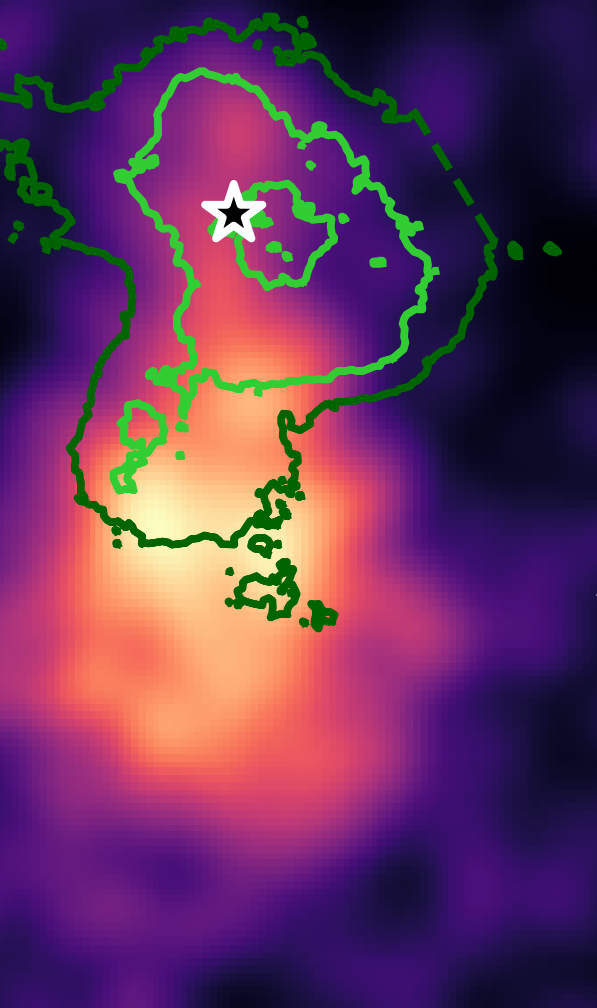
Max-Planck-Institut für Kernphysik

Discovery of a nascent outflow driven by the massive star cluster Westerlund 1



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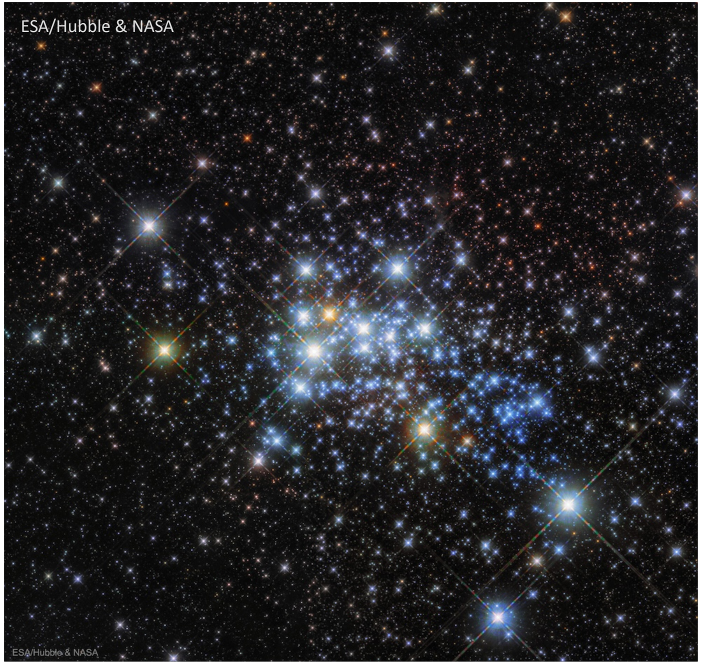
ICRC 2025 — July 17, 2025

The young massive star cluster Westerlund 1

- **Westerlund 1**
  - most massive young star cluster known in our Galaxy
  - rich population of giant stars and Wolf-Rayet stars
  - age $\sim 4\,\mathrm{Myr}$, distance $\sim 4\,\mathrm{kpc}$, total mass $\sim 10^5\,M_\odot$



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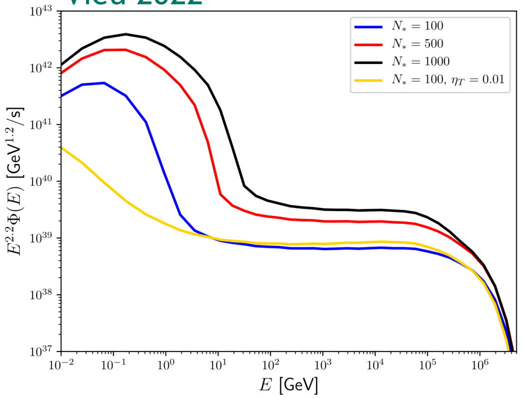
Vieu 2022



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    (e.g. Aharonian 2019, Morlino 2021, Vieu 2022, 2023)

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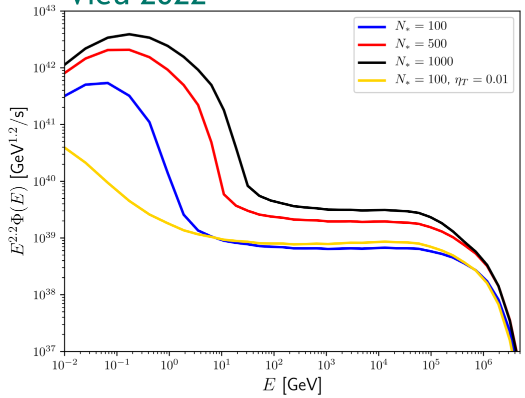
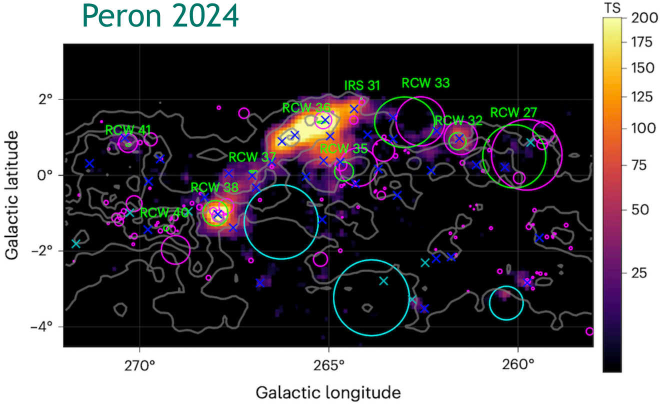
    (e.g. Aharonian 2019, Morlino 2021, Vieu 2022, 2023)
  - supported by detection of GeV/TeV gamma-ray emission from multiple clusters

Vieu 2022



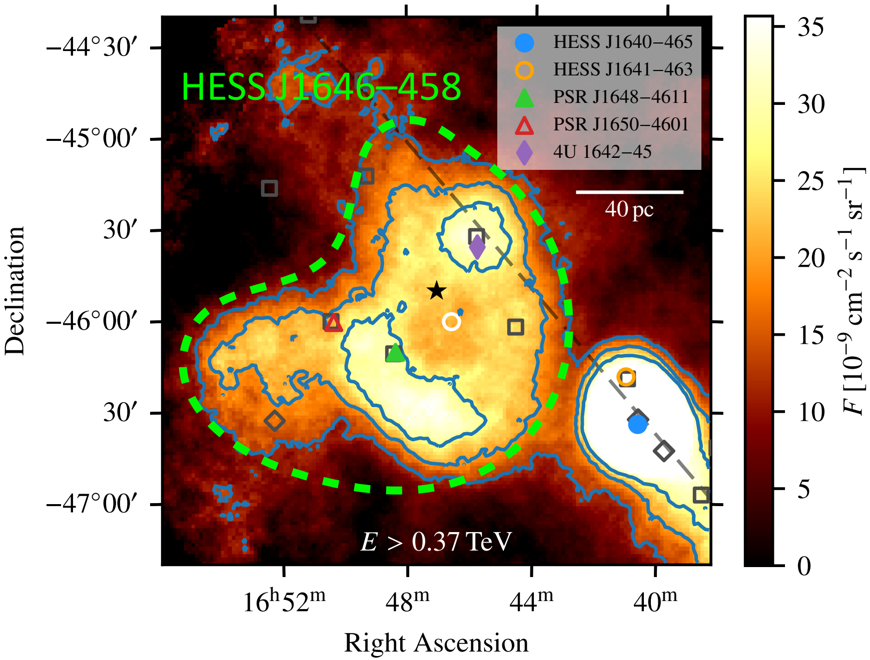
Peron 2024



TeV gamma-ray emission from Westerlund 1

- **HESS J1646–458**
  - extended gamma-ray source (diameter $\sim 140\,\mathrm{pc}$)
  - emission associated with Westerlund 1
  - ring-like structure

HESS 2022



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  - spectral index ~ 2.4
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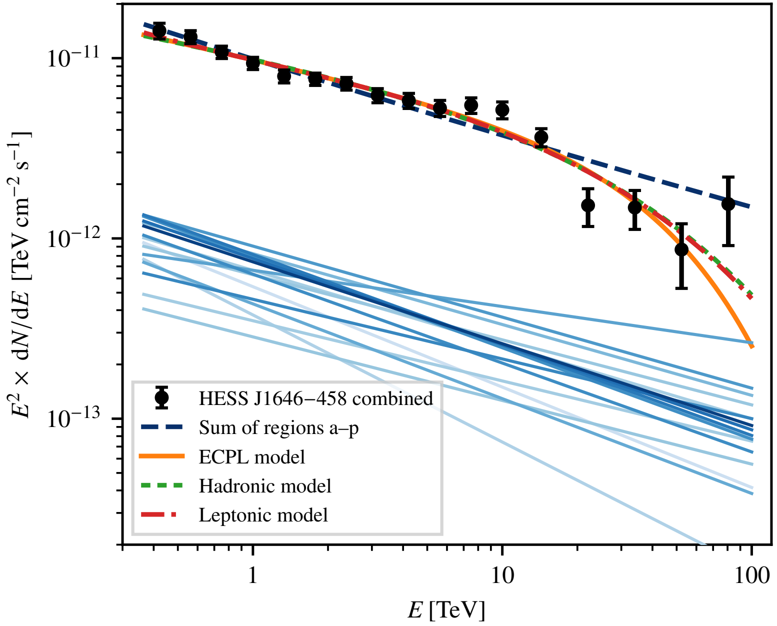

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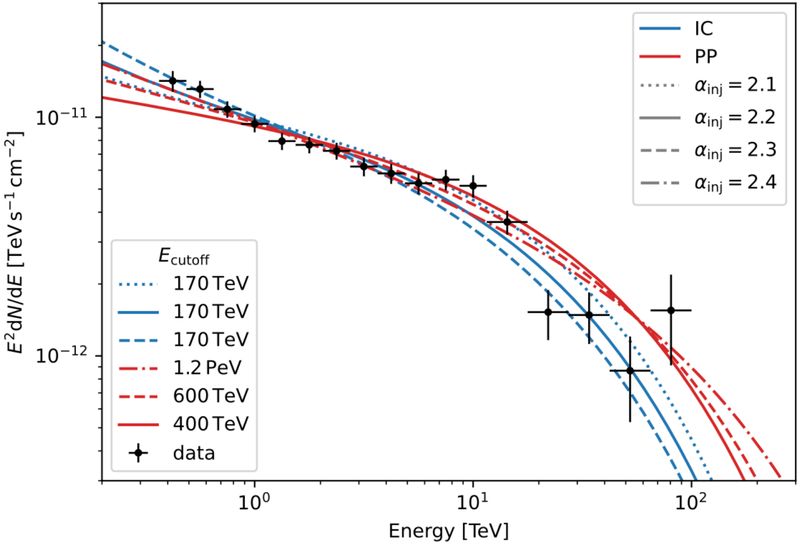
Härer 2023



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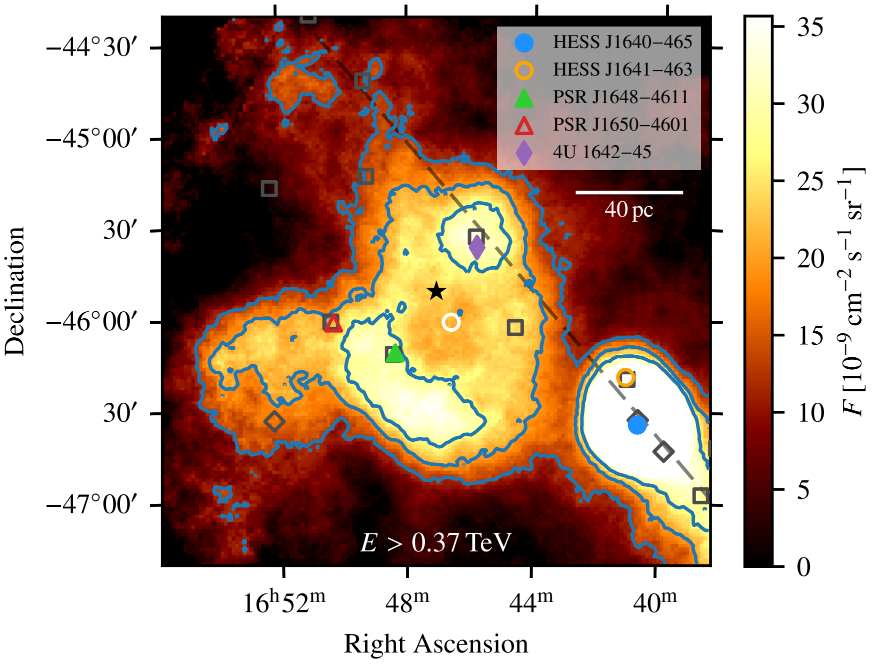

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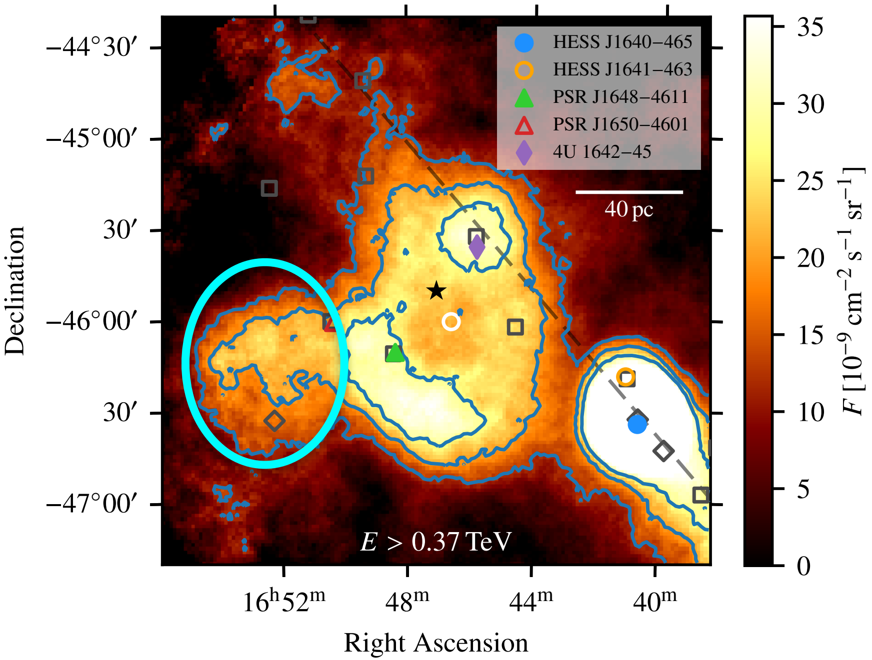
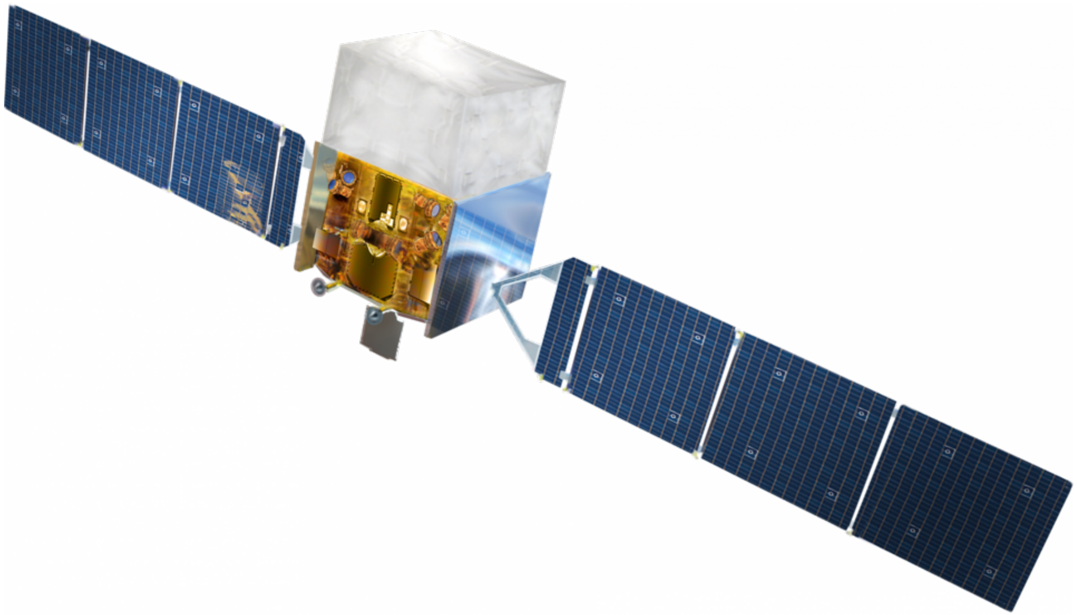
- **What is happening in this "annex"?!**

HESS 2022



The *Fermi*-LAT view of the Westerlund 1 field

- **New *Fermi*-LAT analysis**
  - 15 years of data
  - energy range: $3\,\mathrm{GeV} - 3\,\mathrm{TeV}$
  - non-standard background modelling



NASA

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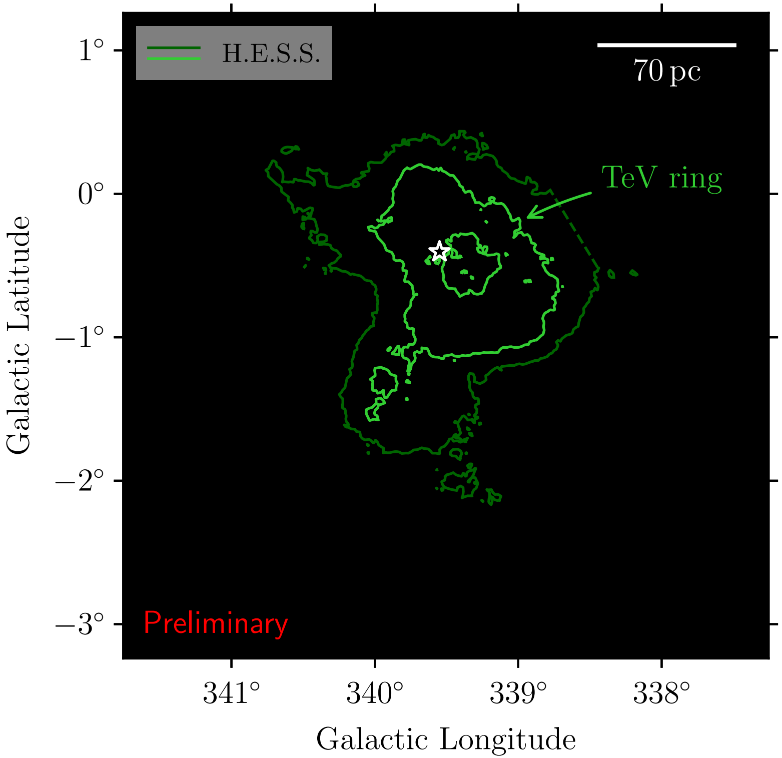

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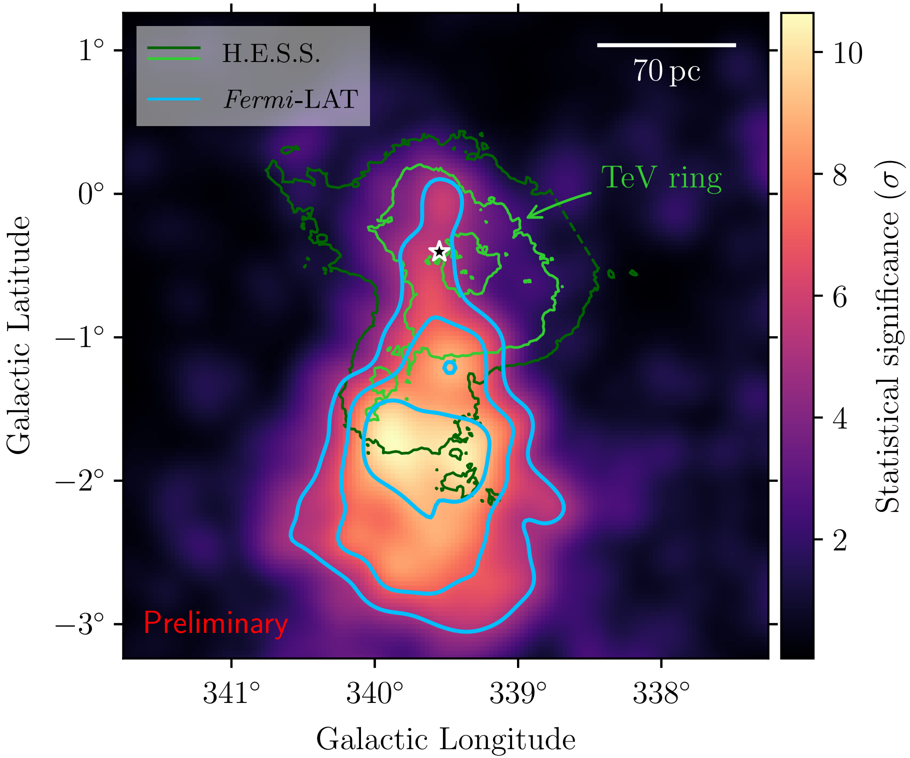

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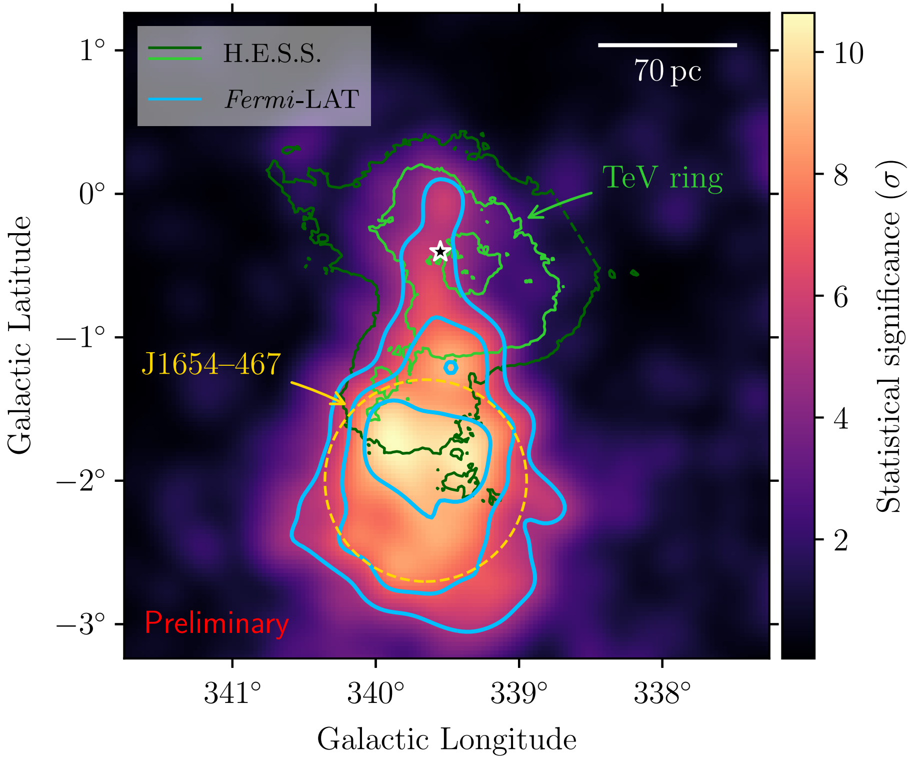

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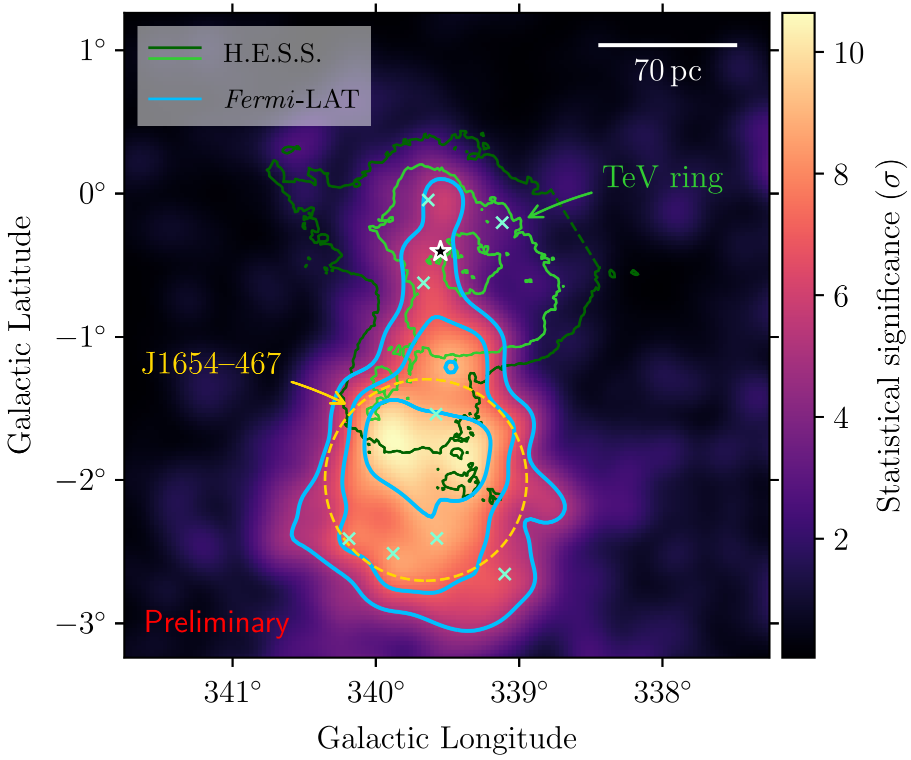

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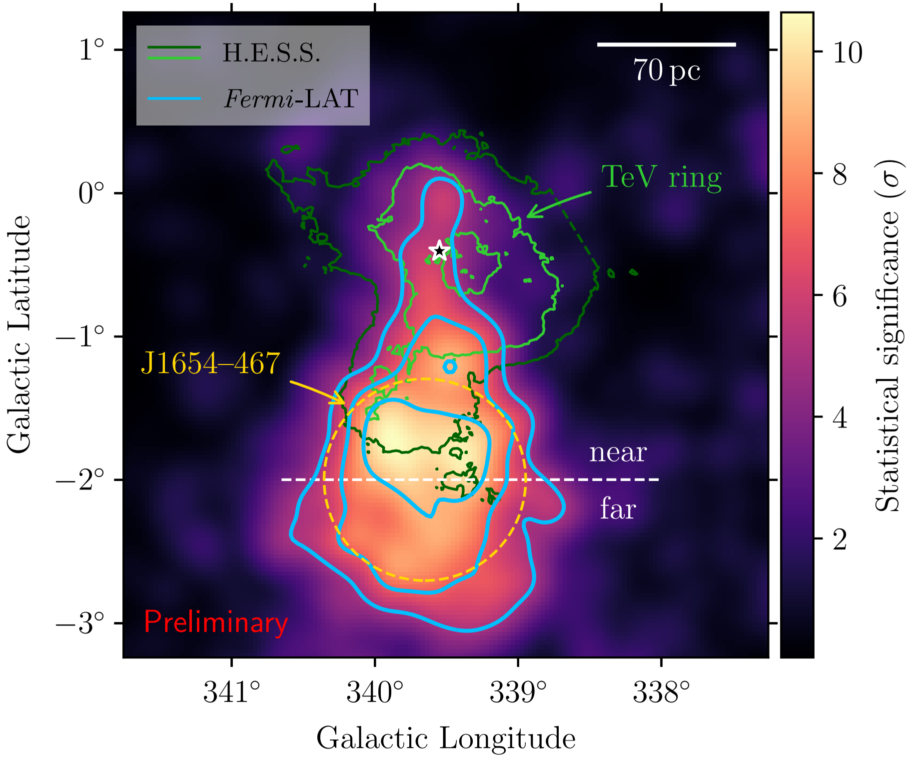

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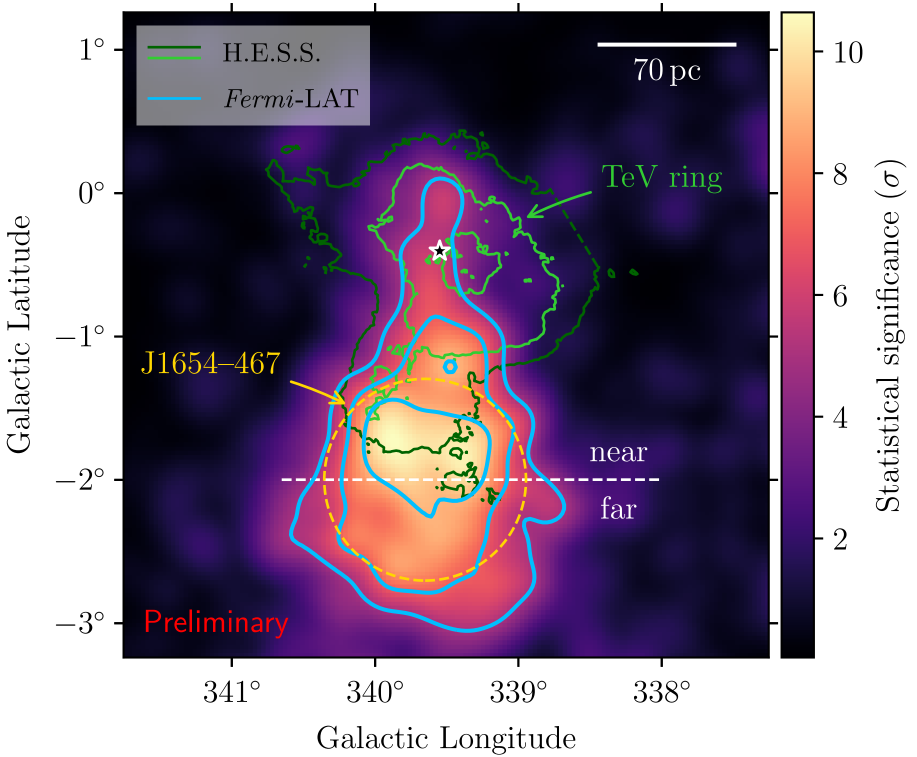
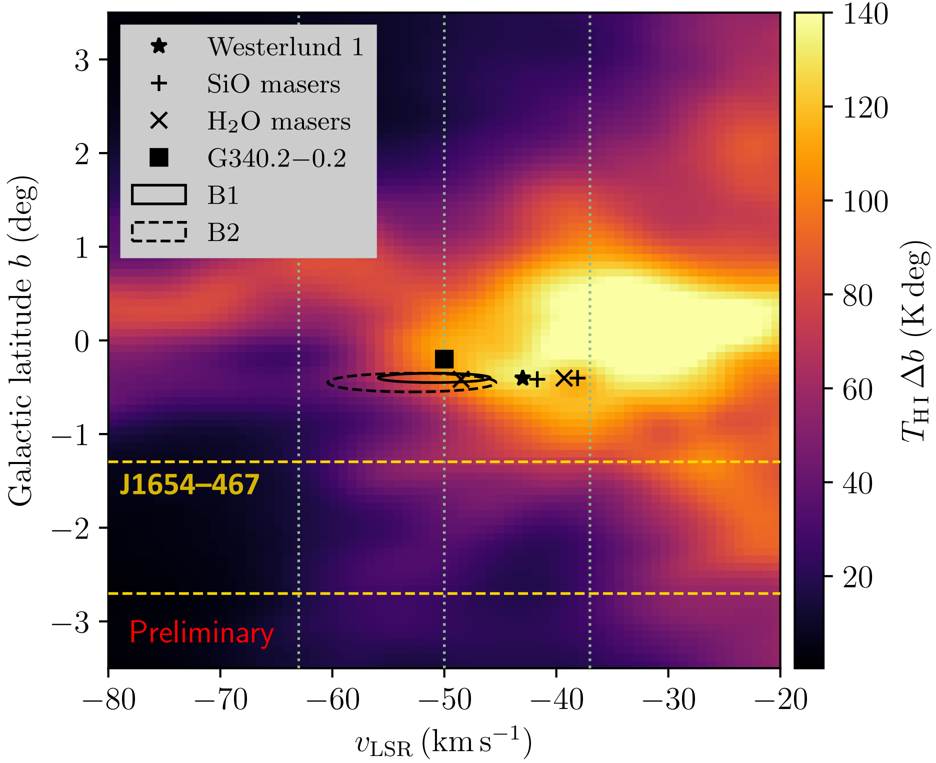
- **J1654–467**
  - smoothly connected with TeV emission
  - *could this be cosmic rays escaping from Westerlund 1…?!*



The interstellar gas density

- **HI emission line** (21 cm)
  - GASS survey (Kalberla 2015)
  - low density in latitude range of J1654–467



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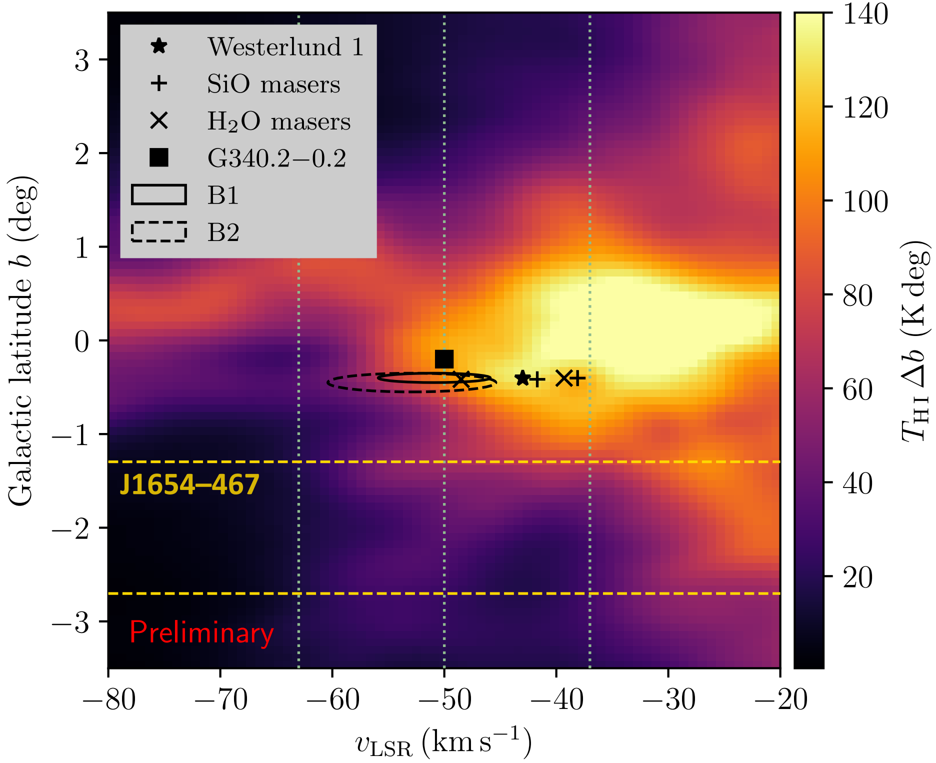
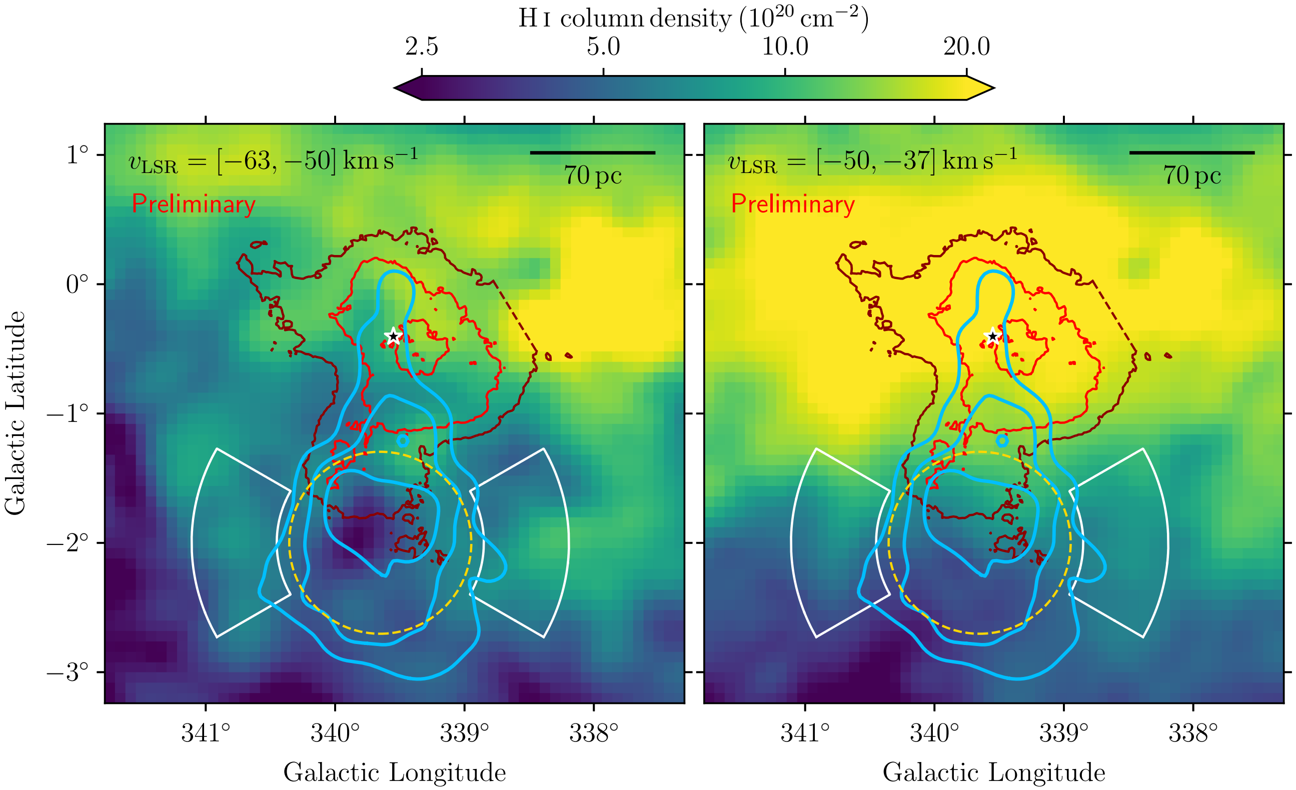
- **Challenge:**
  - need to relate velocity to physical distance
  - gas near Westerlund 1 not moving according to large-scale Galactic rotation curve models (e.g. Negueruela 2022)
  - association of features in gas maps not straightforward
- **Approach:**
  - using two broad intervals in v_{LSR}: $[-63, -50]\,\mathrm{km\,s^{-1}}$ and $[-50, -37]\,\mathrm{km\,s^{-1}}$



The interstellar gas density

- **H I column density maps**
  - clear under-density coincident with J1654–467!
  - difference to neighbouring lines of sight: $(0.7 - 1.5) \times 10^{20}\,\mathrm{cm}^{-2}$

- *Could this be a cavity created by an outflow from Westerlund 1…?!*



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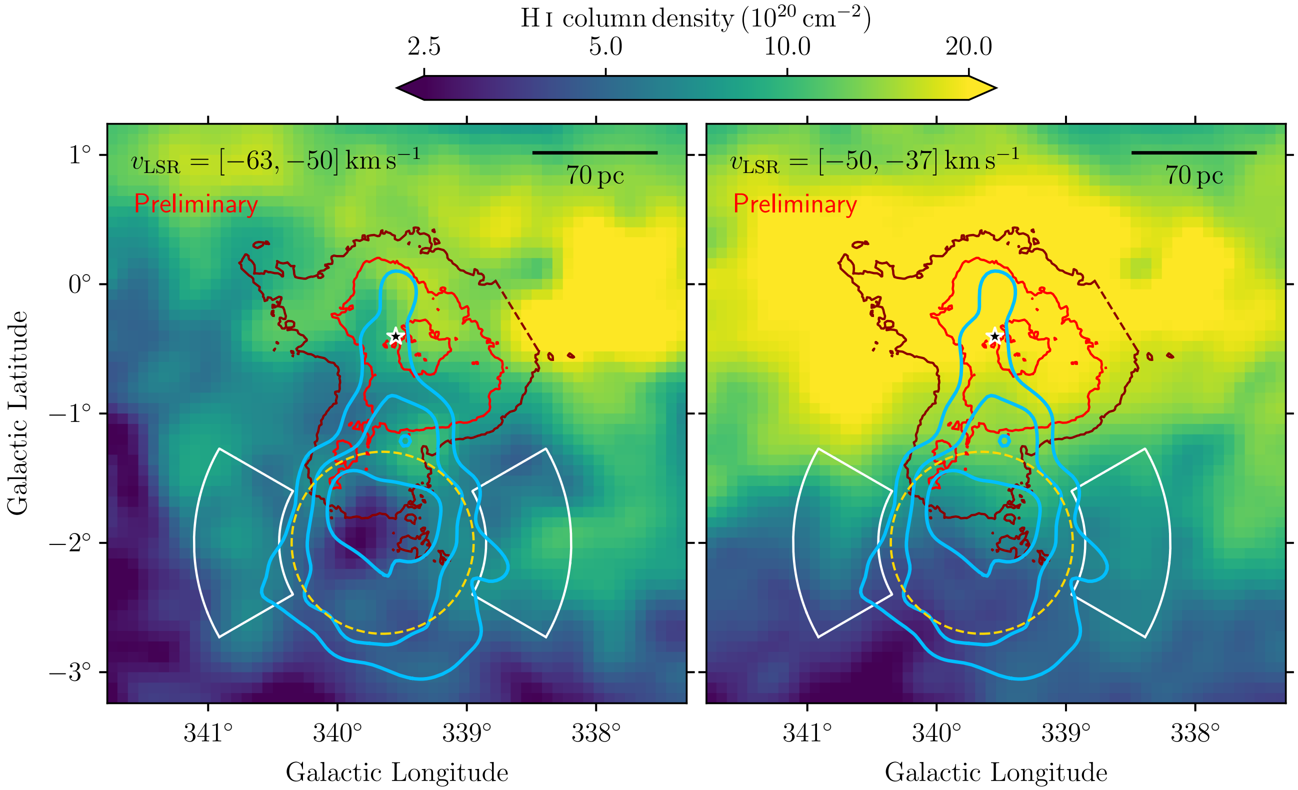
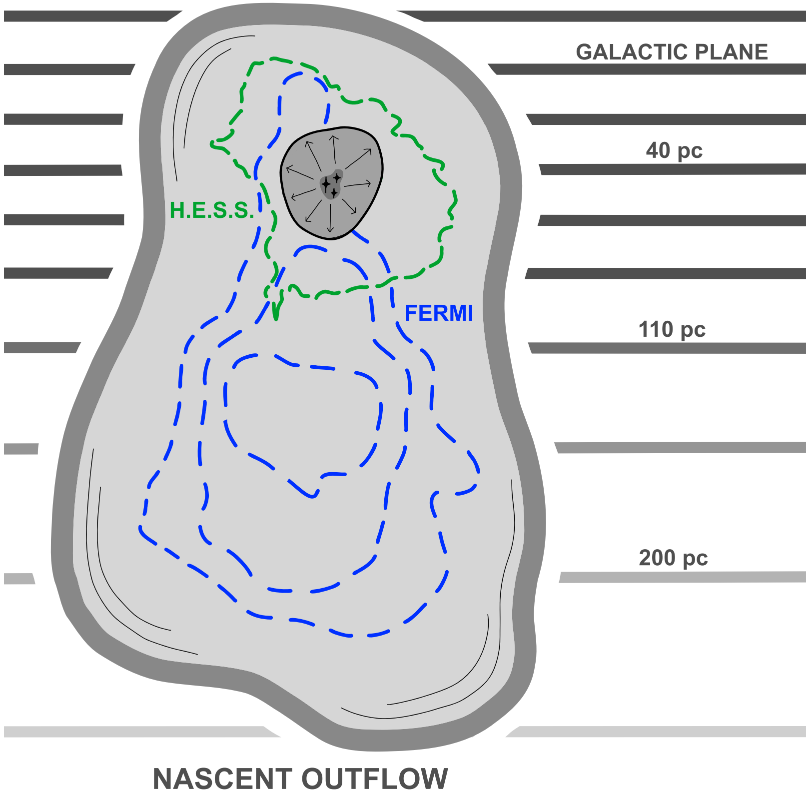
- *Could this be a cavity created by an outflow from Westerlund 1…?!*
- **Properties of the cavity**
  - extent $\sim (70\,\mathrm{pc})^3$
  - $0.3 - 0.7\,\mathrm{atoms\,cm}^{-3}$ excavated
  - energy requirement $\sim 10^{50}\,(T/10^4\,\mathrm{K})\,(n/1\,\mathrm{cm}^{-3})\,\mathrm{erg}$
    → within energy budget!



A nascent outflow from Westerlund 1

- **Proposed scenario: “nascent outflow”**
  - superbubble expands asymmetrically due to ISM density gradient, but has not fully broken out of the galactic disk yet



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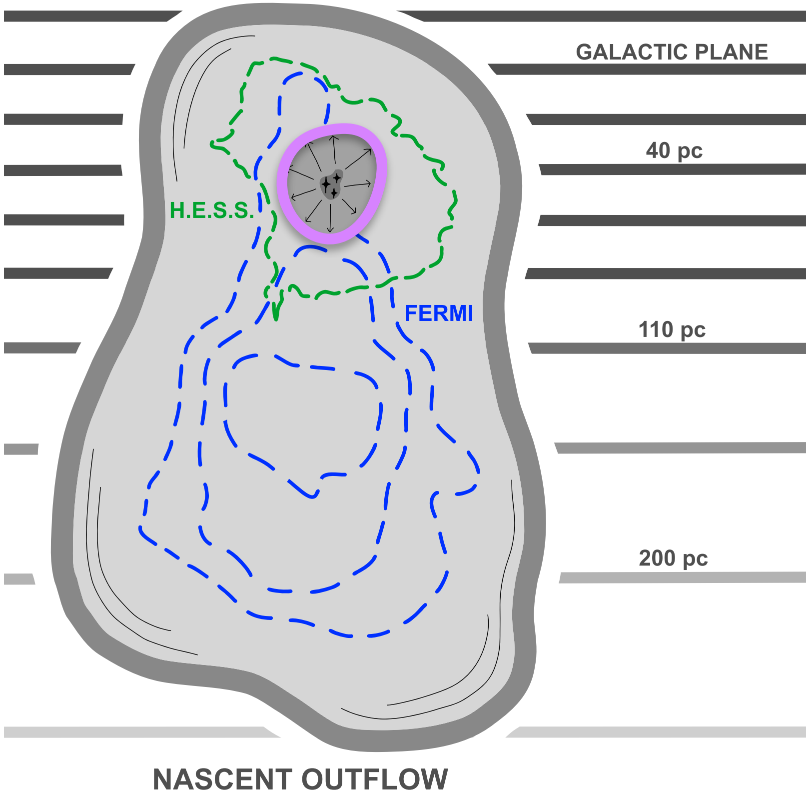

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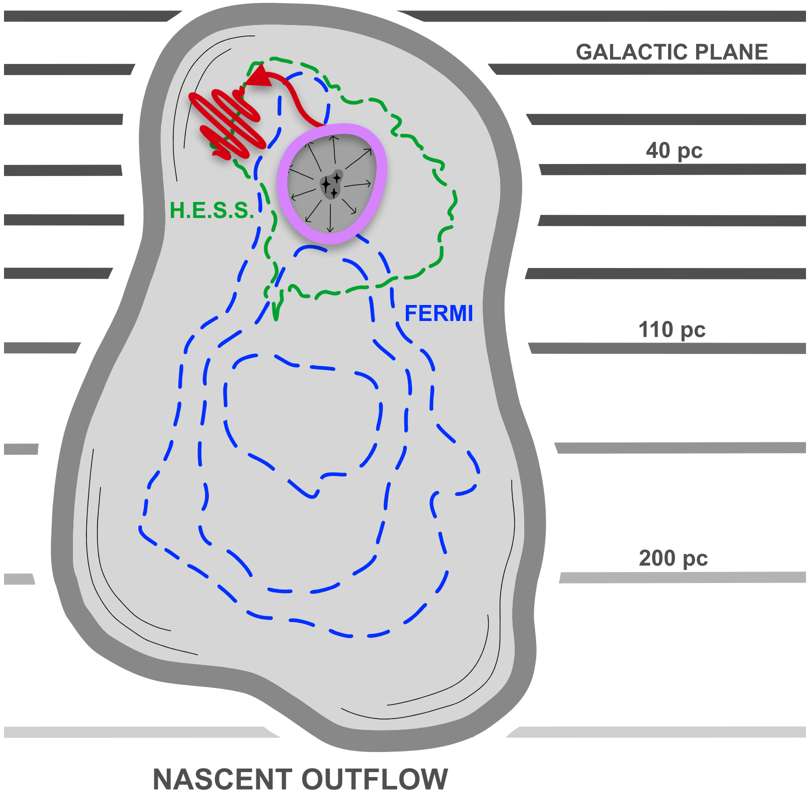

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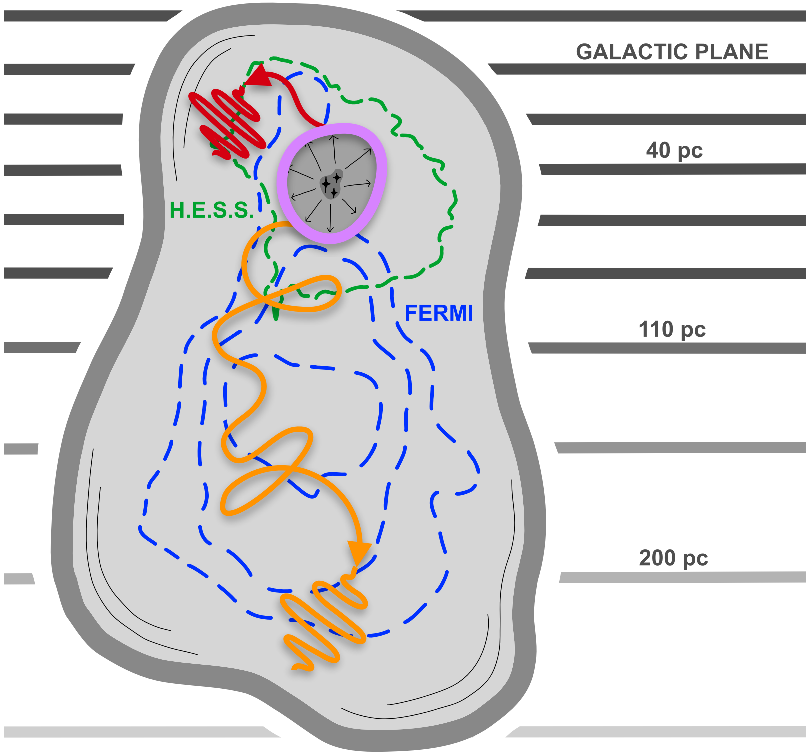
  - low-energy electrons are transported along outflow → produce GeV emission far from star cluster



NASCENT OUTFLOW

Modelling the nascent outflow

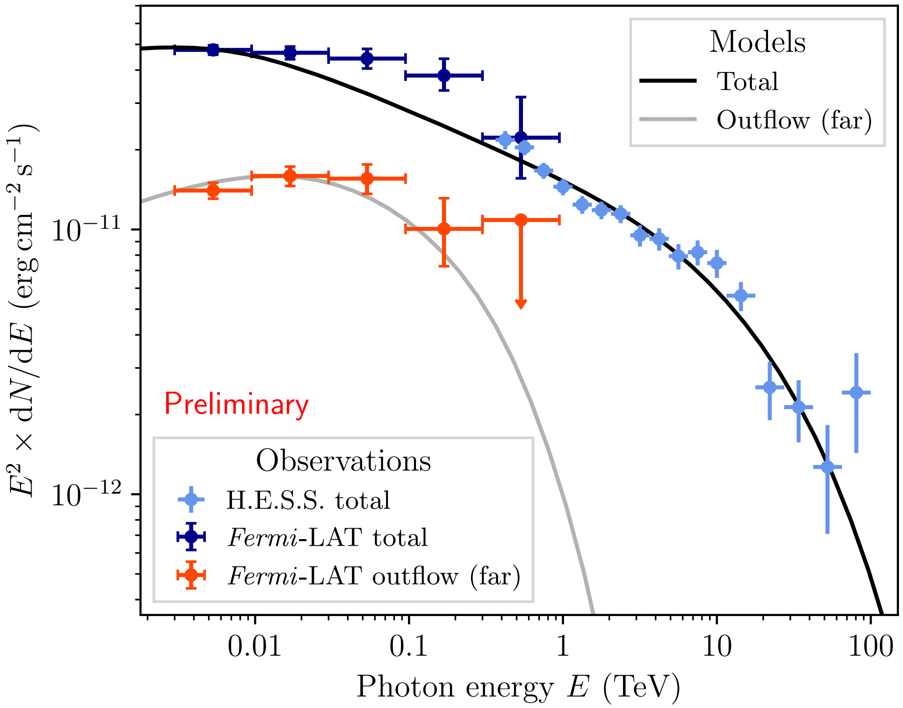
- **Leptonic inverse-Compton (IC) model**
  - extension of model presented in Härer 2023
  - for entire region and "far outflow"

- **Basic assumptions**
  - wind power: $10^{39}\,\mathrm{erg\,s^{-1}}$
  - electron injection index: 2.25
  - cluster age: $4\,\mathrm{Myr}$
  - magnetic field: $2\,\mu\mathrm{G}$
  - transport time to "far outflow": $125 - 200\,\mathrm{kyr}$

  → electron acceleration efficiency: $\eta_e \approx 0.7\,\%$

  → electron energy density in outflow:

  $U_e \sim (1 - 10)\,\mathrm{eV\,cm^{-3}}$



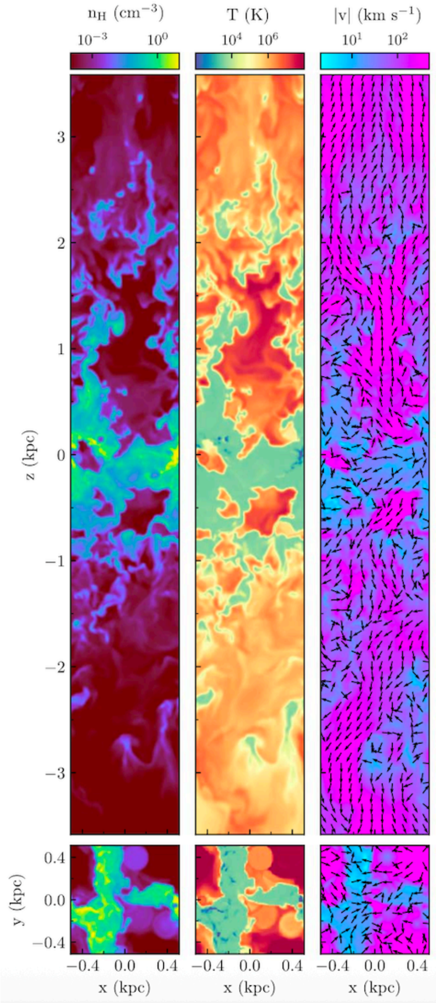
Implications

- **Cosmic rays in the outflow**
  - diffusive shock acceleration theory predicts $\eta_p > \eta_e$
  - expect $U_p > U_e$ and hence $U_p \gg U_{CR,\,\text{local}}$

→ *the outflow is loaded with – and potentially driven by – cosmic rays*

→ strong support for theoretical predictions of such outflows

(e.g. Johnson 1971, Ipavich 1975, Breitschwerdt 1991, Girichidis 2016, Modak 2023, Armilotta 2024)



Armilotta 2024

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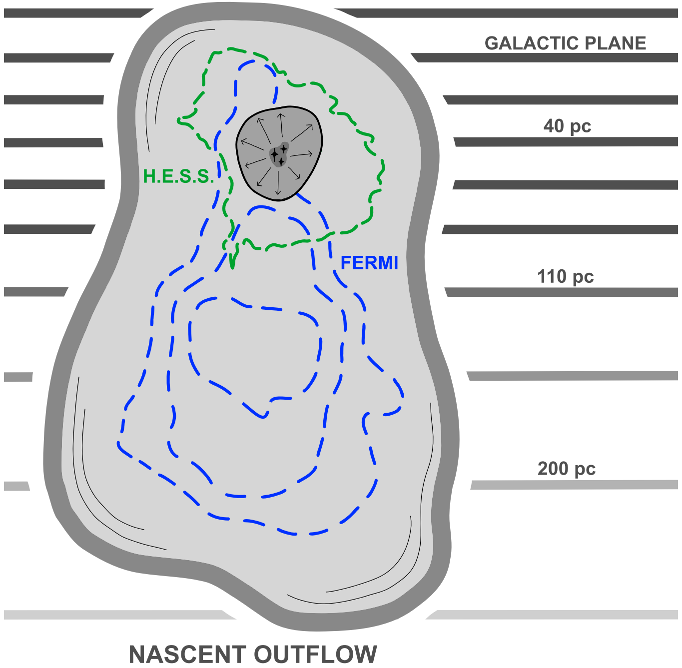
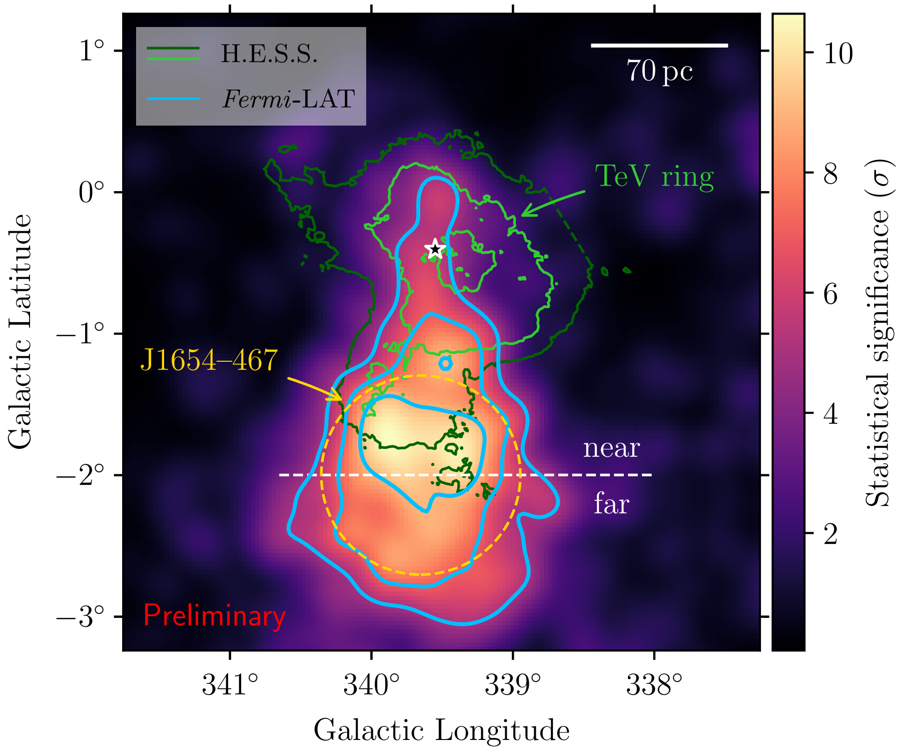
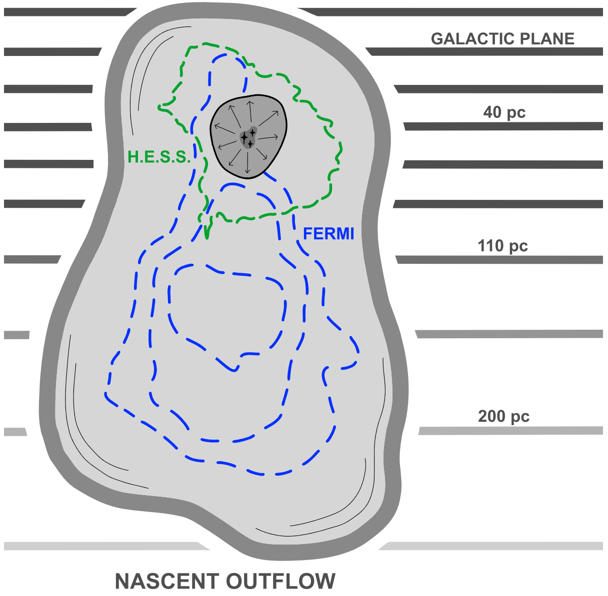
- **Concluding notes**
  - expect significant transport of cosmic rays out of the Galactic disk
  - dramatically different from typical assumption of isotropic diffusion!
  - a common feature of young massive star clusters?



Conclusion:
a cosmic-ray loaded nascent outflow from Westerlund 1



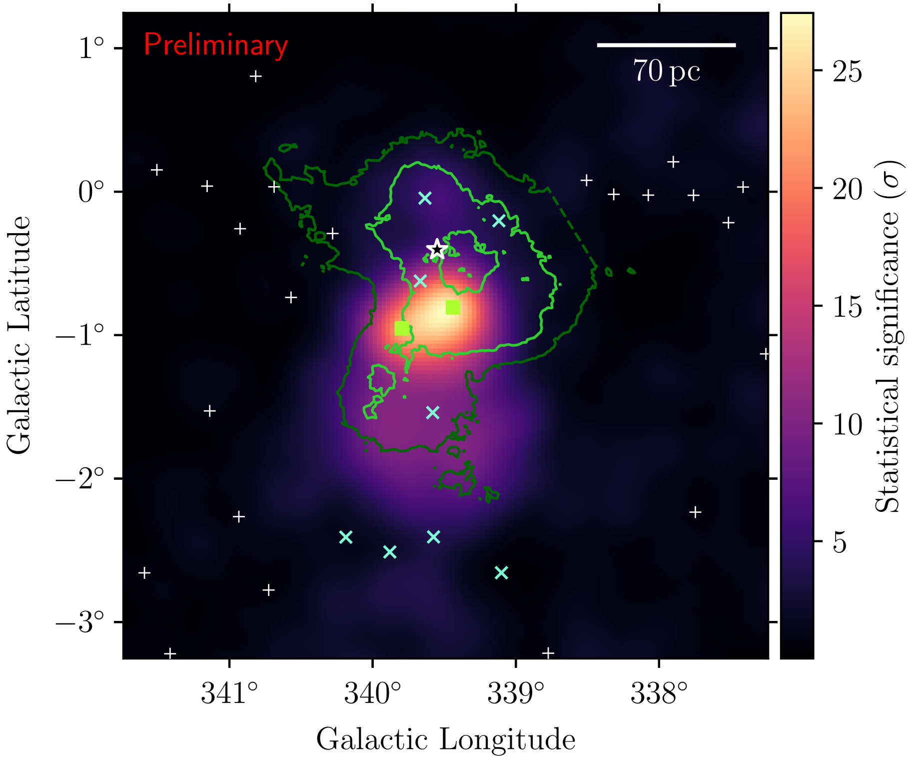


Backup slides

Fermi-LAT analysis details and map of total emission

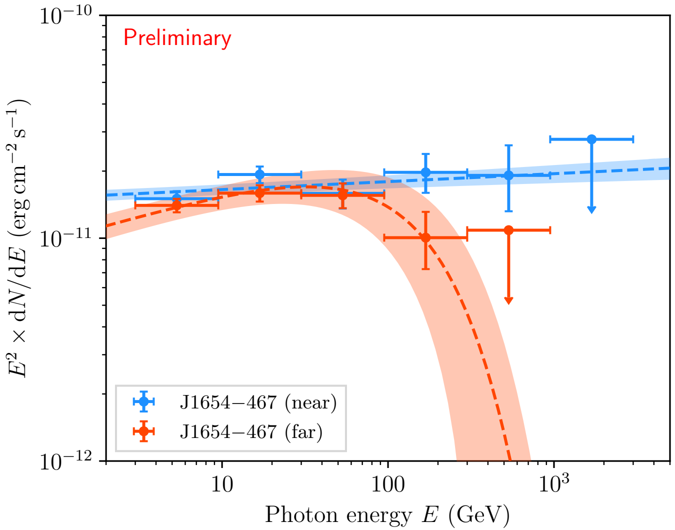
- **Analysis settings**
  - 15 years of data
  - IRFs: P8R3_SOURCEVETO_V3
  - energy range: $3\,\mathrm{GeV} - 3\,\mathrm{TeV}$
  - essential: careful modelling of interstellar emission
    - independent fit of ring templates for HI, CO, DNM
    - removal of “patch” component in standard model

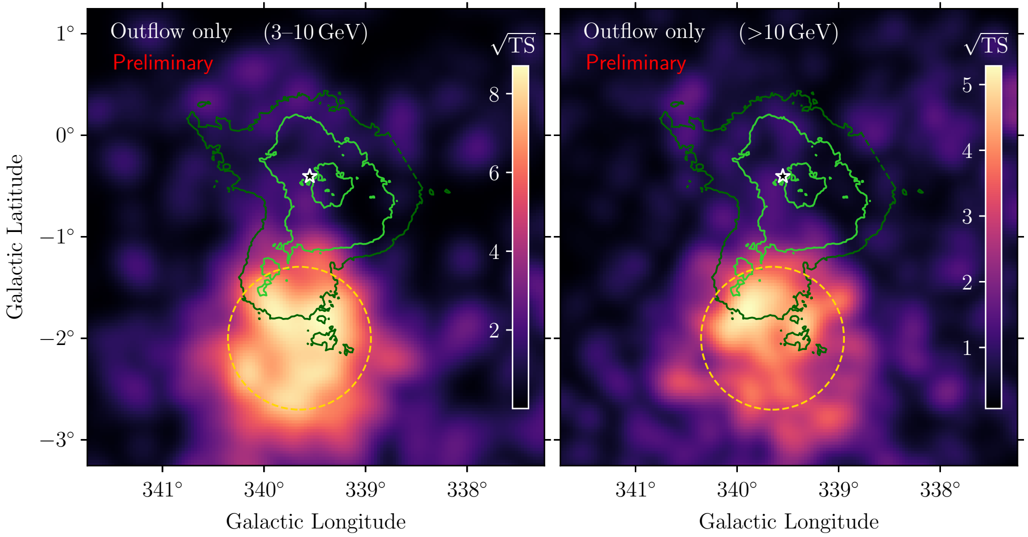
- **TS map of total emission**
  - removed 4FGL sources in vicinity from model (×)
  - emission dominated by two bright pulsars (■)
    → unrelated to Westerlund 1
    → include those in the model again



Energy-dependent morphology

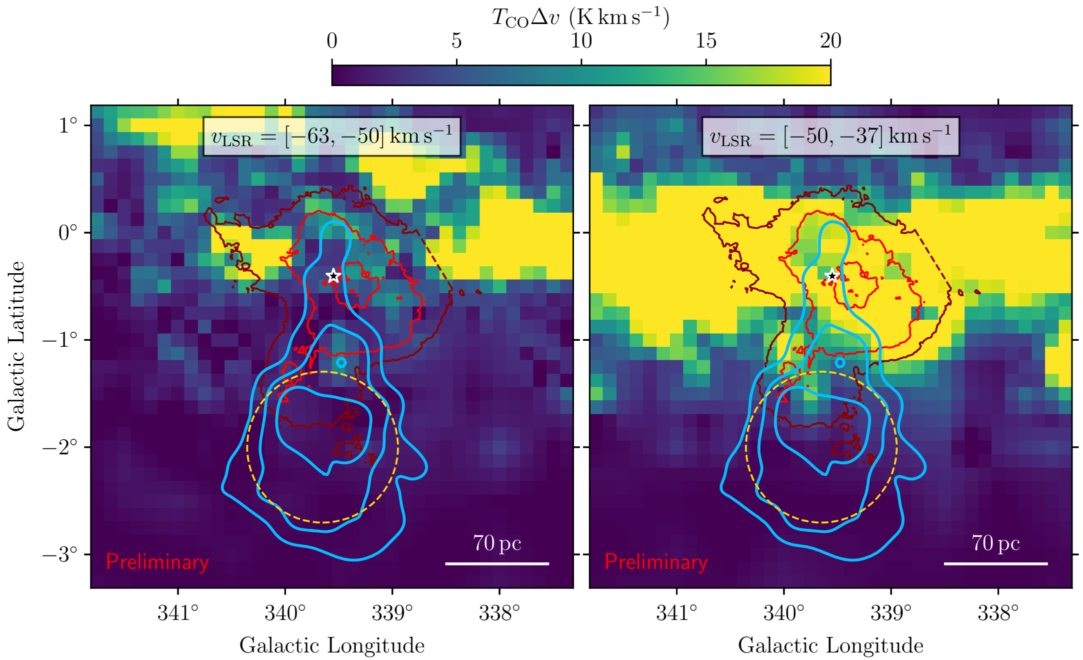
- **Energy-dependent morphology?**
  - hint of a spectral softening in the direction away from Westerlund 1
  - emission predominantly of leptonic origin?





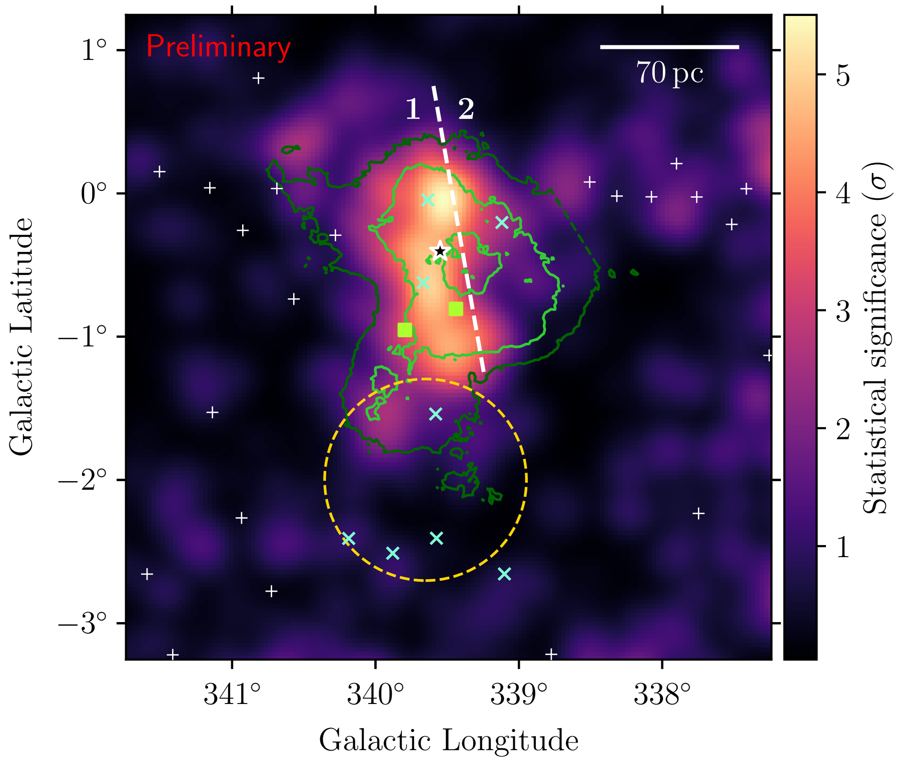
Molecular gas

- **^{12}CO line emission**
  - essentially no molecular gas in cavity
  - impossible to trace nuclei in the outflow



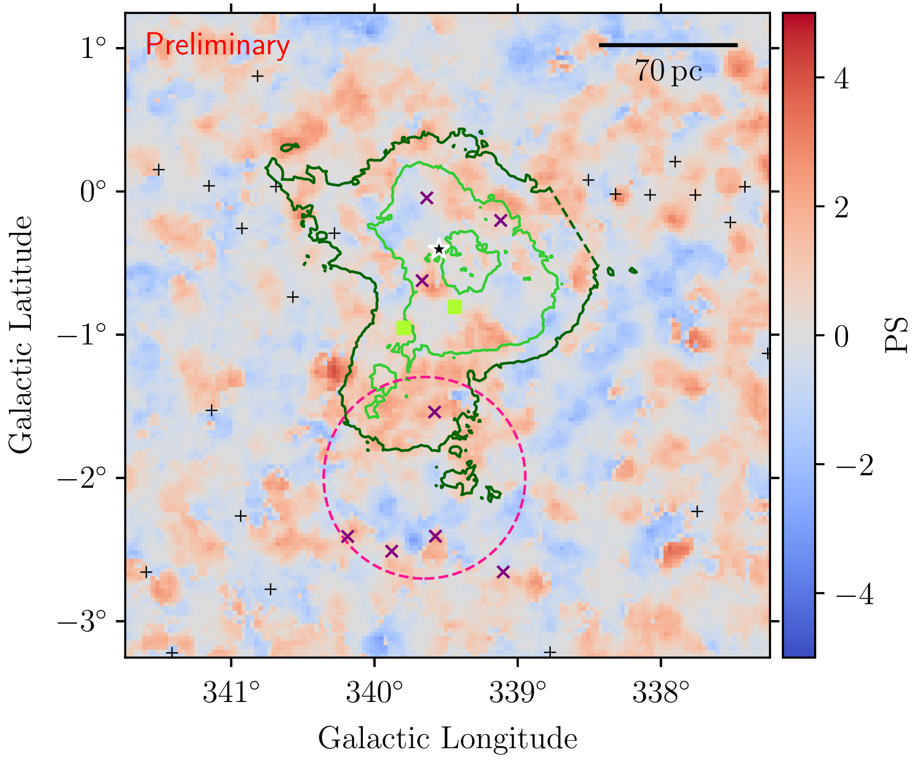
TS map without J1654-467

- Spatial correlation between GeV and TeV emission
- GeV emission brighter in region 1 than in region 2
  - best fit obtained with TeV template split along the white dashed line and independent normalisations for each half



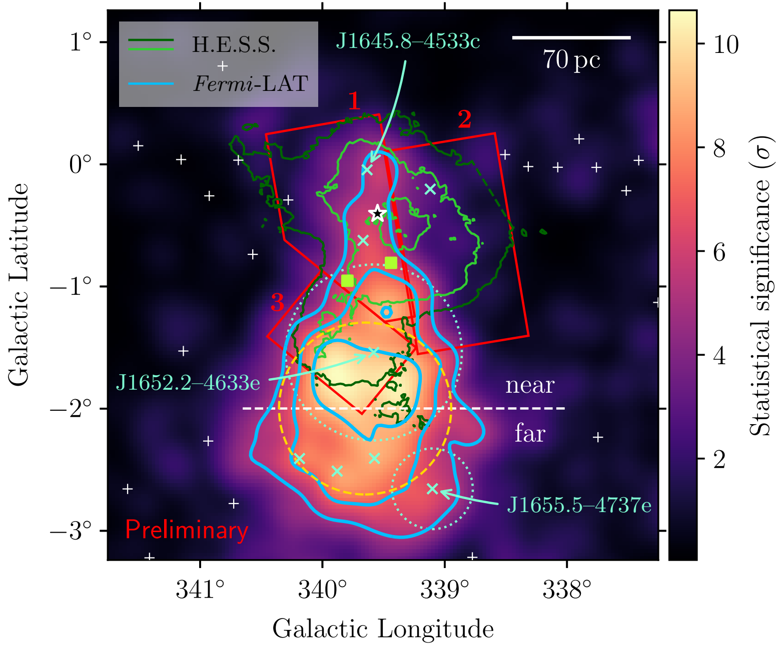
PS map

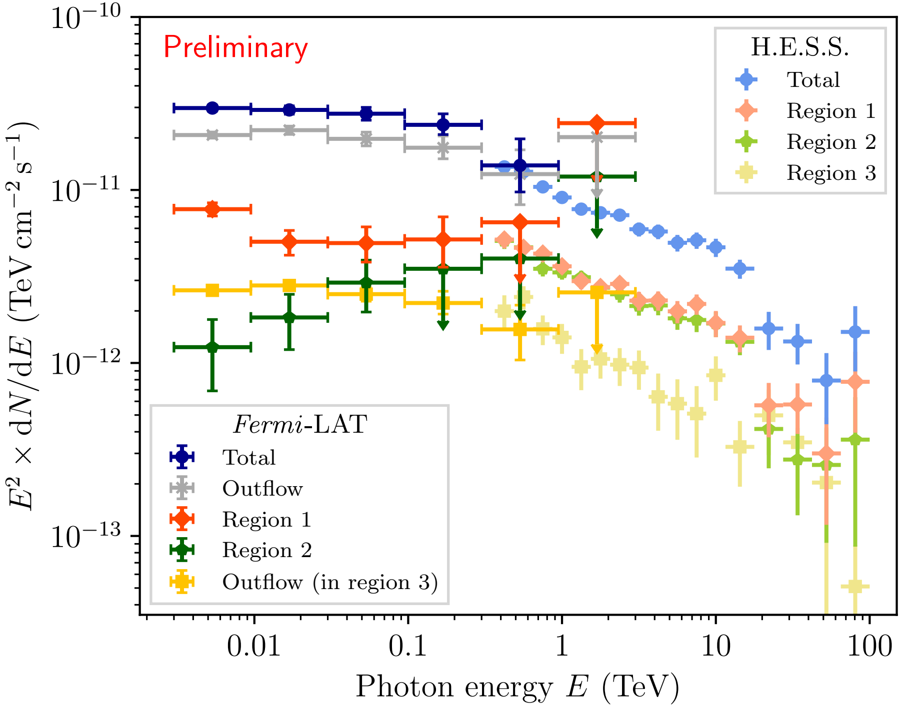
- No significant residual emission with our best-fit model



SEDs in regions

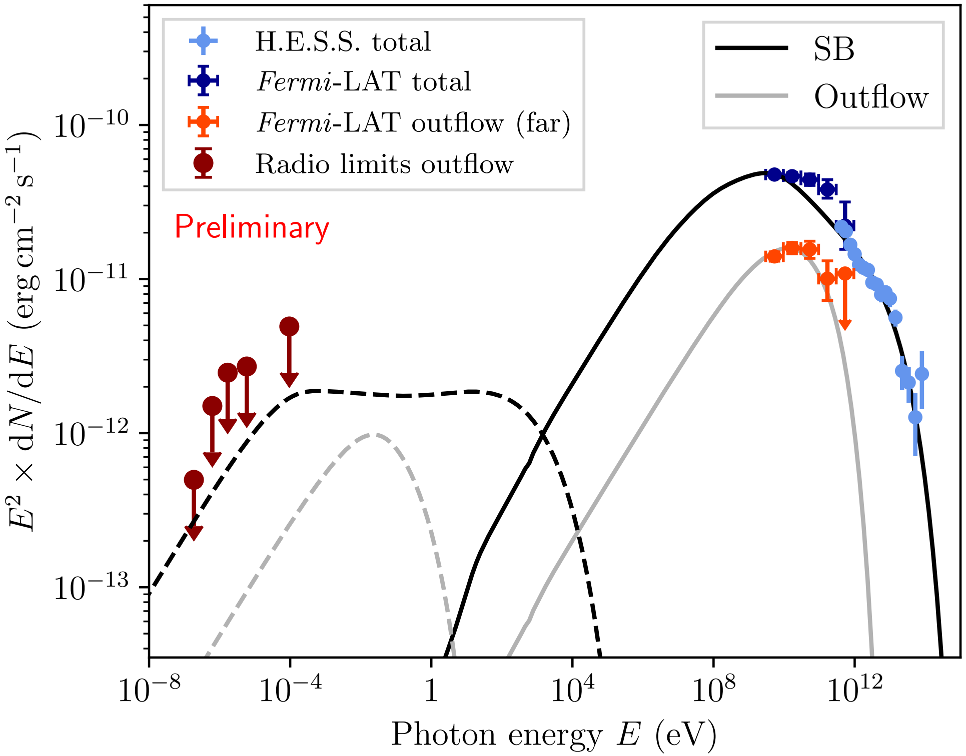
- Smooth connection between GeV and TeV spectra in all regions





SED with radio upper limits

- Radio limits derived from publicly available radio continuum maps
- Synchrotron emission in outflow region predicted by model well below limits



Modelling details

- Cooling time scales and transport