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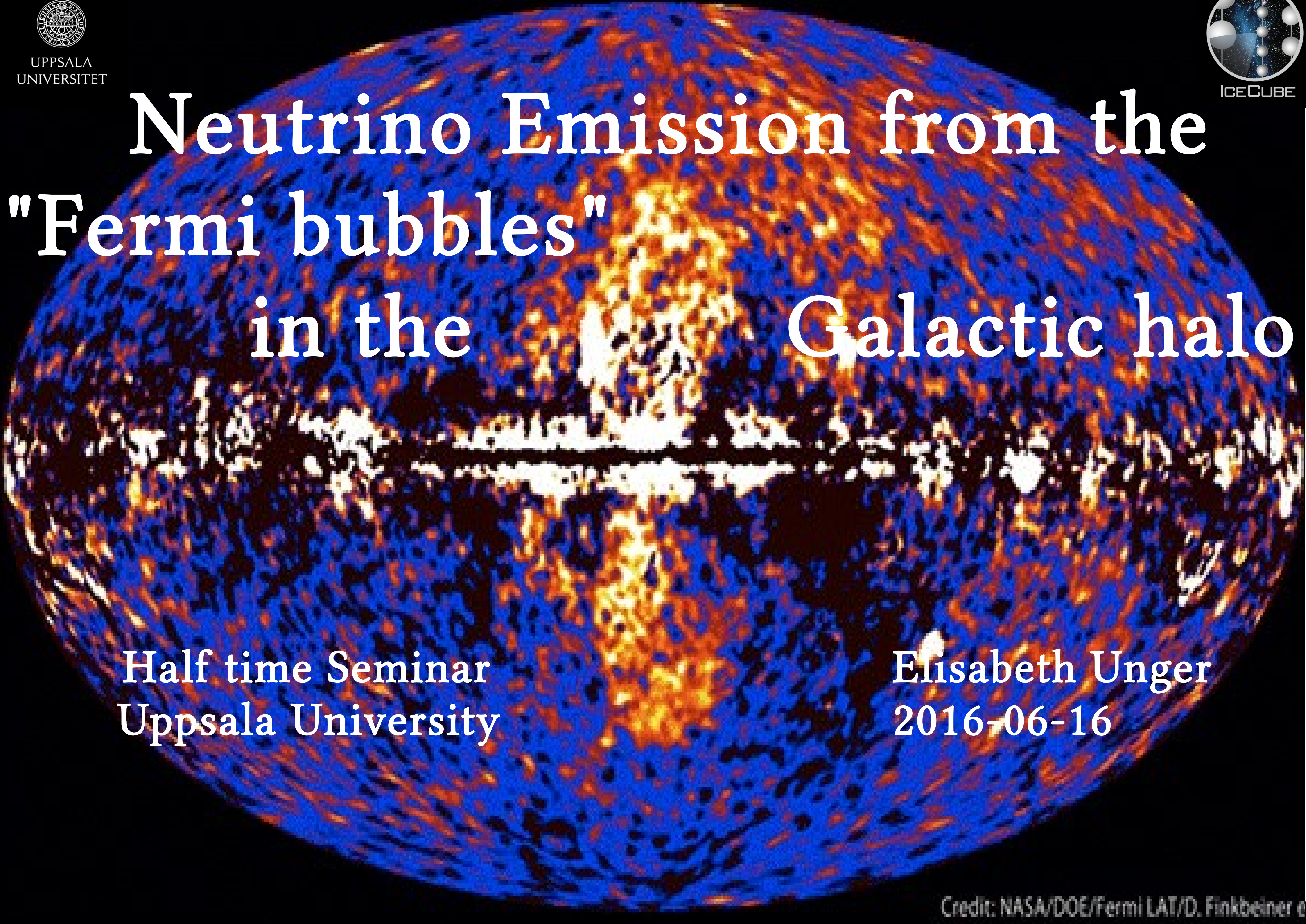

Neutrino Emission from the "Fermi bubbles" in the Galactic halo

Half time Seminar
Uppsala University

Elisabeth Unger
2016-06-16

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner e

Outline

- Multi-messenger astronomy
- Fermi Bubbles
- IceCube
- Event selection
- Fermi Bubble analysis
- Galactic Center analysis
- Results
- Conclusion and outlook

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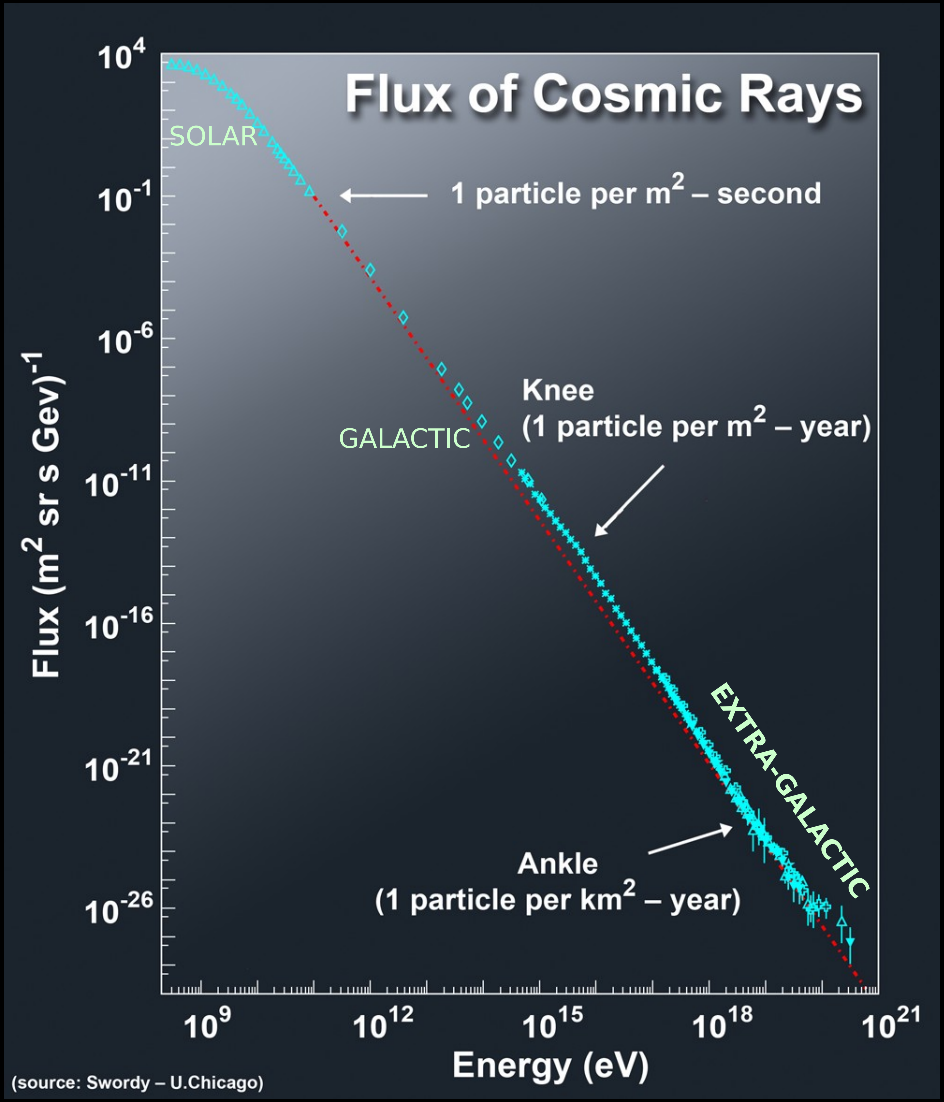
The Cosmic Ray Spectrum

- Cosmic Rays (CRs) consist of:
  - Mostly protons (~90%)
  - He nuclei (~9%)
  - Heavier nuclei (~1%)
- Reach energies up to ~10^{20} eV
- Their origin is unknown
- Possible extra- galactic sources:
  - Active galactic nuclei
  - Gamma Ray Bursts
  - Greisen–Zatsepin–Kuzmin (GZK) neutrinos



(source: Swordy – U.Chicago)

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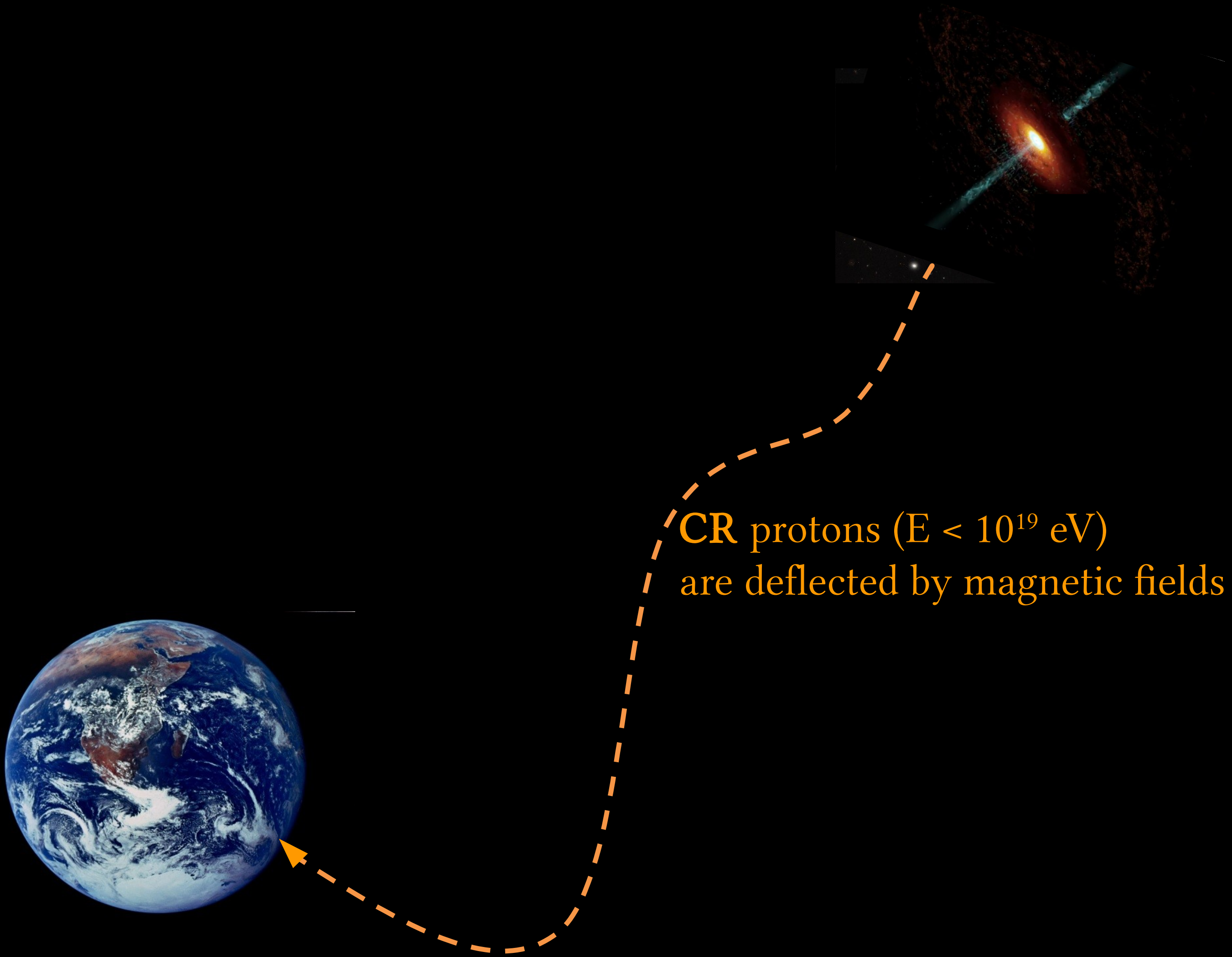
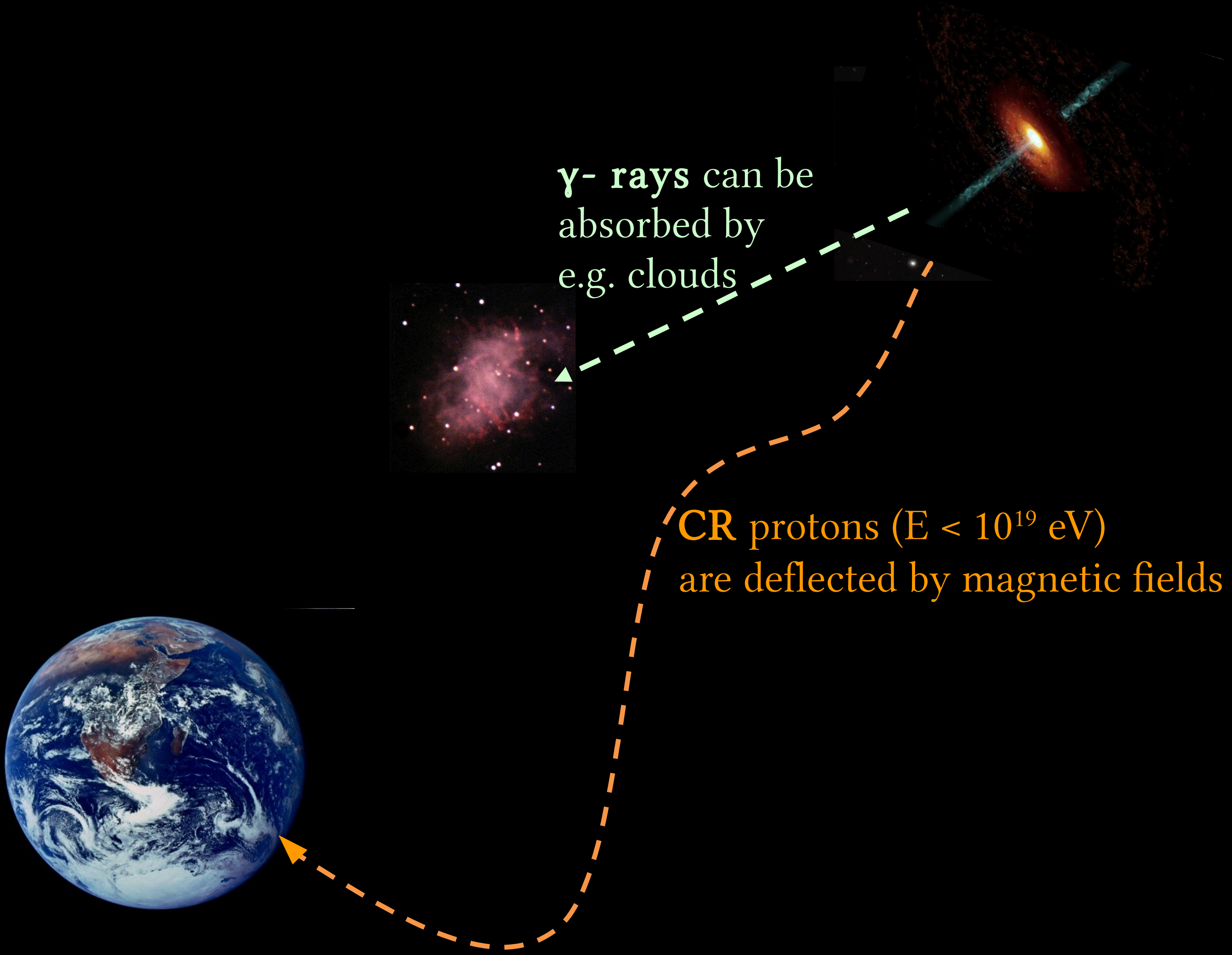
Multi-Messenger Astronomy



CR protons (E < 10^{19} eV)
are deflected by magnetic fields

Multi-Messenger Astronomy



γ- rays can be absorbed by e.g. clouds

CR protons (E < 10^{19} eV) are deflected by magnetic fields

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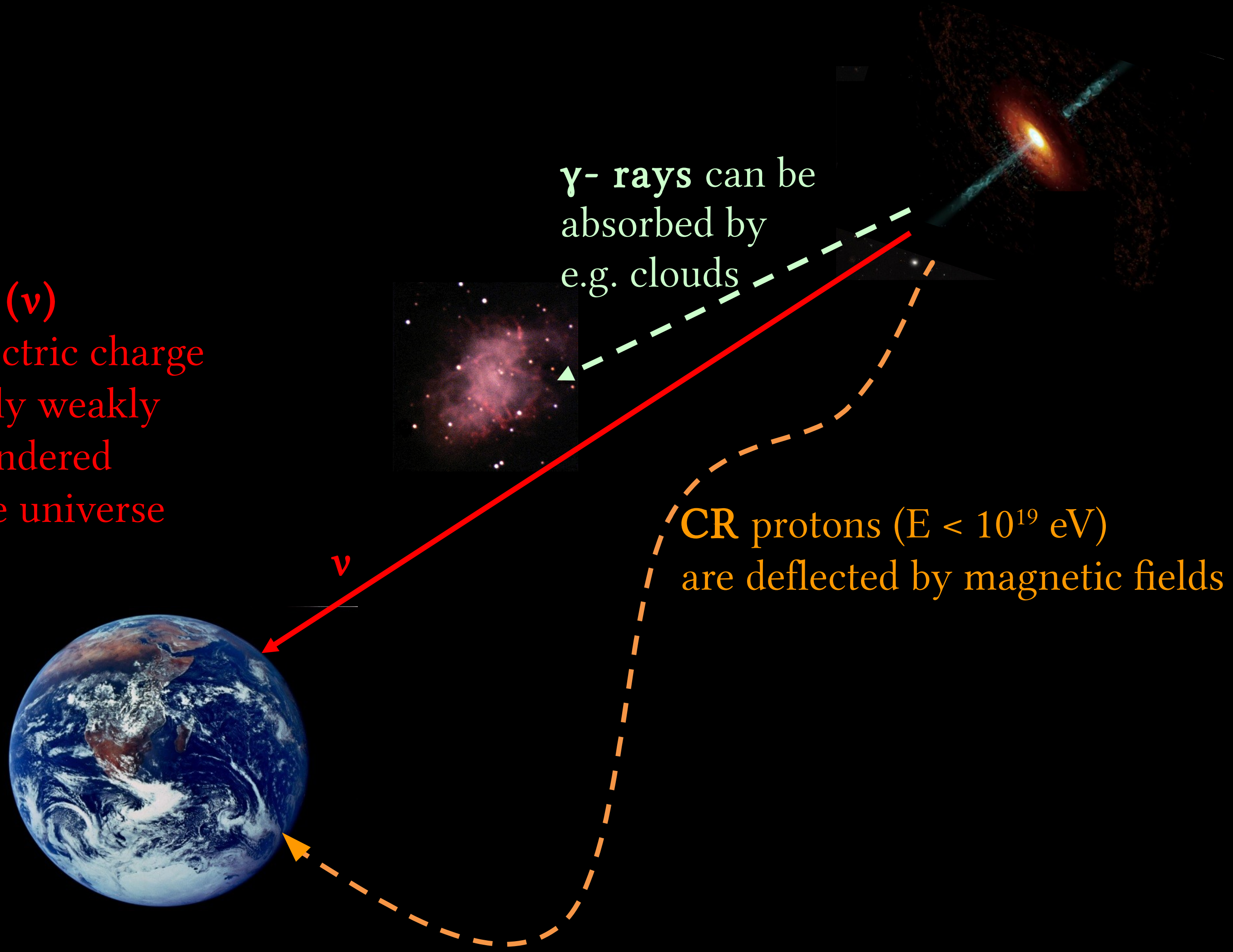
Multi-Messenger Astronomy



γ- rays can be
absorbed by
e.g. clouds

Neutrinos (ν)

- have no electric charge
- interact only weakly
- travel unhindered through the universe
- point back

CR protons (E < 10^{19} eV)
are deflected by magnetic fields

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Selection of possible Galactic Sources

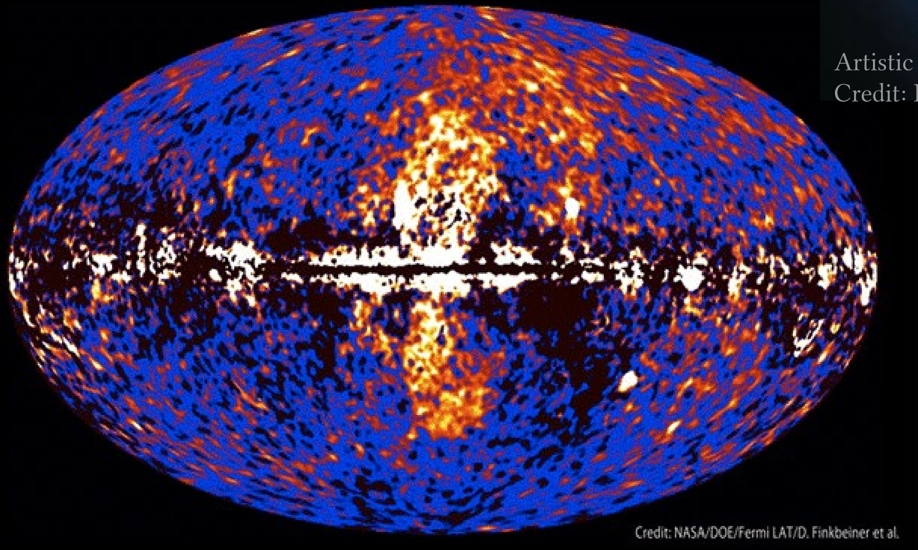
Super Novae remands
in the Galactic Plane

Crab Nebula,
Credit: NASA, ESA, J. Hester, A. Loll

Dark Matter in the
Galactic Center and Halo

Artistic Image of a Galaxy Halo,
Credit: ESO/L. Calada

Fermi Bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

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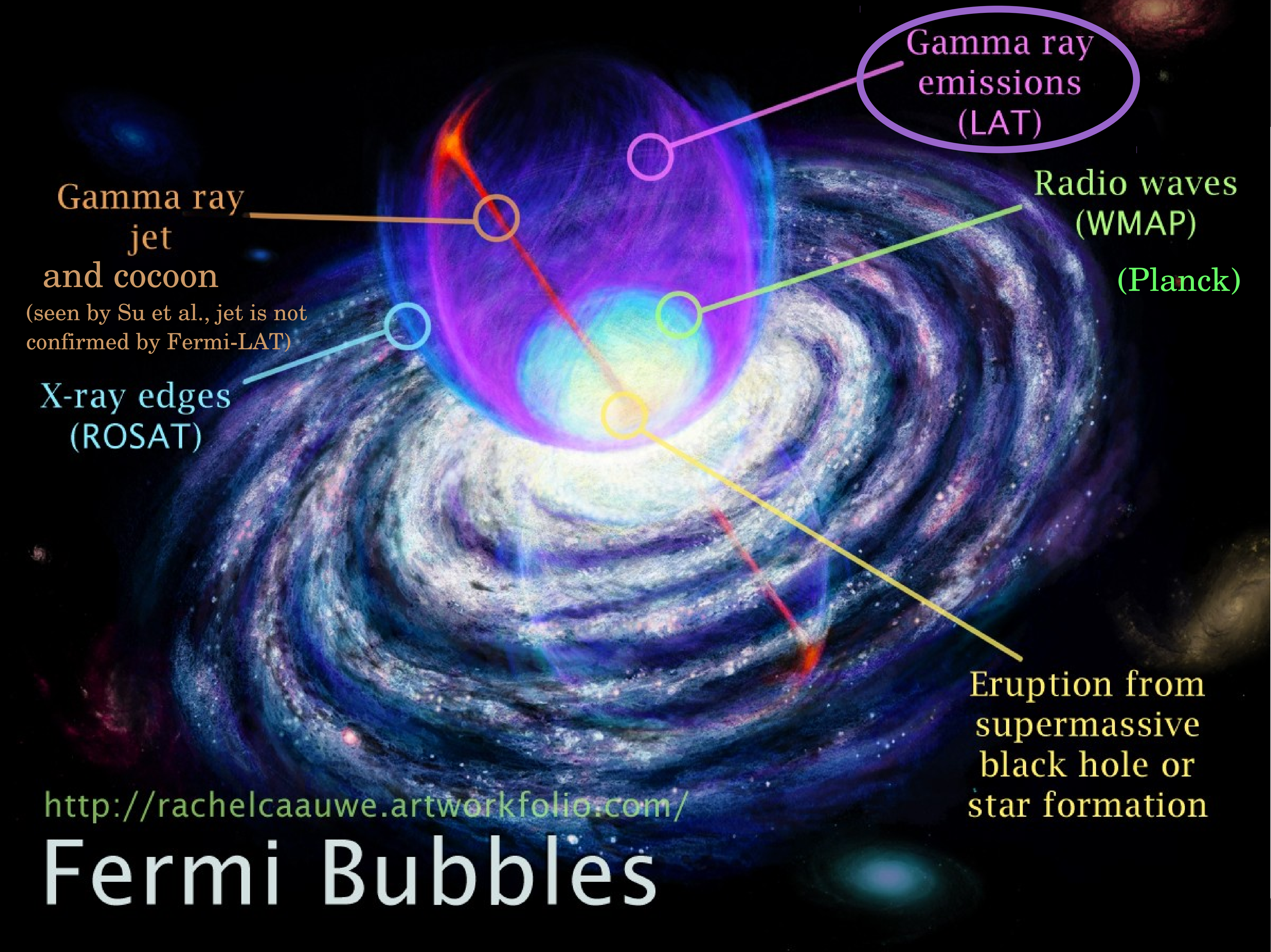


Gamma ray emissions (LAT)

Gamma ray jet and cocoon

(seen by Su et al., jet is not confirmed by Fermi-LAT)

Radio waves (WMAP)

(Planck)

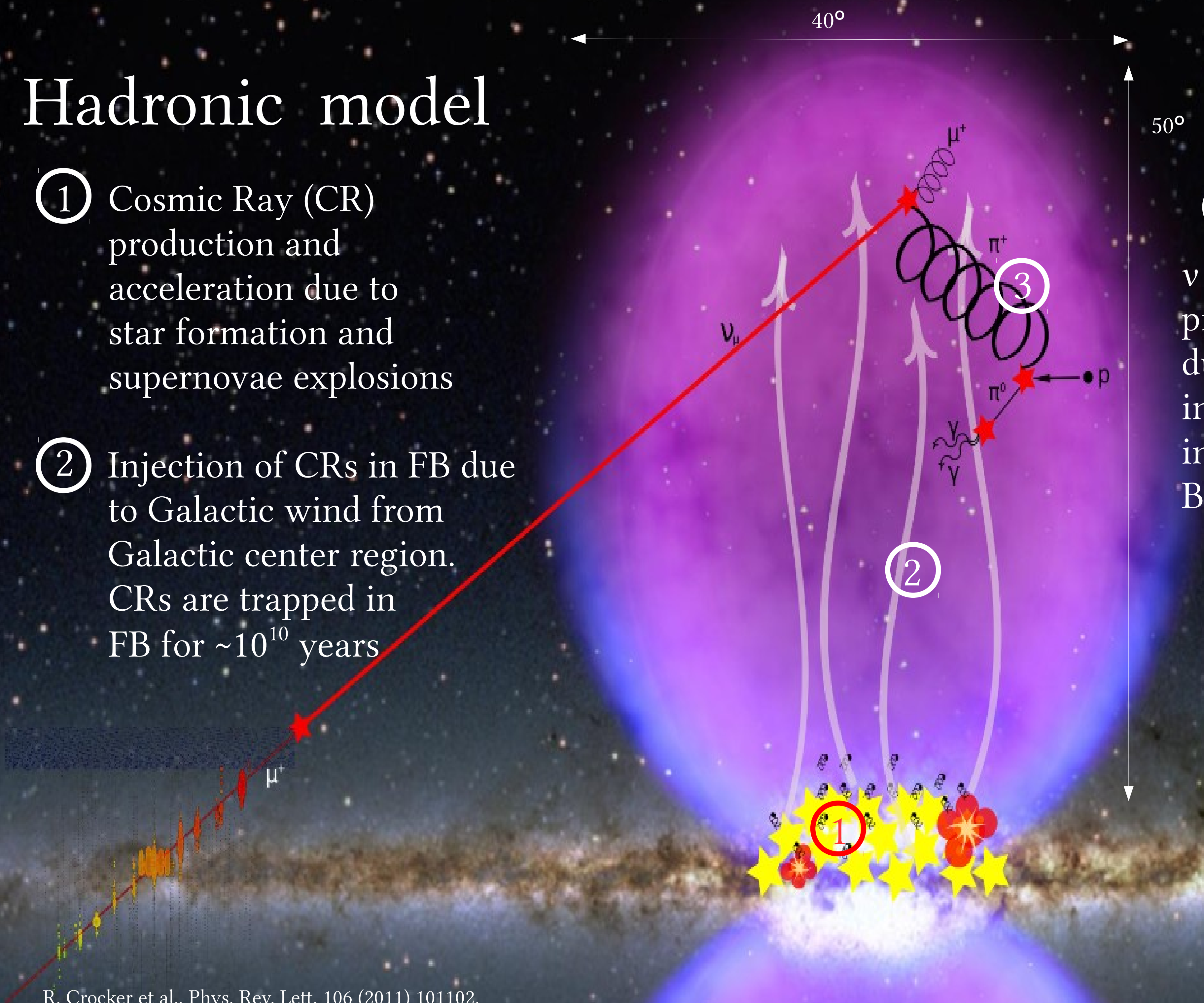
X-ray edges (ROSAT)

Eruption from supermassive black hole or star formation

http://rachelcaauwe.artworkfolio.com/

Fermi Bubbles

Hadronic model



① Cosmic Ray (CR) production and acceleration due to star formation and supernovae explosions

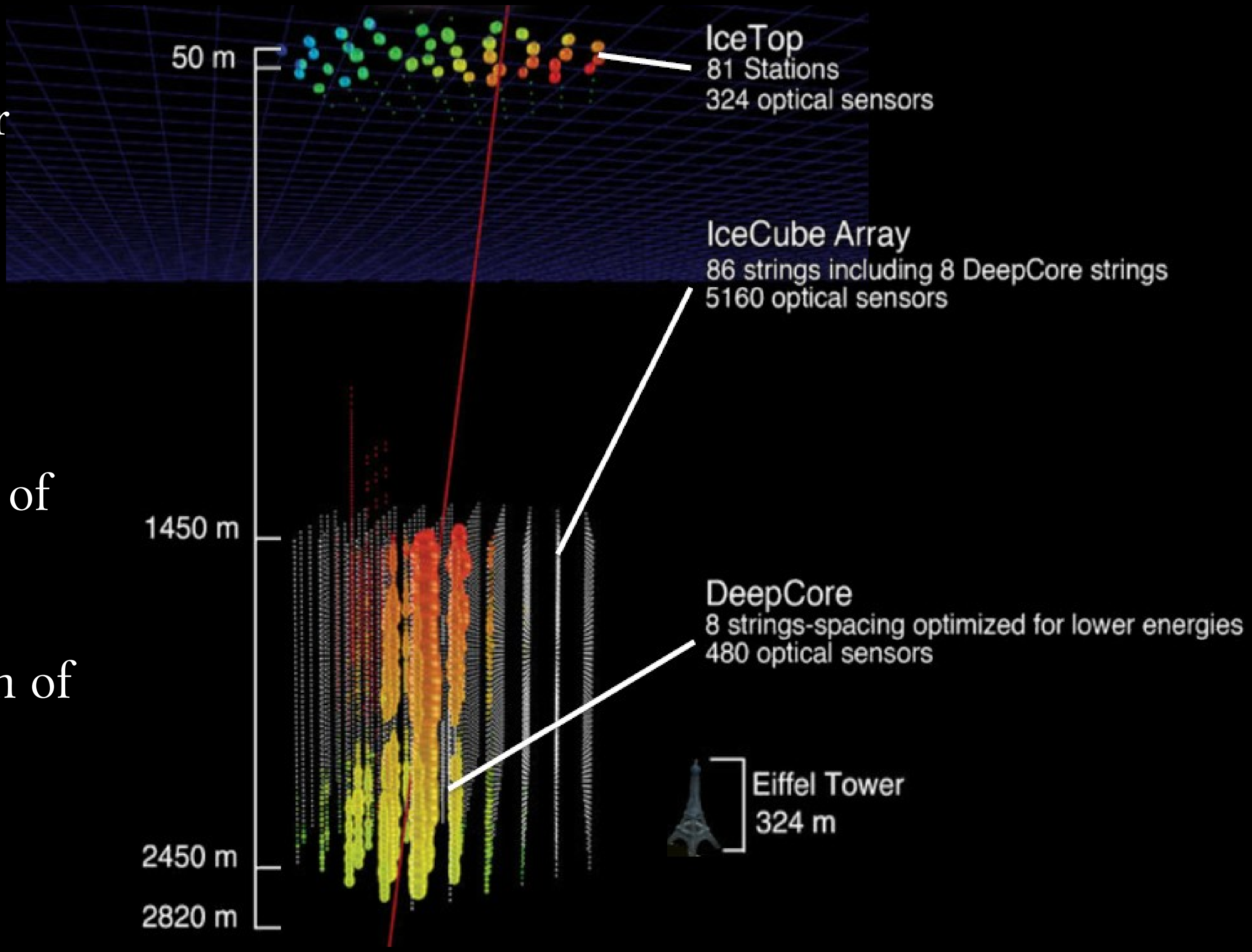
② Injection of CRs in FB due to Galactic wind from Galactic center region. CRs are trapped in FB for ~10^{10} years

③ ν and γ production due to CR interaction in Fermi Bubbles (FB)

R. Crocker et al., Phys. Rev. Lett. 106 (2011) 101102.

IceCube

- IceCube is a cubic-kilometer sized neutrino detector
- Located at the geographic South Pole, Antarctica
- Monitors over 1 billion tons of ultra-clear glacial ice
- Detects Cherenkov radiation of neutrino induced charged particles traversing the ice



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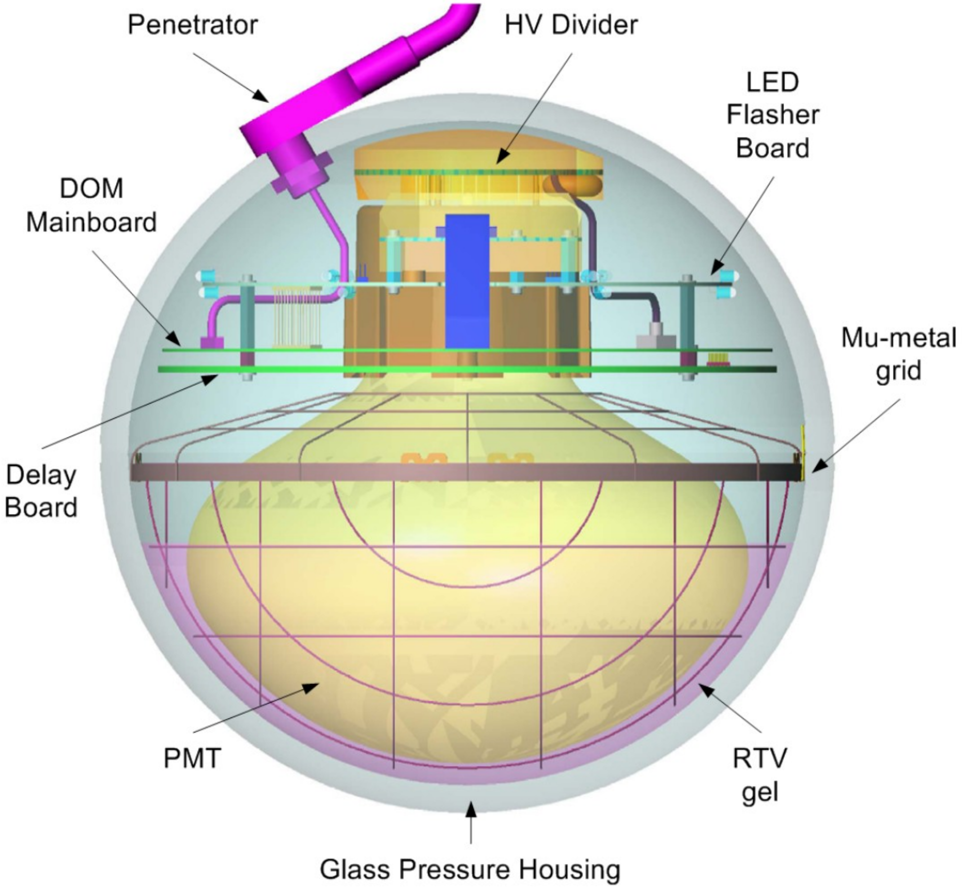
Digital Optical Module

- DOM – Digital Optical Module
- Digitizes and timestamps the output of the photo multiplier
- Communicates with its four closest neighbors
- LED flashers for testing and calibration
- Very low power consumption (< 5 W)



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Event Topology

Charge Current (CC)

muon neutrino track

$$\nu_\mu + N \rightarrow \mu + X$$

CC electron neutrino cascade

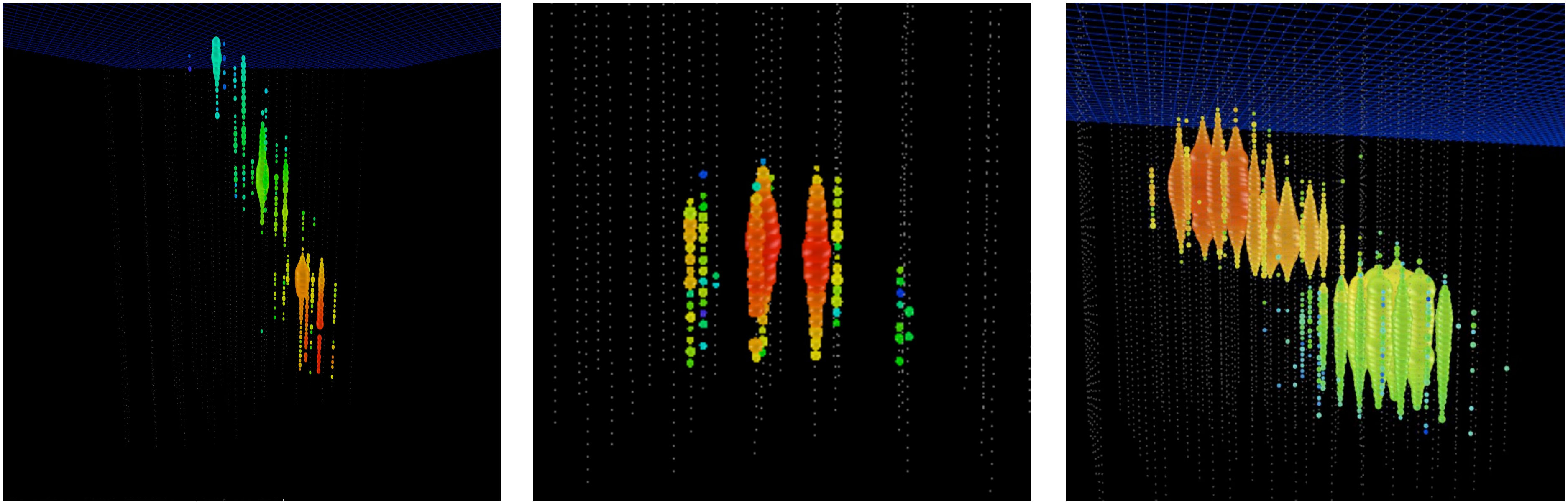
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} \ + X$$

Neutral Current cascade all flavors

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

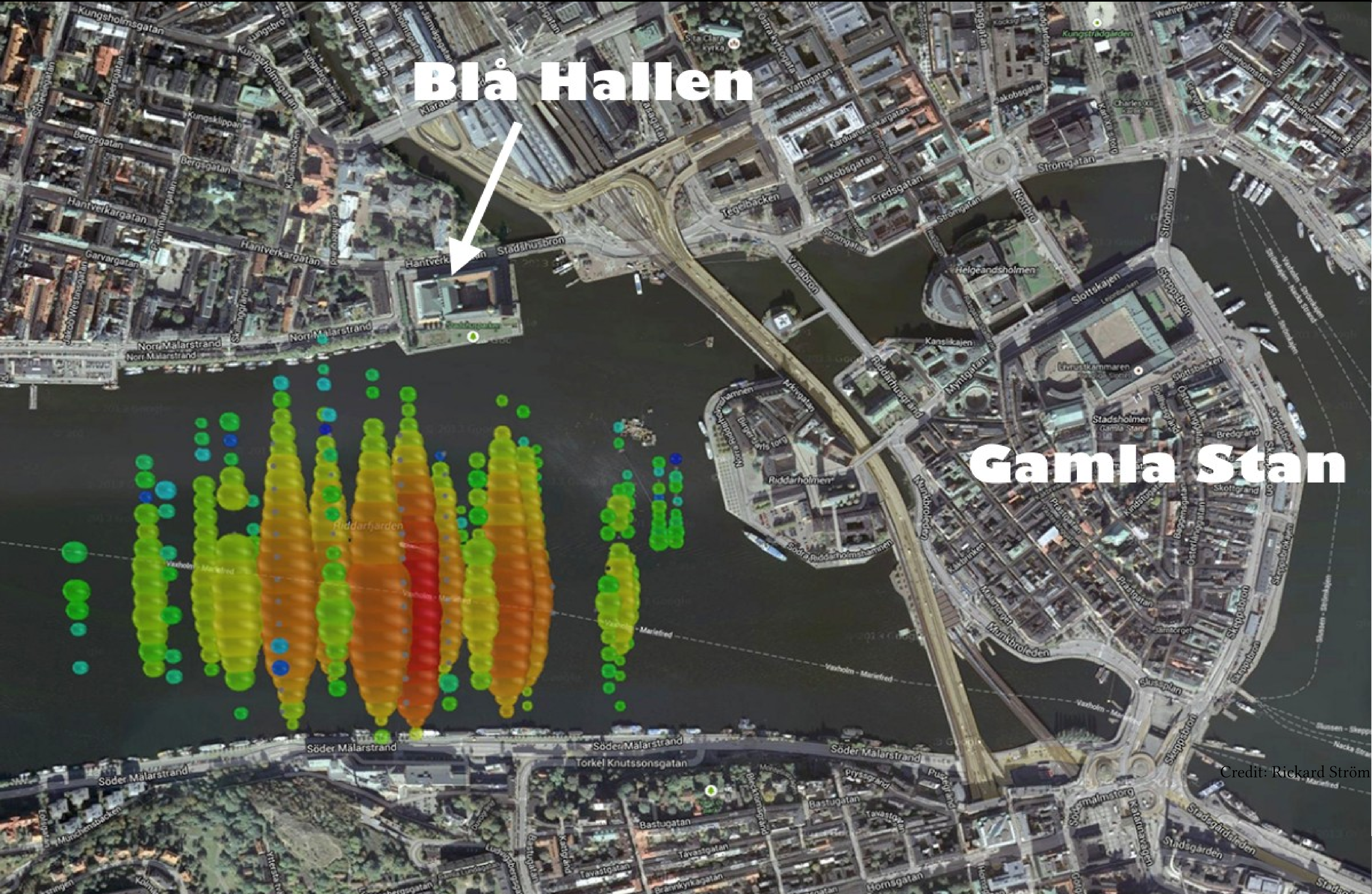
CC tau neutrino cascades

$$\nu_\tau + N \rightarrow \tau + X$$



Simulated IceCube Events

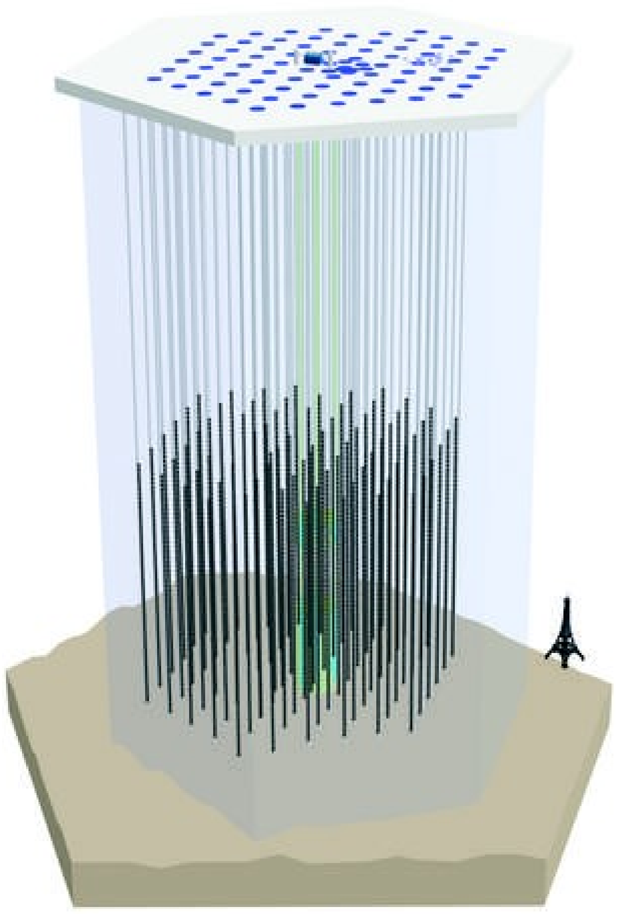
Event vs Stockholm



Credit: Rickard Ström

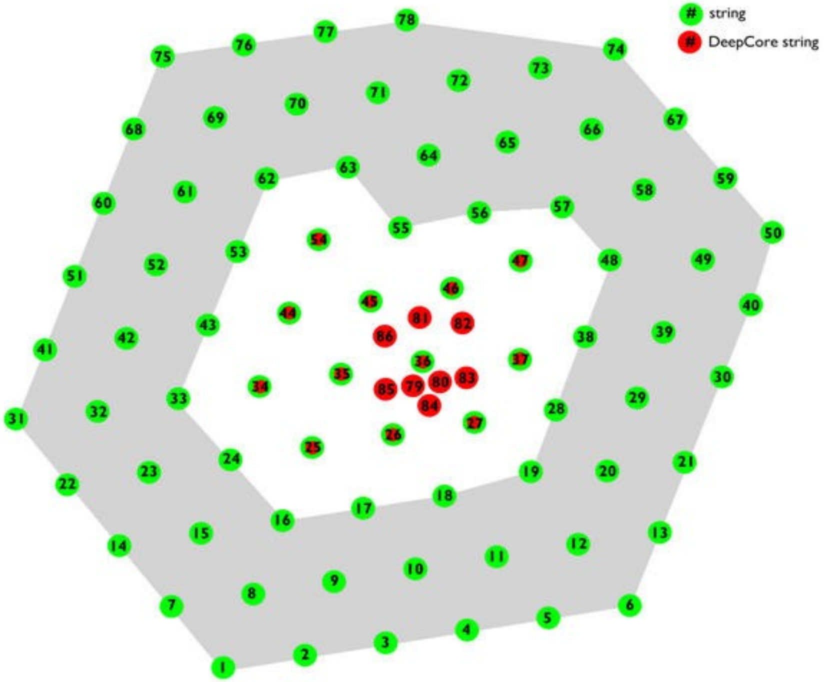
DeepCore

IceCube



ν energy threshold: **100 GeV**

DeepCore



Strings and DOMs are
denser distributed

ν energy threshold: **10 GeV**

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DeepCore Events

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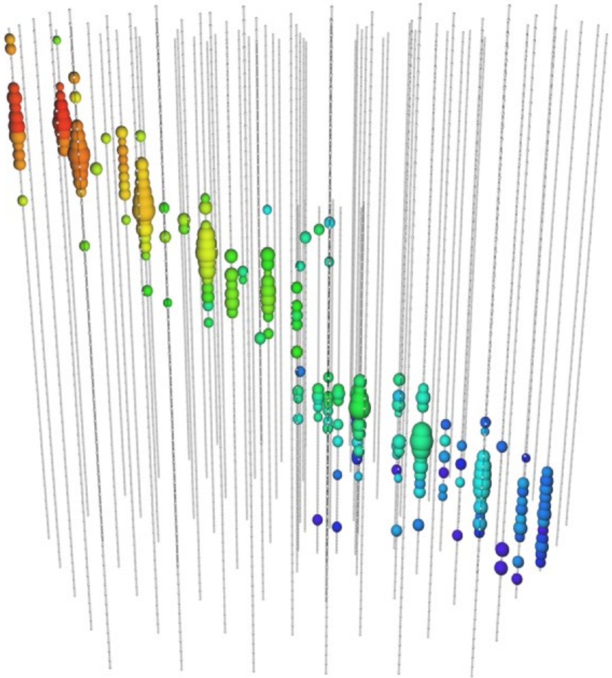
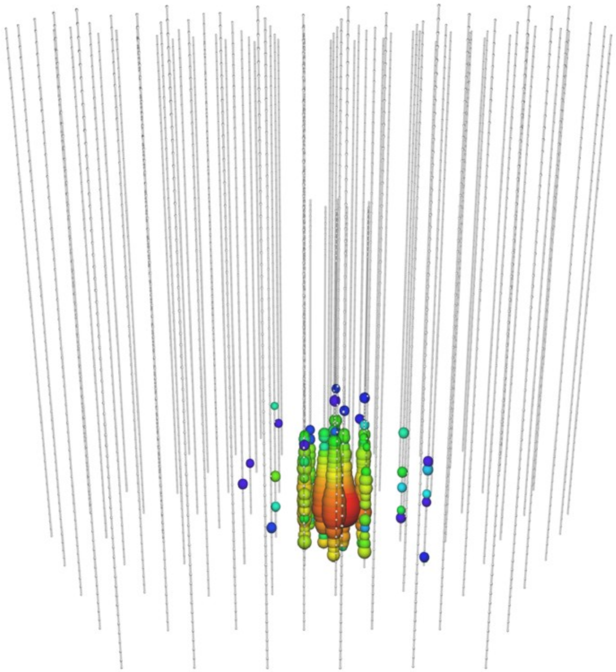
Atmospheric muon bundle

27 TeV



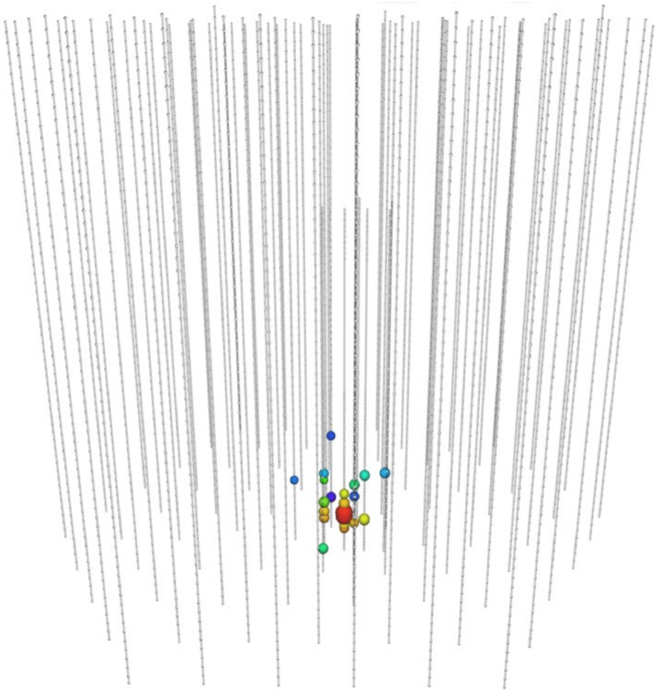
Electron neutrino

1.6 TeV



Electron neutrino

26 GeV



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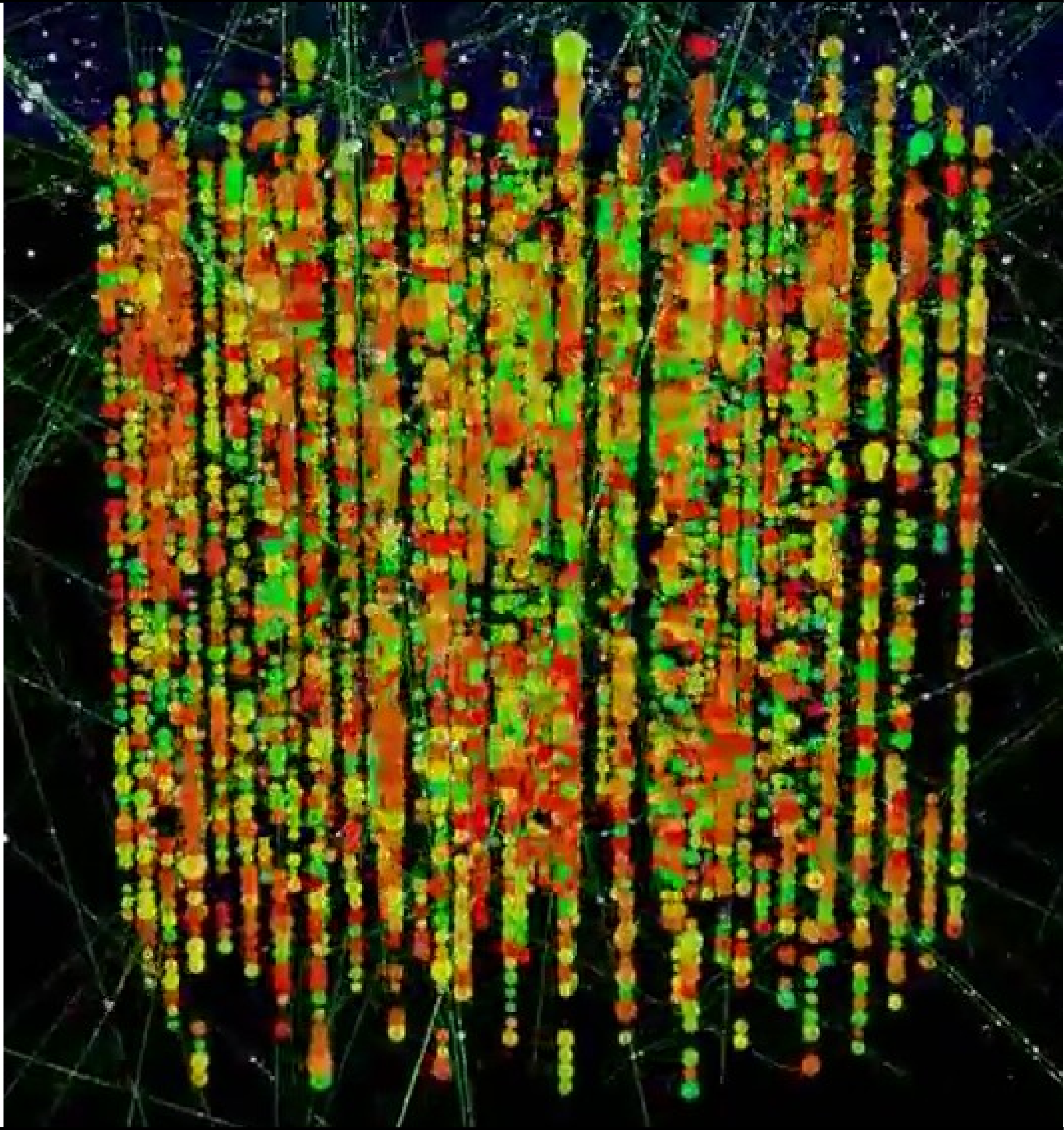
So many events...

IceCube after 10 ms
of simulated events

Events per year:

- Atmospheric muons ~10^{11}
- Atmospheric neutrinos ~ 10^5
- Astrophysical neutrinos ~ 10 (diffuse)



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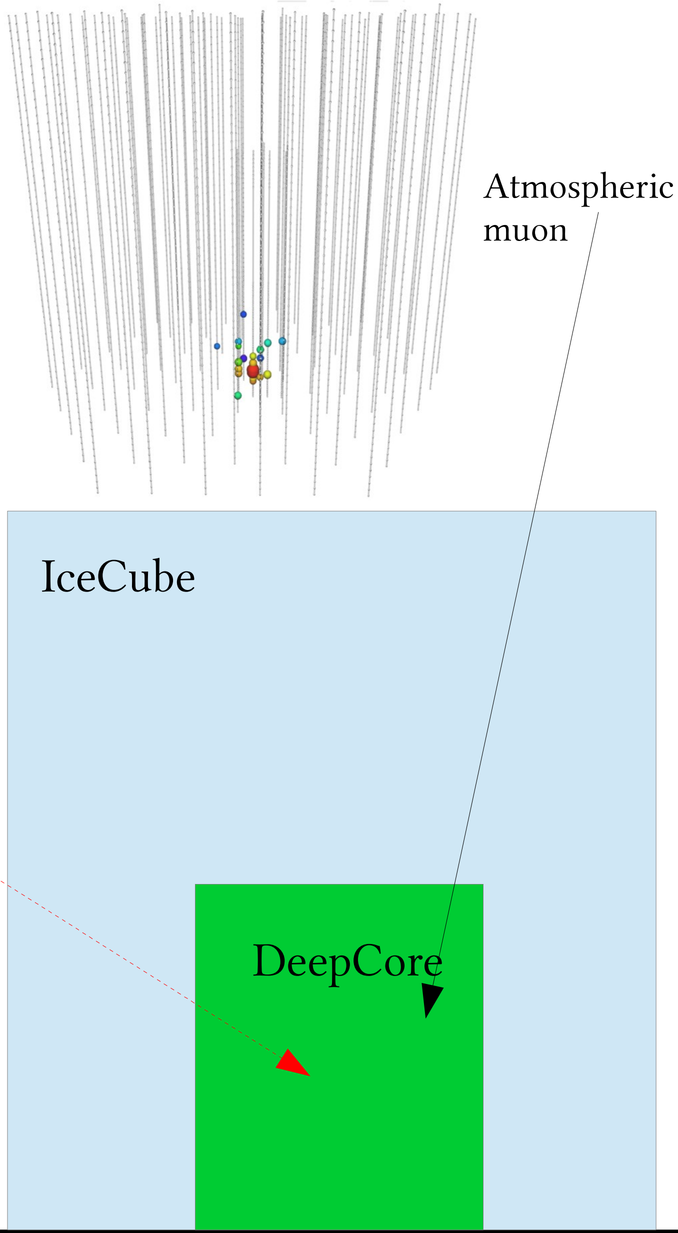
Event selection

- All neutrino flavors
- All directions (full sky)
- Low energies: 10 GeV – 200 GeV
- Only Cascades (muon tracks
  look like cascades at these low energies)
- Background reduction:

  substantially by using
  IceCubes top and side layers as veto

  by investigating different variables e.g.:
  - Event topology
  - Timing
  - direction
- Event sample from Henric Taavola



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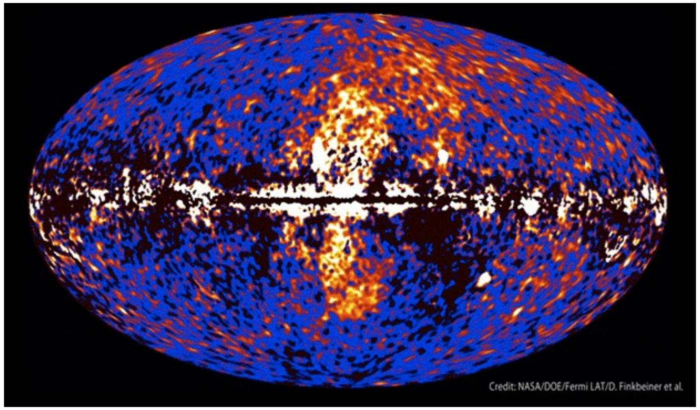
Fermi Bubble γ-ray spectrum

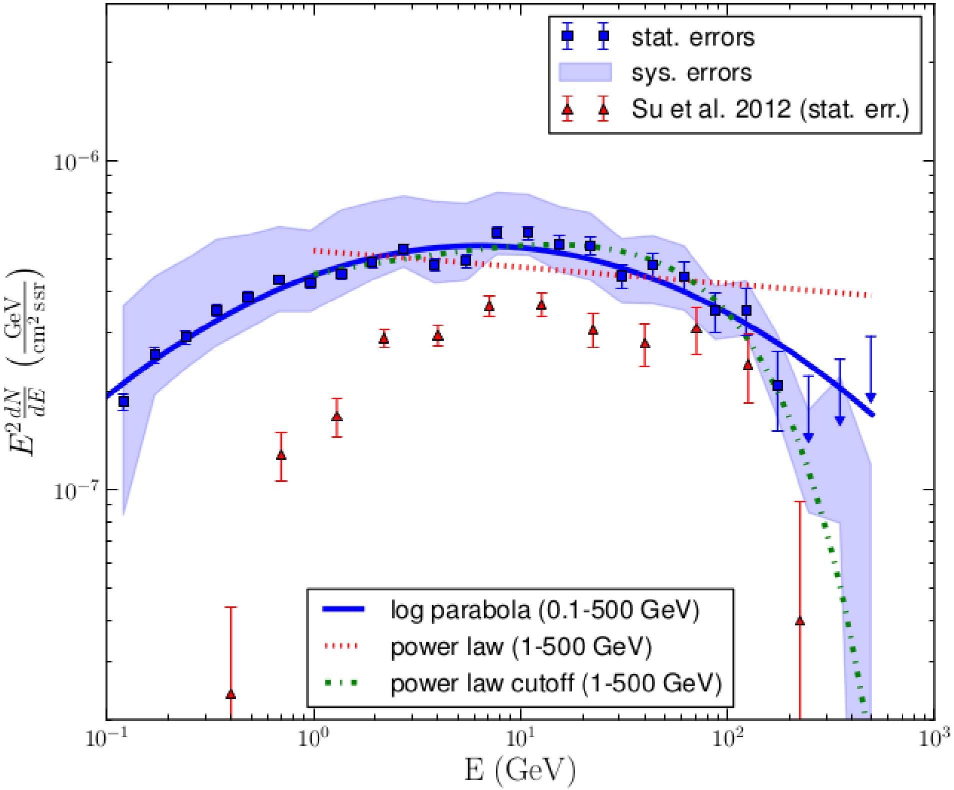
- Constant intensity over emission region
- Normalization shift between Fermi-Lat (blue squares) and
  Su et al. (red triangles):
  - different foreground modeling
  - different definition of FB shape template
  - different Galactic plane mask
- If power law spectrum:
  - index:

$$\gamma = 1.87 \pm 0.02[\text{stat}]^{+0.14}_{-0.17}[\text{syst}]$$

  - exponential cutoff:

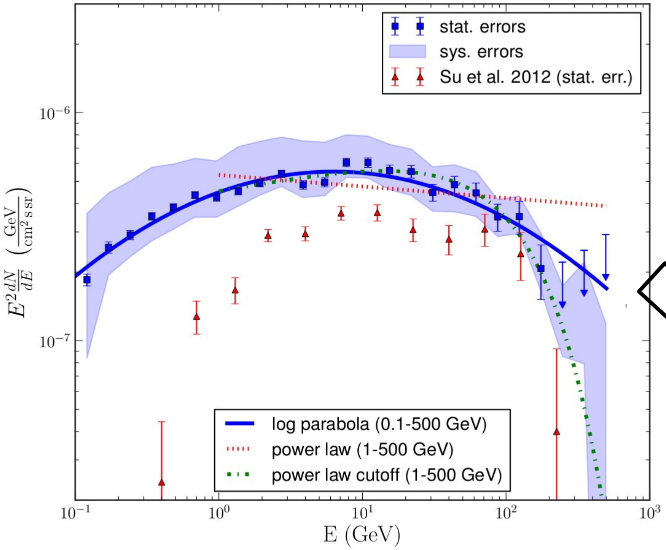
$$E_{cut} = 113 \pm 19[\text{stat}]^{+45}_{-53}[\text{syst}]\ \text{GeV}$$


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.



Fermi-LAT collaboration,The Astrophysical Journal, Volume 793, Issue 1, article id. 64, 34 pp. (2014)

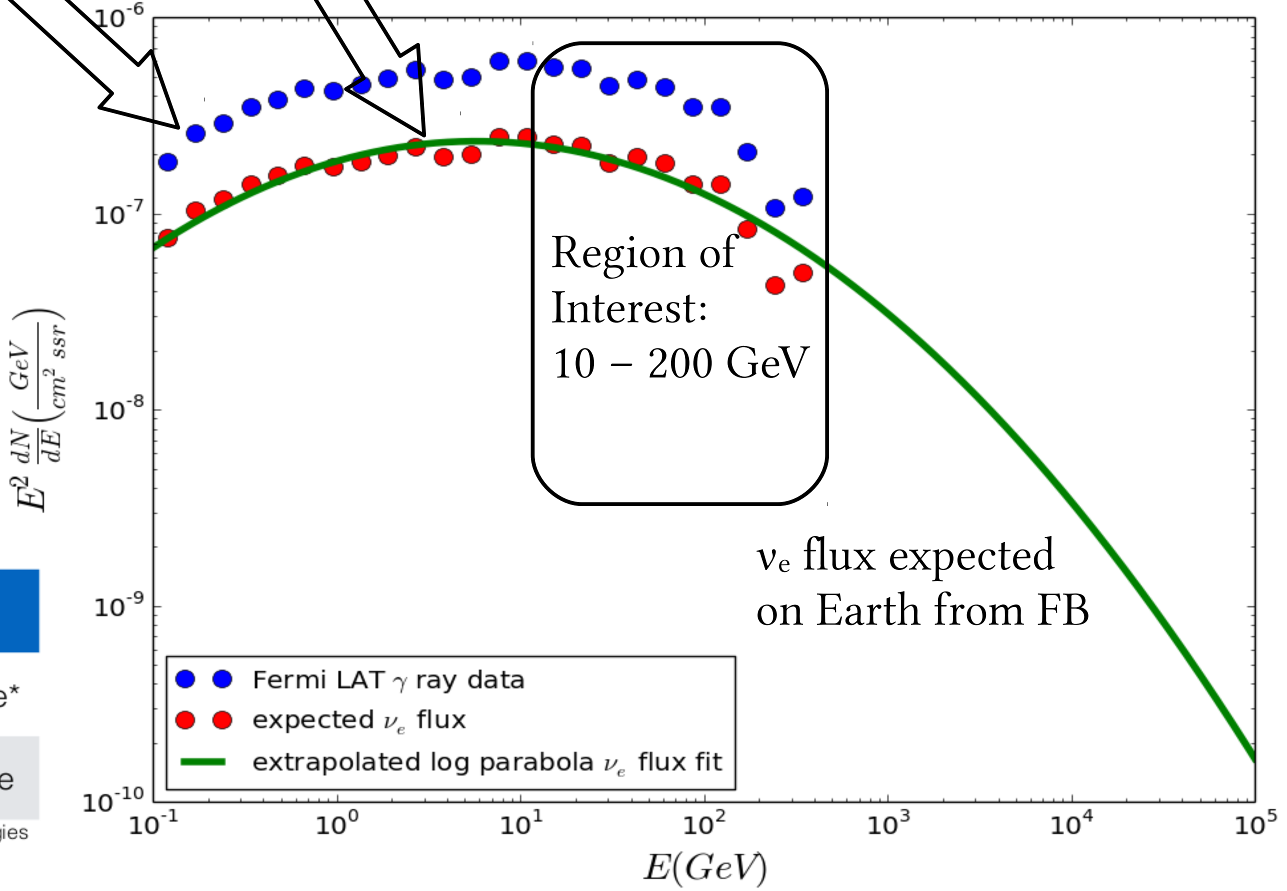
Signal spectrum estimation



$$\Phi_{\nu_e} = \Phi_{\nu_\mu} = \Phi_\gamma \cdot (0.211 + 0.195)$$

ν_μ $\bar{\nu}_\mu$

Neutrino flux calculation from:
F. L. Villante et al., Phys. Rev. D 78, (2008) 103007



Region of Interest: 10 – 200 GeV

ν_e flux expected on Earth from FB

Flux will be tripled, when other neutrino flavors are included due to oscillations [1:1:1].

	ν_e	ν_μ	ν_τ
CC	cascade	track	cascade*
NC	cascade	cascade	cascade

*at low energies

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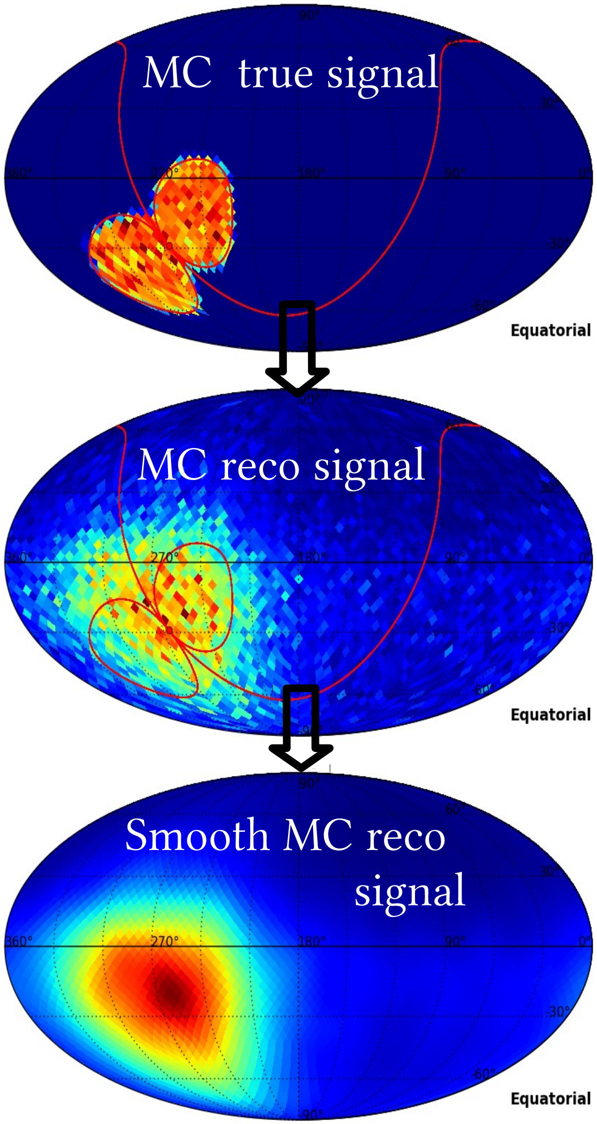
Signal expectation

- Simulated Monte Carlo events are weighted with expected ν - flux from FB per flavor and moved into the FB area
- Reconstruction of the signal
- Smoothing of the signal for a more realistic Probability Density Function (PDF)

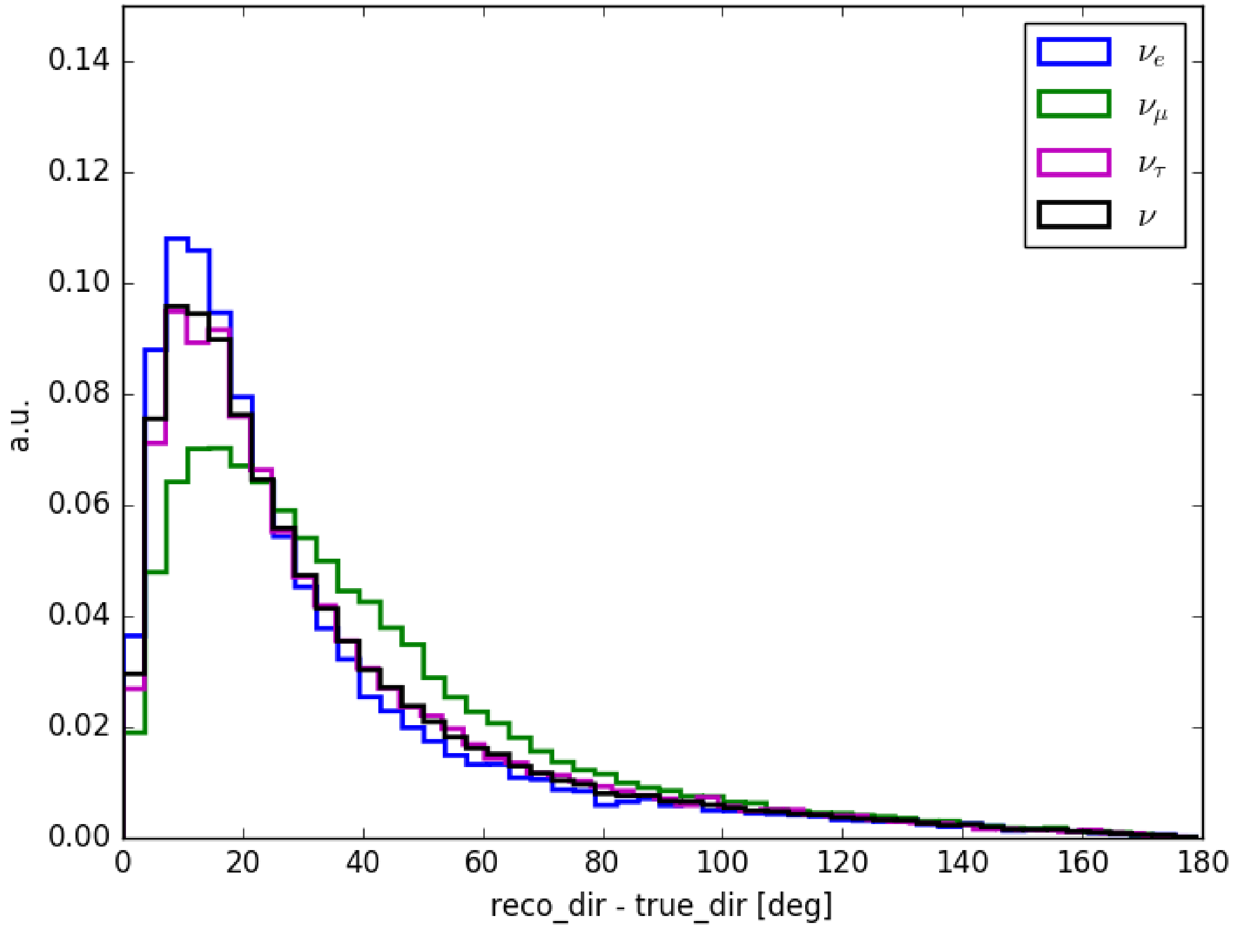


Angular resolution

Median	90% percentile
24°	78°

Fermi Bubbles: 50° long
40° wide

The muon angular resolution is worse because this is a low energy cascade event selection, which misidentifies the worst muon tracks as cascades.



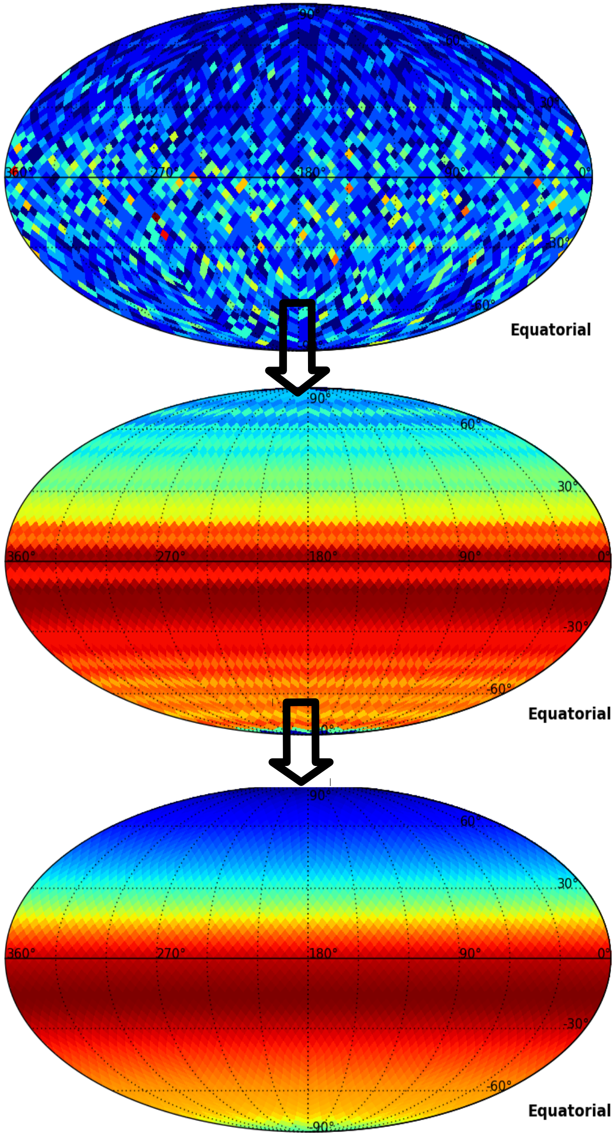
Background expectation

One year of observed data
form May 2011 to May 2012

- scrambled in right ascension
  to avoid the view of the real directions

- Average over right ascension
  for all declinations

- Smoothing of the data
  for a more realistic PDF



Hypothesis Testing

- Shaped Maximum Likelihood Analysis
- Construct a likelihood function using skymap PDFs
- Include possibility of signal in the data background

$$\mathcal{L}(b) = \prod_{i=1}^{n_{obs}} f(b_i|\mu)$$

healpy bins

signal events

$$f(b|\mu) = \frac{\mu}{n_{obs}} f_S(b) + \left(1 - \frac{\mu}{n_{obs}}\right) f_B(b|\mu)$$

signal PDF

background PDF

$$f_B(b|\mu) = f_{sd}(b|\mu) - \frac{\mu}{n_{obs}} f_{ss}(b)$$

scrambled data PDF

scrambled signal PDF

- Using likelihood ratio as a test statistic as in the method developed by Feldman and Cousins

likelihood of signal events

$$R(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

likelihood of best fit of signal events

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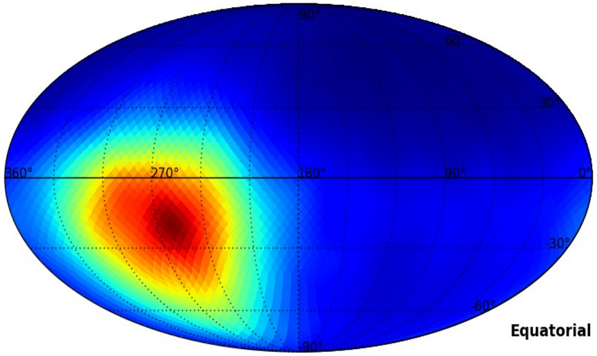
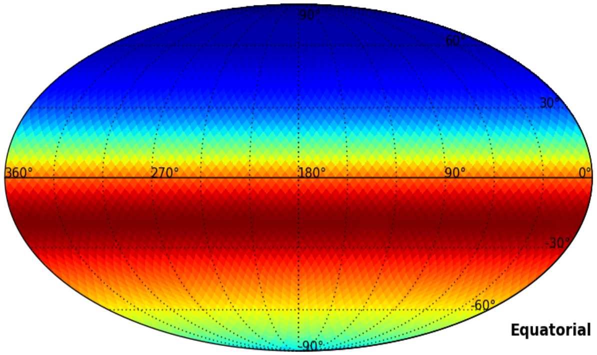
Fermi Bubbles PDFs

$f_S(b)$



MC reconstructed signal

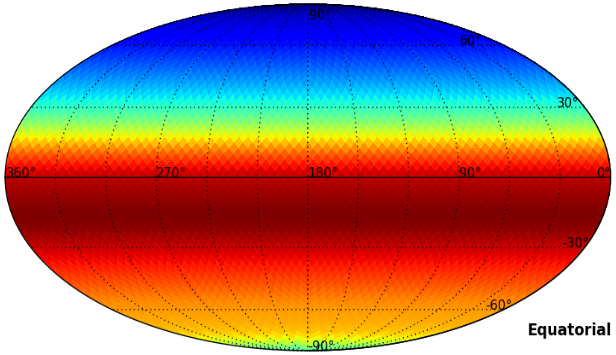
$f_{ss}(b)$



MC reconstructed
scrambled signal

same treatment as BG

$f_{sd}(b|\mu)$



Data scrambled
background

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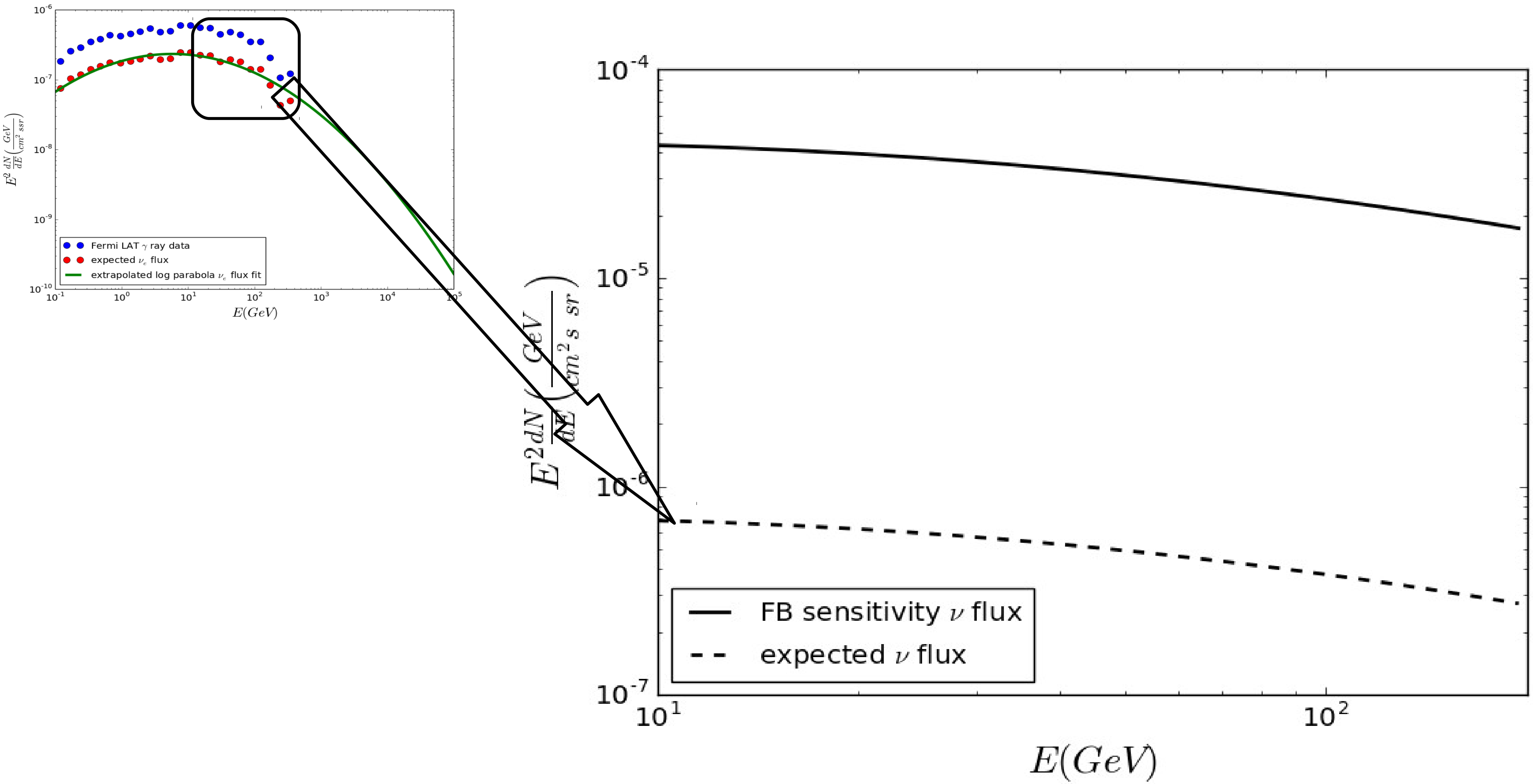
Fermi Bubble Sensitivity



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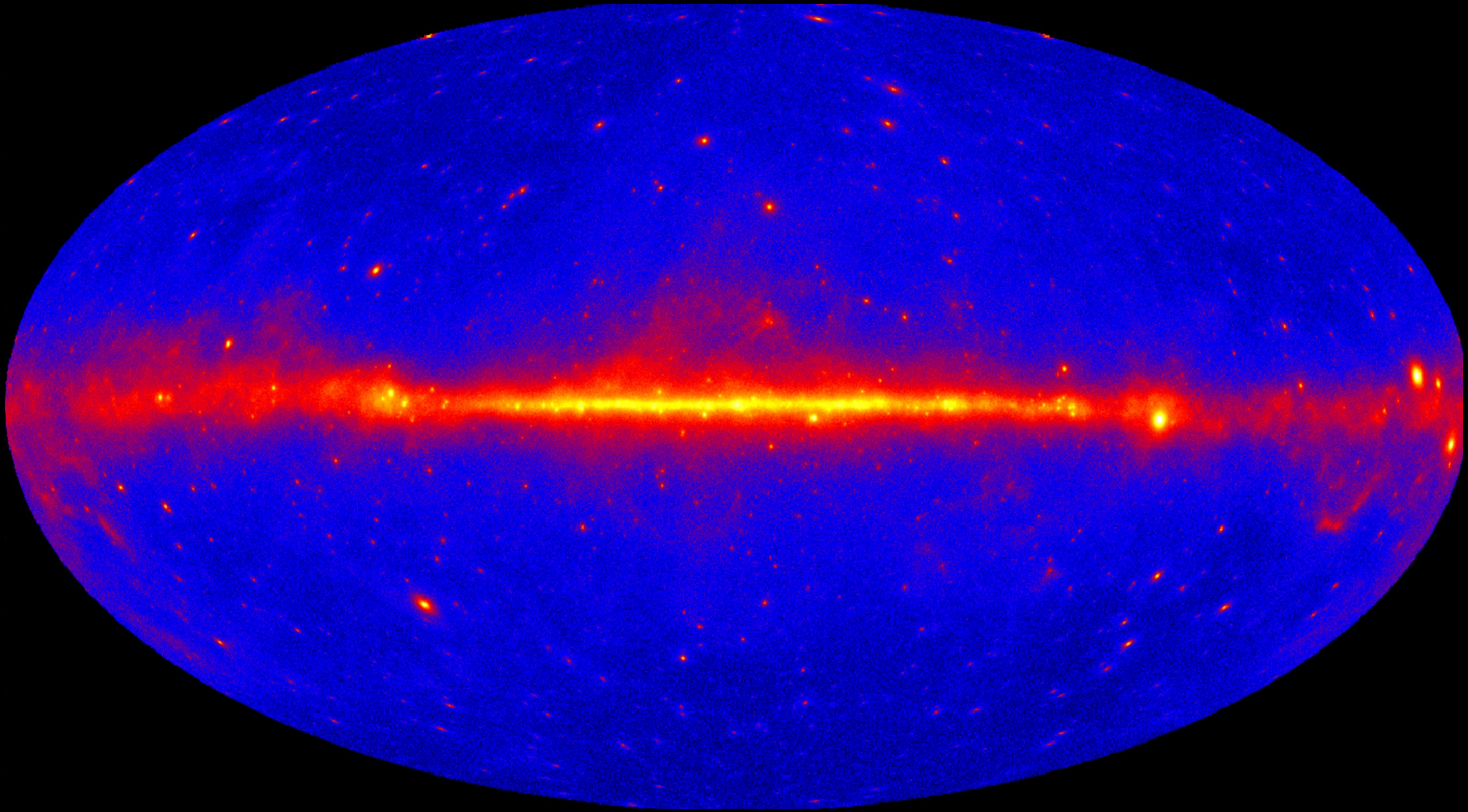
γ-ray skymap



Credit: NASA/DOE/Fermi LAT Collaboration

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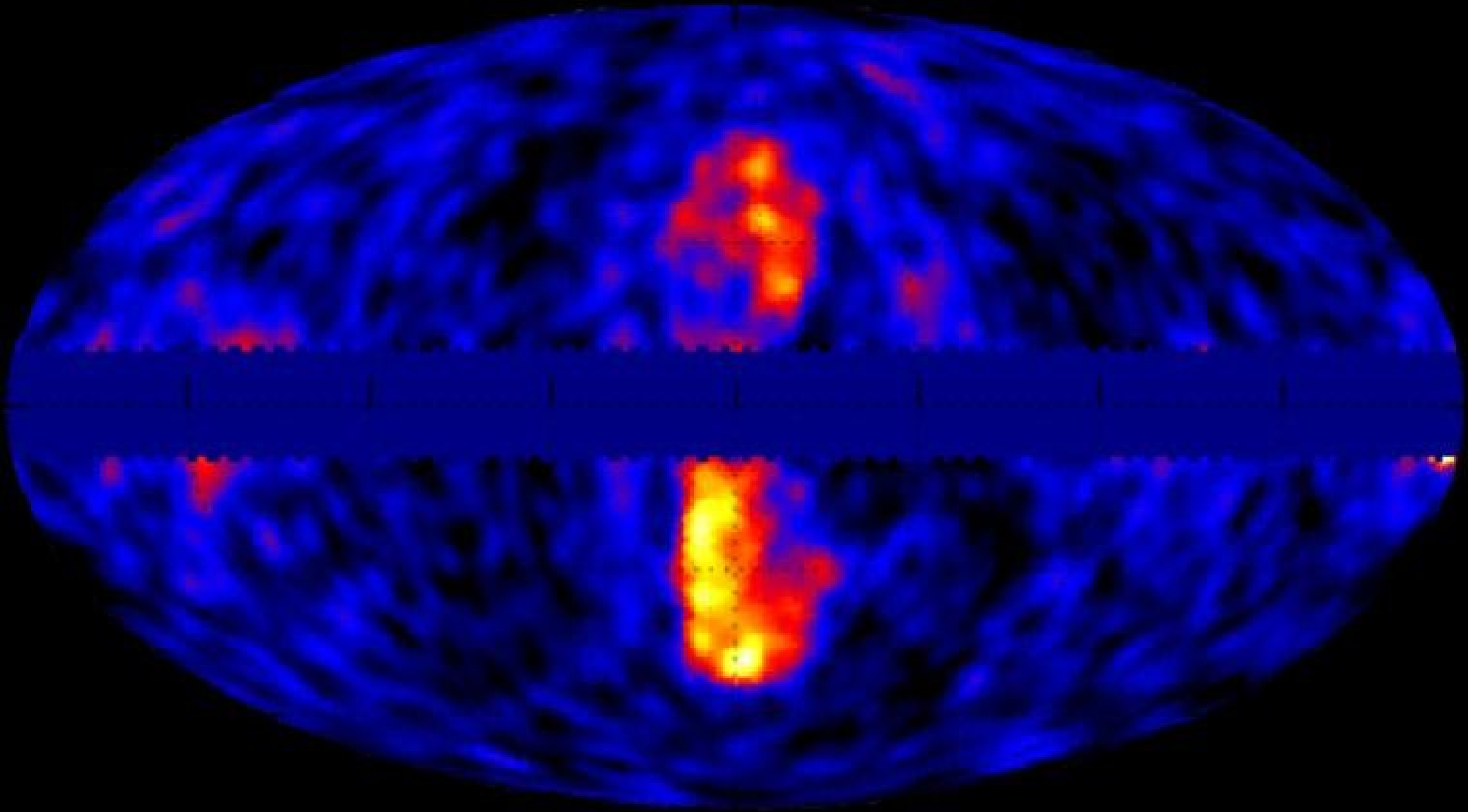
Too much radiation



Credit: NASA/DOE/Fermi LAT Collaboration

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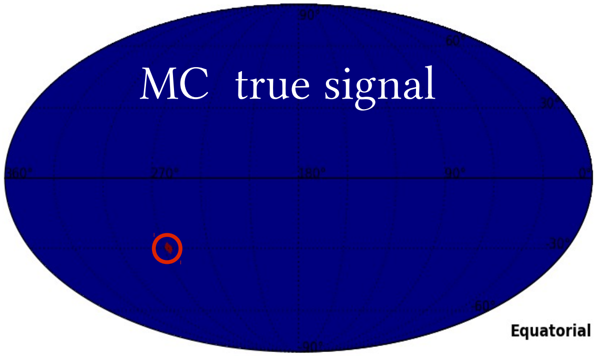
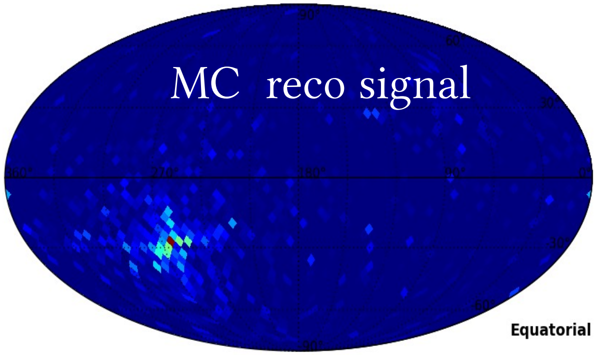
Neutrinos from the Galactic Center?

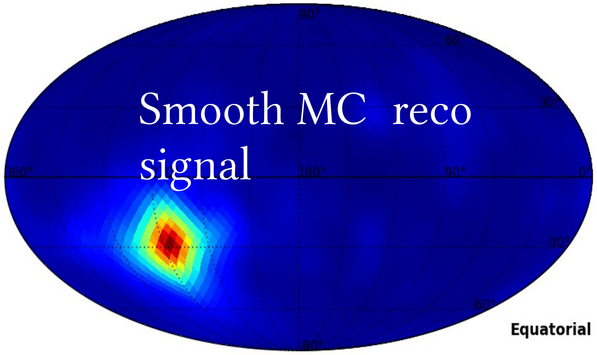
- Using same neutrino flux expectation as for the Fermi Bubbles
- Events distributed within 0.5 degrees radius around the Galactic Center



- Reconstruction of the signal



- Smoothing of the signal for a more realistic Probability Density Function (PDF)



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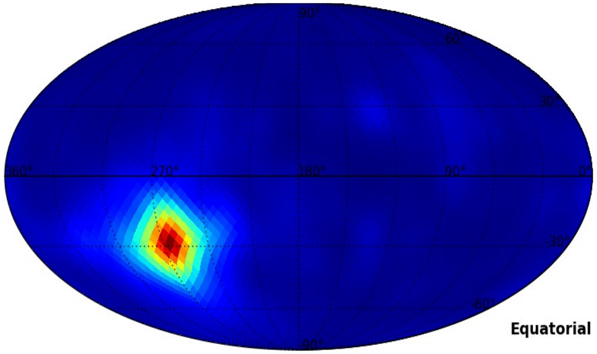
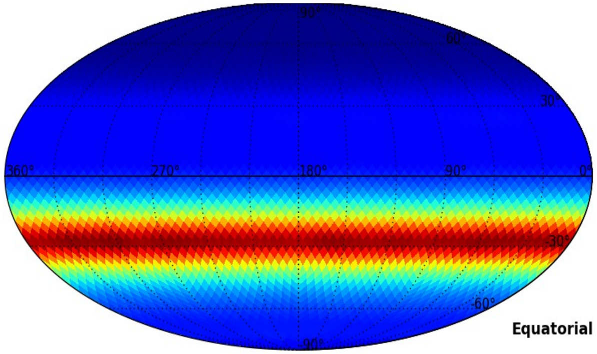
Fermi Bubbles PDFs

$f_S(b)$



MC reconstructed signal

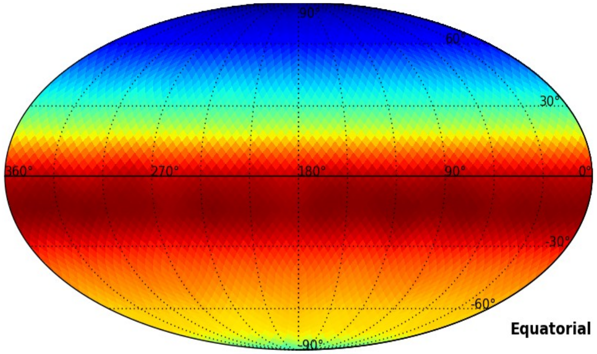
$f_{ss}(b)$



MC reconstructed
scrambled signal

same treatment as BG

$f_{sd}(b|\mu)$



Data
scrambled background

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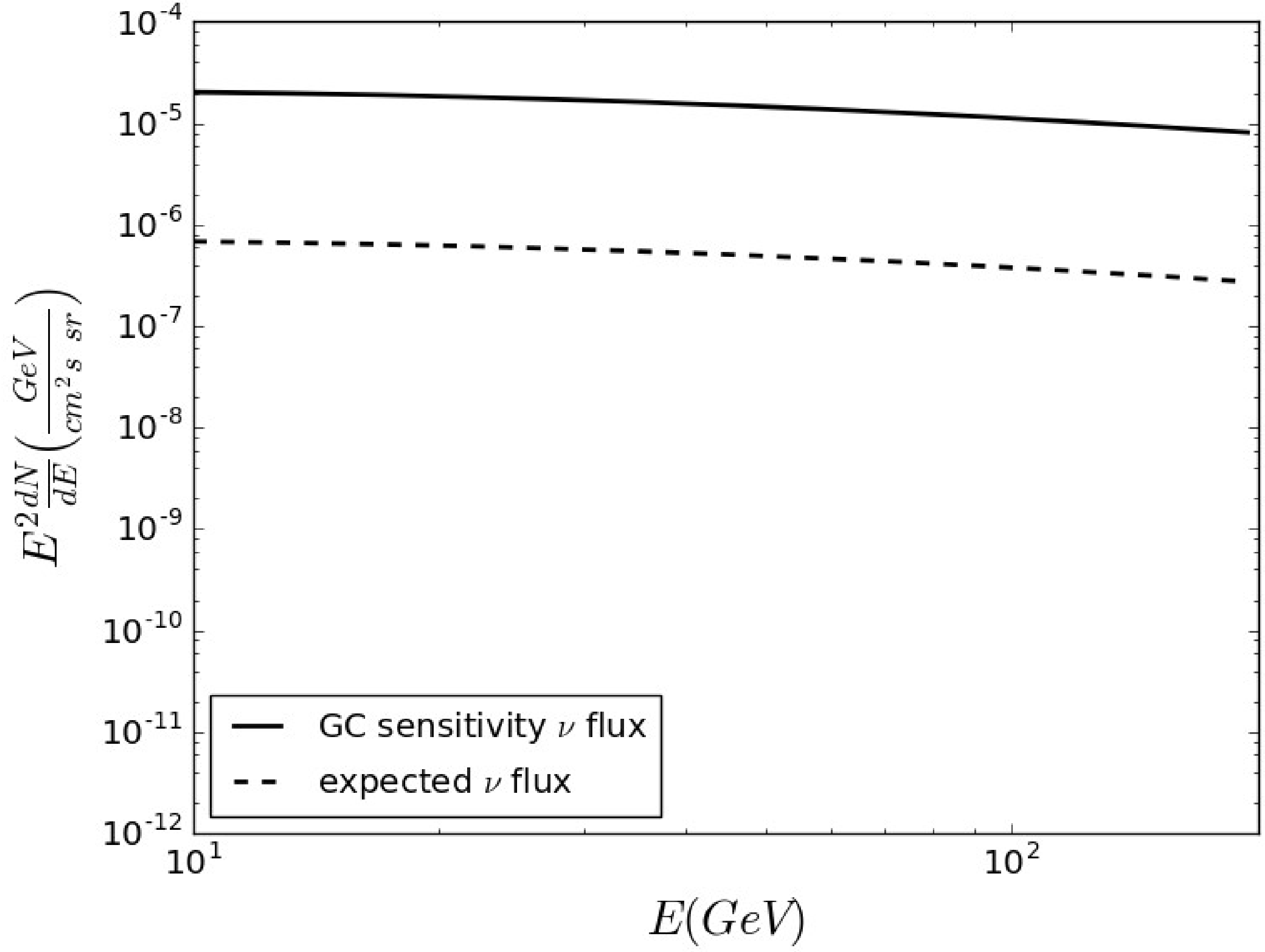
Galactic Center Sensitivity



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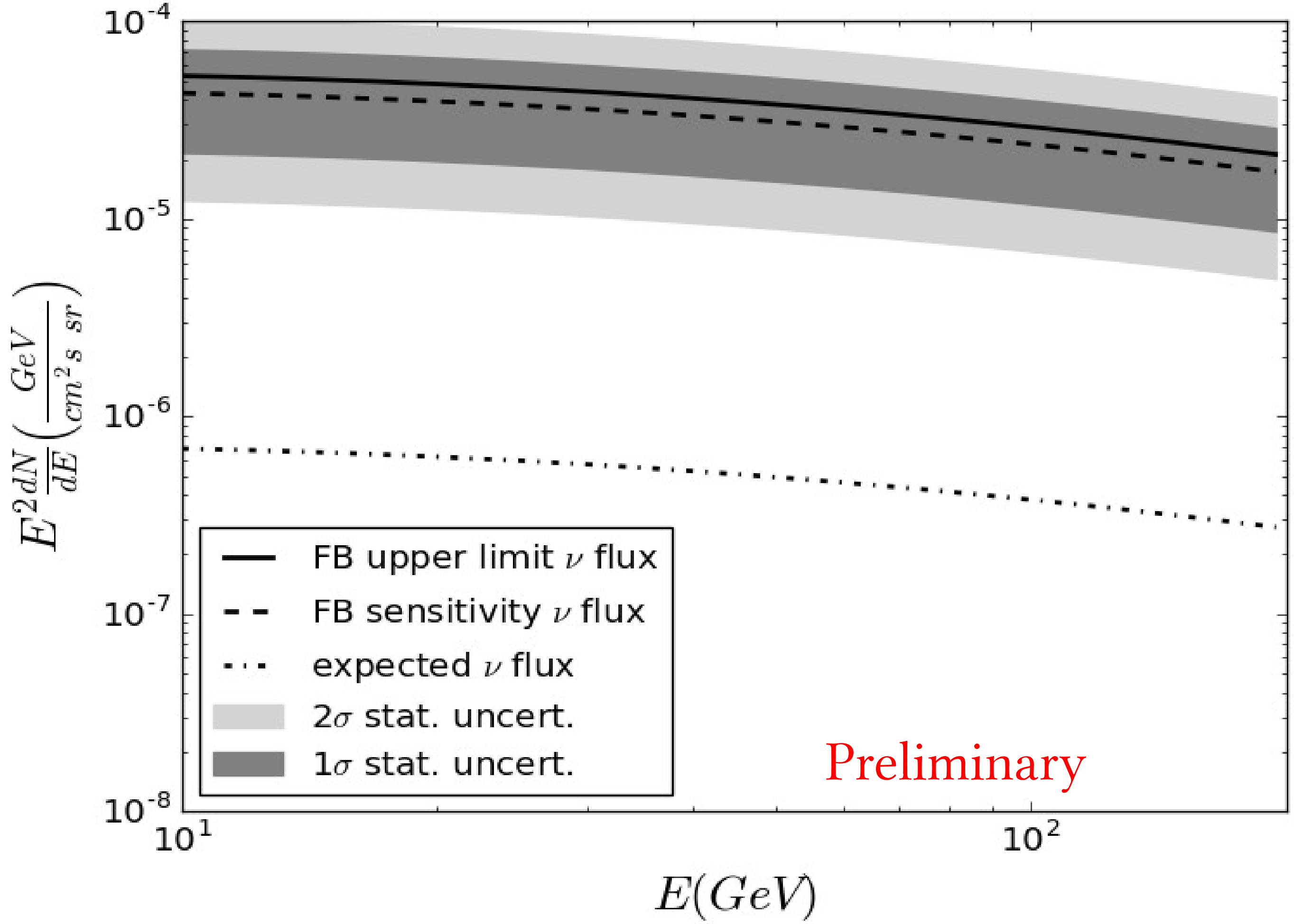
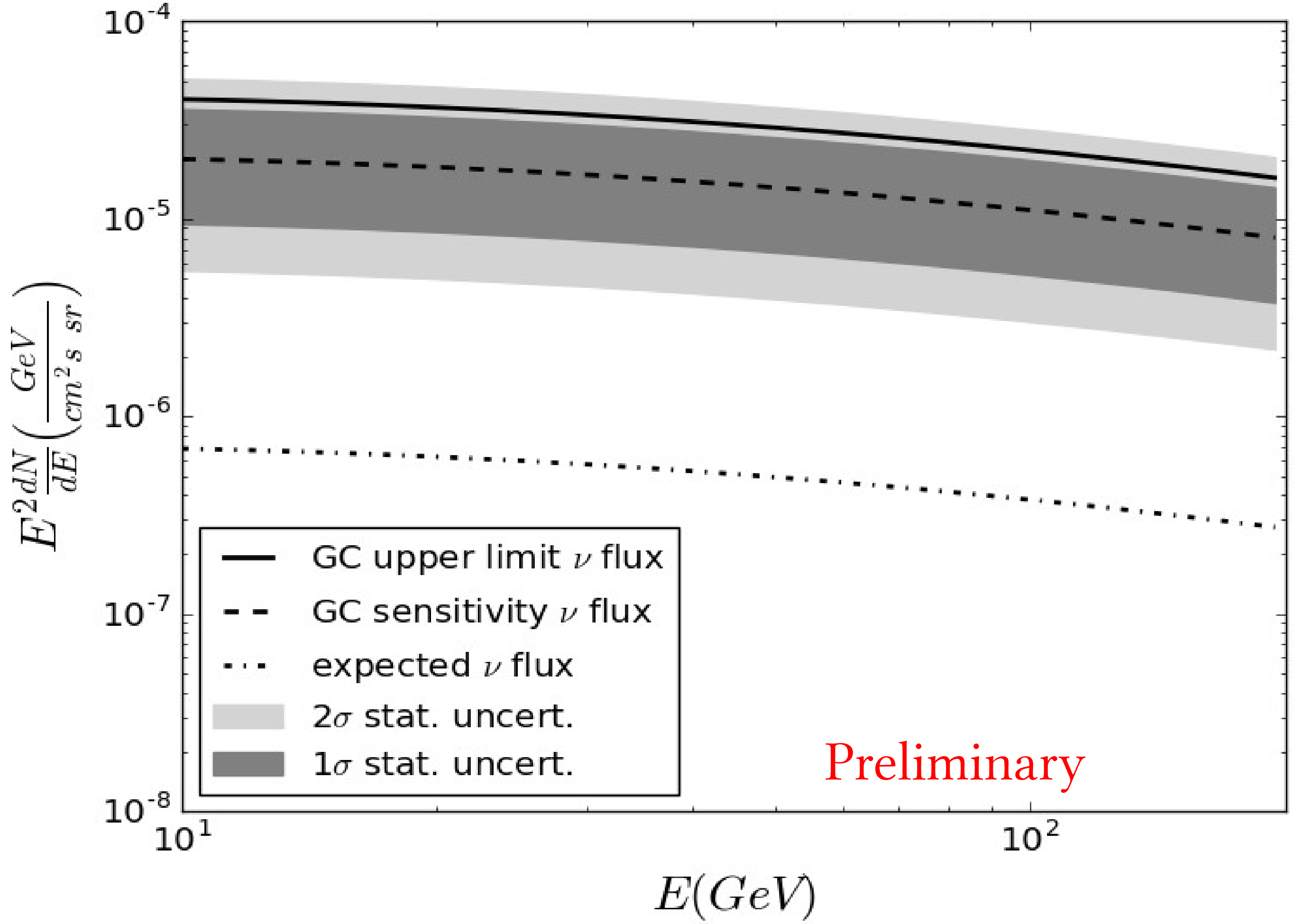
Fermi Bubbles
unblinded results



Upper limit 0.3σ above sensitivity

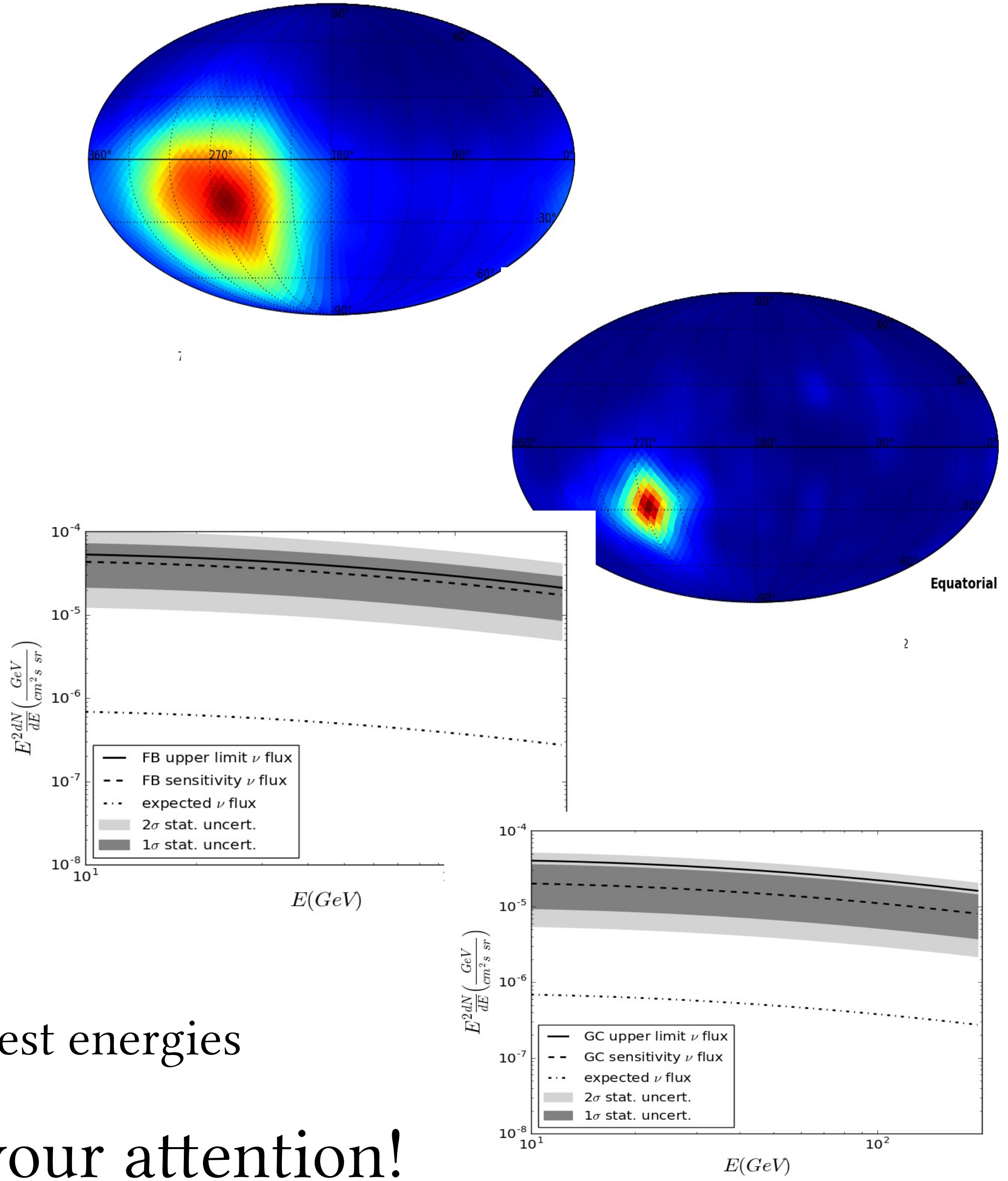
Galactic Center
Unblinded results



Upper limit 1.3σ above sensitivity

Conclusion and Outlook

- First Analysis in IceCube
  - probing the Fermi Bubbles
  - probing the Galactic Center without Dark Matter expectation
- Results compatible with background
- Results consistent with H. Taavolas Galactic Halo analysis
- Upper limits for FB and GC
- Possibilities for improvement
  - Using more available years of data
  - Updated ice model
  - Better understanding of noise at lowest energies



Thank you for your attention!

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