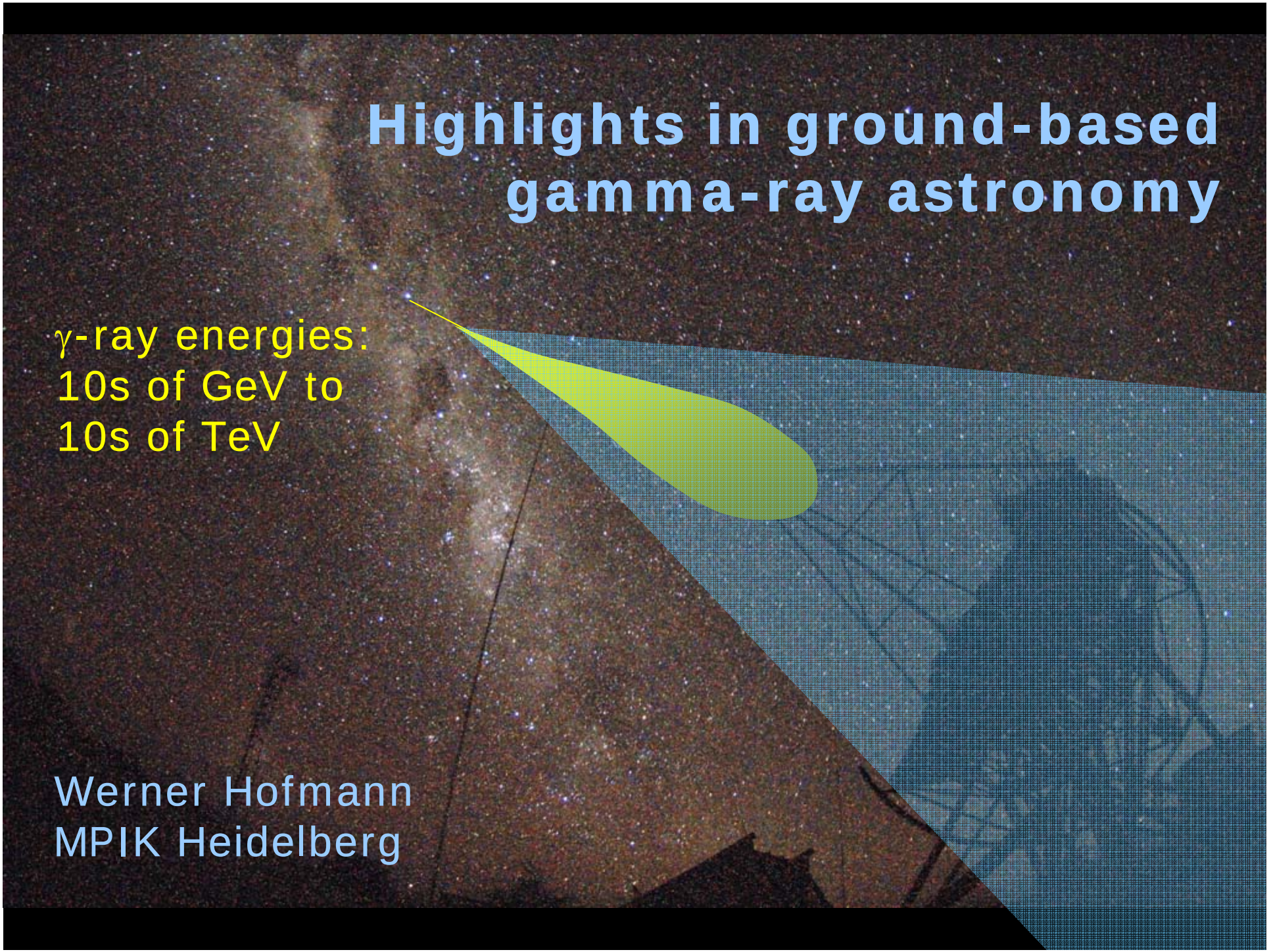
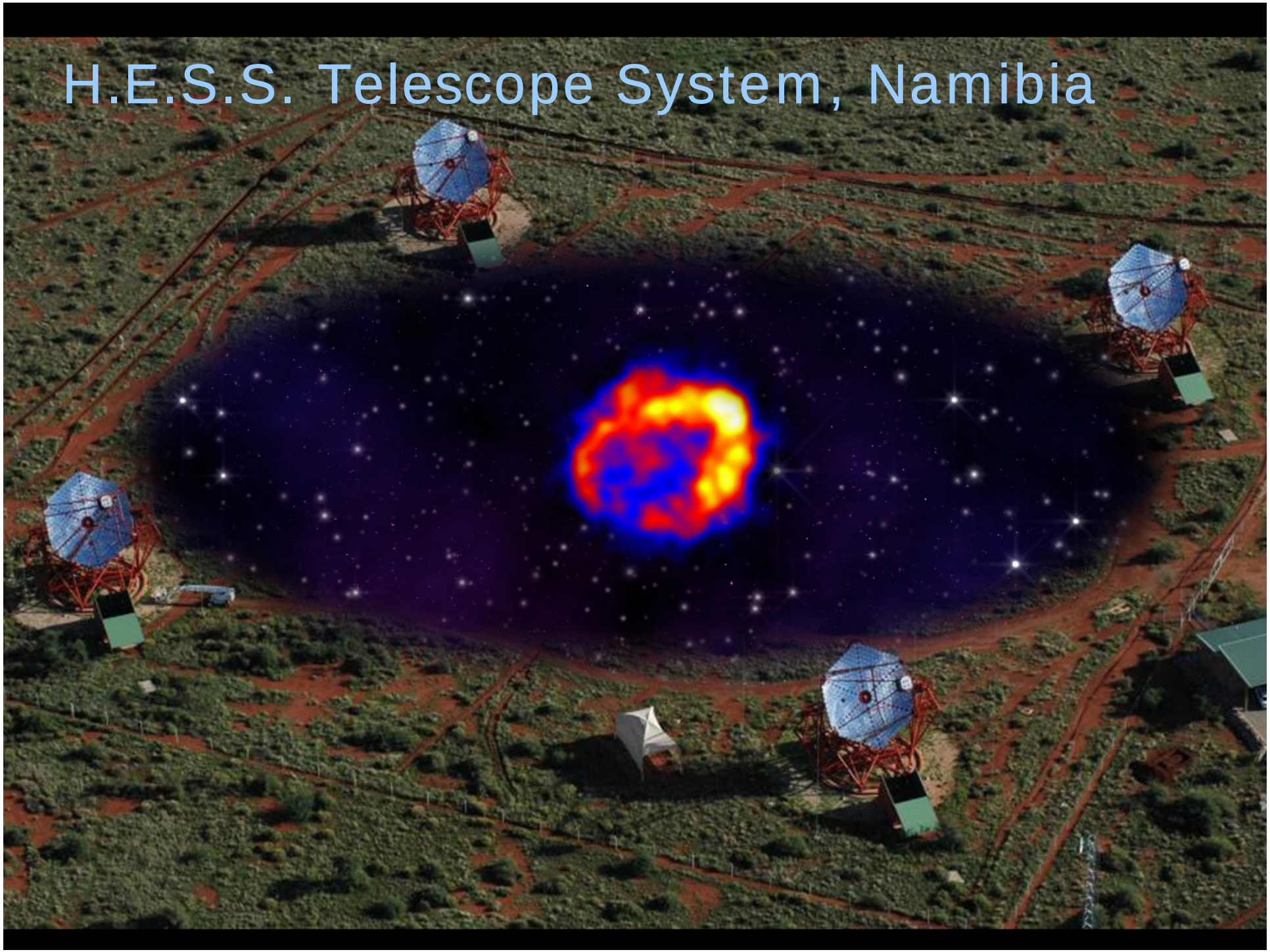
Highlights in ground-based gamma-ray astronomy



γ-ray energies:
10s of GeV to
10s of TeV

Werner Hofmann
MPIK Heidelberg

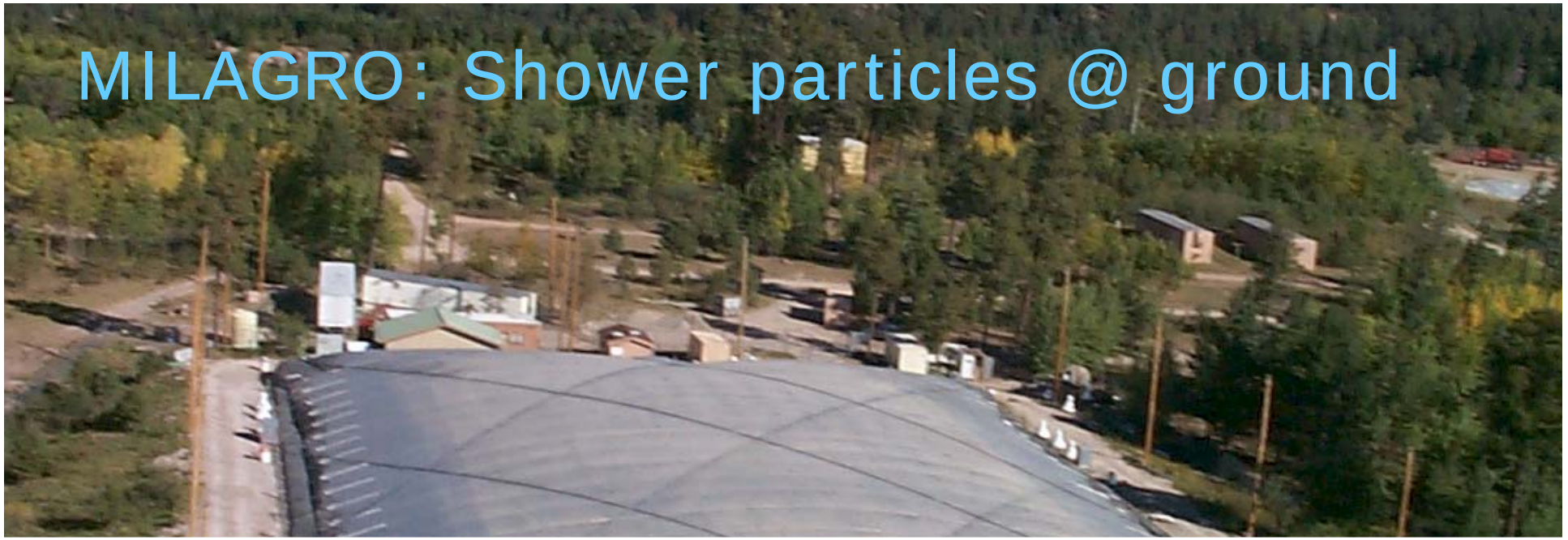
H.E.S.S. Telescope System, Namibia

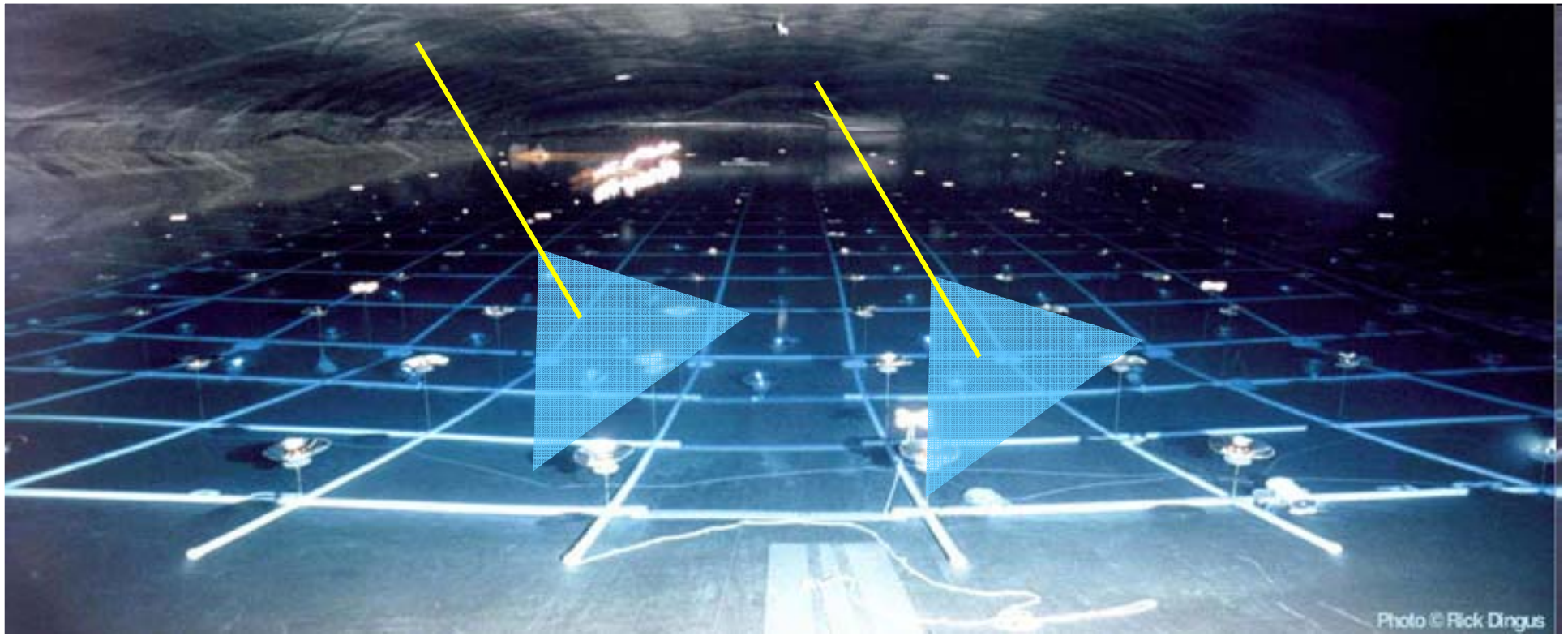


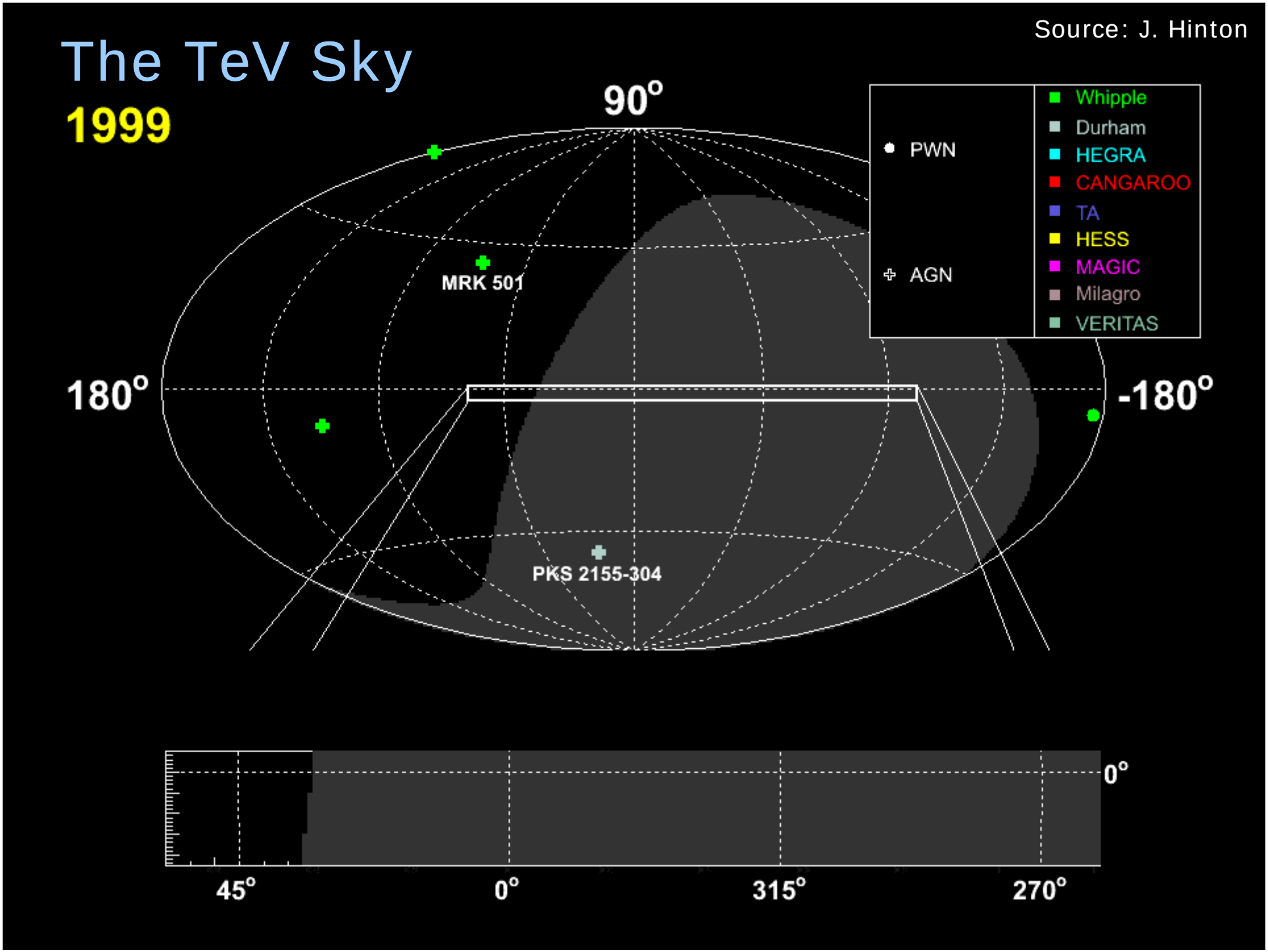

MAGIC II First Light April 24/25

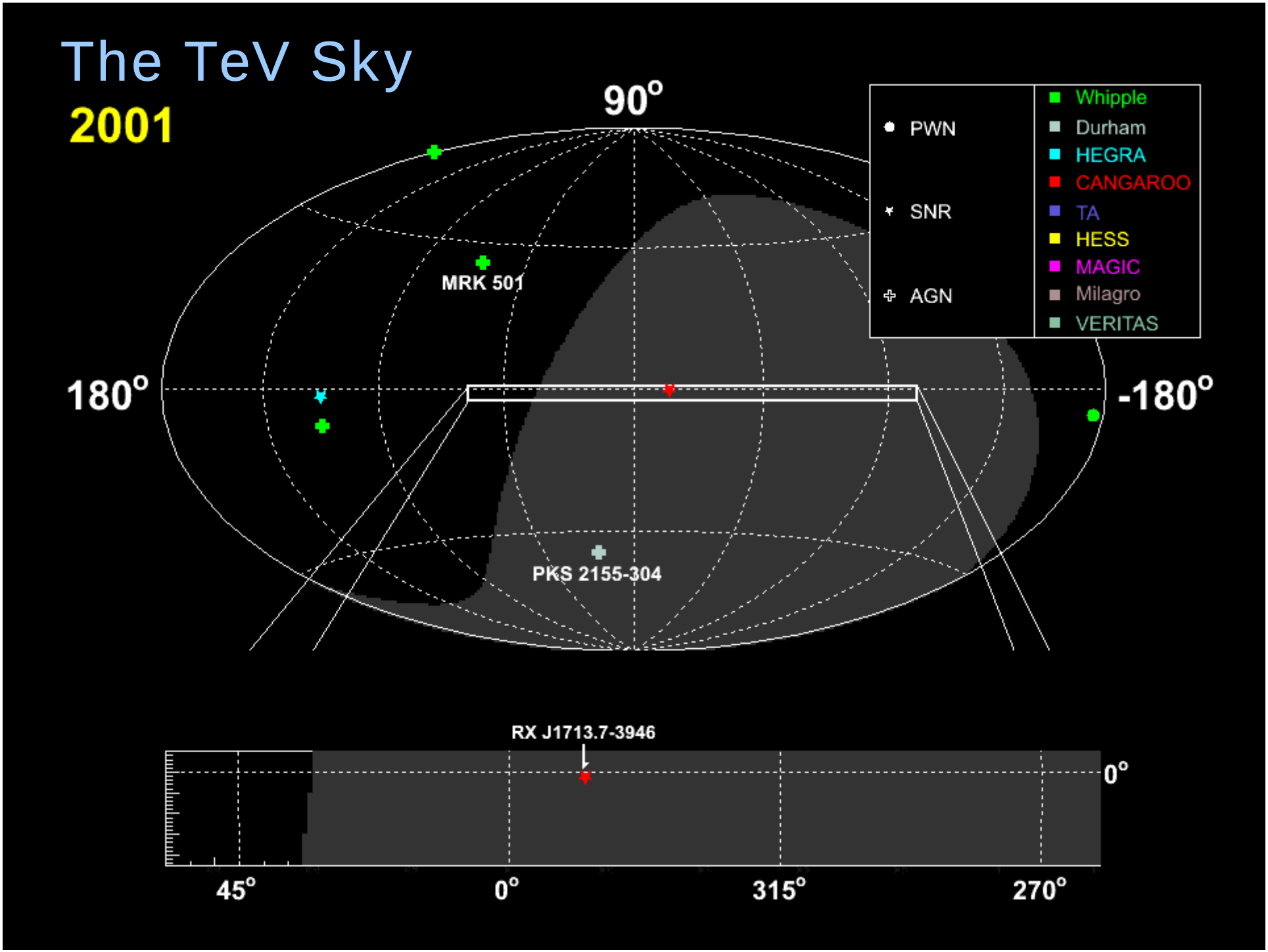

VERITAS

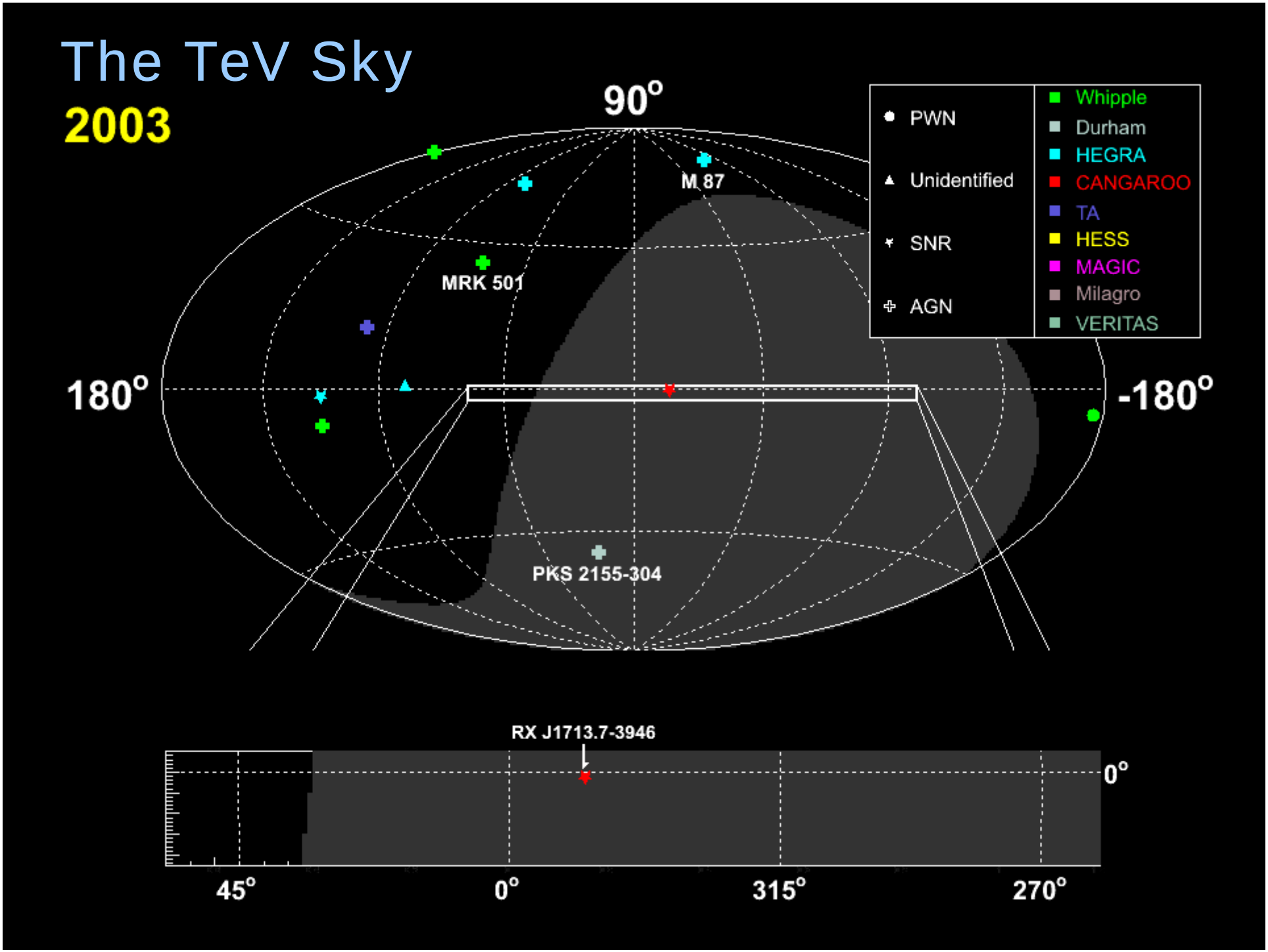
MILAGRO: Shower particles @ ground

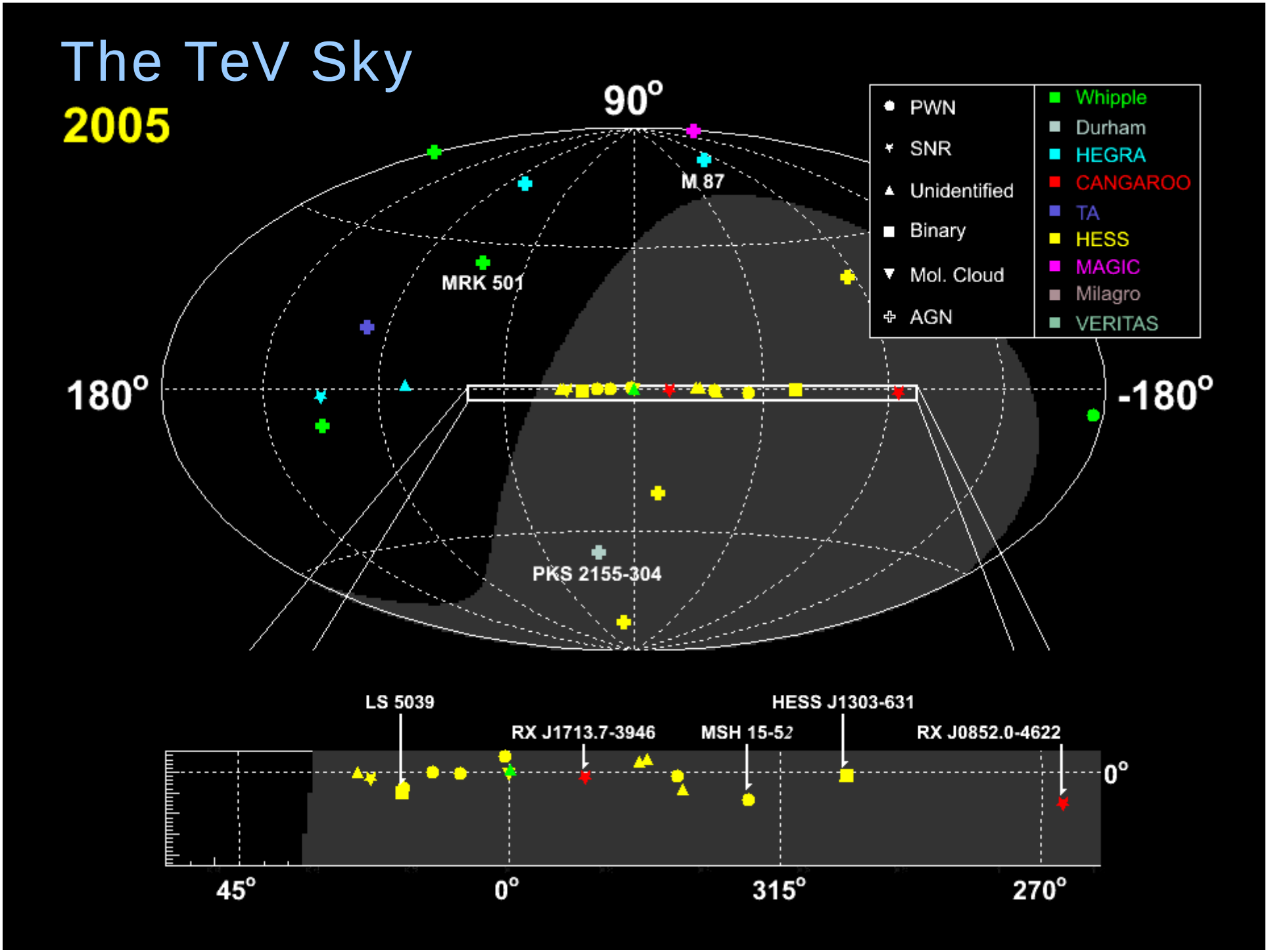


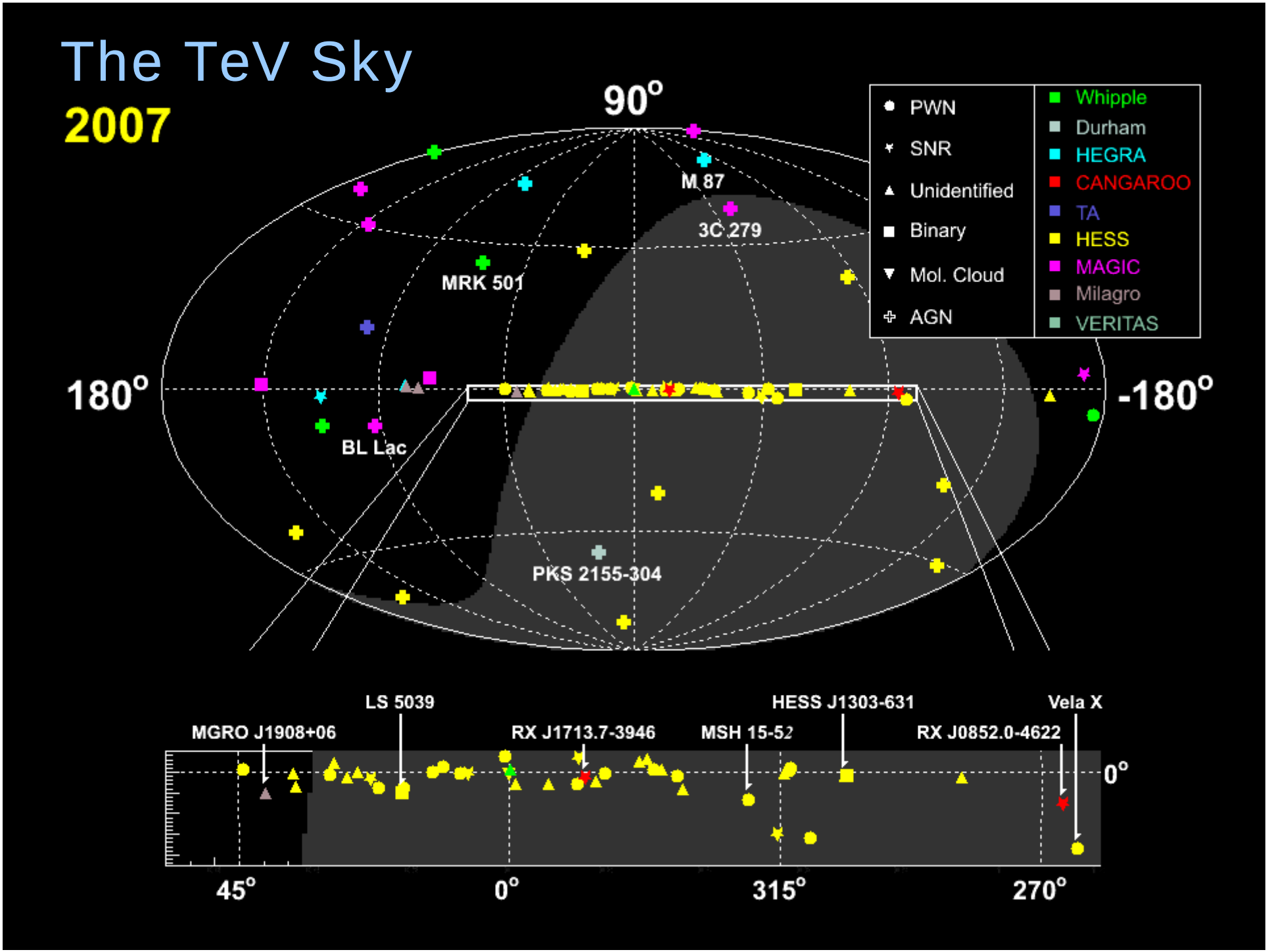


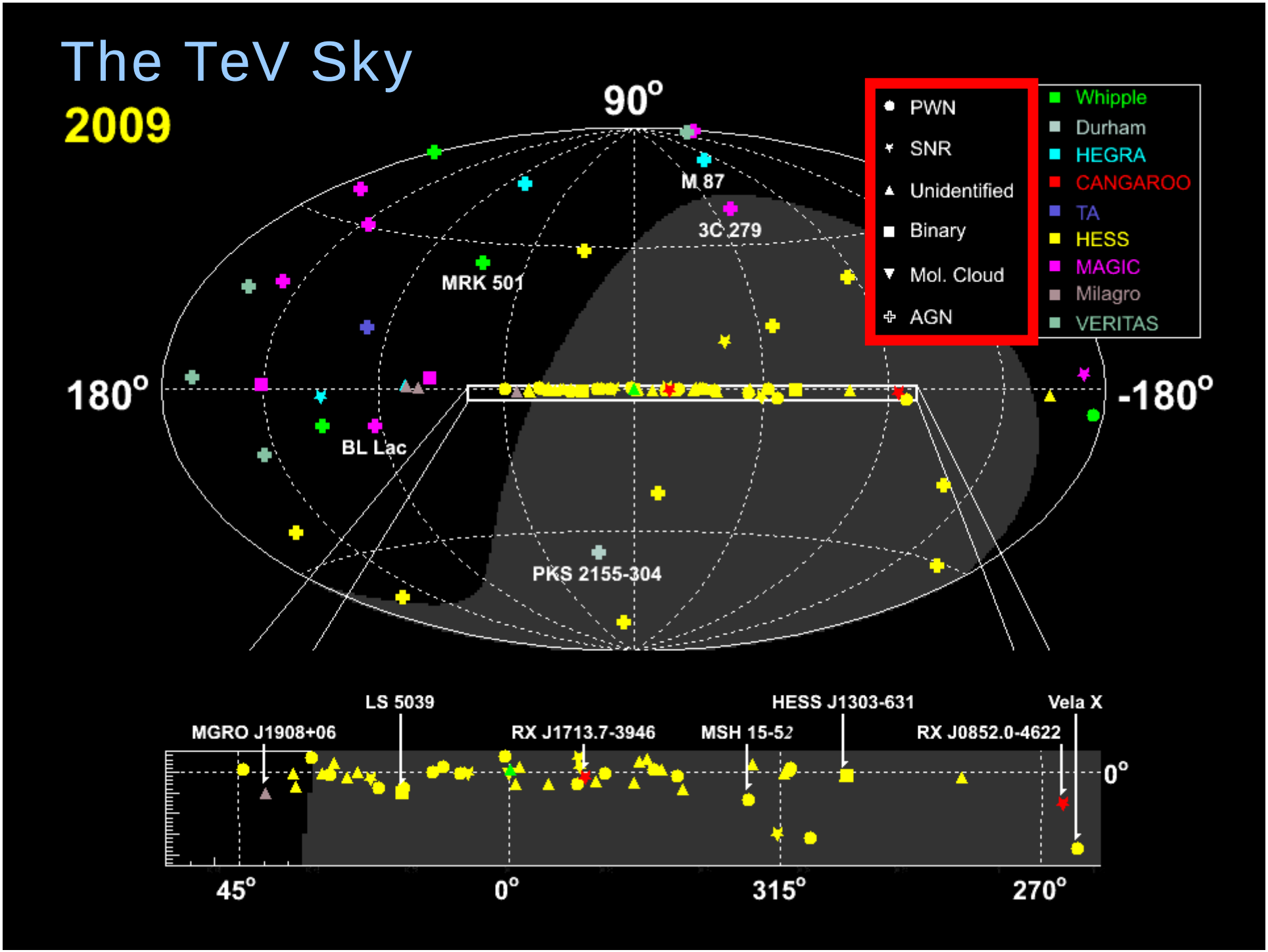

The TeV Sky
1999
Source: J. Hinton
90°
180°
-180°
MRK 501
PKS 2155-304
PWN
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
0°
45°
0°
315°
270°

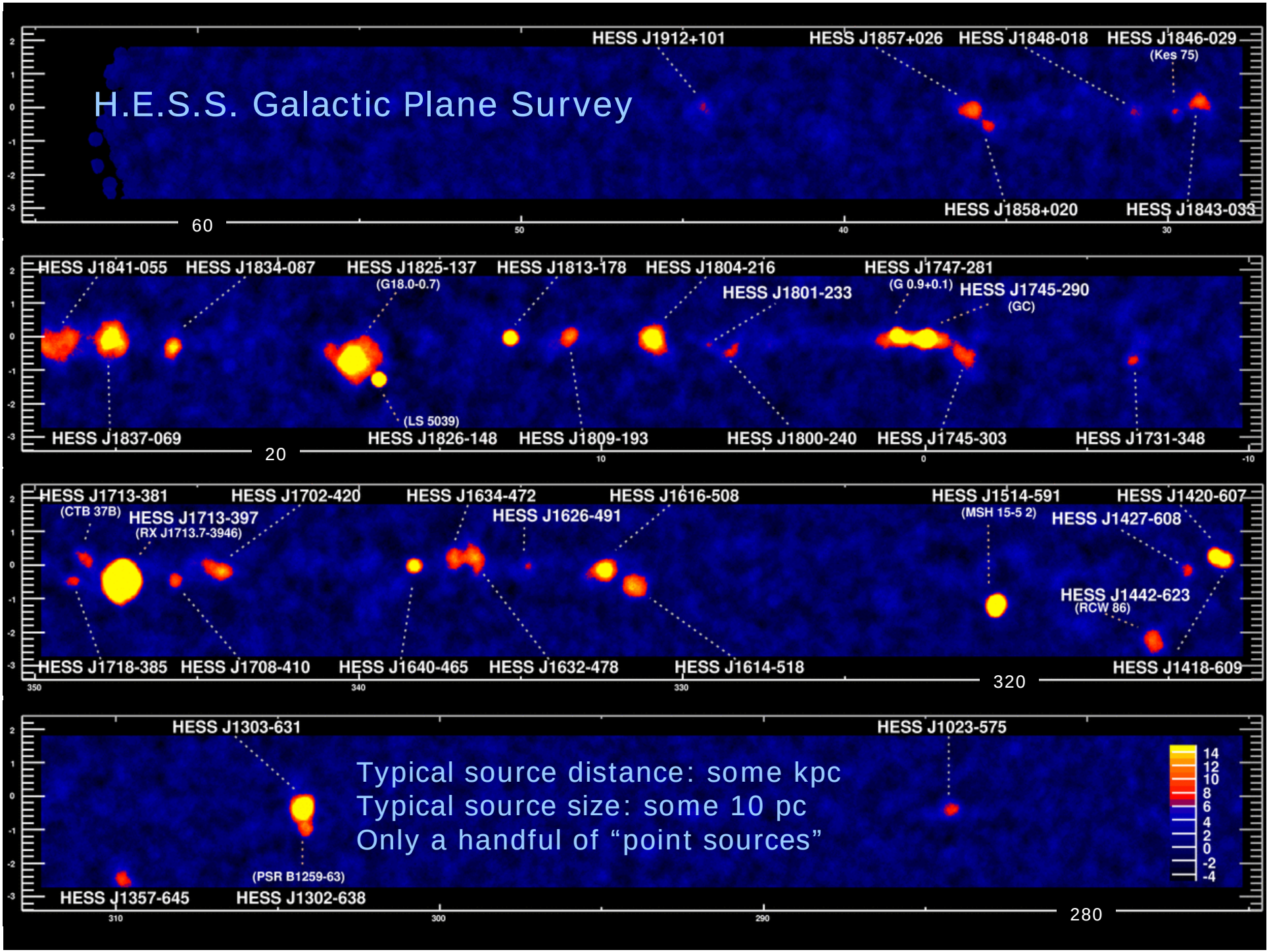

The TeV Sky
2001
90°
180°
-180°
MRK 501
PKS 2155-304
PWN
SNR
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
RX J1713.7-3946
0°
45°
0°
315°
270°


The TeV Sky
2003
90°
180°
-180°
M 87
MRK 501
PKS 2155-304
PWN
Unidentified
SNR
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
RX J1713.7-3946
0°
45°
0°
315°
270°


The TeV Sky
2005
90°
180°
-180°
M 87
MRK 501
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
45°
0°
315°
270°

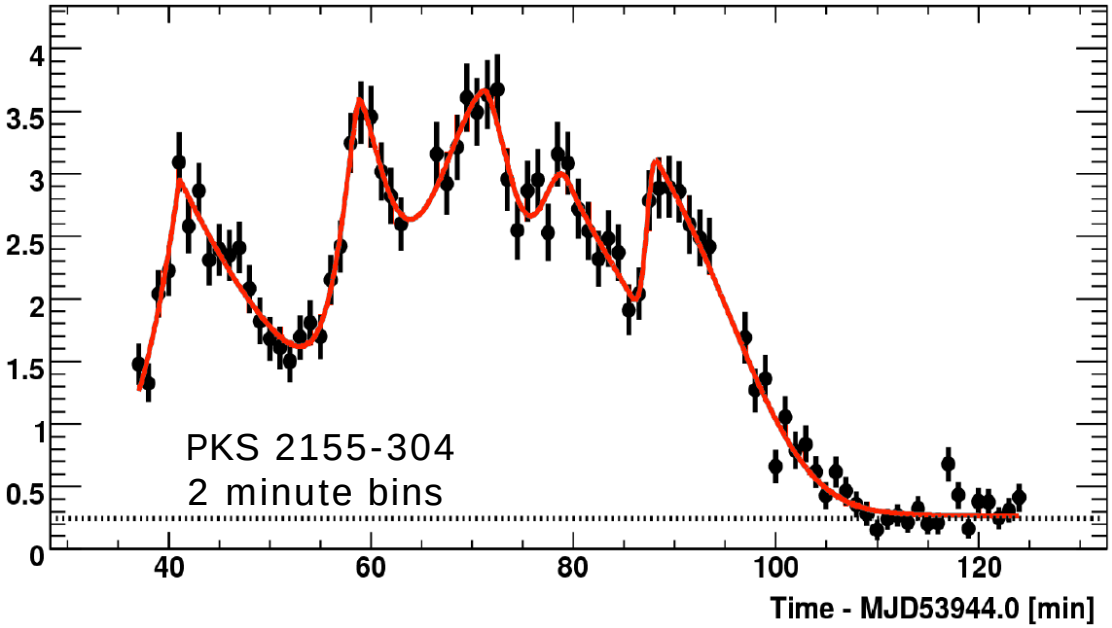

The TeV Sky
2007
90°
180°
-180°
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
LS 5039
HESS J1303-631
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
45°
0°
315°
270°


The TeV Sky
2009
90°
180°
-180°
0°
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
45°
0°
315°
270°


H.E.S.S. Galactic Plane Survey
HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1801-233
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
(CTB 37B)
HESS J1713-397
(RX J1713.7-3946)
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1420-607
HESS J1427-608
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
Typical source distance: some kpc
Typical source size: some 10 pc
Only a handful of “point sources”
(PSR B1259-63)
HESS J1357-645
HESS J1302-638
310
300
290
280
14
12
10
8
6
4
2
0
-2
-4

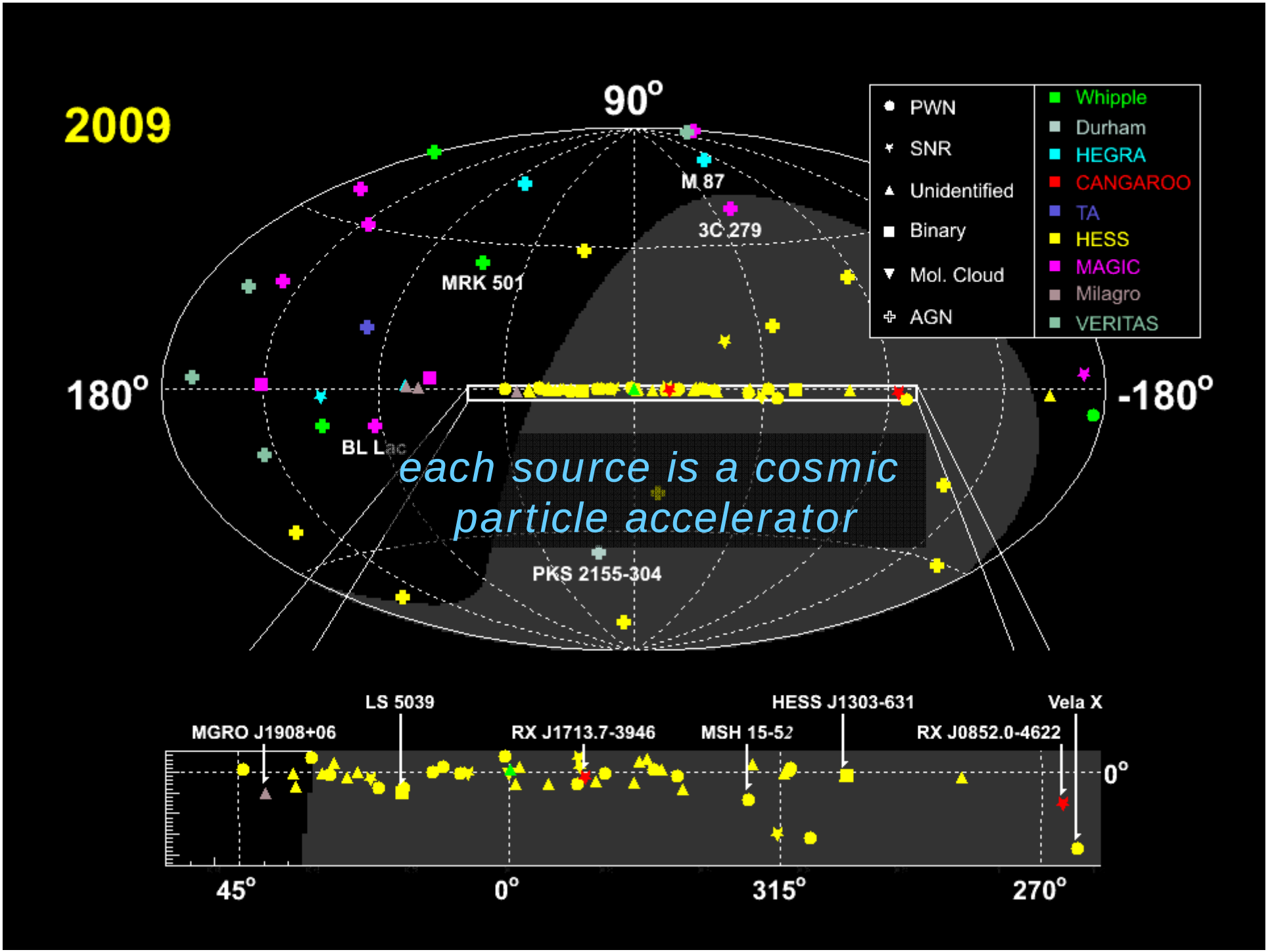
“Real Astronomy”

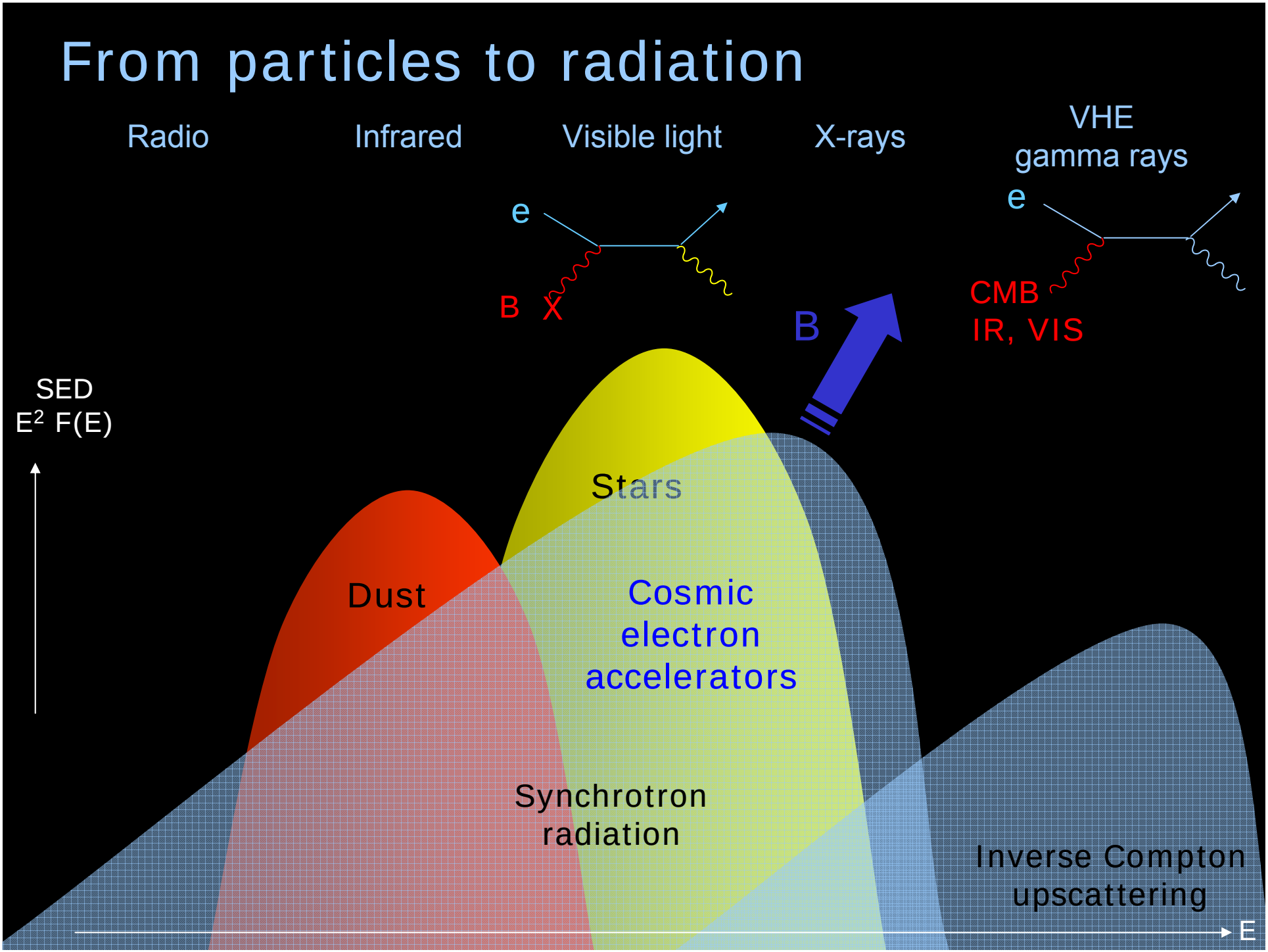
- Sky maps
- Resolved source morphologies
- Highly resolved light curves
- Source catalogs (http://tevcat.uchicago.edu/)
- Several detection techniques
- Firmly embedded in multiwavelength astronomy

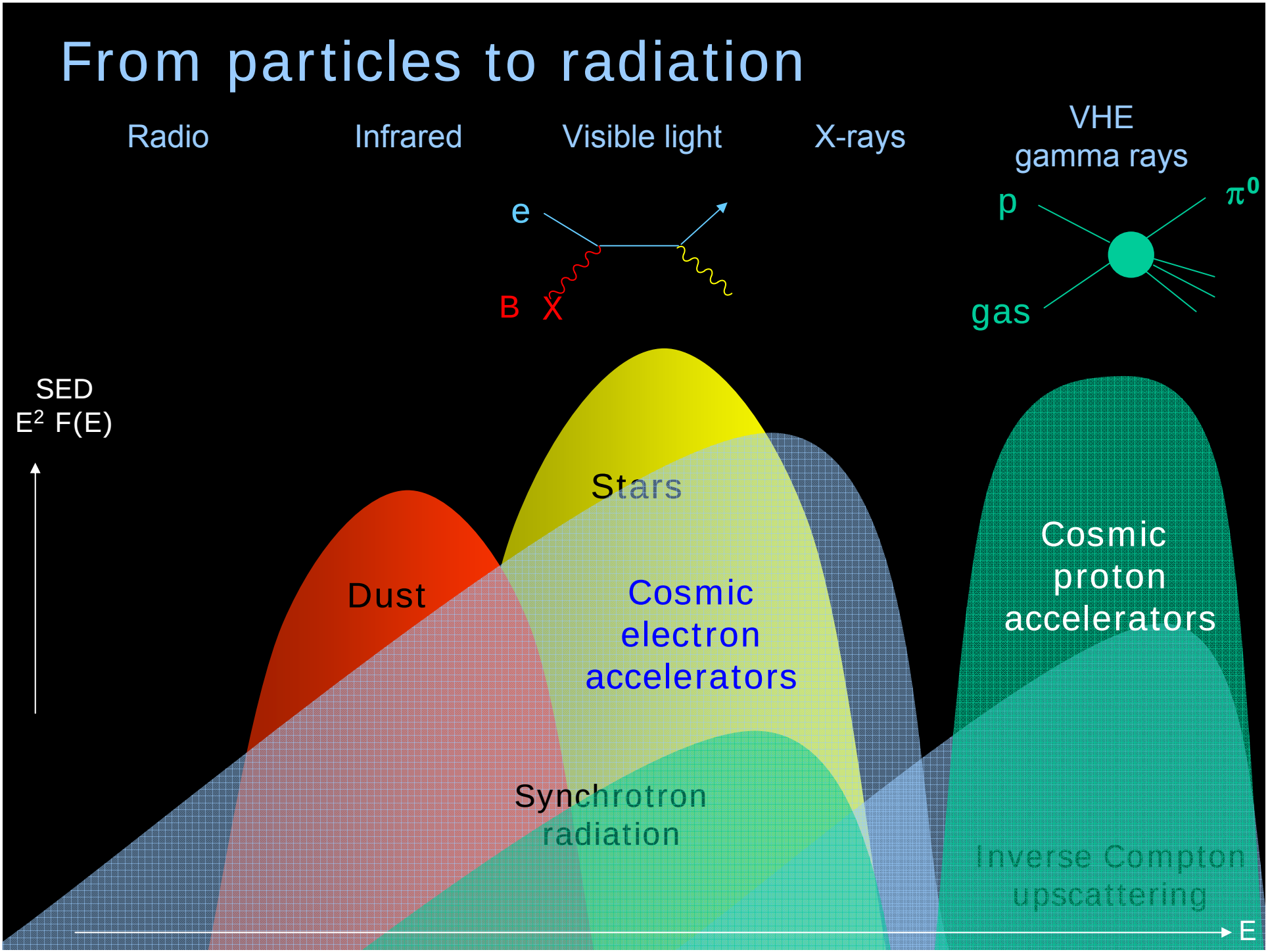


VHE AGN flares with minute rise times

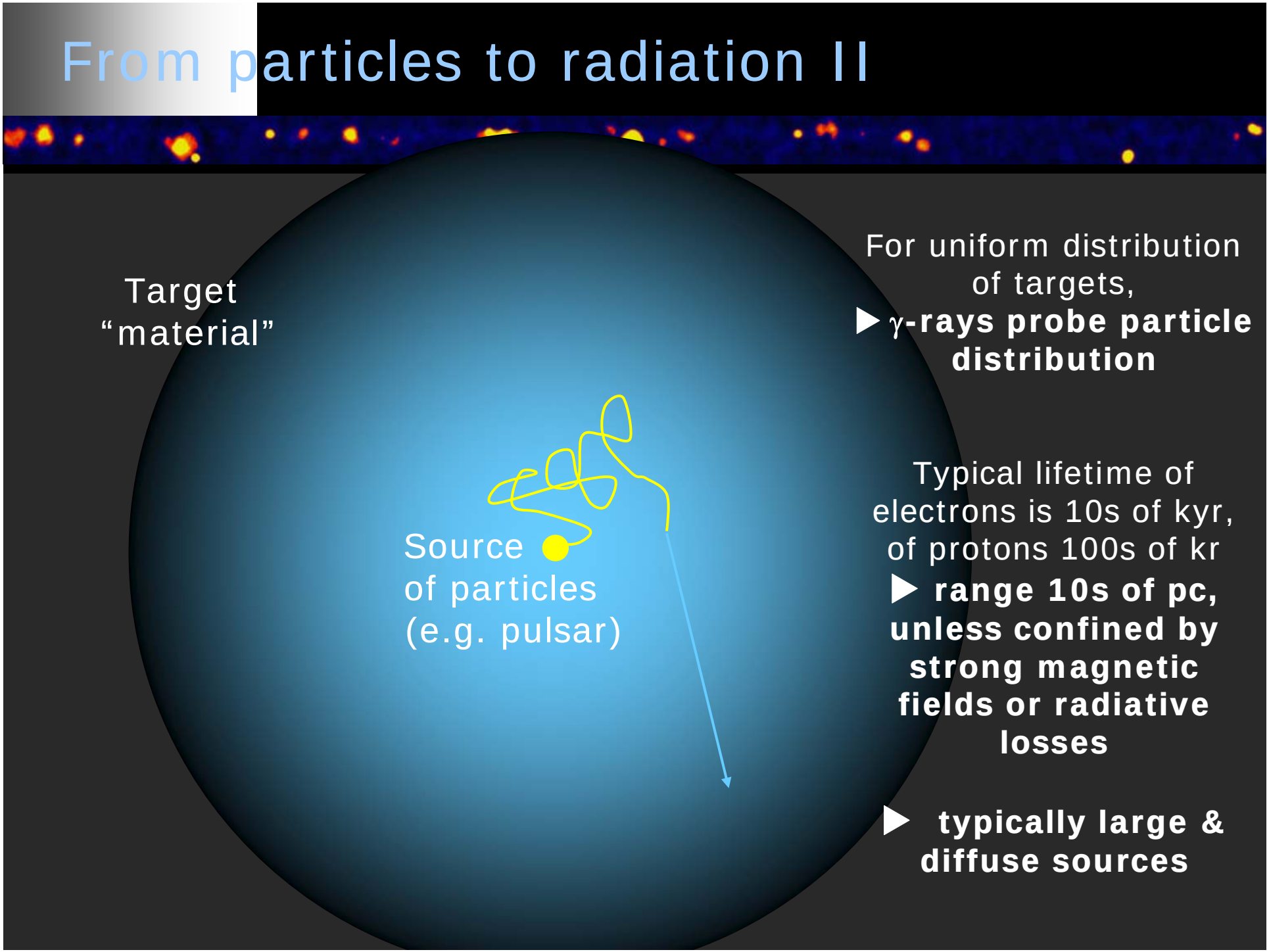
H.E.S.S., MAGIC: speed of light varies by less than $1.5 \cdot 10^{-15}$ over a $\Delta E = 1$ TeV


2009
90°
180°
-180°
M 87
3C 279
MRK 501
BL Lac
PKS 2155-304
PWN
SNR
Unidentified
Binary
Mol. Cloud
AGN
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
VERITAS
each source is a cosmic particle accelerator
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
315°
270°


From particles to radiation
Radio
Infrared
Visible light
X-rays
VHE
gamma rays
e
B
X
B
e
CMB
IR, VIS
SED
E2 F(E)
Stars
Dust
Cosmic
electron
accelerators
Synchrotron
radiation
Inverse Compton
upscattering
E


From particles to radiation
Radio
Infrared
Visible light
X-rays
VHE
gamma rays
e
B
X
p
π0
gas
SED
E2 F(E)
Stars
Dust
Cosmic
electron
accelerators
Cosmic
proton
accelerators
Synchrotron
radiation
Inverse Compton
upscattering
E

From particles to radiation II



For uniform distribution of targets,

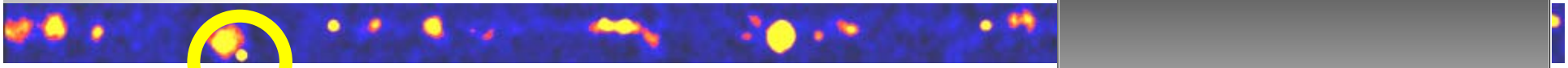
▶ **γ-rays probe particle distribution**

Typical lifetime of electrons is 10s of kyr, of protons 100s of kr

▶ **range 10s of pc, unless confined by strong magnetic fields or radiative losses**

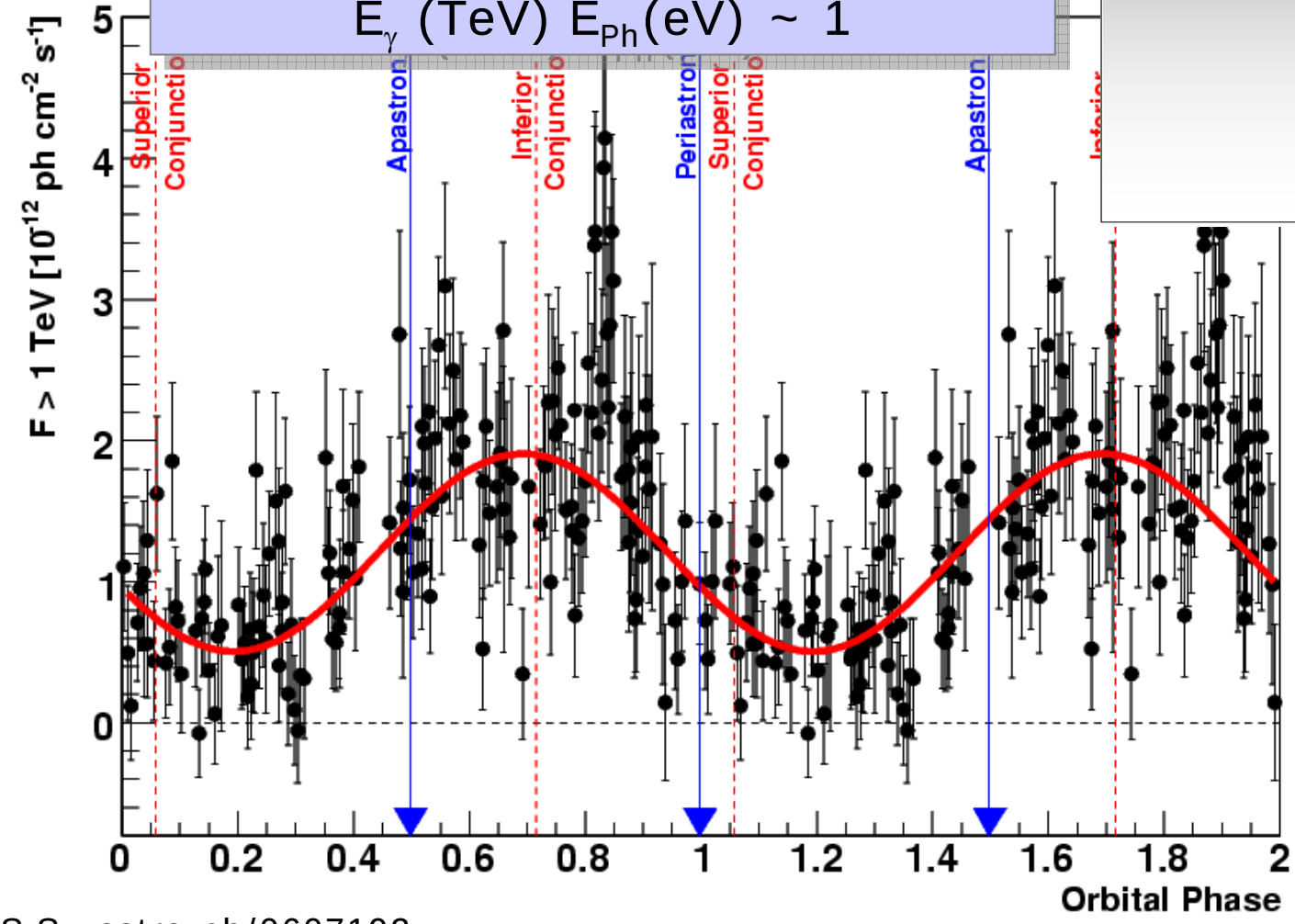
▶ **typically large & diffuse sources**

Source opacity: LS 5039



e^+e^- pair production threshold:

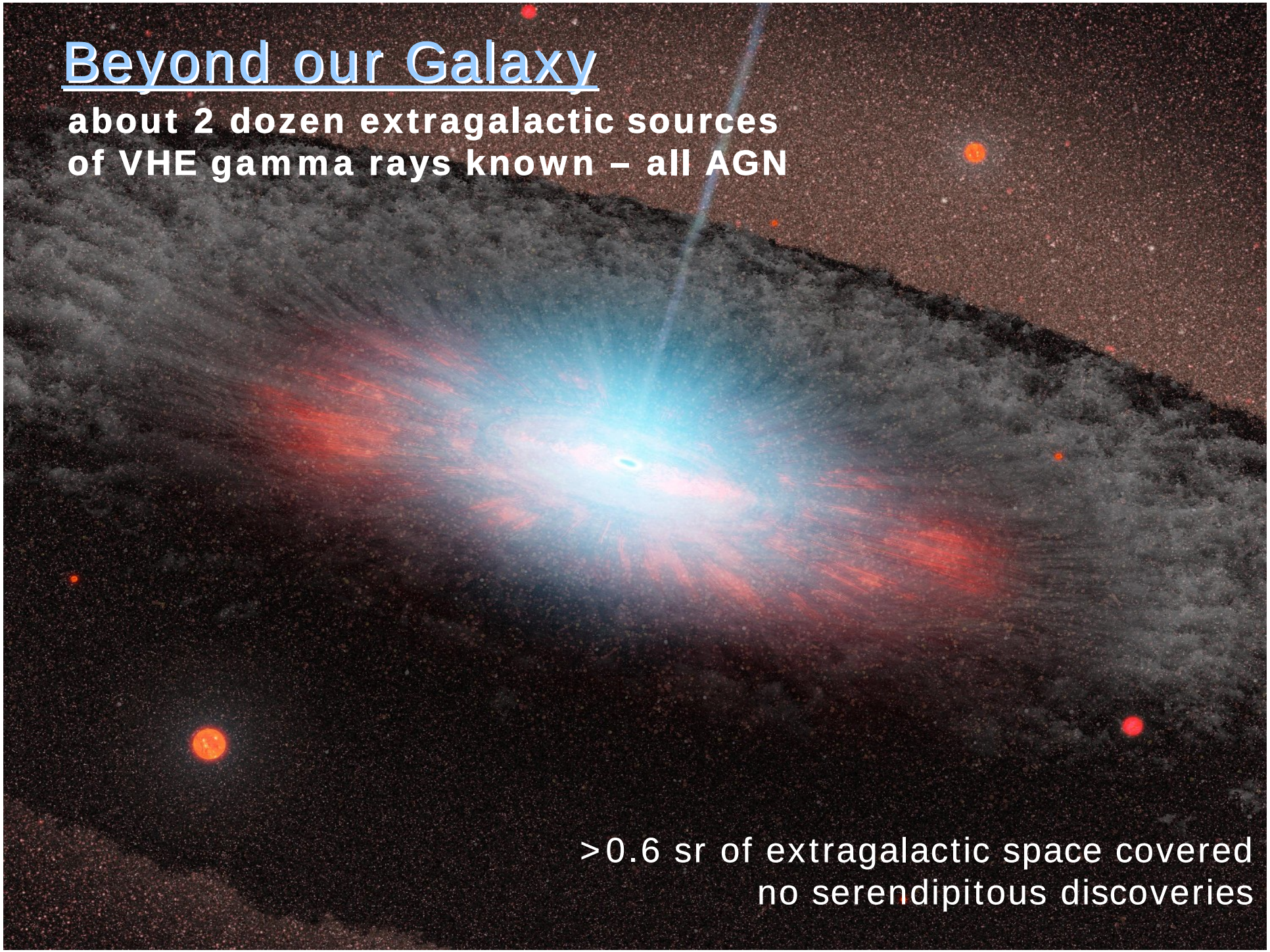
E_γ (TeV) E_{Ph}(eV) ~ 1



Binary LS 5039
VHE gamma-ray light curve folded using optical period

Data repeated for 2 cycles

H.E.S.S., astro-ph/0607192


Beyond our Galaxy
about 2 dozen extragalactic sources
of VHE gamma rays known – all AGN
>0.6 sr of extragalactic space covered
no serendipitous discoveries

Extragalactic VHE gamma-ray sources

1	3C279	FSRQ	2008	z = 0.5362
2	3C66A	LBL	1998	z = 0.444
3	PG 1553+113	HBL	2006	z = 0.35
4	1ES 1011+496	HBL	2007	z = 0.212
5	1ES 0347-121	HBL	2007	z = 0.188
6	1ES 1101-232	HBL	2006	z = 0.186
7	1ES 1218+304	HBL	2006	z = 0.182
8	H 2356-309	HBL	2006	z = 0.165
9	1ES 0229+20	HBL	2006	z = 0.14
10	1ES 0806+524	HBL	2008	z = 0.138
11	H 1426+428	HBL	2002	z = 0.129
12	PKS 2155-304	HBL	1999	z = 0.116
13	W Comae	LBL	2008	z = 0.102
14	RGB J0152+017	HBL	2008	z = 0.08
15	PKS 2005-489	HBL	2005	z = 0.071
16	BL Lacertae	LBL	2001	z = 0.069
17	1ES 1959+650	HBL	1999	z = 0.048
18	Markarian 180	HBL	2006	z = 0.045
19	1ES 2344+514	HBL	1998	z = 0.044
20	Markarian 501	HBL	1996	z = 0.034
21	Markarian 421	HBL	1992	z = 0.031
22	3C66B(?)	FRI	2008	z = 0.021
23	M87	FRI	2003	z = 0.0044
24	Centaurus A	FRI	2009	3800 kpc

soon more, e.g.
RGB J0710+591
VERITAS ATel 1941

Source: http://tevcat.uchicago.edu/

Extragalactic VHE gamma-ray sources

1	3C279	FSRQ	2008	z = 0.5362
2	3C66A	LBL	1998	z = 0.444
3	PG 1553+113	HBL	2006	z = 0.35
4	1ES 1011+496	HBL	2007	z = 0.212
5	1ES 0347-121	HBL	2007	z = 0.188
6	1ES 1101-232	HBL	2006	z = 0.186
7	1ES 1218+304	HBL	2006	z = 0.182
8	H 2356-309	HBL	2006	z = 0.165
9	1ES 0229+20	HBL	2006	z = 0.14
10	1ES 0806+524	HBL	2008	z = 0.138
11	H 1426+428	HBL	2002	z = 0.129
12	PKS 2155-304	HBL	1999	z = 0.116
13	W Comae	LBL	2008	z = 0.102
14	RGB J0152+017	HBL	2008	z = 0.08
15	PKS 2005-489	HBL	2005	z = 0.071
16	BL Lacertae	LBL	2001	z = 0.069
17	1ES 1959+650	HBL	1999	z = 0.048
18	Markarian 180	HBL	2006	z = 0.045
19	1ES 2344+514	HBL	1998	z = 0.044
20	Markarian 501	HBL	1996	z = 0.034
21	Markarian 421	HBL	1992	z = 0.031
22	3C66B(?)	FRI	2008	z = 0.021
23	M87	FRI	2003	z = 0.0044
24	Centaurus A	FRI	2009	3800 kpc

soon more, e.g.
RGB J0710+591
VERITAS ATel 1941

Source: http://tevcat.uchicago.edu/

Extragalactic VHE gamma-ray sources

1	3C279	FSRQ	2008	z = 0.5362
2	3C66A	LBL	1998	z = 0.444
3	PG 1553+113	HBL	2006	z = 0.35
4	1ES 1011+496	HBL	2007	z = 0.212
5	1ES 0347-121	HBL	2007	z = 0.188
6	1ES 1101-232	HBL	2006	z = 0.186
7	1ES 1218+304	HBL	2006	z = 0.182
8	H 2356-309	HBL	2006	z = 0.165
9	1ES 0229+20	HBL	2006	z = 0.14
10	1ES 0806+524	HBL	2008	z = 0.138
11	H 1426+428	HBL	2002	z = 0.129
12	PKS 2155-304	HBL	1999	z = 0.116
13	W Comae	LBL	2008	z = 0.102
14	RGB J0152+017	HBL	2008	z = 0.08
15	PKS 2005-489	HBL	2005	z = 0.071
16	BL Lacertae	LBL	2001	z = 0.069
17	1ES 1959+650	HBL	1999	z = 0.048
18	Markarian 180	HBL	2006	z = 0.045
19	1ES 2344+514	HBL	1998	z = 0.044
20	Markarian 501	HBL	1996	z = 0.034
21	Markarian 421	HBL	1992	z = 0.031
22	3C66B(?)	FRI	2008	z = 0.021
23	M87	FRI	2003	z = 0.0044
24	Centaurus A	FRI	2009	3800 kpc

soon more, e.g.
RGB J0710+591
VERITAS ATel 1941

Source: http://tevcat.uchicago.edu/

Extragalactic VHE gamma-ray sources

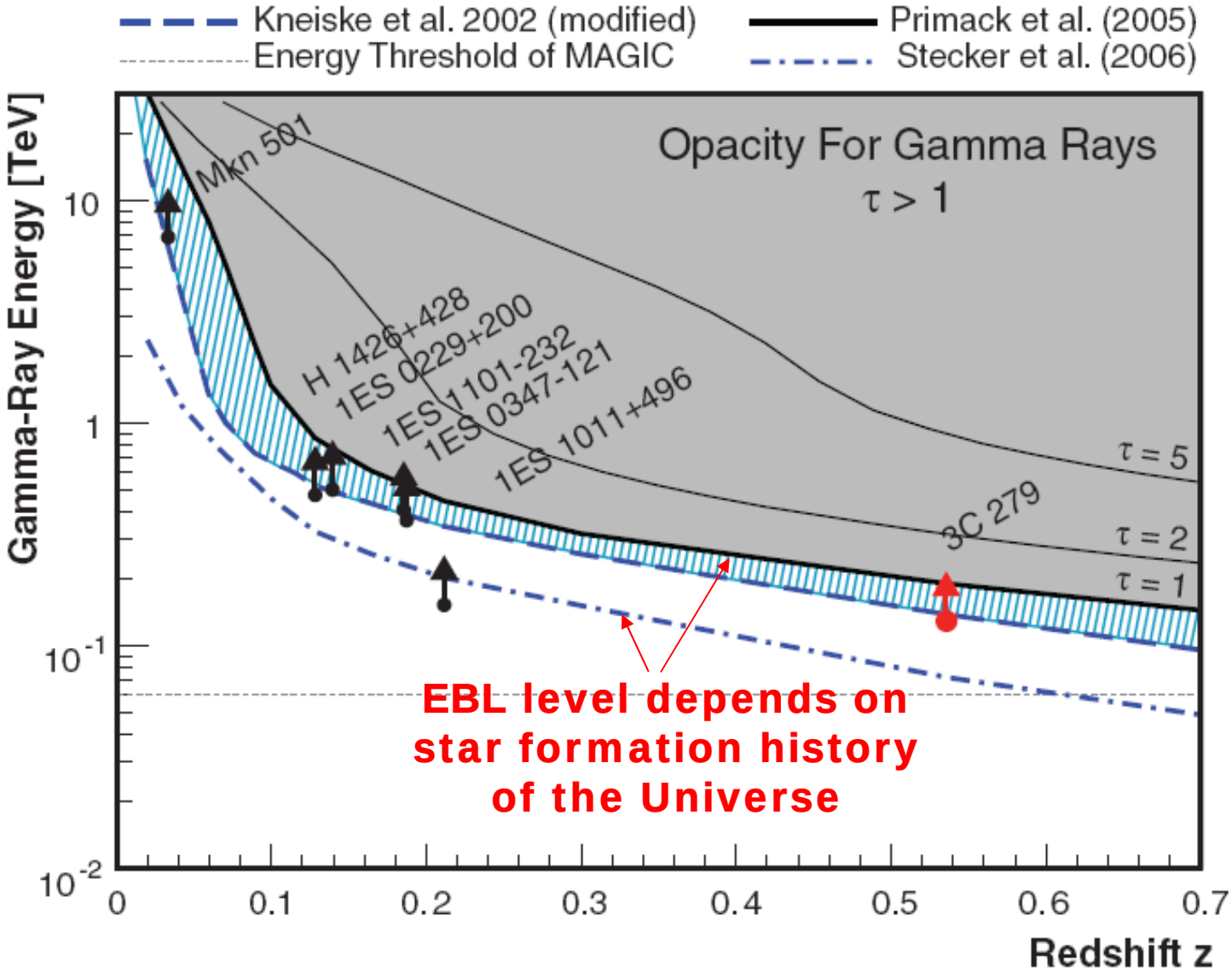
1	3C279	FSRQ	2008	z = 0.5362
2	3C66A	LBL	1998	z = 0.444
3	PG 1553+113	HBL	2006	z = 0.35
4	1ES 1011+496	HBL	2007	z = 0.212
5	1ES 0347-121	HBL	2007	z = 0.188
6	1ES 1101-232	HBL	2006	z = 0.186
7	1ES 1218+304	HBL	2006	z = 0.182
8	H 2356-309	HBL	2006	z = 0.165
9	1ES 0229+20	HBL	2006	z = 0.14
10	1ES 0806+524	HBL	2008	z = 0.138
11	H 1426+428	HBL	2002	z = 0.129
12	PKS 2155-304	HBL	1999	z = 0.116
13	W Comae	LBL	2008	z = 0.102
14	RGB J0152+017	HBL	2008	z = 0.08
15	PKS 2005-489	HBL	2005	z = 0.071
16	BL Lacertae	LBL	2001	z = 0.069
17	1ES 1959+650	HBL	1999	z = 0.048
18	Markarian 180	HBL	2006	z = 0.045
19	1ES 2344+514	HBL	1998	z = 0.044
20	Markarian 501	HBL	1996	z = 0.034
21	Markarian 421	HBL	1992	z = 0.031
22	3C66B(?)	FRI	2008	z = 0.021
23	M87	FRI	2003	z = 0.0044
24	Centaurus A	FRI	2009	3800 kpc

soon more, e.g.
RGB J0710+591
VERITAS ATel 1941

Source: http://tevcat.uchicago.edu/

Gamma-ray horizon due to pair production

target: Extragalactic Background Light (EBL)

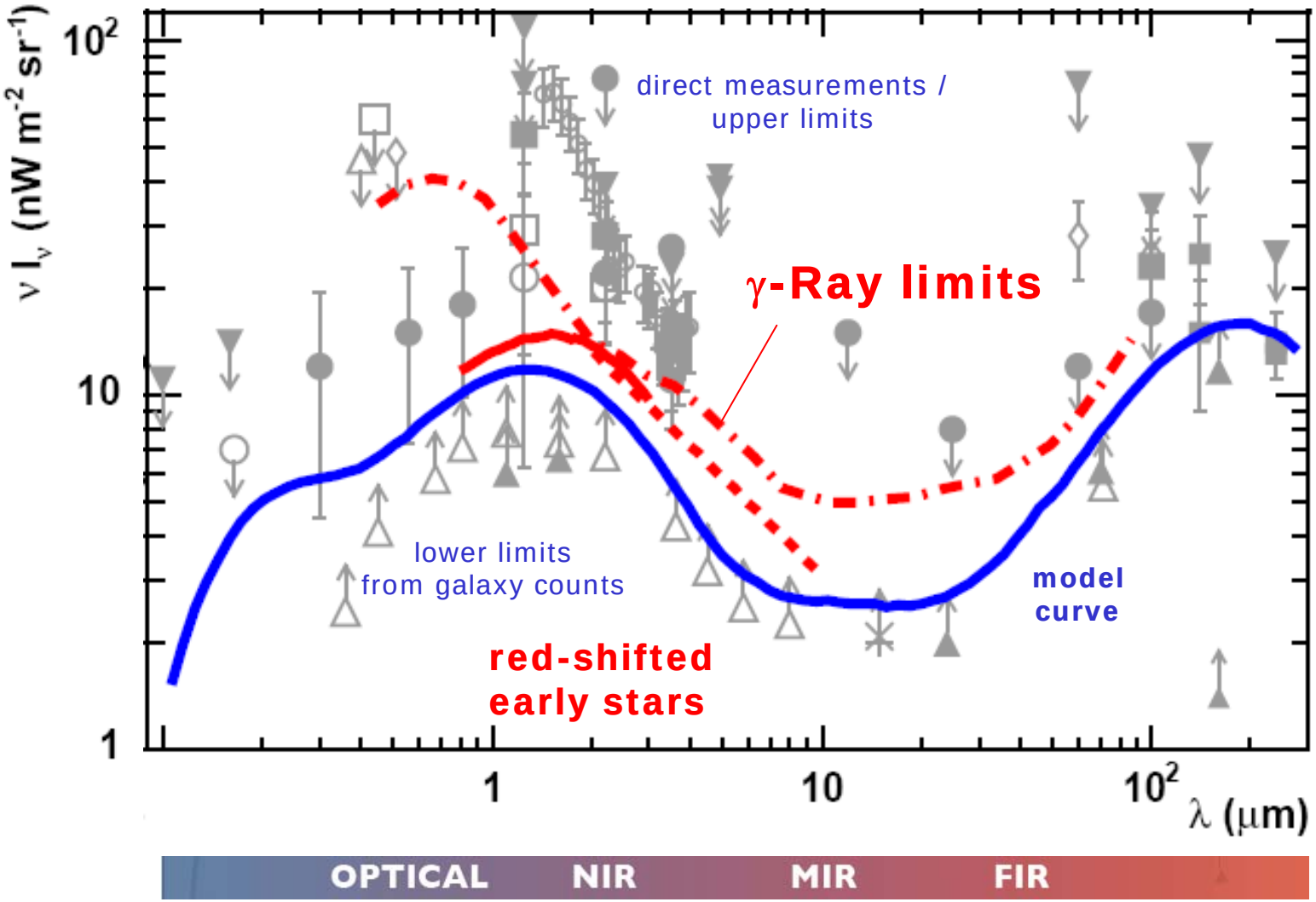


MAGIC
Science
320 (2008)

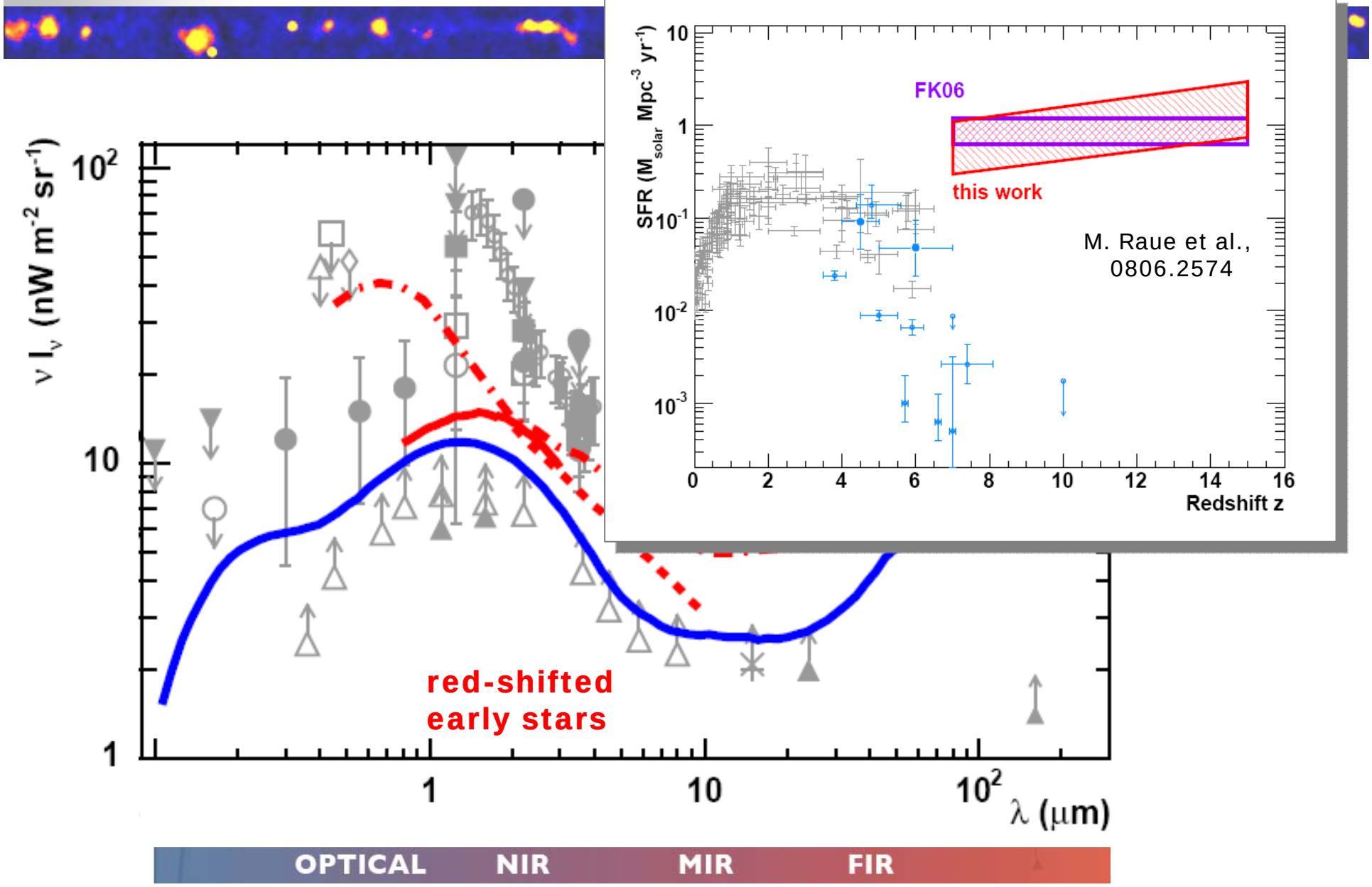
Relevant EBL range: 1-10 μm

EBL limits

Raue & Mazin 0802.0129



Star formation in the early Universe



Understanding TeV Blazars
Mrk 421 flare

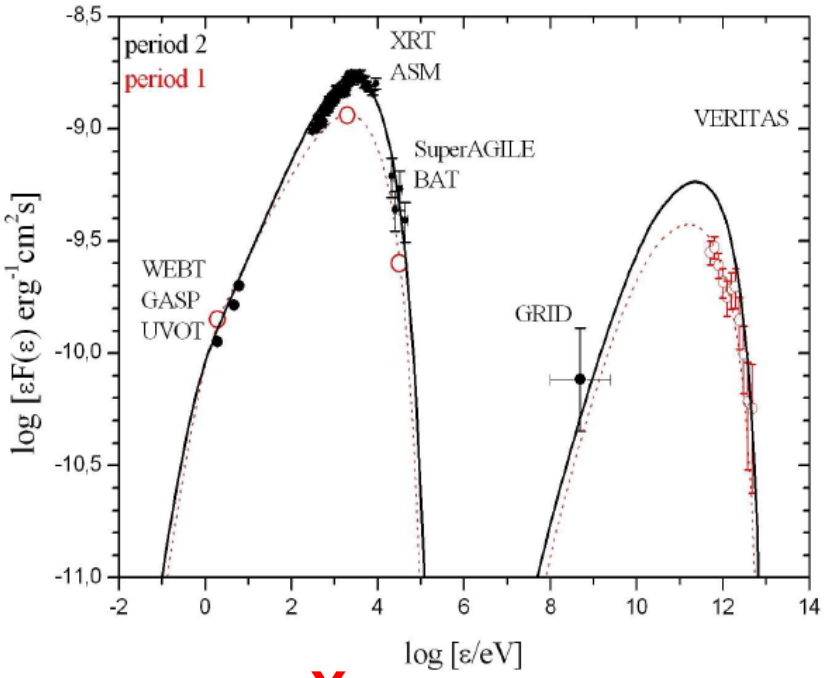
AGILE, Gasp-Webt, MAGIC, VERITAS, arXiv:0812.1500

optical

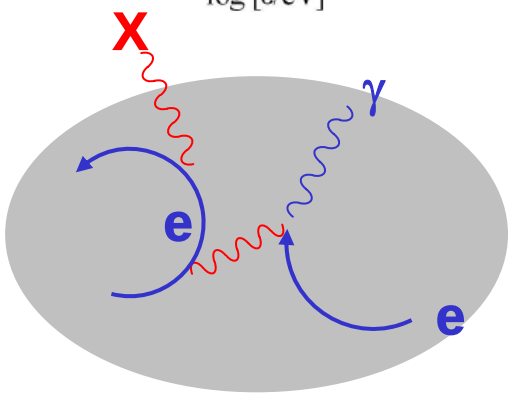
X-ray

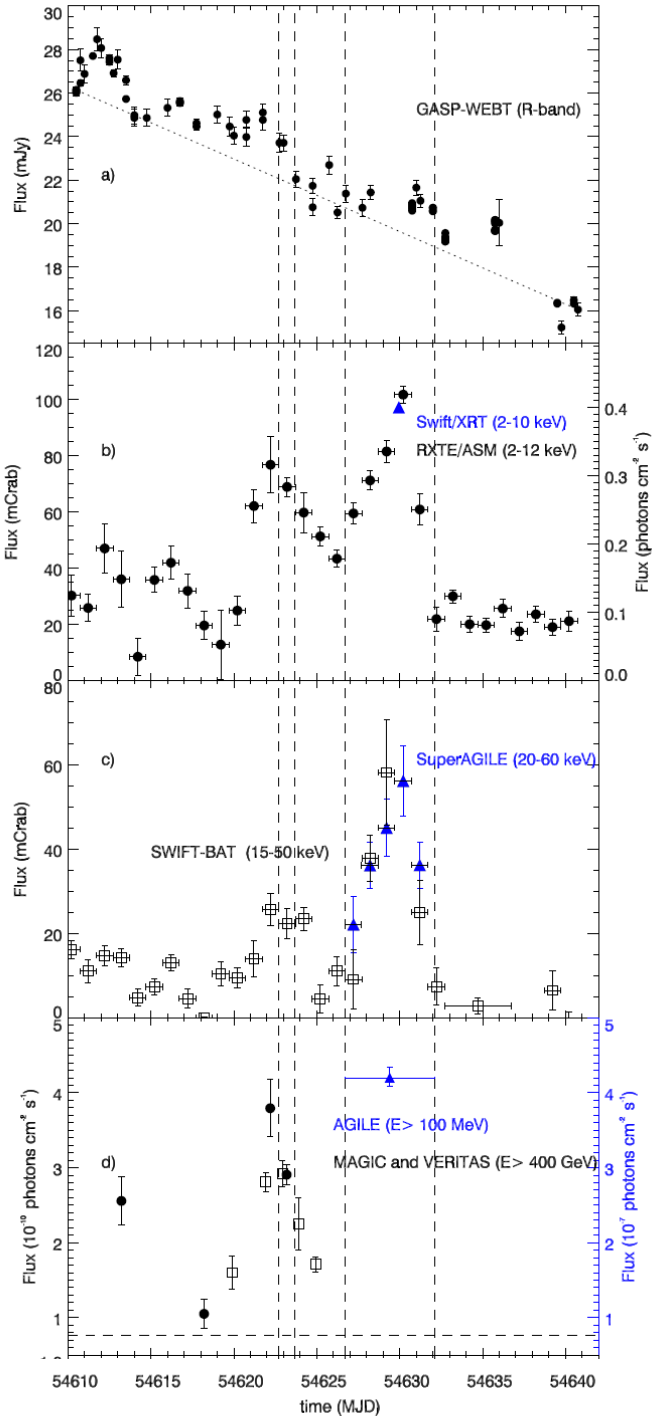
hard X-ray

HE & VHE gamma-ray



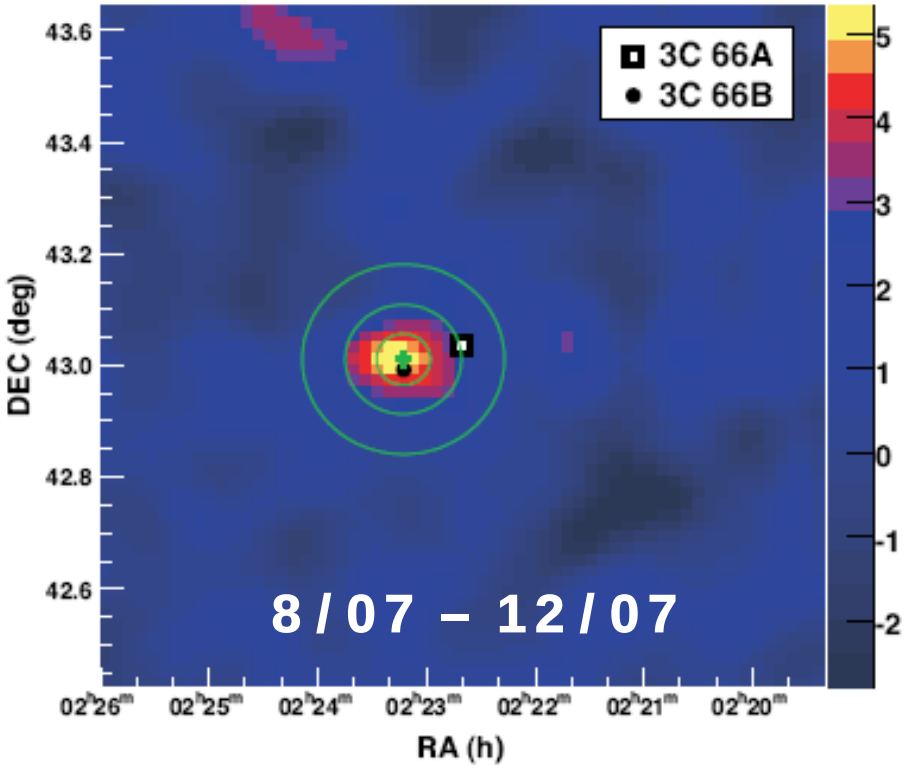
SSC model





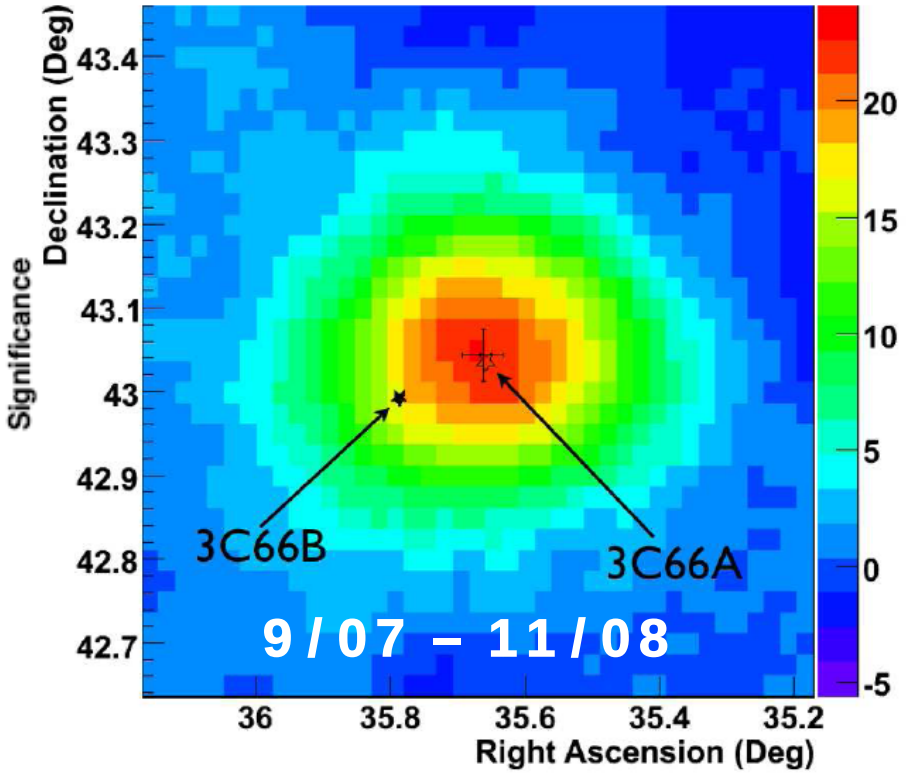
3C 66A (z=0.44) vs 3C 66B (FRI, z = 0.02)

MAGIC, arXiv:0810.4712



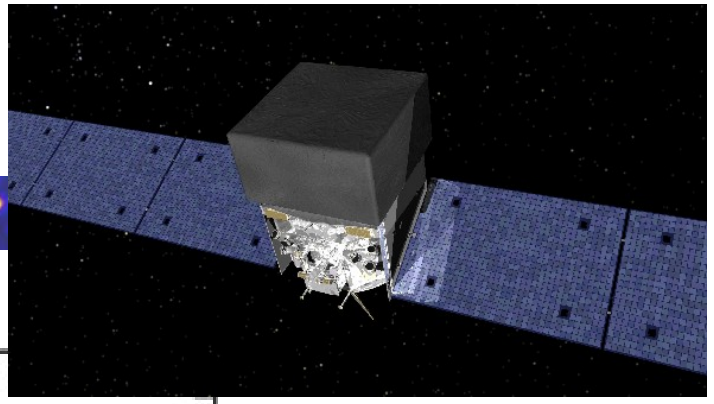
6 σ, with 85% prob. 3C 66B
2% Crab, Index 3.1±0.3±0.2

VERITAS, arXiv:0901.4527

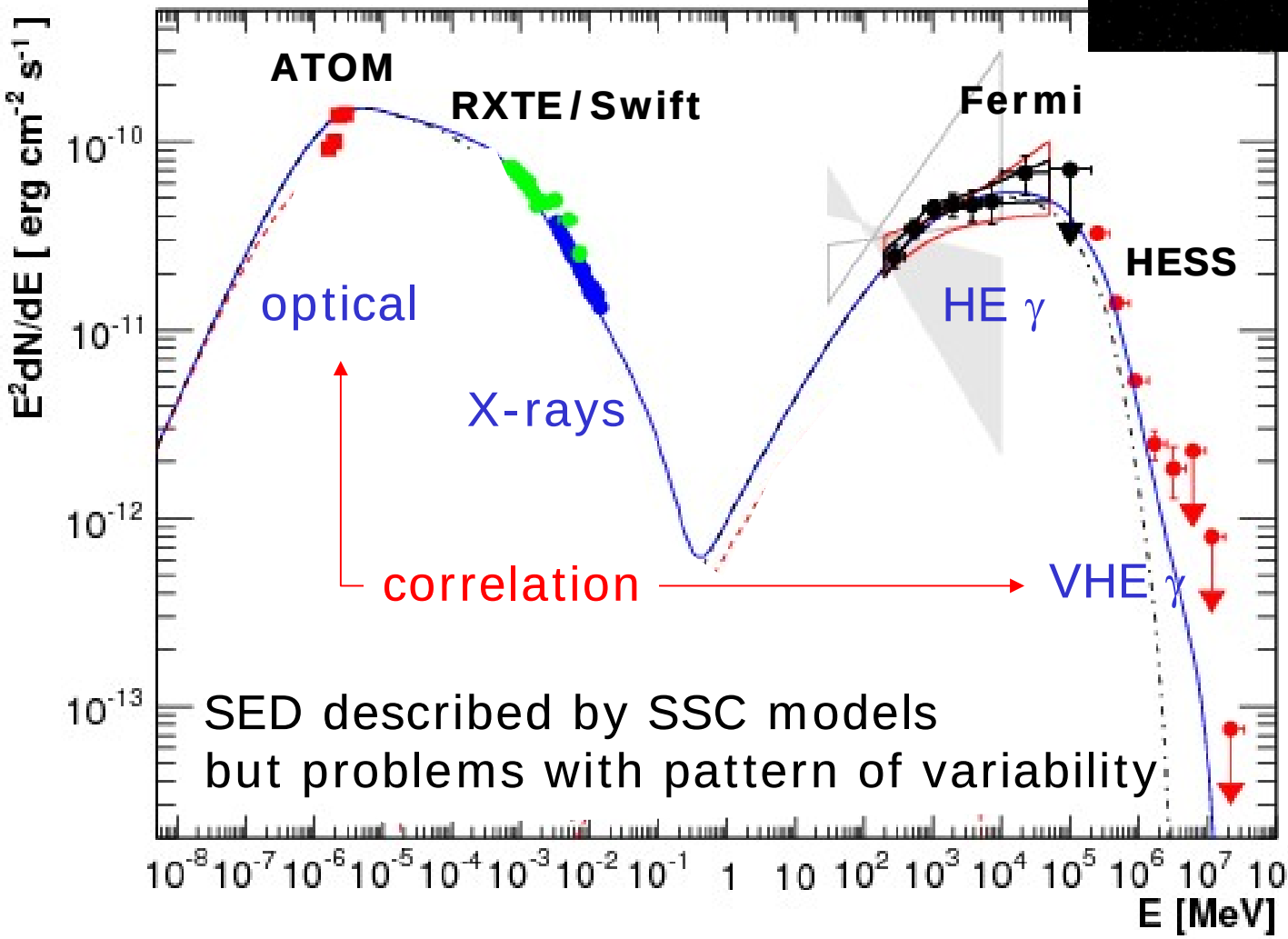


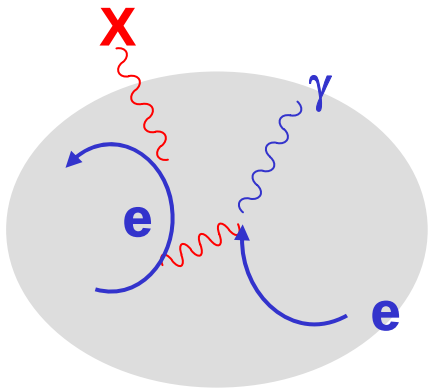
21 σ, 4 σ away from 3C 66A
6% Crab, Index 4.1±0.4±0.6

Understanding TeV Blazars: PSK 2155-304



Fermi & H.E.S.S., arXiv:0903.2924

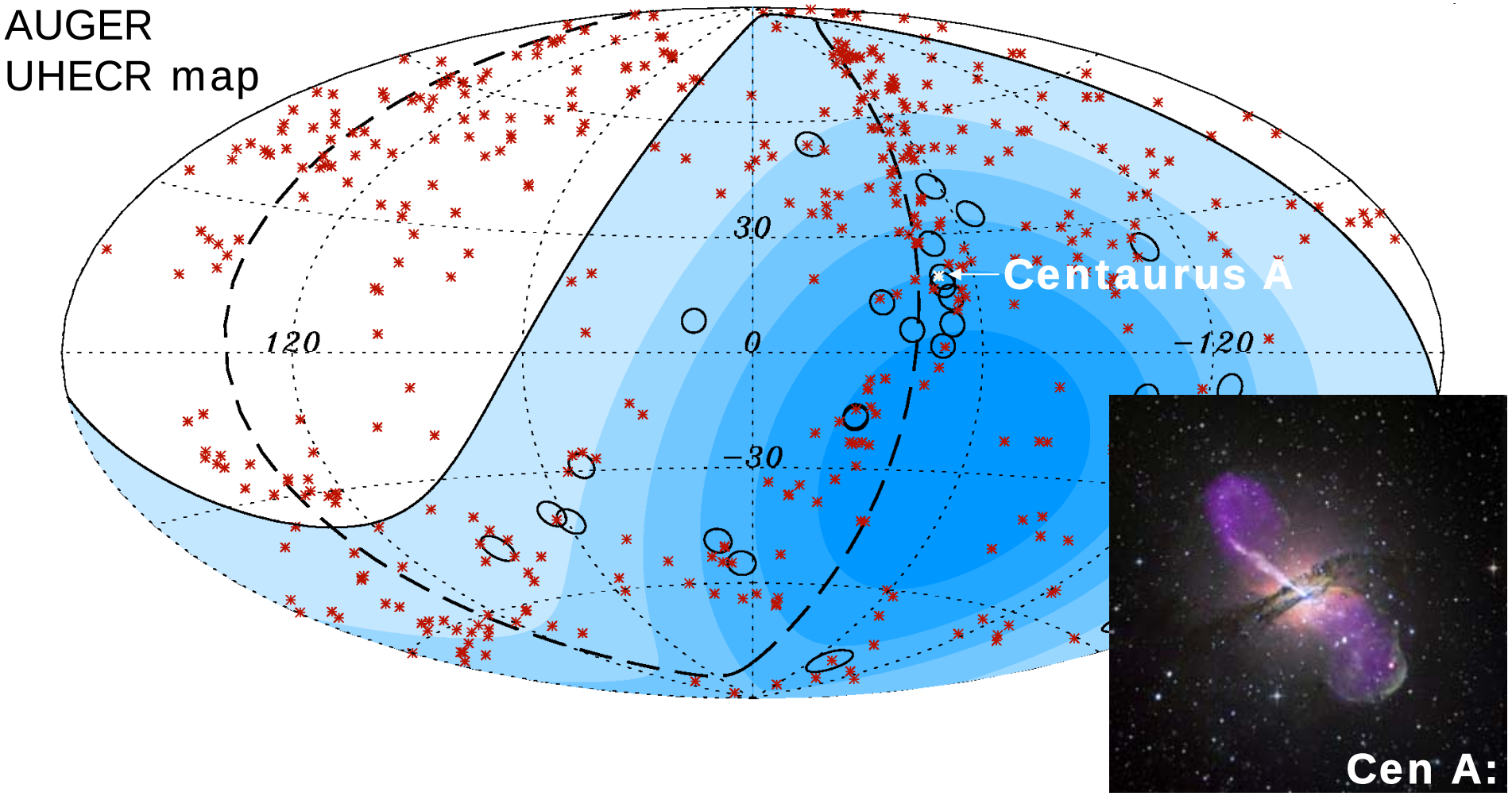




SSC model

"Blob" R ~10^{17} cm
Doppler factor Γ ~30
Field B ~ 0.02 G

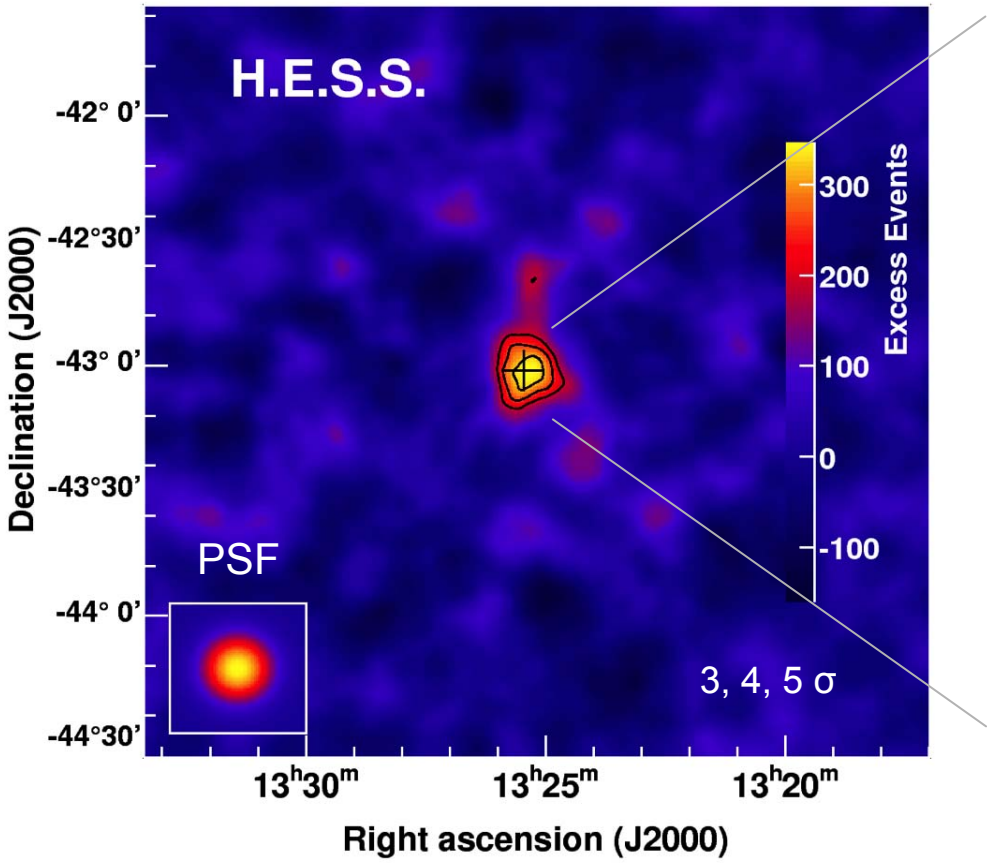
Nearby radio galaxies: Centaurus A

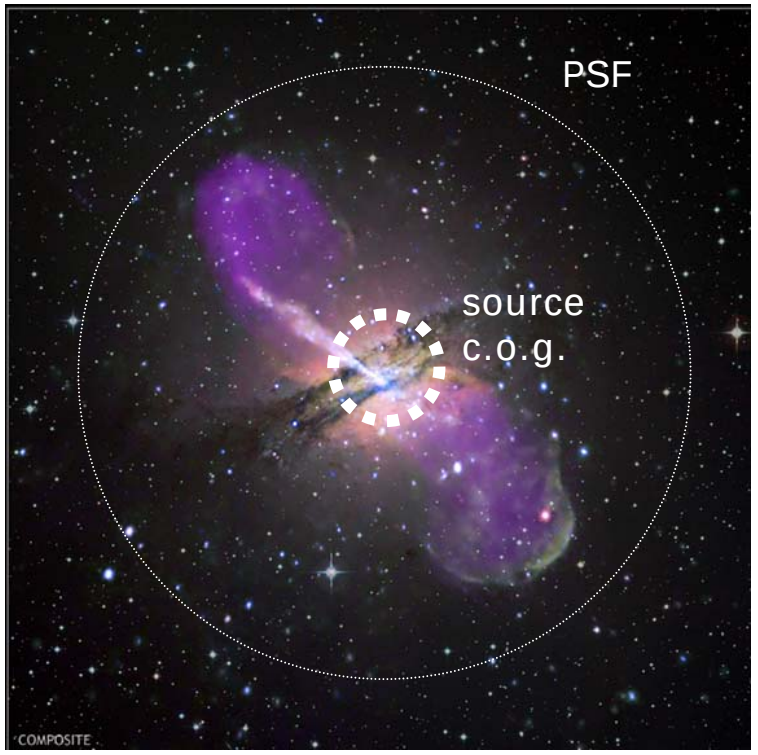


energy flux of one UHECR in AUGER is roughly 10^{-2} x Crab flux

6 x 10^7 solar mass BH
4 Mpc distance

Nearby radio galaxies: Centaurus A



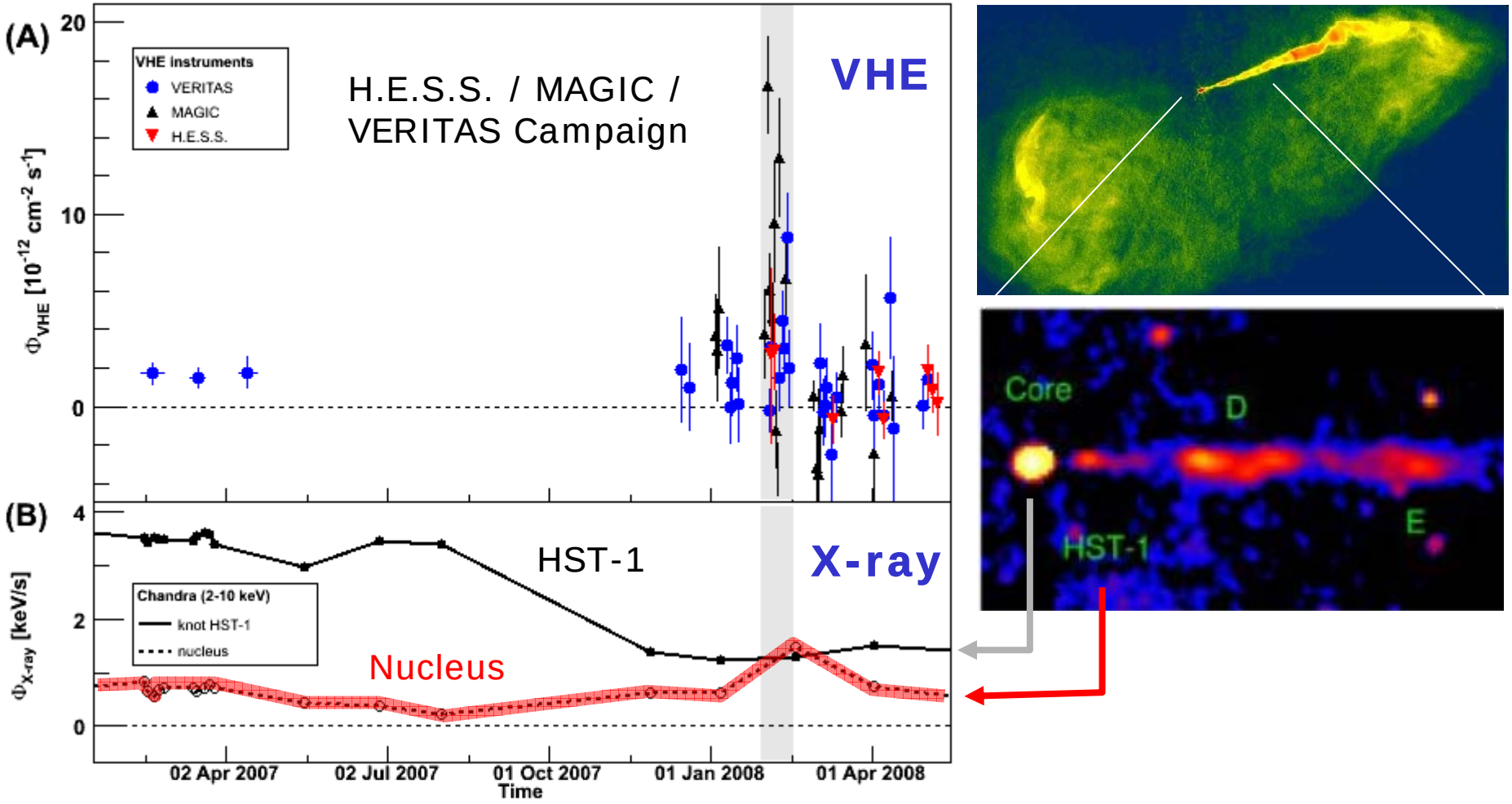


γ-rays from core or from extended jets?

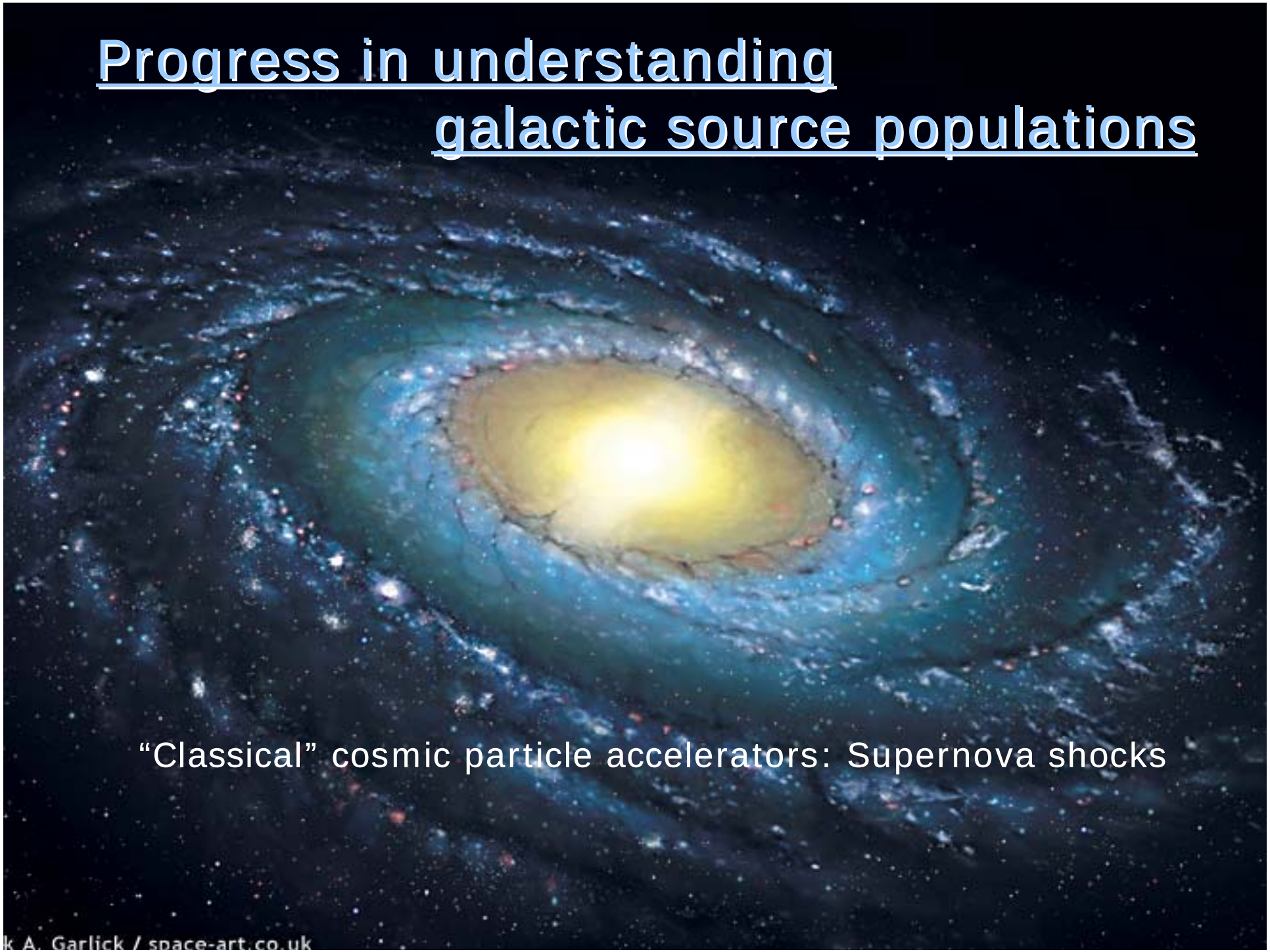
Flux ~0.8% Crab
Spectral index 2.7±0.5±0.2

H.E.S.S., arXiv:0903.1582

Nearby AGN: M 87



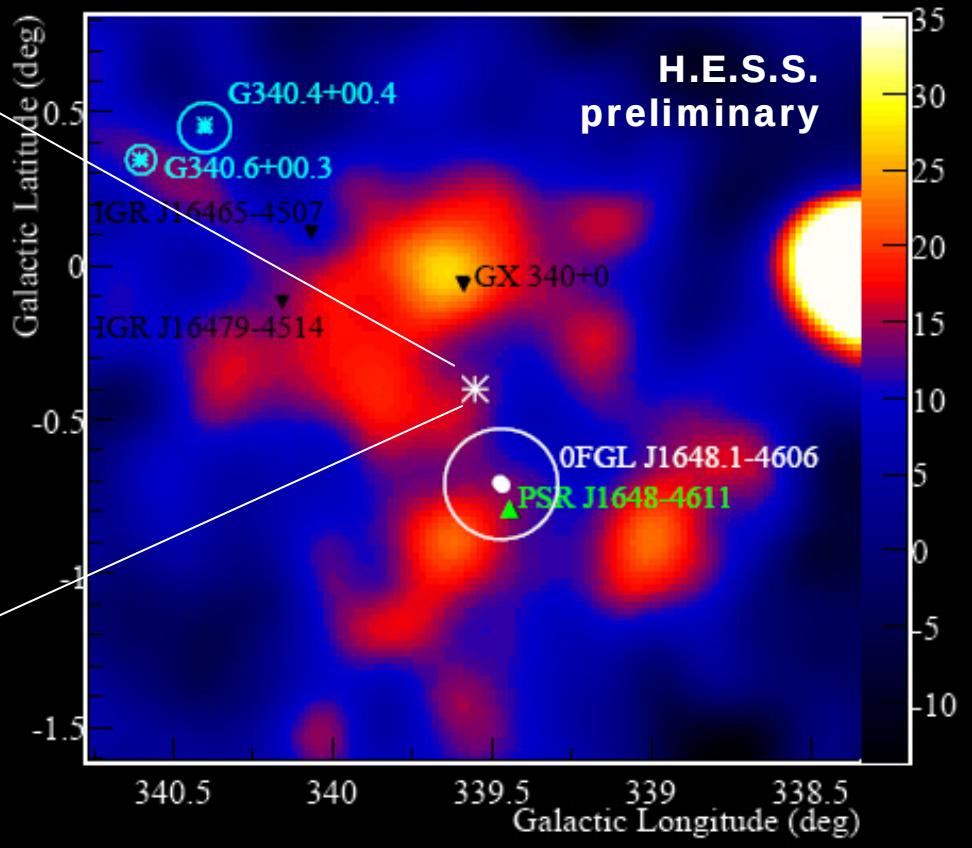
Progress in understanding galactic source populations



"Classical" cosmic particle accelerators: Supernova shocks

Massive stars, the first stage: Stellar winds

Westerlund 1



- most massive compact young star cluster
- 13+ WR stars, 30+ hot supergiant stars
- in 0.5° gas bubble

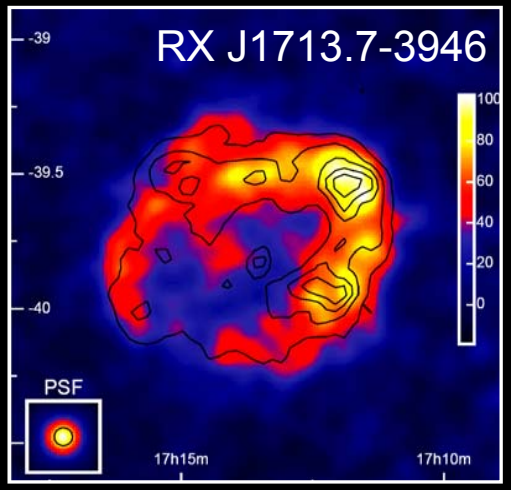
Similar for Wd 2

Supernova shocks

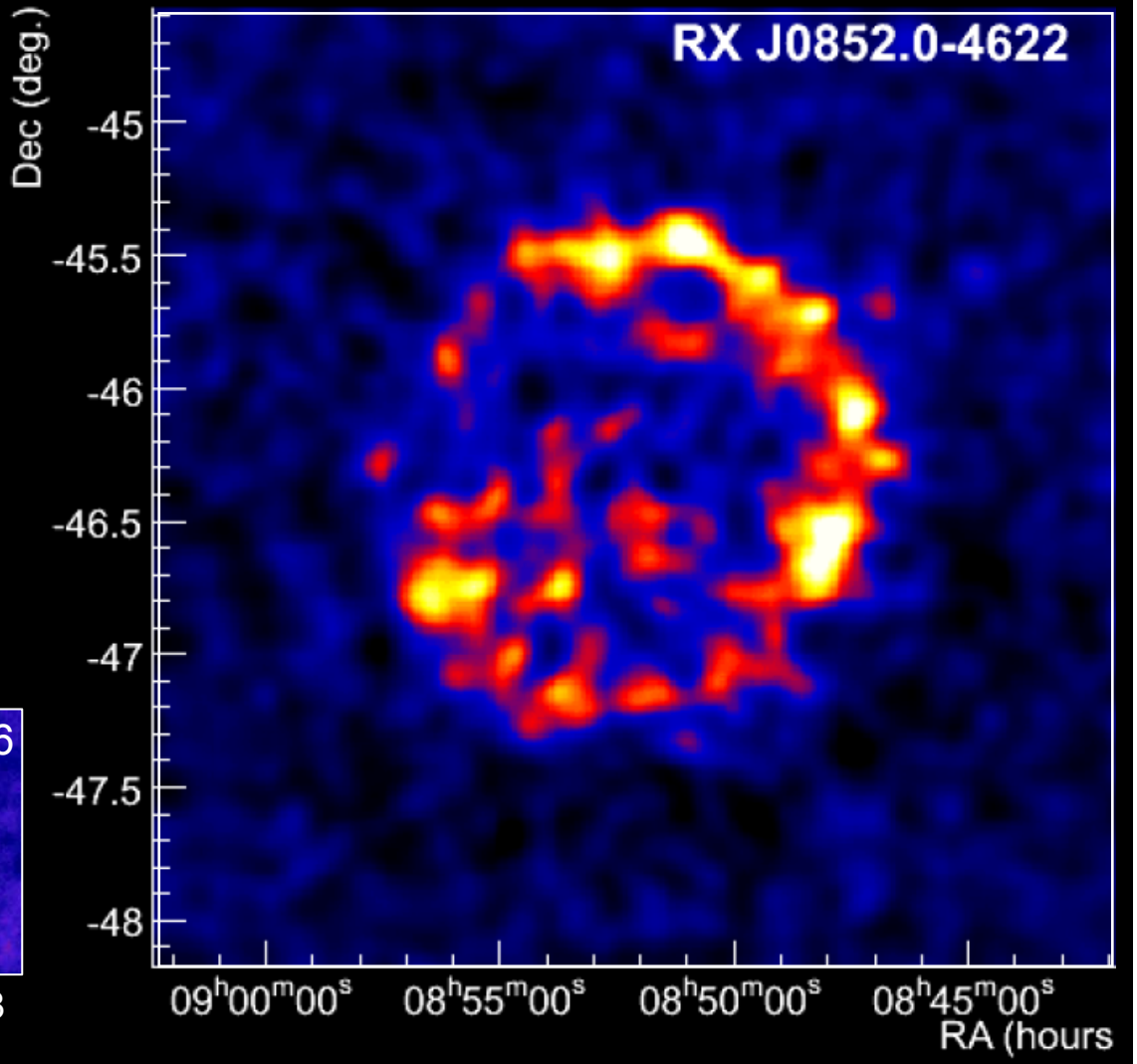
here: resolved shell-type SNR

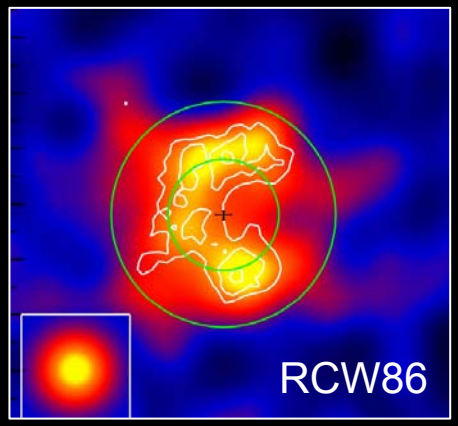
Maps ~ to scale

H.E.S.S. 2004

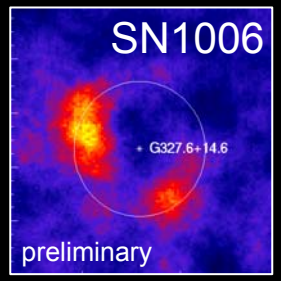


H.E.S.S. 2005





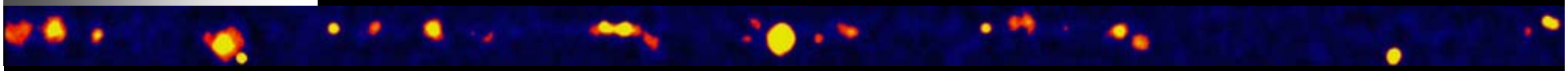
H.E.S.S. 2008



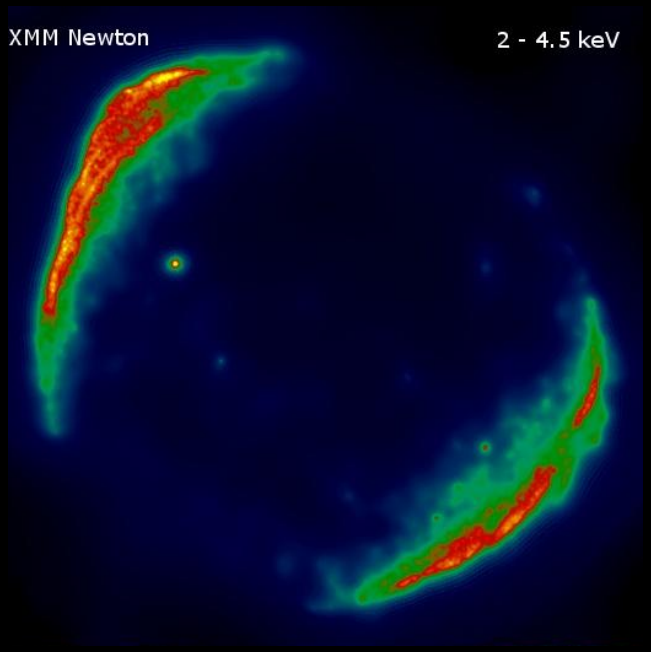
H.E.S.S. 2008

SN 1006

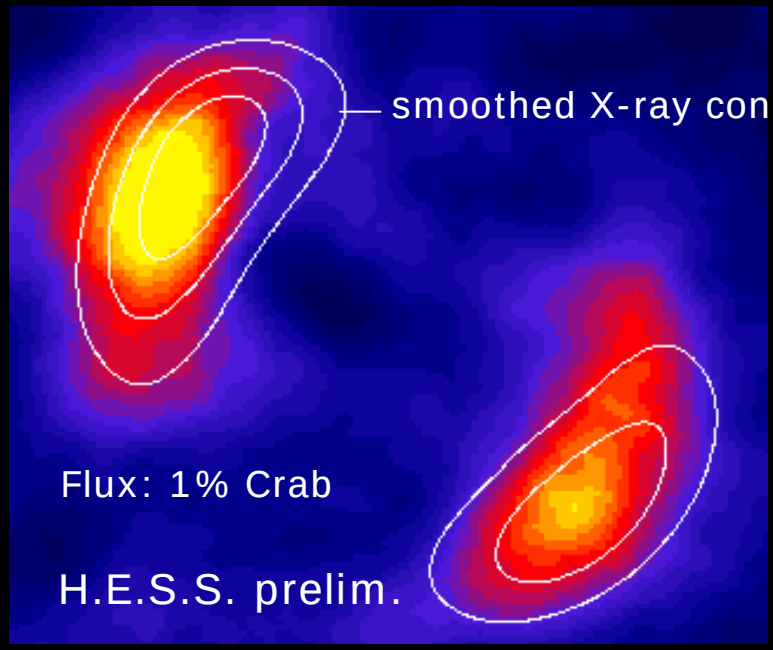
off the Galactic plane in uniform environment



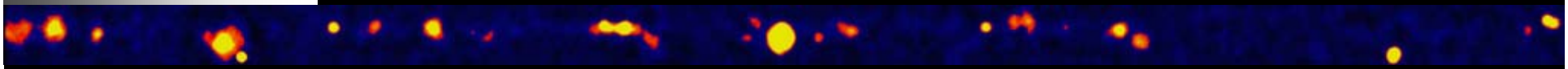
2 – 4.5 keV X-rays



VHE γ-rays



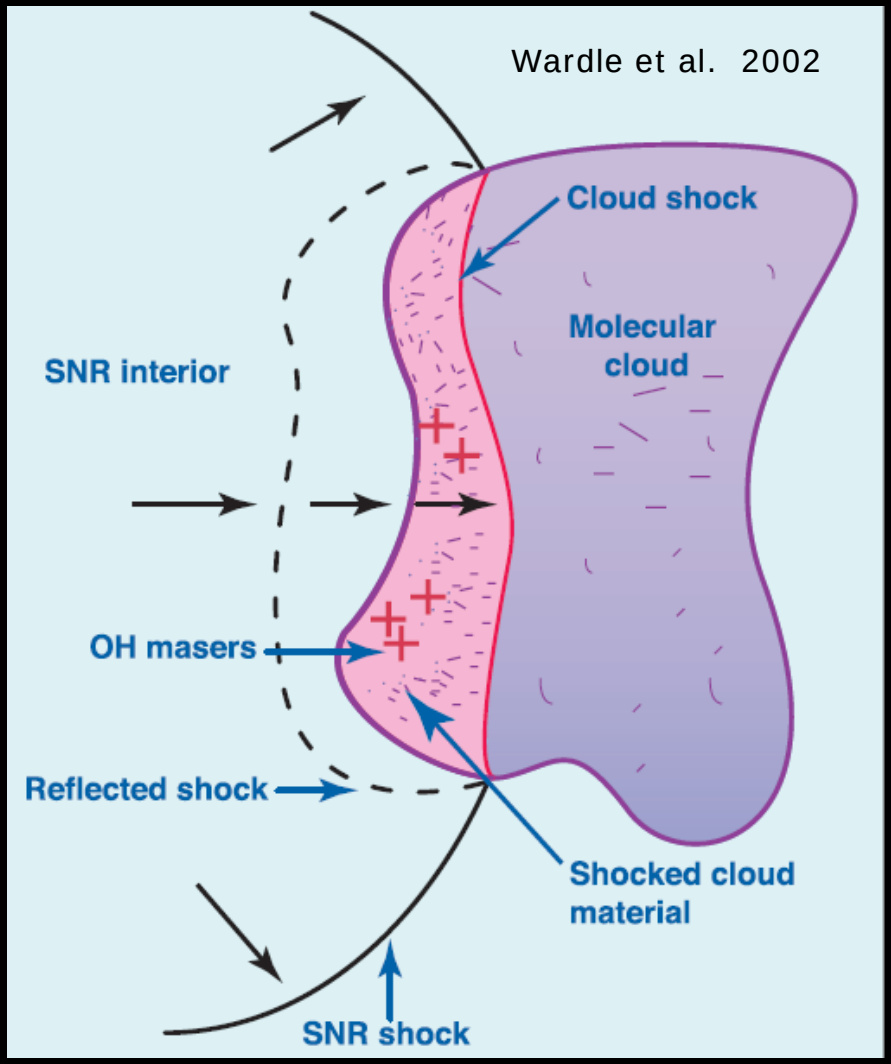
Knowns and unknowns

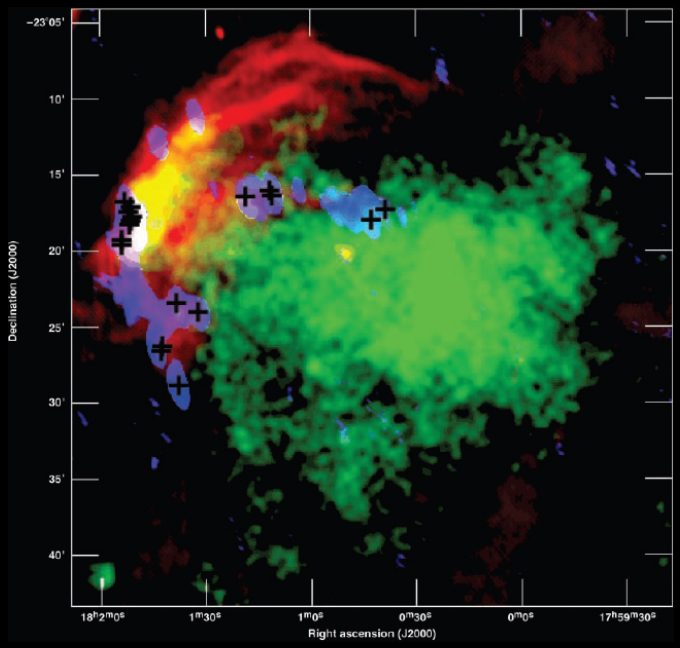


- Supernova shock fronts accelerate particles to energies approaching a PeV
- SEDs can be reproduced with plausible energetics assuming X-rays from electrons and gamma-rays from protons; e/p ~ 10^{-3}
- SEDs can also be approximated as electronic emission only; low magnetic fields (O(10 μG)) required to reproduce gamma-ray/X-ray flux ratio are at variance with data on (local) field strength

- Do (these) SNR really accelerate protons and nuclei ?
- Do we understand the morphology of remnants ?
- Do SNR shocks produce cosmic rays up to the knee and beyond ?
- Do SNR quantitatively account for the observed cosmic-ray density ?

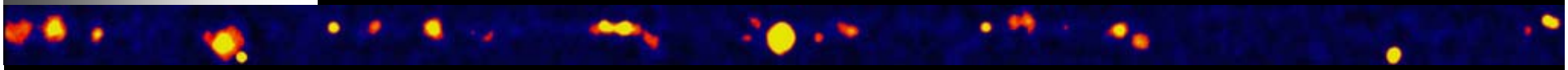
Supernovae interacting with clouds

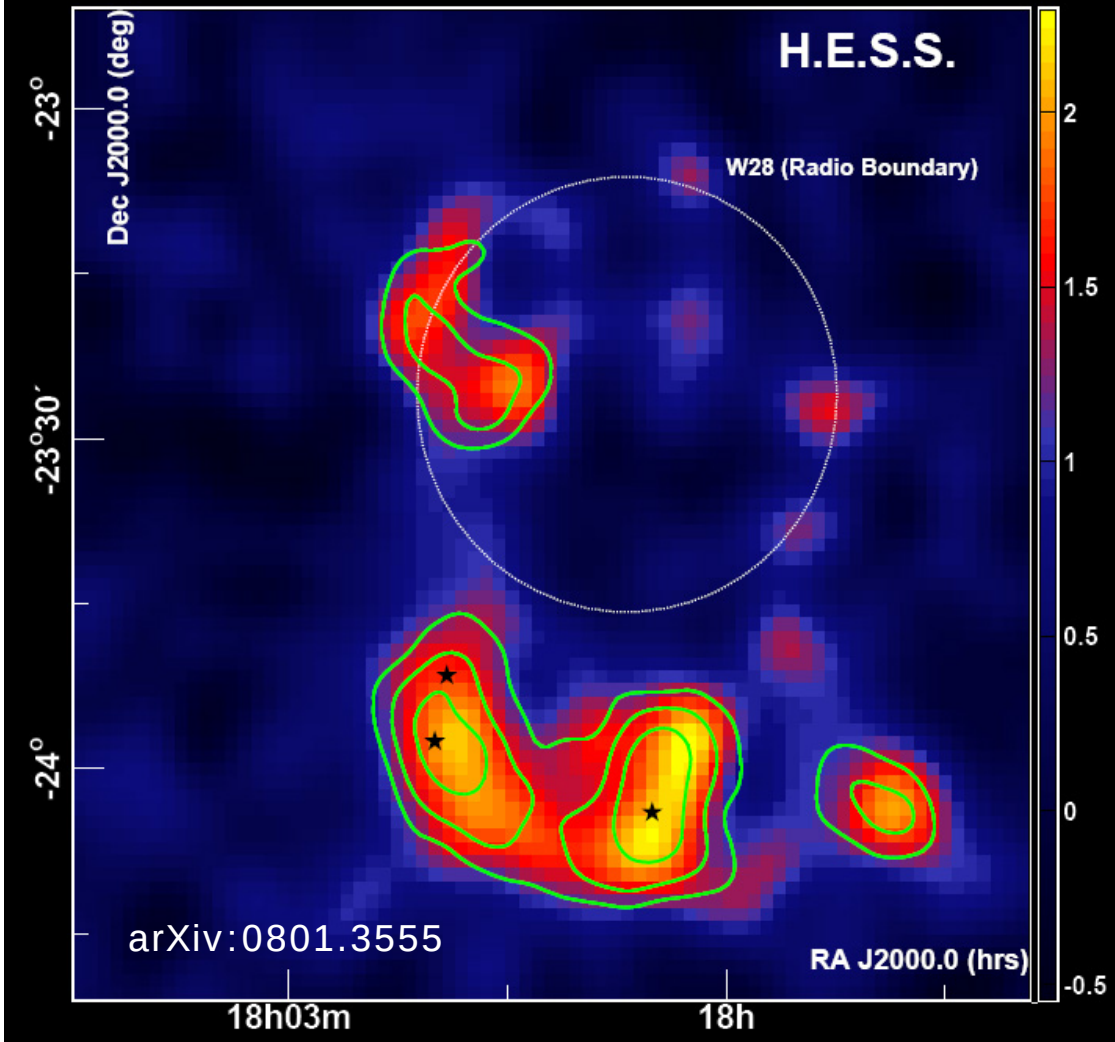


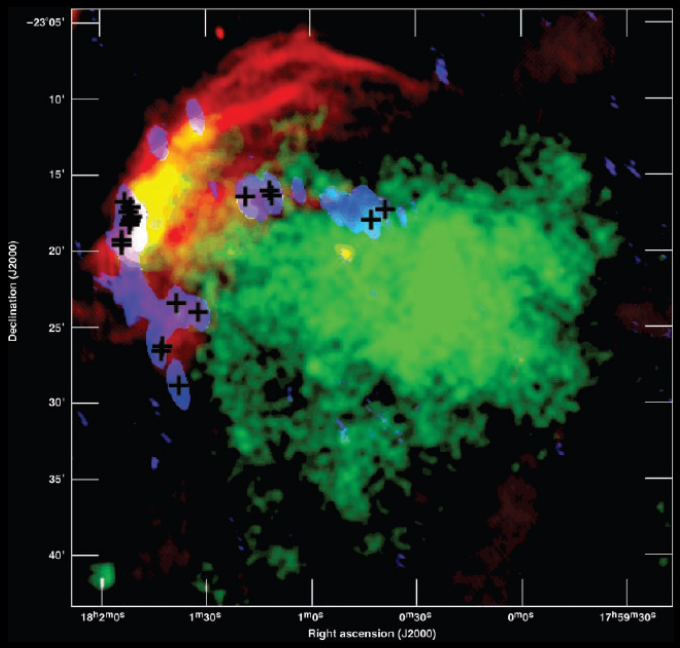


W28

Supernovae interacting with clouds

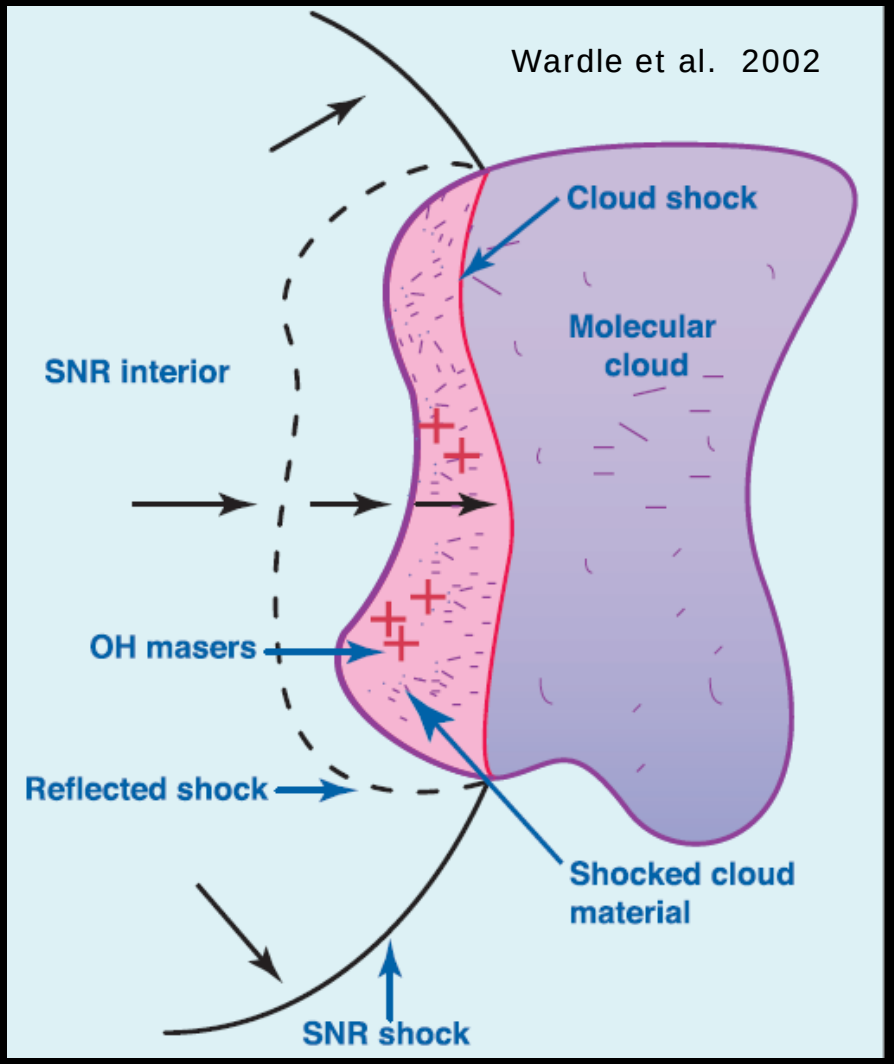


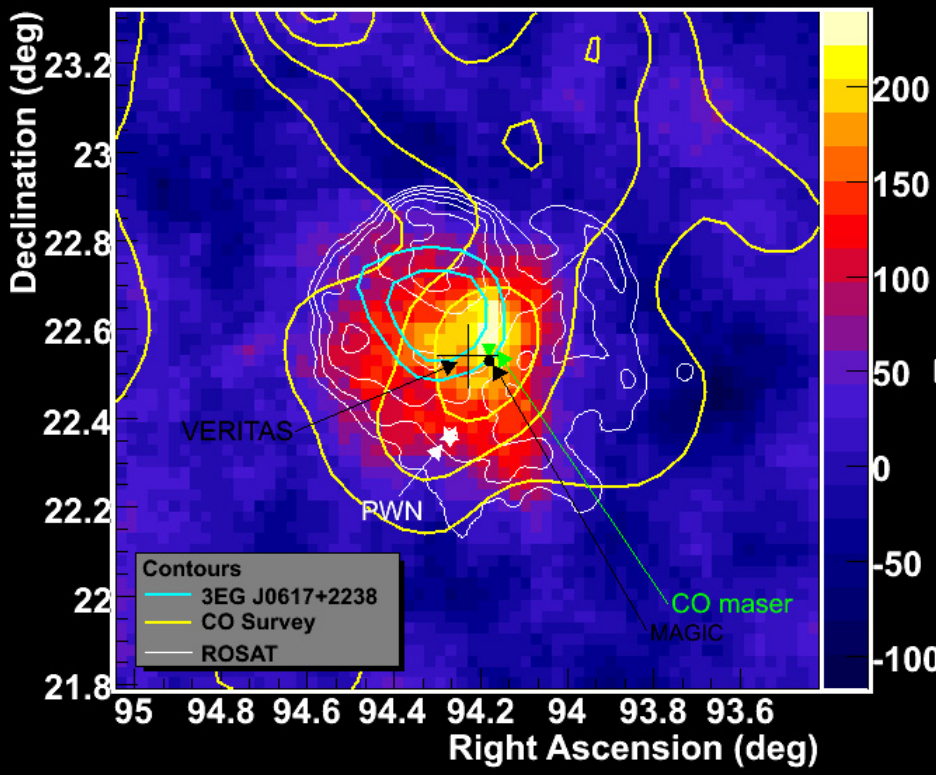




W28

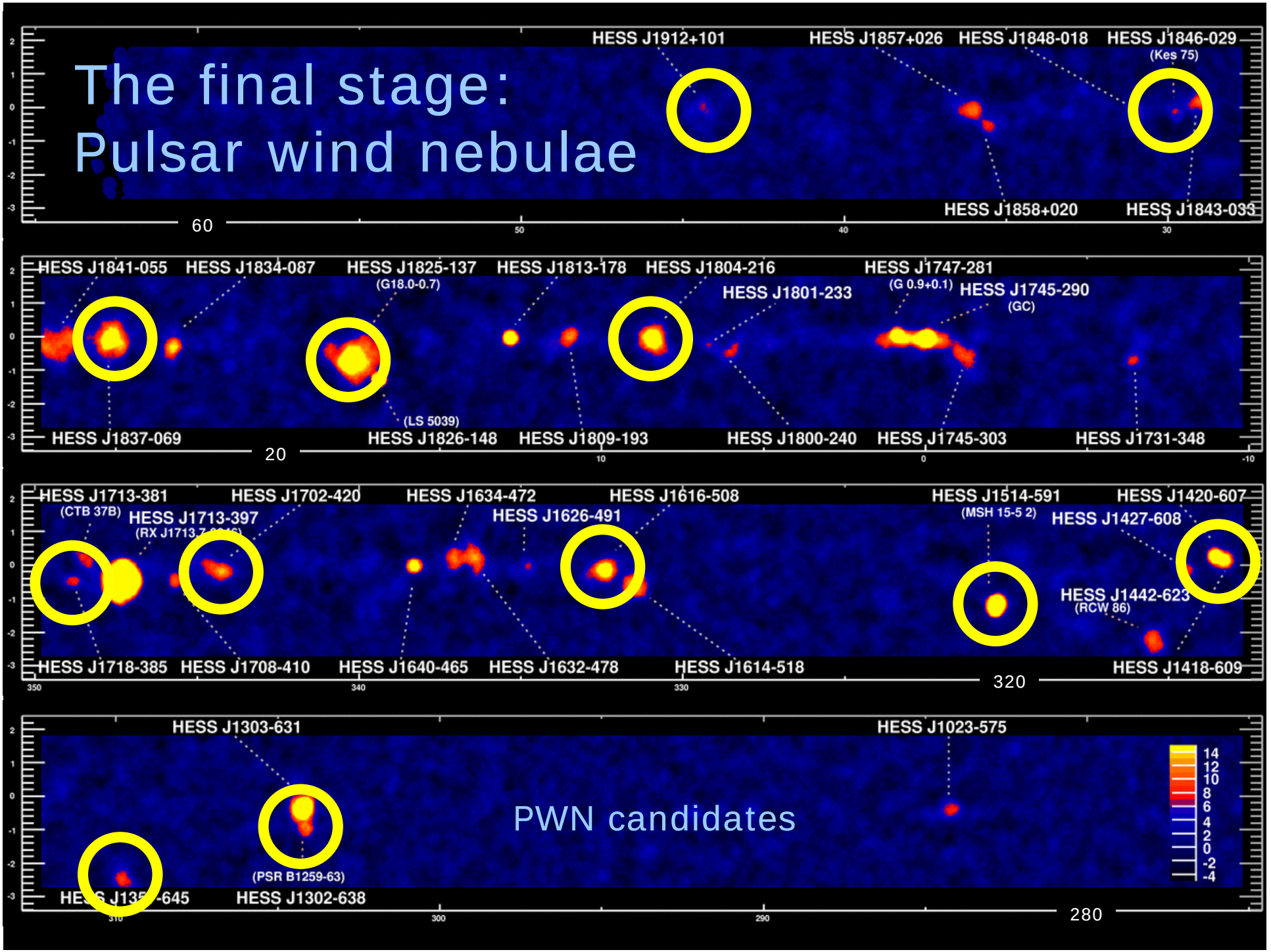
Supernovae interacting with clouds



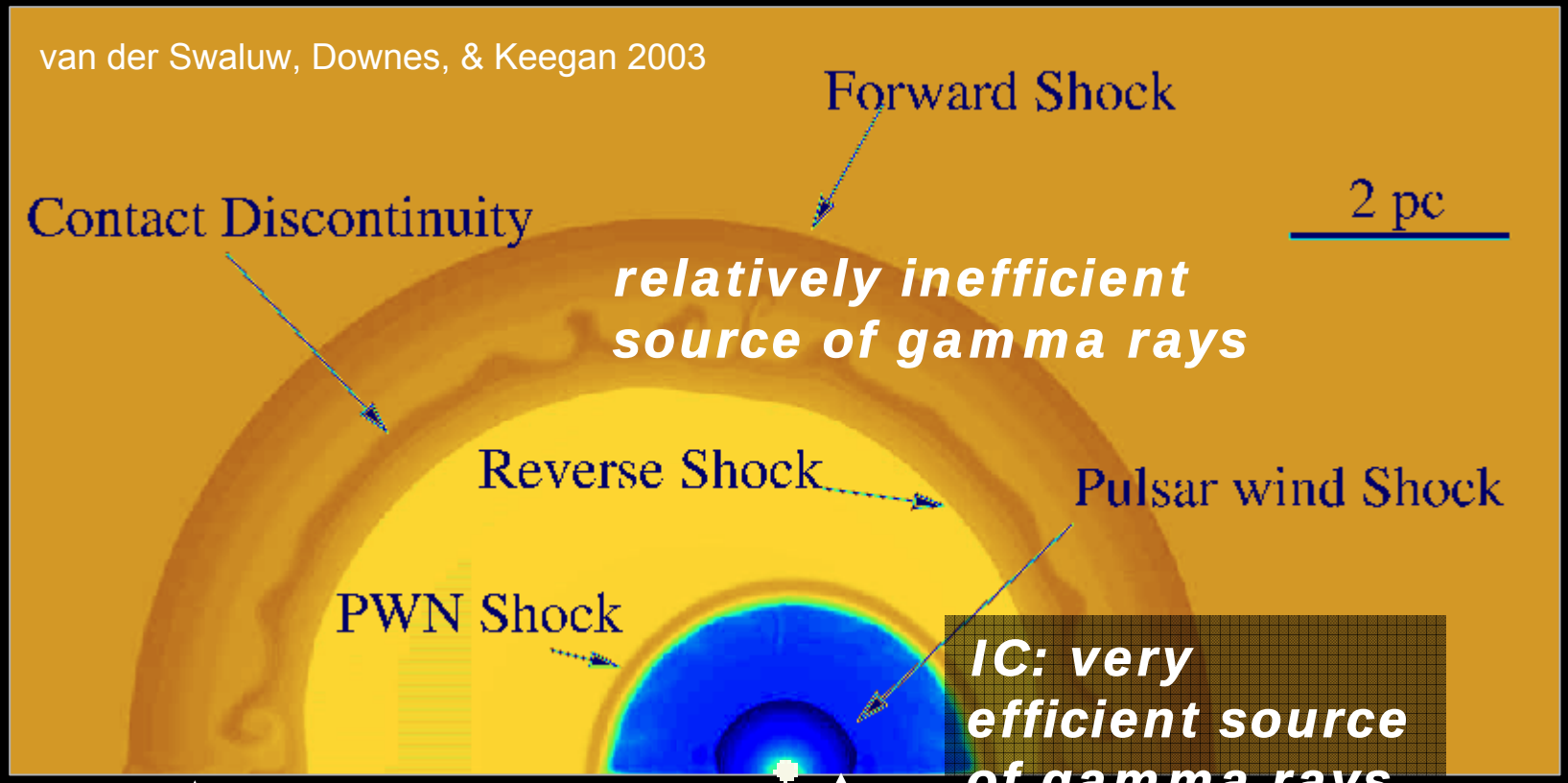


IC 443

MAGIC 2007, arXiv:0705.3119
VERITAS 2007, 2008: arXiv:0810.0799


The final stage:
Pulsar wind nebulae
HESS J1912+101
HESS J1857+026
HESS J1848-018
HESS J1846-029
(Kes 75)
HESS J1858+020
HESS J1843-033
60
50
40
30
HESS J1841-055
HESS J1834-087
HESS J1825-137
(G18.0-0.7)
HESS J1813-178
HESS J1804-216
HESS J1801-233
HESS J1747-281
(G 0.9+0.1)
HESS J1745-290
(GC)
(LS 5039)
HESS J1837-069
HESS J1826-148
HESS J1809-193
HESS J1800-240
HESS J1745-303
HESS J1731-348
20
10
0
-10
HESS J1713-381
(CTB 37B)
HESS J1713-397
HESS J1702-420
HESS J1634-472
HESS J1626-491
HESS J1616-508
HESS J1514-591
(MSH 15-5 2)
HESS J1420-607
HESS J1427-608
HESS J1442-623
(RCW 86)
HESS J1718-385
HESS J1708-410
HESS J1640-465
HESS J1632-478
HESS J1614-518
HESS J1418-609
350
340
330
320
HESS J1303-631
HESS J1023-575
PWN candidates
(PSR B1259-63)
HESS J1302-638
300
290
280
14
12
10
8
6
4
2
0
-2
-4

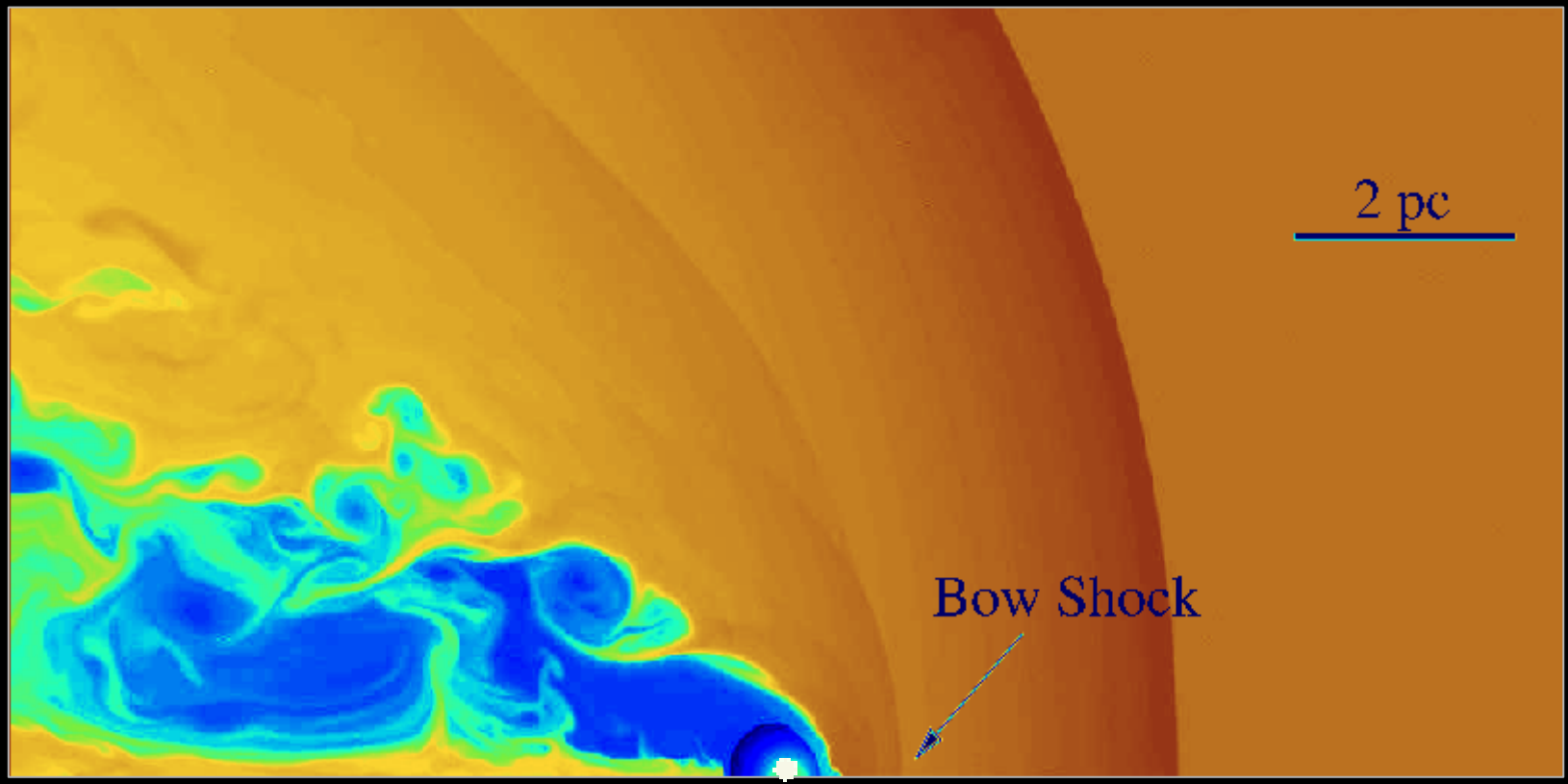
Last stage: Pulsar wind nebulae (& plerions)



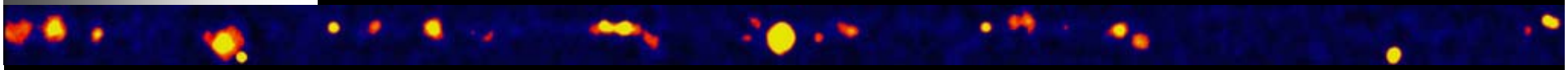
SN shock accelerates particles for O(10 ky)

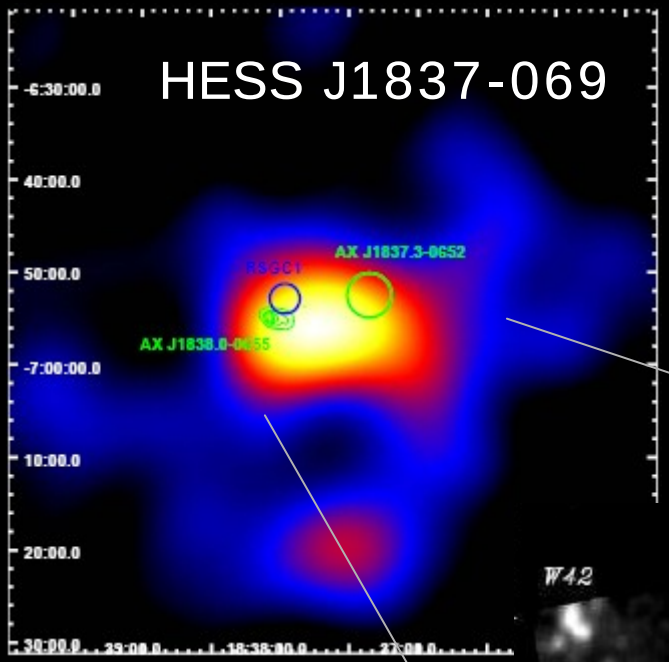
Pulsar sustains pulsar wind nebula for O(100 ky)

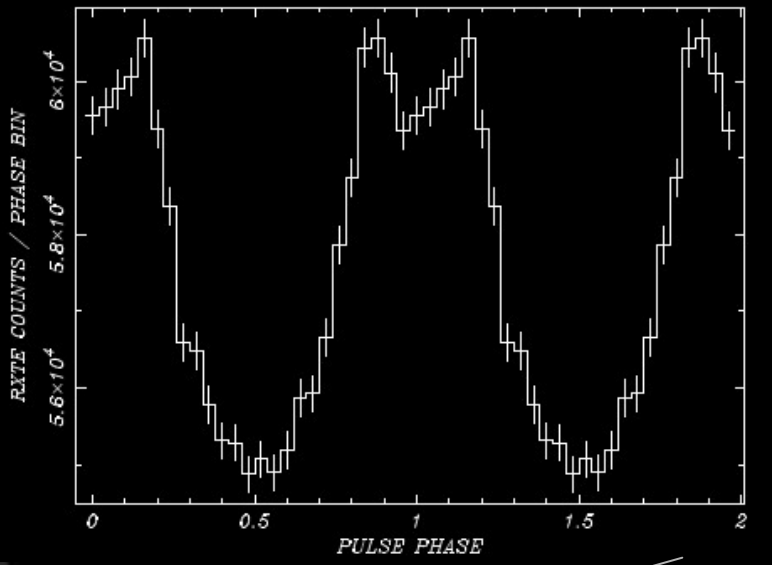
Interaction of shell and PWN



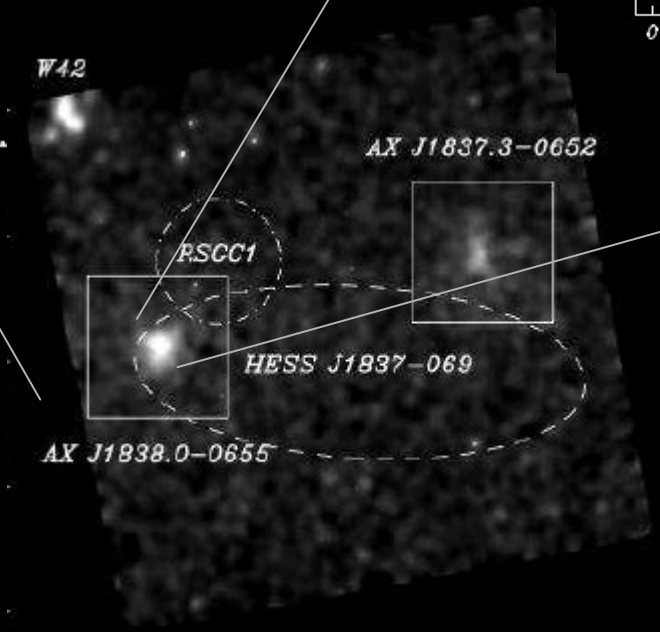
Unidentified sources turning into PWN







RXTE



Chandra

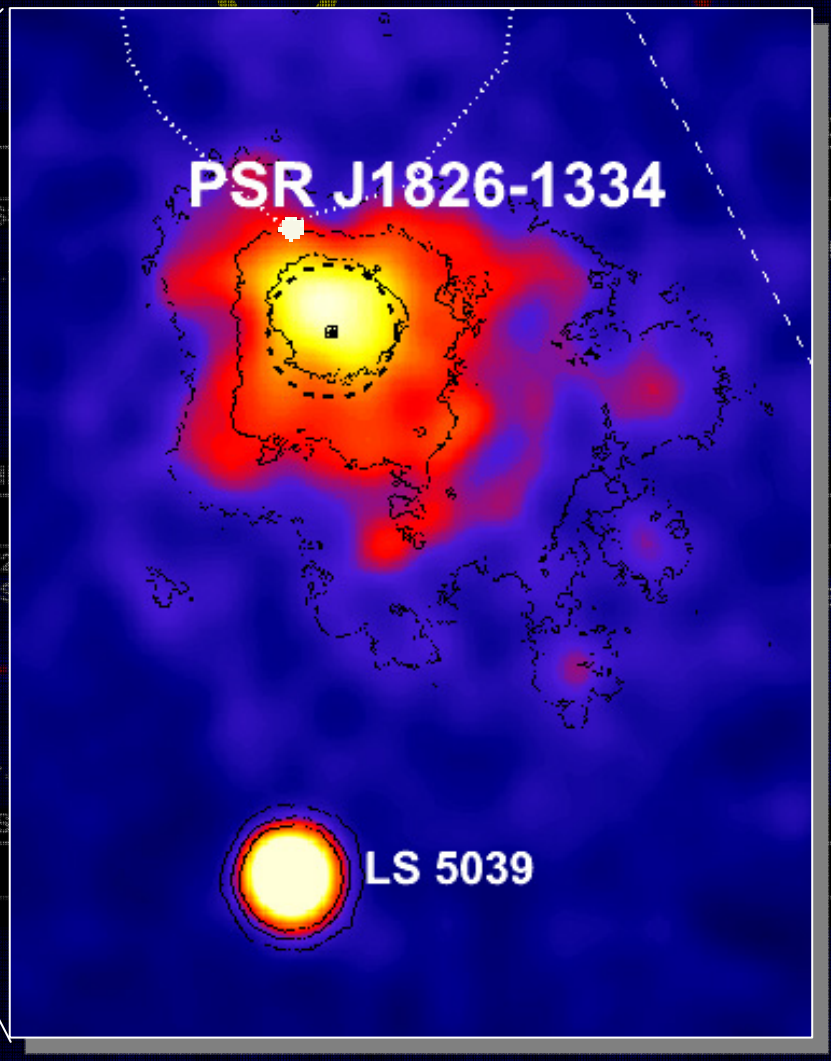
Gotthelf & Halpern 2008

PWN candidates

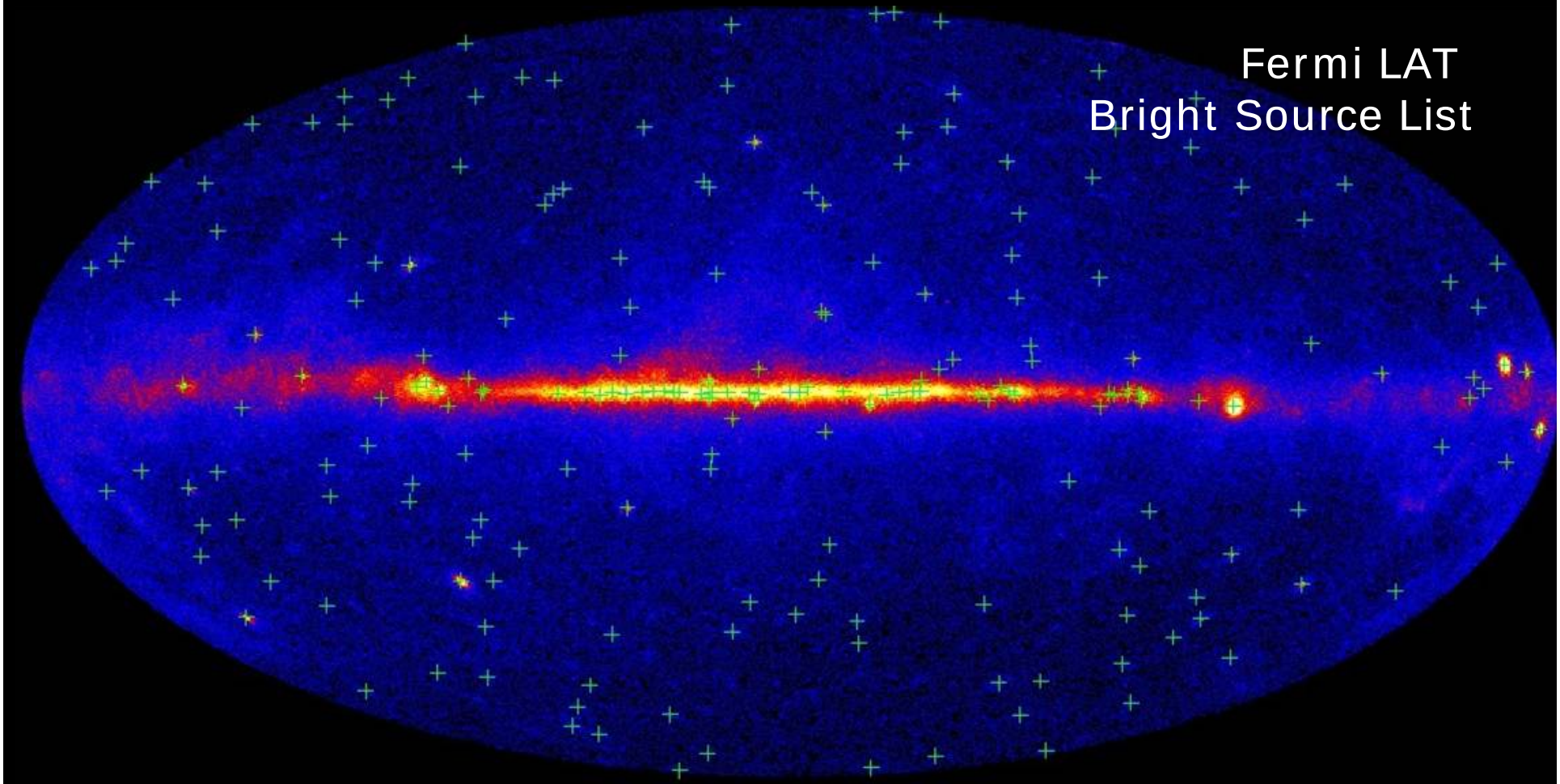
Compact X-ray PWN centered on pulsar - X-ray emitting electrons have livetime O(kyr)

Extended γ-ray PWN – γ-ray emitting electrons have livetime of 10s of kyr

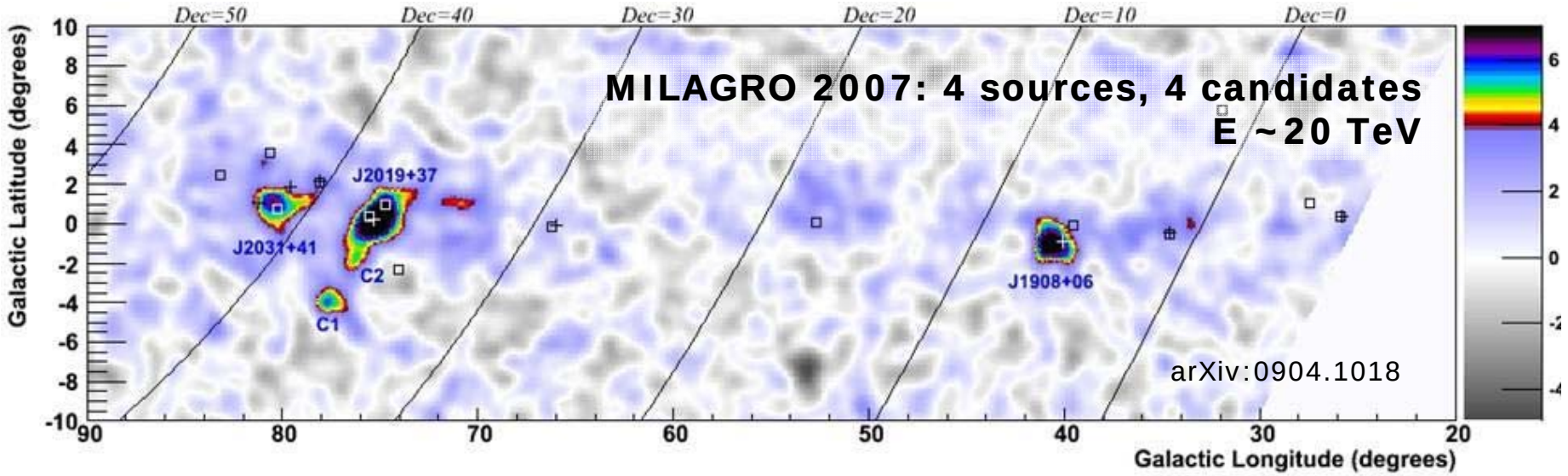
L_γ/L_X can be large since γ-ray emitting electrons accumulate over 10s of kyrs ("relic electrons")



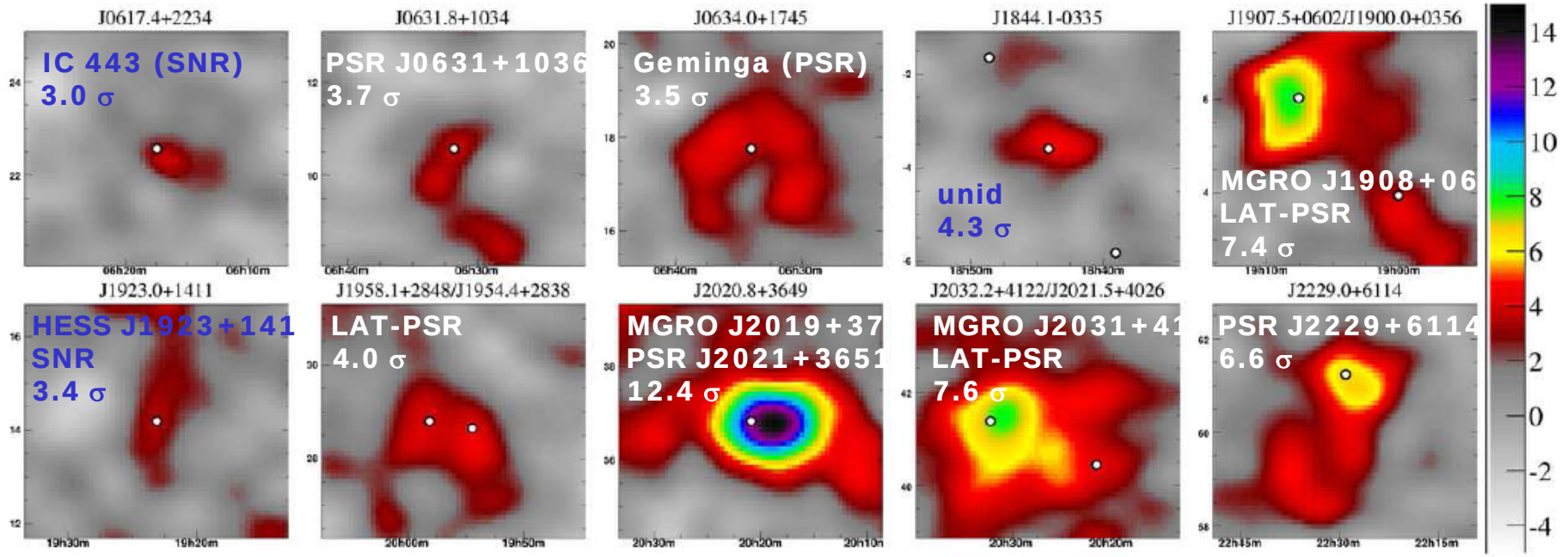
HE vs VHE sky



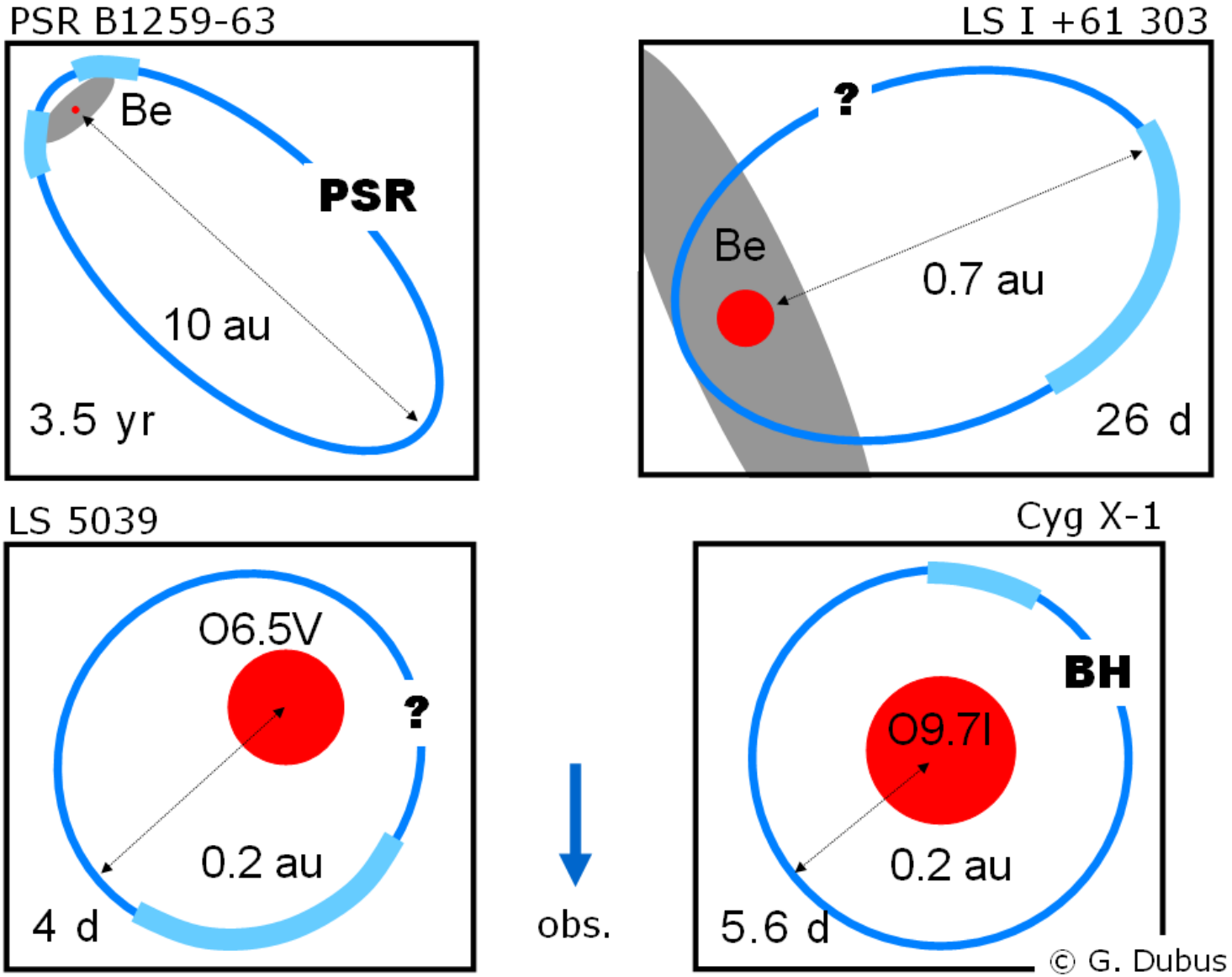
- about 1/4 of LAT galactic sources have VHE counterpart in H.E.S.S. survey



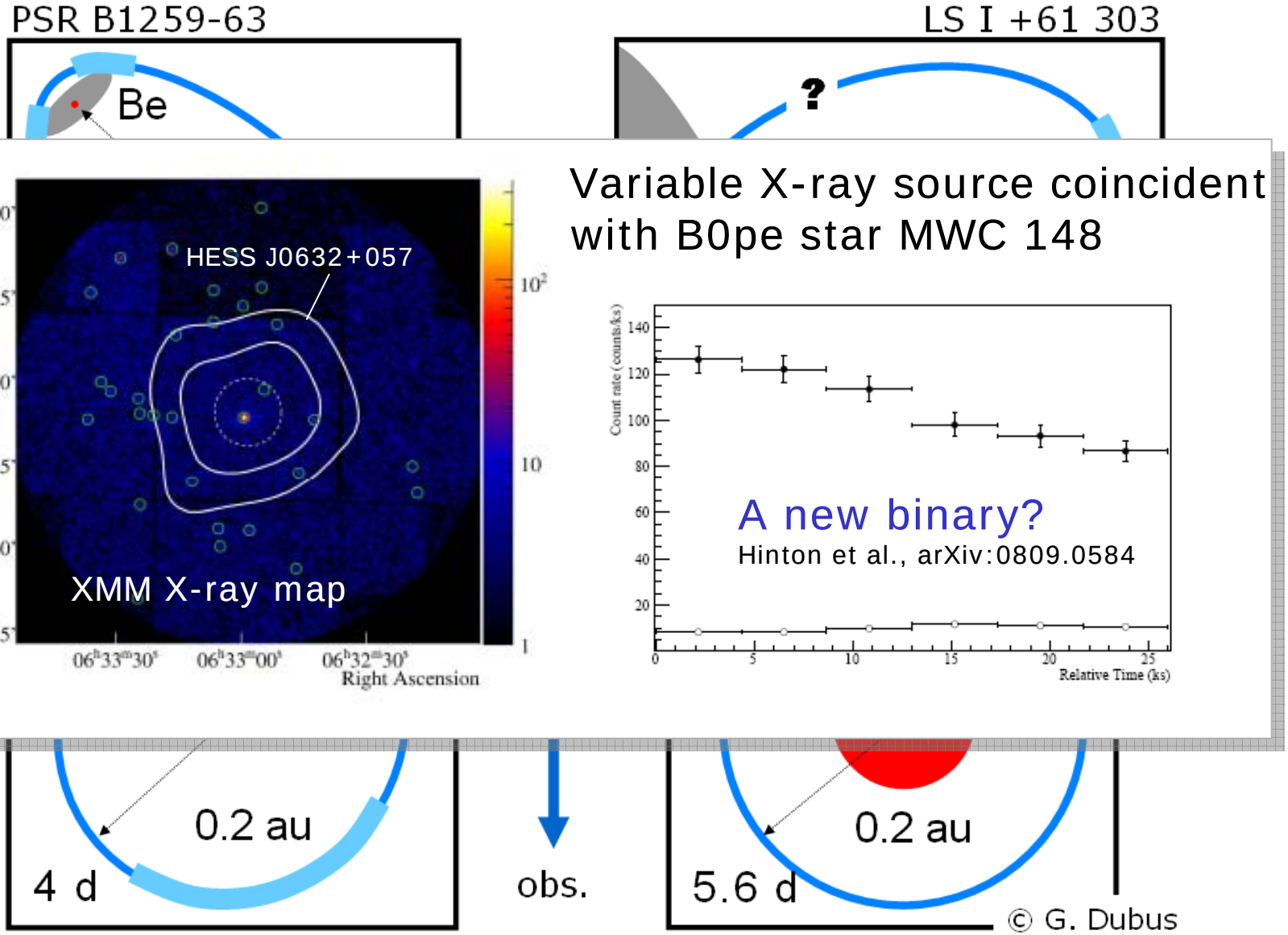
Correlation with LAT bright source list:
of 34 Fermi sources in region, 14 have >3σ in MILAGRO (>10 TeV)
arXiv: 0904:1018



Also: Gamma-ray binaries

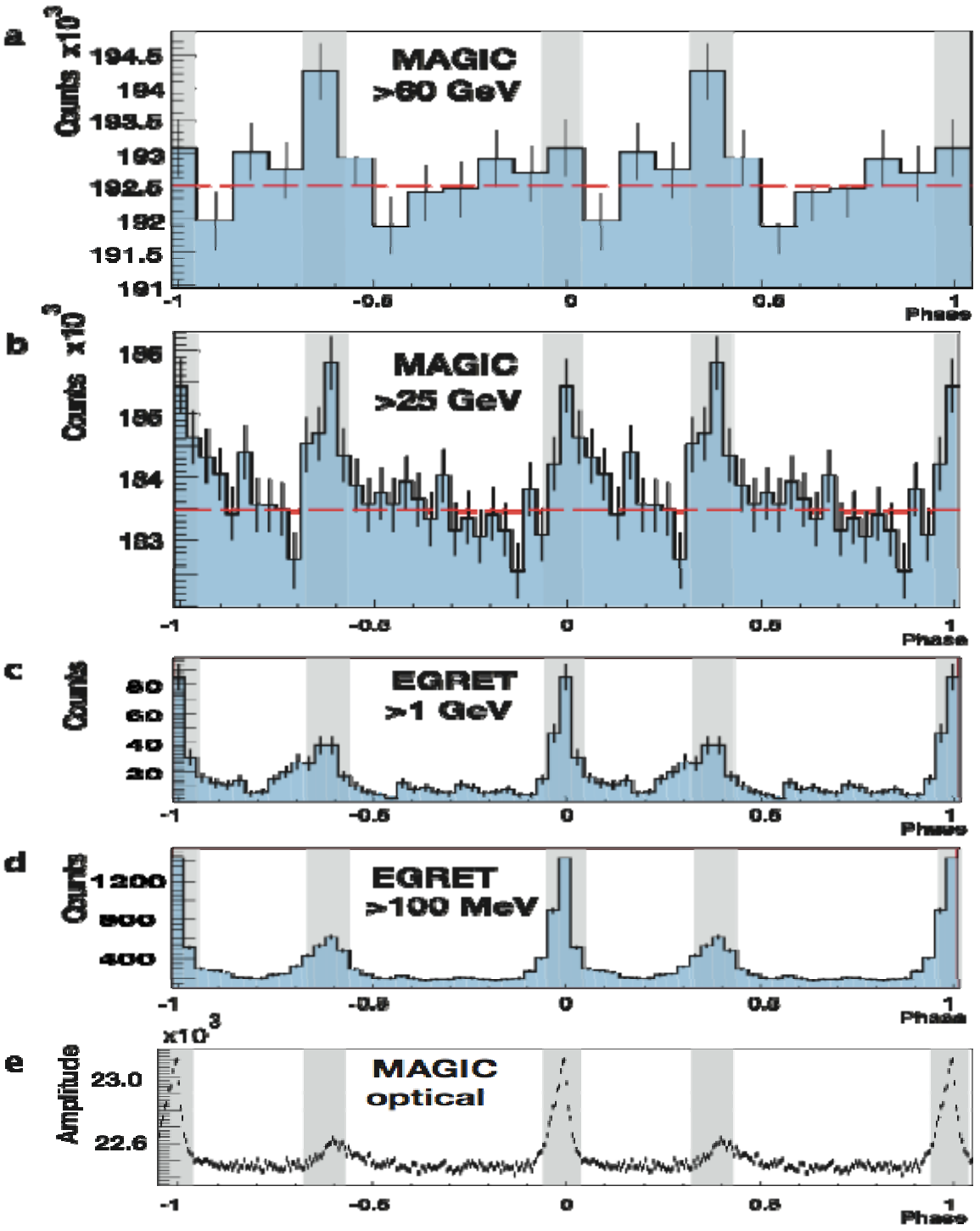


4) Gamma-ray binaries

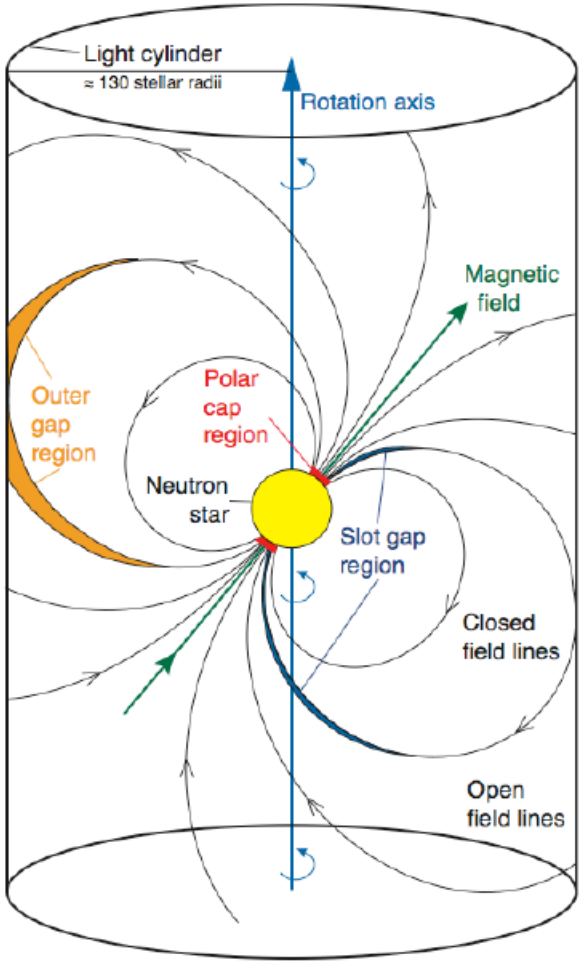


First ground-based detection of pulsed emission from a pulsar

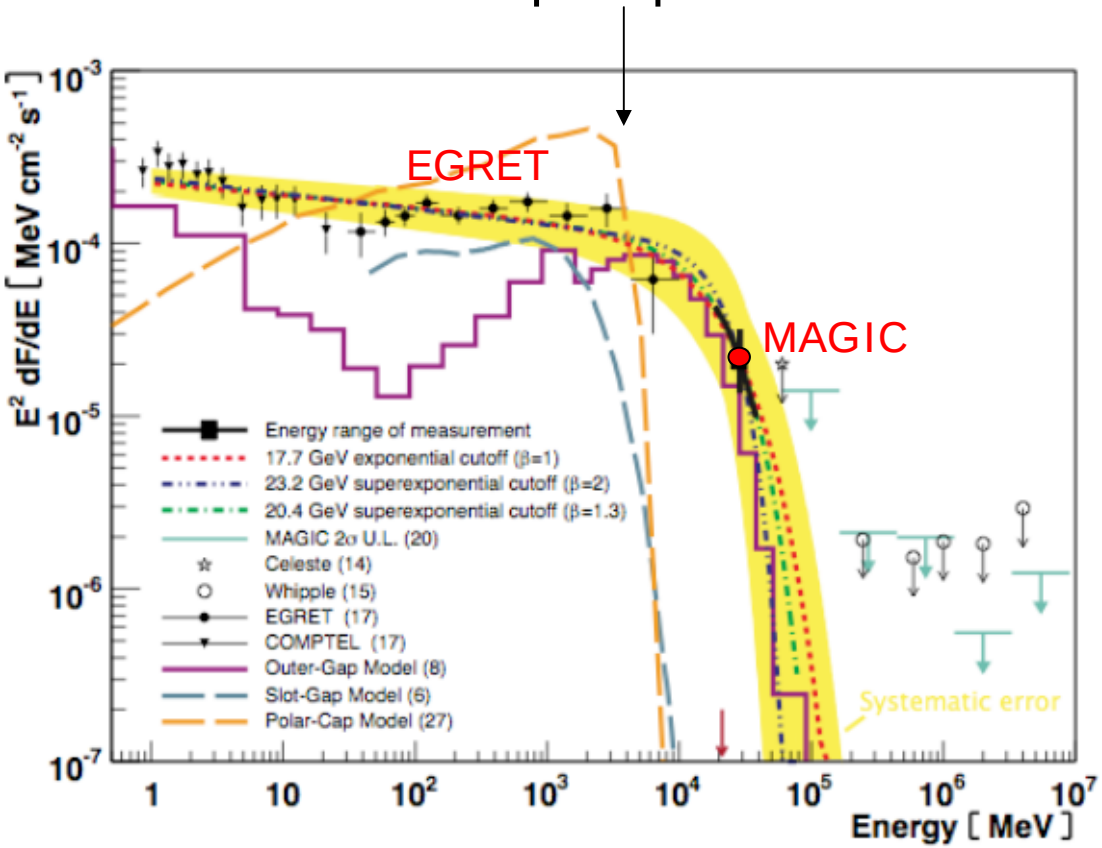
MAGIC, Science 322, 2008
using special low-energy trigger



Origin of pulsed emission: outer gap



Emission from polar cap
and slot gap cut off around
10 GeV due to pair production

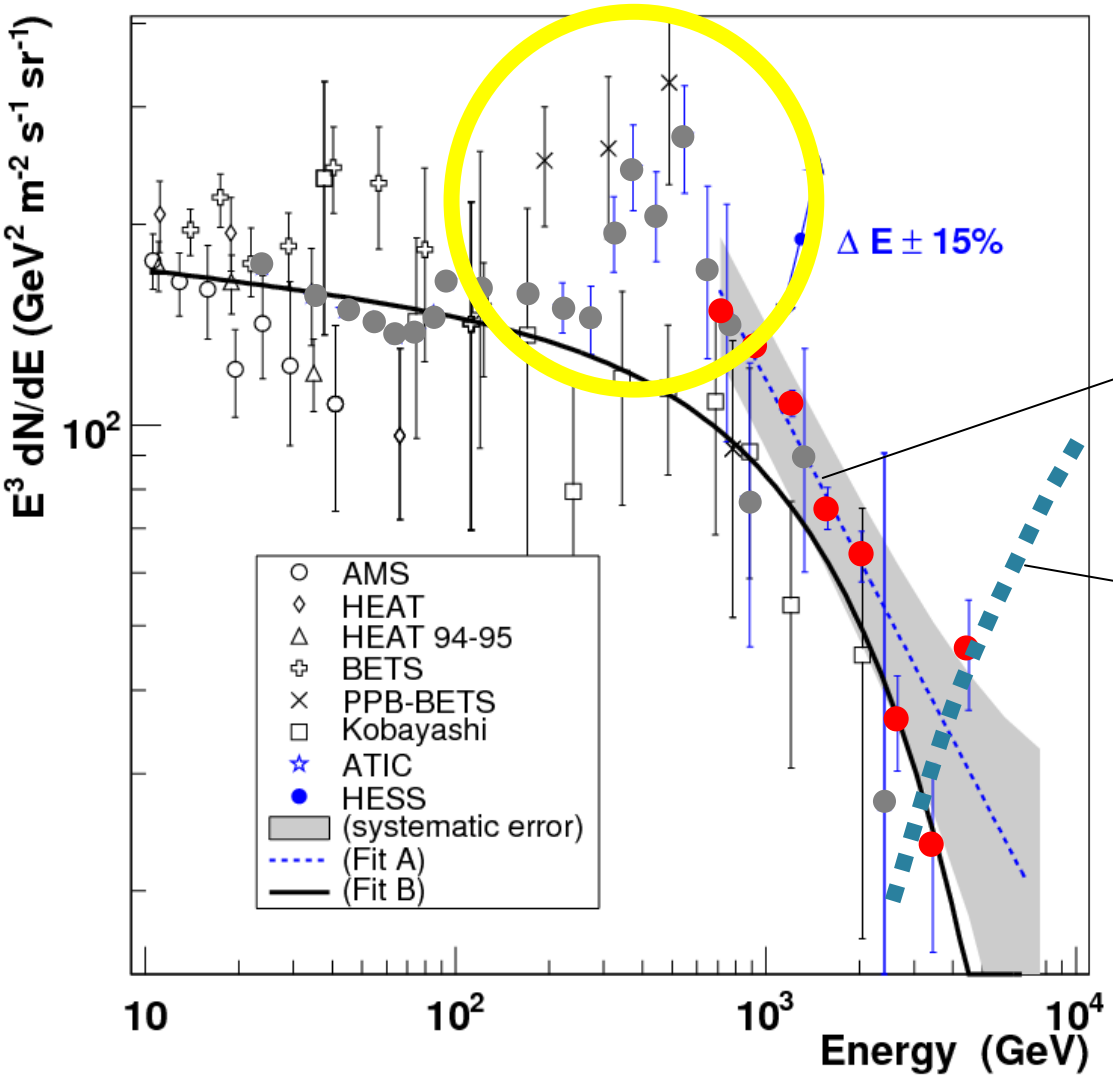


No time for flux limits for …

- Pulsed emission from other pulsars
- Starburst galaxies
- Galaxy clusters
- Dark matter annihilation at/around
  - Galactic center
  - Dwarf galaxies
  - Intermediate mass black holes
- … other potential source classes

- **Limits approaching the interesting range, but not yet constraining**

Cosmic-ray electrons

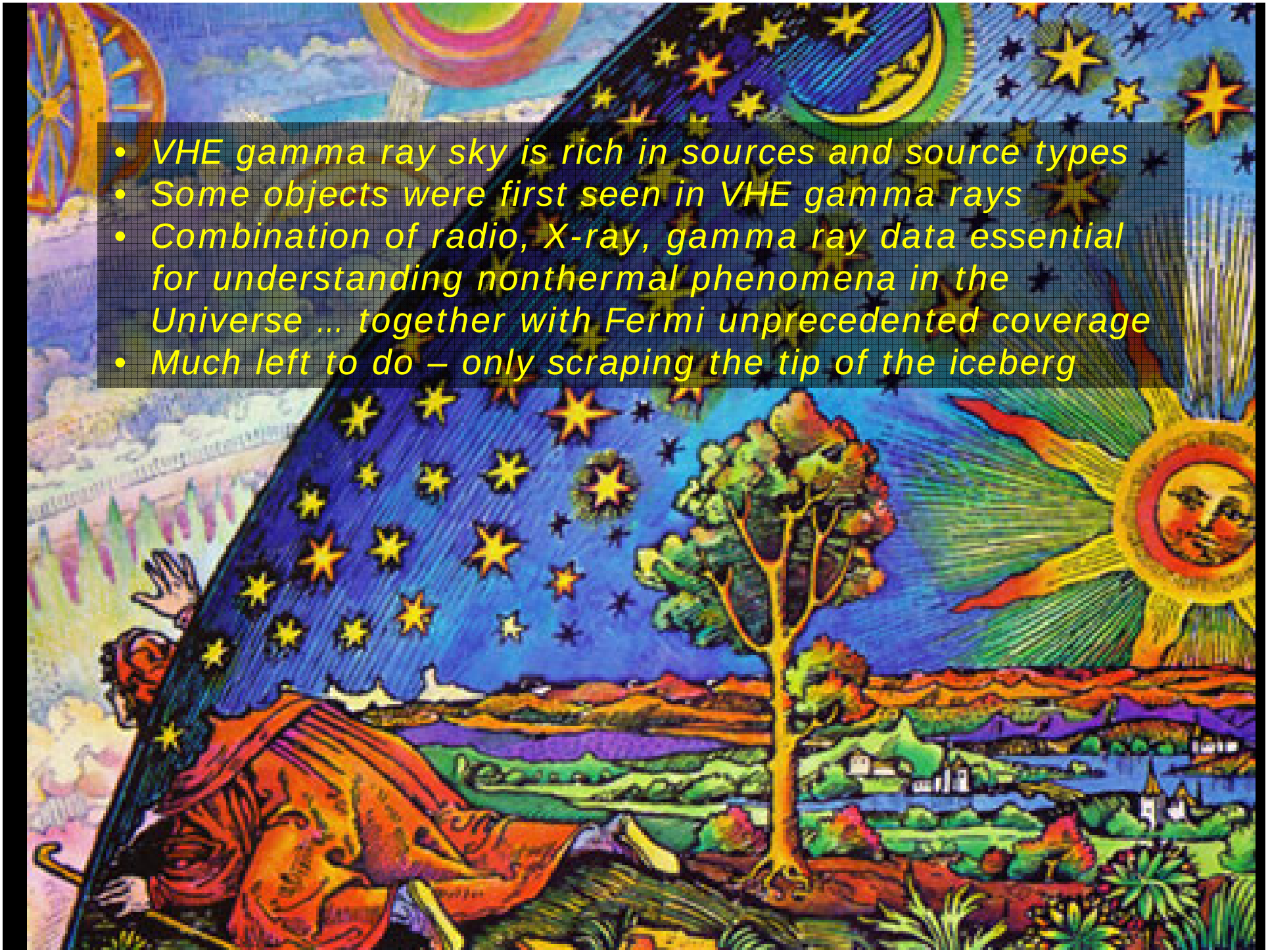


Spectrum of electrons in CR

cutoff due to radiative losses

local sources (e.g. Vela)

H.E.S.S.
arXiv:0811.3894


• VHE gamma ray sky is rich in sources and source types
• Some objects were first seen in VHE gamma rays
• Combination of radio, X-ray, gamma ray data essential for understanding nonthermal phenomena in the Universe … together with Fermi unprecedented coverage
• Much left to do – only scraping the tip of the iceberg

Next-generation observatories

- **CTA:** a Cherenkov Telescope Array 10 x more sensitive than H.E.S.S., MAGIC, VERITAS & wide energy range
  - strong recommendation in ASTRONET, ASPERA roadmaps
  - in ESFRI list for future research infrastructures
- **AGIS:** a Cherenkov Telescope Array 10 x more sensitive than H.E.S.S., MAGIC, VERITAS
- **HAWC:** a high-altitude water Cherenkov detector 10 x more sensitive than MILAGRO
- **LHAASO:** a km^2-sized Large High Altitude Air Shower Observatory in Tibet, combining scintillation detectors, water Cherenkov detectors and Cherenkov telescopes