High Energy Plasmas in Astrophysics and Relevant Basic Processes

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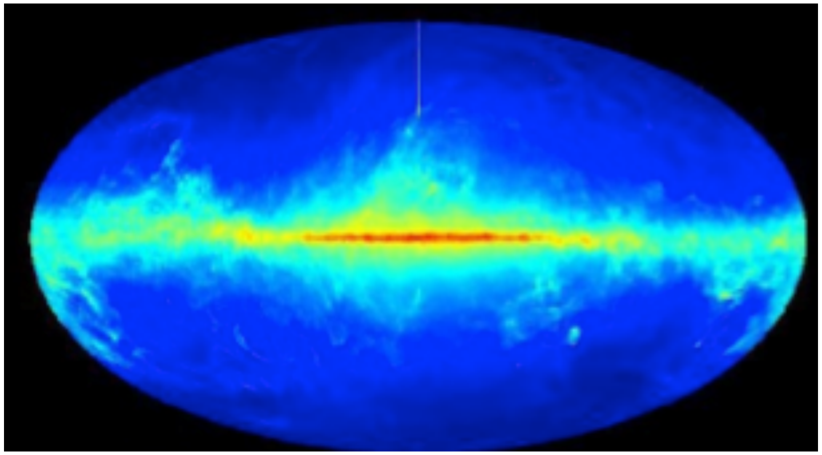
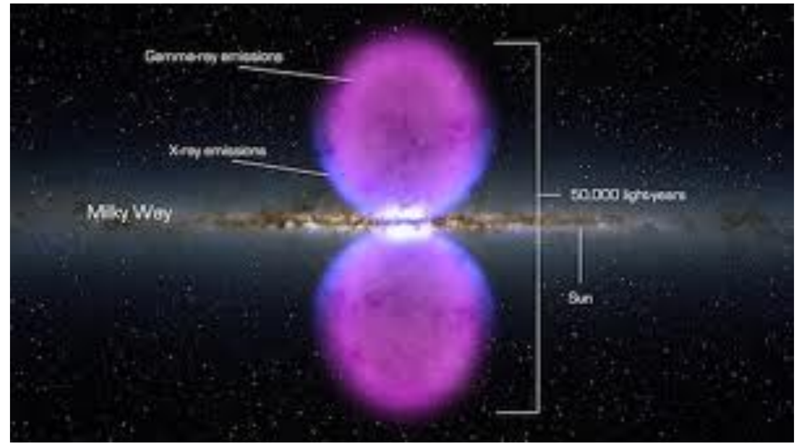
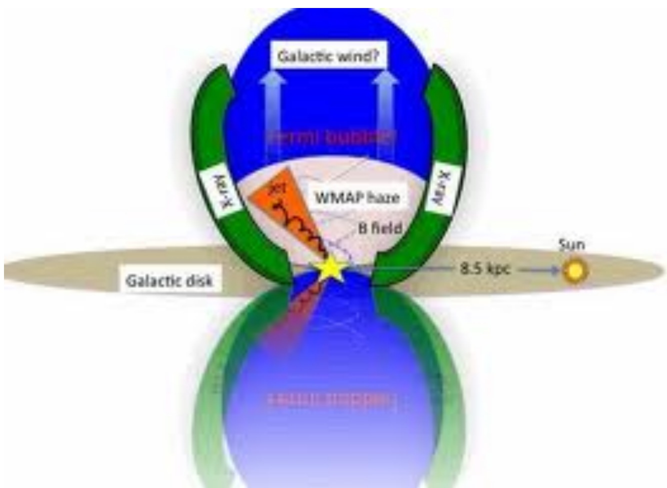
Separately Pursued Areas of Research on Plasma Astrophysics

* Galactic Dynamics involving Gravitational Plasmas
* Heliospheric Plasmas (Confronting in situ experiments)
* Plasmas connected with Neutron Stars
* Plasma Accretion Structures (and jets) associated with black holes
* High Energy Plasmas on the grand scale
  - galactic scale (γ-bubbles)
  - galaxy cluster scale (DM confinement)

Fermi Bubbles !



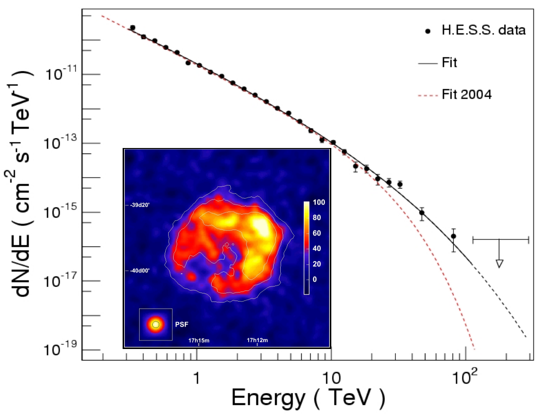




Finkbeiner and collaborators 2010

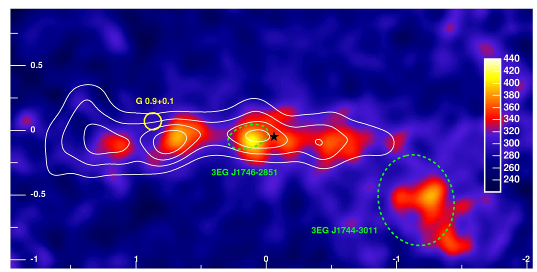
H.E.S.S. : good performance => high quality data

RXJ 1713.7-3946



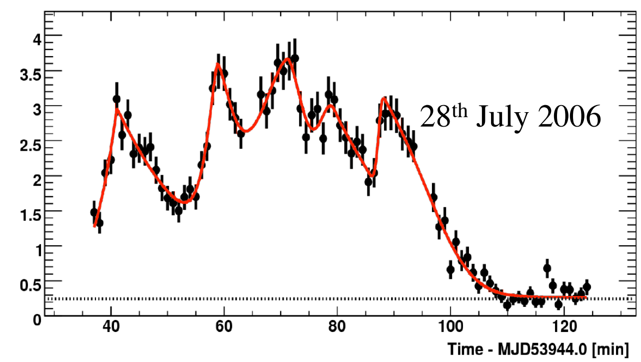
TeV image and energy spectrum of a SNR

Galactic Center



resolving GMCs in the Galactic Center 100pc region

PKS 2155-309



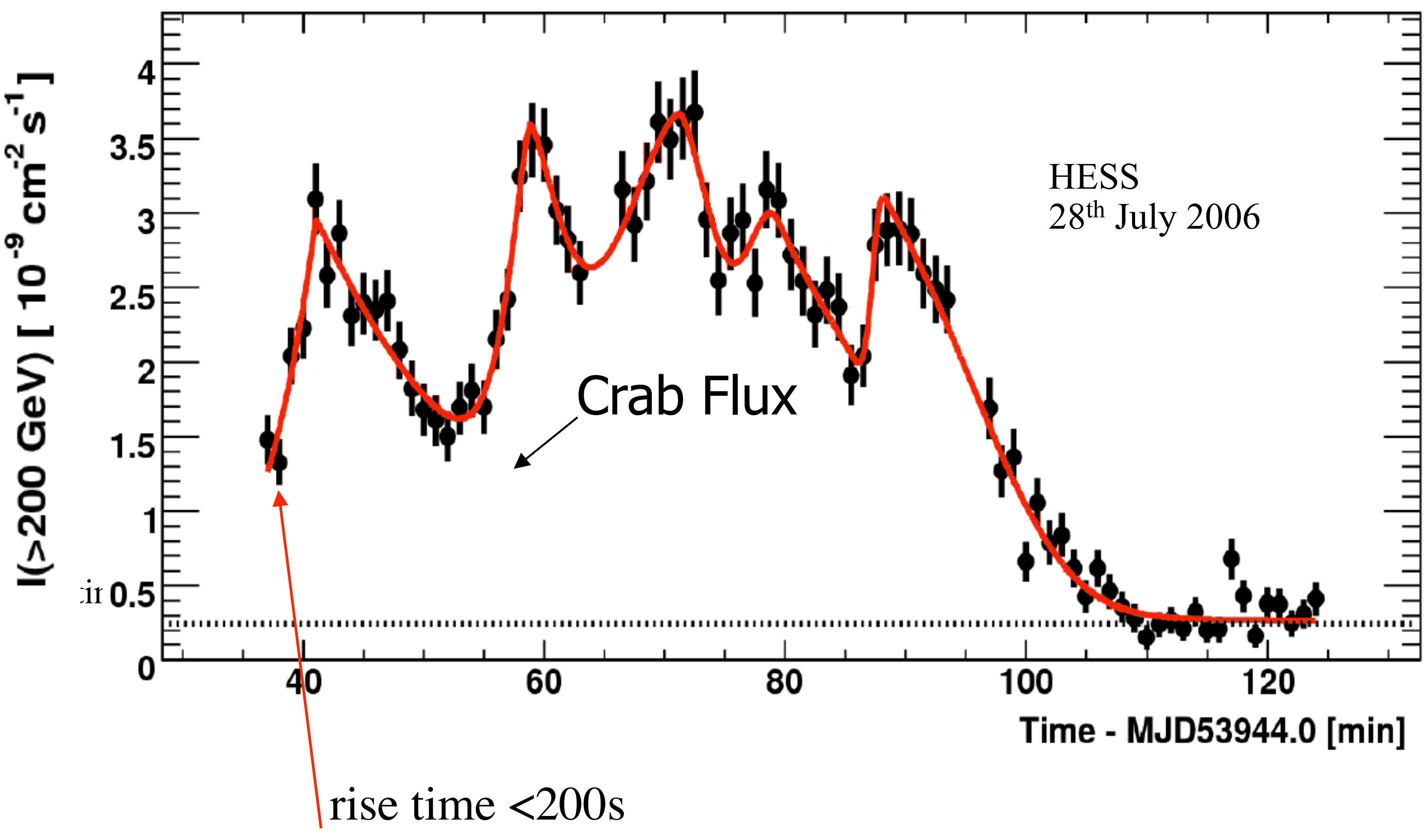
variability of TeV flux of a blazar on minute timescales

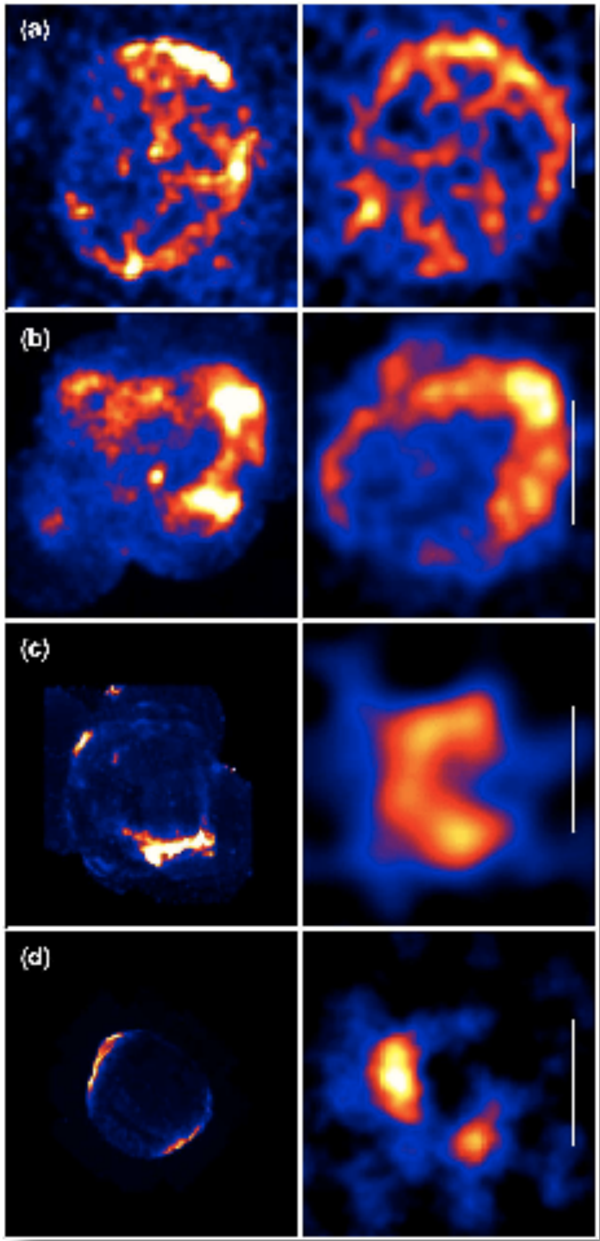
multi-functional tools: *spectrometry* *temporal studies* *morphology*

✓ extended sources: *from SNRs to Clusters of Galaxies*

✓ transient phenomena *QSOs, AGN, GRBs, ...*

Galactic Astronomy | Extragalactic Astronomy | Observational Cosmology several min (200s) variabiliry timescale => R=c ▯t_{var} ▯$_j$=10^{14}▯$_{10}$ cm for a 10^9Mo BH with 3Rg = 10^{15} cm => ▯j > 100, i.e. close to the accretion disk (the base of the jet), the bulk motion ▯ > 100

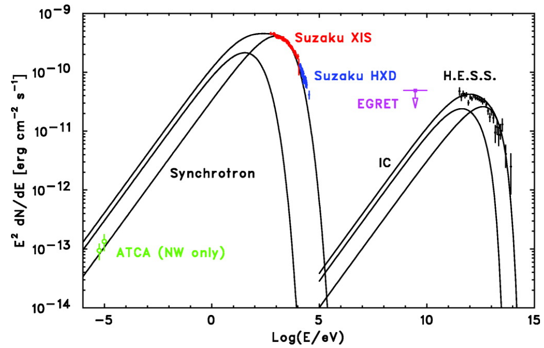


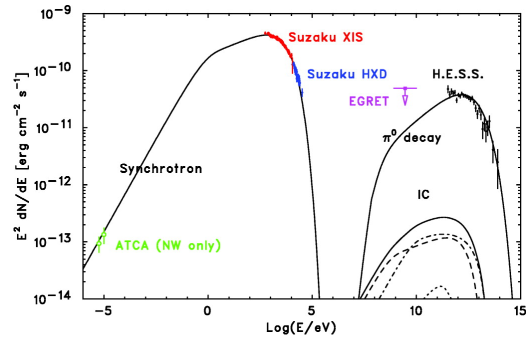


=>

acceleration of protons and/or electrons in SNR shells to energies up to 100TeV

leptonic or hadronic?





RXJ1713.7-4639

e + 2.7K => g

pp => π^o => 2γ

B=15μG

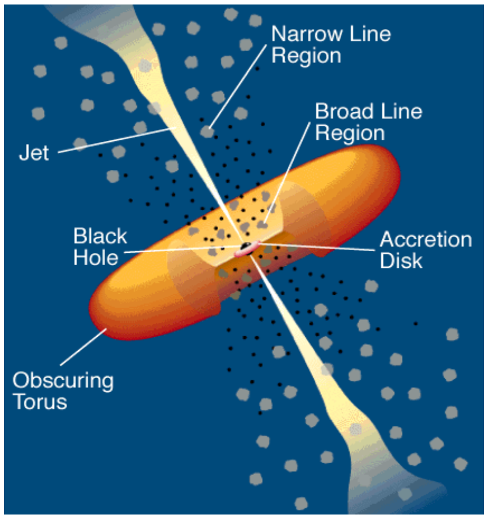
We ≈3 10^{47} erg

B=200μG

Wp ≈ $10^{50}(n/1cm^{-3})^{-1}$ erg

unfortunately we cannot give a preference to hadronic or leptonic models - both have attractive features but also serious problems

Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to γ) radiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines



GeV/TeV gamma-ray observations

strong impact on

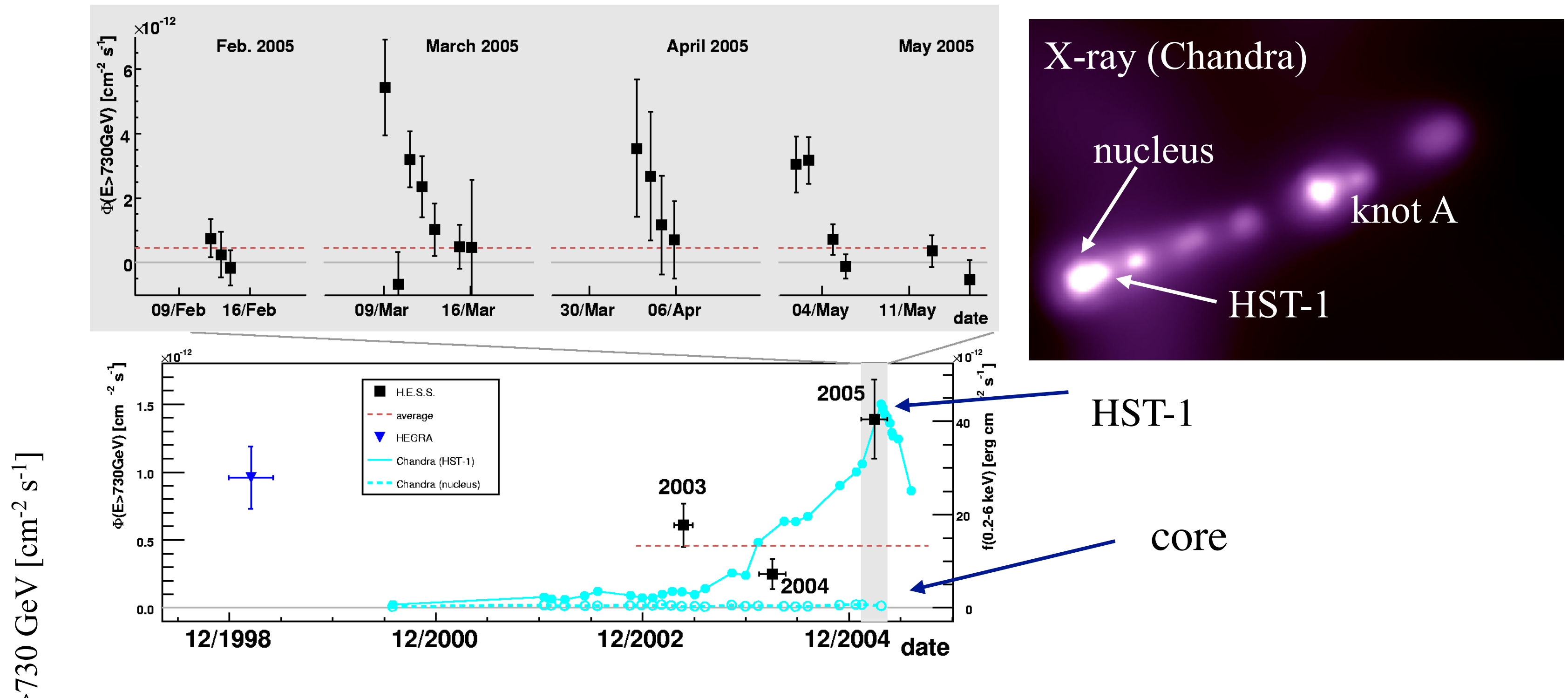
- Blazar physics and astrophysics
- Diffuse Extragalactic Background (EBL) Intergalactic Magnetic fields (IGMF)

most exciting results of recent years

- ultra short time variability (on min scales)
- Jet power exceeds Eddington luminosity
- extremely hard energy spectra
- VHE blazars up to z=0.5

M87: light curve and variabiliy

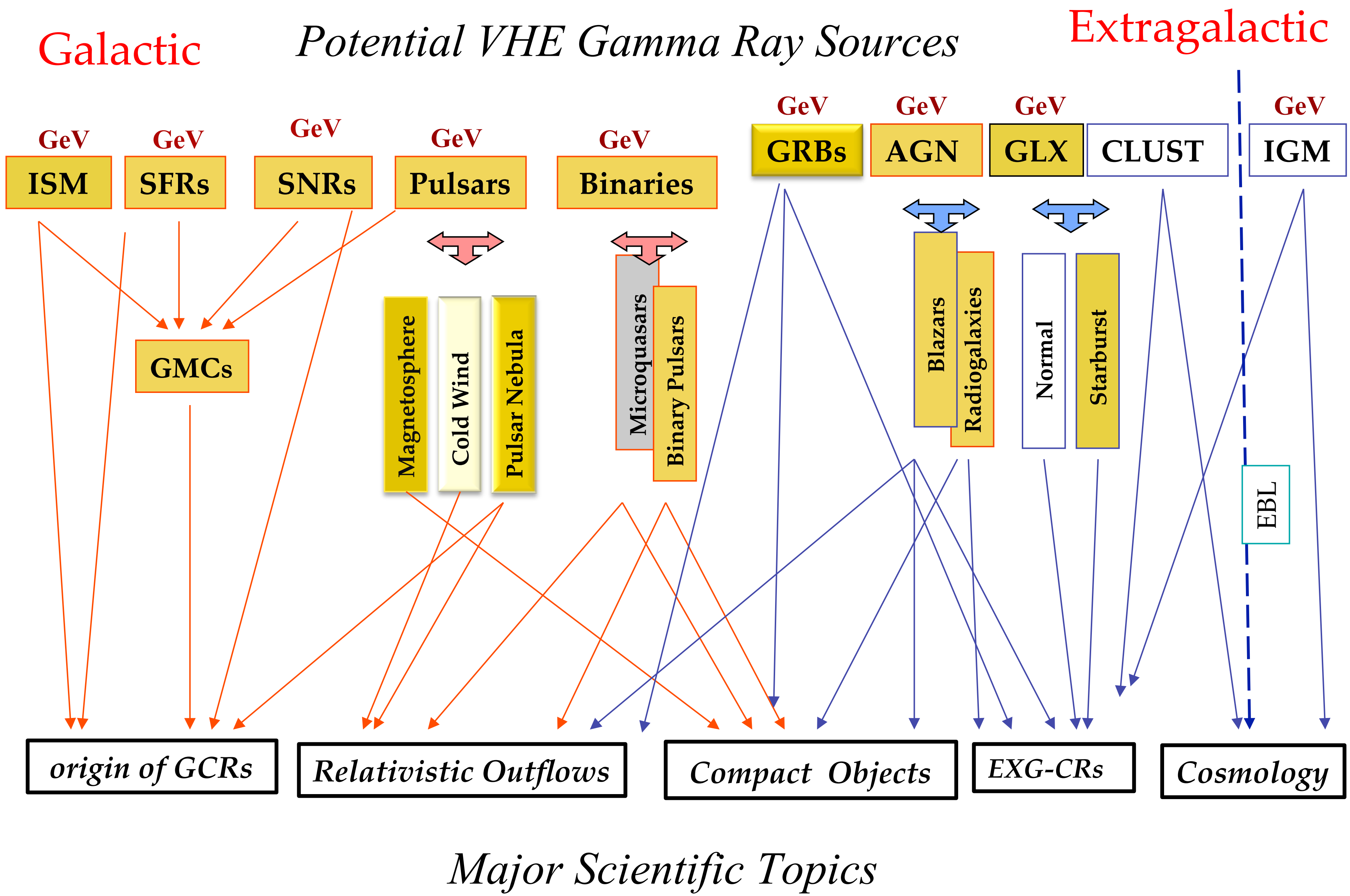
HESS Collaboration 2006, Science, **314**,1427



short-term variability on 1-2 day scales => emission region R ~ 5x10^{15}[illegible]j cm
=> production of gamma-rays very close to the 'event horizon' of BH?

because of very low luminosity of the core in O/IR:
TeV gamma-rays can escape the production region

$L_{IR} \approx 10^{-8} L_{Edd}$



Galactic
Potential VHE Gamma Ray Sources
Extragalactic
GeV
ISM
GeV
SFRs
GeV
SNRs
GeV
Pulsars
GeV
Binaries
GeV
GRBs
GeV
AGN
GeV
GLX
CLUST
GeV
IGM
GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars
Blazars
Radiogalaxies
Normal
Starburst
EBL
origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology
Major Scientific Topics

why next generation ground-based g-ray instruments?

minimum detectable energy flux at 1TeV down to 10^{-14} erg/cm^{2}s

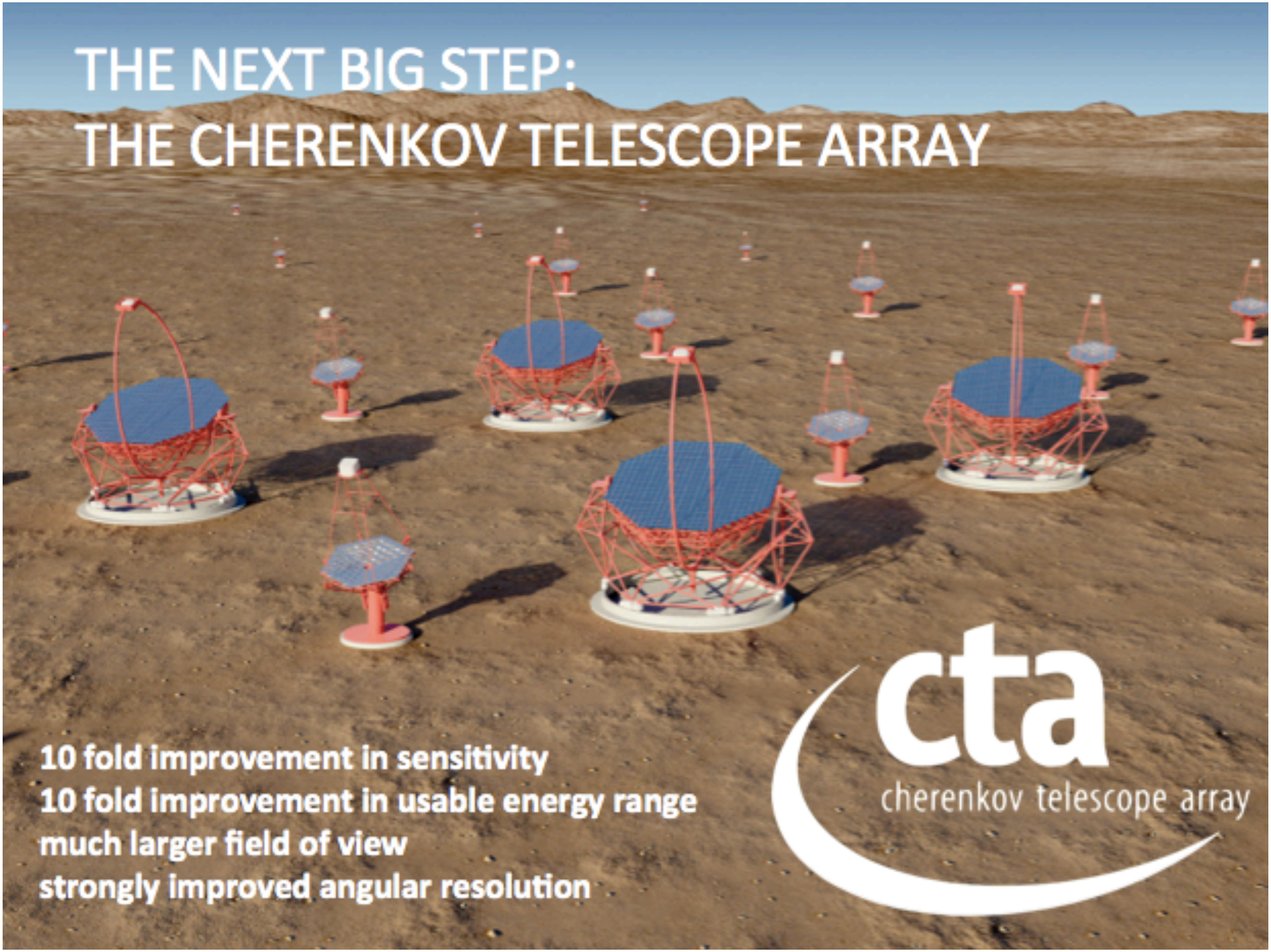
more sources and source populations: $L_{g,min} \sim 10^{30}$ (d/1kpc)^2 erg/s

angular resolution down to 1-2 arcmin - *better morphology*

extension of the energy band

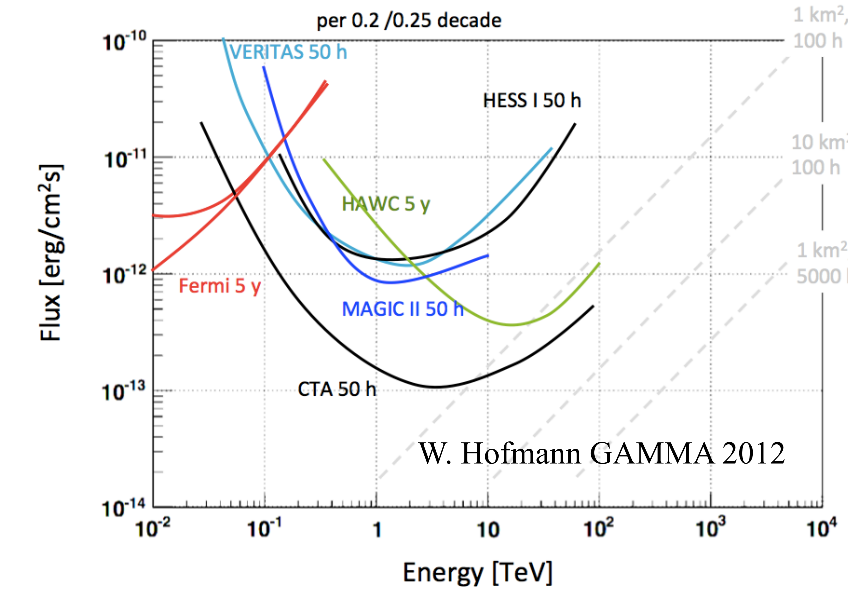
down to 10 GeV (timing explorer) | up to 100 TeV (search for PeVarton)

all sky monitoring – hunt for VHE transient events (HAWC)

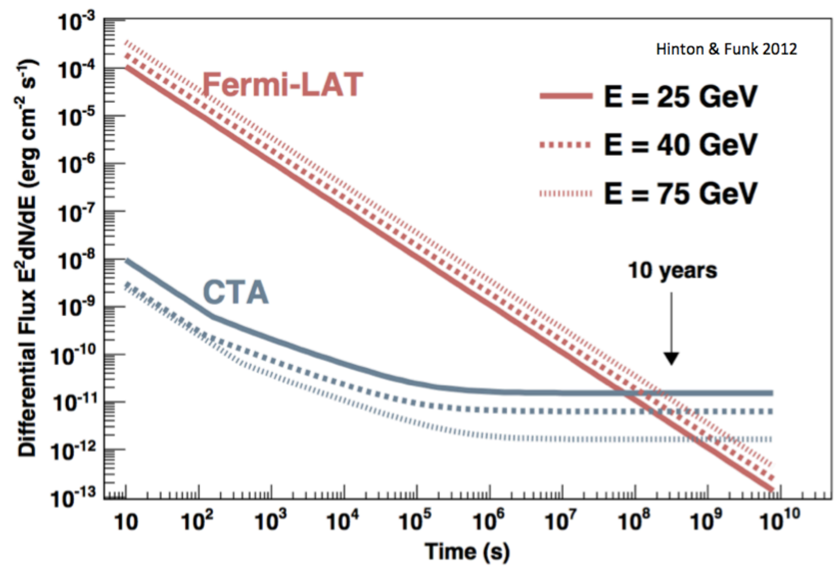

THE NEXT BIG STEP:
THE CHERENKOV TELESCOPE ARRAY
10 fold improvement in sensitivity
10 fold improvement in usable energy range
much larger field of view
strongly improved angular resolution
cta
cherenkov telescope array

CTA – a powerful tool for exploration of the Nonthermal Universe

DIFFERENTIAL SENSITIVITY



CTA VERSUS FERMI – TRANSIENT SOURCES



- detection of `nominal' (Fermi/AGILE) AGN for just 1min,
- detection of >10,000 gamma-rays from (Fermi LAT) GRBs with >10-GeV tails

but above several tens of GeV, the emission could be suppressed at tens of GeV
=> low threshold is critical (as low as 10 GeV is possible!)

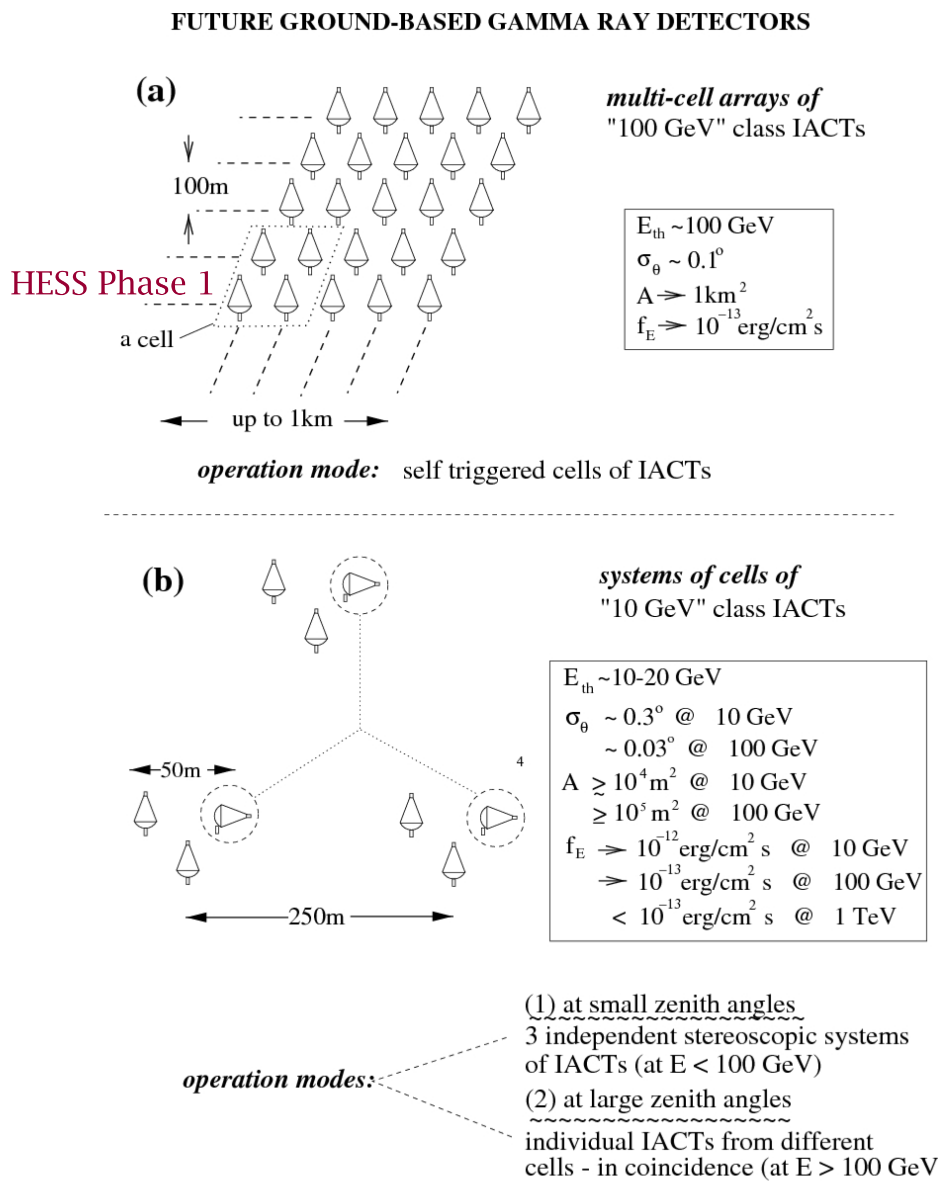
Future of ground-based gamma-ray astronomy

- aim? — sensitivity: F_E => 10^{-14} erg/cm^2 s (0.03-30TeV)
- realization ? — 1 to 10 km^2 scale 10m+ aperture IACT arrays
- timescales — short (years) - no technological challenges
- price — no anymore cheap 100+ MEuro
- expectations — guaranteed success - great results/discoveries

first priority: ”classical” 0.1-30 TeV IACT array with possible extension towards 30 GeV and 100 TeV

next step (parallel?): <10 GeV threshold IACT array

0.1-1 TeV threshold all sky monitor: “HAWK”



two possible designs of IACT arrays (Aharonian 1997, LP97, Hamburg 1997)

5@5 - a GeV timing explorer

- Detector : several 15 to 25m diameter IACTs to study the sky at energies from several GeV to several 100 GeV with unprecedented *photon and source statistics*
- Potential: can detect EGRET/Fermi sources with spectra extending beyond 5 GeV for exposure time from *1 sec to 10 minutes*
- Targets: Gamma Ray Timing Explorer for study of nonthermal phenomena: *AGN, Microquasars, GRBs,, Pulsars ...*

5@5 is complementary to GLAST
in fact due to small FoV needs very much GLAST
and ... GLAST certainly needs a 5@5 type instrument

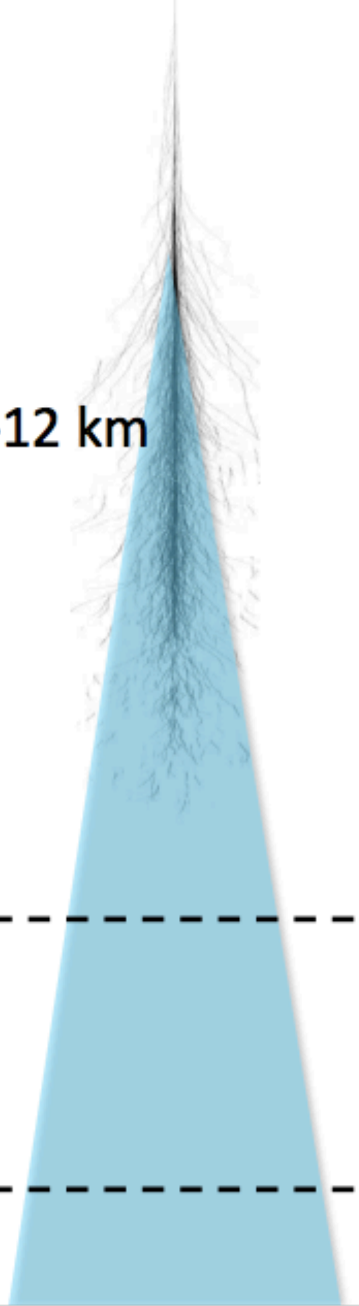
"The rapid development and successful operation of 5@5 during the lifetime of GLAST would represent a major observational coup"

Gamma Ray Group Summary Report, Snowmass "The future of particle Physics" (astro-ph/0201160)

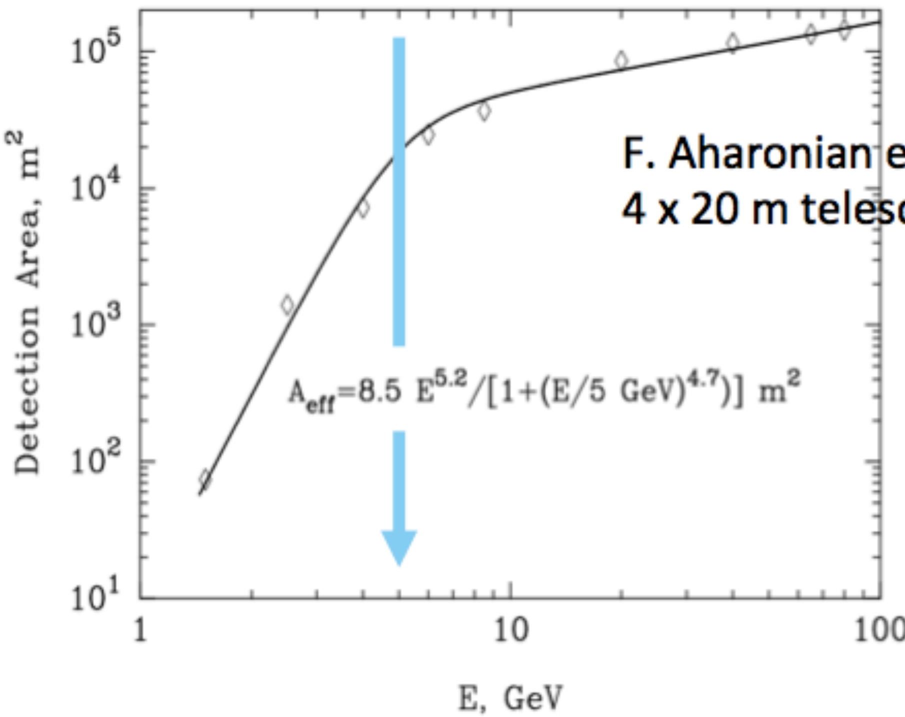

we already are there !

5@5 – a Gamma Ray Timing Explorer

HIGH-ALTITUDE CHERENKOV TELESCOPES



10-12 km



F. Aharonian et al., astro-ph/0006163
4 x 20 m telescopes @ 5000 m asl

higher light intensity (5000 m: x2)
➔lower threshold
smaller light pool area (5000 m: /2)

Reference height ~2000 m

W. Hofmann GAMMA 2012

Discovery of Plasma Collective Modes

- Experiments that are relevant both to nuclear fusion research and X-ray astrophysics (e.g. Alcator series) have been carried out and evolutions of them have been designed

- Collective modes that are important for both fields have been discovered (e.g. electron pitch angle scattering, new form of angular momentum transport and spontaneous rotation, high energy nuclei "conics").

Wave-like Modes with Negligible B-field Fluctuations ("electrostatic" modes)

$$\omega^2 \lesssim \Omega_c^2$$

$$\mathcal{E}_w = \mathcal{H}\omega$$

$$\mathbf{P}_w = \mathcal{H}\mathbf{k}$$

$$\Delta\mathcal{E}_w + = \Delta\mathcal{E}_p = 0$$

$$\Delta\mathcal{E}_w = \omega\left(\Delta\mathcal{H}\right)$$

$$\Delta\mathcal{E}_p = \Omega_c \left(\Delta\mathcal{H}\right) n^0 + m \mathrm{v}_{\|} \left(\Delta \mathrm{v}_{\|}\right)$$

$$\Delta P_{w\|} = \left(\Delta\mathcal{H}\right) k_{\|}$$

$$\Delta P_{p\|} = m\left(\Delta \mathrm{v}_{\|}\right)$$

$$\Delta P_{w\|} + \Delta P_{p\|} = 0$$

$$\omega\left(\Delta\mathcal{H}\right) = \Omega_c n^0 \left(\Delta\mathcal{H}\right) - k_{\|} \mathrm{v}_{\|} \left(\Delta\mathcal{H}\right) = 0$$

$$\text{for } \omega \ll \Omega_c$$

$$\Omega_c n^0 \simeq k_{\|} \mathrm{v}_{\|}$$

Electrostatic Modes

$$\hat{\mathbf{E}} \simeq -\nabla \hat{\Phi}$$

$$\hat{\phi}_k = \tilde{\phi}_k \exp\left(-i\omega t + i\mathbf{k}\cdot\mathbf{x}\right)$$

$$\mathcal{H}_k = \frac{1}{8\pi}\left|k\phi_k\right|^2 \frac{\partial \epsilon_D}{\partial \omega}\Bigg)_{\omega=\omega_k}$$

$$k^2 \epsilon_D\left(\boldsymbol{\omega},\boldsymbol{\kappa}\right)\hat{\phi}_k = 4\pi\hat{\rho}_{ck}^{ext}$$ Relevant Poisson's Equation

$$\omega = \omega_k + i\gamma_k$$

$$\mathrm{Re}\,\epsilon_D\left(\omega_k,\boldsymbol{\kappa}\right) = 0$$

Non-thermal Plasmas Associated with Black Holes

The radiation emission from Shining Black Holes is most frequently observed to have non-thermal features. Therefore, it is appropriate to consider relevant collective processes in plasmas surrounding or emanating from black holes and containing high energy particles with non-thermal distributions in momentum space. In order to use a fluid description the case where significant temperature anisotropies are present is analyzed. Considering plasmas in the vicinity of black holes [1] these anisotropies are shown [2] to have a critical influence on: a) the existence and characteristics of stationary plasma and field configurations; b) the excitation of magneto-gravitational modes driven by temperature anisotropies and differential rotation; c) the generation of magnetic fields over macroscopic scale distances; d) the outward transport of angular momentum.

The γ –ray bubbles emerging from the disk of Our Galaxy are connected to a stream of high energy protons emerging from the central massive black hole and plasma collective modes are considered that are excited by the non-thermal features of the proton distributions and transfer their energy to the radiation emitting electron population. *US DOE partly sponsored.

[1] B. Coppi, *Astron. & Astroph*. 548 **A84** (2012)

[2] B. Coppi, MIT-LNS HEP Report 13/01, submitted to the *Astrophysical Journal* (2013).

2. Sustaining Factors

The sustaining factor of new characteristic field configurations that can emerge in plasmas in the immediate surroundings of black holes can be identified by applying the $\mathbf{e}_\varphi \cdot \nabla\times$ operator [3, 4] to the total momentum conservation equation

$$\rho\left(\nabla\Phi_G - \Omega^2\,\mathrm{R}\,\mathbf{e}_R\right) = -\nabla\cdot\mathbb{P} + \frac{1}{c}\mathbf{J}\times\mathbf{B}. \tag{2.1}$$

Here we refer to an axisymmetric plasma configuration, we assume that only a rotation velocity ΩR is present, R is the distance from the axis of symmetry, Φ_G is the gravitational potential and $\mathbb{P}$ is the relevant pressure tensor. Then we consider

$$\mathbb{P} = p\mathbb{I} + \Delta\mathbb{P}, \tag{2.2}$$

where the non isotropic component $\Delta\mathbb{P}$ is significant, and we identify the sustaining factor for the relevant magnetic field configuration as

$$D \equiv \mathbf{e}_\phi\cdot\nabla\times\left[\nabla\cdot(\Delta\mathbb{P}) + \rho\left(\nabla\Phi_G - \Omega^2 R\mathbf{e}_R\right)\right]$$

in which $\mathbf{A}_N \equiv \nabla \cdot (\Delta\mathbb{P})$ adds its influence to that of the gravitational field and rotation. In particular

$$D \simeq \frac{\partial}{\partial z} A_{NR} - \frac{\partial}{\partial R} A_{Nz}$$

$$-\left(\frac{\partial \rho}{\partial z}\right)\left[R\Omega^2 - \frac{\partial \Phi_G}{\partial R}\right] - R\rho \frac{\partial}{\partial z}\Omega^2 - \frac{\partial \Phi_G}{\partial z}\frac{\partial \rho}{\partial R} \tag{2.3}$$

where $R^2\Omega^2 \simeq \partial\Phi_G/\partial R$ and we consider

$$D_{AN} \equiv \left|\mathbf{e}_\phi \cdot \nabla \times [\nabla \cdot (\Delta\mathbb{P})]\right| \sim \left|\frac{\partial \Phi_G}{\partial z}\frac{\partial \rho}{\partial R}\right|. \tag{2.4}$$

Referring to rotating black holes we consider plasmas located outside the last stable orbit [ ]. Thus, for configurations whose height is much smaller than R_0, we refer to the following asymptotic expression for Φ_G

$$\Phi_G = -\frac{GM_*}{\sqrt{R^2 + z^2}} \simeq -\frac{GM_*}{R}\left(1 - \frac{1}{2}\frac{z^2}{R^2}\right)$$

$$= -RV_k^2\left(1 - \frac{1}{2}\frac{z^2}{R^2}\right) \tag{2.5}$$

where

$$V_K = \left(\frac{GM_*}{R}\right)^{1/2} \tag{2.6}$$

is the Keplerian velocity. Clearly, considering an interval $|R - R_0| \ll R_0$ around $R = R_0$,

$$\Phi_G \simeq -\frac{GM}{R_0} + \frac{GM_*}{R_0^2}(R - R_0) + \frac{1}{2}\frac{GM_*}{R_0^3}z^2. \tag{2.7}$$

The simplest way to avoid having to deal with phase space and to maintain a fluid description is to refer to plasmas with particle populations that can be described by bi-Maxwellian distributions in momentum space with two temperatures $T_{\|}$ and $T_{\perp}$. In particular we take $T_{\|}$ to be the prevalent temperature in a given direction and we assume that the plasma is composed of two populations: a thermal population with an isotropic plasma pressure $p = 2nT$, n being the electron density, and a super thermal population with $p_{\|} > p$ and $T_{\|} > T$.

3. Rigidly Rotating Rings Associated with Non-Thermal Distributions in Momentum Space

We consider a radial interval around $R{-}R_0$ within which the rotation frequency $\Omega(R) \simeq \Omega_0$ in the sense that $|(R/\Omega)\, d\Omega/dR| \ll 1$. Referring to plasmas with two particle populations as indicated earlier.

$$\mathbb{P} = p\mathbb{I} + (p_{\|} - p)\,\mathbf{e}_{\|}\mathbf{e}_{\|}. \tag{3.1}$$

An important special case to analyze is that for which the pressure anisotropy is connected with the direction of the magnetic field. Thus

$$\Delta\mathbb{P} = (p_{\|} - p)\,\frac{\mathbf{BB}}{B^2}. \tag{3.2}$$

Another case is that for which the anisotropy is connected with the direction of the rotation velocity, that is $\Delta\mathbb{P} = (p_{\|} - p)\,\mathbf{e}_{\phi}\mathbf{e}_{\phi}$. In this case if we consider an axisymmetric configuration we have

$$\nabla \cdot (\Delta\mathbb{P}) = -(p_{\|} - p)\,\frac{1}{R}\mathbf{e}_{\phi}. \tag{3.3}$$

In the former case, referring to axisymmetric configurations and defining

$$\bar{\bar{p}} = \frac{4\pi}{B^2} \left(p_{\|} - p\right) \tag{3.4}$$

we find that

$$\nabla \cdot (\Delta \mathbb{P}) = \frac{1}{4\pi} \mathbf{B} \cdot \nabla \left(\bar{\bar{p}} \mathbf{B}\right). \tag{3.5}$$

Therefore

$$-\nabla \cdot \mathbb{P} + \frac{1}{c} \mathbf{J} \times \mathbf{B} =$$

$$-\nabla \left(p + \frac{B^2}{8\pi}\right) + \frac{1}{4\pi} \mathbf{B} \cdot \left[\left(1 - \bar{\bar{p}}\right) \mathbf{B}\right] \tag{3.6}$$

where **B** is represented by

$$\mathbf{B} = \frac{1}{R} \left[\nabla \psi \times \mathbf{e}_{\phi} + I\left(\psi, z\right) \mathbf{e}_{\phi}\right] \tag{3.7}$$

and $\psi\left(R, z\right)$ is the familiar magnetic surface function as $\mathbf{B} \cdot \nabla \psi = 0$

In this case the Master Equation [9] that we use, together with the vertical component of Eq. (1.1), to identify stationary plasma and field configurations is

$$\mathbf{e}_\phi \cdot \{\nabla\rho \times \nabla\Phi_G - \nabla \times (\rho\Omega R\mathbf{e}_R)\}$$

$$\simeq \frac{1}{4\pi}\mathbf{e}_\phi \cdot \{\nabla \times [\mathbf{B} \cdot \nabla\left((1-\bar{\bar{p}})\,\mathbf{B}\right)]\}\,. \tag{3.8}$$

Then, for radially localized configurations, we consider a special class of solutions for which ψ can be represented by

12. Tridimensional Solitary Ring Configurations

When considering the stationary configurations that can be identified by a nonlinear analysis, we may refer again to the rings obtained in the rigid rotor limit. Then we can extend the relevant analysis by taking, for instance,

$$\mathbf{B} = \frac{1}{R}\left[\nabla\psi \times \mathbf{e}_\phi + \frac{\alpha_\phi}{\Delta_z}\psi\mathbf{e}_\phi\right] + \Delta\mathbf{B}_p \tag{12.1}$$

where

$$\psi = \psi_N \exp\left(-\frac{\bar{z}^2}{2} - R_*^2\right)$$

$$\sin\left[R_* - m_\phi\left(\Omega_0 t - \phi\right)\right], \tag{12.2}$$

m_ϕ is a relatively low number, and

$$\nabla \cdot \left(\Delta\mathbf{B}_p\right) + \alpha_\phi\psi_N \frac{m_\phi}{\Delta_z R^2}$$

$$\cos\left[R_* - m_\phi\left(\Omega_0 t - \phi\right)\right]\psi_N$$

$$\exp\left(-\frac{\bar{z}^2}{2} - R_*^2\right) = 0. \tag{12.3}$$

13. Concluding Remarks

The results obtained in the previous sections show that the degree of departure from thermal particle distributions in phase space has an important effects both on the modes that can be excited in the plasmas around black holes and on the new and field stationary configurations that can emerge. We note that the presence of high energy particles with non-thermal distributions is most frequent in the radiation emitting plasmas around black holes as shown by the characteristics of the observed radiation spectra. Therefore, there is a need for analyses to follow which will deal with more general distributions [11] in phase space than anisotropic Maxwellians.

A question that the linearized analysis of excited modes raises is whether their non-linear evolution will lead to a "saturated" state where both temperature anistropy and the differential rotation are not significant or to a state like that described in Section 4 where there is no differential rotation [13] but the anistropy persists.

A further development of the presented theory is suggested by the fact that dusty toroidal structures have been envisioned to exist around massive black holes [14]. Thus it may be appropriate to formulate a parallel analysis, to the one presented here, in which dusty plasmas surrounding massive black holes are considered.

References

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