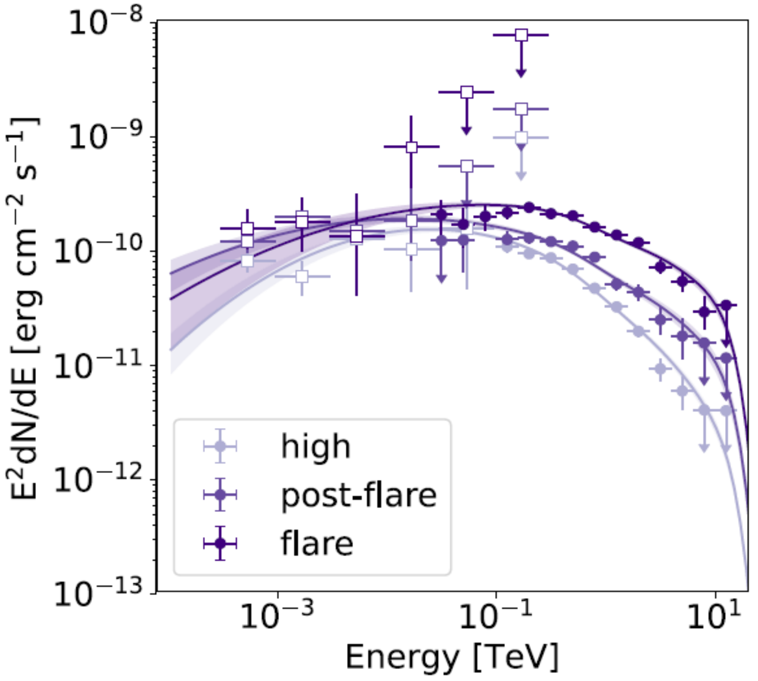
Introduction:
Galactic and Extragalactic Phenomena

Katsuaki Asano
(Institute for Cosmic Ray Research, U. Tokyo)

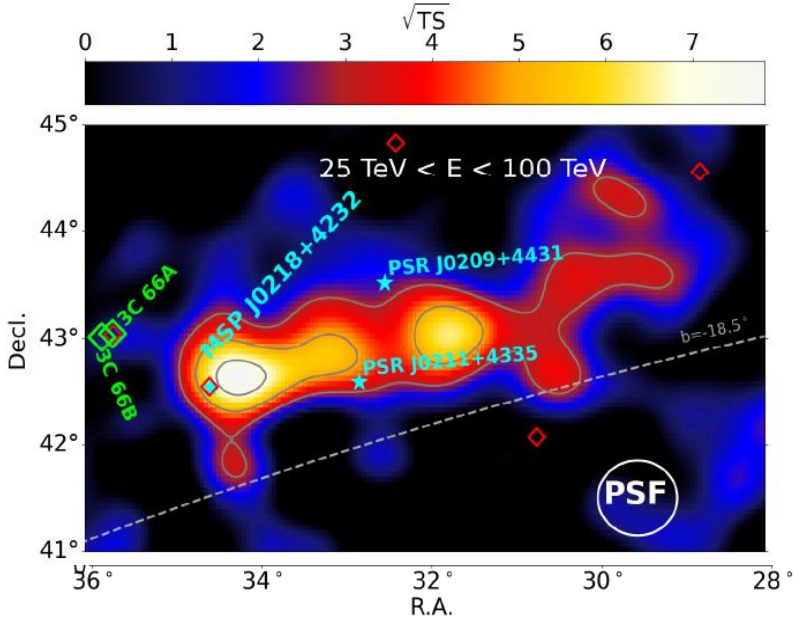
Substitute for Felix

New Perspectives in Gamma-Ray Astronomy and Particle Acceleration

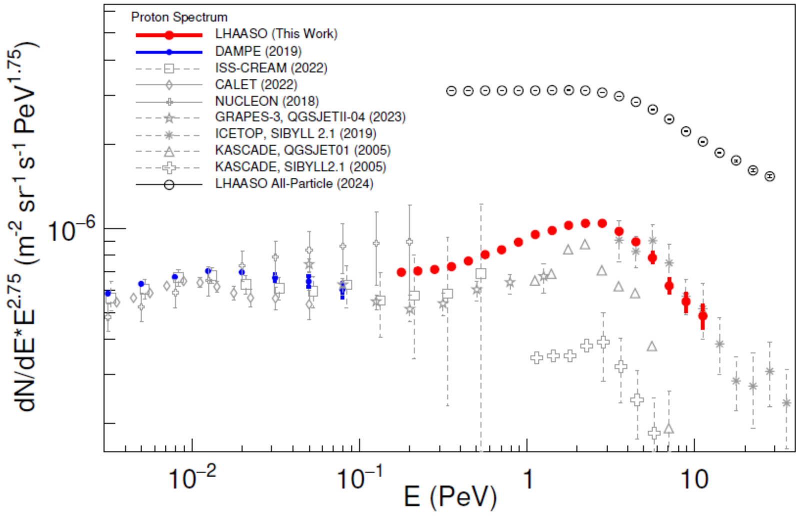
- Era of LHAASO/ALPACA and CTA in gamma-ray astronomy
- LHAASO observes mainly Galactic objects
- CTA not only Galactic, but also Extra-galactic (Vovk, Abe)
- Next generation: MeV (Yoneda, Yoshida, Mizumura, Odaka)

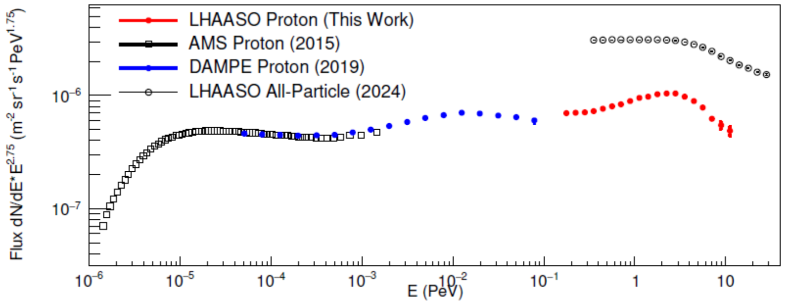


LST-1&Fermi
Mrk 421



LHAASO
Peanut shape
(diffusion from millisecond pulsar?)



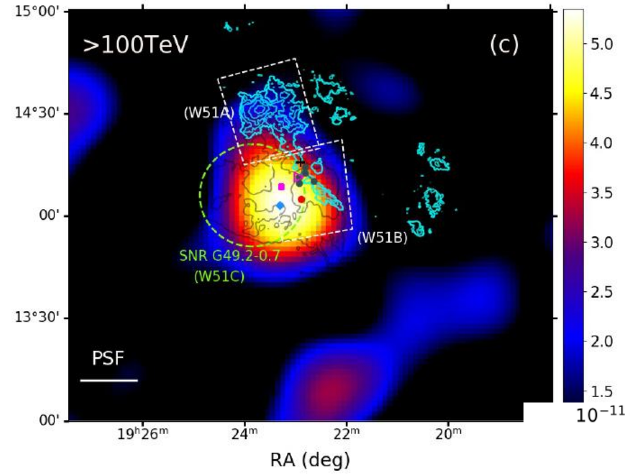


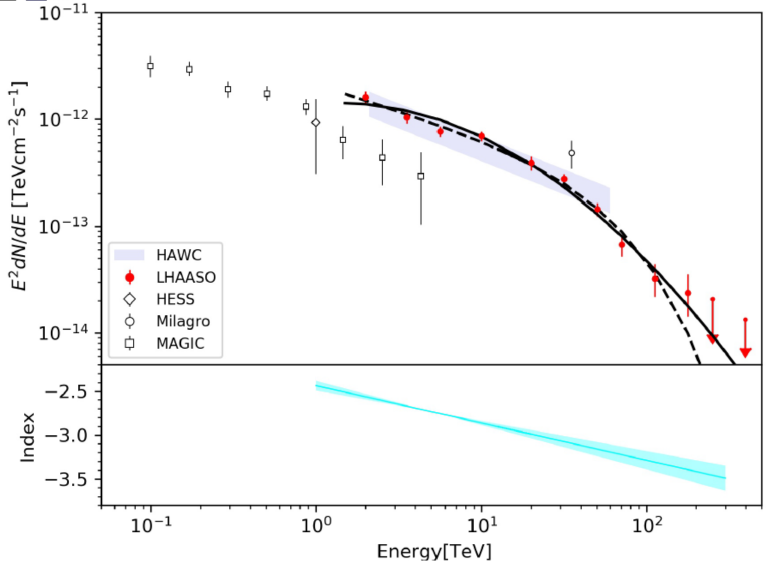
Galactic

- **Felix might comment on possible sources of knee CRs.**

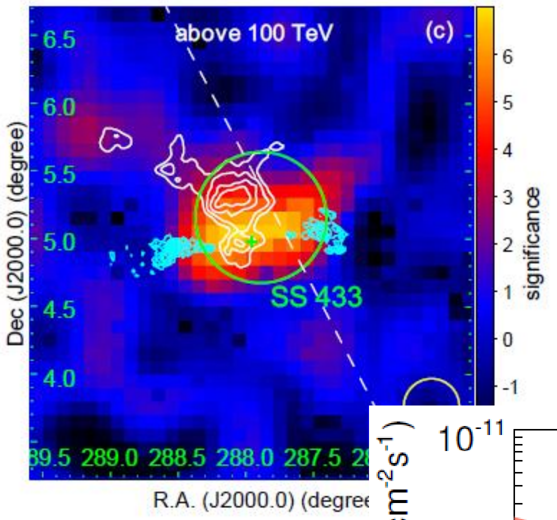
See Khangulyan, Kimura, Tsuji

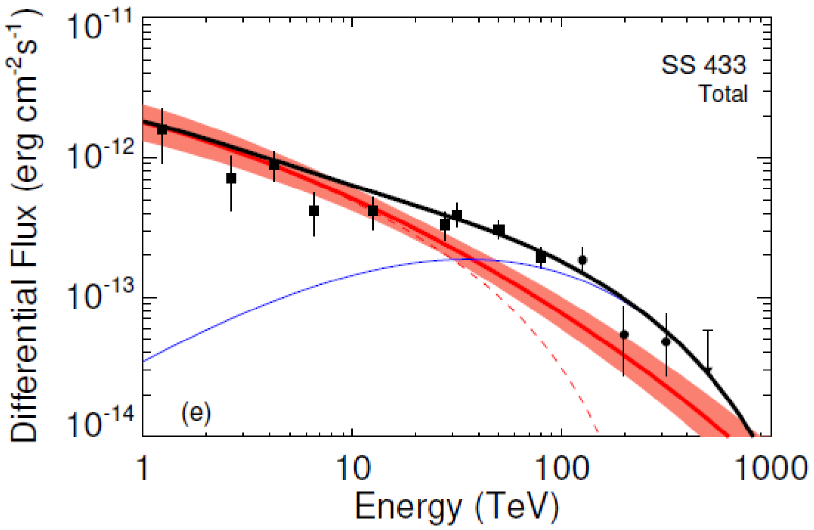
Young massive star cluster





Micro QSO





Felix's slides in LHAASO meeting

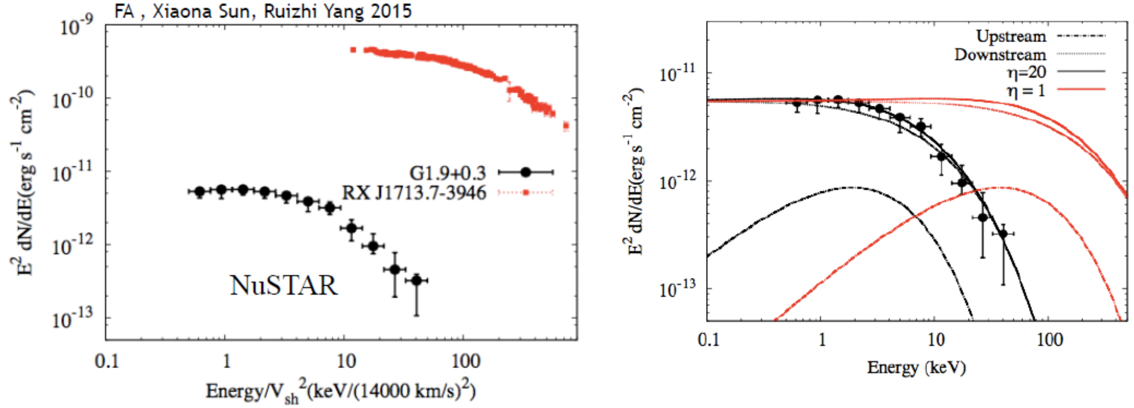
Very young SNRs as Super PeVatrons?

G1.9+0.3 - youngest (100yr-old) known SNR in Galaxy
with the current shock speed $v \approx 14000$ km/s

$h\nu_{max} \simeq 1\,(v_{shok}/3000\,\mathrm{km/s})^2\,\mathrm{keV}$ independent of B-field (!)

in the Bohm diffusion limit the peak should be around 20 keV but is detected at 1 keV as SNR RXJ1713 (but with a speed ≈ 4000 km/s)

FA , Xiaona Sun, Ruizhi Yang 2015



G1.9+0.3 does not operate as PeVatron (as many other young SNRs as well - Tsuji et al 2021) !

very disappointing… should be taken seriously 13

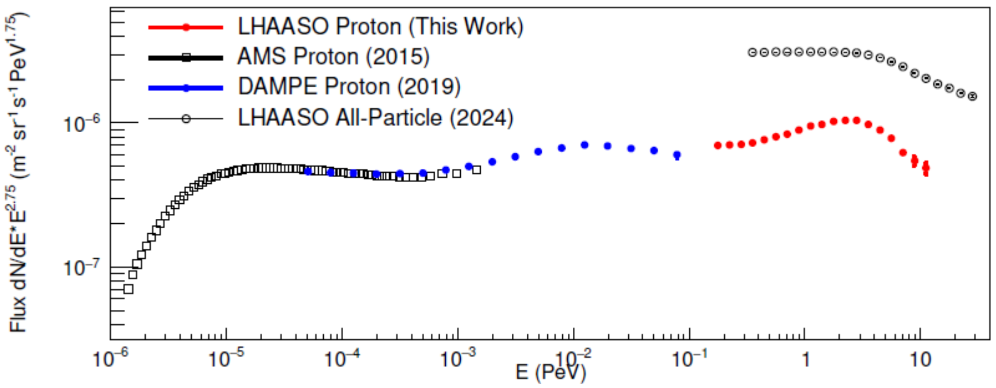
Summary:

Hyper-accreting Microquasars acting as SuperPeVatrons? yes

The major (only) feasibly option to explain GCRs well above 10 PeV: yes (?)

Many galactic topics will be discussed, so I won't need to talk a lot.

How to explain the first bump?



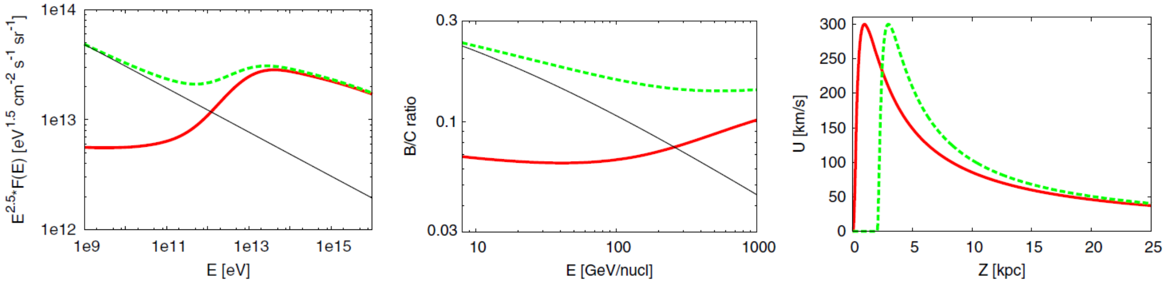
$$D(R) = \beta D_0 \frac{(R/\mathrm{GV})^{\delta}}{[1+(R/R_b)^{\Delta\delta/s}]^{s}},$$

- There are commonly bumps at ~500 GV in all kinds of CRs.
- Modulation of the diffusion coefficient at 500 GV?
- This corresponds to a length of 2×10^{-4}pc.
- What is there at this scale?
- Ad hoc assumption.

Galactic Wind Effect on CRs

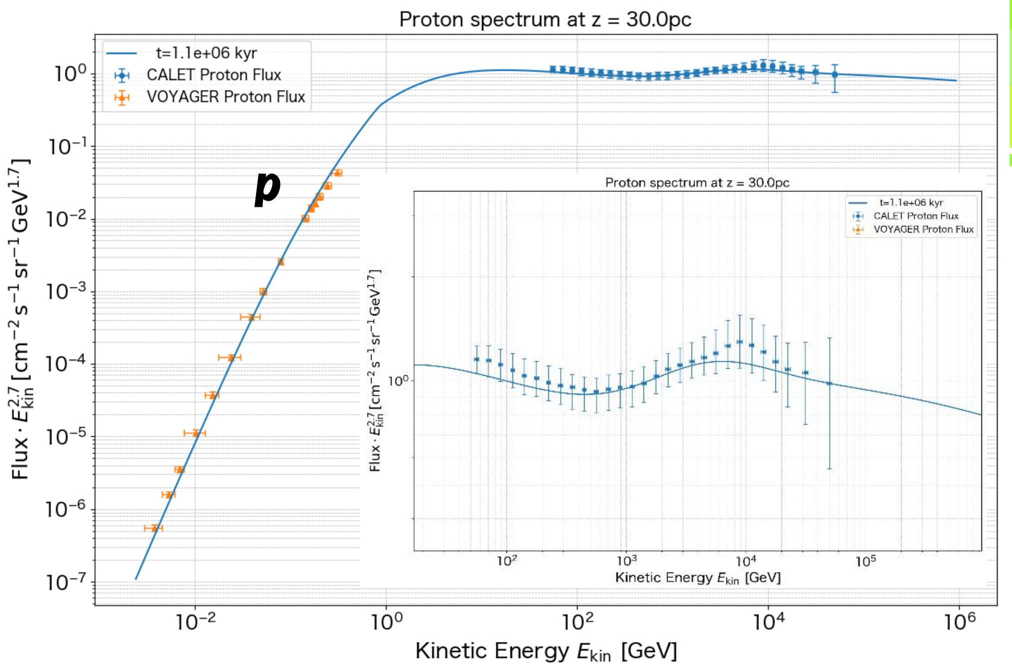
$$\frac{\partial \psi_{\rm CR}}{\partial t} = \boldsymbol{\nabla} \cdot (\mathcal{D} \boldsymbol{\nabla} \psi_{\rm CR} - \boldsymbol{V} \psi_{\rm CR}) + \frac{\partial}{\partial p} \left[\frac{p}{3} (\boldsymbol{\nabla} \cdot \boldsymbol{V}) \psi_{\rm CR} \right] - \frac{\psi_{\rm CR}}{\tau_{\rm CR}} + \mathcal{Q}_{\rm CR},$$

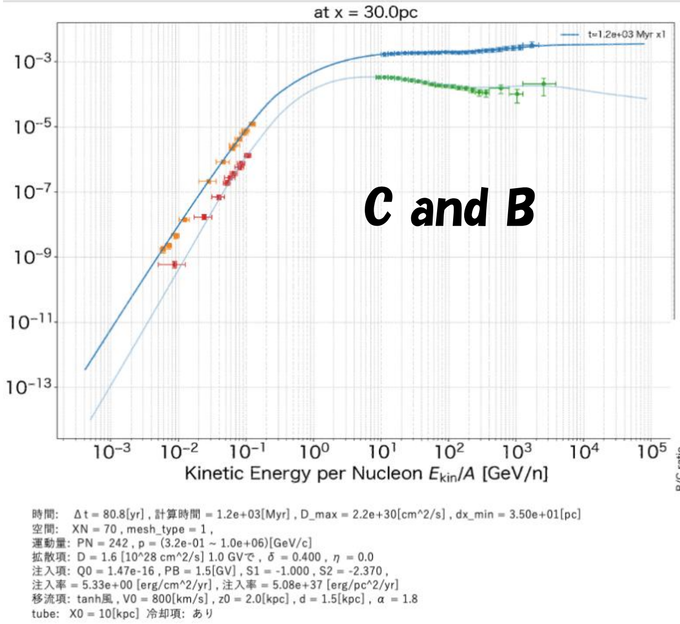
Diffusion VS Advection

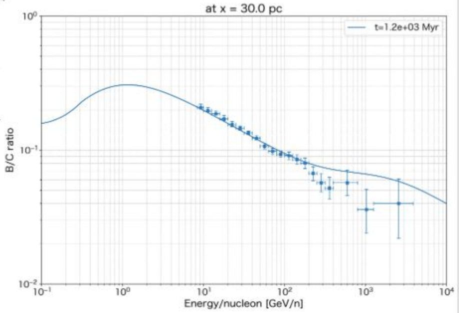


Taylor & Giacinti 17

Galactic wind modulates the CR spectra.
See Shimoda's talk



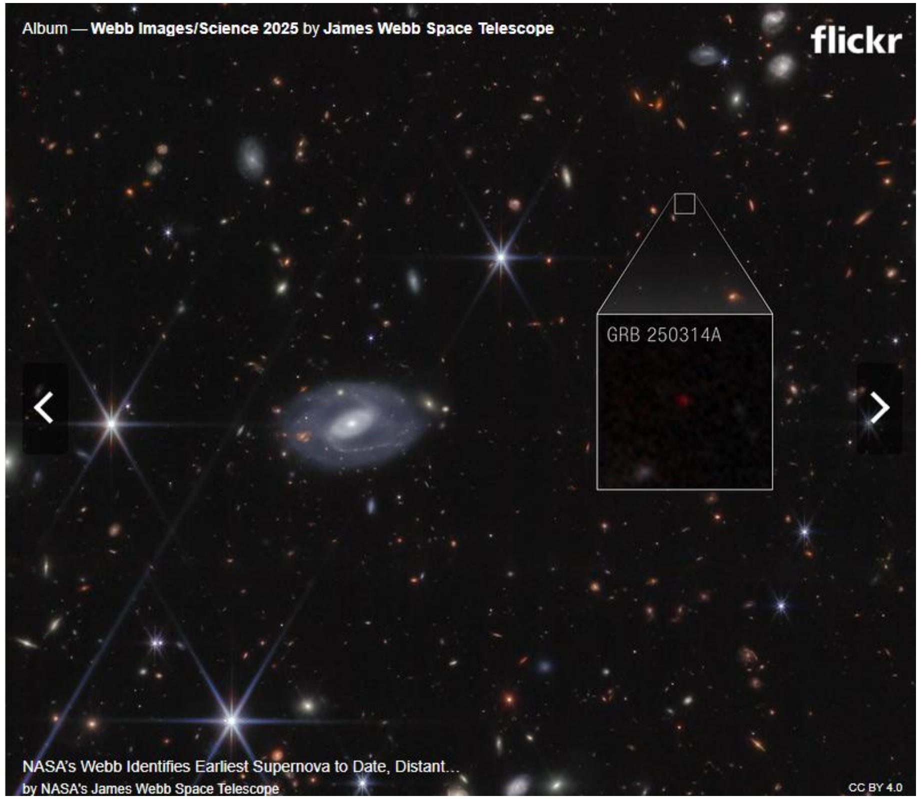


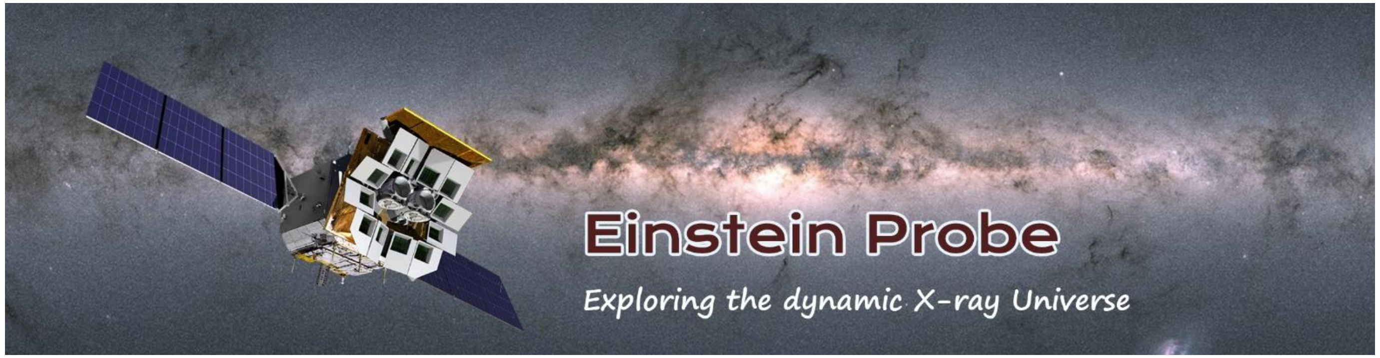


Fukumoto, KA+ in prep.

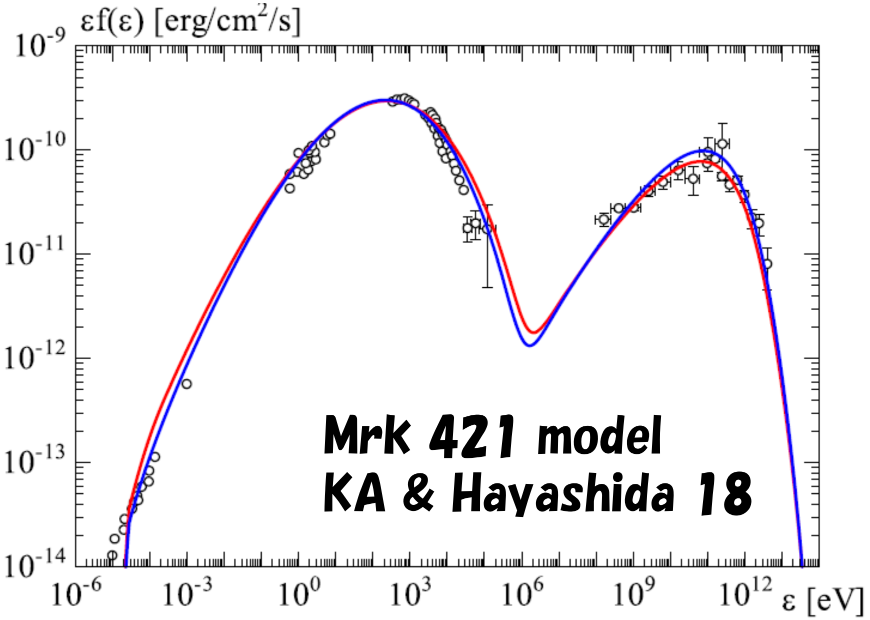
Extragalactic 3-4 talks

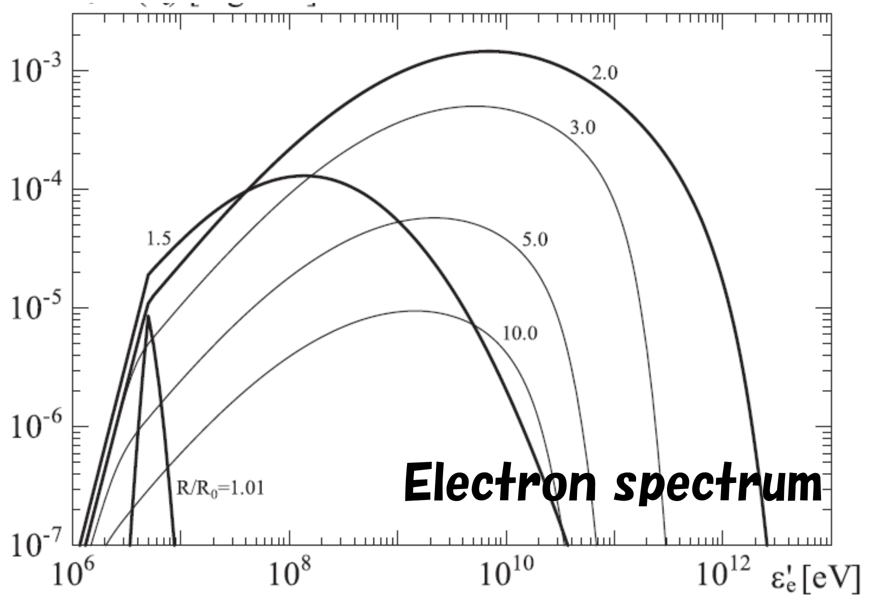
- Centaurus A by Koichiro Yasuda
- Nearby Seyfert galaxies by Yoshiyuki Inoue, Alexander Kusenko (maybe)
- Fornax galaxy cluster by Alvina On





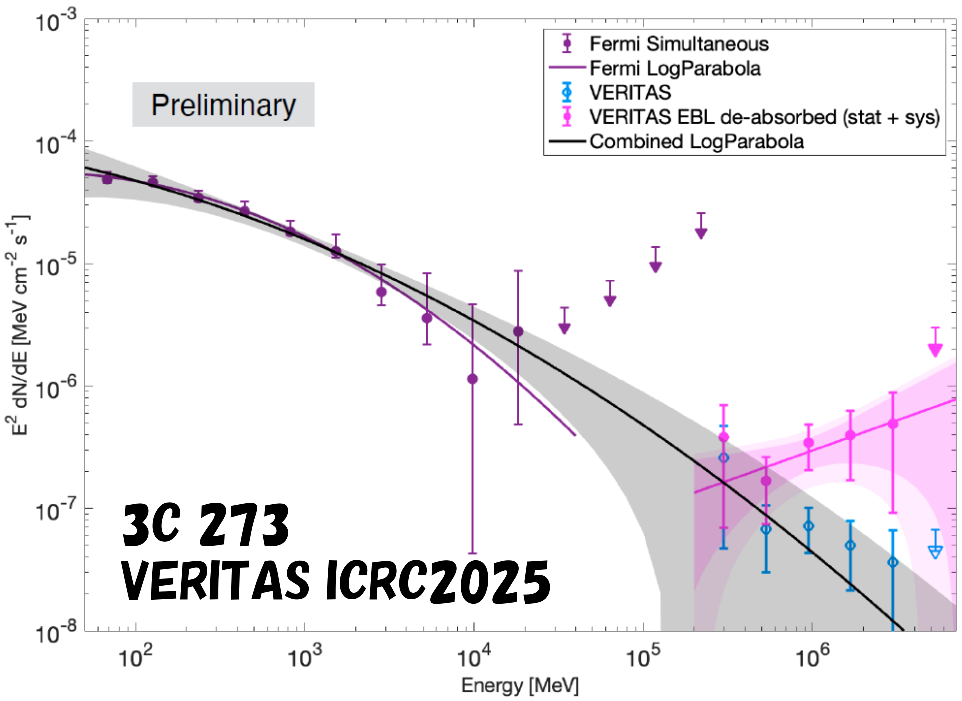
UHECR source: Not Blazar Region



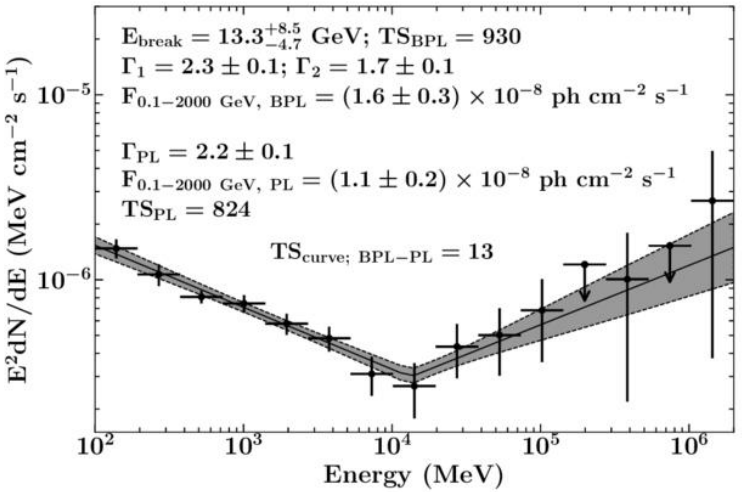


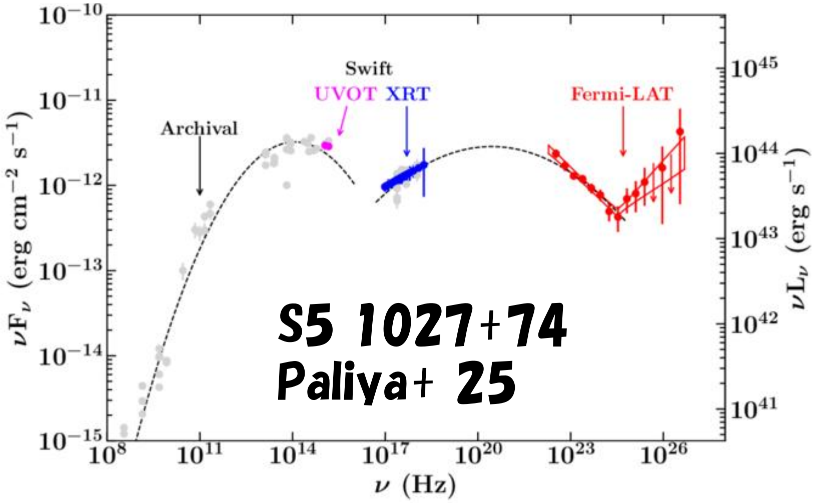
- Gamma-ray emitting region
- Curved spectra (not cooling break) in blazars suggest turbulent acceleration rather than a strong shock.
- Slow acceleration, suppressing maximum energy
- FSRQ brighter, softer, rarer (not compatible with dipole)
- Multiple zones?

TeV gamma from FSRQ

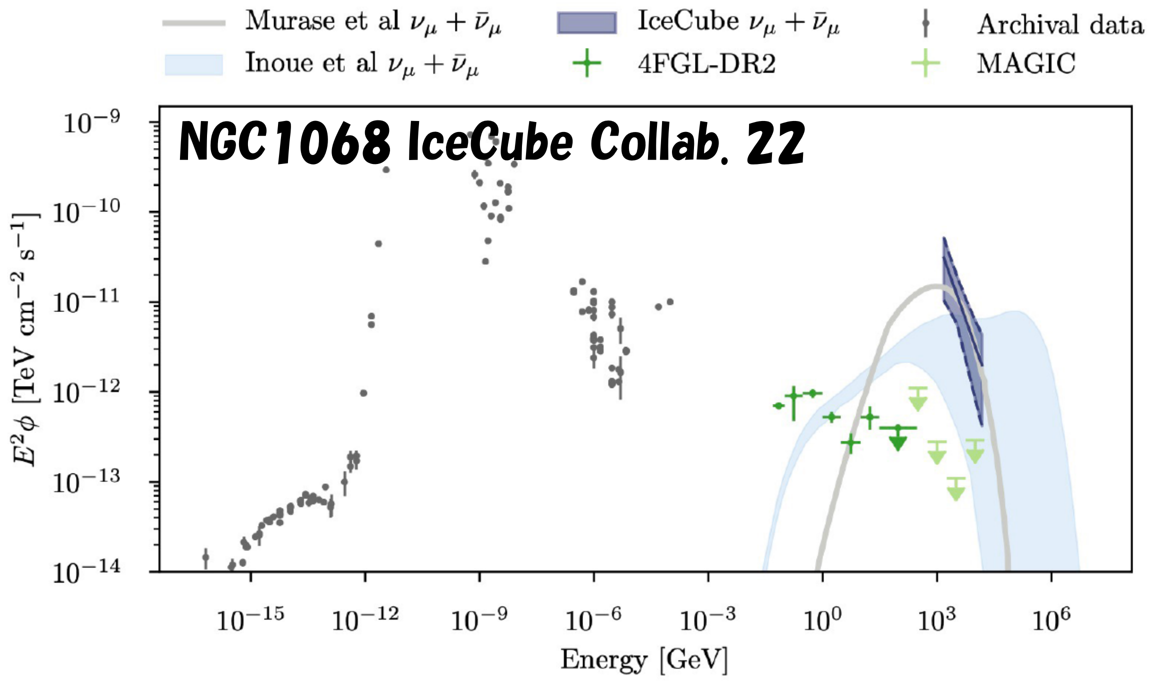


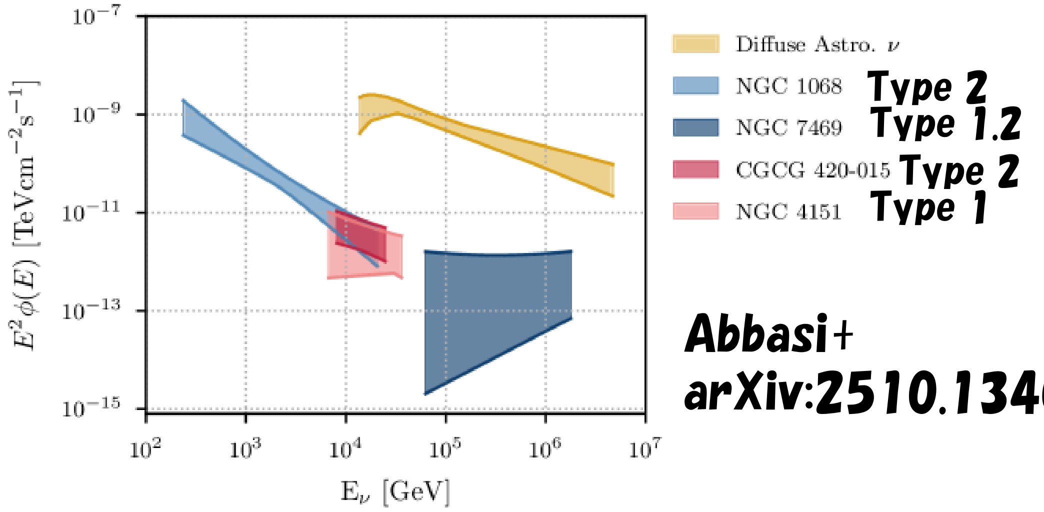
- Possible TeV detections from FSRQs
- Third component
- Probably a more extended emission region (no $\gamma-\gamma$ absorption)
- Likely leptonic (low density)
- UHECR source? But no smoking gun





Seyfert Galaxy: Neutrino Source





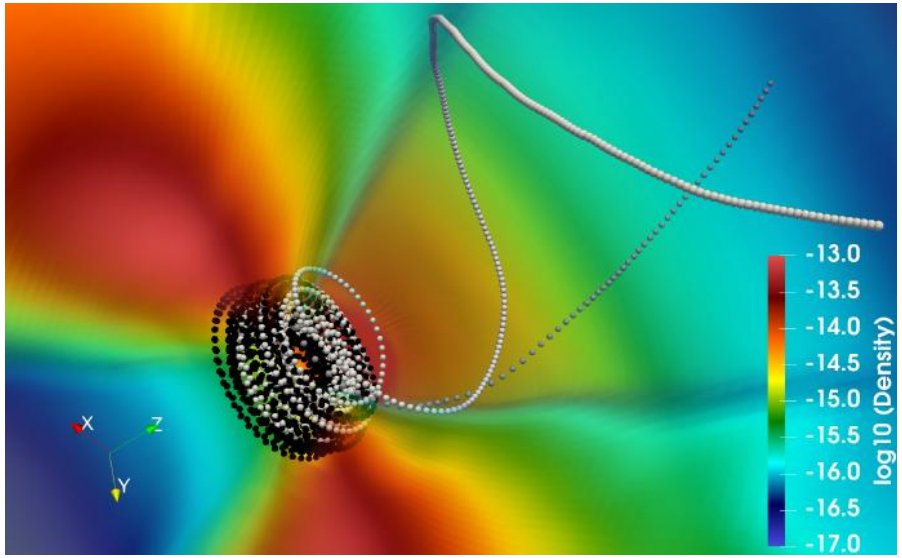
Abbasi+
arXiv:2510.13403

- Increasing significance of the neutrino signal
- **NGC 1068**: Soft spectrum, no TeV gamma implying compact source near SMBH
- Flat(?) spectra for other candidates, compatible with the diffuse neutrino background.

Skip this topic here, see Yoshida, Inoue

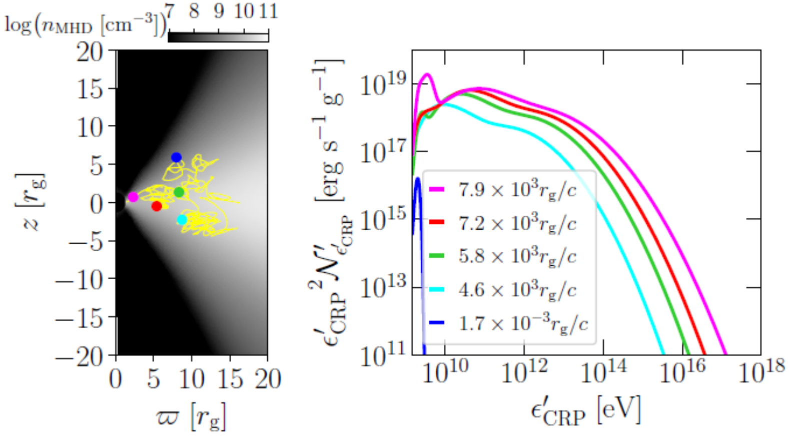
CR acceleration in accretion disks

Kawashima & KA 25
GRMHD sim.+Subgrid model of turbulence acc.

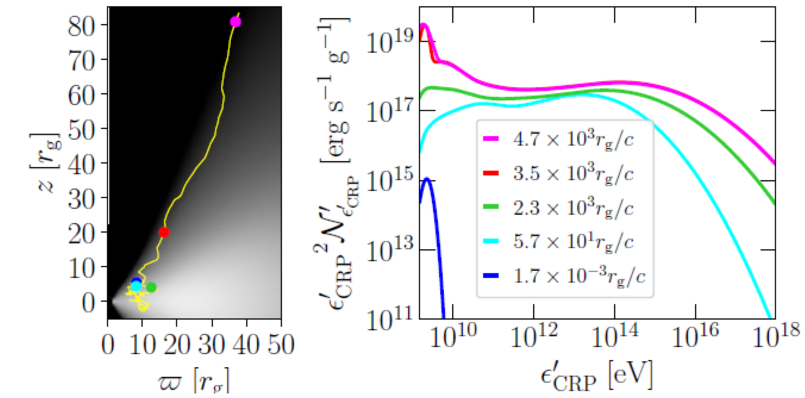


- Simulation data provide a degree of turbulence
- Follow trajectory of advected CRs
- Non-steady injection and acceleration resulting in softer spectra
- Wind with CRs, no distinction of Wind/corona

(a) Inflow CRP



(c) Ouflow CRP (It was inflowing in early phase)

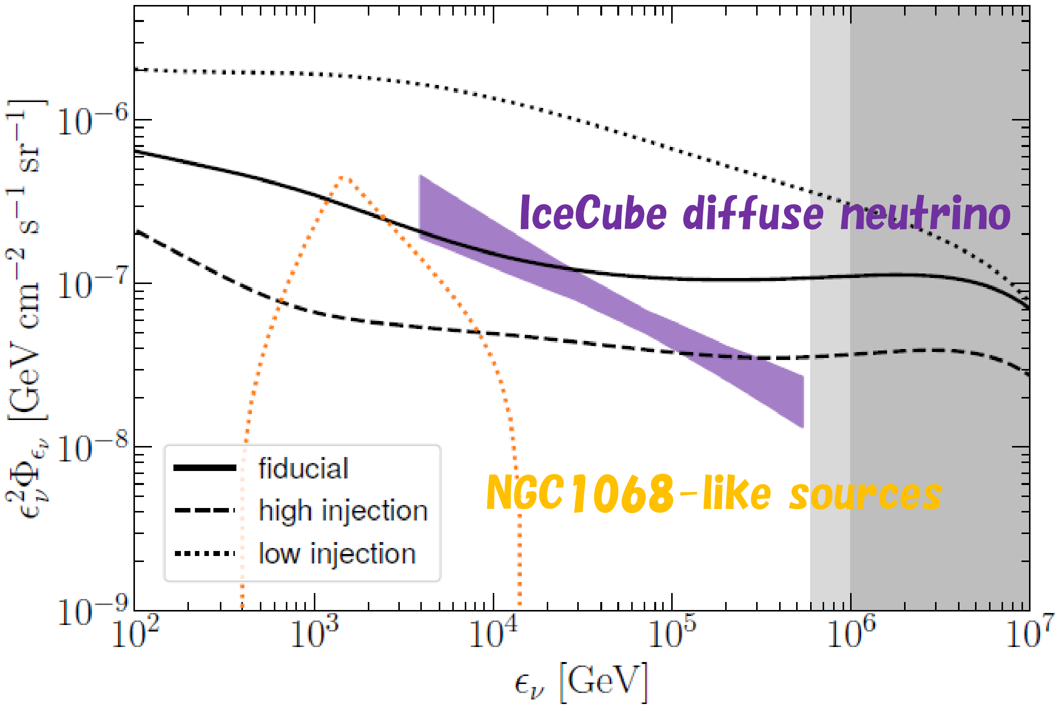


$$\frac{\partial \mathcal{N}'_{\rm CRP}(\epsilon'_{\rm CRP}, t')}{\partial t'} = \frac{\partial}{\partial \epsilon'_{\rm CRP}}\left[D(\epsilon'_{\rm CRP})\frac{\partial \mathcal{N}'_{\rm CRP}(\epsilon'_{\rm CRP}, t')}{\partial \epsilon'_{\rm CRP}}\right] - \frac{\partial}{\partial \epsilon'_{\rm CRP}}\left[\frac{2D(\epsilon'_{\rm CRP})}{\epsilon'_{\rm CRP}}\mathcal{N}'_{\rm CRP}(\epsilon'_{\rm CRP}, t')\right] + \dot{\mathcal{N}}'^{\rm comp}_{\rm CRP}(\epsilon'_{\rm CRP}, t') + \dot{\mathcal{N}}'^{\rm inj}_{\rm CRP}(\epsilon'_{\rm CRP}, t'),$$

See also Kimura+ 15, 19, 21etc.

Neutrino emission from the simulated disk

Kawashima & KA 25
Neutrino spectrum



LLAGN: Accretion rate ~10^{-2} Eddington
Mrk 421-like

NGC 1068-like sources
Accretion rate ~ Eddington

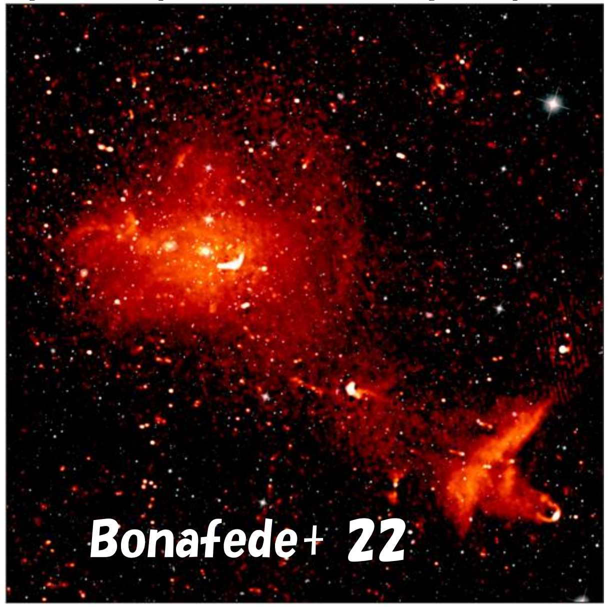
$\sim 5 \times 10^{-5}\ \mathrm{Mpc}^{-3}$

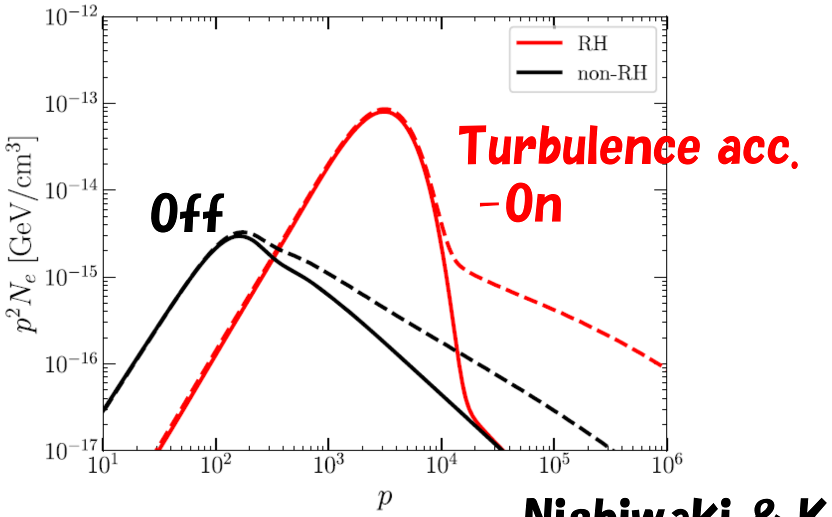
$L_{\rm bol} \sim 10^{45}\ \mathrm{erg\ s}^{-1}$

- Non-steady simulation can produce a hard neutrino spectrum even with turbulence acceleration
- A combination of Soft type + Hard type sources reproduces the IceCube diffuse spectrum
- CR luminosity $10^{43}\ \mathrm{erg\ s}^{-1}\left(\frac{M_{\rm BH}}{10^8 M_\odot}\right)\left(\frac{\dot{M}}{10^{-2} L_{\rm Edd}/c^2}\right)^2$ non-negligible contribution

Galaxy Cluster

IR (white) and radio (red) Image of Coma cluster



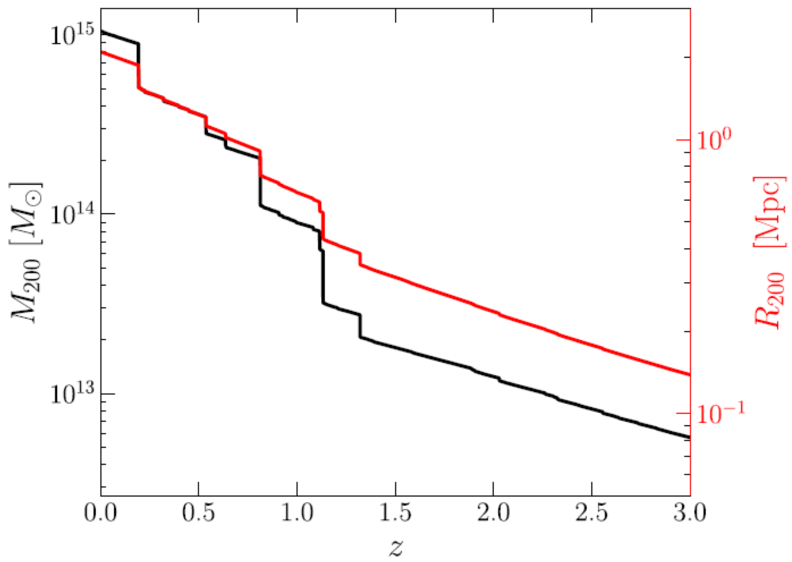


Nishiwaki & KA 25

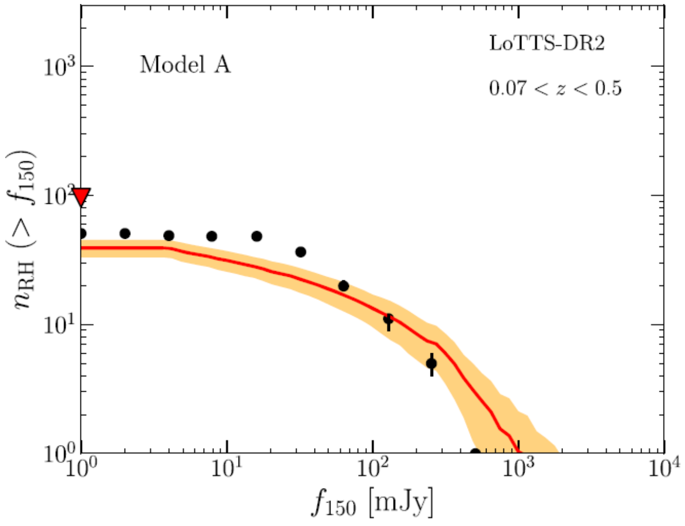
- Diffuse synchrotron emission
- Electron cooling time is short, requiring continuous acceleration.
- Major merger induces turbulence, which accelerates CRs in ICM
- Electrons may be hard to escape from source galaxies
- Secondary electrons from accelerated protons are likely.
- Possible GeV gamma-ray detection (Adam+ 21) suggests hadronic processes.

Cluster Statistics

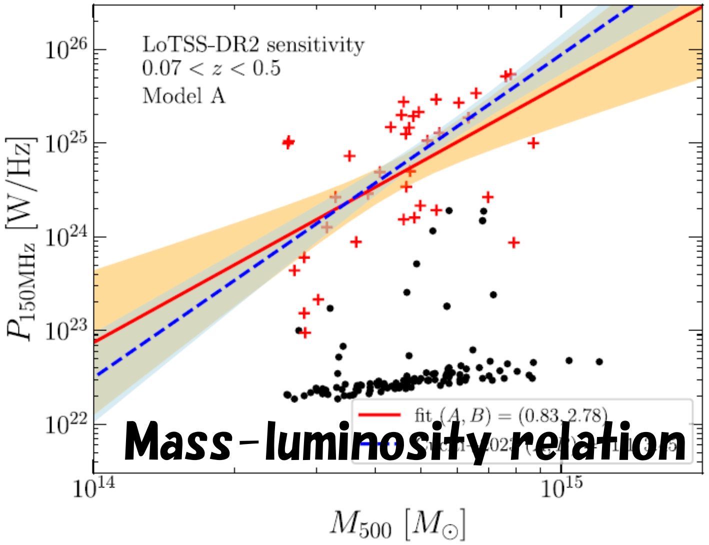
Cluster mass evolution

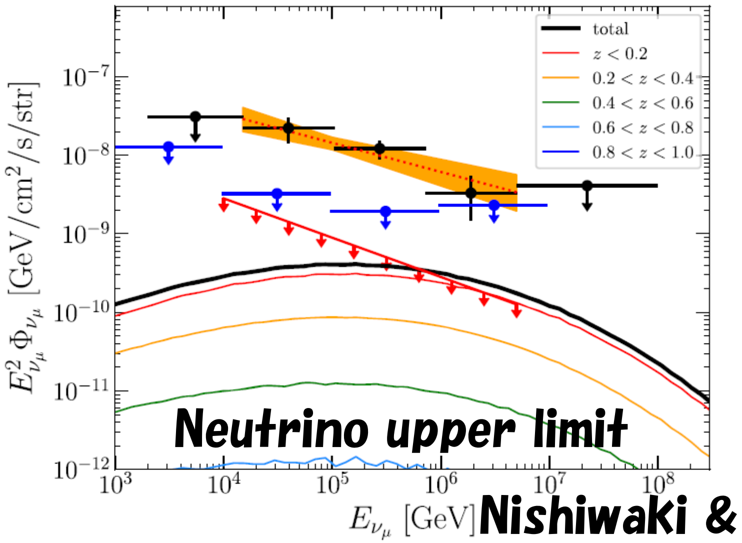


Radio halo LF



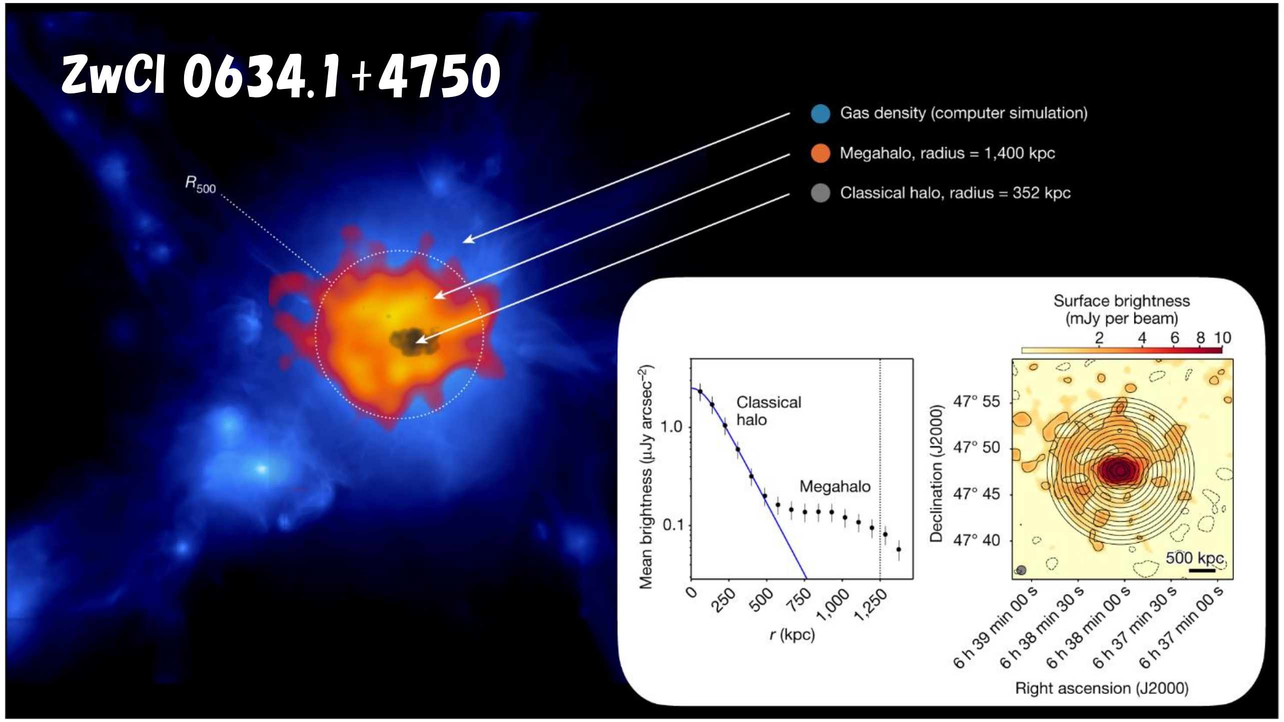
- Based on cosmological simulations, we follow the merger history of clusters.
- CRs are injected proportional to SFR.
- Finite periods of turbulence acceleration by mergers
- Reproducing the radial profile of Coma Radio Halo.
- Reproducing the radio LF and Mass-luminosity relation.
- Consistent with IceCube neutrino.
- Finally, parameters are determined.
- Obtained upper limit of CR injection $< 10^{41}$ erg s^{-1}





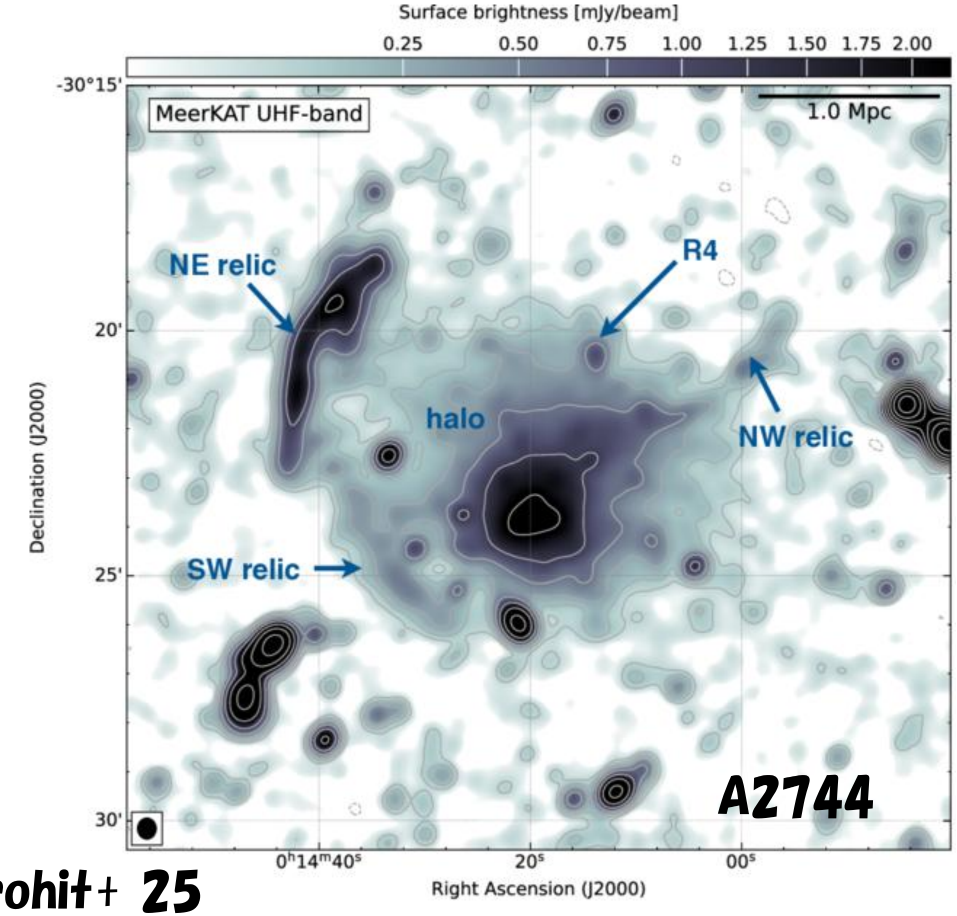
Nishiwaki & KA 25

Megahalo



Cuciti+22

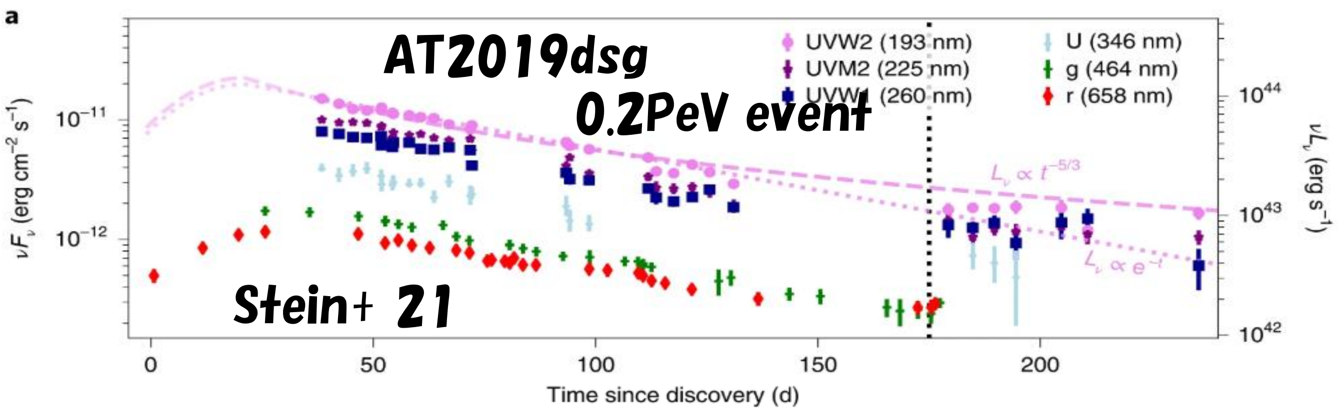
- Mpc extent of radio emission
- CRs exist far beyond radio halos.
- Secondary electrons?



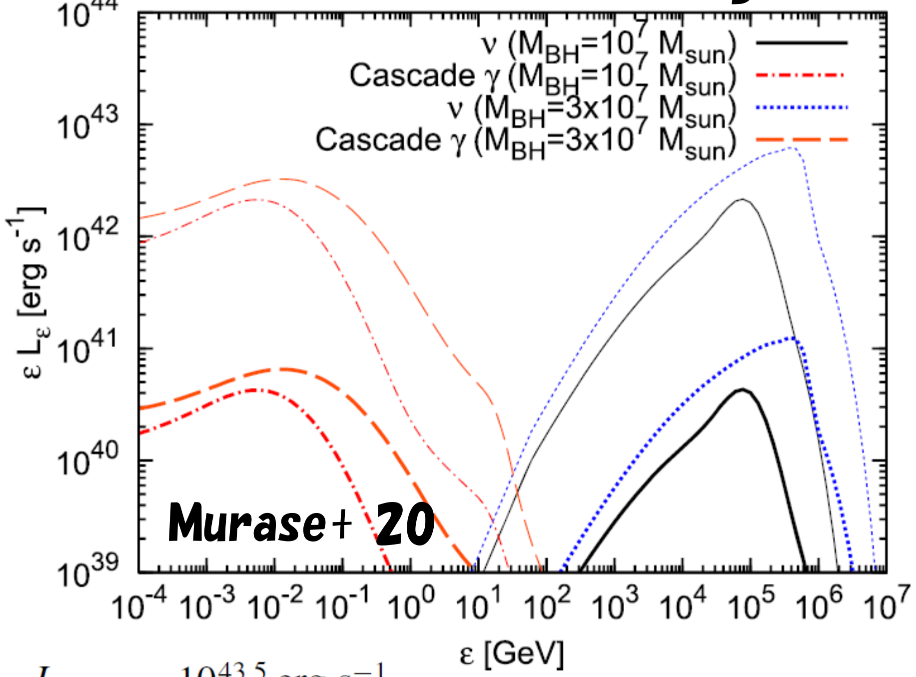
CR protons are not cooled.
Continuous injection of secondary electrons,
which is not favorable for classical radio halos
(Radio halo fraction becomes too large)

Rajpurohit+ 25

Tidal disruption events



TDE corona model for nu and gamma

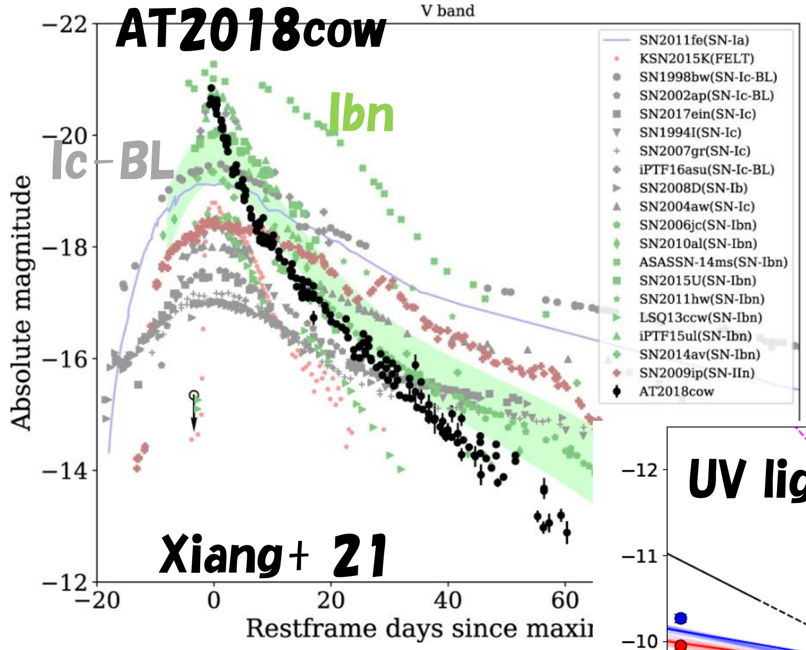


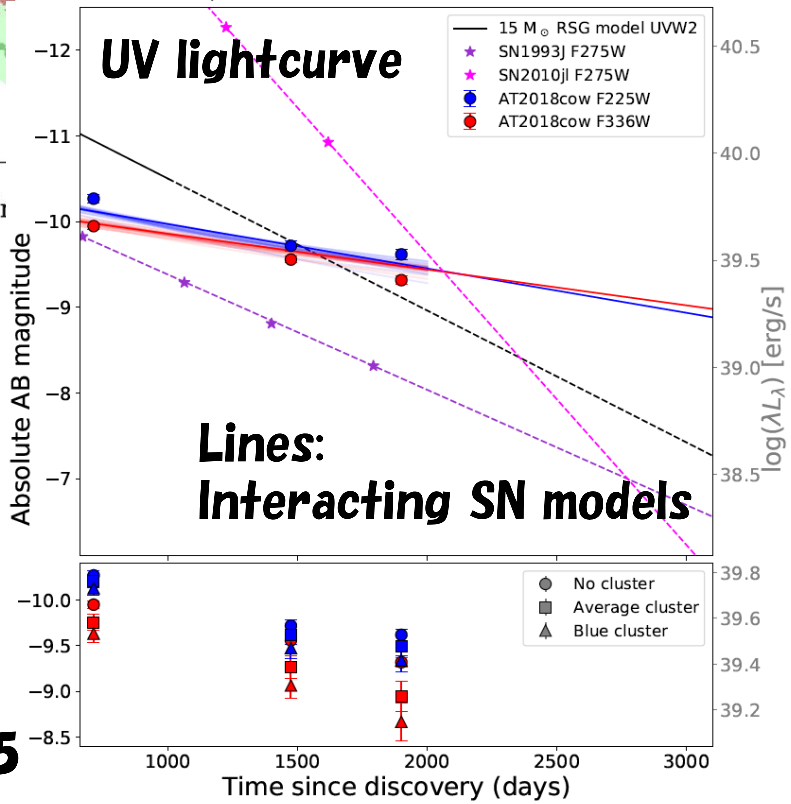
$L_{\rm disk} = L_{\rm OUV} = 10^{43.5}$ erg s^{-1}

- Tidal disruption of a star by SMBH
- Emission from accretion disk with $L \propto t^{-5/3}$
- Several reports of HE neutrino coincidence
- Model or energetics typically give 0.1-0.001 NU events
- TDE contribution to diffuse nu should be below 30% (Stein+19)
- Delayed activity in radio (jet? ~ 1000 days, AT2018hyz, Cendes+ 22)

$$E_\nu^2 \Phi_\nu \sim 1.7 \times 10^{-8}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}} \left(\frac{2K}{1+K}\right) f_{\rm mes} \times \left(\frac{\mathcal{E}_{\rm CR,51}}{\mathcal{R}_{\rm CR}}\right)\left(\frac{\xi_z}{0.5}\right)\left(\frac{\rho_{\rm TDE}}{10^2\ {\rm Gpc^{-3}\ yr^{-1}}}\right).$$

FBOT

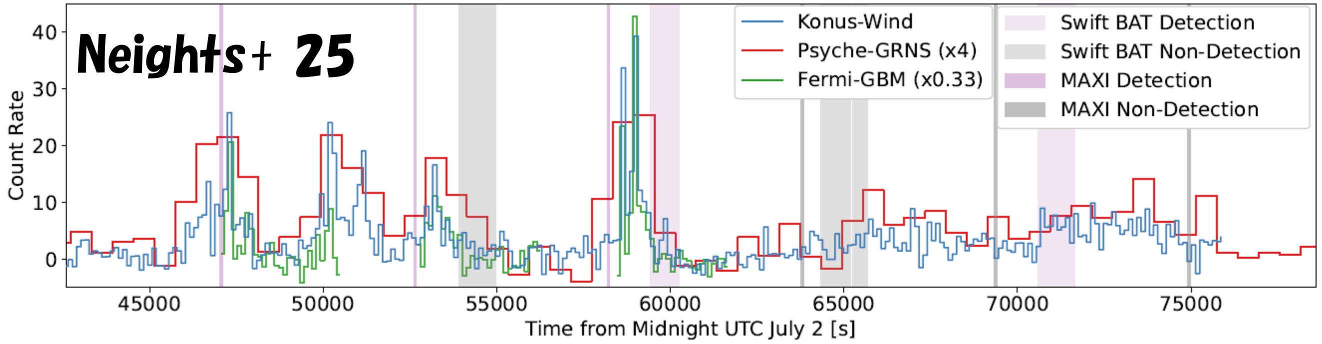


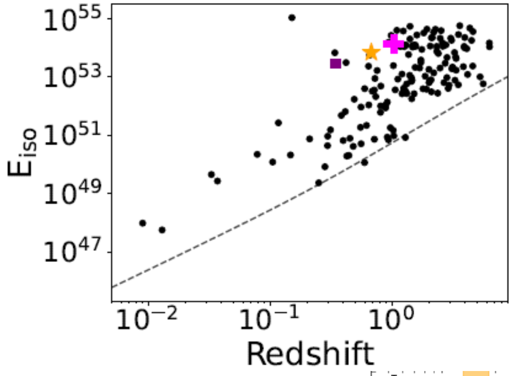


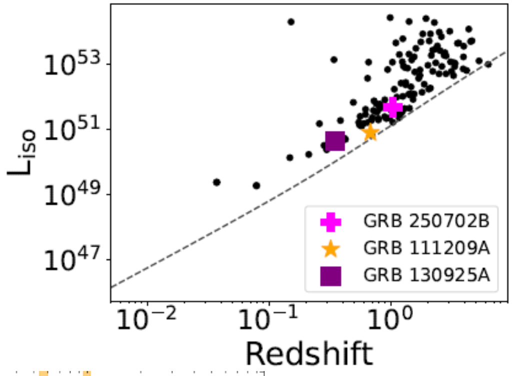
Inkenhaag+ 25

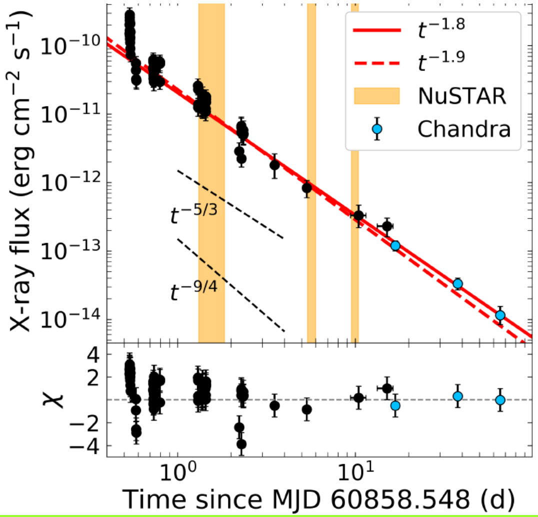
- ***Fast blue optical transient***
- ***Bright*** (*energetic*), ***steep*** (*low mass*) ***lightcurve***
- ***UV lightcurve: long-lasting, slow decay suggests TDE of white dwarf + intermediate mass BH?***

Ultra long GRB 250702B



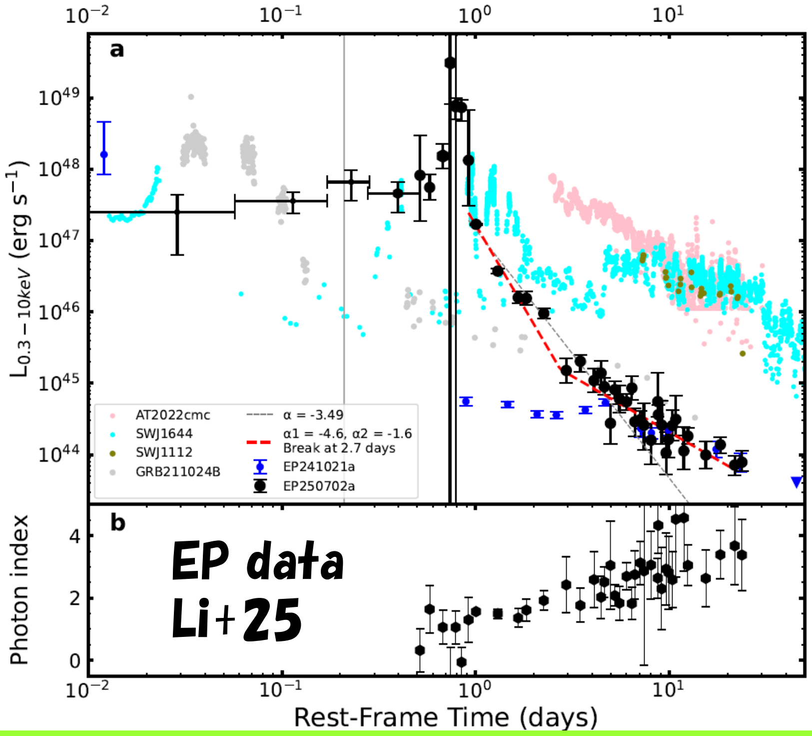




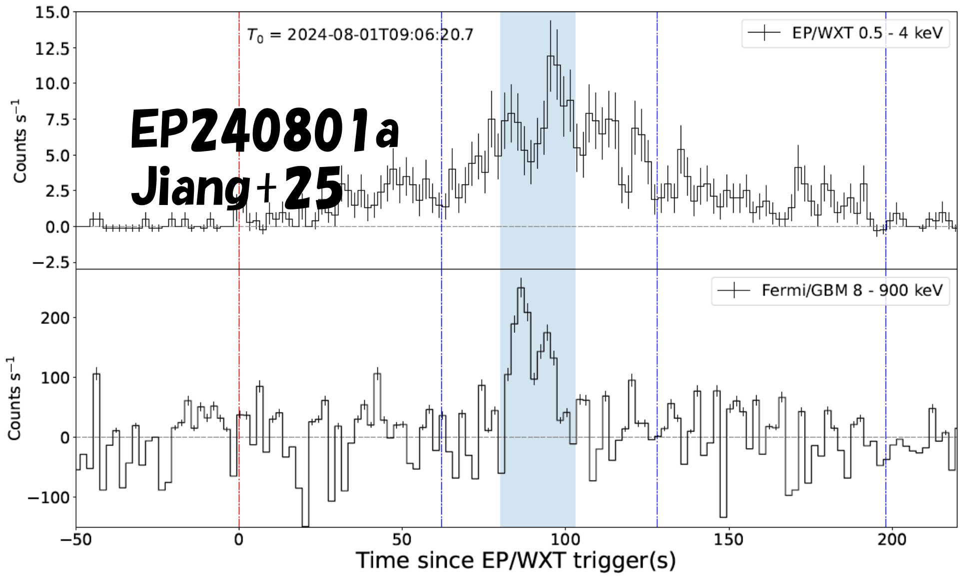


O' Connor+ 25

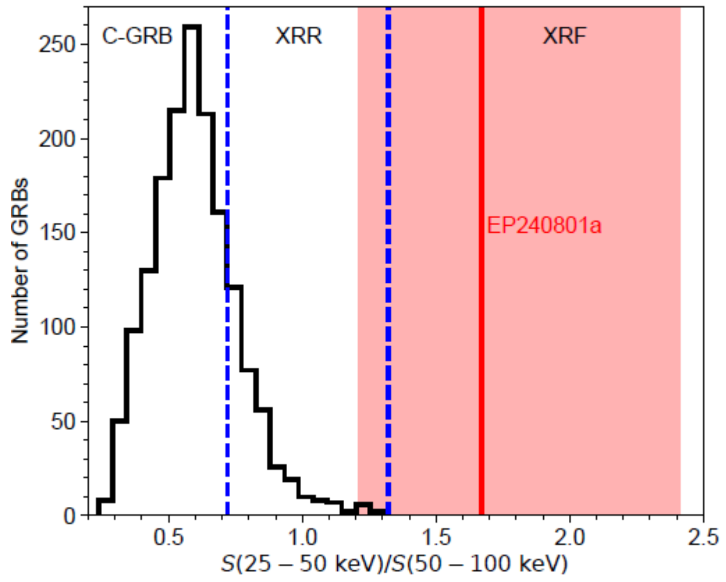
- 25000s duration
- X-ray precursor 1day before
- BH falling into a stripped star (Neights+ 25)?
- TDE of a white dwarf by an intermediate mass BH (Eyles-Ferris+ 25, O' Connor+ 25, Li+25)?

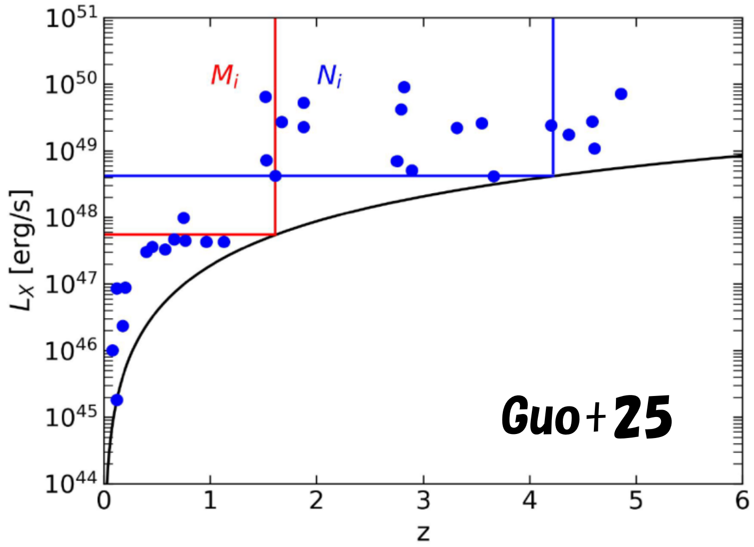


FXT with EP

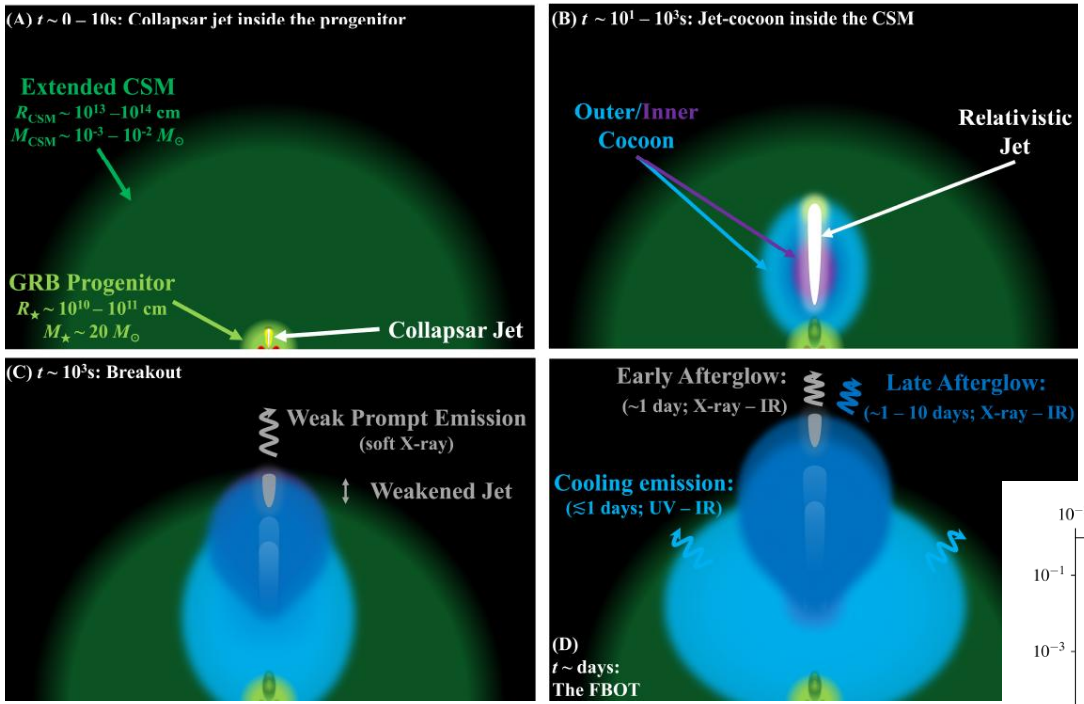


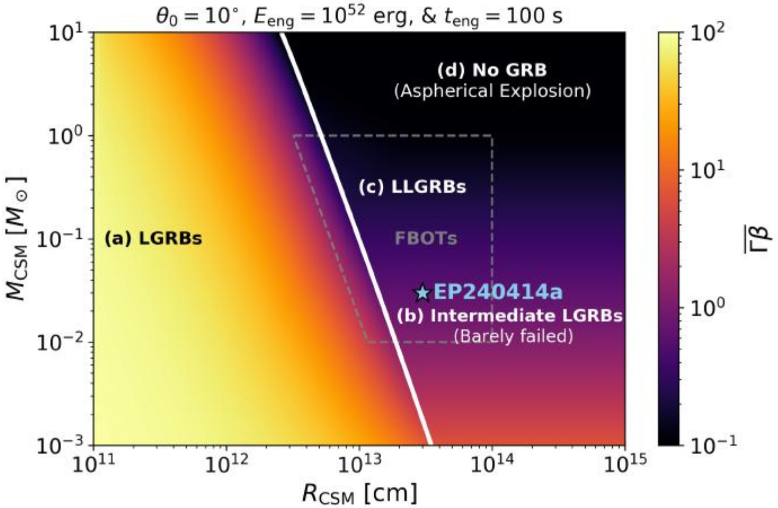
- Fast X-ray transients detected with Einstein Probe
- X-ray Flash (XRF)
- Minutes to hours
- Off-axis GRB?
- BNS mergers?
- EP250108a associated with a Ic-BL SN (Rastinejad+25)



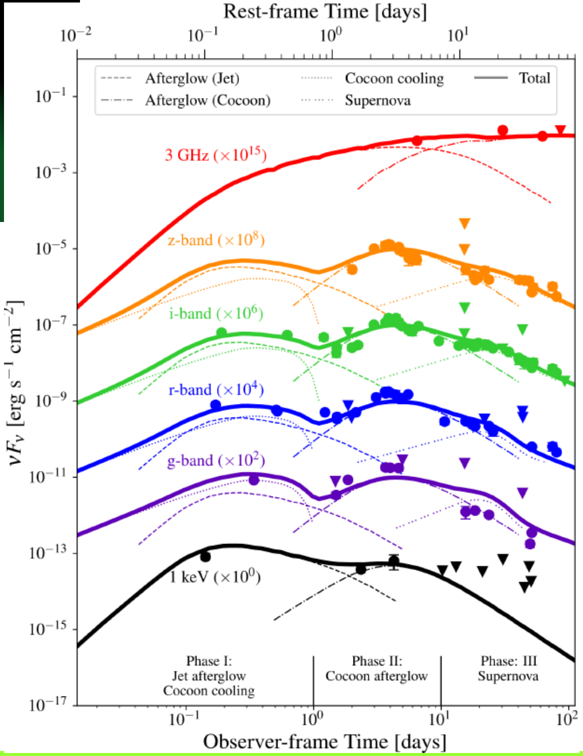


Unified model for GRB/FXT



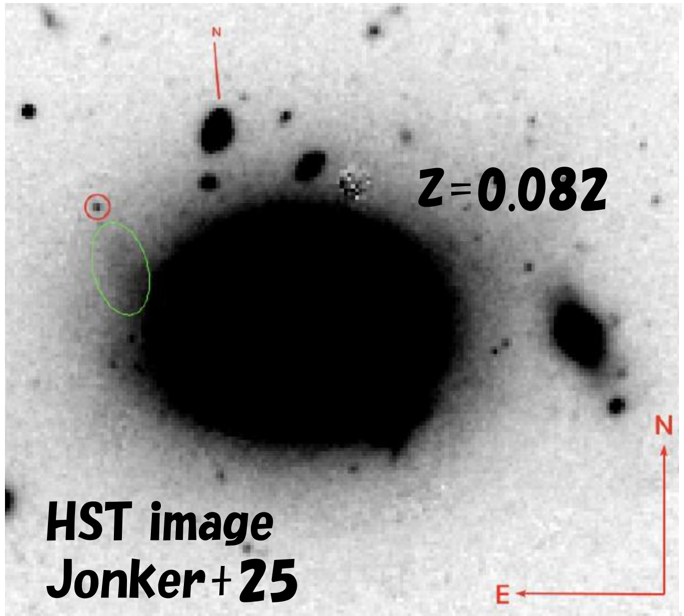


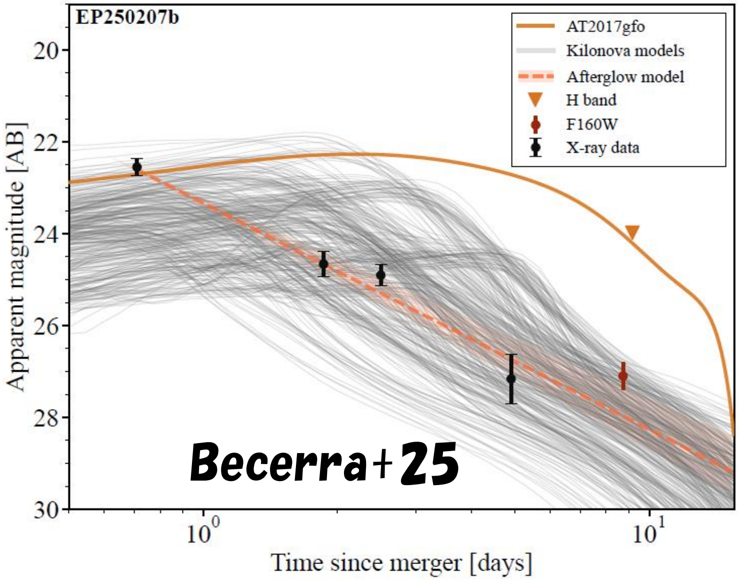
Hamidani+25



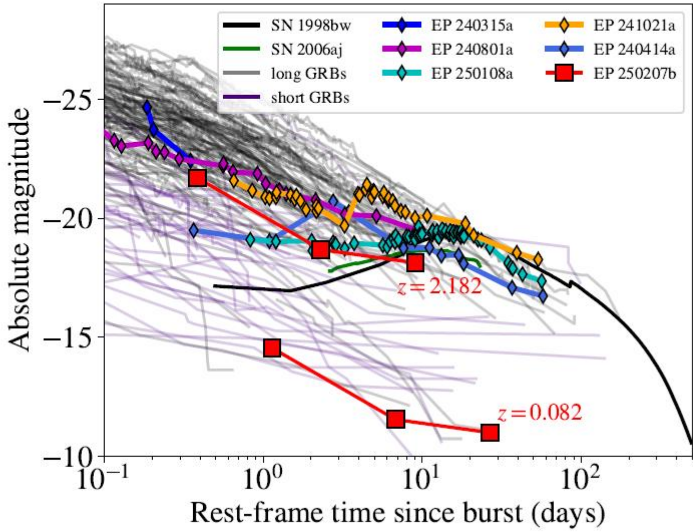
- Model for EP240414a
- Extended CSM
- Jets dissipate a fraction of energy in CSM, producing cocoons.
- Weak prompt
- Mildly relativistic jets produce slowly evolving afterglows
- Cooling cocoons emit late afterglow
- Depending on the CSM radius, we obtain GRB/XRF(Intermediate)/LLGRB

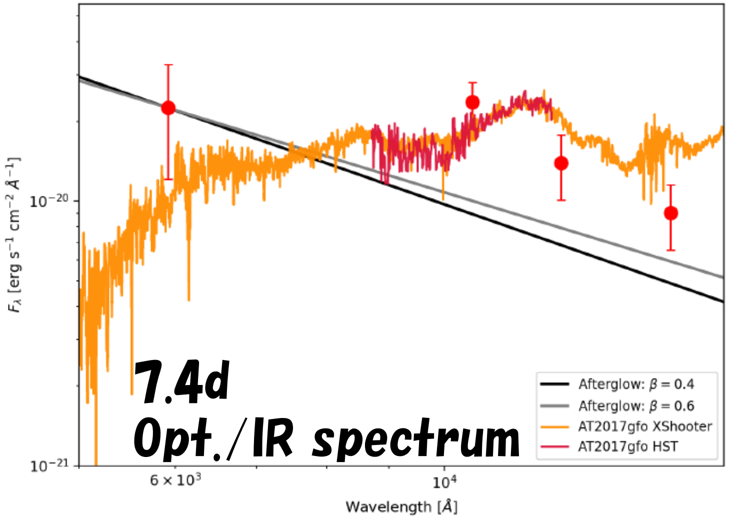
EP 250207b: BNS merger?



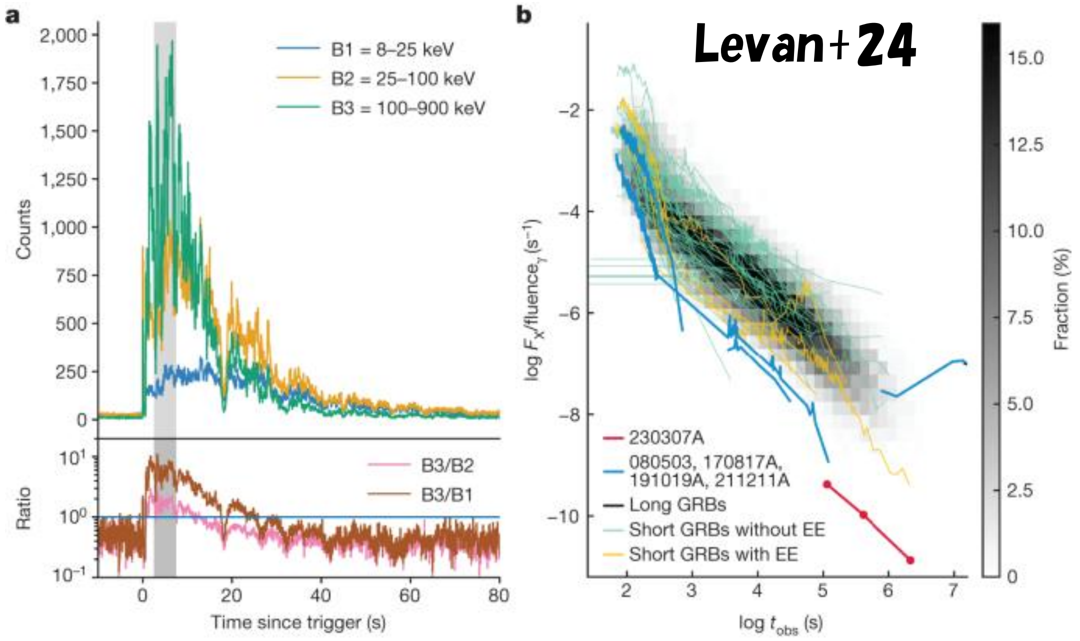


- z=0.082
- No SN emission
- Lightcurve and spectrum are consistent with the kilonova model
- Cannot rule out SN at z>1

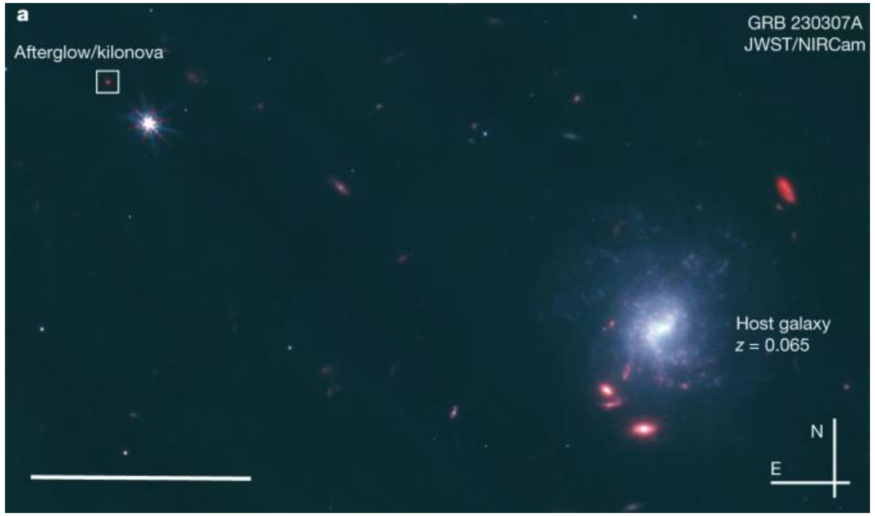


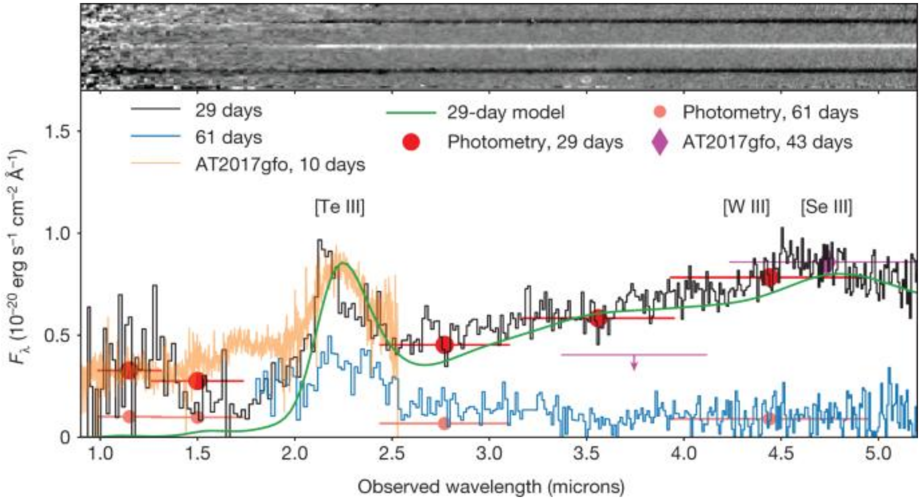


Long GRB from BNS? GRB 230307A

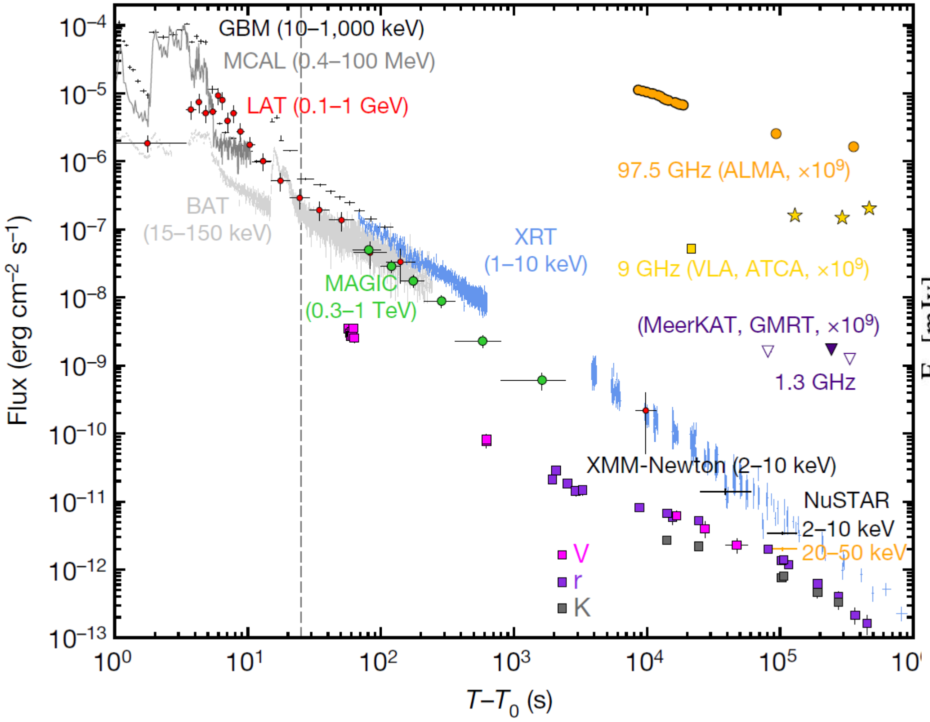


- E_{iso}=4.8×10^{52}erg (Moradi+24)
- Dim and red afterglow
- Lightcurve and spectrum are consistent with the Kilonova AT2017
- r-process nuclei Te line detected with JWST
- NS-WD merger (Wang+24, Chrimes+25)?

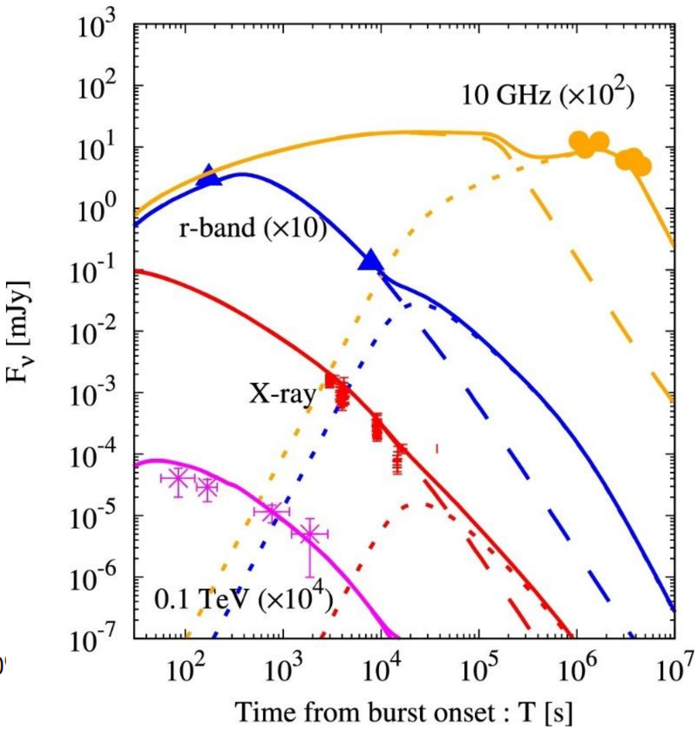




GRB afterglow: Recent progress



GRB 190114C
MAGIC Collab. 2019



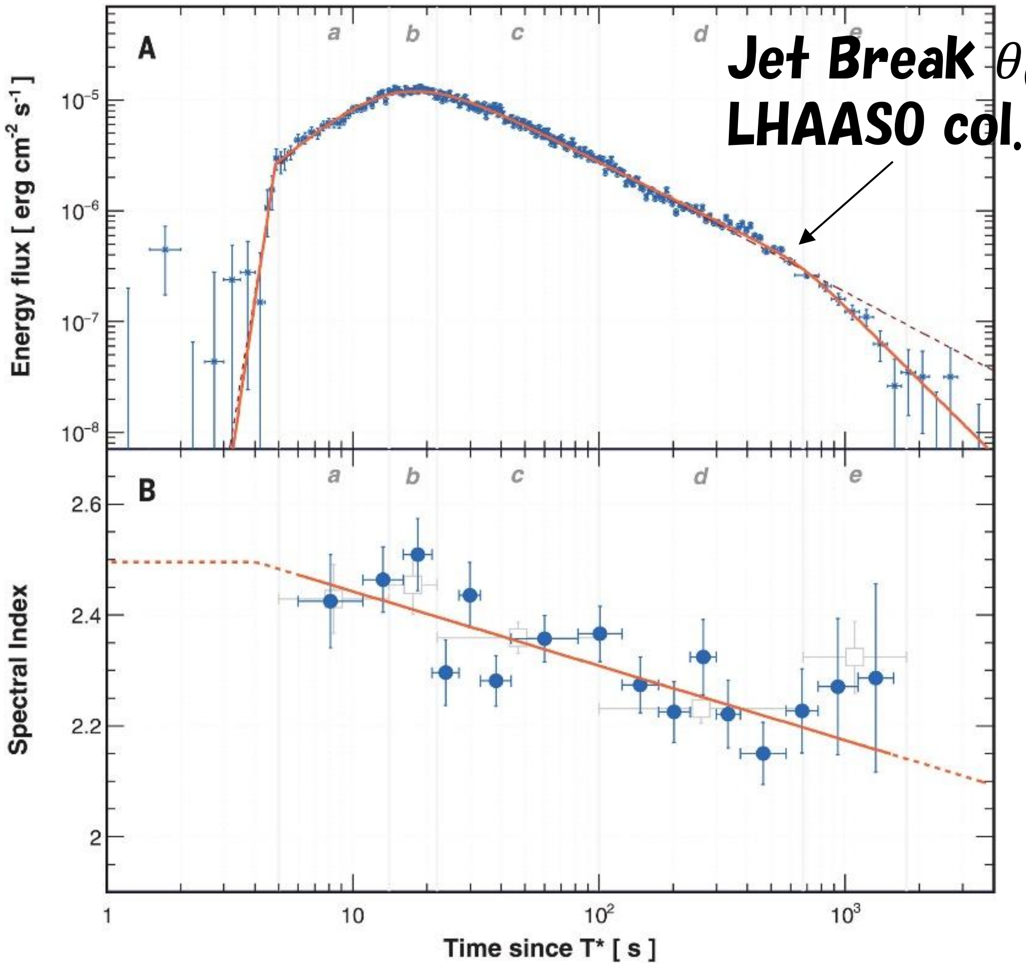
GRB 201216C
Sato+ 25

Wide: $0.1\text{rad}, \Gamma_0 = 20, E_{\text{iso}} = 10^{53}\text{erg},$
$\epsilon_e = 0.1, p = 2.8$

Narrow: $0.015\text{rad}, \Gamma_0 = 350,$
$E_{\text{iso}} = 4 \times 10^{53}\text{erg}, \epsilon_e = 0.035, p = 2.3$

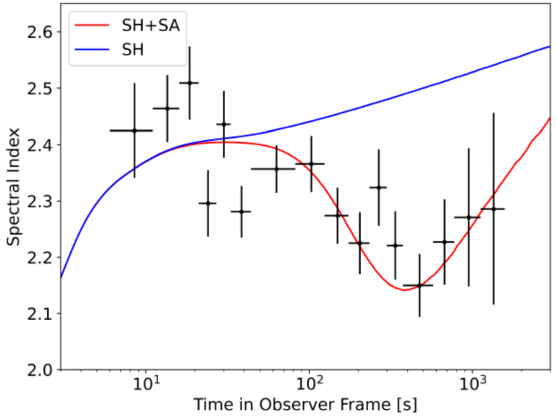
- *Decelerating shock propagating in CSM*
- *TeV afterglow samples are increasing*
- *Synchrotron + Inverse Compton*
- *Variation in microscopic parameters:* $\epsilon_e, \epsilon_B, p$
- *Parameters are constant?*
- *Two-component model: Wide+Narrow jet→break*
- *Main characters change between the early and late phases*
- *Equivalent to parameter evolution?*

BOAT GRB: 221009A



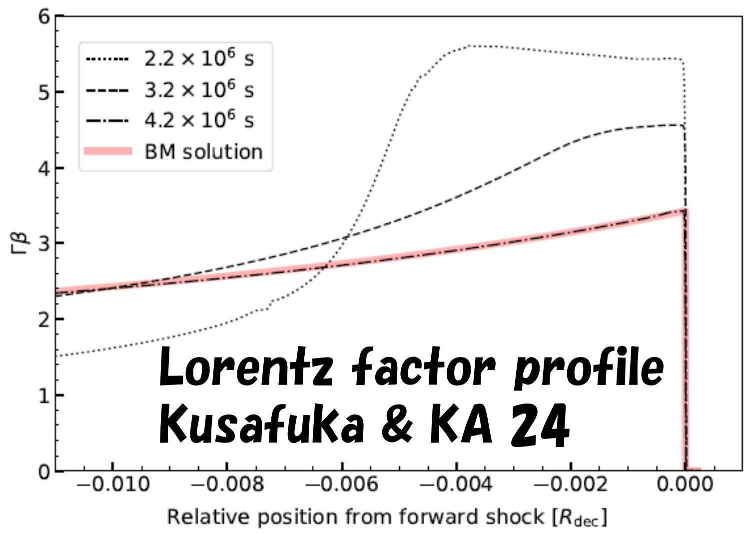
Jet Break $\theta_0 = 0.8°$
LHAASO col. 23

- TeV afterglow detected with LHAASO
- Extremely bright $E_{\rm iso} = 2 \times 10^{55}$erg
- Early jet break suggests a narrow jet with $\theta_0 = 0.8°$(0.014rad)
- On-axis probability $\sim 10^{-4}$
- Typical jet opening angle is $2.5°$(Wang+ 18)
- Late-time hardening (turbulence acceleration?)

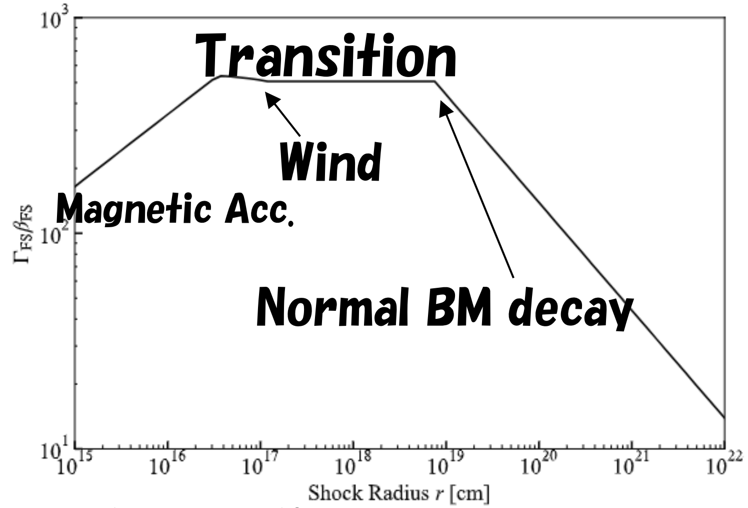


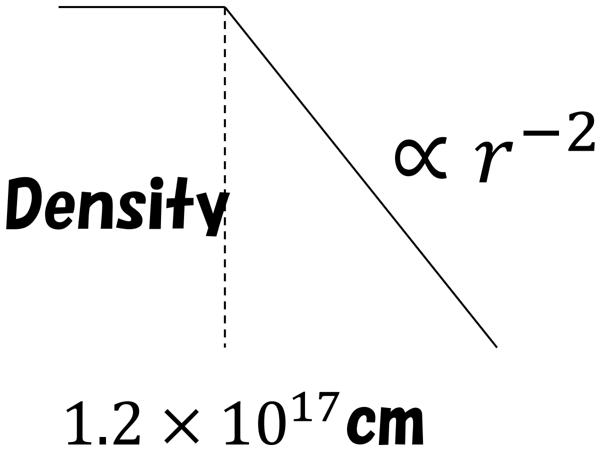
Gong, KA+ 25

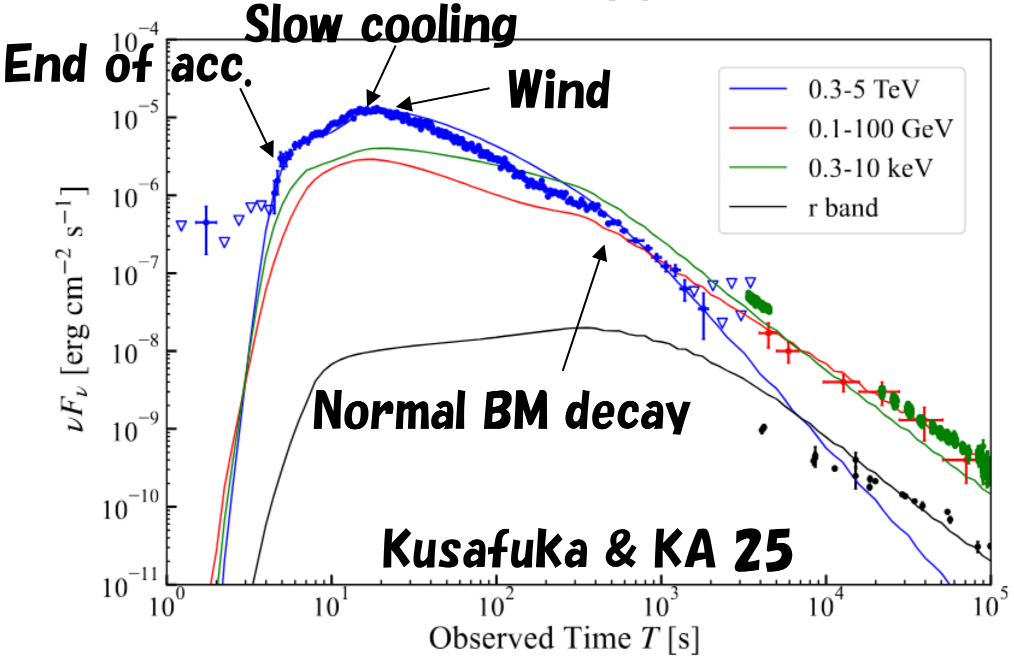
New model for BOAT GRB



Lorentz factor evolution

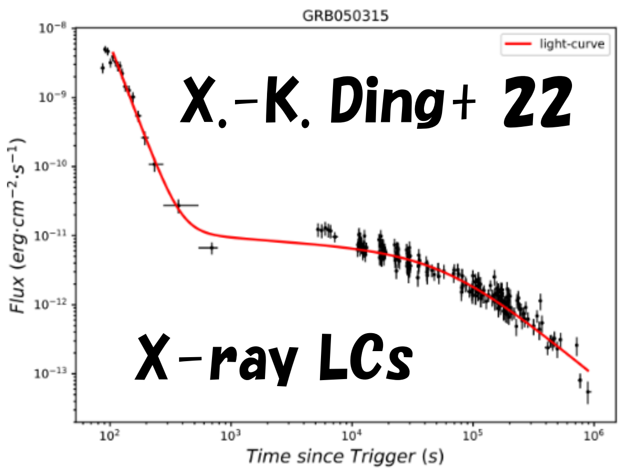


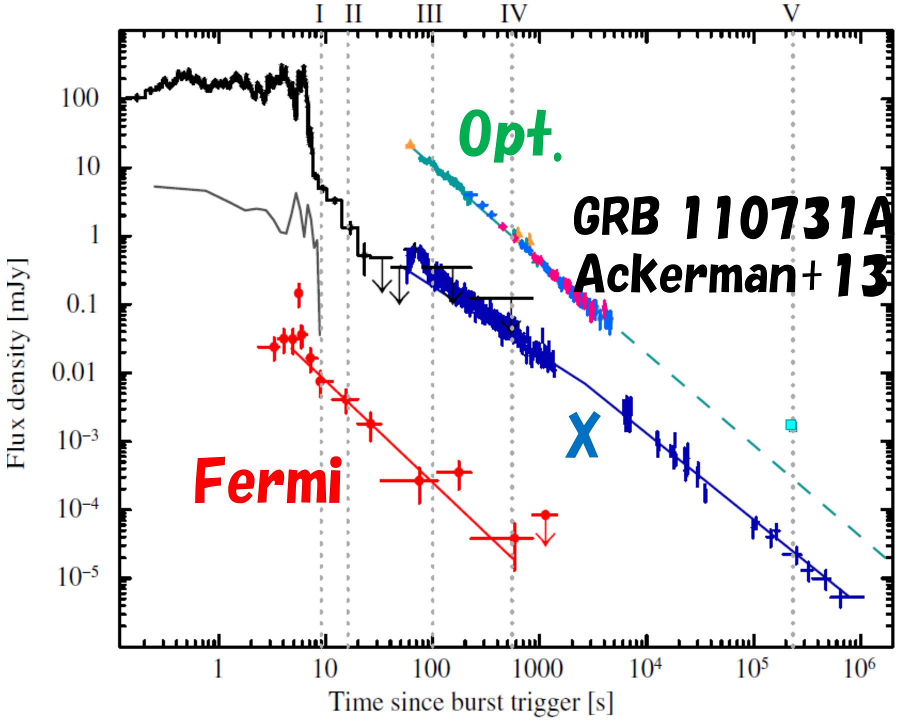




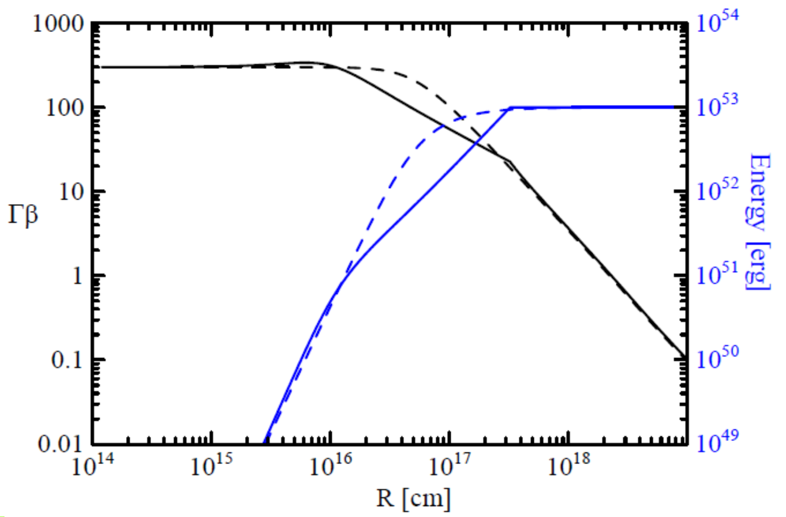
- Single component
- Initially jet is accelerating by magnetic force
- Consistent with the early increase
- Finite thickness of the ejecta→transition phase
- Flat density to wind density
- Late phase: Self-similar BM solution
- Jet opening angle is >1.7 degree

Shallow Decay Phase



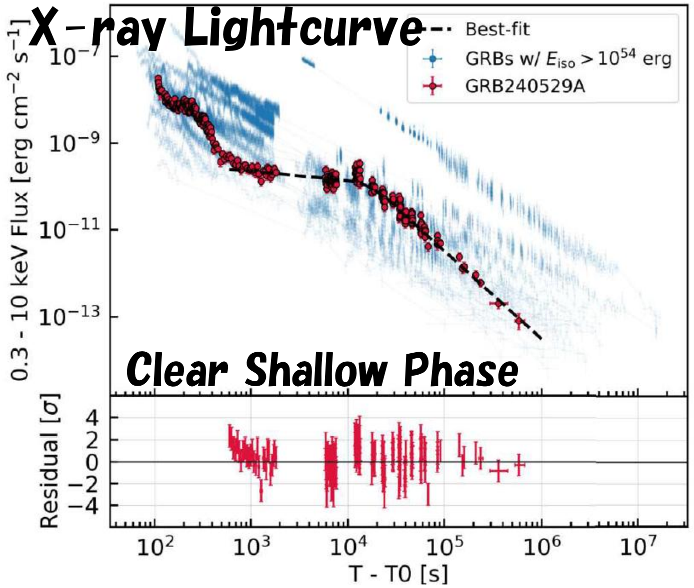


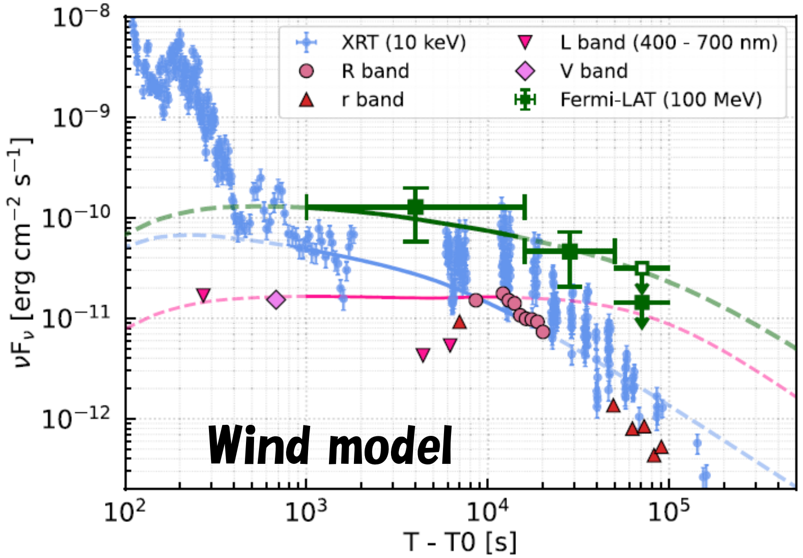
- Flat First 3000s
- Continuous energy injection may hinder deceleration
- Alternative: Slow($\Gamma_0 \sim 30$) ejecta in wind profile (Dereli-Bégué +22)
- This leads to a delayed onset of deceleration.
- Fermi-LAT GRBs tend to show no shallow decay (Yamazaki+20)

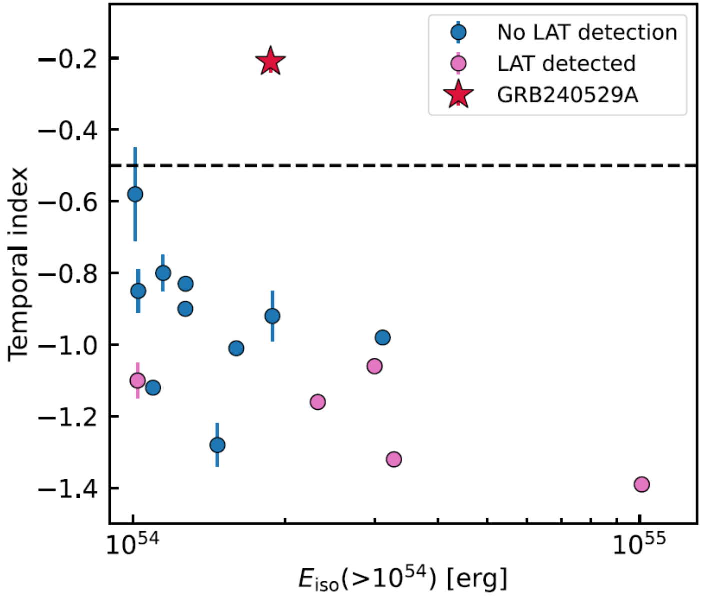


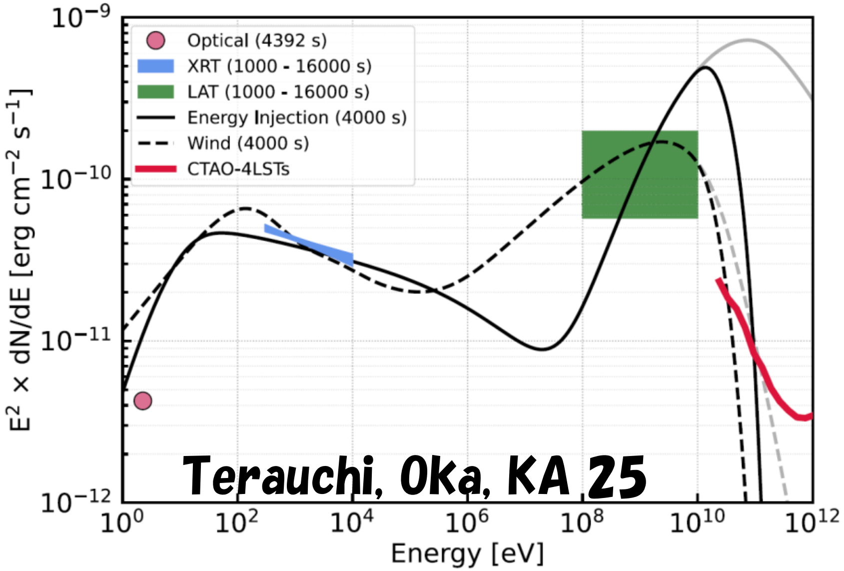
Energy Injection
Asano 24

Fermi GRB 240529A with shallow decay









- **Shallow decay with GeV detection: very rare**
- **Energy injection model (high Γ) is too hard in GeV, too bright in TeV**
- **Wind model**

$$\Gamma_0 = 30 \qquad E_0 = 10^{55}\,\mathrm{erg}$$

Summary

- Stay tuned for talks on Galactic phenomena
- TeV component in FSRQ: another CR acceleration site
- Seyfert galaxies as neutrino sources (disk/corona CR acceleration)
- Enigmatic electron injection in galaxy clusters
- Various TDE events (FBOT, ultra-long GRB, WD)
- FXT with EP: Kind of GRB? BNS merger?
- GeV-TeV GRB afterglow: not so simple (CSM, ejecta thickness, magnetization)
- Cosmological evolution of HE events

BBH merger rate following SFR