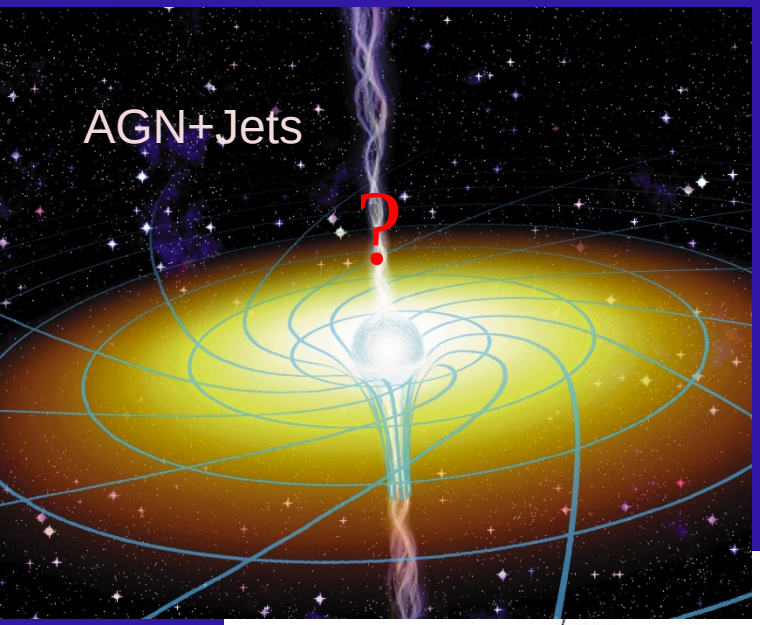
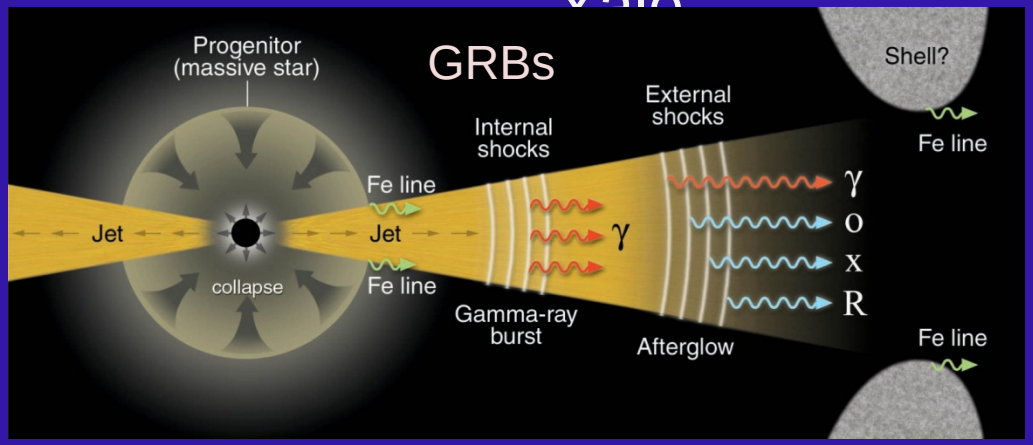
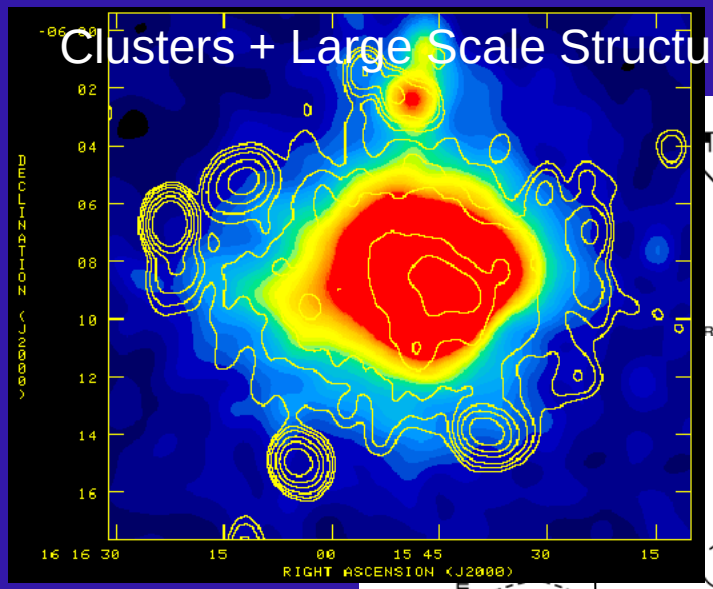
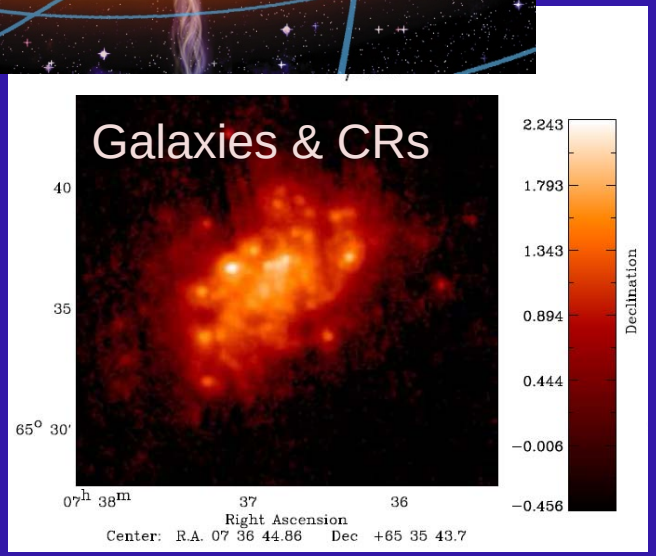
Top 10 Extragalactic Science Questions (Thoughts On What We Need…)

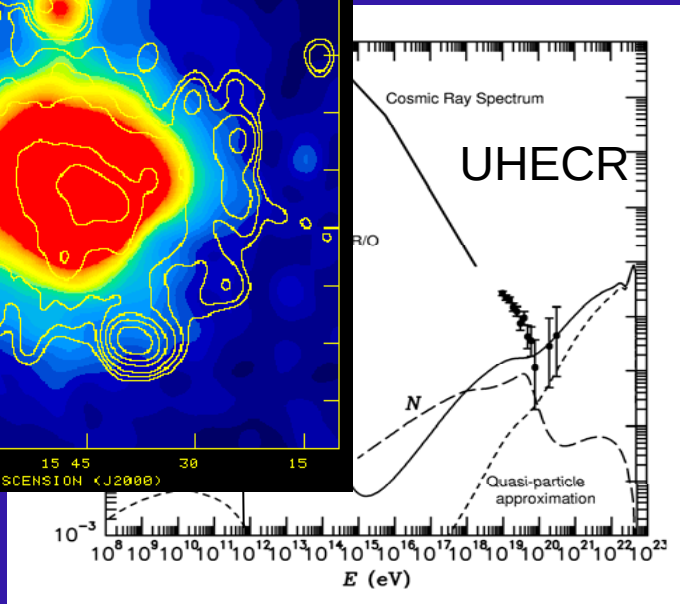
P. Coppi,
Yale







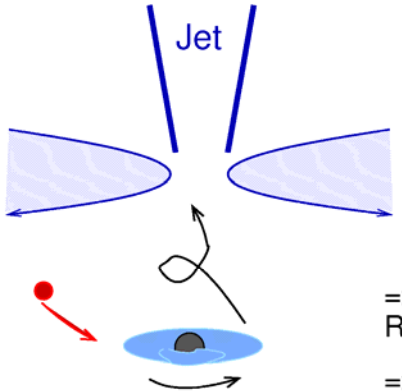




Jet Origin ???

[Jet composition???]

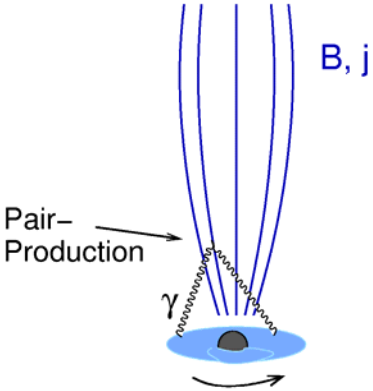
1.) Mass Accretion onto Black Hole



=> Extraction of up to 42.6% of Rest Mass Energy of Infalling Material

=> Accretion Disk => Jet Matter

2.) Extraction of Rotational Energy of Black Hole

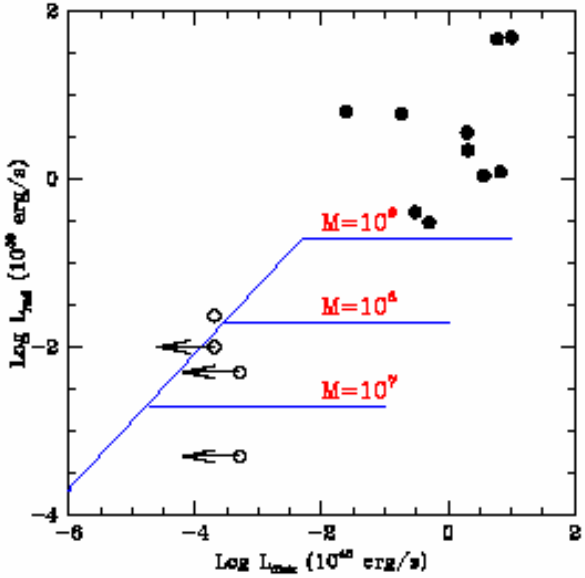


(e.g., Blanford-Znajek mechanism)

=> Extraction of up to 29% of Rest Mass Energy of Black Hole

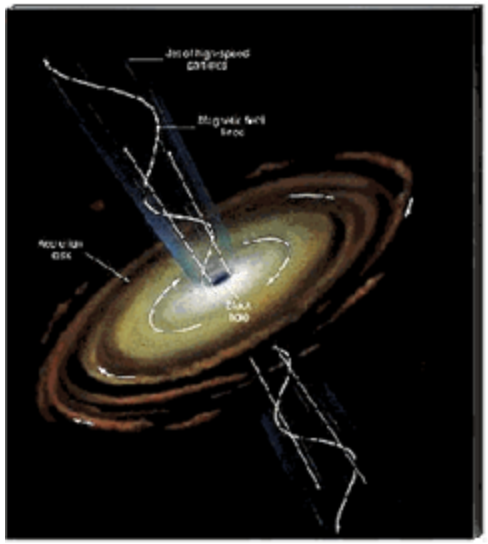
=> Electron/Positron Jet

=> Different Jet Matter
Different AGN Life Time



But…

Electromagnetic Formation of Jets



Strong magnetic field, generated or trapped by accretion disk induces voltage across spinning hole which drives current.

For Cygnus A:

$B \sim 10^4$ G; $M \sim 10^9 M_\odot$

$E \sim \Omega \Phi \sim 10^{20}$ V

$R_{in} \sim R_{out} \sim 100\ \Omega$

$I \sim V / R \sim 10^{18}$ A

$P \sim E\,I \sim 10^{38}$ W

Hadronic vs. Electronic models of TeV Blazars

SSC or external Compton – *currently most favoured models*:

- easy to accelerate electrons to TeV energies
- easy to produce synchrotron and IC gamma-rays

recent results require more sophisticated leptonic models

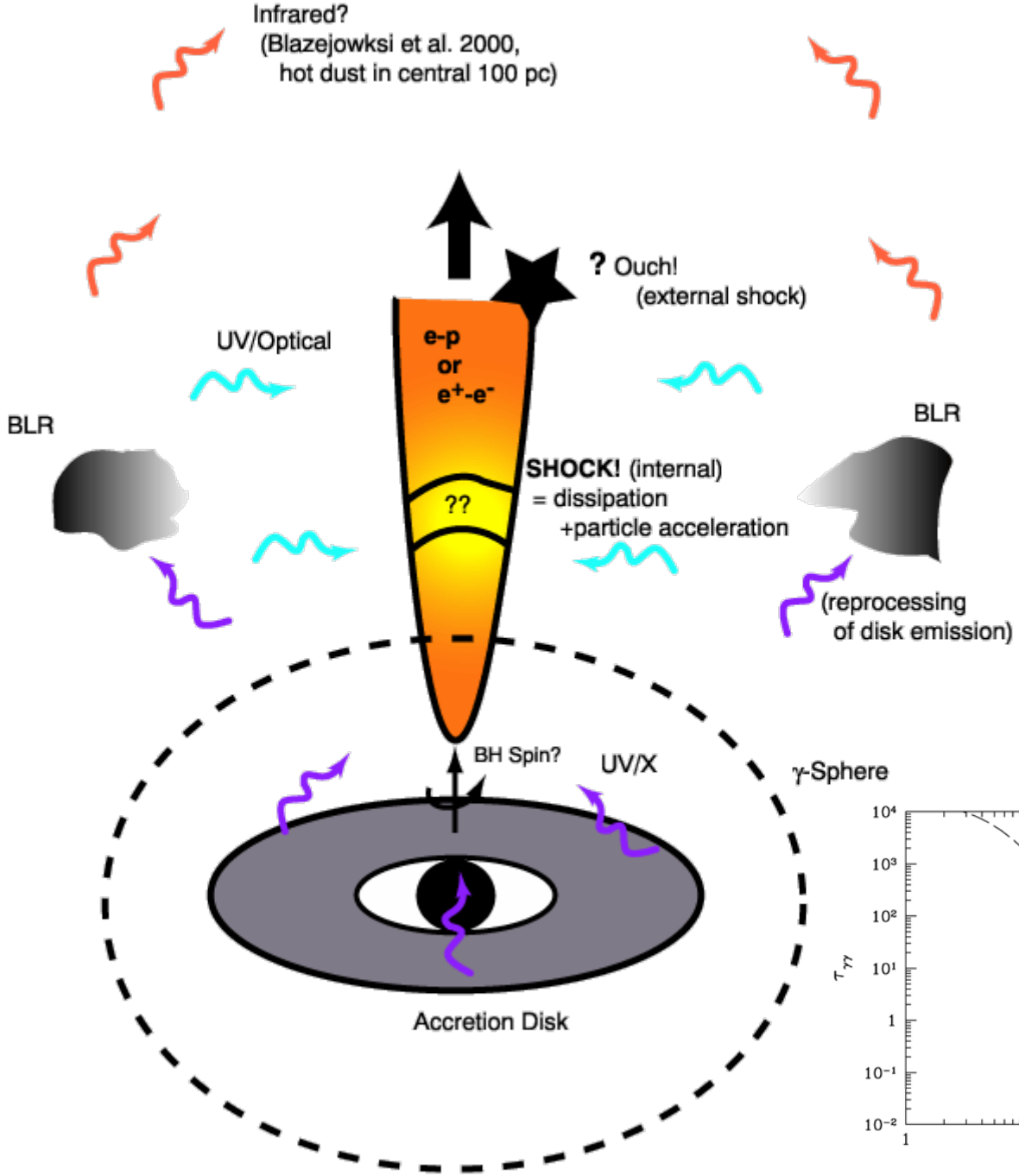
Hadronic Models:

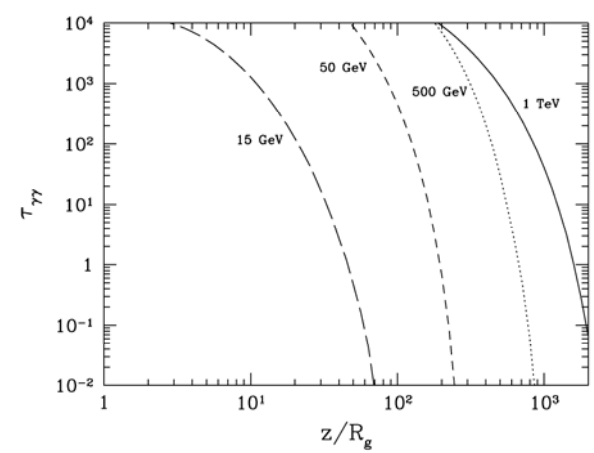
- protons interacting with ambient plasma — neutrinos
  very slow process: $t_{pp} \sim 10^{15}(n/1cm^{-3})^{-1}sec$
- protons interacting with photon fields — neutrinos* (*unlikely*)
  low efficiency + severe absorption of TeV γ-rays
- proton synchrotron — no neutrinos
  very large magnetic field B=100 G + accelaration rate c/r_g

"extreme accelerator" (of EHE CRs) Poynting flux dominated flow

*detectable neutrinos from EGRET AGN but not from TeV blazars

F. Aharonian

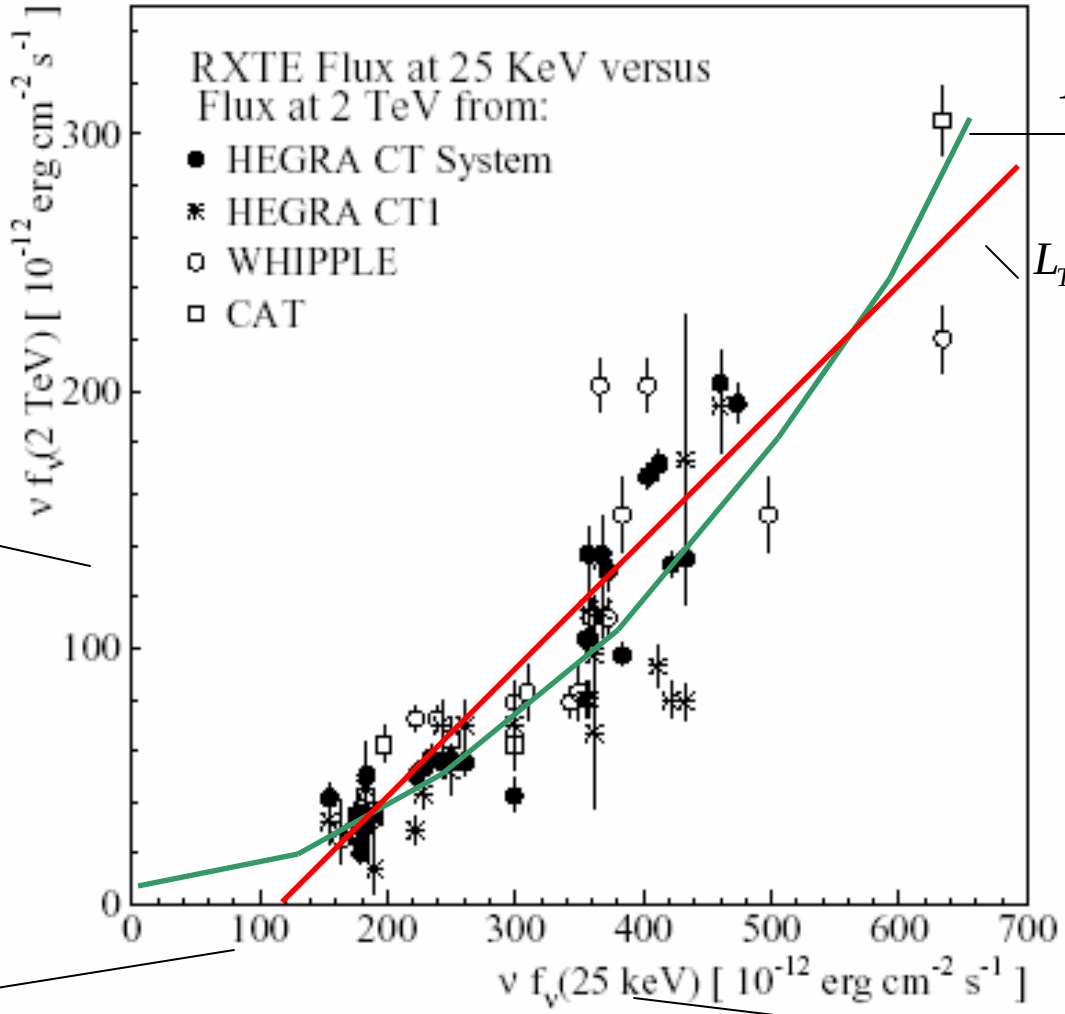




The central engine of a generic gamma-ray blazar is a MESSY place!

Christmas Tree/Internal Shock Model … clearly not right for some objects

Mrk 501 X-TeV correlation STABLE over 3+ months!



$L_{TeV} \propto L_x^2$ (naive SSC)

$L_{TeV} \propto L_x$ (ERC, SSC, hadronic model)

Linear Axes!

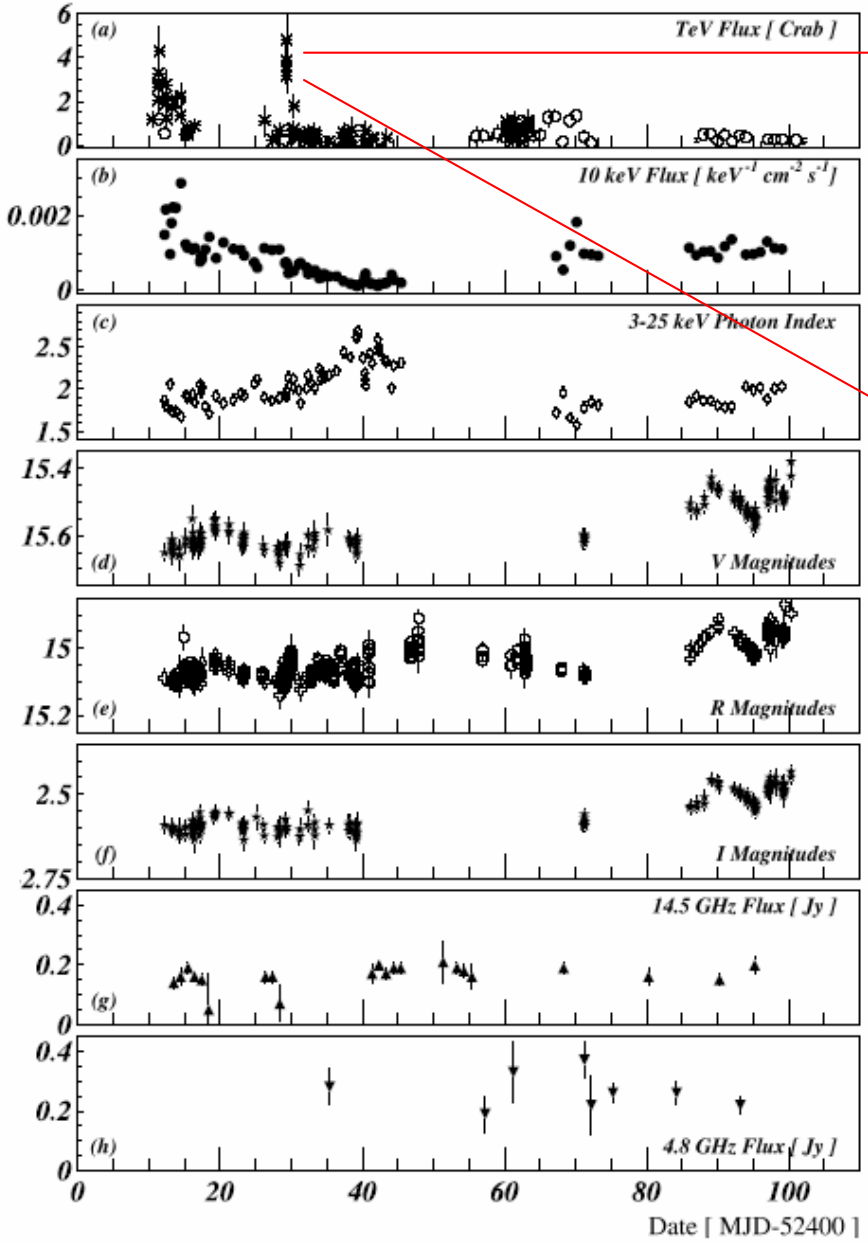
Steady X-Ray Component??

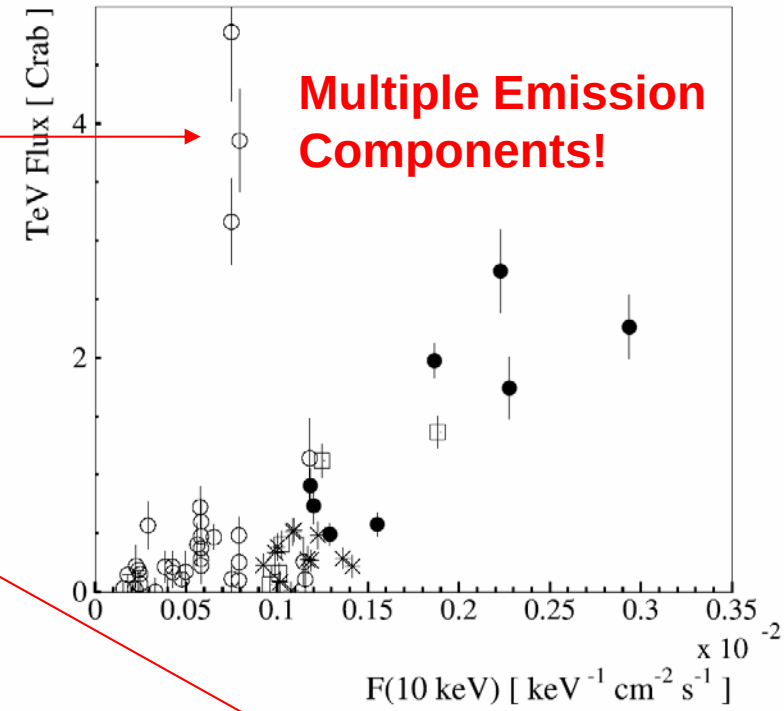
Key – 3 keV flux tracks TeV flux relatively poorly

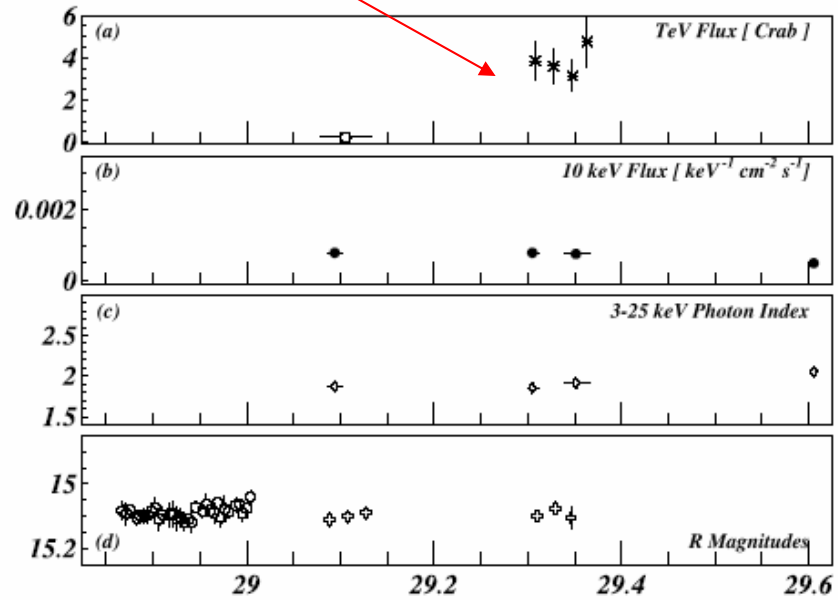
Figure 1. Correlation between X-ray (RXTE) and TeV Gamma-ray fluxes. The Gamma-ray fluxes are from CAT (squares), HEGRA CT System (solid points), HEGRA CT 1 (asterisks), and Whipple (open circles). Only observation pairs with less than 6 hrs time delay have been used.

N.B. June 1997 data (after main flaring) included!

Oops!! -- 1ES1959 May-Aug 2002





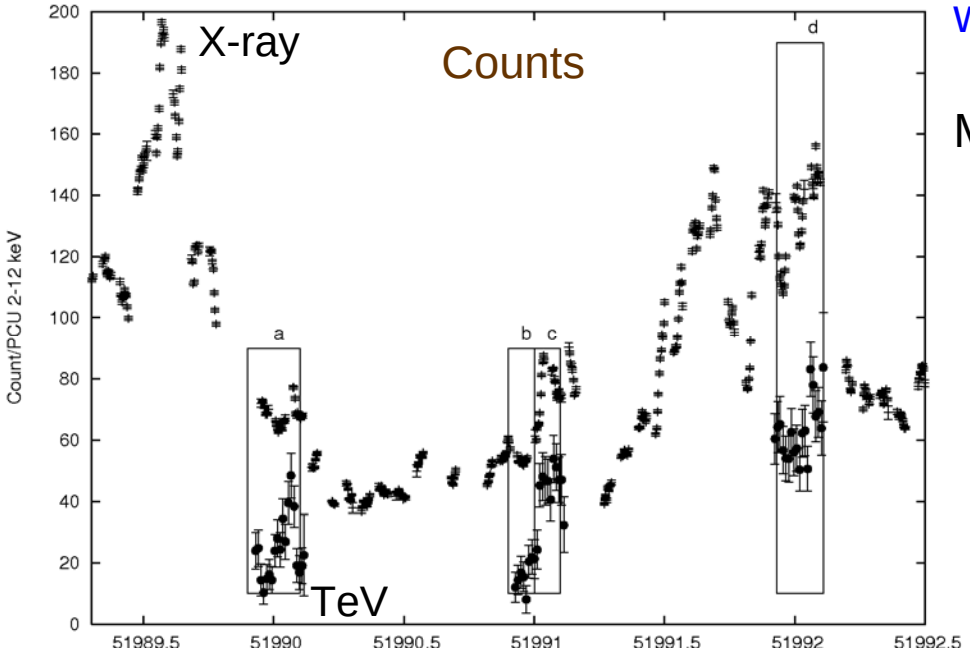


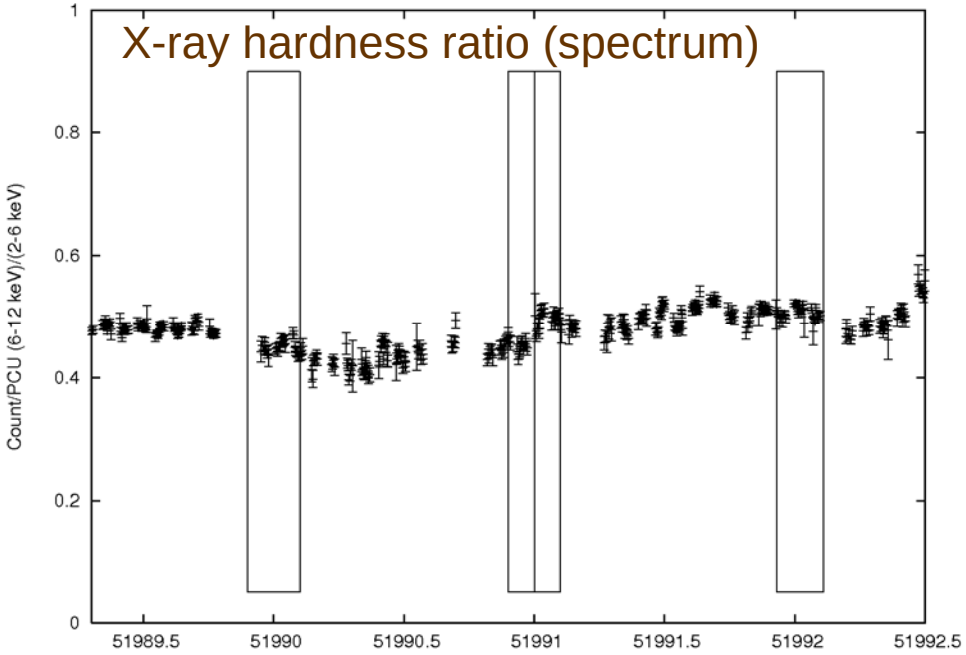
Krawczynski et al. 2004

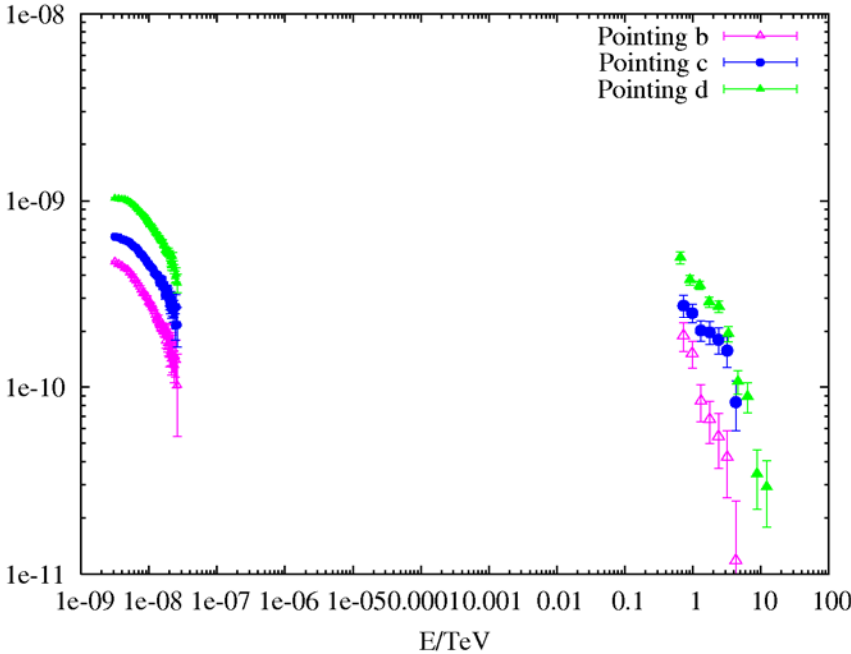
In case you still thought things were simple…

Mkn 421 2002 X-ray/TeV campaign

(Dieter Horns, preliminary)

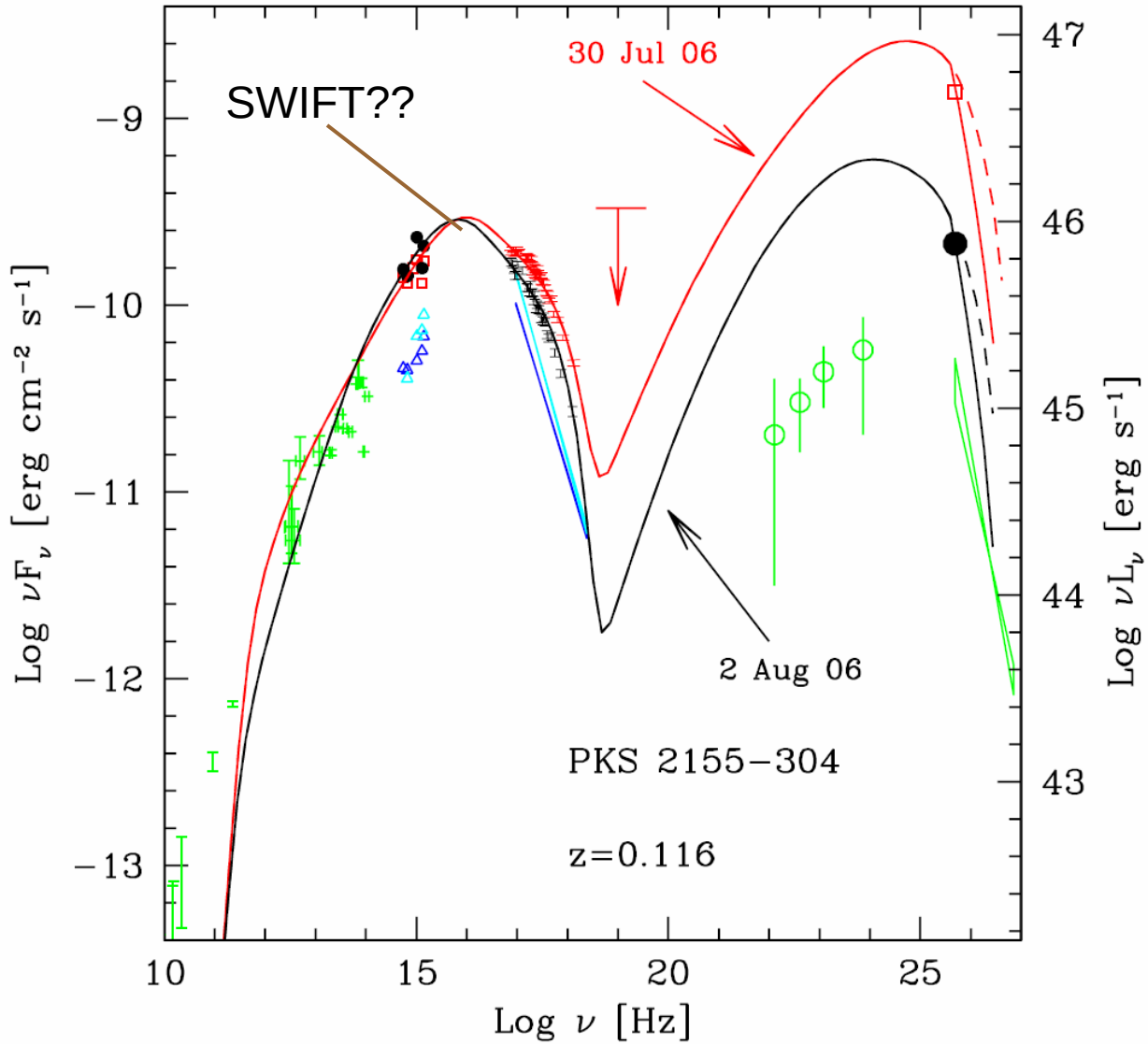






PKS 2155-304: multiwavelength coverage of flares …

Uh, oh….



$\Delta t_{\min} / M_{BH}$

GRB :

10^{-3} sec / 10 $M_{\odot}$ $\sim 10^{-4}$

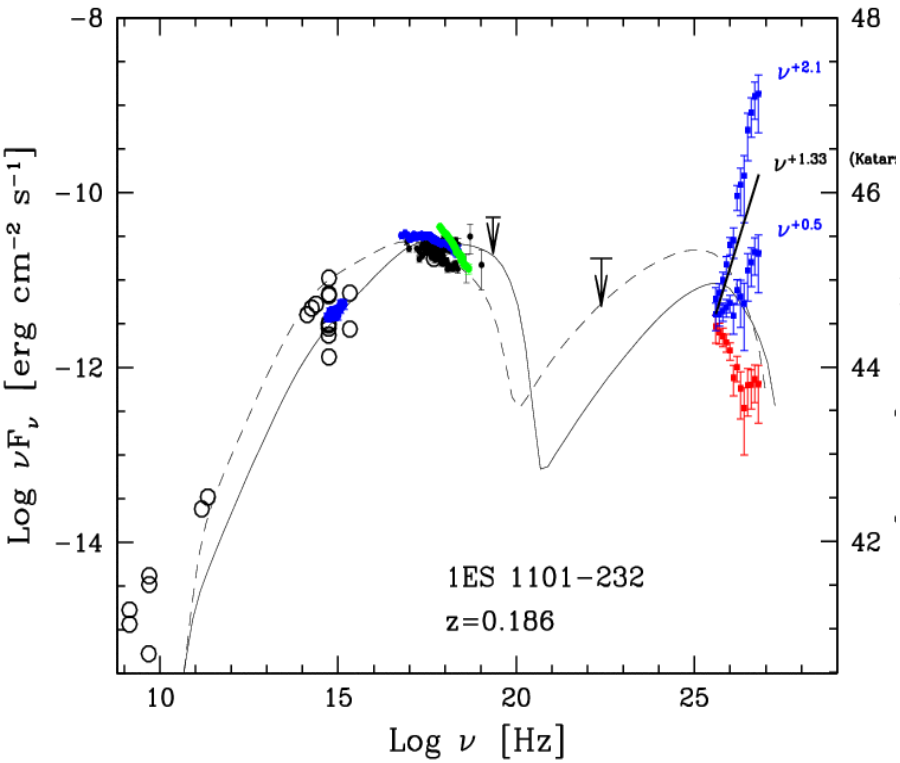
2155 :

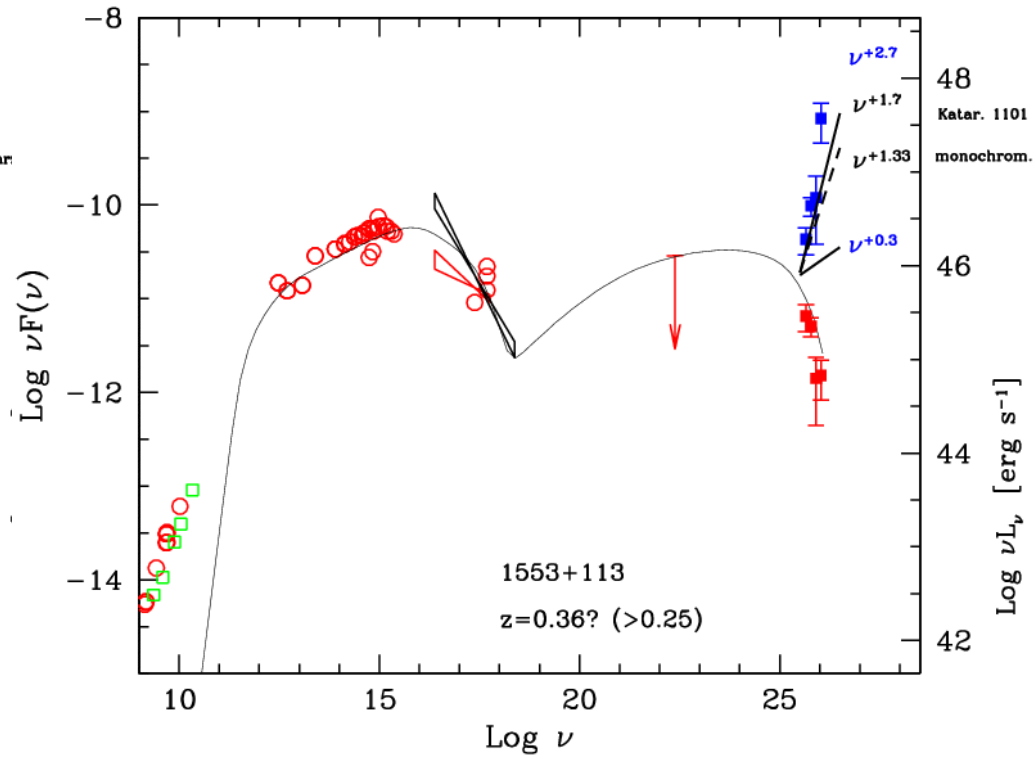
300 / 10^{9} $M_{\odot}$ $\sim$ 3×10^{-7} !

$(\Delta t_{\min} < R_{Schwarzchild} / c)$

Foschini et al. 2007 (astro-ph/07010868)

EBL absorption complications II: Incredibly hard gamma-ray spect





Blazar Problems…

One zone SSC models can match TeV blazars SEDs well but…

Details don't work so well…

Emission region very out of equipartition? (B low? Poynting dom ?

Doppler factor >> 10

Jet very radiatively inefficient, huge jet power?

Very rapid variability, how to accelerate particles so fast?

too small/too efficient emission regions?

Multiple emission components!

Making Compton-dominated TeV sources not so easy …

Mess up "unified" blazar model?

Population statistics! ($\delta \sim 50$? But then why see M87?)

EBL makes all problems worse ☺

[For GLAST, don't forget K-N effects, $\Gamma < 1.5$ at hard X-rays still pro

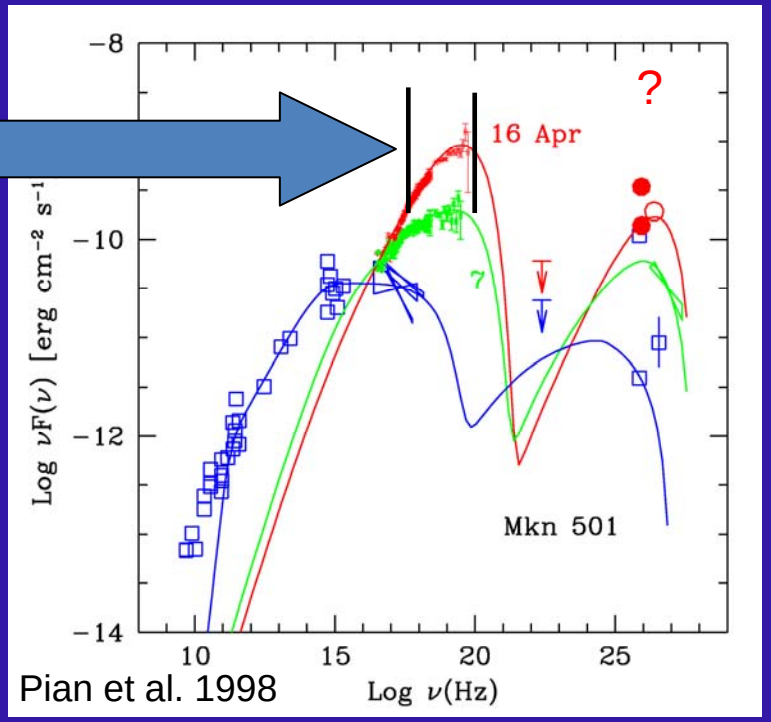
Theorist's Wish List (for AGN)

Rule of thumb: give a theorist a spectrum consistent with a power law (e.g., due to insufficient statistics) and he can fit any model/EBL you like.

Need to detect *curvature!* Ideally measure both sides of low and high energy peaks, simultaneously w/good (< hour-month) continuous *time-sampling*: UV-MeV, 100 MeV-TeV coverage. ☺ [Also very good to get below IR/O absorption threshold – N.B. EBL absorption *not* dependent.]

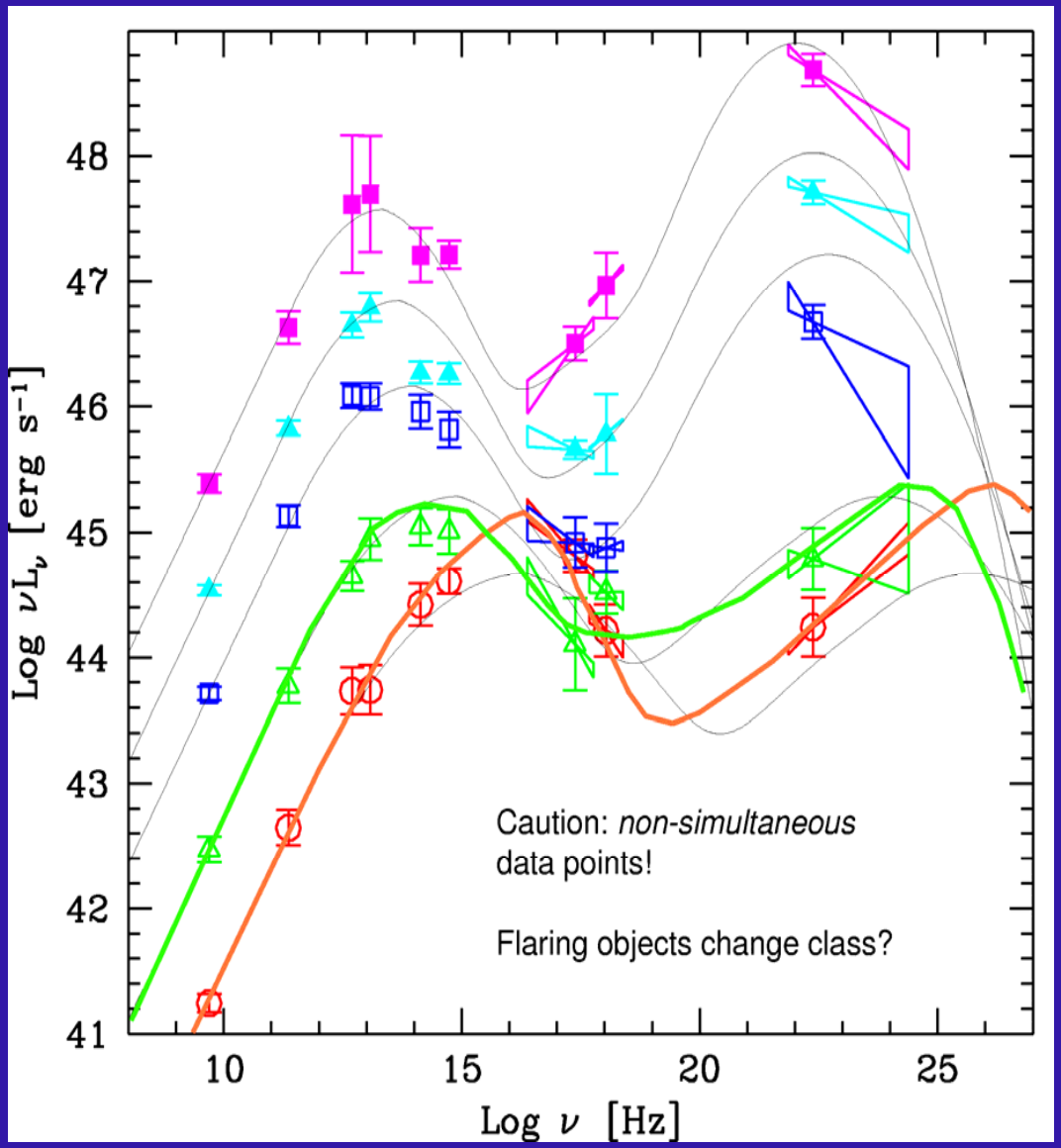
Find (HAWC) and follow low duty cycle flaring activity.

Monitor synchroton peak up to ~MeV!



Pian et al. 1998

The Grand Unified Blazar Model/Blazar Sequence

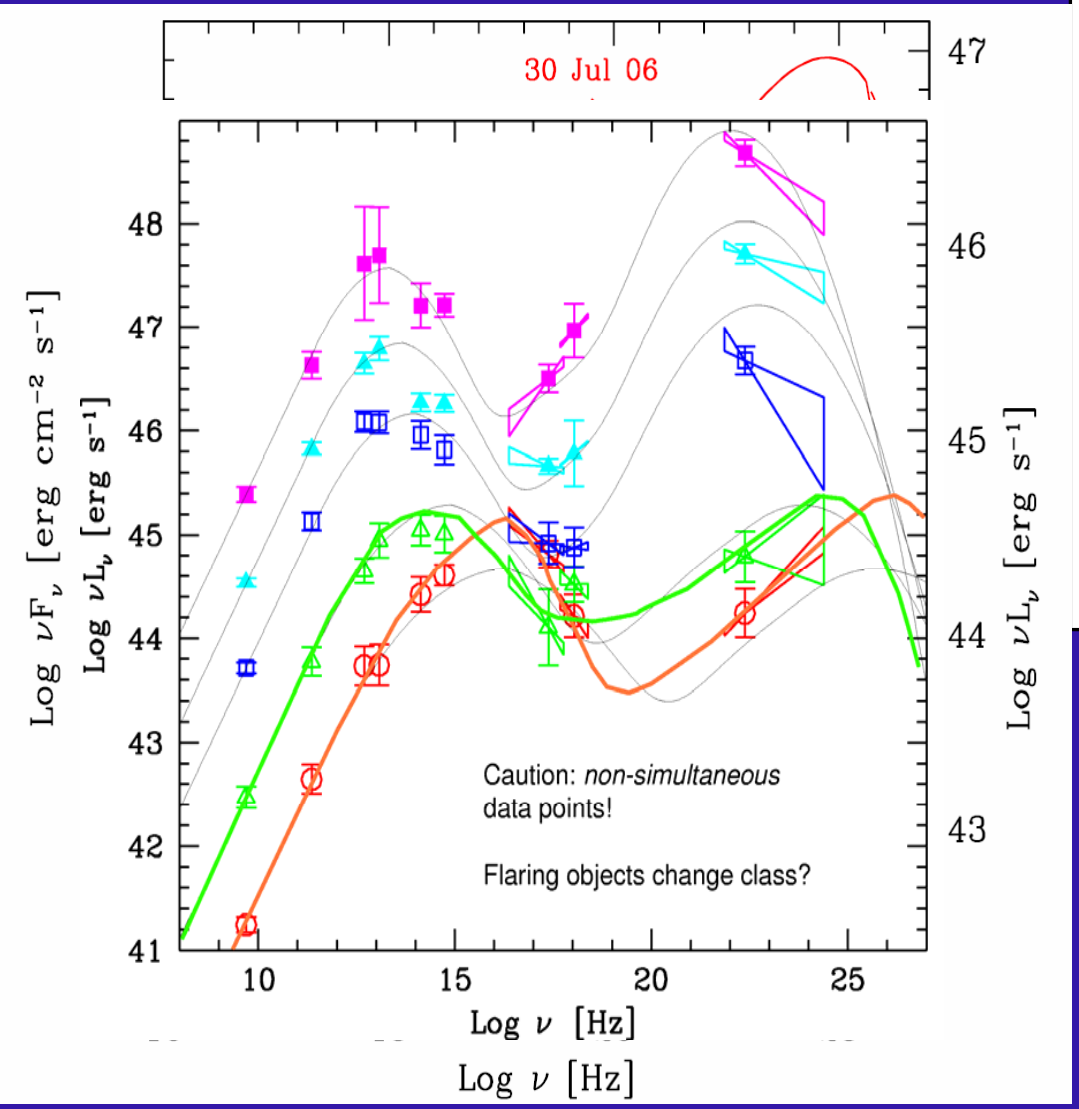


But every new object shows different behavior!

And same objects change classification.

Donato et al 2000

But what about objects like PKS 2155?



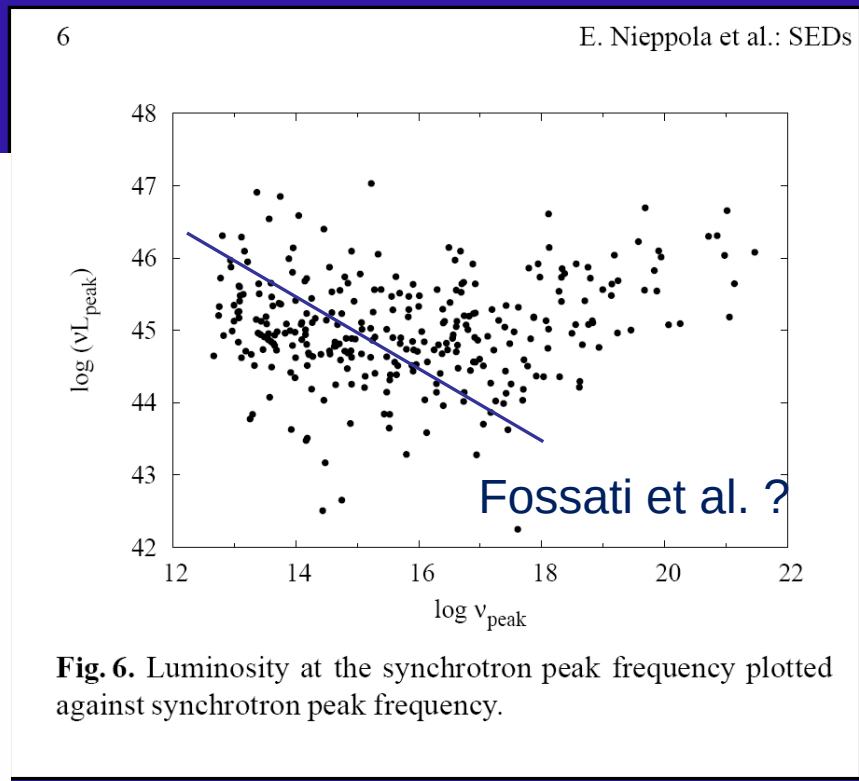


Fig. 6. Luminosity at the synchrotron peak frequency plotted against synchrotron peak frequency.

Foschini et al. 2007 (astro-ph/07010868)

Many Small vs. 1 Large Telescope?

Common debate in optical astronomy …. Answer would seem to be need both!

Large telescopes find furthest objects, but for those objects have marginal statistics/resolution. Understanding relevant physics can come only from studying *many* local objects *in detail*, for which small telescope sufficient.

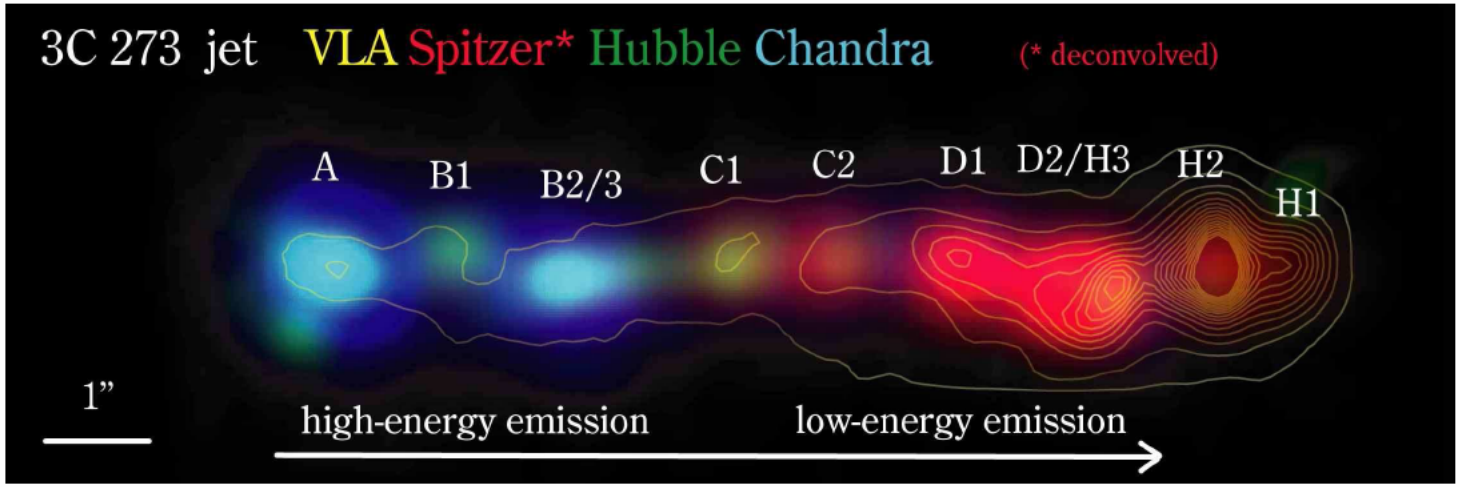
Especially for AGN, field is very number limited (need to move up Kifune plot!). In volume currently accessible by HESS, we are probably missing most objects! = don't need more collection area, higher sensitivity, just need *more* HESS telescopes!

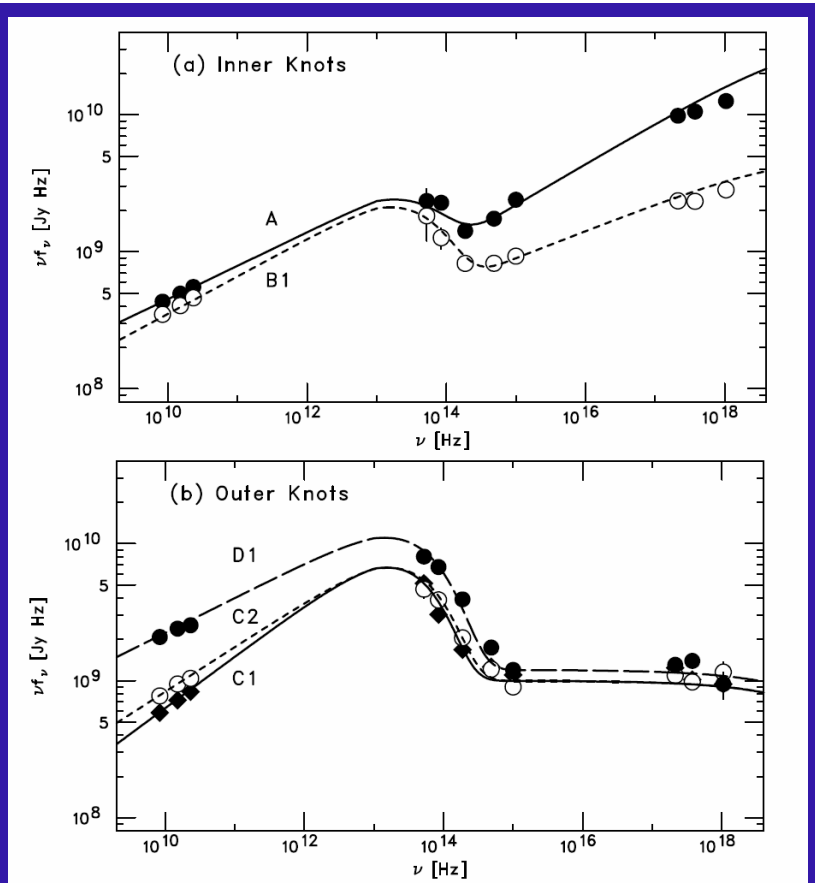
If we're limited to relatively nearby universe (=not that many sources), need good latitude coverage + for continuous observations , we need good longitude coverage => **NETWORK!**

Are "Incremental" (factor 2-3x sensitivity , medium term) Telescopes Worth Pursuing?

Yes, if are good in some particular parameter which opens new population.

3x sensitivity = ~10x decrease in integration time for known sources = non-





Two components!

Optical polarized
⇒Synchrotron
⇒ TeV+ electrons!

Uchiyama et al. 2007

Another quasar jet (1136) …

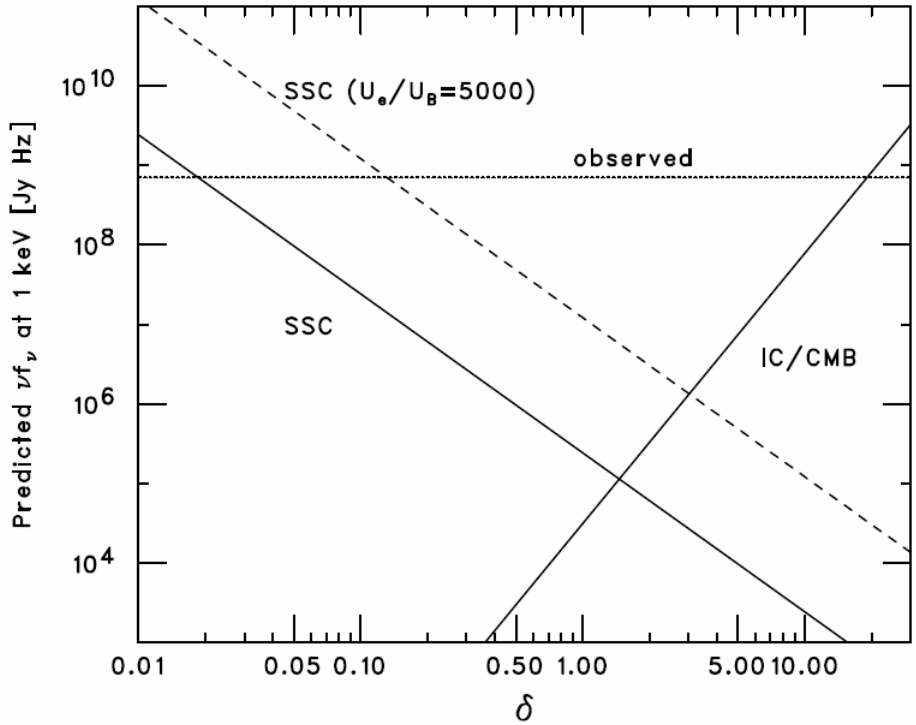
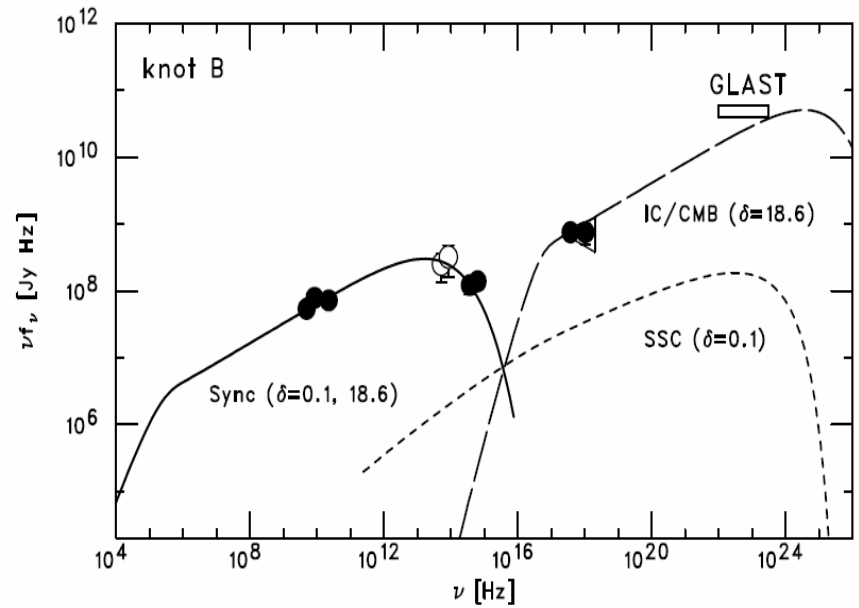
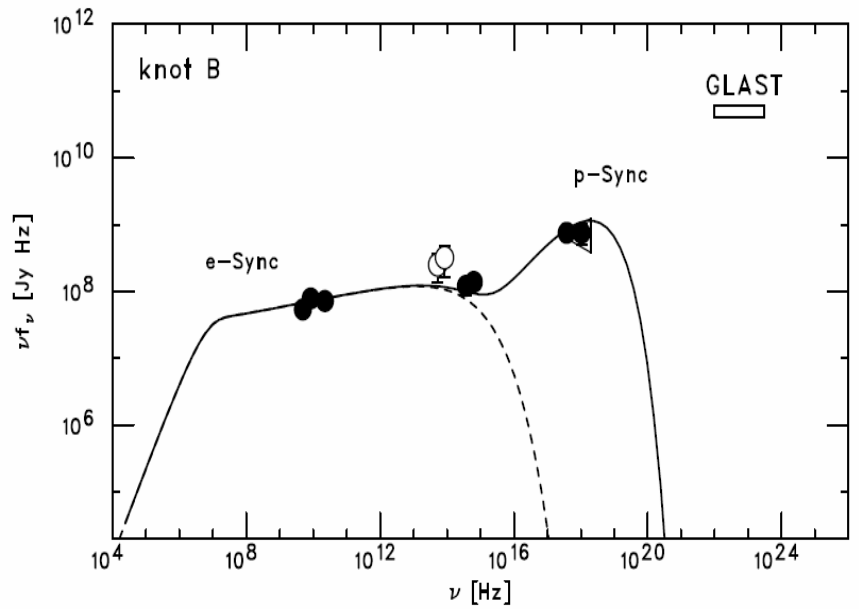


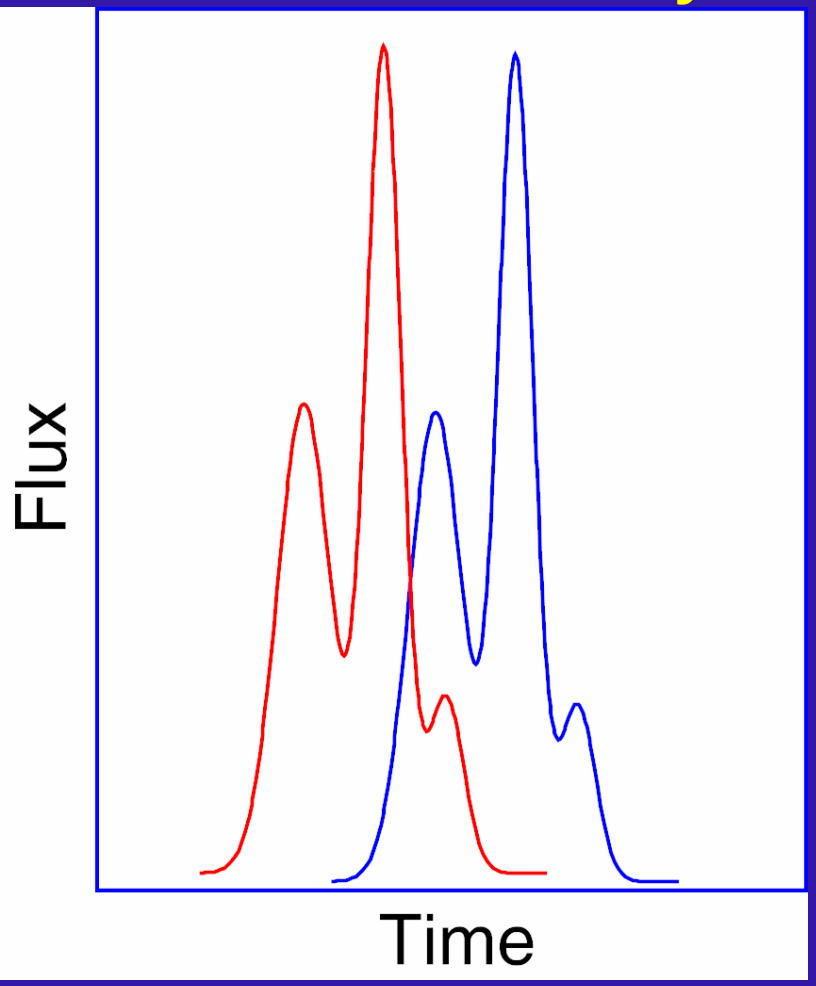
FIG. 4.— Predicted flux of IC/CMB and SSC at 1 keV as a function of the beaming factor (δ) based on the observed radio flux of knot B. The observed X-ray flux is 7×10^8 JyHz (a horizontal *dotted* line). The IC/CMB emission is dominant for a large δ, while SSC dominates the X-ray emission for de-beaming cases ($\delta < 1$). A dashed line shows the SSC prediction with the assumption of a significant deviation from equipartition ($U_e/U_B = 5000$).





Uchiyama et al. 2007

Gamma-Rays and Probing Spacetime

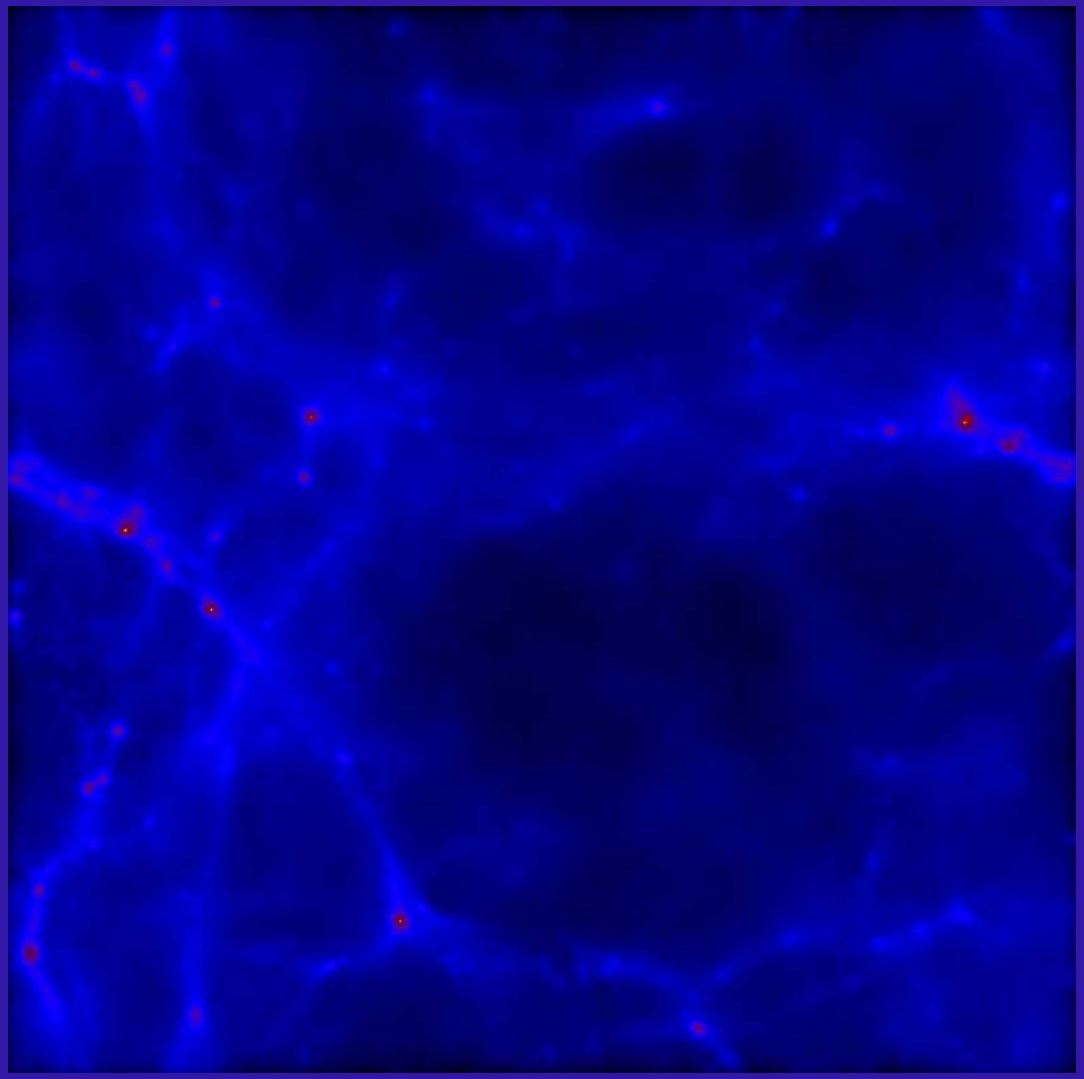


- Probe refractive index of vacuum giving rise to energy dependence in velocity of light
  - Quantum Gravity
  - Large extra dimensions
  - TeV to Planck scale physics
  - Lorentz invariance violation
- Best limit to date from Whipple Mkn 421 flare (Biller et al., Phys Rev Letters 1999).

Lots of controversy

-- how do you disentangle effect from INTRINSIC source evolu

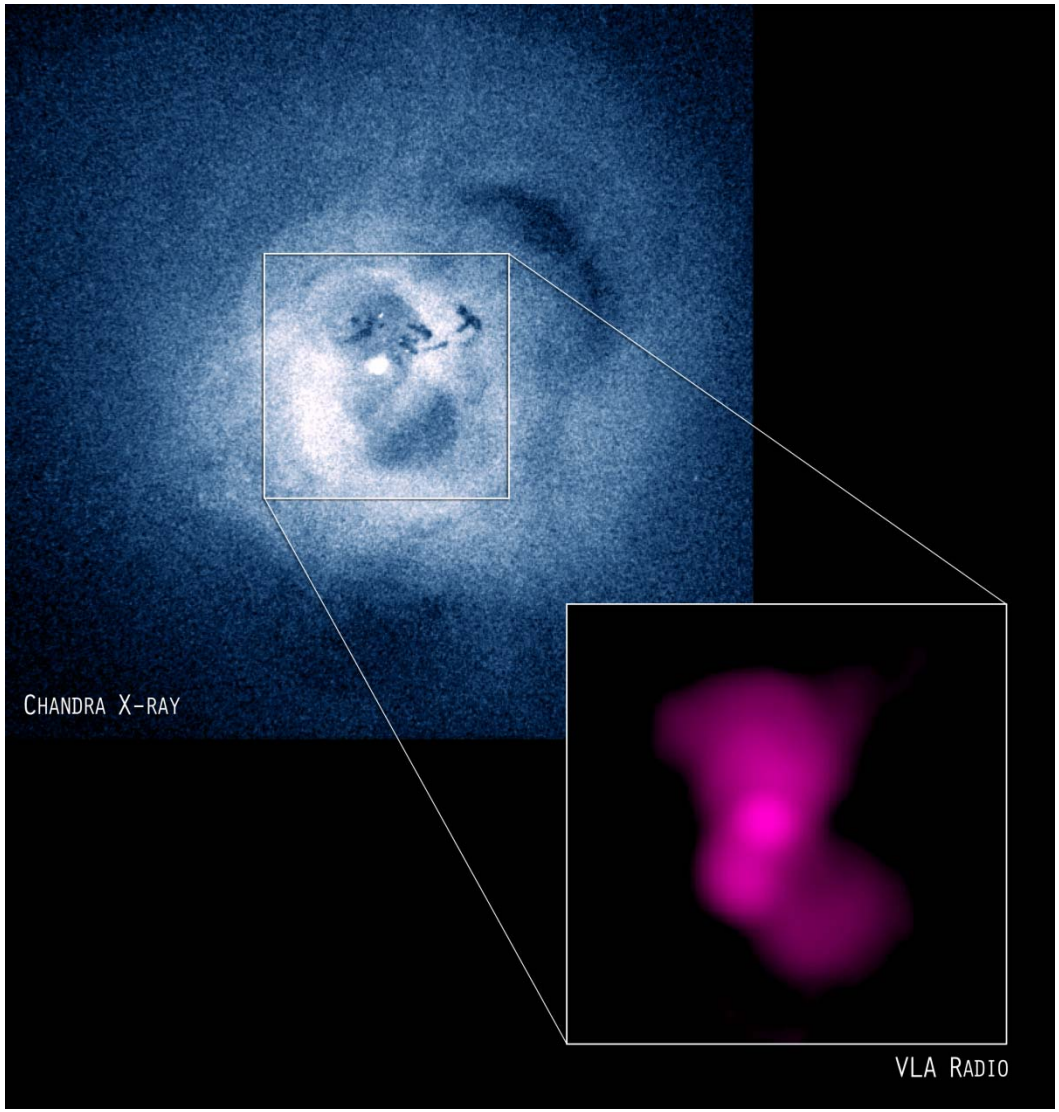
Most sources can think of, even decaying/annihilating CDM particles, trace large scale structure…
look for *clustering* signal/cosmic web (anisotropy)!



Bromm et al. 2003, cosmological structure formation calculation

The rarer/more biased the source, the stronger the clustering signal!

Chandra Image of Perseus Cluster with VLA Radio Inset



Chandra Ripple Image of Perseus

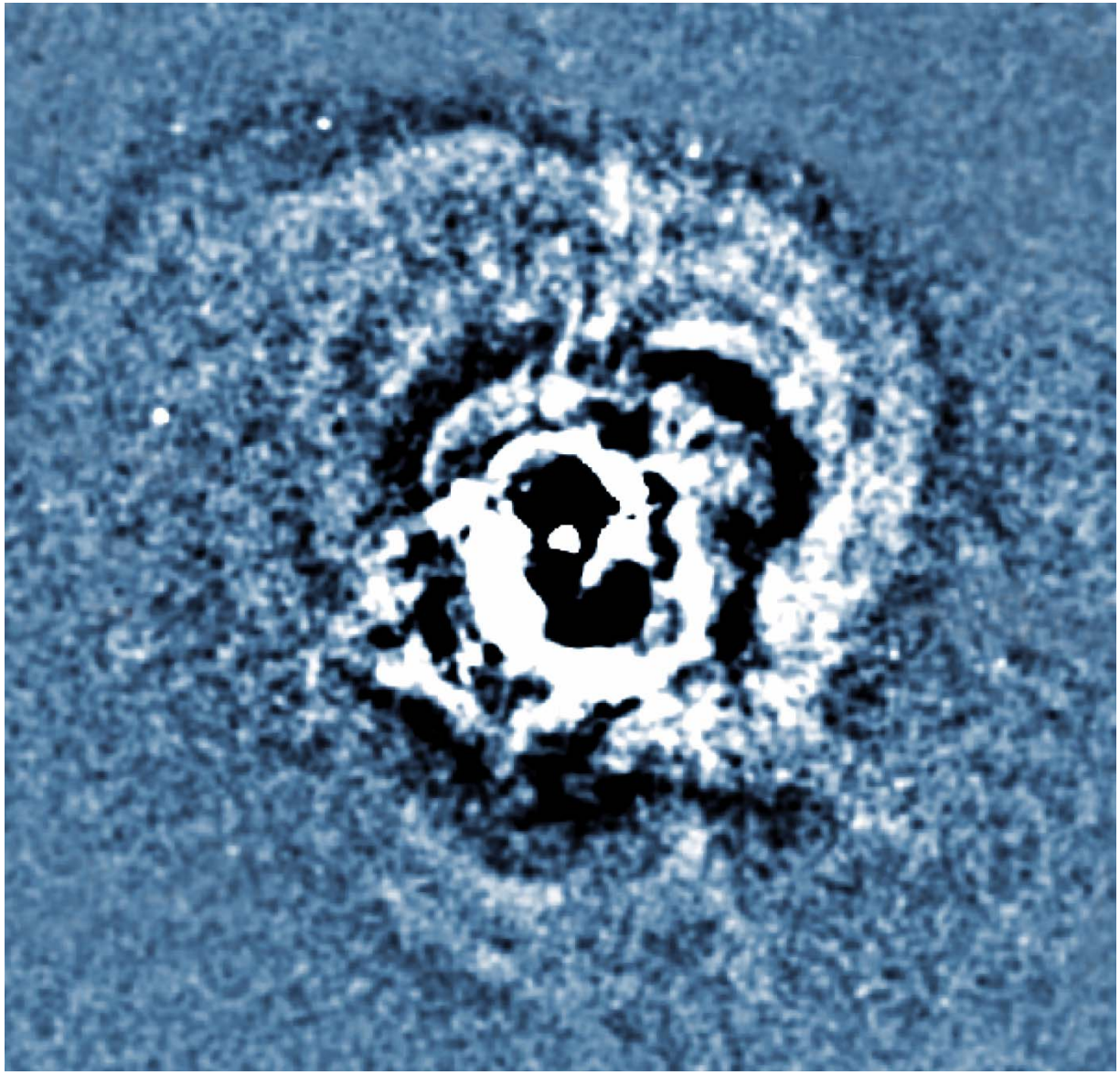
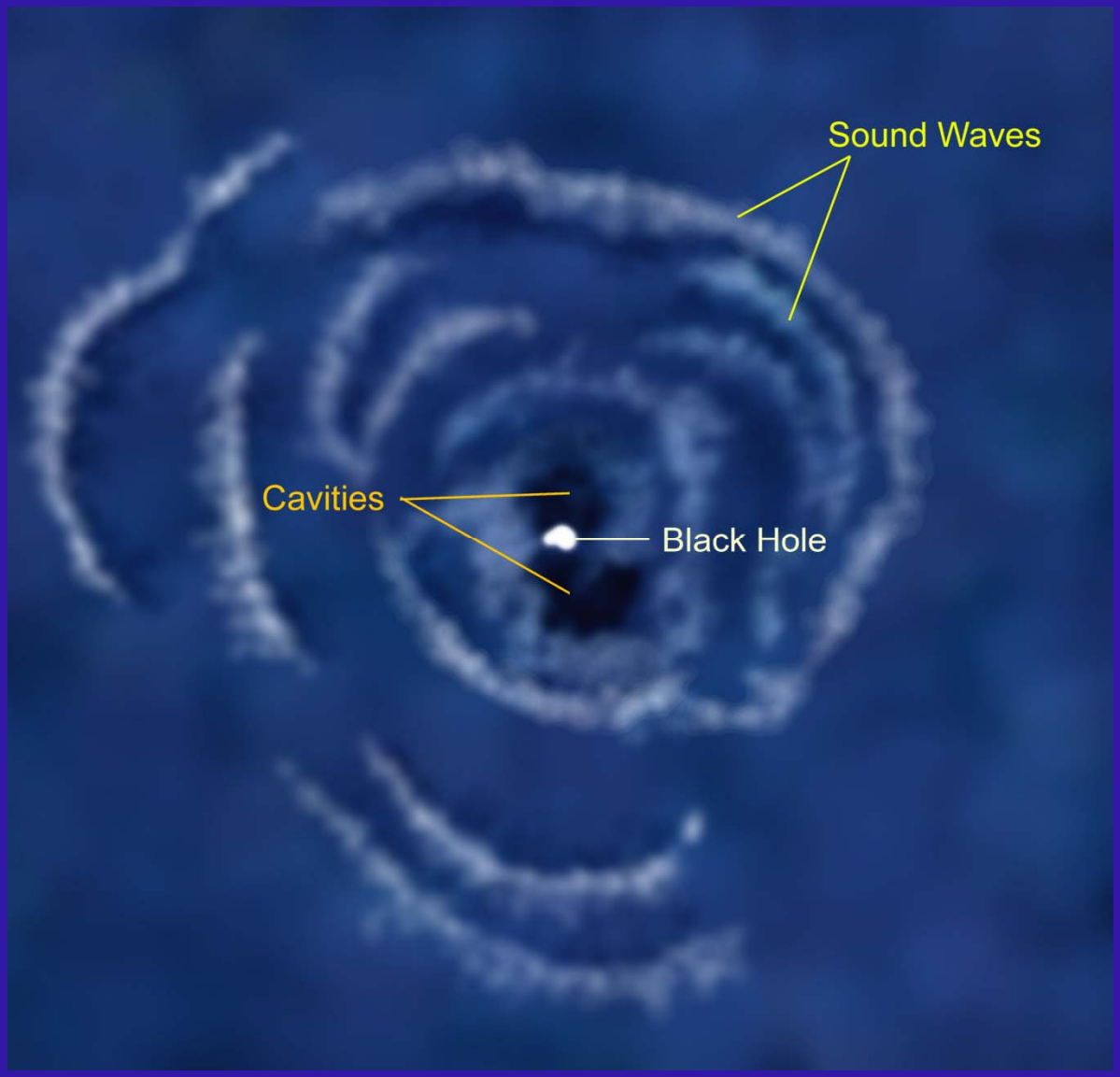
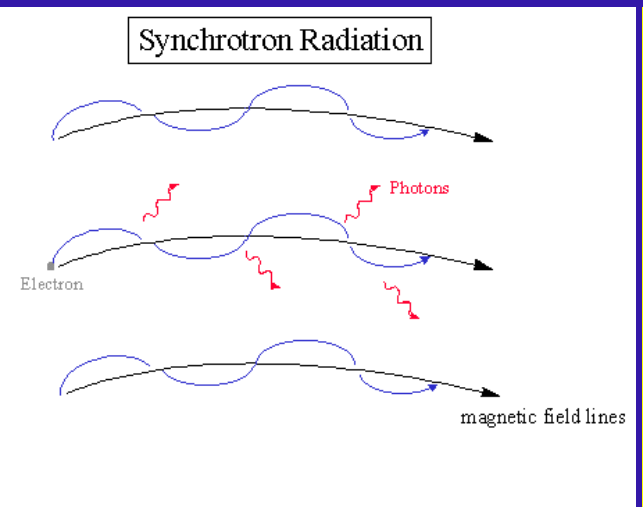


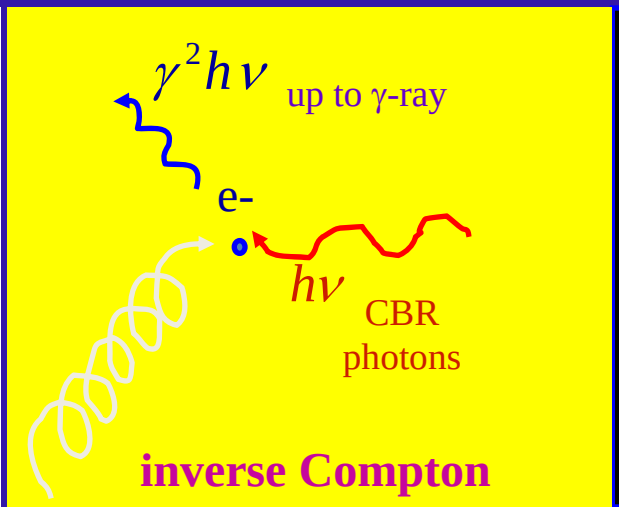
Illustration of Ripples in Perseus

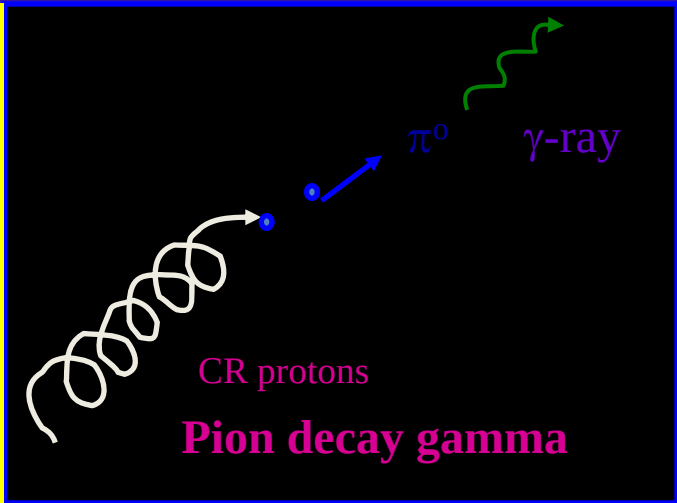


Observational evidences for CRs & B in the ICM

- **diffuse radio halos and relics in over 30 clusters**
  radio synchrotron (CR electrons + magnetic field)
  (Govoni, Feretti, Giovannini, ..)
- **hard X-ray & EUV emission *in excess of thermal radiation***
  inverse Compton scattering of CBR by CR electrons
  (Fusco-Feminao, Boywer, Lieu, Sarazin)
- **Pion decay (or IC) γ-rays from clusters *yet to be observed***
  CR p + p → π^o decay → GeV γ-ray or electron IC
  (Scharf & Mukherejee, Colarfrancesco, Reimer)
- **cluster γ-ray contribution to EGDB** (extrag. diffuse γ-ray background)
  (Colarfrancesco & Blasi, Totani & Kitayama, Kesht & Loeb, Miniati, …)





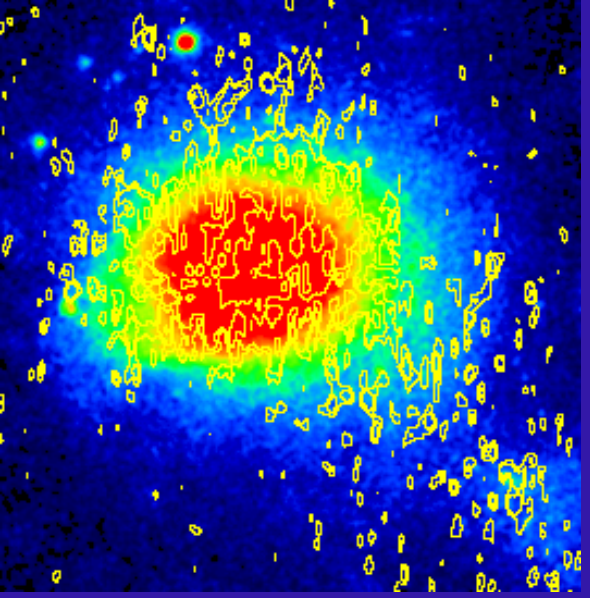


Clusters with a radio halo:

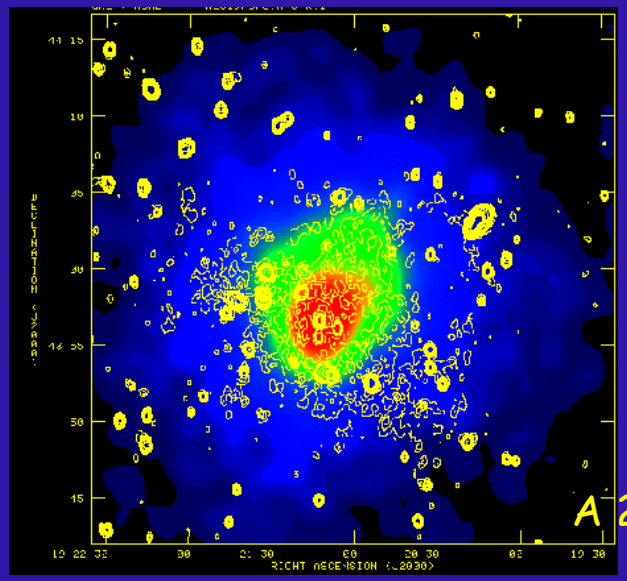
CR electrons of GeV &

B of 0.1-1 μG on Mpc scale

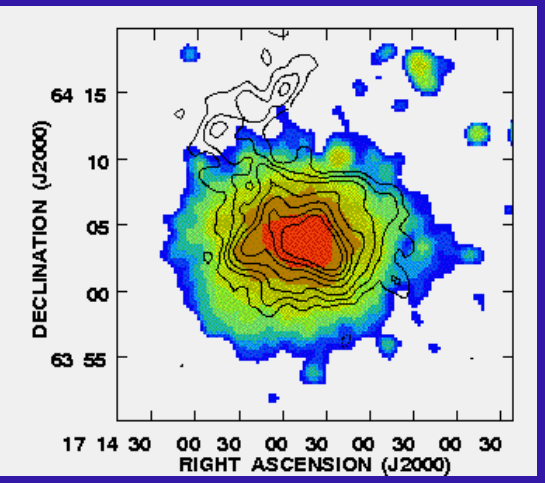
are required.



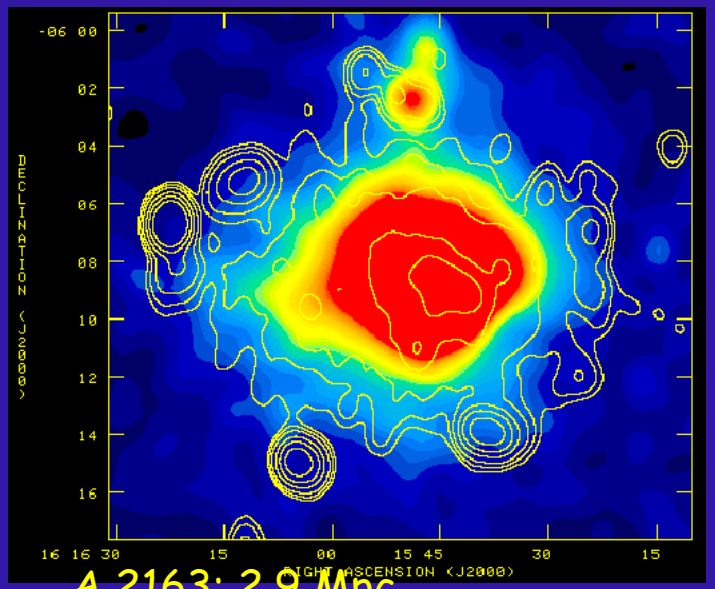
COMA: 1.1 Mpc



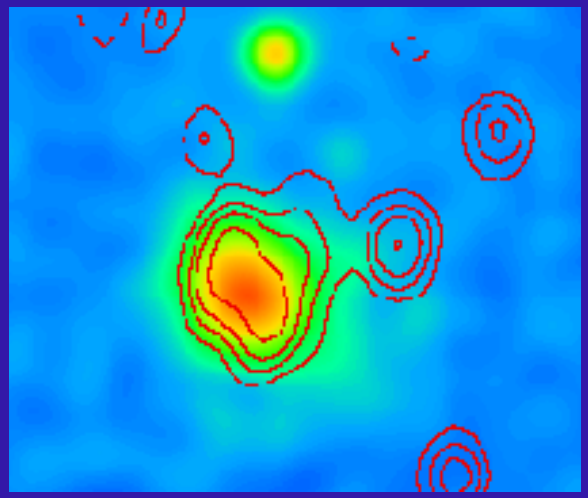
A 2319: 1.4 Mpc



A 2255: 1.2 Mpc



A 2163: 2.9 Mpc

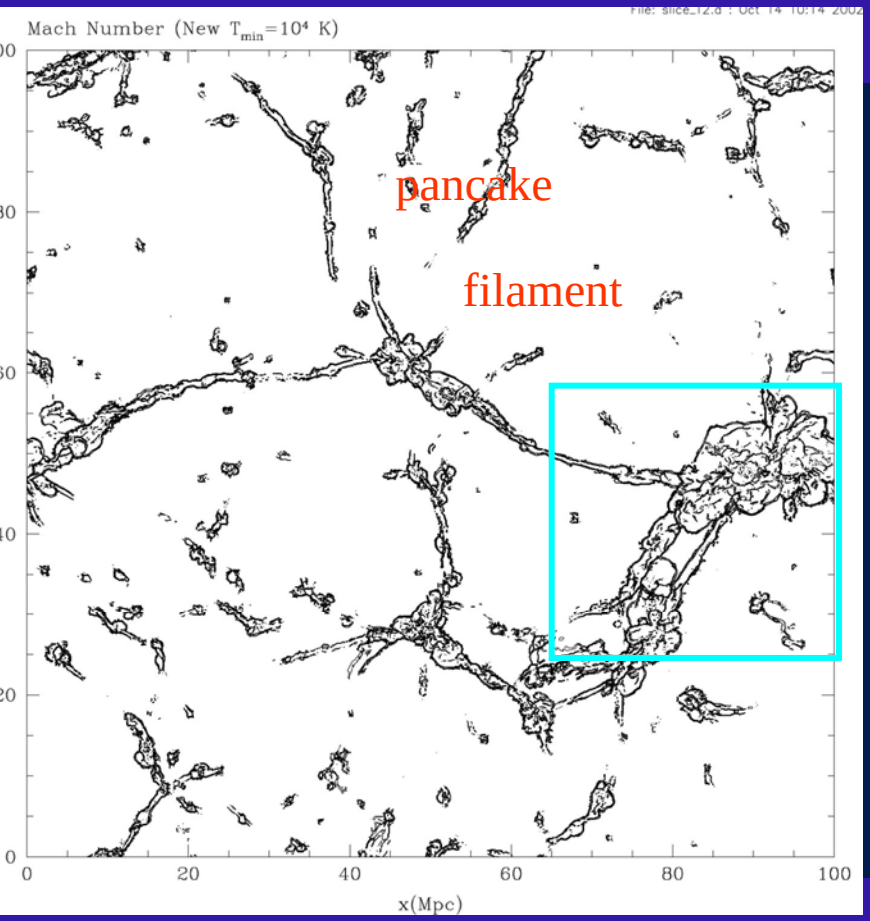


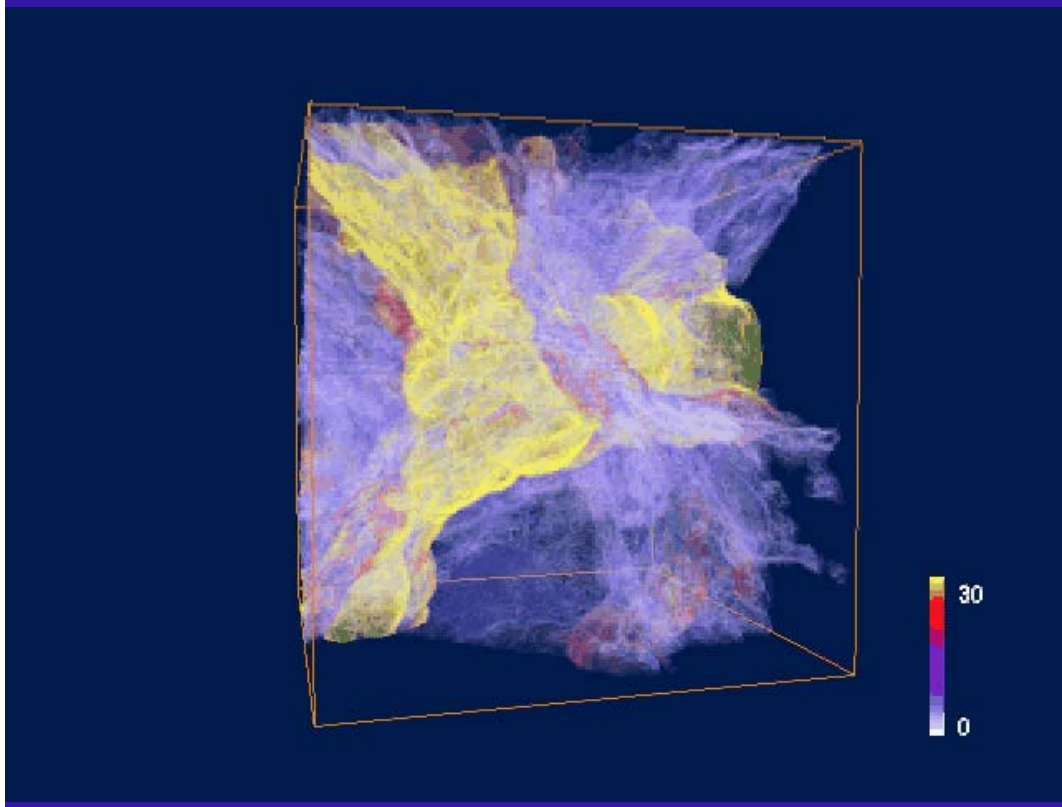
CL0016+16: 1.1 Mpc
z = 0.5545

Radio Halos of Clusters of Galaxies (contour) + X-ray (color)

Slide from L. Feretti (KAW3)

Shocks in LSS: Mach Number





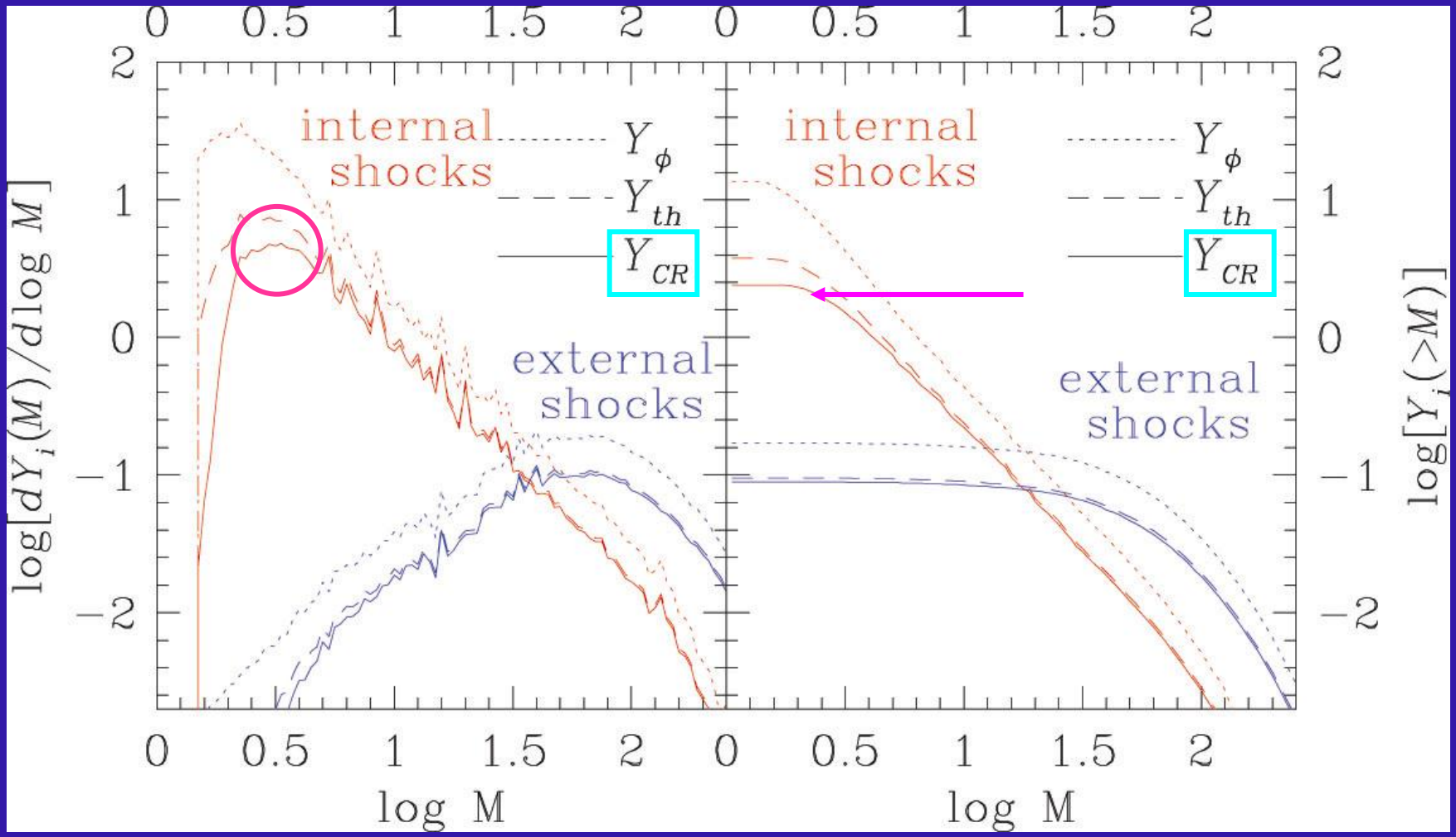
Location of shocks: color=Mach number

rich, complex shock morphology

Shocks "reveal" filaments and sheets

LCDM simulation with 1024^3 cells, computational box: $(100h^{-1}\ \mathrm{Mpc})^3$,
TVD: grid-based Eulerian hydro code (Ryu et al 2003)

Energies passed through and produced at shocks: integrated from z=2 to 0



-CR acceleration : most important for shocks with M = 2~4

(low Mach no. internal shocks in the ICM)

-E_{CR} accelerated at shocks = ~1/2 x E_{th} generated at shocks

(Ryu et al 2003)

"Energy Budget of the ICM"

$E_{CR,p} \sim (0.1 - 1)E_{thermal}$: AGN injection

$\sim (0.1\text{-}0.5)\, E_{thermal}$: Shock acceleration

$\sim E_{turb} \sim 0.1\, E_{thermal}$: 2nd order acceleration

$E_{CR,e} \sim 0.01\, E_{thermal}$ (observation)

$E_{turb} \sim 0.1 E_{thermal}$ **(subsonic turbulence, observation & simul.)**

$E_B \sim E_{turb} \sim 0.1 E_{thermal}$ (observation & simulation)

Merger shock
- DSA of CRs
- generate turbulence

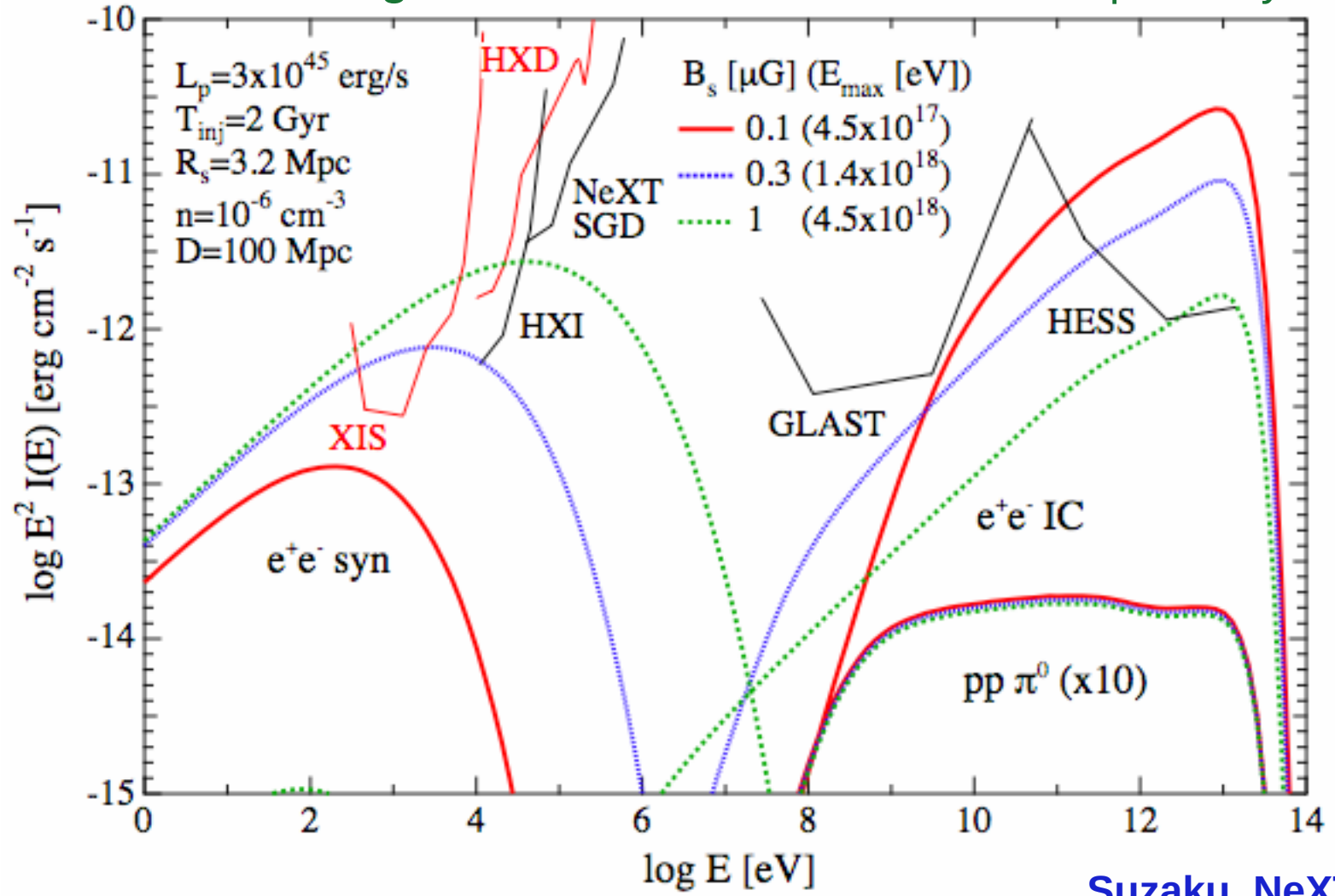
Turbulence
-Fermi 2nd order: CR
-turbulent dynamo: B

emitted flux & detectability

Coma-like cluster at D=100 Mpc

sensitivities for 1 deg² extended source

> TeV "absorption" by IRB+CMB



Suzaku, NeXT

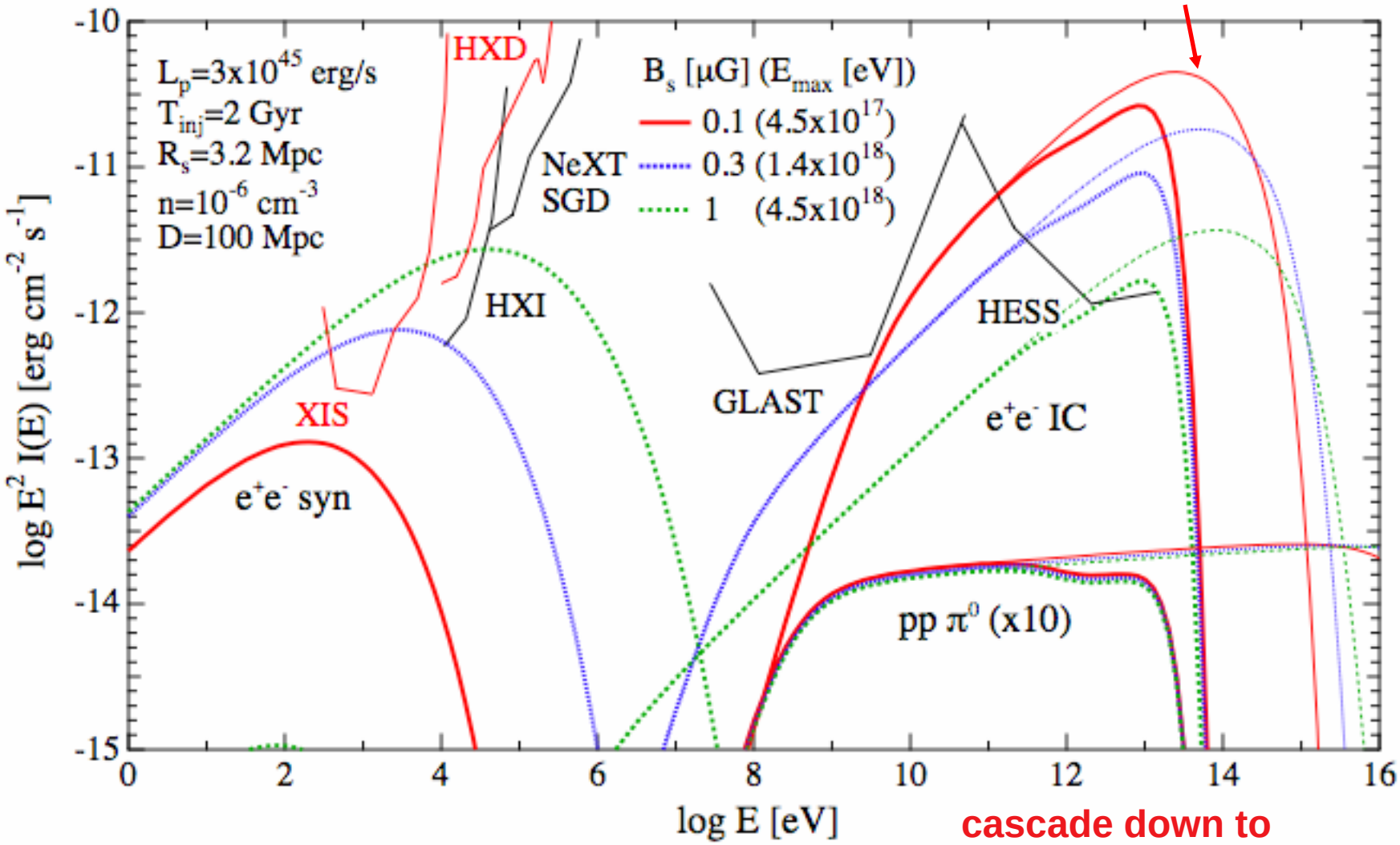
HESS, CANG.3 & other IACTs

- **large radiative efficiency from protons**
- **hard (Γ~-1.5) spectrum + rollover**
- **sensitive to B**

c.f. primary IC, pp π^0 (Γ~-2)

cascade emission: pair halo, background

pre-"absorbed" flux



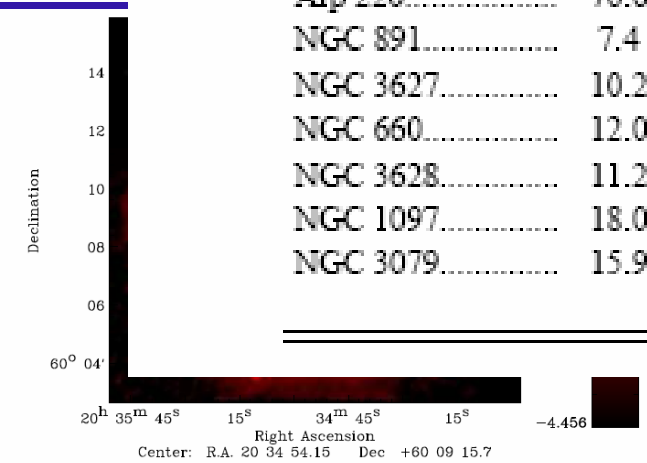
cascade down to GeV-TeV range?

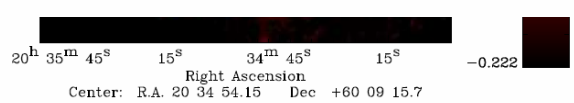
more on cascading -> Coppi

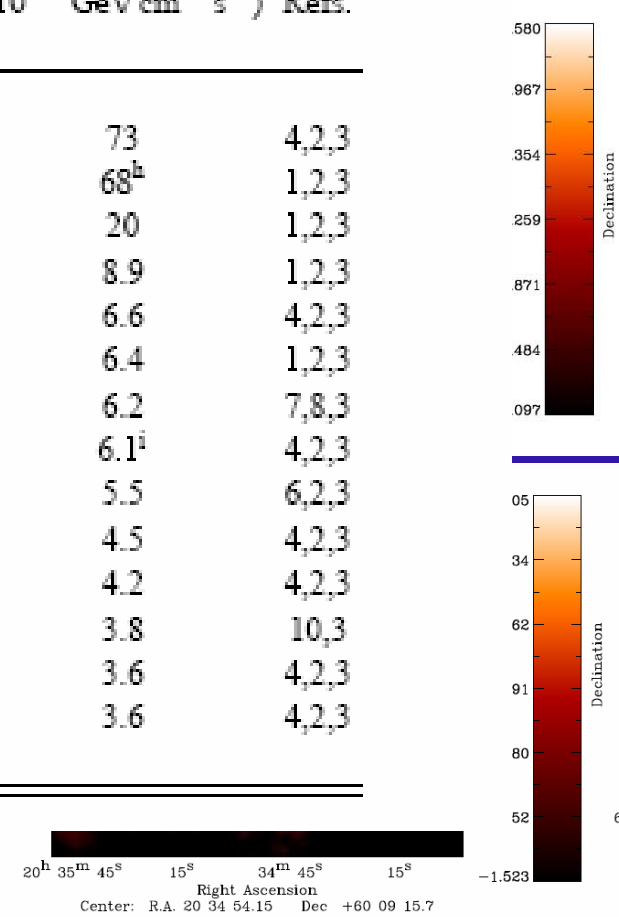
Two galaxies in

TABLE 1
PROPERTIES OF LOCAL STARBURST & STAR-FORMING GALAXIES

Object Name	D[a] (Mpc)	Σ_g[b] (g cm^{-2})	$S_{60\mu m}$[c] (Jy)	$S_{100\mu m}$[d] (Jy)	S_{TIR}[e] (Jy)	$S_{1.4\,GHz}$[f] (mJy)	νF_ν(GeV)[g] (10^{-11} GeV cm^{-2} s^{-1})	Data Refs.
NGC 3034 (M82)...	3.3	0.69	1313.5	1355.4	8302.4	7657.0	73	4,2,3
NGC 253.....	3.5	0.47	997.7	1857.8	7755.8	5594.0	68[h]	1,2,3
IC 342.....	4.4	0.02	255.9	660.7	2311.6	2250.0	20	1,2,3
NGC 2146.....	12.6	0.14	144.5	204.2	1009.8	1074.6	8.9	1,2,3
NGC 3690.....	42.2	0.04	119.7	118.6	748.0	678.3	6.6	4,2,3
NGC 1808.....	14.2	0.09	104.5	147.2	729.4	529.0	6.4	1,2,3
NGC 1365.....	18.6	0.09	84.1	185.4	704.2	530.0	6.2	7,8,3
Arp 220.....	76.6	12.0	107.4	118.3	691.9	326.9	6.1[i]	4,2,3
NGC 891.....	7.4	0.09	61.1	198.6	623.4	701.0	5.5	6,2,3
NGC 3627.....	10.2	0.04	56.2	144.9	507.3	458.0	4.5	4,2,3
NGC 660.....	12.0	0.08	65.5	103.8	477.4	387.0	4.2	4,2,3
NGC 3628.....	11.2	0.02	48.4	121.9	431.9	525.0	3.8	10,3
NGC 1097.....	18.0	0.10	46.7	116.1	414.0	415.0	3.6	4,2,3
NGC 3079.....	15.9	3.7	50.2	103.5	407.8	849.0	3.6	4,2,3





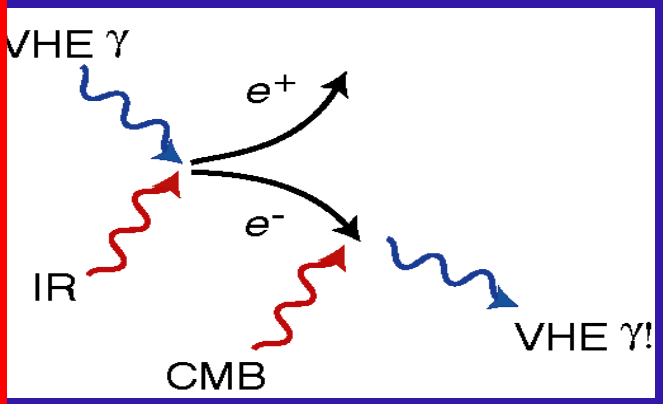


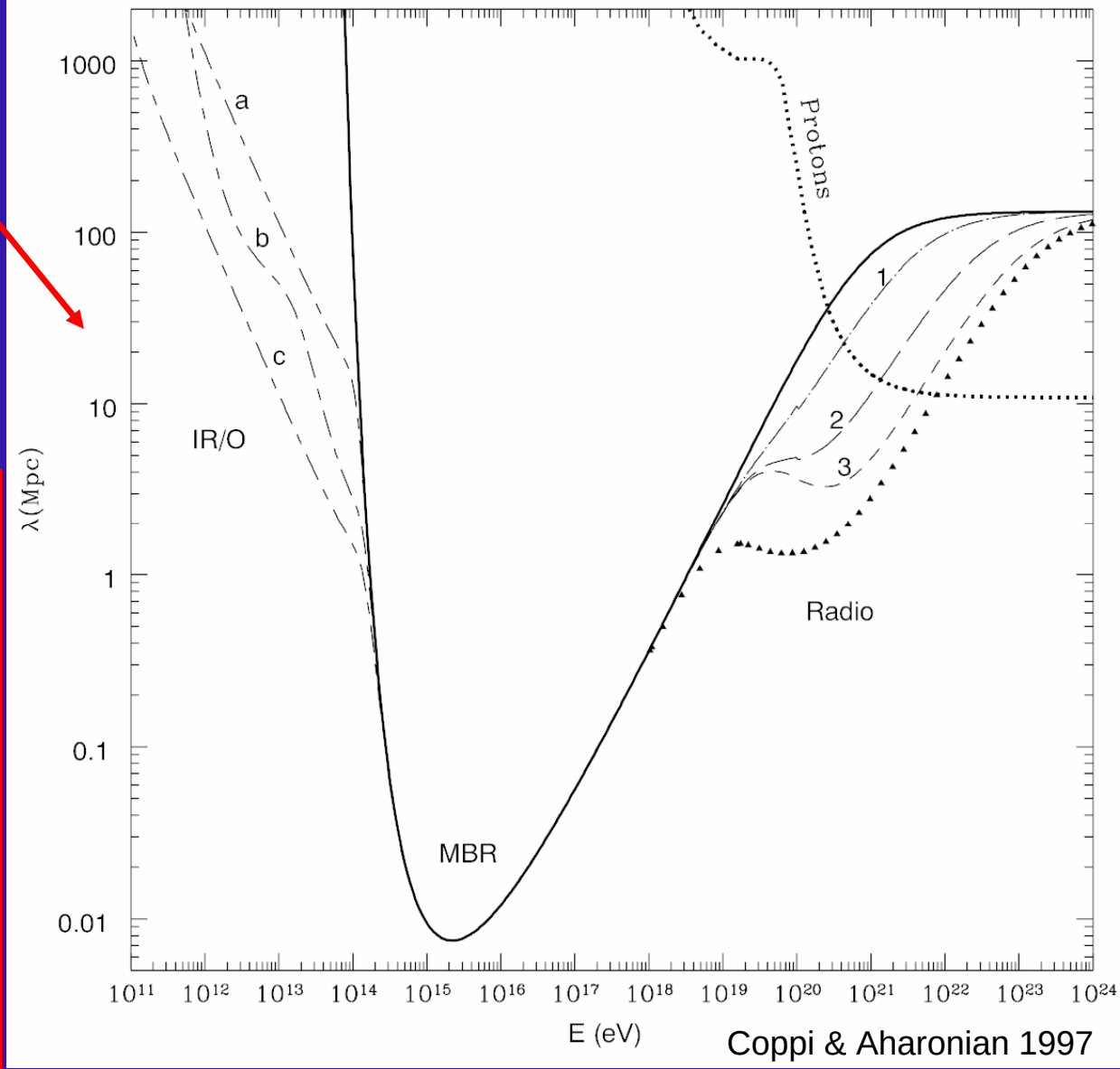
Eric Murphy, thesis

NGC 6946

Mean free path
for VHE photons

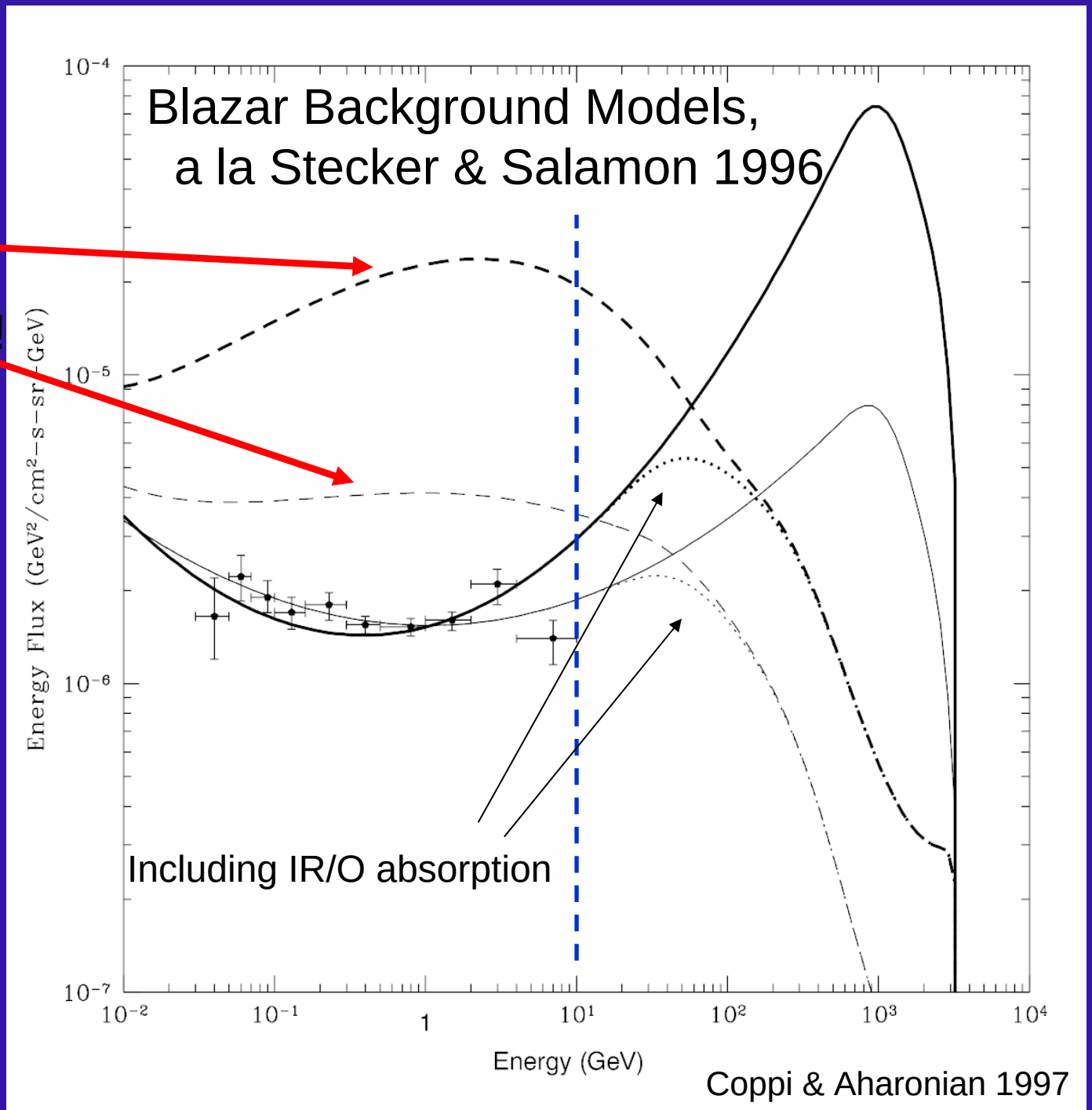
Absorption
(pair production)
and
Cascading
important for
cosmological
VHE sources.





Coppi & Aharonian 1997

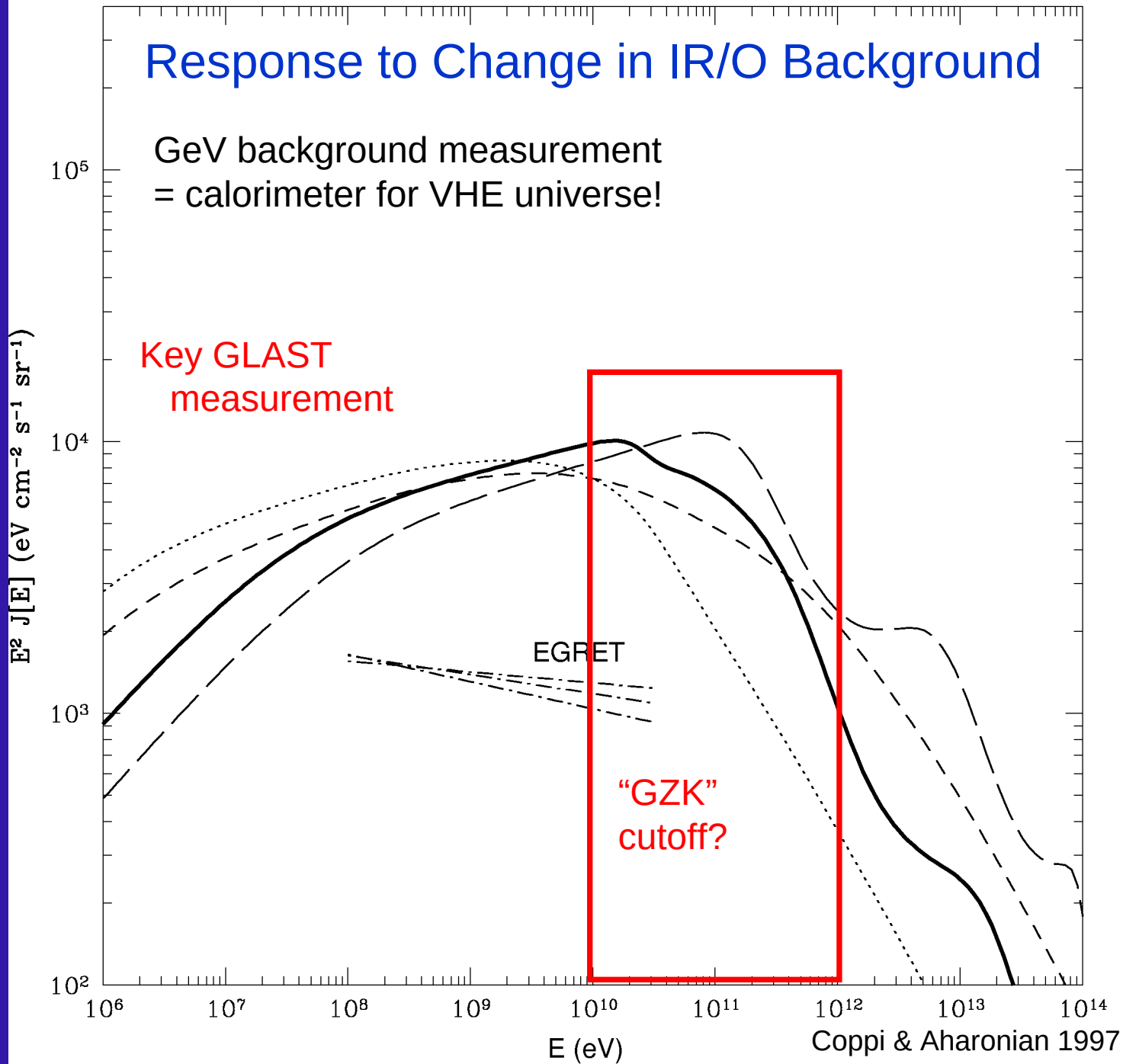
Don't forget cascades!



Coppi & Aharonian 1997

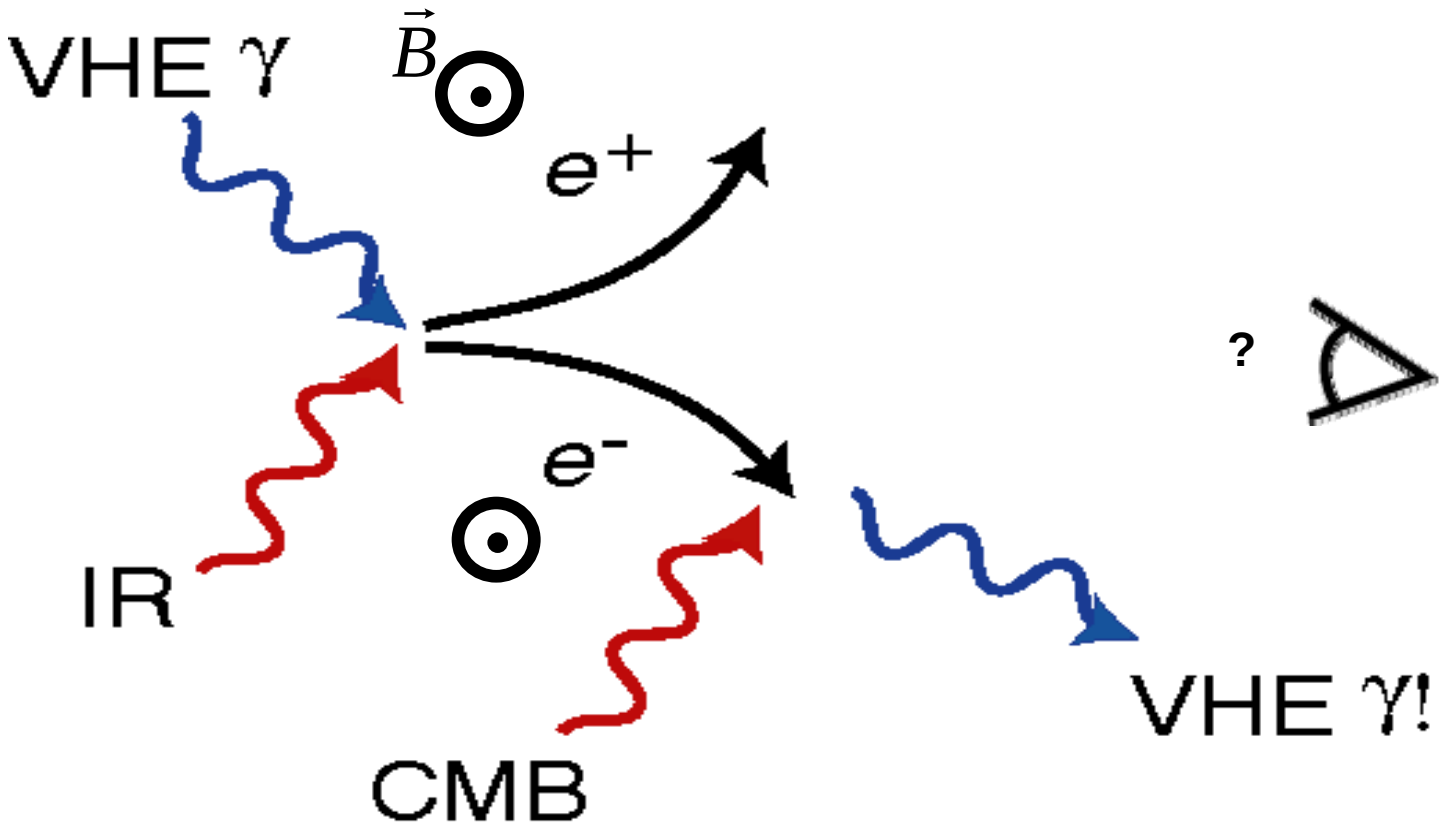
Response to Change in IR/O Background

GeV background measurement
= calorimeter for VHE universe!



Coppi & Aharonian 1997

Can we see cascade radiation from individual sources?



Due to likely IGMF, “No” is the standard answer, but …

If VHE source
(e.g., cluster)
is isotropic emitter

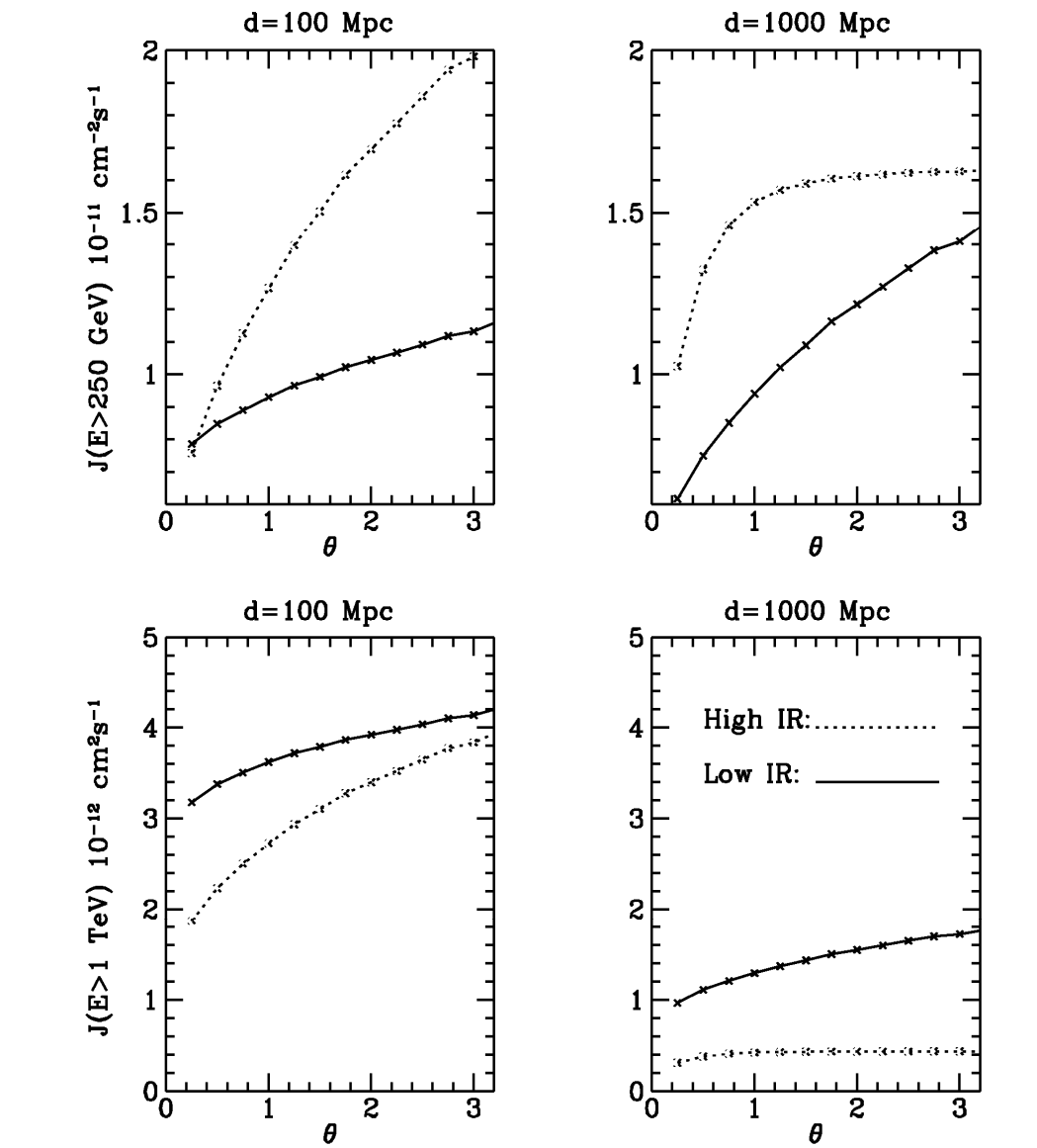
or

B field is large
enough ($B>10^{-11}$ G),

pair deflection doesn't
matter!

Get "Pair Halo" !

Angular size determined
by *local* IR/O background



Coppi, Aharonian, & Voelk 1994, Madau & Phinney 1996

If IGMF is weak, don't get halo but introduce *dispersion* in arrival times – probes IGMF !

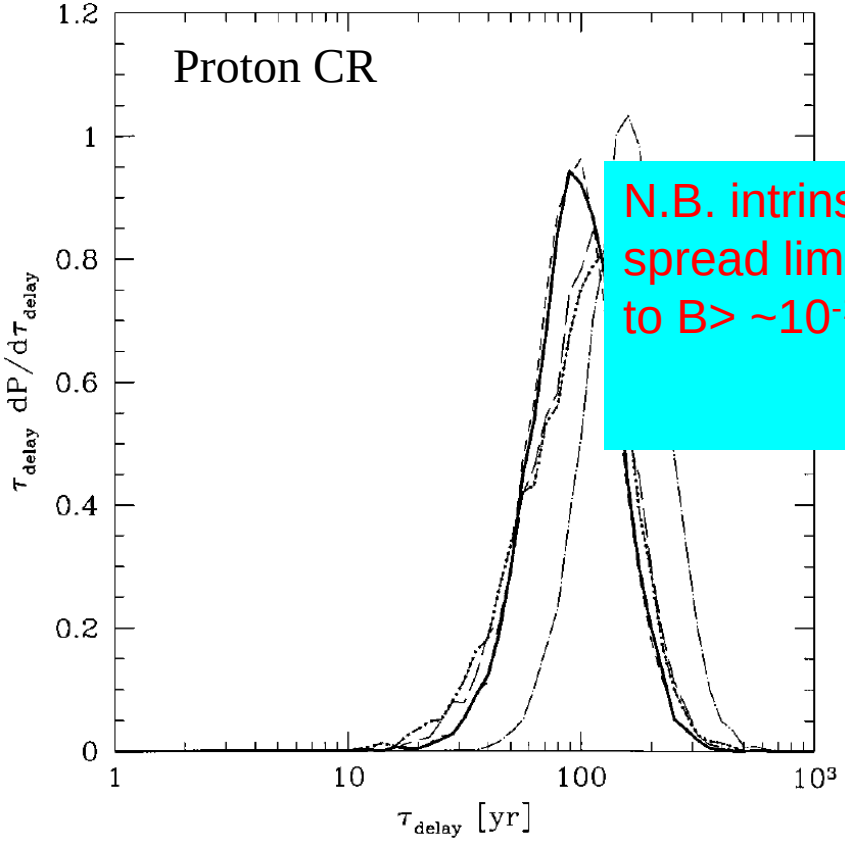


FIG. 1.—The distribution of arrival-time delays of greater than 10^{20} eV protons produced by a burst at a distance of 100 Mpc, for various IGMF structures where a fraction ~0.2 of the intergalactic space is occupied by ~1 Mpc regions of a coherent 4×10^{-11} G field.

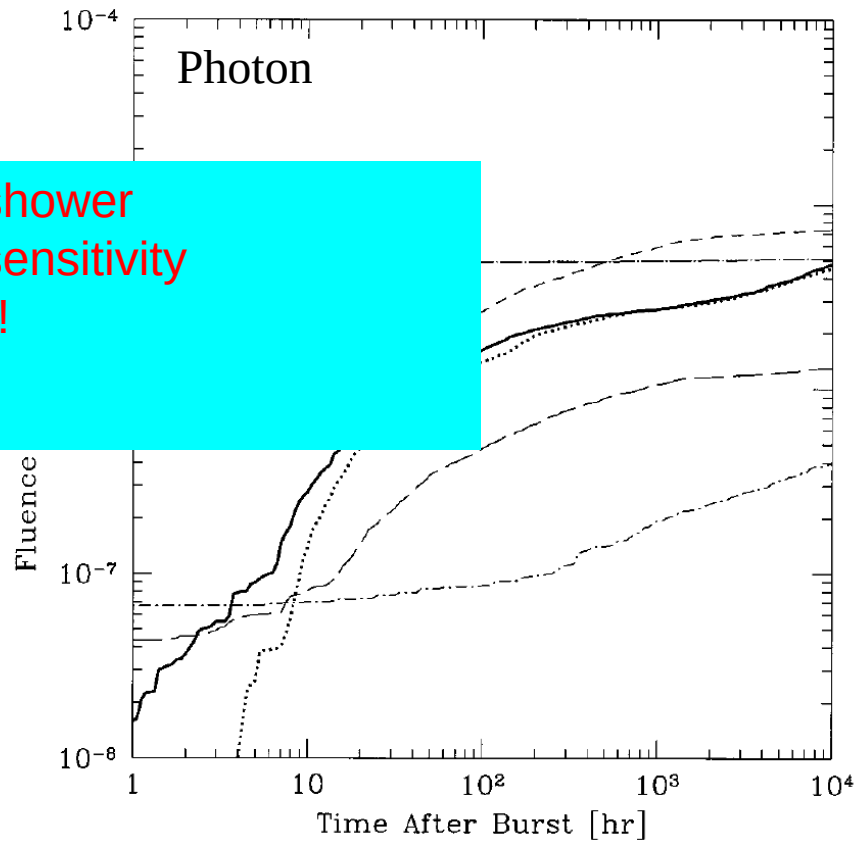


FIG. 2.—The fluence of greater than 1 TeV secondary photons, following a GRB producing 10^{51} ergs as greater than 10^{20} eV protons at a distance of 100 Mpc. The IGMF structures are the same as those used in Fig. 1, and similar line styles correspond to the same field structure in both figures. The heavy dotted line gives the fluence obtained when a 1 μG host galaxy magnetic field is added to the field structure corresponding to the heavy solid line.

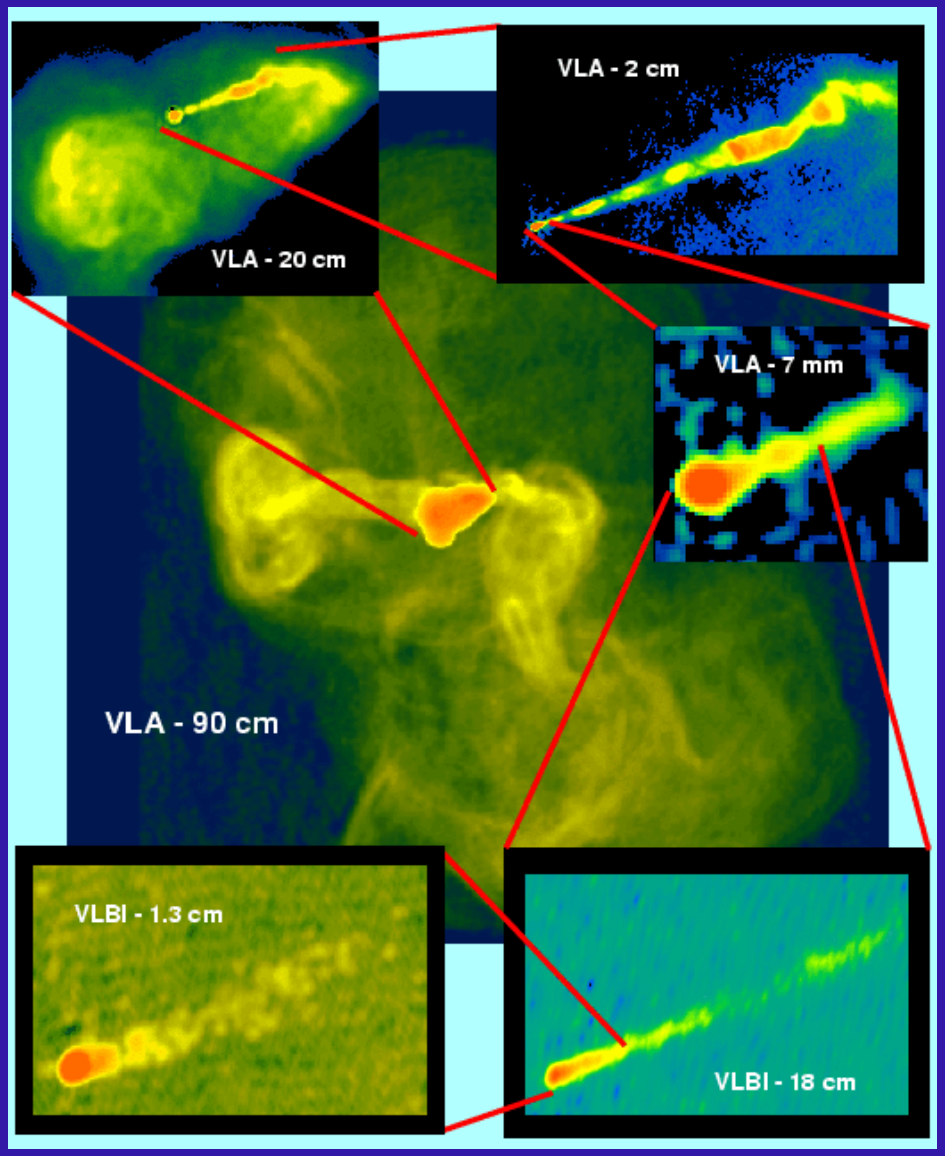
N.B. intrinsic shower spread limits sensitivity to B> ~10^{-16} G!

Waxman & Coppi 1996

See also Plaga 1995, Cheng 1996, Dai et al. 2002, Wang et al. 2002, Razzaque et al. 2004

A “boring” object in the sky: the nearby elliptical galaxy M87

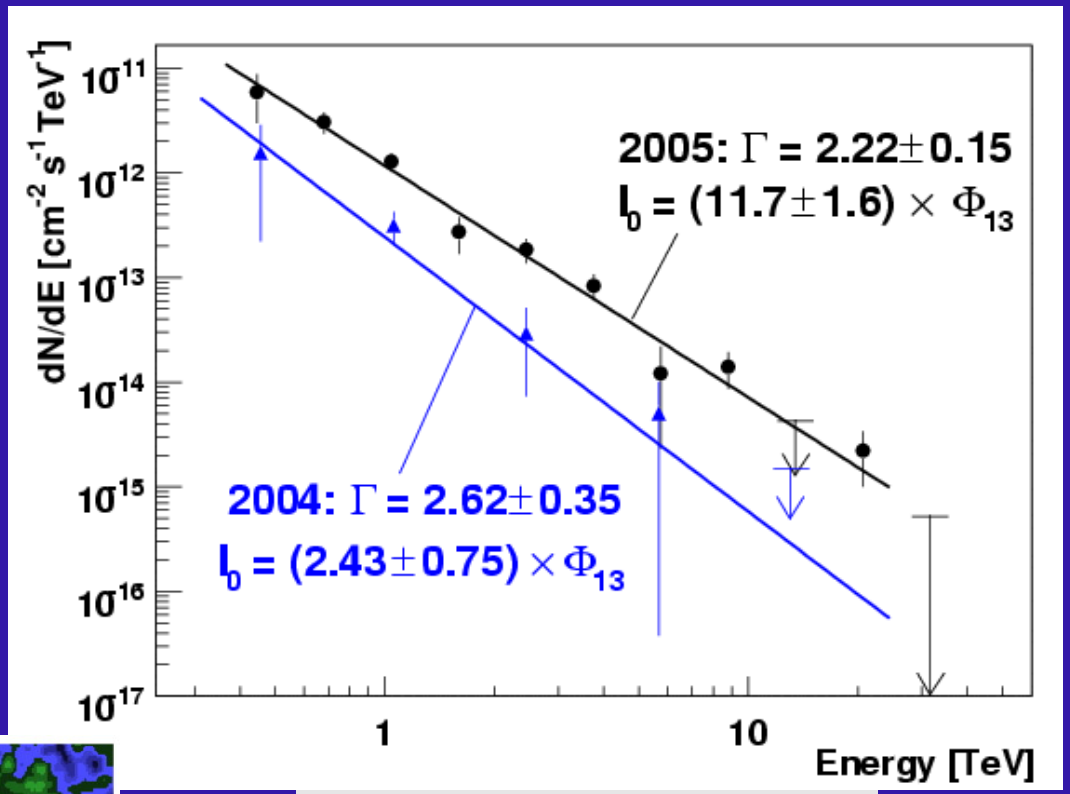
Opt



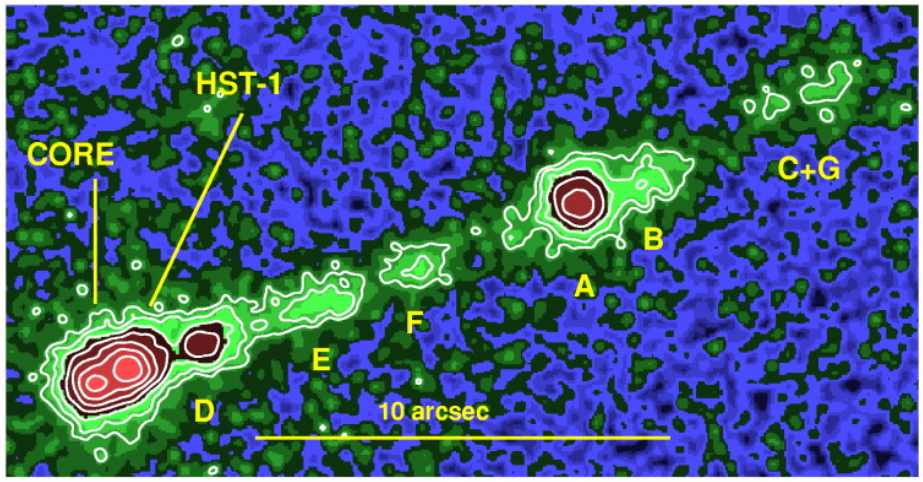
Radio

M 87 – evidence for production of TeV γ-rays close to BH

- Distance: ~16 Mpc
- central BH: $3 \cdot 10^9\ M_\odot$
- Jet angle: ~15-30°
  ⇒ not a blazar!
- discovery (>4σ) of TeV γ-rays by HEGRA (1998) confirmed by HESS (2003)

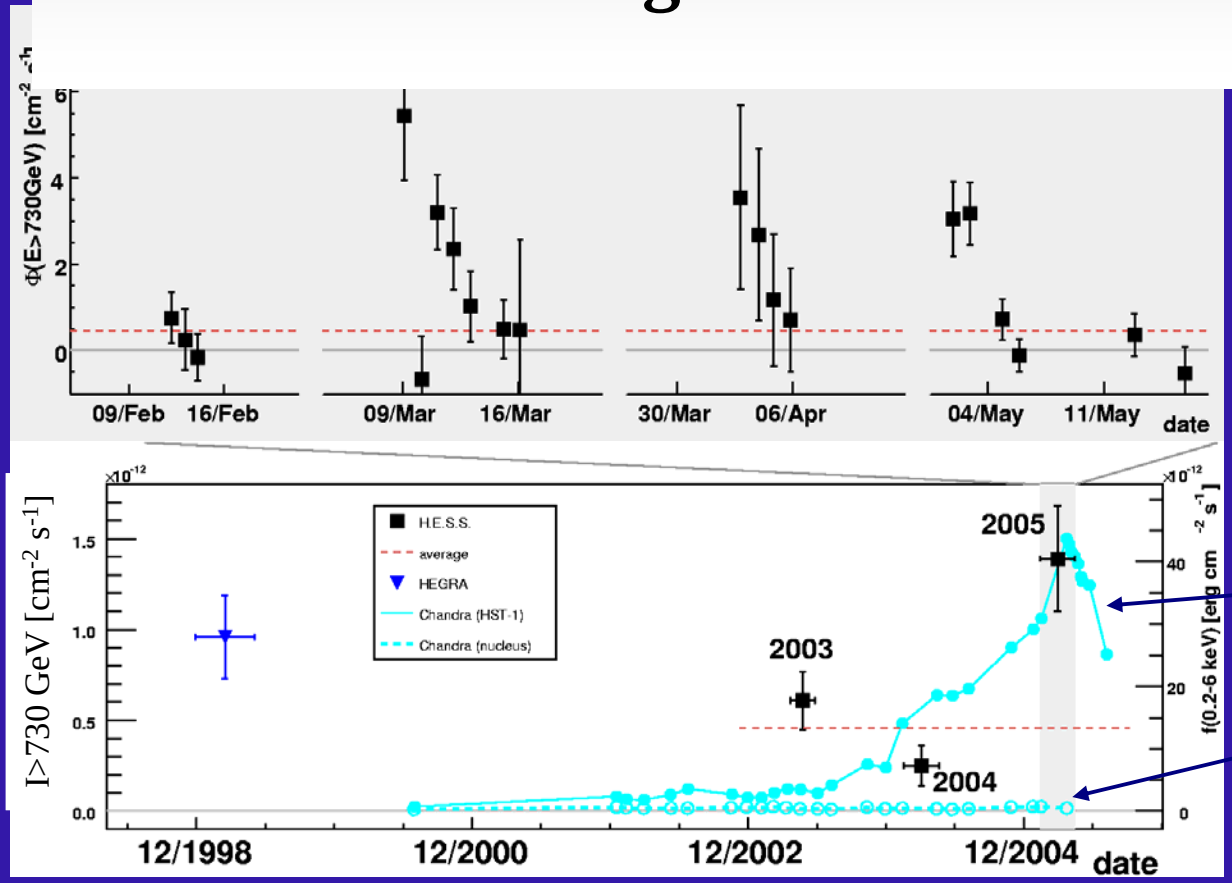


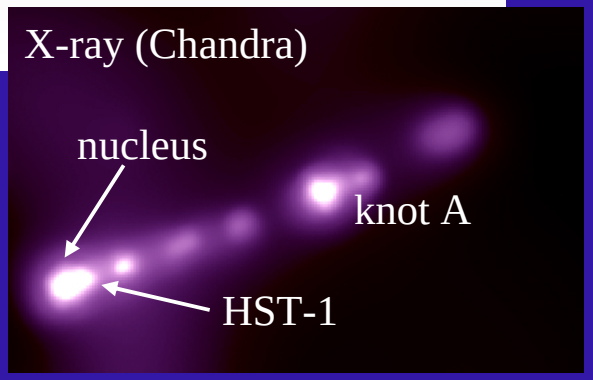
$\Phi_{13} = 10^{-13}\ cm^{-2}\ s^{-1}\ TeV^{-1}$



F. Aharonian, HESS

M87: light curve and variabiliy





X-ray emission:

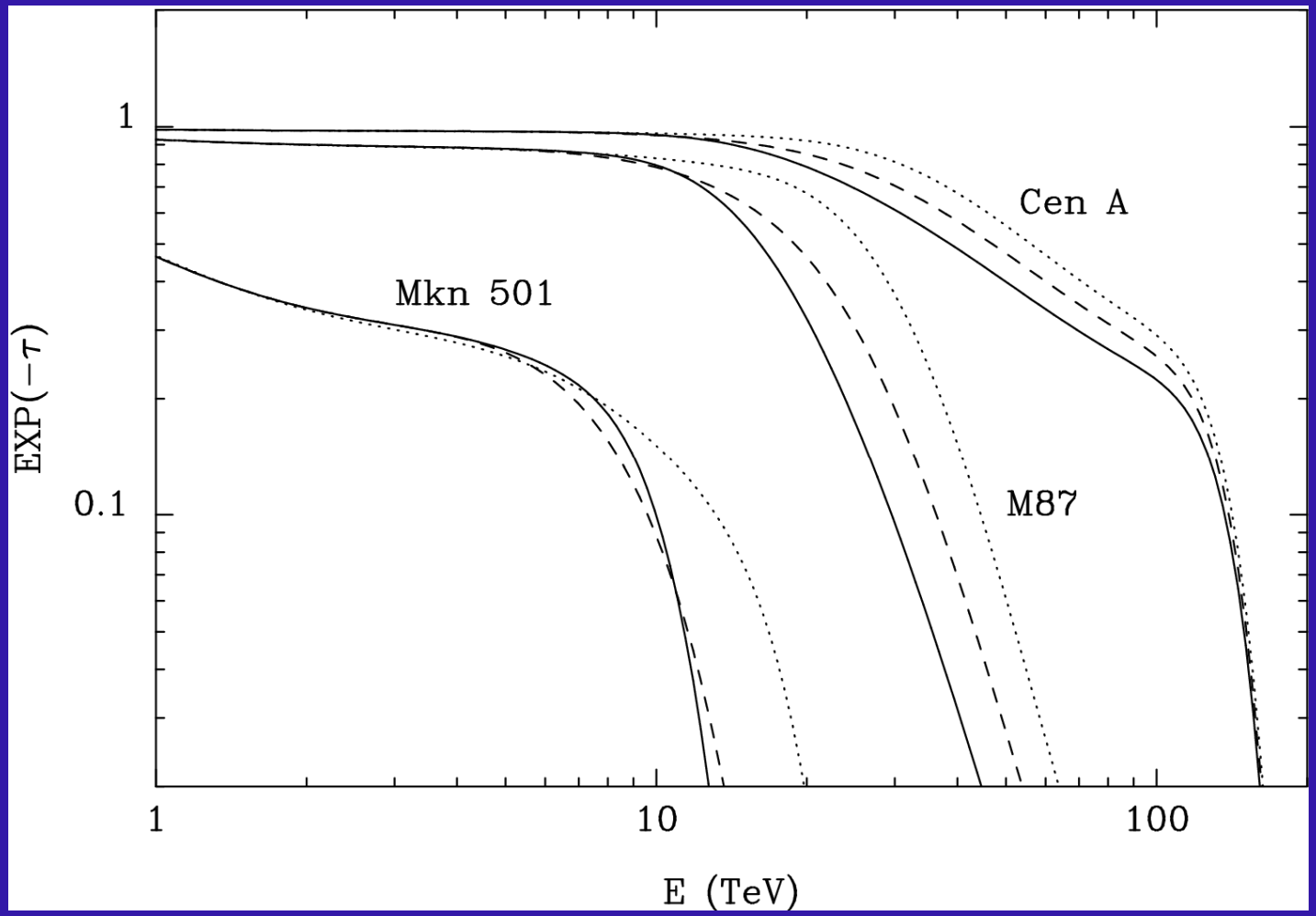
- knot HST-1
  [Harris et al. (2005), ApJ, 640, 211]
- nucleus
  (D.Harris private communication)

short-term variability within 2005 (>4σ)

⇒ constrains size of emission region ($R \sim 5x10^{15}\ \delta j$ cm)

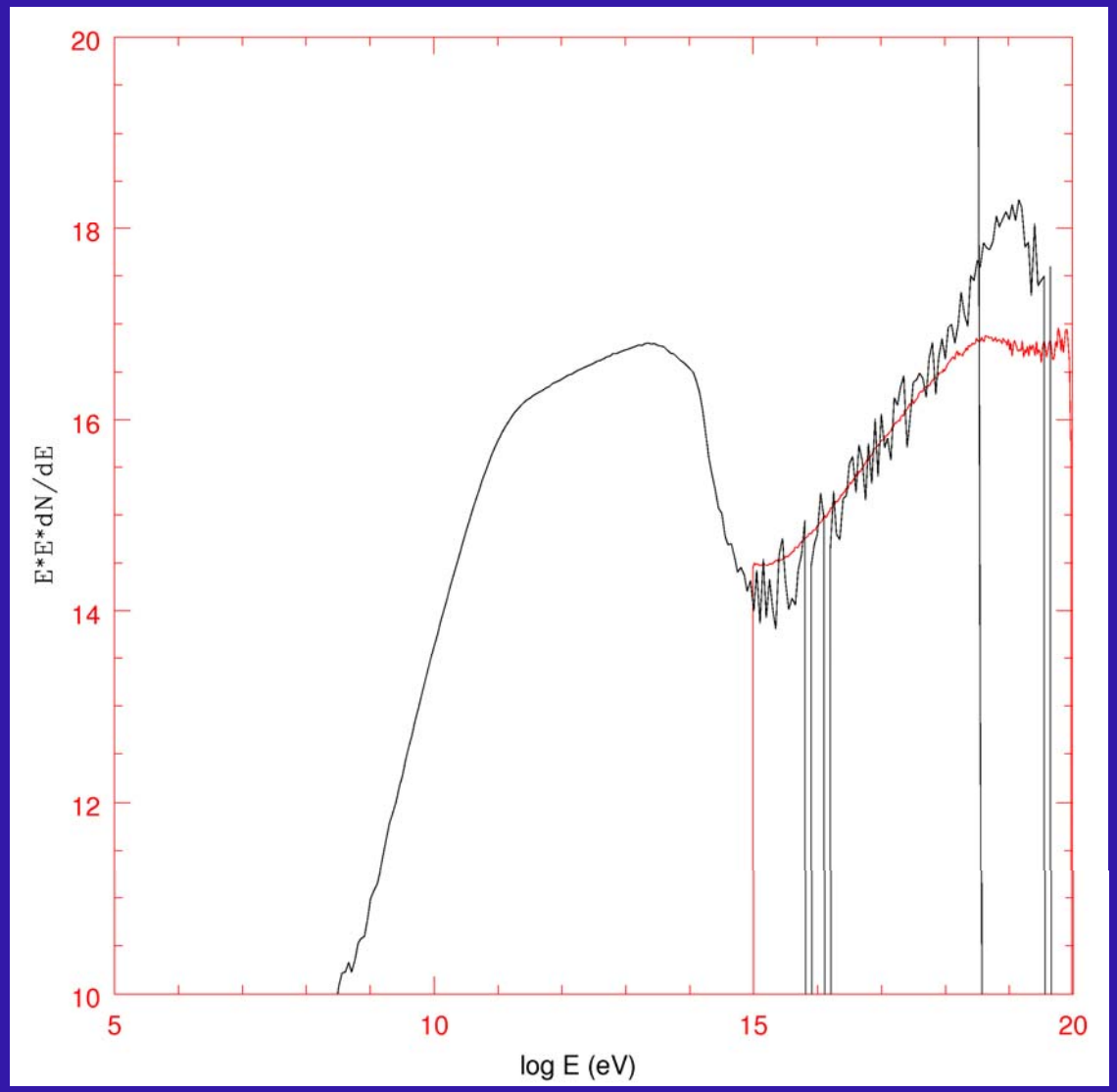
F. Aharonian, HESS

Aside: Can use M87 [Cen A?] to probe diffuse background at MIR /FIR wavelengths with E_γ > 10 TeV γ-rays!



F. Aharonian

Individual UHECR Sources – Cascade Radiation



Summary

Extragalactic field still wide open!

Discovered many new phenomena,
but … more questions than answers!

More to do with AGN… ! Have only seen tip of iceberg. GLAST will need lots of help.

On threshold of observing galaxies & clusters = worth it, significantly strengthens connection to main stream astronomy .

Auger & UHECR …

Don’t throw away old telescopes … IMHOm, need diversity and network of instruments?