The Hunt for the Sources of the Galactic Cosmic Rays

—

A multi-messenger approach

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TeVPA 2008

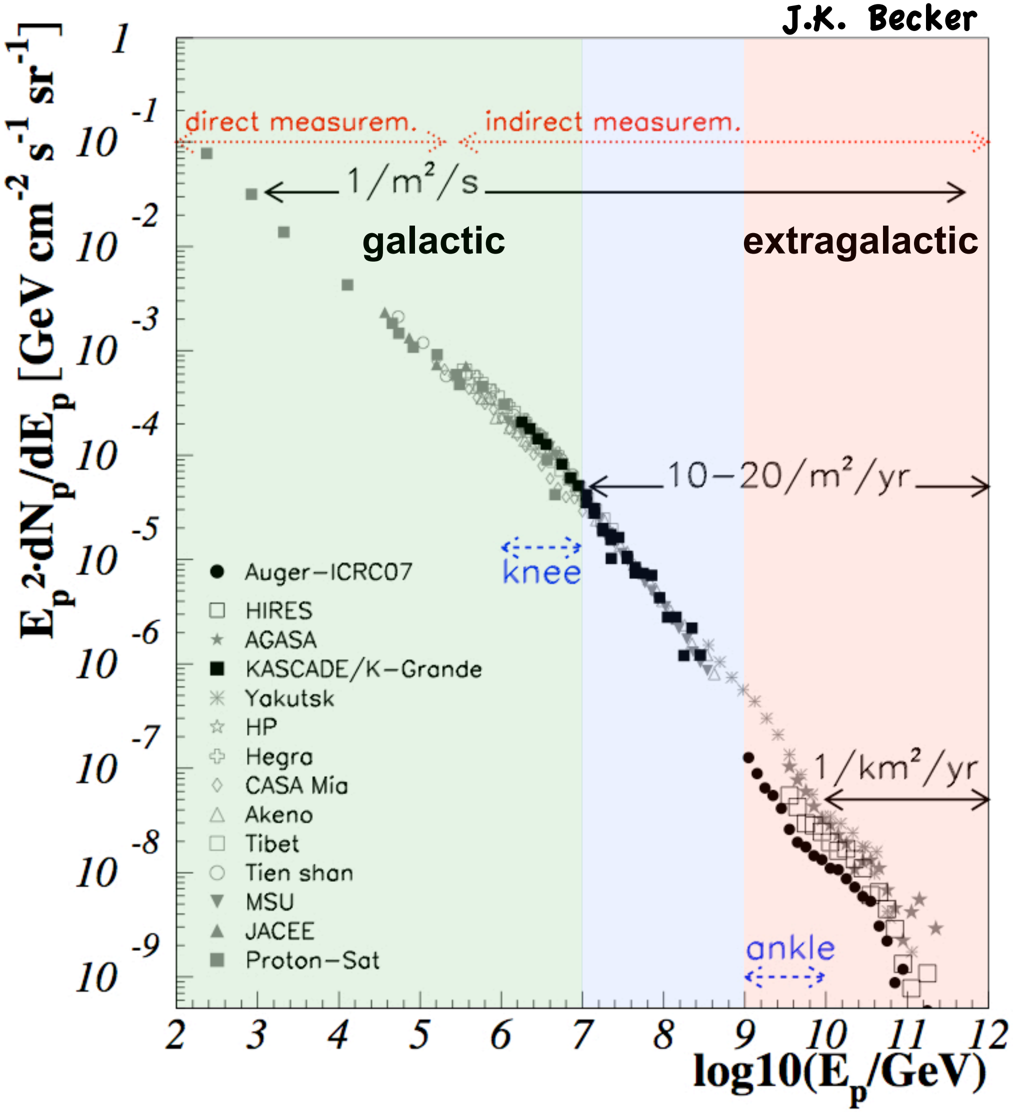
Marie Curie Actions
Human Resources and Mobility Activity

Outline

- Energetics of Galactic CRs and source candidates
- The missing PeVatrons and the Milagro skymap
- Neutrino fluxes from Galactic CR source candidates

Energetics of Cosmic Rays

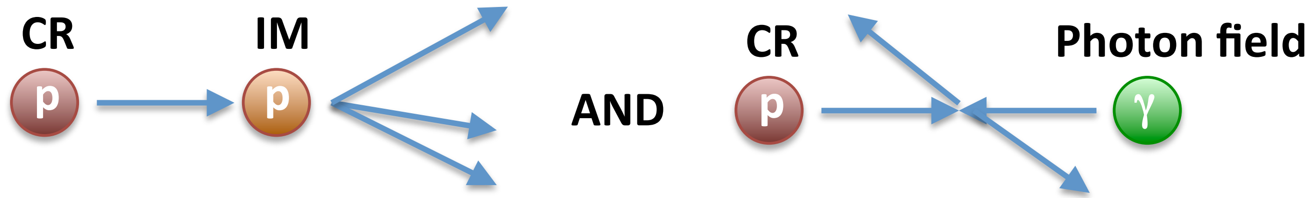
- **Galactic component:**
  – GeV – PeV
  – $\rho_E \approx 10^{-12}$ erg cm^{-3}
    $\# \approx 4\times10^{-14}$ cm^{-3}
  – similar to energy density in light and magnetic field
- **Transition:** somewhere between 10^7 and 10^9 GeV
- **Extra-Galactic component:**
  – > EeV
  – ~10^{-19} erg cm^{-3}



Multi-messenger Astronomy: Cosmic Rays, γ-Rays and Neutrinos

- Even after 100 years sources of (Galactic) cosmic rays (CRs) unknown
  (CRs not back-traceable due to Galactic magnetic field)

- Multi-messenger astronomy is key:



$$p + p(\gamma) \rightarrow \pi^0 + X$$
$$\hookrightarrow \gamma\ \gamma$$

γ-Cherenkov telescopes:
✓ Very mature
✓ Discovered many (Galactic) sources
✗ Problem of synch/IC-pion ambiguity not overcome yet

$$p + p(\gamma) \rightarrow \pi^\pm + X$$
$$\hookrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_e + \nu_\mu$$

Neutrino telescopes:
✓ Unambiguous prove for CR acceleration
✗ Still under development
✗ No sources found yet

Flux ratios (for E^{-2}): (p+p) $\phi(\nu) \approx \frac{1}{2}\phi(\gamma)$ (p+γ) $\phi(\nu) \approx \frac{1}{8}\phi(\gamma)$

Estimate of Gamma Flux from pp Interactions

- Steady Galactic CR density (~10^{-12} erg cm^{-3}) requires 10^{41} erg s^{-1} (finite CR containment time)
- Corresponds to release of 10^{50} erg in CRs every 30 years
- Emissivity in γ-rays for interaction of CRs with interstellar medium:

$$Q_\gamma(>1\,TeV) \approx c\, n_{CR}\, \lambda_{pp}^{-1} \left\langle \frac{E_\pi}{E_p} \right\rangle \approx 10^{-29}\, cm^{-3} s^{-1} \left(\frac{n_{IM}}{cm^{-3}} \right)$$

$\approx 4\times10^{-14}$ cm^{-3}

$(n_{IM}\,\sigma_{pp})$

$\sigma_{pp} \approx 40$ mb

for E^{-2}: ≈ 0.2

$$L_\gamma(>1\,TeV) \approx Q_\gamma \frac{W}{\rho_E} \approx 10^{33}\, s^{-1} \left(\frac{W}{10^{50}\, erg} \right)$$

energy released in CRs

$\approx 10^{-12}$ erg cm^{-3}

F. Halzen, arXiv:0809.1874

Estimate of Gamma Flux from pp Interactions cont'd

$$E\frac{dN_\gamma}{dE}(>1TeV) = \frac{L_\gamma}{4\pi d^2} \approx 10^{-12} - 10^{-11} cm^{-2} s^{-1} \left(\frac{W}{10^{50} erg}\right)\left(\frac{n_{IM}}{cm^{-3}}\right)\left(\frac{d}{kpc}\right)^{-2}$$

The sources of the Galactic CR should have fluxes visible to current γ-ray detector
(in particular, they have to show up in the Milagro sky map)

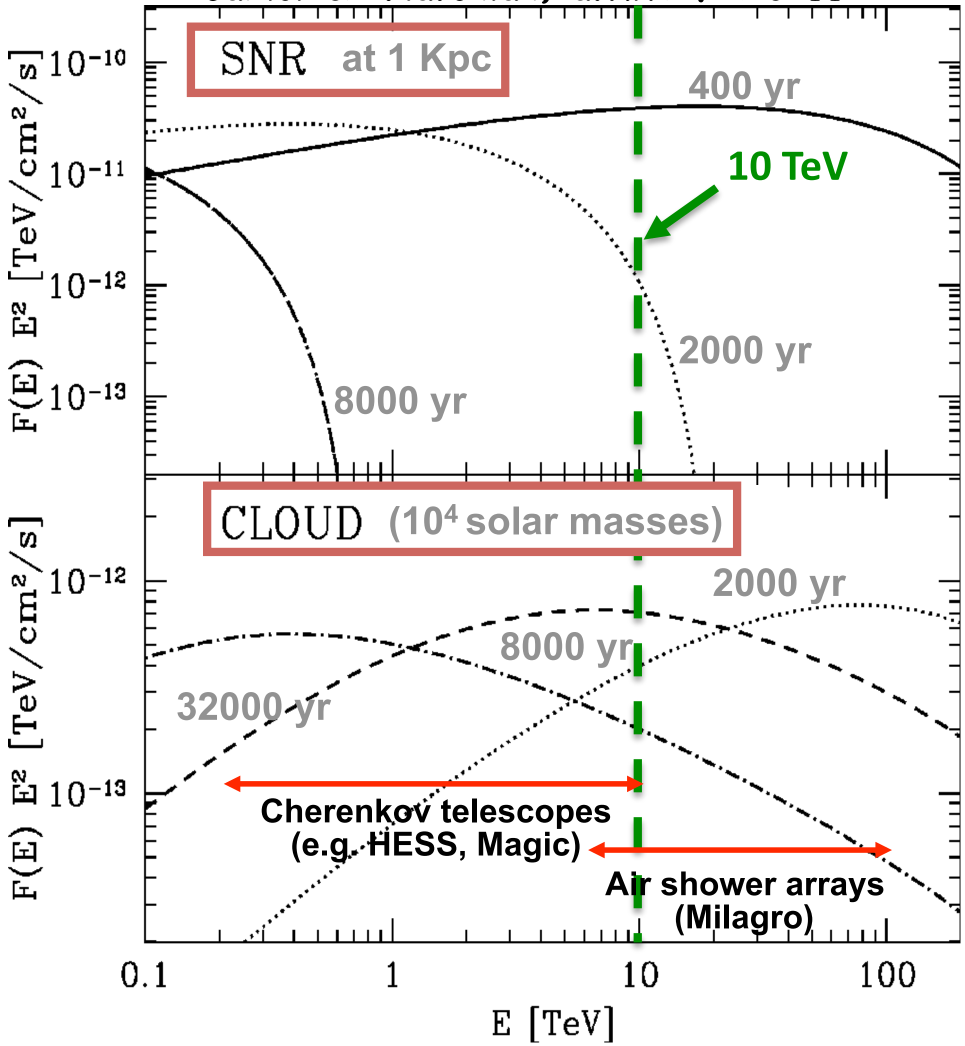
Source candidates with known TeV γ-ray emission:

- **Supernovae** (release ~10^{51} erg every ~30 years):
  - n_{IM} 100 – 1000 cm^{-3} in star-forming regions where SN typically occur
  - why don't we see more SNe in TeV, why have all SNe cutoffs << 100 TeV?
- **Binaries:** only few observed up to now; again cutoffs << 100 TeV (absorption?) not visible in Milagro map
- **Pulsar wind nebula:** thought to accelerate (mainly) electrons
- Maybe something **unknown**!?

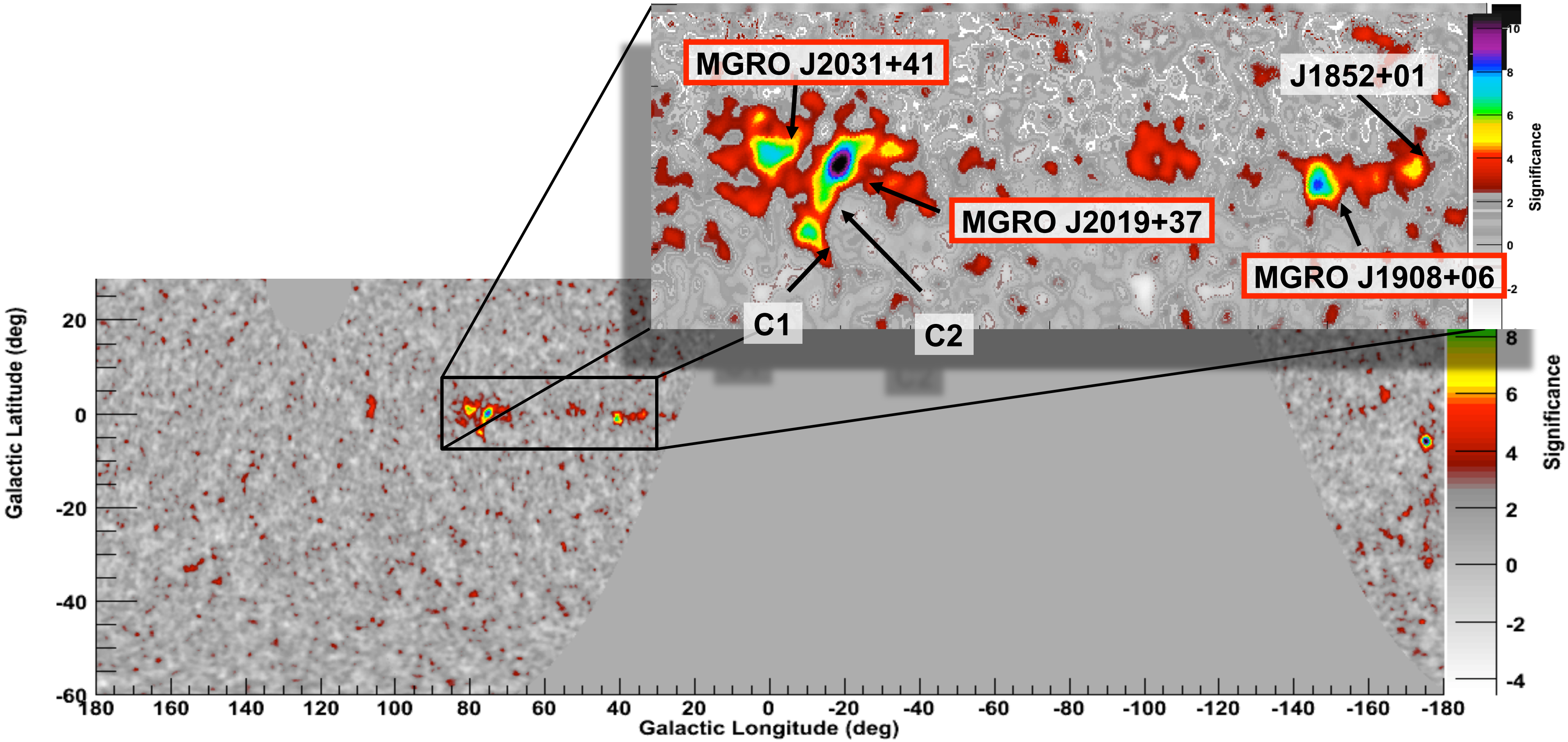
The Missing PeVatrons

- SNRs generally considered as best candidates for Galactic cosmic ray accelerators
- But no SNR γ spectrum extends above a few 10 TeV
  (“knee” corresponds to ~300 TeV)
- Possible reason:
  “Direct” high energy γ-ray emission only in first few hundred years
- Detection still possible by observing secondary γ-rays produced in nearby clouds
- Milagro-like experiments better suited than Cherenkov telescopes

Gabici & Aharonian, arXiv:0705.3011



2007 Milagro Sky Survey At 12 TeV

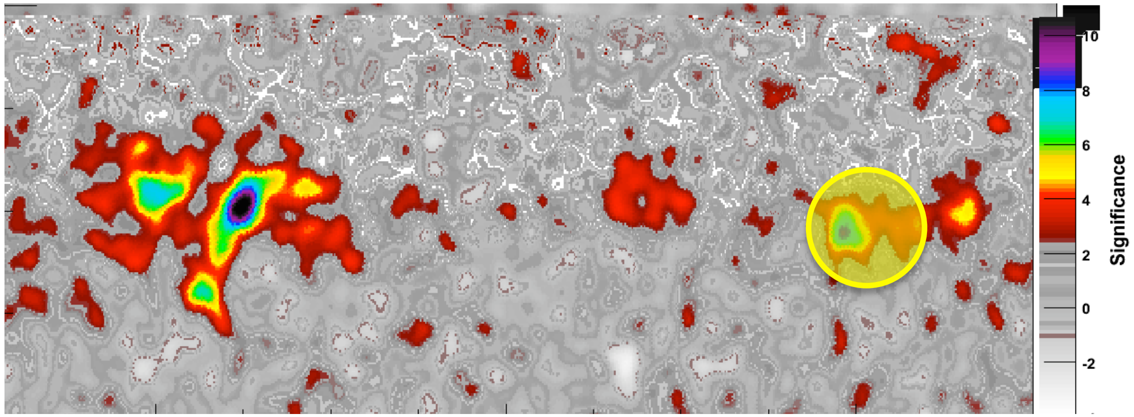


- Several sources along Galactic plane
- Large accumulation in the Cygnus region
- Additional small “cluster” at l = 40°

MGRO J1908+06

Milagro:

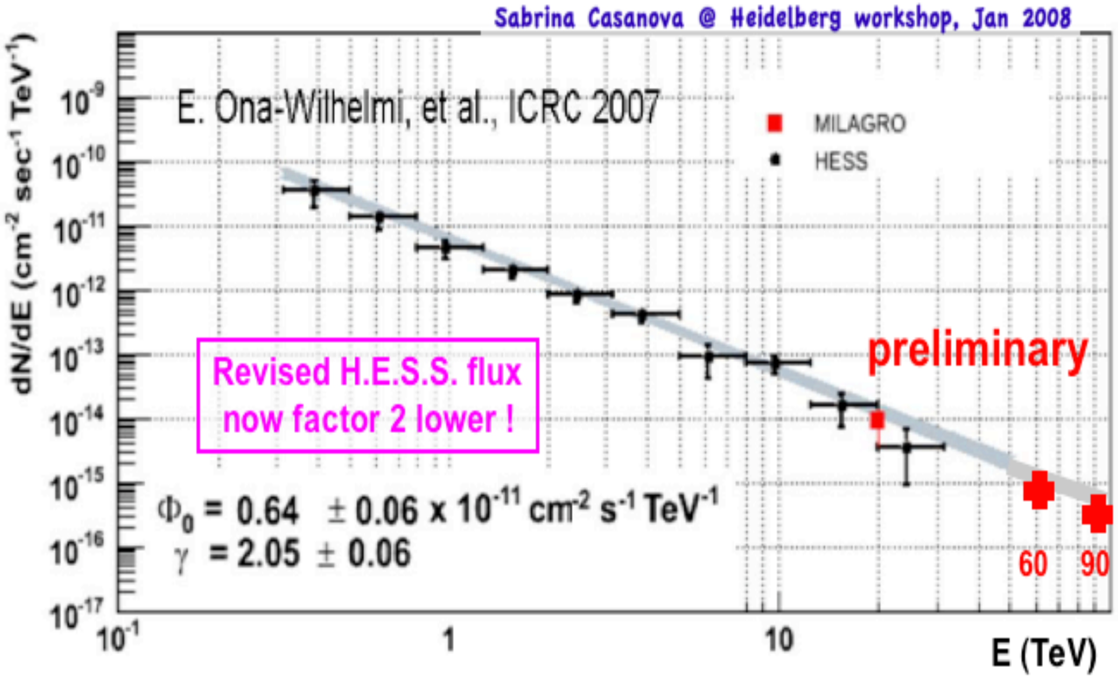
- Spectrum extends up to 100 TeV !
- Strong indicator for proton acceleration in this source



H.E.S.S.:

- E^{-2} spectrum without cutoff indication
- Flux @ 1TeV: 3.2×10^{-12} cm^{-2} s^{-1} TeV^{-1}

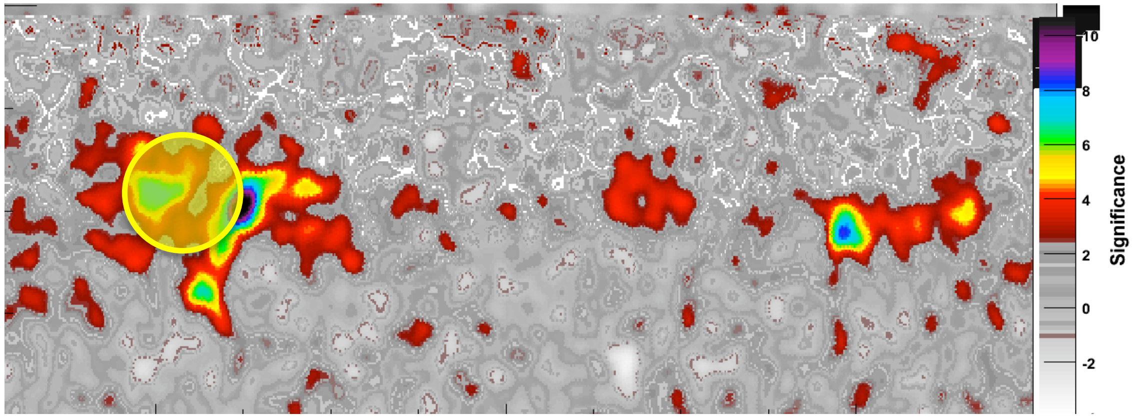
(H.E.S.S. Coll., ICRC'07 proceedings)



MGRO J2031+41

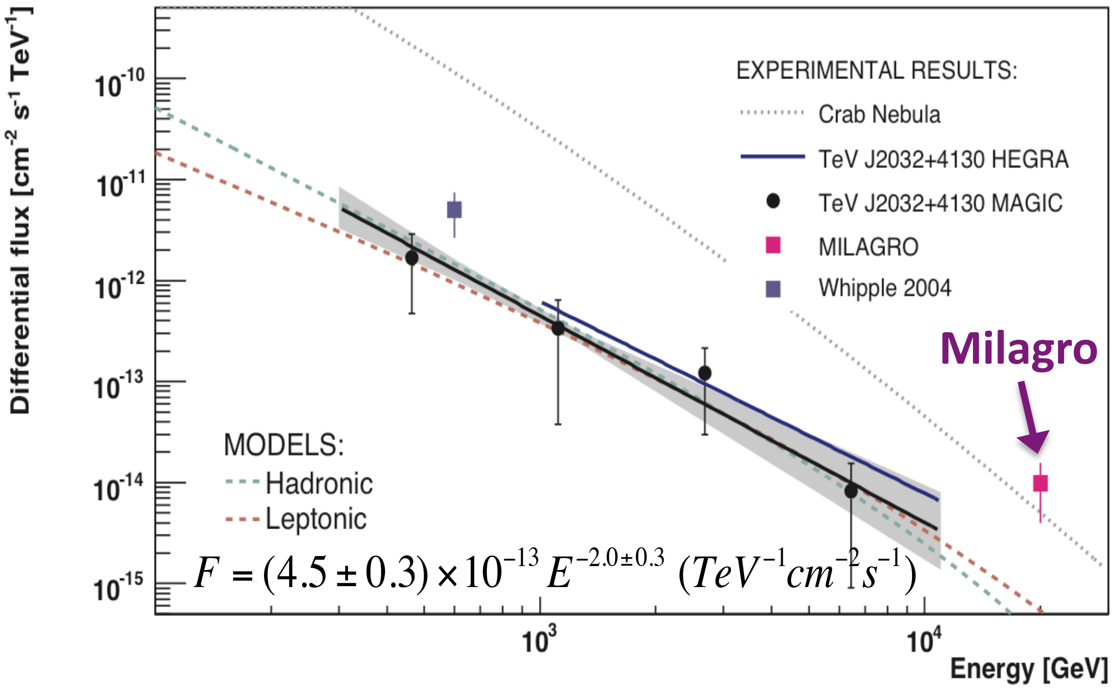
Milagro:

- Flux @ 1TeV for E^{-2}:
  $2.4\times10^{-12}\ cm^{-2}\ s^{-1}\ TeV^{-1}$
  (Milagro Coll., ApJ 658:L33, 2007)



MAGIC:

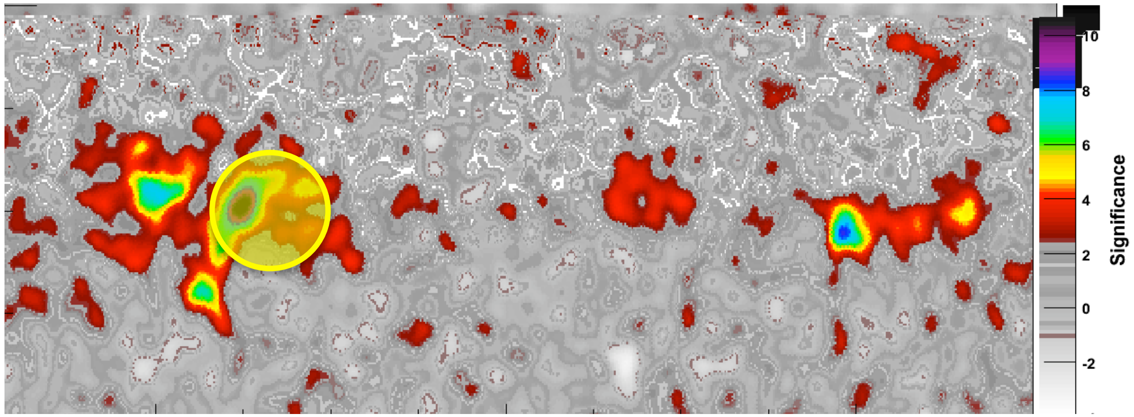
- E^{-2} spectrum
- Flux @ 1TeV:
  $0.45\times10^{-12}\ cm^{-2}\ s^{-1}\ TeV^{-1}$
  (MAGIC Coll., ApJ 675:L25, 2008)
- Lower flux probably due to high photon background in Cygnus region



MGRO J2019+37

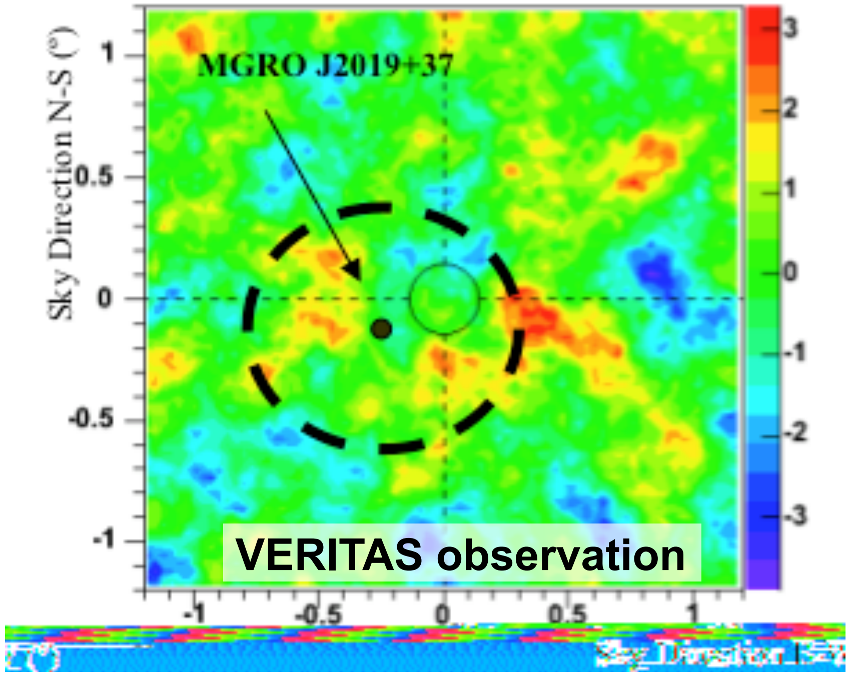
Milagro:

- Flux @ 1TeV for E^{-2}:
  $3.5\times10^{-12}\ \mathrm{cm^{-2}\ s^{-1}\ TeV^{-1}}$
  (Milagro Coll., ApJ 658:L33, 2007)

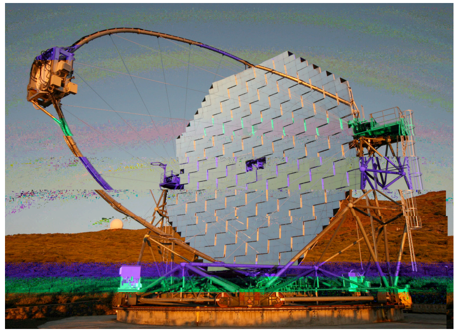


VERITAS:

- Not seen in first observation:
  $F_\gamma < 30$ mCrab (99% C.L.)
  $\Rightarrow$ consistency with Milagro requires $\Gamma < 2.2$
  (VERITAS Coll., ICRC'07 proceedings)

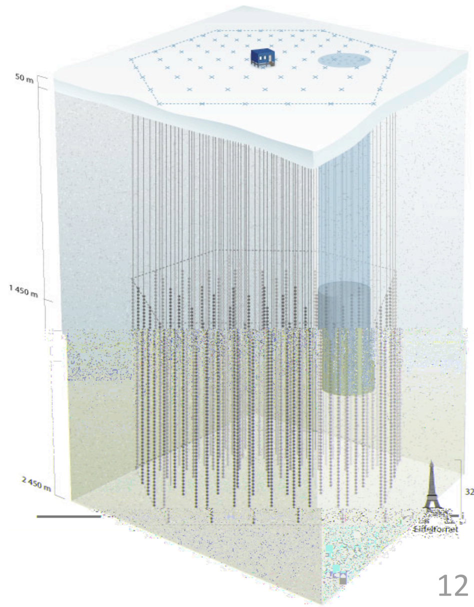


The Role of Neutrino Telescopes



- Several γ-ray sources with hard spectra
- Photon production ambiguous

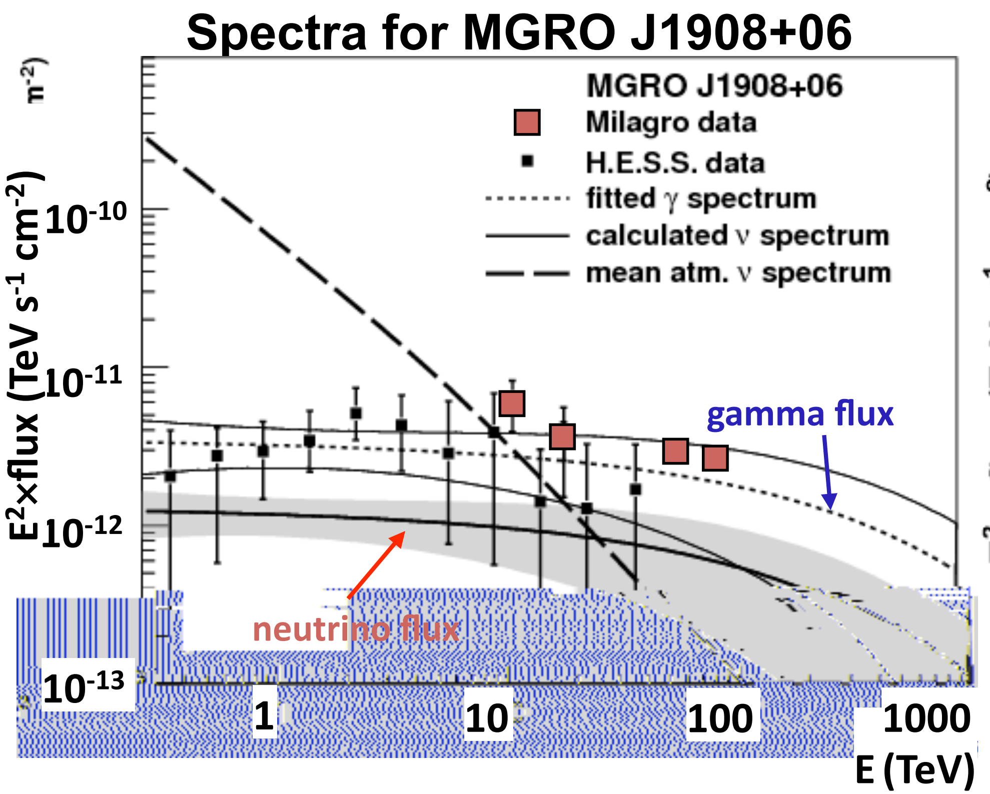
- Air-shower array currently only in Northern Hemisphere
- Cherenkov telescopes only small field of view (few deg^2)
  - cover only small part of sky (at a time)
  - large photon background in star-forming region (e.g. Cygnus) can hide sources

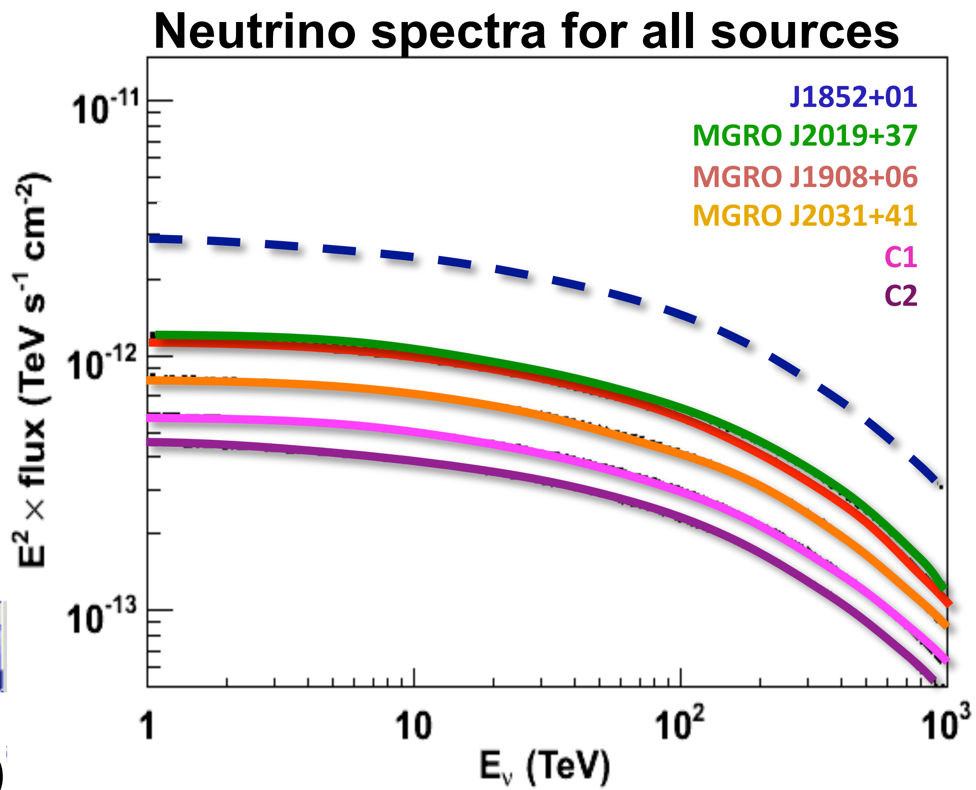


- Neutrinos unambiguous sign for hadronic acceleration
- Neutrino telescope properties very similar to air shower arrays
  - "all sky" sensitivity
  - increasing sensitivity with energy (fast decreasing background)
  - angular resolution $\mathcal{O}(1°)$

Gamma and Neutrino Spectra

Halzen etal, Phys.Rev. D78, 063004 (2008)

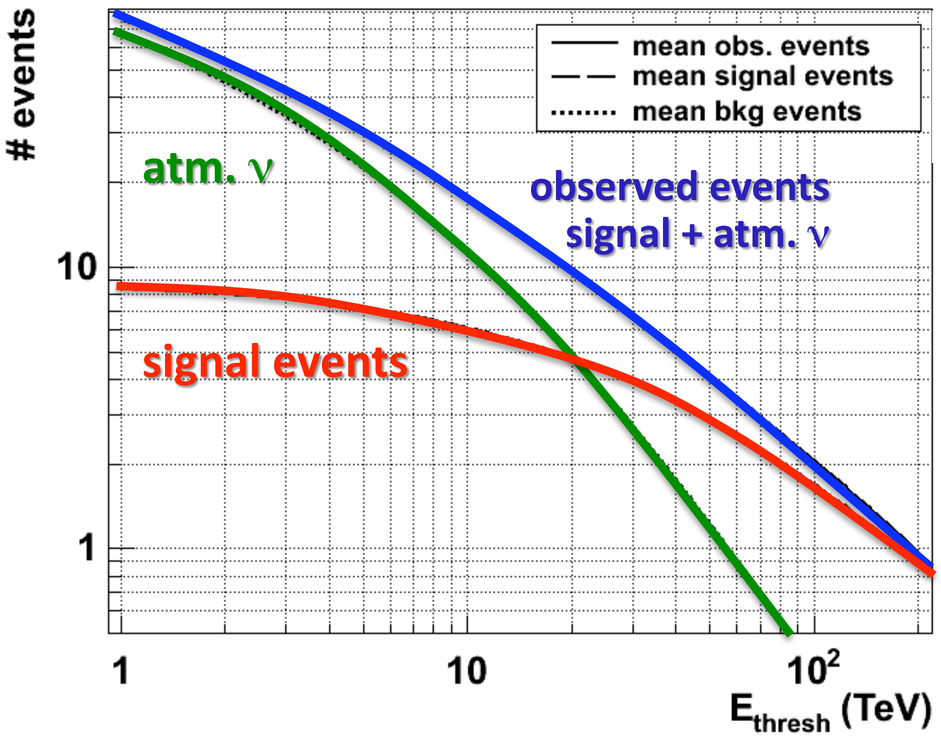


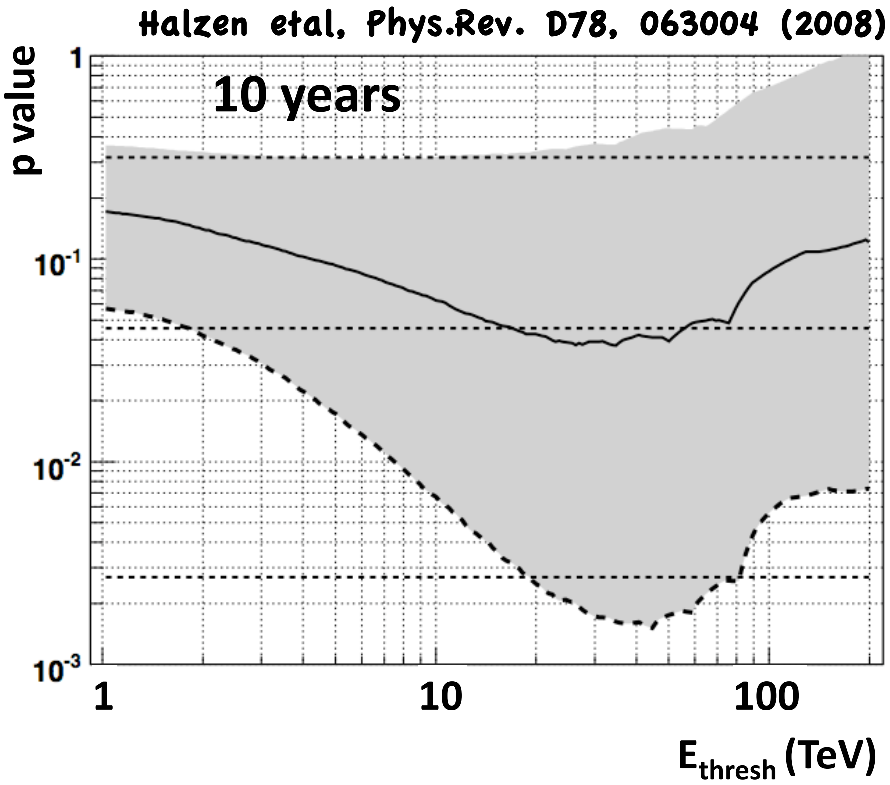


- E^{-2} with Milagro normalization assumed (MGRO J1908+06 index = 2.1)
- ν spectrum cutoff @ 180 TeV

Significance for MGRO J1908+06

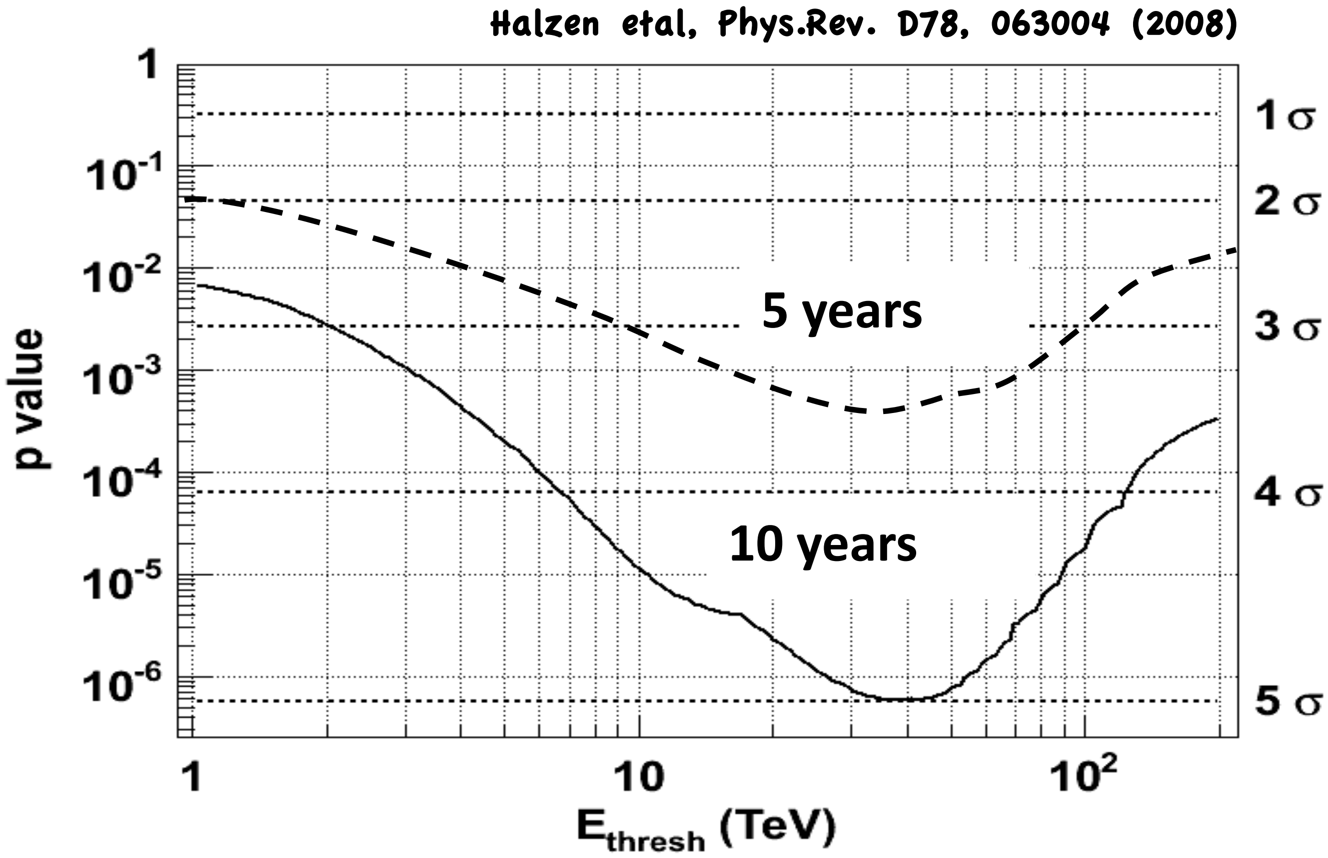
IceCube with 80 strings





- Source size and detector angular + energy resolution taken into account
- Milagro measurements favor lower sensitivity curve (dashed line)
- Individual sources probably hard to detect for IceCube

Significance for stacked Sources

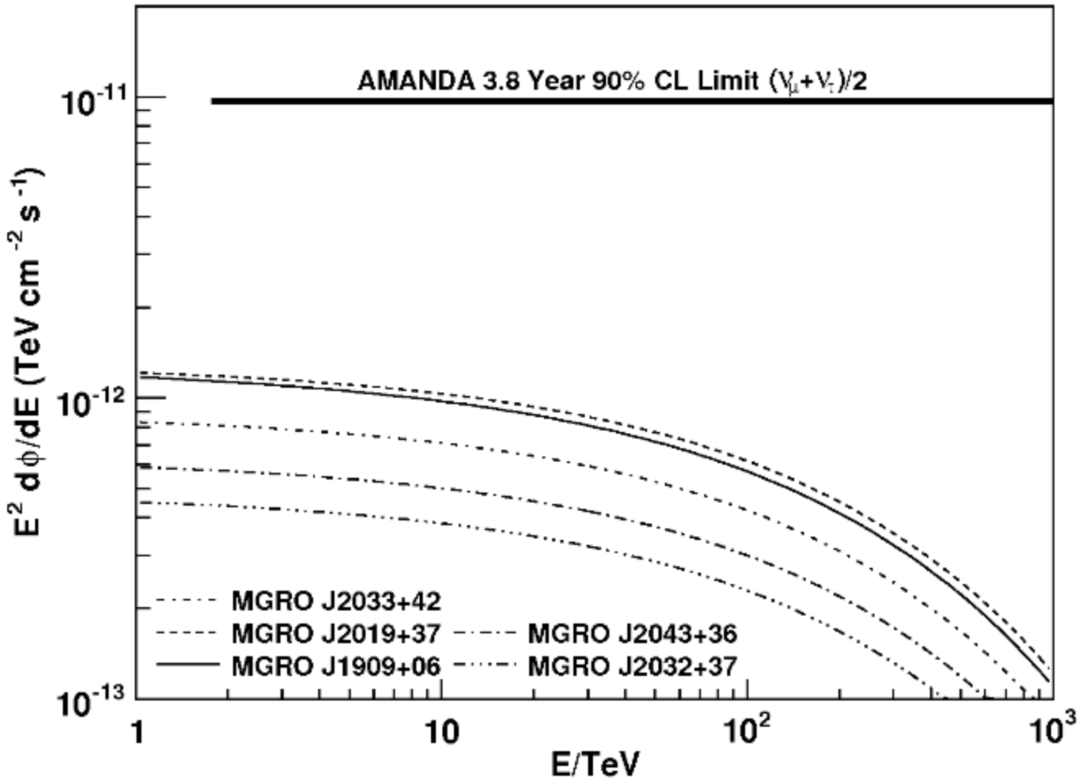


- p-value = 10^{-4} after 5 years but large error band (not shown)
- Optimal threshold @ 30–40 TeV (determined by loss of signal events)

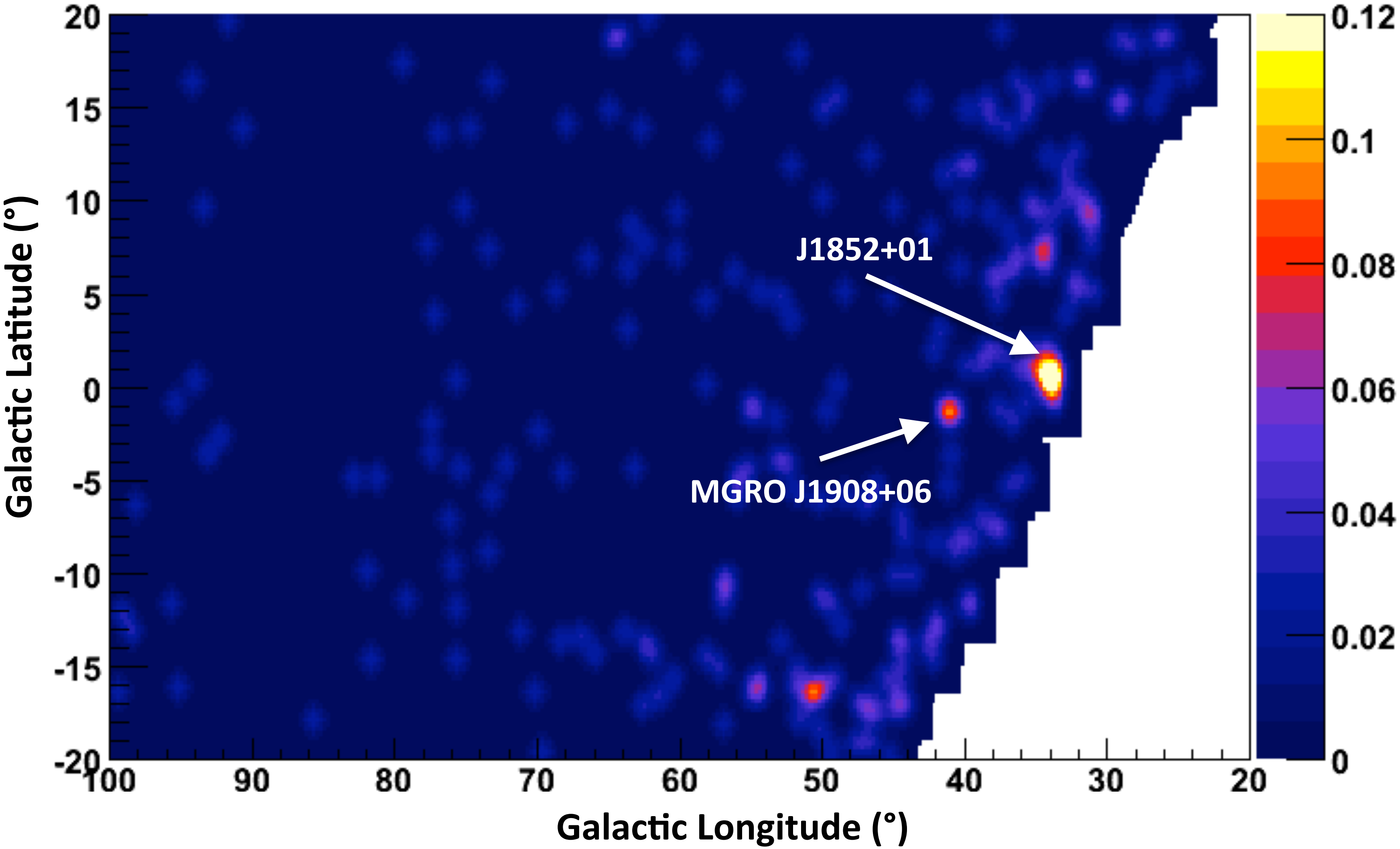
AMANDA II

- Search for muon neutrinos in 6 Milagro source regions in AMANDA II 7 year data set (3.8 years livetime)
- Per-source flux sensitivity improved by a factor of 4 compared to fixed-point search for any of the six sources

Shown by J. Braun @ COSMOS'08



Simulated Neutrino Skymap IC80 (5 years)

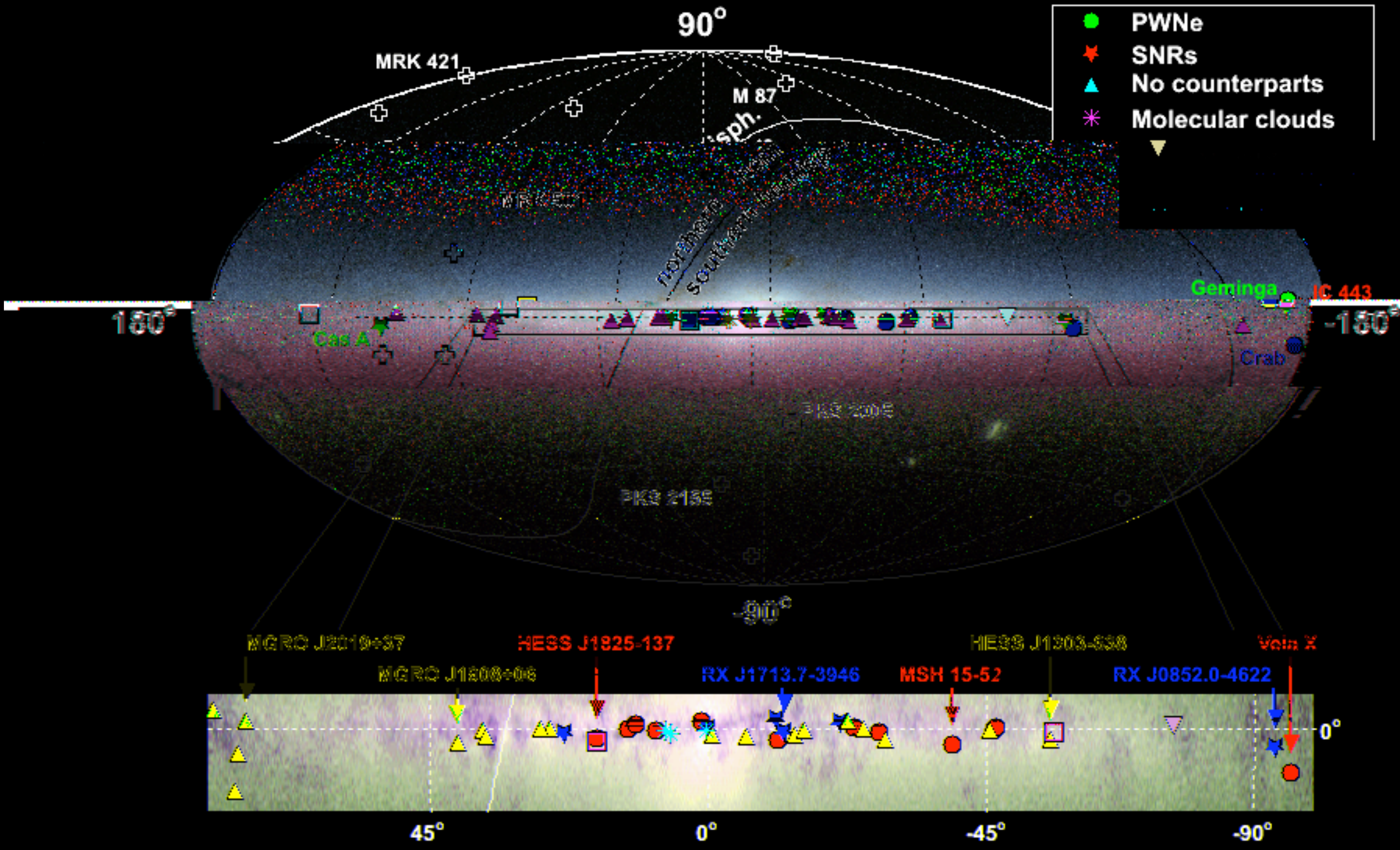


Conclusions

- Straight forward calculations show that sources of Galactic CR should show up in Milagro sky-map
- Sources might not be (easily) visible for Cherenkov telescopes
  - largest energy density might be at several 10 TeV (interactions of CR in molecular clouds)
  - large photon background in SN regions, e.g. Cygnus
- Several Milagro sources show indications for hard E^{-2} spectra with one (MGRO J1908+06) possibly extending to at least 100 TeV
- Hard to decide from γ-ray signal alone whether γ-ray sources are CR sources
- Neutrino telescopes can unambiguously identify sources of cosmic rays
- IceCube will be able to detect stacked Milagro sources after several years (individual sources difficult)

Backup Slides

TeV Gamma-Ray Sky Map



Simulated Neutrino Skymaps IC80 (5 years)