EXTRAGALACTIC GAMMA-RAY SOURCES

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In particular...

- AGNs
- GRBs
- SFGs, SBGs (star-forming or starburst gals)
- GMSs, GSs (galactic merger or gal. shocks)
- IGB, INB (intergal. gamma or neutrino bkg)
The extragalactic TeV sky is dominated by blazars (mainly BL Lacs)
AGN as UHE $\gamma$ sources

- Massive BH ($10^7$-$10^8$ M$_{\text{sun}}$) fed by accretion disk $\rightarrow$ jet
- Lorentz factor $\Gamma_{j,\text{agn}} \sim 10^{-30}$
- UV target photons from (1) accr. disk, (2) BLR line clouds
- Typical ("leptonic") model: $e^\pm$ accel. in jet shocks, and SSC (sync-self-compton); SEC(sync-exter.compton)
- Typical hadronic model: p accel, in jet shocks, py photomeson interactions, $\rightarrow$ EM cascades
AGN Jet lepto-model

- Archetypal model of the AGN VHE $\gamma$-ray emission, from:
  - (a) upscattering of synchrotron photons by same emitting $e^\pm$ (SSC),
  - (b) upscattering of external (disk, cloud) target photons (EIC)

- Many previous and subsequent authors & versions

MRK 421: leptonic

Ghisellini et al, Spada et al, leptonic IS model, 2004

- Random intermittently ejected shells of variable bulk Lorentz factor → “internal” shocks
- Leptons accelerated to PL distribution via Fermi in these internal shocks
- Emit synchrotron and upscatter self- or external photons
Mrk 421

leptohadronic:

- Two models: LHpi ($\gamma$ from pi-decay) and LHsy ($\gamma$ from p-sync.)
- Use kinetic eqs. for primaries & second'y, SOPHIA code for p,$\gamma$
- Fit requires very flat $\Gamma_p, \Gamma_e \sim 1.2, 1.5$ (e.g. Niemec-Ostrowski)

Dimitrakoudis, Petropoulou, Mastichiadis '14 ApPh 54:61

Same shocks also accelerate protons

Black pts: March 22/23 2001
Grey pts: Fermi (non-simult.)
Thin dark line: photon fit
Grey line: nu fit (all flavors)
Blue thick line: muon nu fit
FSRQ 3C273

Leptonic vs. leptohadronic multi-band photon fits
Boettcher, Reimer, Sweeney, Prakash '14, apj 768:54

- Compare two models:
  - (1) leptonic SSC, EC
  - (2) leptohadronic w. semi-analyt. cascades
- Photon targets from accr. disk, BLR clouds
- Fit 6 FSRQ, 4 LBL, 2 IBL
Blazars (IBL, LBL) fits

Boettcher et al’14, apj 768:54

IBL 3C66A

lep

LBL OJ 287

lep

IBL 3C66A

had

LBL OJ 287

had
GRBs: flood the gamma-ray sky

- Cataclysmic stellar event (stellar core collapse, or compact bin. merger)
- \( \approx \) smaller, turbocharged AGNs
- \( M_{\text{bh}} \sim 3-15 \, M_\odot \), \( \Gamma \sim 10^2 - 10^3 \)

When “ON”, a GRB outshines blazars by up to \( 10^5 \) - or even the Sun (in gamma-rays)
GRBs in Cosmological Context

Pop. III Stars Form (First Light)

Epoch of Recombination (CMB)

QSOs

Epoch of Reionization

GRBs

Dark Ages

13 Gyr
1 Gyr
30 Myr
0.6 Myr

$\tau_{age}$
GRB 080916C

Spectrum: up to $\sim 10$ GeV (obs.)

- “Band” (broken power-law) fits, joint GBM/LAT, in all time intervals
- “Soft-to-hard” spectral time evolution
- Long-lived ($10^3$ s) GeV afterglow
- Little evidence for 2nd spectr. comp. (in some cases)
Evidence of the “extra components” (>3-5σ)

But: in other bursts,

GRB 090510

GRB 090902B

- Constrains main keV-MeV component
- Spectral evolution during prompt phase
- Additional PL component seen at high and low energies

Joint spectral fit (of binned data):
GBM<40MeV
standard LAT data>100MeV
Some observed photon energies and redshifts

<table>
<thead>
<tr>
<th>$E_{\text{obs}}$(GeV)</th>
<th>$z$</th>
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<tr>
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<td>2.8</td>
<td>0.897</td>
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<tr>
<td>4.3</td>
<td>1.37</td>
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</table>

- Even $z>4$ bursts result in $E_{\text{obs}} \sim 10$ GeV photons
- Some $z \sim 1$ bursts produce $E_{\text{obs}} \geq 30$ GeV photons (130 GeV in rest frame!)

⇒ encouraging for low $E_{\text{th}}$ ACTs: HAWC, CTA...
**GRB 080916c**

**Light-curve**

E↓

Abdo, A. and Fermi coll., 09, Sci. 323:1688

**Note:**

GeV photons ←“lag” behind MeV!
**Fireball Shock Model of GRBs**

- **Internal Shock**
  - Collisions between different parts of the flow
  - n, p decouple
  - Photospheric thermal radiation

- **External Shock**
  - Flow decelerating into the surrounding medium
  - Reverse shock ⇐
  - Forward shock ⇒

- **Several shocks** - also possible cross-shock IC

- **GRB**
  - ≈ 10^{11} cm

- **Afterglow**
  - ≈ 10^{13} cm
  - > 10^{16} cm
(A) Evolving Fireball paradigm:

Old paradigm: internal + external shock

New paradigm: photosphere + external shock

≤ 2005

≥ 2005
A “leptonic” model: Photosphere and internal shock of the GRB jet

The photospheric emission can naturally provide a high \( \gamma \)-ray efficiency and the typical photon energy of the Band spectrum, \( \sim 1 \) MeV (Paczynski 86; Goodman 86).

The dissipation below the photosphere could cause the emission to be non-thermal (Meszaros & Rees 00; Rees & Meszaros 05; Pe'er et al. 05; Ioka et al. 07; Beloborodov 09)

We discuss the general properties of the photospheric emission and upscattered photospheric (UP) emission off the internal shock electrons.
Recent thrusts in exploring the GRB prompt emission:

A) De-emphasize internal shocks (inefficient)
→ *dissipative photospheric models*

or:

B) *Modify* internal shocks: *slow heating*,
(i) turbulence behind shocks (Fermi 2nd ord),
(ii) magnetic dissipation (high rad. efficiency),
(iii) hadronic cascades (naturally slower heat’g)
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
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,γ→ν

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

**New Feature:**

Hadron accel. + photomeson → “dissipation” → inject copious relativistic sec’y leptons

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

IS w. hadronic cascades, $\gamma$

The PeV $\nu - \gamma$ Bkg Connection:
GRBs? AGNs? SFGs? HNe? GMSs?

- **PeV nu bkg (INB)** obs. by IC3 is $\sim 10^{-8}$ GeV/cm$^2$/s/sr, but **IC3 limit** on GRB nus is factor $\sim 10$ below the “standard” IS or photospheric models-ICRC13) $\rightarrow$ could be **EM dim/nu-bright GRBs?** (Liu & Wang 13, ApJ 766:73, Murase & Ioka, 13, PRL 111:121102)

- **PeV nu INB** from hadronic low lum. **AGNs ?**: scaling $L_p$ from $L_e$ via $L_{\text{phot}}$, argue that **FRI RGs** (higher density knots) $\sim$ reproduce via $pp$ the PeV nu bkg (Becker Tjus+, arXiv:1406.0506) $\rightarrow$ **and also IGB?**

- **PeV nus** from individual bright radio-gamma **AGNs?** (**blazars** in TANAMI sample), if $X-\gamma$ flux is due to $p\gamma$ photohadronic interactions, conclude that 6 of these blazars within $1\sigma$ error box of the three PeV events could account for the **INB** (Krauss, et al, 1406.0645) $\rightarrow$ **IGB?**

- Starburst galaxies (**SBGs**)? if responsible for PeV nu **INB** via $pp$, can contribute $\sim 20\%$ of the gamma background (**IGB**) (Chang et al, 1406.1099)
• Black triangles: Fermi IGB spectrum, Abdo+2010, PRL 104:101101

• Red line: FSRQ contributions; blue line: BL Lac contributions

• Magenta star/green circle: upper/lower 95% CL forecast of Fermi-LAT 95% CL 5 year sensitivity

Abazajian+11, PRD 84:103007
INB & IGB from pp sources

Murase, Ahlers, Lacki 13
PRD 88, 121301

- Stress pp vs. pγ because no >>GeV threshold
- Use IC3 det. of PeV vs, consider π± → ν INB & π⁰ → 2γ IGB & satisfy Fermi/LAT bound, also lack of Glashow reson.
- Conclude Γ_p ~ 2.0-2.18 with cutoff < 3-4 GeV
- Sources could be galaxy cluster shocks (IGS) or SFG/SBG - cutoff may be t_diff ~ t_inj (or t_diff ~ t_pp, t_adv)

See also He+13, PRD 87:063011, Liu+14, PRD 89:083004, Tamborra+, 1404.1189, Chang & Wang, 1406.1099, Kashiyama & Mészáros, 1405.3262
SFG-SBG and the IGB


- Red: CXB; blue: SMM; green X: COMPTEL; gold star: EGRET; blue triangle: EGR error est; magenta square: Fermi

- Black line: total $\gamma$ IGB (i) from SFG (normal) & (ii) from SBG (SB), inc. $\pi^\pm$ (pionic bump), etc. Gray shade: uncertainty estimate of SF IGB

- One-zone leaky box CR evolution, input from SNR $\alpha$ SFR, PL injection $E_{p,\text{max}} \sim \text{PeV}$, $E_{e,\text{max}} \sim \text{TeV}$, w. diffusive & $\gamma\gamma$ losses, constrain by GHz radio

[ Fiducial $(L_p/L_k)\text{snr}=0.1$, SBG/SFG=0.15 (0.8, 0.05) ]
SBG & IGB - host sy losses

Chang & Wang, 1406.1988

- Calibrate $\pi^0 \rightarrow 2\gamma$ flux using IC3 PeV nu obs. flux,
- Assume due to SBG
- Inside host galaxy, consider $\gamma\gamma$ casc. of primary $\pi^0$ & $\pi^\pm$ IC upscatt. photons.
- If no sync. losses, $\Phi_{\gamma,\text{casc}} \sim 0.5 \Phi_{\gamma,\text{IGB}}$
- If incl. sync. losses inside host SBG ($B_{\text{ISM}} \sim mG$) then $\Phi_{\gamma,\text{casc}} \sim 0.2 \Phi_{\gamma,\text{IGB}}$

However: if IGB & INB arise in less excited galaxies (e.g. SFGs), $B_{\text{ISM}}$ may be smaller → the sy losses are smaller, and $\Phi_{\gamma,\text{casc}}$ larger
INB, IGB & SFGs

Anchordoqui+14, 1405.7648

- Consider $\pi^\pm \rightarrow \nu$ ING & $\pi^0 \rightarrow 2\gamma$ IGB, so that spectrum does not violate Glashow ✔

- Check location of showers (blue circles) and tracks (♦) versus known SFGs

- M82, NGC253, NGC4945, SMC, IRAS18293 “corr” w. showers - but no track corr.

- Will need 10 yrs w. IC3, or a next gen. detector, to detect >5 track events which corr. with SFGs at > 99% CL
- Use Herschel PEP/herMES
  Lum.Fcn of FIR bright gals
- From this deduce distribution of SFG, SBG up to z~<4
- Use this and the Fermi correl
  $L_\gamma \sim L_{\text{FIR}}^{1.17}$ to deduce an IGB
  which fits Fermi obs. IGB
- Under same assumptions, find also that if 100 PeV CRs can
  be confined in host galaxies,
  can fit also IC3 PeV INB
Galaxy mergers, INB & IGB

Kashiyama & Mészáros, 1405.3262

- **Every galaxy** merged at least **once** in the last **Hubble time**

  - **Major mergers** →
    - \( E_{\text{gms}} \sim 10^{58.5} \) erg,
    - \( R \sim 10^{-4} \) Mpc\(^{-3}\) Gyr\(^{-1}\)
    - \( v_s \sim 10^{7.7} \) cm/s
    - \( Q_{\text{cr,gms}} \sim 3 \times 10^{44} \) erg Mpc\(^{-3}\) yr\(^{-1}\)
    - \( \varepsilon_{\text{cr,max}} \sim 10^{18.5} \) Z eV

- **\( pp \)** → PeV vs, 100 GeV \( \gamma \)s

- **\( \nu \)**: Indiv. GMS: 0.01 \( \mu \) yr, INB: **20-60%** IC3 obs. flux

- **\( \gamma \)**: Individual GMS flux:
  - \( \sim 3 \times 10^{-13} \) erg/cm\(^2\)/s → CTA?
  - IGB \( \sim 10^{-8} \) GeV/cm\(^2\)/s/sr , about **10-30%** Fermi IGB

- Minor mergers: uncertain, could add up to 70-100%
Outlook & Issues

- Both in AGNs and GRBs, major question is whether basic emission is leptonic or hadronic - contribution to the observed CRs/UHECRs and PeV nus?
- Location of the GeV(TeV) emission region (inner/outer jet, photosphere?) Role of (which?) target photon sources
- Role of pair cascades in VHE spectrum formation
- Do galaxy/cluster shocks and/or galaxy merger shocks contribute much (all?) of SFG/SBG VHE radiation?
- Relative contribution of AGNs, SFG/SBG/GMS to the IGB and/or the INB? is pp, p\gamma or leptonic dominant in \gamma?