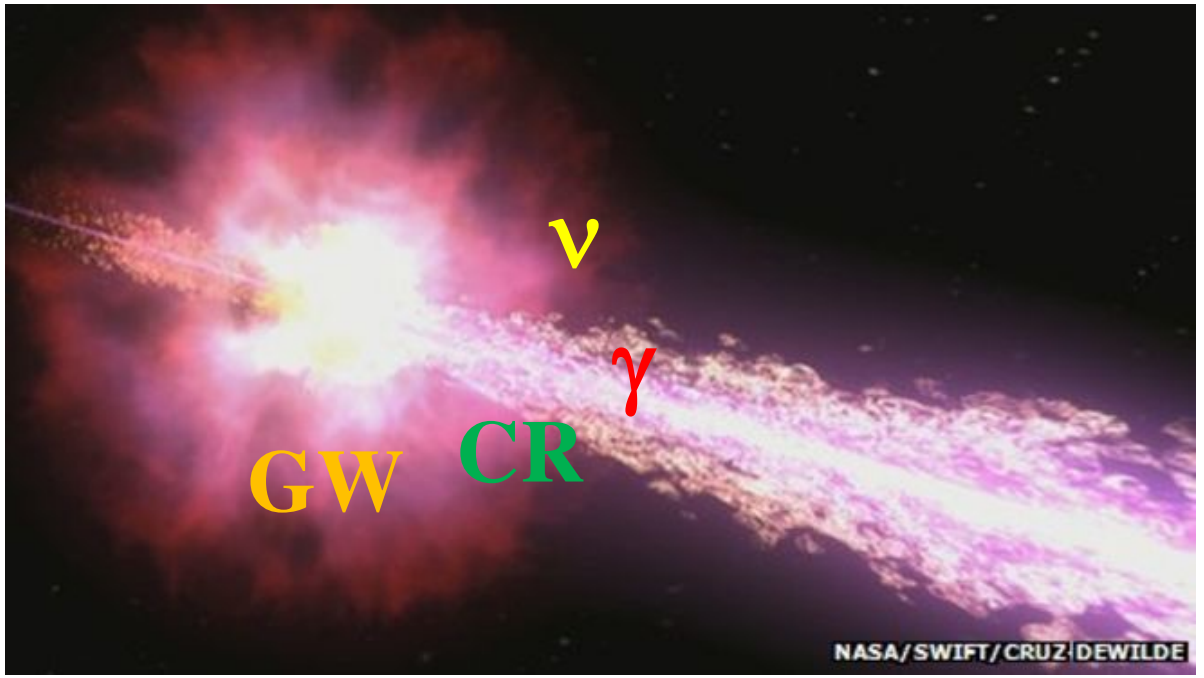
Gamma-Ray Bursts: Multi-Messenger Synergies

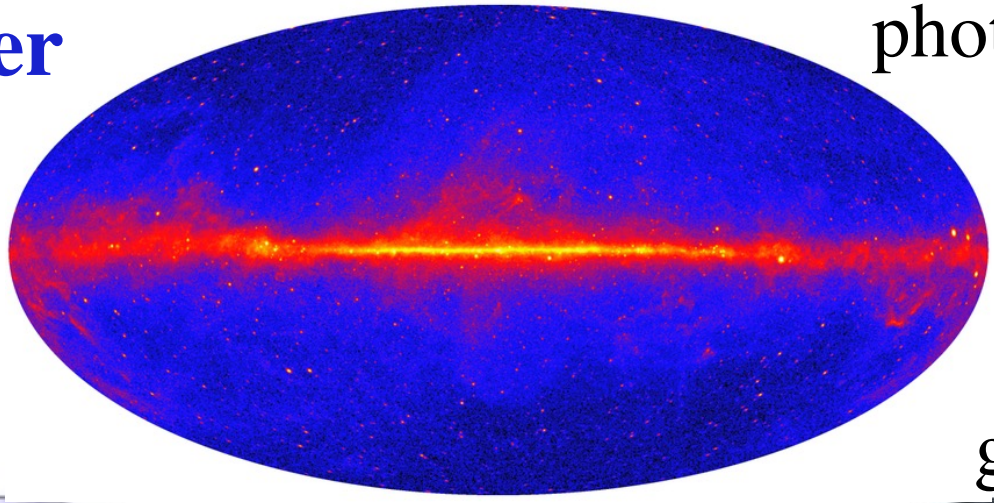
Susumu Inoue (Chiba U./ICRR)



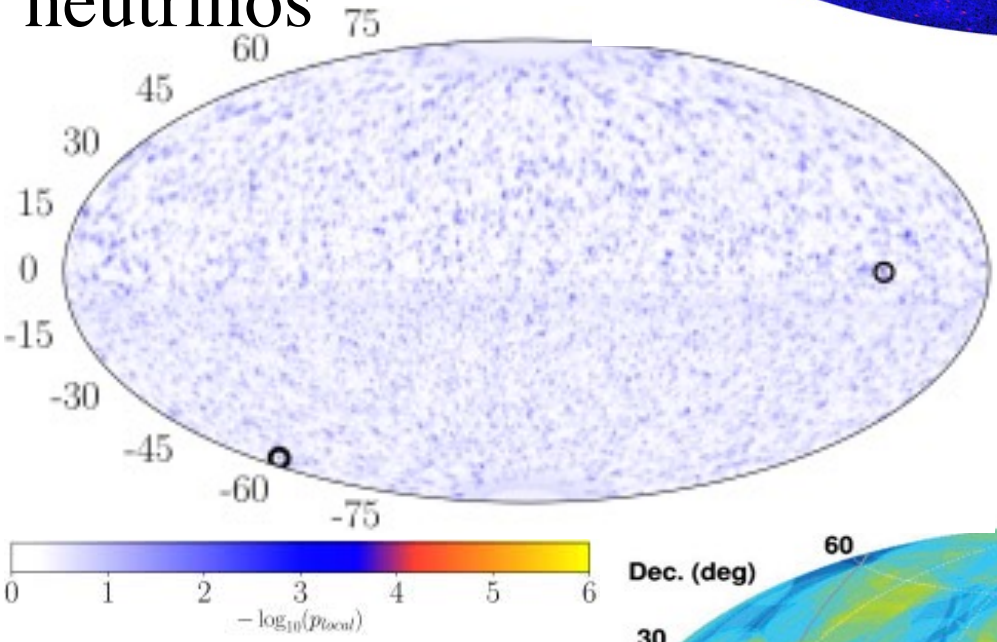
1. General remarks on multi-messenger synergies
2. GRBs in photons, especially TeV
3. GRBs in neutrinos / UHECRs + photons
4. GRBs in GWs + photons

multi-messenger channels: suggested terminology

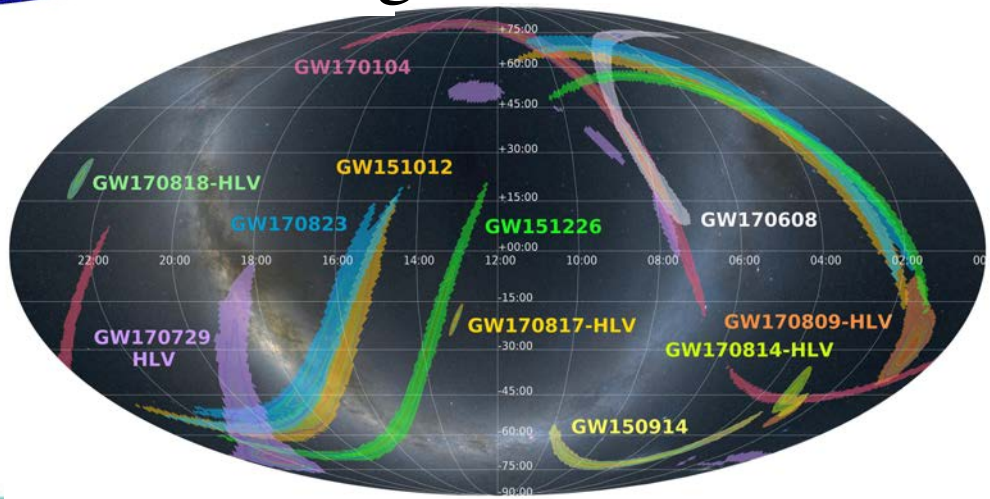
photons



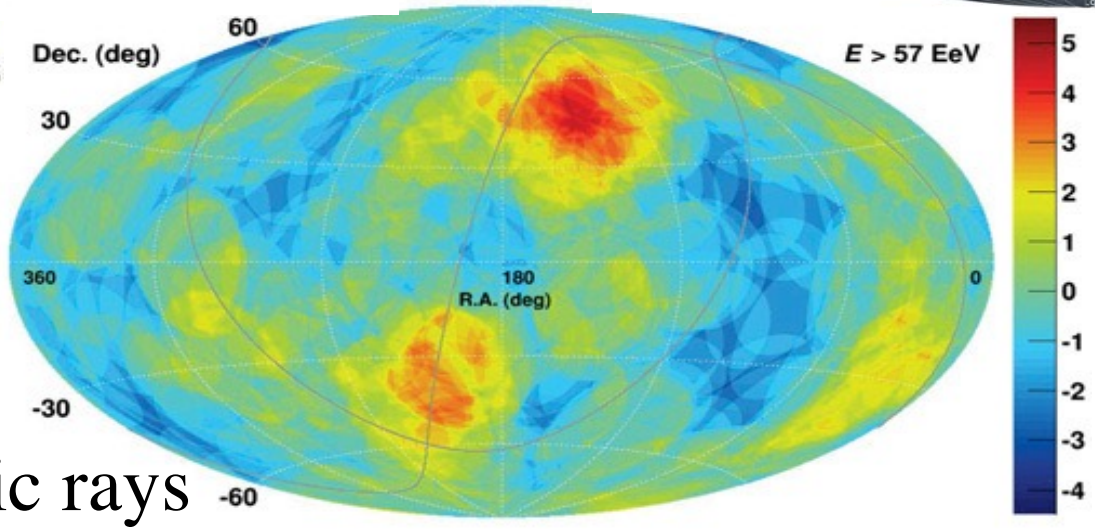
neutrinos



gravitational waves



cosmic rays



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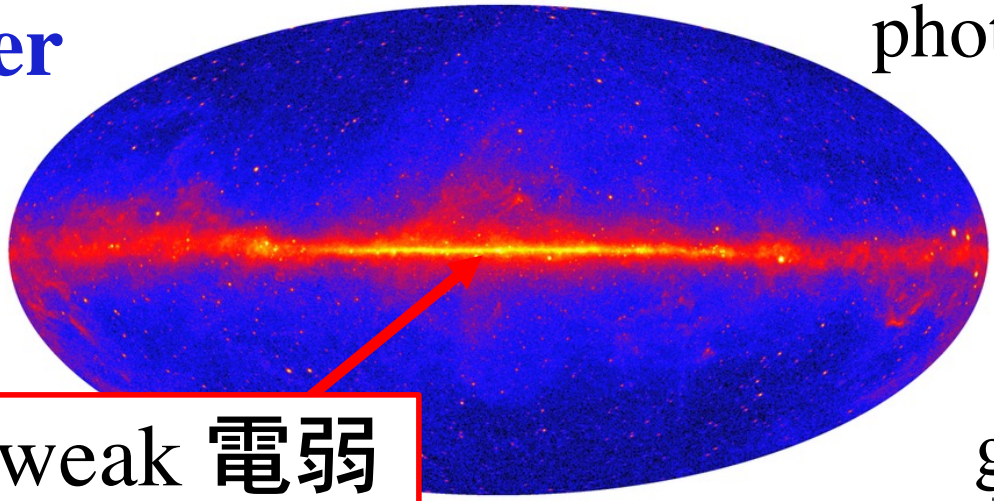
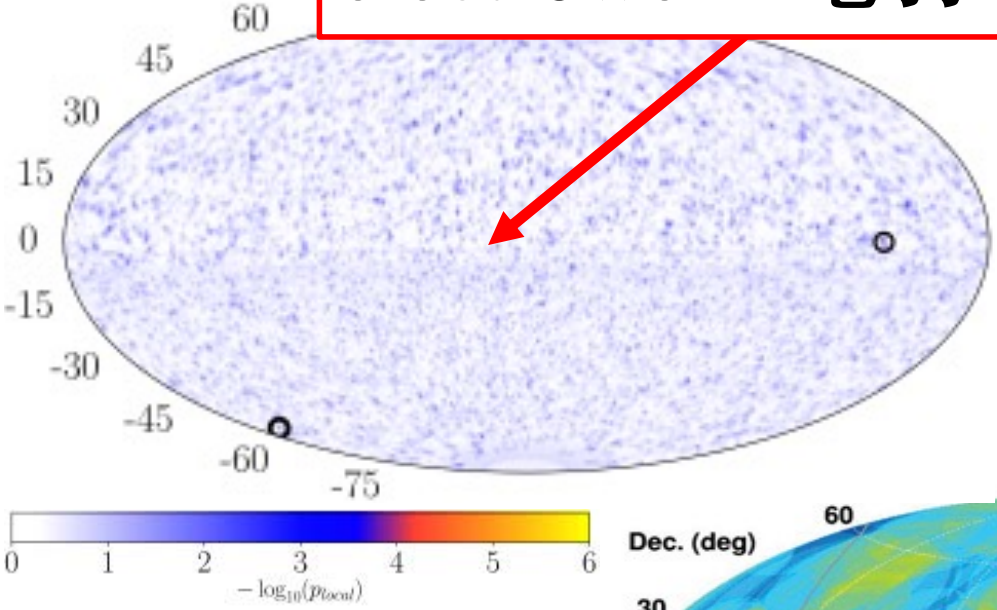


neutrinos

electroweak 電弱



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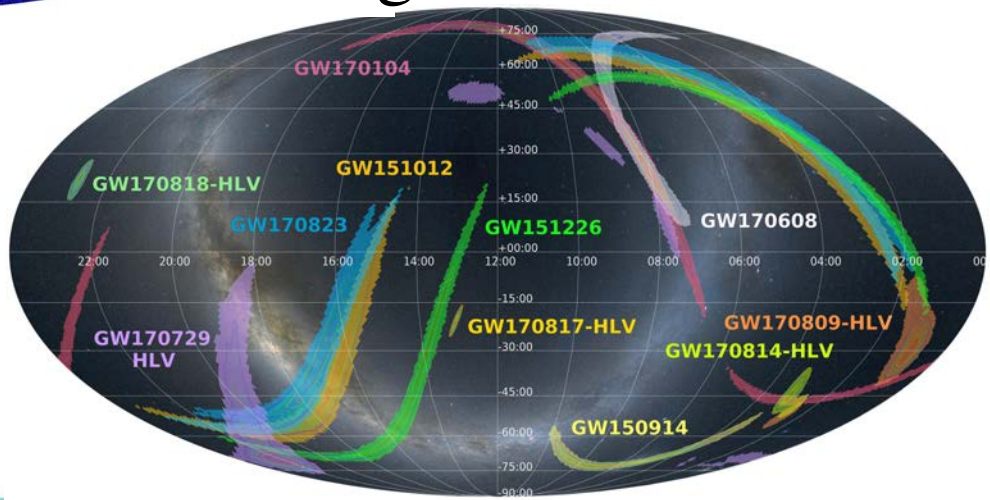

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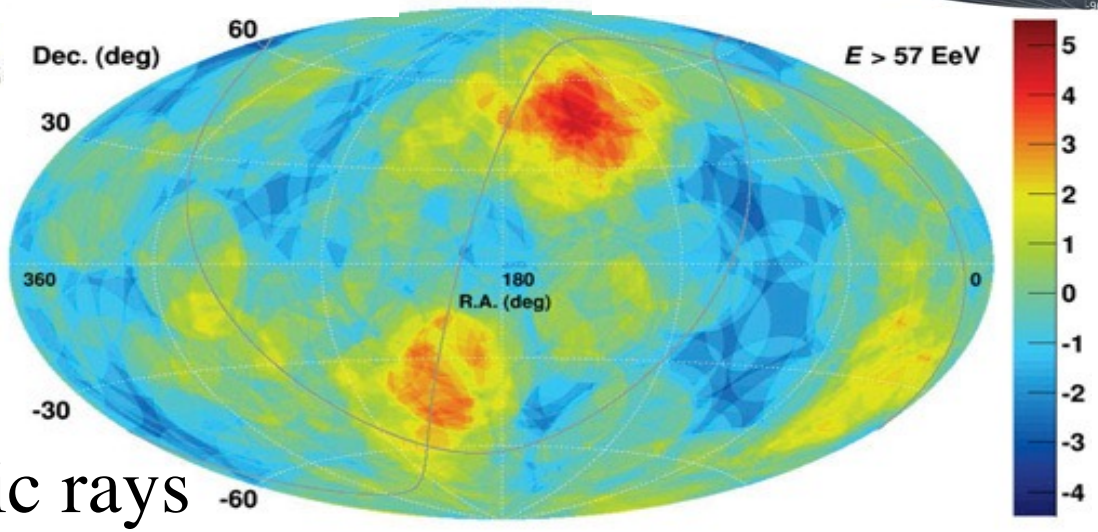

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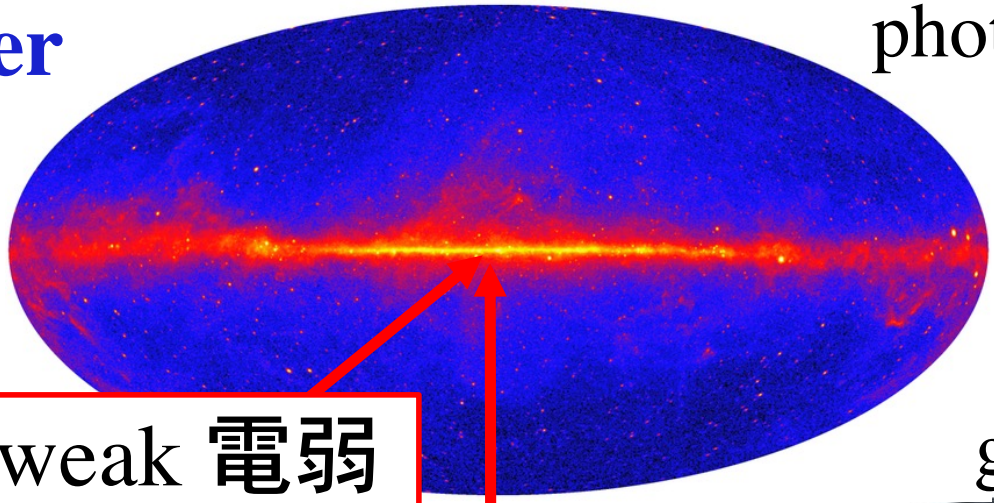
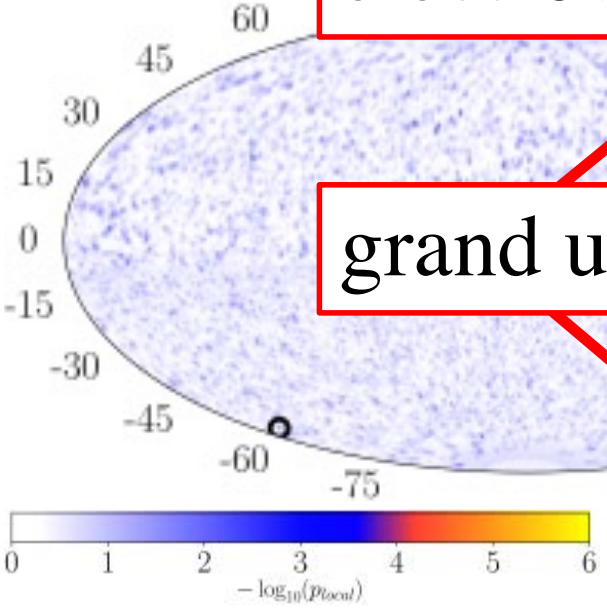


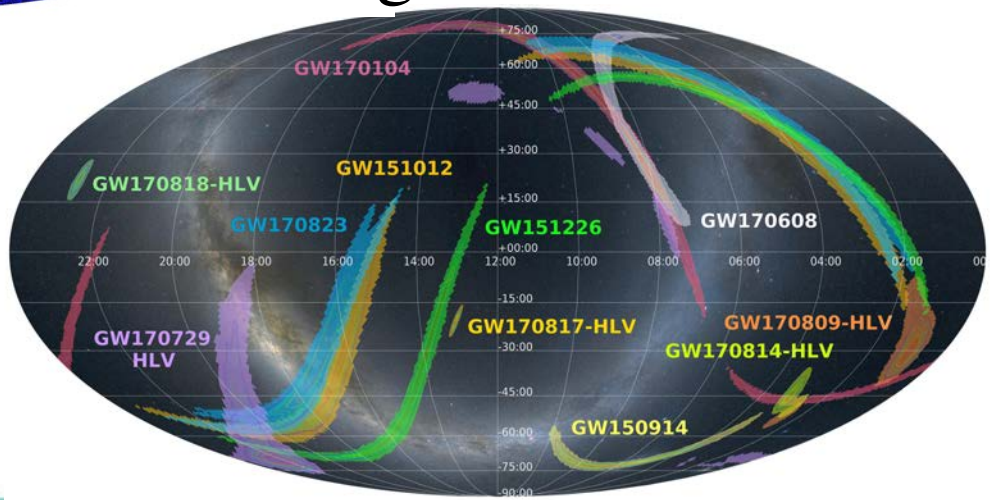
neutrinos



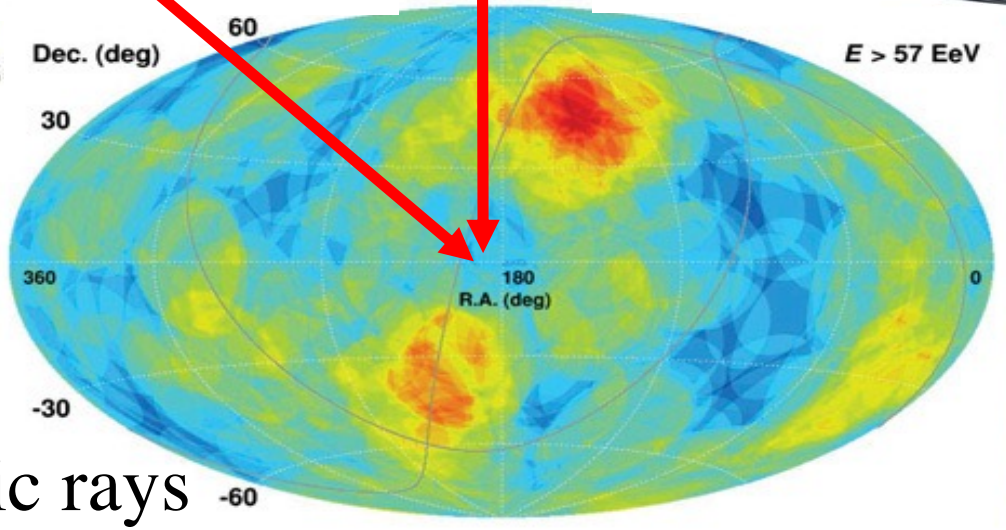
electroweak 電弱

grand unified 大統一

gravitational waves



cosmic rays



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classical unified -> electrogravitational?
古典統一 -> 電重?

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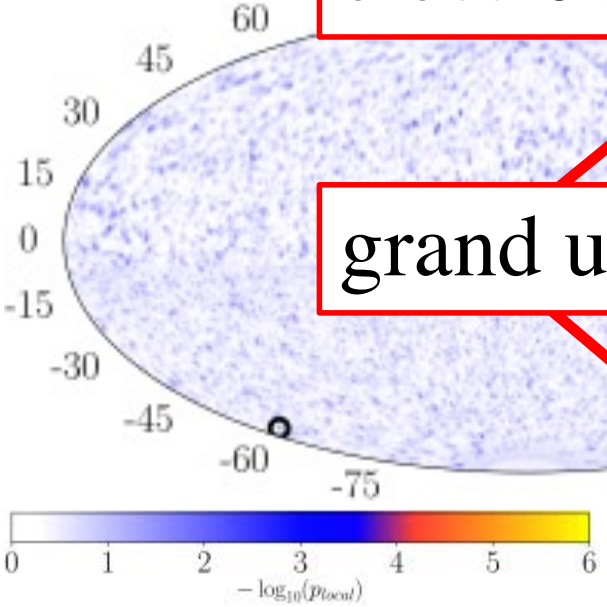
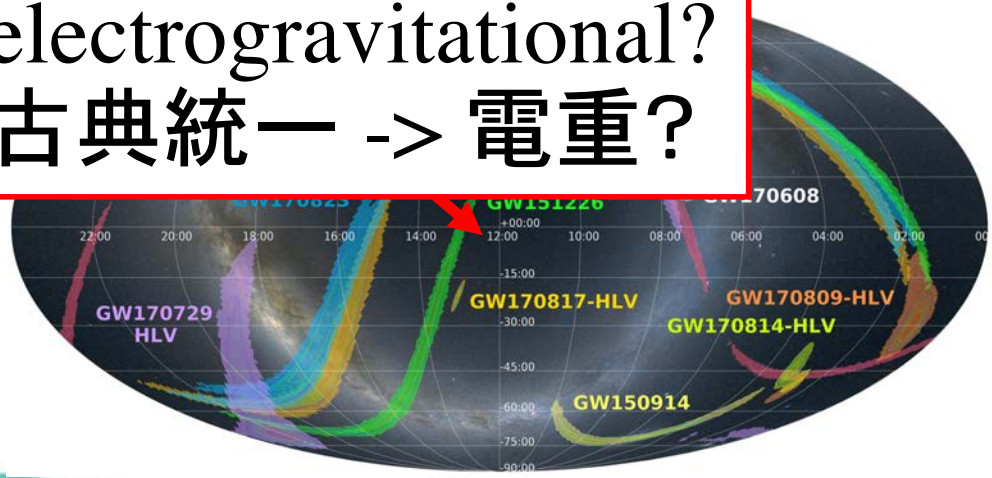
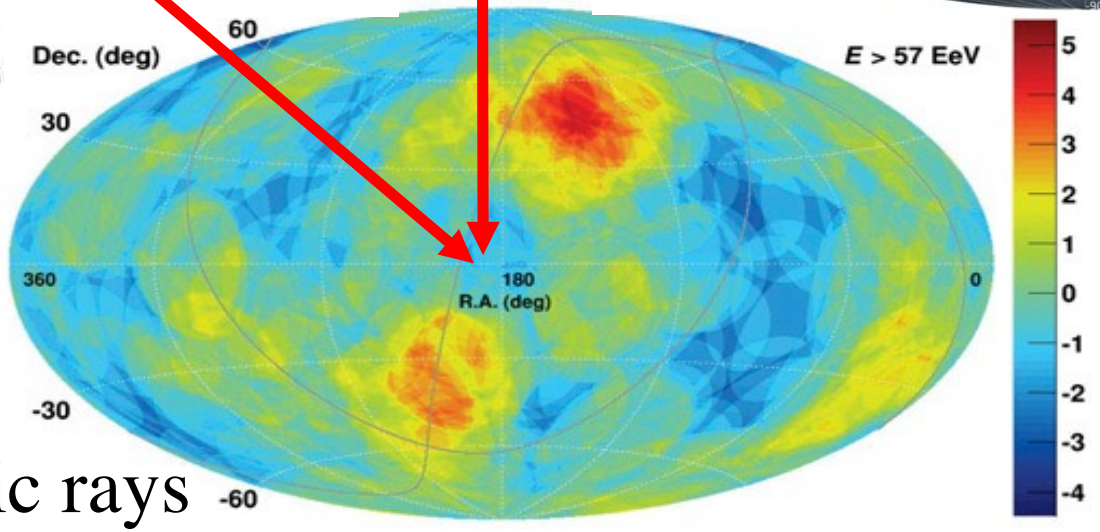
l waves







cosmic rays

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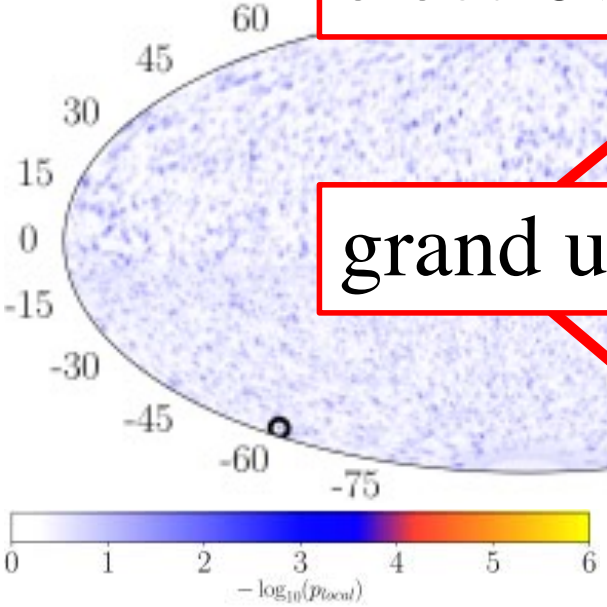
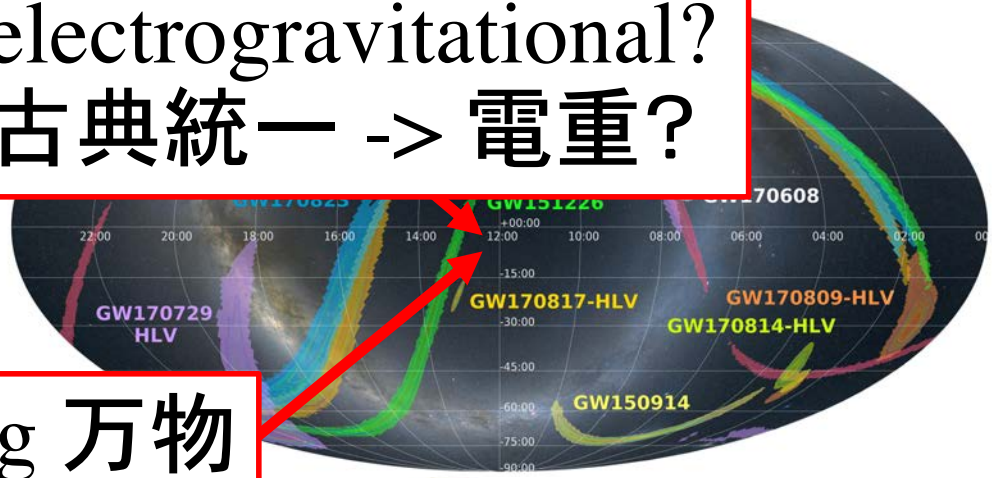
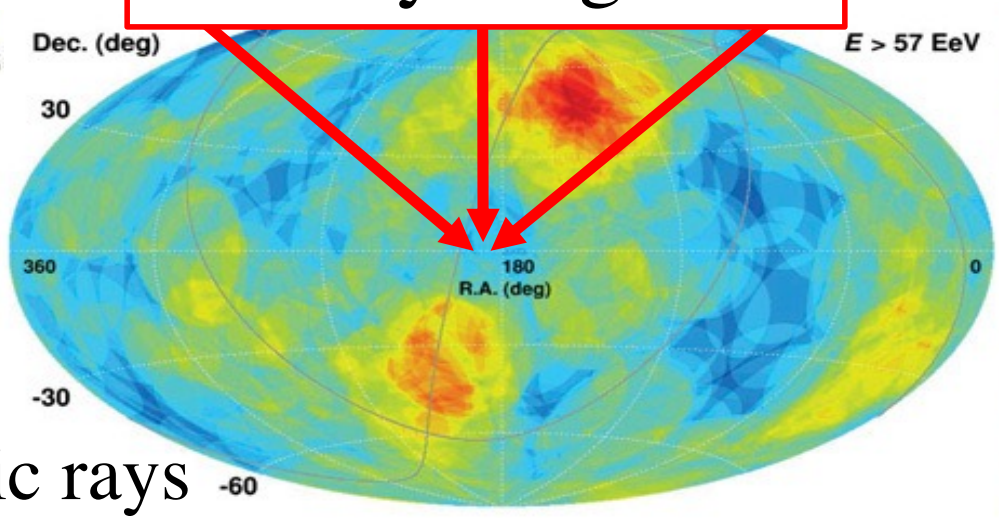
of everything 万物

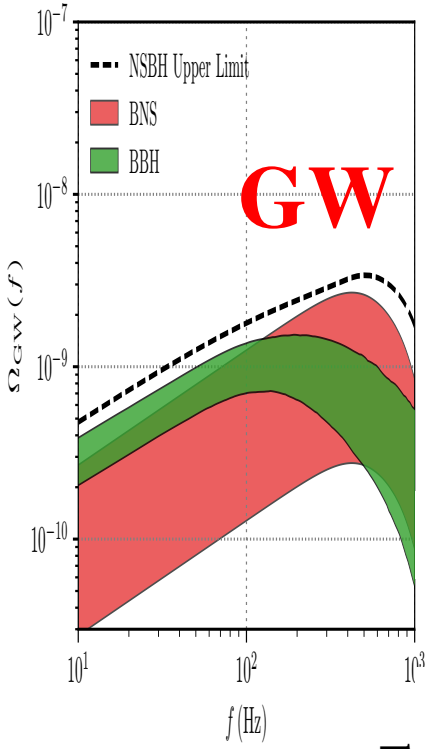
cosmic rays





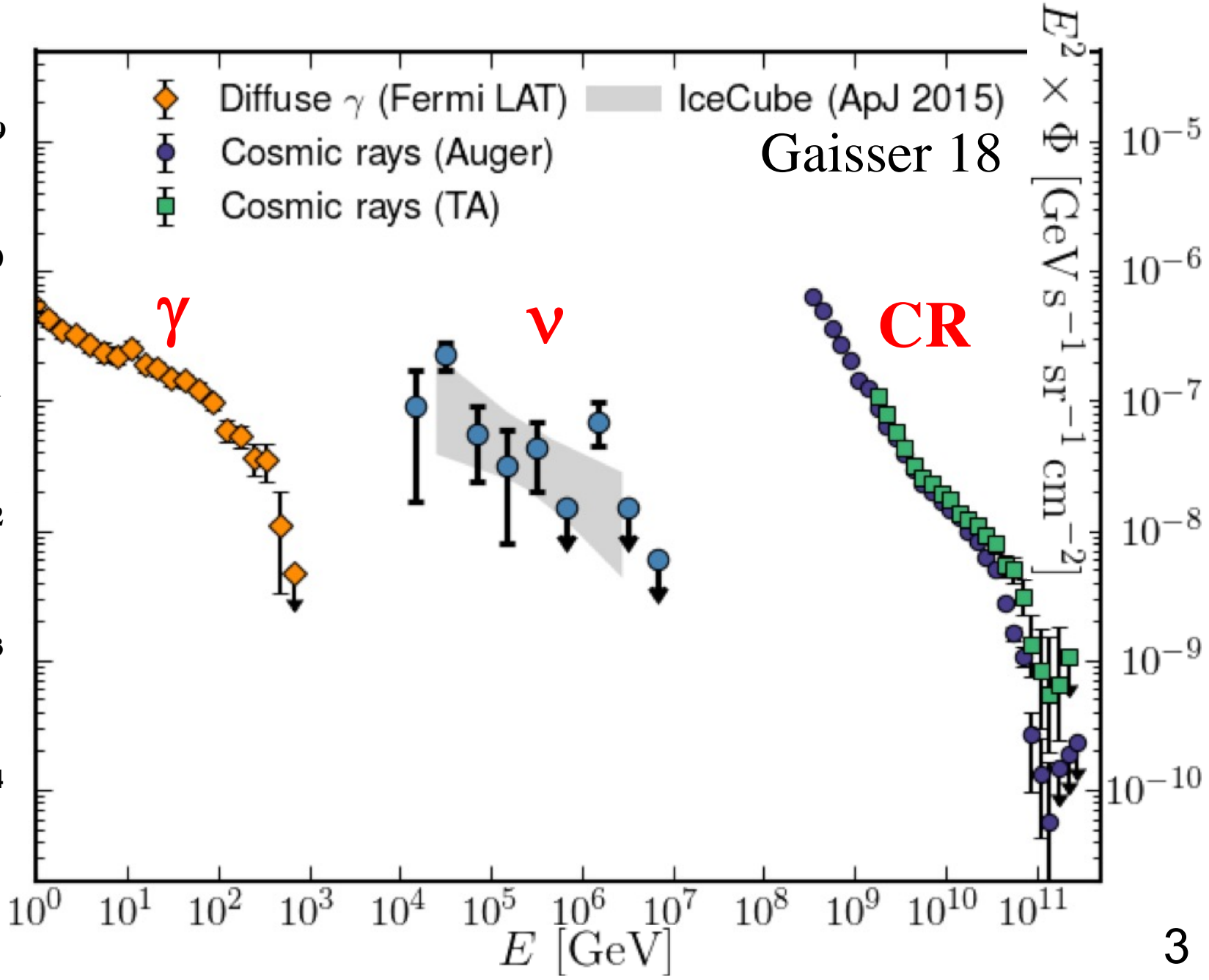


multi-messenger backgrounds



LIGO 21

Ω_{bkgd}



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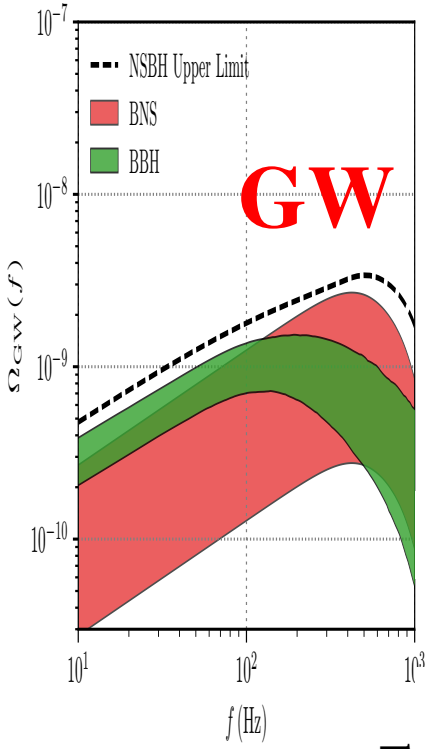

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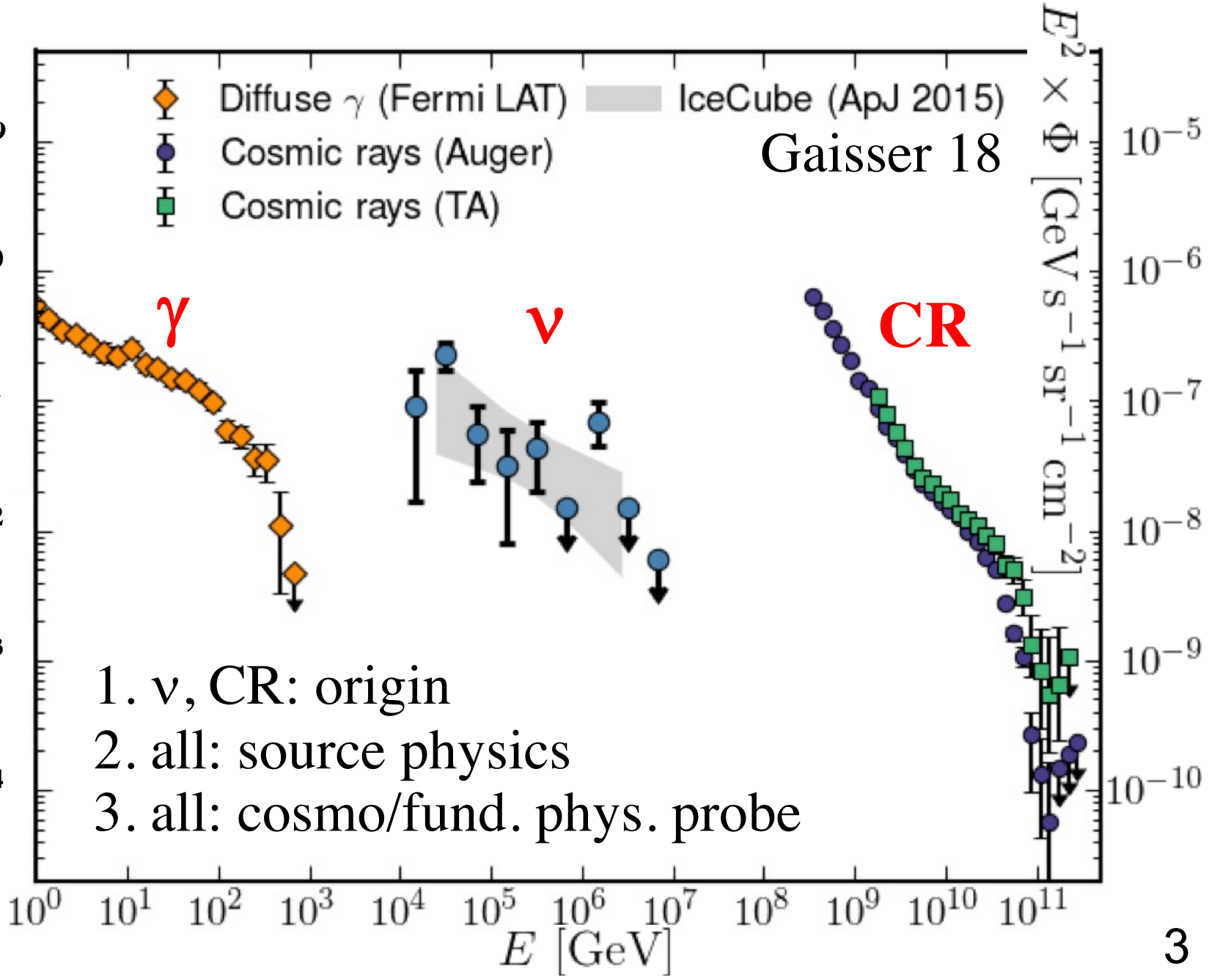
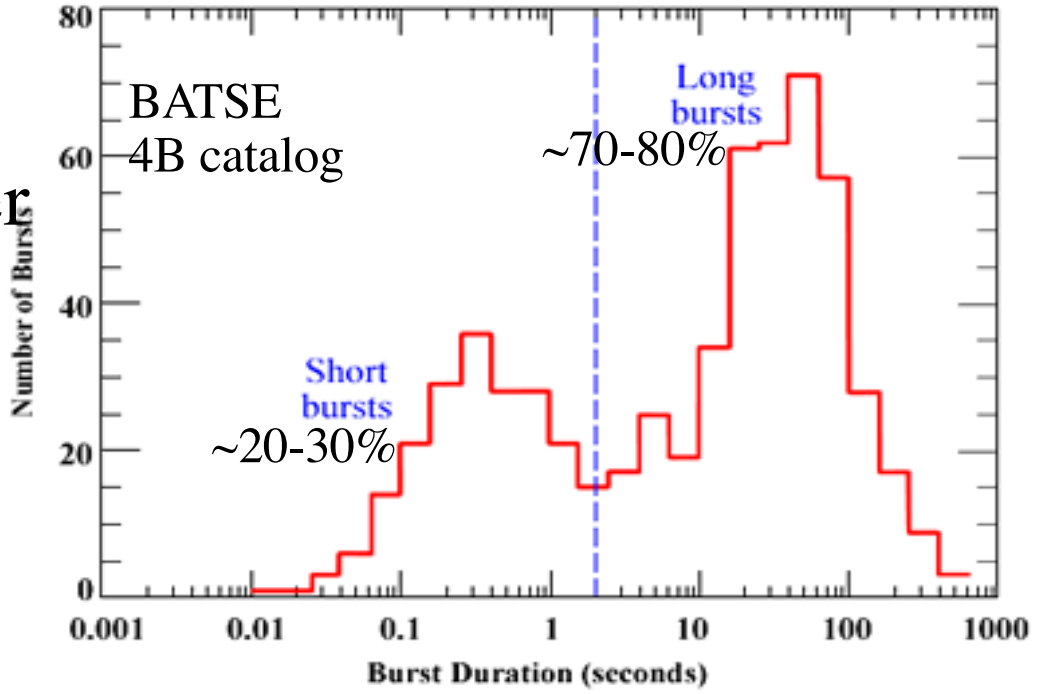
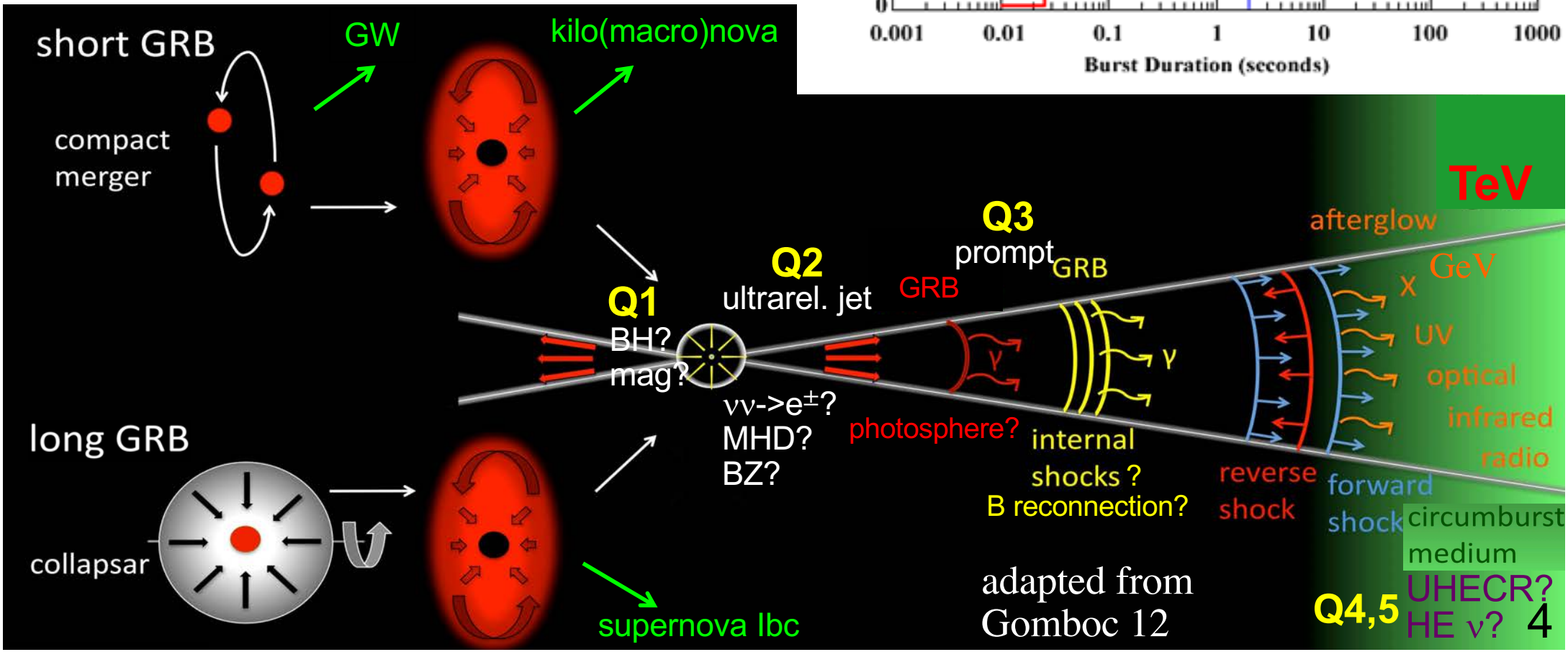


GRBs: key facts & questions

long (>~2s): massive star collapse
short (~<2s): compact binary merger
-> ultrarelativistic jets
-> prompt: X-MeV
+ afterglow: radio-opt-X-GeV-TeV
(low-luminosity: ?)





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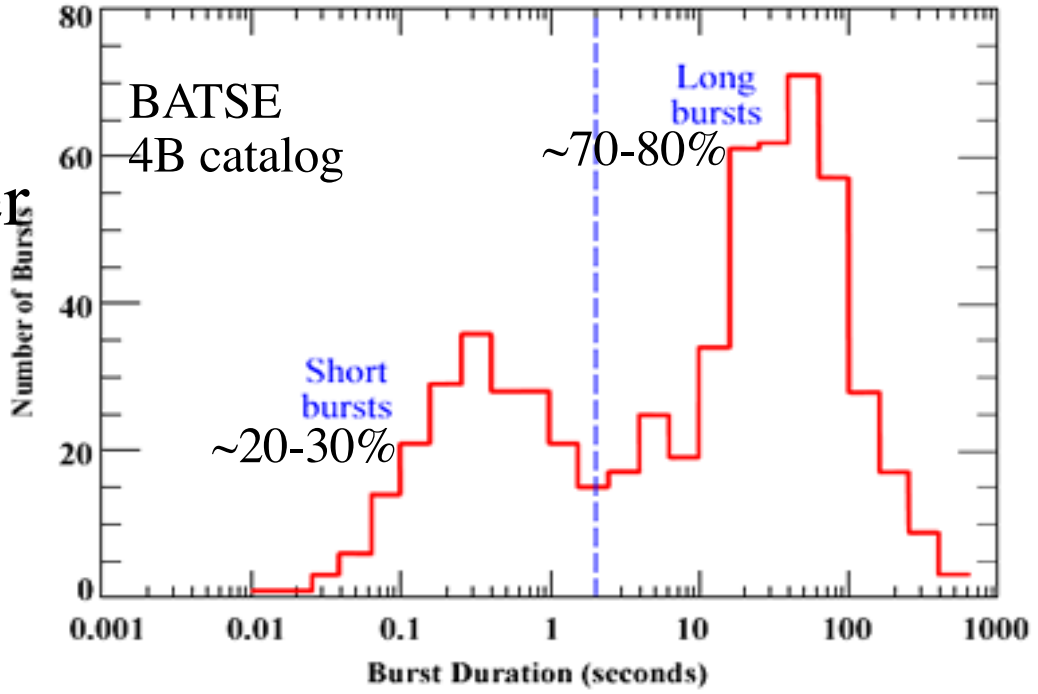

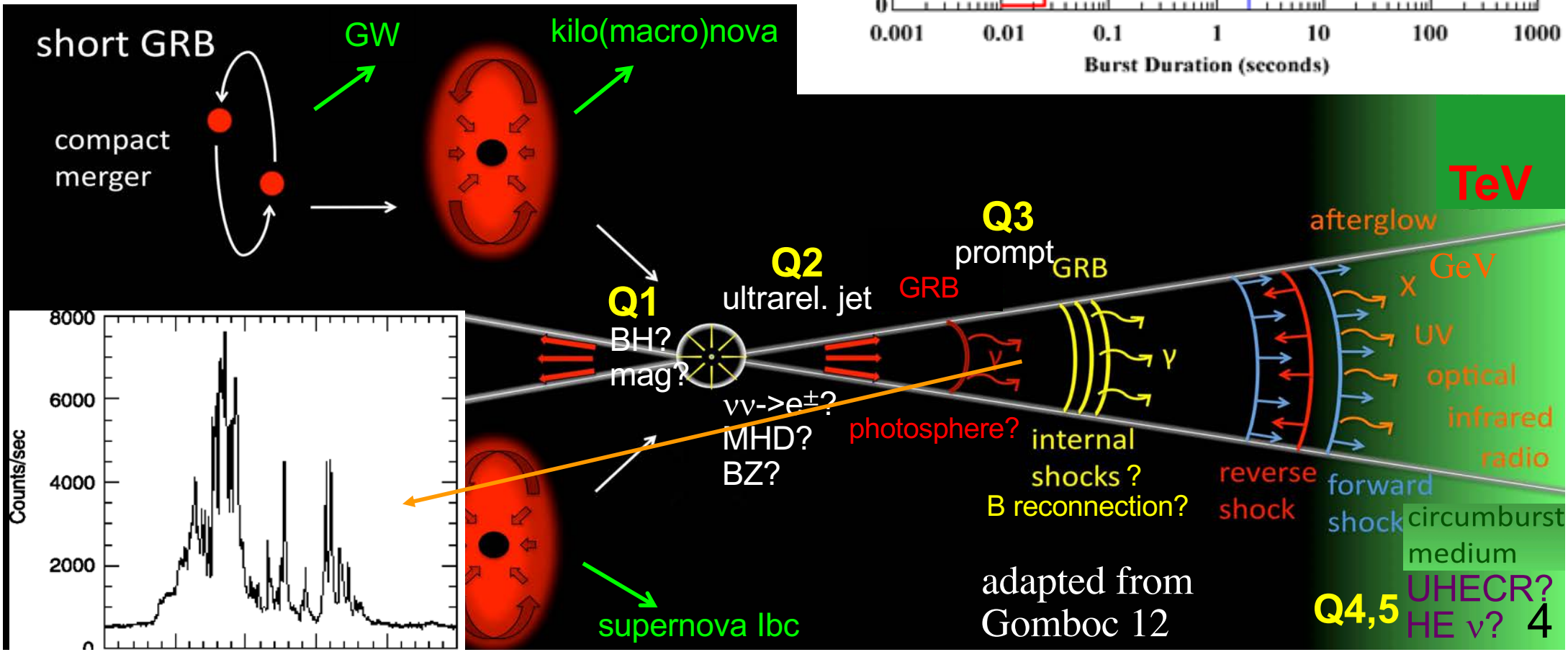

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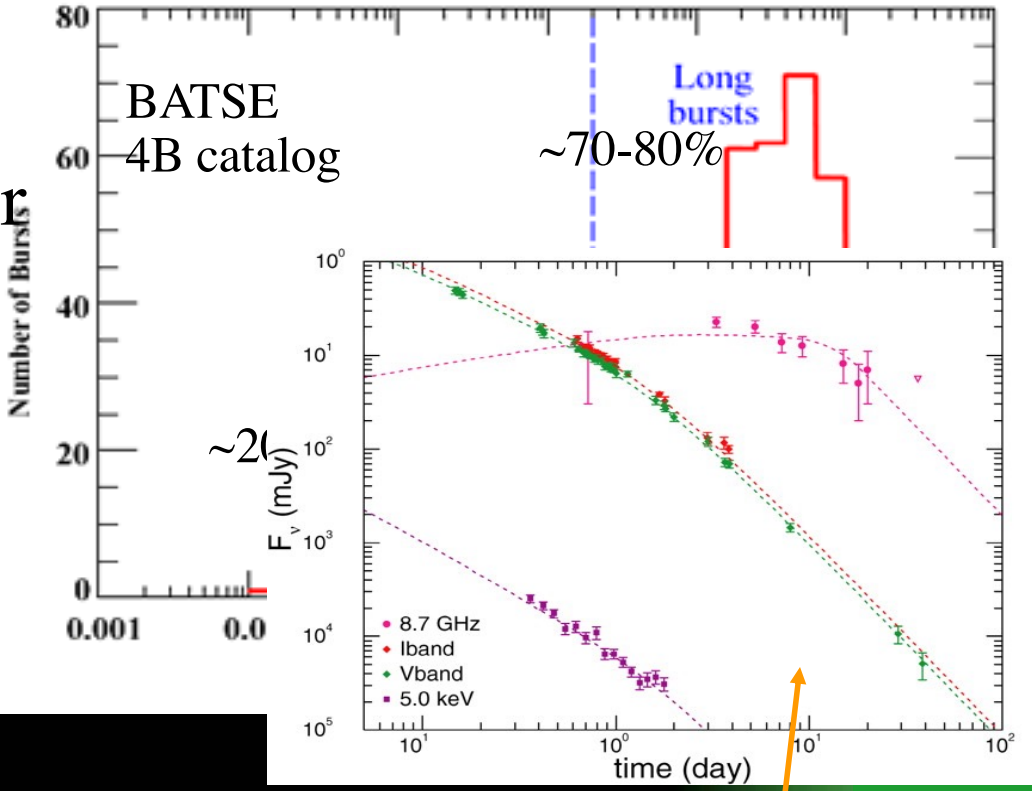
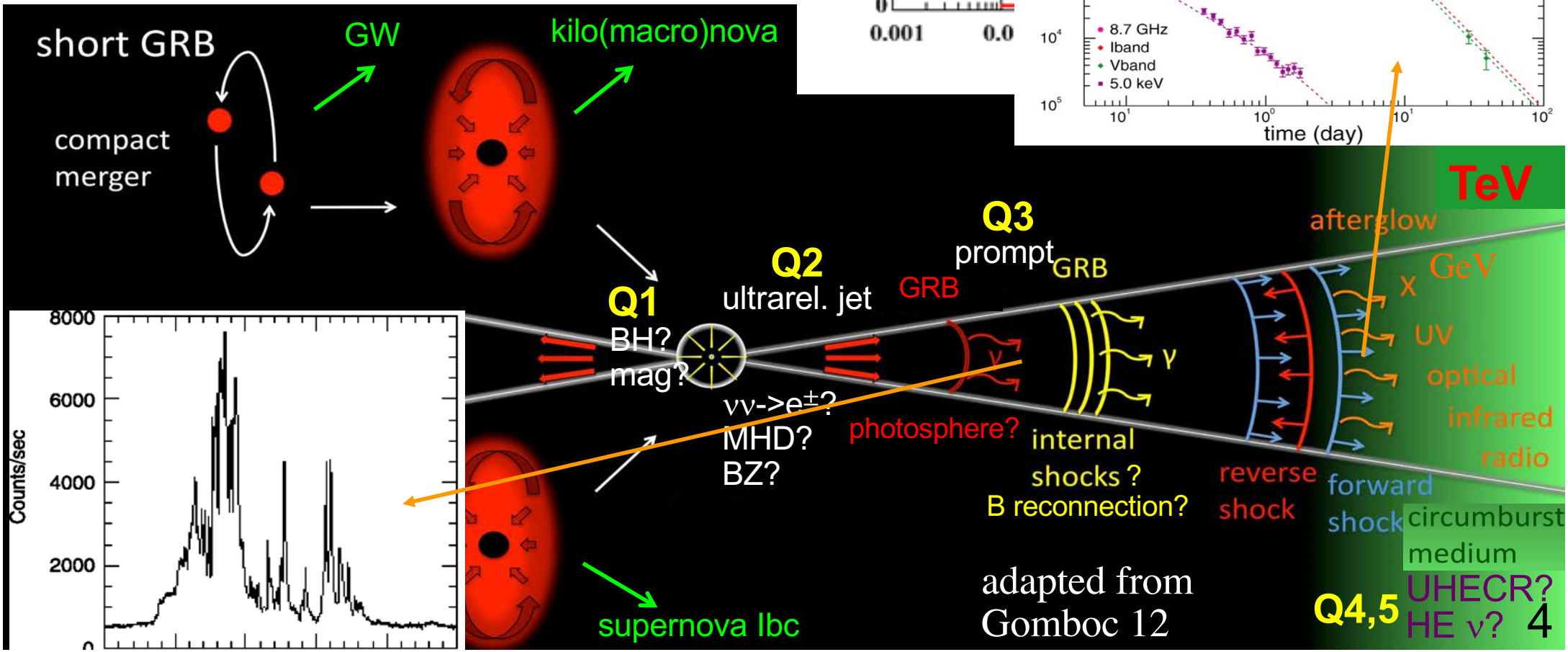
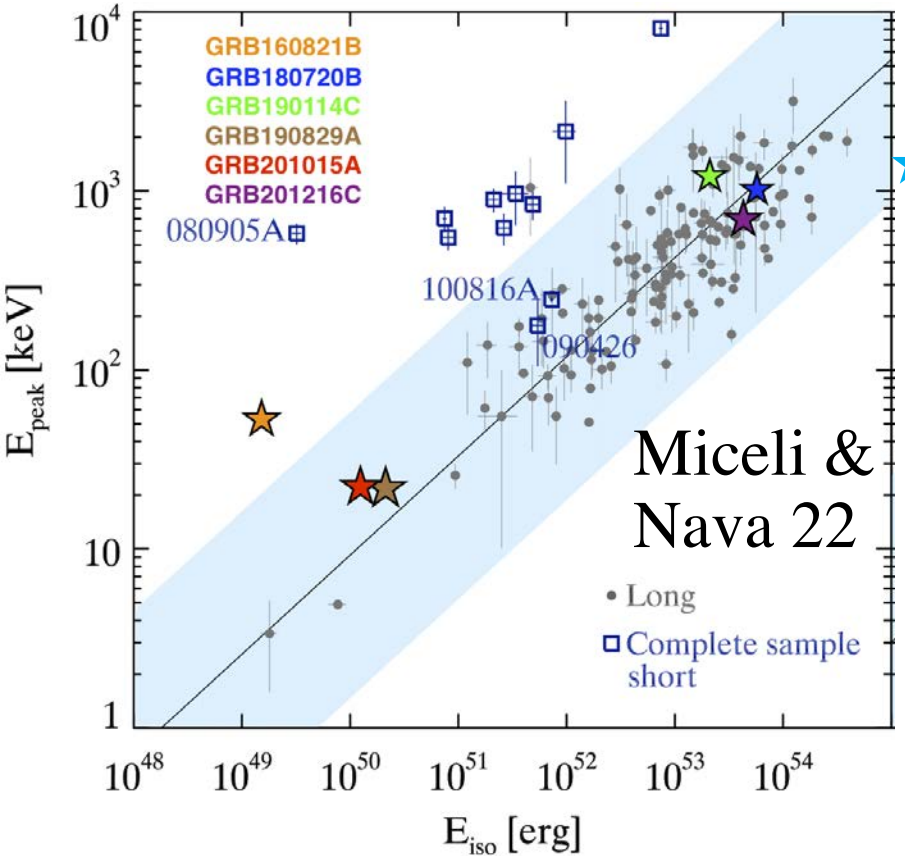




GRBs at TeV: latest EM window

		T_{90} s	$E_{\gamma,iso}$ erg	z	T_{delay} s	E_{range} TeV	IACT (Sign.)
short	160821B	0.48	1.2×10^{49}	0.162	24	0.5–5	MAGIC (3.1σ)
long	180720B	48.9	6.0×10^{53}	0.654	3.64×10^{4}	0.1–0.44	H.E.S.S. (5.3σ)
long	190114C	362	2.5×10^{53}	0.424	57	0.3–1	MAGIC (>50σ)
low-L	190829A	58.2	2.0×10^{50}	0.079	1.55×10^{4}	0.18–3.3	H.E.S.S. (21.7σ)
low-L	201015A	9.78	1.1×10^{50}	0.42	33	0.14	MAGIC (3.5σ)
long	201216C	48	4.7×10^{53}	1.1	56	0.1	MAGIC (6.0σ)
long	221009A	600	1.2×10^{55}	0.151	~226	0.2-13	LHAASO (>250σ)



★GRB 221009A

- diversity of GRB types:
  3 long (1 extremely high-L)
  1 short(?)
  2(?) low-L

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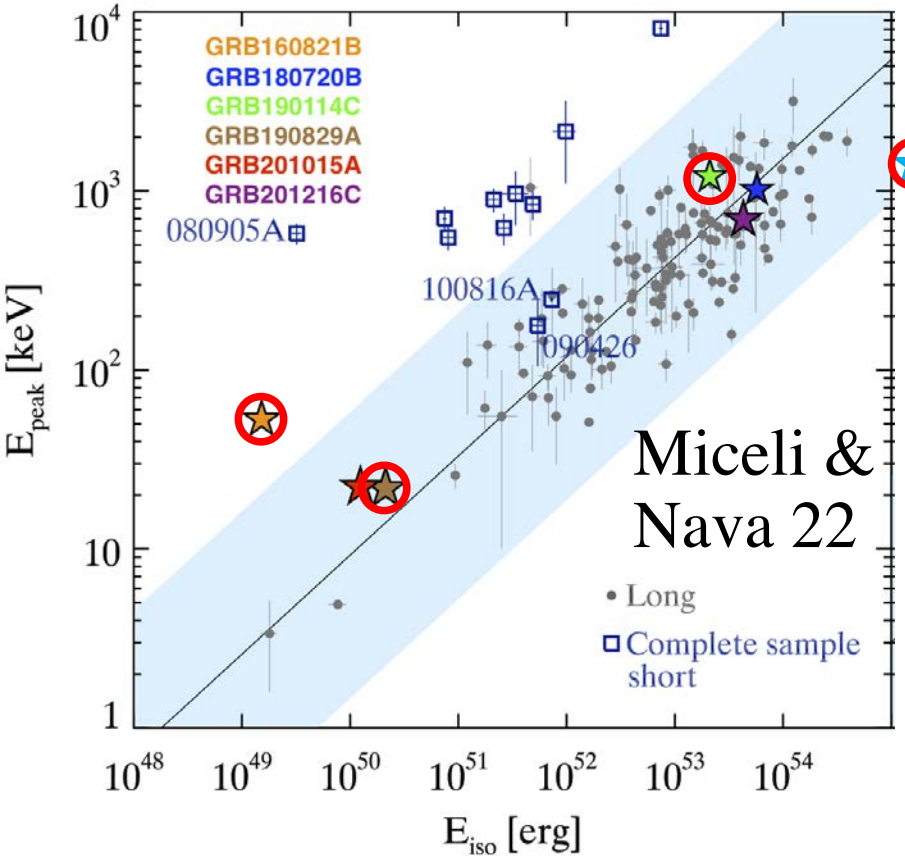

GRB 221009A

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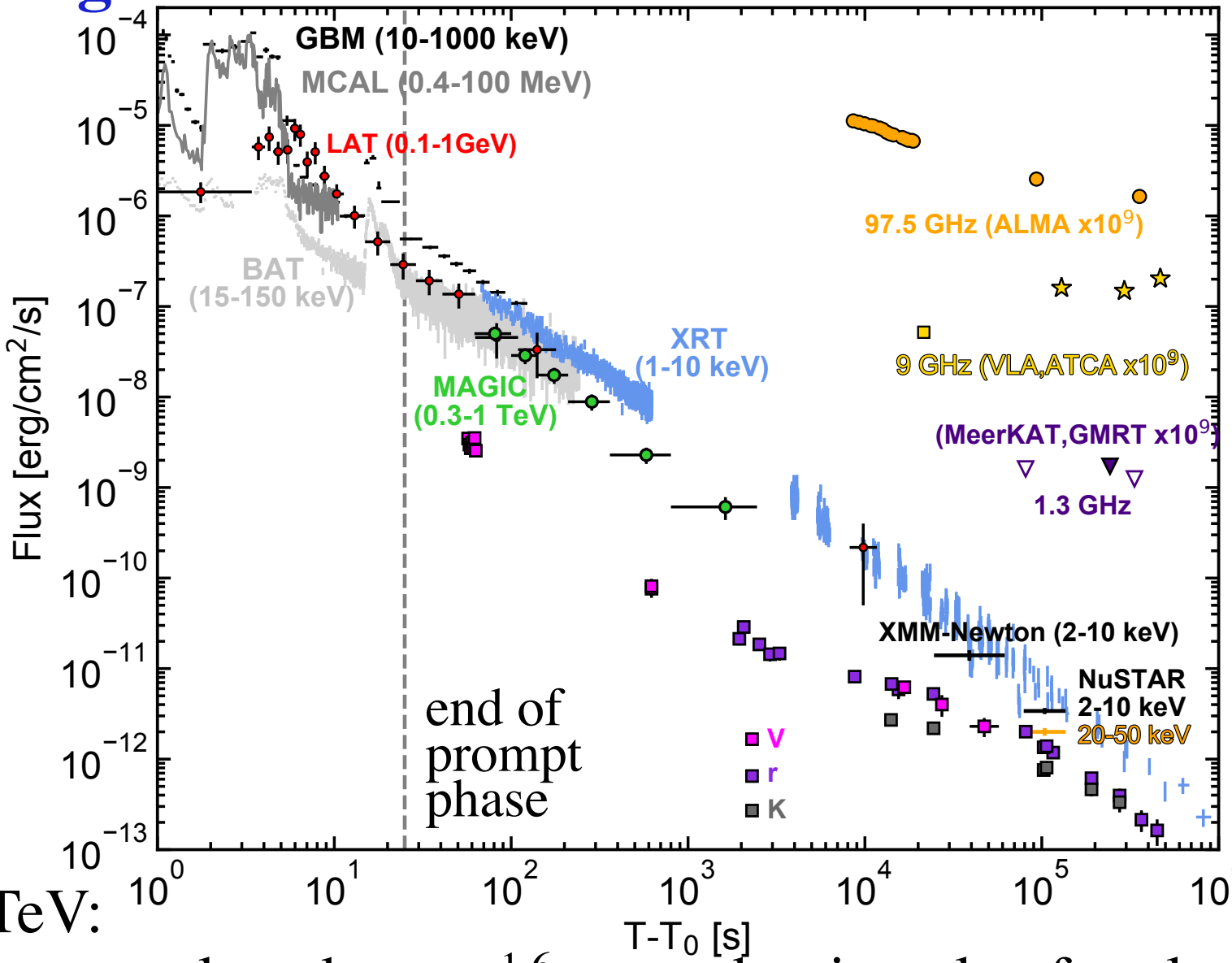
long GRB 190114C: TeV vs other wavelengths



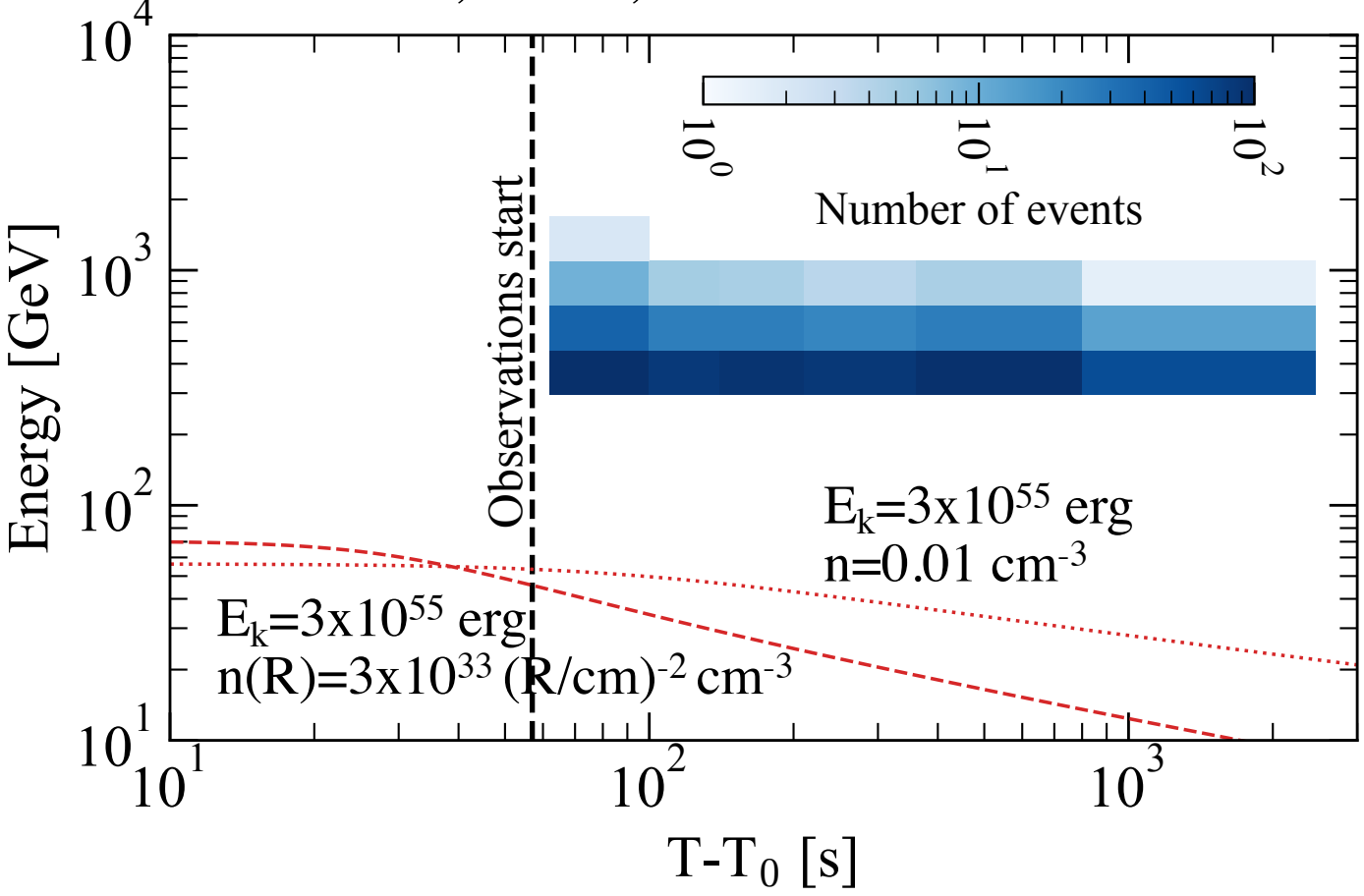
MAGIC Coll.+ 19
Nature 575, 459

>50σ detection
at 0.2-1 TeV
t~1-30 min

TeV:
- power-law decay $t^{-1.6}$ -> predominantly afterglow
- radiated power comparable to X-ray and GeV
- correlation with X-ray -> close relation with electron sync.

long GRB 190114C: photons beyond sync. burnoff limit

MAGIC Coll. 19, Nature 575, 455
corr. authors: SI, Noda, Berti+



maxi sync. photon energy for electrons dominated by sync. cooling

$\tau_{accel} \propto \gamma_e B^{-1}$, $\tau_{syn} \propto \gamma_e^{-1} B^{-2}$

$\tau_{accel}=\tau_{syn}$ -> $\gamma_{e,max} \propto B^{-1/2}$

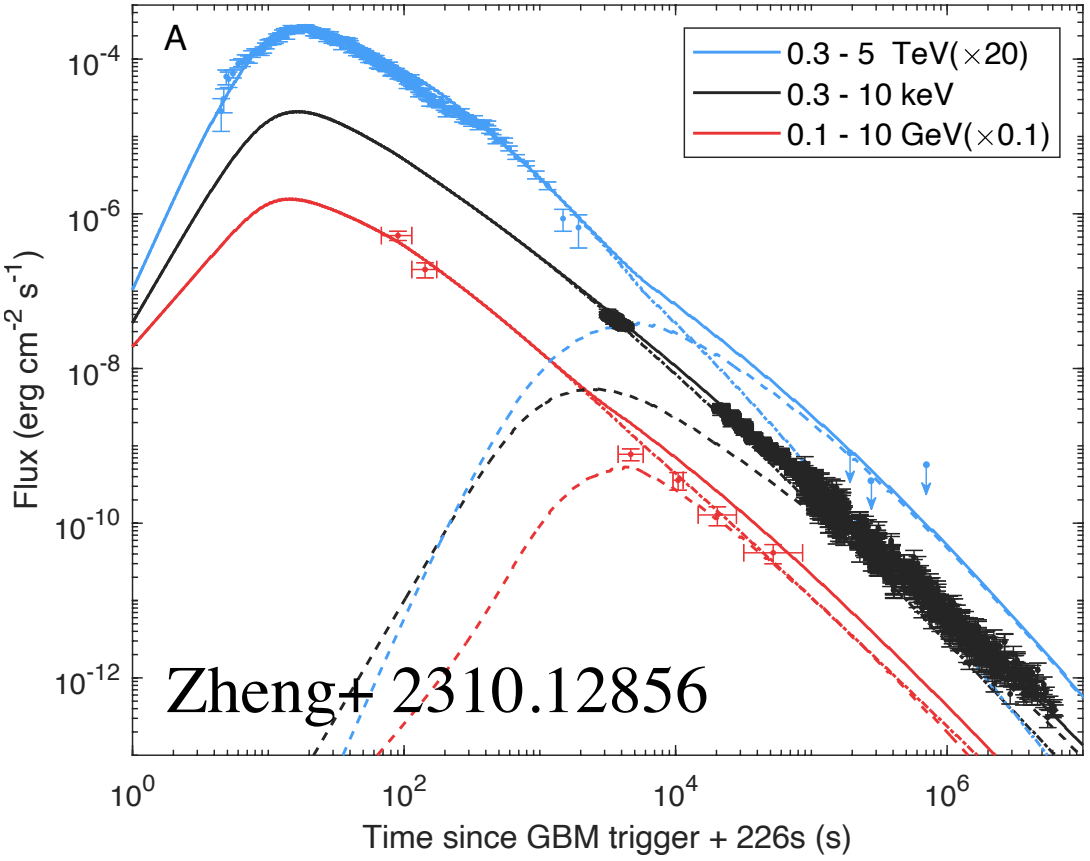
$\nu_{syn,max} \propto B\gamma_{e,max}^2$

$E_{syn,max} \sim 2^{3/2}[27/(16\pi\alpha_f)]m_e c^2$
x $\Gamma(t)(1+z)^{-1}$
$\sim 106\ \Gamma(t)(1+z)^{-1}$ MeV

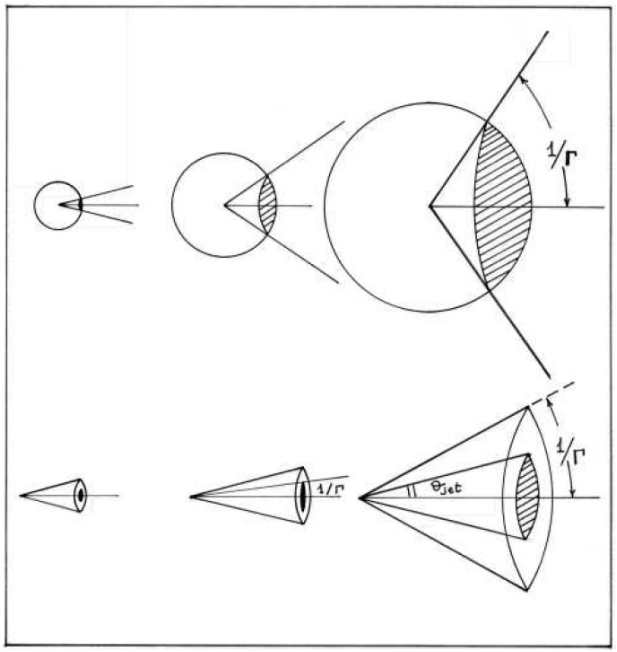
Nakar & Piran 10
c.f. Kumar+ 12

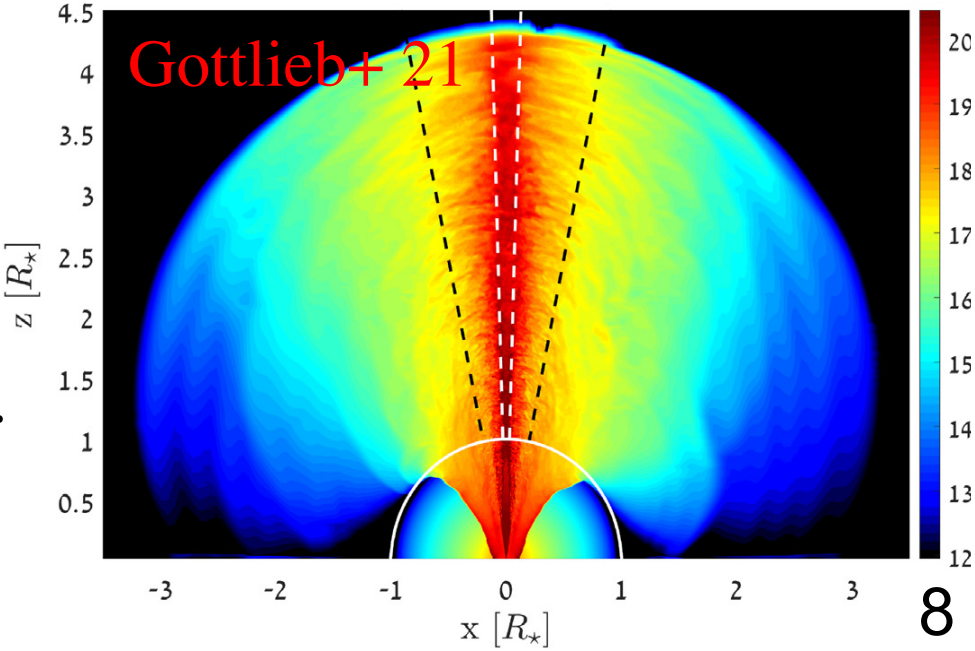
- observed photon energies >> plausible estimates of $E_{syn,max}$
  -> strong evidence for emission separate from sync.
- likely synchrotron-self-Compton (SSC)
  -> valuable new info on physics of rel. shocks, particle accel.

long GRB 221009A: strong evidence for a structured jet



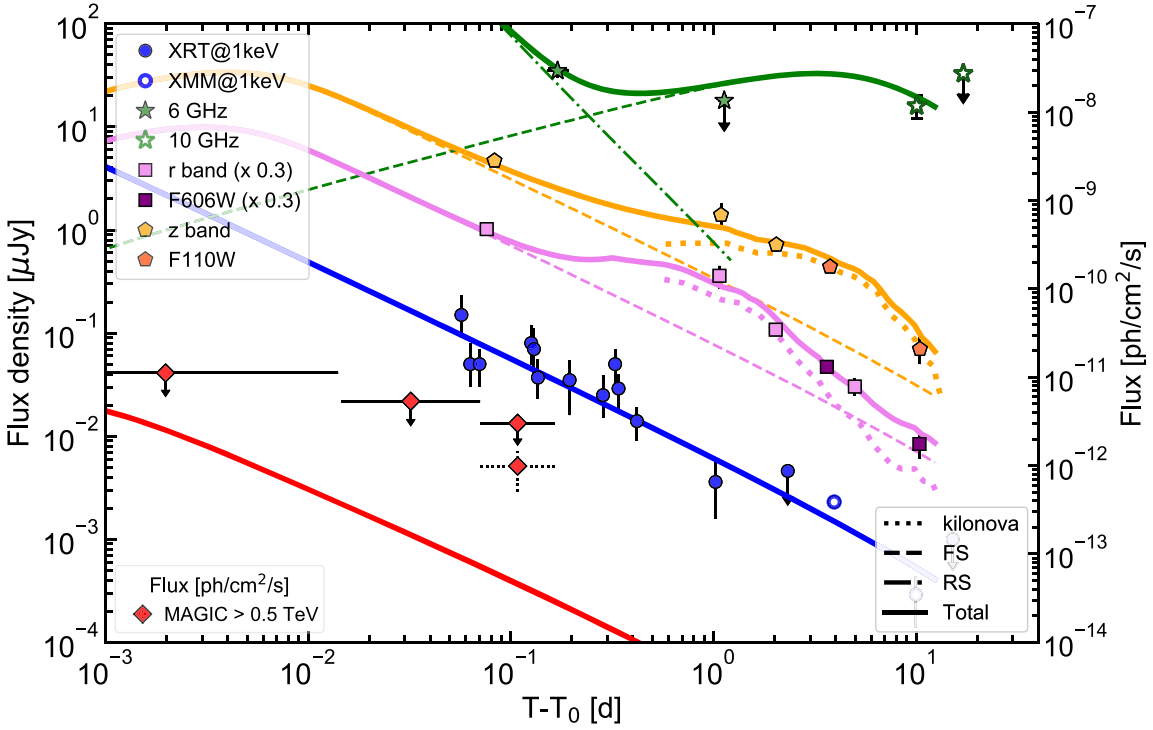
jet break in light curve





- LHAASO light curves similar in different energy bands (achromatic) -> jet break in a narrow inner jet
- later time emission from wider outer jet (consistent with simulations)

short GRB 160821B



MAGIC Coll. 21, ApJ 908, 90
corr. authors: Nava, Noda, SI

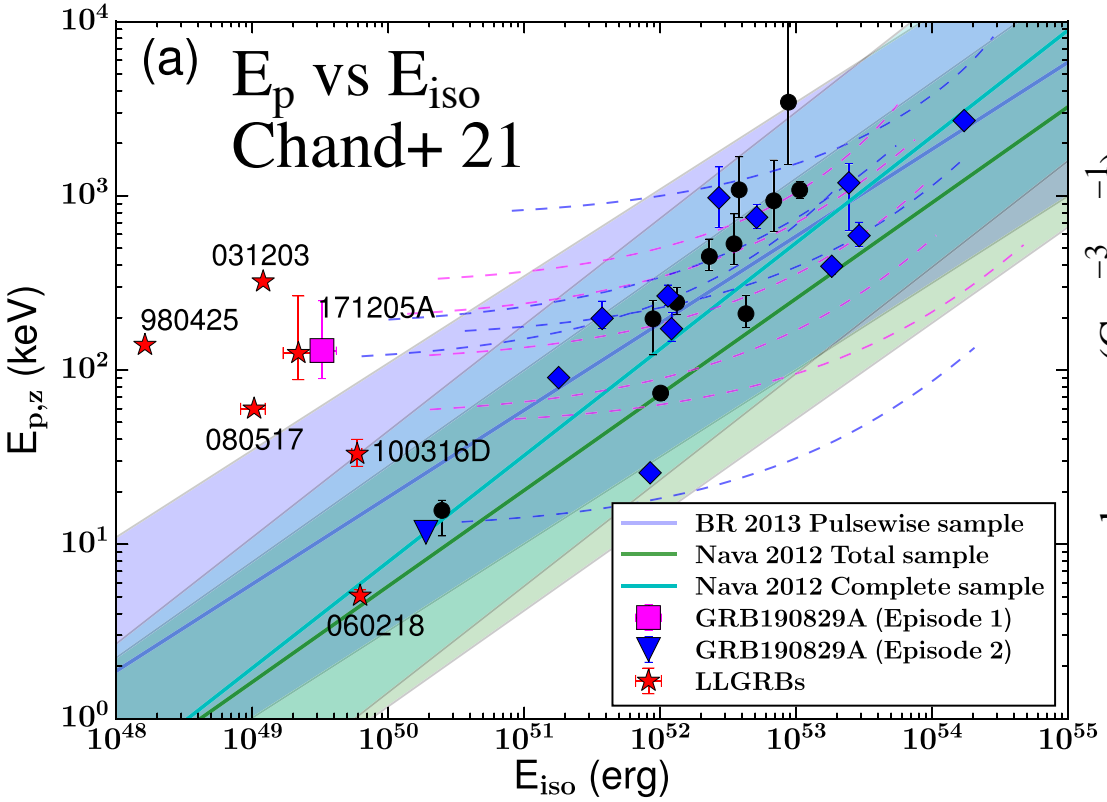
- typical short GRB (z,T_{90},E_{iso})
- opt.-NIR: kilonova
  X-ray: extended + plateau emission
- TeV: 3.1σ hint of signal at t~1.5-4h
- IF signal real, exceeds simple SSC -> external IC?

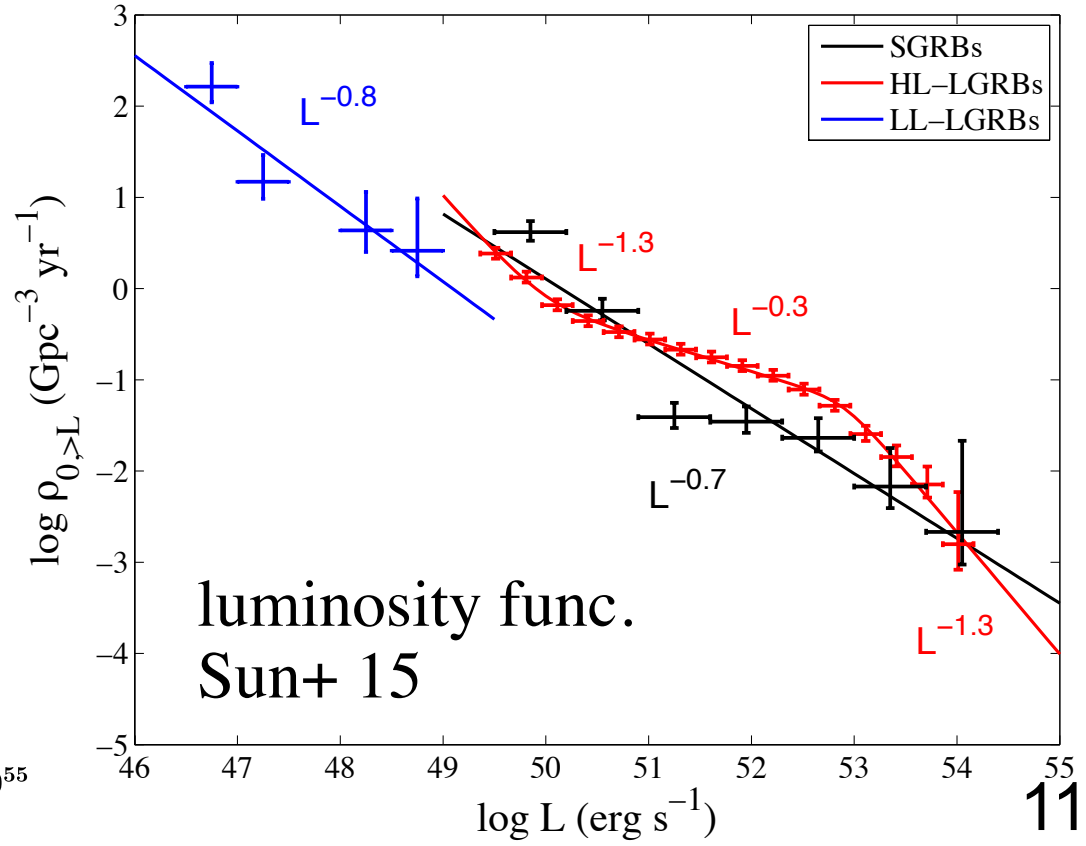
Zhang+ 21

future implications for TeV
- aid in disentangling kilonova in short GRBs
- potential counterparts of NS mergers in GW
  -> more info on jet physics

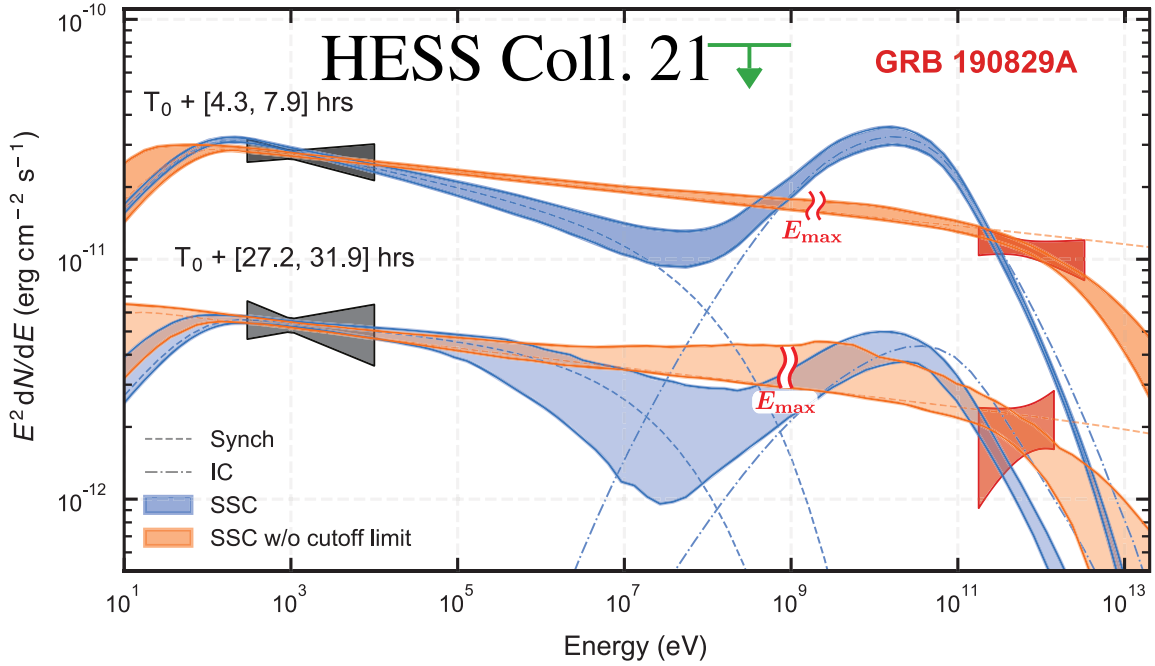
low-luminosity GRBs

- only dozen or so known, class possibly distinct from long GRBs
- basic nature unknown: off axis? dirty fireballs? shock breakout?
- integrated energetics possibly dominant over high-L GRBs
  -> potential HE neutrino/UHECR sources,
  more promising than high-L GRBs

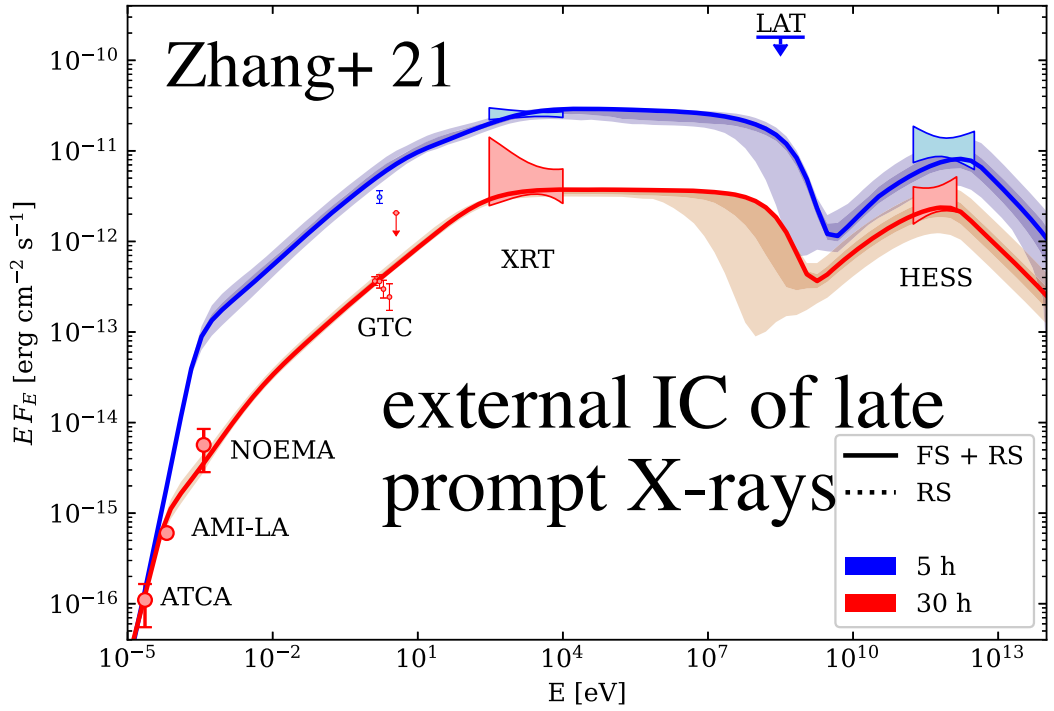




low-luminosity GRB: 190829A



- TeV detection at t~4.3-56 h
- t evolution similar to X-rays
  - TeV spectrum inconsistent with SSC?
  - extension of synchrotron, significantly exceeding burnoff limit?

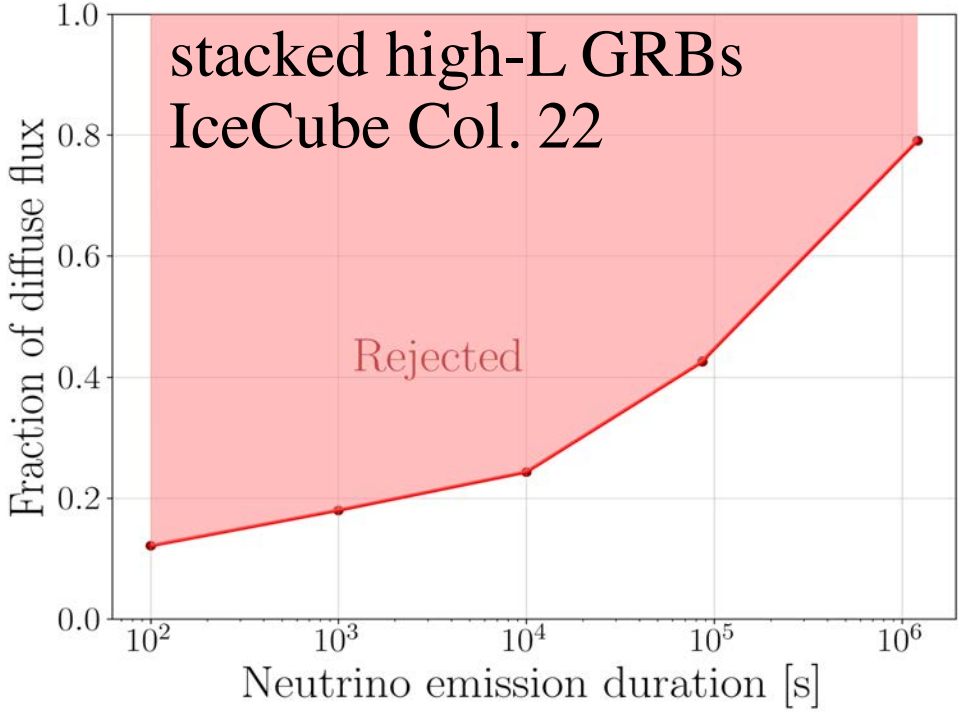


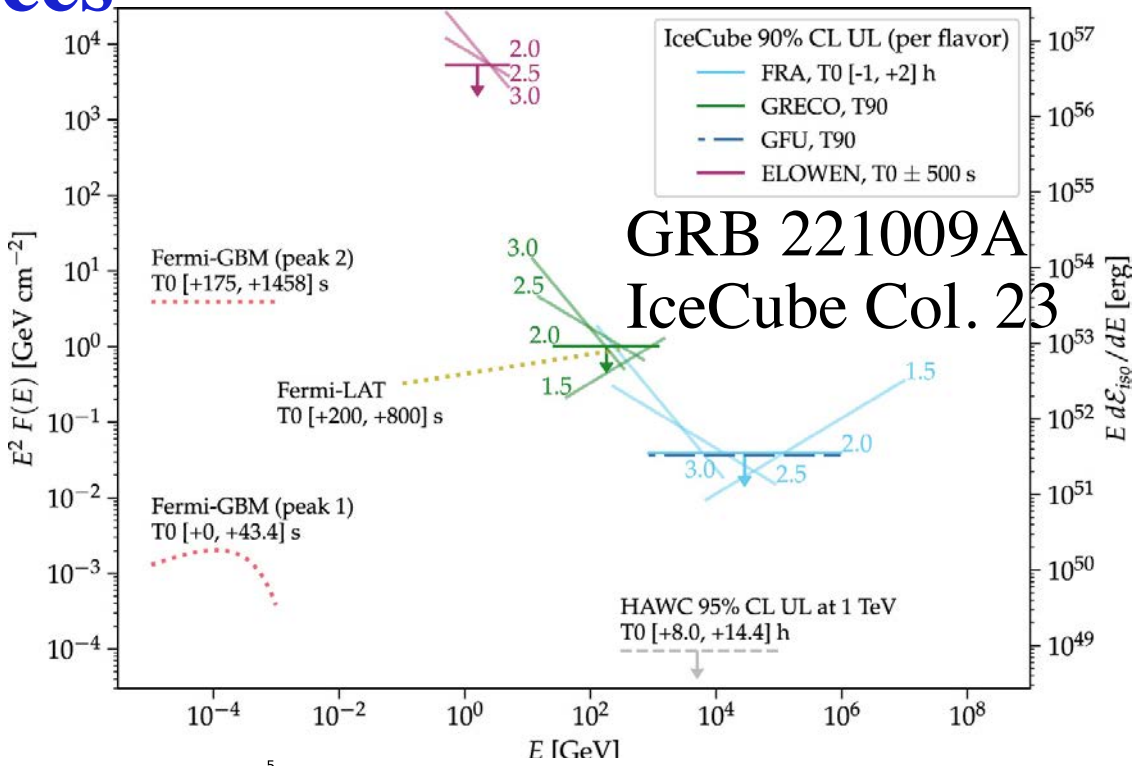
new insight into:
- physical nature of low-L GRBs
- relevance as sources of neutrinos, UHECRs

GRB with abnormally low prompt efficiency?

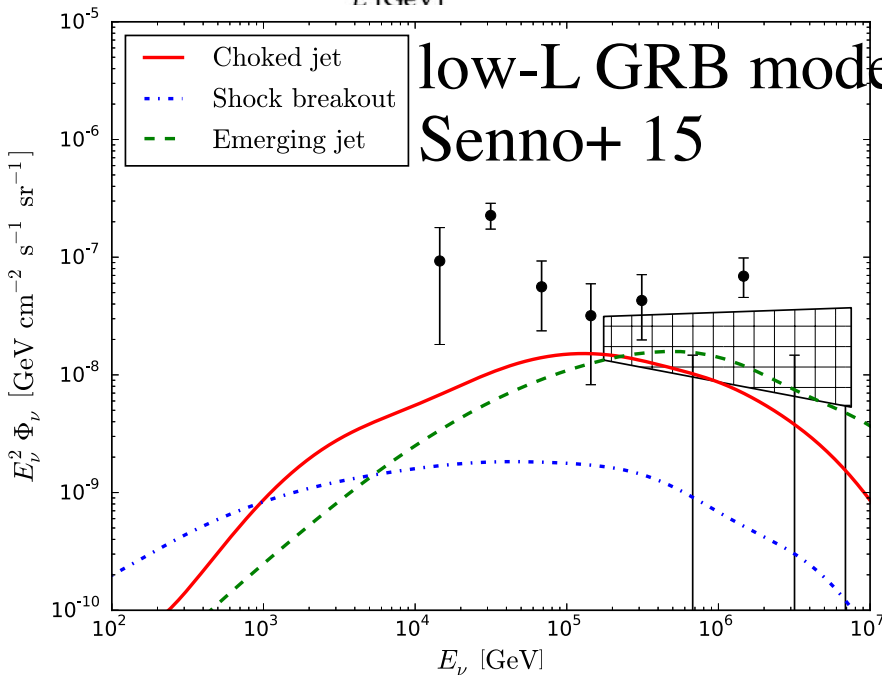
Zhang+ 21, also Salafia+ 22

GRBs as HE neutrino sources



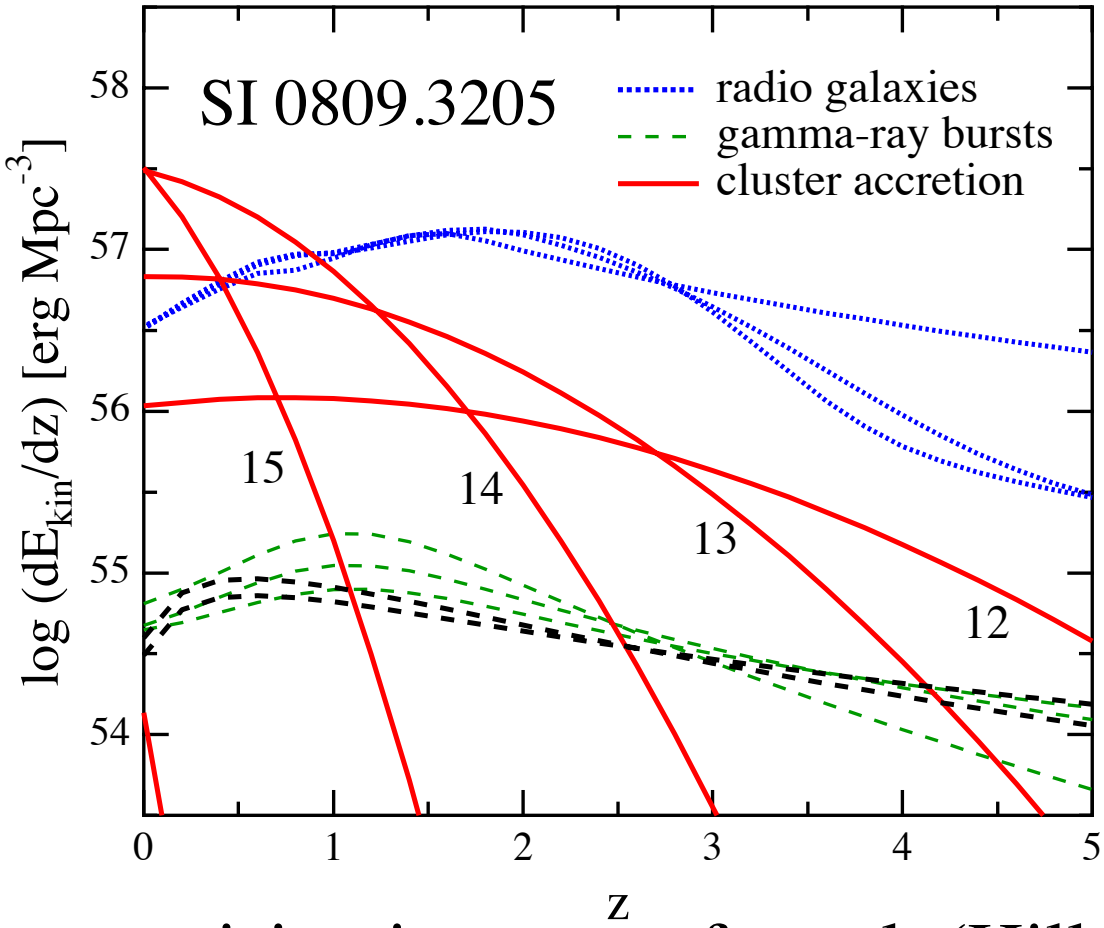


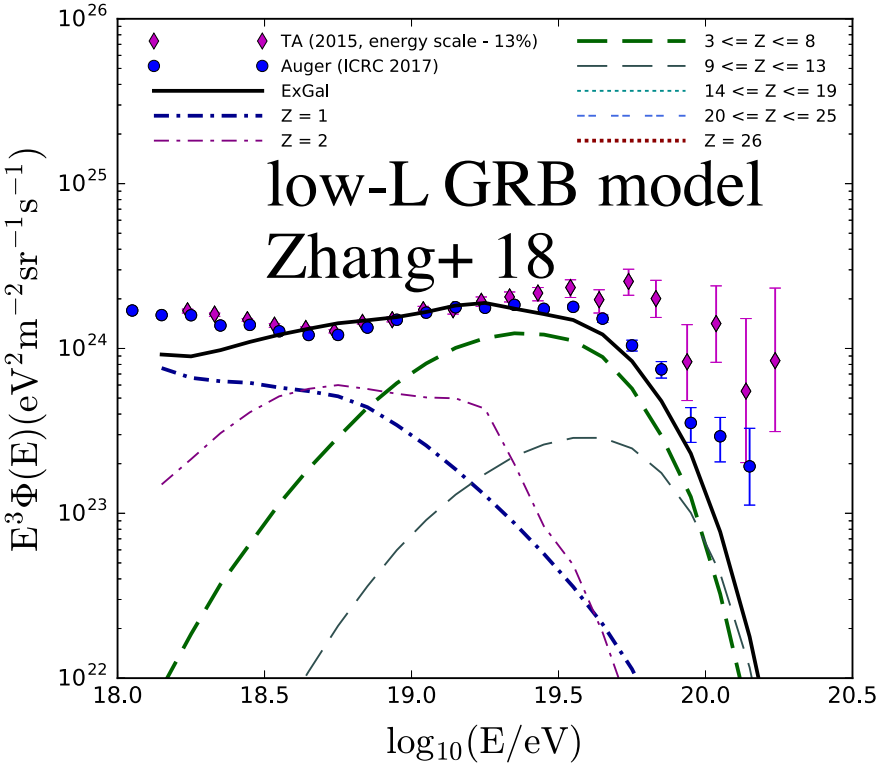
- promising in terms of proton accel., ν production efficiency
- BUT high-L GRBs severely constrained by IceCube obs.
  -> low-L GRBs still viable
- EM signatures desirable

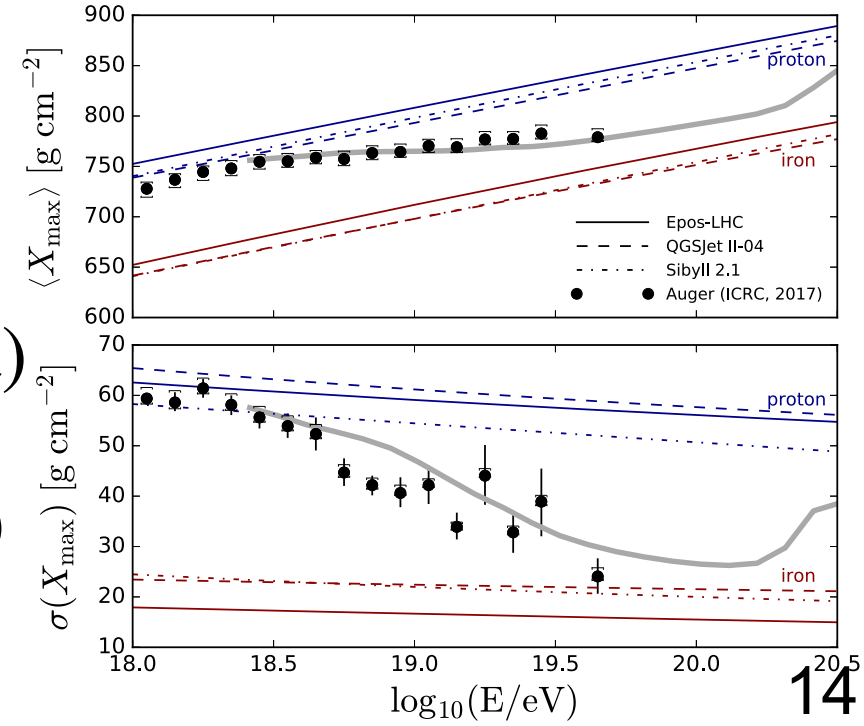


GRBs as UHECR sources

energetics of candidate UHECR sources

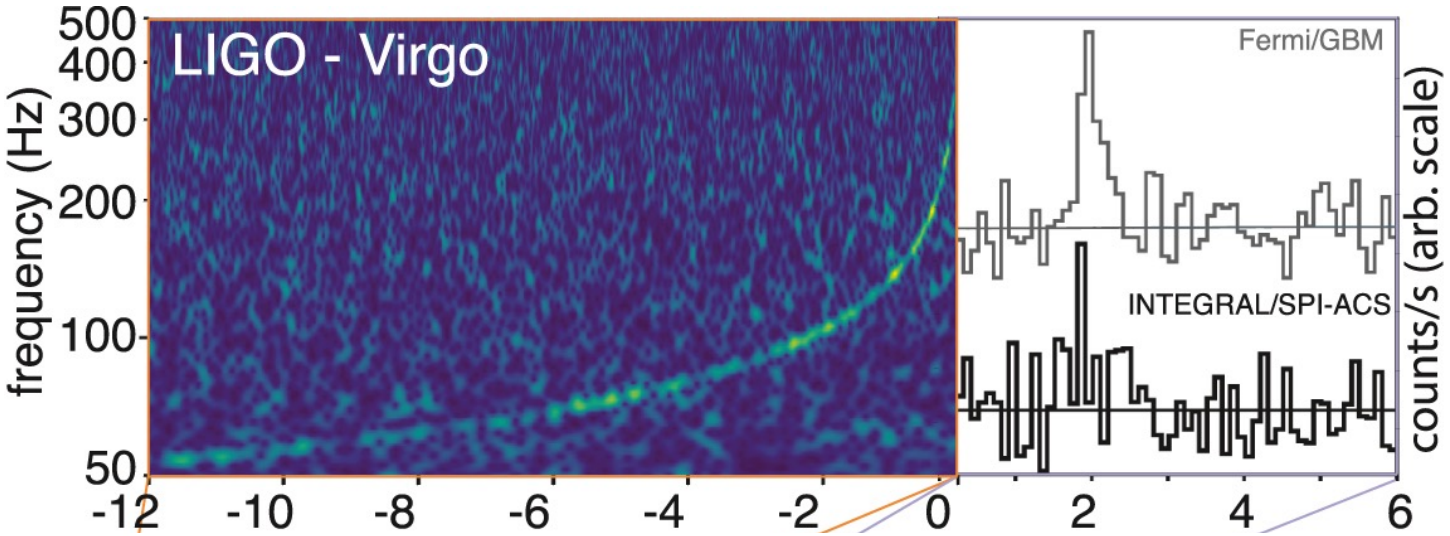




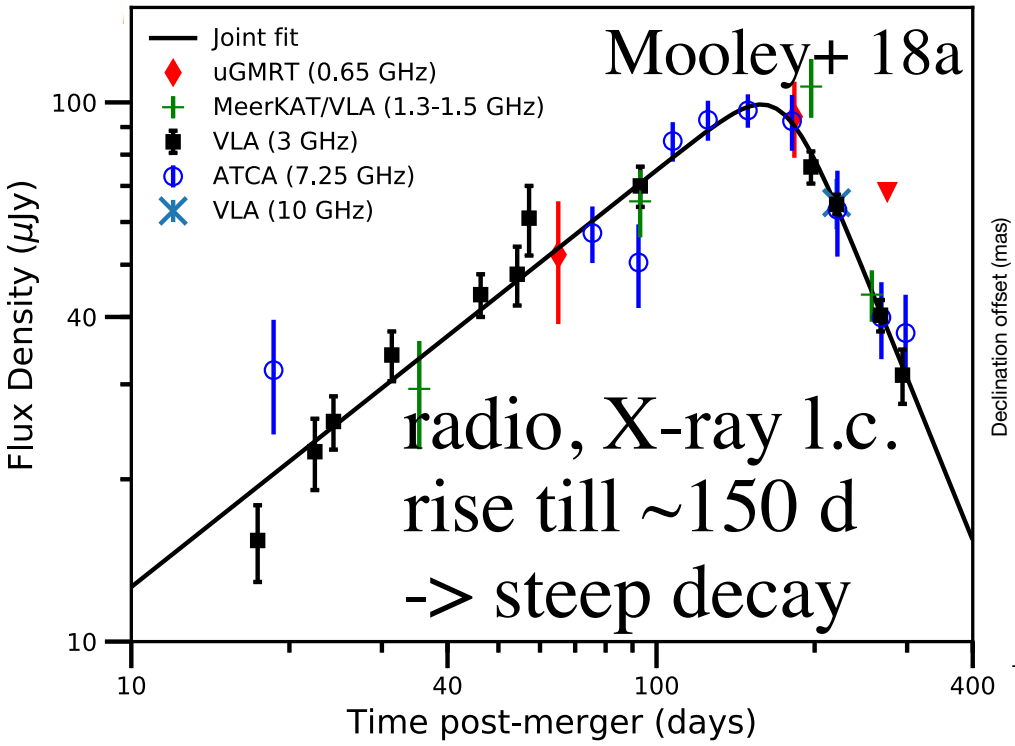


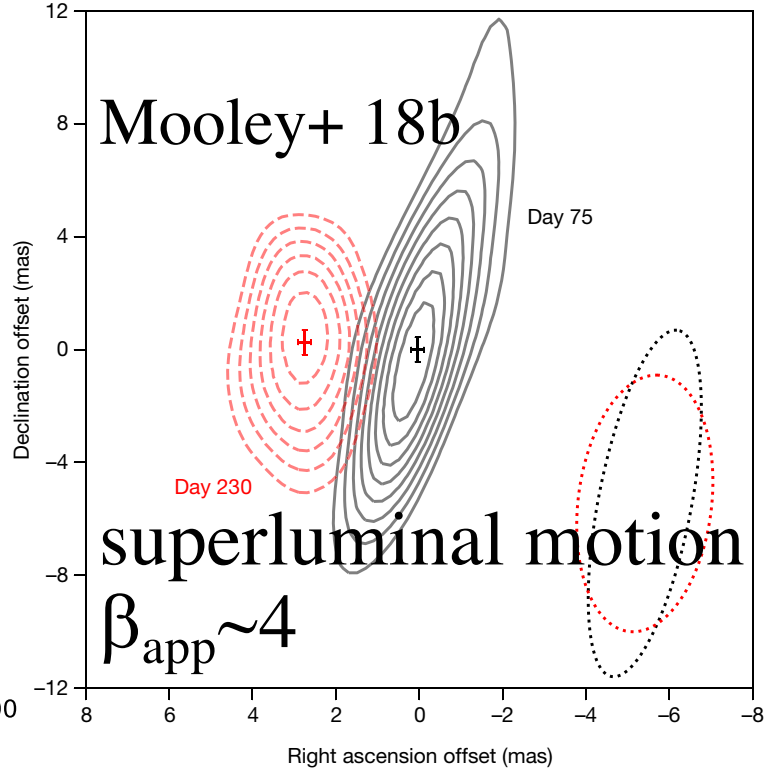
- promising in terms of accel. (Hillas plot)
- BUT high-L GRBs challenged due to limited energetics at z~0 (GZK horizon)
  -> low-L GRBs still viable
- EM/neutrino signatures desirable

GRB 170817A: "short" GRB but atypical



ε_p~200 keV
E_{iso}~5x10^{46} erg/s
inconsistent with typical SGRB seen off-axis
-> shock breakout?

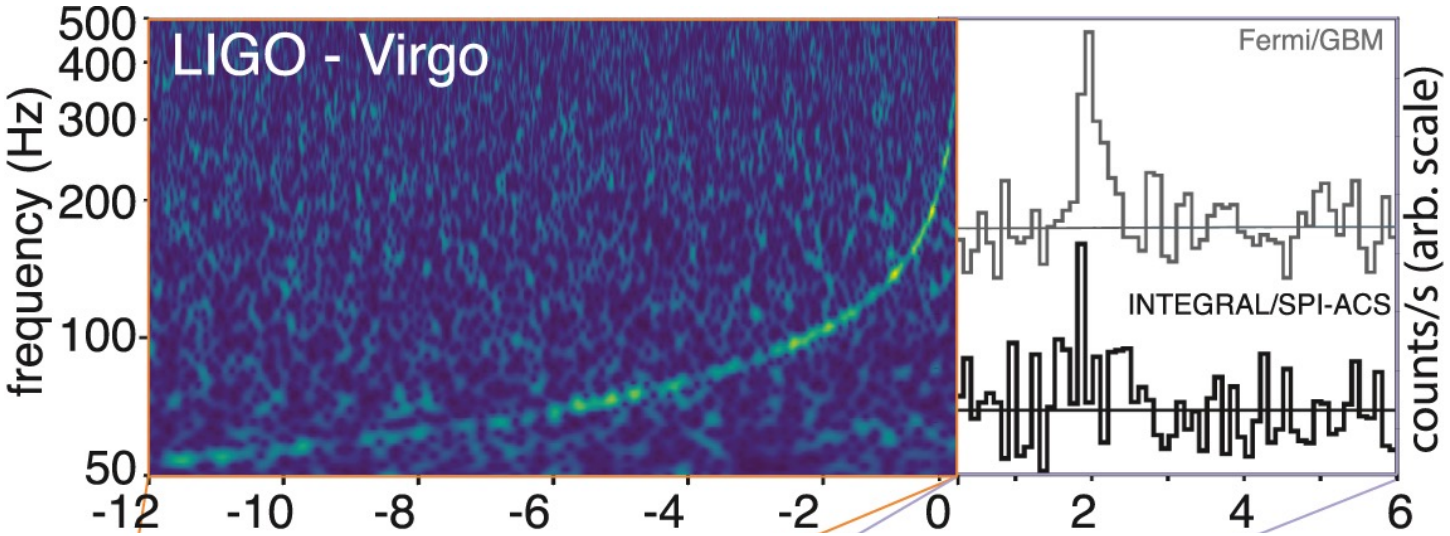




kilonova:
->
r-process nucleo-synthesis

-> good evidence for successful SGRB jet from BNS merger

GRB 170817A: “short” GRB but atypical



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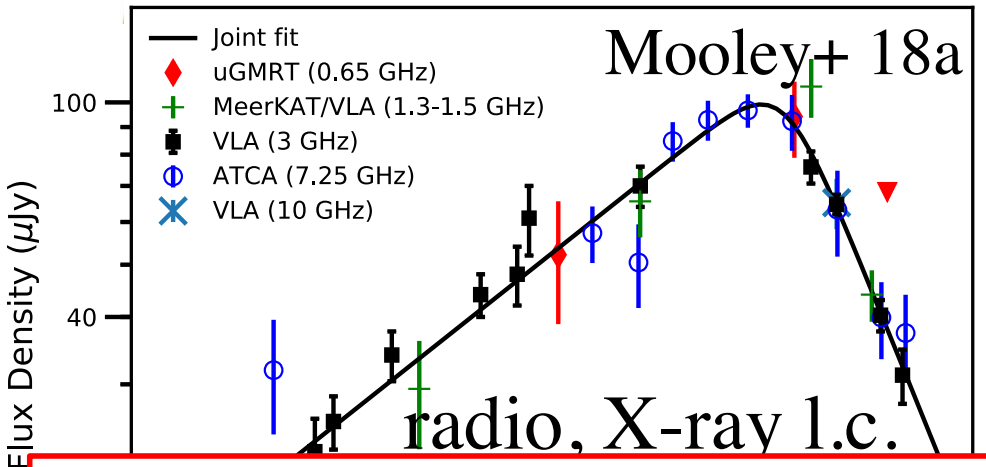
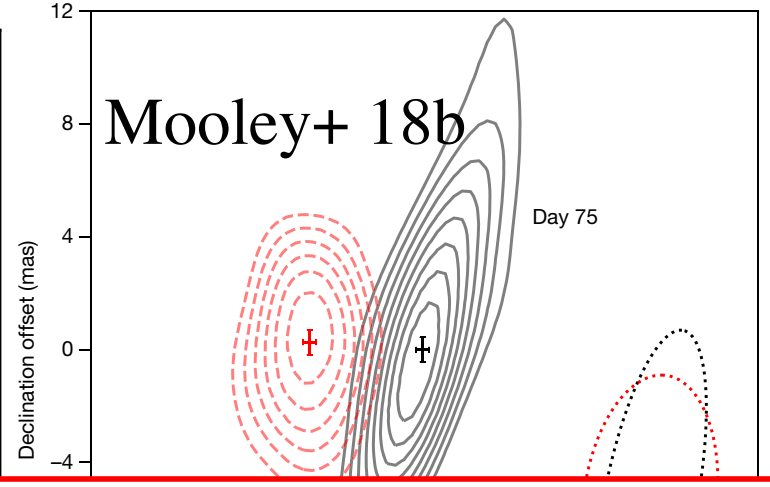




kilonova:
->
r-process nucleo-synthesis

coincident GW + on-axis short GRBs
-> GW: pre/post-merger NS/BH masses, spin
EM: jet properties
-> elucidate SGRB progenitor -> jet formation

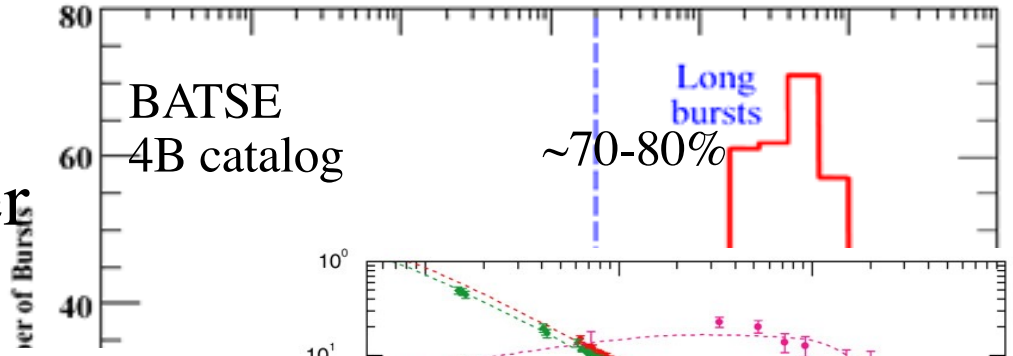
Summary: GRBs: Multi-Messenger Synergies

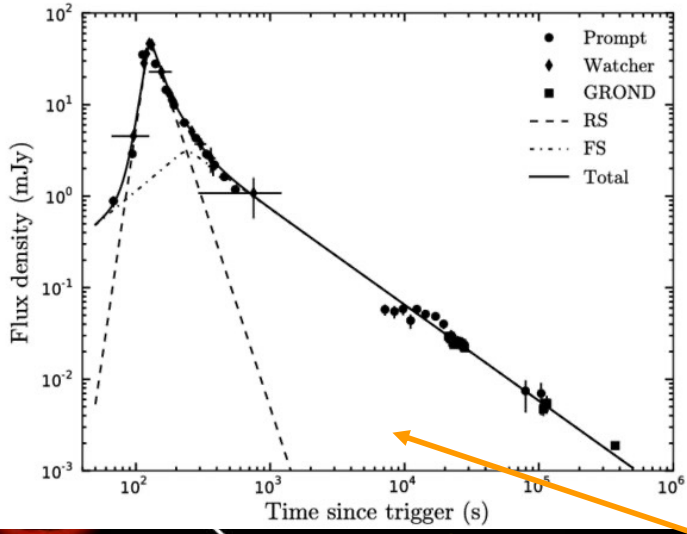
- Different types of MM channels need distinct names.
- TeV photons latest observational window.
  Diversity of GRB types: long GRBs, short GRB, low-L GRBs
- Likely emission components beyond synchrotron.
  Valuable new info on particle accel. in rel. shocks, structured jets, nature of low-L GRBs.
- HE neutrino / UHECR origin:
  High-L GRBs challenging but low-L GRBs still viable.
  EM signatures desirable.
- GW + on-axis short GRBs
  Progenitor vs jet properties -> probe jet formation.

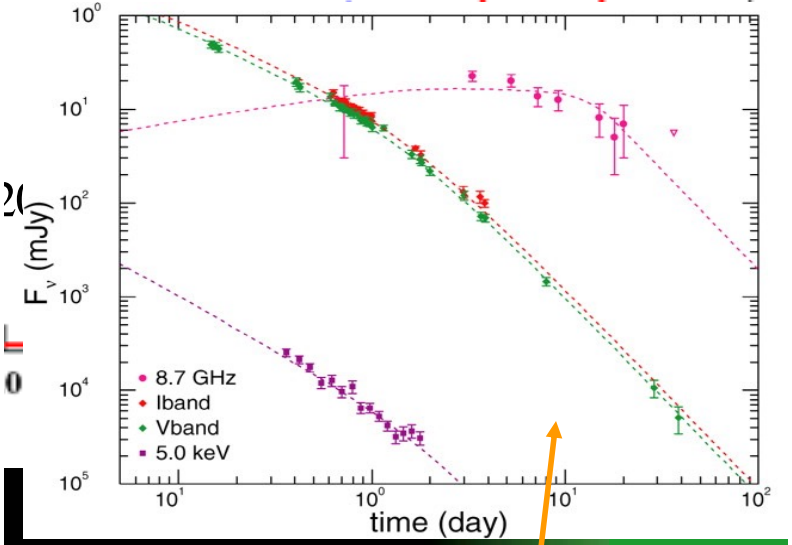
backup slides

GRBs: key facts & questions

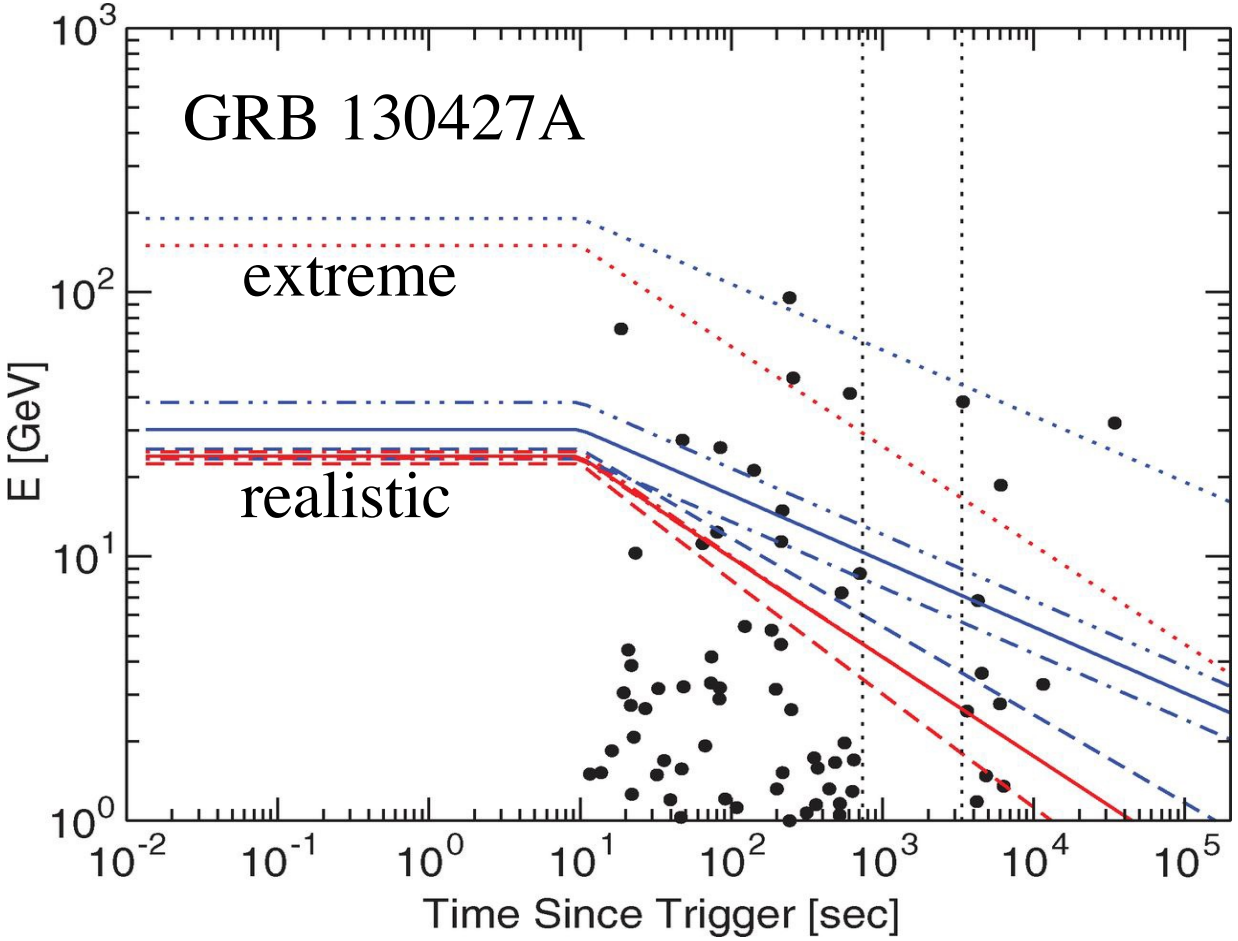
long (>~2s): massive star collapse
short (~<2s): compact binary merger
-> ultrarelativistic jets
-> prompt: X-MeV
+ afterglow: radio-
(low-luminosity: ?)







synchrotron burnoff limit in afterglow emission: Fermi-LAT results



Fermi-LAT Coll. 2014, Science 343, 42

maximum synchrotron photon energy for electrons dominated by synchrotron cooling

$\tau_{accel} \propto \gamma_e B^{-1}$, $\tau_{syn} \propto \gamma_e^{-1} B^{-2}$

$\tau_{accel} = \tau_{syn} \rightarrow \gamma_{e,max} \propto B^{-1/2}$

$\nu_{syn,max} \propto B\gamma_{e,max}^2$

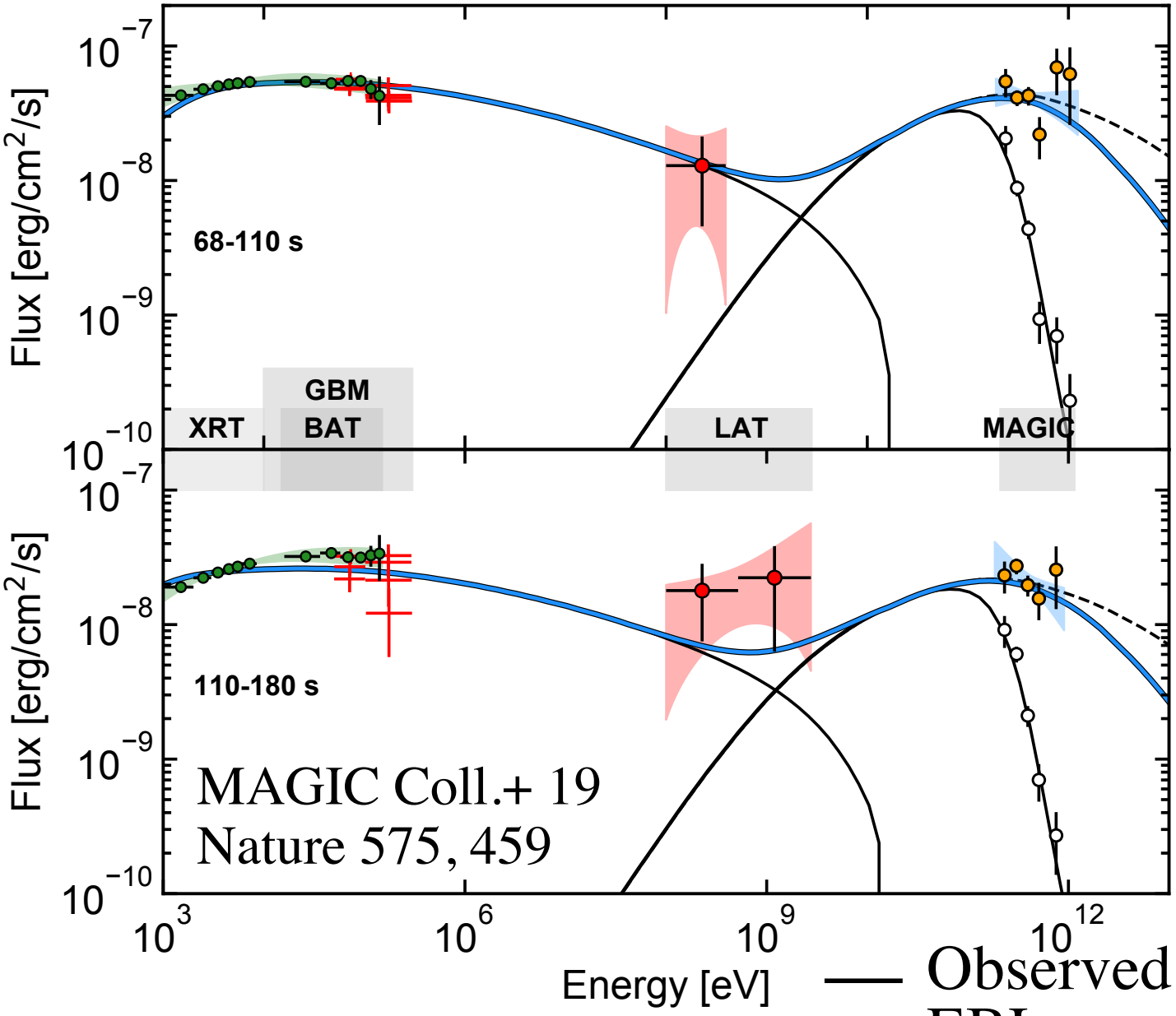
$E_{syn,max} \sim 2^{3/2}[27/(16\pi\alpha_f)]m_e c^2 \times \Gamma(t)(1+z)^{-1}$

$\sim 106\, \Gamma(t)(1+z)^{-1}$ MeV

Nakar & Piran 10

c.f. Kumar+ 12

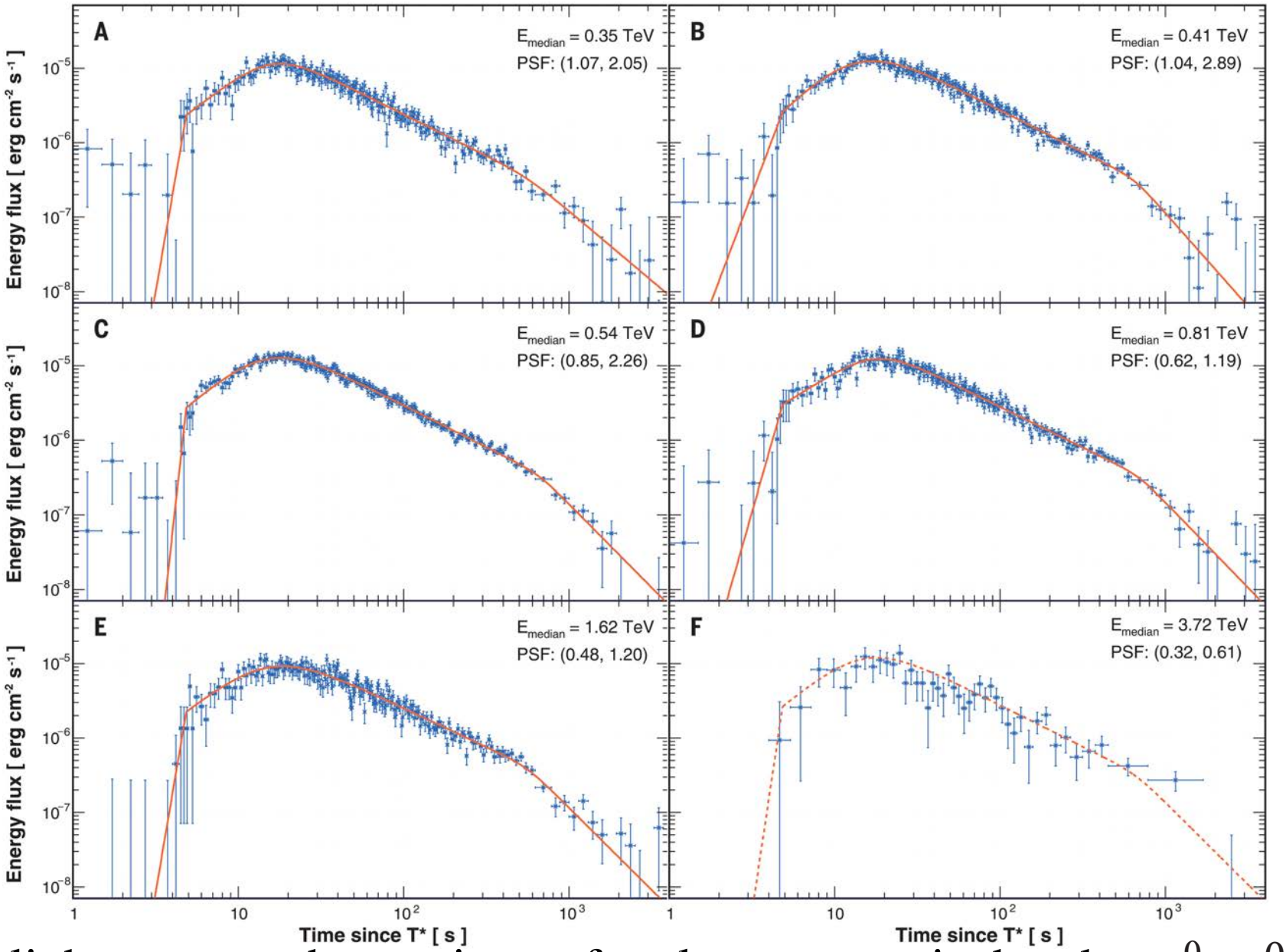
GRB 190114C: time-resolved spectra vs SSC model



- reasonable SSC interpretation with plausible parameters:
  $s=0$, $n_0=0.5$ cm^{-3}
  $\varepsilon_e=0.07$, $\varepsilon_B=8\times10^{-5}$
  $E_k=8\times10^{53}$ erg, $p=2.6$
- supports inference that TeV emission may be common

LHAASO results on GRB 221009

LHAASO Col. 23, Sci. 380, 1390



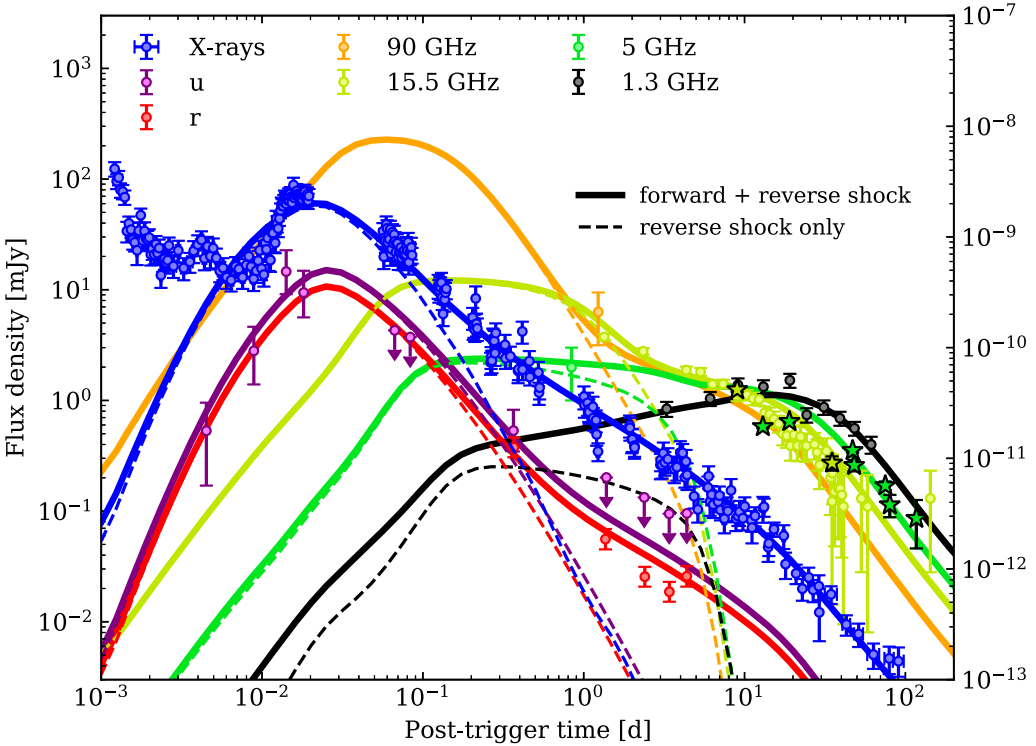
light curves achromatic -> afterglow onset + jet break

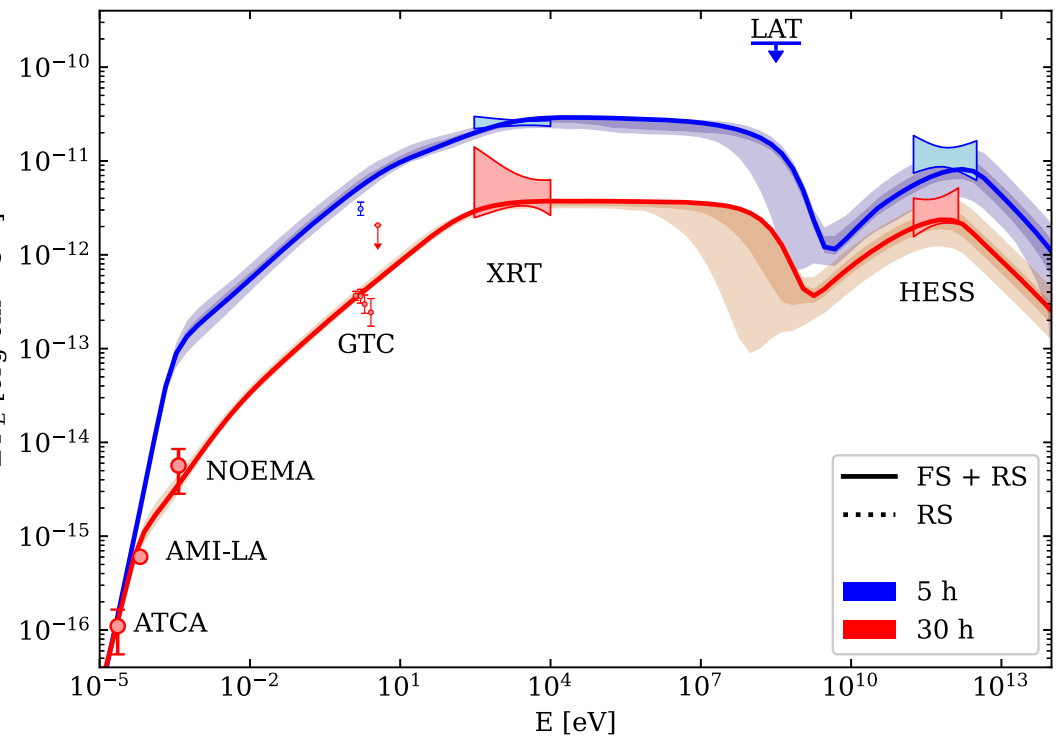
$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{\rm b,2}}{670\ {\rm s}}\right)^{3/8}$$

-> very narrow jet -> tolerable energetics

$$E_{\gamma,j} \equiv E_{\gamma,\rm iso}\theta_0^2/2 \sim 5.5 \times 10^{50} E_{\gamma,\rm iso,55} \left(\frac{\theta_0}{0.6^\circ}\right)^2 \ {\rm erg}$$

low-luminosity GRB 190829A





- SSC feasible if early X-rays from reverse shock Salafia+ 22
- external IC of late prompt X-rays Zhang+ 21

Miceli & Nava 22	E_k erg	ϵ_e	ϵ_B	n cm^{-3}	p	ξ_e	θ_j rad
Hess Coll. (SSC)	2.0×10^{50}	0.91	5.9–7.7 $\times 10^{-2}$	1.	2.06–2.15	1.	/
Hess Coll. (Sync)	2.0×10^{50}	0.03–0.08	$\approx$1	1.	2.1	1.	/
Salafia + 2021	1.2–4.4 $\times 10^{53}$	0.01–0.06	1.2–6.0 $\times 10^{-5}$	0.12–0.58	2.01	<6.5 $\times 10^{-2}$	0.25–0.29
Zhang + 2021	9.8×10^{51}	0.39	8.7×10^{-5}	0.09	2.1	0.34	0.1

- low-L GRB: bursts with abnormally low prompt efficiency?