GeV - TeV Astronomy; A New View Of Our Universe

Frank Krennrich, Iowa State University

Outline

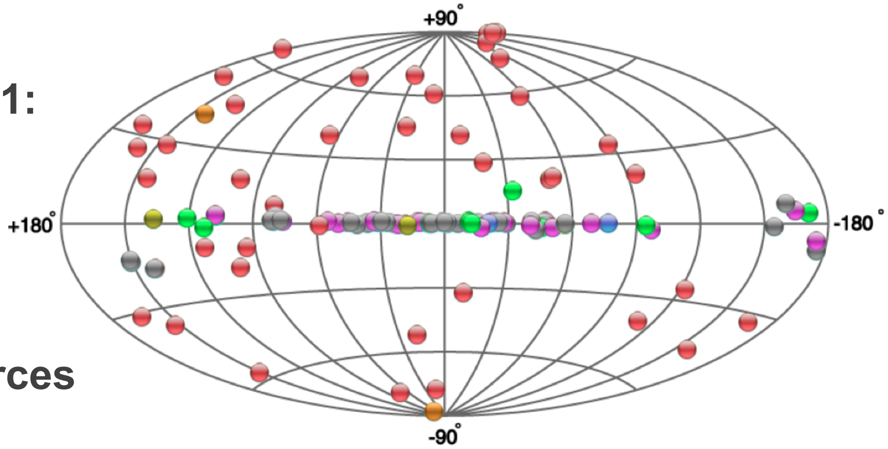
- Overview & Physics motivations.
- VERITAS & IACT technique.
- Key science results & highlights.
  - cosmic-ray origin (Tevatrons & Pevatrons).
  - the role of pulsars (emission models)
  - active galactic nuclei (closing in on a SMBH).
  - extragalactic background light (EBL).
- What have we not seen (yet)?
  - dark matter, LIV, …
- What is next? - CTA
- Summary.

Overview

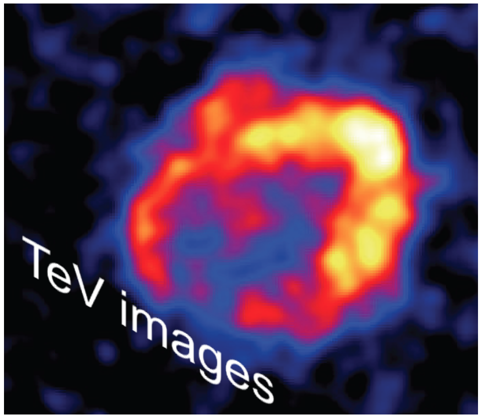
<u>What has been learned with gamma-ray experiments?</u>

- GeV/TeV radiation is **ubiquitous** to a wide range of astrophysical environments showing that **non-thermal processes** are major contributors to the **energy budget** of:
  - our galaxy (compact objects, SNRs, unidentified sources)
  - our galactic neighborhood (satellite galaxies & starburst galaxies)
  - distant cosmological sources (active galaxies and gamma-ray bursts).

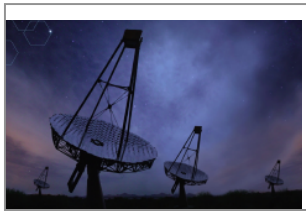
TeV sky:
March 2011:



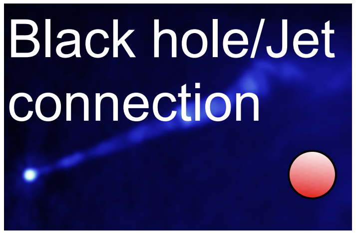
> 120 sources



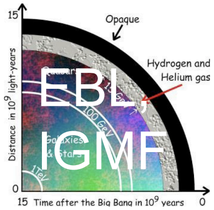
- TeV observations expanded γ-ray observations in energy and opened up a **new window** for astrophysics and studies of **fundamental physics** previously out of reach.



Science Drivers

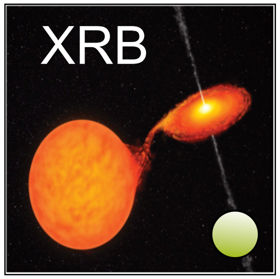


Black hole/Jet connection

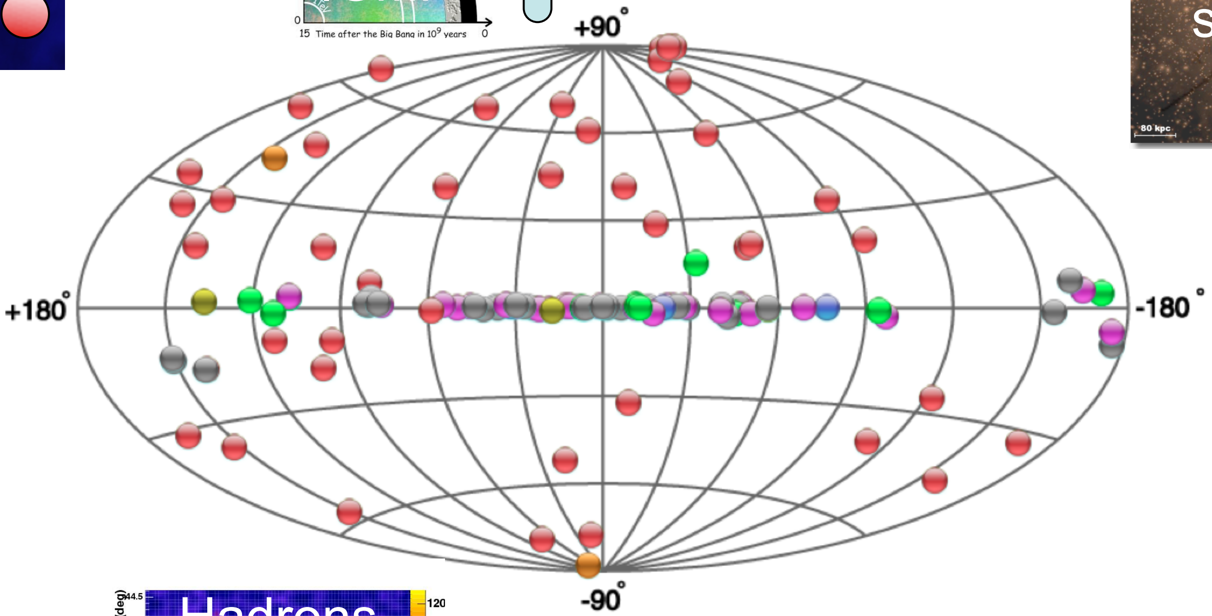


**Fundamental physics/
Particle physics/
Cosmology**

Dark Matter Annihilation signal?

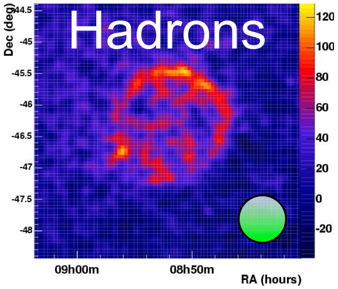


XRB

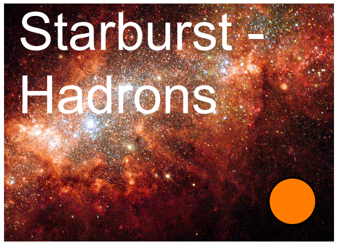


Pulsar Wind Nebulae

Jets - from Collapse?



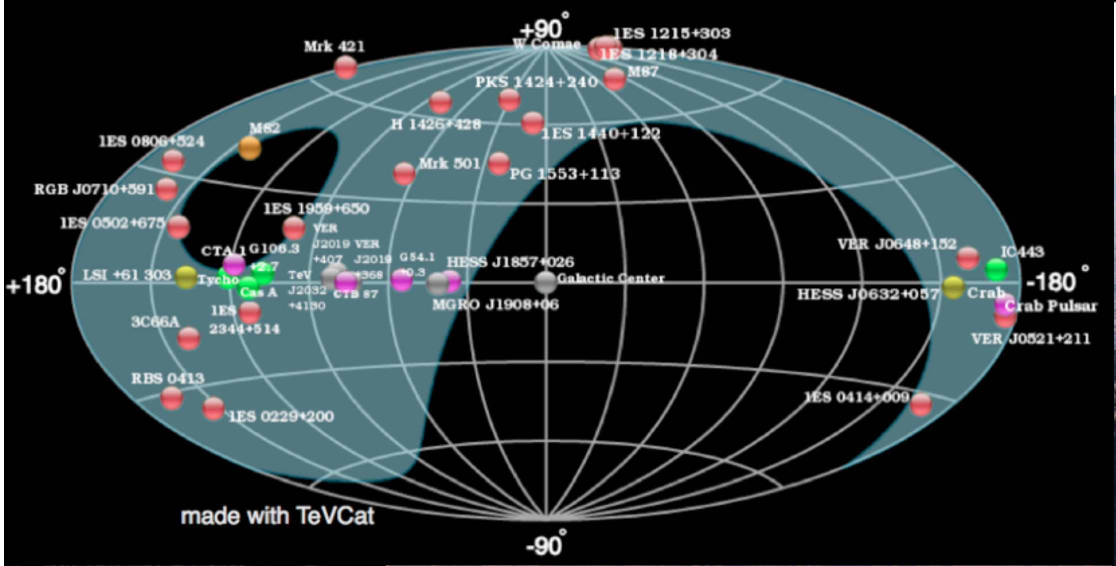
Hadrons



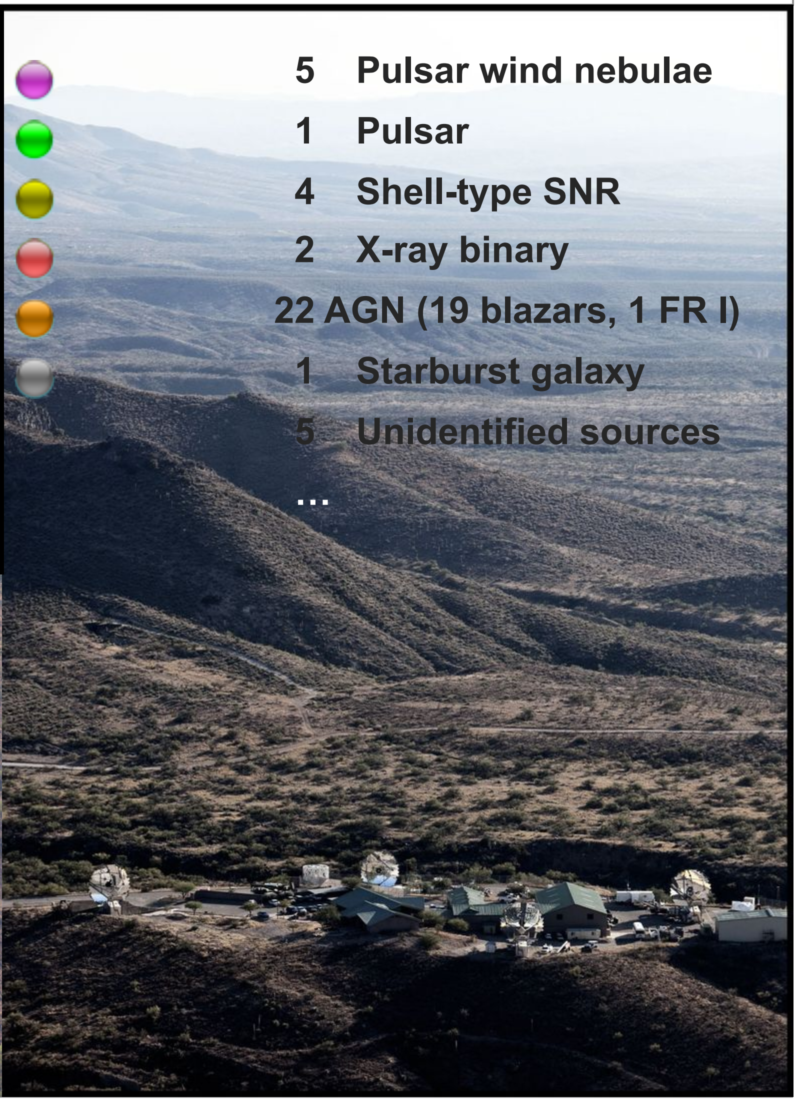
Starburst - Hadrons

● ?

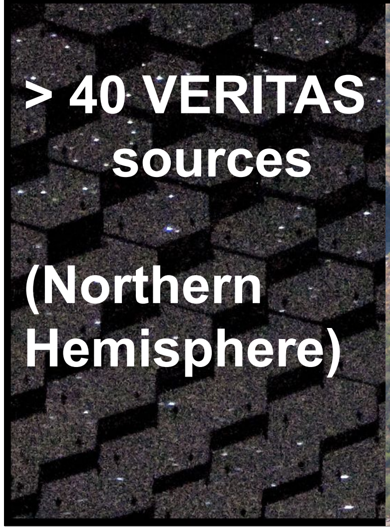
VERITAS



made with TeVCat



🟣	5	**Pulsar wind nebulae**
🟢	1	**Pulsar**
🟡	4	**Shell-type SNR**
🔴	2	**X-ray binary**
🟠	22 AGN (19 blazars, 1 FR I)	
⚪	1	**Starburst galaxy**
	5	**Unidentified sources**
	…	



> 40 VERITAS sources

(Northern Hemisphere)

VERITAS Collaboration

Collaboration Mtg. July 2010
Cork, Ireland

86 Scientists

22 Institutions in
4 Countries

Support from:

U.S. DOE
U.S. NSF
Smithsonian
STFC (U.K.)
NSERC (Canada)
SFI (Ireland)

U.S.

Adler Planetarium
Argonne Nat. Lab
Barnard College
DePauw Univ.
Grinnell College
Iowa St. Univ.
Purdue Univ.
SAO
UCLA
UCSC
Univ. of Chicago
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Univ. of Iowa
Univ. of Minnesota
Univ. of Utah
Washington Univ.

Canada

McGill Univ.

U.K.

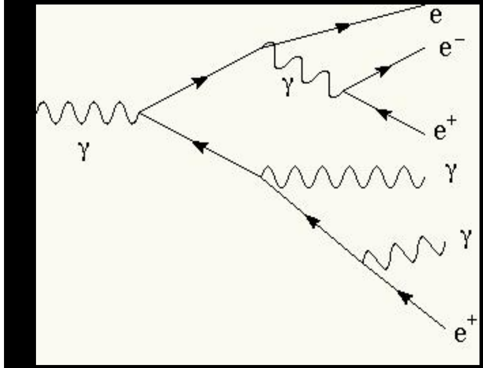
Leeds Univ.

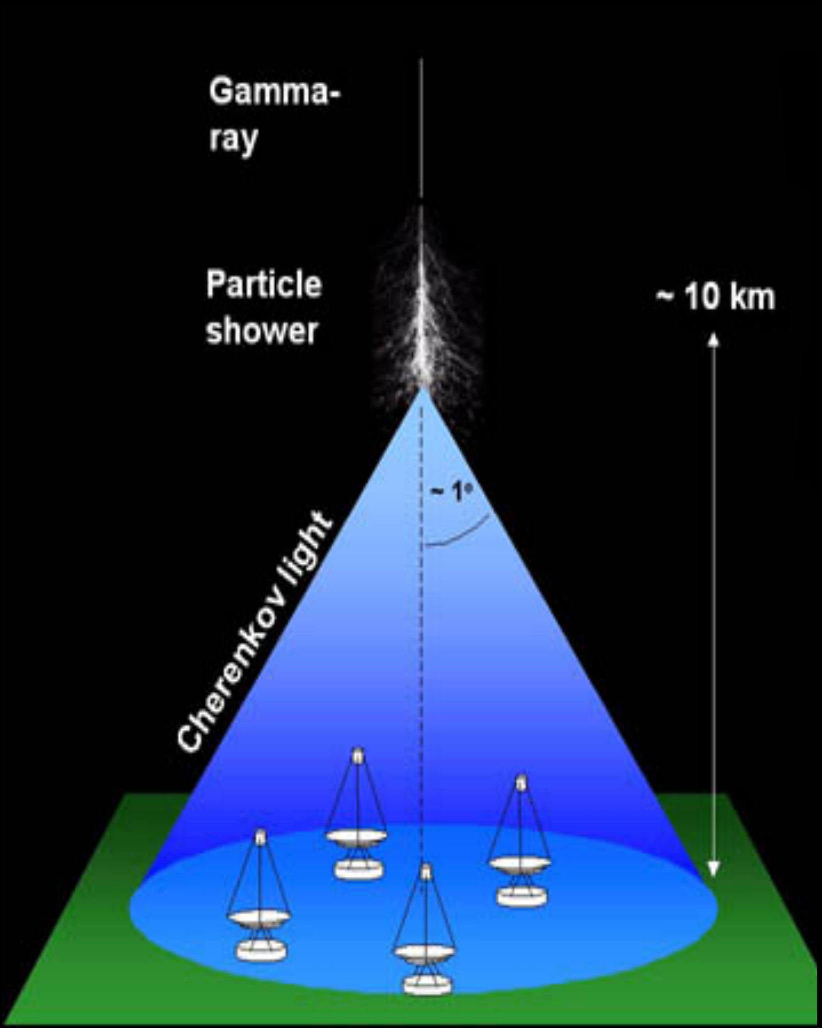
Ireland

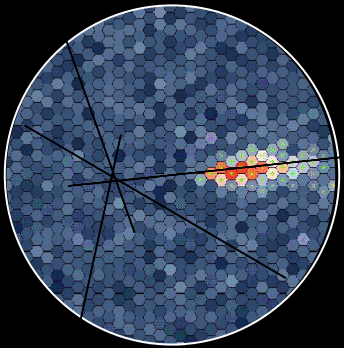
Cork Inst. Tech.
Galway-Mayo Inst.
N.U.I. Galway
Univ. College Dublin

+ 35 Associate Members, incl. theorists, MWL partners, IceCube, Fermi, Swift, etc.

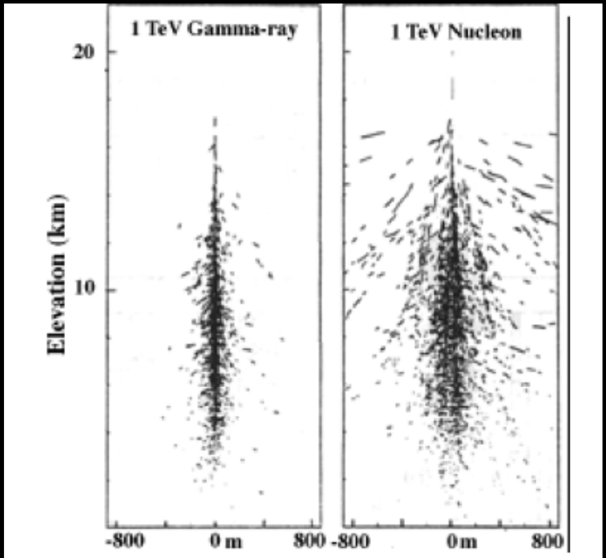
Atmosph. Cherenkov Technique

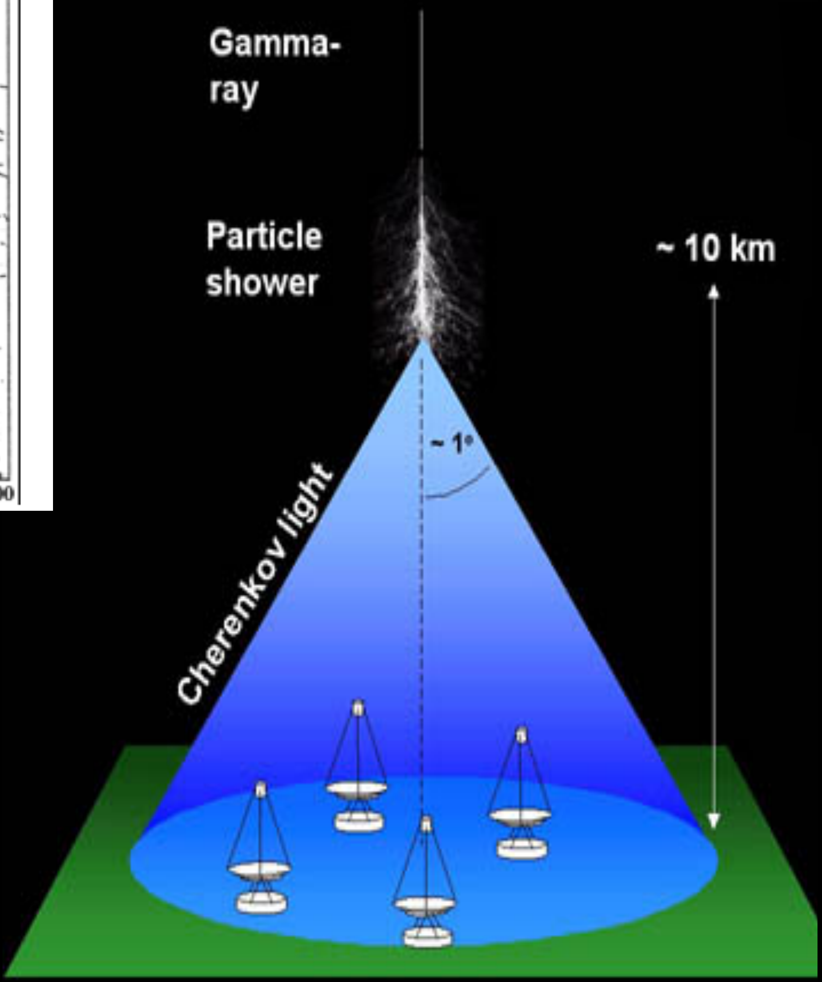


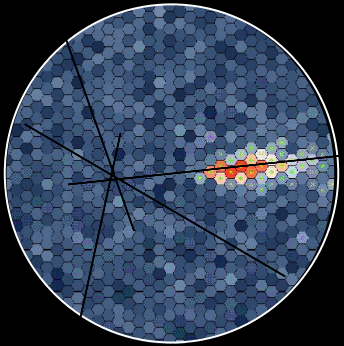




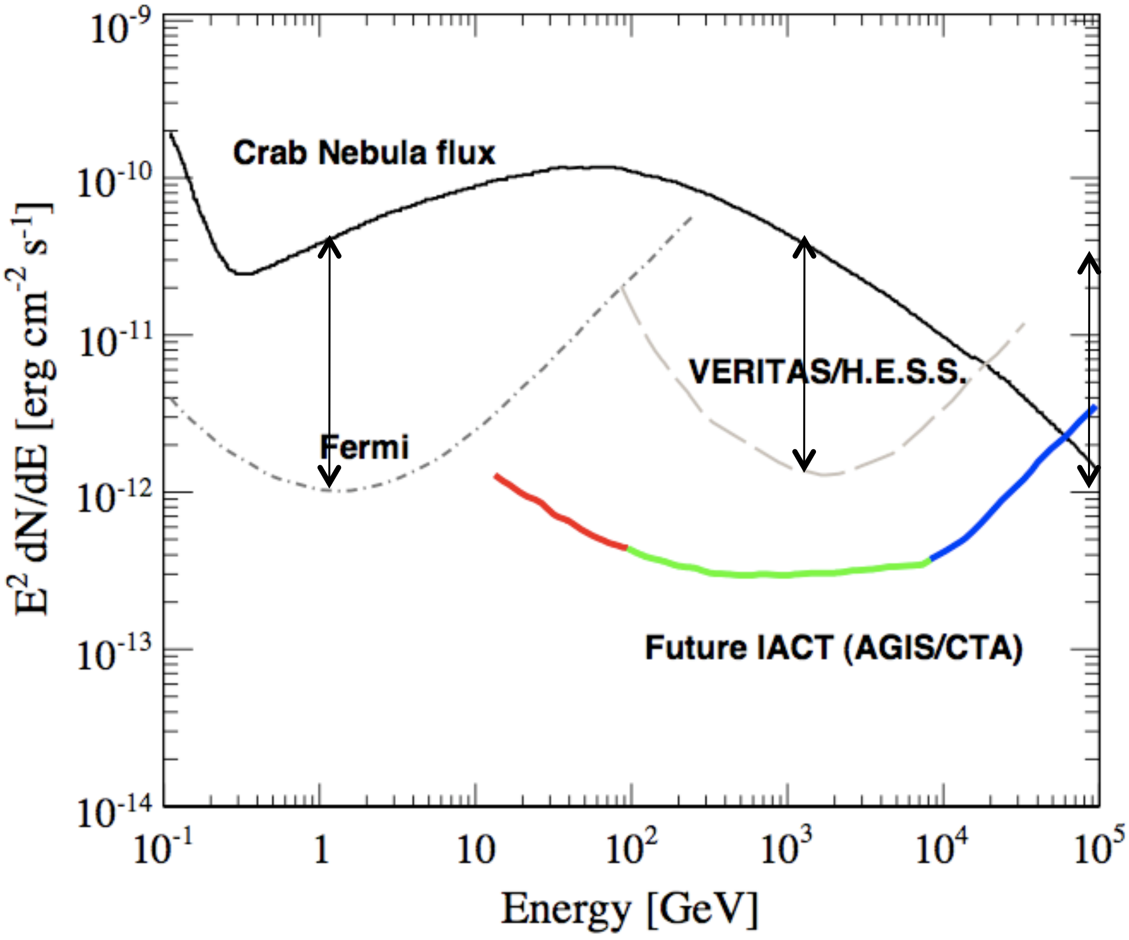
Atmosph. Cherenkov Technique







Instrument Performance Parameters



	Fermi	IACTs
Collection area	~ 1 m^2	~10^5 m^2
Angular resolution	0.8° – 0.1°	0.1° – 0.05°
Field of view	2 sr	4×10^{-3} sr

Fermi exposure 1 year (5 σ detection)
VERITAS exposure 50 hours (5 σ detection)

Sensitivity Typical 1% of Crab

Key Science Questions

(1) Galactic Tevatrons and Pevatrons

(2) Black Holes

(3) Cosmology

(4) Particle Physics and Fundamental Laws

Key Science Questions

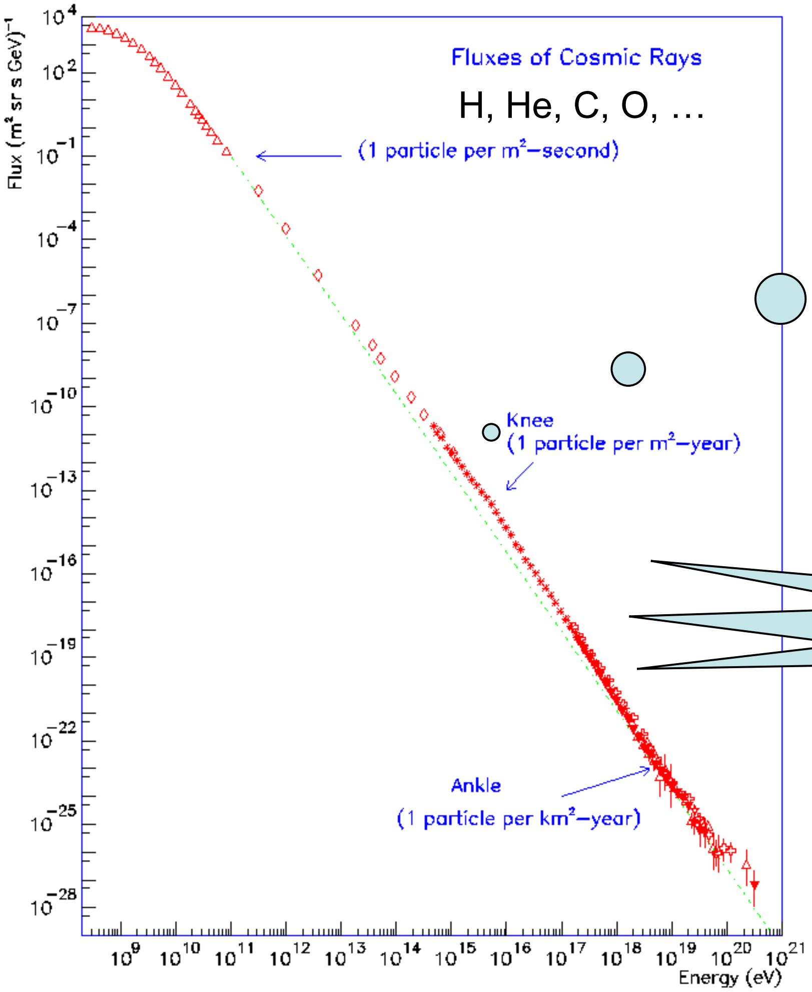
(1) **Galactic Tevatrons and Pevatrons**

(2) Black Holes

(3) Cosmology

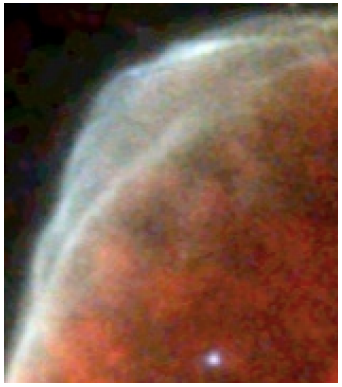
(4) Particle Physics and Fundamental Laws

Cosmic Ray Origin?



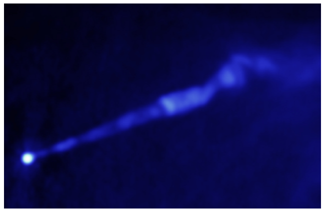
S. Swordy

Supernova Remnants?



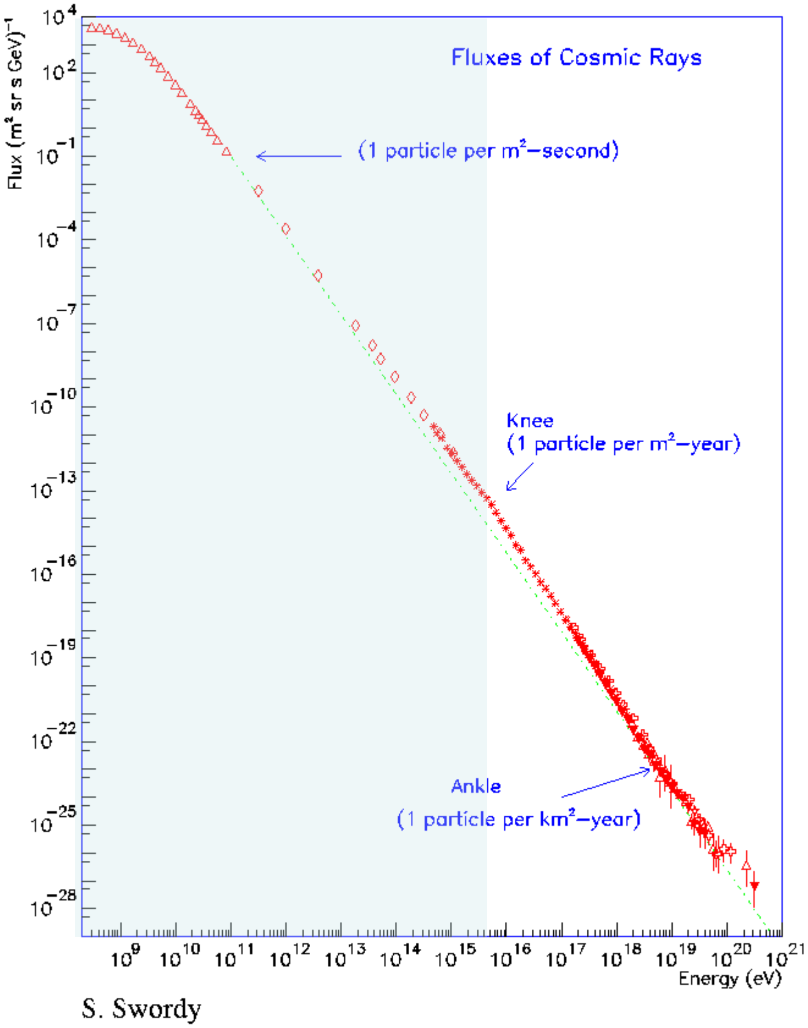
SN1006 10 keV

Relativistic Jets?



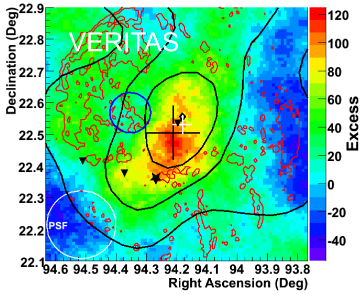
M87 radio

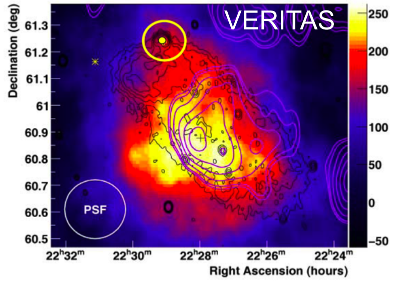
Cosmic Ray Accelerators: Where?



S. Swordy

Supernova Remnants:

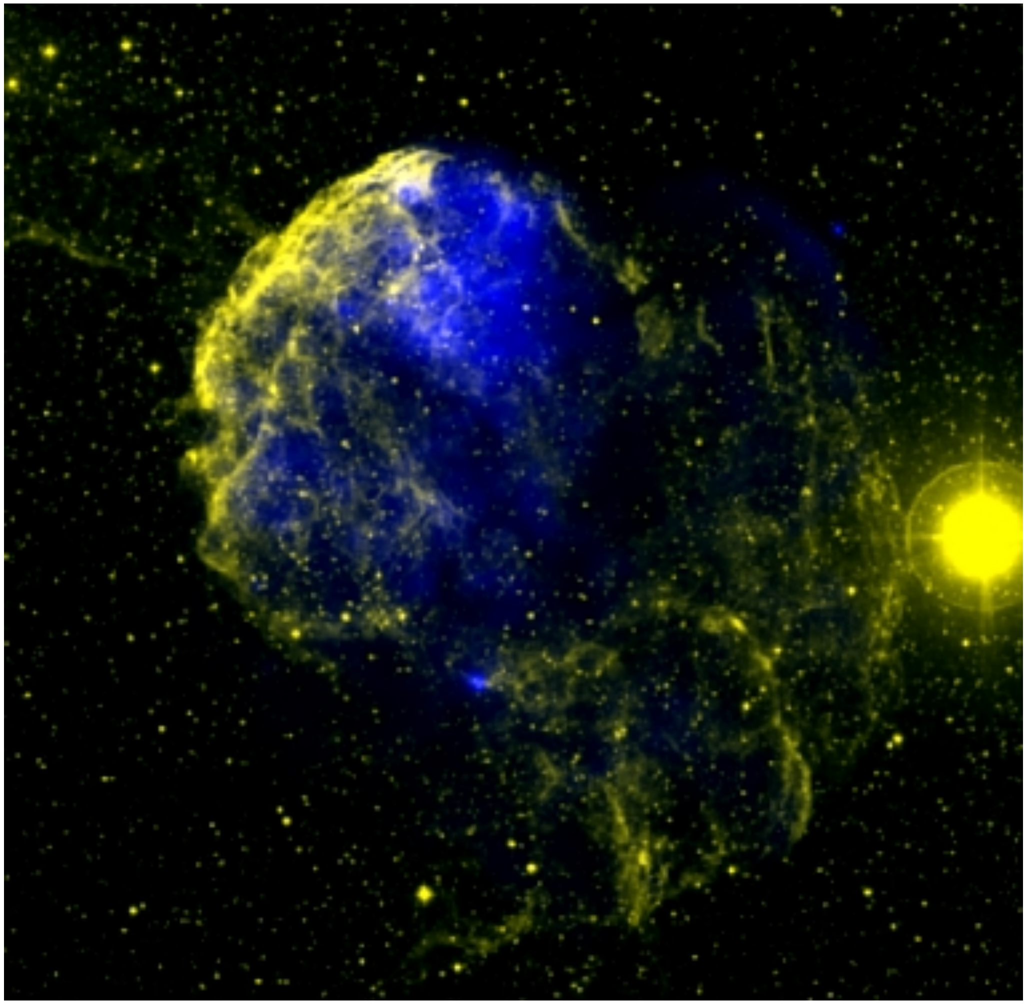




Galaxies Colliding (star factories)

Relativistic Jets: nearby AGN, GRBs

Supernova Remnants – IC 443



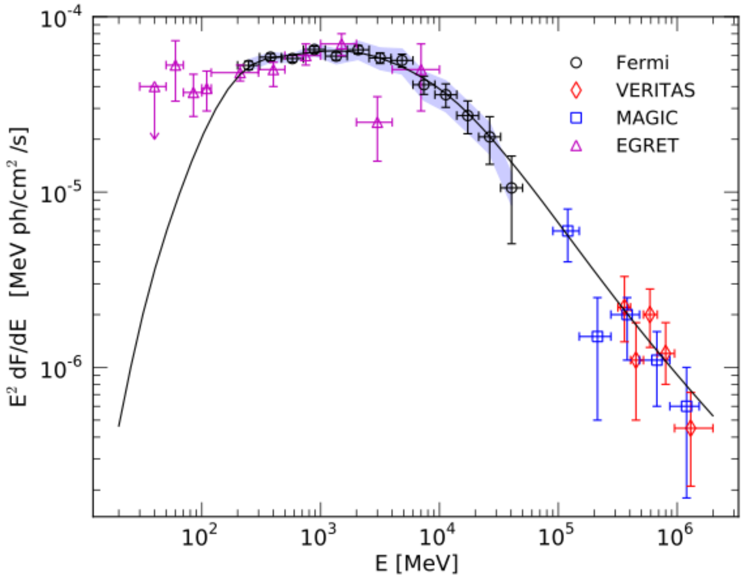
- SNR from Type II SN, age ~ 3 – 30 ky.
- SF region, strong molecular lines.
- pulsar nearby.
- well studied at other wavelengths.
- rich environment with SNR interacting with molecular cloud.
- PWN CXOU J061705.3+222127 (possible progenitor)

optical

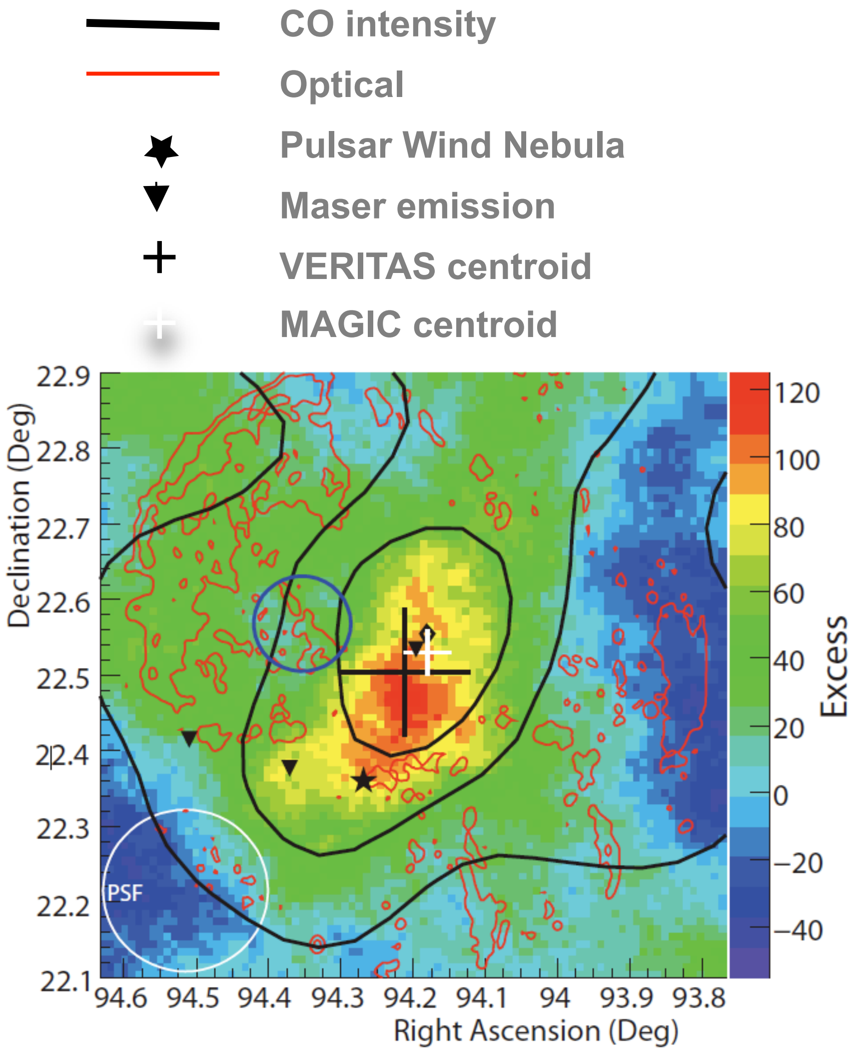
X-ray.

Supernova Remnants – IC 443

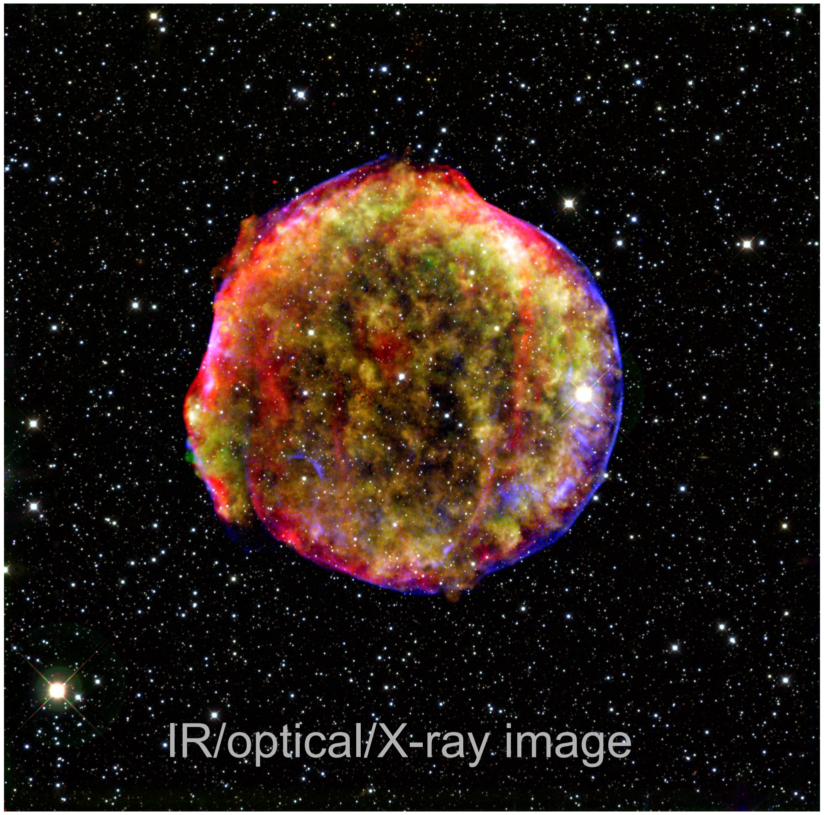
- Try to disentangle PWN emission from SNR shell emission or molecular cloud interactions



- Fermi & VERITAS → consistent with extended emission region, θ_{68}~ 0.24°
- offset from PWN, correlated with CO



Supernova Remnants – Tycho’s



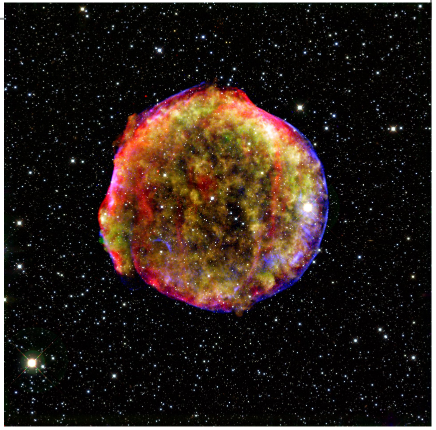
- SNR from Type Ia SN, age = 439 y.
- X-ray filaments of non-thermal
  - → electron acceleration
- shell-like morphology
- northeastern ridge expanding at slower rate
  - → interaction with molecular cloud
- molecular cloud seen in HI and CO.
- one of the best contenders for hadronic accel.
- distance ~ 2.5 – 4.5 kpc

optical/IR

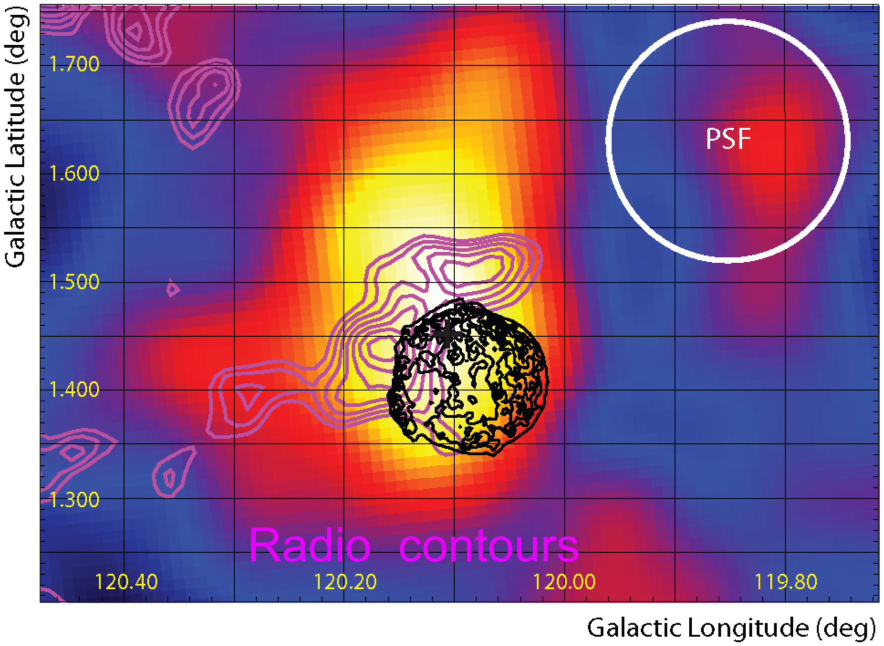
X-ray.

Supernova Remnants – Tycho's

- Unveiling a hadronic accelerator?

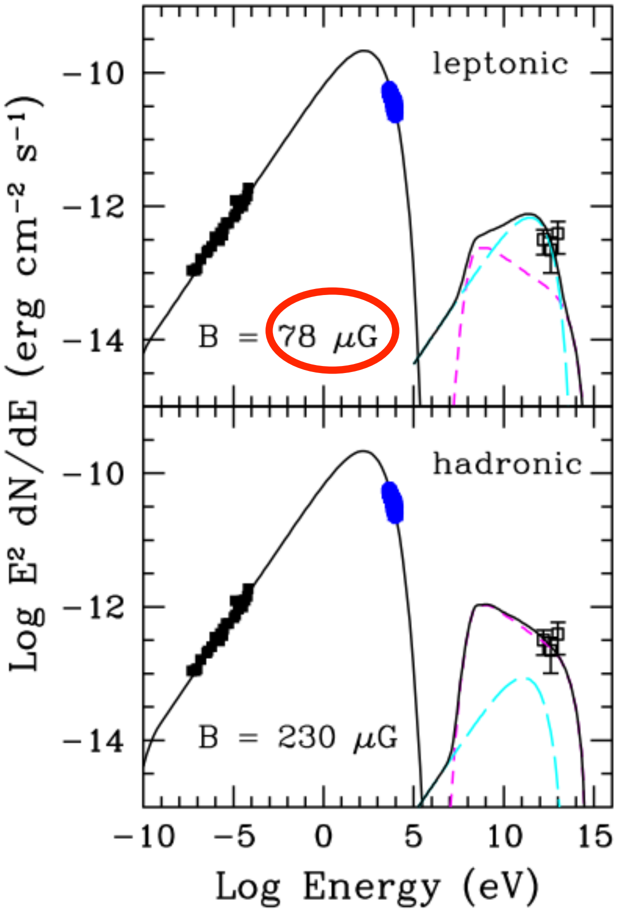


- TeV emission
  - → compatible with a point source.
  - → is offset from center of SNR (0.04 degree).
  - → is displaced towards the CO cloud (2 σ).



Supernova Remnants – Tycho's

- Unveiling a hadronic accelerator?

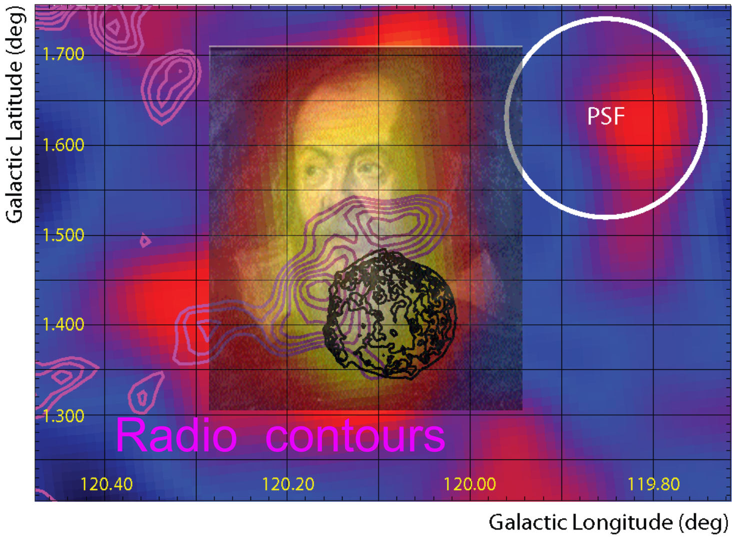


IC emission (CMB+synch.)

π decay

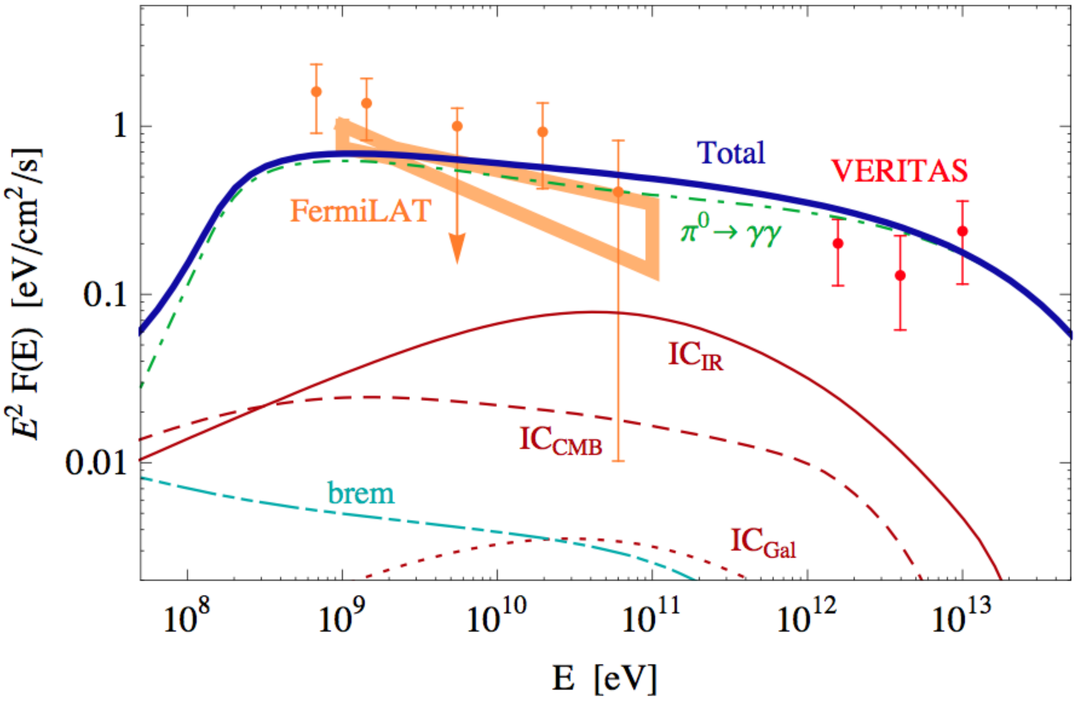
- energy spectrum hard.
- simple leptonic+hadronic model.
- radio/X-ray for normalization.
- IC(CMB) & pion decay.
- leptonic → 78 uG
- hadronic → 230 uG

  → **magnetic field amplification in shocks!**



Supernova Remnants – Tycho’s

- Unveiling **a hadronic** accelerator?



Morlino & Caprioli, arXiv:1105:6342v1

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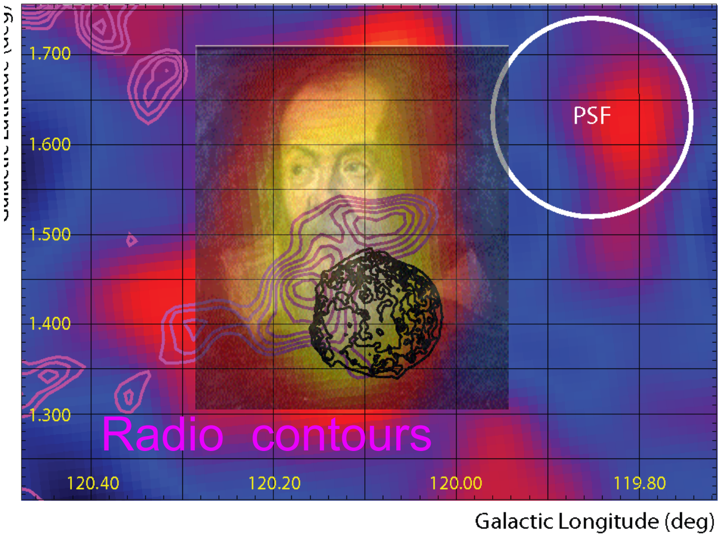
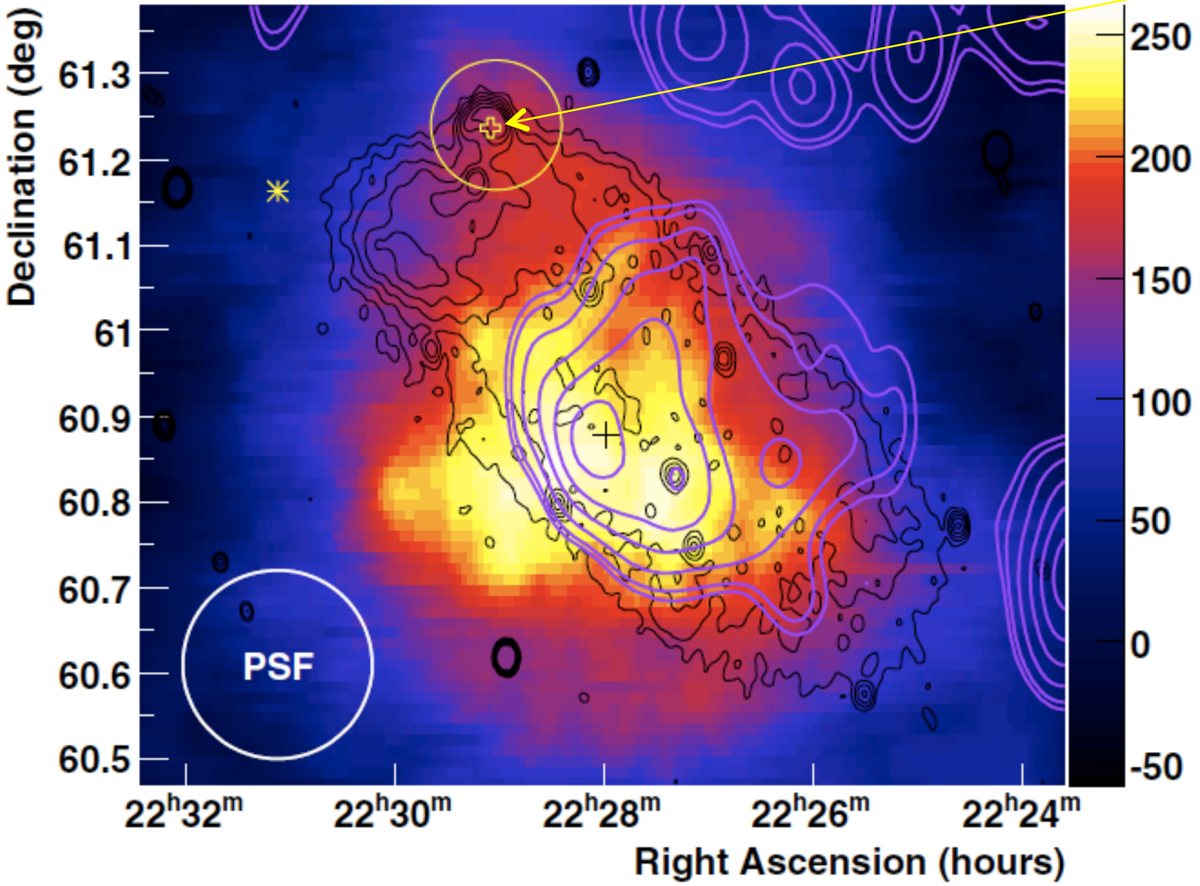


G106.3+2.7 / Boomerang

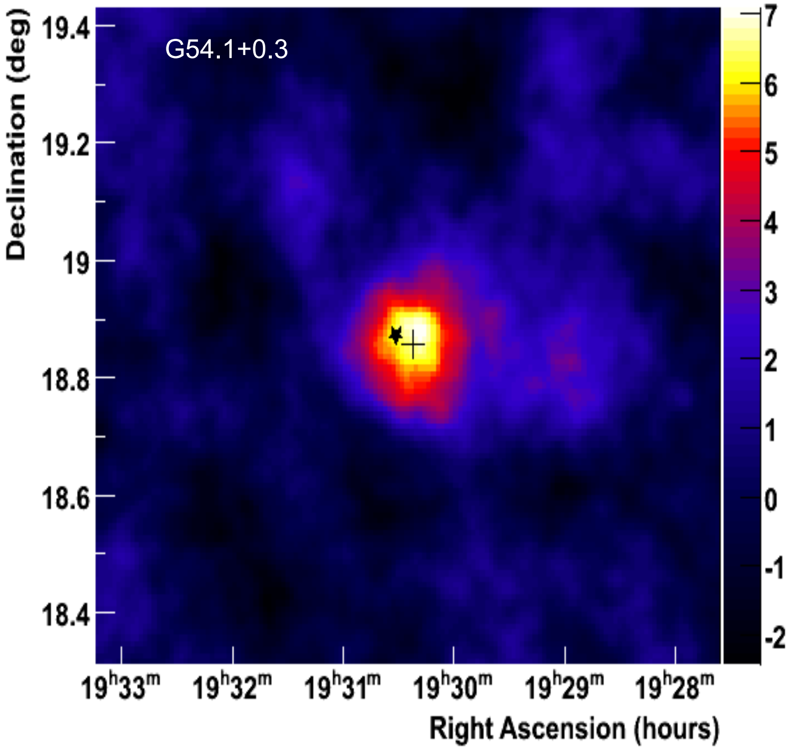


PSR J2229.0+6114
G106.6+2.9 PWN
(Boomerang)

- pulsar PSR J2229+6114.
- high spin down ~ 10^{37} ergs/s.
- **Milagro detection ~ 1° size**.
- VERITAS image:
  ~ **0.6° x 0.4°**
- coincides with MC emission.
- hard TeV spectrum!
- VERITAS + Milagro (35 TeV)
  may indicate hadronic accel.

radio contours (115 GHz; ^{12}C line)

Galactic Tevatrons & Pevatrons



- SNR G54.1+0.3 is a PWN.
- young pulsar PSR J1930+1852.
- age ~ 2,900 yr.
- high spin down ~ 10^{37} ergs/s.
- TeV emission co-located with X-ray and radio PWN and a molecular cloud.
- compactness due to young age and possibly symmetrical expansion of the supernova!
- X-ray/TeV flux lowest among all PWN
  → particle dominated

$$-\left(\frac{dE}{dt}\right)_{IC} = \sigma_T c U_{rad}\left(\frac{v^2}{c^2}\right)\gamma^2$$

$$-\left(\frac{dE}{dt}\right)_{synch.} = \sigma_T c U_{mag}\gamma^2$$

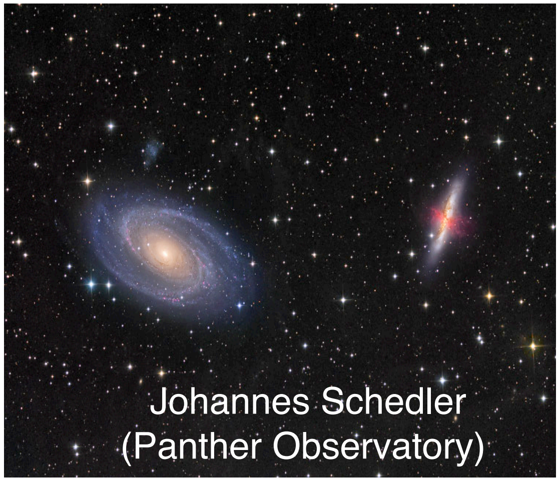
Cosmic Ray Sources in bulk: Discovery of TeV Emission from the first starburst galaxy!

Starburst Galaxies: M82

- M82 is the prototype starburst galaxy
- Distance ~ 3.9 Mpc
- Diameter ~ 1’ (0.016^{o})
- SMBH ~ 3×10^{7} M_{solar} (no activity)
- Interacts with group of galaxies (M81)
- Hubble ST: 200 massive star clusters
- High supernova rate ~ 0.1 - 0.3 per year
- High gas density 150 particles/cm^{3}

-> excellent candidate for
cosmic ray interactions &
gamma ray emission.

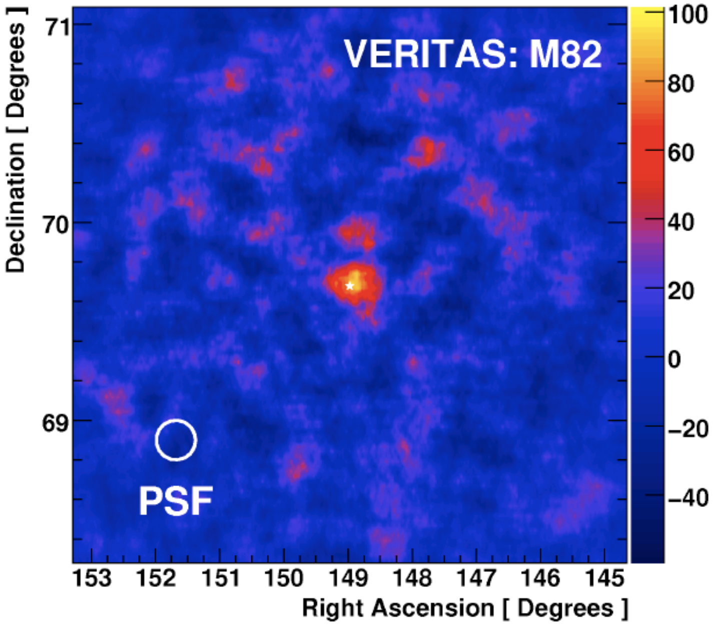
-> probing paradigm that SNRs
are the origin of C.R.s.

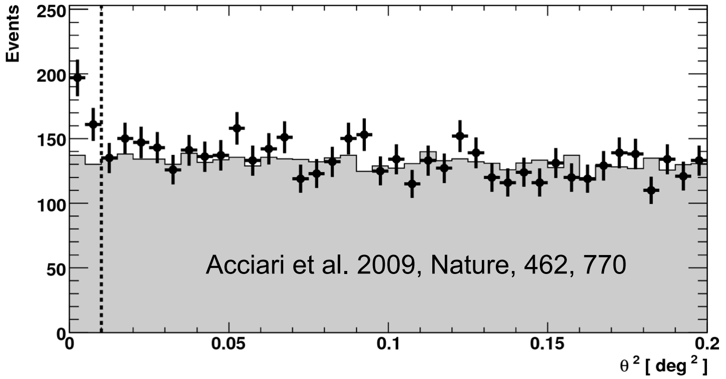

Johannes Schedler
(Panther Observatory)


NASA, ESA, The Hubble
Heritage Team, (STScI / AURA)

Starburst Galaxies: M82

- VERITAS data ~ 137 h livetime
  - only astronomical dark time, large zenith angle ~ 39°
  - increased E_{thres}
  - bad weather removed
- Standard VERITAS analysis (“hard cuts”)
  - Et_{hres} ~ 700 GeV
  - cuts a priori optimized on Crab
  - hard spectrum expected from theory
  - but we count for 3 trials (standard, hard & soft)
- Point-like excess of 91 γ; 5.0 σ (pre-trial)
  - 3 independent analyses
  - many systematic checks performed
- Post-trial: 4.8 σ
  - steady signal
  - excess consistent with instrument PSF
- M82 weakest source ever detected @ VHE
  - 0.9% of Crab
  - Gamma-ray rate: 0.7 γ/hour

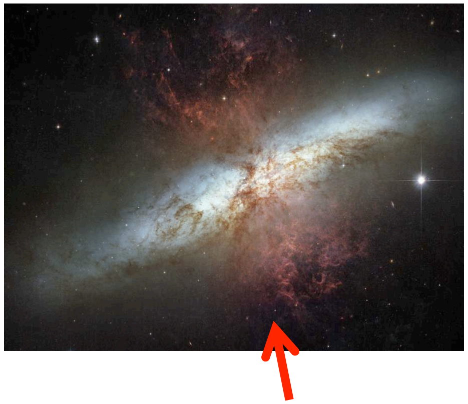


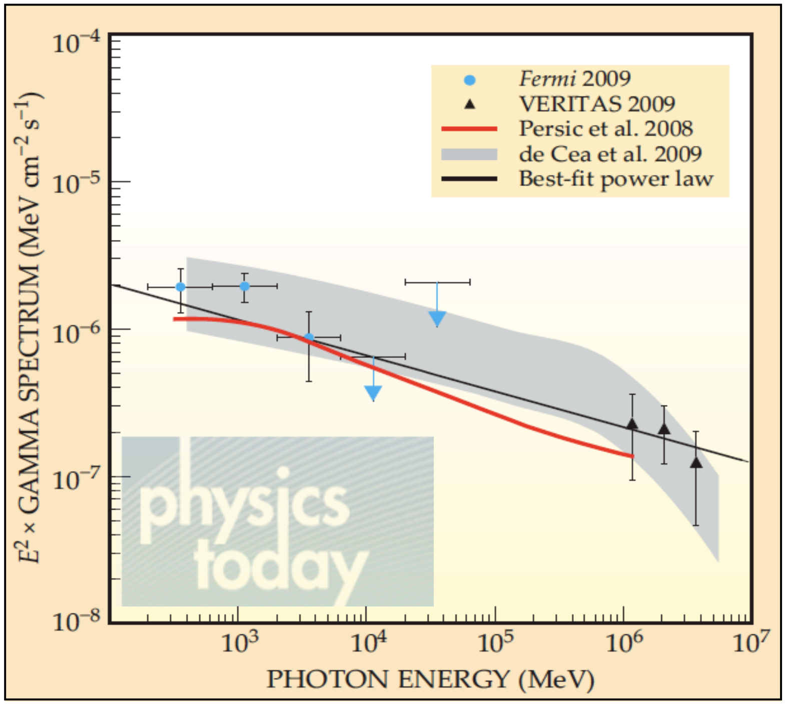


Acciari et al. 2009, Nature, 462, 770

Cosmic Ray Origin – M82

Connection between star formation & acceleration of hadronic cosmic particles





Acciari et al. (VERITAS Collab.), Nature, 462, 770 (2009)
Abdo et al. (Fermi Collab.), arXiv:0911.5327
B. Schwarzschild, Physics Today, vol. 63, p 13 (2010)

- Starburst galaxy M82 (nearby Milky Way) exhibits a glut of **supernova** remnants (**accelerator providing beam …**)!
- Combined with high **gas** density (**… on target**).
- M82 provides the "perfect storm" for a high yield of GeV – TeV emission.
- Strong evidence that **supernova remnants** accelerate **protons**!

Key Science Questions

(1) Galactic Tevatrons and Pevatrons

(2) Black Holes

(3) Cosmology

(4) Particle Physics and Fundamental Laws

The Role of Pulsars

(1) **Galactic Tevatrons and Pevatrons**

(2) Black Holes

(3) Cosmology

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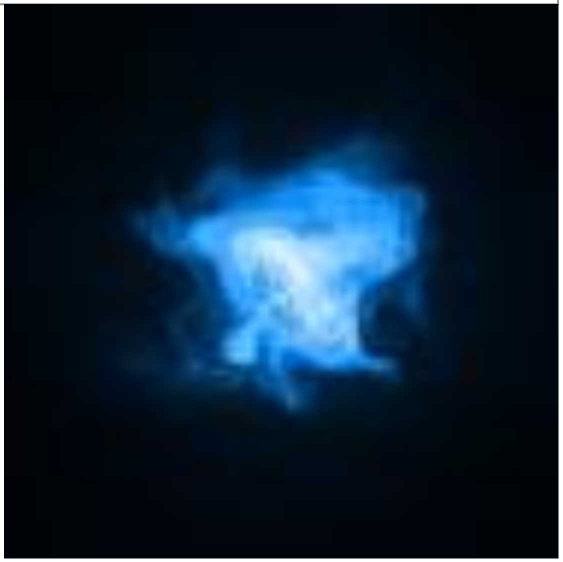
The Crab Pulsar



- at GeV energies ~ 100 pulsars are known γ-ray emitters
- generally break at 0.1 – few GeV
- exponential cutoff (curvature radiation, outer gap model)

- Crab nebula one of the most powerful pulsars
- detected by Fermi up to ~ 15 GeV, by MAGIC at 25 GeV
- spectral cutoff at 5.8 GeV

- Detection above 100 GeV was pursued for decades, ‘Holy Grail of TeV astronomy’ T.C. Weekes

- VERITAS observations: 107 hours
- energy threshold 120 GeV
- results checked by independent software package

The Crab Pulsar

Wait for publiction

The Crab Pulsar

Wait for publiction

Key Science Questions

Galactic Tevatrons and Pevatrons

→ strong evidence for hadronic acceleration.

→ strong evidence for magnetic field amplification.

→ SNR **maybe** efficient particle accelerators.

Can SNRs explain the bulk of galactic CRs?

→ find a few SNRs with spectrum up to ~ 100 TeV.

→ spectral cutoff should depend on age.

→ molecular clouds offer opportunity to probe C.R. interactions!

→ starburst galaxies: correlate SN rate x gas density with γ-ray flux.

Key Science Questions

(1) Galactic Tevatrons and Pevatrons

(2) **Black Holes**

(3) Cosmology

(4) Particle Physics and Fundamental Laws

Supermassive Black Holes

- “Standard Model” of AGN Physics
  - SMBH
  - Accretion disk
  - Relativistic jet
- Point of view changes appearance
  - Blazar
  - Quasar
  - Radio galaxy
- Physics questions
  - Black hole - jet - connection
  - Acceleration mechanism (Where?)
  - Emission mechanism
  - Maximum energy
  - hadrons and leptons?
  - UHE cosmic ray connection?
  - Axion emission?

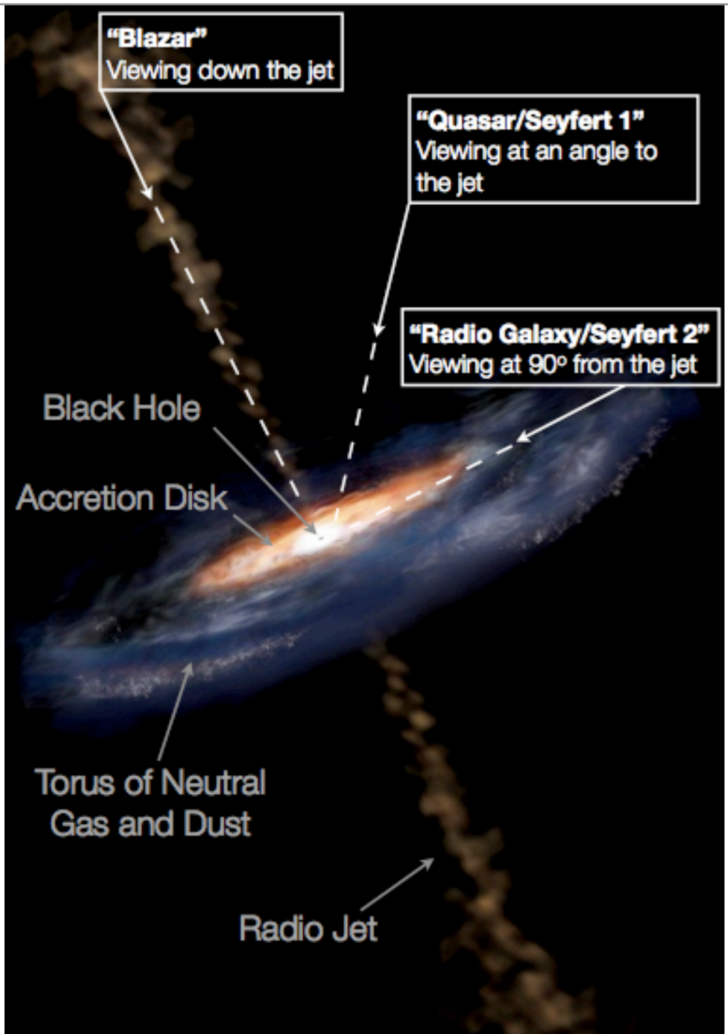
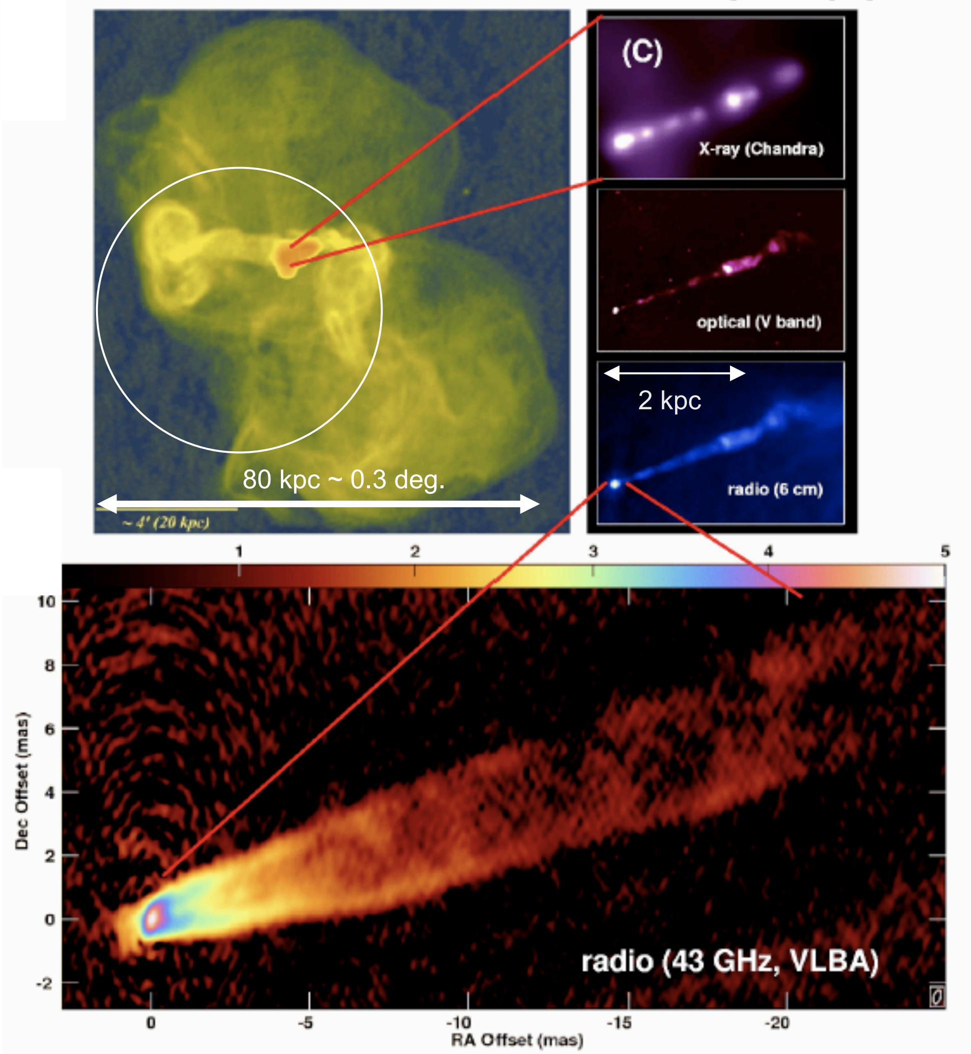
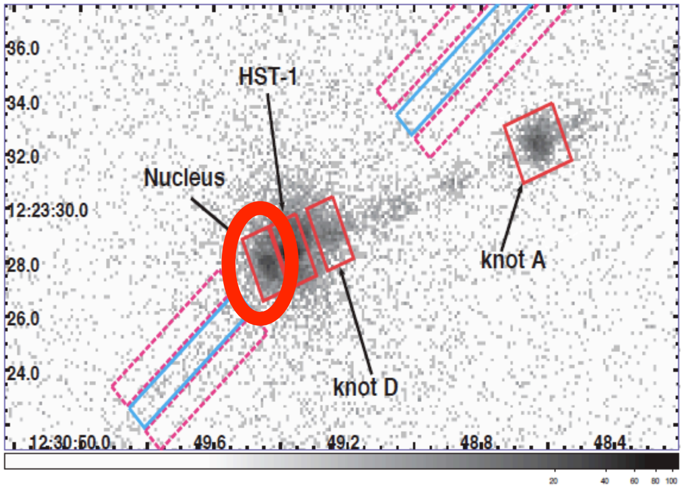


Image: Aurore Simonnet, Sonoma State University
Illustration: Robert Naeye, NASA GSFC

Radio Galaxies: M87

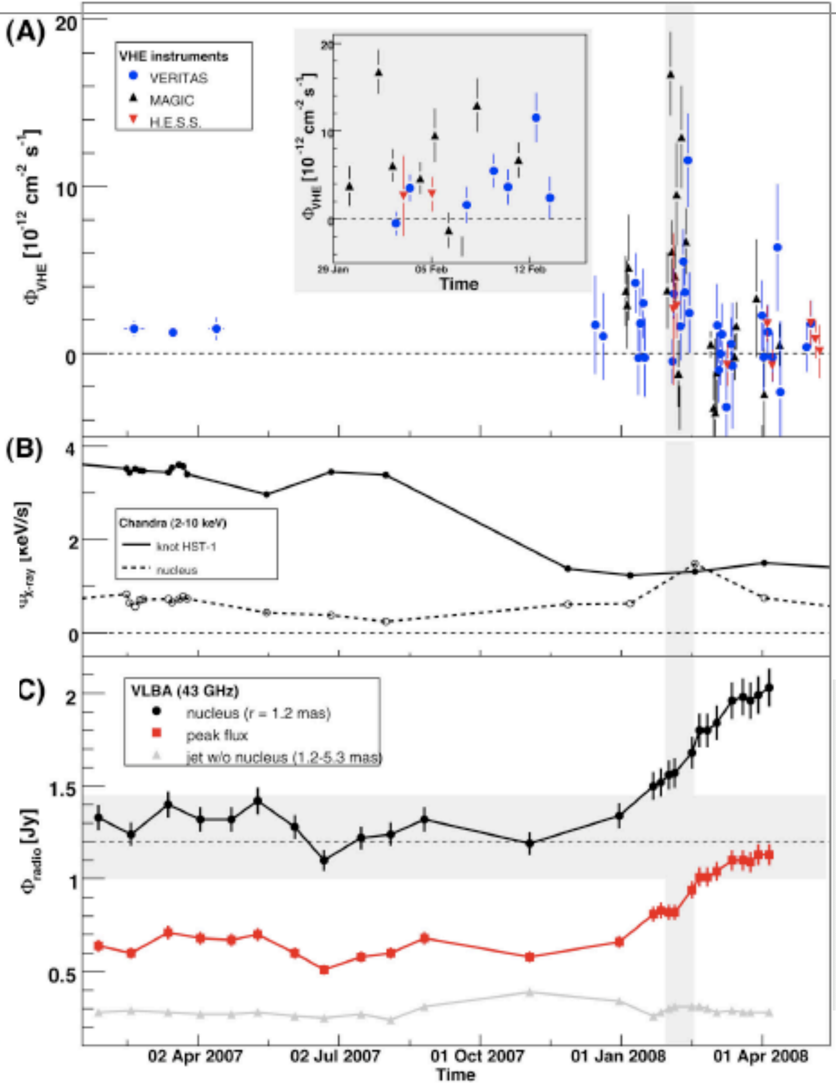


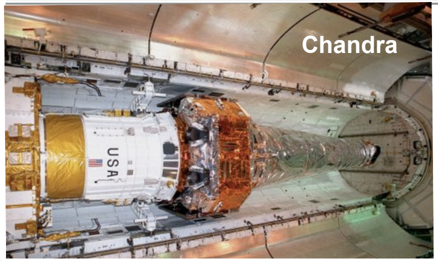
- Nearby giant radio galaxy, 16 Mpc
  SMBH ~ 6 x 10^9 M_{sun}
  Jet angle ~ 15 - 30 deg. (not a blazar)
  resolved jet (radio, optical X-ray)
  variable emission
- TeV emission
  Evidence in Hegra data
  Confirmed by HESS, MAGIC, VERITAS
  angular resolution of TeV instruments 0.1 deg.
  TeV emission from where?

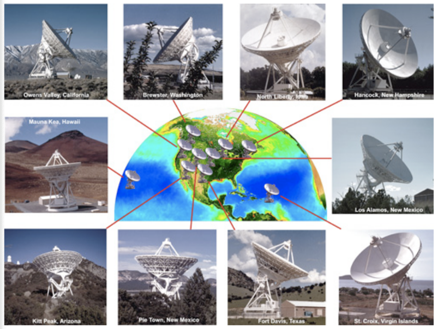


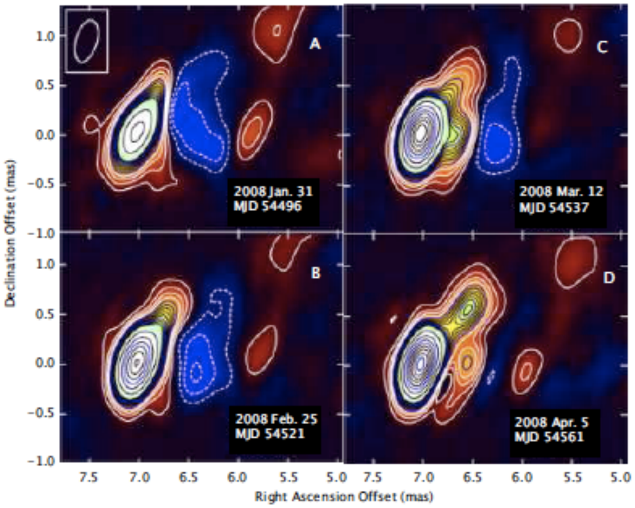
Radio Galaxies: M87

- **Joint TeV campaign:**
  MAGIC, HESS, VERITAS
  Jan. - May 2008
  95 hrs. combined
  MAGIC ToO
- **VLBA movies**
  14 shots in 2008, every 5 days
  ang. resolution 0.2 x 0.4 mas









Radio Galaxies: M87

- Picture?

radio, X-ray and TeV flare are likely related ($P < 0.5\%$).

TeV flares on time scales of 1 day: ~ few R_s

X-ray quiet at HST-1, but shows a historically high state for core.

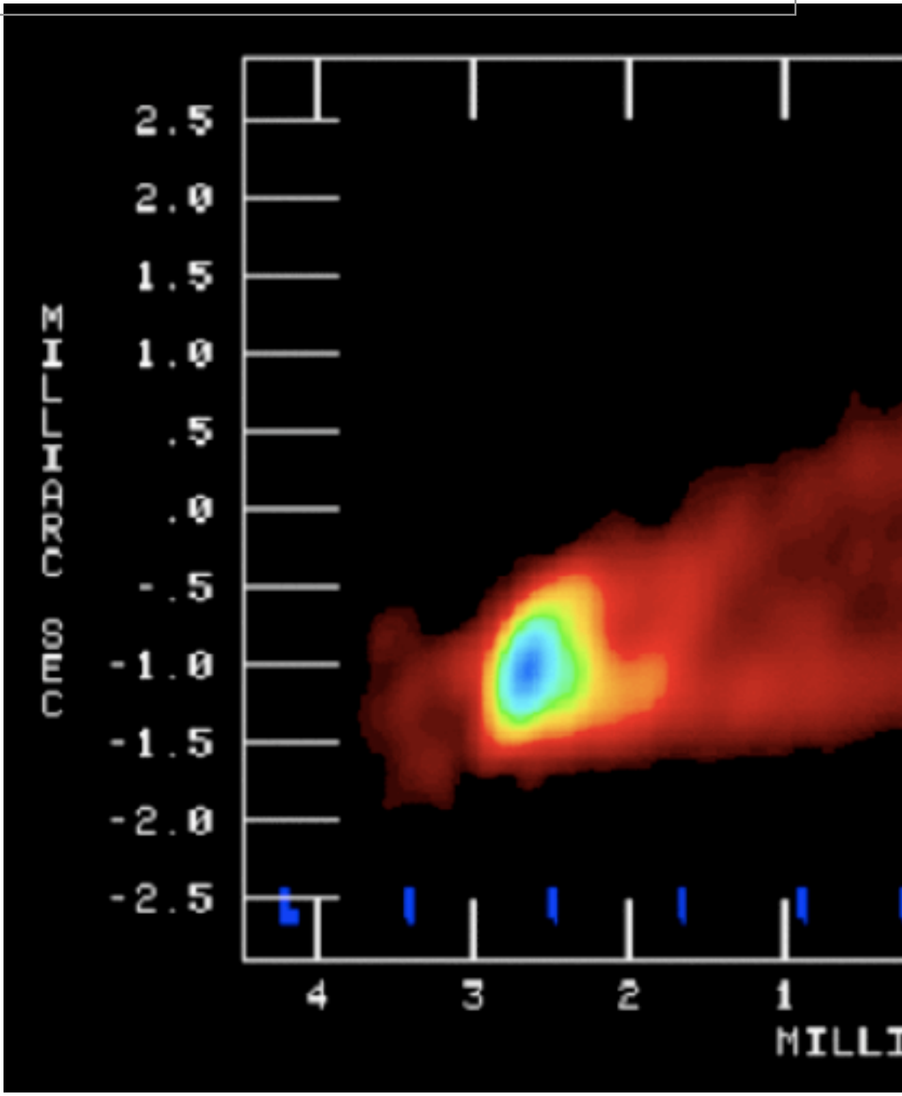
VLBA flare at core (**30 x 60 R_s**), but slow rise.

- What does this mean?

Model:

- we have observed plasma traveling down the jet.
- transparent at TeV and X-ray energies.
- region is initially opaque in radio (synchr. Self-absorption).
  and smoothens the radio flare and a delay in peak.
- TeV/X-ray emission region well within radio blob.

- TeV emission produced close to the SMBH?



Acciari et al. 2009 (VERITAS Collaboration, VLBA 43 GHz Monitoring team,
Hess Collaboration, MAGC Collaboration), Science DOI: 10.1126/science.1175406

Key Science Questions

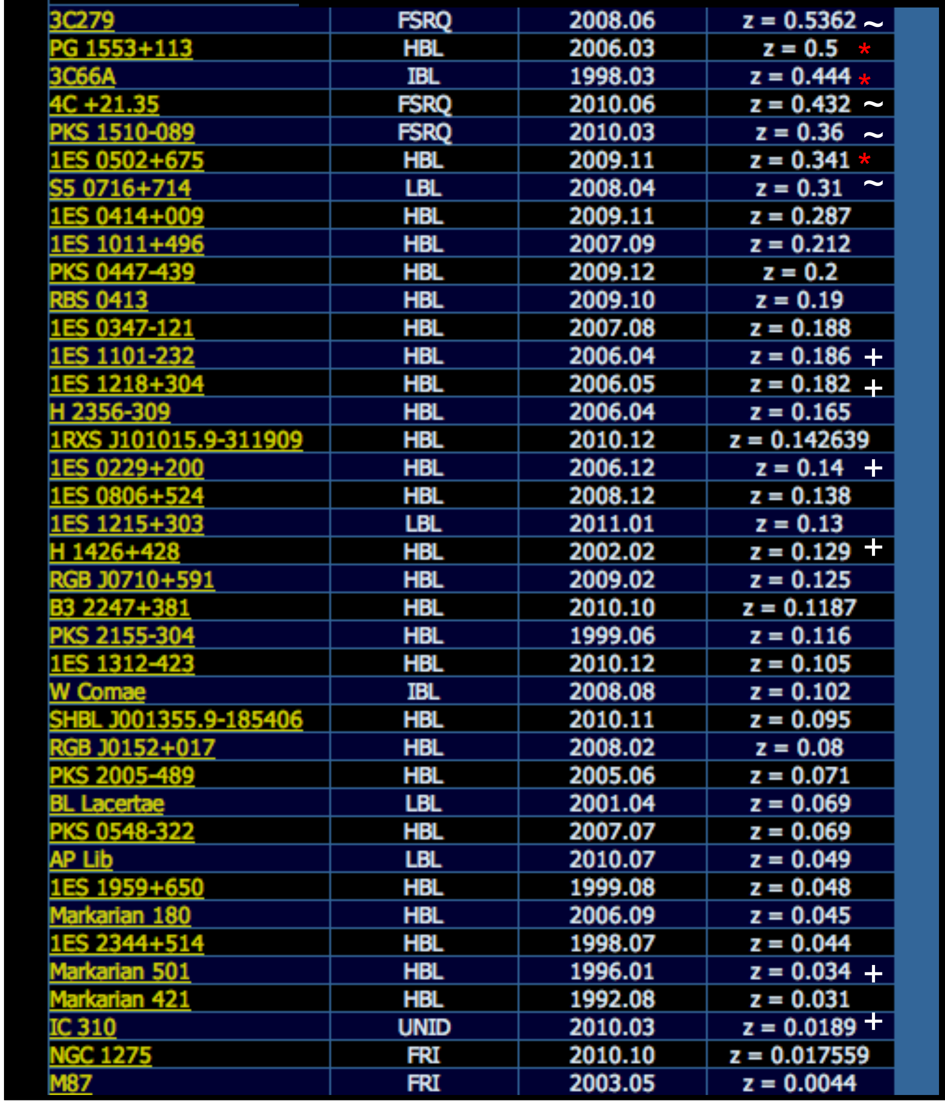
(1) Galactic Tevatrons and Pevatrons

(2) Black Holes

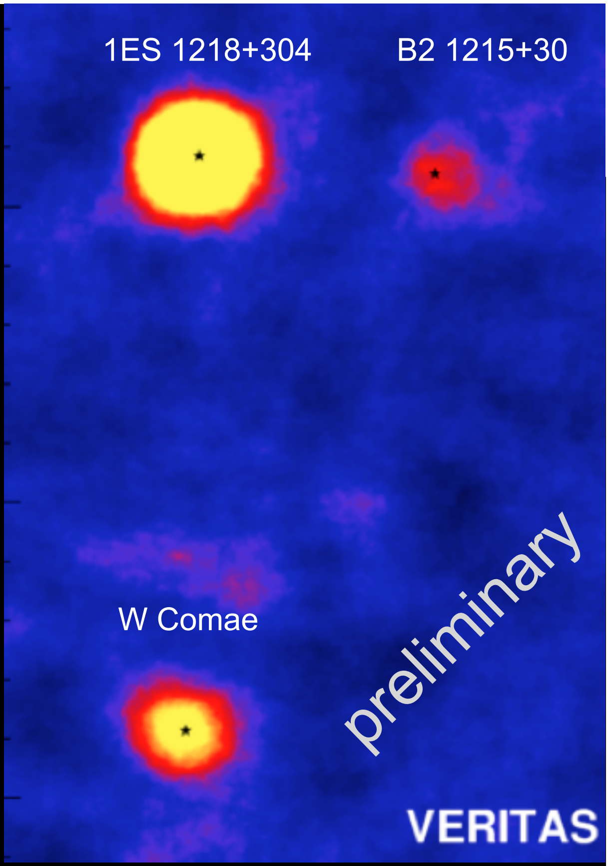
(3) **Cosmology**

(4) Particle Physics and Fundamental Laws

TeV AGN ``directory''



3C279	FSRQ	2008.06	z = 0.5362 ~
PG 1553+113	HBL	2006.03	z = 0.5 *
3C66A	IBL	1998.03	z = 0.444 *
4C +21.35	FSRQ	2010.06	z = 0.432 ~
PKS 1510-089	FSRQ	2010.03	z = 0.36 ~
1ES 0502+675	HBL	2009.11	z = 0.341 *
S5 0716+714	LBL	2008.04	z = 0.31 ~
1ES 0414+009	HBL	2009.11	z = 0.287
1ES 1011+496	HBL	2007.09	z = 0.212
PKS 0447-439	HBL	2009.12	z = 0.2
RBS 0413	HBL	2009.10	z = 0.19
1ES 0347-121	HBL	2007.08	z = 0.188
1ES 1101-232	HBL	2006.04	z = 0.186 +
1ES 1218+304	HBL	2006.05	z = 0.182 +
H 2356-309	HBL	2006.04	z = 0.165
1RXS J101015.9-311909	HBL	2010.12	z = 0.142639
1ES 0229+200	HBL	2006.12	z = 0.14 +
1ES 0806+524	HBL	2008.12	z = 0.138
1ES 1215+303	LBL	2011.01	z = 0.13
H 1426+428	HBL	2002.02	z = 0.129 +
RGB J0710+591	HBL	2009.02	z = 0.125
B3 2247+381	HBL	2010.10	z = 0.1187
PKS 2155-304	HBL	1999.06	z = 0.116
1ES 1312-423	HBL	2010.12	z = 0.105
W Comae	IBL	2008.08	z = 0.102
SHBL J001355.9-185406	HBL	2010.11	z = 0.095
RGB J0152+017	HBL	2008.02	z = 0.08
PKS 2005-489	HBL	2005.06	z = 0.071
BL Lacertae	LBL	2001.04	z = 0.069
PKS 0548-322	HBL	2007.07	z = 0.069
AP Lib	LBL	2010.07	z = 0.049
1ES 1959+650	HBL	1999.08	z = 0.048
Markarian 180	HBL	2006.09	z = 0.045
1ES 2344+514	HBL	1998.07	z = 0.044
Markarian 501	HBL	1996.01	z = 0.034 +
Markarian 421	HBL	1992.08	z = 0.031
IC 310	UNID	2010.03	z = 0.0189 +
NGC 1275	FRI	2010.10	z = 0.017559
M87	FRI	2003.05	z = 0.0044

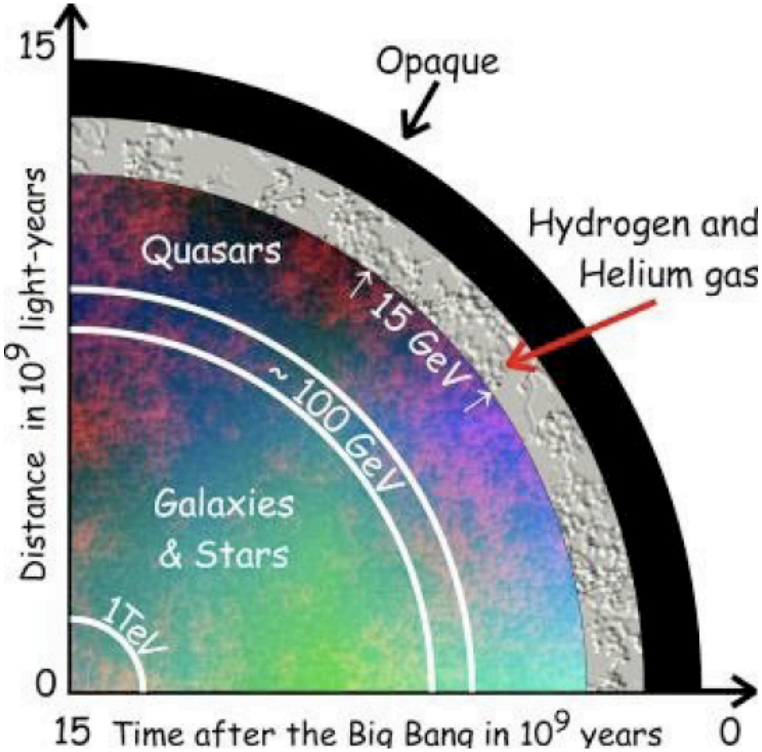


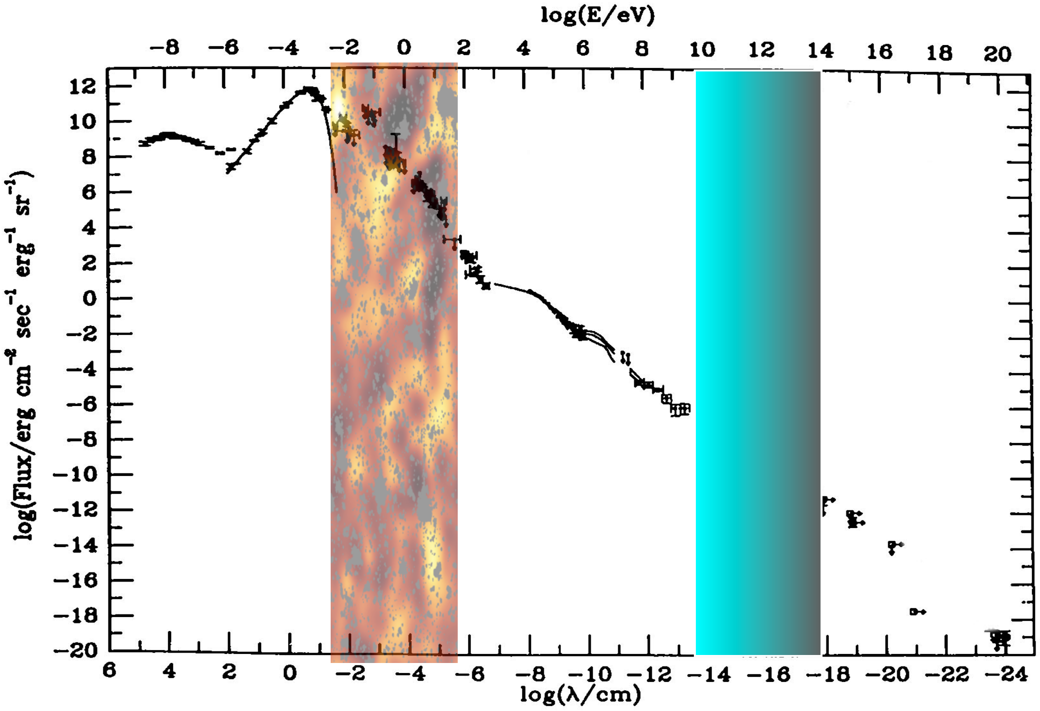
* redshifts uncertain

~ Soft - low E spectra

\+ Hard TeV spectra

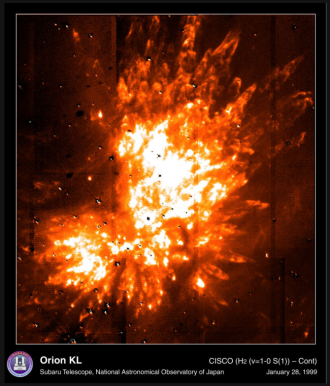
Extragalactic Background Light



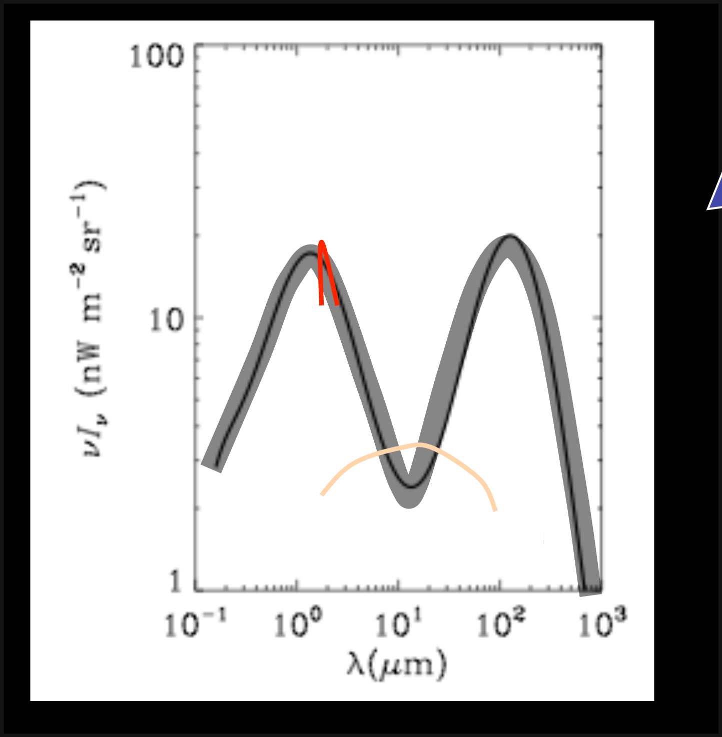


$$\gamma_{TeV} + \gamma_{soft} \rightarrow e^+ + e^-$$

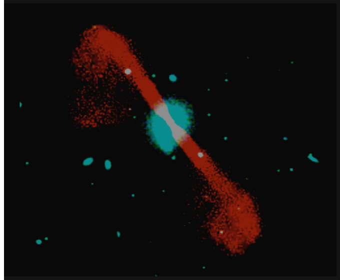
Extragalactic Background Light



Nuclear:
star
formation
z < 5



Population III stars?
(rapid)
z ~ 7-30



Accretion:
AGNs
z < 5

Exotic contribution?
Decay z ~ ?

EBL – why do we care?

EBL - a repository of all radiative energy dissipation processes since the time of decoupling.

The EBL contains astrophysical contributions;

star/galaxy formation
accretion onto supermassive black holes
decay of relic particles produced in the early universe

EBL radiation field consists of diffuse ultraviolet – optical – infrared light;

provide information about particle physics processes otherwise not detectable

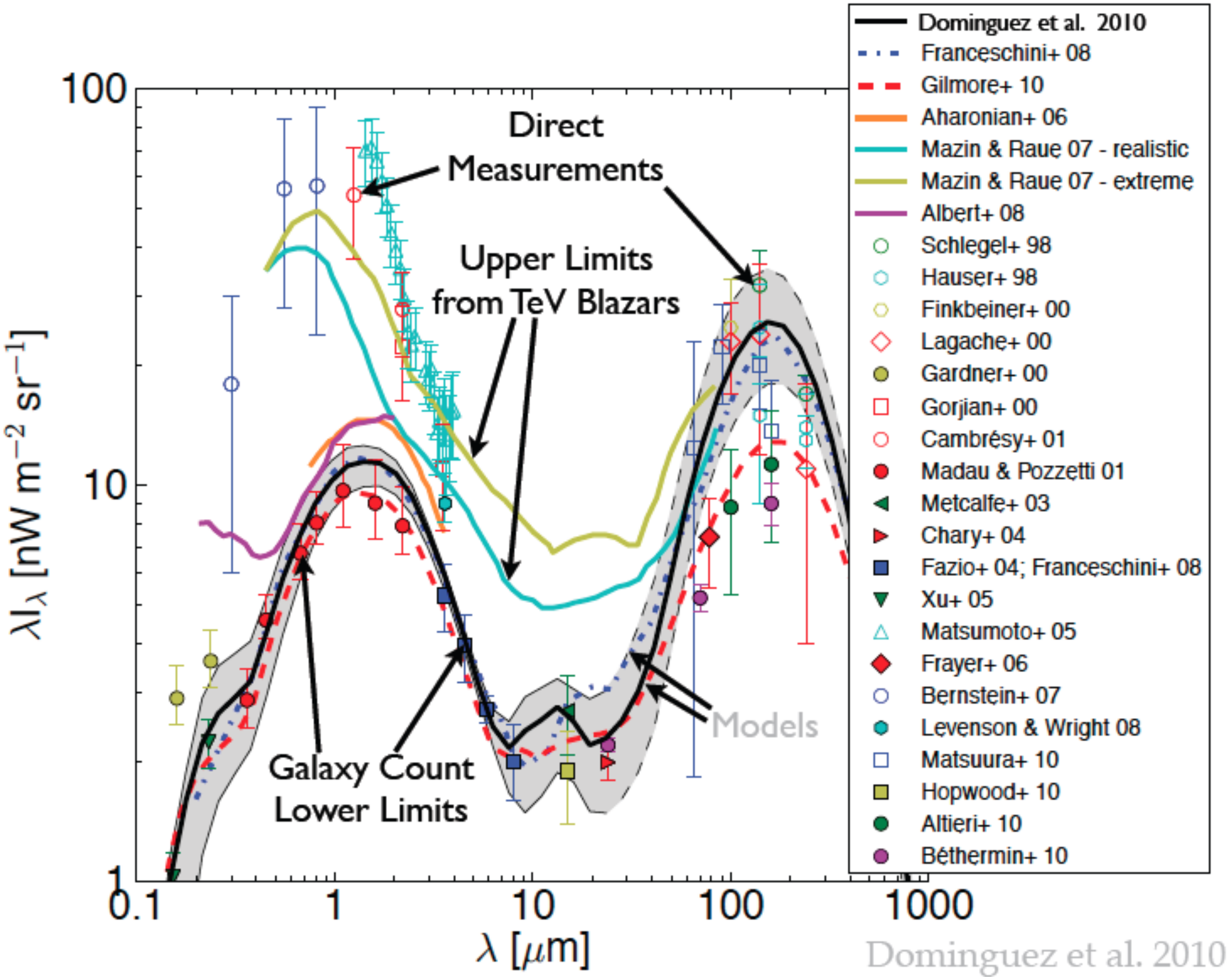
Future view:

direct observations with the JWST will likely (?) detect the EBL in the optical to near-IR
mid-IR likely to remain elusive due to strong foreground from zodiacal light.
VHE γ-ray observations do not suffer from the same limitations.
VHE γ-ray observations cover the entire range of UV – optical – infrared light.

γ-ray technique is also unique;

allows one to **probe the EBL at different redshifts** (pairproduction absorption effect can be measured as a function of redshift/epoch) → **EBL evolution** whereas direct measurements always just measure the local cumulative density from all epochs combined.

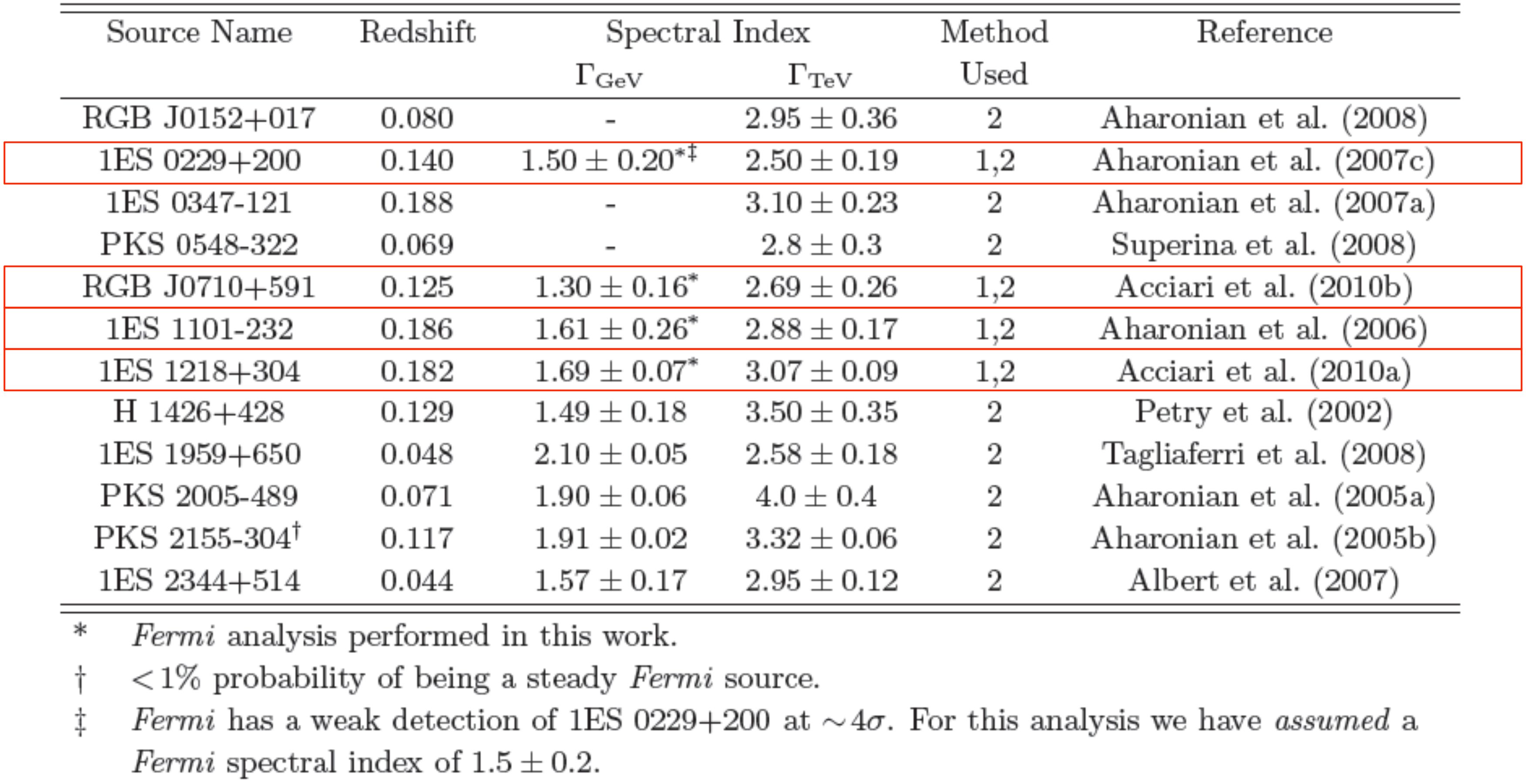
EBL Models – Data



Dominguez et al. 2010

Pre-Fermi/VERITAS

Sample Blazars



Source Name	Redshift	Spectral Index $\Gamma_{\rm GeV}$	Spectral Index $\Gamma_{\rm TeV}$	Method Used	Reference
RGB J0152+017	0.080	-	2.95 ± 0.36	2	Aharonian et al. (2008)
1ES 0229+200	0.140	$1.50 \pm 0.20^{*\ddagger}$	2.50 ± 0.19	1,2	Aharonian et al. (2007c)
1ES 0347-121	0.188	-	3.10 ± 0.23	2	Aharonian et al. (2007a)
PKS 0548-322	0.069	-	2.8 ± 0.3	2	Superina et al. (2008)
RGB J0710+591	0.125	$1.30 \pm 0.16^{*}$	2.69 ± 0.26	1,2	Acciari et al. (2010b)
1ES 1101-232	0.186	$1.61 \pm 0.26^{*}$	2.88 ± 0.17	1,2	Aharonian et al. (2006)
1ES 1218+304	0.182	$1.69 \pm 0.07^{*}$	3.07 ± 0.09	1,2	Acciari et al. (2010a)
H 1426+428	0.129	1.49 ± 0.18	3.50 ± 0.35	2	Petry et al. (2002)
1ES 1959+650	0.048	2.10 ± 0.05	2.58 ± 0.18	2	Tagliaferri et al. (2008)
PKS 2005-489	0.071	1.90 ± 0.06	4.0 ± 0.4	2	Aharonian et al. (2005a)
PKS 2155-304†	0.117	1.91 ± 0.02	3.32 ± 0.06	2	Aharonian et al. (2005b)
1ES 2344+514	0.044	1.57 ± 0.17	2.95 ± 0.12	2	Albert et al. (2007)

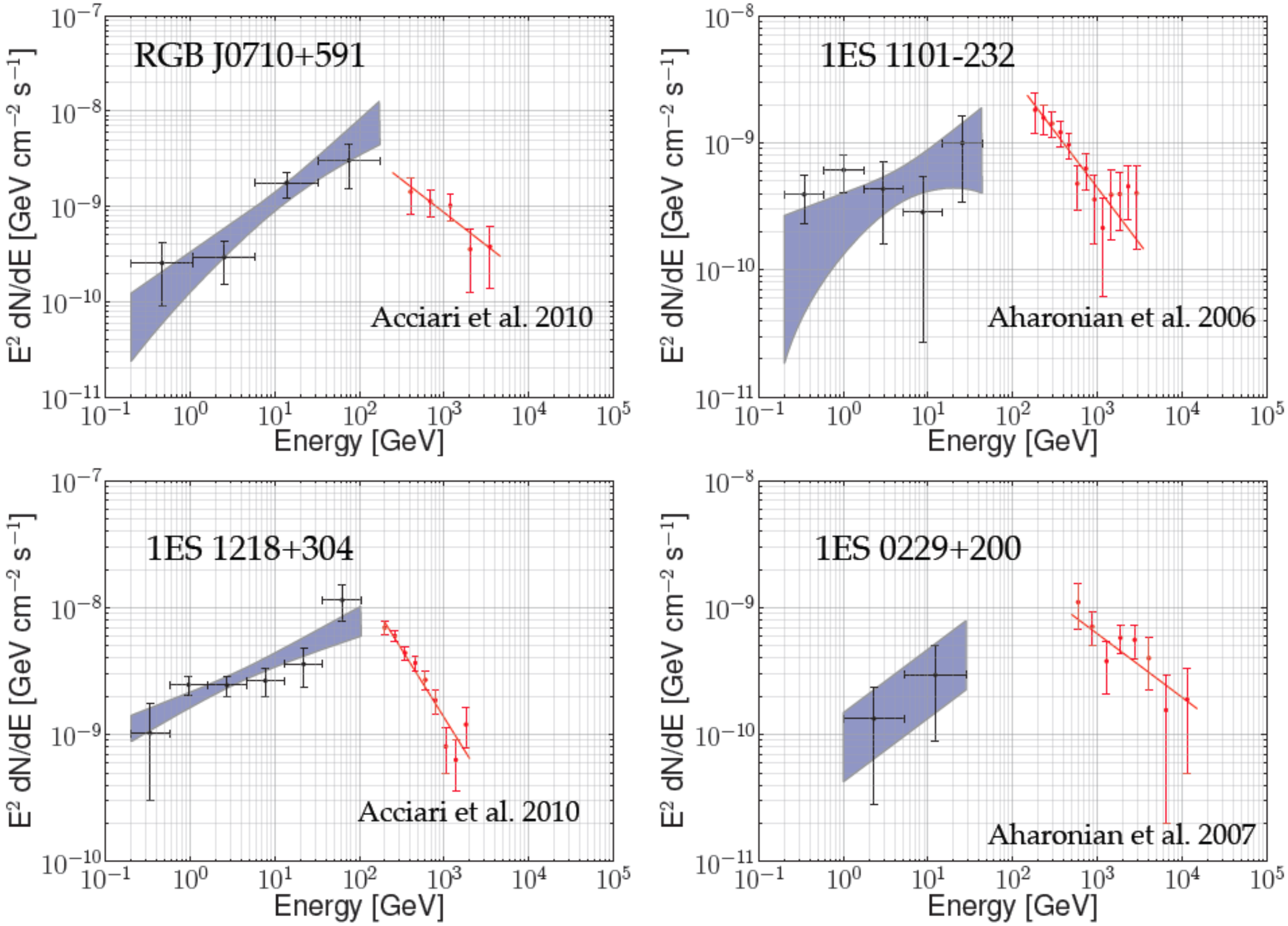
* *Fermi* analysis performed in this work.

† $<1\%$ probability of being a steady *Fermi* source.

‡ *Fermi* has a weak detection of 1ES 0229+200 at $\sim 4\sigma$. For this analysis we have *assumed* a *Fermi* spectral index of 1.5 ± 0.2.

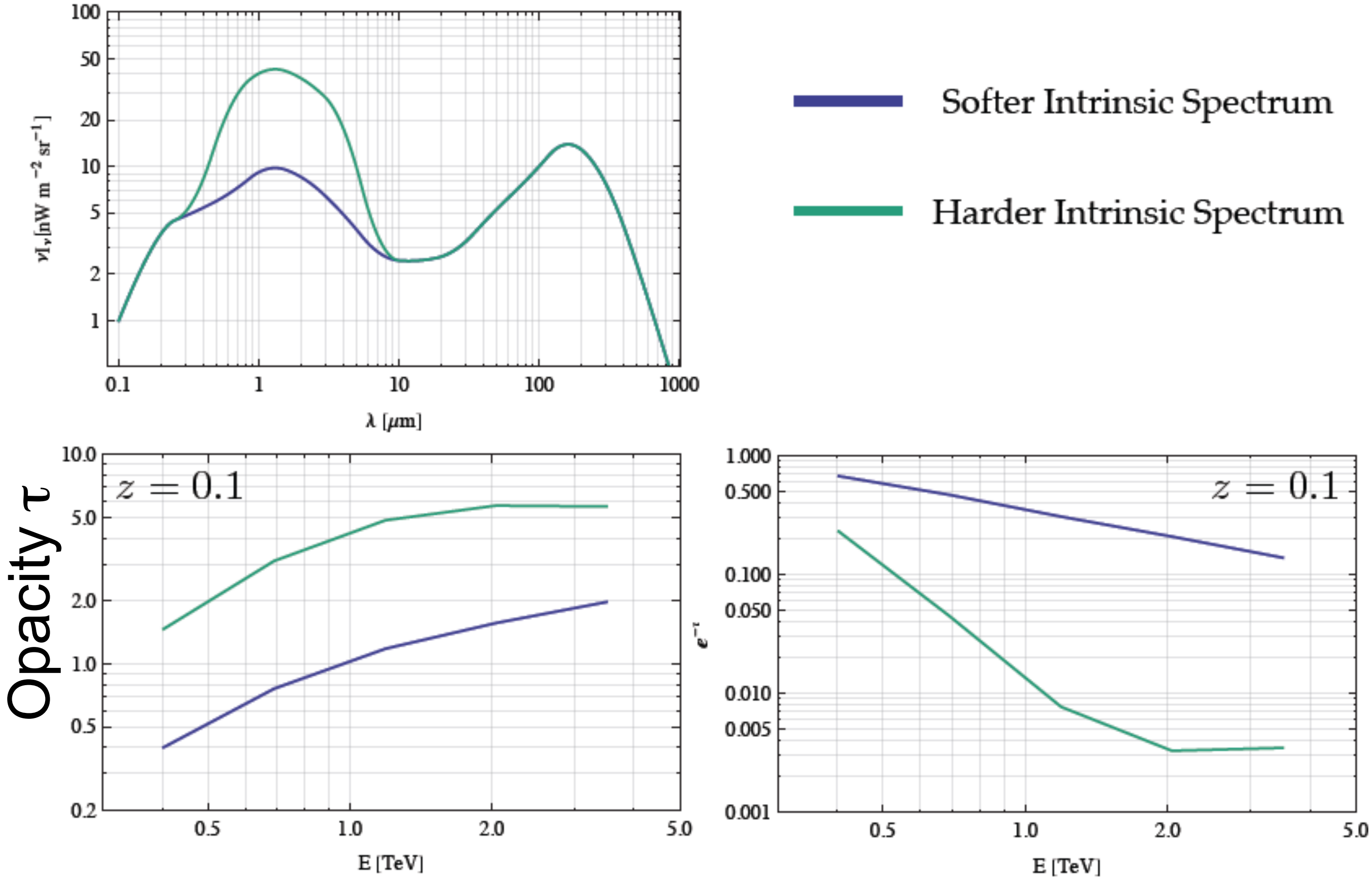
M. Orr, FK, E. Dwek, ApJ, 733, 77 (2011)

Hard Spectrum Blazars

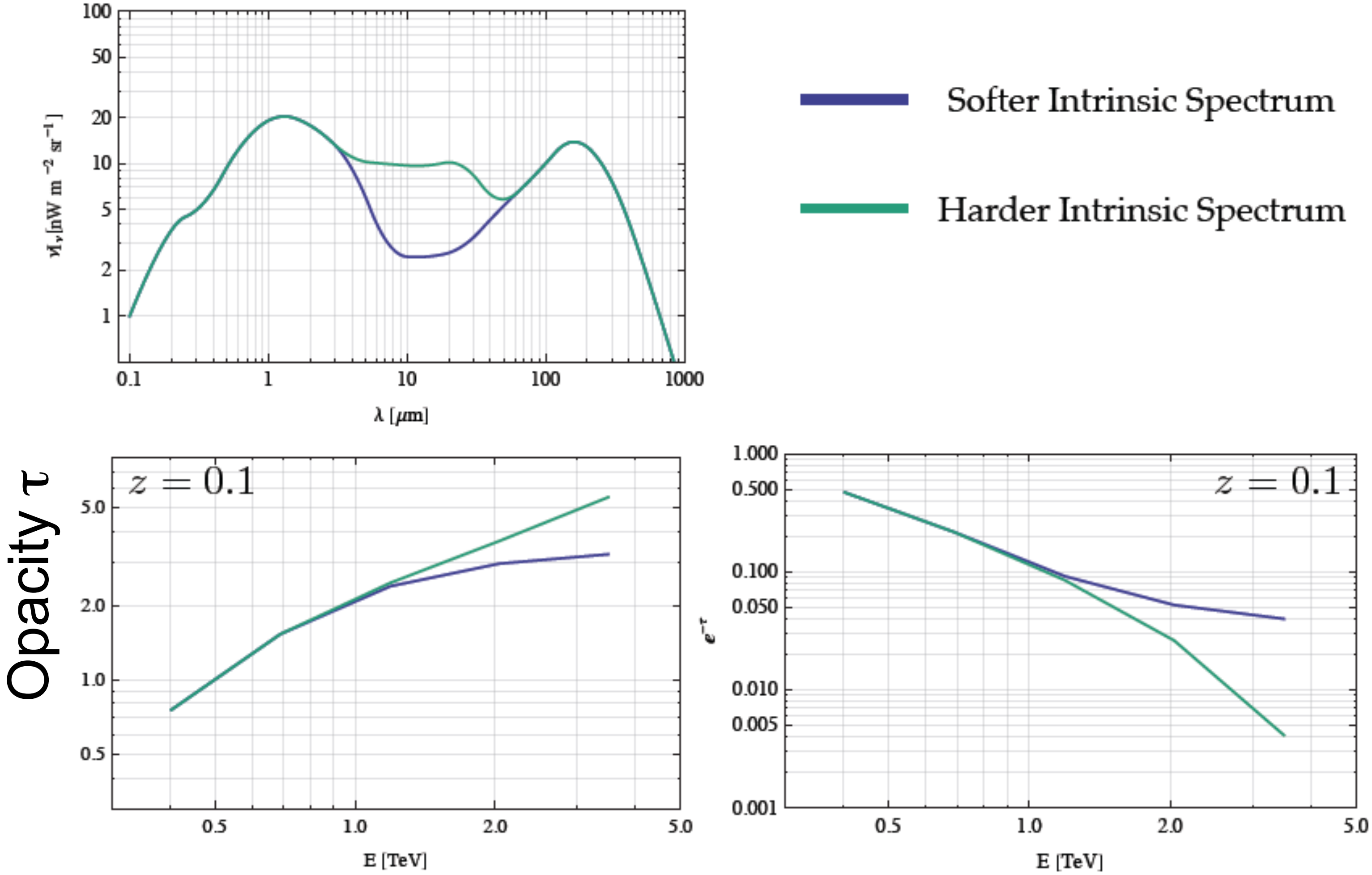


Fermi + IACTs

Method 1


100
50
20
10
5
2
1
νI_ν [nW m^{-2} sr^{-1}]
0.1
1
10
100
1000
λ [μm]
Softer Intrinsic Spectrum
Harder Intrinsic Spectrum
Opacity τ
10.0
5.0
2.0
1.0
0.5
0.2
$z = 0.1$
0.5
1.0
2.0
5.0
E [TeV]
1.000
0.500
0.100
0.050
0.010
0.005
0.001
$e^{-\tau}$
$z = 0.1$
0.5
1.0
2.0
5.0
E [TeV]

Method 2

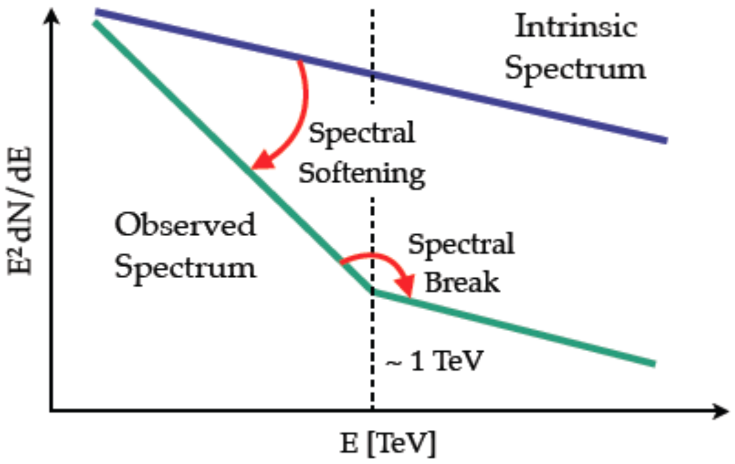

100
50
20
10
5
2
1
νI_ν [nW m^{-2} sr^{-1}]
0.1
1
10
100
1000
λ [μm]
Softer Intrinsic Spectrum
Harder Intrinsic Spectrum
Opacity τ
$z = 0.1$
5.0
2.0
1.0
0.5
0.5
1.0
2.0
5.0
E [TeV]
1.000
0.500
0.100
0.050
0.010
0.005
0.001
$e^{-\tau}$
$z = 0.1$
0.5
1.0
2.0
5.0
E [TeV]

Method 1 + Method 2

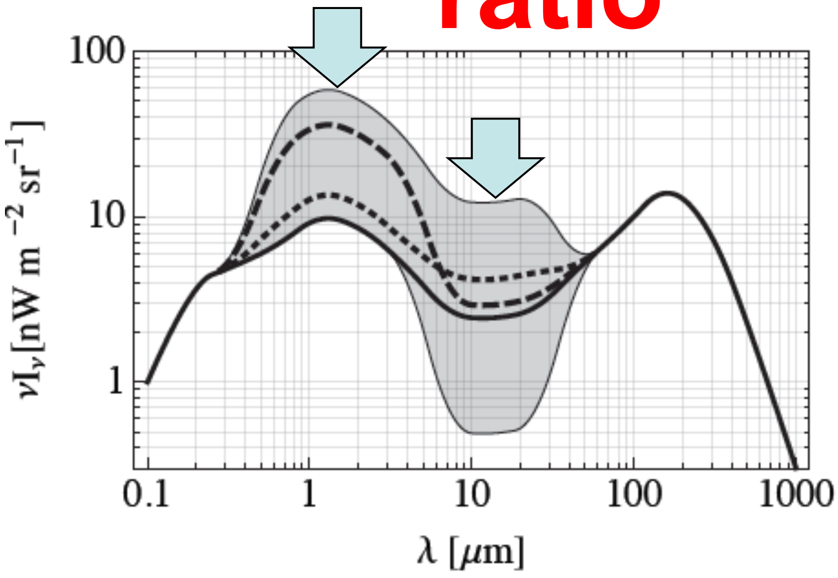
EBL Absorption

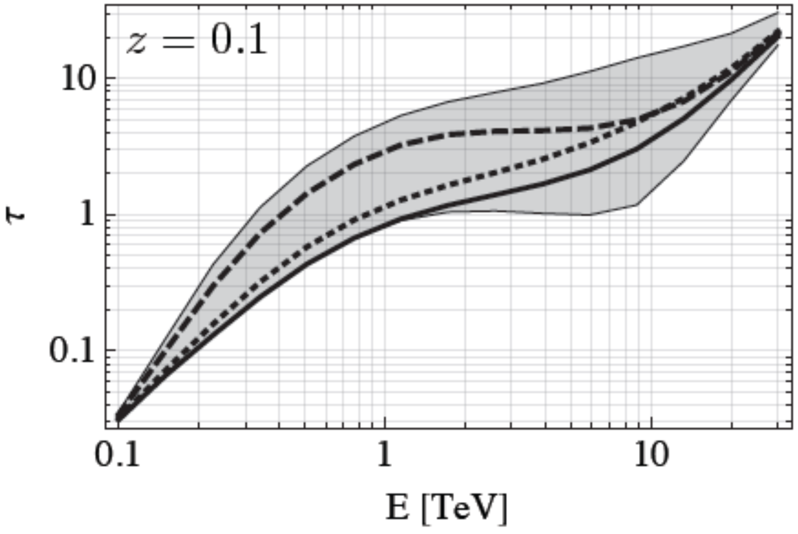
$$\gamma_{\mathrm{EBL}} + \gamma_{\mathrm{VHE}} \rightarrow e^{+} + e^{-}$$

$$\phi_{\mathrm{obs}}(E_{\gamma}) = \phi_{\mathrm{intr}}(E_{\gamma})e^{-\tau_{\gamma\gamma}(E,z)}$$

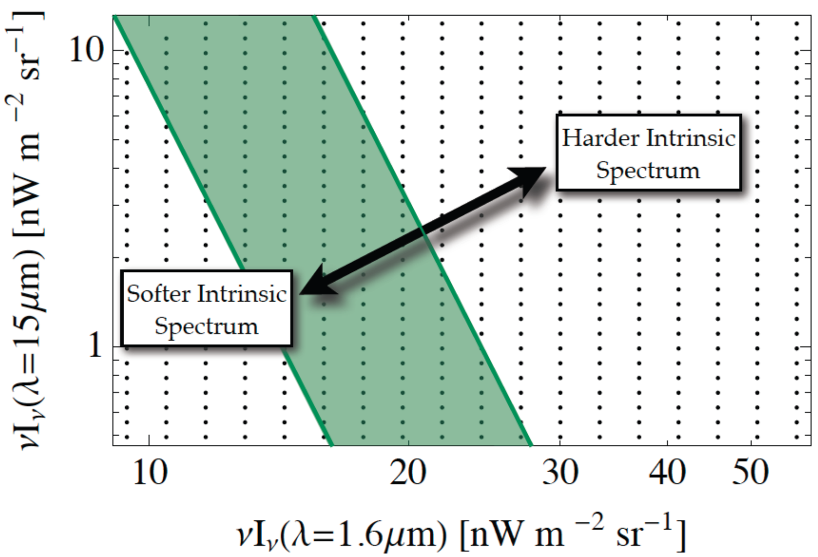


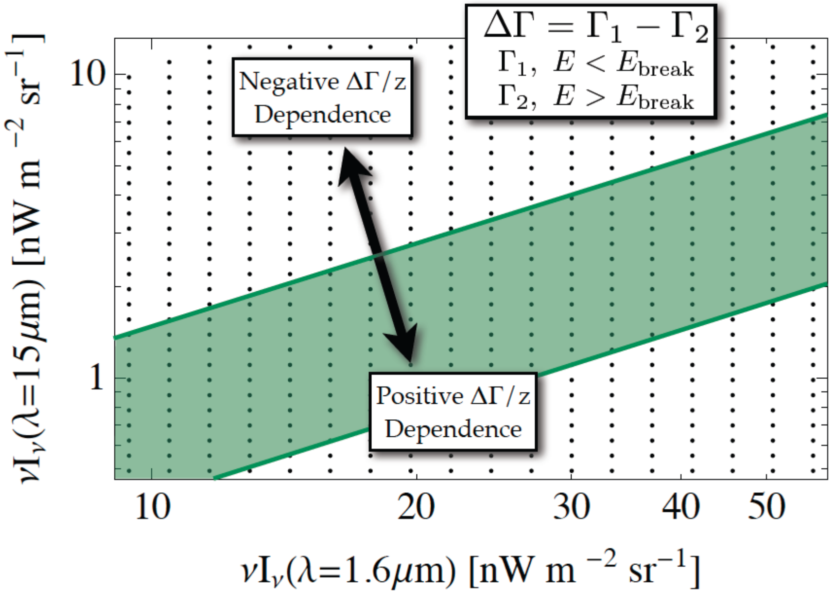
ratio





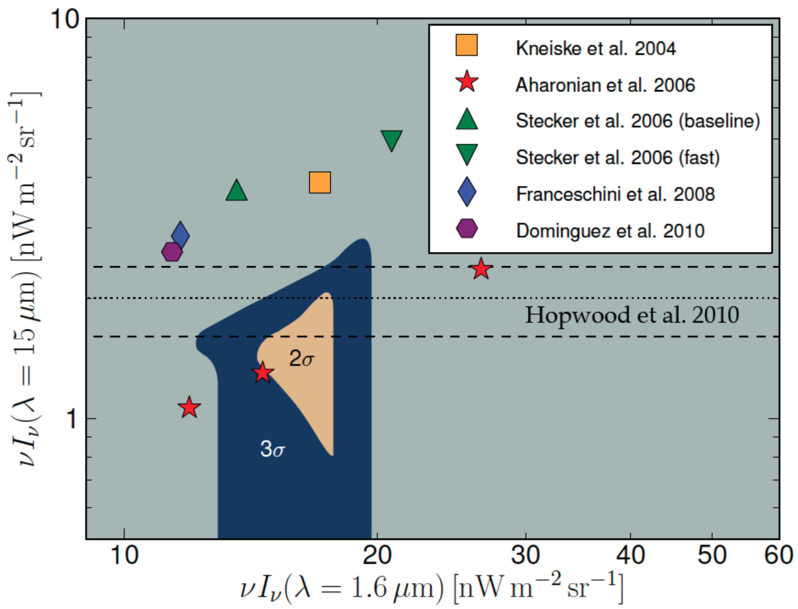
Constraints from M1 & M2





high-E IACTs

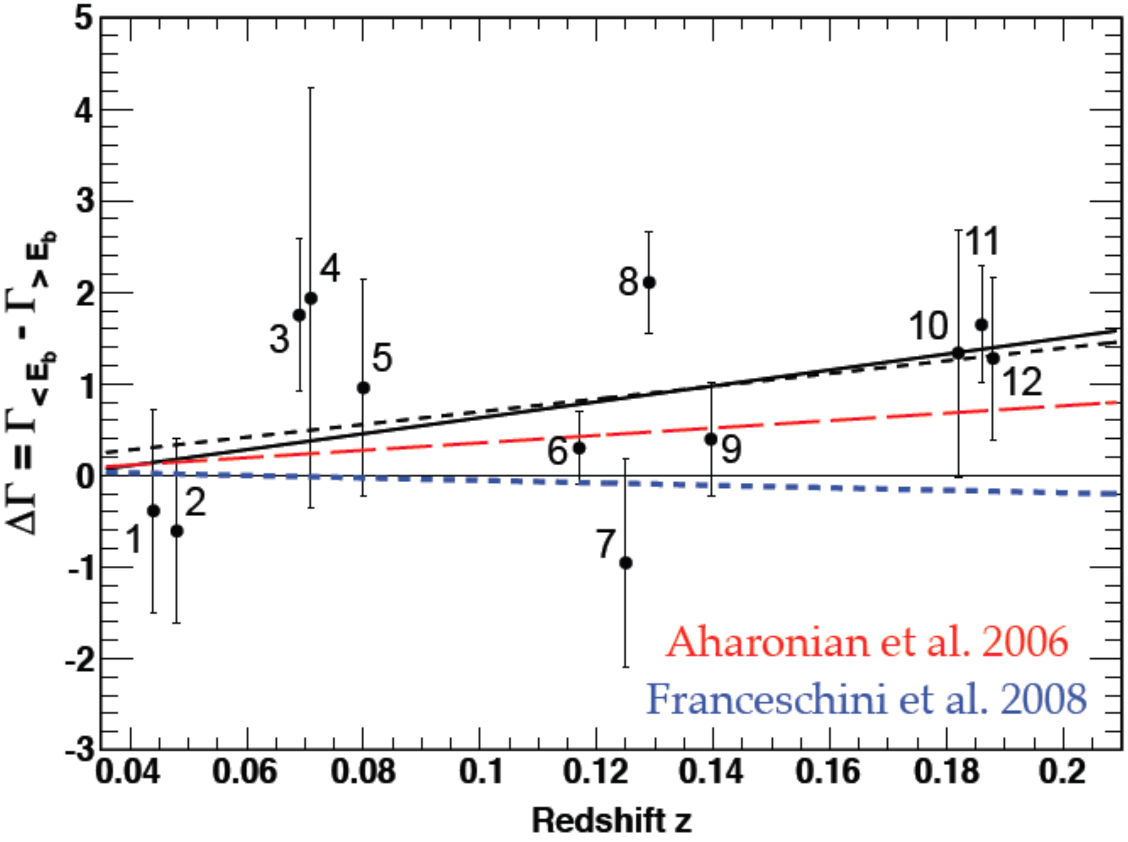
mid-IR



Fermi +low-E IACT

near-IR

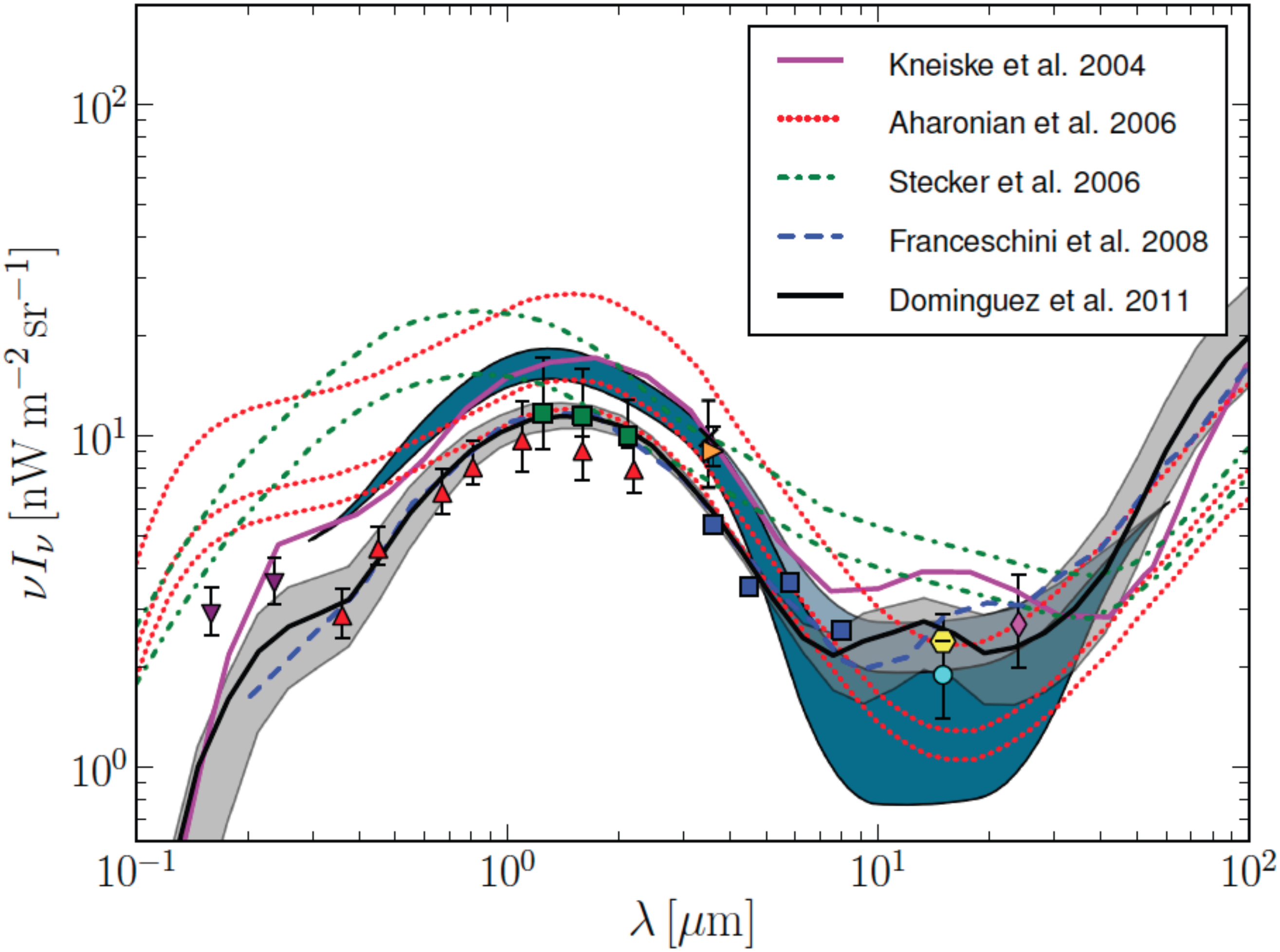
Spectral Break - Redshift



1. 1ES 2344+514
2. 1ES 1959+650
3. PKS 0548-322
4. PKS 2005-489
5. RGB J0152+017
6. PKS 2155-304
7. RGB J0710+591
8. H 1426+428
9. 1ES 0229+200
10. 1ES1218+304
11. 1ES 1101-232
12. 1ES 0347-121

Evidence for spectral break: 3.5 σ

New EBL Constraints



EBL this work

M. Orr, FK, E. Dwek, ApJ, 733, 77 (2011)

EBL Conclusions

Cosmology

→ ~ 40 AGN detected above 0.5 TeV; ~ 700 at GeV.

→ EBL is generally lower than expected – see farther in VHE γ-rays.

→ constraints on shape of EBL through γ-ray spectral ``break''.

→ unique signature from EBL absorption (~ 3.5 σ)

→ lower limits from galaxy counts and γ-ray constraints not converged in the optical/near-IR.

What have we not seen (yet)?

Key Science Questions

(1) Galactic Tevatrons and Pevatrons

(2) Black Holes

(3) Cosmology

(4) **Particle Physics and Fundamental Laws**

Physics: Dark Matter

Fermilab Tevatron

Large Hadron Collier

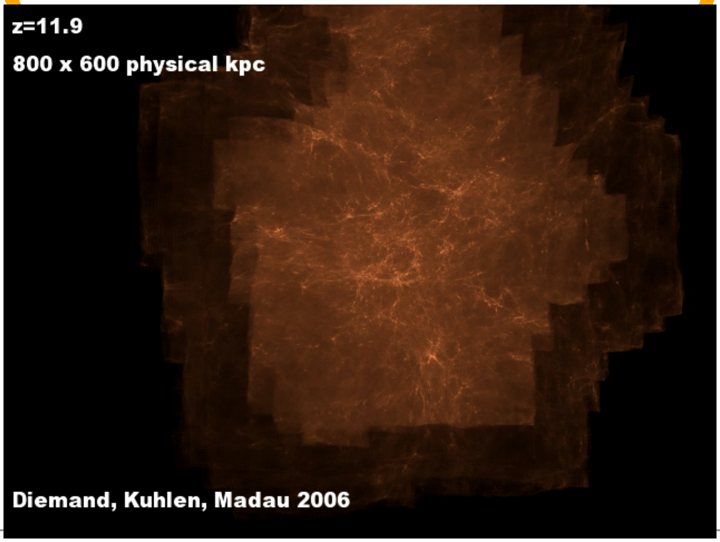
Produce neutralino

in laboratory

CDMS @ Soudan

Directly detect DM WIMP in specialty detectors in (underground) labs

Three complementary approaches



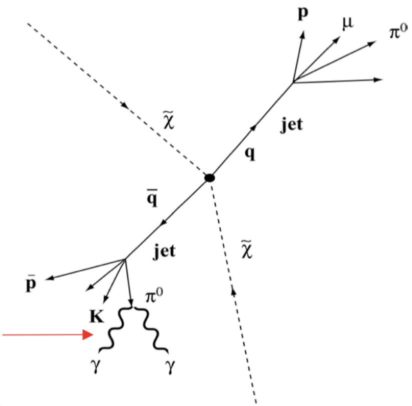
Diemand, Kuhlen, Madau 2006

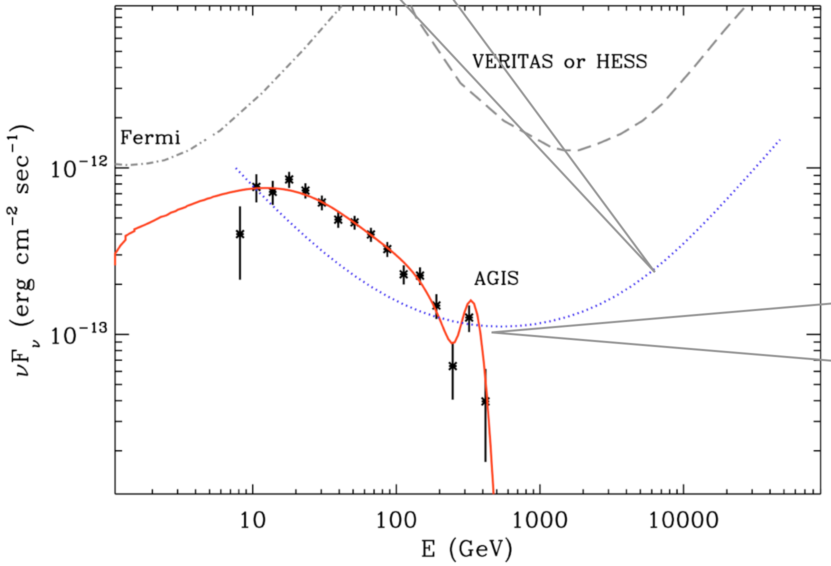
Indirect detection of astrophysical γ-rays from DM self-annihilation

Only direct link between a neutralino and dark matter halo profiles

Science Requirements

effective area





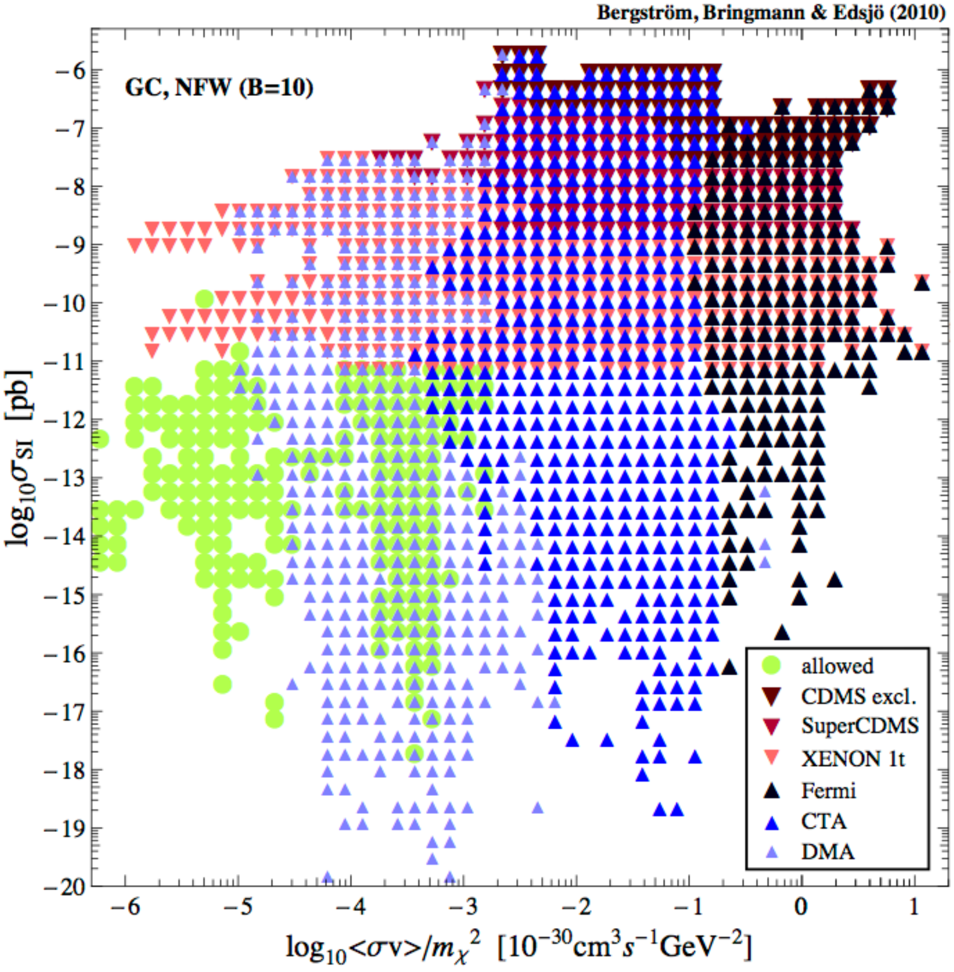
CTA:

- probe the annihilation cross-section
- measure the WIMP mass
- usher the era of "dark matter astronomy"

sensitivity – angular resolution

Dark Matter

Direct detection



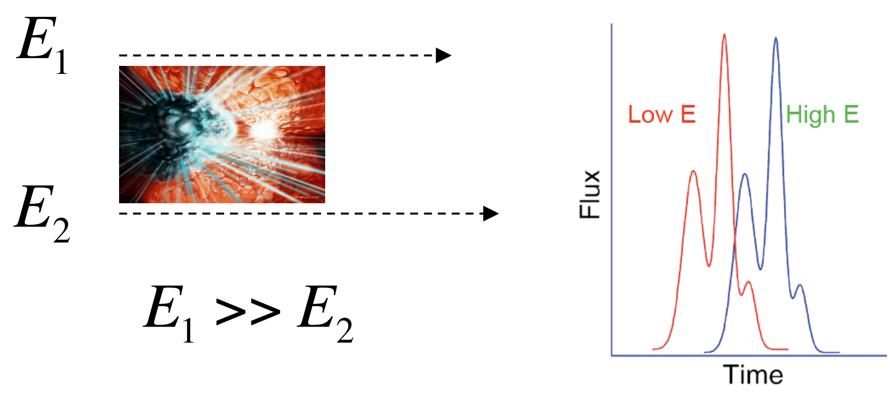
Indirect detection

"...We also show the remarkable, and somewhat surprising, fact that indirect detection rates for gamma-ray detection of dark matter annihilation in the galactic halo (or sub-halos) are very weakly correlated with direct detection rates. This means that *a dedicated gamma-ray detector for dark matter detection may probe from an orthogonal direction the parameter space of viable dark matter models, down to direct detection levels that would never be realistically achievable otherwise."*

[hep-ph] arXiv:1011.4514 L. Bergstrom et al.

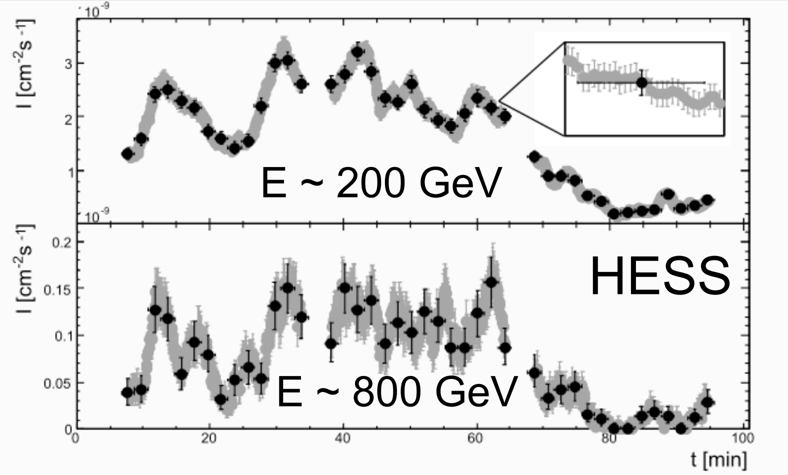
Figure shows random scan of MSSM and mSUGRA models. Various symbols indicate models excluded by the corresponding experiments. Indirect detection assumes offset Galactic Center position. "CTA" exclusion region is for default design (without CTA-US contribution) and nominal 50 hours exposure. "DMA" exclusion region assumes hypothetical IACT observatory with 10 times larger collecting area and 100 times exposure. CTA-US contribution will increase relevant default CTA collecting area by a factor of 3 and exposure by a factor of 10.

Lorentz Invariance Violation (LIV) at the Planck energy?

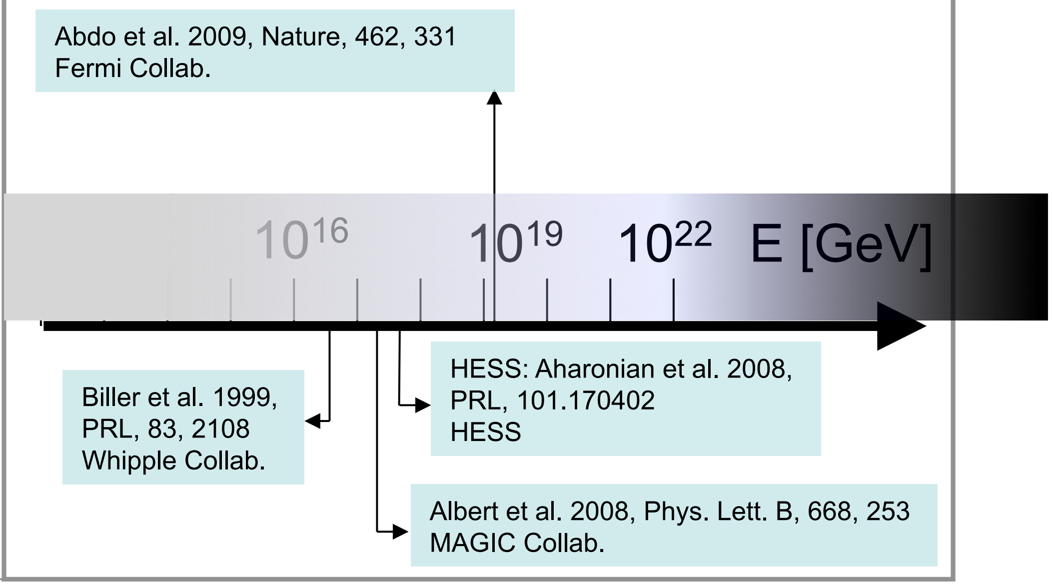


Amelino-Camelia, G., Ellis, J. et al. 1998 , Nature, 395, 525

- **Flares** from relativistic jets (active galaxies, gamma-ray bursts) provide strong **limits to Lorentz invariance violation**.
- TeV and GeV data give lower limits to the quantum gravity energy scale of ~ **10^{19} GeV (Planck energy)**



- Flare of active galaxy PKS2155-304 → no deviation found! $E_{QG} > 7.2\times10^{17}\,GeV$



Abdo et al. 2009, Nature, 462, 331
Fermi Collab.

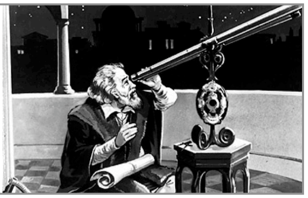
Biller et al. 1999,
PRL, 83, 2108
Whipple Collab.

HESS: Aharonian et al. 2008,
PRL, 101.170402
HESS

Albert et al. 2008, Phys. Lett. B, 668, 253
MAGIC Collab.

What is next?

IACT Technique



1968

1989

2007

2004

40 year old technology!

Camera ~ 1 PMT
- Sensitivity ~ 10 Crab
- No 5 σ detection

Camera ~ 37 PMTs
- Sensitivity ~ 1 Crab
- 9 σ detection

Cameras ~ 500-1000 PMTs
- Sensitivity ~ 1% of Crab
- 5 σ detection of 1 Crab in 30 s

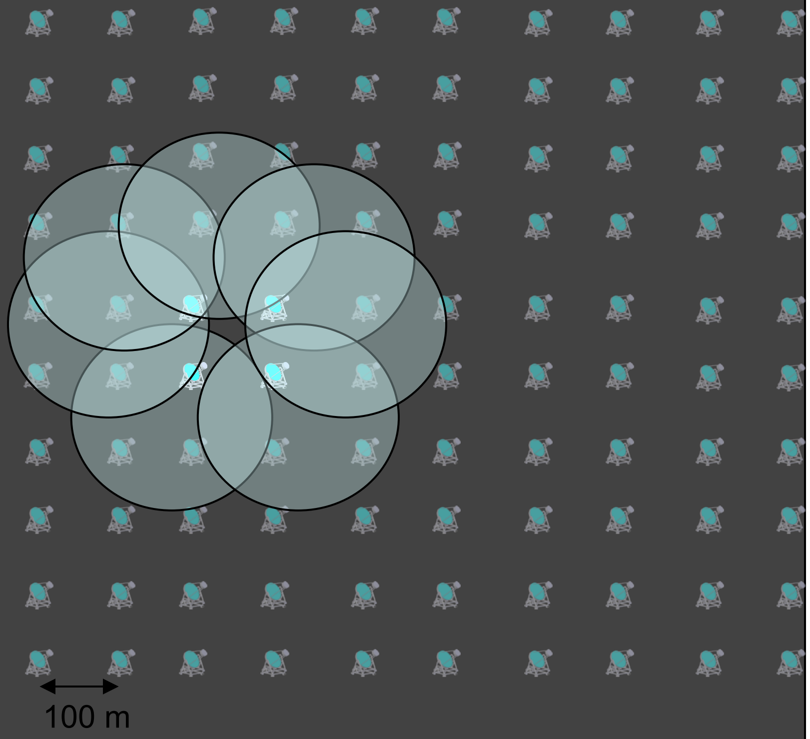
Whipple: Weekes et al. 1989, ApJ, 342, 379

Large Array Concept

Event containment:

- angular resolution Θ x 3
- background rejection x 2
- collection area x 10
- solid angle Ω x 4

$$S \propto \Theta \times \sqrt{back} / \sqrt{area} \; / \sqrt{\Omega}$$



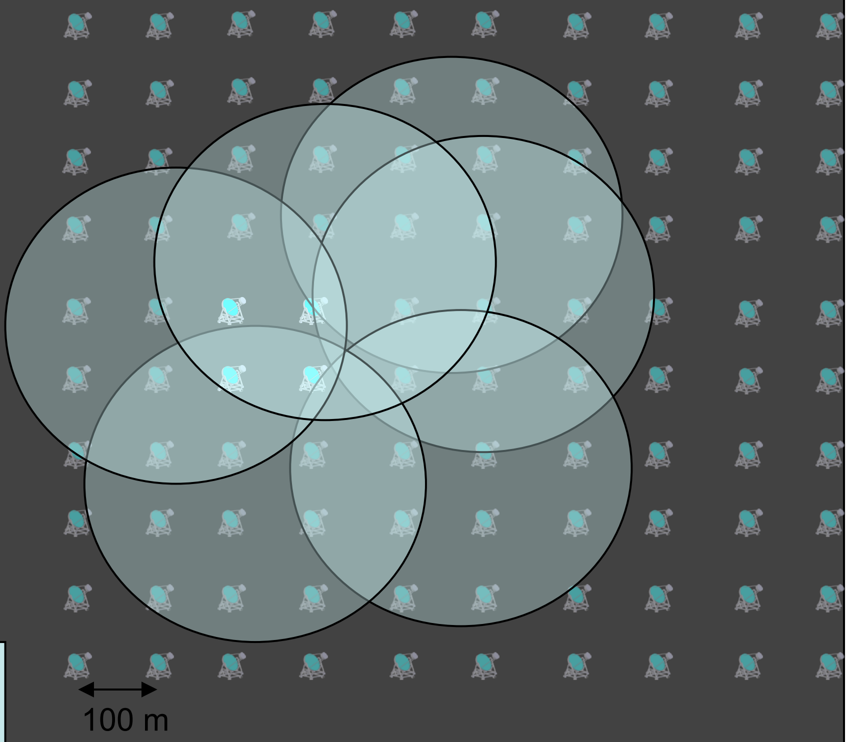
Large Array Concept

Event containment:

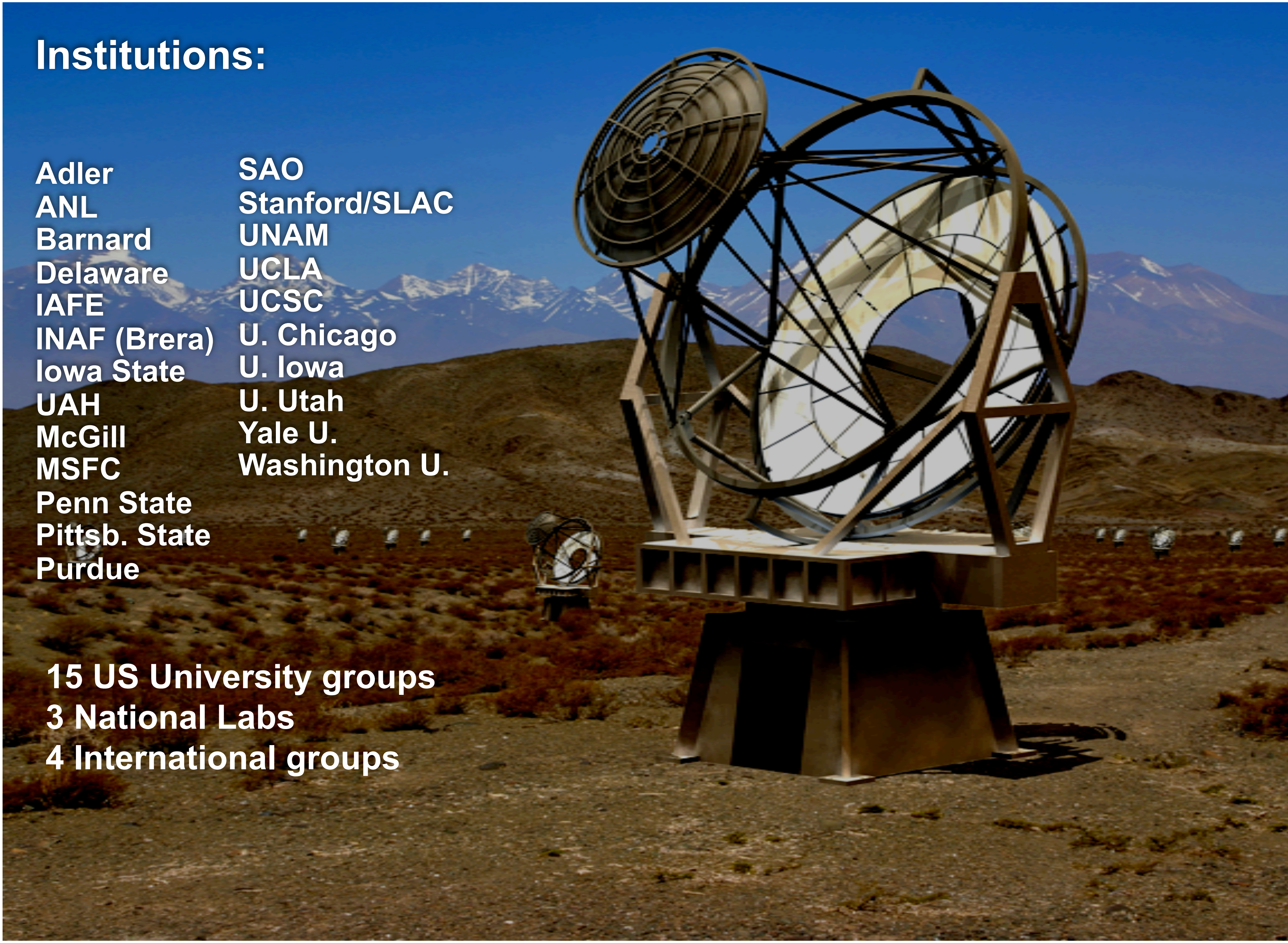
- angular resolution x 3
- background rejection x 2
- collection area x 10
- FOV x 4

Photon statistics!

$$S \propto \Theta \times \sqrt{back} / \sqrt{area} \;\; / \sqrt{\Omega}$$



Event containment only works for large size array, so that combination of collection area and angular resolution are achieved!



Institutions:

Adler
ANL
Barnard
Delaware
IAFE
INAF (Brera)
Iowa State
UAH
McGill
MSFC
Penn State
Pittsb. State
Purdue

SAO
Stanford/SLAC
UNAM
UCLA
UCSC
U. Chicago
U. Iowa
U. Utah
Yale U.
Washington U.

15 US University groups
3 National Labs
4 International groups

Endorsements: AADS2010

NEWS OF THE WEEK

Wide-Field Infrared Telescope (builds on Joint Dark Energy Mission)

Goal: Investigating dark energy, searching for exoplanets
Total cost: $1.6 billion
Cost to U.S. government (2012–2021): $1.6 million
Launch date: 2020

Augmenting the Explorer program

Goal: Small to midsize missions that target specific topics such as brown dwarfs and gamma-ray bursts
Total cost: $463 million
Cost to U.S. government (2012–2021): $463 million
Launch date: Rolling

CREDITS (LEFT TO RIGHT): NASA; JAXA

CREDITS (LEFT TO RIGHT): NASA

Laser Interferometer Space Antenna (LISA)

Goal: Detecting gravitational waves and black-hole mergers; testing general relativity
Total cost: $2.4 billion
Cost to U.S. government (2012–2021): $852 million
Launch date: 2025

International X-ray Observatory (IXO)

Goal: Studying black-hole accretion and neutron-star physics; stellar astrophysics
Total cost: $5.0 billion
Cost to U.S. government (2012–2021): $200 million
Launch date: 2020s

SPACE-BASED PROJECTS

ASTRONOMY

U.S. Astronomers Unveil Stripped-Down 'Short List'

In 2008, when a committee of U.S. astronomers led by Stanford University astrophysicist Roger Blandford was asked to recommend funding priorities in astronomy and astrophysics for the next decade, it was clear what the panel was not supposed to do. "The message from Congress was: Don't give us a list of 50 things to fund," says panelist Debra Elmegreen, an astronomer at Vassar College in Poughkeepsie, New York. "Give us the things you really, really want to do."

That's exactly what the panel says it has done in its report of the sixth decadal survey, released last week by the National Research Council. Unlike previous decadal surveys, which often produced unrealistically long "wish lists" of priorities, the new report claims to have made some hard choices that hew to the realities of a tough budgetary climate. And for the first time, the survey had estimates of project costs vetted independently, which the panelists say makes those figures more realistic than in the past.

The report identified four major projects each in the space- and ground-based categories (see graphic). The top choices in both groups concern dark energy, the mysterious force that is accelerating the expansion of the universe. On land, the panel chose the $463 million Large Synoptic Survey Telescope (LSST), an 8.4-meter optical telescope that will help investigate dark energy, supernovae, and other areas. In space, the top choice was the $1.6 billion Wide-Field Infrared Survey Telescope (WFIRST)—until now known as the Joint Dark Energy Mission—which should enable researchers to study dark energy, find Earth-like planets, and survey galaxies, including our own.

"It's great that the committee saw the excitement and possibility of studying dark energy," says Adam Riess, an astrophysicist at Johns Hopkins University in Baltimore, Maryland. Riess says he is especially pleased with the endorsement for WFIRST, which he calls a "crucial capability in space that a number of disparate investigations need for their science."

Both projects have been in the works for a few years and have received public and private funds for planning and design. In fact, LSST was among three major ground-based initiatives recommended for support in the 2001 decadal survey. Led by a consortium of institutions headed by astronomer J. Anthony Tyson of the University of California, Davis, the project has already picked out a site in Chile and finished casting its primary mirror.

"We are recommending that the National Science Foundation enter LSST into its MREFC line as soon as possible," says Blandford, referring to the account through which NSF funds the construction of major research facilities. NSF officials seem receptive to that message. "We're very excited by having LSST as number one among ground-based projects," says Jim Ulvestad, NSF's director for astronomical sciences.

WFIRST's fate appears to be less certain, partly because delays in the $4.5 billion James Webb Space Telescope, scheduled for launch in 2014, could curtail NASA's ability to fund new missions. However, the project that WFIRST builds on has the support of both NASA and the Department of Energy. The two agencies are in talks with the European Space Agency about a possible partnership, which would boost WFIRST's prospects of being launched by the panel's recommended date of 2020. "The U.S. should play a leading role in such a partnership," Blandford says.

Blandford says the panel considered two budget scenarios: one in which U.S. funding for the physical sciences doubles over the next decade, and one that sees only modest increases. All of the projects recommended in the report could be implemented under a doubling. In the less-rosy scenario, Blandford says, a number of existing observatories—particularly ground-based ones—should be shut down to make room for the new initiatives.

Of course, the viability of the panel's recommendations hinges on the accuracy of cost estimates of the different projects. Previous surveys have drawn fire for providing estimates as low as a fifth of the ultimate costs for some missions. This report's estimates are more believable, Blandford says, because they were evaluated by an independent contractor, Aerospace Corp., instead of by other astronomers as in previous surveys. "Astronomers are not really good business managers," says panelist Marcia Rieke, an astronomer at the University of Arizona, Tucson. In this survey, some of the estimates submitted to the panel "drew gasps from the independent evaluators," she says. "They looked at some of the concepts and said it was impossible to cost them because so much engineering needed to be done to even begin to estimate the project cost."

Blandford says the panel also tried to strike a balance between large and small projects. "We strove to protect the smaller and nimbler activities," he says. That's why ranked second in the space category is a proposed augmentation to the Explorer program, which supports small- and medium-sized missions with specific science goals. Similarly, in the category of large-scale, ground-based projects, right behind LSST is a recommendation to fund a Mid-Scale Innovations Program within NSF to fund projects that cost more than $4 million and less than $135 million.

–YUDHIJIT BHATTACHARJEE

GROUND-BASED PROJECTS

Large Synoptic Survey Telescope

Goal: Studying dark energy, dark matter, supernovas, near-Earth objects
Total construction cost: $465 million
Cost to U.S. government (2012–2021): $421 million
Annual operating cost: $42 million
Science begins: Late 2010s

Mid-Scale Innovation Program

Goal: Funding projects that cost between $4 million and $135 million, such as a new radio array to study the sun
Total cost: $93 million to $200 million
Science begins: Mid-to-late 2010s

Frequency-Agile Solar Radiotelescope

CREDITS (LEFT TO RIGHT): T. MASON, MASON PRODUCTIONS INC./ LSST CORP.; FASR

CREDITS (LEFT TO RIGHT): TMT; GIANT MAGELLAN TELESCOPE/GMTO CORP.; AGIS

Thirty Meter Telescope

Giant Magellan Telescope

Giant Segmented Mirror Telescope

Goal: Studying the earliest galaxies and galaxy evolution; detecting and characterizing planetary systems
Total construction cost: $1.1 billion to $1.4 billion
Cost to U.S. government (2012–2021): $257 million to $350 million
Annual operating cost: $36 million to $55 million
Science begins: Mid-2020s

Atmospheric Čerenkov Telescope Array

Goal: Detecting dark matter, investigating active galactic nuclei
Total construction cost: $400 million
Cost to U.S. government: $100 million
Operating cost: Unknown
Science begins: Early 2020s

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CTA-US (CTA):

- selected as one of three ground-based observatories.
- technical risk judged to be medium low.

Atmospheric Čerenkov Telescope Array

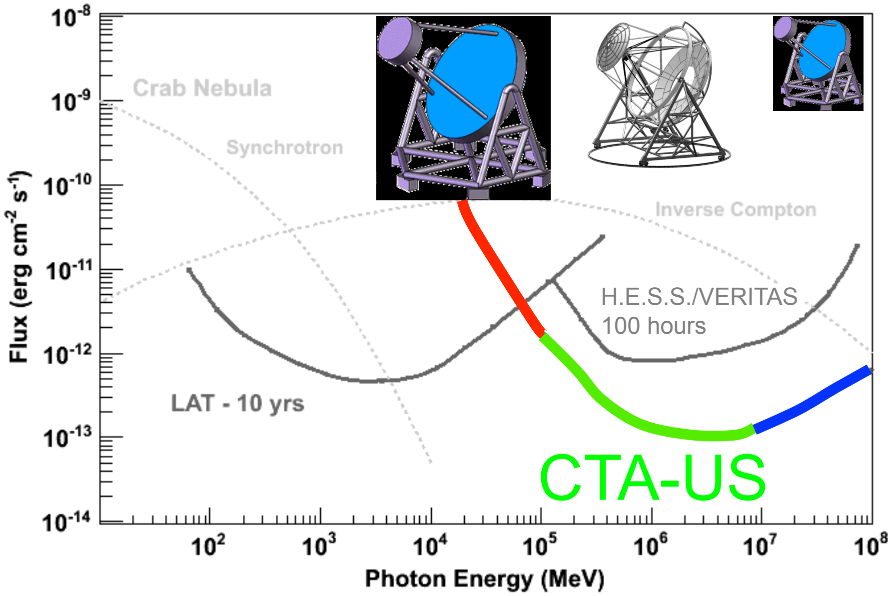
Goal: Detecting dark matter, investigating active galactic nuclei
Total construction cost: $400 million
Cost to U.S. government: $100 million
Operating cost: Unknown
Science begins: Early 2020s

CTA-US (CTA):

- strong endorsement based on astronomy, astrophysics and fundamental physics (NSF/AST, NSF/Physics & DOE)!

Plan of CTA-US

CTA



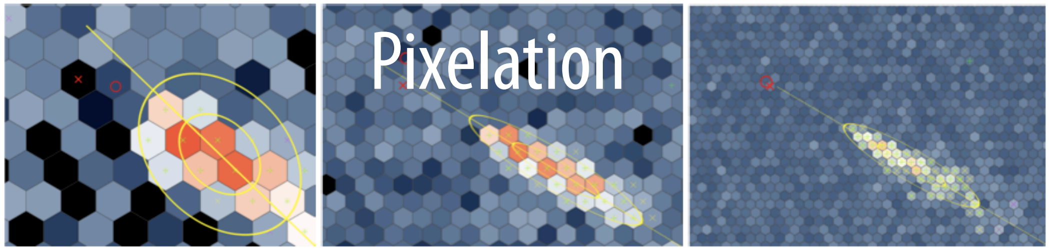
- **100 GeV - 10 TeV** regime
- overlay the MST array
- 23+36 → 59 element array
- wide FOV
- high resolution camera

-> angular resolution
-> better background rejection
-> better sensitivity

Approaching the limit of the IACT technique in mid-energy regime, where it works best!

A Novel Telescope

Schwarzschild-Couder



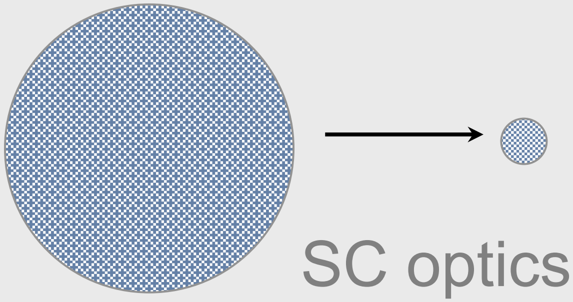
Pixelation

0.28° 0.20° 0.07°

FOV

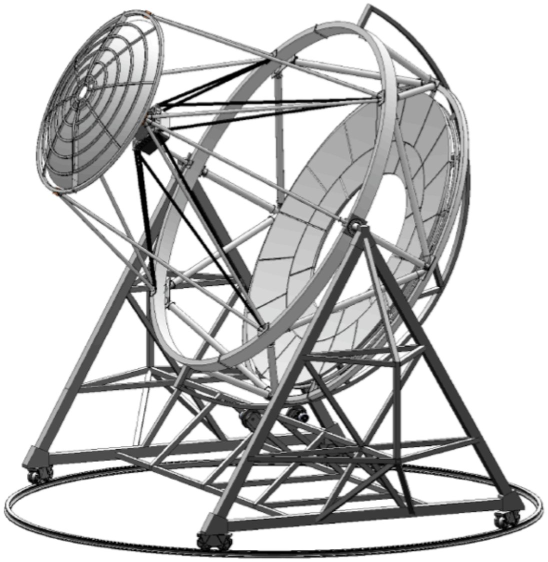
3.5 deg. → 8 deg.

Camera Size



DC optics

SC optics



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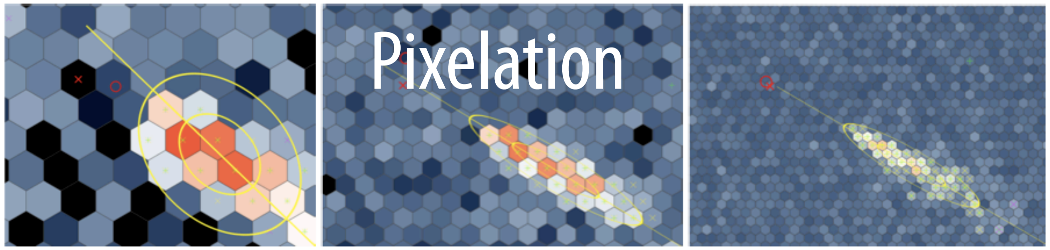

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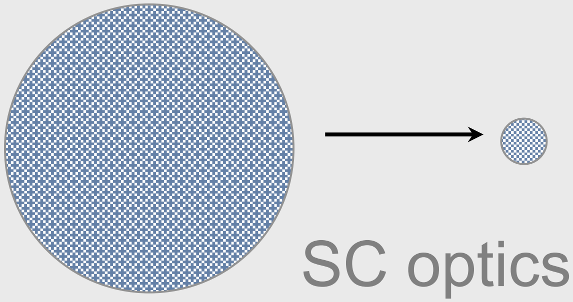

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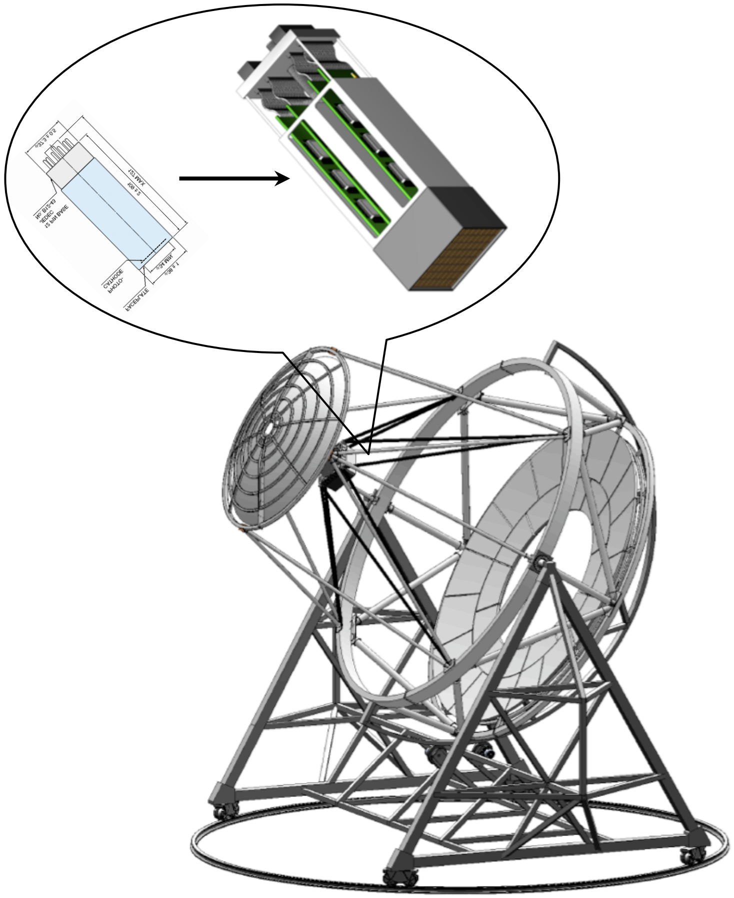

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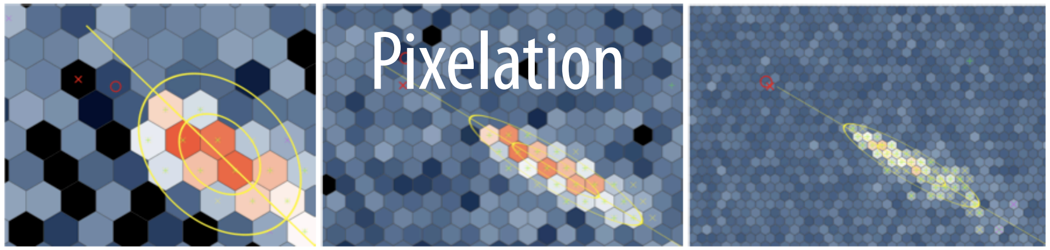

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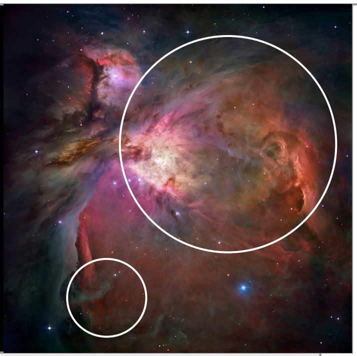

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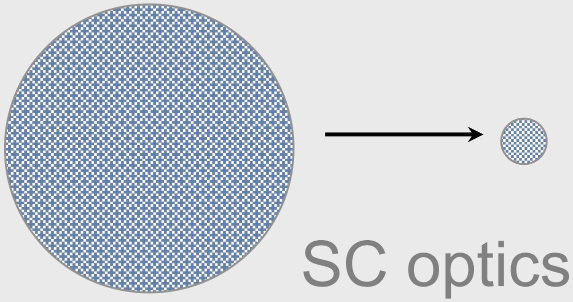

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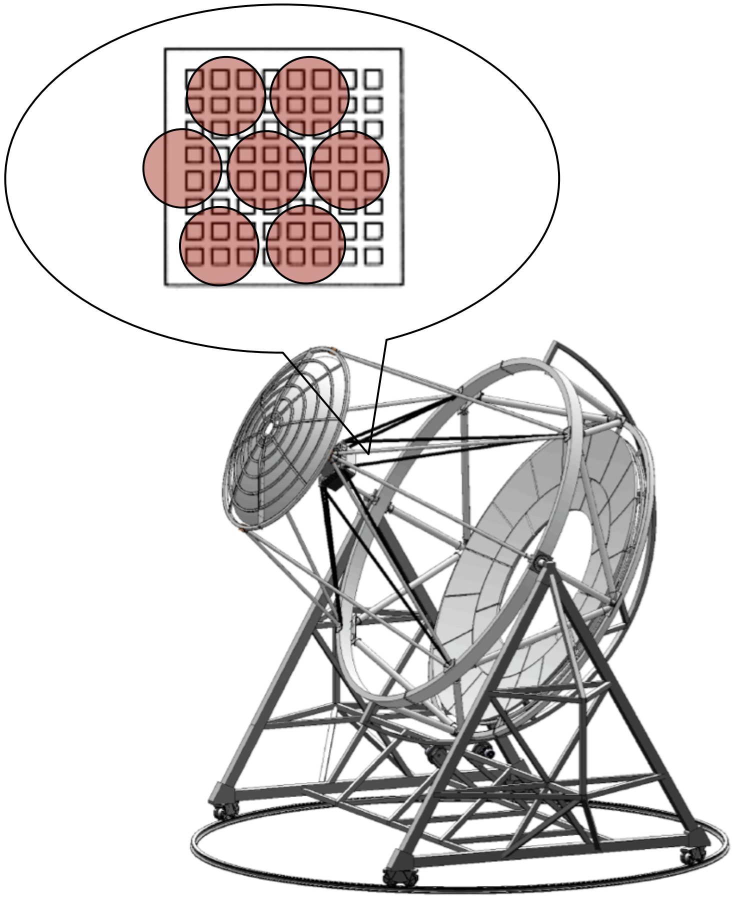
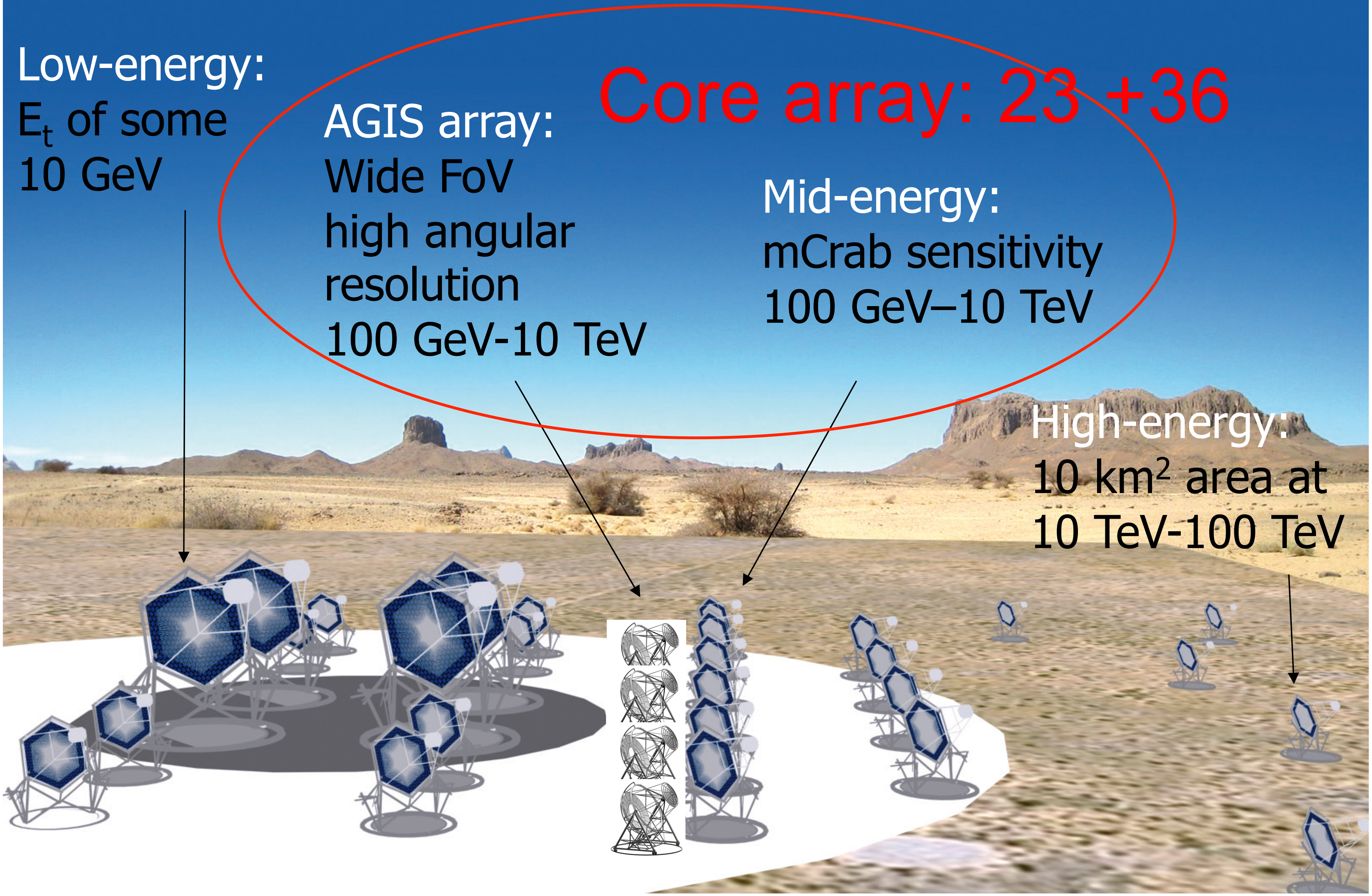


CTA/CTA-US Conceptual design



Core array: 23 +36

Low-energy:
E_t of some
10 GeV

AGIS array:
Wide FoV
high angular
resolution
100 GeV-10 TeV

Mid-energy:
mCrab sensitivity
100 GeV–10 TeV

High-energy:
10 km^2 area at
10 TeV-100 TeV

Summary

Gamma rays:

- → provides a view of non-thermal processes in a broad range of celestial objects: SNRs, PWN, binary systems, AGNs, starburst galaxies, ...
- → image the particle accelerator responsible for cosmic particle populations.
- → probe the magnetic field in interaction regions - efficiency of accelerator.
- → are emitted in the vicinity of SMBHs – connection to relativistic jets.
- → probe the EBL and provide more complete account of its contributors.

CTA/CTA-US:

- → order of magnitude better sensitivity through large array concept.
- → factor of 2-3 better angular resolution.
- → reach the sensitivity necessary for indirect dark matter detection.
- → substantial survey capabilities through wide FOV instrumentation.


STOP