ICRR
Institute for Cosmic Ray Research
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Recent developments in studies of extragalactic high-energy phenomena

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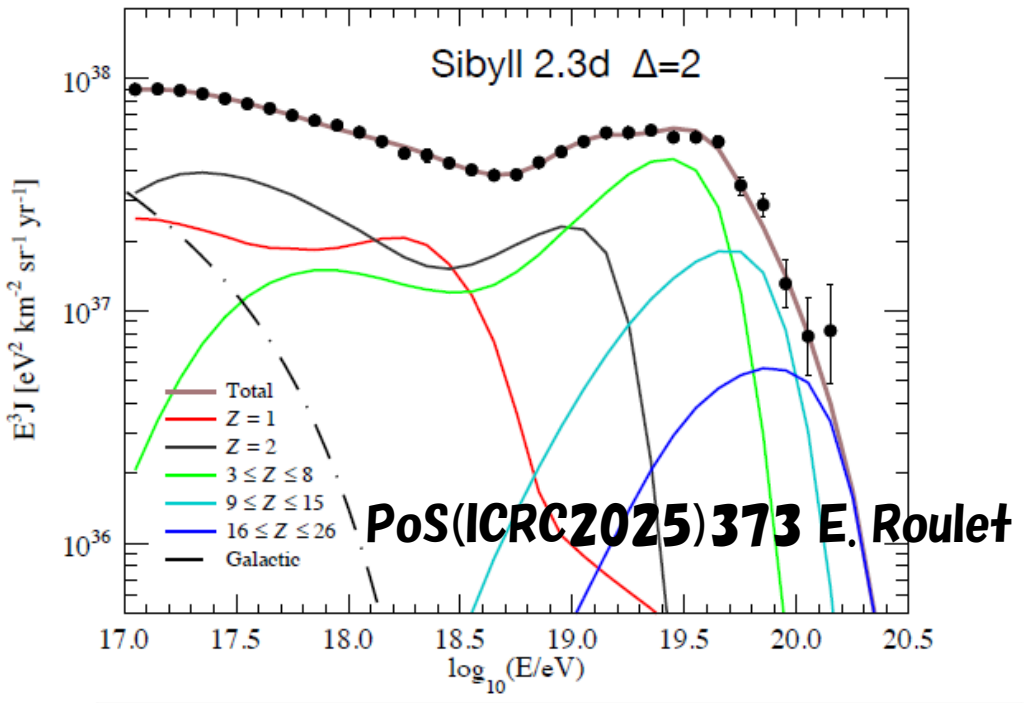
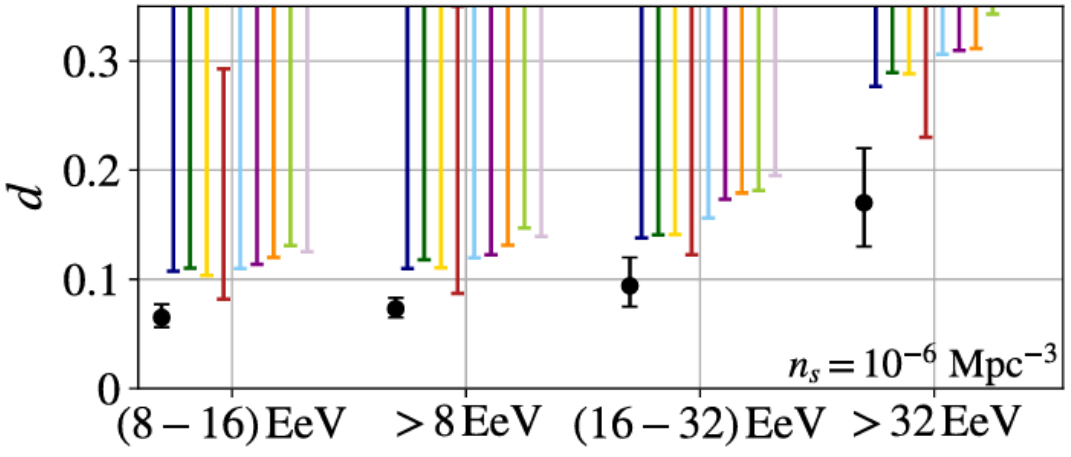
Key Questions in Extragalactic High Energy Phenomena

- **Astroparticle**
  - Ultra-High-Energy Cosmic Rays (Sources, Composition, Acceleration Mechanism)
  - High-Energy Neutrinos (Sources, Seed CRs, Hint for UHECRs?)
  - Gamma-Rays (Leptonic/Hadronic, Acceleration Mechanism, Hint for CR sources)
- **HE Objects**
  - Steady objects: AGNi (Blazars), Star Forming Galaxies, Galaxy Clusters
    - Accretion Disk, Jet, CR Production, ISM, Star Formation History
  - Transients: SNe (SLSN, FBOT…), GRBs, Tidal Disruption, BNS merger, FRB
- **Cosmological History**
  - Evolutions of CR production, Luminosity Function, Event Rate

Ultra-High-Energy Cosmic Rays



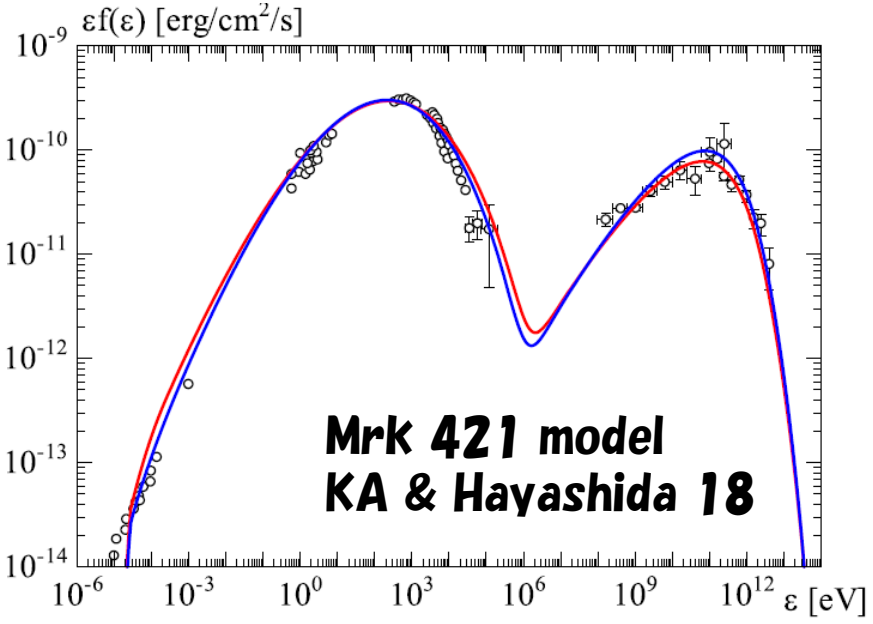
PoS(ICRC2025)373 E. Roulet

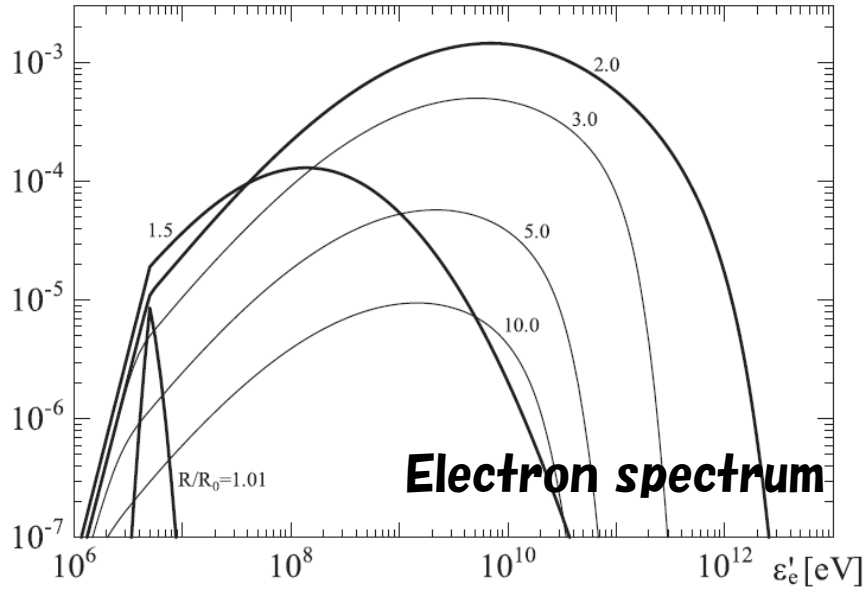


Bister+ 24

- Extragalactic origin
- Likely CNO-dominated
- Amaterasu event (TA 23, 244EeV <10Mpc) from void region
- AGN correlation (TA+Auger): 3.3 σ
- Starburst gal correlation: 4.2 σ
- Just following large-scale structure
- Dipole anisotropy suggests $n \sim (10^{-3} - 10^{-5})$ Mpc^{-3}
- Excluding high-luminosity AGNs (10^{-6} Mpc^{-3})

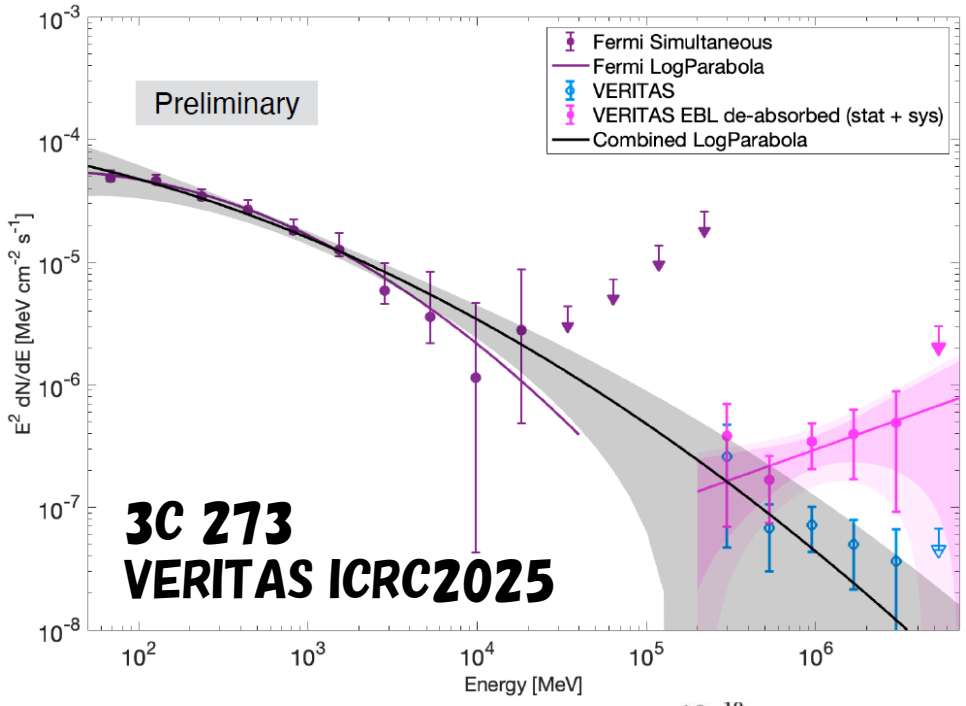
UHECR source: Not Blazar Region



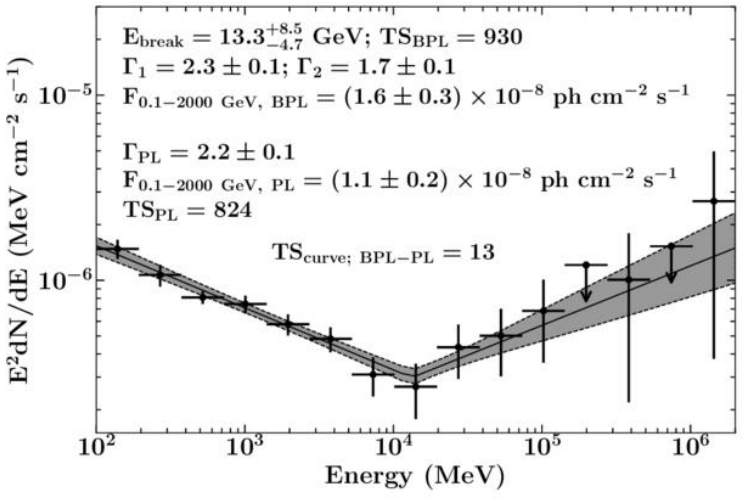


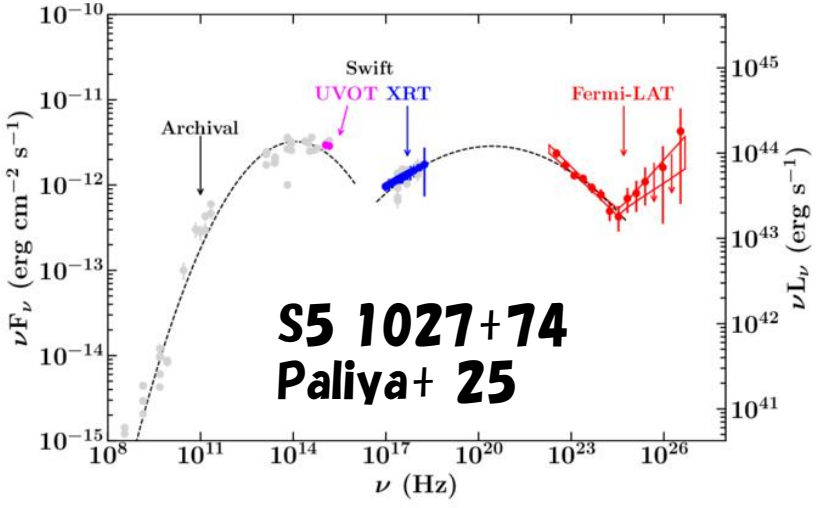
- Gamma-ray emitting region
- Curved spectra (not cooling break) in blazars suggest turbulent acceleration rather than a strong shock.
- Slow acceleration, suppressing maximum energy
- FSRQ brighter, softer, rarer (not compatible with dipole)
- Multiple zones?

TeV gamma from FSRQ

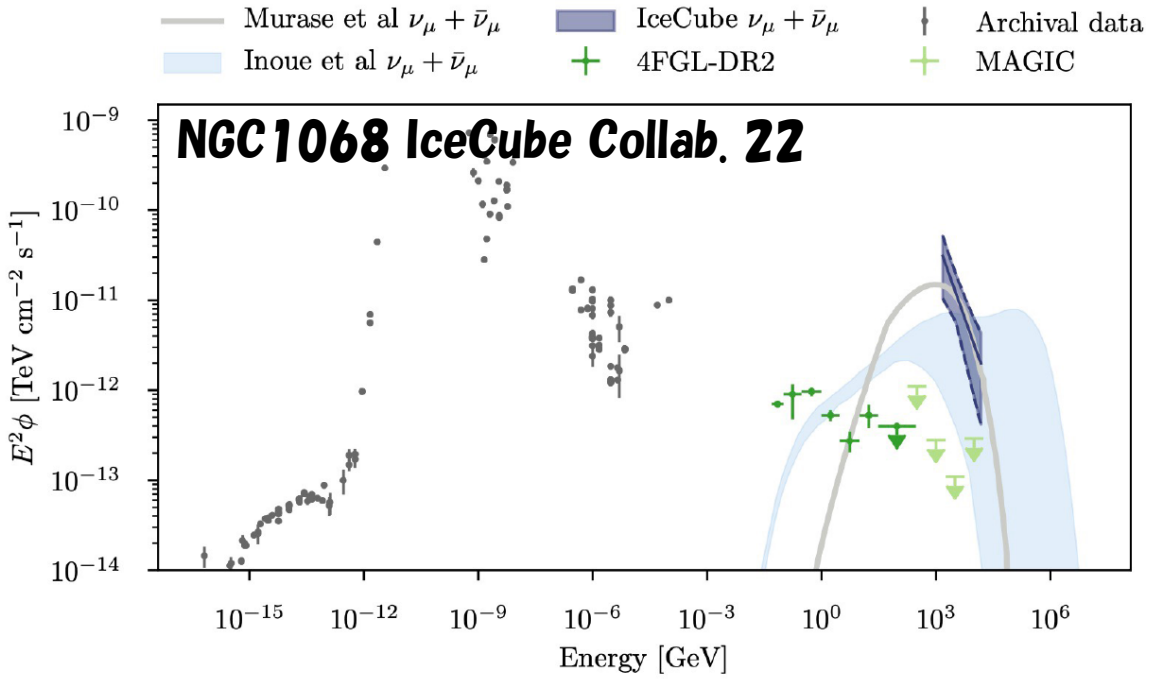


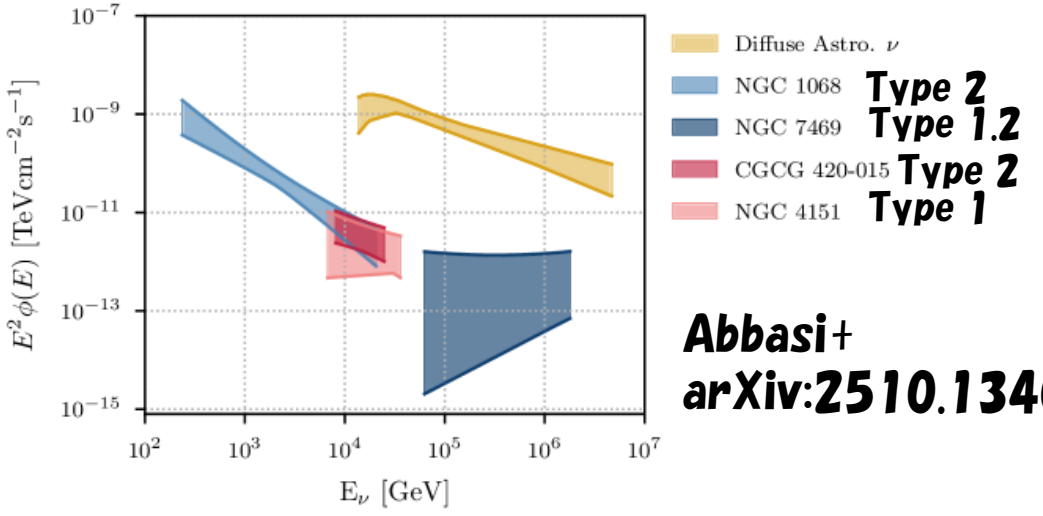
- Possible TeV detections from FSRQs
- Third component
- Probably a more extended emission region (no $\gamma - \gamma$ absorption)
- Likely leptonic (low density)
- UHECR source? But no smoking gun





Seyfert Galaxy: Neutrino Source



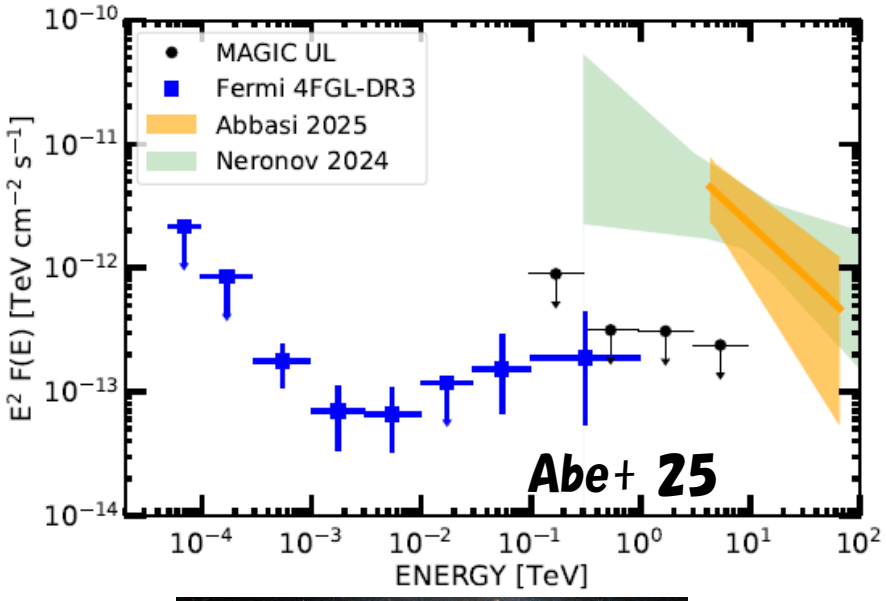


Abbasi+ arXiv:2510.13403

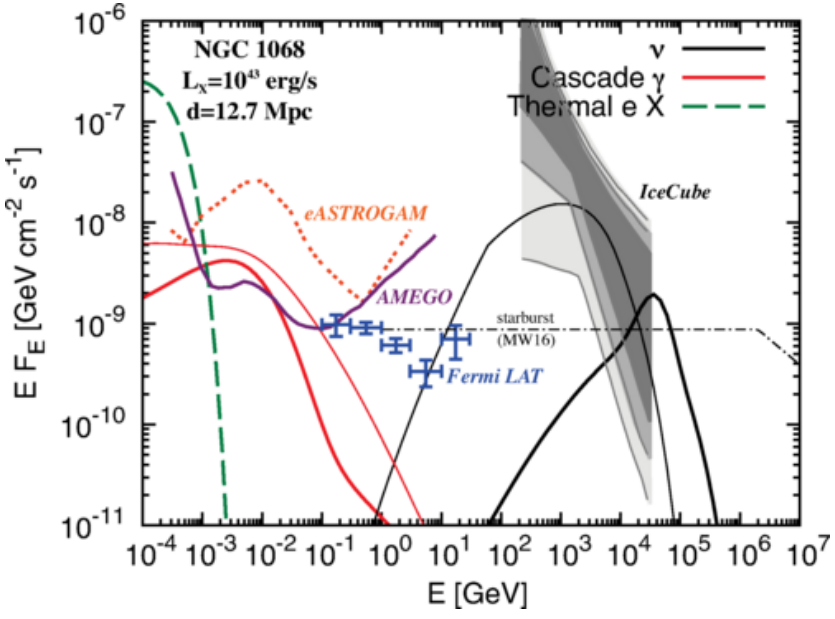
- Increasing significance of the neutrino signal
- NGC 1068: Soft spectrum, no TeV gamma implying compact source near SMBH
- Flat(?) spectra for other candidates, compatible with the diffuse neutrino background.

NGC 4151: 2nd neutrino emitting Seyfert

MAGIC upper limit for NGC 4151



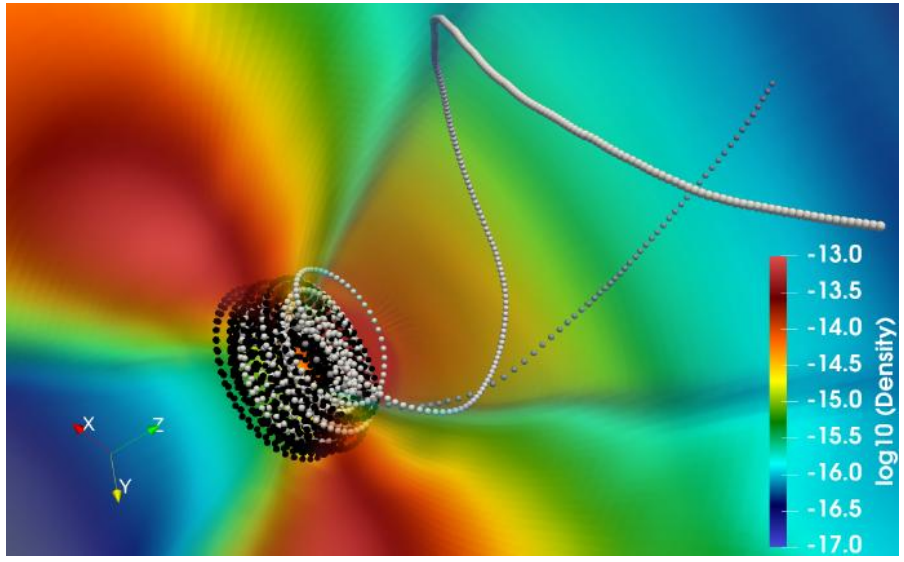
- Neutrino signal 3.1 σ
- Upper limit in TeV again
- Implying source < 10^3 r_g
- AGN corona model (Inoue+19, Murase+20)



Murase+20
Turbulence acc.

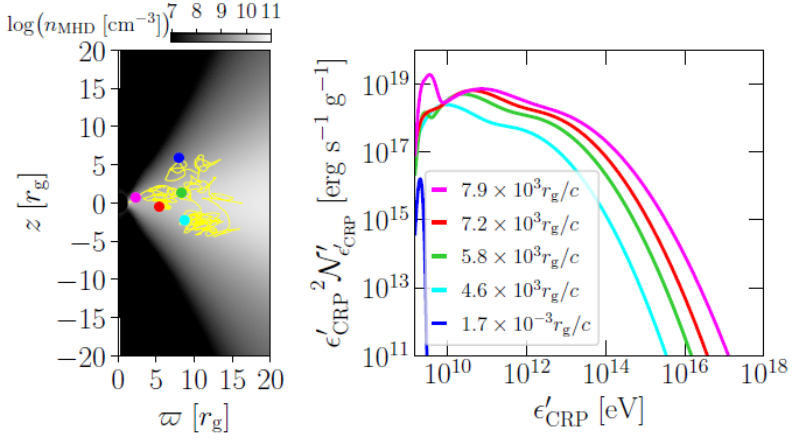
CR acceleration in accretion disks

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

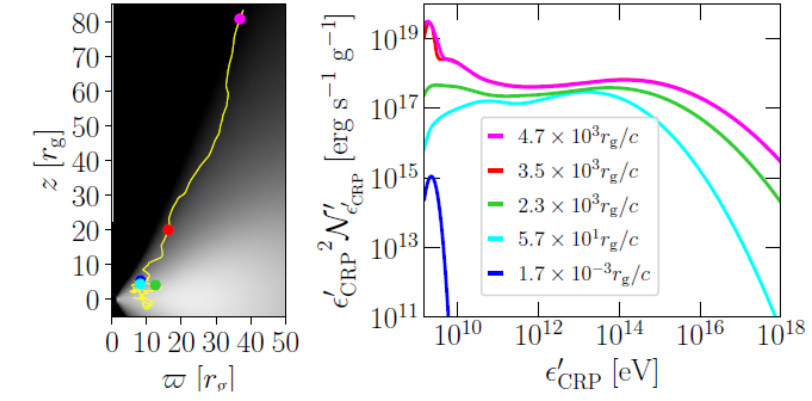


- Simulation data provide a degree of turbulence
- Follow trajectory of advected CRs
- Non-steady injection and acceleration resulting in softer spectra
- Wind with CRs, no distinction of Wind/corona

(a) Inflow CRP



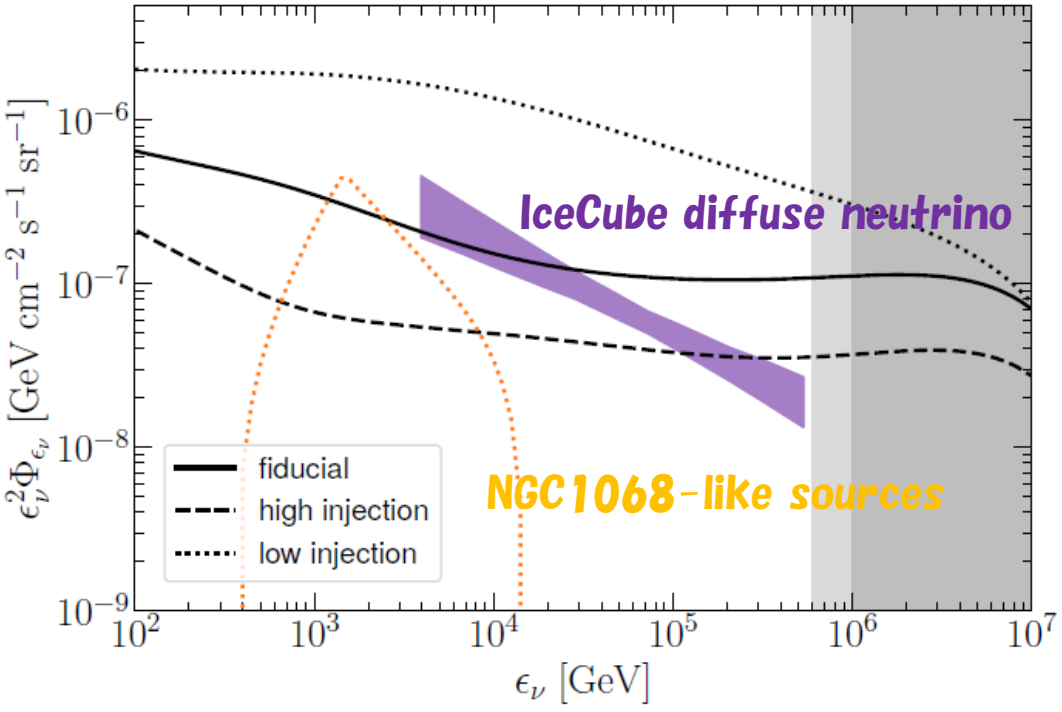
(c) Ouflow CRP (It was inflowing in early phase)



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

Neutrino emission from the simulated disk

Kawashima & KA 25
Neutrino spectrum



- 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} 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

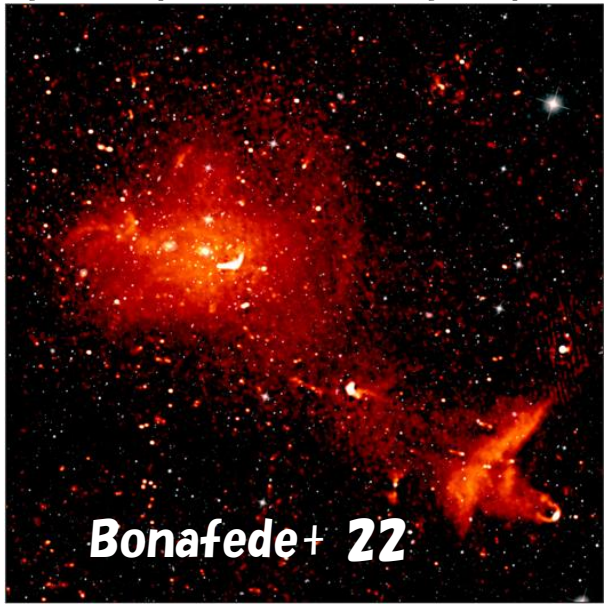
LLAGN: Accretion rate ~10^{-2} Eddington
Mrk 421-like

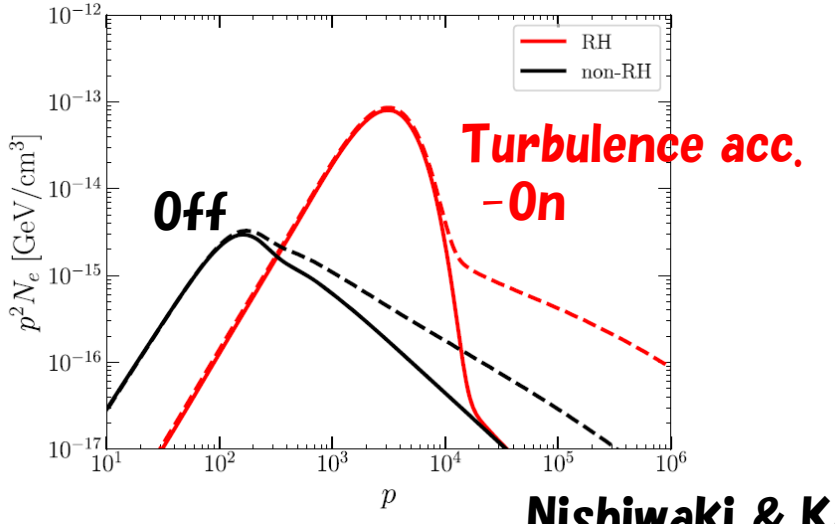
NGC 1068-like sources
Accretion rate ~ Eddington

$\sim 5 \times 10^{-5}\,{\rm Mpc}^{-3}$
$L_{\rm bol} \sim 10^{45}\,{\rm erg\,s}^{-1}$

Galaxy Cluster

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



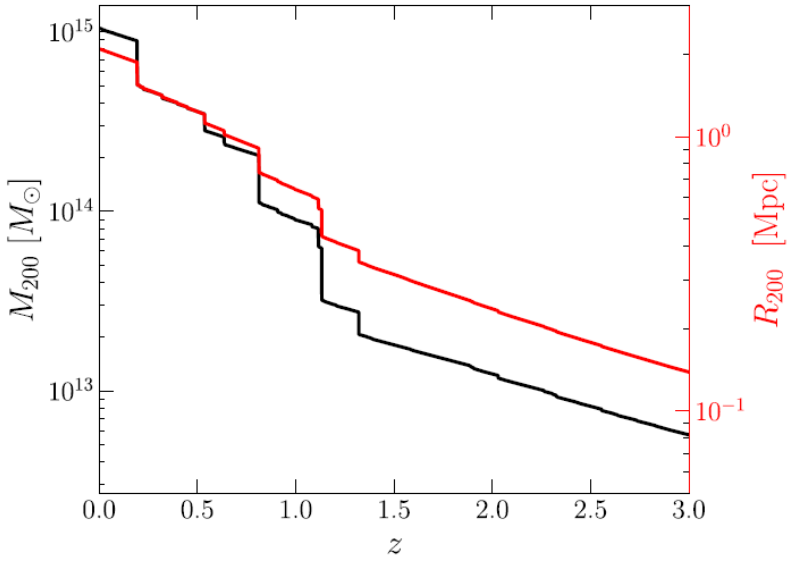


Nishiwaki & KA 25

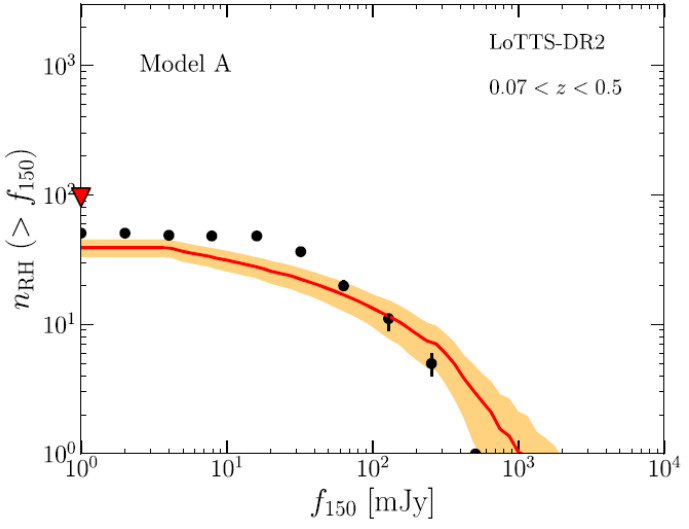
- Diffuse synchrotron emission
- Electron cooling time is short, requiring continuous acceleration.
- Major merger induces turbulence, which accelerates CRs in ICM
- Electrons may be hard to escape from source galaxies
- Secondary electrons from accelerated protons are likely.
- Possible GeV gamma-ray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

Cluster Statistics

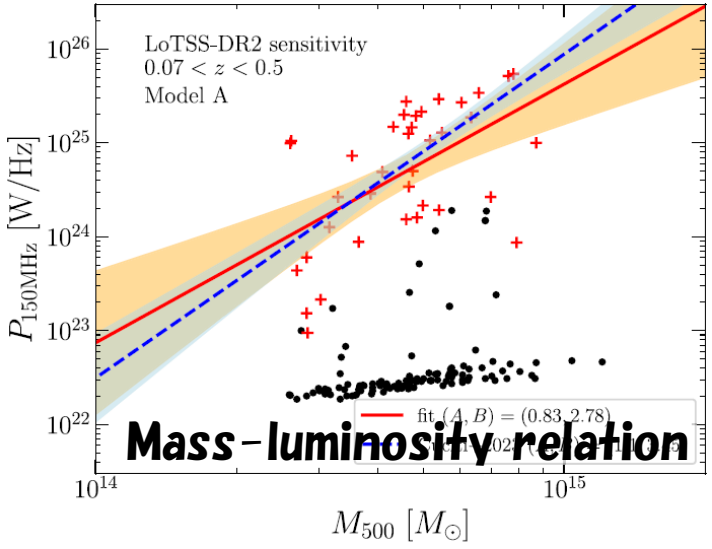
Cluster mass evolution

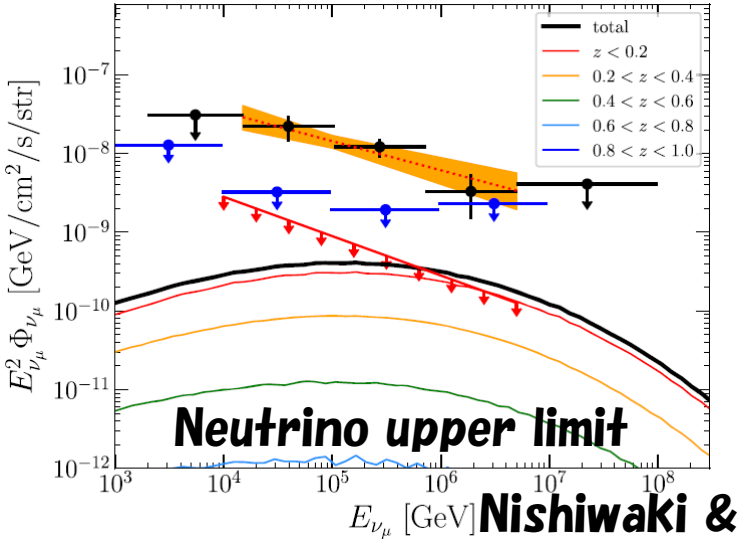


Radio halo LF



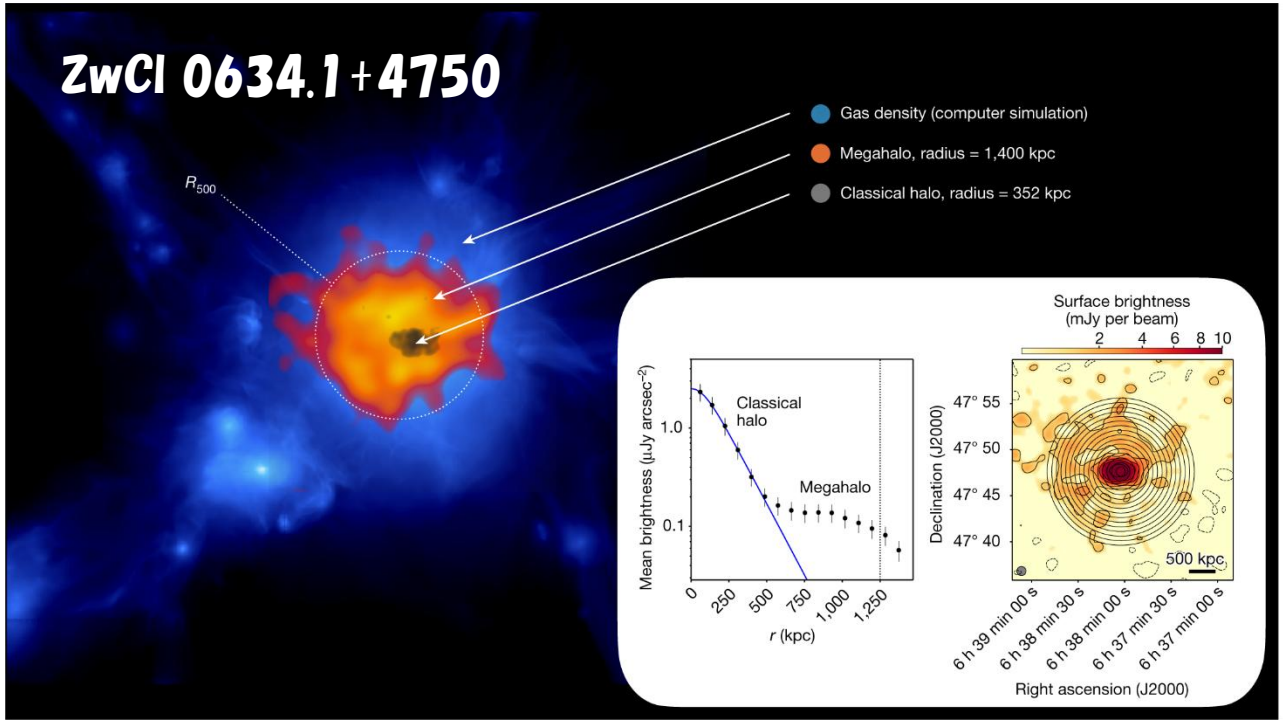
- Based on cosmological simulations, we follow the merger history of clusters.
- CRs are injected proportional to SFR.
- Finite periods of turbulence acceleration by mergers
- Reproducing the radial profile of Coma Radio Halo.
- Reproducing the radio LF and Mass-luminosity relation.
- Consistent with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





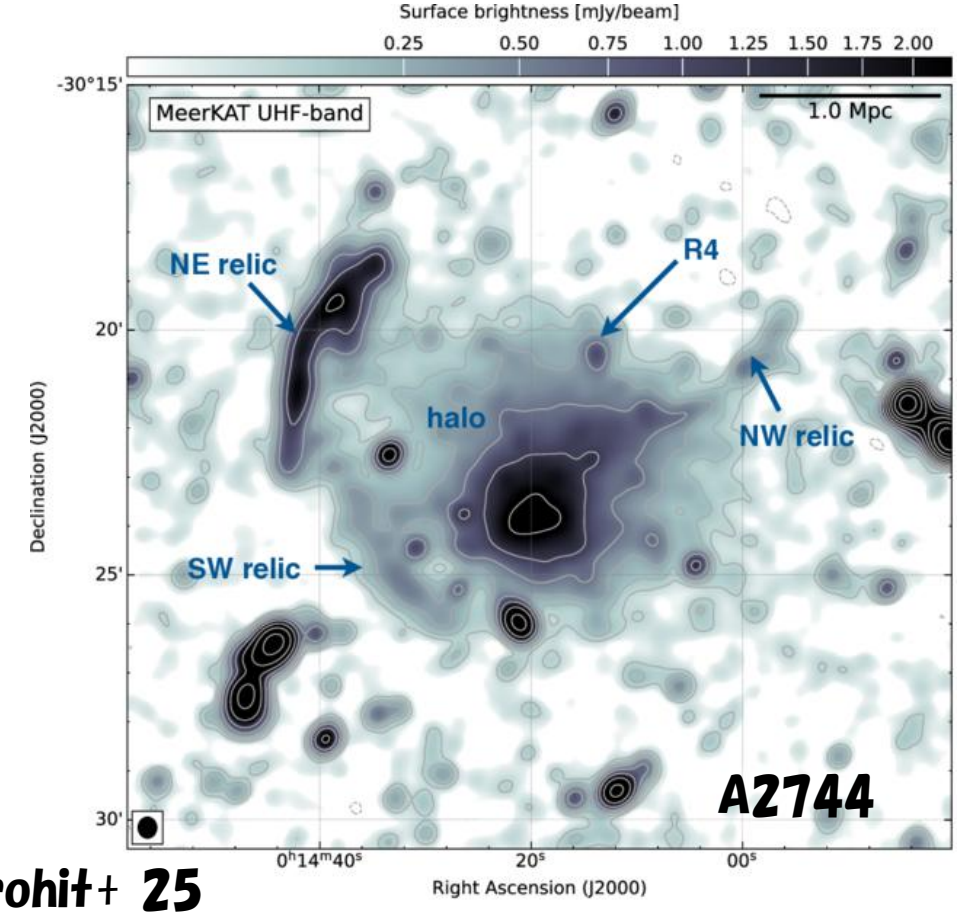
Nishiwaki & KA 25

Megahalo



Cuciti+22

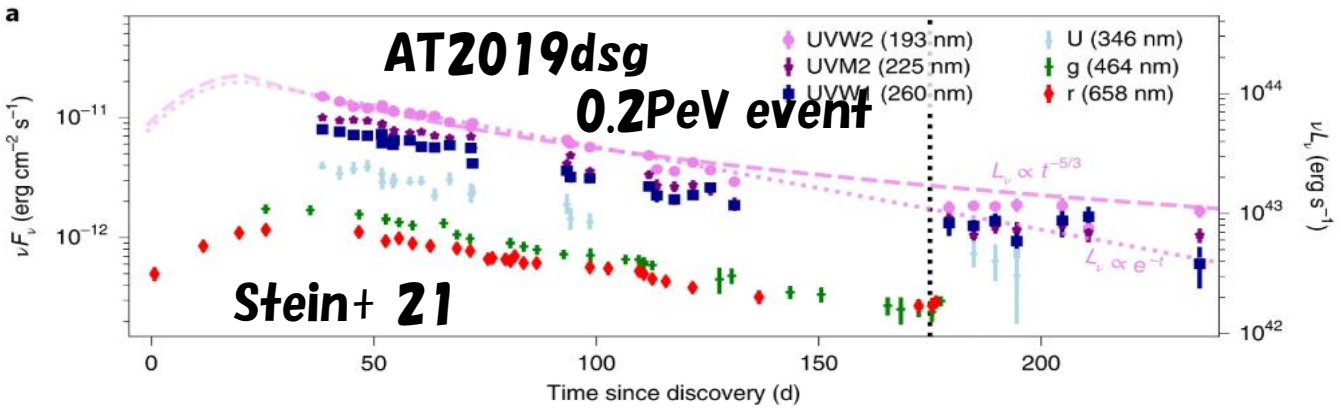
- Mpc extent of radio emission
- CRs exist far beyond radio halos.
- Secondary electrons?



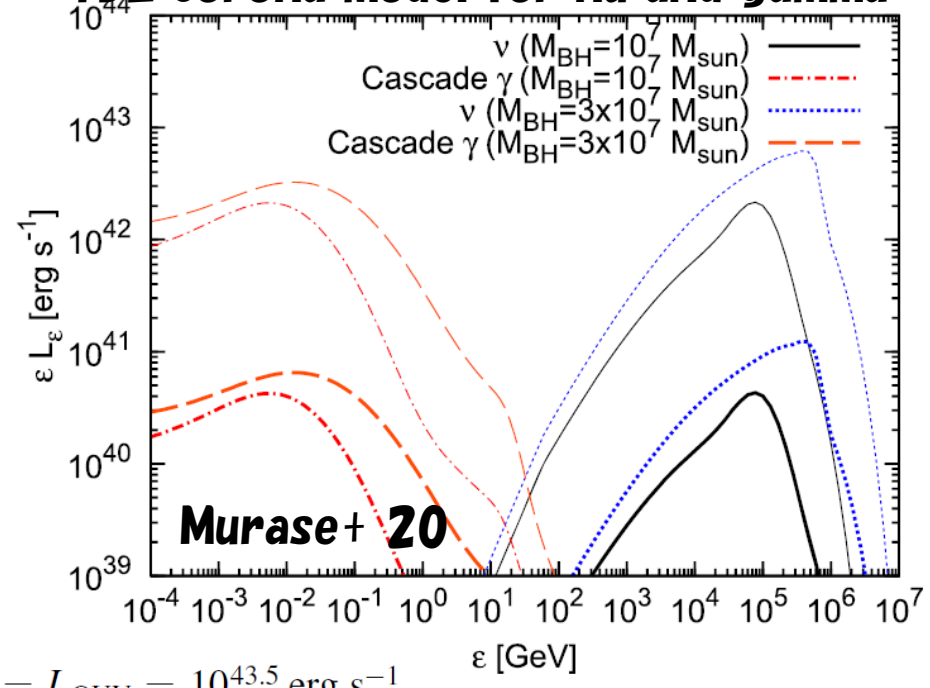
Rajpurohit+ 25

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

Tidal disruption events



TDE corona model for nu and gamma

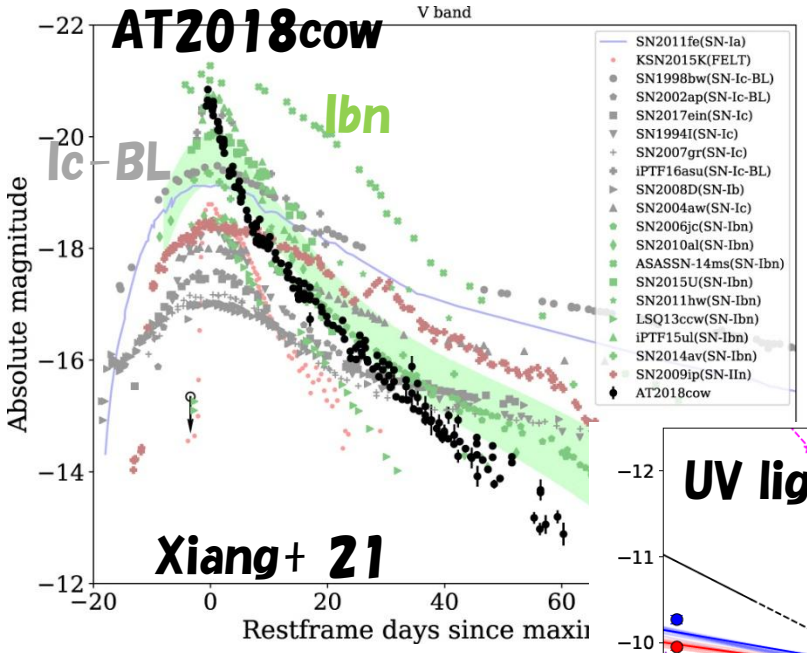


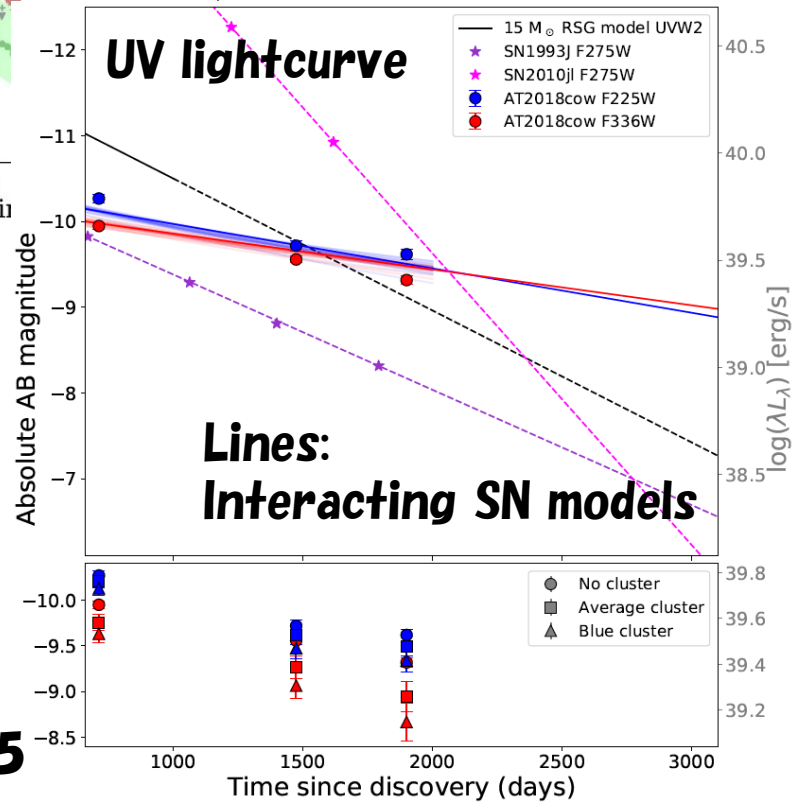
$L_{\rm disk} = L_{\rm OUV} = 10^{43.5}\,{\rm erg\ s^{-1}}$

- 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)

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

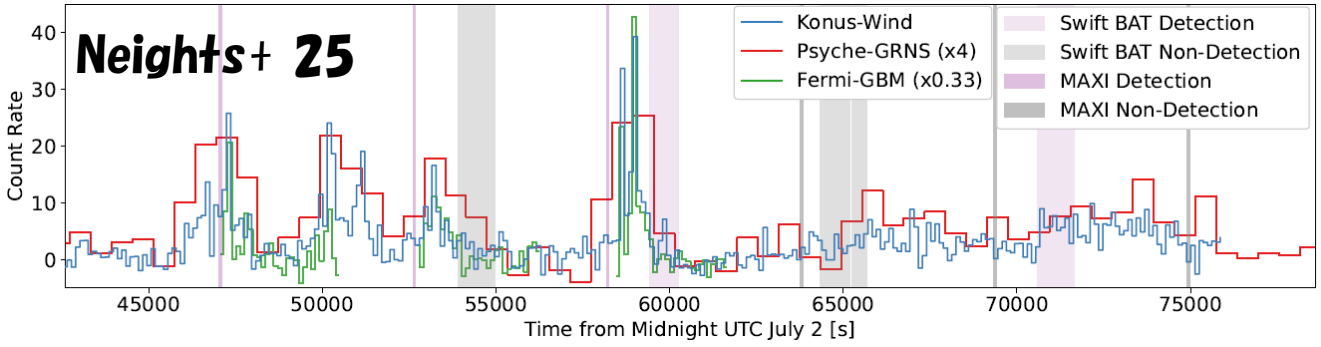
FBOT

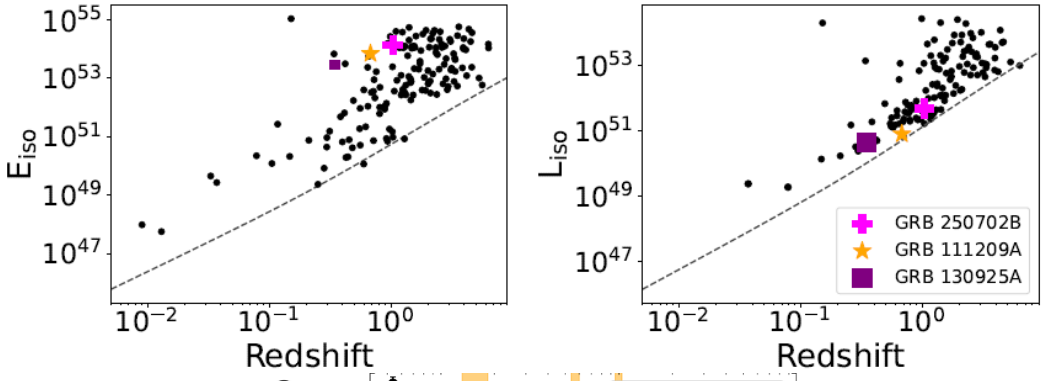


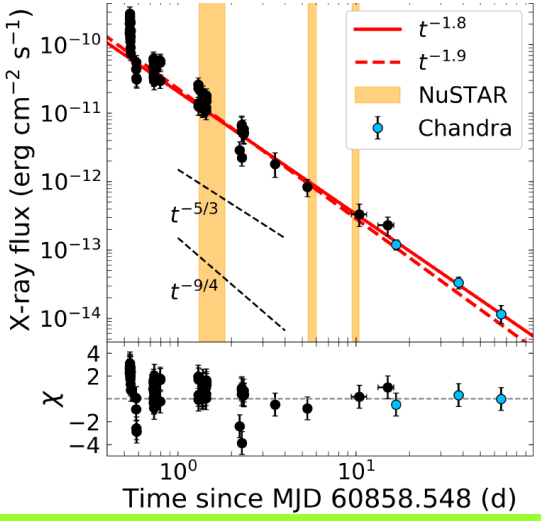


- Fast blue optical transient
- Bright (energetic), steep (low mass) lightcurve
- UV lightcurve: long-lasting, slow decay suggests TDE of white dwarf + intermediate mass BH?

Ultra long GRB 250702B

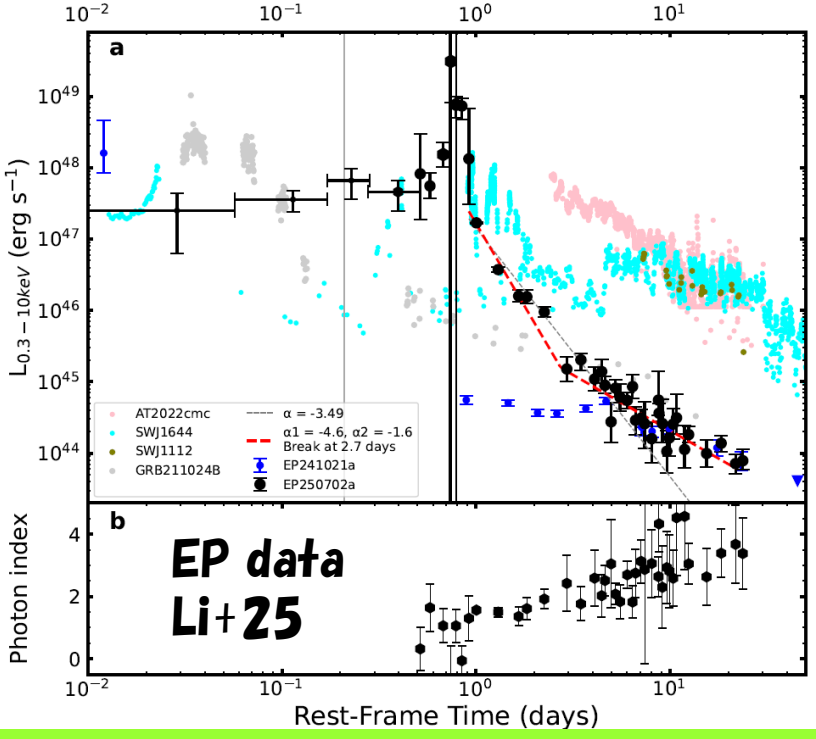




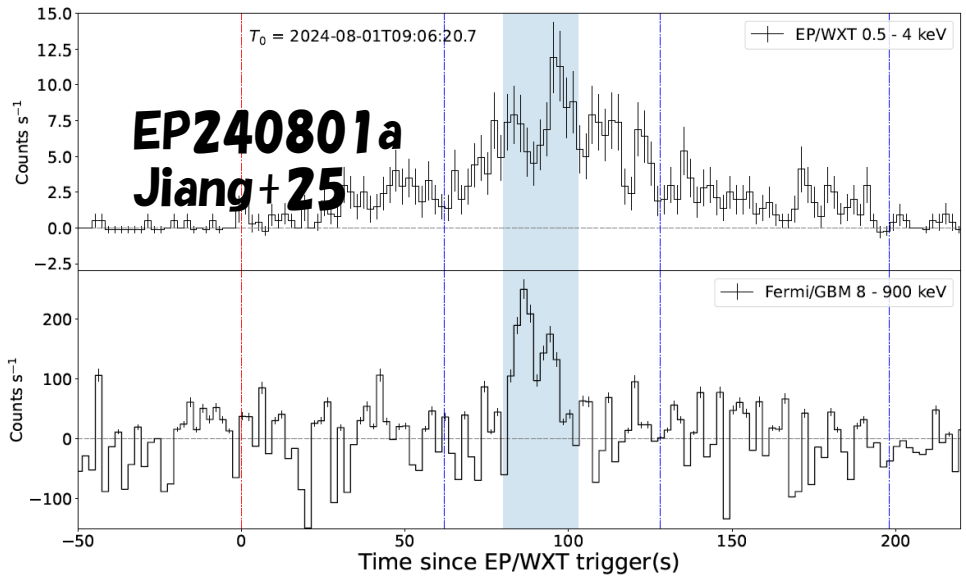


O' Connor+ 25

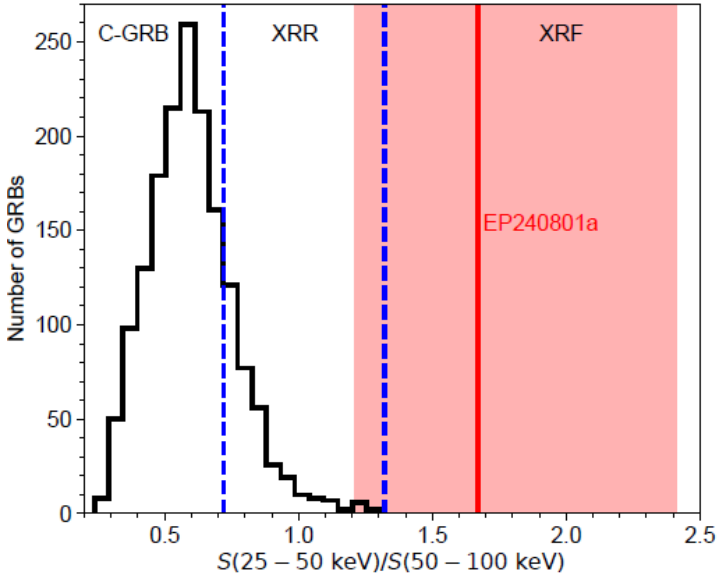
- **25000s duration**
- **X-ray precursor 1day before**
- **BH falling into a stripped star (Neights+ 25)?**
- **TDE of a white dwarf by an intermediate mass BH (Eyles-Ferris+ 25, O' Connor+ 25, Li+25)?**

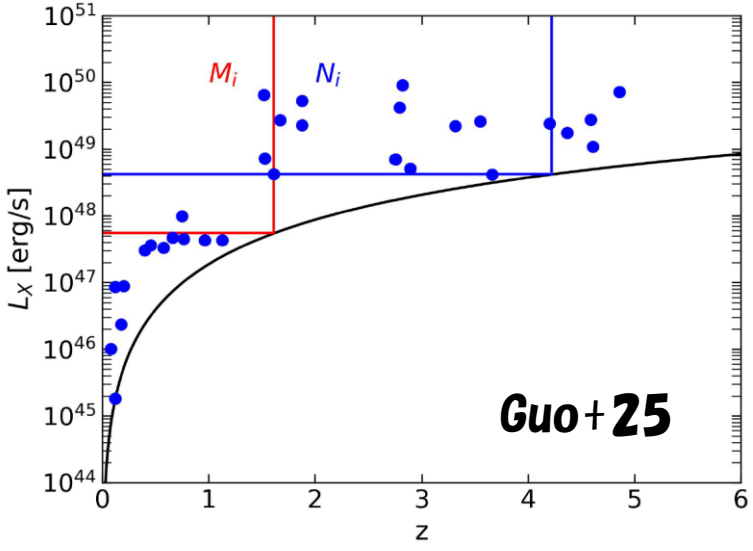


FXT with EP

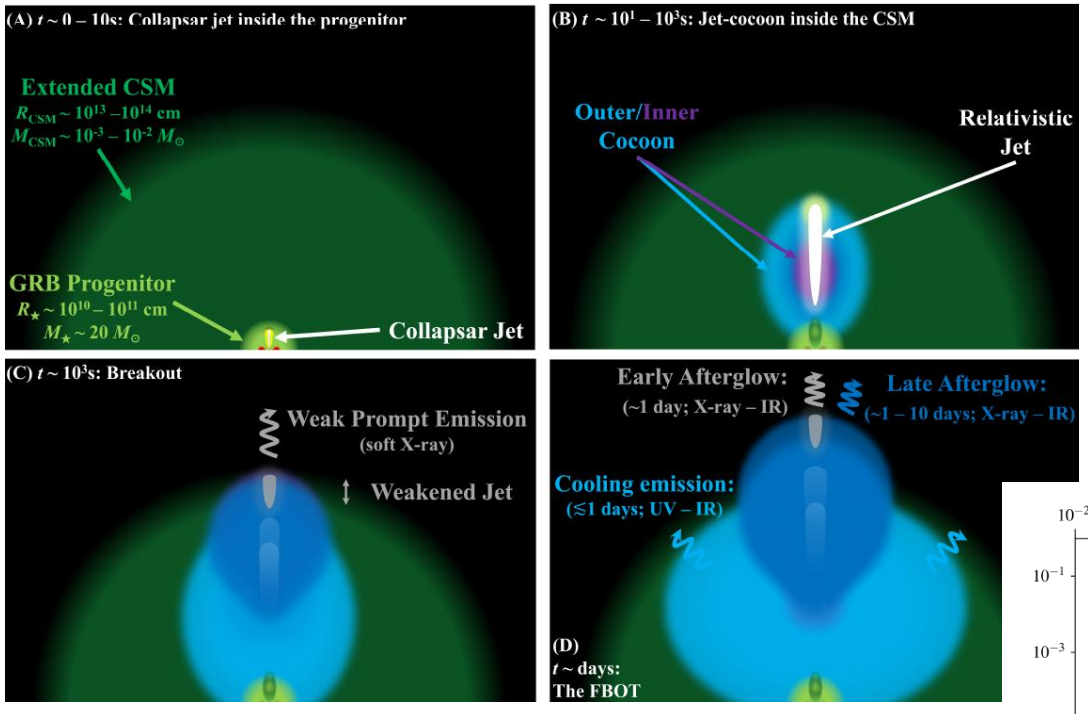


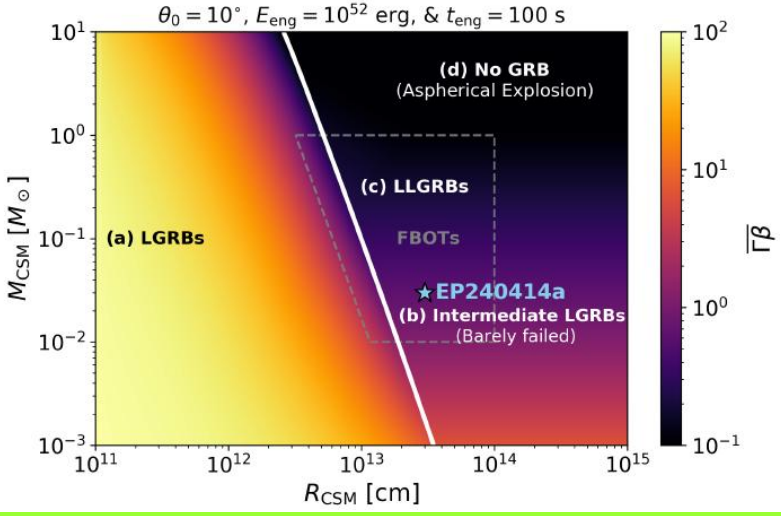
- Fast X-ray transients detected with Einstein Probe
- X-ray Flash (XRF)
- Minutes to hours
- Off-axis GRB?
- BNS mergers?
- EP250108a associated with a Ic-BL SN (Rastinejad+25)



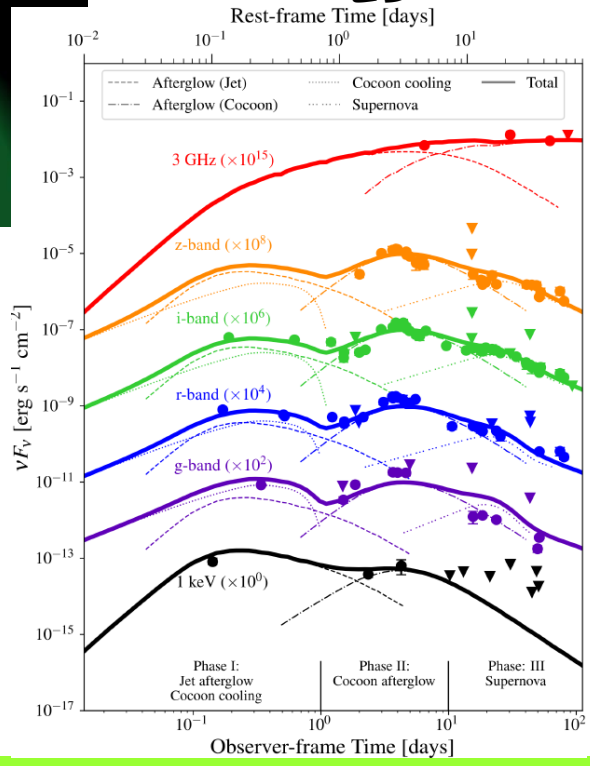


Unified model for GRB/FXT



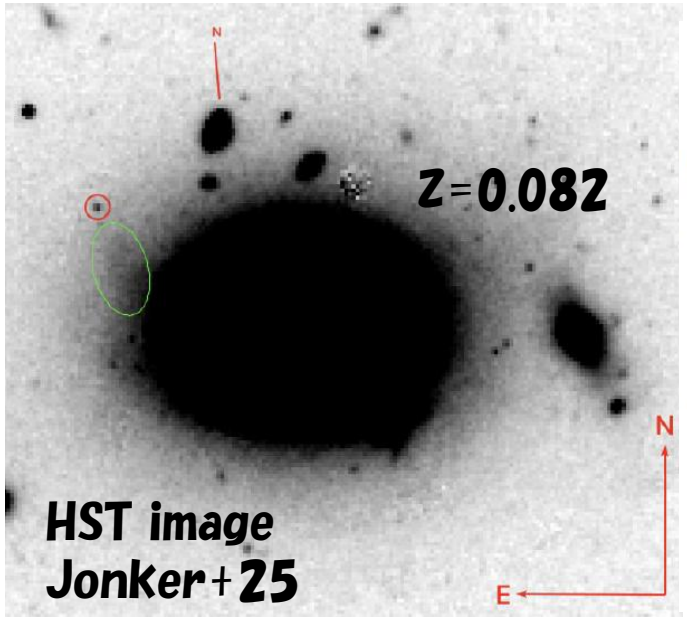


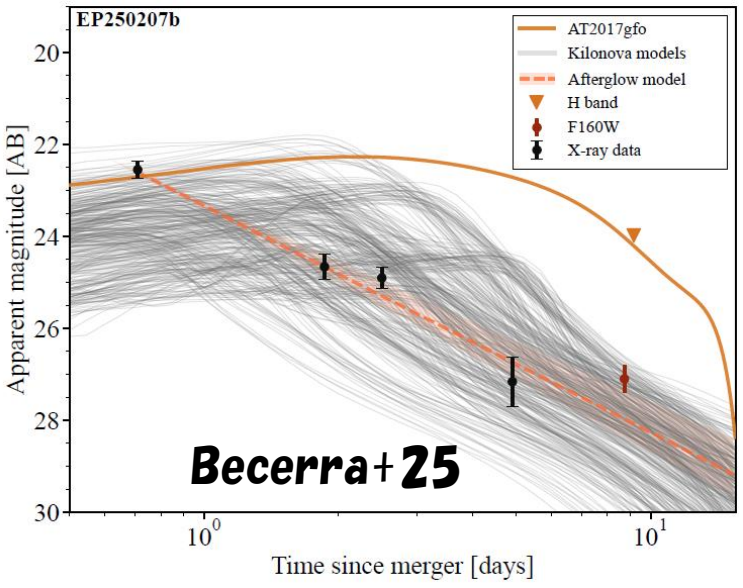
Hamidani+25



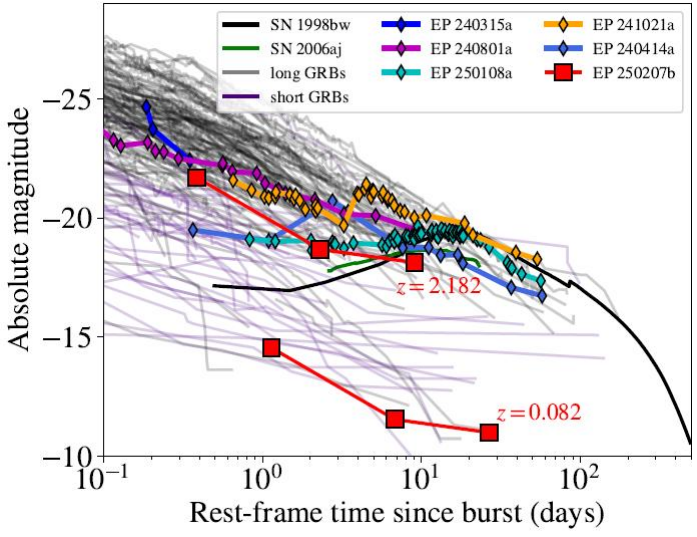
- Model for EP240414a
- Extended CSM
- Jets dissipate a fraction of energy in CSM, producing cocoons.
- Weak prompt
- Mildly relativistic jets produce slowly evolving afterglows
- Cooling cocoons emit late afterglow
- Depending on the CSM radius, we obtain GRB/XRF(Intermediate)/LLGRB

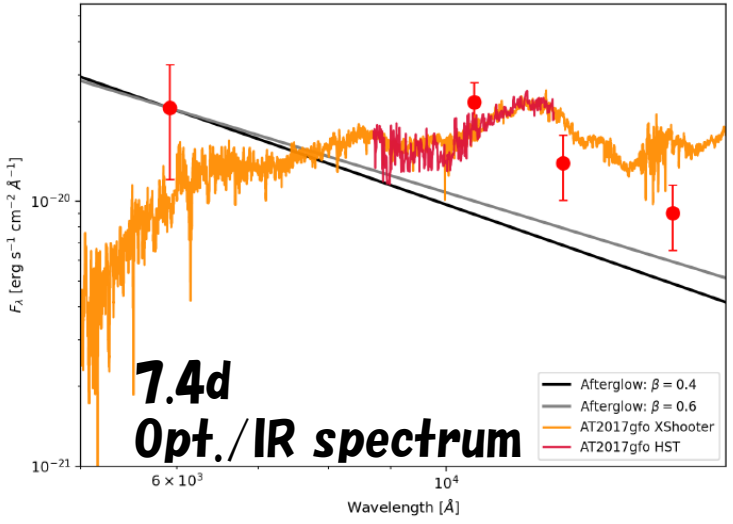
EP 250207b: BNS merger?



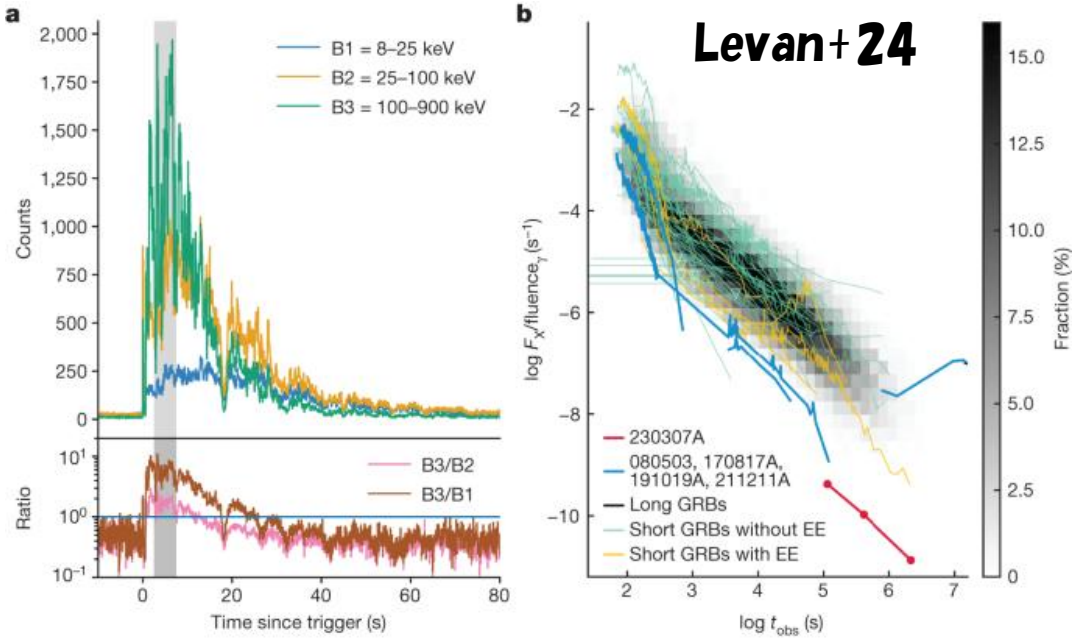


- z=0.082
- No SN emission
- Lightcurve and spectrum are consistent with the kilonova model
- Cannot rule out SN at z>1

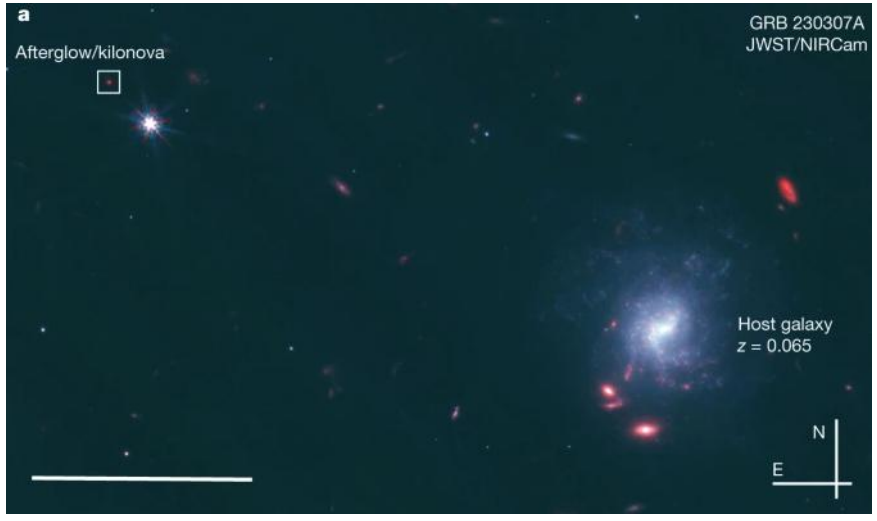


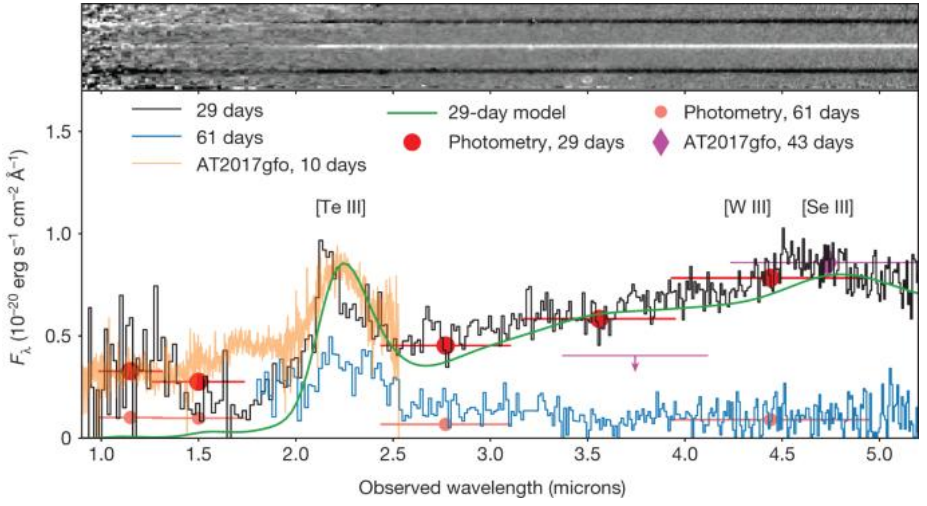


Long GRB from BNS? GRB 230307A

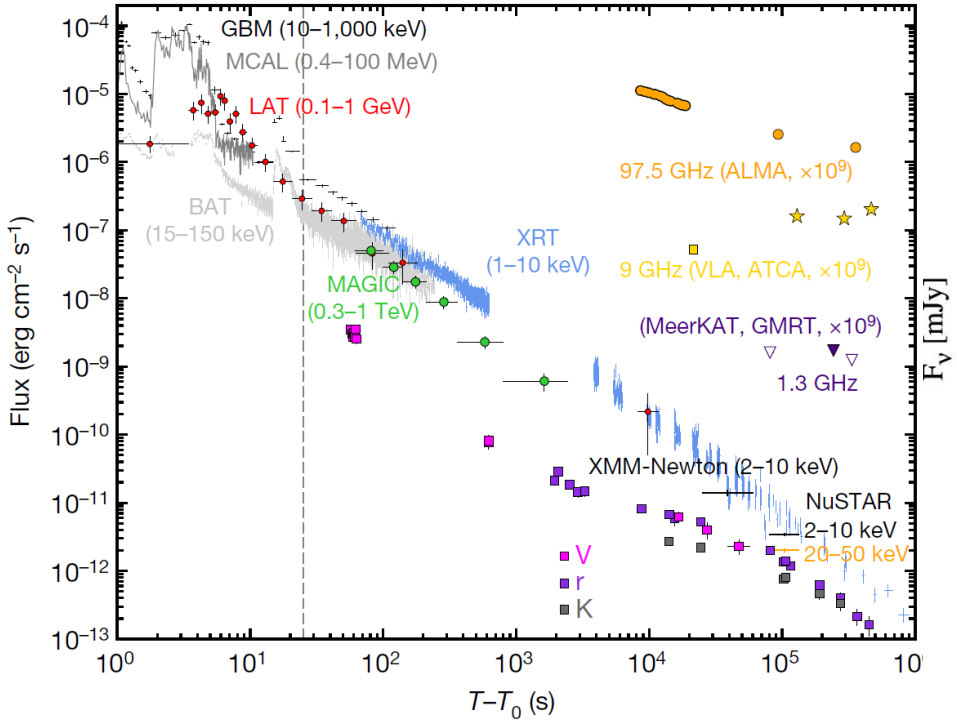


- $E_{iso} = 4.8 \times 10^{52}$ erg (Moradi+24)
- Dim and red afterglow
- Lightcurve and spectrum are consistent with the kilonova AT2017
- r-process nuclei Te line detected with JWST
- NS-WD merger (Wang+24, Chrimes+25)?

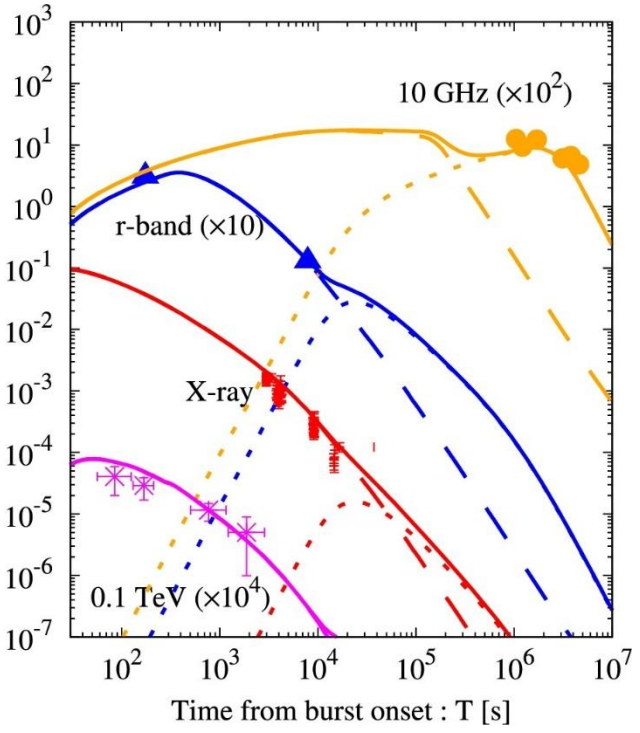




GRB afterglow: Recent progress



GRB 190114C
MAGIC Collab. 2019



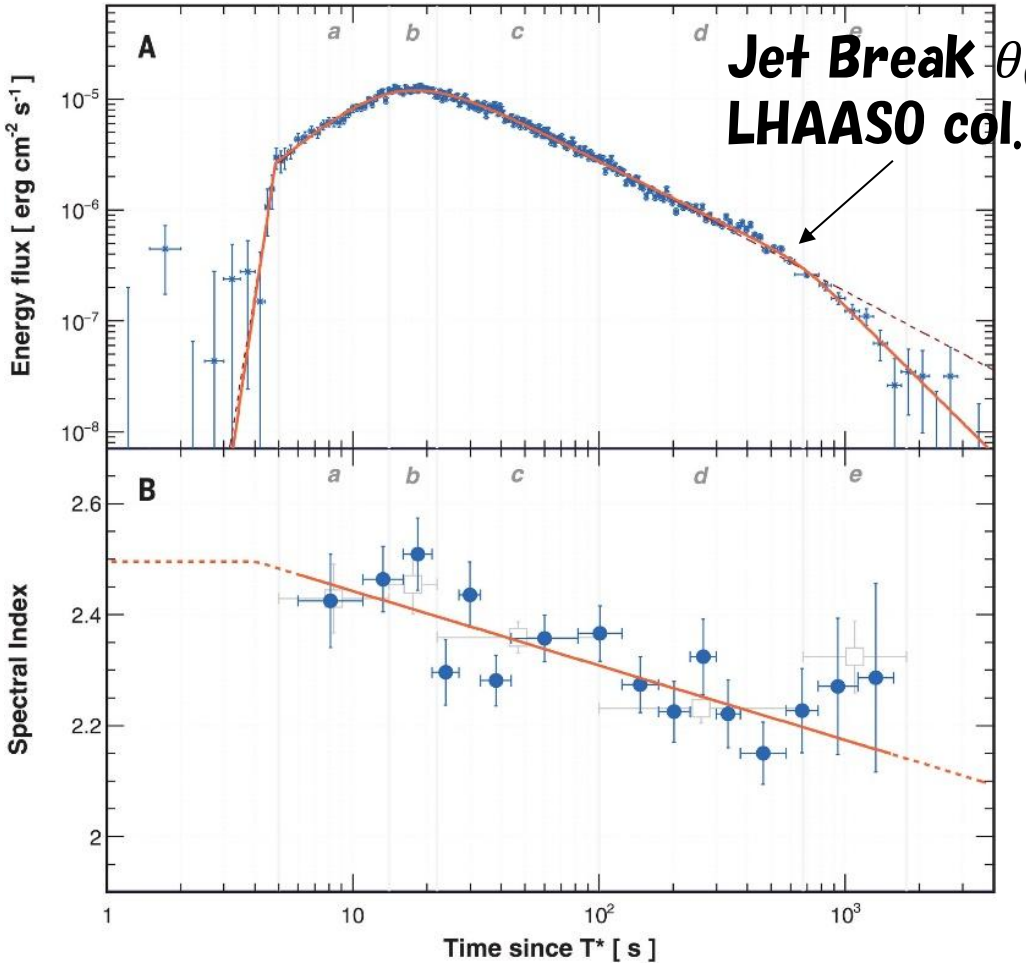
GRB 201216C
Sato+ 25

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

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

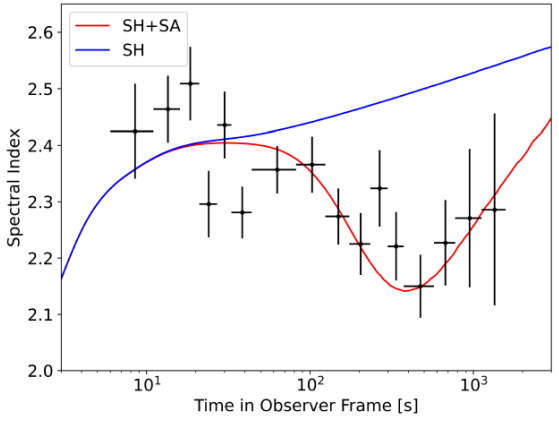
- Decelerating shock propagating in CSM
- TeV afterglow samples are increasing
- Synchrotron + Inverse Compton
- Variation in microscopic parameters: $\epsilon_{\mathrm{e}}, \epsilon_B, p$
- Parameters are constant?
- Two-component model: Wide+Narrow jet→break
- Main characters change between the early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

BOAT GRB: 221009A



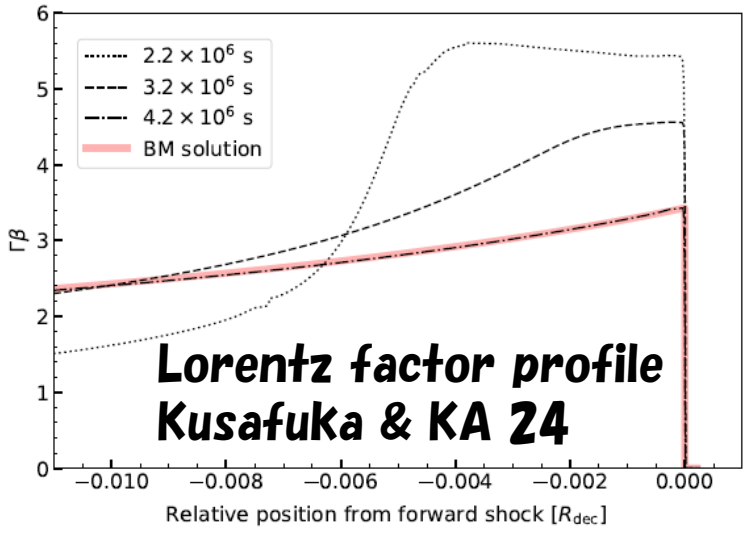
Jet Break $\theta_0 = 0.8°$
LHAASO col. 23

- 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?)

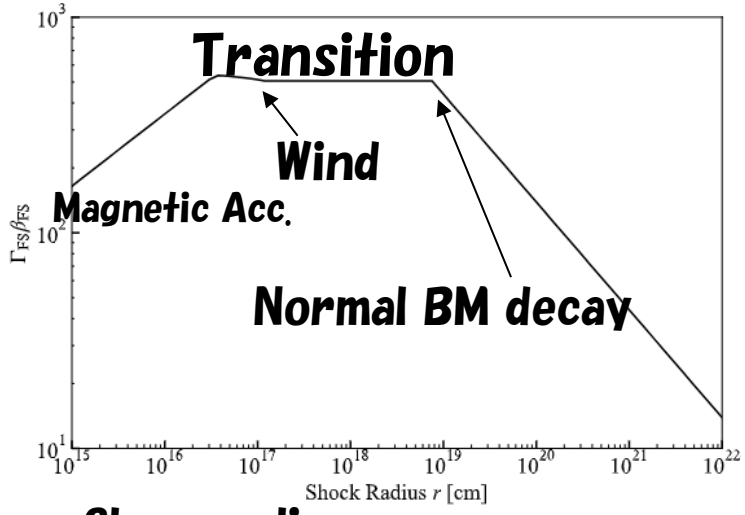


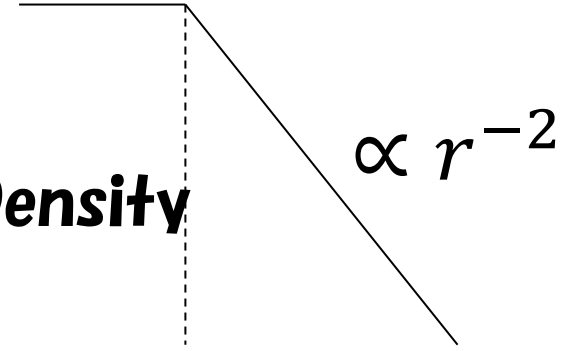
Gong, KA+ 25

New model for BOAT GRB

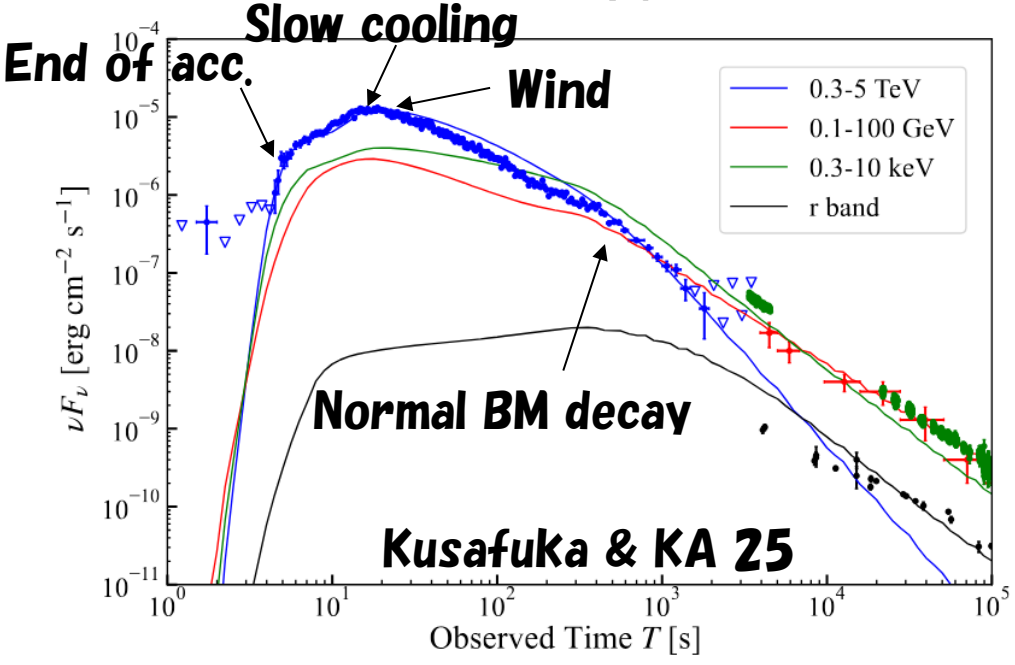


Lorentz factor evolution



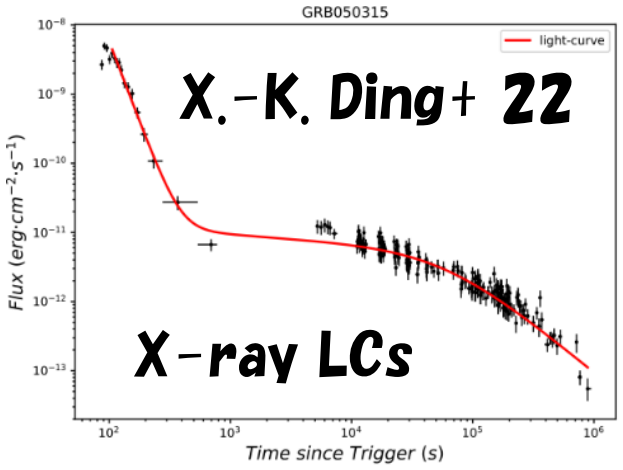


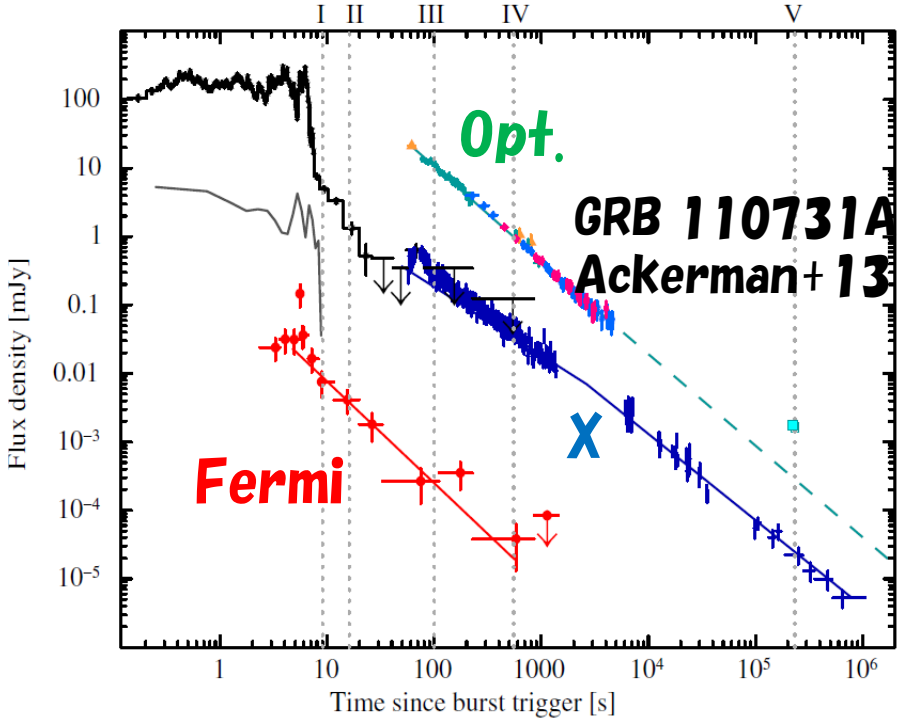
1.2×10^{17}cm



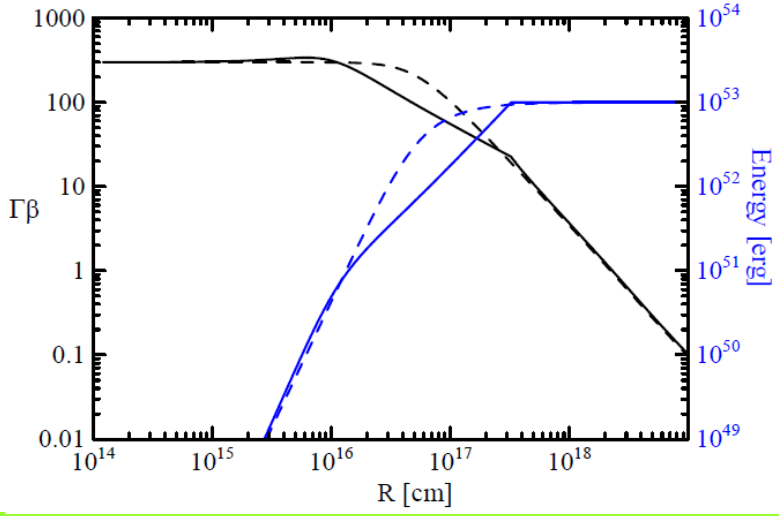
- Single component
- Initially jet is accelerating by magnetic force
- Consistent with the early increase
- Finite thickness of the ejecta→transition phase
- Flat density to wind density
- Late phase: Self-similar BM solution
- Jet opening angle is >1.7 degree

Shallow Decay Phase



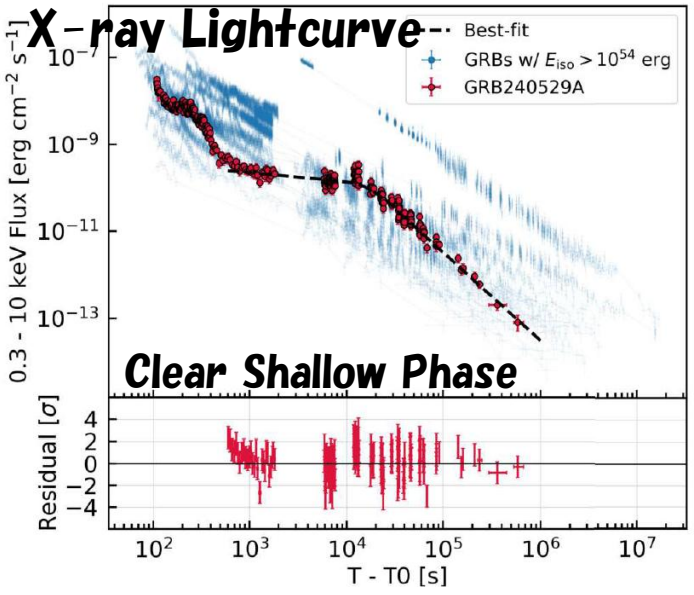


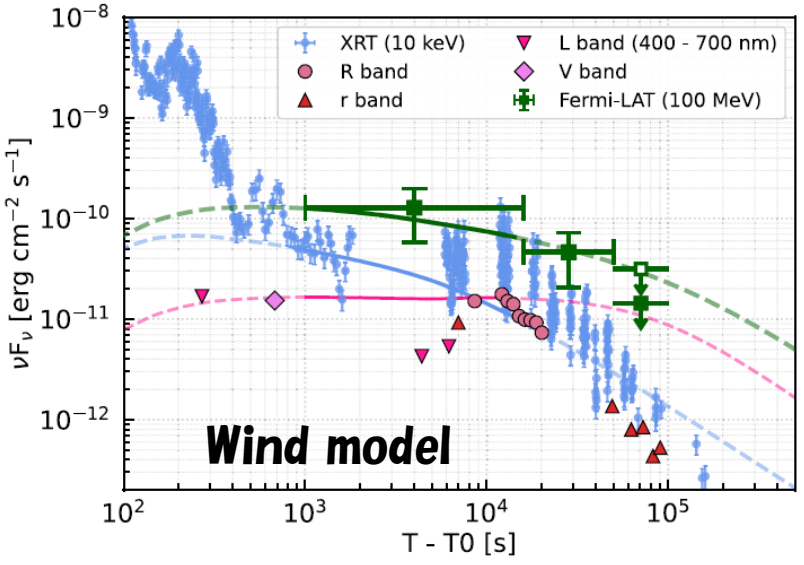
- Flat First 3000s
- Continuous energy injection may hinder deceleration
- Alternative: Slow($\Gamma_0 \sim 30$) ejecta in wind profile (Dereli-Bégué +22)
- This leads to a delayed onset of deceleration.
- Fermi-LAT GRBs tend to show no shallow decay (Yamazaki+20)

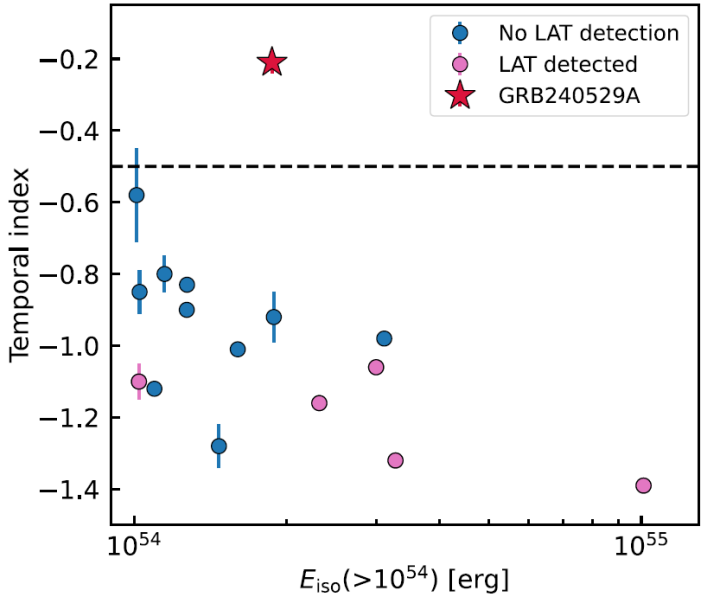


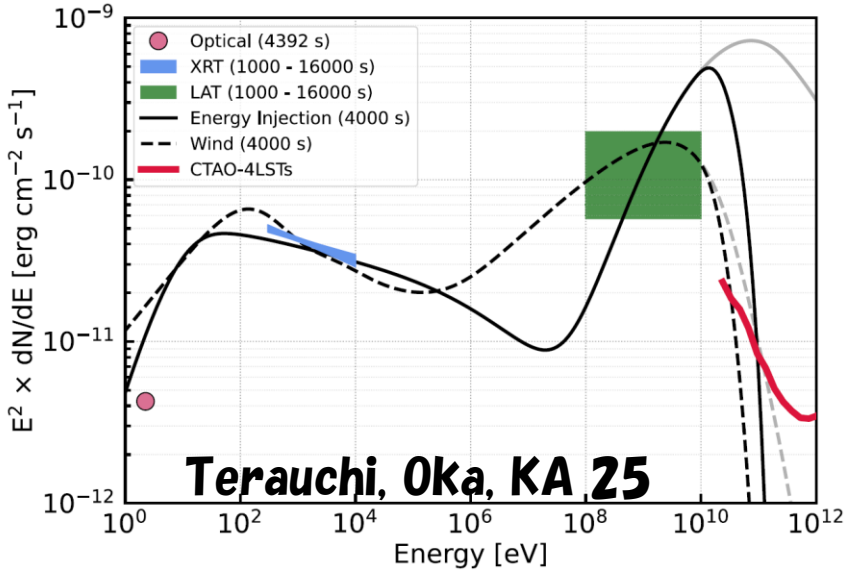
Energy Injection
Asano 24

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

- 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