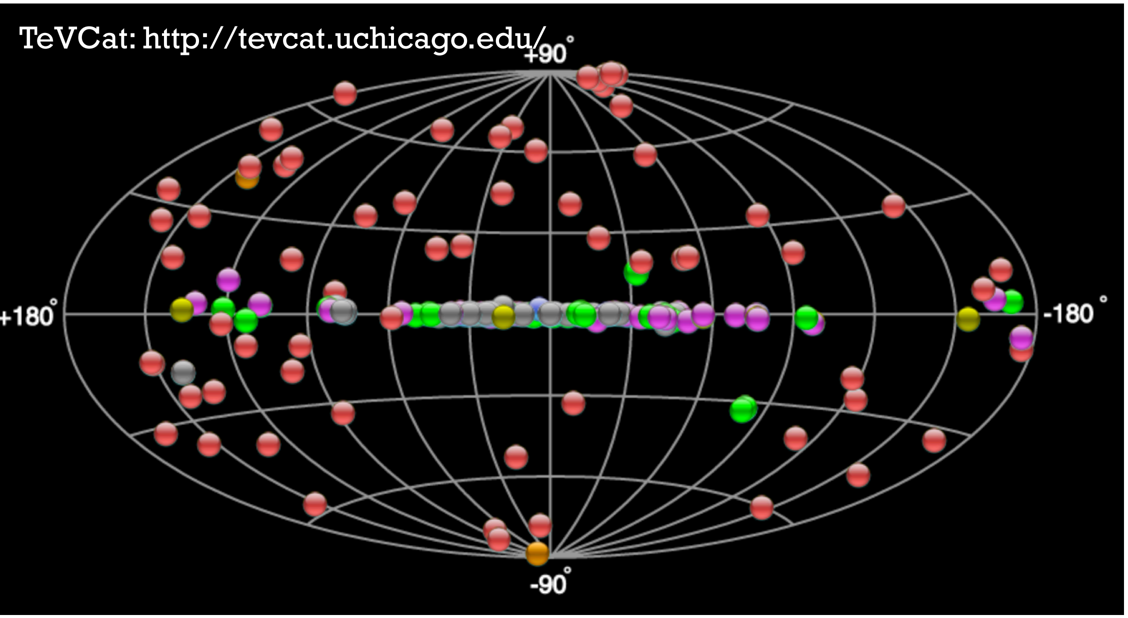
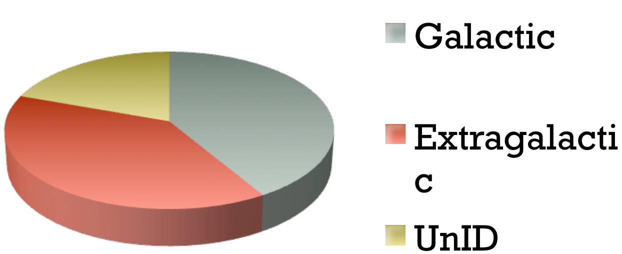
Review of the present status on VHE gamma-ray observations

Takayuki Saito
Kyoto University, Hakubi center

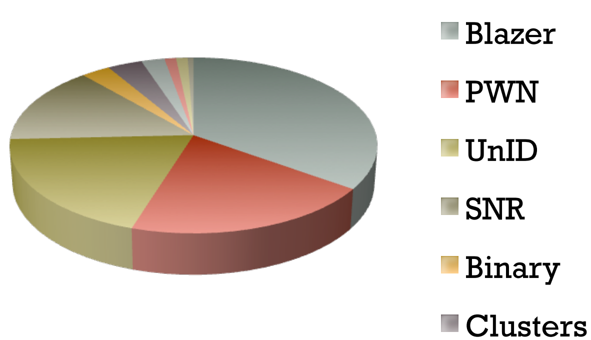
+ TeV sky



Gal/Extragal.



Source Class



Galactic	70	
- SNR		24
- PWN		34
- PSR		2
- Binary		5
- Clusters		5
- Star forming region		1
Extragal.	70	
- LMC		3
- Blazer		61
- FRI		4
- Starburst gal.		2
UNID	34	
Total	174	

Galactic Sources

- SNR (4 pages)
- PWN (3 pages)
- Pulsar (2 pages)
- Binary (4 pages)
- Stellar Cluster (1 page)
- Galactic Center (1 page)

Supernova Remnants (24 detected)

- Supernova Remnants: ~400 in the Galaxy (SNRcat).
  - Shock wave accelerates proton and e- up to PeV.
  - Thought to be origins of galactic CR.
  - 4 types,
    - Shell-type(~250),
    - Filled (mainly PWN, ~50),
    - Plerionic Composite (PWN+Shell, ~50)
    - Mixed Morphology (Thermal X-ray at center + Radio Shell, ~40)

Type	# of VHE srcs	Tev Source
Shell-type	15	Tycho, Cas A, SN1006, Vela Jr. etc
Filled	-	Counted as PWN
Mixed Morphology	8	IC443, W28 (4 sources around), W49B, W51?, CTB37A
Plerionic Composite	1	G015

+ Young SNRs (Shell-type, < 3000 yrs)

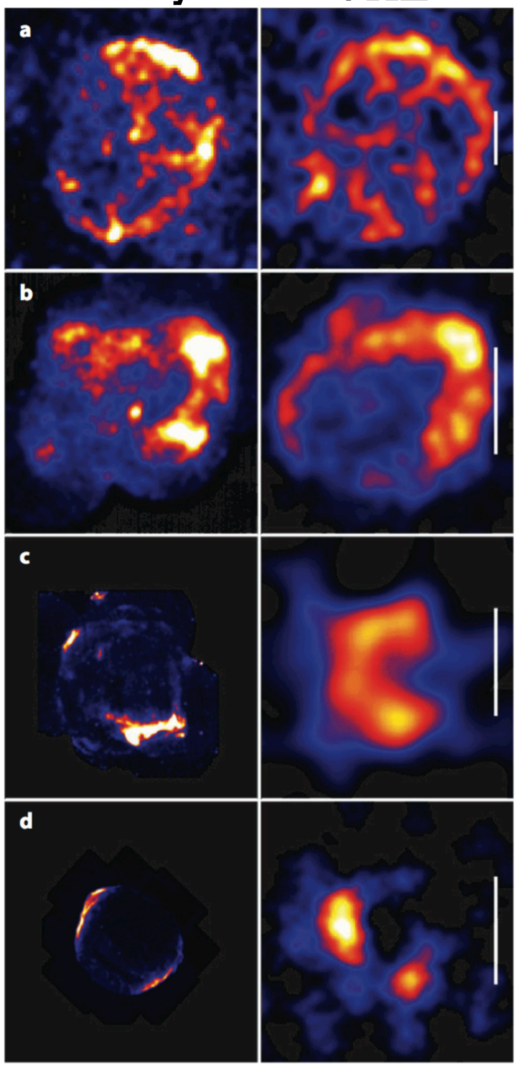
X-rays VHE

Vela Jr. (2500 yrs)

RX J1713 (2000 yrs)

RCW86 (2000 yrs)

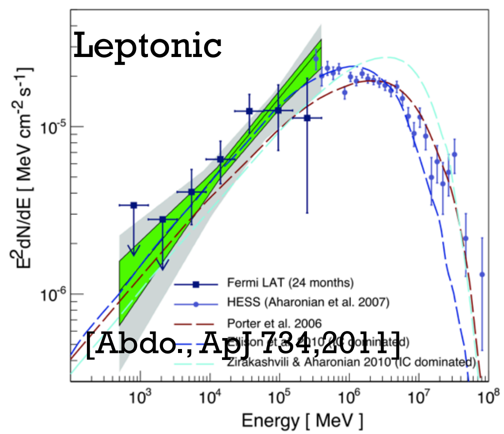
SN1006 (1000 yrs)



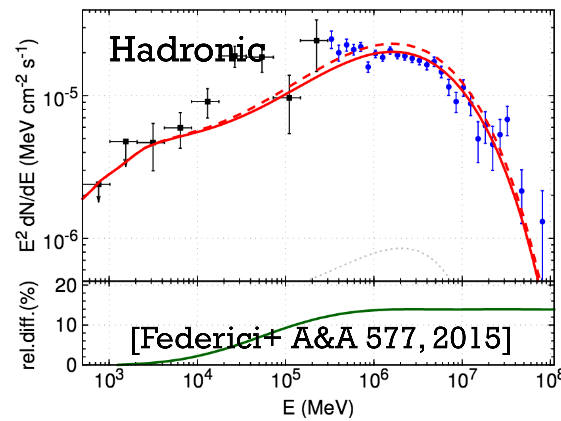
[Hinton & Hoffmann ARAA, 2009]

In general, Radio, X-ray and VHE are spacially well-correlated, showing shell structure.

Leptonic origin? -> Not very clear yet.



[Abdo., ApJ 734, 2011]

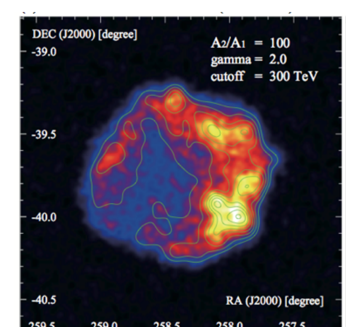


[Federici+ A&A 577, 2015]

Both hadronic and leptonic can explain the GeV-TeV spectrum of RX J1713

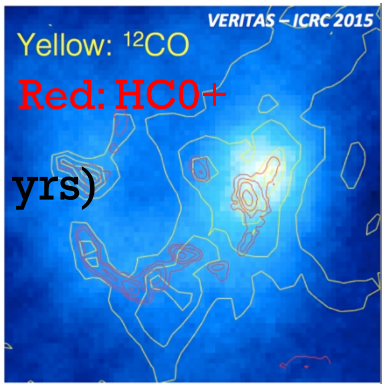
Expected hadronic morphology according to proton column density ->

Nakamori et al., in prep



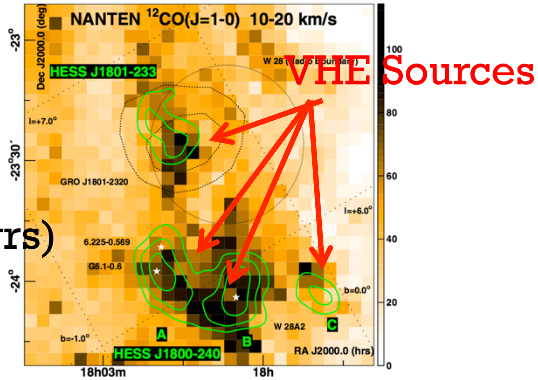
+ Older SNRs (M-M, > 3000 years)

IC443
(10000 yrs)

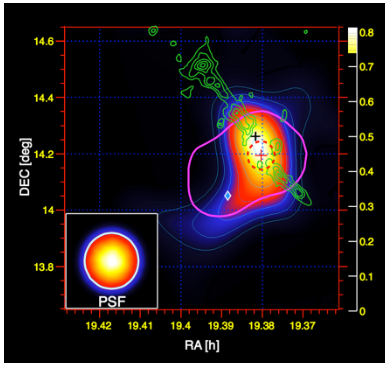


No correlation with radio shell.
Good correlation with cloud/gas.

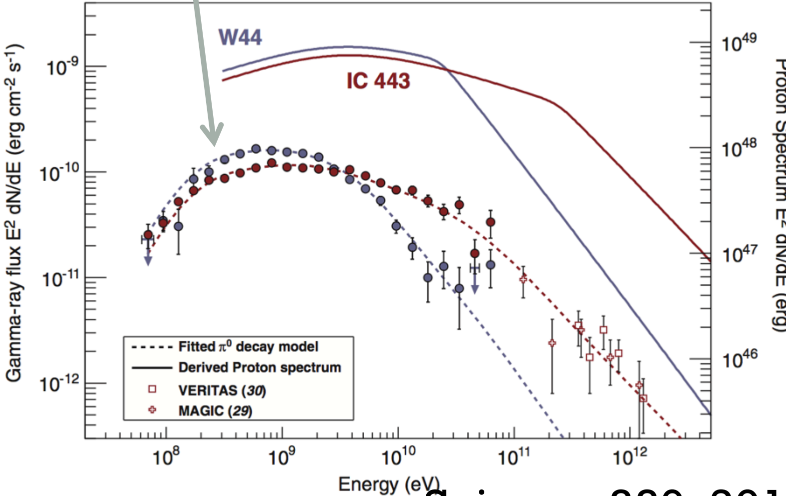
W28
(30000 yrs)



W51C
(35000 yrs)

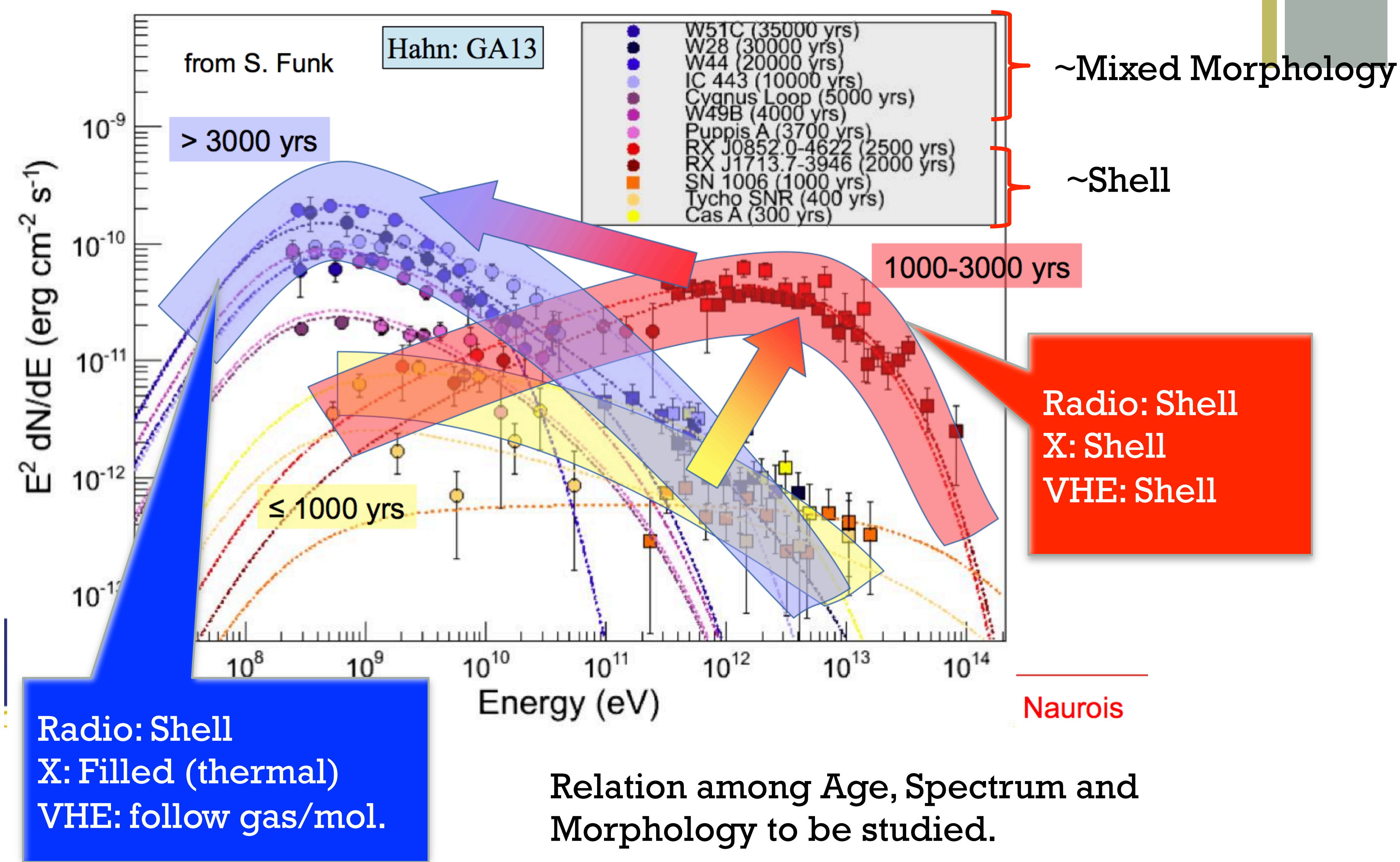


Actually, pion bump was discovered in IC443 and W44 spectra. Clear Hadronic emission. (W44 not deteded in VHE)



Science 339, 2013

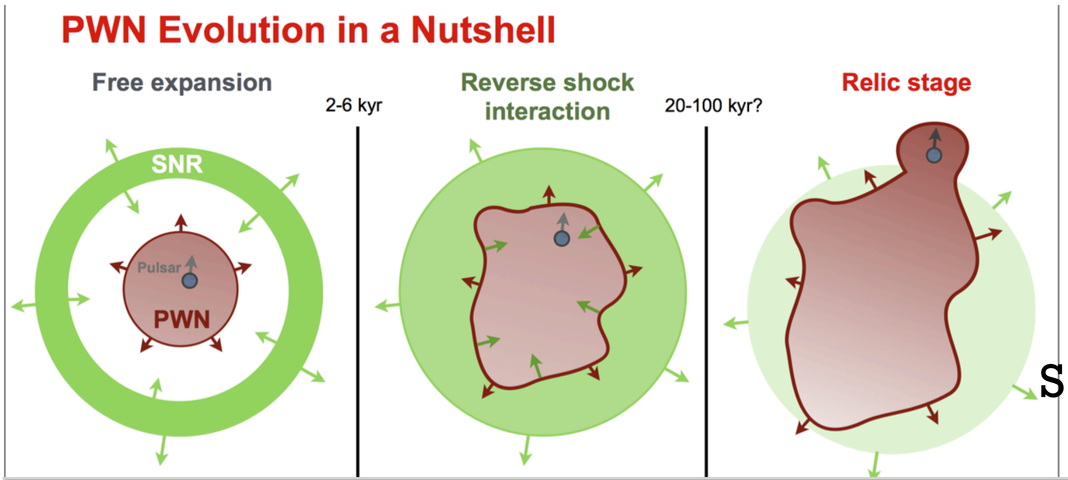
Evolution of spectrum



Relation among Age, Spectrum and Morphology to be studied.

Pulsar Wind Nebula (34 detected)

- Pulsar Wind Nebula: 7-80 known in the Galaxy
  - Termination Shock of the pulsar wind
  - Powered by the pulsar spindown
  - Majority of galactic VHE sources



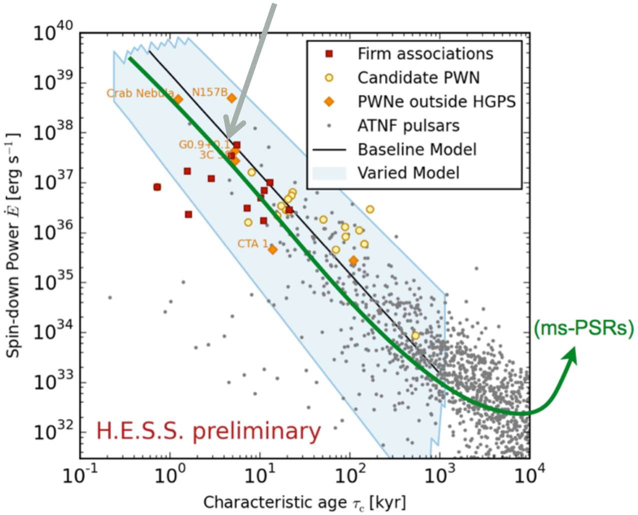
S. Klepsar, ICRC2015

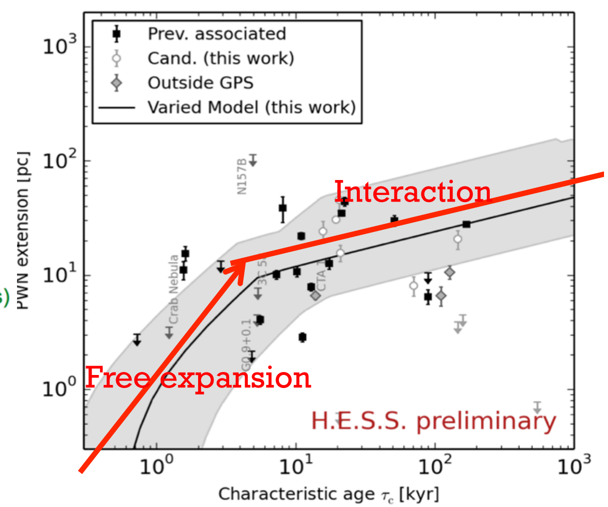
Age	Phase	# of VHE srcs	Tev Source
0-7k yrs	Free Expansion?	9	Crab, G0.9
7k – 30 kyrs	Interaction?	16	CTA 1
>30 kyrs	Relic?	9	

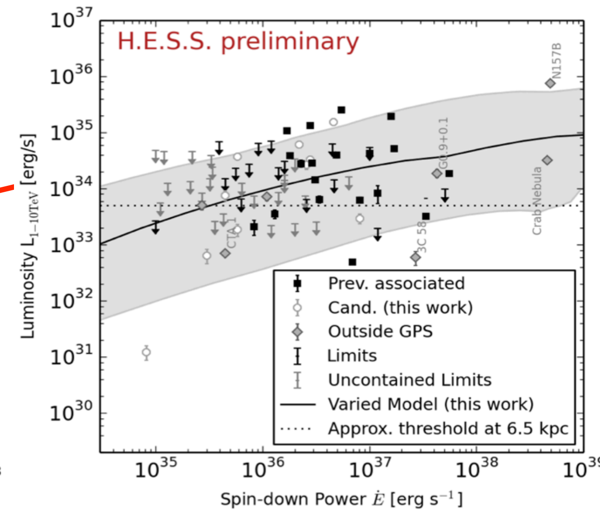
+ Population Study

Young Energetic pulsar has Nebula

S. Klepsar, ICRC2015







Edot vs Age

TeV Extension vs Age

TeV Luminosity vs Edot

Correlation is not clear, but more or less consistent with theory.

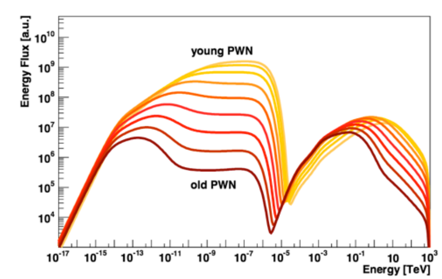
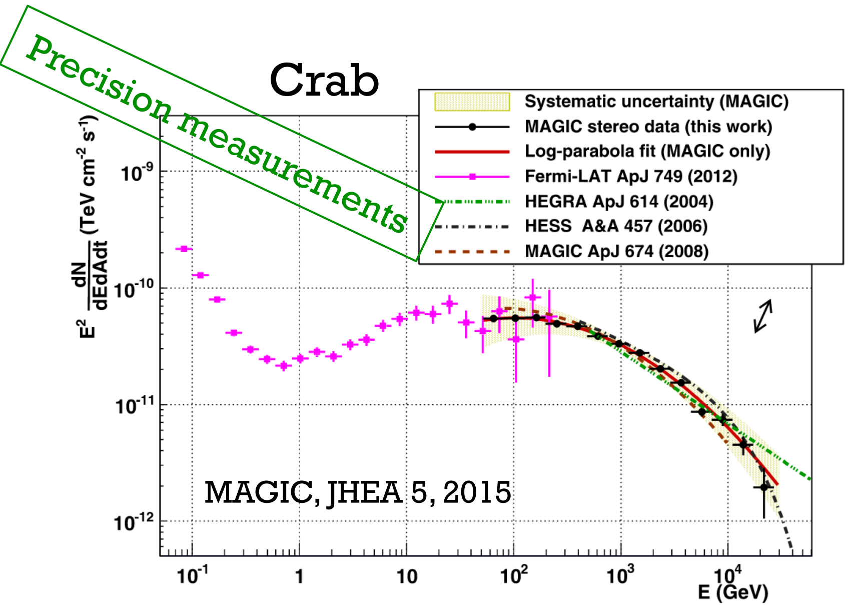


FIG. 1. Typical evolution of the modeled spectral energy distribution of a PWN with time. The color scale represents the age of the PWN, starting with a young system (500 years, yellow) and proceeding in equidistant steps on a logarithmic time scale to an old system (150 kyr, dark red).

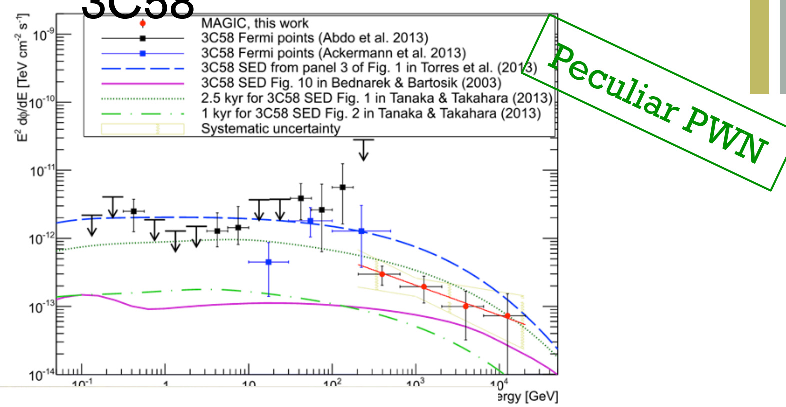
Crab and 3C58

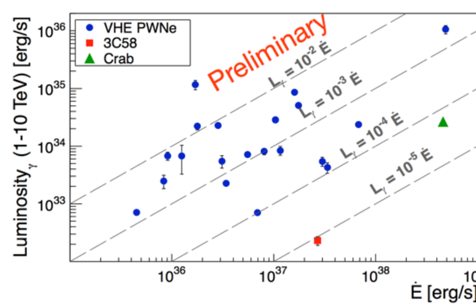
Crab

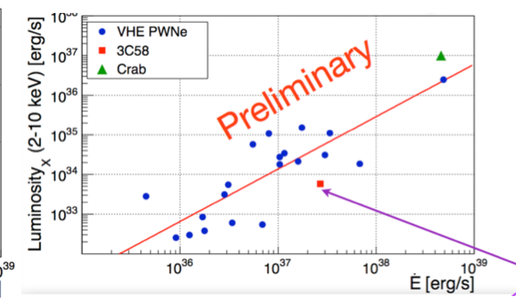


- Curved spectra measured up to 20 TeV
- Existence of the cutoff unclear due to systematics
- Uniform B field (time dep/indep) cannot reproduce the spectrum precisely.
- Spectral enhancement during GeV flare is not detected.

3C58





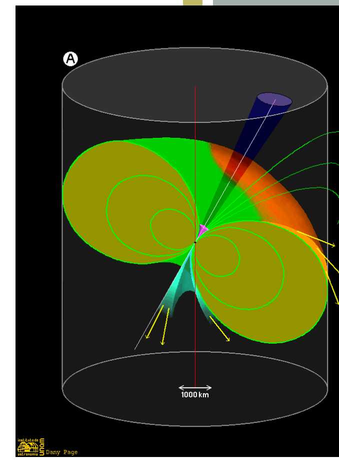


- Young (τ =5kyr) and energetic (log10(Edot) = 37.5, 10% Crab)
- Lowest VHE luminosity
- Most inefficient conversion to VHE
- Conversion to X-ray is OK

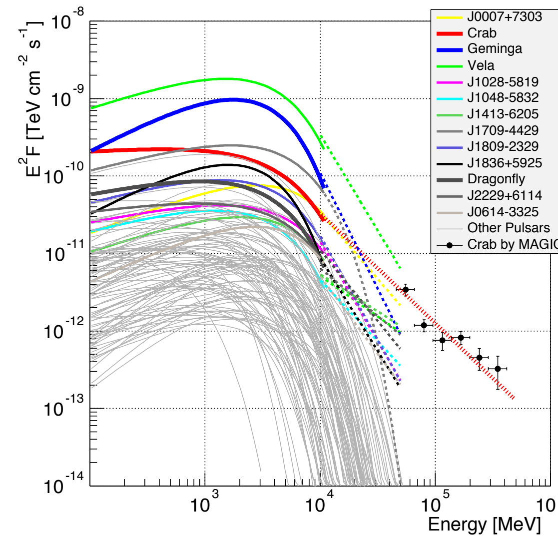
+ Pulsars (2 detected)

- Pulsars: ~ 2500 in the Galaxy.
  - Rapidly rotating neutron star with strong B field.

- Gamma-ray pulsars: > 150 in the Galaxy
  - 1/3 are milisecond pulsars
  - Some are radio quiet
  - Curvature radiation from outer magnetosphere
  - Spectral break/cutoff at a few GeV
  - Lowering the IACT threshold is the key



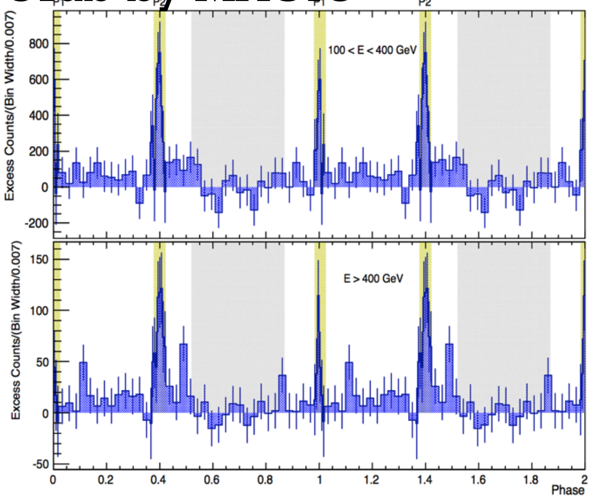
Spectra of gamma-ray pulsars

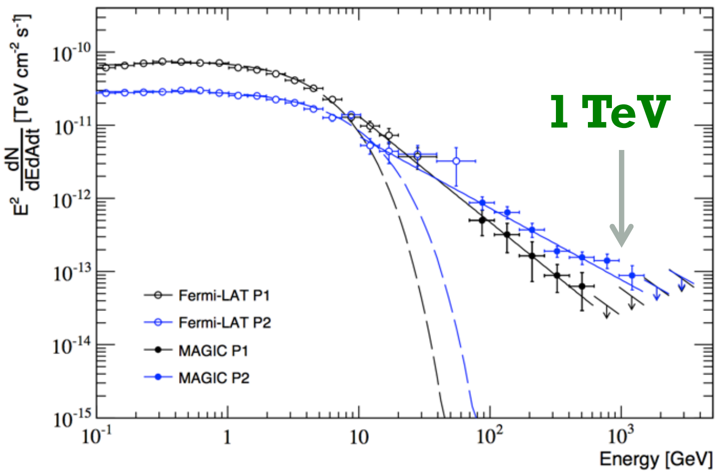


VHE Source	Age	Spindown Luminosity	B_{LC}
Crab	1260 yrs	4.5e38 erg/s	2e6 Gauss
Vela	11300 yrs	6.9e36 erg/s	9.5e4 Gauss

Crab and Vela pulsar

Crab by MAGIC

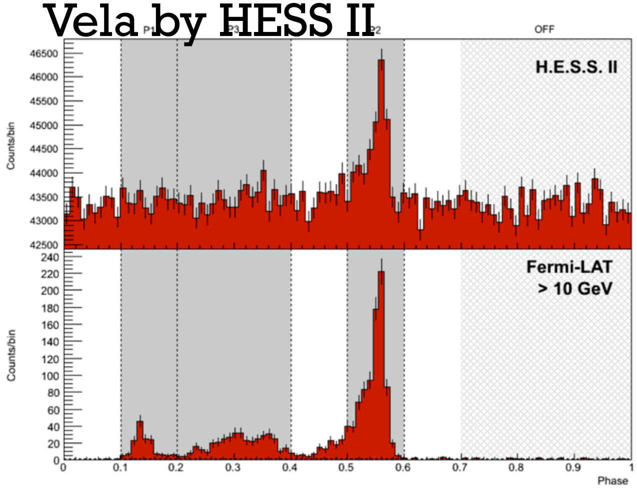


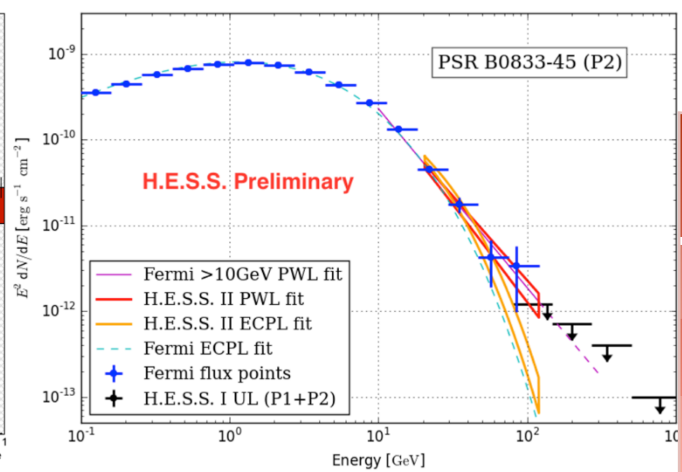


Broken power law rather than cutoff PL.

At least Crab emission should be inverse Compton, rather than Curvature radiation.

Vela by HESS II

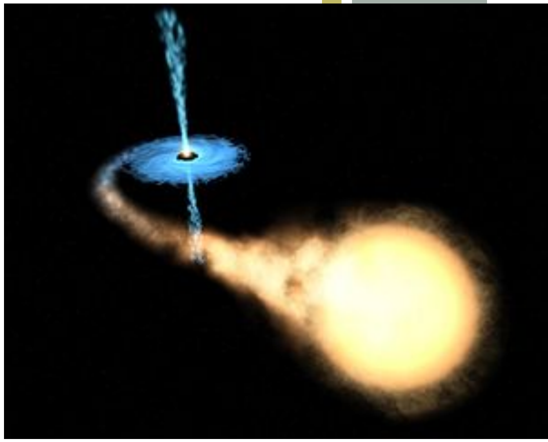




	Γ_1	E_c [GeV]	Γ_2
Crab	2.0	5	~3
Vela	1.5	3	~4
Geminga	1.0	1	~5

Binary (5 detected)

- X-ray binary (XB), 299 in the Galaxy.
  - A binary system containing a compact object with matter accretion from the companion star
- High mass X-ray binary (HMXB), 114 in the Galaxy
  - XB with O or B type companion
- Low mass X-ray binary (LMXB), 185 in the Galaxy
  - The rest of XB
- Microquasar, >15 in the Galaxy
  - XB with relativistic jets. Some are LMXB, some are HMXB.



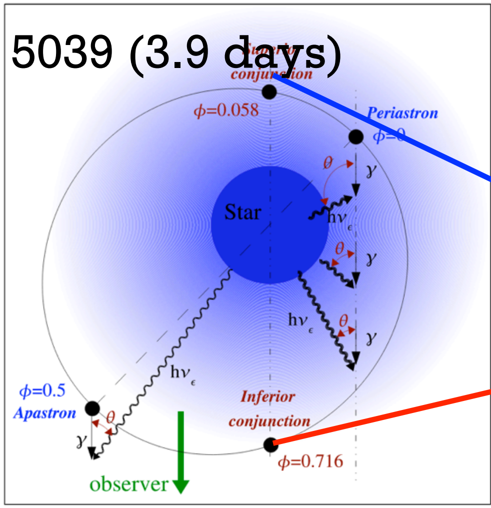
VHE Source		period	e	M_{comp}/M_{sun}
LS 5039	Compact + O6.5V star	3.9 days	0.35	23
B1259	NS + Be star	3.4 years	0.87	31
LS I 61	Compact + Be star	26.5 days	0.55	12
HESS J1018	Compact + O6V star	16.6 days	--	31
HESS J0632	Compact + B0V star	315 days	0.83	16
TeV J2032	NS + Be star	20-30 yrs	0.94	10-20

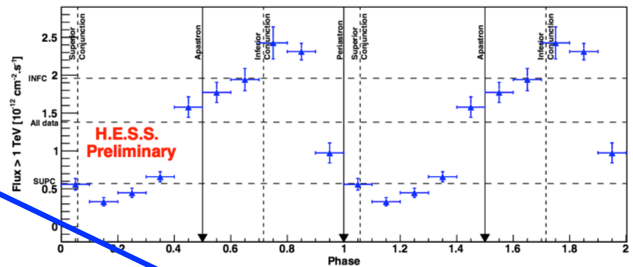
All HMXB

Very old friend,
New categorization!?
(MNRAS 451, 2015)

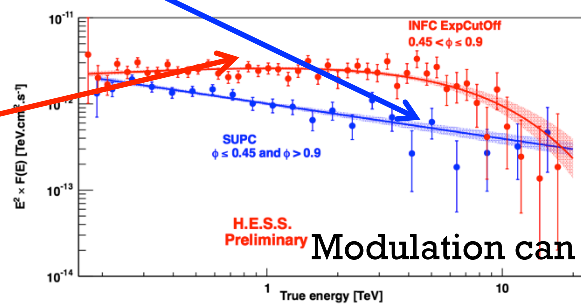
+ LS 5039 & PSR B1259

LS 5039 (3.9 days)





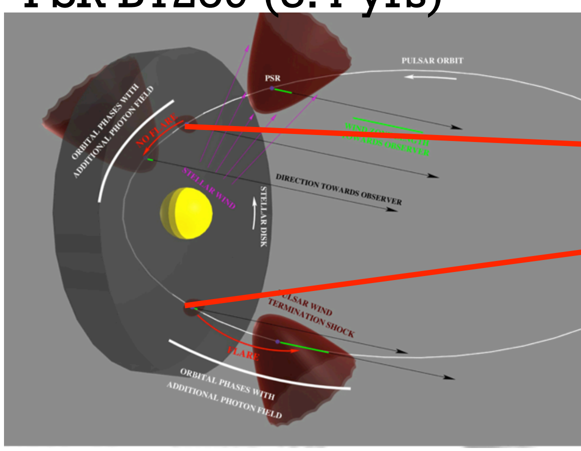
<Flux vs orbital phase>
Orbital modulation is seen.

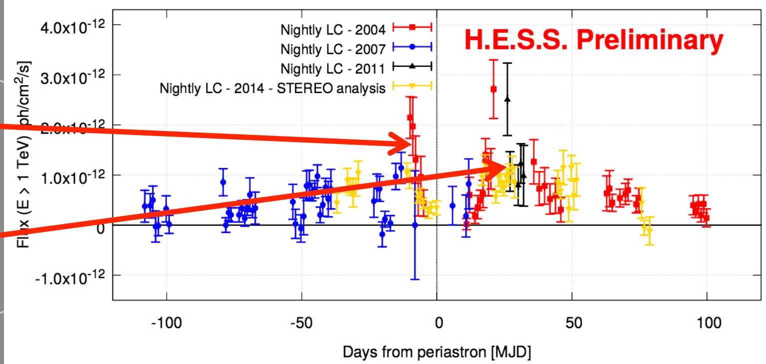


< SED vs orbital phase>
Orbital modulation is seen.

Modulation can be explained by photosphere absorption.

PSR B1259 (3.4 yrs)

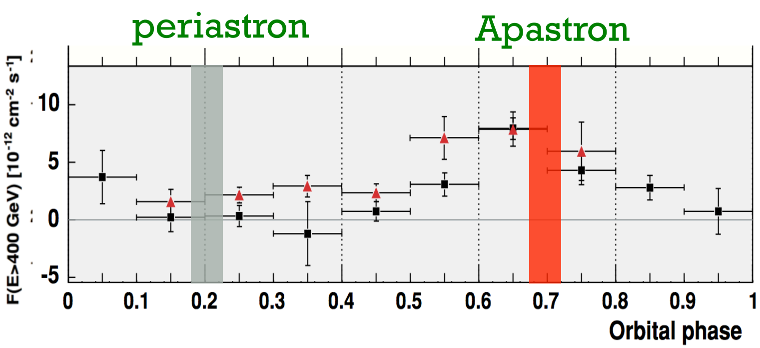




<Flux vs orbital phase>
Two peaks near priastron.

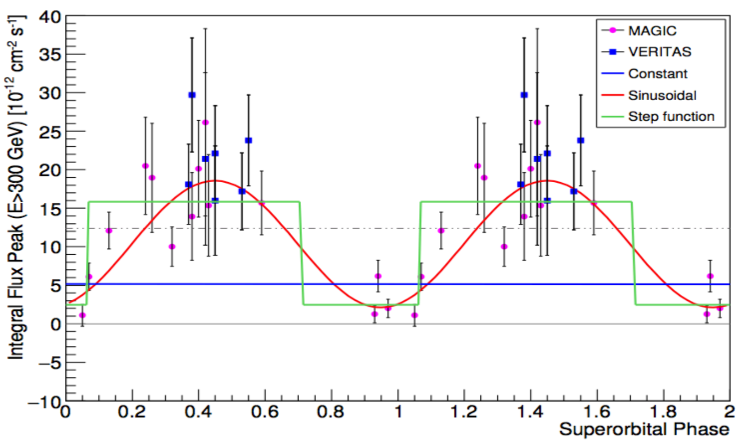
Two peaks can be explained interaction between pulsar wind and inclined circumstellar disc.

+ LSI +61 303



<Flux vs orbital phase>

Orbital modulation is seen.

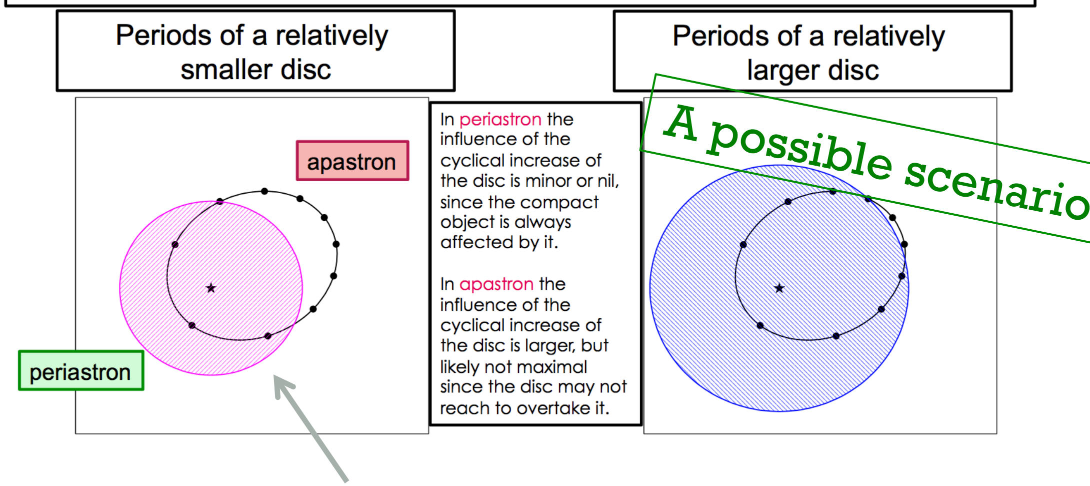


<Apastron flux vs superorbital phase>

Superorbital modulation is also seen.

The superorbital variability in Be binary is a cyclical increase of the circumstellar disc size and mass decretion rate

The stellar disk of Be stars is well known to grow larger as the equivalent width of the Hα emission line increases (e.g., Hanushik et al. 1988; Grundstrom & Gies 2006, etc).

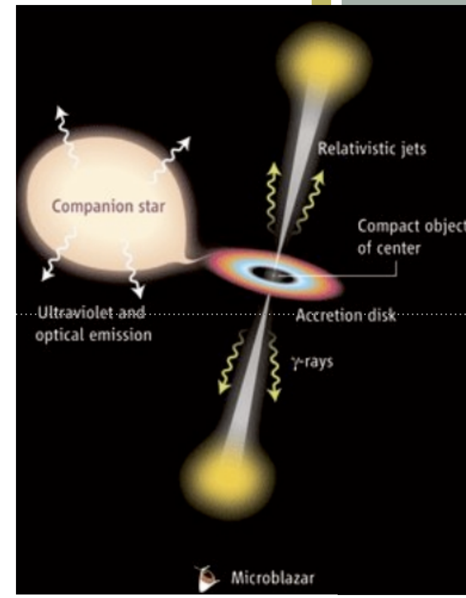


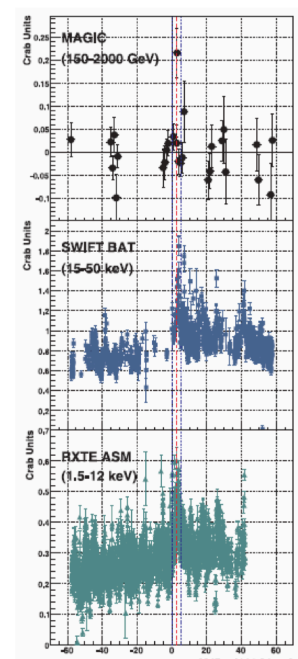
This disc oscillates with 1667 days = superorbital period.

ejector state		propeller state
Low accretion	flip-flop	High accretion
$R_{alfven} > R_{LC}$		$R_{alfven} < R_{LC}$
Pulsar Wind blow		Pulsar Wind disrupted
Strong shock, & emission		No shock, no emission

Microquasors

- TeV emission expected from the Jets.
- The following 4 are deeply observed by HESS, MAGIC and Veritas. None of them are detected.
  - GRS 1915
  - Cyg X-1
  - Cyg X-3
  - SS 443
- Upper limits are a few % Crab level.
- There was a 4 sigma hint of hourly scale flare from Cyg X-1 reported by MAGIC

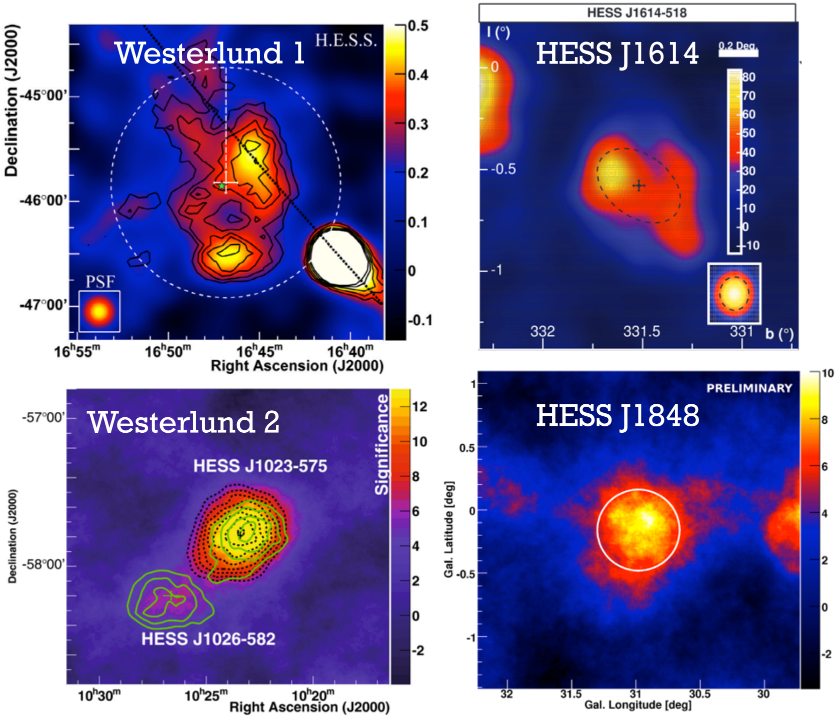




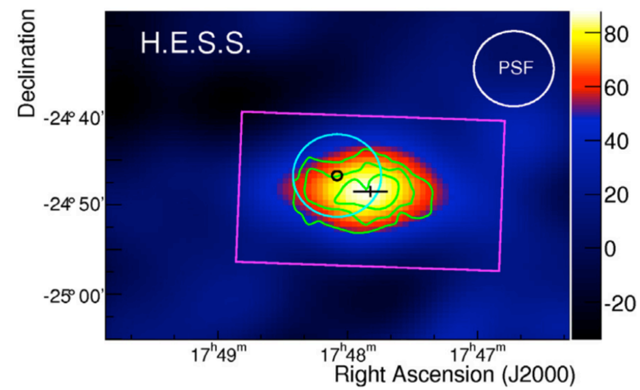
Albert et al. 2007, ApJ 665, L51

Stellar/globular clusters (5 detected)

■ Massive Stellar Clusters (4 srcs)



■ Globular Cluster: Tarzan 5

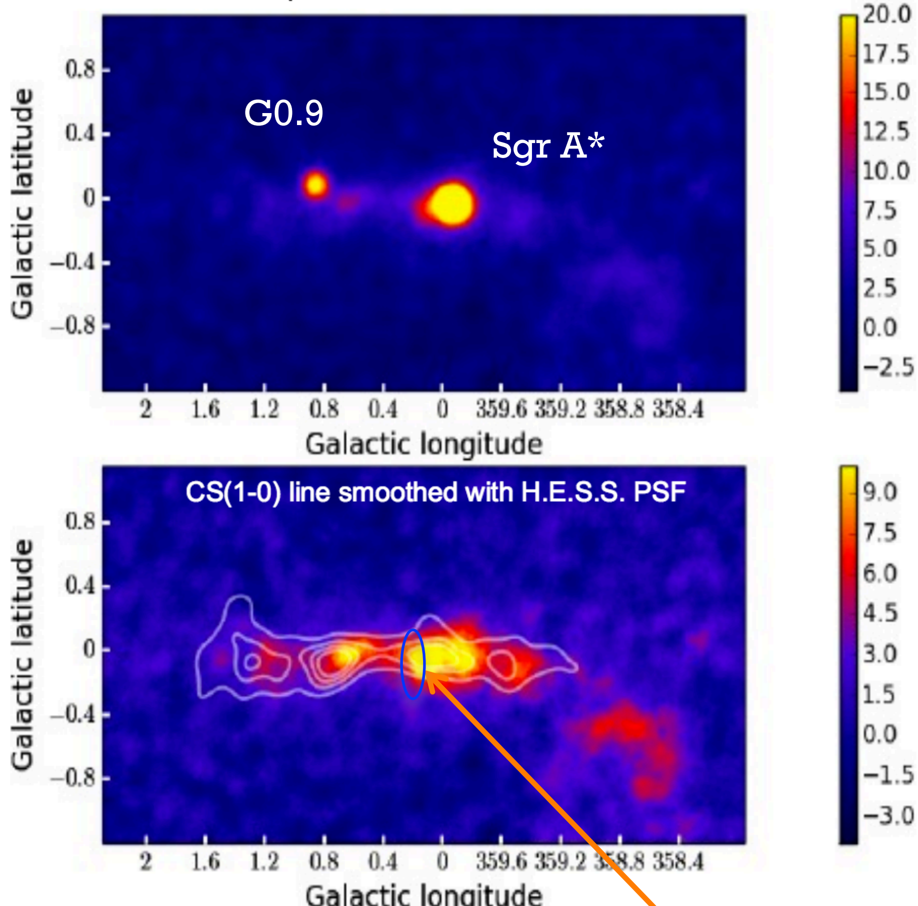


- Massive Steller cluster can accelerate particles by
  - ➢ Colliding winds
  - ➢ Collective wind bubble
  - ➢ SN explosions
- It is not clear which mechanism is at work for each system

- The only VHE GC.
- Extended large than the GC tidal radius
- 4 arcmin offset from the GC center
- Millisecond pulsars in GC produce leptonic VHE?

Galactic Center

Excess map smoothed with H.E.S.S. PSF



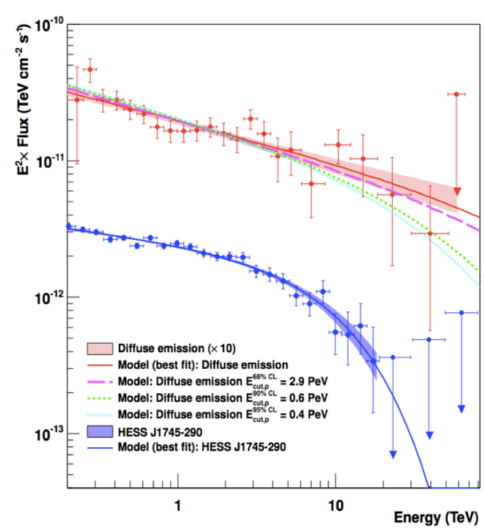
Excess map point-sources subtracted, smoothed with H.E.S.S. PSF

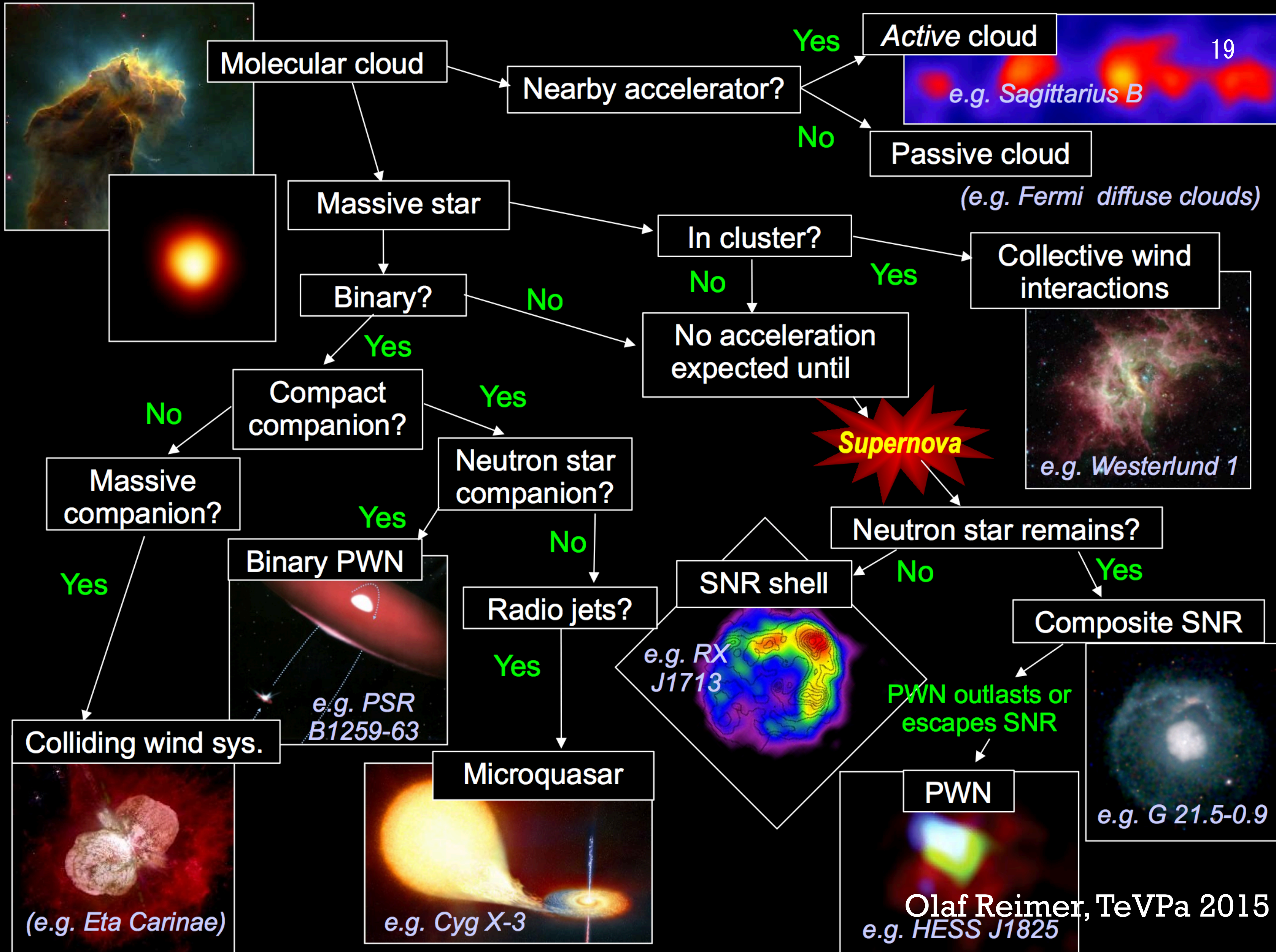
Radio arc

Apart from Sgr A* and G0.9,

- Point-like source coinciding with radio arc
  - PWN?
- 0.1 degree source at GC
  - Radial gradient of CR in central molecular zone?
- Diffuse emission tracing CS line
- Large Scale diffuse emission

Central source spectrum shows cutoff at 10 TeV, while diffuse emission shows no cutoff.





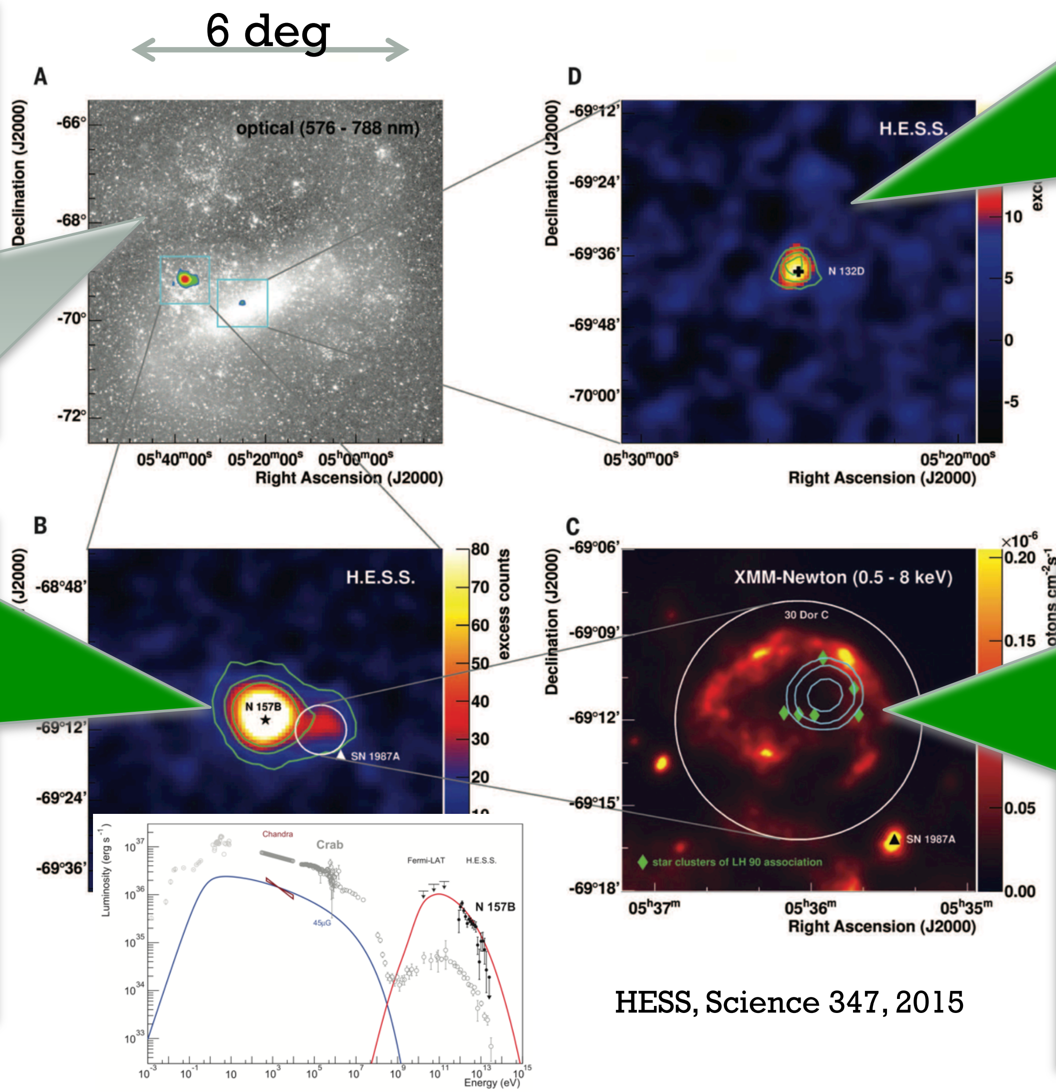
Olaf Reimer, TeVPa 2015

Extragalactic Sources

- LMC – 50 kpc (1 page)
- Star Burst Galaxies – 4 Mpc (1 pages)
- AGN
  - Blazer (z = 0.03 – 0.944)
  - FR I (4 – 200 Mpc)

Large Magellanic Cloud (3 srcs)

LMC
- Satellite galaxy of the Milky way
- 48.5 kpc away,
- 10% of Milky way mass,
- 5% of Milky way size



N132 D
- SNR (shell?)
- 2500 yrs
- Bright Sync. Radio
- Bright thermal X
- Leptonic?
- Hadronic?

N157 B
- PWN
- PSR J0537-6910 in it. Crab twin (Edot larger than Crab!)
- Eefficient gamma-ray emitter, but spindown power lost somewhere

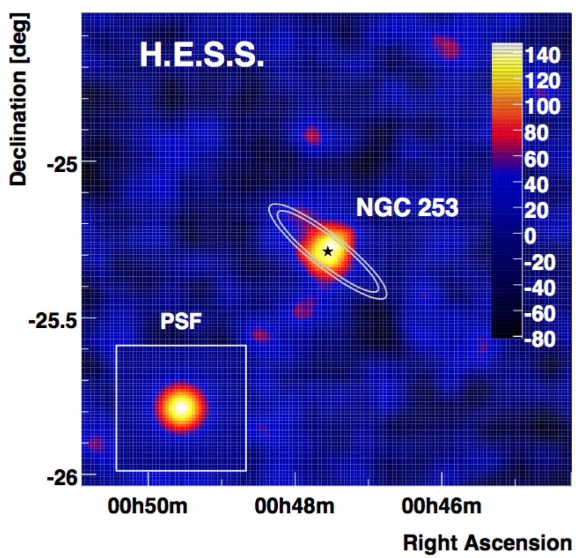
30 DorC
- Superbubble – collective mechanical output of massive star cluster into ISM
- OB assoc. LH90 is the power. 5 SN explosions and stellar winds

HESS, Science 347, 2015

Starburst Galaxies (2 detected)

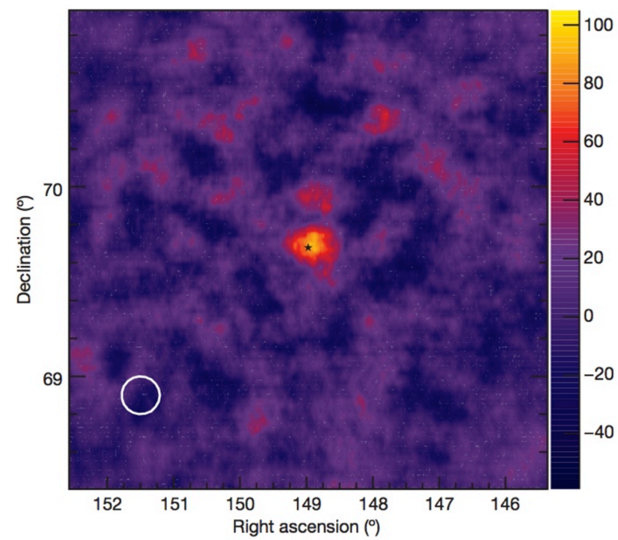
- Galaxy with a high star forming region. CR density is higher there.
- "Diffuse" VHE emission is expected through interaction with interstellar gas and radiation in the galaxy.

NGC 253



- 2.6 – 3.9 Mpc away
- Starburst core size ~ a few 100 pc
- Supernova rate 0.03 /year in the core
- Based on VHE obs. CR density is estimeted to be 2000 times larger than the Milky way

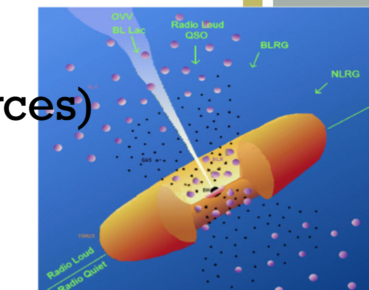
M82



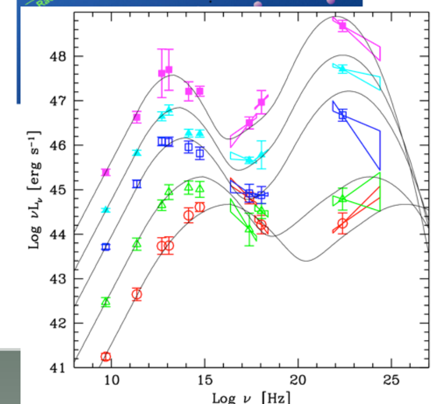
- 3.5- 3.8 Mpc away
- Starburst core size ~ 300 pc
- Supernova rate 0.1 – 0.3 /year in the core
- Based on VHE obs. CR density is estimeted to be 500 times larger than the Milky way.

"High Supernova rate = High Cosmic ray density" proved.

+ (radio loud) Active Galactic Nuclei

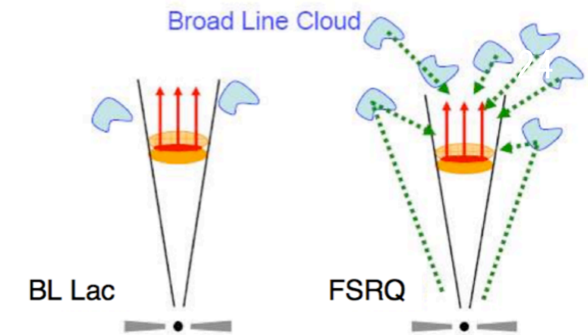


- Supermassive Black hole with a relativistic jet.
- Majority of VHE sources (65 sources, 1/3 of all VHE sources)
- Jet pointing at us -> Blazer
  - 4 types, based on synchrotron peak
    - HBL: Peak > 10^{15} GHz (UV, X)
    - IBL: 10^{14} GHz < Peak < 10^{15} GHz (UV, IR)
    - LBL: Peak < 10^{14} GHz (IR)
    - FSRQ: Radio index >-1.5. Normally peak < 10^{13} GHz. Line emission visible.
- Jet not pointing at us -> FR I

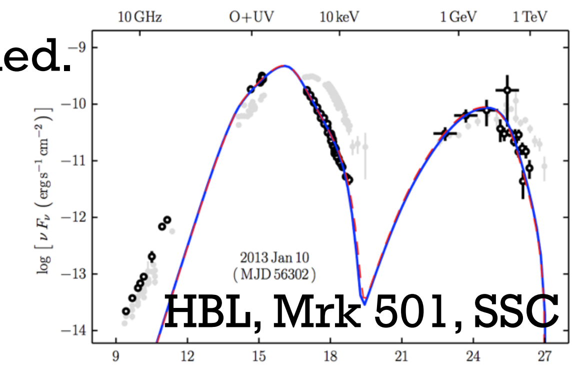


Type	Sub-Type	# of srcs	TeV Sources
Blazar	HBL	46	Mrk 421, 501, PKS 1424 etc.
	IBL	8	3C66A, BL Lac, W Comae, etc
	LBL	1	AP Librae
	FSRQ	5	3c279, PKS 1441, PKS1510, S4 0954, 4C+21.35
	Gravitationally lensed blazer	1	S3 0218+35
FR I		4	NGC 1275, PKS0625, M87, Centaurus A

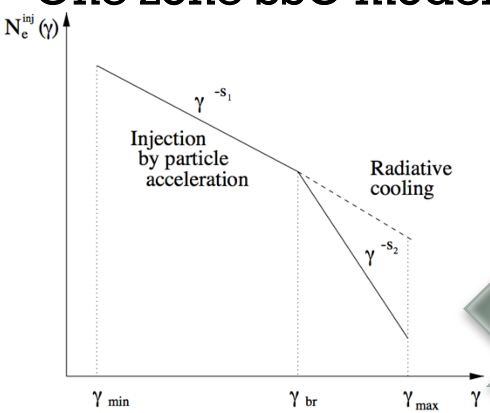
Blazar Spectrum (General)



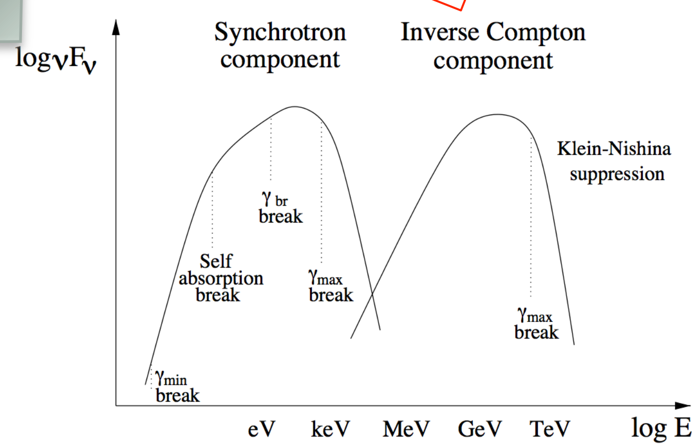
- Picture: Radiative Blob moving toward us.
- In general, one zone SSC model with a Doppler boosting can explain the broad band SED of BL Lacs (especially HBLs).
- For FSRQs, external photon field or two zone is needed.

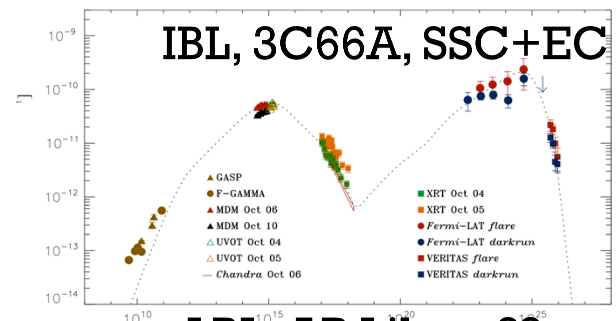


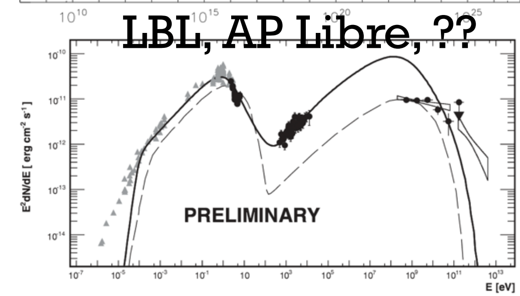
One zone SSC model



Very simple.
But works most of the cases





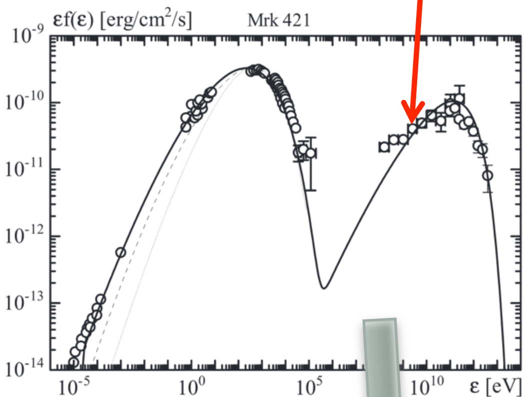


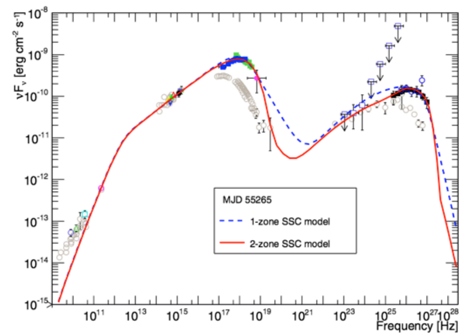
Input parameters.

- Broken PL electron spectrum
- Electron number density
- Blob size
- B field strength
- Doppler factor

Broad IC peak: e.g. Mrk 421

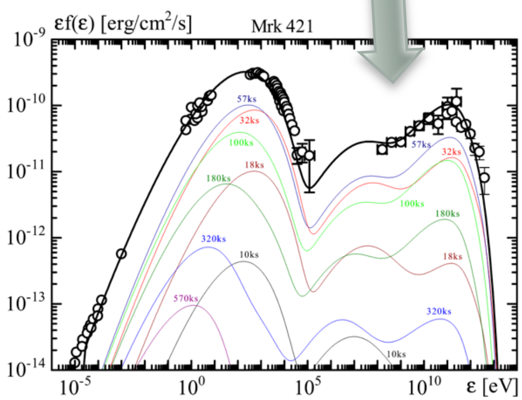
- IC peak is too broad for SSC?



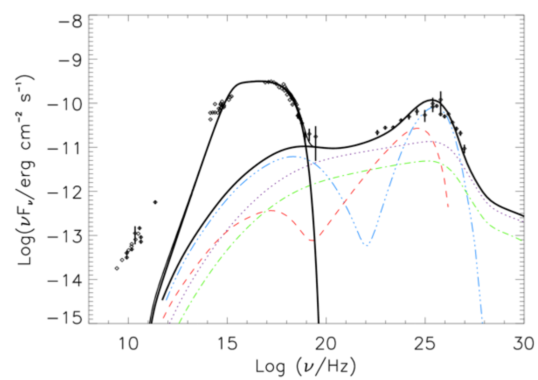


(a) MJD 55 265.

2 zone model (steady blob + flareing blob)
[MAGIC, A&A578, 2015]

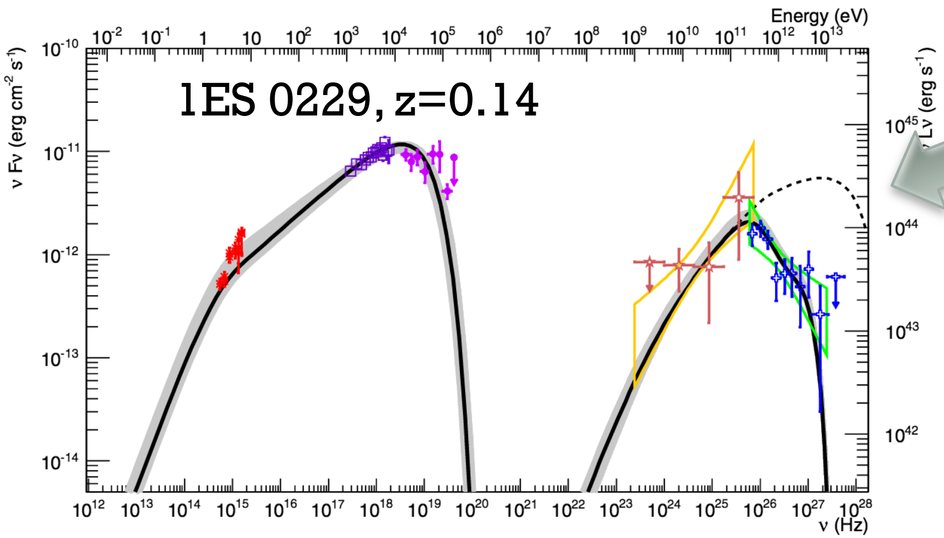


External Compton model
[Asano, ApJ 780, 2015]

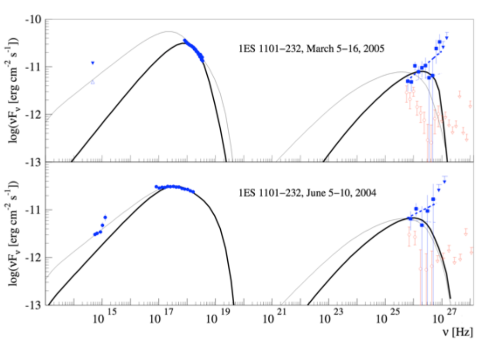


Hadronic model
[Abdo, ApJ 736, 2011]

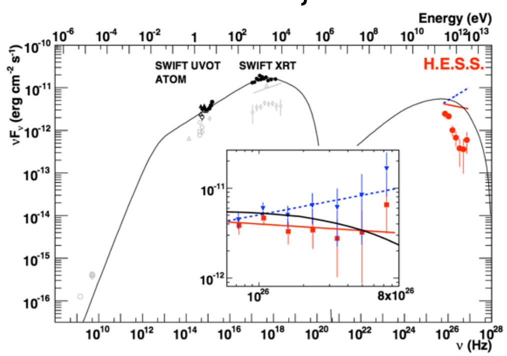
Extreme HBL



1ES 1101, z=0.186



1ES 0347, z=0.188

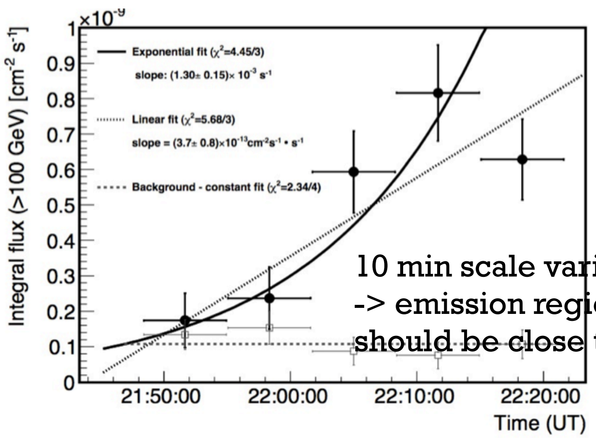


- Sync. and IC peak ~2 orders higher than classical HBLs.
- Very hard at GeV (Bad for Fermi)
- One zone SSC still works, but input parameters are largely different than classical ones. -> Further understanding of AGN emission mechanism.
- Substantial EBL absorption. -> Useful for EBL and IGMF study.

Variability

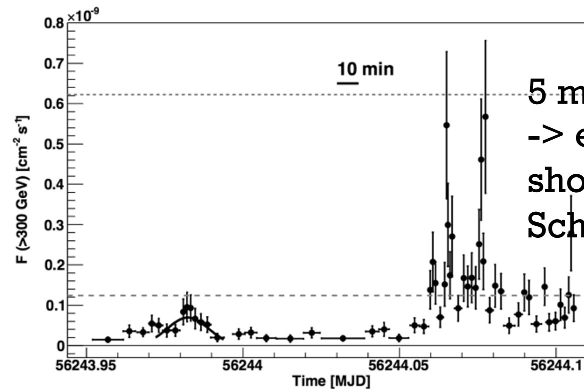
- Variability time scale is a powerful probe for emission region (causality).

FSRQ PKS 1222+21 (z = 0.432)

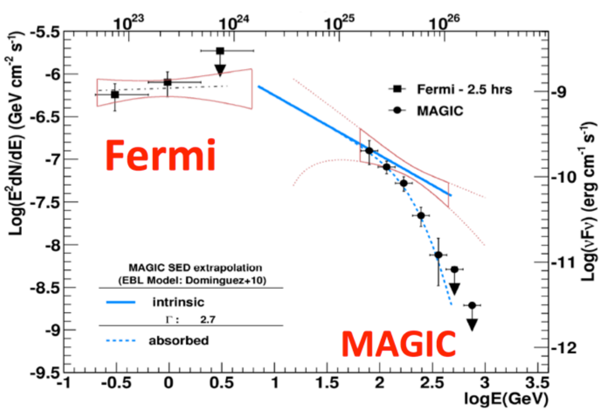


10 min scale variability
-> emission region
should be close to BH

IC310 (z = 0.0189)



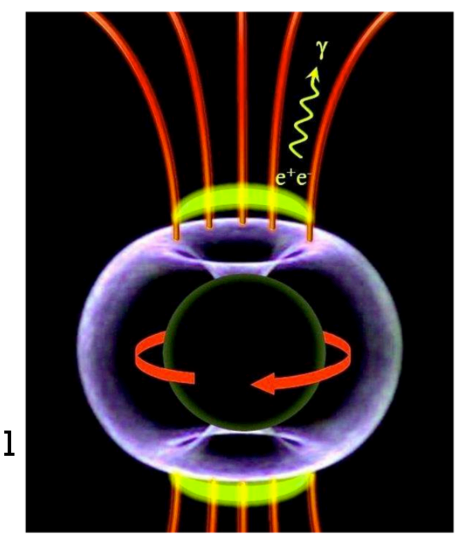
5 min variability
-> emission region
should be smaller than
Schwarzschild radius.



No BLR absorption feature
-> emission region out of BLR

MAGIC, ApJ 730, 2011

Strong constraints on the emission mechanism

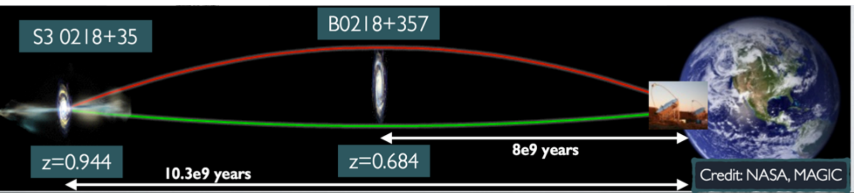


Black hole Polar Cap model proposed

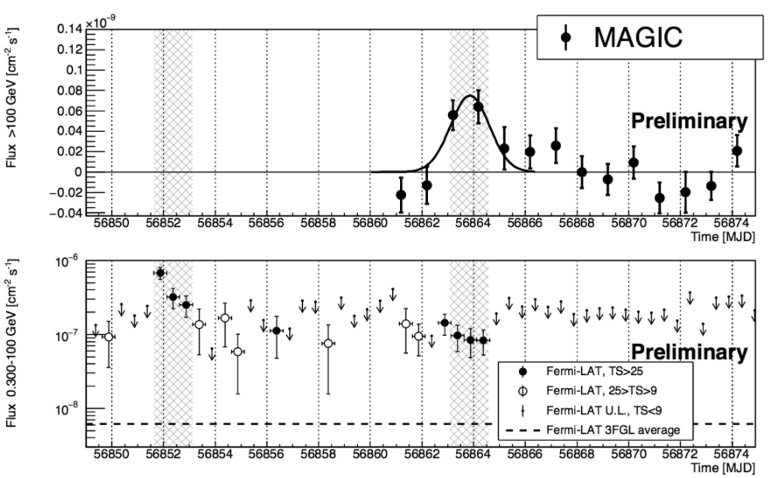
MAGIC, Science 346, 2014

How far we can see?

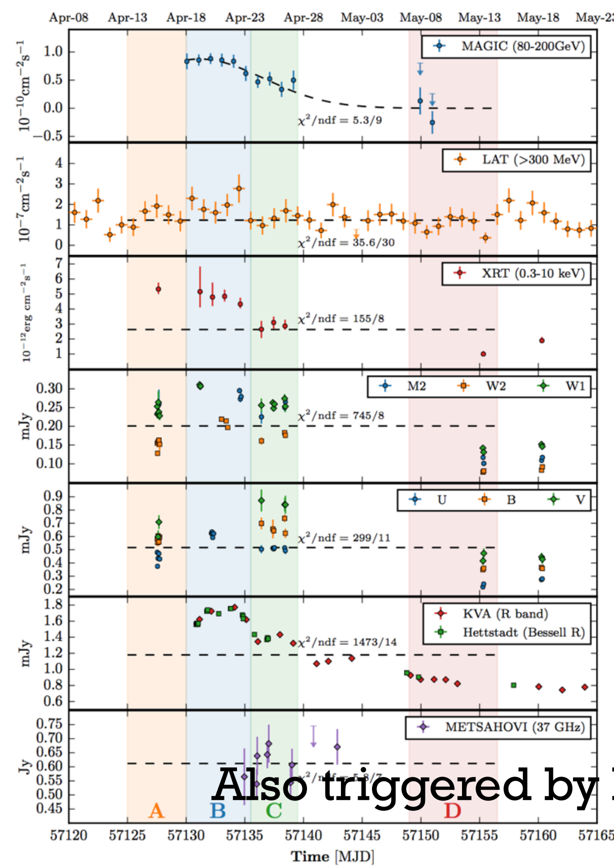
Gravitationally lensed Blazar
S3 0218+35 (z = 0.944)



Thanks to the lensing effect and LAT, the flare timing (of the second image) could be known ~10 days in advance



FSRQ PKS 1441+25
(z = 0.940)

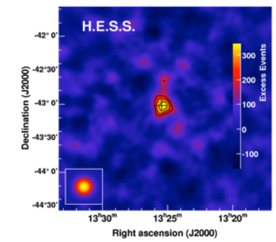


Also triggered by LAT detectio

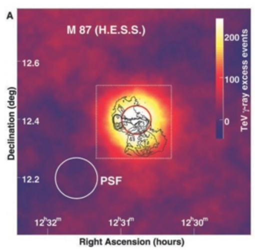
These are the record, important for EBL study.

Fanaroff - Riley Class I (4 detected)

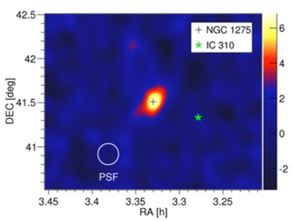
- Jet not pointing at us. Thus, no/weak Doppler boosting.
- Emission is not fully dominated by jets.



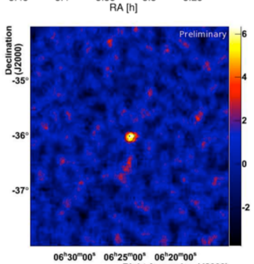
Cen A,
- 3.8 Mpc
- θ =15-80 deg



M87
- 16 Mpc
- θ = ~30 deg

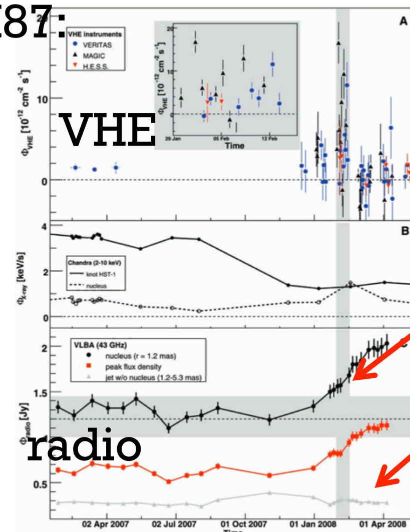


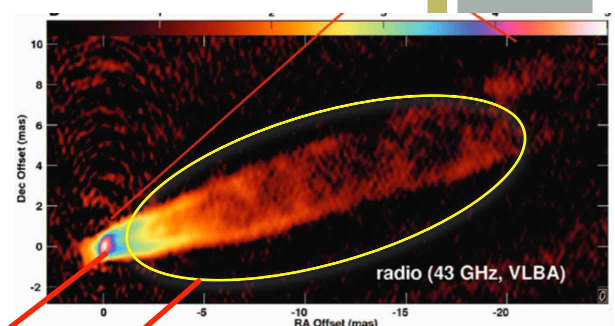
NGC 1275
- 75 Mpc
- θ =30-50 deg

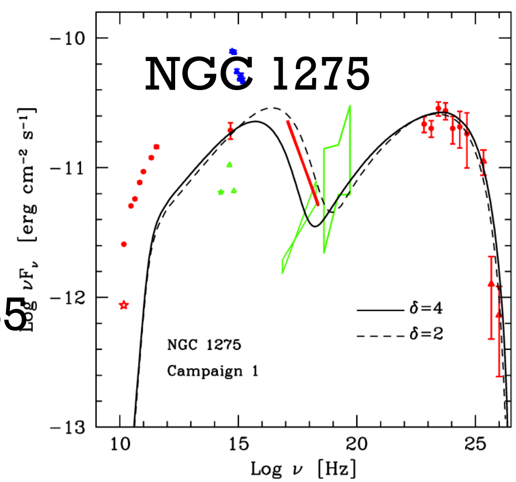


PKS0625
- 230 Mpc, z=0.055
- θ =50 deg?

M87:



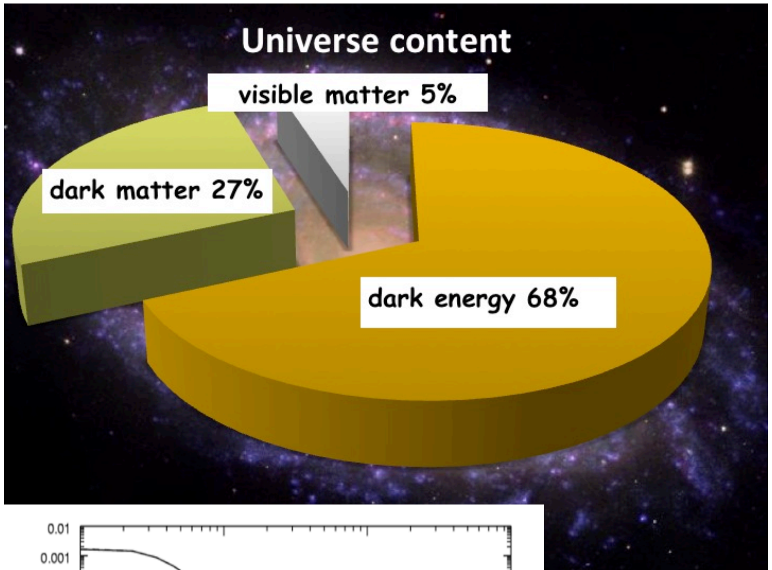


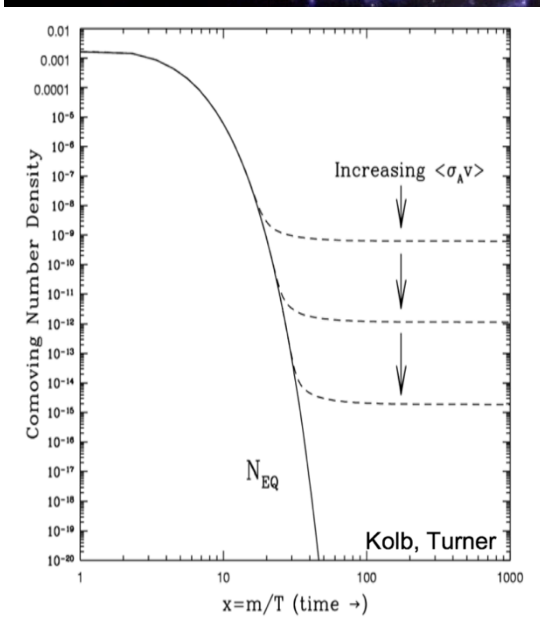


- VHE emission comes from the nucleus
- SSC can describe the spectrum
- Hadronic Scenario etc are also considered.

Dark matter indirect Search

Dark Matter





- Electrically neutral
- Non-baryonic
- Stable
- Non-relativistic (cold)

→ No candidate in Standard model

- Mass 10 GeV to a few TeV

New physics such as SUSY, Kaluza-Klein and etc. predict weekly-interacting massive particles (WIMPs).

=>The best Dark matter candidates.

In the early hot universe, WIMPs should be in thermal equilibrium with standard particles.
To explain the relic Dark matter density, cross section at "freeze-out" should be

$\sigma_{ann} v$ = 3x10^-26 cm3/s

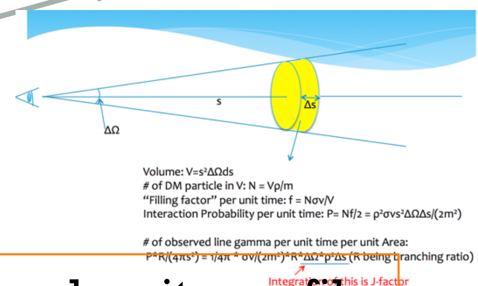
+ VHE Gamma-rays from WIMPs

- WIMP annihilation

X + X -> W + W- -> γ + …
-> b + b- -> γ + …
-> τ + τ - -> γ + …
-> γ + γ
-> …

$$\frac{dN}{dEdAdt} = J \times \frac{1}{4\pi} \frac{\sigma_{ann} v}{2m_\chi^2} \sum Br_i \frac{dN_i}{dE}$$

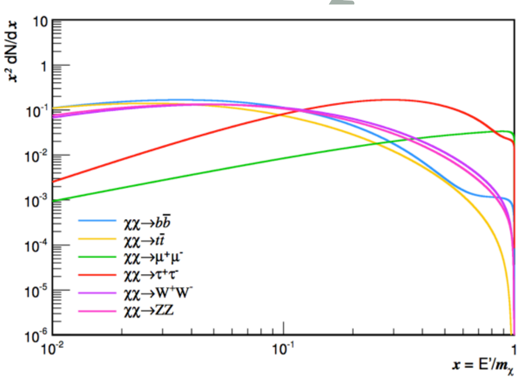
$$J = \int_{\Delta\Omega} \int_{los} \rho^2(l,\Omega)\, dl\, d\Omega$$

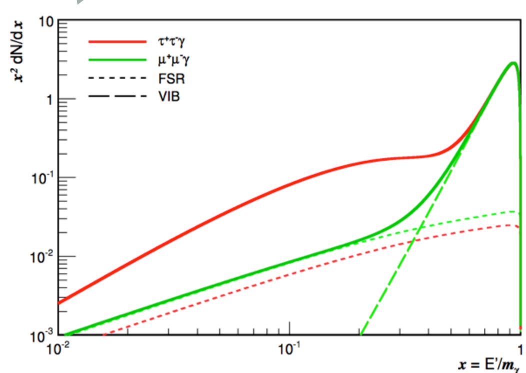


Branching ratio is particle physics model dependent

γ Spectrum from SM particle is known

Dark matter density profile is also model dependent





JCAP 02, 2014

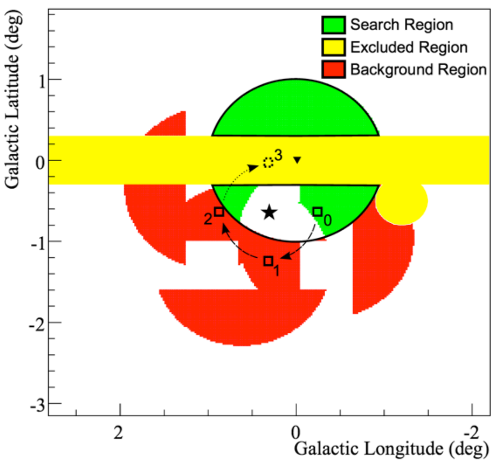
VHE observation sets upper limits on $\sigma_{xx\text{->}kk}$ v assumig a certain J-factor. To convert it to σ_{ann}v, branching ratio must be assumed.

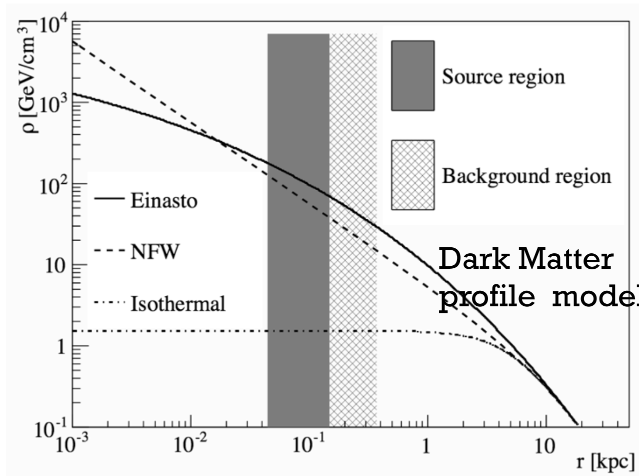
Targets should have

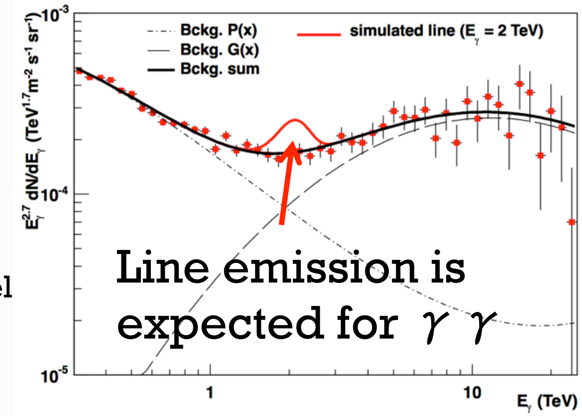
- Large J factor
- Low astrophyscal gamma BG

+ Observations:

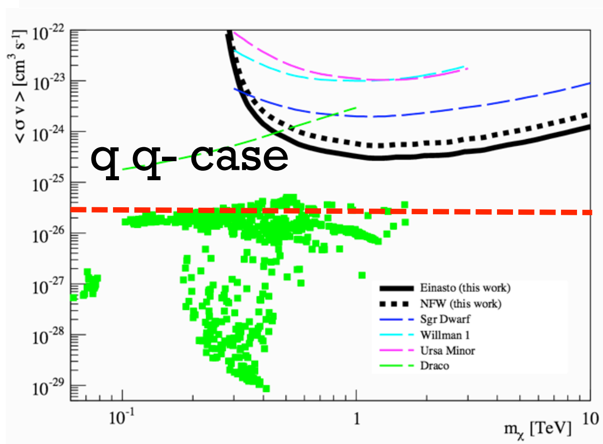
- Galactic Center region by HESS (112 hours)



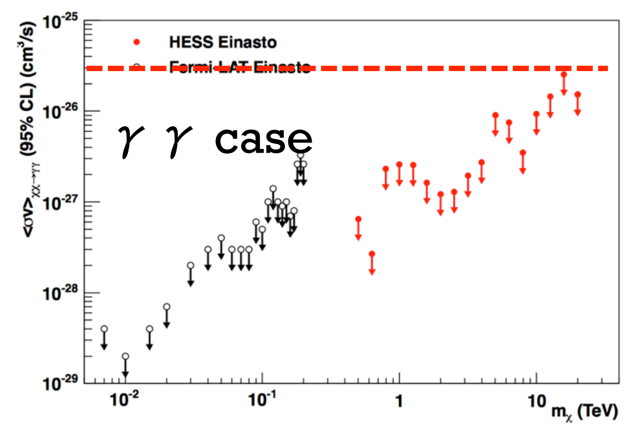




J_{ann}~ 1e22 GeV^2/cm^5 (1 deg)



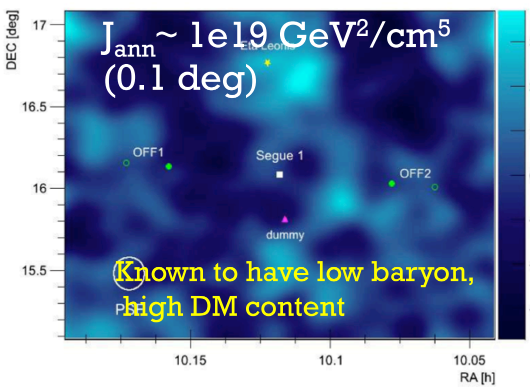
HESS, PRL 106, 2011

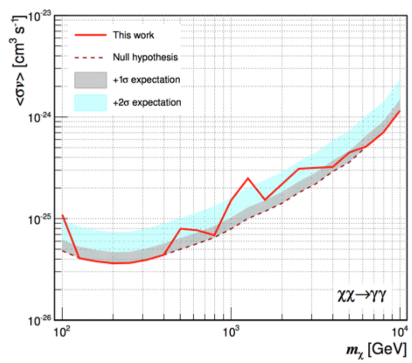


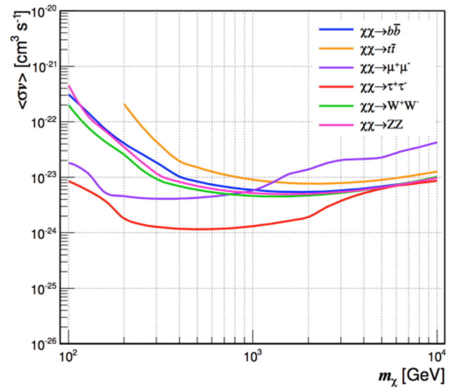
HESS, PRL 110, 2013

+ Observations

- Dwarf Spheroidal Galaxy "Segue 1" by MAGIC (158 hours)



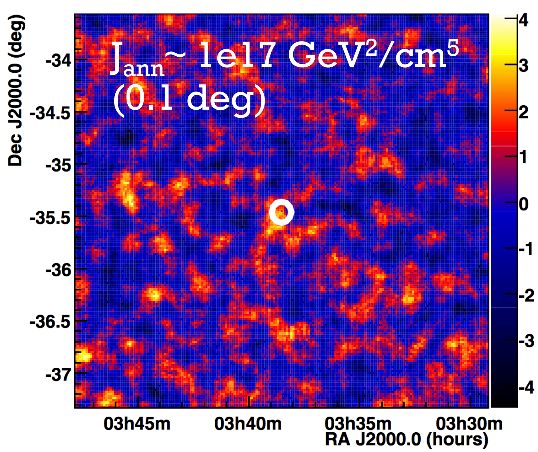


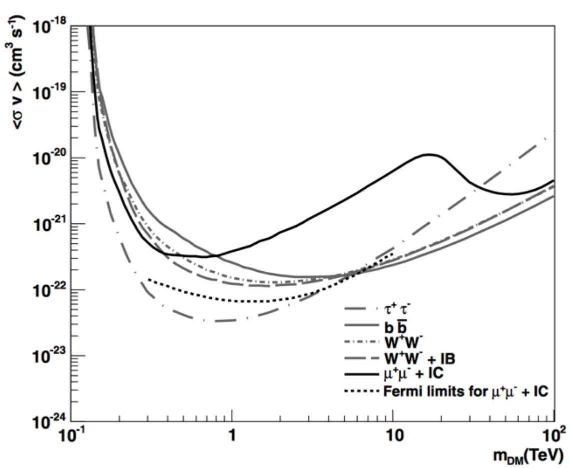


MAGIC, JCAP 02, 2014

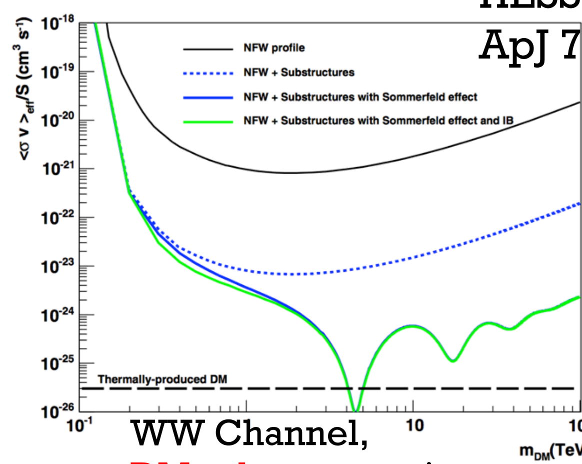
- Fornax Galaxy Cluster by HESS (14.5 hours)

HESS, ApJ 750, 2012





Different Decay Channels
With NFW profile



WW Channel,
DM substructure is assumed.
Sommerfeld effect is taken into accou

Conclusion

- VHE astronomy is blooming