Deducing UHECR sources, guided by observations

Glennys R. Farrar
Center for Cosmology and Particle Physics
New York University

Research supported by NSF, NYU and international agencies

Auger AGN correlation produces a big puzzle

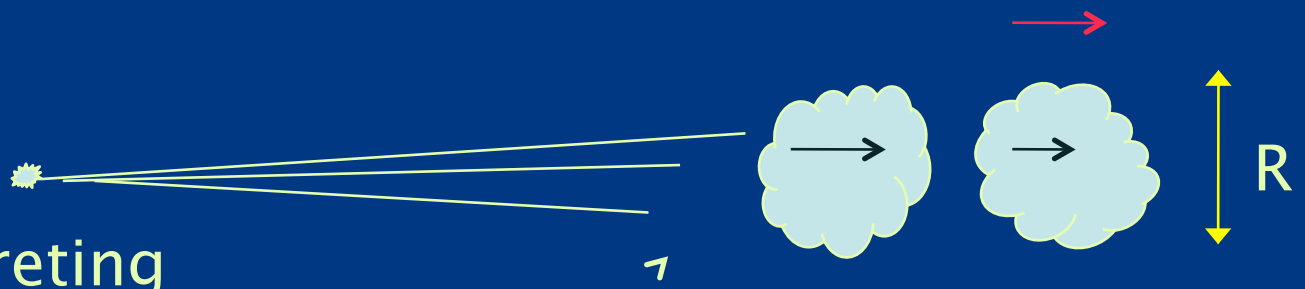
- Acceleration powered by a supermassive BH *must* be accompanied by radiation:
  - from the accretion disk:

$$L_{bol} \geq \sim 10^{45}\, E_{20}^{2}\ \mathrm{erg/s}$$

  - probably more from the jet

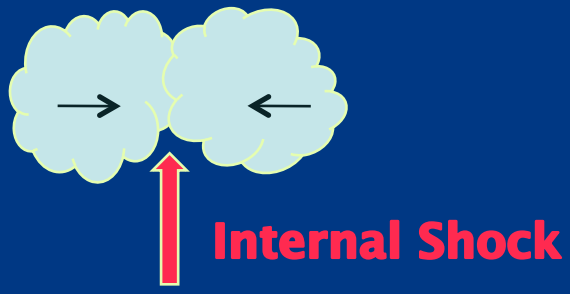
UHECR acceleration

Illustrative case – internal shocks



Accreting Supermassive Black Hole

Inhomogenieties in jet



CM moves with bulk Lorentz factor Γ

Theoretical Challenge

GRF + A. Gruzinov "AGN flares and Cosmic Ray Bursts", astro-ph:0802.1074

Requirements of UHECR acceleration and avoidance of energy losses are *almost* mutually exclusive. E.g., protons accelerated in internal shocks (Γ,*R,B)*

To confine UHECRs: $RB \gtrsim 3 \times 10^{17}\,\Gamma^{-1}\,E_{20}$

To avoid synchrotron losses: $B \lesssim \Gamma^2\,E_{20}^{-2}$

To avoid photopion losses: $RB^2 \lesssim 10^{17} E_{20}^{-1}\Gamma$

Isotropic equivalent $L_{\rm bol} \sim \frac{1}{6} c\Gamma^4 B^2 R^2 \gtrsim 10^{45}\Gamma^2\,E_{20}^2\,{\rm erg/s}$

Photon Counterpart:

$$\nu L_\nu \gtrsim 10^{44}\Gamma^2 E_{20}^2, \quad 0.01\ \Gamma B\ {\rm eV} \lesssim h\nu \lesssim 10\ \Gamma\ {\rm MeV}$$

Observational Constraints

Conservative:

- CR energy injection rate:

$$\Gamma_{lnE} > 0.7\text{-}20\ 10^{44}\ \text{erg Mpc}^{-3}\ \text{yr}^{-1}$$

- source density: $n_{src} > 3\ 10^{-5}\ \text{Mpc}^{-3}$
- Arrival time delay: $\tau_{CR} \sim 10^{5}\ \text{yr}$

Additional:

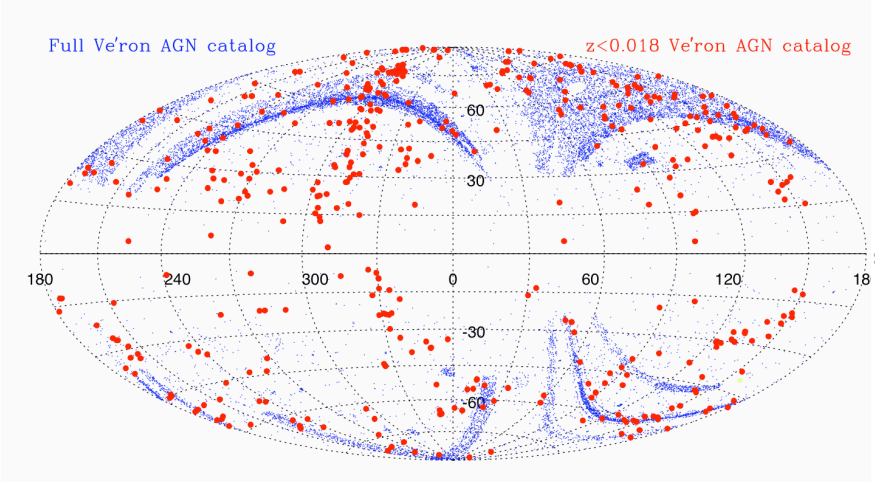
- Auger Correlation with AGN
- Properties of the "Ursa Major" UHECR cluster

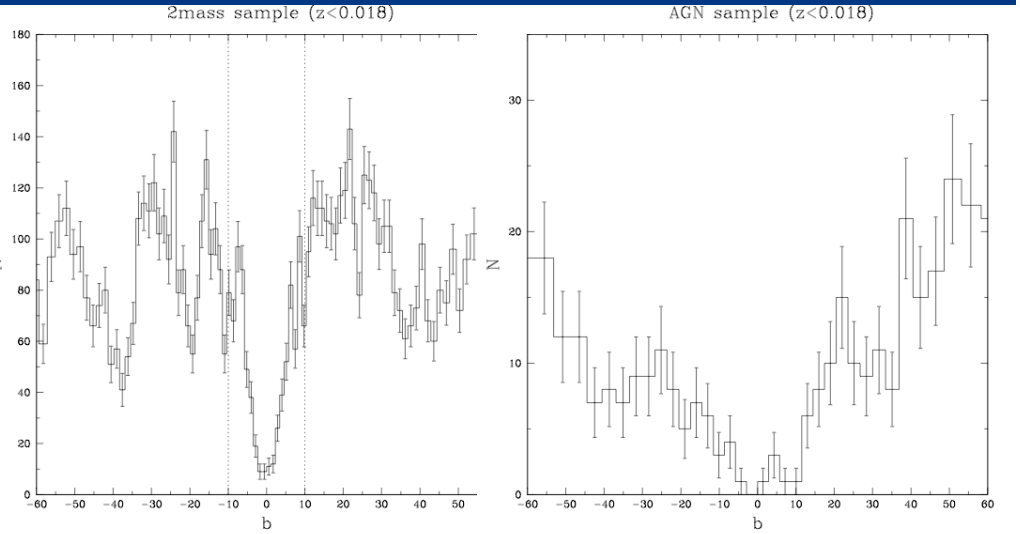
Auger UHECR correlation with Veron-Cetty Veron galaxies

- VCV catalog -- mostly AGNs, but not pure or complete
- L_{bol} : Most correlations are with too-weak AGNs
  (Zaw, Farrar, Greene 08)
- Morphology of correlated galaxies: few have jets
  (Moskalenko, Stawarz, Porter, Cheung 08)

- A statistical fluke? *a priori* chance probability < 1%
- VCV galaxies just tracers? NO!

Problems with Veron-Cetty Veron AGN Catalog (Plots by A. Berlind)





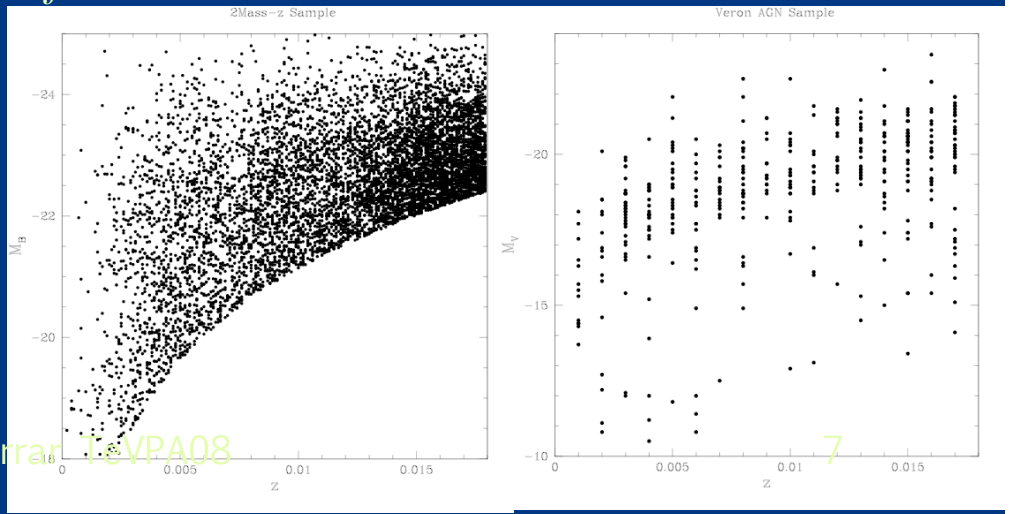
Veron-Cetty -- A compendium of all reported *optically identified* AGNs.

Selection is non-uniform both spatially and in flux limits.

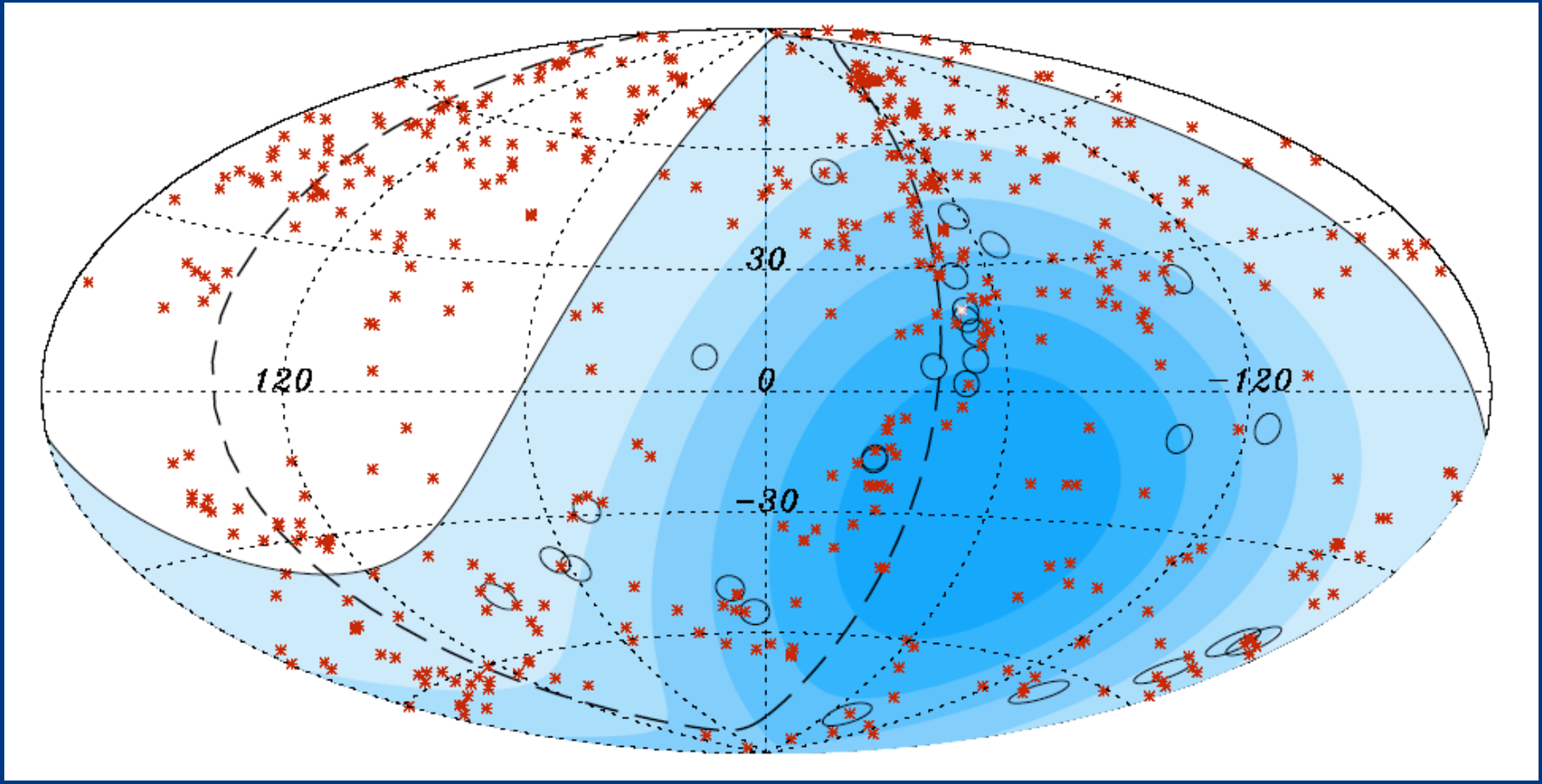
Upper left plot: SDSS is the "deepest" of the large AGN-reporting surveys. Its footprint clearly shows in the V-CV catalog.

Upper right histograms: Reduced sensitivity for |b| <~10° due to dust in Galactic plane is evident in 2MASSzK=11.25* galaxies (left) and V-CV AGNs (right). Bins have equal areas so distribution would be flat for a uniform population; variation for |b|> ~10° is a manifestation of the "cosmic variance" in local large scale structure. (* courtesy J. Huchra.)

Lower right scatter plots: Absolute magnitude vs redshift for (left) galaxies with z < 0.018 from 2MASSz and (right) AGNs with z < 0.018 from V-C. The sharp arc for 2MASS reflects its uniform cut in flux while only a hint of the arc characteristic of a flux-limited sample is seen in the AGNs.



UHECR-VCV correlation from Large Scale Structure?



Subsampling 2MASS Galaxies

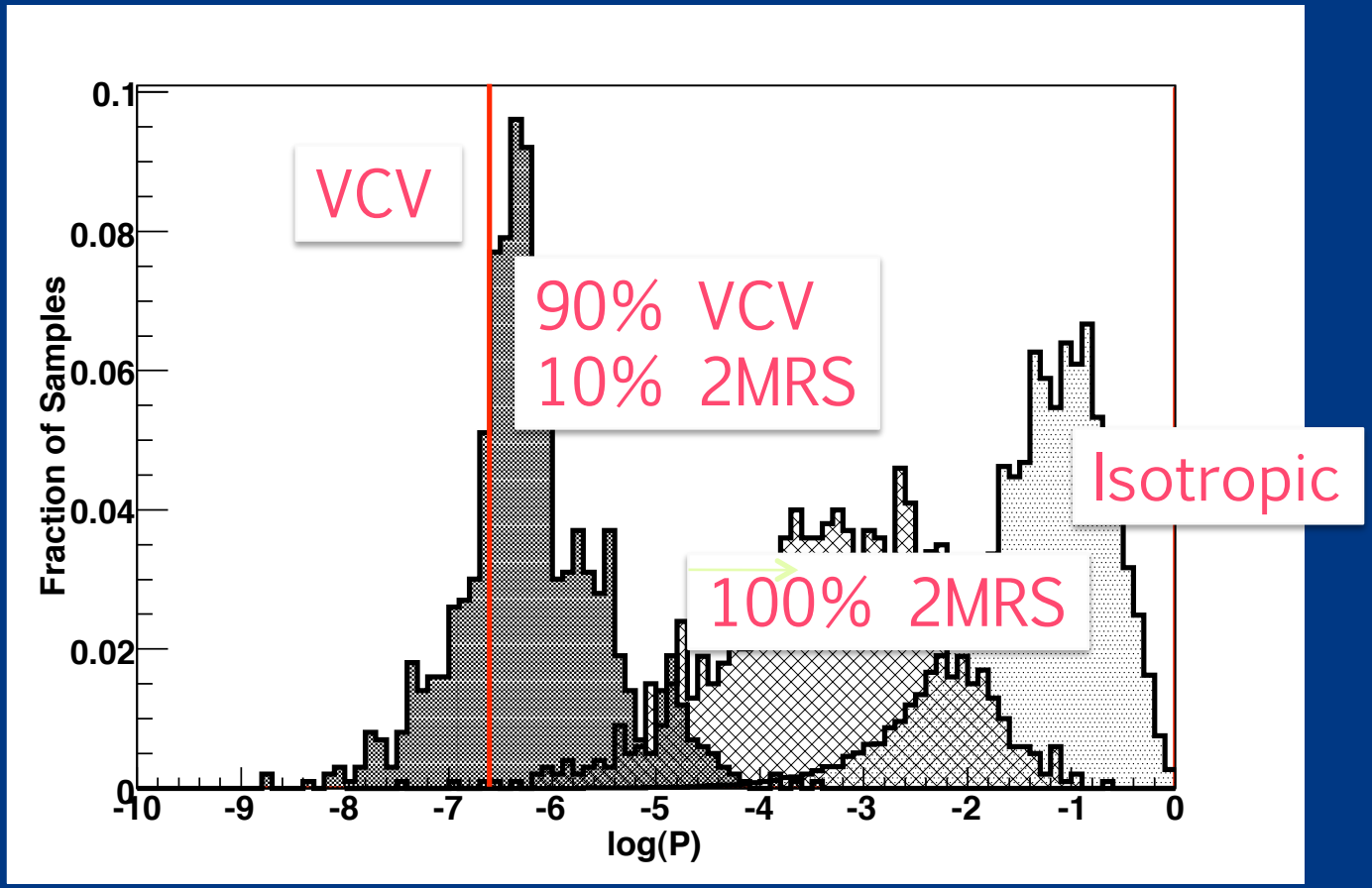
Farrar, Berlind, Zaw *(to appear soon)*

- VCV: 694 galaxies $|b|>10^{o}$, $z<0.024$
- 2MASS Redshift Survey$K=11.25$
  - 11,851 galaxies $|b|>10^{o}$, $z<0.024$
- Subsample 2MRS to mock VCV:
  - 1000 mock catalogs with 694 galaxies
  - [redshift distribution as VCV]
  - [volume limited]

1000 mocks, scanned like Auger

Farrar, Berlind, Zaw to appear

fraction of trials



CONCLUSION: VCV galaxies are not "just tracers"

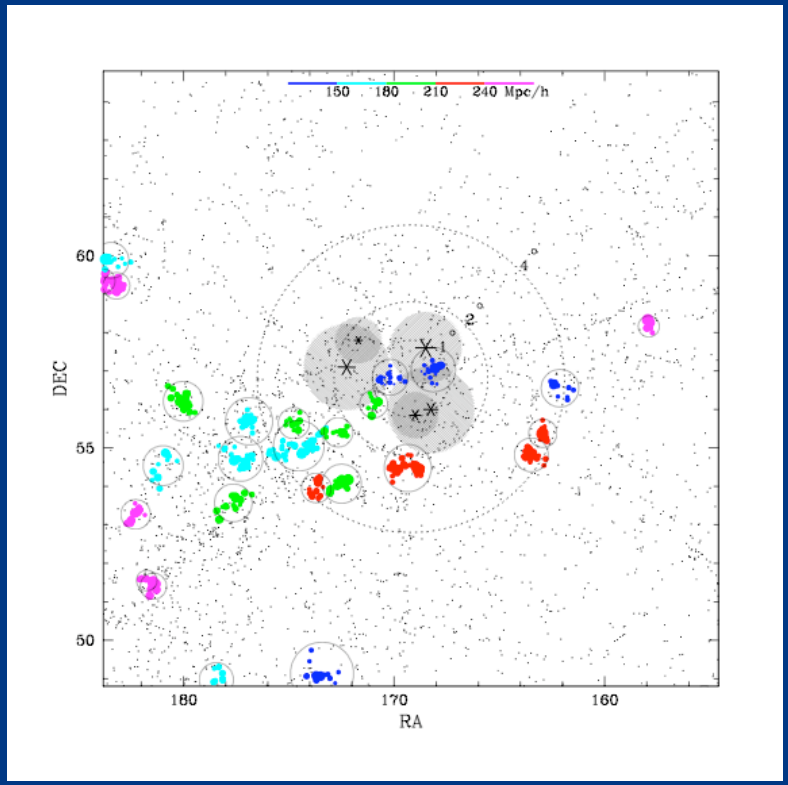
Standard Scenarios don't work!

- Powerful AGN jets, radio galaxies:
  too few that are powerful enough
  - [Correlated AGNs mostly weak, MSPC08, ZFG08]
- GRB (Waxman, 95): *local rate too low*

  $n = (0.05 - 0.27)\ \mathrm{Gpc^{-3}\ yr^{-1}}$ (Guetta Piran 06)
  - Too few visible sources ($n_{src} = n\ \tau_{CR}$)
  - Too little UHECR power, unless $L_{CR} > 100\ L_{gamma}$
  - [Don't explain AGN correlation]

Ursa Major Cluster

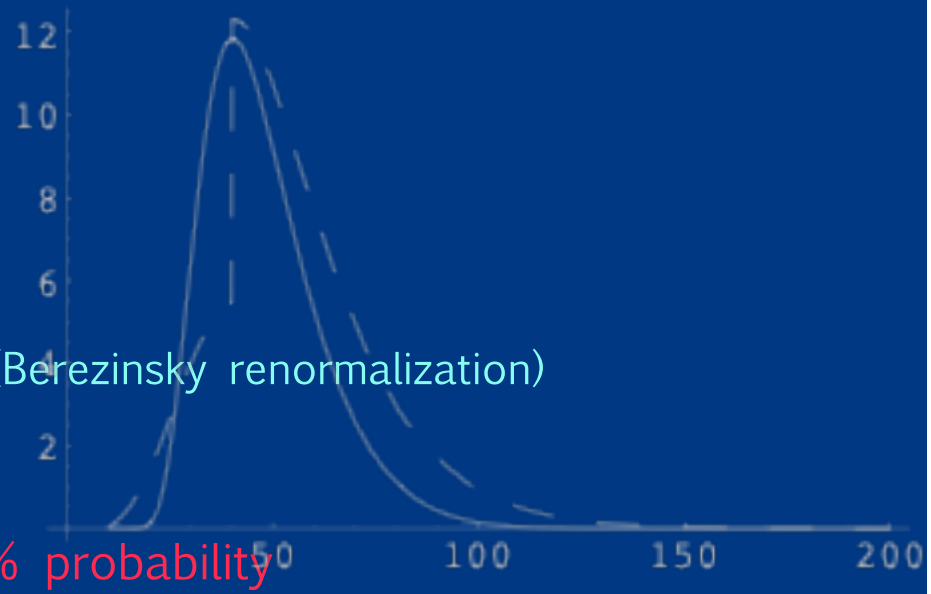
- 4 events in AGASA + HiRes, in ~ 3000 km^2 sr yr
- Chance probability: $2\ 10^{-3}$
- SDSS => foreground empty!
  - Magnetic deflection low
  - "confusion" problem reduced



SDSS: GRF, Berlind, Hogg 06

Spectrum of UM Cluster

- Observed Spectrum of an individual source allows to discriminate bursting from continuous:
  - Continuous source: spectrum same as at source (modulo GZK)
  - *Bursting source: observed spectrum is peaked:*



- Ursa Major events:
  - Hi-E sample (37 events)
    4 in cluster: 46, 48, 50, 70 EeV (Berezinsky renormalization)
  - Lo-E sample (234 events)
    0 or 1 in cluster.
  - 1 in 234 same as 4 in 37: 0.2% probability
- *=> UM source is bursting, not continuous*

UHECR production in Giant AGN flares

(GRF & Andrei Gruzinov, 2008)

- Black Hole tidal disruption of a passing star
  - Occurs every 10^4-10^5 yr (Magorrian & Tremaine 99)
  - In AGN, produces a Super-Eddington jet
  - Duration ~ debris return time, ~1 month
  - event energy: ~0.01 M_{sun} $> 10^{52}$ ergs
- Easily achieves $L > 10^{45}$ erg/s required for UHECR acceleration
- Correct prediction for UHECR flux and density of sources

Consequences of Giant AGN Flare scenario

- UHECRs:
  - Accretion disk needed to produce a flare => source is a weak AGN most of the time. *[Auger AGN correlation]*
  - Little relationship between observed AGN luminosity or type, and its flux in UHECRs. *[as in Auger correlated galaxies]*
  - Events from a single source display bursting spectrum *[as observed in Ursa Major cluster]*
  - Composition may include heavy nuclei

- Predicts new class of optical and soft-gamma-ray bursts:
  - SDSS: Search of archival data underway
  - Fermi/GLAST: should see many events per year
  - N.b., photon bursts arrive ~10^5 years before UHECRs!

Predicted Photon Flares

- Spectrum roughly flat

$$\nu L_\nu \gtrsim 10^{44}\Gamma^2 E_{20}^2, \quad 0.01\ \Gamma B\ \mathrm{eV} \lesssim h\nu \lesssim 10\ \Gamma\ \mathrm{MeV}$$

B ~ 3, Γ > 3 => spectral range ~0.1 eV to ~30 MeV

- Duration: ~ 30 days (shorter if disk instability)
- Density of flaring objects:

$$n_{\mathrm{GAF}} \approx 3 \times 10^{-7}\,\mathrm{Mpc}^{-3} \left(\frac{\Delta ln E}{20} \frac{\Gamma_{44.6}}{1} \frac{10^{45}}{f_{\mathrm{CR}} L_{\mathrm{GAF}}} \right)$$

- Annual Rate in GLAST/Fermi etc (in LAT range?)

$$N_{\mathrm{GAF,yr}} \approx 30 \frac{b_\gamma}{0.1} \left(\frac{\nu L_{\nu,\mathrm{GAF}}}{10^{45}} \frac{10^{-9}}{(\nu F_\nu)_{\mathrm{sen}}} \right)^{\frac{3}{2}} t_d^{-\frac{1}{4}} \frac{n_{\mathrm{GAF}}}{3 \times 10^{-7}}$$

Typical Parameters

- Stellar tidal disruption $M_{BH} = 3\ 10^6\ M_{sun}$
- UHECR acceleration constraints satisfied with
  $B = 3$ G, $\Gamma = 3$, $R = 3\ 10^{16}$ cm
- Isotropic Equivalent Jet Luminosity: 10^{46} erg/s
- Duration (EvansKochanek89, Ulmer99) ~$3\ 10^6$ s =>
  $E_{tot} \sim 3\ 10^{52}$ erg => CORRECT $\Gamma_{\ln E}^{UHECR}$
- $\Gamma = 3$ => beaming factor 0.1 => ~400 sources in Auger fov
- Photon Counterpart:
  $\nu L_\nu \sim 10^{45}$ erg/s, 0.1 eV < $h\nu$ < 30 MeV
- Density of flares ~ $3\ 10^{-7}$ -- look in SDSS
- Swift expects 10^{-4} per year
- Should be seen by GLAST and next-generation surveys.

EXCITING TIMES!

- Next few years of Auger South:
  - composition (p?, Fe?,...)
  - UHE particle physics
  - Begin to establish where UHECRs are made
- Telescope Array: Collect more Ursa Major UHECRs
- Auger North:
  - factor ~10 greater aperture
  - *Individual Sources* (spectrum, magnetic fields,...)
- GLAST/Fermi, SDSS, Quest, ... :
  - Detect predicted Giant AGN bursts ???