Unidentified gamma-ray sources

New source classes and possible extended detections with GLAST

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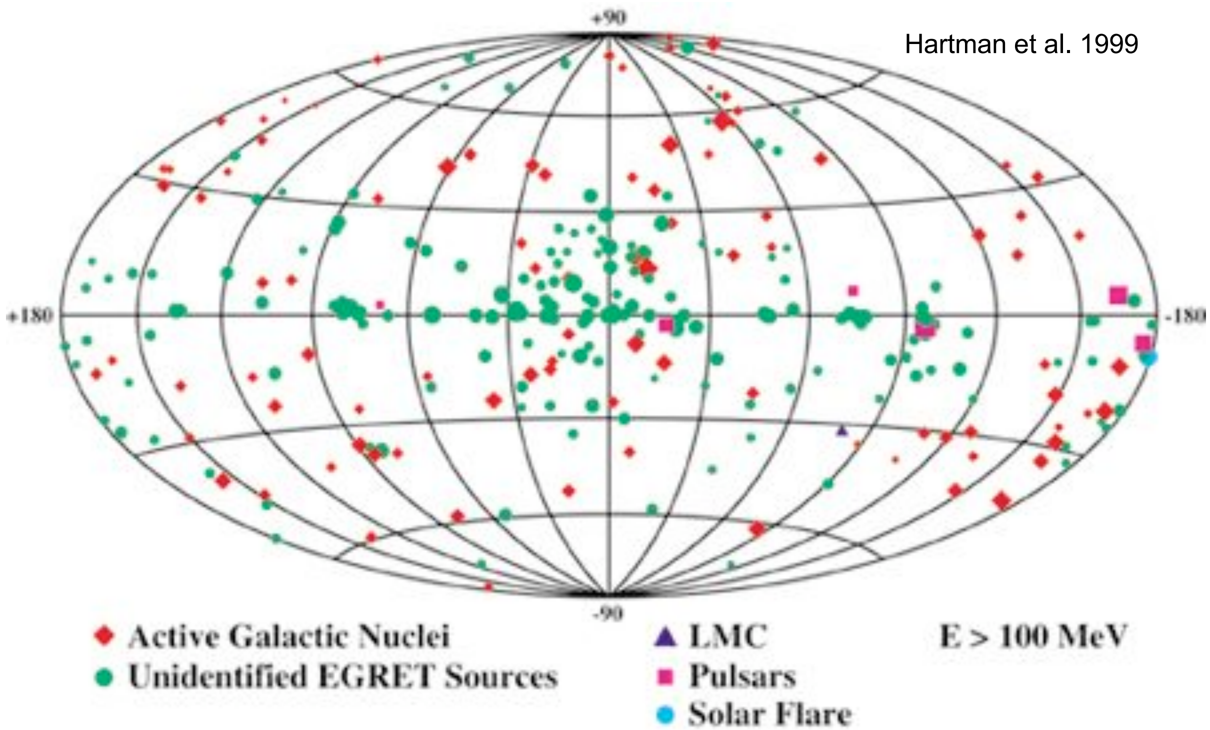
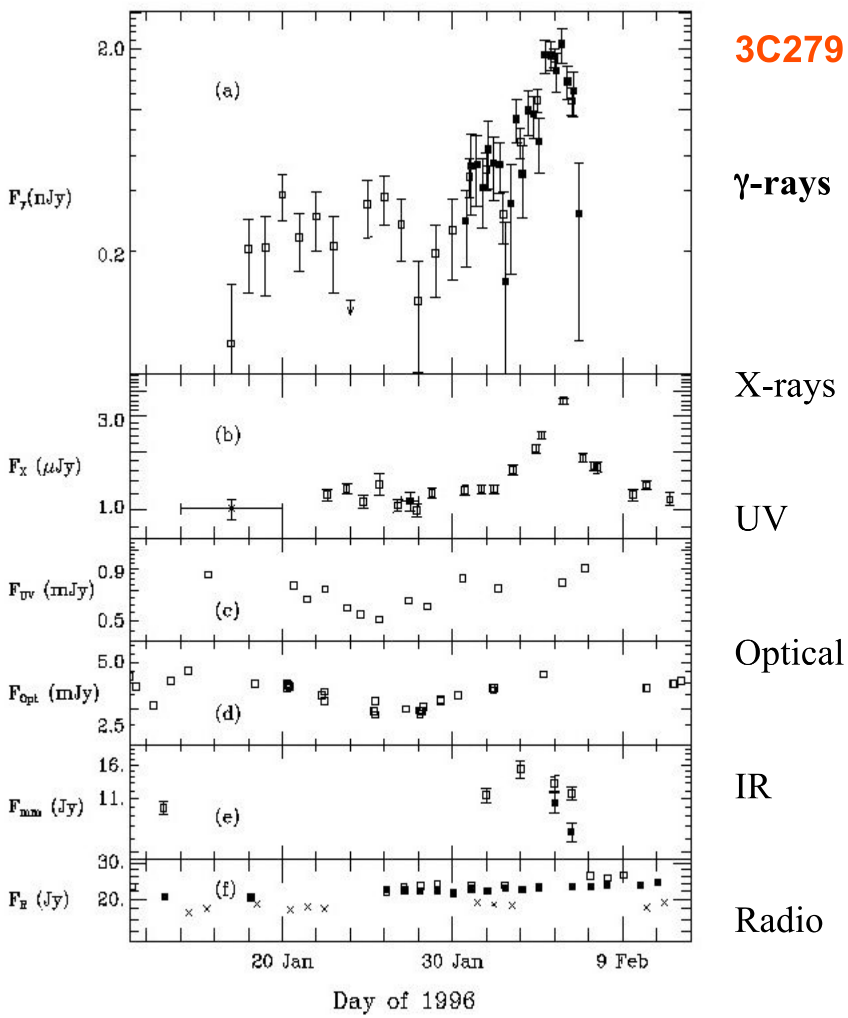
EGRET sources

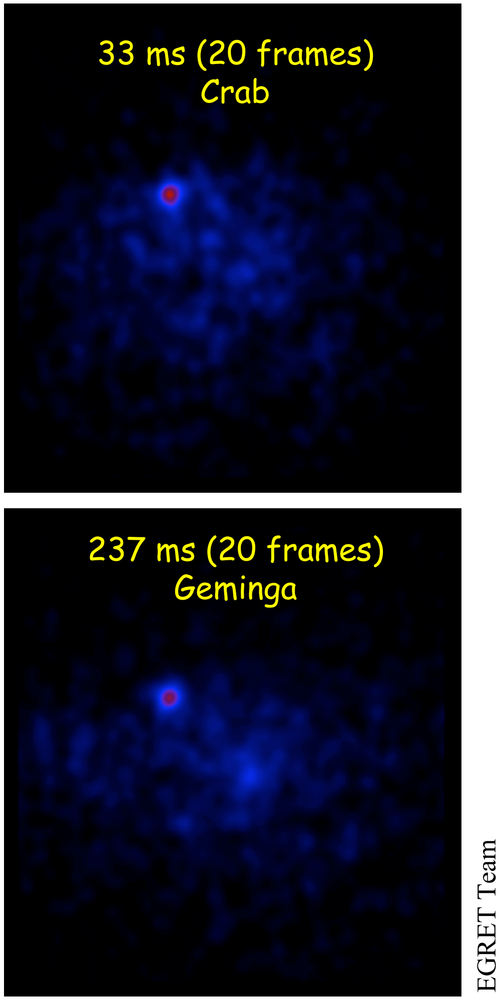


Unidentified sources: ~120 at high latitudes, ~80 at low (|b|<10) latitudes. ~66 Possible gamma-ray active galactic nuclei. ~6 pulsars.

Which populations? AGN & Pulsar



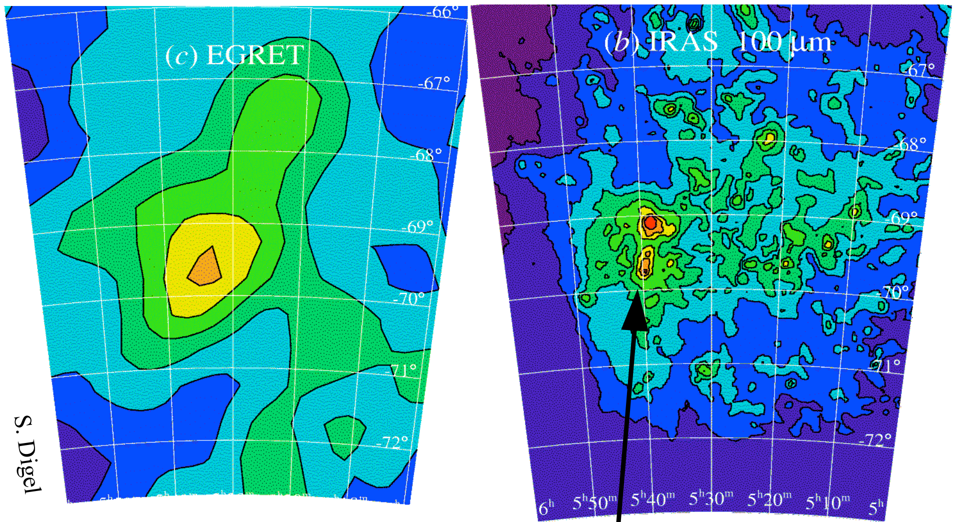
Simultaneous variability, at least for some members



periodicity

Diffuse emission from external galaxies: just the LMC

EGRET IRAS



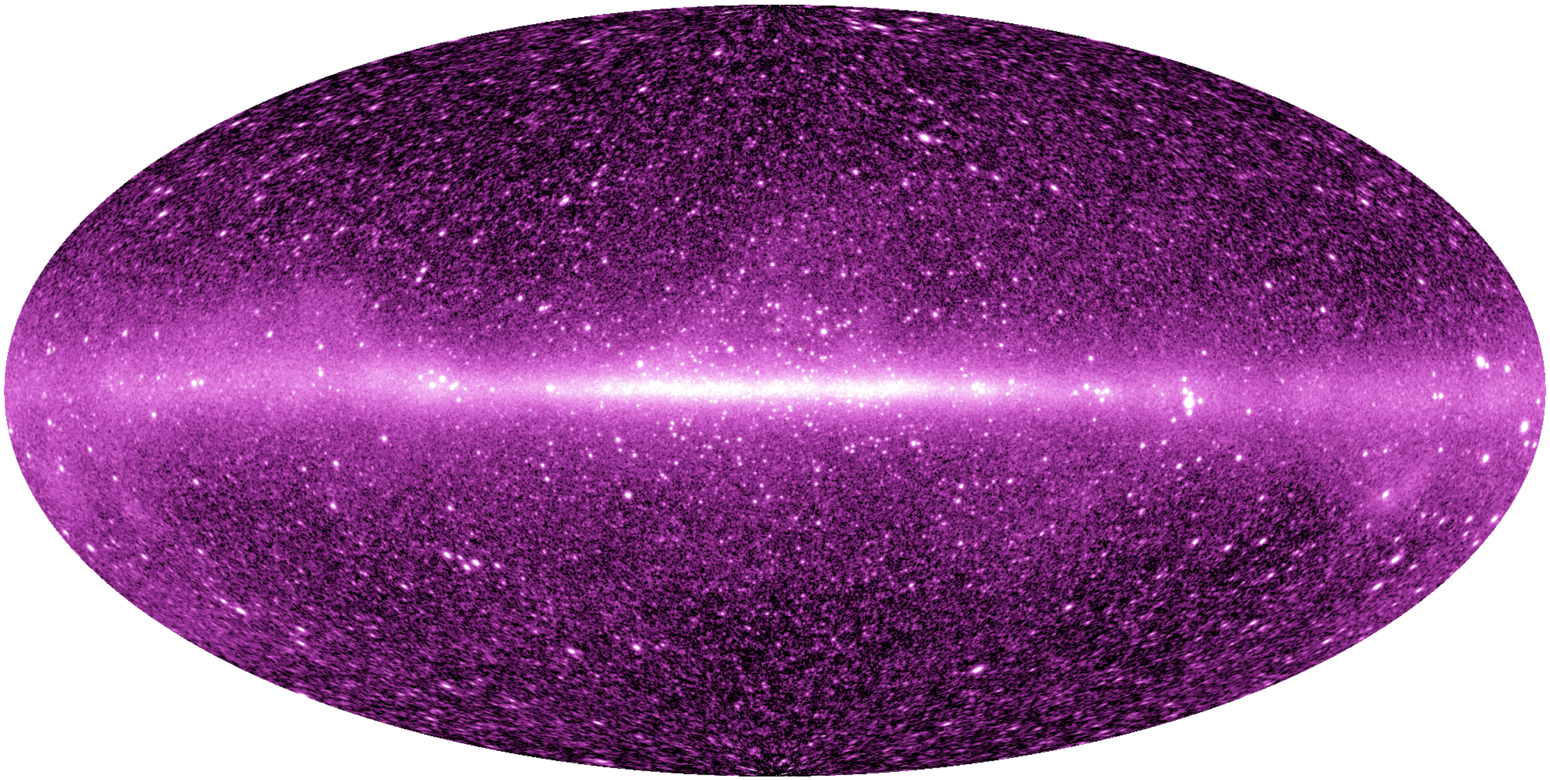
(1.9 ± 0.4) x 10^{-7} cm^{-2} s^{-1}

30 Doradus: extensive massive SFR and molecular clouds

Source Extension is key to detection reliability

- ✓ Distance limited: Milky Way at 1 Mpc would have a flux of about 2.5 x 10^{-8} cm^{-2} s^{-1} (>100 MeV), below EGRET's detection limit
- ✓ The **non-detection of the SMC proves** that the cosmic ray distribution is not universal but rather galaxy-related (Sreekumar et al. 1993), settling an issue being around for decades!

GLAST gamma-ray sky



Simulated LAT maps (>100 MeV, >1 GeV, 1 yr).

S. Digel's simulations

Why do we expect new classes of sources?

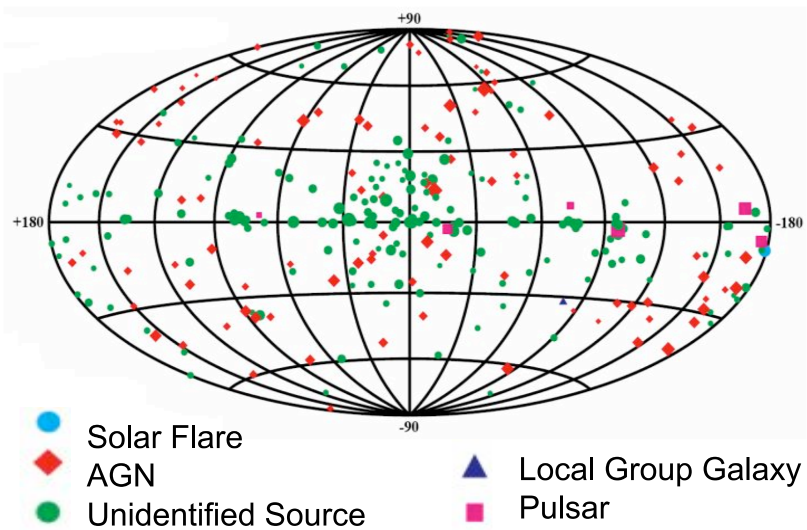
- **Phenomenological reasons:**
  - Low chance probability for spatial coincidences between EGRET sources & members of new classes
    - In particular, SNRs/stars/etc. Even with the caveats of non-uniform EGRET coverage and over subscription
  - Gamma-ray features that are hard to encompass within detected populations
    - Variability behavior beyond the known source classes, and the known distributions in sky
    - Extension & confusion (even admitting composite sources)
    - FoM approaches pointing to gamma-ray sources orphan from known counterparts - despite dedicated searches
  - Detection of new populations in nearby energy bands, especially at higher energies (HESS - MAGIC recent discoveries of new source classes)

- **Theoretical expectations:**
  - Expected gamma-ray output for different objects above the sensitivity of EGRET (for some cases) and LAT (for many more cases)

Keys to the challenge of detecting new populations

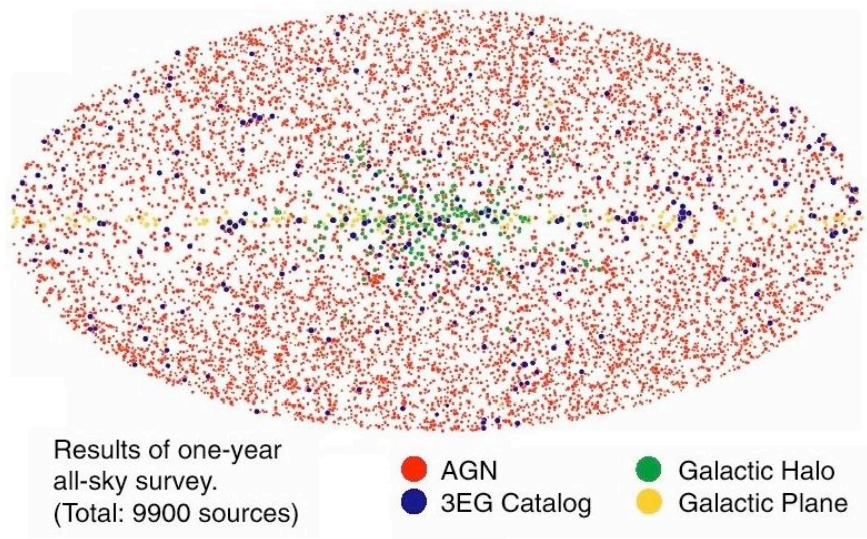
EGRET 3rd Catalog: ~270 sources

5σ Sources in Plane + 4σ Sources outside Plane
Four Years Pointed Observations



Anticipated LAT 1st Catalog: >9000 sources possible

5σ Sources from Simulated
One Year All-sky Survey



Source classification: Bottom – Up

Concept: **the largest class of identified gamma-ray sources is blazars, all of which have radio emission.**

IF a flat-spectrum radio source with strong, compact emission at 5 GHz or above is found in a gamma-ray source error box, it becomes a blazar candidate.

The approach: **use radio catalogs to search for flat-spectrum radio sources. If a candidate is found, follow up with other observations to locate other blazar characteristics such as polarization and time variability.**

The EGRET team used this approach in assigning catalog IDs. Mattox et al. quantified the method based on proximity and radio intensity. Sowards-Emmerd et al. have expanded the number of known blazars with this approach.

Concept by D. Thompson

Source classification: Top – Down

Concept: **at some level, gamma-ray sources will have (non-thermal) X-ray counterparts. Nowadays we can start going down from TeV energies.**

IF **such X-ray counterpart can be "found", the better X-ray position information allows deep searches at longer wavelengths.**

The approach: **X-ray imaging of a individual gamma-ray source error box, eliminate unlikely X-ray sources based on their X-ray, optical, and radio properties. Look for a non-thermal source with a plausible way to produce gamma rays.**

The classic example is Geminga. Bignami, et al. started this search in 1983. The final result appeared in 1992 with the detection of X-ray pulsations.

Concept by D. Thompson

Some intrinsic limitations - number of sources

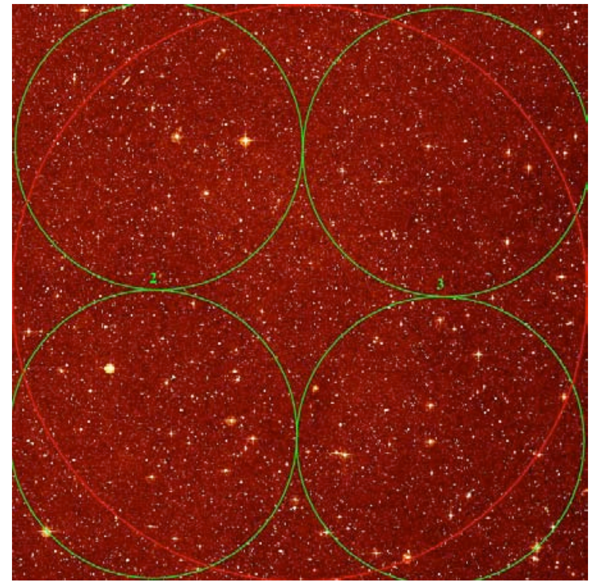
An "average" EGRET source: 3EG J1249-8330
[Θ_{95} =0.66 ° , 2 x 10^{-7} ph cm^{-2} s^{-1}]

1) 4 XMM-EPIC pointing -> 148 X-ray sources
2) statistical evaluation of counterparts
3) does computing a counterpart probability, or (redefined) FoM

$$p_c = p_{pos} \times p^{(i)}_{SED} \times p^{(i)}_{var} \times p^{(i)}_{ext} \times \dots$$

will yield a source identification here ?

Most likely not since for such values of N, the probability p_c will be undistinguishable in the systematics of its computation



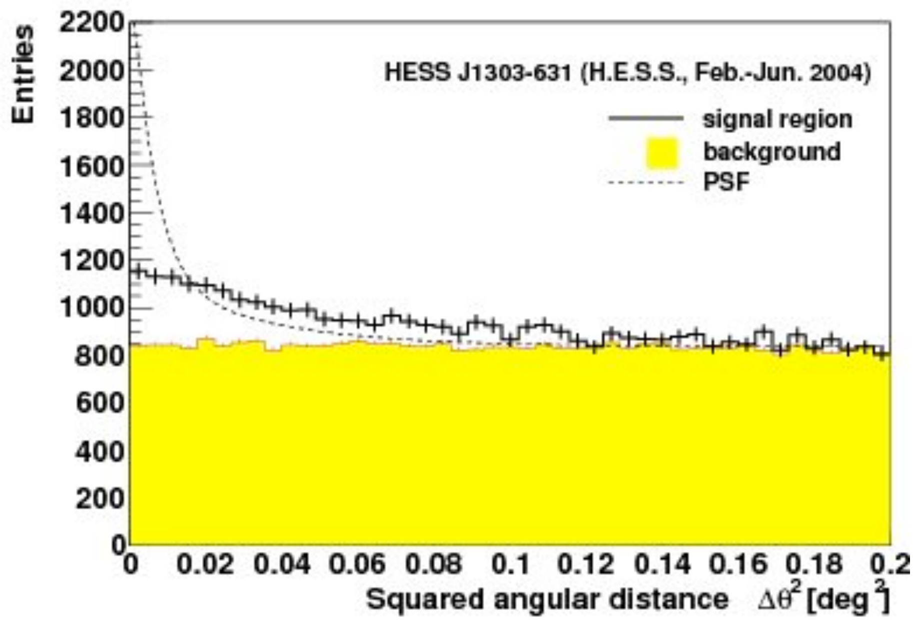
EGRET field	3EG J1249–8330
EPIC pointings	5-8
Total number of X–ray sources	148
Classified X–ray sources	22 (15 %)
X–ray sources with candidate counterparts	32 (22 %)
Total number of candidate optical counterparts	61
X–ray sources without candidate counterparts	94 (63 %)

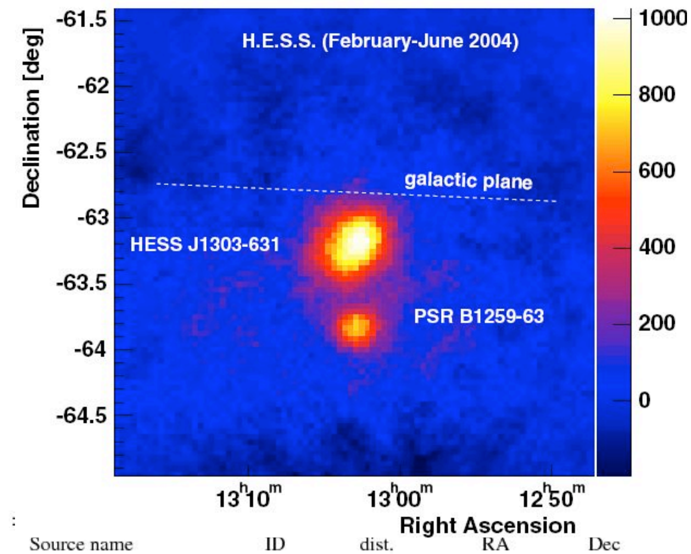
La Palombara et al. 2006

Limitations not only based in the smallness of localization error

HESS J1303-631 (13h03m00.4s±4.4s and δ=−63°11'55"±31") at least 5 catalog counterparts listed in *several counterpart categories*

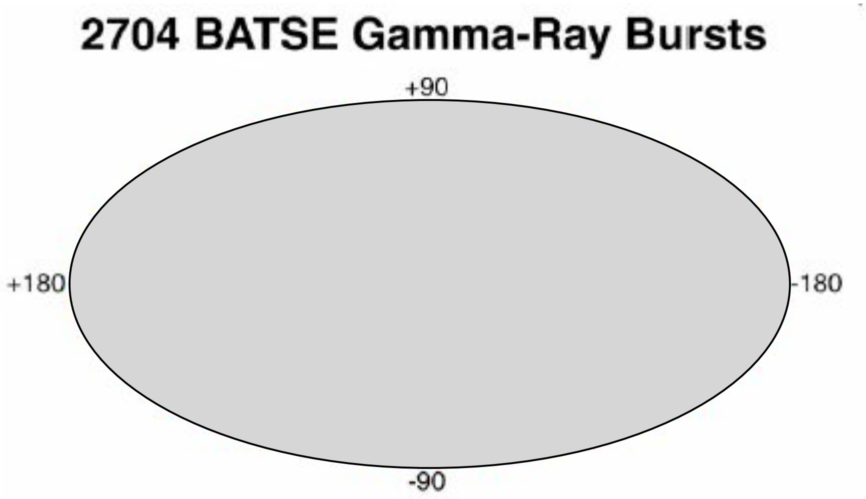
worse yet… the source is extended…





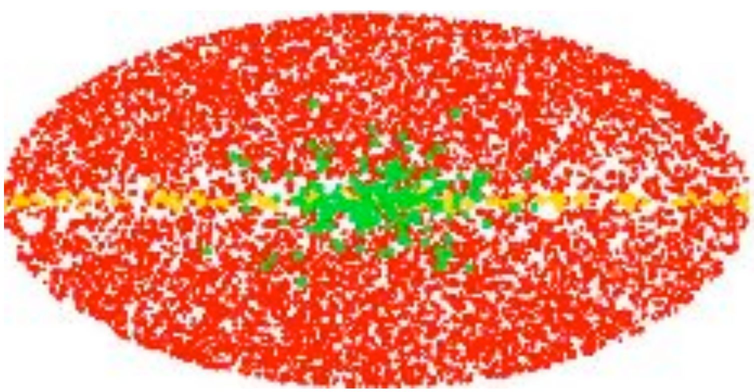
Source name	ID	dist.	RA	Dec
X-ray sources (ROSAT)				
1WGA J1303.8-6319	WGA	9.1′	13 03 50.9	−63 19 06
2RXP J130257.9-632750	RXP1	15.9′	13 02 57.9	−63 27 50
2RXP J130540.5-631839	RXP2	19.2′	13 05 40.5	−63 18 39
2RXP J130622.7-632210	RXP3	24.9′	13 06 22.7	−63 22 10
2RXP J130200.4-633730	RXP4	26.4′	13 02 00.4	−63 37 30
2RXP J130337.8-634045	RXP5	29.1′	13 03 37.8	−63 40 45
radio sources				
PMN J1302-6257	PMN1	14.3′	13 02 38.9	−62 57 48
PMN J1300-6253	PMN2	24.6′	13 00 34.4	−62 53 43
PMN J1303-6339	PMN3	28.2′	13 03 52.6	−63 39 29
PMN J1259-6333	PMN4	29.7′	12 59 59.1	−63 33 37
PMN J1302-6321	PMN5	9.4′	13 02 56.7	−63 21 20
H II regions				
G 303.9-0.1	G1	25.4′	12 59 56.6	−62 57 22
G 303.9-0.7	G2	28.9′	13 00 07.3	−63 33 20
pulsars				
PSR J1302-6313	PSR1	4.9′	13 02 19.2	−63 13 29
PSR J1303-6305	PSR2	6.9′	13 03 00.0	−63 05 01
PSR J1301-6310	PSR3	10.4′	13 01 28.3	−63 10 41
PSR J1301-6305	PSR4	10.6′	13 01 45.8	−63 05 34
PSR J1305-6256	PSR5	22.6′	13 05 28.0	−63 56 39

Correlation depends on completeness of catalogs



Correlation analysis potential is lost

In the last BATSE catalog, if one gives account of the positional error boxes, there was a detection of one or more GRB everywhere.



LAT simulations: AGN (red dots) dominate the catalog, sources in the Galactic bulge (yellow), and a Galactic halo source population (green) are included. Symbol size has been enlarged to represent source location uncertainty contours

Log N–log S predictions: if faint sources below the EGRET detection limit, not tremendously better localized by GLAST-LAT.

Fast assessment: how far is LAT from full coverage?

At low Galactic Latitude (no priors)

1000 LAT sources	in the Galactic Plane (|b|<10)	with 12' uncertainty	= 20% coverage

At high Galactic Latitude (no priors)

10^4 LAT sources	out of Galactic Plane (|b|>10)	with 30' uncertainty	= 20% coverage

Need to classify populations of sources, even before the identification of individuals, which will succeed only in the most favorable cases:

- we do not over-identify by positional coincidence with known classes,
- we do not compare FoM from different classes,

  - which populations *have been detected* in the GLAST sky,
  - which is the *statistical confidence for the detection of each population* (systematically quantified using the *same* technique)
  - which are the *most likely detected individuals* of each class

[See Torres and Reimer 2005 for such an approach]

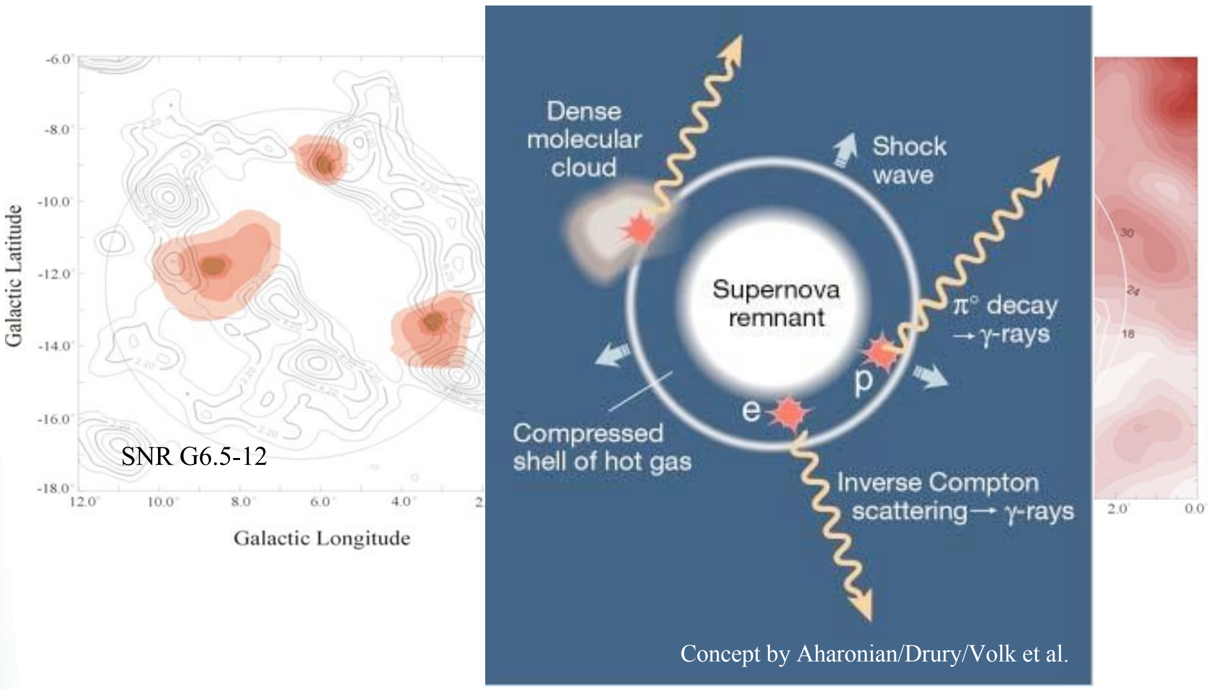
A tour to the likely new populations

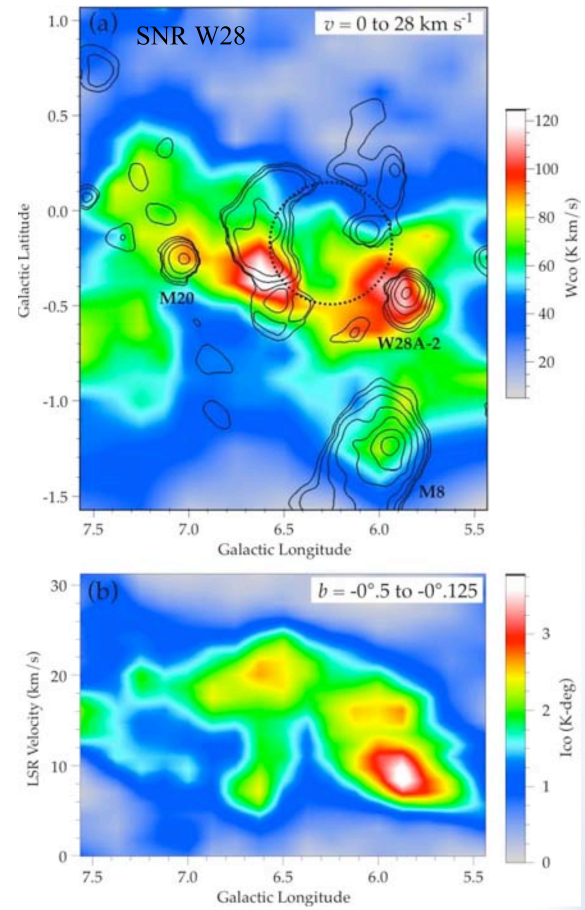
At least

- SNRs/PWN
- Gamma-ray binaries
  - microquasars
  - pulsar-star winds interation
  - jet-ISM interaction
- Binary star systems
  - OB-WR, WR-WR stars
- Collective effects in stars / pulsars
  - OB associations, strong stellar winds close to accelerator
  - Globular clusters
- Molecular clouds, especially those that are close and at high b
- Galaxies: Normal galaxies to ULIRGs
  - Local group, starbursts, LIRGs, WR galaxies (combined effects)
- Galaxy clusters

Supernova remnants: exploring the relation between target and accelerator at GeV

- At least 19 positional coincidences between EGRET sources and SNRs [their molecular environment studied in all cases, Torres et al. Physics Reports 2003]
- Multiple sources expected in some cases from the same accelerator, possbility to study diffusion of cosmic rays (e.g, Aharonian & Atoyan 1996)





Torres et al. 2003

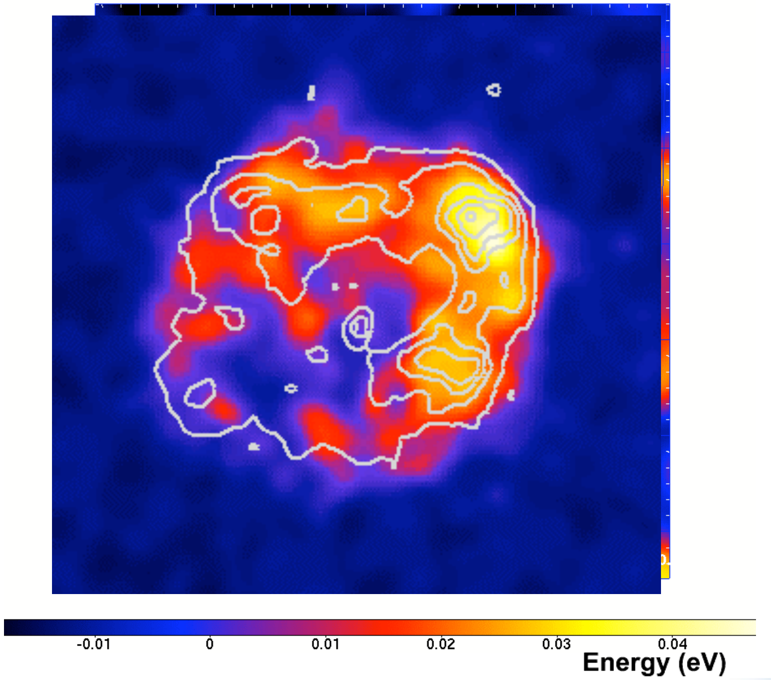
Supernova remnants: hadronic vs. leptonic models

•A much discussed candidate to exemplify a general situation:

• γ-ray imaging 'may' directly resolve acceleration sites
• γ-ray spectroscopy (GeV to TeV) distinguishes p from e

•π^0 decay from p-p collisions
-direct evidence for CR acceleration to > 10 TeV
-MW: π^0 decay should trace thermal X-rays

•Inverse Compton (IC) emission
- Synch. e^- scatter CMB, starlight, dust IR
- MW: IC should trace non-thermal radio/X-rays

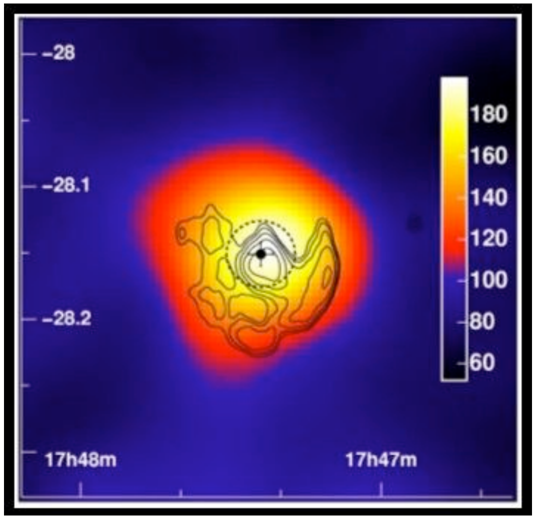


•RXJ 1713.7-3946
–First HESS shell-type SNR
–HESS cannot finally distinguish between p and e
–Flux ~70% Crab > 1TeV
–Extension: 0.5° in radius
–Bright EGRET source close-by (1deg) probably unrelated

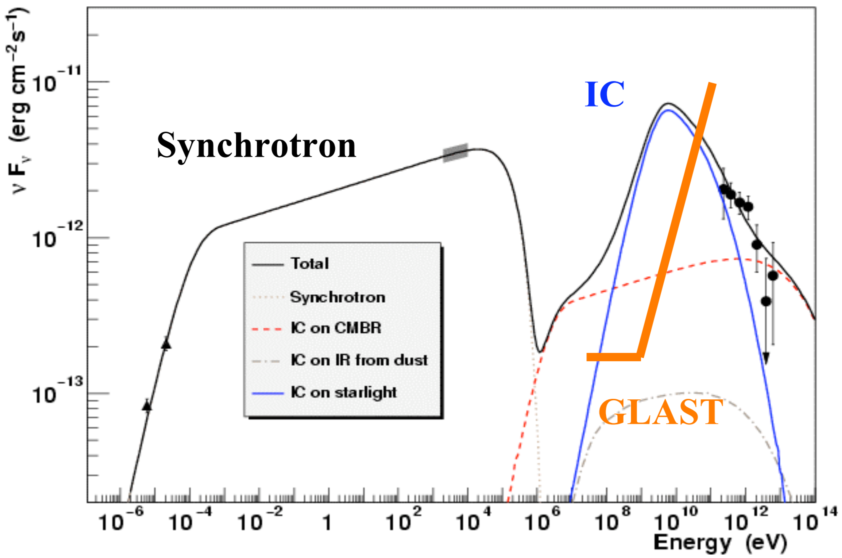
PWNe expected in the LAT sky

Several pulsar wind nebulae now seen with HESS

- inverse Compton emission from CMB, starlight, IR from dust
- Cerenkov detectors usually see high-energy tail
- Key features in the modeling of spectrum (spectral peak + overlap with synchrotron) for GLAST to test

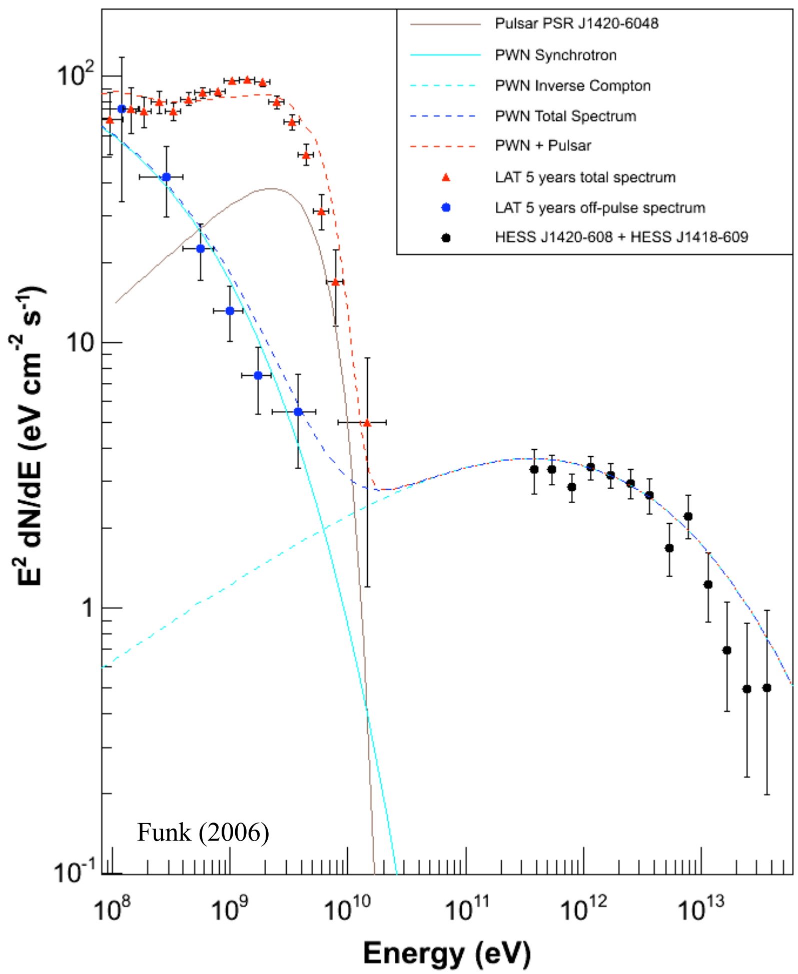


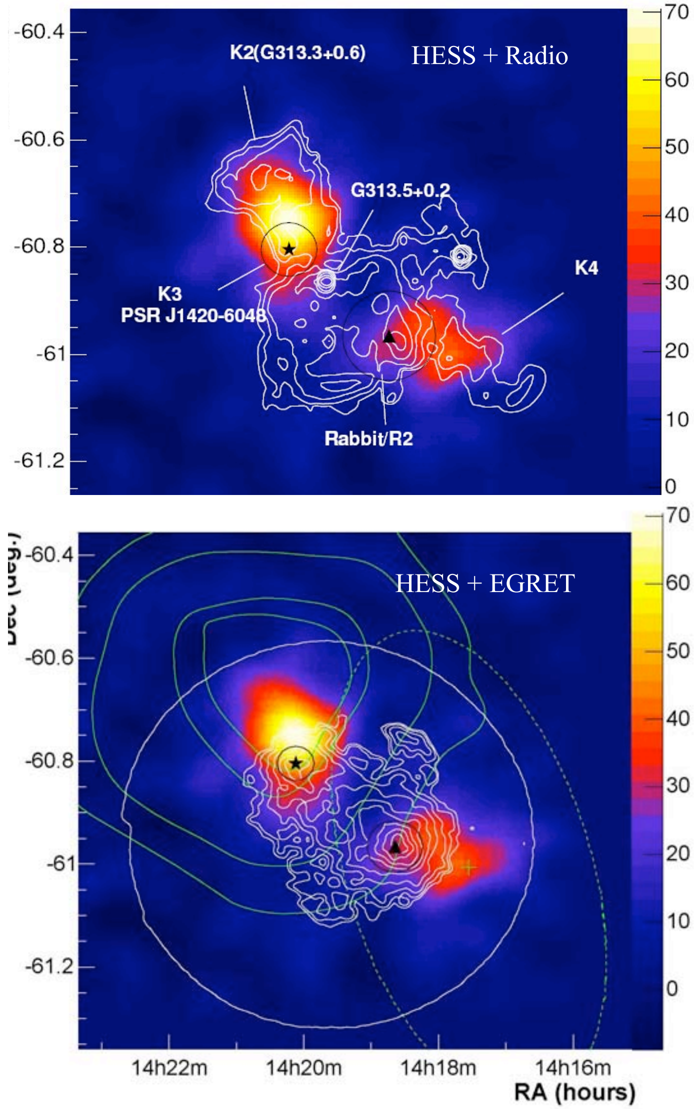
PWN G0.9+0.1 (HESS/VLA; Aharonian et al. 2005)



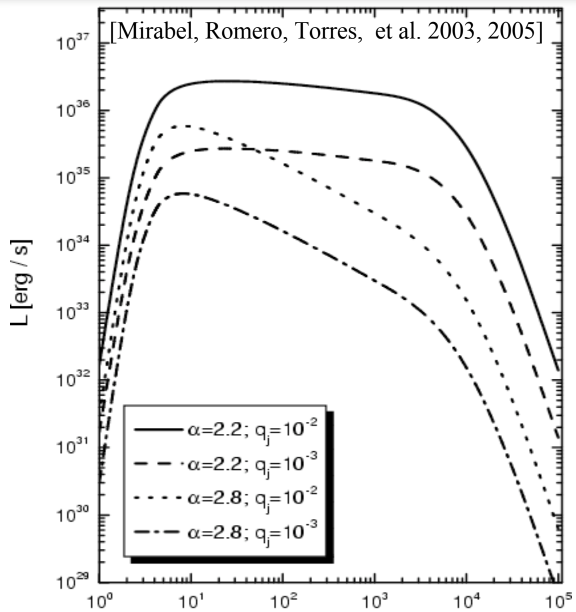
Broadband spectrum of G0.9.+0.1 (Aharonian et al. 2005)

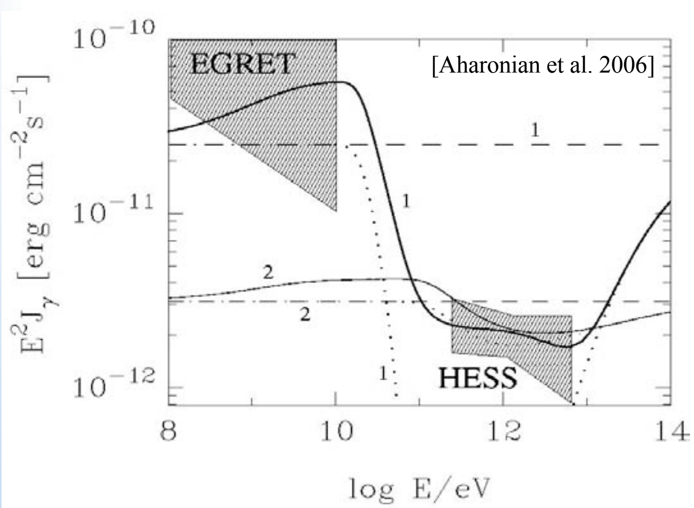
PWN spectral analysis with LAT



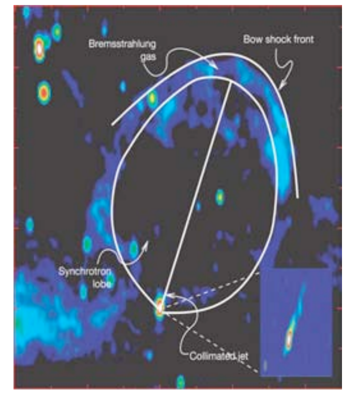


Gamma-ray binaries: expectations from theory

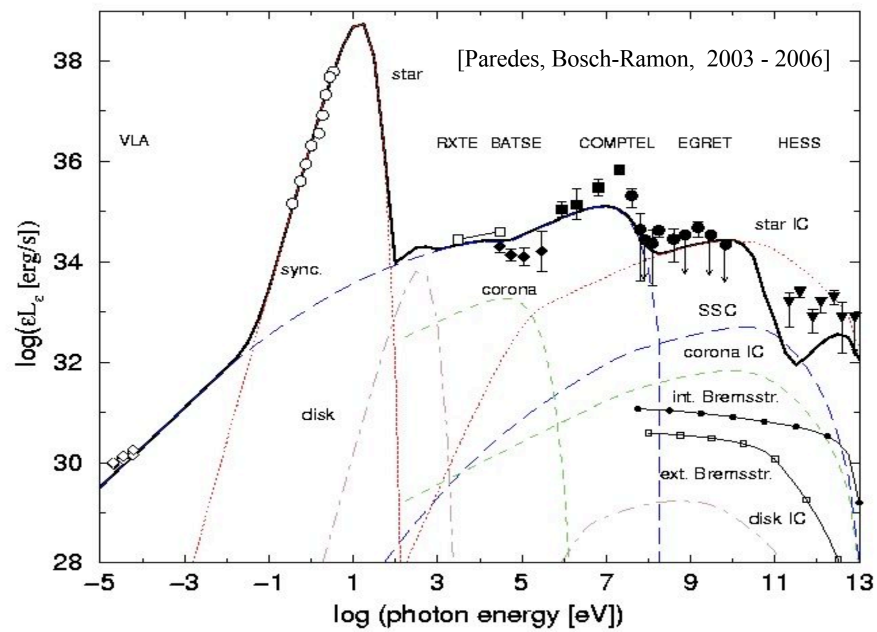




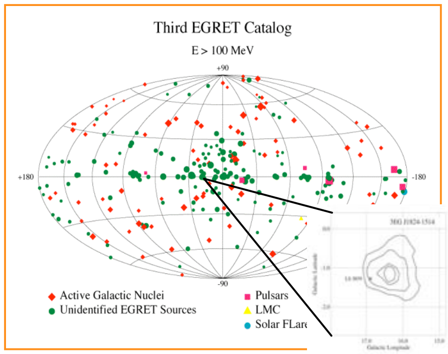
- Strong wind ion/jet hadron mixing resulting in a hadronic domination of emission. Significant neutrino counterparts.
- Leptonic jets, SSC, EC
- Cascading/Absorption (Bednarek 2006, Dubus 2006, Dermer et al. 2006)
- Interaction of jets with ISM (Heinz & Sunayev 2002, Aharonian et al 1996, Bosch-Ramon et al. 2005)

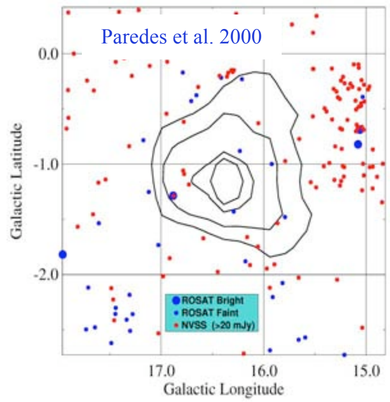


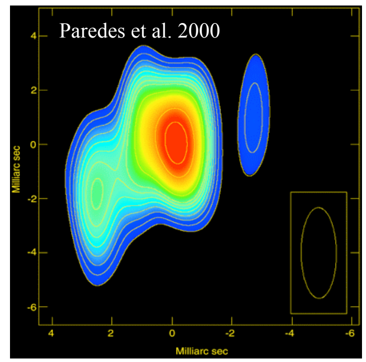
[Gallo et al. 2005]

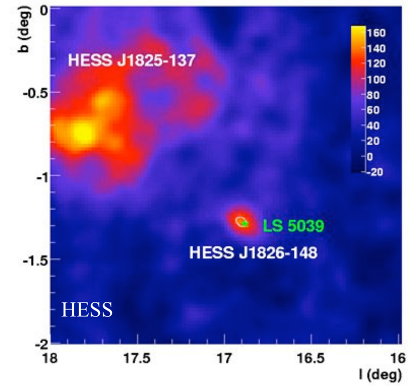


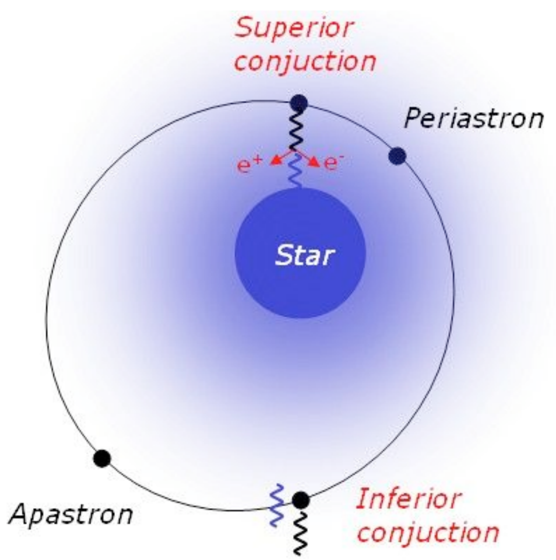
Gamma-ray binaries: LS 5039

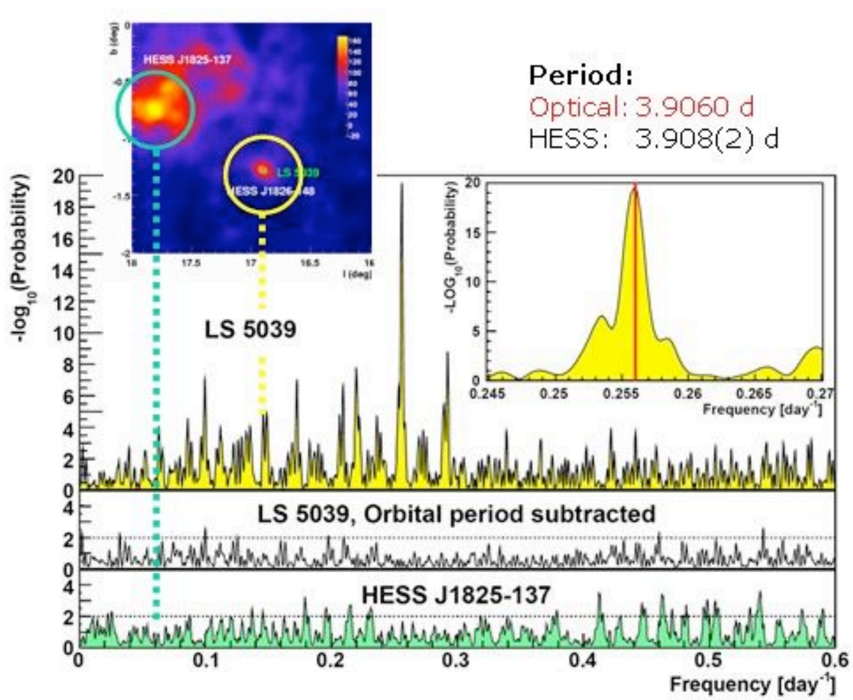




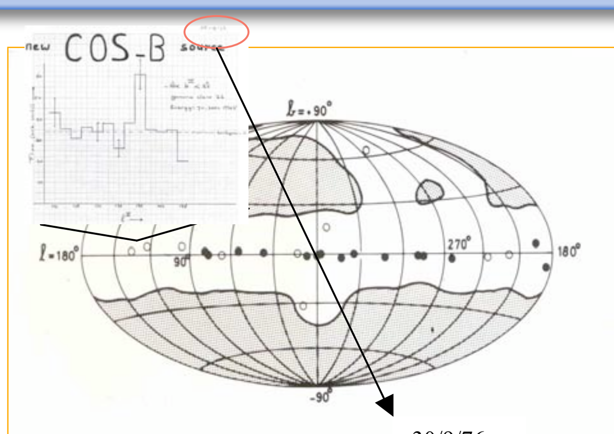








Gamma-ray binaries: LSI +61 303



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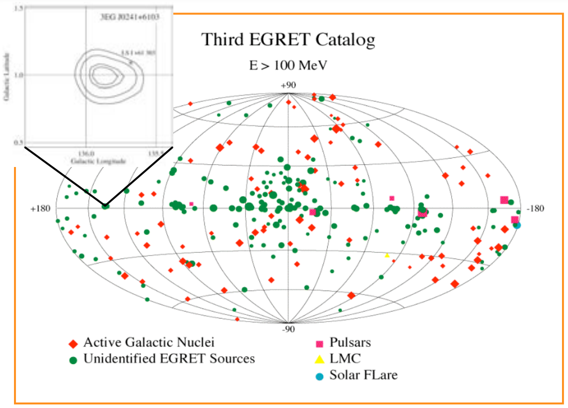
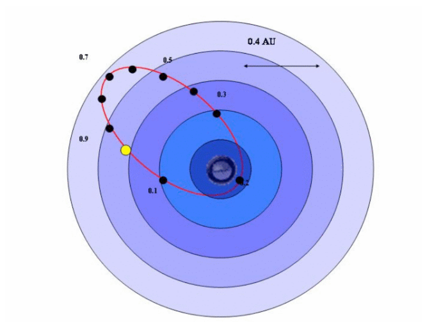
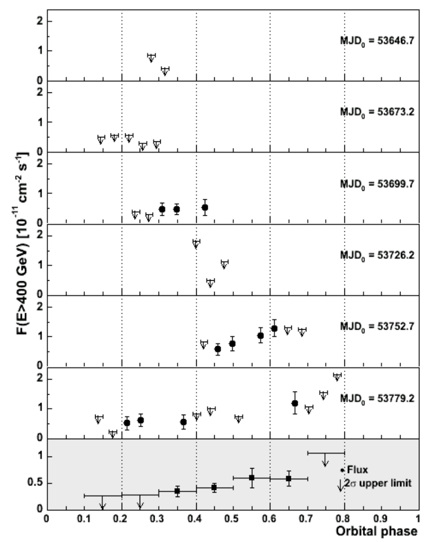
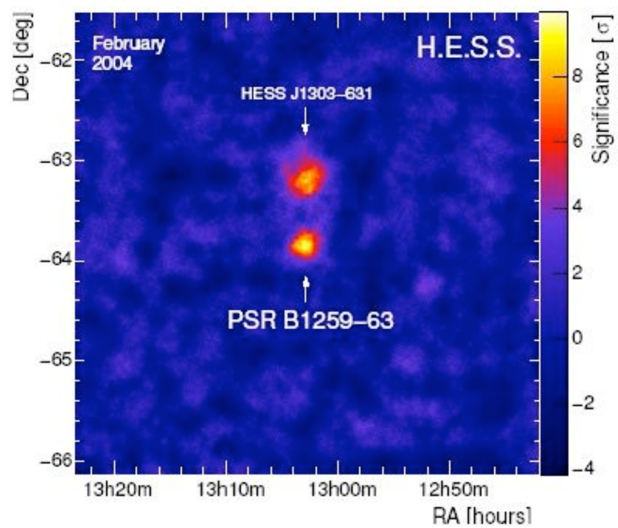
Hermsen

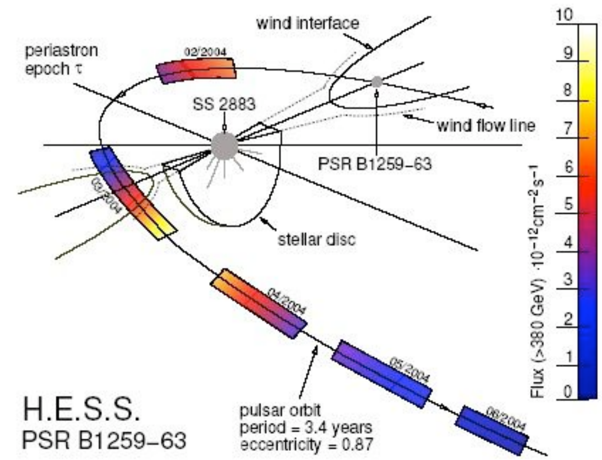


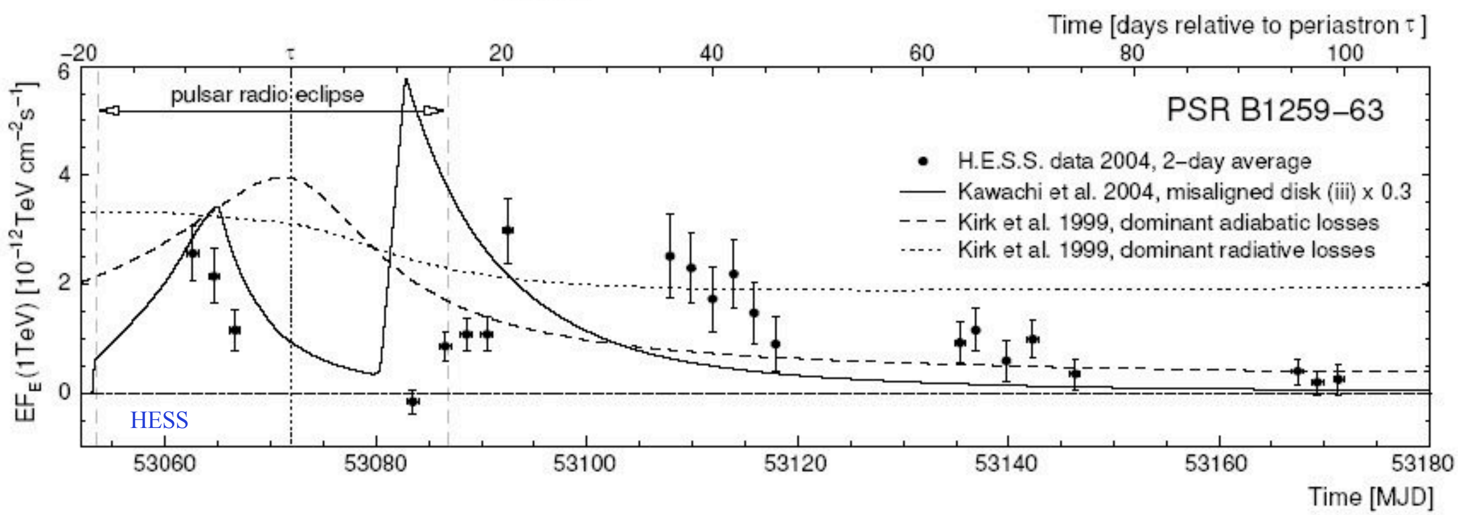




Gamma-ray binaries: PSR 1259-63



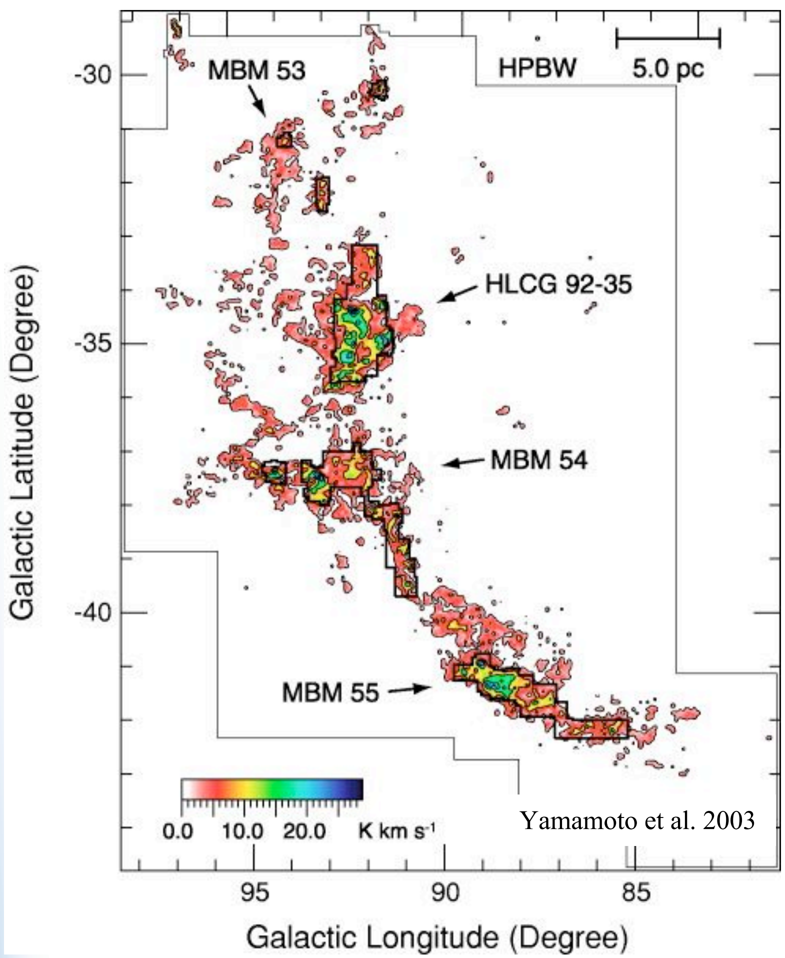




Open questions for GLAST

- After GeV detection of particular individuals:
  - Correlation/anti-correlation with TeV?
  - Periodicity with orbital phase?
  - Impact on theoretical models for specific candidates? MW observations (from radio to TeV)
    - Parameters impacting degree of absorption
    - Magnetic field, region of emission
    - Emission mechanism (hadronic, leptonic?)
- After GeV detection of the population:
  - How many? All radio emitting? Are REXRBs gamma-ray sources? Are REXRBs MQs?
    - Low mass or high mass X-ray binaries?
    - Log N - Log S?
    - Distribution in the galaxy? (halo sources?)
  - Always variable sources (...probably not, why?)
  - Correlation with INTEGRAL sources?

Molecular clouds & cloudlets at high latitude



A hundred molecular clouds, whose total mass is estimated to be ~1200 M_{sun}.

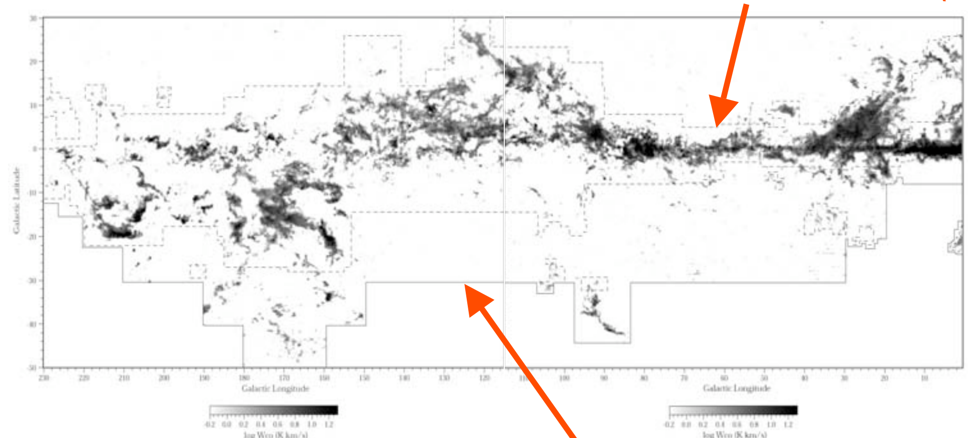
There is no detection in $C^{18}O$ (J=1-0) line in the observed region, indicating that there are no clouds dense enough to form stars in the near future.

These observations discover a massive cloud, HLCG 92-35, whose mass is ~330 M_{sun}.

pp interaction (even with no-accelerator nearby) make of some of these clouds gamma-ray sources, some extended

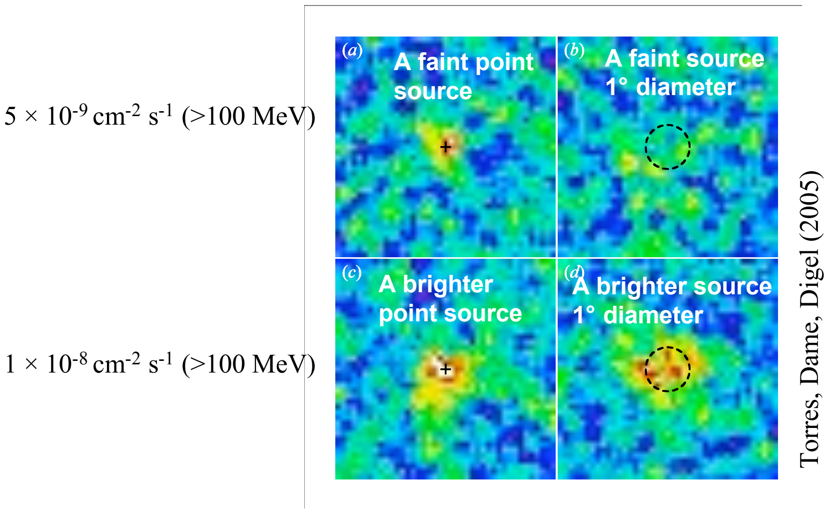
High-latitude translucent clouds are small (typically < 1°) and faint (~1 K km s^{-1} deg^2) in CO and being revealed by an unbiased 0.25° sampling CO survey (Dame & Thaddeus)

Dame, Hartmann & Thaddeus (2001)



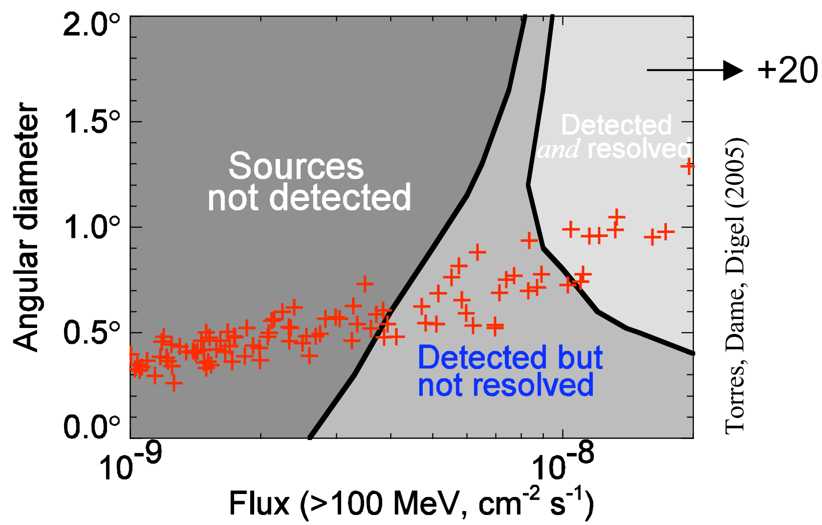
Dame & Thaddeus (2004)

Molecular clouds & cloudlets at high latitude



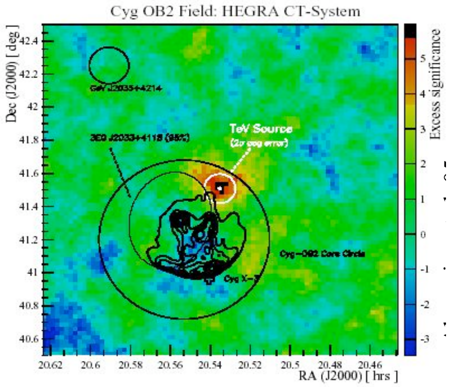
Once you guess a value for X = $N(H_2)/W_{CO}$, simulation of LAT observations and analysis can be used to figure out which clouds will be detected and/or resolved

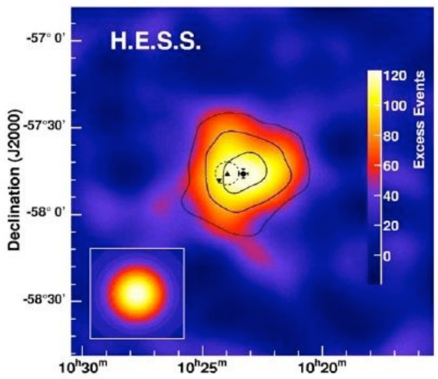
- not misidentifying sources in the catalog
  - Otherwise, many of these clouds would appear to be point sources that are faint enough so that nothing much could be inferred from their lack of variability or their spectra
  - Approx. 150 such clouds over the whole sky at |b| > 10, most at about 100 pc-scales
  - Map of the nearby ISM? CR distribution?



Massive star phenomenology

Final results of the HEGRA experiment around the Cygnus OB 2 association. A yet unidentified gamma-ray source co-spatial with an enhancement of the stellar density.





Westerlund 2 region/HESS J1023–575. The upright triangle shows te location of WR20a, the other triangle WR20b. The dashed circlee illustrates the extent of the Westerlund 2 stellar cluster.

hot ($T \sim 3...6\ 10^4$K), massive ($M \sim 20...80\ M_o$) & luminous ($L \sim 10^{6\text{-}5} L_o$)

large mass loss rates in stellar winds: $M \sim 10^{-6...-4}\ M_o$/yr

supersonic winds: $>10^3$ km/s

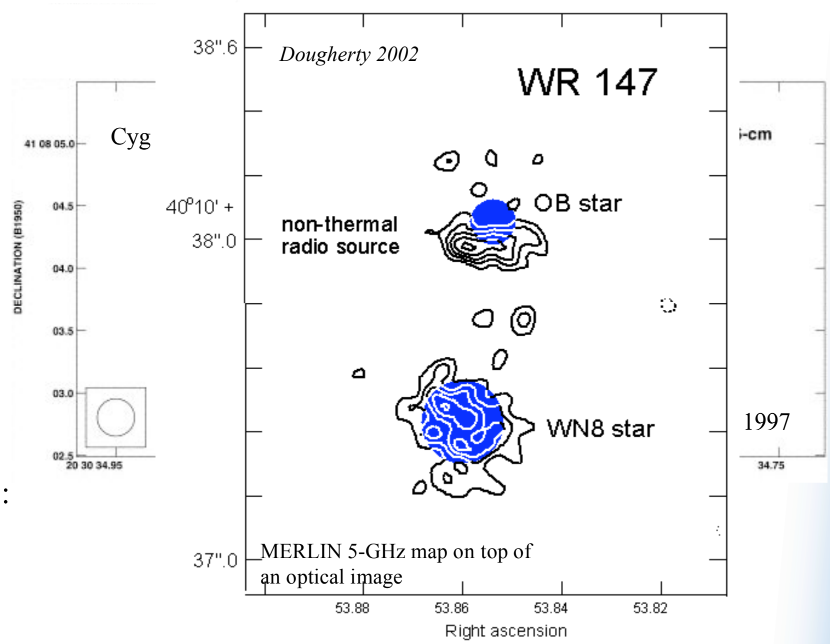
Intra-Wind interactions:

shocks from line-driven instabilities (chaotic wind model)

Wind-Wind + Wind-ISM collisions

Collective effects of stellar winds and associations (already Montmerle 1979):

large scale shocks at core of association (e.g. Bykov et al. 1992)



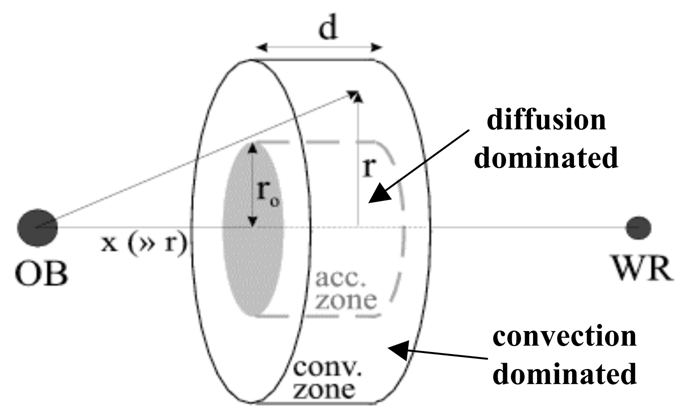
Massive star binaries

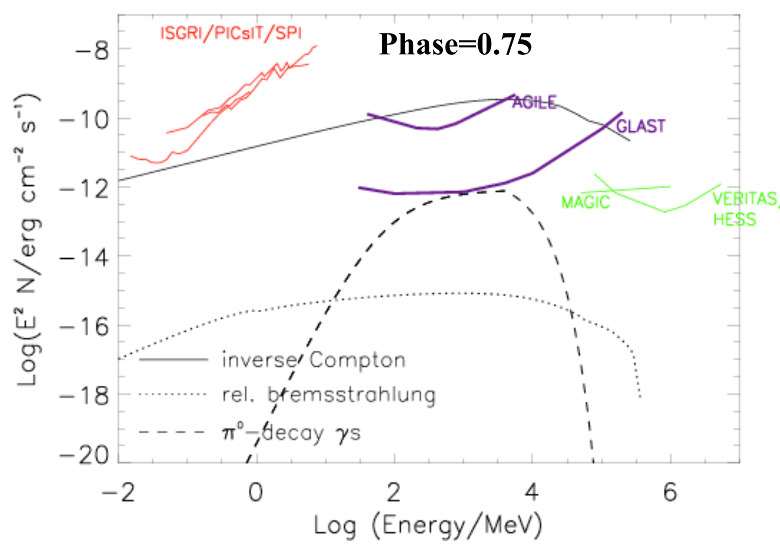
Model details:

- **uniform wind**
- neglect interaction of stellar radiat. field on wind structure
  restrict to **wide binaries**
- **cylinder-like** emission region (x >> r, emission from large r negligible)
- radiation field from WR-star negligible (**D >> x**)
- **photon field** of OB-comp. **monochromatic**
- convection velocity **V = const.**
- magnetic field **B = const.** throughout emission region

Positional coincidences between binaries and EGRET sources, ok (Romero, Benaglia, Torres 1999)

Possible detectable periodic modulation due to modulation of (target) radiation field density in eccentric orbits, of emitting region (size, geometry), changes in wind outflow, KN effects affect spectral shape

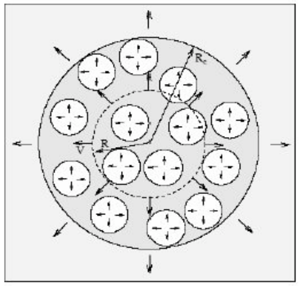




Anita Reimer et al. 2006 - WR 147

Stars in associations

Diffusion & convection operate in stellar winds:

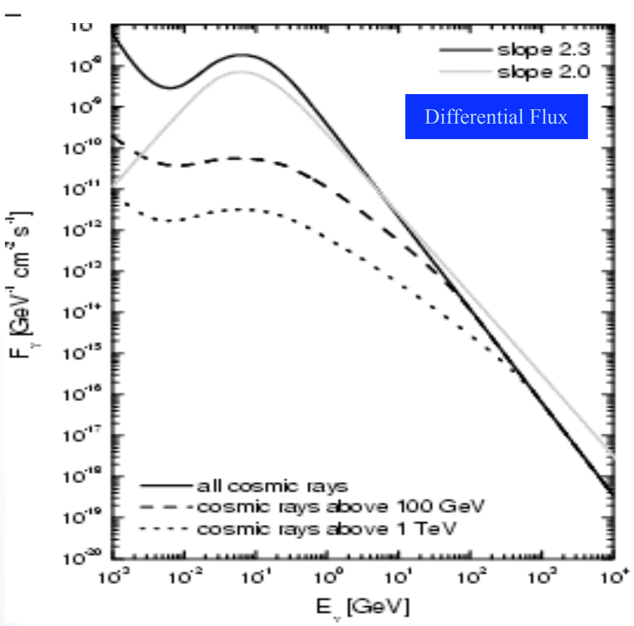


$$\varepsilon \equiv \frac{t_d}{t_c} = f\left(B_*, E_p, V_\infty, V_{rot}, R_*, r\right)$$

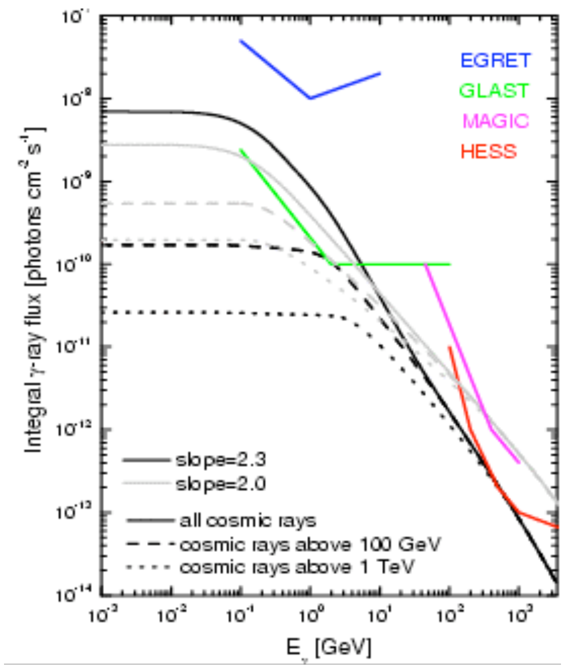
If **ε>1** ⇒ Convection due to wind flow dominates
If **ε<1** ⇒ Diffusion dominates

only protons with energies $$[E^{\min}(r \gg R_\star)]^{\mathrm{assoc}} \sim 0.8 \left(\frac{B(R_c)}{1\mu\mathrm{G}}\right)\left(\frac{R_c}{0.1\mathrm{pc}}\right)\mathrm{TeV}.$$

enter into the wind, lower energy protons are convected away: "***wind modulation effect***"



pp-interact. on wind material near acceleration region is most important γ-ray production channel

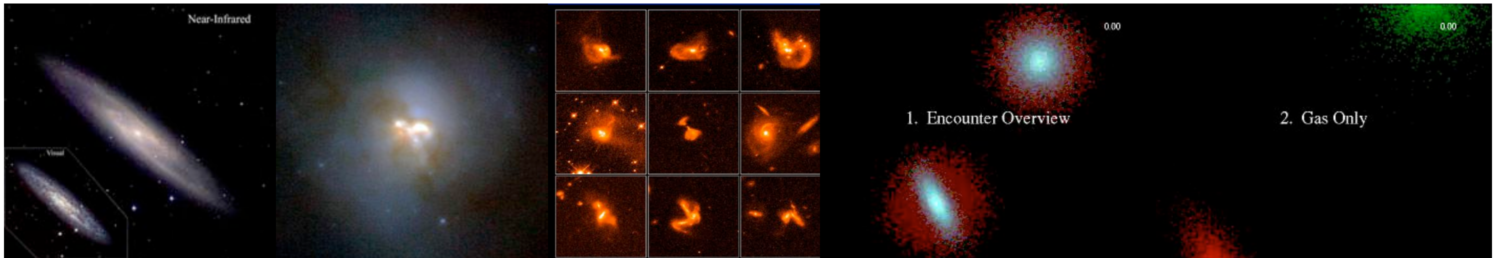


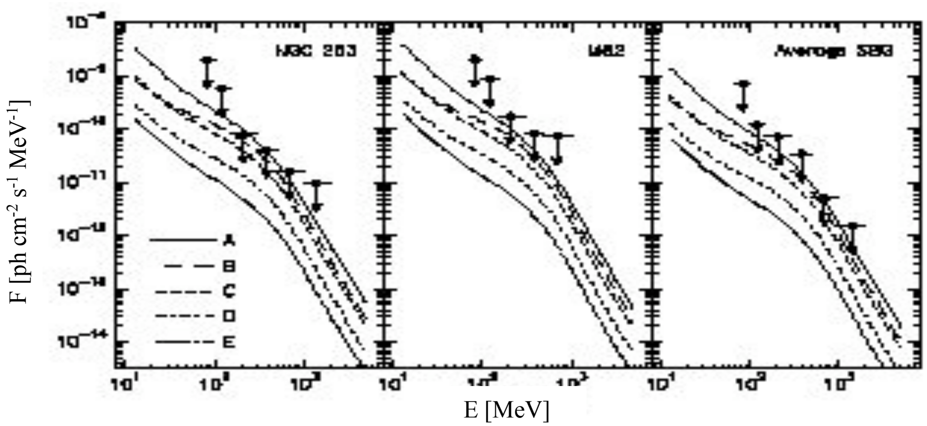
[Domingo-Santamaria & Torres, 2006]

MeV-GeV γ-ray flux substantially reduced in active/expanding targets (e.g. winds)

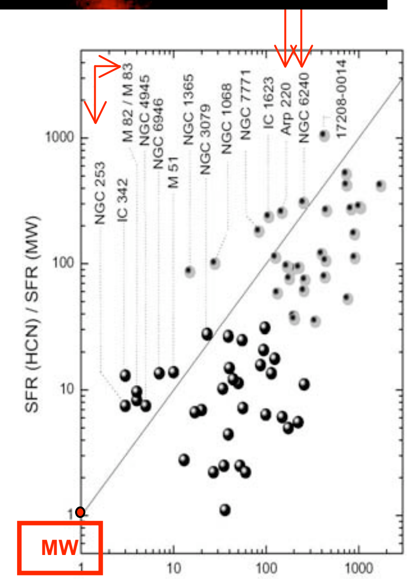
No modulation effects in inactive targets (e.g. ISM)

Nearby starbursts - LIRGs - ULIRGs - WR galaxies



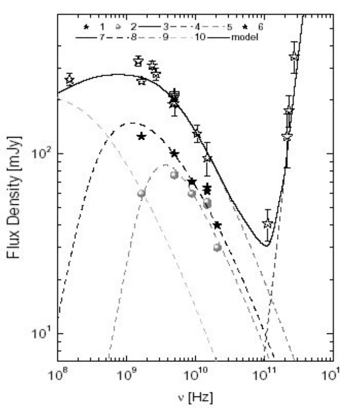


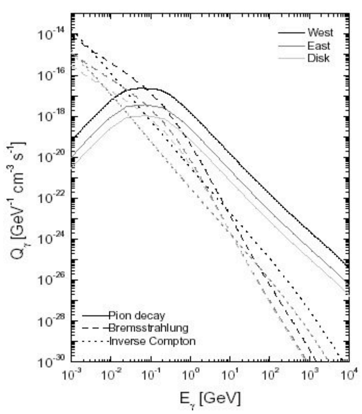
Blom et al. 1999

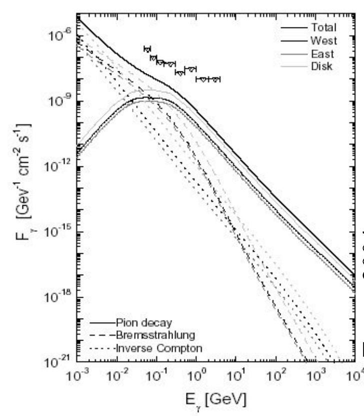


Torres et al. 2004

Minimum *Emissivity Enhancement* required f/LAT detection

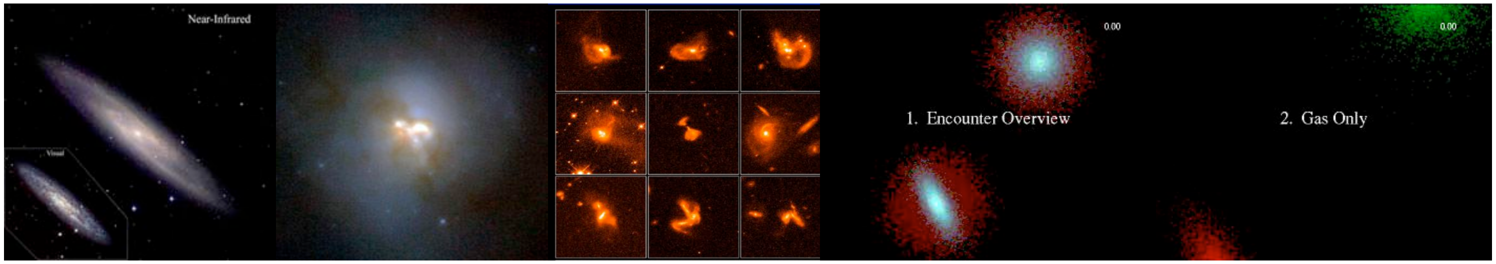






Torres 2004

Nearby starbursts - LIRGs - ULIRGs - WR galaxies



Observational Status (see Torres et al. 2004 - Cillis, Torres & Reimer 2005)

None detected so far (NGC253, M82, M83, Arp220, Arp 299, Mrk231... nor galaxies in the local group)
many with predictions on the verge of EGRET detectability - theorist's sure bet at this energy regime
Population undetected under stacking

Expected features if detected by LAT:

spatial coincidences, several cases
non-variability.
SED comparison [interesting targets for TeV telescopes - upper limits for the moment]
Point like sources (except perhaps LMC, SMC, M31 where morphology resemblance is important…)

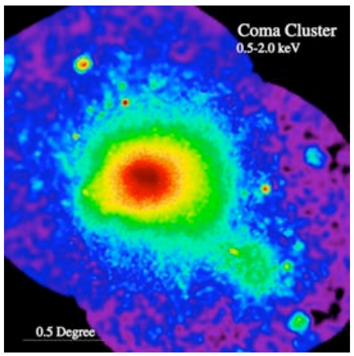
Galaxy clusters

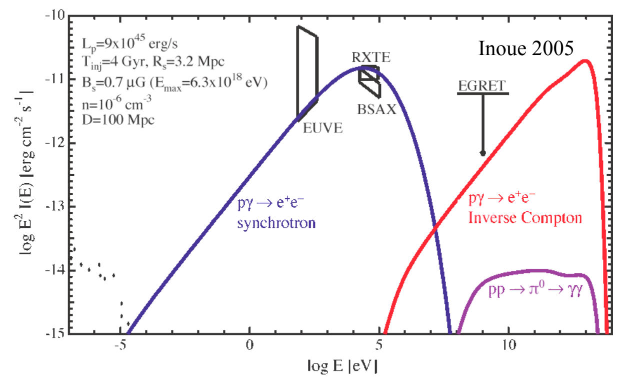
Why do we expect them to be gamma-ray emitters?

-multifrequency observations confirm non-thermal activity (non-thermal X-rays, diffuse radio halos)

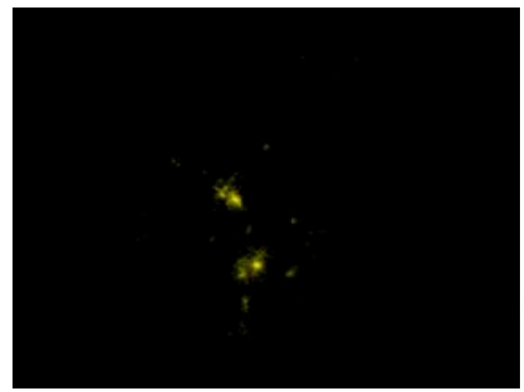
-hierarchical merging scenarios imply merging, which implies Fermi 1st order acceleration

-theoretical expectations from individuals, and their contribution to EGDB (well… varying from 0 to 100%)





Formation of a galaxy cluster in the tCDM, starting at a redshift of 2.5. Larger structures evolve from mergers of adjacent but smaller structures baryonic matter condenses in form of galaxy clusters dark matter halos interact/merge

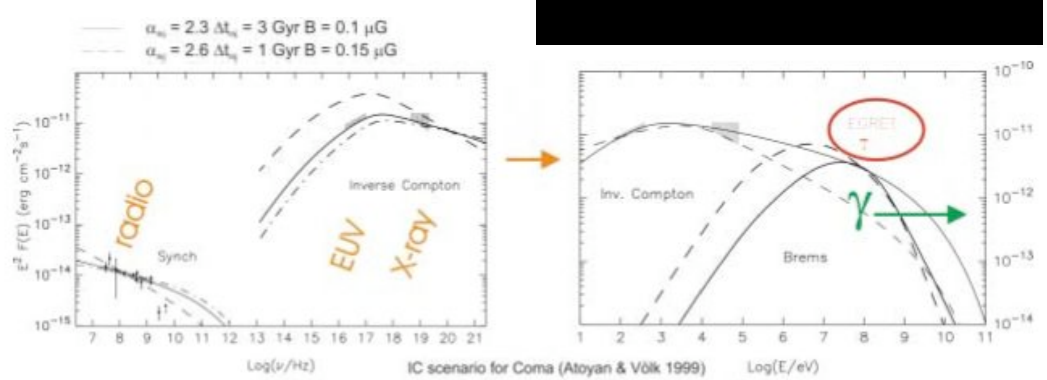


Observational Status (see Reimer et al. 2003)

None detected so far
(Coma, Virgo, Perseus, A2256, A754, A3395, A85...)
Population undetected under stacking

Expected features if detected by LAT:

spatial coincidences,
non-variability (unless a dominating central AGN?),
SED construction,
size / spectrum of nonthermal emission (radio, X-rays),
and for some individuals: source extension



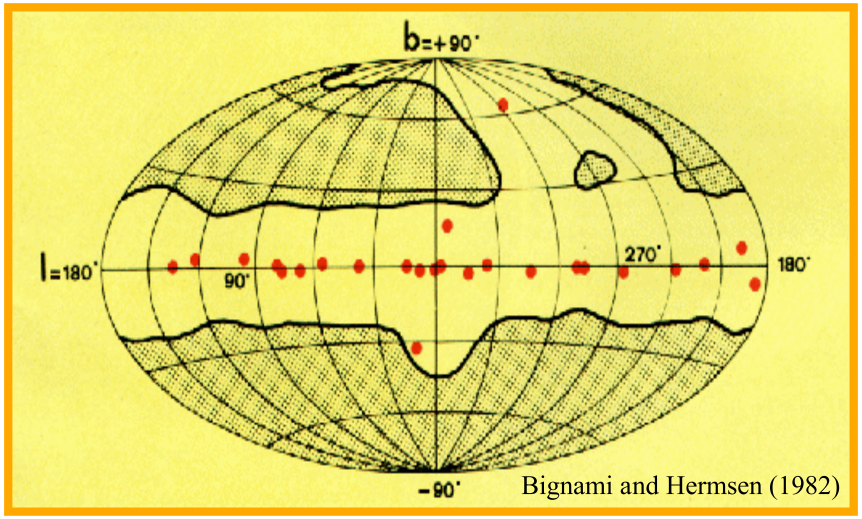
Concluding remarks

- Need to apply a method of classification and identification of classes
  - Difficulties in assessing population identifications with FoM generally defined within a particular class, intercomparison of FoM may be difficult or impossible
  - Systematics problems from number of sources and not only limited to the size of error localization boxes

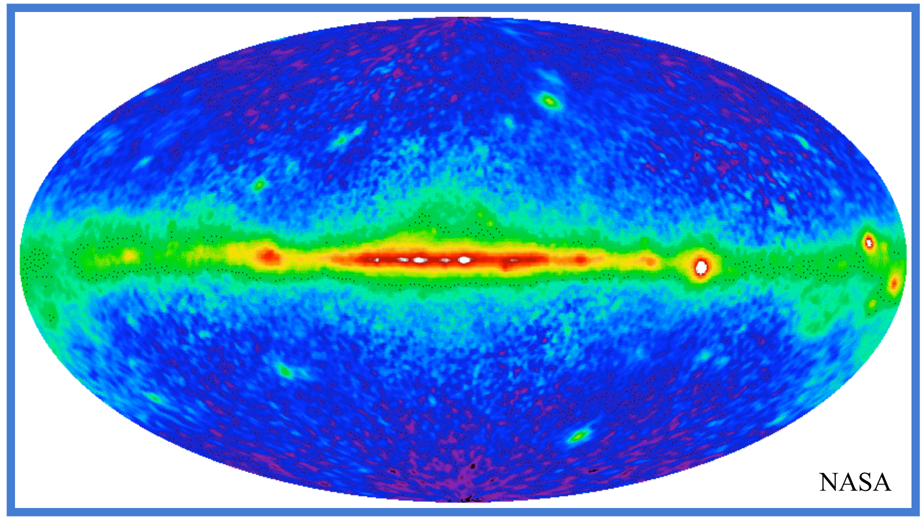
- Good chance to identify many new populations of EGRET gamma-ray sources with LAT (at least many key objects with solid predictions above GLAST sensitivity, many of them detected already at higher energies)
  - Both galactic and extragalactic
  - Variable and steady
  - Extended and point like
  - Significant astrophysics for every population

- Surprises are to come, as have always
  - Sources intrinsically different from EGRET unids. New LAT unidentified(s)?

The evolution of the gamma-ray sky

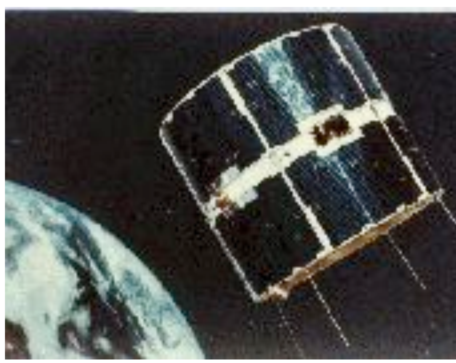


Bignami and Hermsen (1982)


NASA

1975-1982, COS-B sources detected above 100 MeV. The circles are fluxes above 1.3 10^{-8} ph cm^{-2} s^{-1}, ~200000 γ-rays.

1991-2000, EGRET, larger effective area, long mission life, improved background rejection, and >1.4 × 10^{6} γ-rays



Massive star phenomenology

New evidence at X-ray and COS-B γ-ray frequencies for non-thermal phenomena in Wolf-Rayet stars

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[1] Department of Space Research, University of Birmingham, Birmingham B15 2TT, England
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Received January 17, accepted August 6, 1986

[after A. Reimer]	Massive binary systems (WR 140 [Pollock 1987], 146, 147, 137, 138, 112, 125,..)	Collective winds/several stars (Cyg OB2, Westerlund, Cen OB6…)
Number of known systems	>100 catalogues, many more expected in galaxies, some nearby	>1000
Spatial distribution	typically at low galactic latitude towards spiral arms, in vicinity of molecular clouds	typically at low galactic latitude towards spiral arms, in vicinity of molecular clouds
Source extension	No	No (no?)
Source variability	Pronounced, due to orbital periodicity	no
Spectrum in gamma-rays	DSA, absorption	Similar to SNRs, with a low energy cut-off if wind convection is active
Multi-wavelength features	Non-thermal radio in long P binaries	No bright counterparts expected
Some recent references	Benaglia et al. 2001, Benaglia & Romero 2003, Reimer, Pohl, Reimer. 2006,…	Torres et al. 2004, Domingo-Santamaria & Torres 2006

ON GAMMA-RAY SOURCES, SUPERNOVA REMNANTS, OB ASSOCIATIONS, AND THE ORIGIN OF COSMIC RAYS

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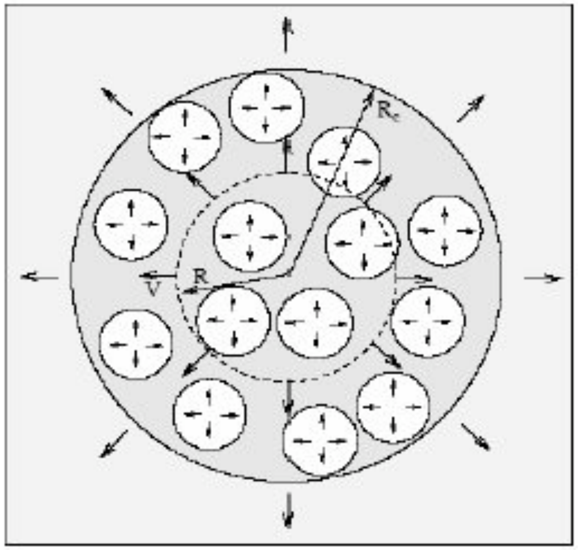
Received 1978 July 26; accepted 1979 January 5

Stars in associations



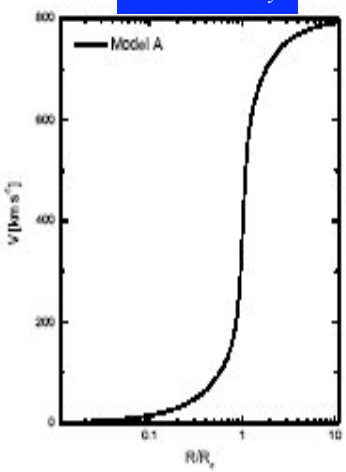
Typical for system of dozens of massive stars:

M_{assoc}~$10^{-5...-4}$ M_o/yr, $V_{wind\ gas}$~1000 km/s

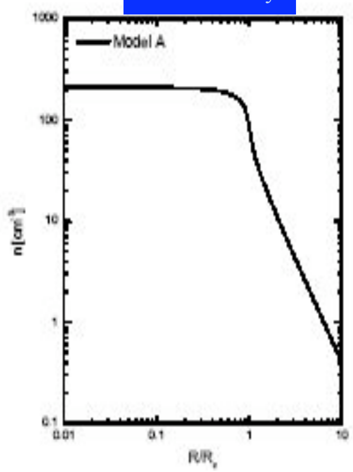
Table 1. Examples of configurations of collective stellar winds. The mass is that contained within 10 R_c. n_0 is the central density.

Model	$\dot{M}_{assoc}$ [$M_\odot$ yr^{-1}]	V_w [km s^{-1}]	R_c pc	n_0 cm^{-3}	Wind mass [$M_\odot$]
A	10^{-4}	800	0.1	210.0	0.13
B	10^{-4}	800	0.3	23.3	0.39
C	5×10^{-5}	1000	0.2	20.9	0.11
D	2×10^{-4}	1500	0.4	13.9	0.56
E	2×10^{-4}	2500	0.2	33.5	0.17

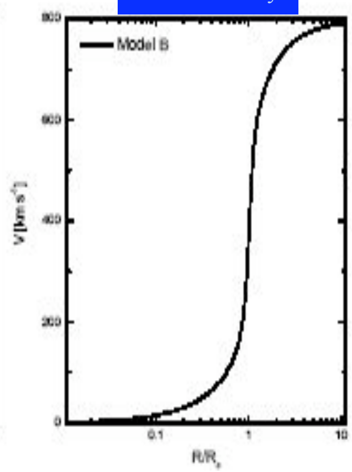
Wind Velocity



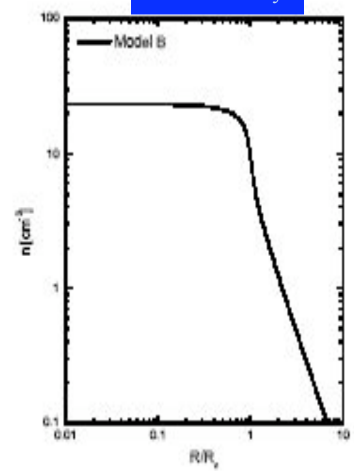
Wind Density



Wind Velocity



Wind Density



[Domingo-Santamaria & Torres, 2006]

Protocol for population search in gamma-rays

- Three steps
  - Theoretical selection: which populations to search?
  - Discovery protection: budgeting in a limited sample, avoid overtesting, manage the budget intelligently to test the best physics cases
  - Quality evaluation: precise the level of confidence in a equal basis for all populations

- **Key idea, Test the null hypothesis:** Finding a population is ruling it out. E.g., "X-ray binaries are not gamma-ray sources". Quantify it simply (see Gherels 86, Feldman & Cousing 98):

$$\mathbf{E(A) \quad = \quad C(A) - \; P \times N(A)}$$

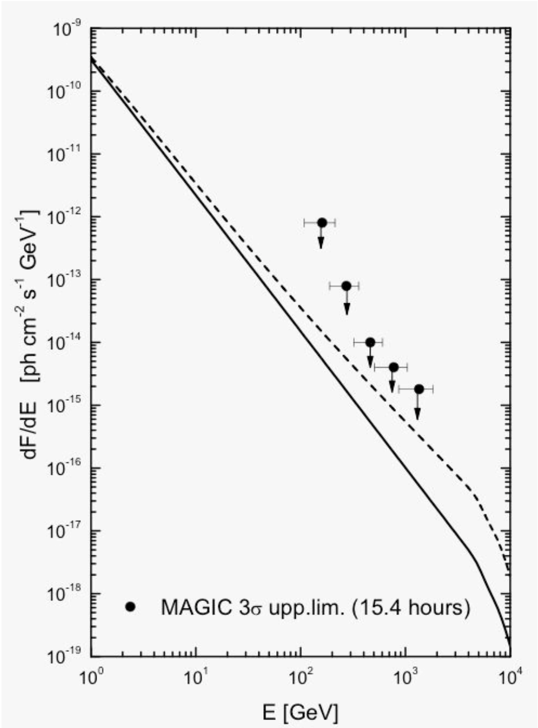
(Excess = Coincidences - Random Noise)

For X-ray binaries: We have 0 predicted signal events (coincidences) in the null hypothesis and P x N(A) of background or random associations. With N(A) ~ 200 and P~ 3 x 10^{-3}, detecting more than 5 coincidences rules out the null hypothesis at 95% CL (see Feldman and Cousins). If the budgeted P(X –ray bin.) < P^{exp} (X –ray bin.) have uncovered a new population of sources with 95% CL.

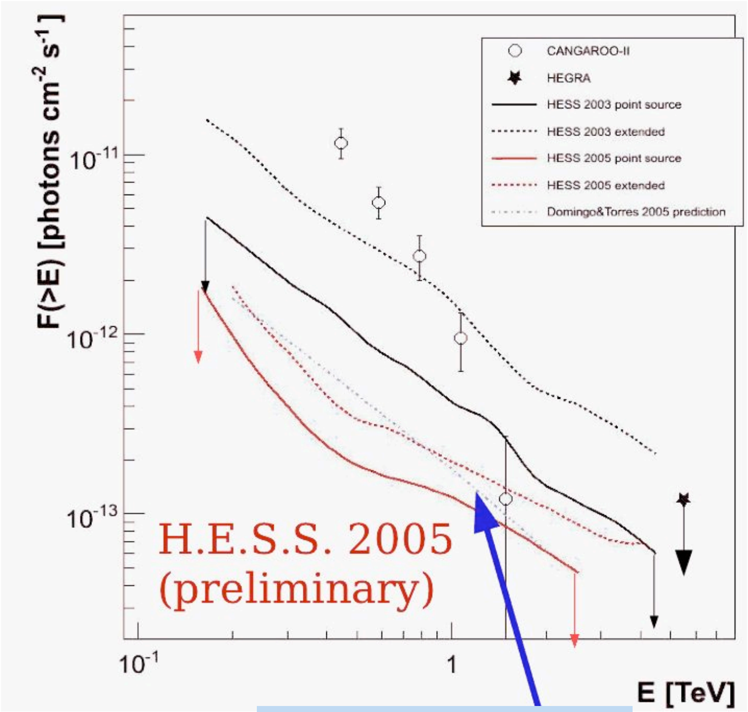
[See Torres and Reimer 2005 for such an approach]

From Starbursts to ULIRGs: testing cosmic-ray populations in other galaxies - relation with star formation activity

The starburst galaxy NGC 253 Distance: 2.6 Mpc H.E.S.S. 2003 observations (~28h, construction phase) + 12 h with full array: upper limits derived Aharonian et al. (2005), A&A,442, 177



Model
Torres 2004, ApJ + Torres & Domingo 2005, MPLA



Model
Torres & Domingo 2005, A&A

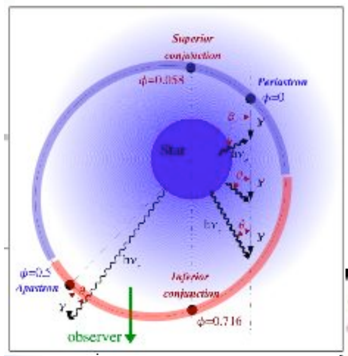
The ULIRG galaxy Arp 220 Distance: 72 Mpc MAGIC 2006 observations (~18h, construction phase): upper limits derived Albert et al. (2007) ApJ in press

Open questions for GLAST

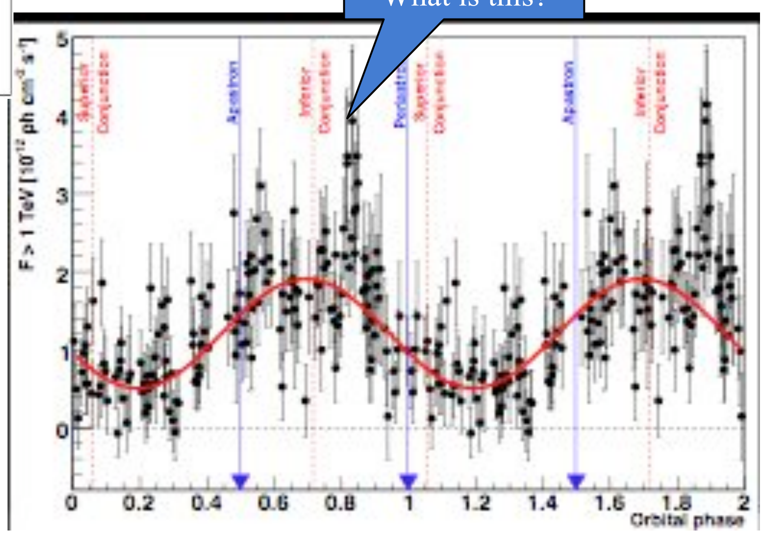
- After GeV detection of particular individuals:
  - Correlation/anti-correlation with TeV?
  - Periodicity with orbital phase?
  - Impact on theoretical models for specific candidates? MW observations (from radio to TeV)
    - Parameters impacting degree of absorption
    - Magnetic field, region of emission
    - Emission mechanism (hadronic, leptonic?)
- After GeV detection of population:
  - How many? All radio emitting? Are REXRBs gamma-ray sources? Are REXRBs MQs?
    - Low mass or high mass X-ray binaries?
    - Log N - Log S?
    - Distribution in the galaxy? (halo sources?)
  - Always variable sources (...probably not, why?)
  - Correlation with INTEGRAL sources?

Gamma-ray binaries

- Small timescale variability - detailed evolution of spectrum
- All/large sky coverage -> population studies
  - Detectable timescales in XR bursts much beyond what is achievable by GLAST



What is this?



Need variations in acceleration and absorption to explain spectra