Gamma-Ray Bursts and Gamma-ray Astronomy

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@ GammaSIG session, HEAD Mtg Monterey, CA, March. 2019
**GRB**: Standard paradigm

Has held up for >25 years!

**Bimodal distribution of** $t_\gamma$ **duration**

$\leftarrow \downarrow$ **Short**

$(t_\gamma < 2 \text{ s})$

$\rightarrow \uparrow$ **Long**

$(t_\gamma > 2 \text{ s})$

**NS - NS merger**

very, very fast jet

$0.01 M_\odot$ torus

$0.1 M_\odot$ torus

$1 M_\odot$ torus

**BH - NS merger**

**BH - WD merger**

**NS/BH - He core merger after common envelope**

collapsar = rotating, collapsing "failed" supernova


Mészáros grb-gen06
GRB “Standard” Baryonic Model

Several shocks -- also possible cross-shock IC

Internal Shock
Collisions between different parts of the flow

External Shock
Flow decelerating into the surrounding medium

Reverse shock ↔ Forward ⇒ shock

n, p decouple
Photospheric th. radiation

Jet

GRB

= 10^{11} cm

= 10^{13} cm

> 10^{16} cm

Afterglow

X O R

e.g. Rees, Mészáros, 1992, 1997, etc; Sari, Piran, Waxman, Kumar, Zhang, etc.
GRB MHD Models

Drenkhahn & Spruit, 2002
Blandford & Lyutikov, 2003
Thompson & Metzger 2010
Zhang, B & Yan, H., 2011
McKinney & Uzdensky 2012
Giannios et al 2012, 2016,..
Blandford, 1901.05164
Synchrotron shock simplest paradigm:

**Snapshot (leptonic) Afterglow Fits**

- Simplest case: $t_{\text{cool}}(\gamma_m) > t_{\exp}$, where $N(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$ (i.e. $\gamma_{c(ool)} > \gamma_m$)

- 3 breaks: $\nu_{a(bs)}$, $\nu_m$, $\nu_c$

- $F_\nu \propto \nu^2 \left(\nu^{5/2}\right)$; $\nu < \nu_a$

  $\propto \nu^{1/3}$; $\nu_a < \nu < \nu_m$

  $\propto \nu^{-(p-1)/2}$; $\nu_m < \nu < \nu_c$

  $\propto \nu^{-p/2}$; $\nu > \nu_c$


Break frequency decreases in time (at rate dep. on whether ext medium homog. or wind (e.g. $n \propto r^{-2}$))
BUT: for prompt emission:

Synchrotron Deathline?

Single particle limit of synchrotron spectrum
\[ \frac{dN}{dE} \sim E^{-2/3} \] (below peak)

With cooling
\[ \frac{dN}{dE} \sim E^{-3/2} \]

(but: not to worry - easy to see ways how slopes steeper than -2/3 or -3/2 could arise)

Kaneko et al 2006

\[
\alpha_{\text{eff}} = \alpha - \frac{25 \text{ keV}}{E_{\text{peak}}} (2 + \alpha) = \alpha - \frac{25 \text{ keV}}{E_0}
\]
Possible Solution: E.g., a photospheric

Origin of steep spectrum?

Thermal emission provides an attractive solution

Needs to dominate the \(~\text{MeV}~\) bump

Any realistic temperature or $\gamma_{\min}$ distribution can reproduce almost any slope steeper than $-2/3$ in $N_{\nu}$ (flatter than $4/3$ in $\nu F_{\nu}$)
Alternatively

- Usual synchrotron model may be OK in >95% cases…

- provided track the electron cooling during emission process in time-dep. manner

- Burgess et al. arXiv: 1810.06965

- Ravasio et al. arXiv: 1903.02555

- (earlier work: LLoyd-Roning, Petrosian ’00, etc)

- Previous objections to synchrotron shock vanish…
Evolving $\gamma$-Fireball paradigm, I

Old paradigm: internal + external shock

New paradigm: photosphere + external shock

$\leq 2005$

$\geq 2005$

e.g. PM & Rees, 2000, 2005, etc....
**Paradigm shift**

- **OLD**: *internal + external shock* (weak phot.)
  - Photosphere: low rad. effic., wrong spectrum
  - Internal sh.: good for variability, *easy to model*; but *poor radiative efficiency* (?)
  - External sh.: was, and is, *favored for afterglow model*

- **NEW**: *phot. + (int.sh? mag.diss?)+ext. shock*
  - Photosphere: if dissipative, $\rightarrow$ *good rad. efficiency*
  - *Int. sh*: if magnetic, may be absent; but *mag. dissip*?*
  - **External** shock: most of GeV and soft afterglow
To be efficient, dissipation must occur in photosphere

What can be the Photospheric Dissipation Mechanisms?

- MHD reconnection, accel. $\rightarrow$ rel. $e^\pm, \gamma$
- Shocks @ photosphere (& below, above) $\rightarrow$ same
- p-n decoupling ($\perp, ||$) $\rightarrow$ relativistic $e^\pm, \gamma$
- Or else, hadronic interactions @ internal shocks
- ........
A hadronic “thermal” photosphere PL spectrum?

**p-n collisions in sub-photosphere**

Beloborodov, ’10, MN 407:1033

- Long history: Derishev-Kocharovsky 89, Bahcall-Mészáros 00, Rossi et al 04, etc
- Either p-n decoupling or internal colls. → relative p-n streaming, inelastic colls.
- Highly **effective dissipation** (involves baryons directly)- can get >50% effic’y
- Sub-photospheric dissipation can give strong photospheric component
p-n coll. → e± → photosphere γ-spectrum

- The result is a thermal peak at the ~MeV Band peak, plus
- a high energy tail due to the non-thermal e±, whose slope is comparable to that of the observed Fermi bursts with a “single Band” spectrum
- The “second” higher energy component (when observed) must be explained with something else

Beloborodov, 2010, MN 407:1033

Magnetic dissipation
ICMART model in shocks


(a) Initial collisions only distort magnetic fields

(b) Finally a collision results in an ICMART event
also:

GRB 090510 and others:

Spectrum: *clear* 2nd comp (>5σ)

(unlike in 0809916C & some others, which show pure Band)

Abdo, et al. 09 (LAT/GBM coll.)
Nature, 462:331
Photosphere + IS model

Toma, Wu, Mészáros, 2011, MN 415:1663

- Photosphere: prompt, variable MeV
- IS occur at $r \gtrsim 10^{15}$ cm (high $\Gamma$) : $Sy=XR$, $IC(UP)=GeV$

High energy 2nd component: Leptonic?
Leptonic magnetic & baryonic photosphere + external shock model

- Leptonic photosph. spectrum extend to $\Gamma_{ph} m_e \sim 50-100$ MeV
- Ext. shock upscattering spectrum extend to $\Gamma_{es} \gamma_{e,KN} m_e \rightarrow$ TeV

**Photosphere + Extern. shock IC Leptonic model**

\[090510A \rightarrow \text{magphot}\]

\[090510A \rightarrow \text{barphot}\]

Self-consistent hadronic int. shock

Calculate **self-consistent** CR proton, photon & neutrino spectra

- Originally: Waxman & Bahcall ’97 consider standard int. shock as **leptonic** for photons, **hadronic** for $p, \gamma \rightarrow \nu$

- Afterglow
  - FS: X-ray, etc.;
  - RS: Opt. flash

- New Feature:
  - Hadron accel. + photomeson $\rightarrow$ “dissipation” $\rightarrow$ inject copious relativistic sec’y leptons

- Asano & PM, 09-12 on, calculate second’y **photons** & second’y **neutrinos** from both original & hadronic sec’y leptons

IS w. hadronic cascades


- Assume dissipation region at \( R_0 \) (photosphere, IS, etc.)
- Inject Fermi (1st ord) accelerated \( e^-, p^+ \), spectrum \( \sim E^{-2} \)
- Allow cool, subject to \textit{Sy, IC, pair-form., photomeson}
- Secondary leptons are \textit{reaccelerated} by scattering on turbulence/MHD waves behind shocks
- Modulo some plausible assumptions about mag. field growth, turbulence, etc, reaccelerated lepton spectrum leads to a \textit{self-consistent} “Band” photon spectrum plus a \textit{2nd hard} high en. power law, \( \sim \) similar to Fermi LAT.
- \textbf{Good radiative} efficiency for \( \gamma \); but below IceCube \( \nu \) limit

$EF(E) \text{[erg/cm}^2\text{/s]} \quad r=10^{13} \text{cm}, \Gamma=500, U_B/U_p=0.01$

$L_p=10^{53} \text{erg/s}, L_{th}=4.3 \times 10^{53} \text{erg/s},$
Then, very recently:

**GRB190114C: MAGIC**

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration* on 15 Jan 2019; 01:03 UT

Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.
• Bright optical, XR, radio, etc
• $z=-0.4245$
• And: MAGIC $E_\gamma > 300$ GeV!
• A 2nd. Flatter (-1) spec. comp. above Band
• EBL cutoff? Intrinsic continues to... TeV?
• How far? Leptonic? Hadronic?
GRB 1901114C light curve

(Caveat: not Fermi/Swift analysis)

- Similarity to GRB090902B, GRB130427A

- Substantial thermal comp. $kT \sim 150$ keV

- $E_{\gamma,\text{iso}} \sim 2.5 \times 10^{53}$ erg

(Wang et al, 1901.07505)
GRB 1901114C spectrum

(Ravasio et al, 1902.01861)

- (Caveat: not Fermi/Swift analysis)

- LAT emiss. and GBM nonthermal PL belong to same component (afterglow)

- Conclude Lorentz factor \( \sim 500 \)

Fig. 2. The X–ray to GeV SED of GRB 190114C at three specific times: at 6–6.3 s, when the power law component has its peak in the GBM data (see panel (B) of Fig.1, blue symbols), at 47–61 s and at 87–232 s (as labelled). We show the GBM, BAT and XRT data (the latter de-absorbed as described in the text). Errors and upper limits on the data points represent 1\(\sigma\).
Short GRBs

The dream of Multimessenger Astrophysics fulfilled ...
GRMHD simulations:

BNS merger $\rightarrow$ HMNS $\rightarrow$ jet, √

e.g., M. Ruiz+16 ApJL 824:L6

Observational proof: GRB/GW 170817

Fermi
Reported 16 seconds after detection

LIGO-Virgo
Reported 27 minutes after detection

INTEGRAL
Reported 66 minutes after detection
i.e.

\[ \text{BNS} \rightarrow \left[ \text{GW, sGRB, KN} \right] \]

- Along and off-axis of structured jet (or cocoon), see the SGRB $\gamma$-rays

- at large angles, see *kilonova* caused by slower neutron-rich outflow where rapid neutron-capture *r-process* $\rightarrow$ very heavy elements, whose opacity and slow decay $\rightarrow$ optical/IR

- at all angles, see GWs
so, with

**SGRB/GW 170817**

*re-confirmed* that:

- SGRBs are indeed BNS mergers
- and BNS/SGRBs are also GW sources

- Multi-messenger astronomy now takes off in earnest (beyond SN1987a 1/100 yr events)
- A long awaited development!
Expected $\gamma$-ray facilities that can play a crucial role in future advances

- SVOM (Space Variable Object Monitor)
- ULTRASAT (Ultraviolet transient, 250-280 nm, 250 sq.deg FoV)
- ISS-TAO (Transient Astrophysics Observer; with GTM + WFI XR Lobster Imager)
- CTA Cherenkov Telescope Array
- AMEGO (All-Sky Medium Energy Gamma-ray Observatory, 0.2 MeV - 10 GeV)
Thanks!
Are there arguments for relativistic hadronic **secondaries** in the GRB $\gamma$-emission?

- **YES**
  - Hadrons *solve* the radiative efficiency and the gamma-spectrum issues in *photospheres*
  - They also solve this for *internal shocks*
  - And of course, if electrons are accelerated, why would hadrons *not* be accelerated?

**BUT:** no conclusive proof yet
As a test, can we detect UHECRs and/or Neutrinos from both or either standard IS and photospheric models?
pp or pγ neutrino production

\[ p + p/\gamma \rightarrow N + \pi^\pm + \pi^0 + \ldots \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu , \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
\[ K^+ \rightarrow \mu^+ + \nu_\mu \]

\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu , \]
\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]
\[ \pi^0 \rightarrow \gamma + \gamma \]

- Both \( \nu_e \) and \( \nu_\mu \) are produced by charged pion decay,
- \( \gamma \)-ray photons are produced by neutral pion decay
Confront with observations:

IceCube data on astrophysical VHE vs
IC3 HE $\nu$-bkg

![Graph showing atmospheric and astrophysical neutrino fluxes.](Image)

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Ahlers&Halzen, 1805.11112
As far as the Classical GRBs:

Observational tests made:

- If $L_p/L_\gamma \sim 10$, expect that $L_\nu/L_\gamma \sim 1$,
- \textbf{but} IC3 + Swift: \( \lesssim 1\% \text{ of } \nu \) can come from standard intern. shock model GRBs where $\gamma$, $\nu$ are produced in the same shocks,

Model dependent constraint: $\gamma \leftrightarrow \nu$

Low optical depth \( \rightarrow \) no hiding!

(IC3 team, 2015, ApJL, 805: L5)
Another possibility:

**Choked GRB - Shock Breakout - LLGRB**

- IceCube 1807.11492, model-independent constraints on transients

- For **GRB-like** (orange) upper limit: $\lesssim 5-30\%$ for spectrum $s=2.13$ ($s=2.50$)

- For **ccSN-like** (gray), i.e. choked jet, could provide much or all of diffuse flux

(see also Ismaili+18, 1809.09610)
Thanks!
Caption for fig. IC3 limit GRB/ccSNe

- Define doublets and multiplets as 2 more $\nu$s within 100 s and 3.5 deg
- Very low rate of multiplet alerts allow to define limits on a transient source population with durations up 100 s
- Use typical distributions of GRBs and ccSNe @z<8, assume GRB peak $L_\nu$ propto peak $L_\gamma$, fluctuating
- Region above red (ccSN/choked GRB) or gray (GRB) is ruled out, for 2.5 (upper) and 2.5 (lower) spectrum
- Dashed line: where ccSNe or GRB provide 100% of $\nu$ background, for 2.5 spectrum (lower by 13 for 2.13)
A different question:

Can we expect any Vs from short GRBs (SGRBs)?

Highly relevant, in view of GW/GRB170817, a confirmed multimessenger source!
• IceCube found that <1% of the EM-observed “classical” GRBs can be contributing to this observed neutrino flux (or <5-30% in model-indep. analysis)

• And these are mostly long GRBs from ccSNe; and short GRBs (BNS) are much fainter; so would assume SGRBs are even less likely sources;

• But these were tests for neutrinos in close time / direction coincidence w. prompt (main) jet MeV γs
SGRB are not always “short”!

in 30-50% of cases:

- **Extended** emission (EE) in 30-50% cases
- EE spectrum is **softer** than that of the “prompt”
  - Prompt: $E \sim 1-3$ MeV
  - Ext’d: $E \sim 30-60$ KeV
  - $\Delta t_{EE} \sim \leq 10^2$ s

However:

- Extended emission (EE) in 30-50% cases
- EE spectrum is softer than that of the “prompt”
- $\Delta t_{EE} \sim \leq 10^2$ s

When one calculates BNS Merger

**Neutrino light curves**

including also *delayed* components

e.g. SGRB extended emission (EE), etc

Neutrino fluence from *on-axis* SGRB

for

EE-mod, EE-opt,
prompt, flare &
plateau component
@ $d_L=200$ Mpc
(e.g. aLIGO)

\(\nu\)-dominance of BNS EE:

- Caused by \textit{lower} \(\Gamma\), \textit{higher baryon} load
- \(\Rightarrow\) \textit{higher photon} density and \textit{shorter} \(t_{\gammaY}\)
- \(\rightarrow\) \textit{higher} \(B\)-field, stronger \textit{pion cooling}
- \(\rightarrow\) \textit{lower} pion cooling break, TeV-PeV spectra
- \textit{Still}, fluence \textit{low} for IC3, unless \textit{very} nearby
And observationally,

**IceCube, Antares, Auger test**

\[ \nu \text{-limits on GW170817:} \]

- GW indicates off-axis jet, \( \theta_{\text{obs}} \in [0^\circ, 36^\circ] \),
- Kimura et al. models for Doppler factor at various \( \theta_{\text{obs}} - \theta_j \) offset
- No detection (OK, ✅)

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The detection probability $P(N_\mu \geq k)$ for $d_L = 200$ Mpc. The upper and lower panels are for EE-mod-dist and EE-opt-dist, respectively. The solid and dashed lines are for the cases with $\sigma_T = 2$ and $\sigma_T = 4$, respectively. The vertical thin-dotted line shows $N_\mu = 1$.

(IceCube-averaged includes down-going events)

Figure 2.

The detection probability $P(N_\mu \geq 1)$ as a function of luminosity distance $d_L$. The upper and lower panels are for EE-mod-dist and EE-opt-dist, respectively. The thick and thin lines are for the cases with $\sigma_T = 2$ and $\sigma_T = 4$, respectively. The vertical thin-dotted lines show $d_L = 300$ Mpc and $d_L = 600$ Mpc.

Figure 3.

i.e., IC3: maybe - Gen-2: likely

Another possible HENU mechanism for SGRB:

Jet choked in the merger dynamical ejecta

Trans-Ejecta HE Neutrinos
Internal and collimation shocks in BNS jet-cocoons within the dynamical ejecta

Kimura, Murase, Bartos, Ioka, Heng, Mészáros+18, PRD 98:043029
Allowed parameters for Fermi acceleration by internal & collimation shocks inside ejecta

- **Internal Shock** ($\tau_u = 1$)
- **Internal Shock** ($\tau_u = \tau_{cr}$)
- **Internal Shock** ($R_{dis} = R_{cs}$)
- **Collimation Shock** ($\tau_u = 1$)
- **Collimation Shock** ($\tau_u = \tau_{cr}$)
- **Choked condition** ($R_h = R_{ej}$)

**Graph:**
- **Jet Lorentz factor** ($\Gamma_j$) vs. **Isotropic equivalent kinetic luminosity** ($L_{iso}$) [erg s$^{-1}$]
- **Observed GRBs**
- **Inside ejecta**
- **Outside ejecta**

**Legend:**
- Blue line: Internal Shock ($\tau_u = 1$)
- Red line: Collimation Shock ($\tau_u = 1$)
- Blue dashed line: Internal Shock ($\tau_u = \tau_{cr}$)
- Red dashed line: Collimation Shock ($\tau_u = \tau_{cr}$)
- Green dashed line: Internal Shock ($R_{dis} = R_{cs}$)
- Black dashed line: Choked condition ($R_h = R_{ej}$)
Note: Due to strong pion cooling, the initial flavor ratio at source is (0,1,0). After oscillations, using the tri-bimaximal matrix for propagation, the flavor ratio at Earth is (4,7,7), so nue/numu ~1/2. Also, the IceCube eff. area for cascades is lower than for tracks at this energy, so here we neglected nue fluence.
### Detection probability

#### TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

<table>
<thead>
<tr>
<th></th>
<th>IceCube (up+hor)</th>
<th>IceCube (down)</th>
<th>Gen2 (up+hor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.6</td>
<td>0.55</td>
<td>29</td>
</tr>
<tr>
<td>B</td>
<td>0.36</td>
<td>0.023</td>
<td>1.5</td>
</tr>
</tbody>
</table>

- Number of detected neutrinos from single event at 40 Mpc
- Number of detected neutrinos from single event at 300 Mpc

<table>
<thead>
<tr>
<th></th>
<th>IceCube (up+hor+down)</th>
<th>Gen2 (up+hor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td>B</td>
<td>0.076</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Possible \(\uparrow\) (?)
Thanks!
Evolving Fireball Paradigm

Internal Shocks Redux: modified internal shocks

(address/mitigate or even solve IS problems)

Modifications currently of two main types:

• **Magnetic dissipation** in int.shock, $R \sim 10^{15}$ cm, allow GeV photons - but hard to calculate quantitatively details of reconnection, acceleration and spectrum, e.g. McKinney-Uzdensky ‘12, MN 419:573, Zhang & Yan ’11, ApJ 726:90

• **Hadronic internal shocks**, protons are 1st order Fermi accelerated, and secondaries are subsequently re-accelerated by 2nd order Fermi (“slow heating”), e.g. Murase et al, 2012, ApJ 746:164 - more susceptible to quantitative analysis
Hadronic models: e.g. 080319B

Fig. 2.— Model spectrum for parameters listed at the top as thick red curve compared with observations of GRB 080319B, for which the gray shaded area represents the spectrum measured between $T_0 + 12$ s and $T_0 + 22$s by Swift/BAT and Konus-Wind. The contemporaneous optical flux observed by “Pi of the Sky” is the black diamond. The best-fit Band component is shown separately as the thin black curve. Individual contributions of synchrotron and inverse Compton from secondary electron-positron pairs, as well as muon synchrotron and proton synchrotron are denoted by thin blue curves as labelled, not including the effects of $\gamma\gamma$ absorption or synchrotron self-absorption.
Of course, there is also

Blazar TXS 0506+056

• IC3 detects an ap. 300 TeV **EHE neutrino**

• Coincident at 3σ level, blazar TXS 0506 is in **γ-flaring** state (days, weeks), obs. by:

• Swift XRT/UVOT, Fermi, NuSTAR, MAGIC...
TXS 0506+056 obs.

Swift XRT, UVOT

Swift + Fermi

**TXS 0506 one-zone $\nu$-$\gamma$ models:**

- **Hadronic $\rightarrow$ EM cascades $\rightarrow$ XRs** which **fill in** the Sy and IC peak gap
- Pure hadronic one-zone model (for both $\nu$ and $\gamma$): can be **ruled out**
- Lepto-hadron. one-zone model: low by x2-3  ✔, **very constrained**

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If $3\sigma$ flare coincidence is true, one-zone models severely constrained.

$E_\nu F_{E_\nu} \leq 3.6 \times 10^{-12}$ erg/cm$^2$/s $\rightarrow$ Poisson prob. $< 1\%$ one event in 6 mo.

2- or more zones explain it $\checkmark$ (?), but w. extra uncertain parameters.

But such blazar flares may not account for $>10\%-30\%$ of entire $\nu$-bkg.

Also previous attempts at finding correlations via stacking have failed.

At the very least, may need other sources.