhere else
- We predicted possible detectable EM signals from NSM remnants in the future under a set of well-defined conditions