GALACTIC PHYSICS
WITH CTA

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THE NEXT GENERATION: CTA
THEME 1

**Understanding the origin and role of relativistic cosmic particles**

*What are the sites of high-energy particle acceleration in the Galaxy?*

*What are the mechanisms for cosmic particle acceleration?*

*What role do accelerated particles play in feedback on star formation?*

THEME 2

**Probing extreme environments**

*What physical processes are at work close to neutron stars and black holes?*

*What are the characteristics of relativistic jets, winds, and explosions?*
Galactic Plane Survey

Dubus+ (CTA) 13

Cosmic-ray PeVatrons / Supernova remnant RX J1713.7-3946
Large Magellanic Cloud

Credit: R. Gendler

Star Forming Systems

Credit: R. Gendler
A unique target to study extreme Galactic-type VHE sources & diffuse emission (CRs)

Face-on satellite galaxy:
- No source confusion
- Relatively nearby, and no distance ambiguity

Very active:
- Only 1% mass of the Milky Way
- Yet 10% the SFR

N.B. Advantage of large CTA FoV

Potential pointing pattern overlaid on starry sky image
Include:

- known VHE sources
  - N 157B: most energetic pulsar, $\sim 10^{38}$ erg/s
  - 30 Dor C: superbubble
  - N 132D: radio-loud SNR (50% $L_{\text{radio}}$ Cas A)
- luminous point-like sources
- CR-enriched regions
- Youngest SNR: SN 1987A
H.E.S.S.-like performance
1 pointing, 16 h, 0.8-100 TeV

atomic gas contours

CTA performance
6 pointings, 340 h, 0.2-100 TeV
Key science questions:

What is the impact of CRs on the ISM & how do they propagate?

What is the relationship between star formation & particle acceleration in systems on different scales?

Motivated also by:

• well-established correlation in FIR

• correlation seen recently in GeV $\gamma$-rays
Cygnus & Carina regions will be mapped at high resolution
Complementary Galactic and extragalactic science

Estimated calorimetric gamma-ray flux

Estimated CTA sensitivity

Current detections
GPS IN CONTEXT

CTA Survey

Stars: Galactic TeV sources outside HGPS region
Triangles: Galactic GeV sources (1FHL)
Image: Planck CO map

H.E.S.S. (2015) Preliminary

The Future of Research on Cosmic Gamma Rays - Galactic Physics with CTA, August 2015
## GPS IN CONTEXT

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Hemisphere</th>
<th>Galactic Plane Coverage</th>
<th>Energy (GeV)</th>
<th>Sensitivity (mCrab)</th>
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<tbody>
<tr>
<td>H.E.S.S.-I</td>
<td>S</td>
<td>$-70^\circ &lt; l &lt; 60^\circ$, $</td>
<td>b</td>
<td>&lt; 2^\circ$</td>
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<td>VERITAS</td>
<td>N</td>
<td>$67^\circ &lt; l &lt; 83^\circ$, $-1^\circ &lt; b &lt; 4^\circ$</td>
<td>$\geq 300$</td>
<td>20 – 30</td>
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<td>ARGO-YBJ</td>
<td>N</td>
<td>Northern Sky</td>
<td>$&gt; 300$</td>
<td>240 – 1000</td>
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<td>HEGRA</td>
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<td>$-2^\circ &lt; l &lt; 85^\circ$, $</td>
<td>b</td>
<td>&lt; 1^\circ$</td>
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<td>Milagro</td>
<td>N</td>
<td>Northern Sky</td>
<td>$&gt; 10,000$</td>
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<tr>
<th>Observatory</th>
<th>Hemisphere</th>
<th>Energy</th>
<th>Threshold</th>
<th>Angular Resolution</th>
<th>Pt. Source Sensitivity</th>
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<tr>
<td>CTA</td>
<td>N, S</td>
<td>125 GeV</td>
<td>$\sim 0.10^\circ$ at 300 GeV</td>
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<td>2 – 4 mCrab</td>
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<td>HAWC</td>
<td>N</td>
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<td>STP (Years 1 – 2)</td>
<td>300 2.7 mCrab</td>
<td>480</td>
<td>780</td>
<td>1.8 mCrab</td>
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<td>LTP (Years 3 – 10)</td>
<td>180 4.2 mCrab</td>
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<td>2.6 mCrab</td>
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<td>Total (Years 1 – 10)</td>
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<td>2.7 mCrab</td>
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~mCrab and uniform sensitivity with CTA GPS in just 2 years
**GRADED SENSITIVITY APPROACH**

**First 2 years:** \(~2–4\) mCrab

**10-yr program**
GPS OBJECTIVES

**Increase** population of known Galactic VHE sources x 3–9+

**Discover** new VHE source classes and unexpected phenomena

**Search** for Galactic CR PeVatrons

**Measure** large-scale diffuse emission

**Detect** new $\gamma$-ray binaries & other variable or transient sources

**Provide** first-look science data to other KSPs & General Observers

**Produce** a multi-purpose legacy dataset to MWL community
**SOURCE POPULATION**

*Increase* population of known Galactic VHE sources x 3–9++

![Log N - log S plot](image)

- **TARGET RANGE**
- **spiral arms**
- **thin disk**

Renaud+09

The Future of Research on Cosmic Gamma Rays - Galactic Physics with CTA, August 2015
NEW SOURCE CLASSES

**Discover** new VHE source classes and unexpected phenomena

Deil, Chaves+ (H.E.S.S.) 15

CTA discovery space

Preliminary

Mostly sources with multiple associations

Deil, Chaves+ (H.E.S.S.) 15
Search for Galactic CR PeVatrons

CTA South

SSTs further improve multi-TeV sensitivity

Access to inner Galaxy
Source populations modeled:

- Both **SNRs & PWNe**
- Fitted to known detections (TeVCat)

**Expected diffuse emission:** Both IC & $\pi^0$ components (GALPROP)

Energy range: 1-10 TeV

c**tools** open-source software with latest IRFs for North & South arrays

Actual GPS observation scheme (**1620 h**)

Most realistic simulations to date & work on-going
**GPS SIMULATIONS**

**Full-plane coverage:** longitude ± 180°, latitude $b$ ± 10°

**Deeper inner galaxy exposure:** $\ell$ ± 80°

**Fine detail** revealed with $\sim$arcmin PSF

Knoedlseder+ (CTA)
GPS SIMULATIONS: ZOOM
Discover Galactic CR PeVatrons responsible for CR knee

Specifically:

Where & how in the Galaxy are CRs accelerated up to PeV energies?

What is the distribution of PeVatrons in the Galaxy?

Are we sitting in a particular location of the Galaxy, or is there a uniform CR sea within the whole Galaxy (understanding diffusion by observing gamma-ray accelerators and their surroundings)?

Do young shell-type SNRs accelerate hadronic CRs up to PeV energies?

If so, up to which energies, and how effective is this acceleration (probing the theory of non-linear DSA)?
WHERE ARE THE PEVATRONS?

One way to get to CR knee (~3 PeV) energies, quite specific:
Young, fast (20,000 km s\(^{-1}\)) SNR shock in dense wind (CSM) from a Type II SN & RSG progenitor

e.g. 330-yr-old Cas A, but \(\Gamma = 2.6 \pm 0.2_{\text{stat}} \pm 0.2_{\text{syst}}\)

Other historical SNRs are challenging as well, c.f. updated Tycho (SN Ia) spectrum from VERITAS (\(\Gamma = 1.95 \pm 0.51_{\text{stat}} \pm 0.30_{\text{syst}} \rightarrow \Gamma = 2.92 \pm 0.41_{\text{stat}}\))

Are PeVatrons short lived?
MHD instability quenched after ~1000 yrs (~age RX J1713), e.g. Schure & Bell 2013
\(E_{\text{max}} \sim \text{PeV for only } \sim 100 \text{ yrs or less}\)

Observation strategy for Cherenkov telescopes?
Hidden in the existing data but confused/obscured?
Just need more statistics / better sensitivity at multi-TeV \(E\)?
Not looking at the right objects, biased by well-known SNRs? Molecular clouds?
WHERE ARE THE PEVATRONS?

GPS ideal strategy to identify PeVatron candidates

- few mCrab sensitivity along entire plane
- E-range up to hundreds of TeV
- arcmin PSF to reduce source confusion

Adapted from Carrigan, Chaves+ (H.E.S.S.) 13
Specifically, candidates should exhibit:

- No VHE cut-off or break: 3-σ signal above 50 TeV
- Hard photon spectrum: $\Gamma \approx 2.0$

![Graph showing differential sensitivity](image)
KSP follow-up of top 3 candidates:

+50 h deep observations of each to confirm & measure spectra
Deeper obs. (+50 h min.) of most prominent $\gamma$-ray SNR

To disentangle leptonic / hadronic acceleration

e.g. through precision imaging of shell morphology

To probe surrounding molecular environment (e.g. Gabici & Aharonian 07)

Leveraging next-gen PSF to better match gas studies
MORPHOLOGICAL APPROACH

50 h CTA simulation

(a) CTA leptonic dominant case ($A_2/A_1=0.01$)

(b) CTA hadronic dominant case ($A_2/A_1=100$)

DEC (J2000) [degree]

RA (J2000) [degree]

5 pc
If leptonic component dominant, search for hidden hadronic component.
CONCLUSIONS

CTA Galactic physics program to focus on:

**Galactic Plane Survey** for discovery, foundation for deeper observations, and legacy for MWL community

**LMC** to probe Galactic-type sources & diffuse CRs in face-on galaxy

**PeVatrons**, not only detection but characterization, and

**SNR RX J1713** as unique SNR and potential hadronic accelerator
## Galactic KSPs

### Research questions

A wide coverage of core science themes that drive CTA

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<tr>
<td>1 Understanding the Origin and Role of Relativistic Cosmic Particles</td>
<td>1.1 What are the sites of high-energy particle acceleration in the universe?</td>
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<td>1.2 What are the mechanisms for cosmic particle acceleration?</td>
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<td>1.3 What role do accelerated particles play in feedback on star formation and galaxy evolution?</td>
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<td>2.1 What physical processes are at work close to neutron stars and black holes?</td>
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<td>2.2 What are the characteristics of relativistic jets, winds and explosions?</td>
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<td>2.3 How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?</td>
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<td>3 Exploring Frontiers in Physics</td>
<td>3.1 What is the nature of Dark Matter? How is it distributed?</td>
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<td>3.2 Are there quantum gravitational effects on photon propagation?</td>
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<td>3.3 Do Axion-like particles exist?</td>
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The Large Magellanic Cloud

0.05° ~ 3' angular resolution

sensitivity ~10^{35} \text{ erg s}^{-1}
N 132D: A radio-loud middle-aged SNR

50% $L_{\text{radio}}$ of Cas A

Not quite VHE detection $\sim 5 \sigma$
N 157B: The Crab Nebula's twin

Pulsar has largest known $\dot{E} \sim 4.8 \times 10^{38}$ erg s$^{-1}$
30 Dor C: A TeV superbubble

Largest SFR in Local Group

Largest X-ray synchrotron shell known (47 pc)

10x as bright as SN 1006

\[ l_{\text{diff}} = \sqrt{2 \cdot D \cdot t} < \sim 47 \text{ pc} \]

\[ D(10 \text{ TeV}) < \sim 3.3 \times 10^{26} \left(\frac{t}{10^6 \text{ yr}}\right)^{-1} \text{ cm}^2 \text{ s}^{-1} \]

2-3 orders lower than \sim \text{Galactic}

requires MFA / B turbulence

still open question: leptonic vs. hadronic
SN 1987A: The youngest SNR

High shock speed
High ambient density
Hadronic?

Upper limit only for now, but more observation planned & emission predicted to increase

Predicted:
~8 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} in 2013
~2.5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} in 2010

F (> 1 \text{ TeV}) < 5 \times 10^{-14} \text{ cm}^{-2} \text{ s}^{-1}
99\% \text{ CL}
during 2003-2012
The LMC in VHE γ-rays: Recap
The LMC in VHE γ-rays: Spectra

<table>
<thead>
<tr>
<th>Source</th>
<th>H.E.S.S. Identifier</th>
<th>Exposure Time</th>
<th>γ rays</th>
<th>Significance</th>
<th>Photon Index Γ</th>
<th>( \phi(1 \text{ TeV}) ) [10(^{-12}) cm(^{-2}) s(^{-1}) TeV(^{-1})]</th>
<th>( L_\gamma(1-10 \text{ TeV}) ) [10(^{35}) erg s(^{-1})]</th>
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<tr>
<td>N 157B</td>
<td>HESS J0537–691</td>
<td>181 h</td>
<td>613</td>
<td>33.0 ( \sigma )</td>
<td>2.8 ± 0.1</td>
<td>1.3 ± 0.1</td>
<td>6.8 ± 0.3</td>
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<td>30 Dor C</td>
<td>HESS J0535–691</td>
<td>183 h</td>
<td>74</td>
<td>8.8 ( \sigma )</td>
<td>2.6 ± 0.2</td>
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<td>N 132D</td>
<td>HESS J0525–696</td>
<td>148 h</td>
<td>43</td>
<td>4.7 ( \sigma )</td>
<td>2.4 ± 0.3</td>
<td>0.13 ± 0.05</td>
<td>0.9 ± 0.2</td>
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SFS KSP
New Simulations
VHE source distribution

Roughly fits plausible counterpart distributions

Still lack statistics to disentangle? Not sensitivity limited in latitude?

The Future of Research on Cosmic Gamma Rays – Galactic Physics with CTA, August 2015
HGPS Sensitivity

along $b = -0.3^\circ$ for a 5-$\sigma$ detection

FYI: CTA GPS by ~2022
Triple the exposure

Improved gamma-hadron separation

Improved angular resolution

RX J1713.7-3946
H.E.S.S. (2015) Preliminary

Excess
Are cosmic rays escaping the shell and interacting with molecular clouds? i.e. is there TeV emission beyond the shell?
Precision VHE spectra to ~50 TeV
Precision VHE spectra to ~50 TeV

Exp. cut-off around ~10 TeV (≠ not a PeVatron)

RX J1713.7–3946
H.E.S.S.(2015) Preliminary
START WITH SIMPLE CASES

May not be conclusive, but can be an example of analysis strategy based on 1-zone scenario

Determine the major component by **image analysis**

- **hadronic**
  - This source wouldn’t be a PeVatron

- **leptonic**
  - Search for hadronic component by **spectral analysis**

**complimentary indication**

**Time evolution of** $E_c$

(Knoedlseder+ 13)