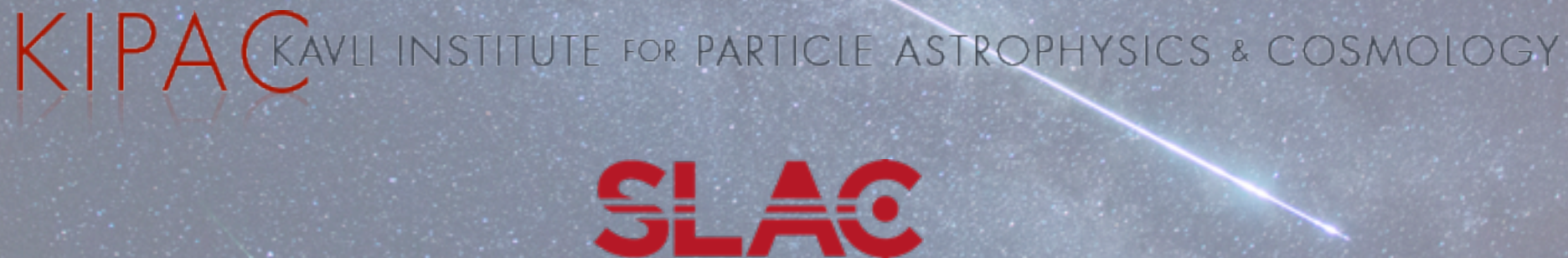


# Galactic interstellar $\gamma$ -ray emission

**Luigi Tibaldo**  
**[ltibaldo@slac.stanford.edu](mailto:ltibaldo@slac.stanford.edu)**



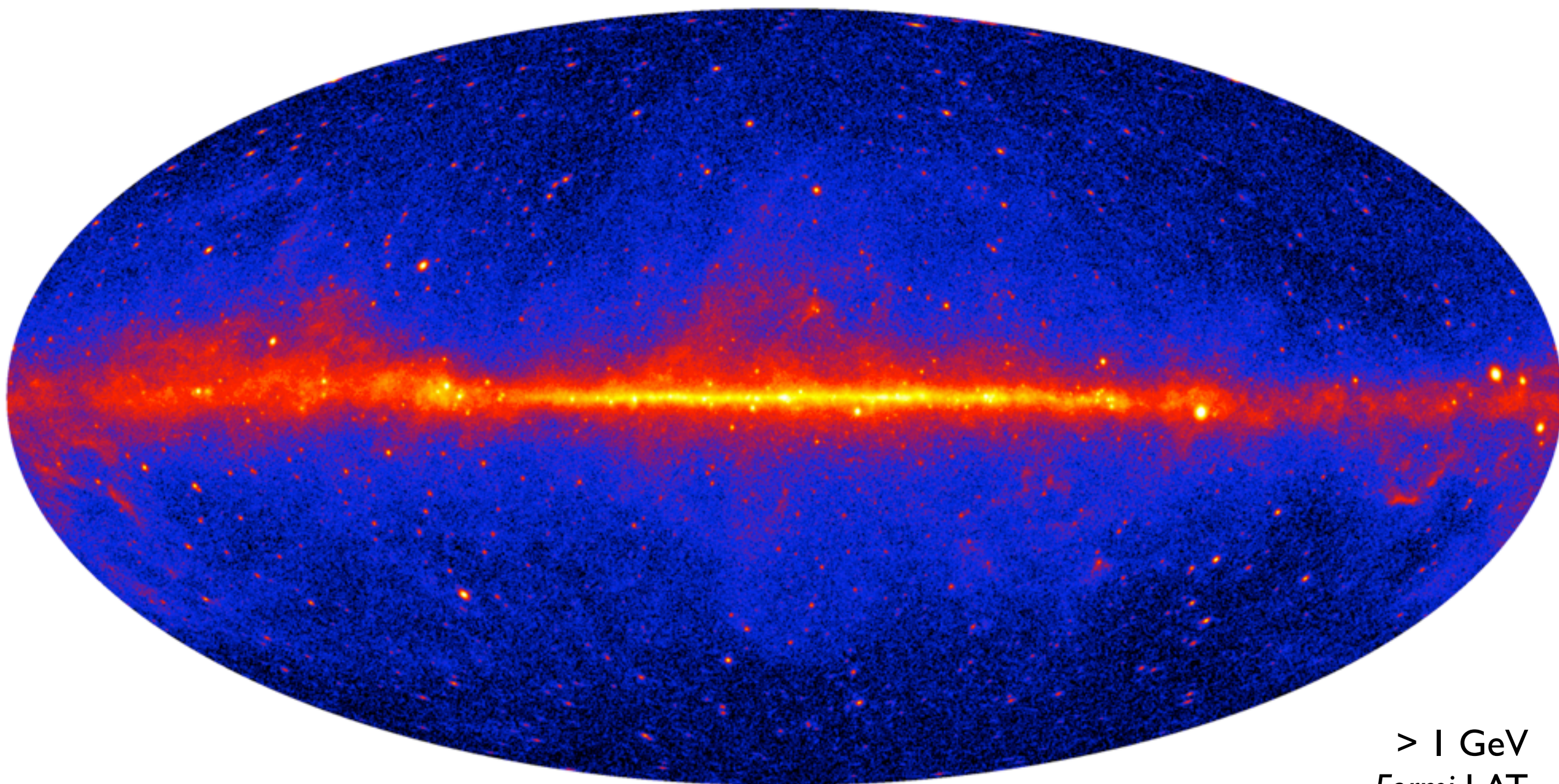
**Astroparticle Physics**  
**June 25 2014**



# Outline

- Introduction: on the physics of interstellar  $\gamma$ -ray emission
- Recipe(s) to cook an interstellar emission model
- Observations and interpretation
- (My) top 3 for the coming years

# The sky in $\gamma$ rays



$> 1$  GeV  
*Fermi* LAT  
2008-2013

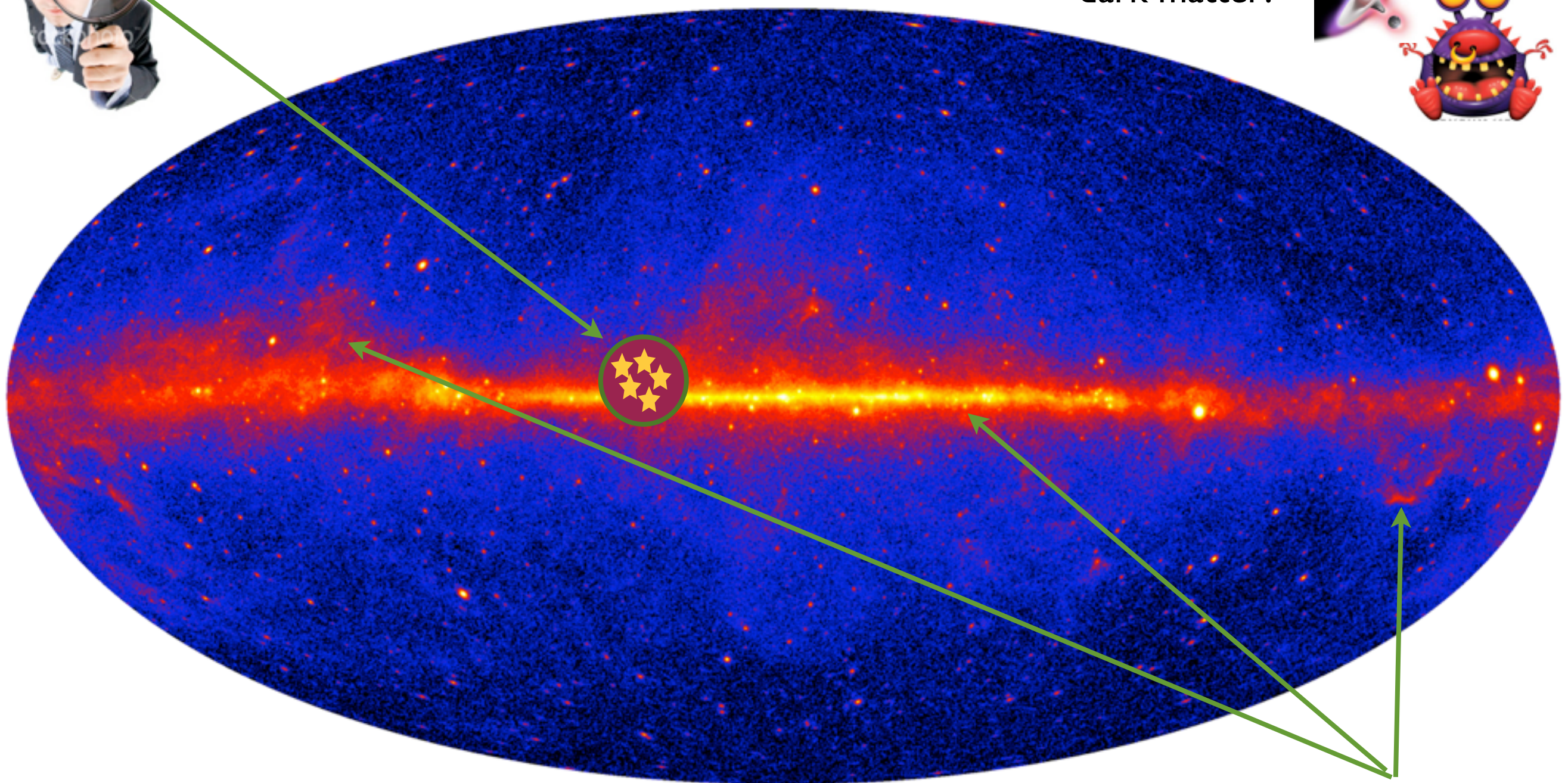
NASA/DoE/*Fermi*-LAT collaboration



# Diffuse $\gamma$ -ray emission

unresolved  
sources

exotic Physics?  
dark matter?

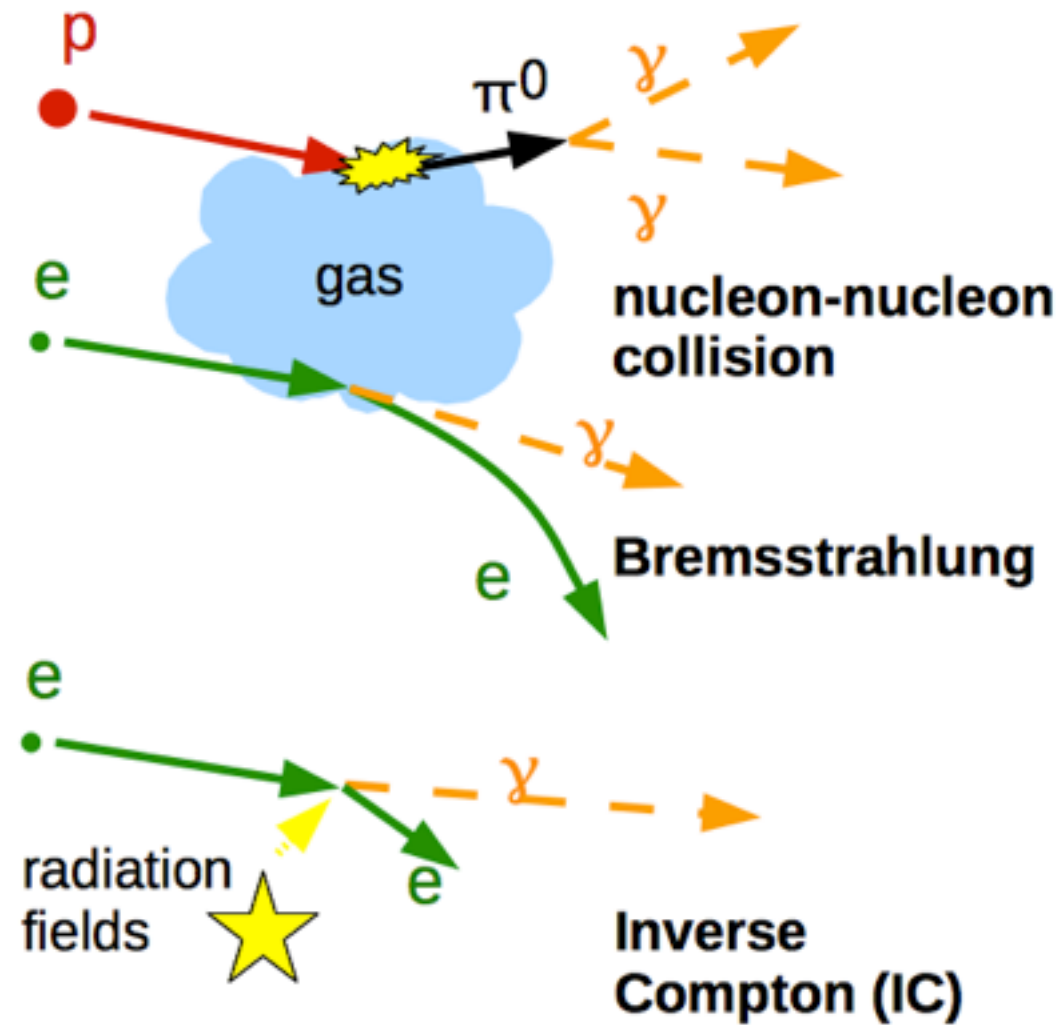


diffuse emission (no individual sources)  
= interstellar + unresolved sources + exotic processes(?)

interstellar emission



# Galactic interstellar $\gamma$ -ray emission



- trace cosmic rays  $\otimes$  gas&radiation fields
- background for sources and other diffuse emissions



# Outline

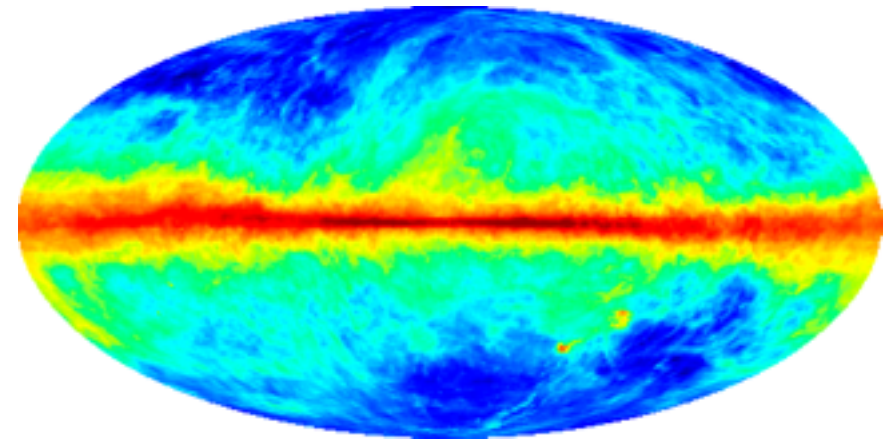
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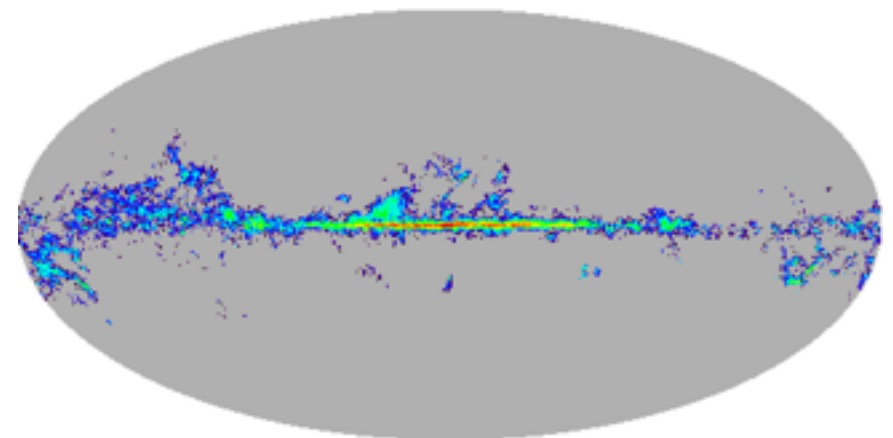
# Ingredients

- CR and target distribution in the Milky Way
  - ─ gas: Doppler shift of lines
- interaction models
  - ─ uncertainties 5-15% for hadronic interactions

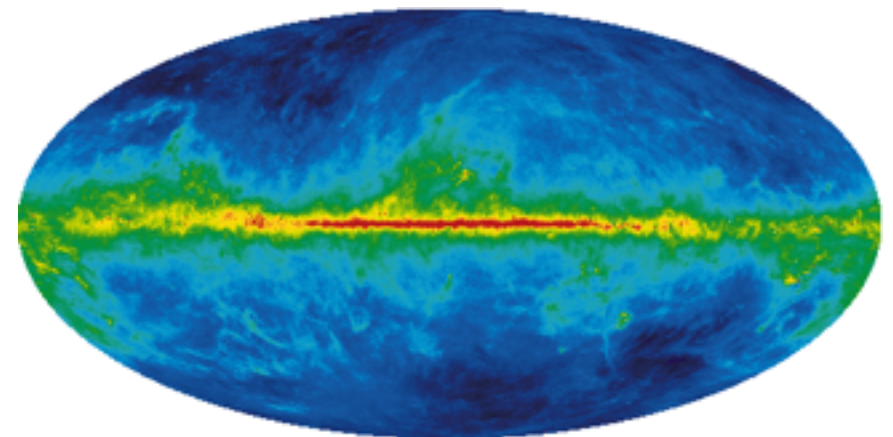
H I: atomic gas



CO: dense molecular gas



dust (also  $\propto$  total gas)

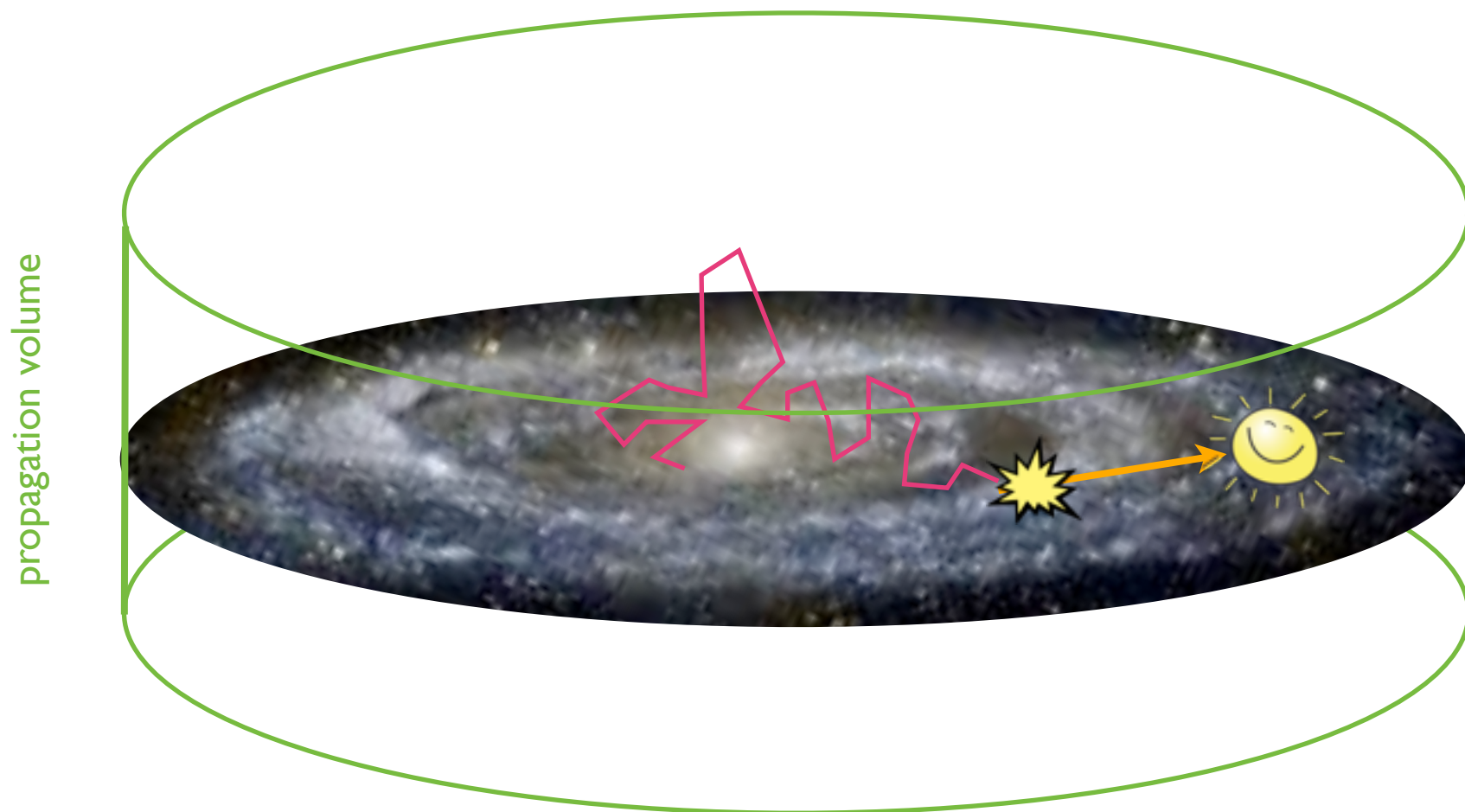


NASA/LAMBDA



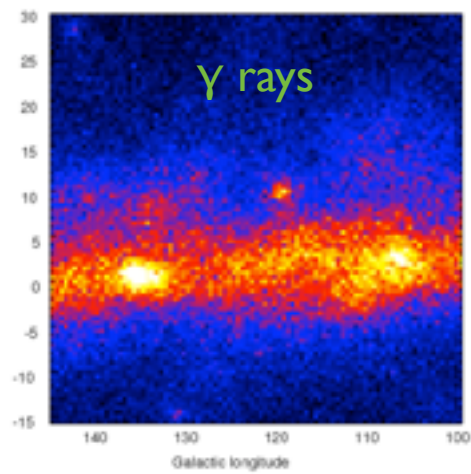
# Recipe I: CR propagation codes

- simplified but realistic model of the Galaxy
- aims at reproducing all related observables at the same time
- GALPROP (Strong, Moskalenko et al.), DRAGON, Picard ...

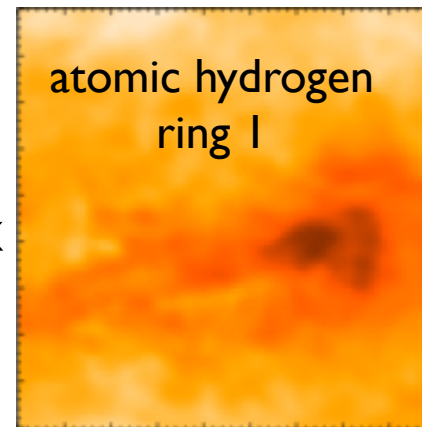




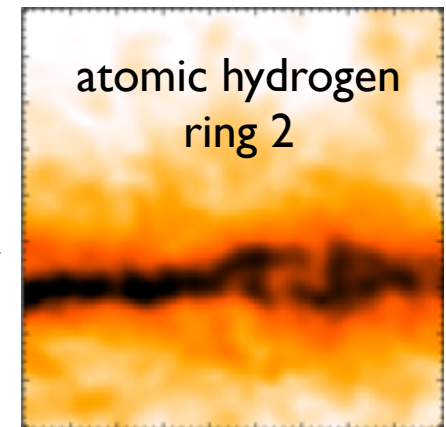
# Recipe 2: templates



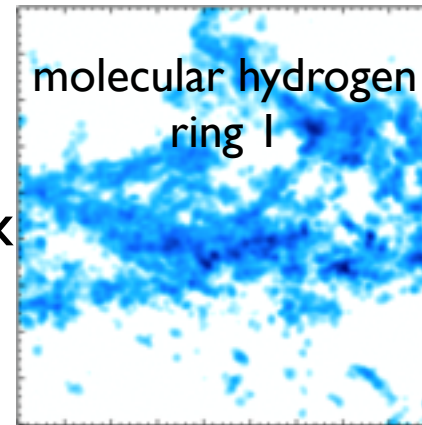
$$= \text{PSF} \oplus \text{exposure} \times [q(\text{H I})_1 \times$$



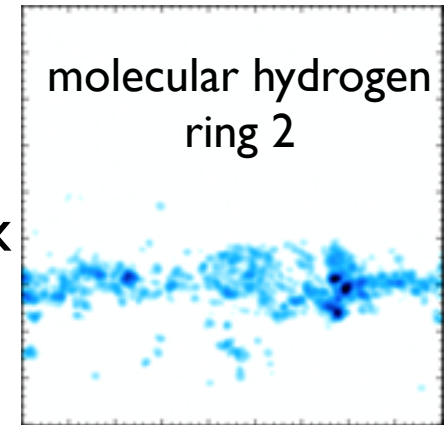
$$+ q(\text{H I})_2 \times$$



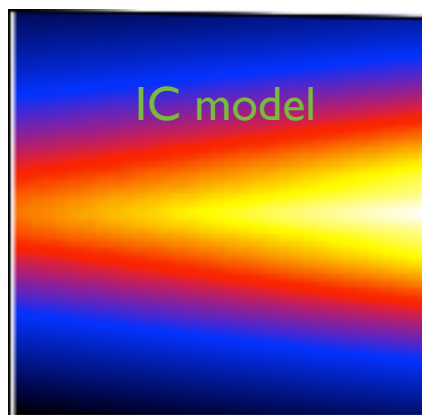
$$+ q(\text{CO})_1 \times$$



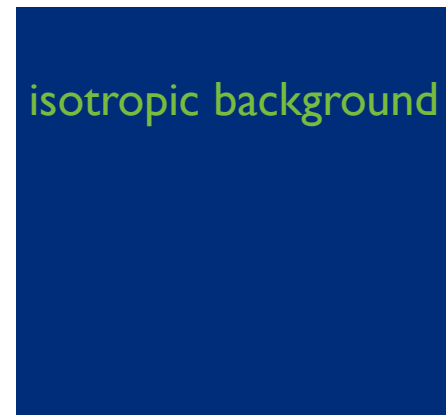
$$+ q(\text{CO})_2 \times$$



$$+ \alpha_{\text{IC}} \times$$



$$+ I_{\text{iso}} \times$$



$$+ \text{sources}]$$



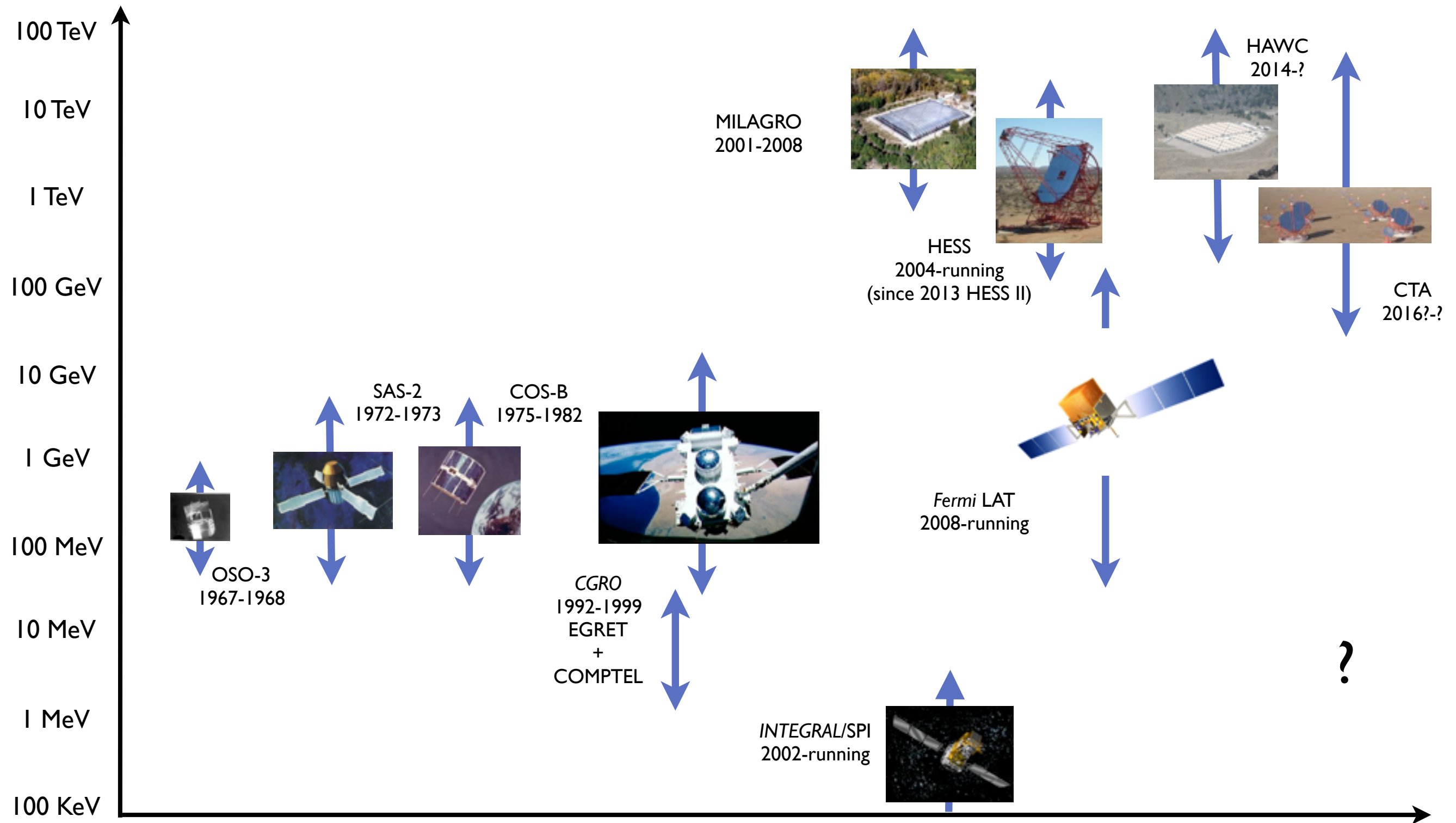


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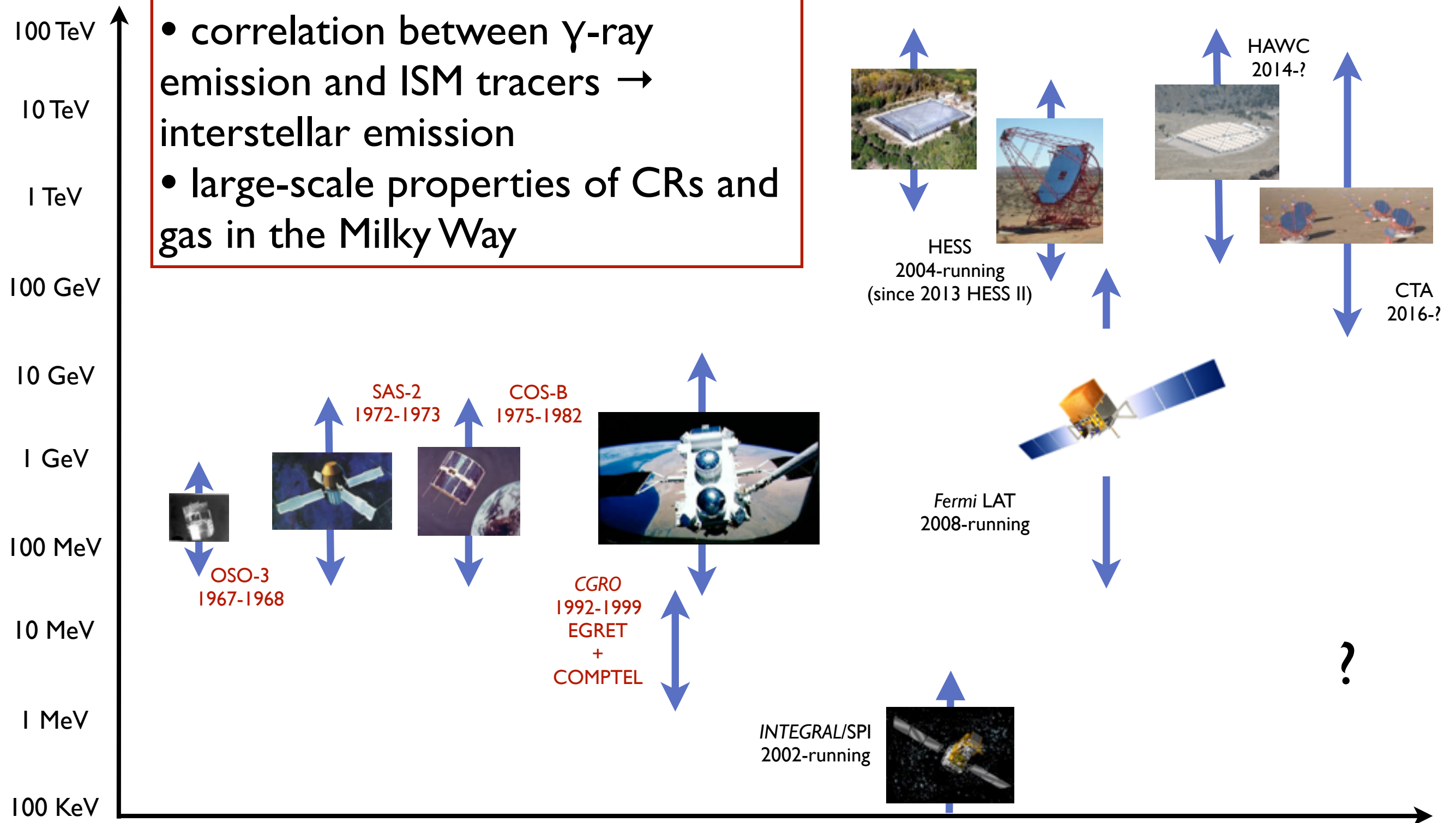
# A bit of history





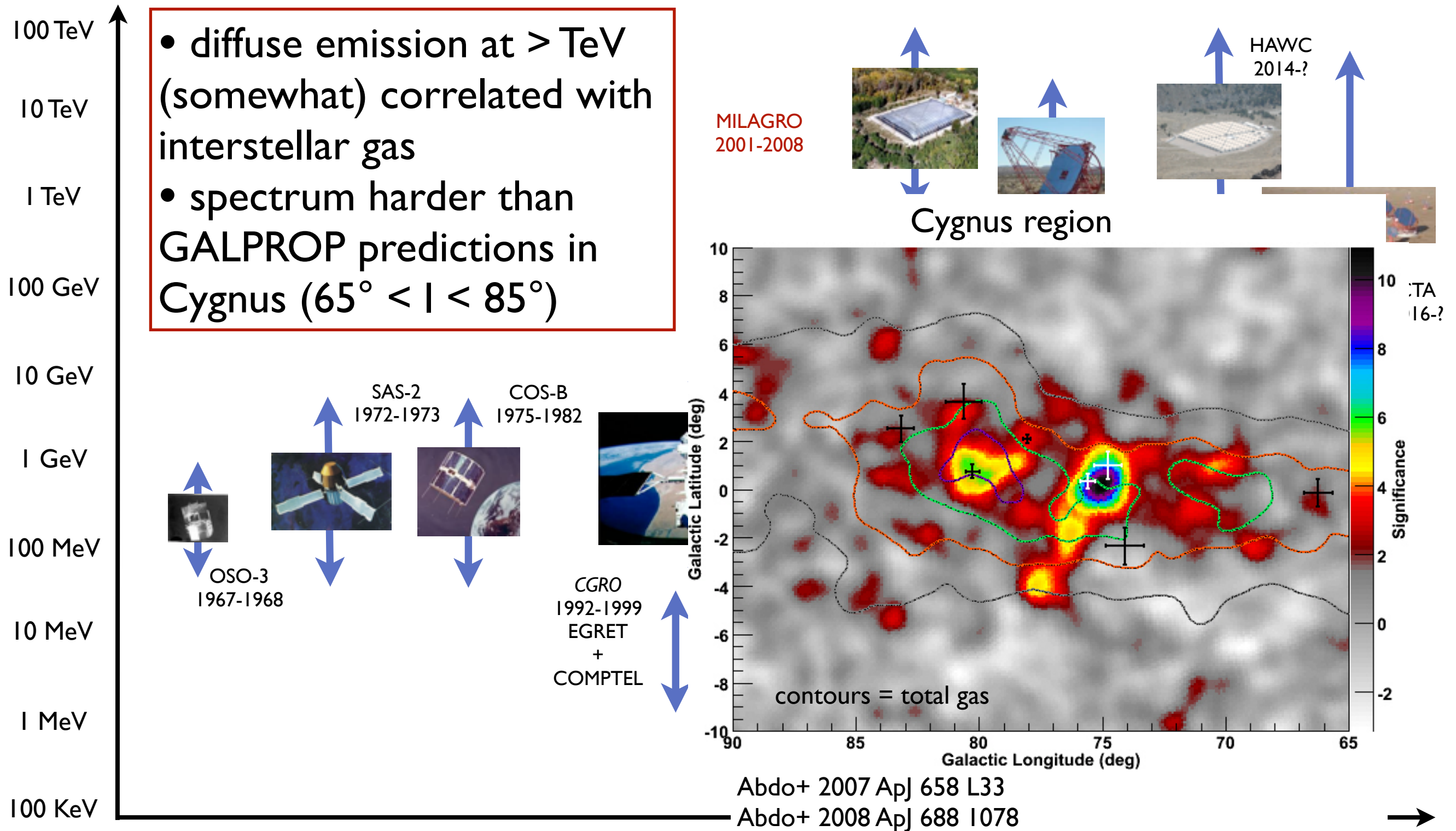
# 20<sup>th</sup> century

- correlation between  $\gamma$ -ray emission and ISM tracers  $\rightarrow$  interstellar emission
- large-scale properties of CRs and gas in the Milky Way



# MILAGRO

- diffuse emission at  $> \text{TeV}$  (somewhat) correlated with interstellar gas
- spectrum harder than GALPROP predictions in Cygnus ( $65^\circ < l < 85^\circ$ )



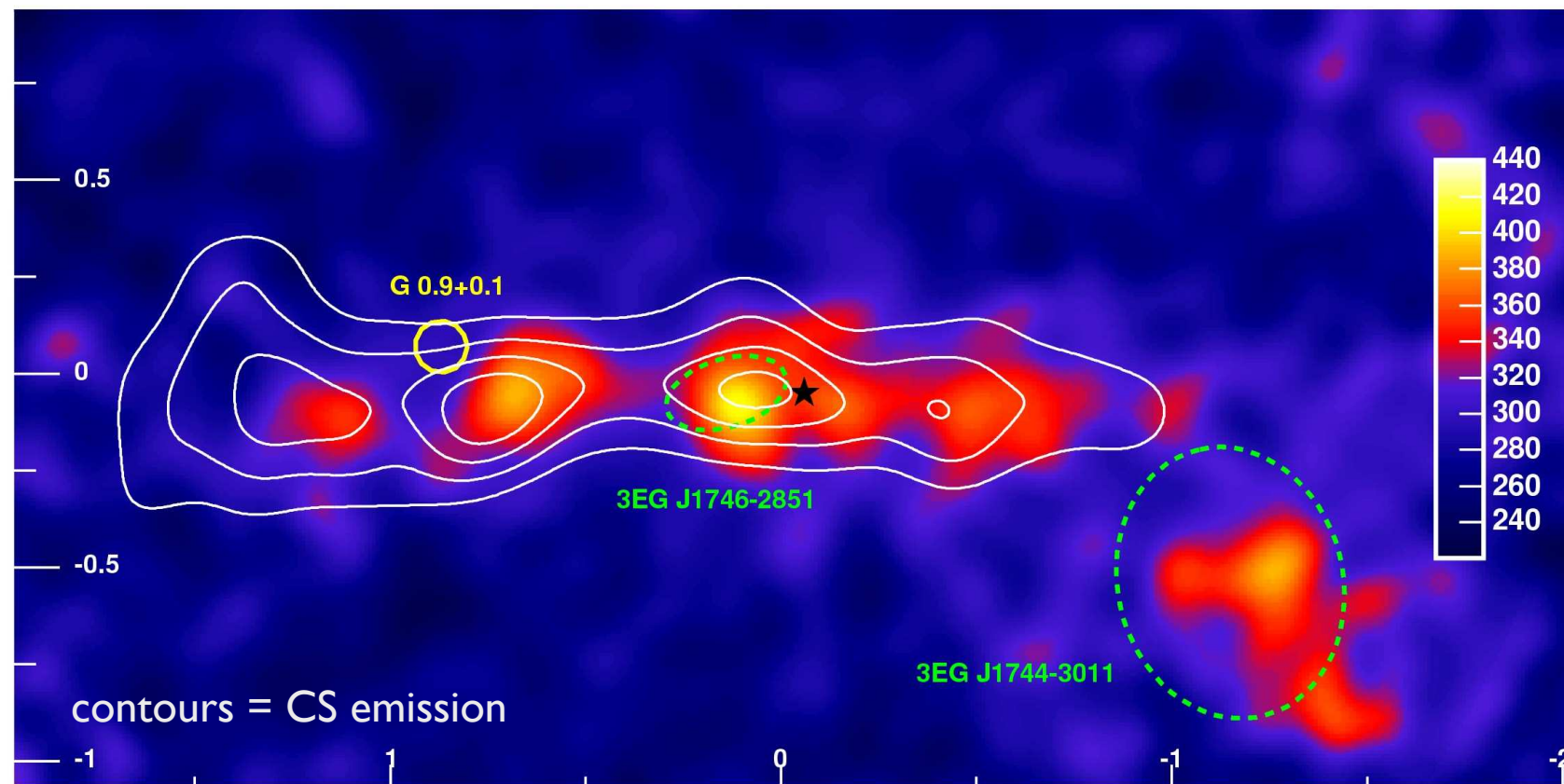
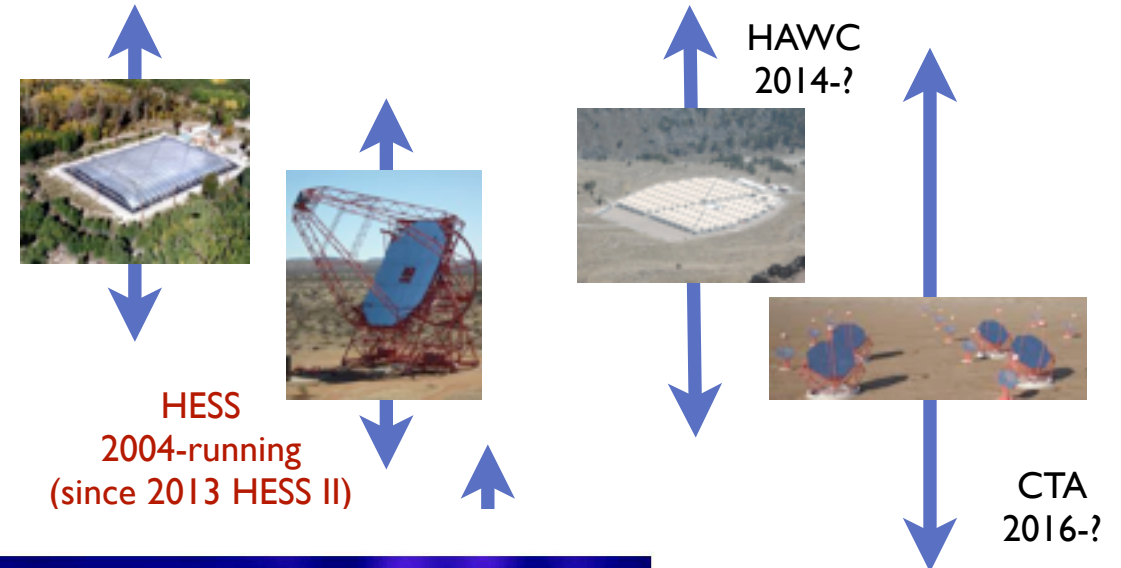


# HESS

- diffuse emission  $> 100$  GeV from Galactic ridge and around massive-star clusters
- spectrum harder than from local CRs

Galactic ridge

GRO 2008

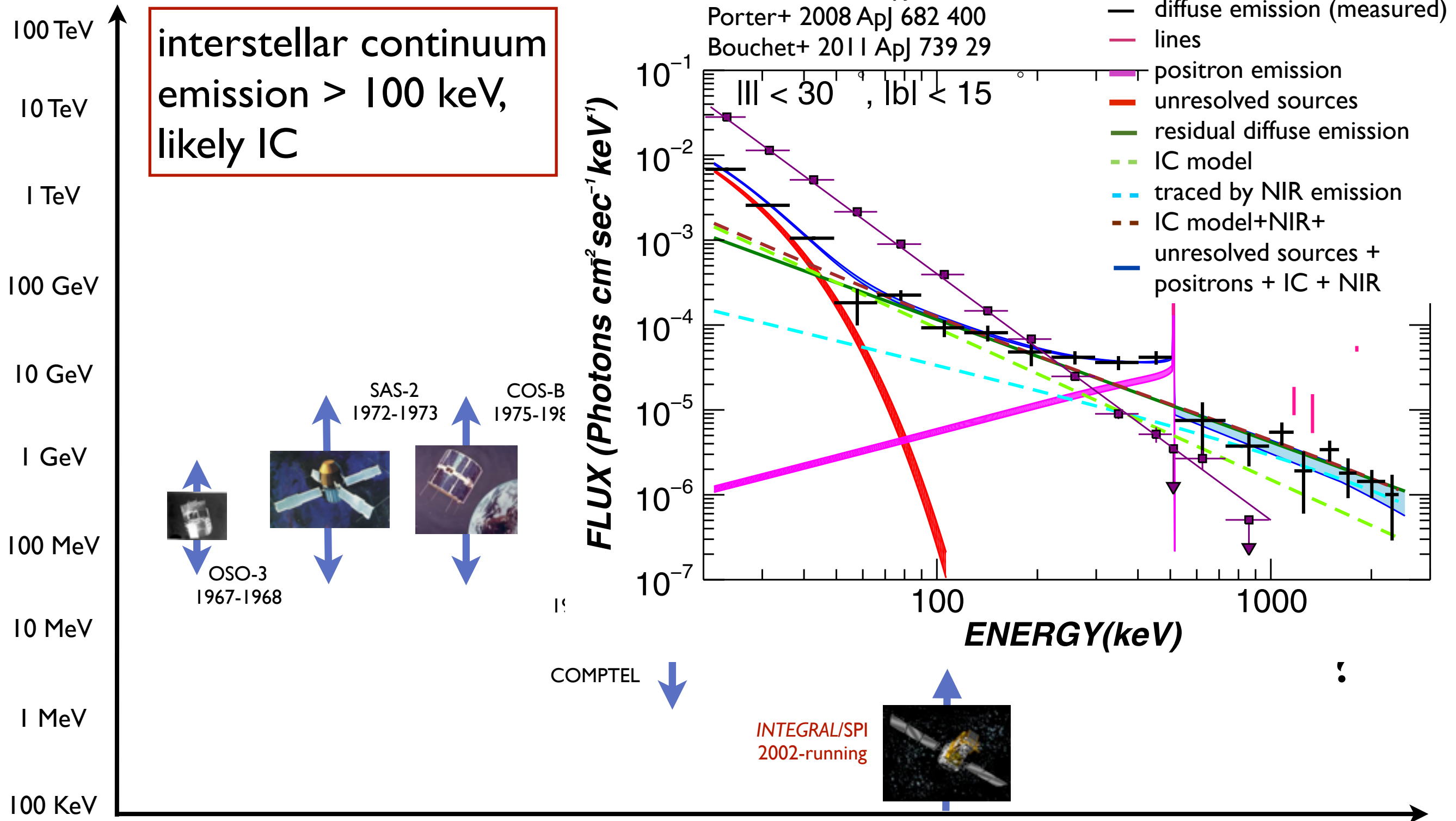


HESS collaboration 2006 Nature 439 695  
 HESS collaboration 2011 A&A 525 A46  
 HESS collaboration 2012 A&A 537 A114

?

# INTEGRAL

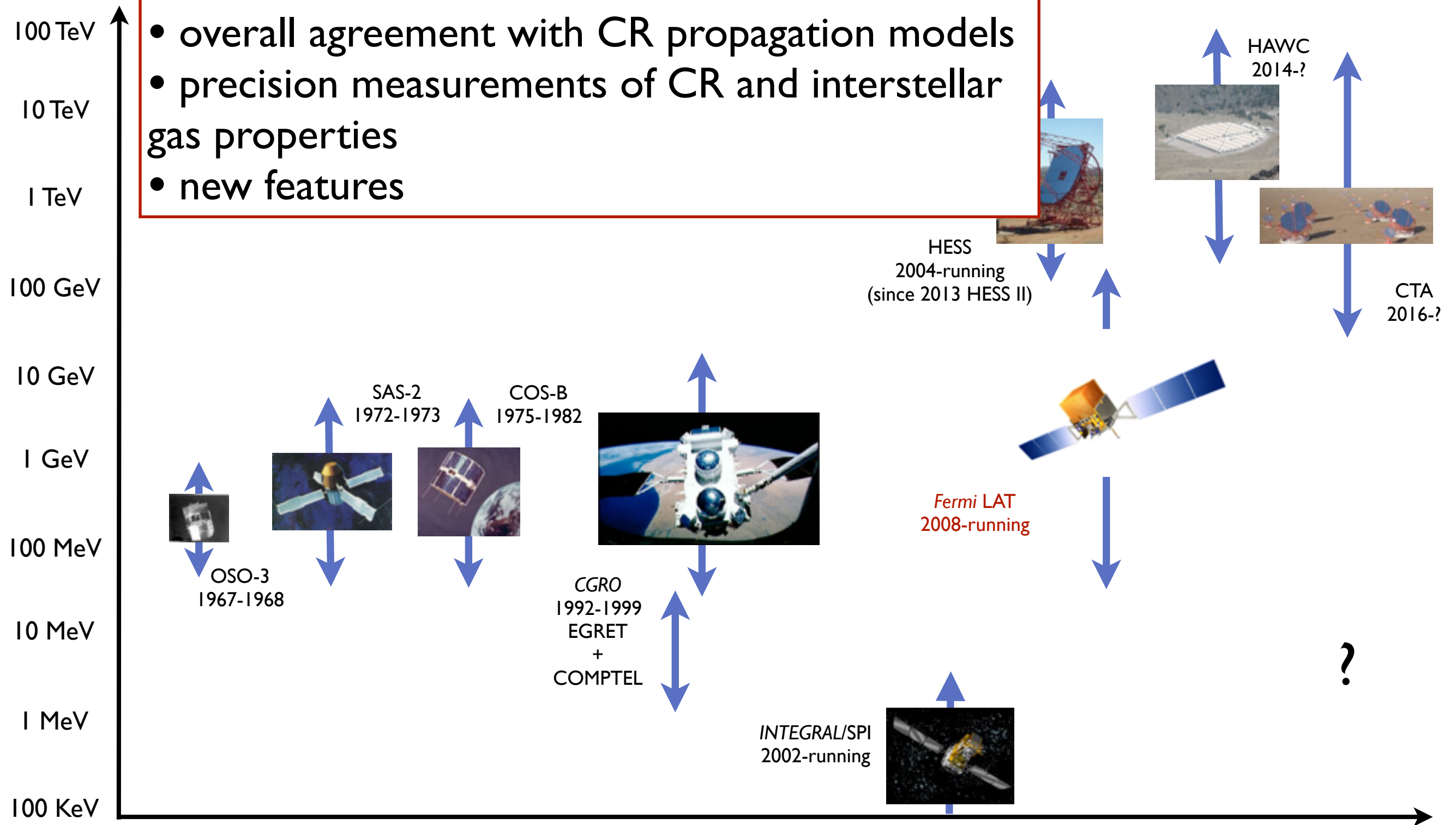
interstellar continuum  
emission  $> 100$  keV,  
likely IC





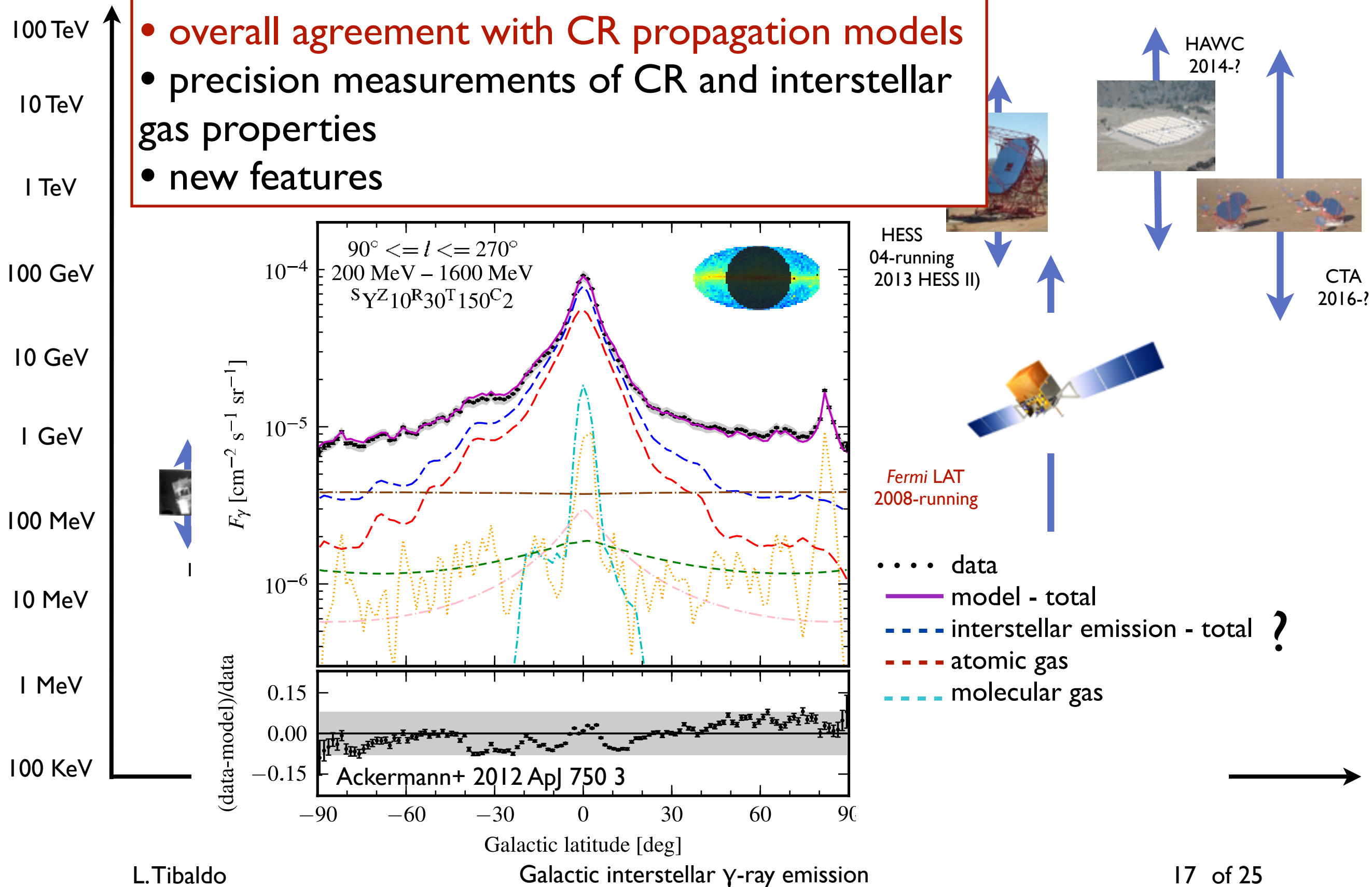
# Fermi LAT

- overall agreement with CR propagation models
- precision measurements of CR and interstellar gas properties
- new features



# Fermi LAT

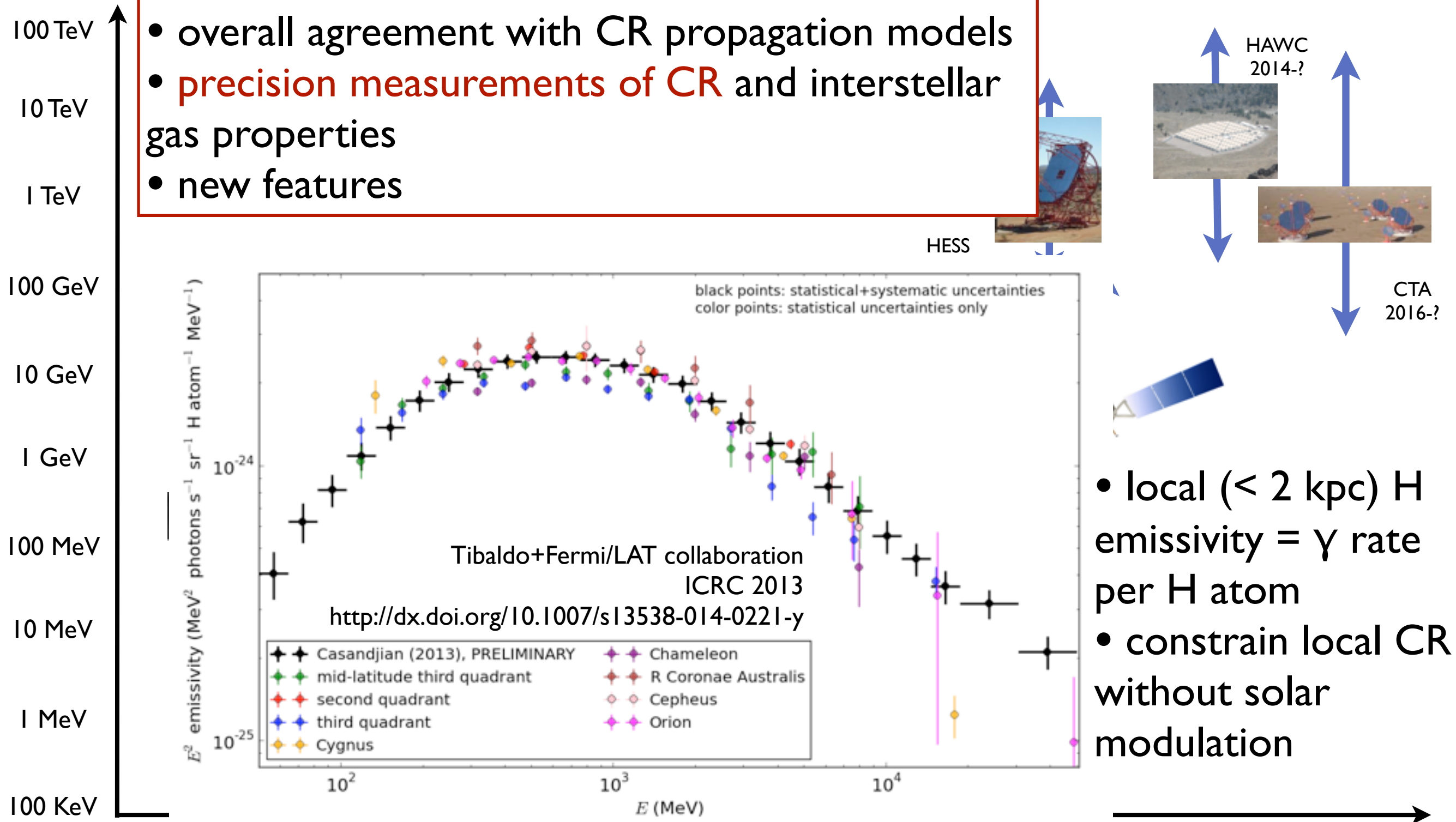
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# Fermi LAT

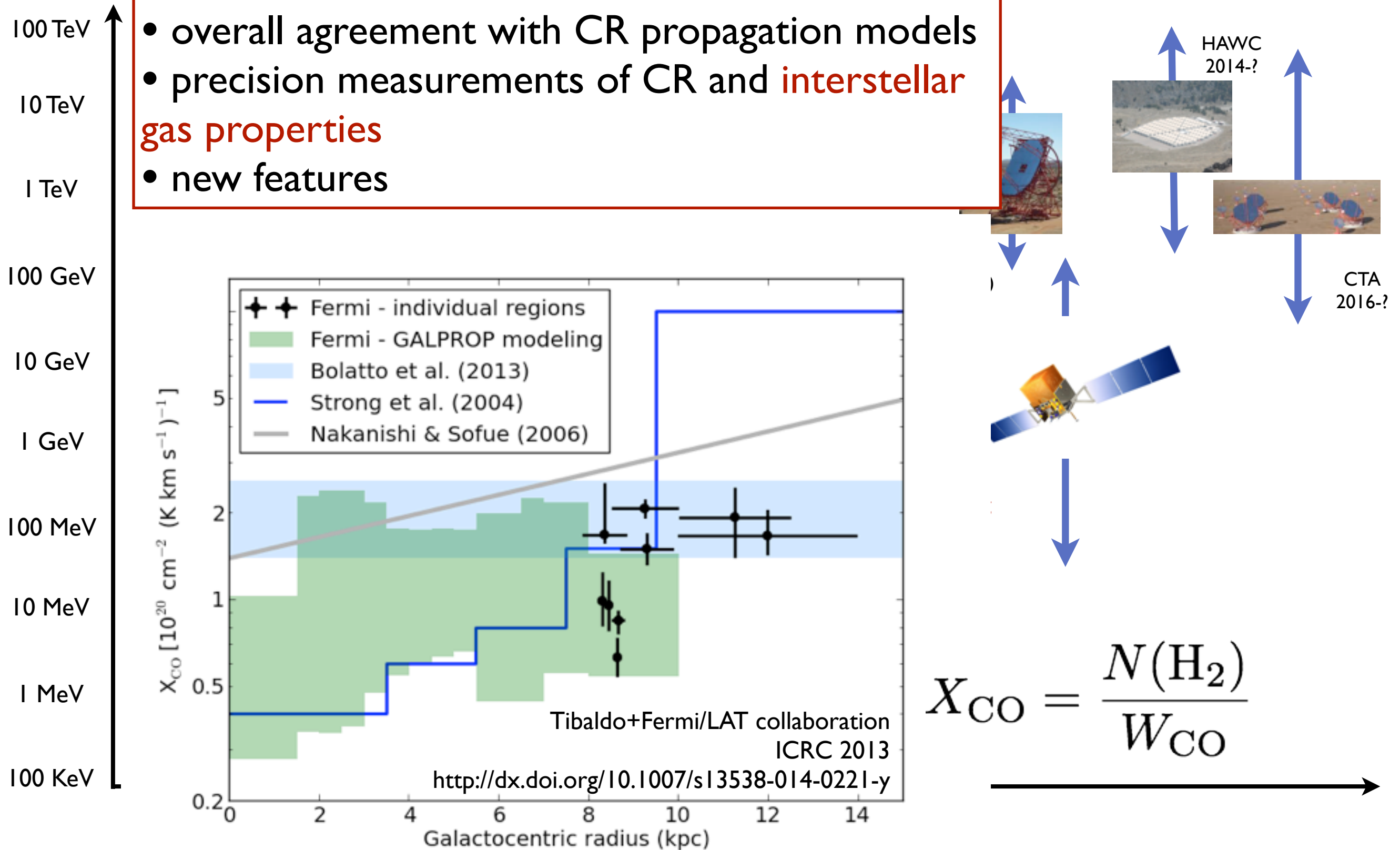
- overall agreement with CR propagation models
- **precision measurements of CR** and interstellar gas properties
- new features



- local (< 2 kpc) H emissivity =  $\gamma$  rate per H atom
- constrain local CR without solar modulation

# Fermi LAT

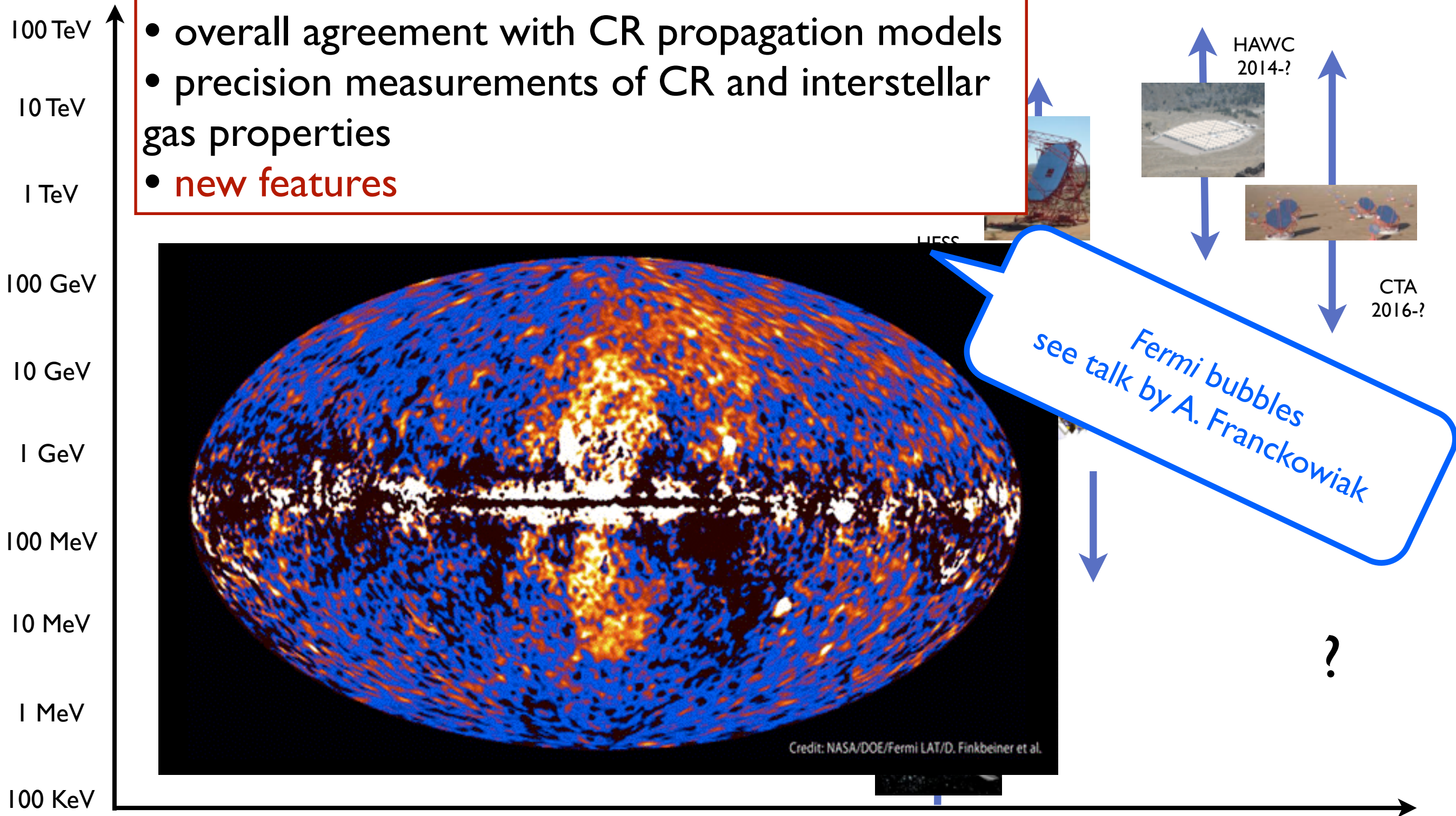
- overall agreement with CR propagation models
- precision measurements of CR and **interstellar gas properties**
- new features





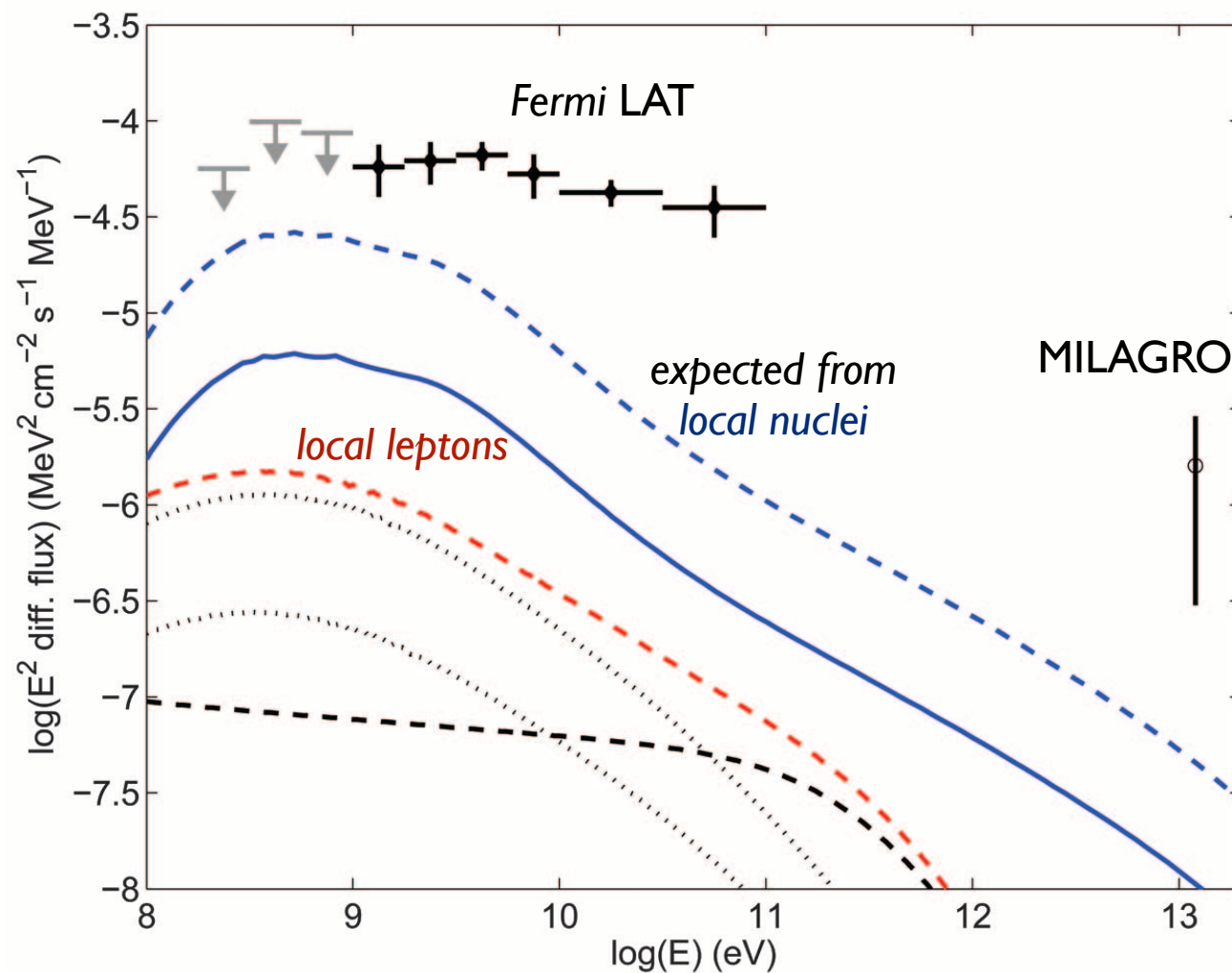
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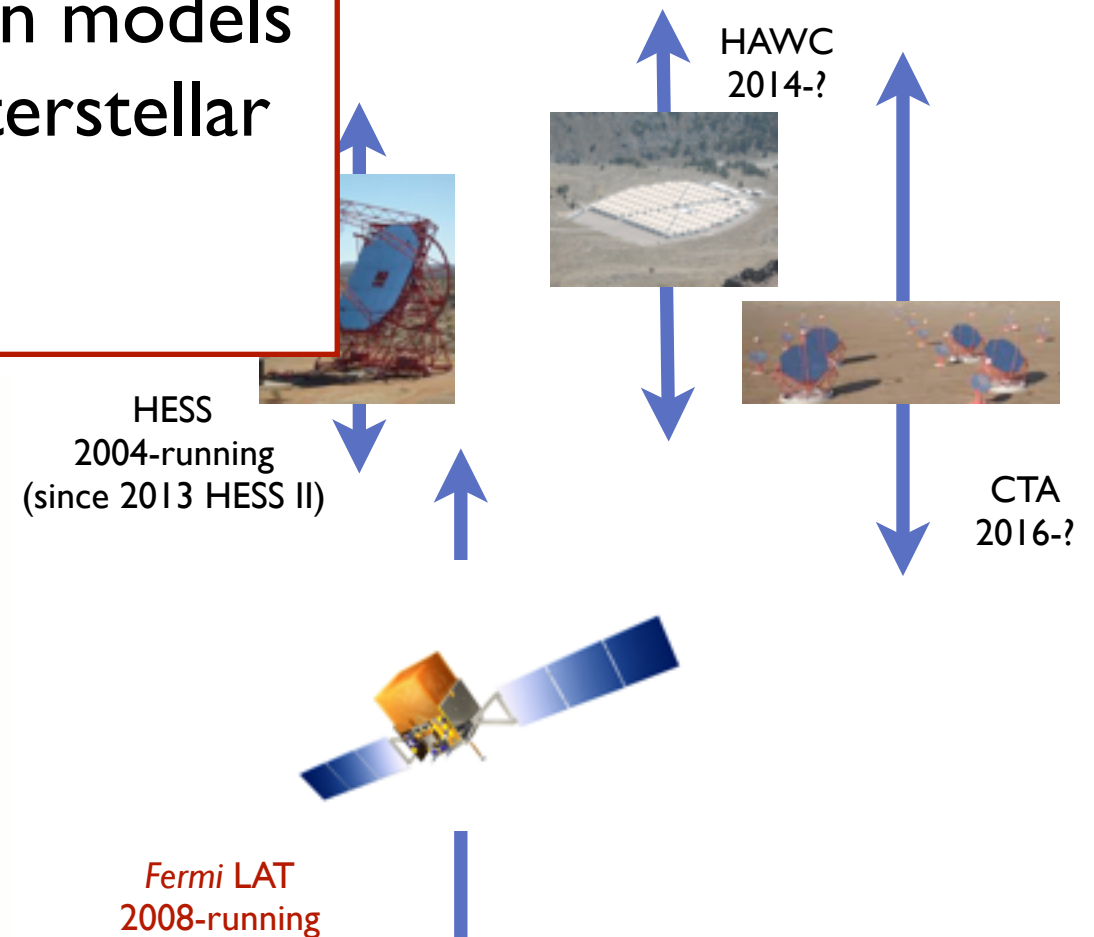


# Fermi LAT

- overall agreement with CR propagation models
- precision measurements of CR and interstellar gas properties
- **new features**



Ackermann+ 2011 Science 334 1103



- excess hard diffuse emission from Cygnus X
- morphology matches interstellar structures
- freshly-accelerated particles vs. large-scale CR population

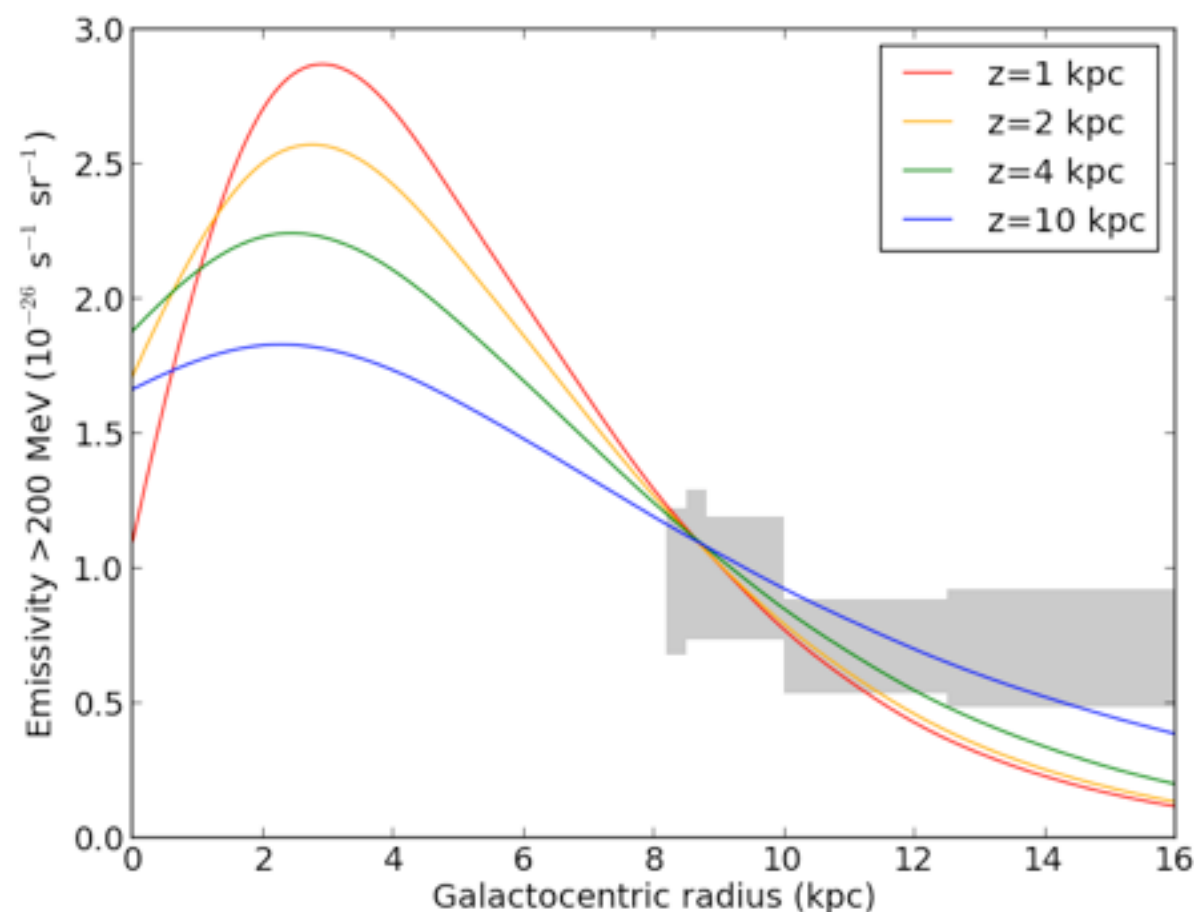
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# The quest for a universal CR propagation model

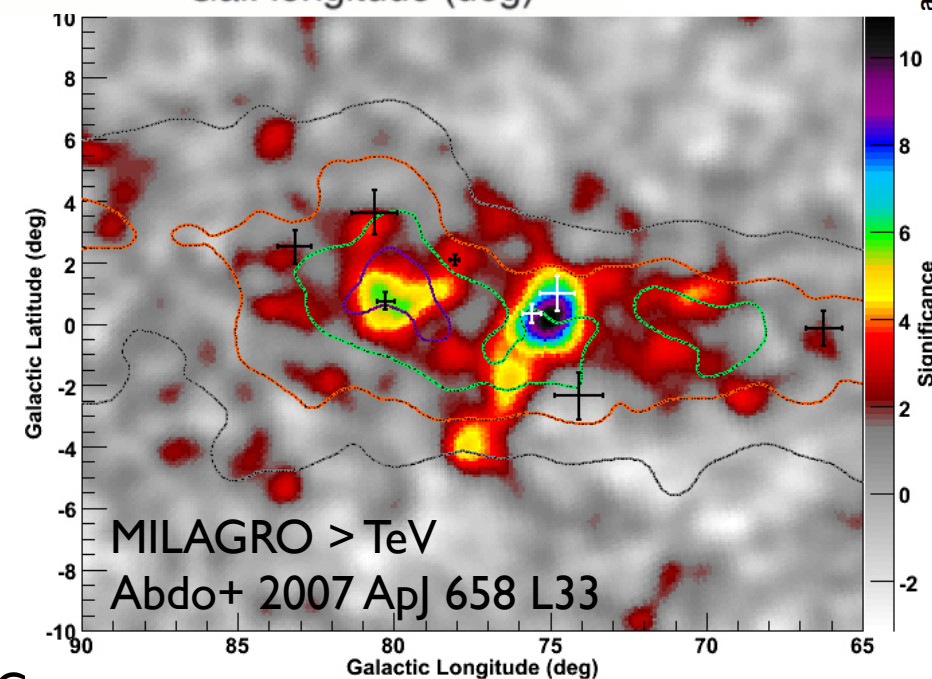
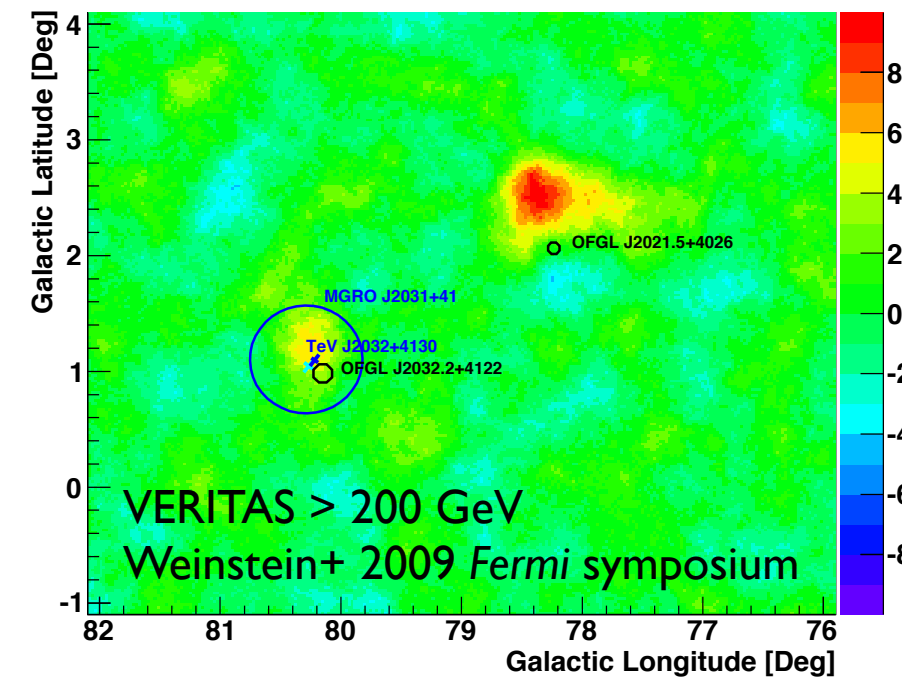
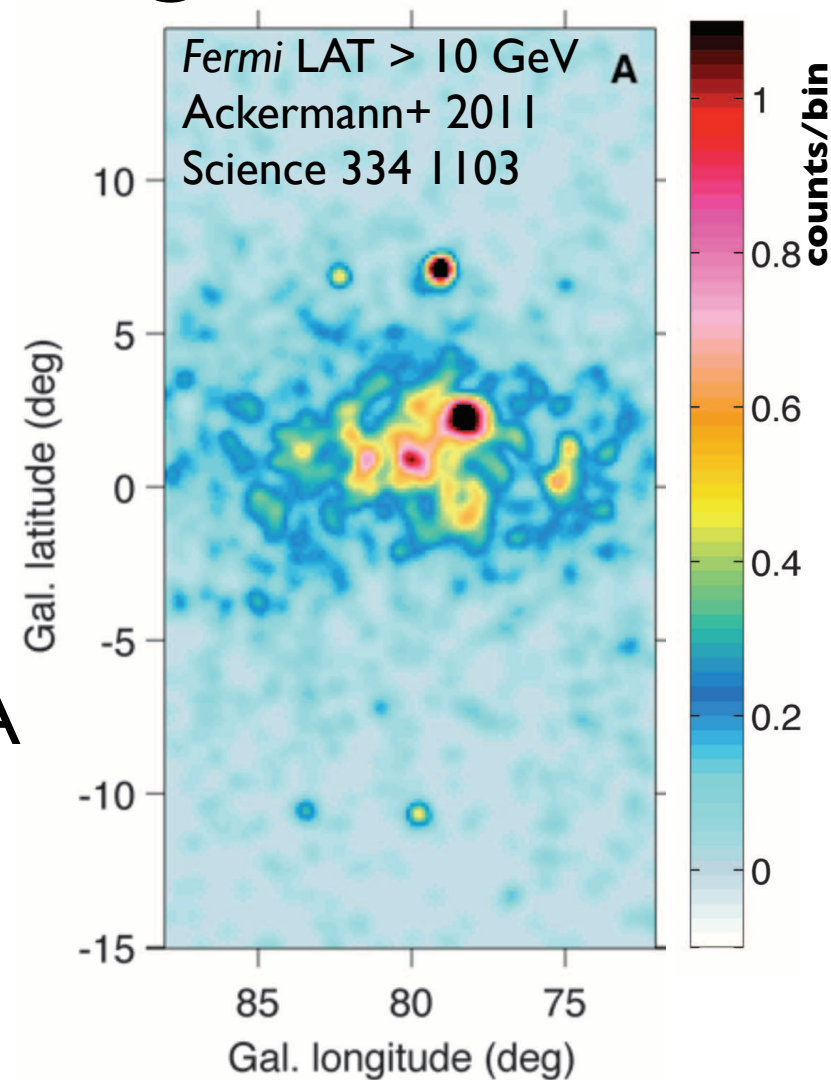
- reproduce all observables
- challenges
  - complex phenomena, e.g. gradient problem outer Galaxy  $\rightarrow$  non-uniform diffusion/coupling CR interstellar plasma ???
- local features



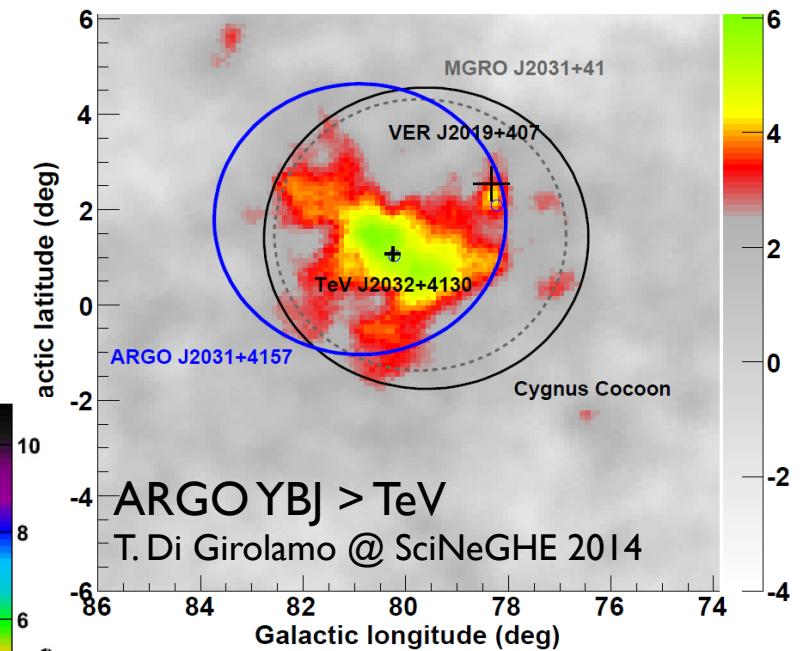
*Fermi* LAT:  
local and outer Galaxy  
Abdo+ 2010 ApJ 710,133  
Ackermann+ 2011 ApJ 726 81  
Ackermann+2012 A&A 538 A71

# Understanding VHE diffuse emission

- reconciling atmospheric Cherenkov with space-based and shower detectors
- next 10 years: *Fermi* + CTA + HAWC (North only)
- source confusion
- locally-accelerated particles vs large-scale CR population



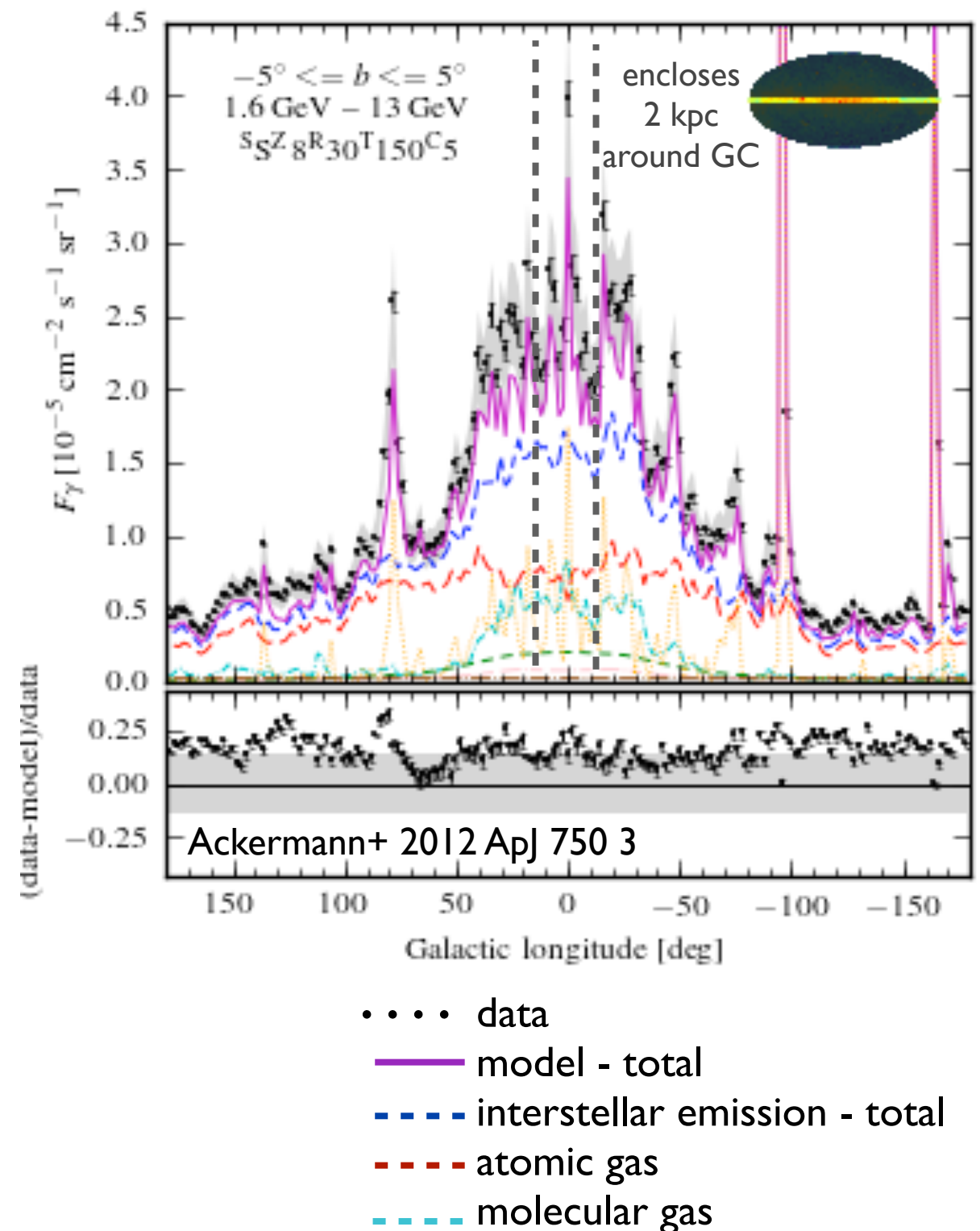
Galactic interstellar  $\gamma$ -ray emission



broad-band VHE Cygnus

# Diffuse emission around Galactic center

- several claims of “excesses”
- origin:
  - dark matter
  - unresolved sources
  - local CR populations
- limitations of interstellar emission models toward GC:
  - pile up along line of sight
  - lack of kinematic separation
  - uncertainties in radiation fields
  - particle acceleration/transport in turbulent regions





A night sky photograph featuring the Milky Way galaxy as a bright, hazy band of light stretching diagonally across the frame. Several bright, colorful meteor streaks are visible, including a prominent one in the lower right and others in the upper left and center. The background is a deep blue-black space filled with numerous stars.

**Thank you**