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Prospects for heavy WIMP searches with H.E.S.S. and CTA

L. Rinchiuso, N. L. Rodd, E. Moulin, T. R. Slatyer

**IRN Terascale,
Annecy-Le-Vieux 20/05/2019**

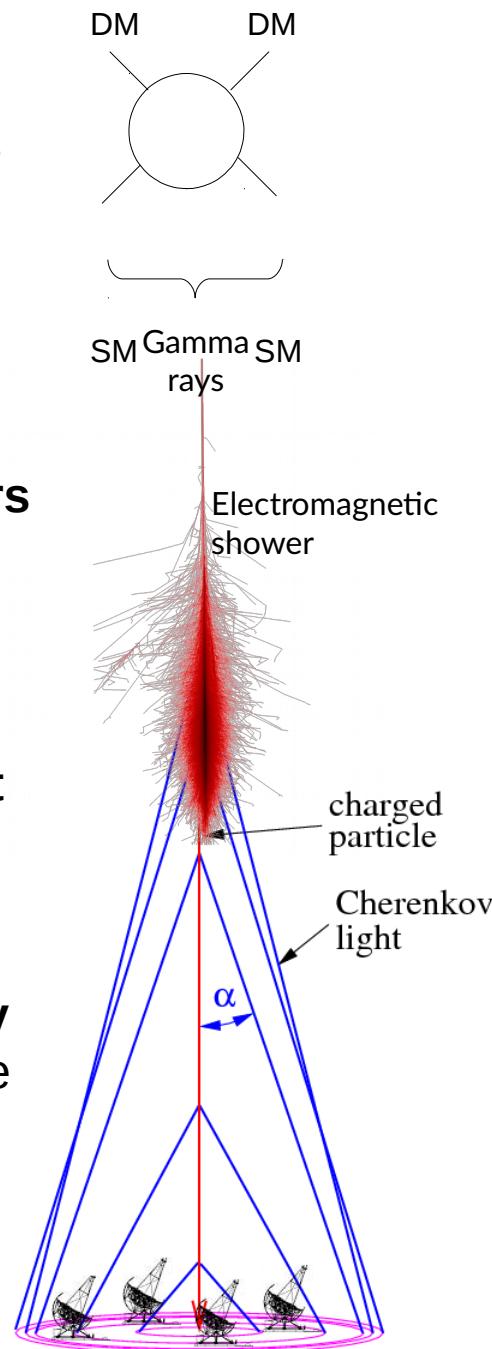
Indirect dark matter search with IACTs

Dark matter (DM)
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very-high-energy (VHE)
photons in the final state

The gamma rays initiate
electromagnetic showers
in the atmosphere

The e^+/e^- in the showers
produce **Cherenkov light**

Ground-based Imaging
Atmospheric Cherenkov
Telescopes that fall in the
light cone detect the
gamma ray



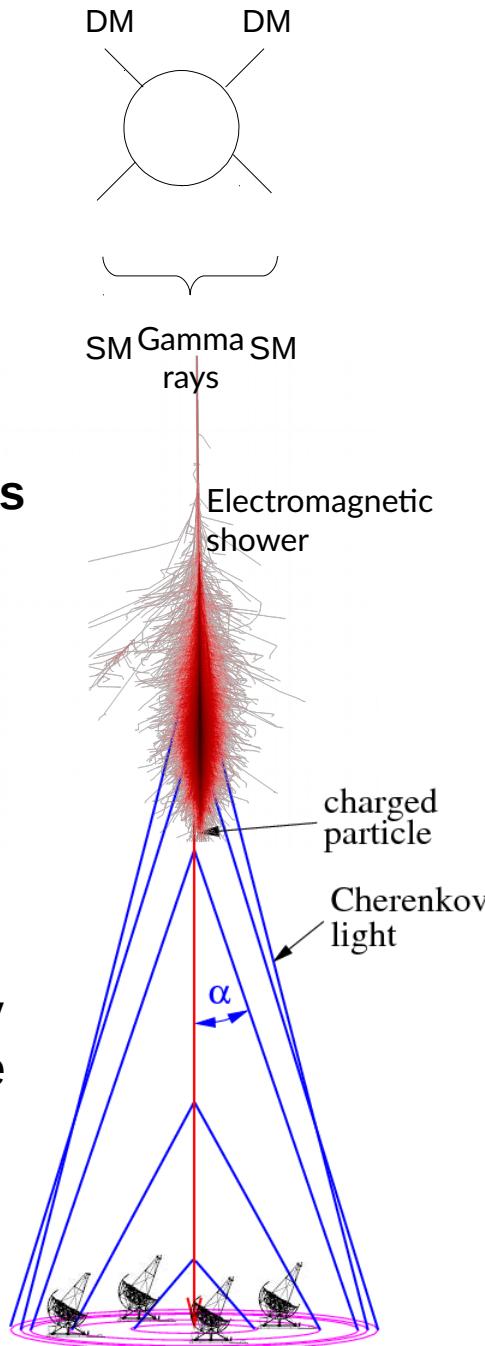
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The flux of gamma rays

$$\frac{d\phi_\gamma}{dE}(E, \Delta\Omega) = \underbrace{\frac{1}{4\pi} \frac{\langle\sigma v\rangle}{m_{\text{DM}}^2} \sum_i Br_i \frac{dN_i}{dE}(E)}_{\text{particle physics}} \times \underbrace{J(\Delta\Omega)}_{\text{astrophysics}}$$

depends on the dark matter

- Mass m_{DM}
- annihilation cross section $\langle\sigma v\rangle$
- annihilation spectrum dN/dE
- density distribution \rightarrow
- J-factor $J = \int_{\Omega} \int_{\text{los}} \rho^2(r(s, \theta)) ds d\Omega$.

The measured number of gamma rays

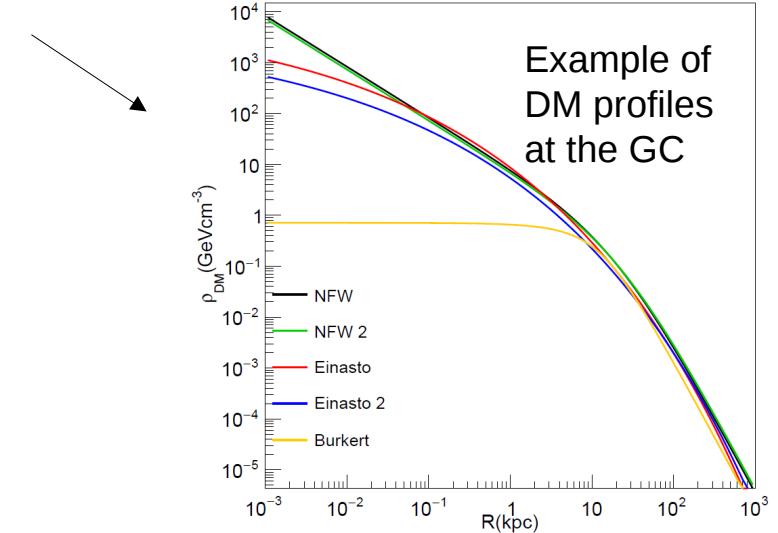
$$N_S^\gamma = T_{\text{obs}} \int_{\Delta E} \frac{d\phi_\gamma}{dE}(E, \Delta\Omega) A_{\text{eff}}^\gamma(E) G(E) dE$$

depends on
the instrument IRFs: energy
resolution $G(E)$, effective area A_{eff}
Observation live time T_{obs}

Targets and candidates for indirect DM search

Targets for indirect DM search

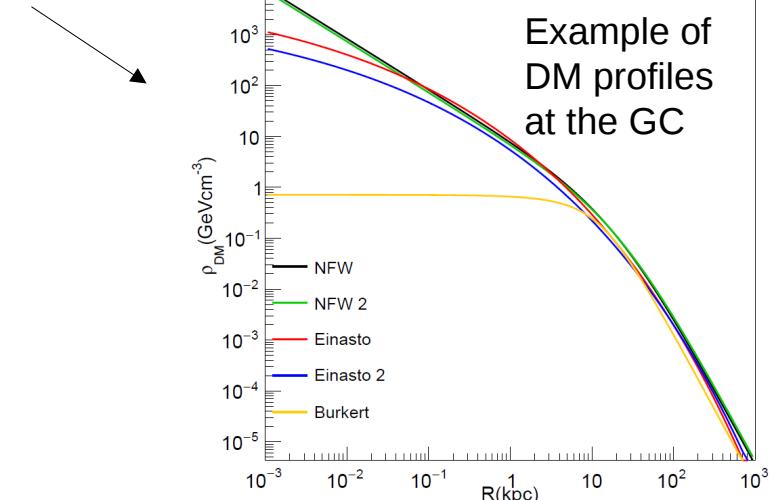
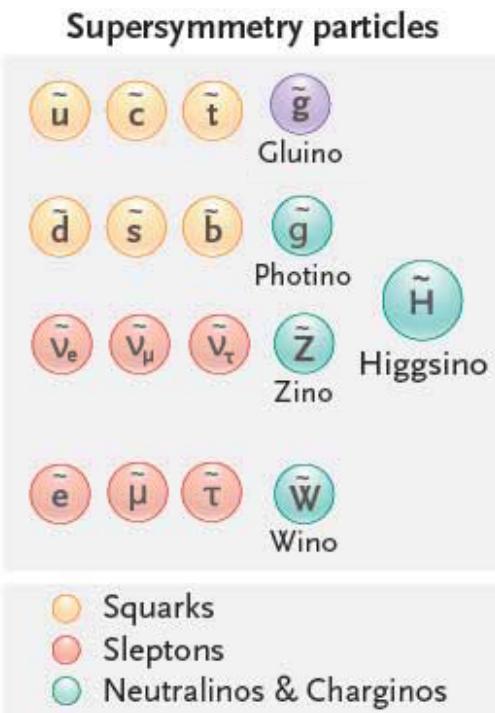
- **Galactic Center (GC)** → **largest expected DM signal**
- nearby dwarf galaxies → lowest gamma-ray background
- galaxy cluster → low background but small signal
- Outer GC halo → less background than the GC but significantly smaller signal
- DM clumps → difficult to localize



Targets and candidates for indirect DM search

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- **Galactic Center (GC)** → **largest expected DM signal**
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Most promising candidates for heavy DM indirect search:

SUSY extension of the Standard Model → WIMPs

- **Wino** weak triplet fermion with hypercharge 0, superpartner of the W boson
- **Higgsino** weak isodoublet with hypercharge half, superpartner of the Higgs field

Instruments for VHE γ -ray observations of the GC

H.E.S.S.

Currently operating

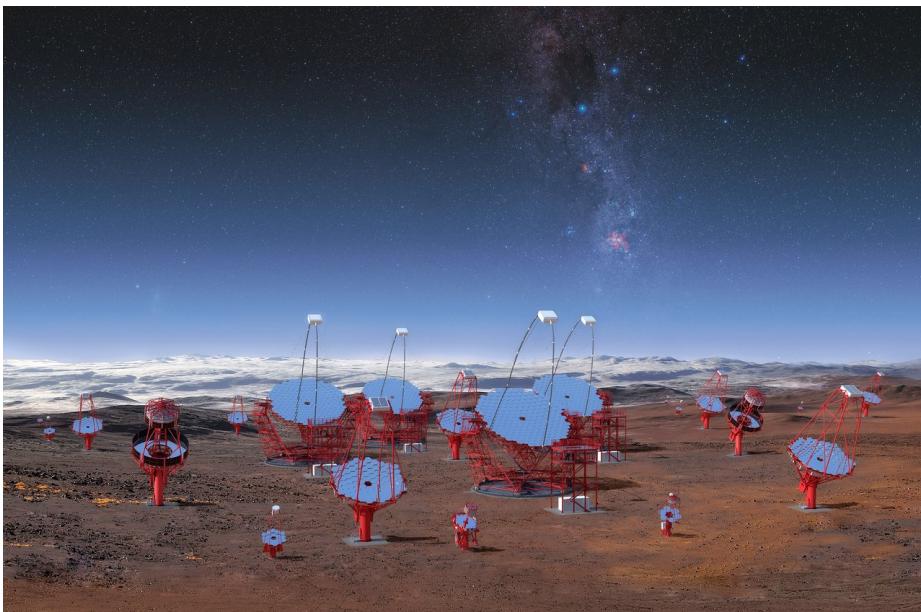
Namibia

4 (5) telescopes

Energy range: 100 (30) GeV-70 TeV

Energy resolution down to 10%

<https://www.mpi-hd.mpg.de/hfm/HESS/>



CTA South

In preparation

Chile

99 telescopes

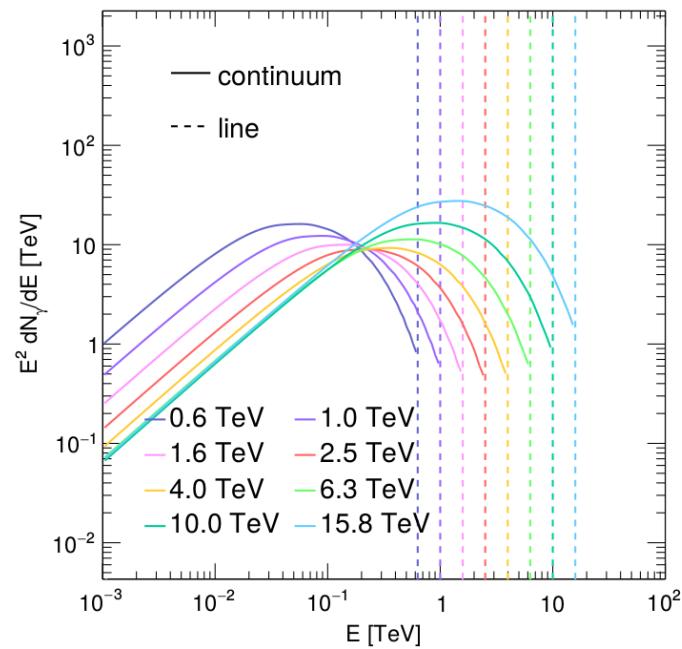
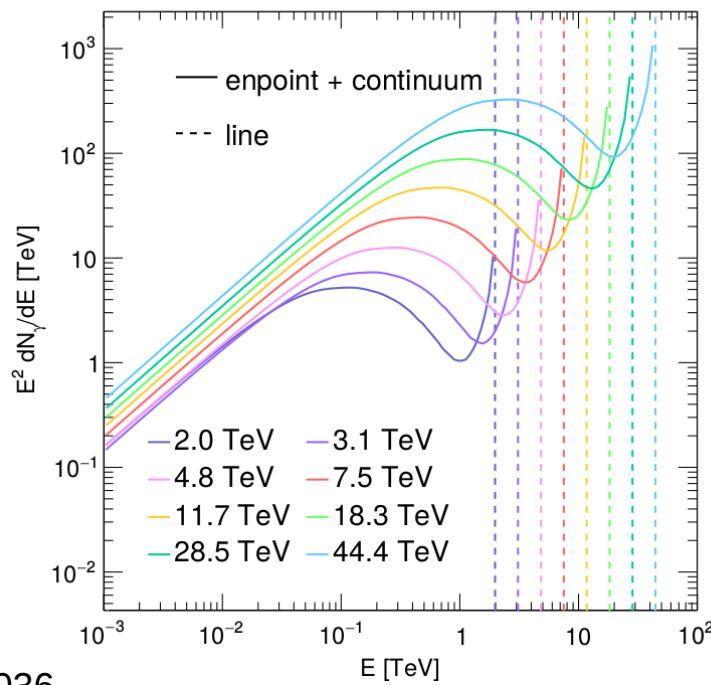
Energy range 20 GeV-300 TeV

Energy resolution down to 5%

<https://www.cta-observatory.org/>

Wino and Higgsino spectra

- In the **endpoint region** (E_γ near m_{DM})
 - Contributions for precision calculation introduce
 - perturbative Sudakov double logarithms
 - Sommerfeld enhancement
 - EFT framework was developed for calculations at NLL**
 - Full spectrum = line + endpoint contribution + continuum
- Tree-level (LO) calculation
 - Including the
 - Continuum contribution
 - Sommerfeld enhancement
 - Two mass splittings are considered
 - $\delta m_N = 200 \text{ keV}, \delta m_+ = 350 \text{ MeV}$
 - $\delta m_N = 2 \text{ GeV}, \delta m_+ = 480 \text{ MeV}$

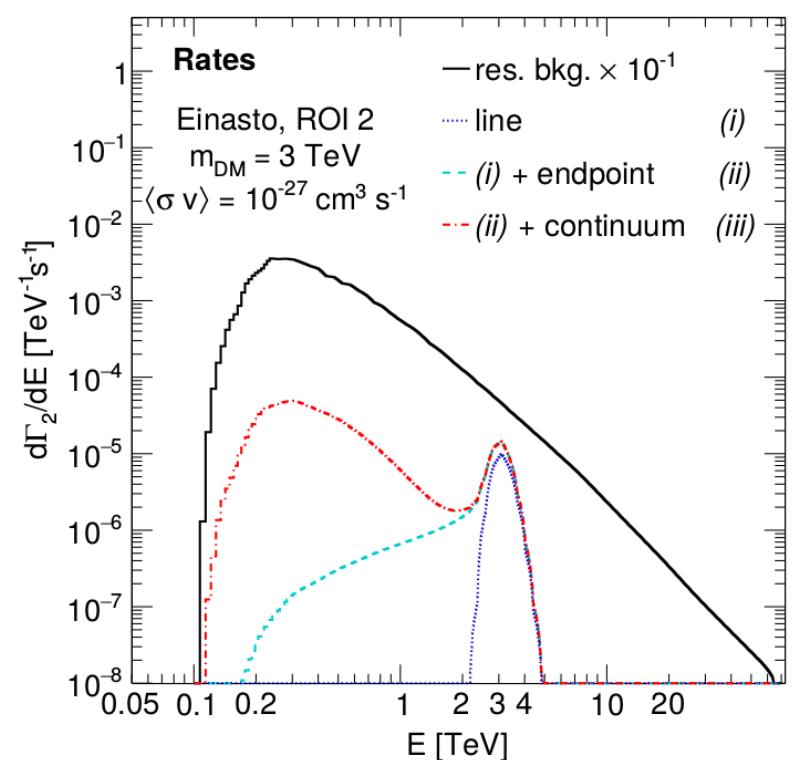


J. Hisano et al.,
Phys. Rev. D71 (2005) 063528

H.E.S.S.-I mock analysis

Phys. Rev. Lett. 120,
201101 (2018)

- H.E.S.S.-I-like events distributions
 - Rols defined as in the H.E.S.S.-I data analysis, $T_{\text{obs}} = 250 \text{ h}$
 - Exclusion of the main VHE emissions (Galactic plane, HESS J1745-303)
 - **Residual Background modeled from CR p, He and e spectra**
 - Hadron efficiency factor: 0.1
- **Wino signal**
 - Line
 - Line + endpoint
 - **Line + endpoint + continuum**
- From spectra to number of γ
 - Observation live time
 - Energy resolution
 - Effective area



L. Rinchiuso et al., Phys. Rev. D98 (2018) 123014

Likelihood technique

- Poisson likelihood 2D/3D: energy, space

$$\mathcal{L}_{ijk} = \text{Pois}(s_{\gamma,ijk} + b_{\gamma,ijk}, m_{\gamma,ijk}) \times \text{Pois}(\alpha_{jk} b_{\gamma,ijk}, n_{\gamma,ijk}),$$

Expected DM signal in the signal region

Expected background in the signal region

Measurement in the signal region

Measurement in the control region

Ratio between the angular size of the signal and control regions

- Test statistics:

- Log-likelihood ratio test statistics

$$TS = -2 \sum_{ijk} \ln \lambda_{ijk}$$

with

$$\lambda_{ijk} = \frac{\mathcal{L}_{ijk}(s_{\gamma,ijk}, \hat{b}_{\gamma,ijk})}{\mathcal{L}_{ijk}(\hat{s}_{\gamma,ijk}, \hat{b}_{\gamma,ijk})}$$

- TS=2.71 gives the 95% expected upper limits on the parameter of interest $\langle\sigma v\rangle$

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 Measurement in the signal region
 Measurement in the control region
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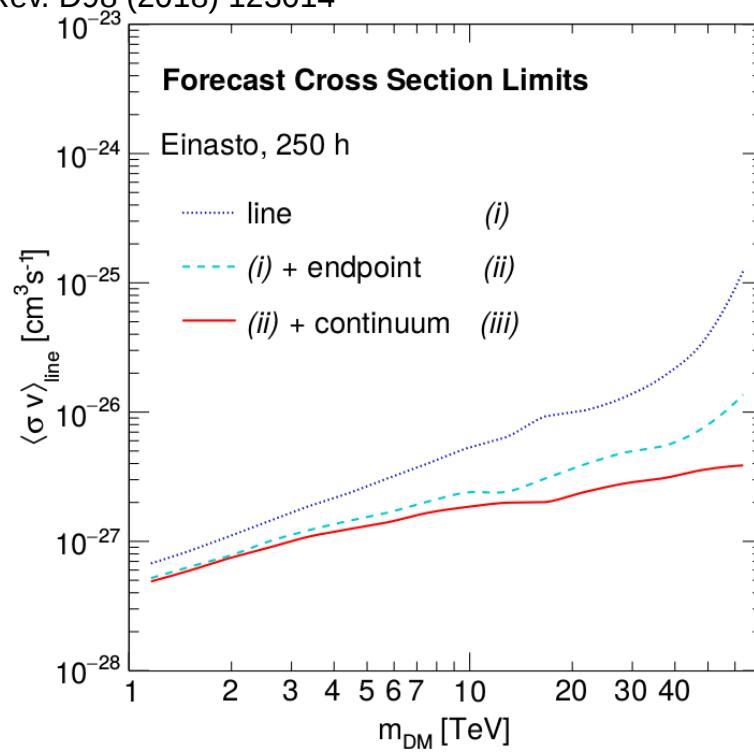
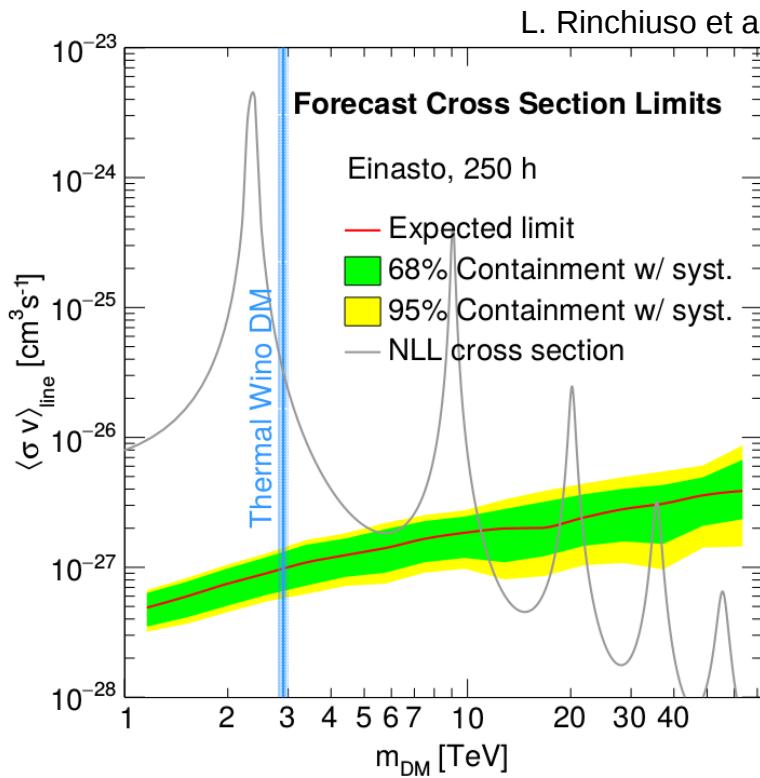
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- TS=2.71 gives the 95% expected upper limits on the parameter of interest $\langle\sigma v\rangle$
- Containment bands at Nσ
 - Poisson realizations of the measurements (see H.E.S.S. paper) → N std dev of the distribution of the obtained $\log_{10}\langle\sigma v\rangle$ values
 - Asimov dataset $TS = (\Phi^{-1}(0.95) \pm N)^2$.

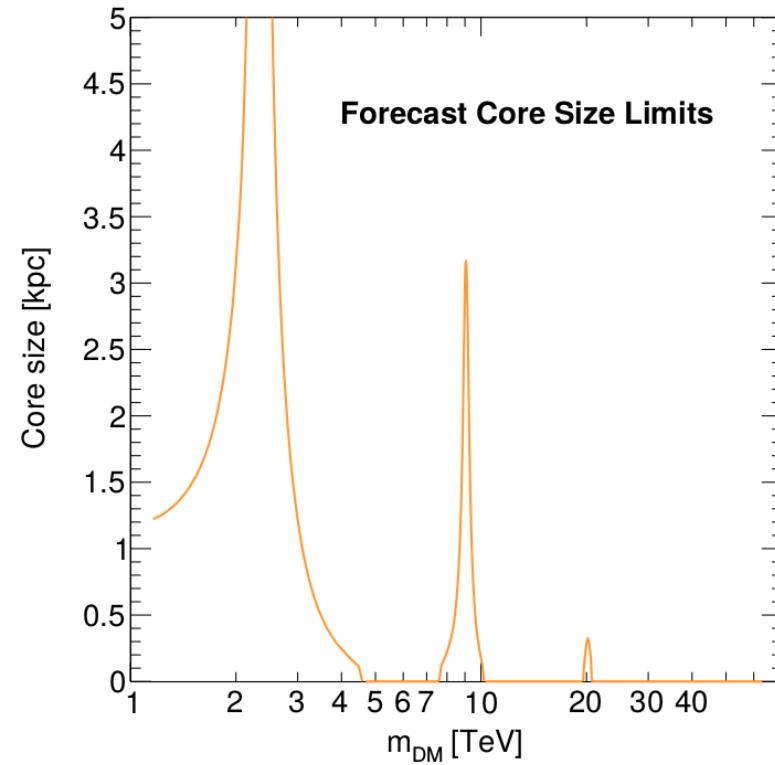
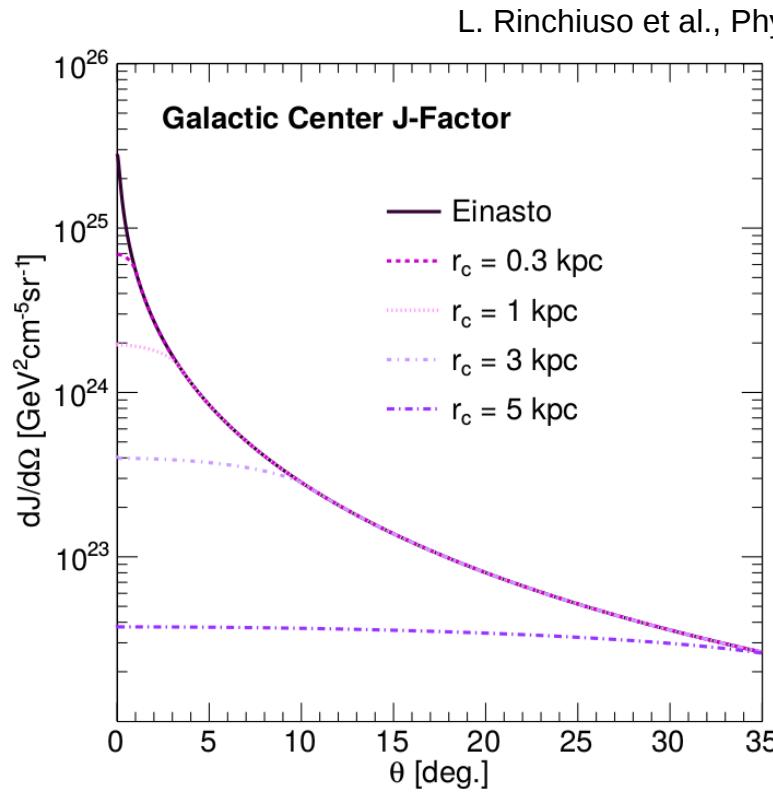
Forecast H.E.S.S.-like limits for the Winos

- **Significant endpoint contribution** to the line limits on $\langle\sigma v\rangle$:
 - 1.4 at 2.3 TeV, 1.5 at 3 TeV, 2.1 at 9 TeV
- Continuum contribution:
 - 8% at 2.3 TeV, 12% at 2.9 TeV, 27% at 9 TeV
- **Important wino mass range probed**



Testing DM cores

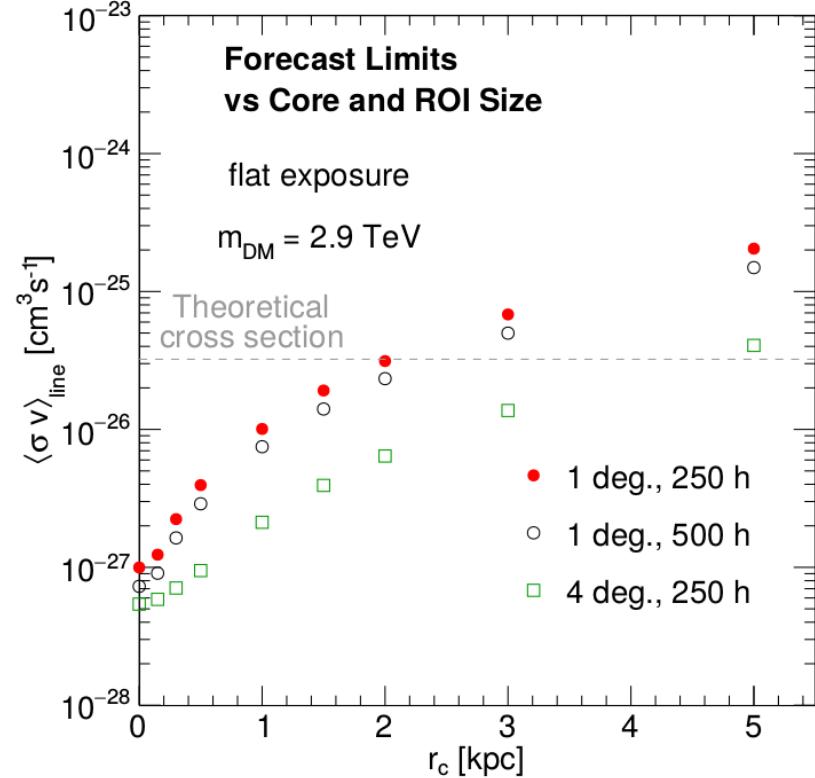
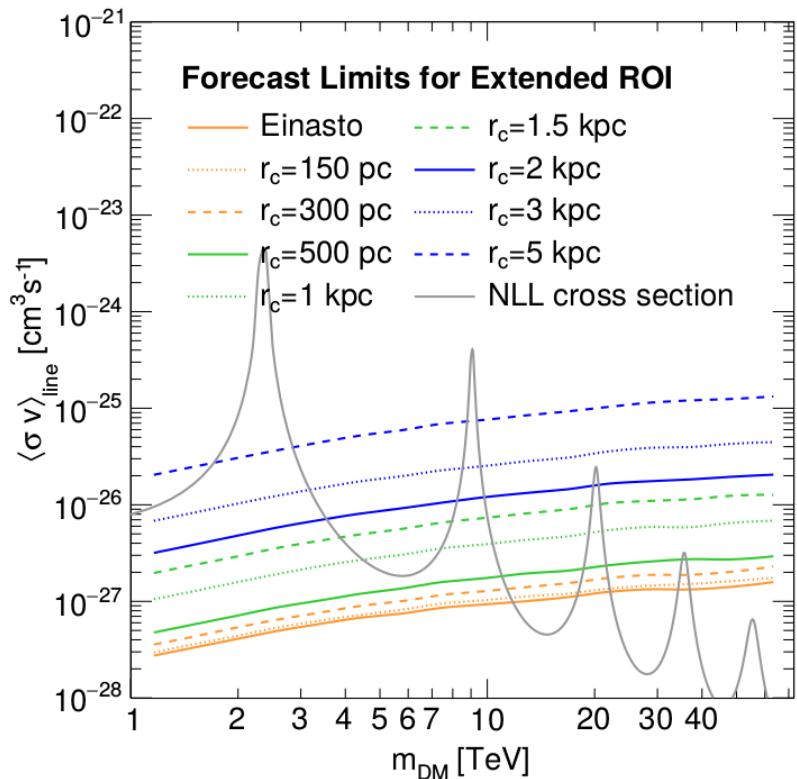
- Several cores tested: 300 pc to 5 kpc
- Limits on $\langle \sigma v \rangle$ degrade up to a factor 200 for 5 kpc cores
- Limits can be interpreted in terms of J-factor or core size
 - **Cores up to >5 kpc excluded at 2.3 TeV,**
 - **up to 3 kpc at 9 TeV**



DM cores and forecast H.E.S.S.-2-like limits

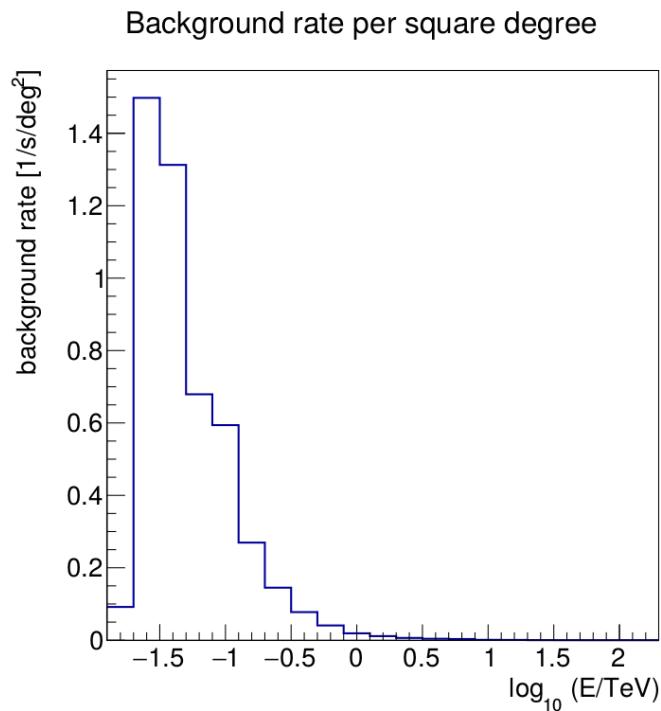
- **ON region extended** up to 4 deg: **H.E.S.S.-II-like strategy** (large-latitude observations)
- **More sensitive to large cores**:
 - limits on $\langle \sigma v \rangle$ for large cores degrade only of factor 70 wrt Einasto
- Improvement for a 4 deg region wrt doubling the observation in 1 deg:
 - Up to a factor 2.8 better for a 5 kpc core

L. Rinchiuso et al., Phys.Rev. D98 (2018) 123014



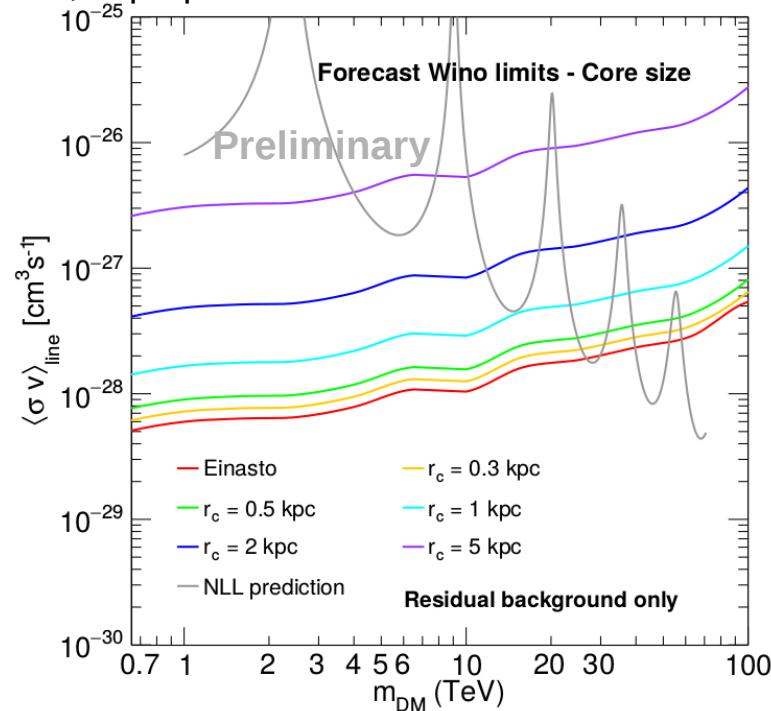
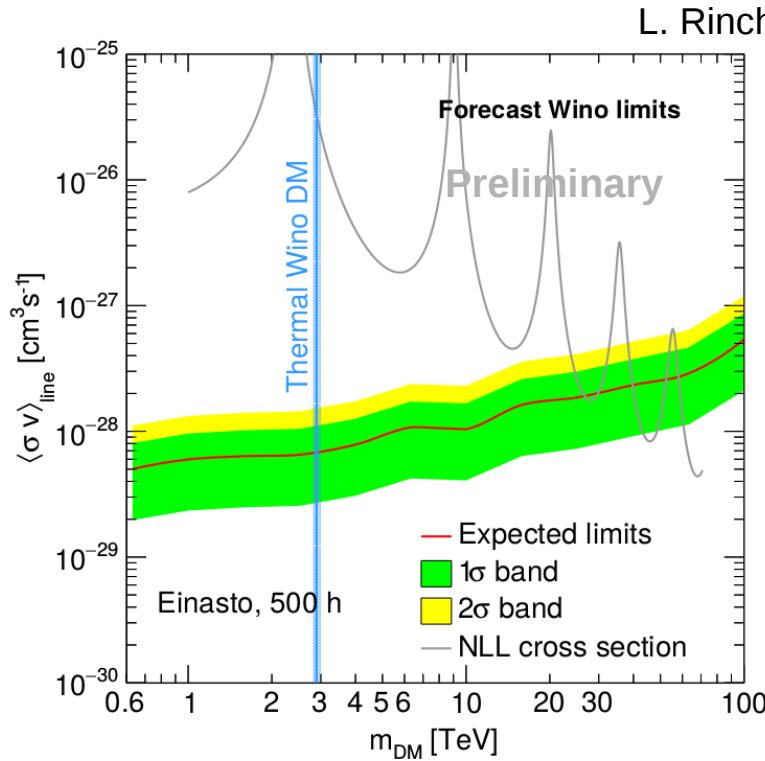
CTA mock analysis

- Event distributions and expected signal for CTA are built following the same principle as for H.E.S.S., but using CTA IRFs
- CTA events distributions
 - Signal region: square $\pm 5^\circ$ around the GC, $T_{\text{obs}} = 500$ h
 - Rols: squares of side 0.5°
 - **Residual Background: misidentified hadrons and electrons**
- **Wino signal**
 - Line
 - Line + endpoint
 - **Line + endpoint + continuum**
- **Higgsino signal**
 - Line
 - **Line + continuum**
 - **No endpoint contribution so far**



Wino searches with CTA

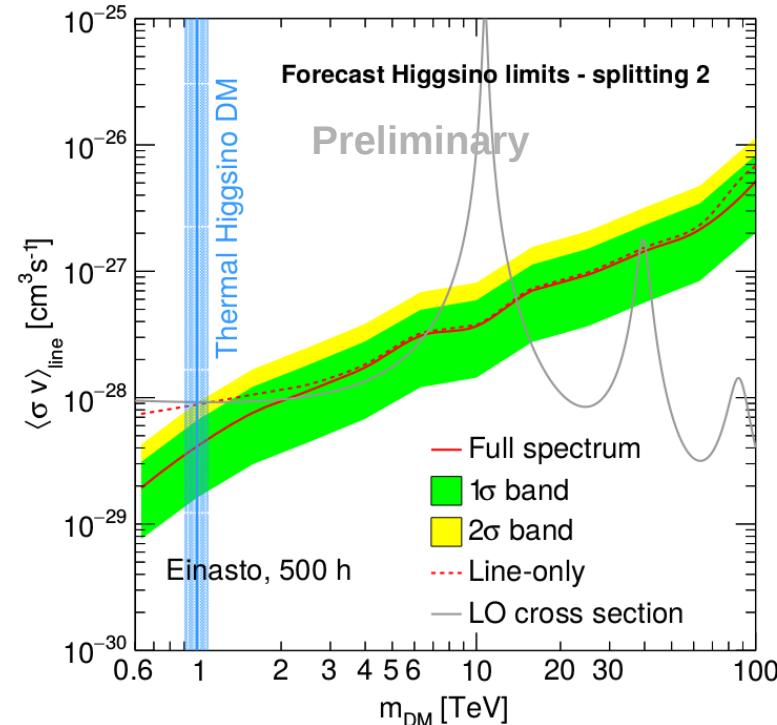
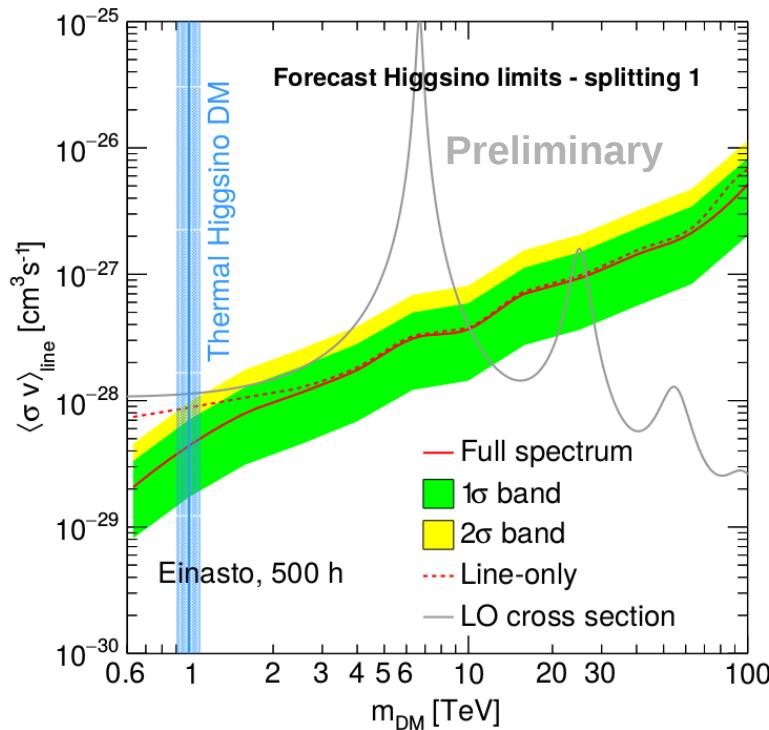
- **Significant endpoint contribution** 1.5 at 1 TeV, 3 at 10 TeV, 7 at 50 TeV
- Continuum contribution: 1-5%
 - The difference from H.E.S.S. comes from the better CTA energy resolution → endpoint more dominant
- **Wino probed up to mass 40 TeV**
- Kpc-size cores probed up to several TeV (and beyond at resonances)



Higgsino searches with CTA

- Continuum contribution
 - Up to a factor 4
- **CTA can reach the Higgsino parameter space** → mass range probed:
 - Up to 10 TeV and at ~25 TeV for splitting 1
 - Up to 2 TeV and at 6-15 TeV for splitting 2
- Important higgsino mass range **probed**, including **the thermal mass**

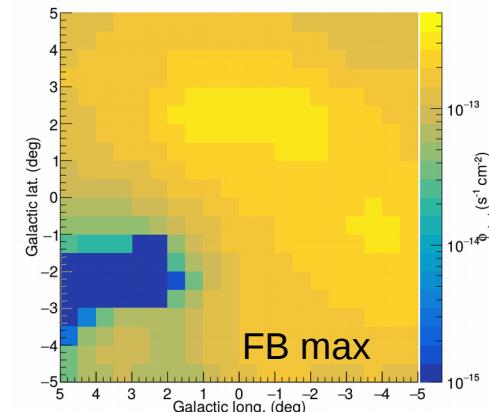
L. Rinchiuso et al., in prep.



Standard astrophysical background at the GC

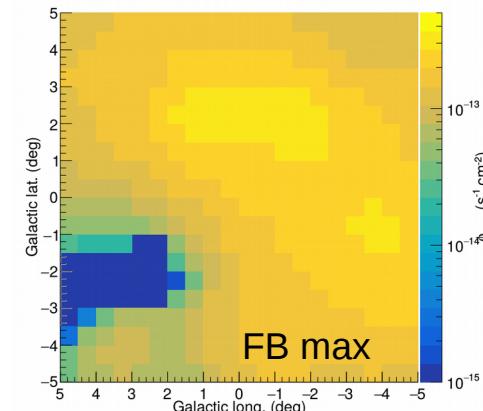
- Low-latitude Fermi Bubbles
 - Power-law with exponential cut-off
- Fermi-LAT Collaboration, *Astrophys.J.* 840 (2017) no.1, 43

Model	ϕ_0 [TeV $^{-1}$ cm $^{-2}$ s $^{-1}$ sr $^{-1}$]	Γ	E_{cut} [TeV]
FB max	1×10^{-8}	1.9	20
FB min	0.5×10^{-8}	1.9	1



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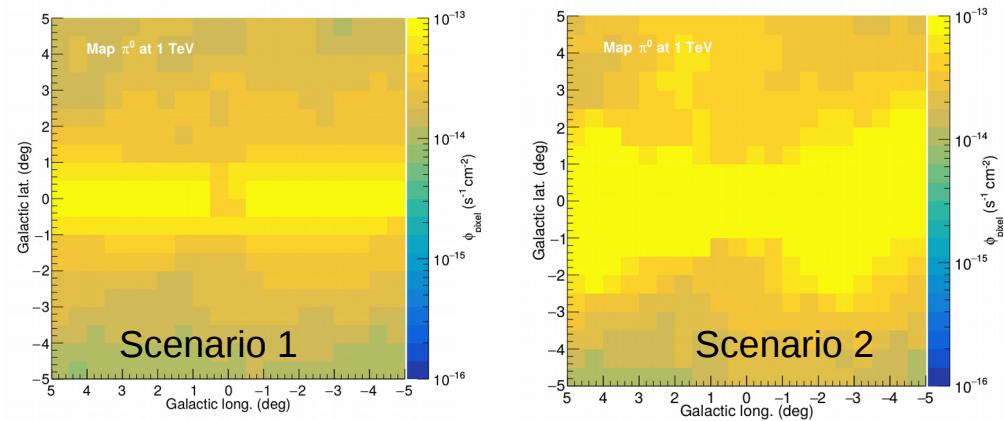
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- Galactic Diffuse Emission
 - Power-law (π^0) and power-law with exponential cutoff (ICS)
 - Scenario 1: O. Macias et al., <https://arxiv.org/abs/1901.03822>
 - Scenario 2: Fermi-LAT Collaboration, *Astrophys.J.* 840 (2017) no.1, 43 + D. Schlegel et al., *Astrophys.J.* 500 (1998) 525 + M. Su et al. *Astrophys.J.* 724:1044-1082, 2010

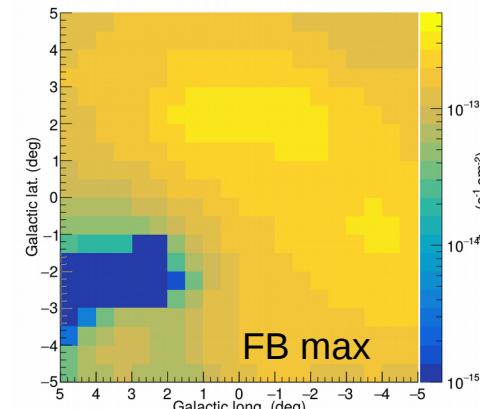
Scenario 1			
Component	ϕ_0 [$\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]	Γ	E_{cut} [TeV]
π^0	1.3×10^{-9}	2.48	-
ICS	0.5×10^{-9}	2.46	70

Scenario 2			
Component	ϕ_0 [$\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]	Γ	E_{cut} [TeV]
π^0	2.1×10^{-9}	2.48	-
ICS	1.5×10^{-9}	2.40	100

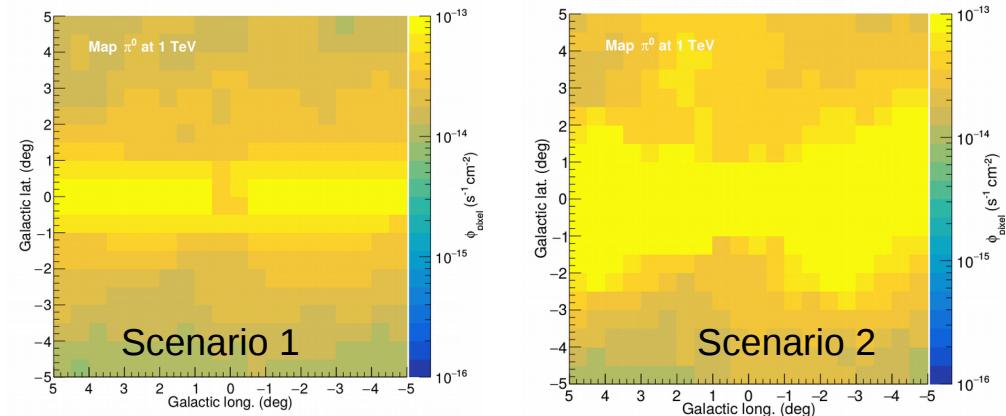


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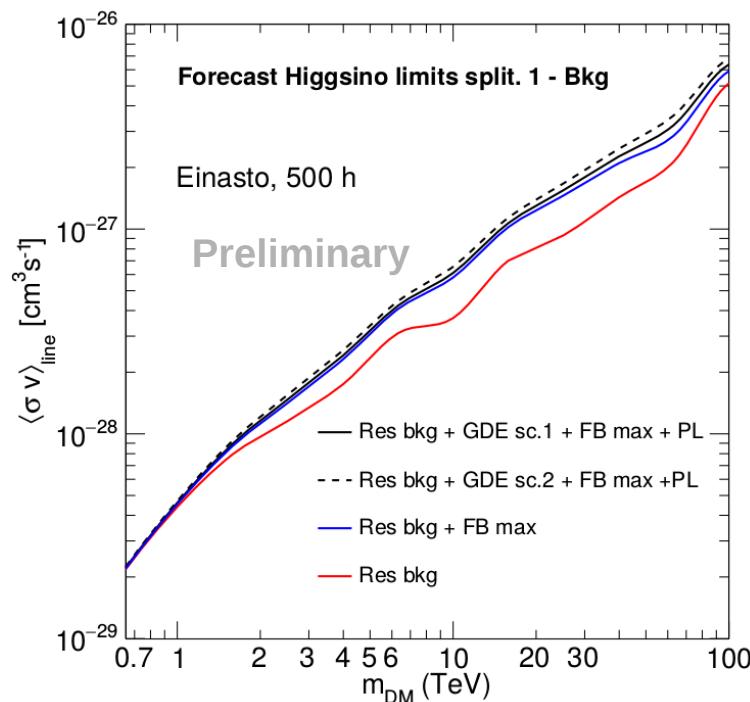
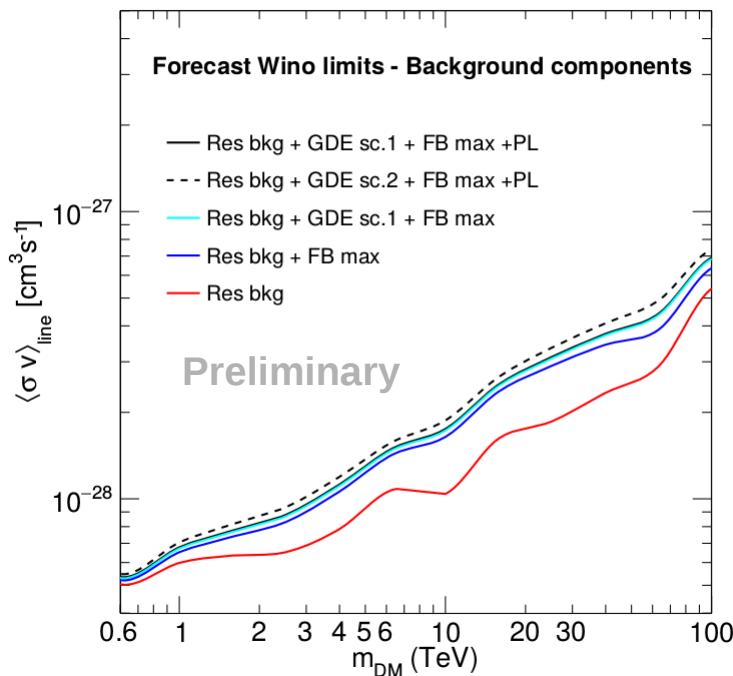
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- Point-like sources (Fermi-LAT Collaboration, *Astrophys.J.Suppl.* 232 (2017) no.2, 18)
 - Masks of $0.2^\circ \rightarrow$ negligible

Impact of astrophysical background of CTA limits

- Impact of the Galactic Diffuse Emission ($\pi^0 + \text{ICS}$)
 - 5-20% for scenario 1
 - Up to 25% for scenario 2
- Impact of low-latitude Fermi Bubbles
 - Up to 30%
- **Overall impact of the standard astrophysical background**
 - **Up to 50-55%** (same for Wino and Higgsino)



Summary

- **Most of Wino mass range probed by H.E.S.S. I**
- H.E.S.S.-II-like pointing strategy better than increasing time in the same region, better prospects for cored DM profiles
- Precise computation of the endpoint contribution to the Wino spectrum has a significant impact on the H.E.S.S. and CTA sensitivity
- **CTA will have the sensitivity to probe also the Higgsino**
 - A refined computation of the endpoint contribution is expected to improve the probed mass range
- **The standard astrophysical background at the Galactic Center has an impact on the CTA sensitivity to dark matter**
 - Precise modeling of the background is foreseen in order to reduce the degradation due to the background