Gamma-ray emission from star-forming regions: status of observations and challenges ahead

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TOSCA 2024
Siena

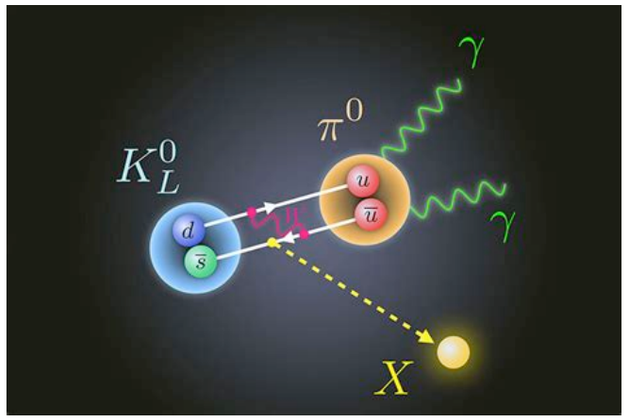
Outline

- Crash course on gamma-ray astronomy
- Observations of gamma-ray emission towards star-forming regions
- The challenges ahead

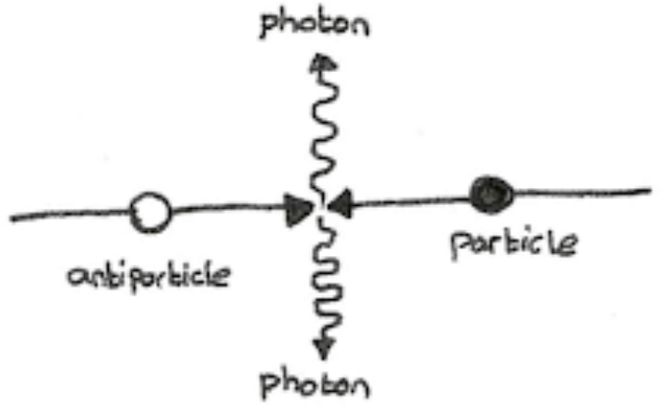
Gamma-ray production

Roland Diehl

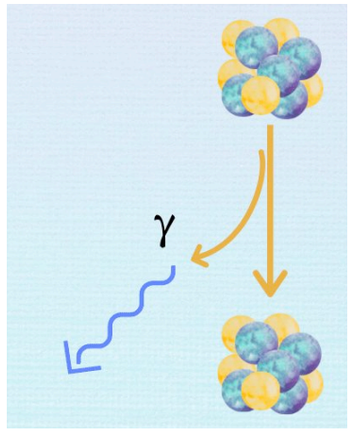
Particle decays



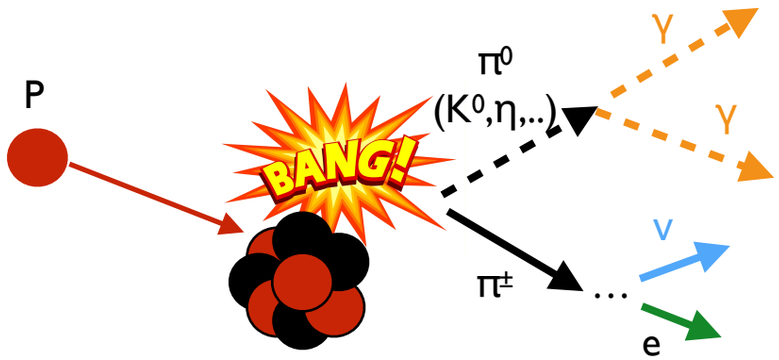
Particle annihilation

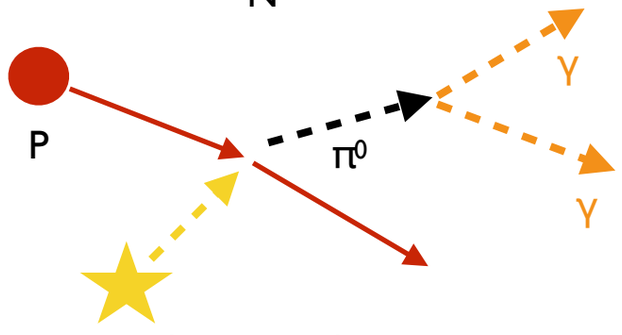


Nuclear decays



nucleon-nucleon inelastic collisions
target: matter

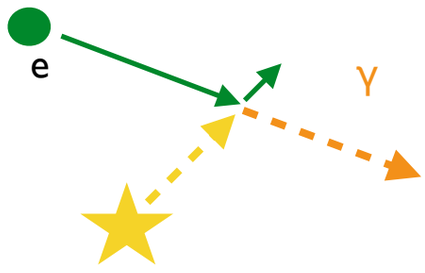




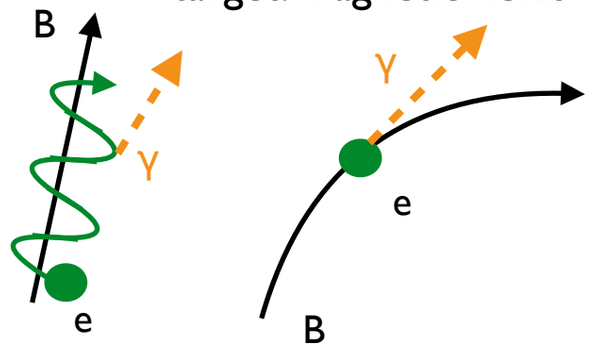
photoproduction
target: photons

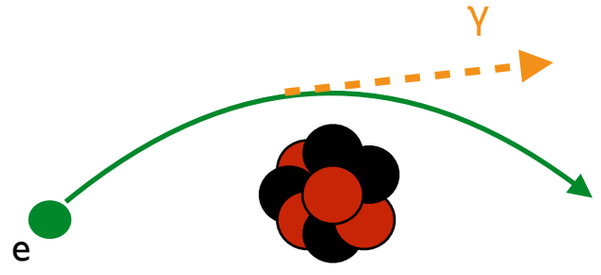
Particle acceleration + interactions

inverse-Compton scattering
target: photons



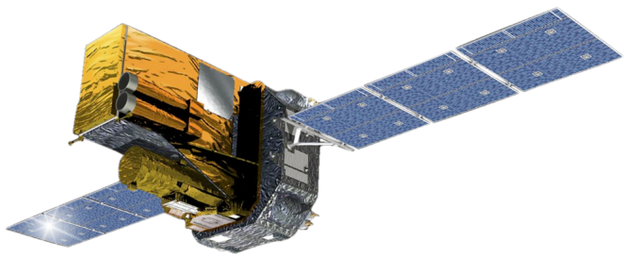
synchrotron/curvature radiation
target: magnetic fields





Bremsstrahlung
target: matter

Space telescopes

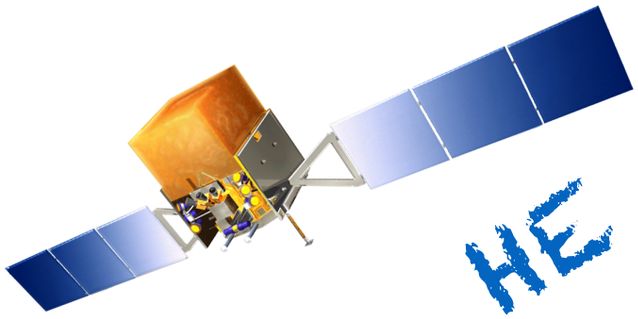


coded mask
INTEGRAL IBIS&SPI
2002-2024
15 keV-10 MeV

LE

Compton telescope
COMPTEL
1991-2000
800 keV-30 MeV
& ballons (COSI, SMILE)

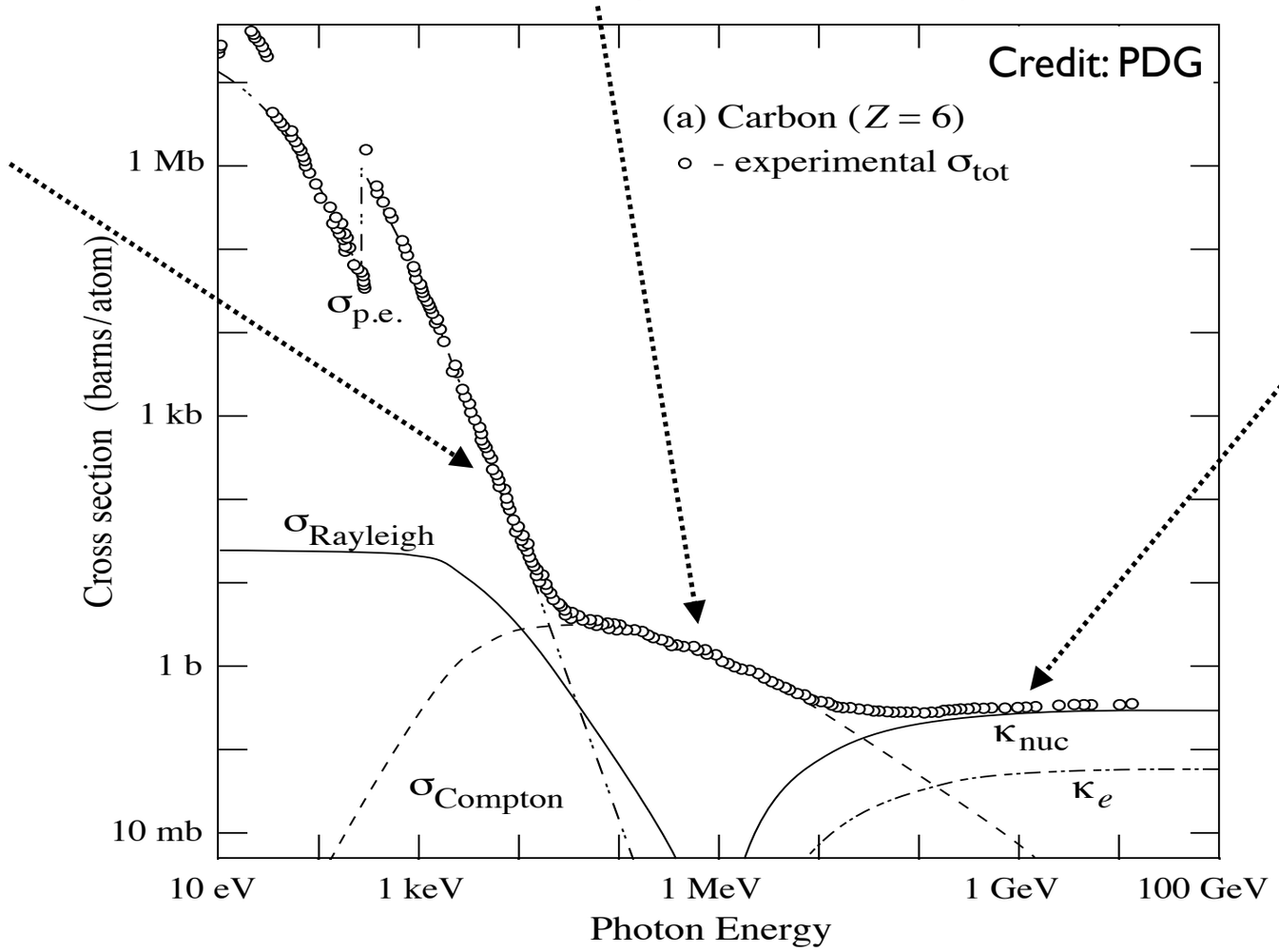
ME



HE

pair tracking
Fermi LAT
2008-present
30 MeV-1 TeV

and AGILE
2007-present
DAMPE
2015-present
CALET
2015-present

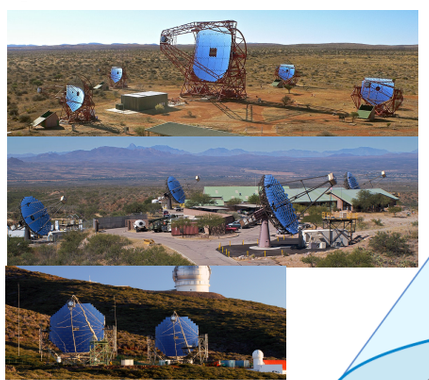


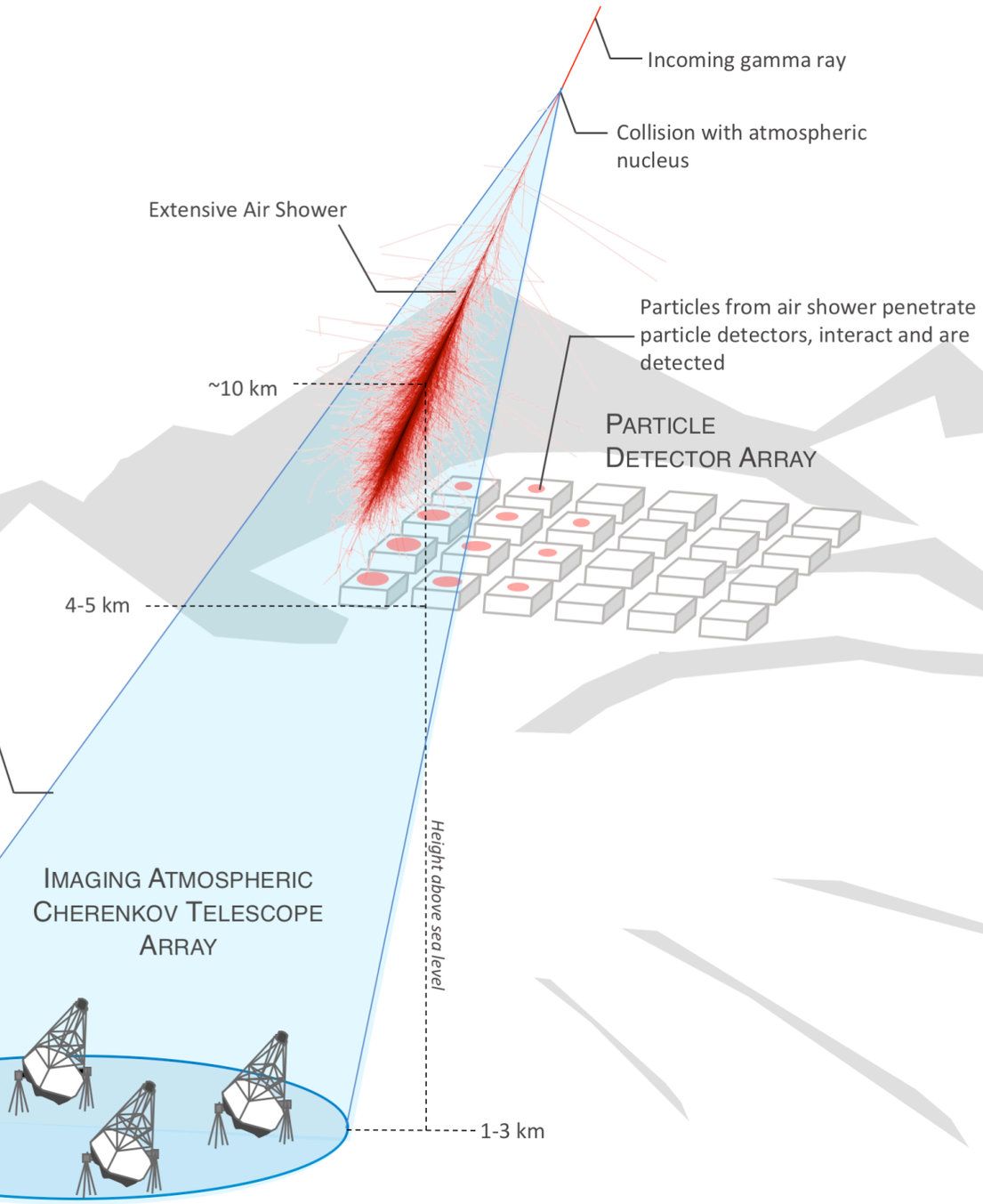
Ground-based telescopes

Better PSF
Modest FoV
Low duty cycle

VHE

H.E.S.S.,
VERITAS,
MAGIC
0.03 - 100 TeV
Early 2000-present



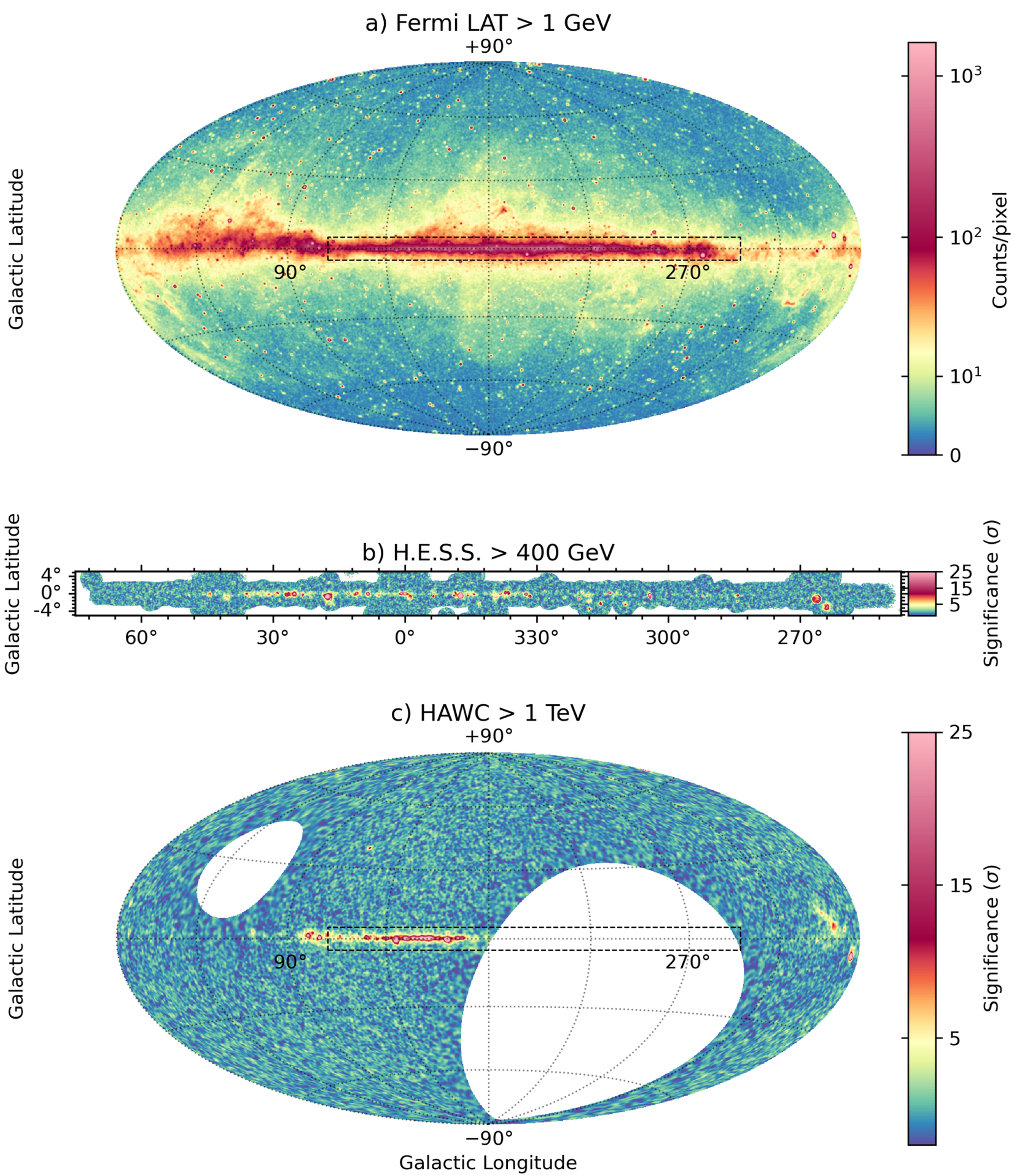


VHE-UHE

HAWC,
LHAASO,
Tibet AS Gamma
1 TeV - 2 PeV

Modest PSF
Large FoV
High duty cycle

Credit: Richard White

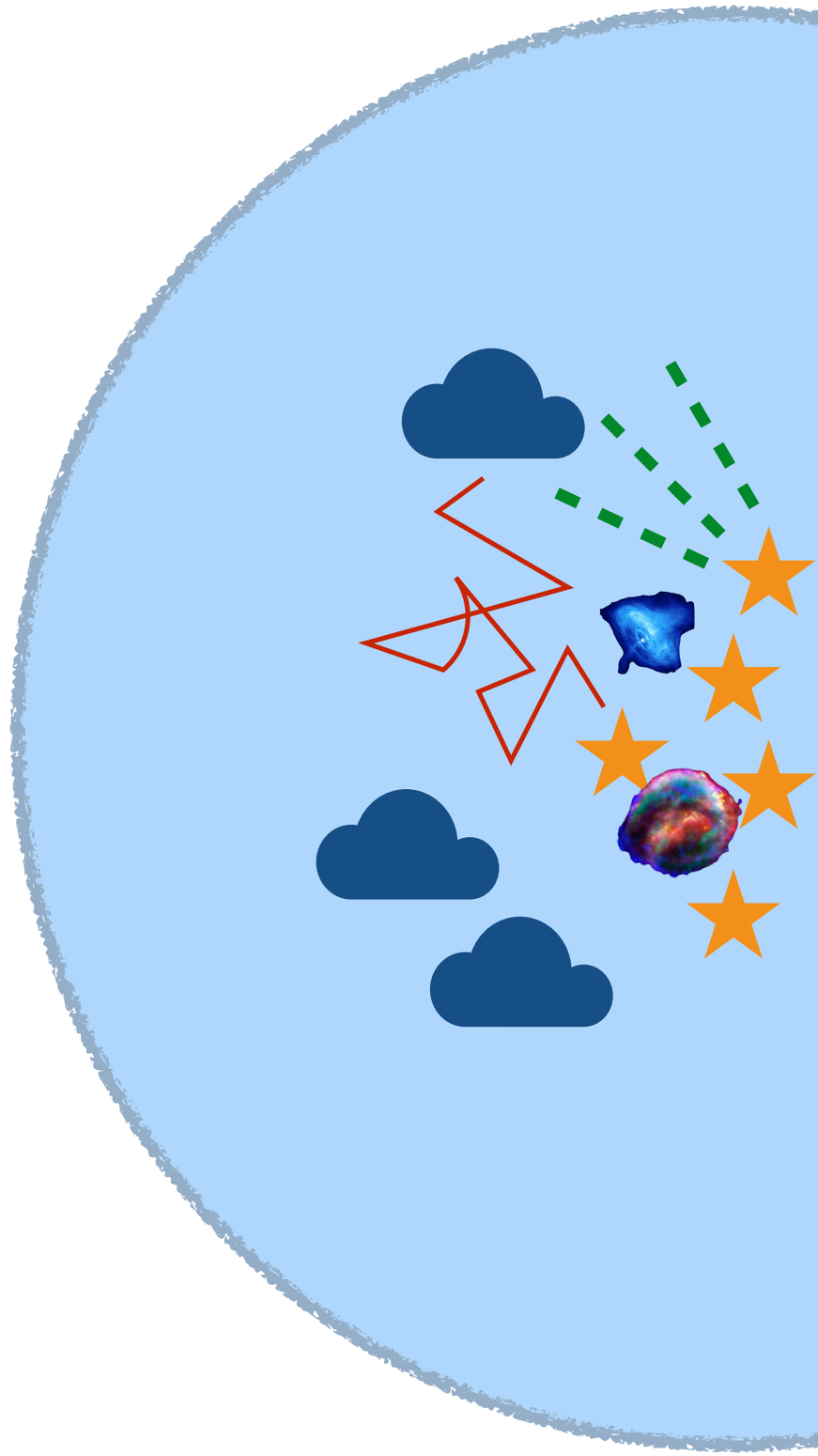

a) Fermi LAT > 1 GeV
+90°
90°
270°
−90°
Galactic Latitude
10^3
10^2
10^1
0
Counts/pixel
b) H.E.S.S. > 400 GeV
4°
0°
-4°
60°
30°
0°
330°
300°
270°
25
15
5
Significance (σ)
c) HAWC > 1 TeV
+90°
90°
270°
−90°
Galactic Latitude
Galactic Longitude
25
15
5
Significance (σ)

Outline

- Crash course on gamma-ray astronomy
- Observations of gamma-ray emission towards star-forming regions
- The challenges ahead

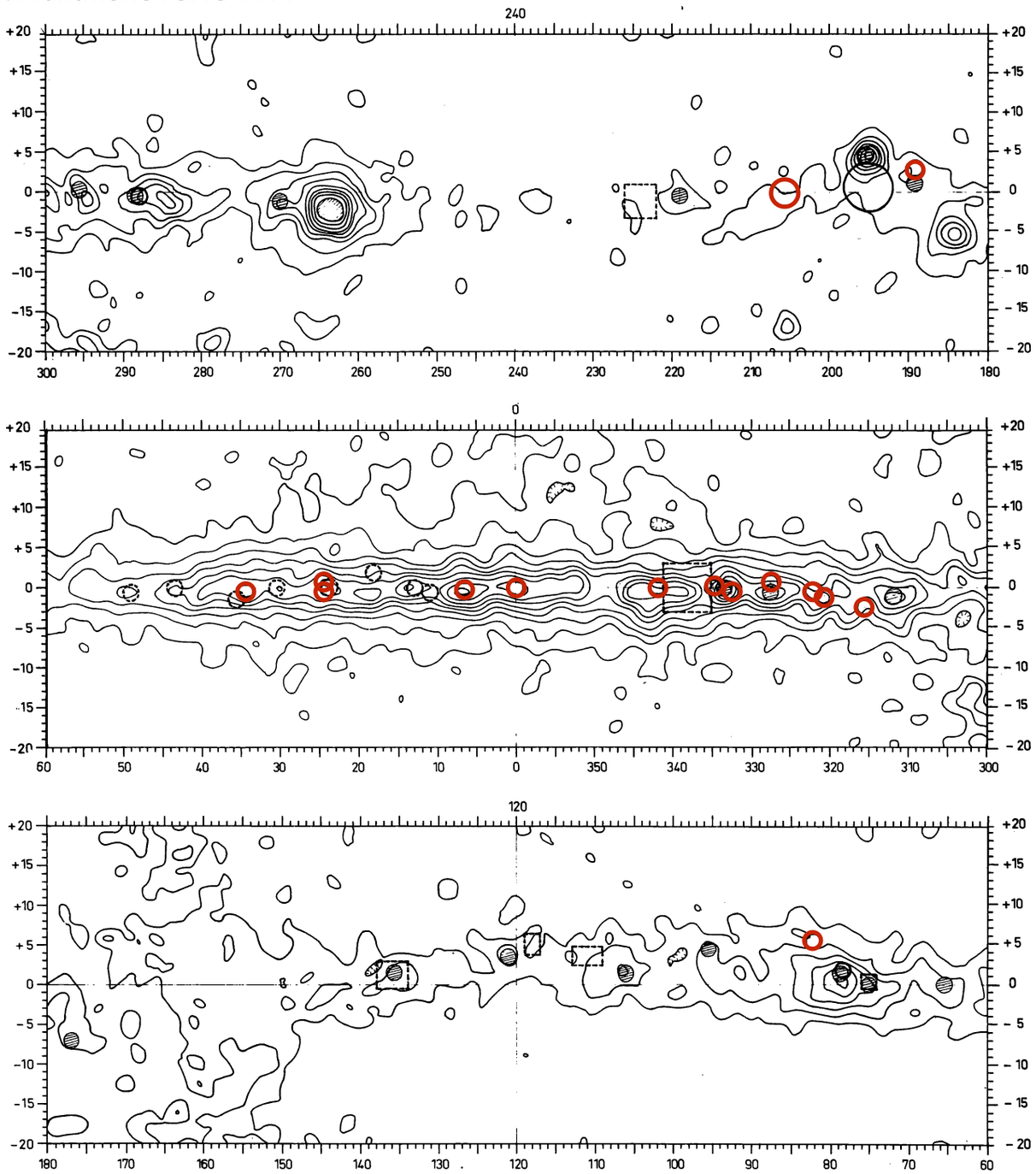
Foreword

- Concentration of accelerators and targets → gamma-ray emission!
- A complex physical problem?
  - Particles released over time (E-dependence)
  - Propagation in complex medium
  - Feedback from the particles (non-linearities)
- Evidence for any specific processes in SFRs other than hosting supernovae, pulsar wind nebulae …?



A bit of history

T. Montmerle ICRC 1979



1980

- Proposed association of COS-B gamma-ray sources with SNOBs (supernova remnants in OB associations)
- First theoretical studies of particle acceleration by massive star winds
- WR stars invoked to explain CR abundances

1990

Improved EGRET gamma-ray catalogs do not confirm associations with SFRs

2000

Improved measurements of CR heavy elements. Renewed interest in acceleration in SFRs (superbubble model)

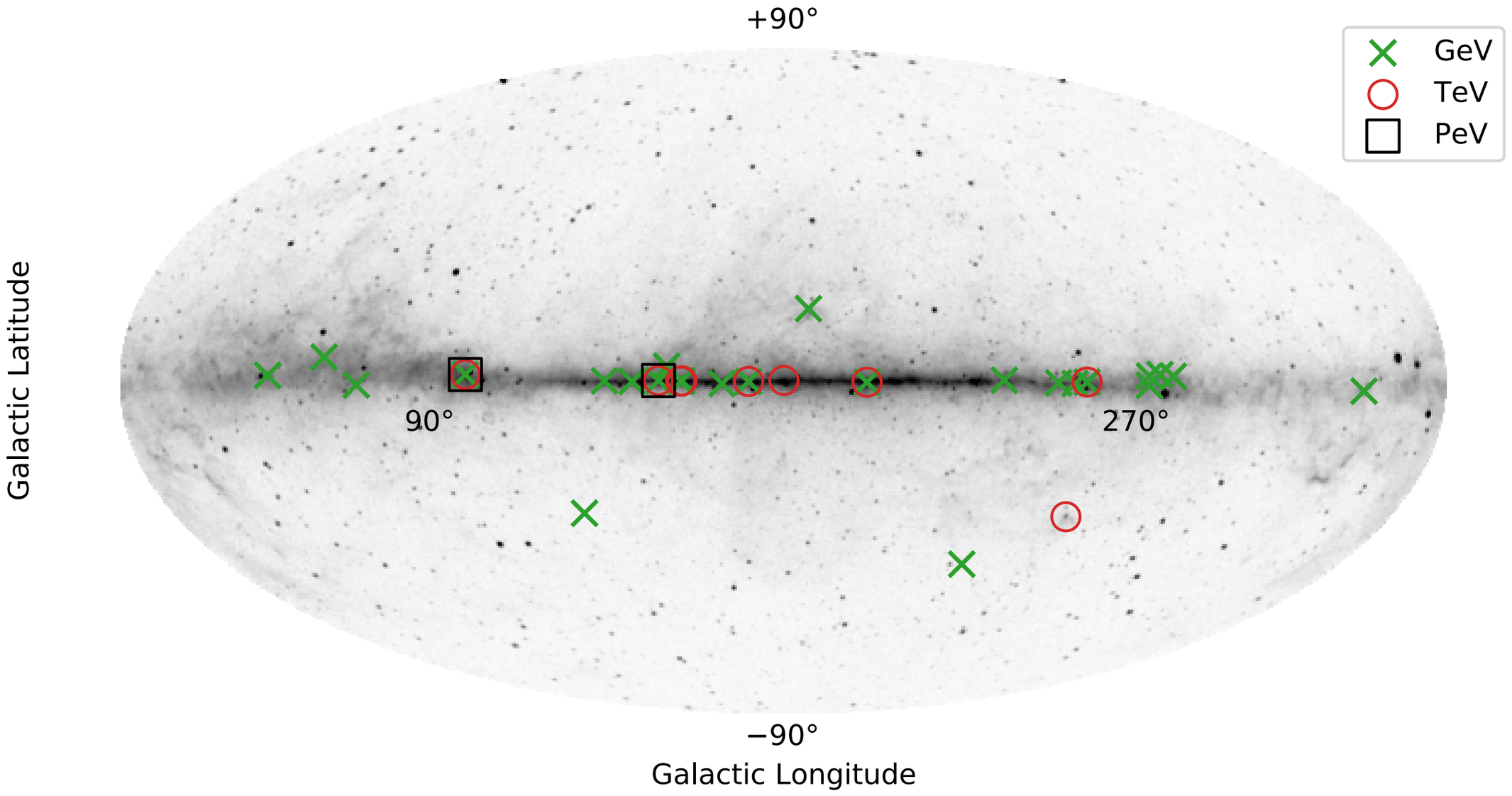
2010

Current generation of space- and ground-based telescopes online: **first detections of gamma-ray emission towards SFR**

2020

Several theoretical models emerge. Gamma-ray detections keep increasing

Gamma-ray sources towards SFRs

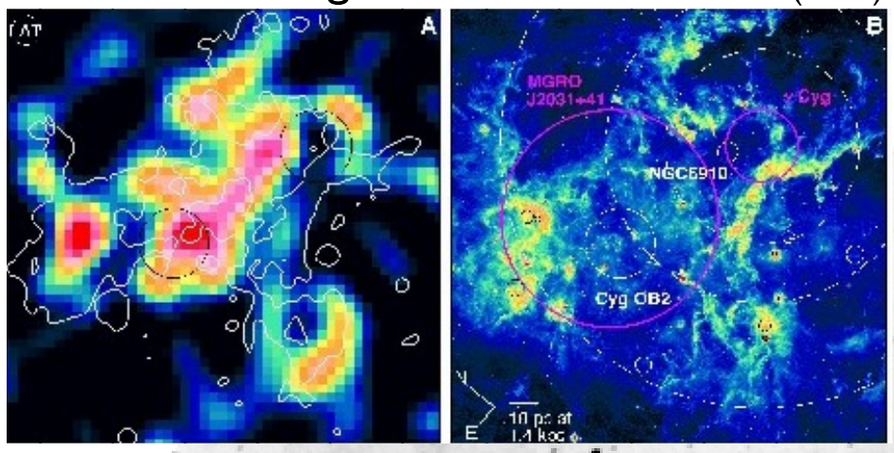


Compilation of results in Astiasarain (PhD, 2023)
plus Liu et al. (2023, 2024), Peron et al. (2024), Wu et al. (2024), Ge et al. (2024), Lhaaso Collaboration (2024), H.E.S.S. collaboration (2024)

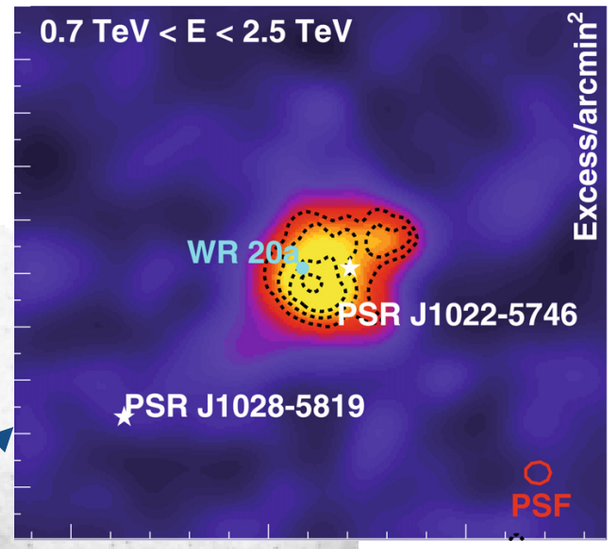
Gamma-ray sources towards SFRs

Cygnus (OB2)
1.5 kpc, 3-5 Myr
P = 4-8×10^{38} erg/s

Fermi LAT collaboration (2011)



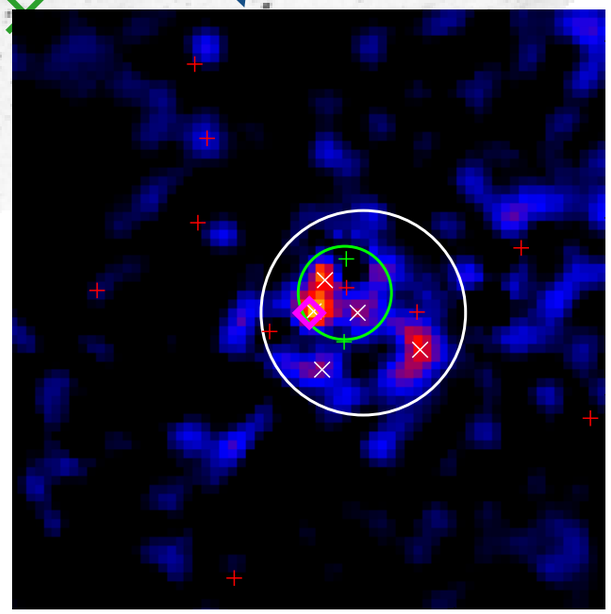
Westerlund 2
4 kpc, 1-2 Myr
P = 1-2×10^{38} erg/s



H.E.S.S. collaboration (2011)

H.E.S.S. collaboration (2012)

Westerlund 1
4 kpc, 5-10 Myr
P = 10^{39} erg/s

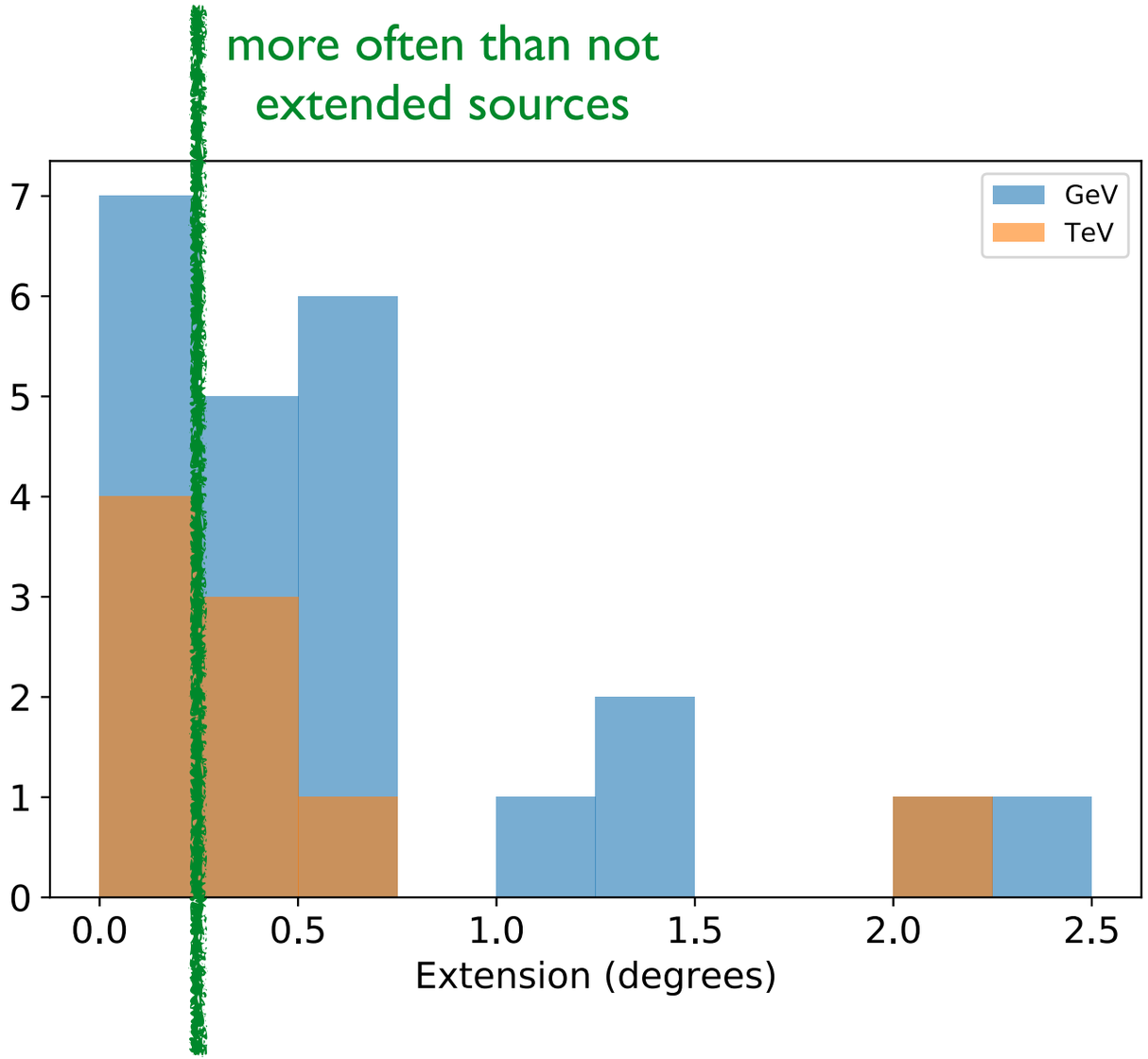


Yang et al. (2017)

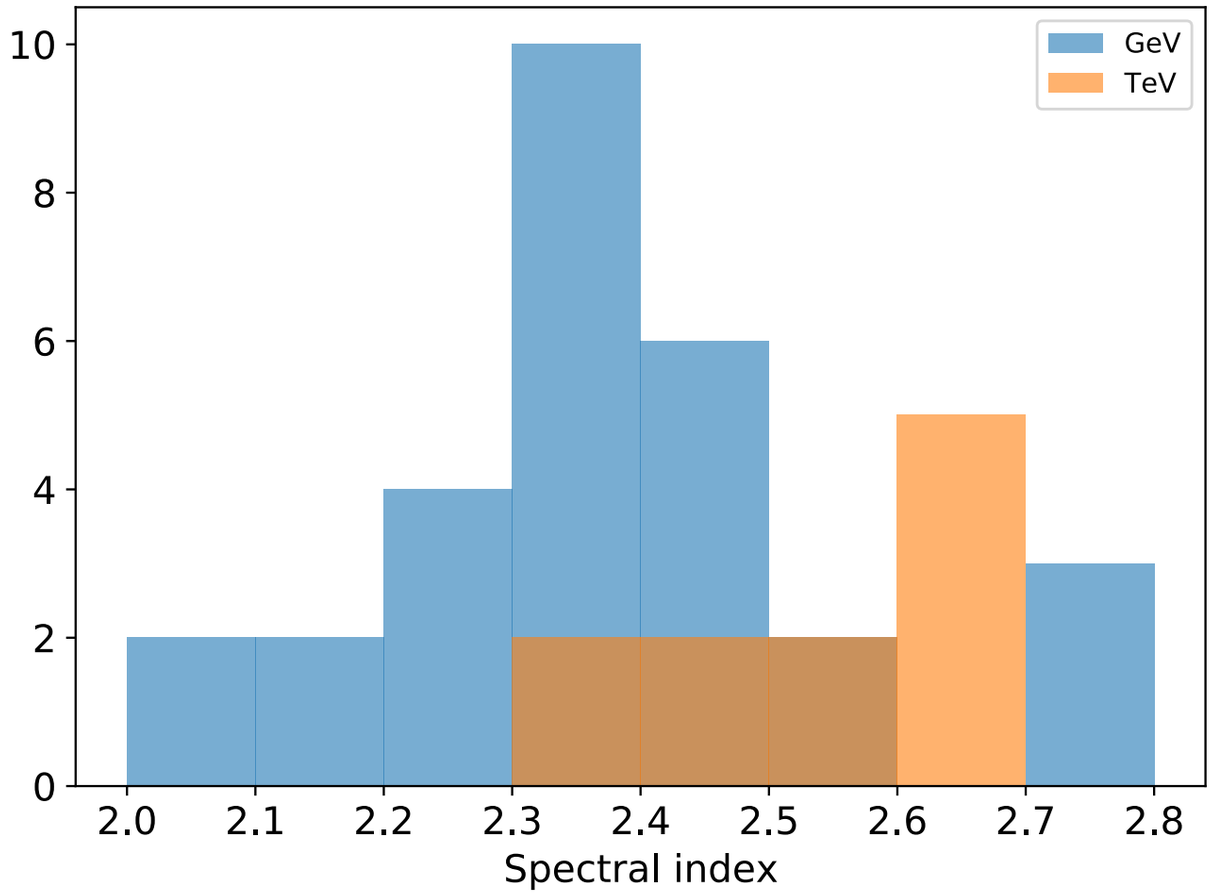
NGC 3603
6-8 kpc, 2-3 Myr
P = 8×10^{38} erg/s

Emission properties

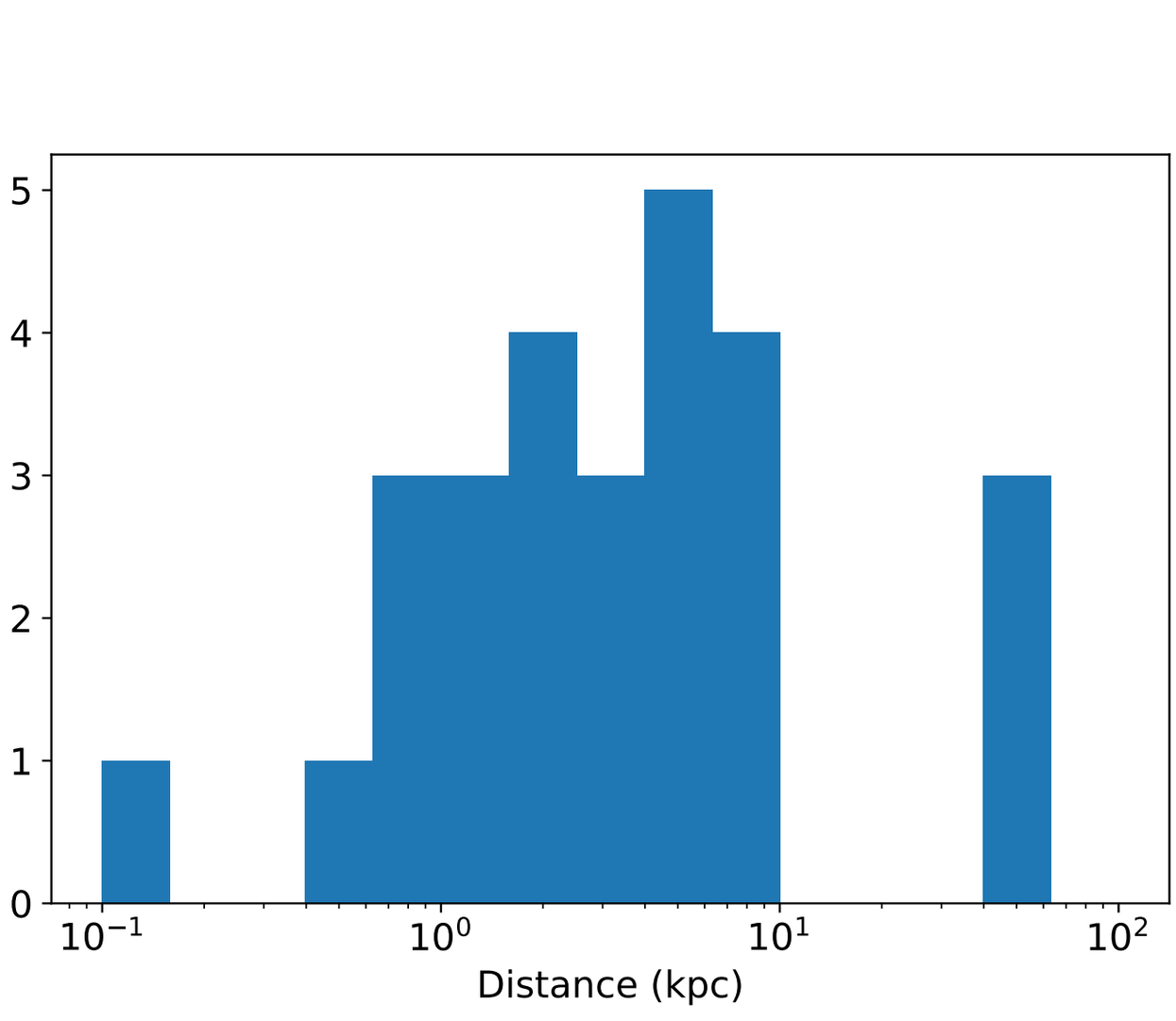
more often than not
extended sources

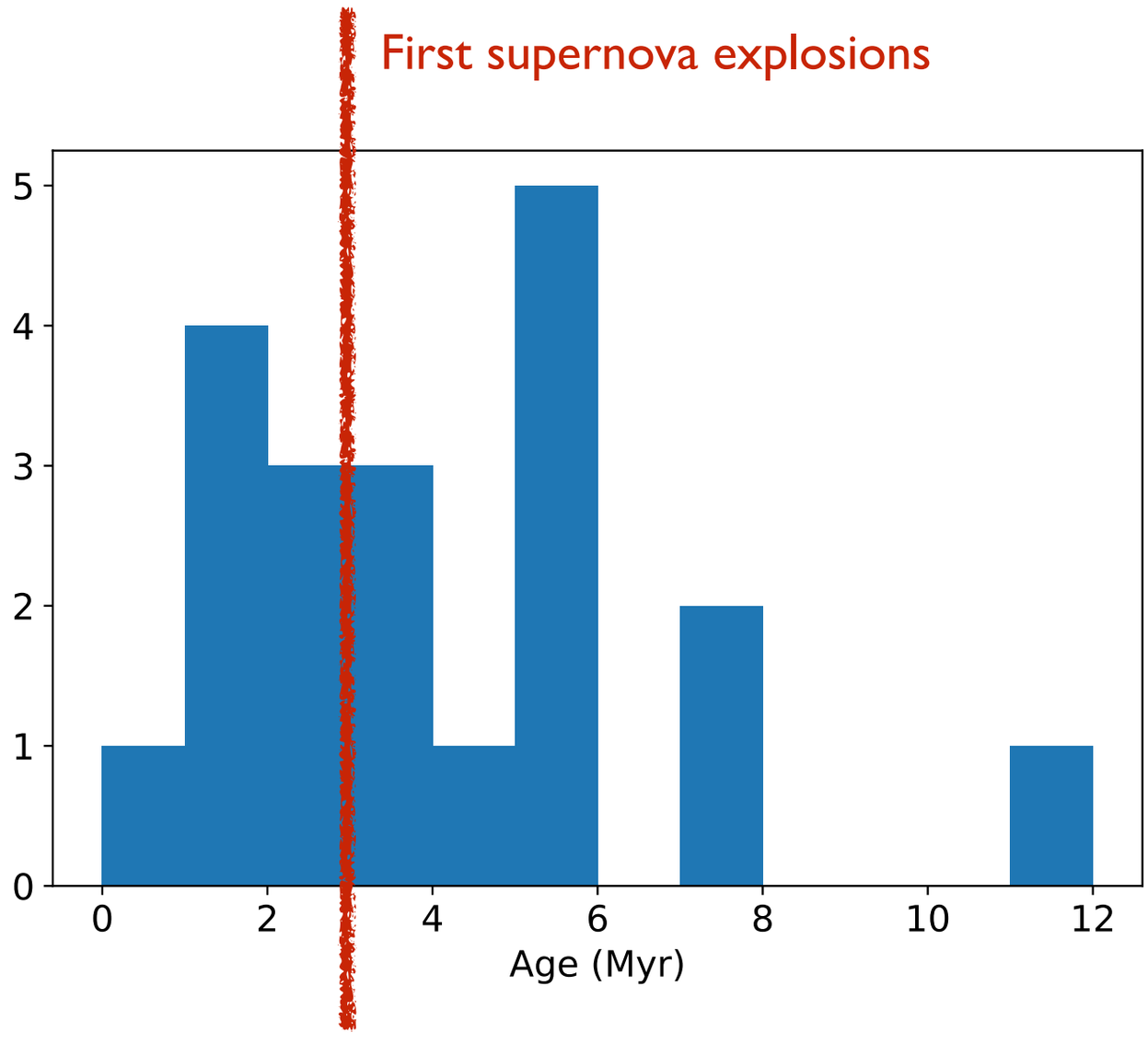


$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\Gamma}$$



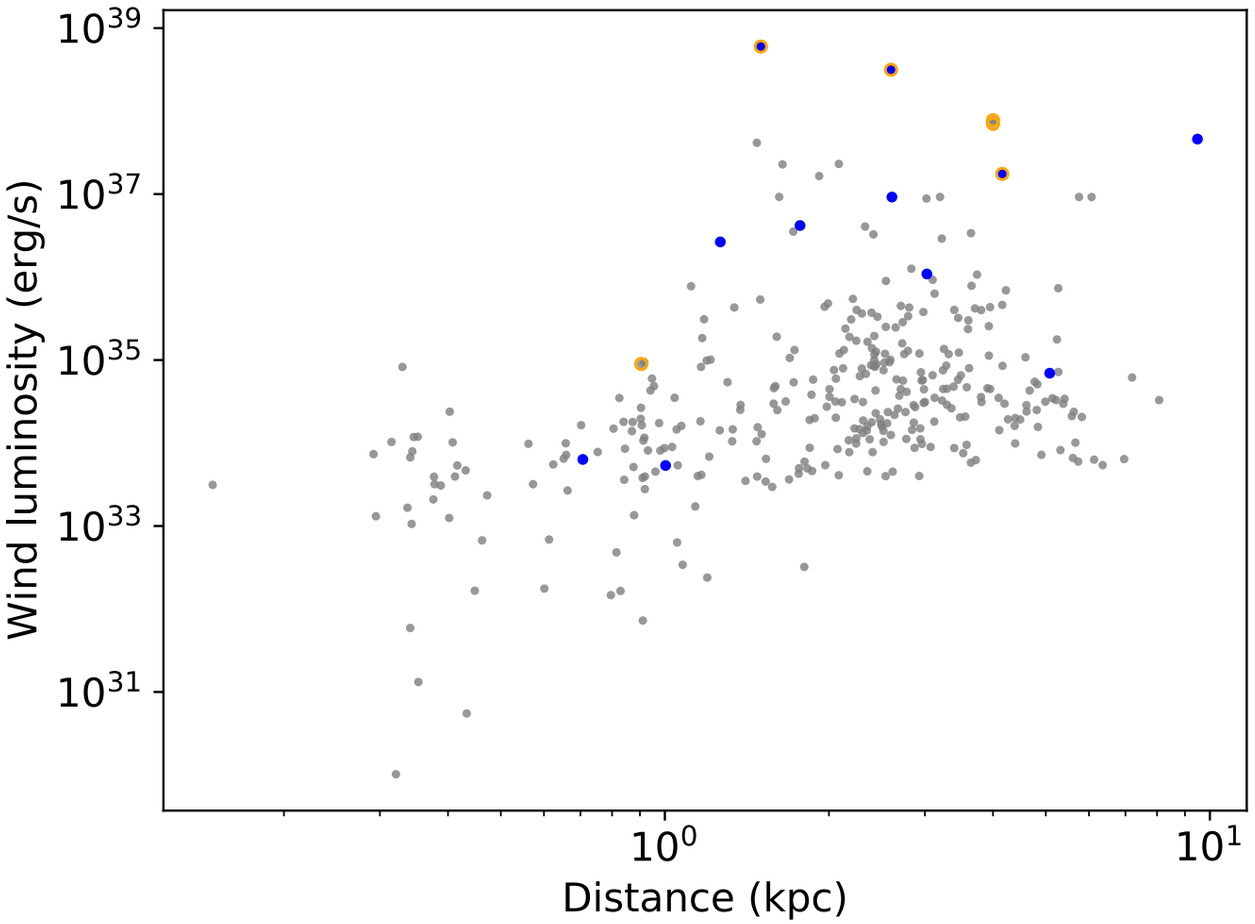
SFR distances and ages

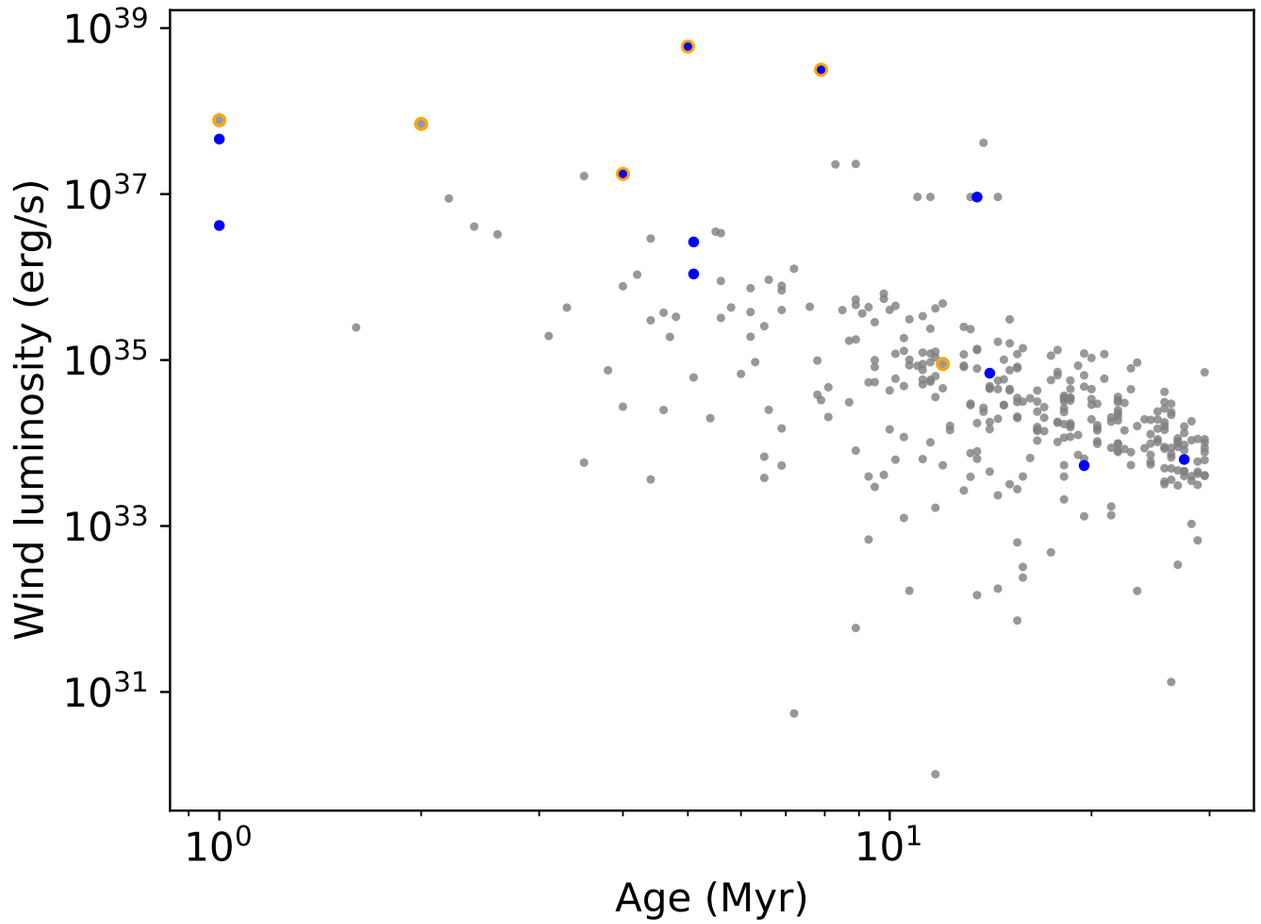




Comparison with Gaia clusters

O stars (spectral)
Gamma-ray detections





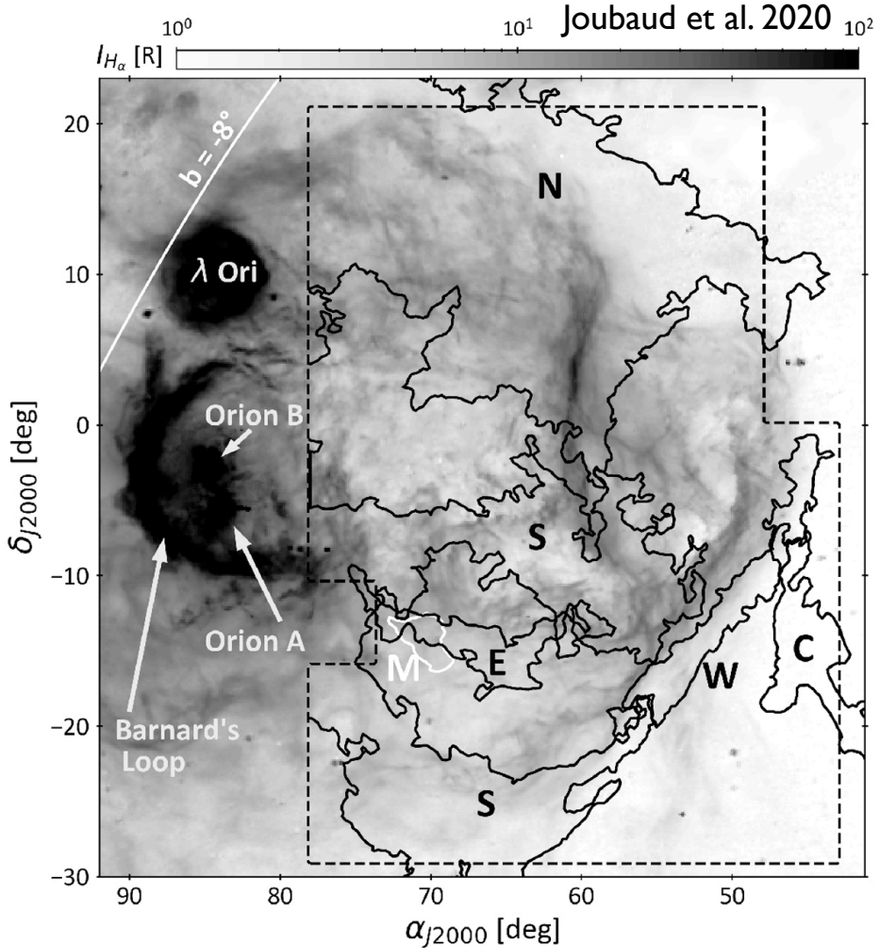
Massive stellar clusters from Gaia/Cantant-Gaudin et al. (2020), with wind luminosity estimates from Celli et al. (2024)
Systems with O stars in Villafranca catalog/Maíz Apellániz et al. (2020)
Ad-hoc information added for Cygnus OB2, Westerlund 1, Westerlund 2, NGC 3603, Trumpler 16, NGC 6357

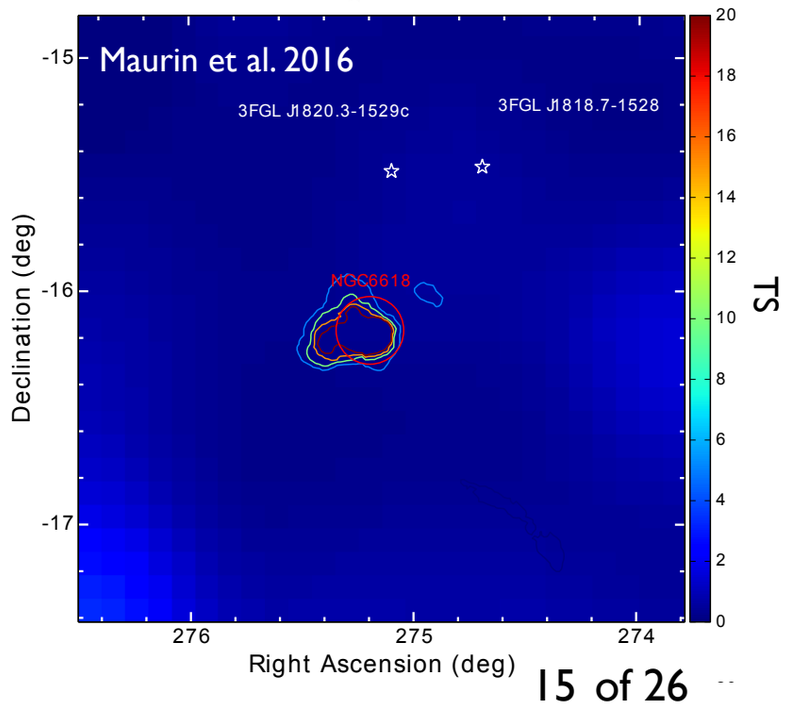
Ava Webber
Alison Mitchell

The SFRs we don't see

- No gamma-ray emission from Orion-Eridanus superbubble: 12 Myr, multiple SNe
- Eight clusters with O stars < 10 Myr embedded in HII regions
  - no detections: efficiency of particle acceleration < 1-10%
  - later claim of detection for NGC 6618 and NGC 2244

(Liu et al. 2022, 2023)





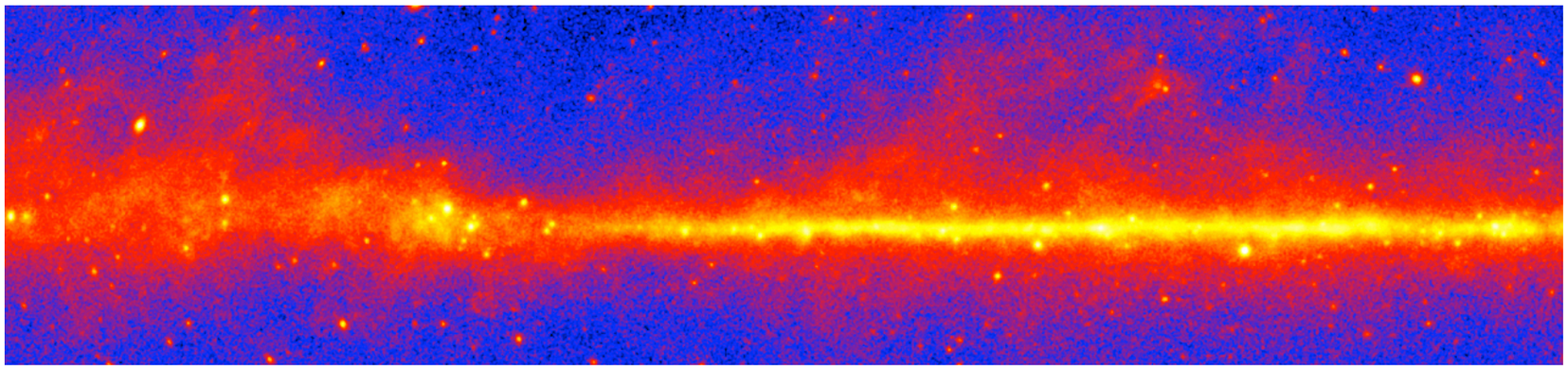
Outline

- Crash course on gamma-ray astronomy
- Observations of gamma-ray emission towards star-forming regions
- The challenges ahead

Overview

- Characterise gamma-ray emission
  - Backgrounds: interstellar gamma-ray emission, charged cosmic rays
  - Characterise complex extended sources
- Interpret gamma-ray measurements
  - Discriminate between multiple sources and acceleration/ transport mechanisms
  - Take into account complex multi-wavelength information
- Unbias the gamma-ray view of SFRs: from individual objects to populations

Analysis challenges: backgrounds

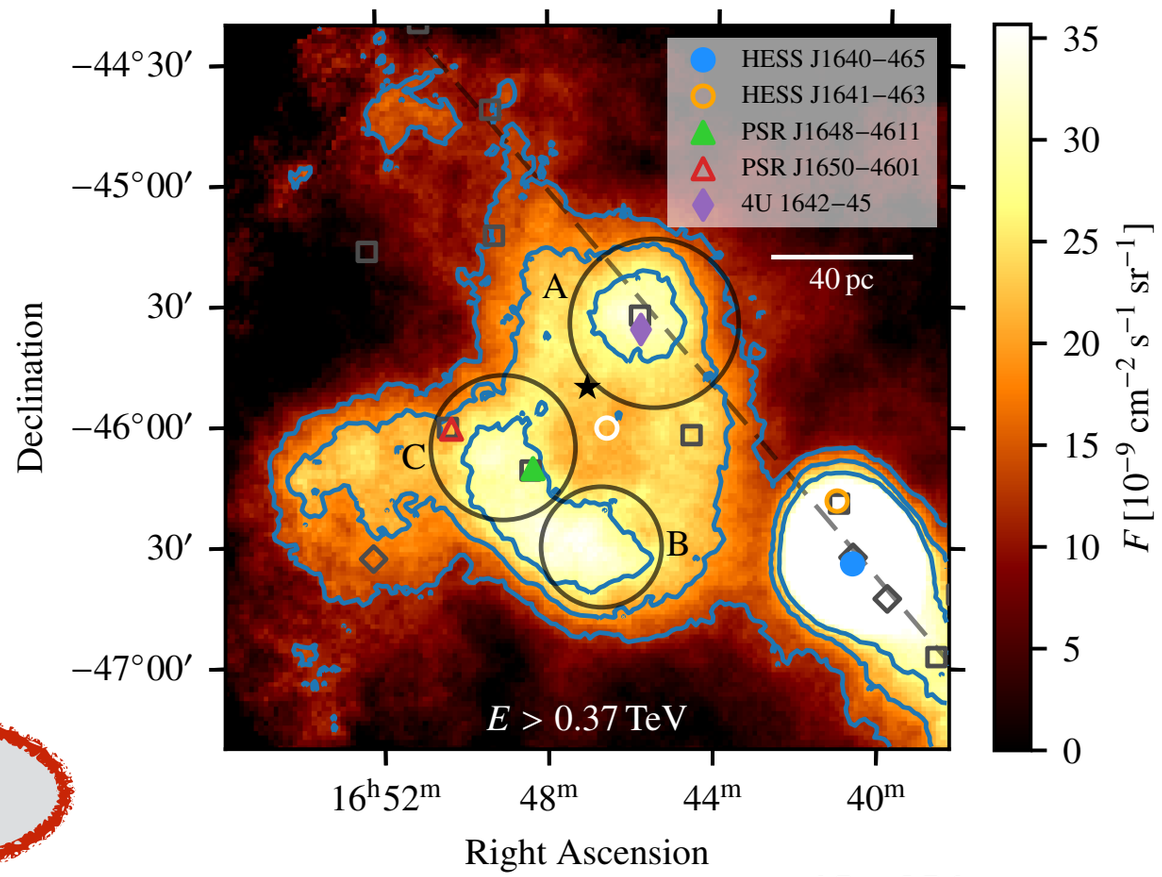


GeV: bright structured interstellar emission
complex modelling required

H.E.S.S. collaboration (2022)

IACTs

- CR background from FoV → challenge for extended sources
- recent progress: multi-component likelihood based on "background" observations library



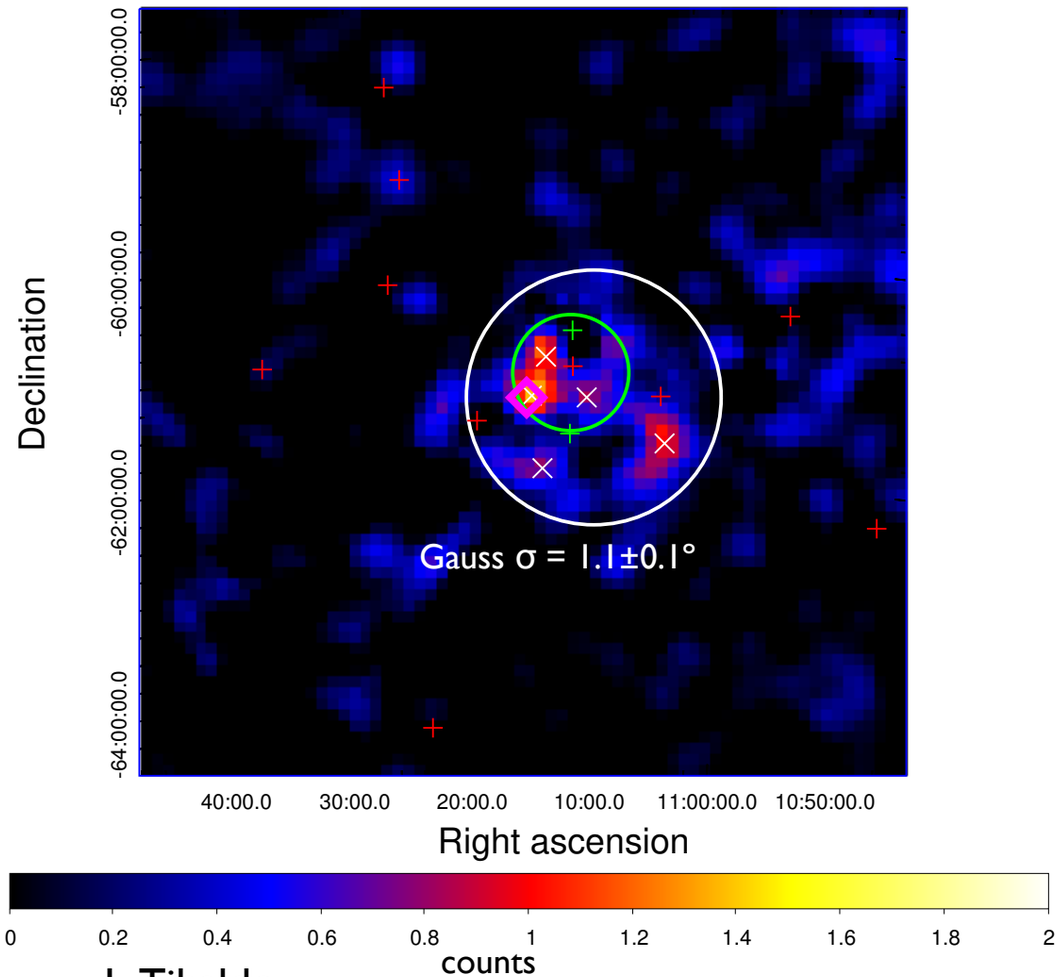
Lars Mohrmann

The case of NGC 3603

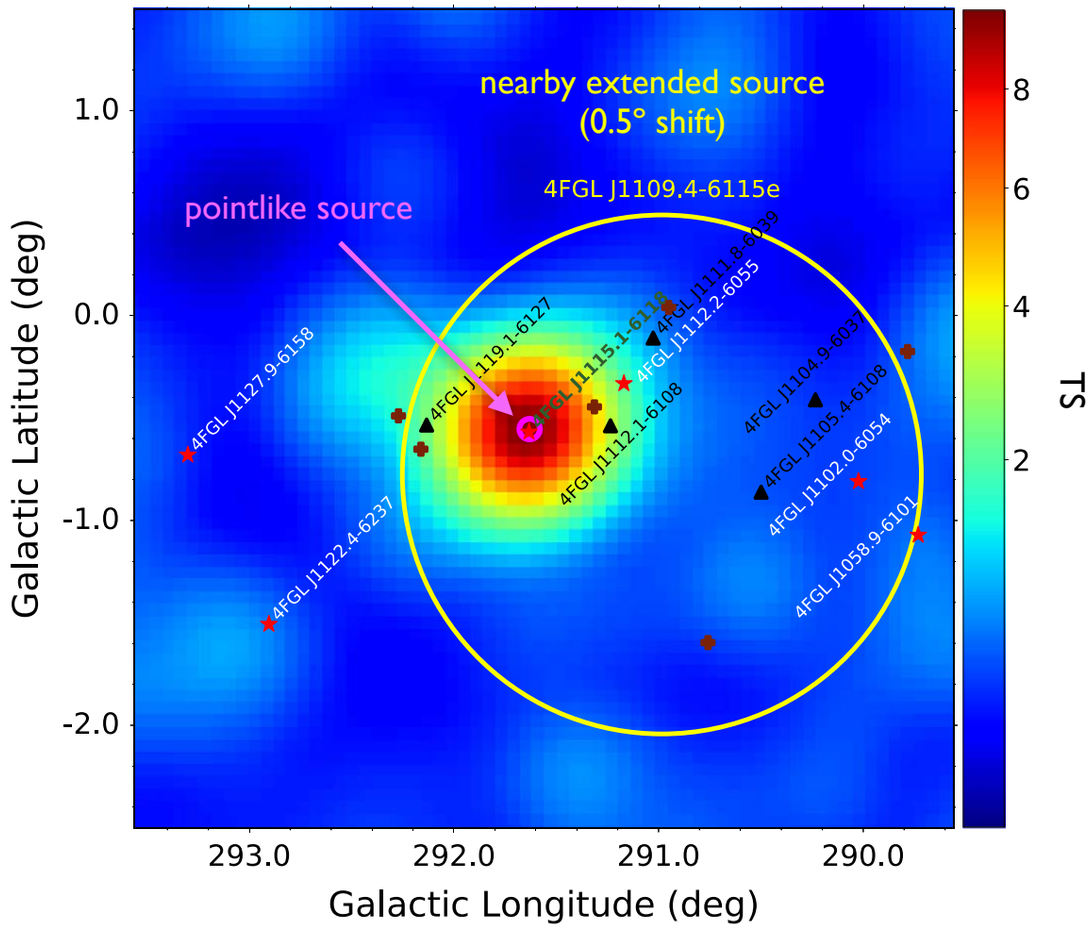
NGC 3603 with *Fermi* LAT: two analyses with different interstellar models (also different models for nearby sources)

- significant extension Gauss σ = 1.1±0.1°
- pointlike source preferred

Yang et al. (2017)



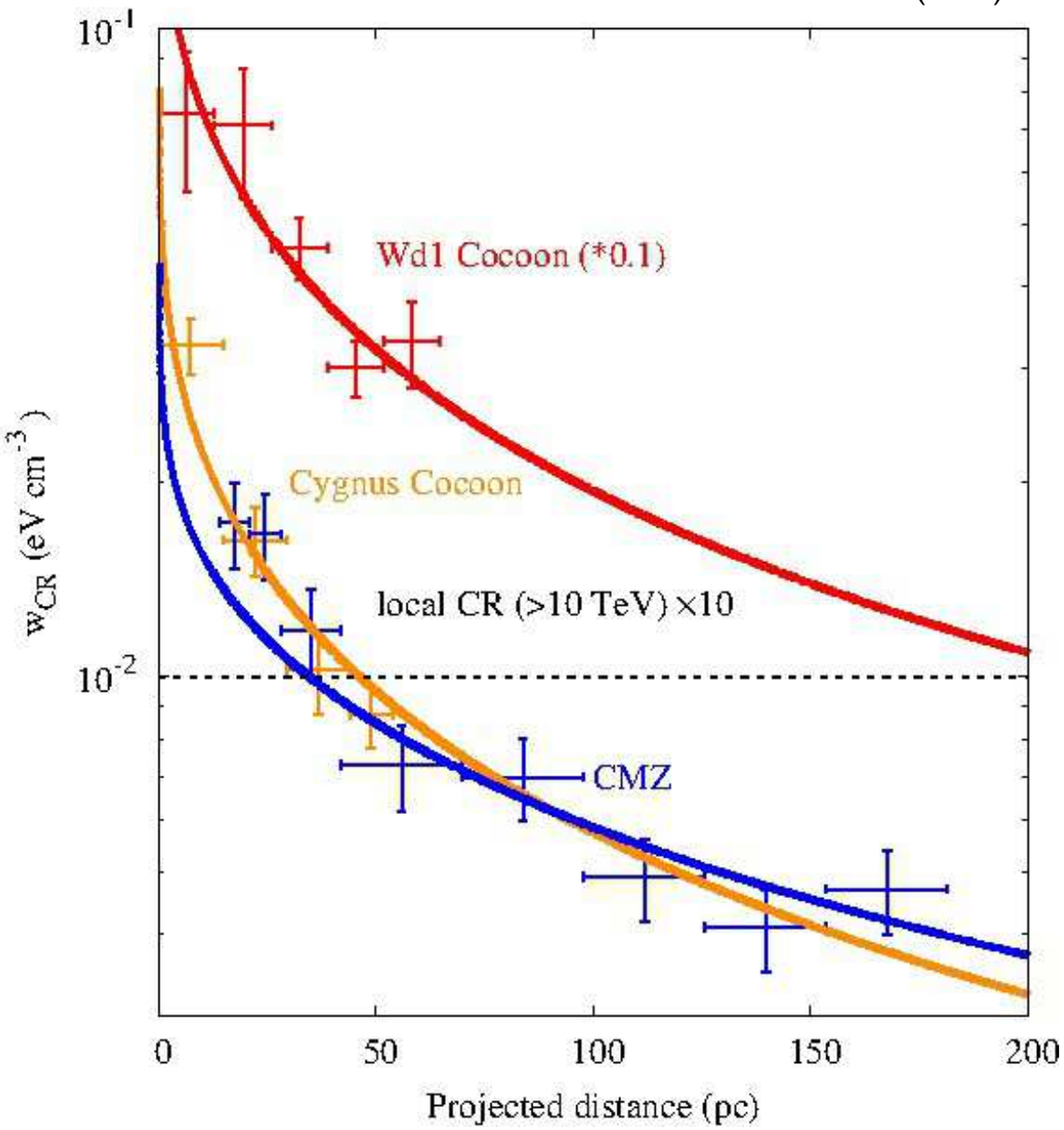
Saha, Dominguez, LT et al. (2020)



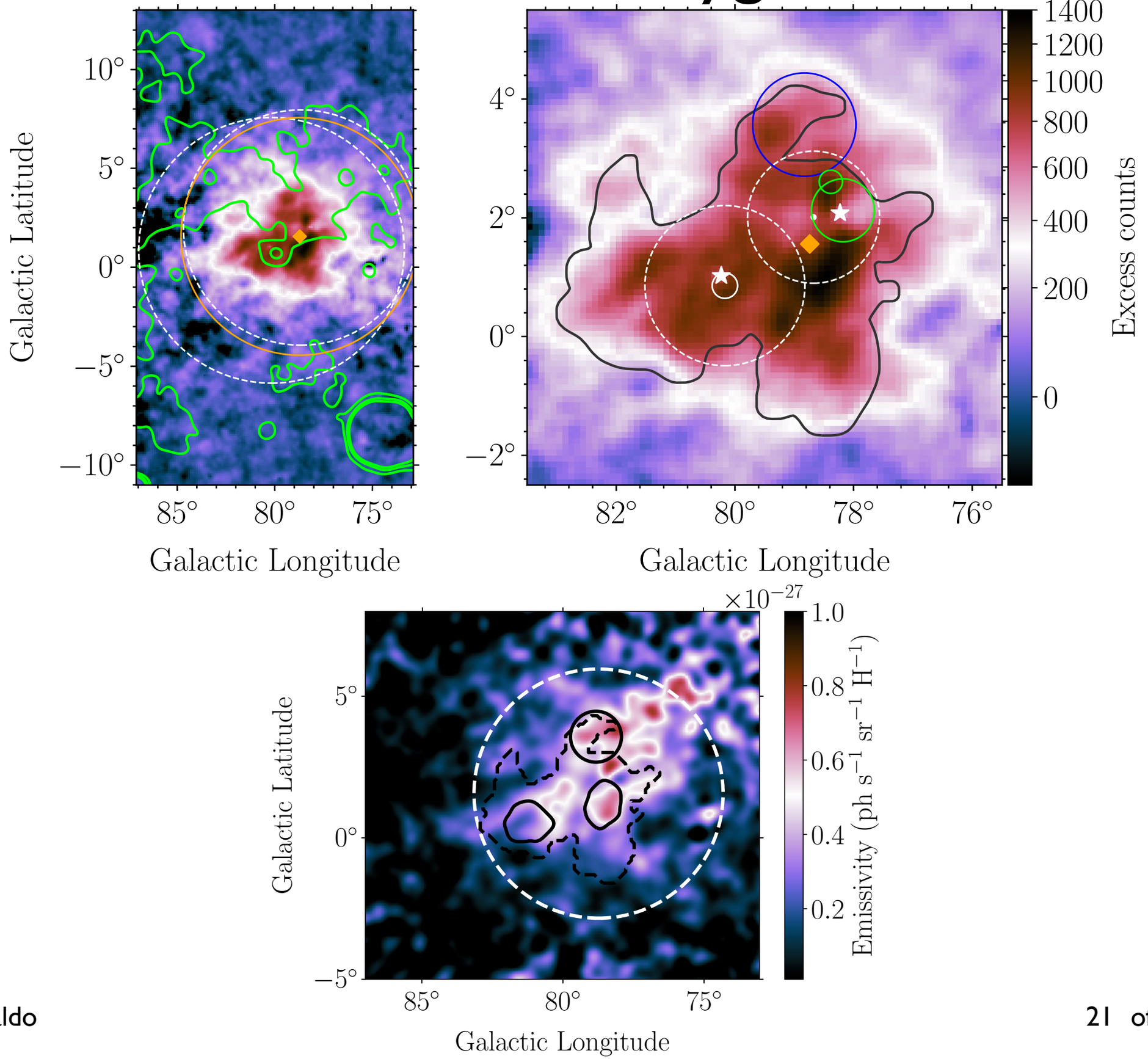
A simple universal interpretation?

- Inferred 1/r particle distribution
- Nuclei injection over Myr plus diffusion
- Westerlund 1: diffusion coefficient reduced by two orders of magnitude w.r.t. interstellar average

Aharonian et al. (2019)



A close look at Cygnus X



Astiasarain, LT et al. (2023)

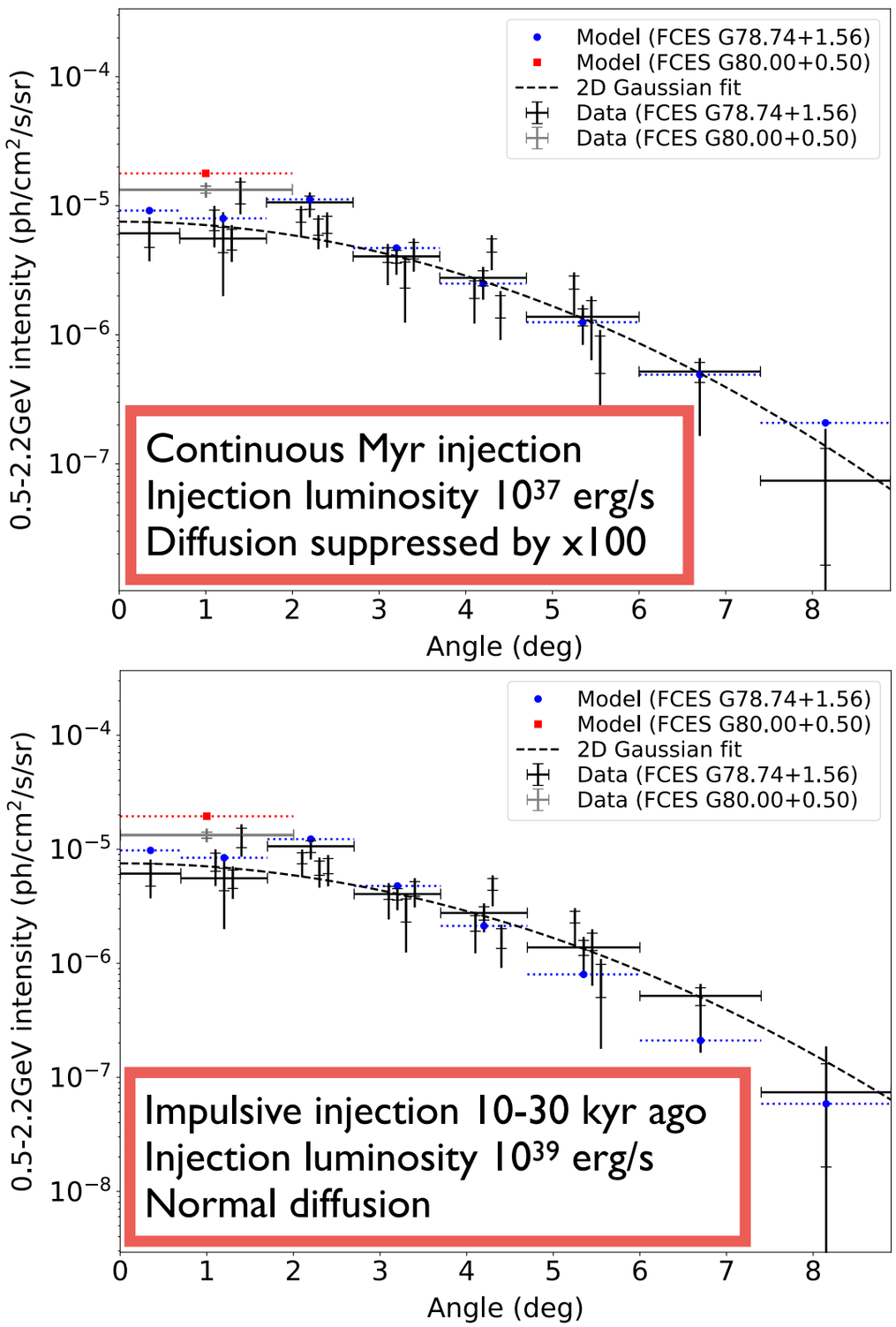
Cygnus X: multiple interpretations

Ruizhi Yang
Thibault Vieu

- The spatial properties do not clearly trace back the particle source to any known stellar clusters or energetic objects
- Simple modelling → variety of viable scenarios compatible with *Fermi* LAT
  - hadronic OR leptonic
  - injection/diffusion scenarios relevant for stellar cluster OR supernova remnant

Bhadra et al. 2022: similar conclusions for Westerlund 1

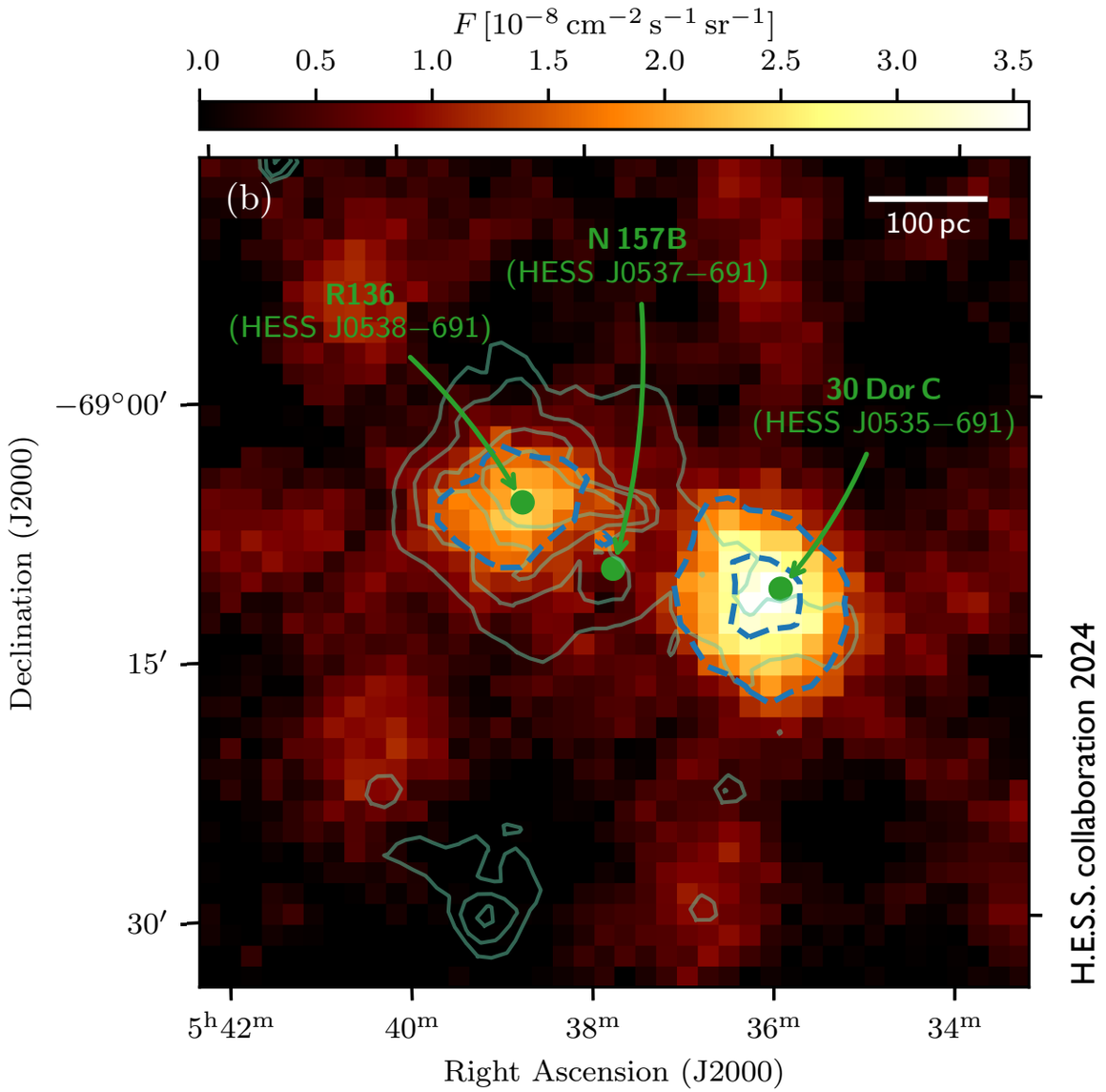
Astiasarain, LT et al. (2023)



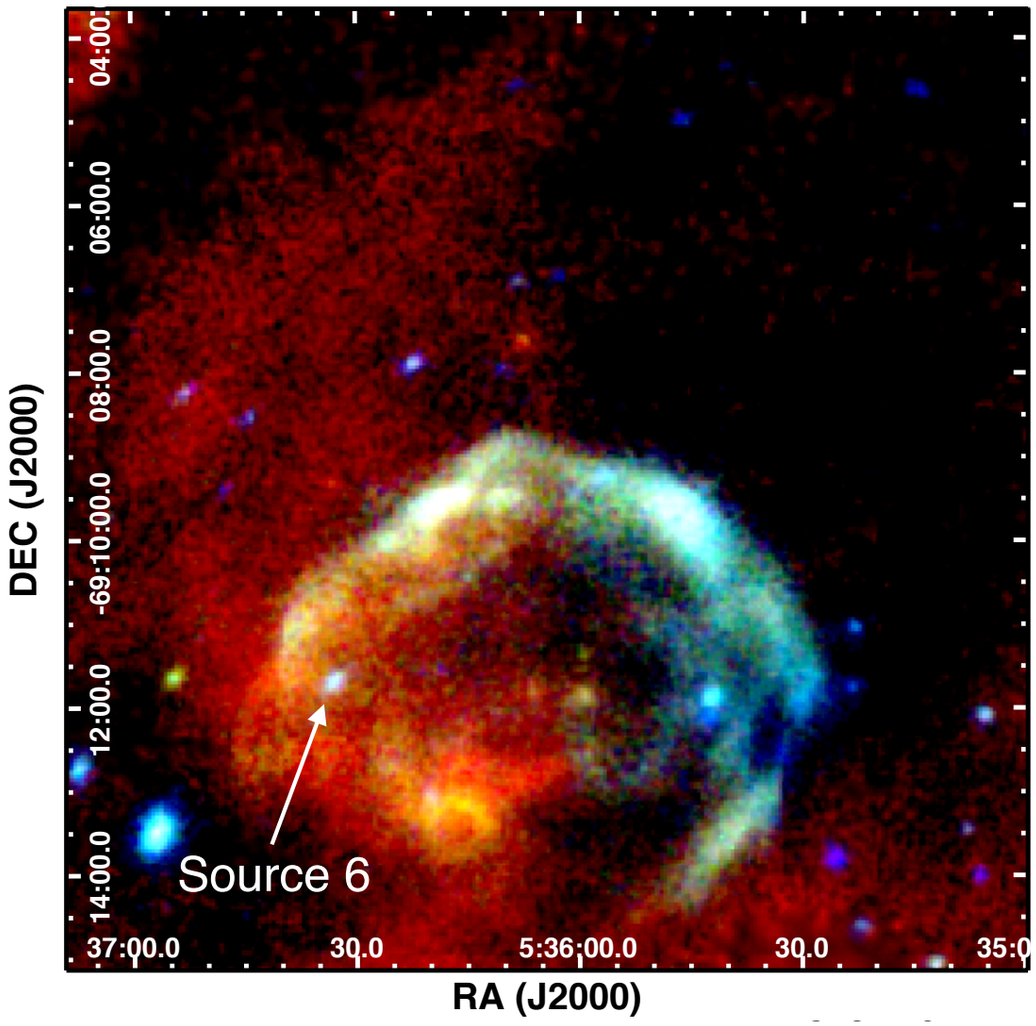
Another ambiguous case: 30 Dor C

Lars Mohrmann

- TeV emission in the direction of 30 Dor C
- X-ray data: morphological and spectral features of a supernova remnant



XMM-Newton Kavanagh et al. 2019



Unbiasing the gamma-ray view of SFRs

- Current results mostly based on individual cherry-picked regions
- Challenges:
  - Systematise associations to SFRs in gamma-ray catalogs
  - Population studies of promising targets
  - Which multiwavelength source lists to consider?

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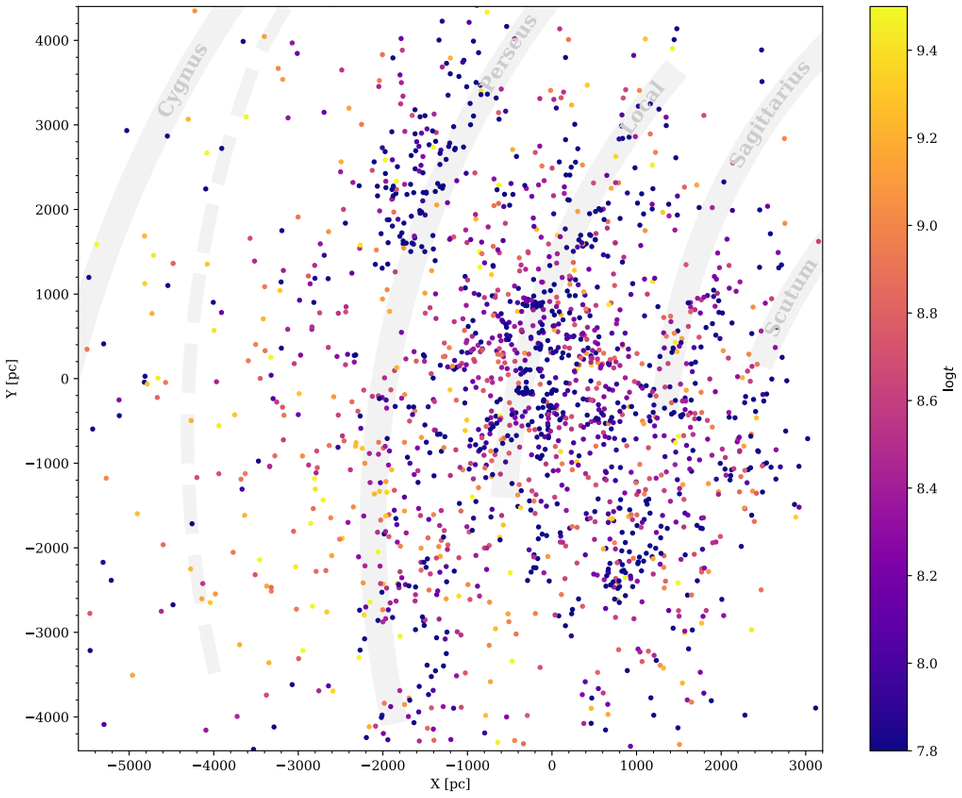
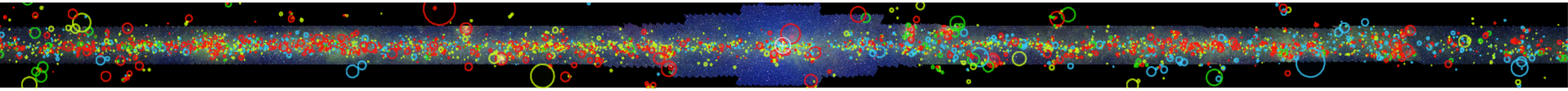
Ava Webber
Alison Mitchell

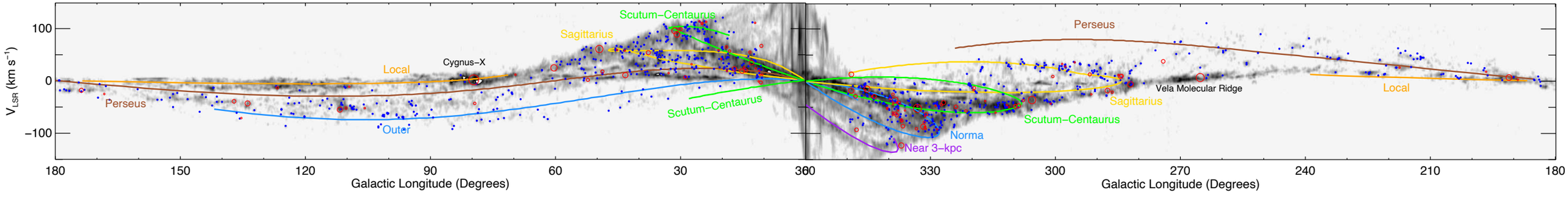
Gaia DR2 catalog of stellar clusters, Cantat-Gaudin et al. 2020



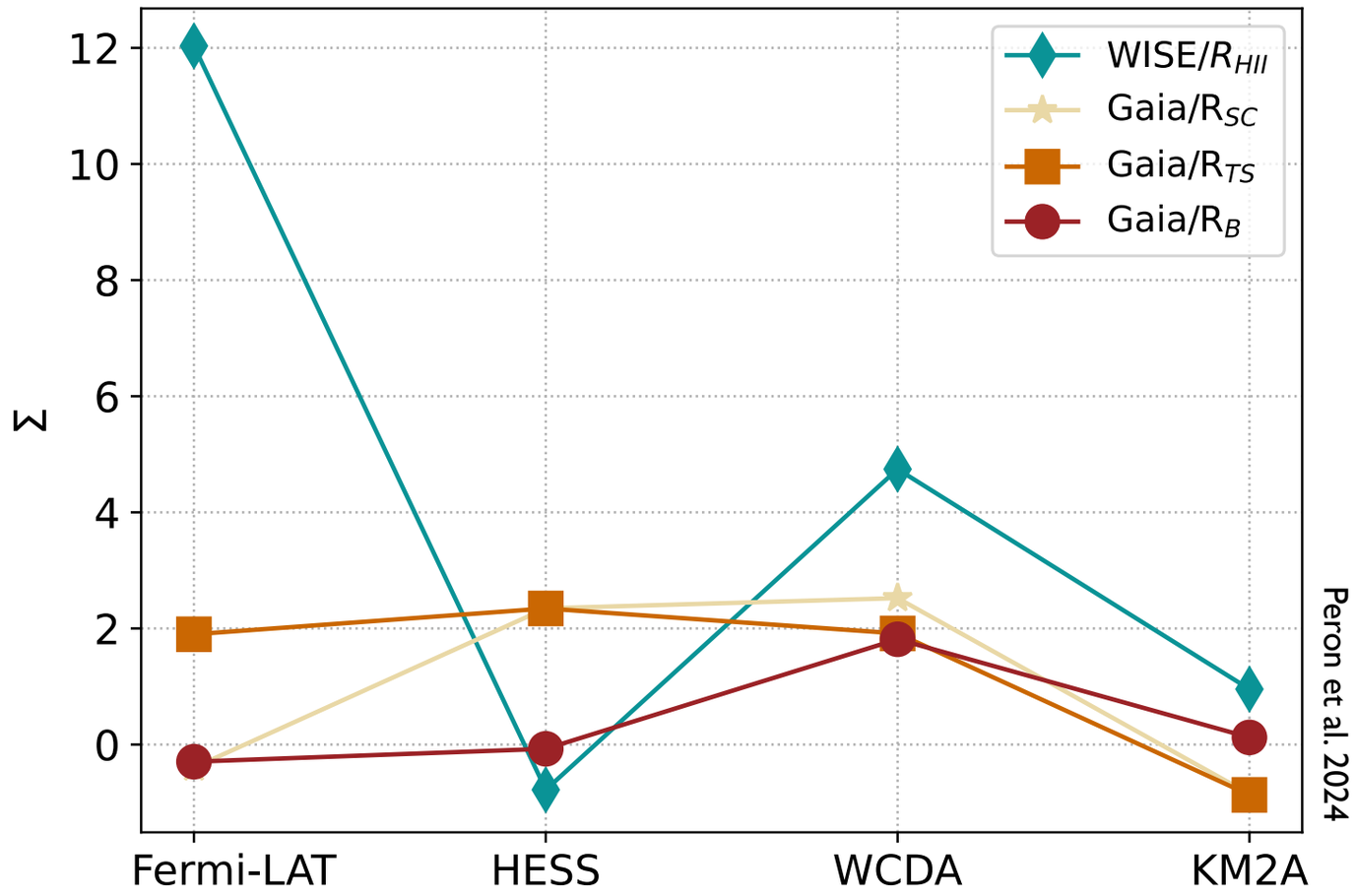
WISE list of HII regions, Anderson et al. 2014



Red MSX MYSOs catalog, Urquhart et al. 2014



Young SFRs shining in gamma-rays?



Giada Peron

- 138 unassociated *Fermi*-LAT sources coincident with WISE HII regions (~50 chance coincidences)
- Lower significance for more evolved Gaia clusters
- LAT catalogs are based on pointlike source detection: could miss extended sources

Final remarks

- Growing evidence that star-forming regions are gamma-ray emitters
- We still have work to do
  - Robust characterisation of gamma-ray emission
  - Discriminate between multiple interpretations
  - Develop a population view of star-forming regions in gamma rays
- Synergies with the theoretical and multi-wavelength/ messenger community are essential!