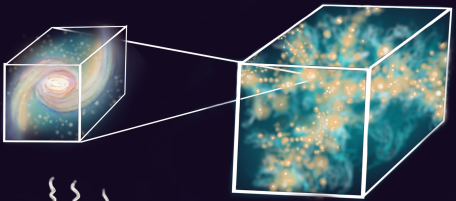
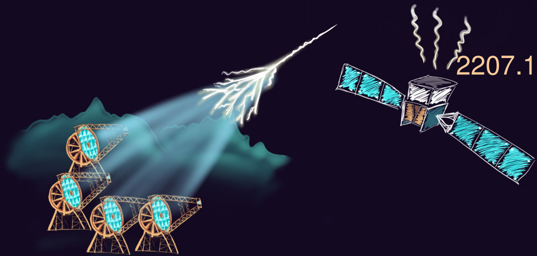
The road to Higgsino DM

MITP DM Workshop 2024



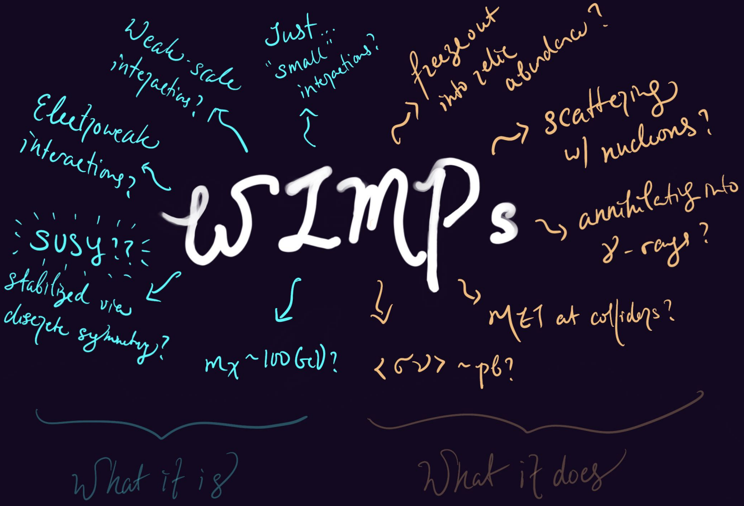


2207.10090 w/ C. Dessert, J. Foster, B. Safdi, Y. Park

2405.13104 w/ N. Rodd, B. Safdi

Weishuang Linda Xu

UC Berkeley/LBNL ($\rightarrow$ SLAC)


WIMPs
Weak-scale interactions?
Just "small" interactions?
Electroweak interactions?
SUSY!?
stabilized via discrete symmetry?
$m_\chi \sim 100$ GeV?
freezeout into relic abundance?
scattering w/ nucleons?
annihilating into γ-rays?
MET at colliders?
$\langle \sigma v \rangle \sim$ pb?
What it is
What it does

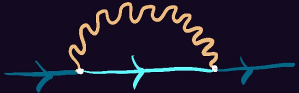
Conclusions

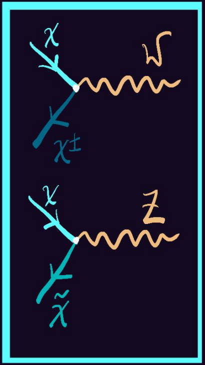
1. The nearly-pure higgsino is still one of our best DM theories
2.
3.
4.
5.

An SU(2) Doublet (by any other name)

Higgsino:

$\delta m_+ \gtrsim 350\,\mathrm{MeV}$ (Radiative)

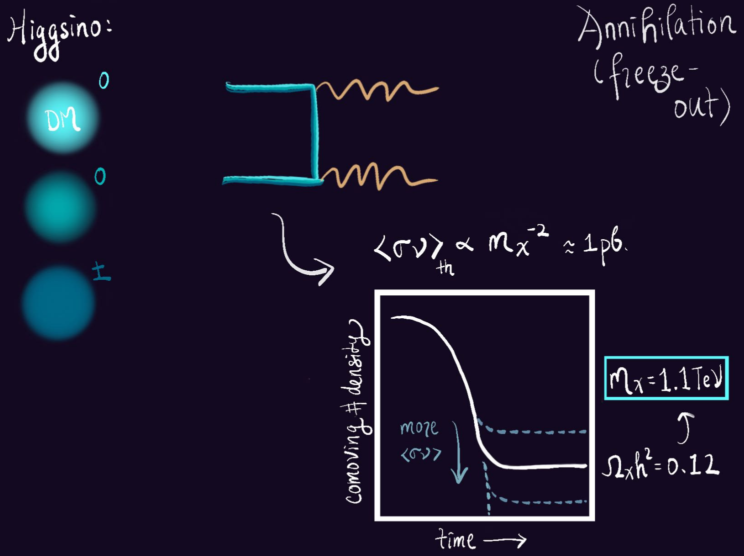




$$\delta m_0 \sim \frac{m_Z^2}{M_{1,2}} \text{ (from mixing)}$$

$\mu \ll M_1, M_2$

An SU(2) Doublet (by any other name)



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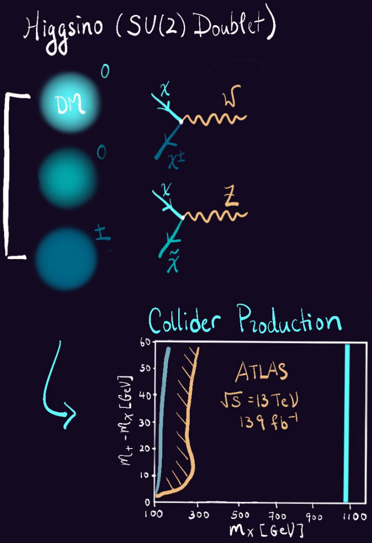

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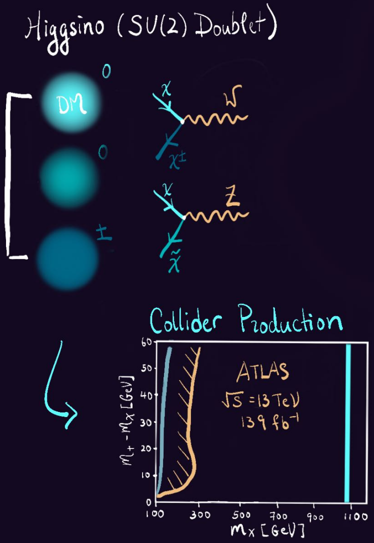

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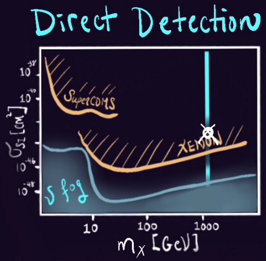
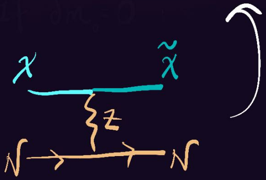


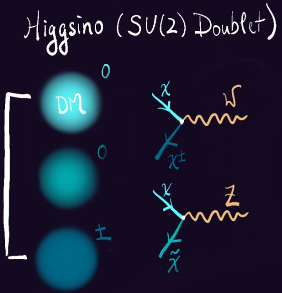
Only if kinematically allowed

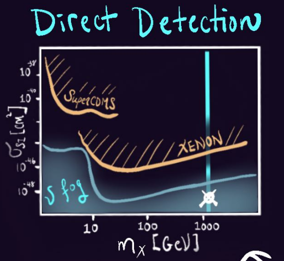
$\delta m_0 \lesssim m_\chi v^2$



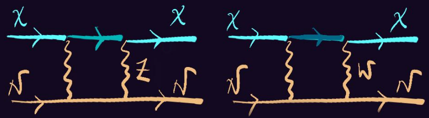
$\sigma_{SI} \sim 10^{-43}\ cm^2$

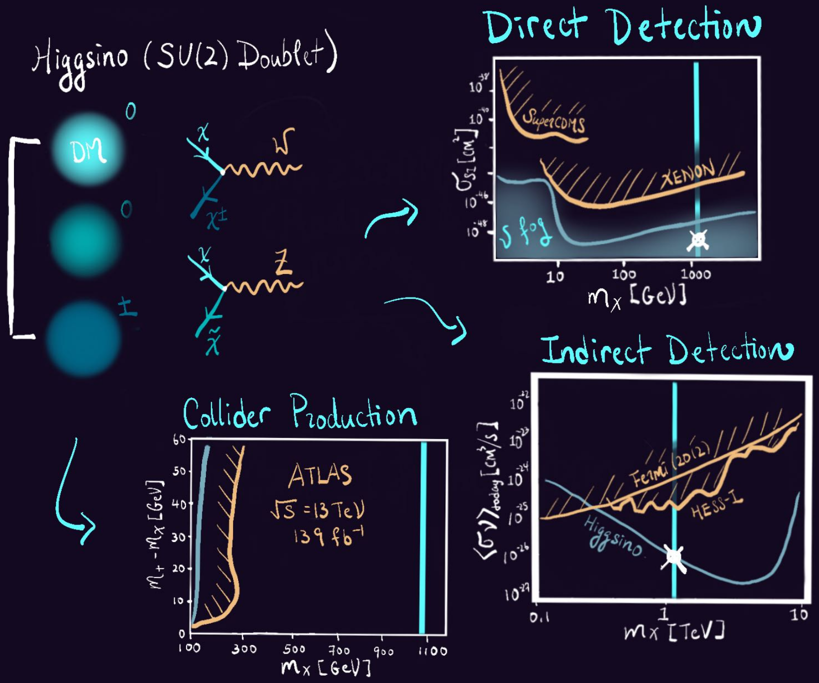
An SU(2) Doublet (by any other name)





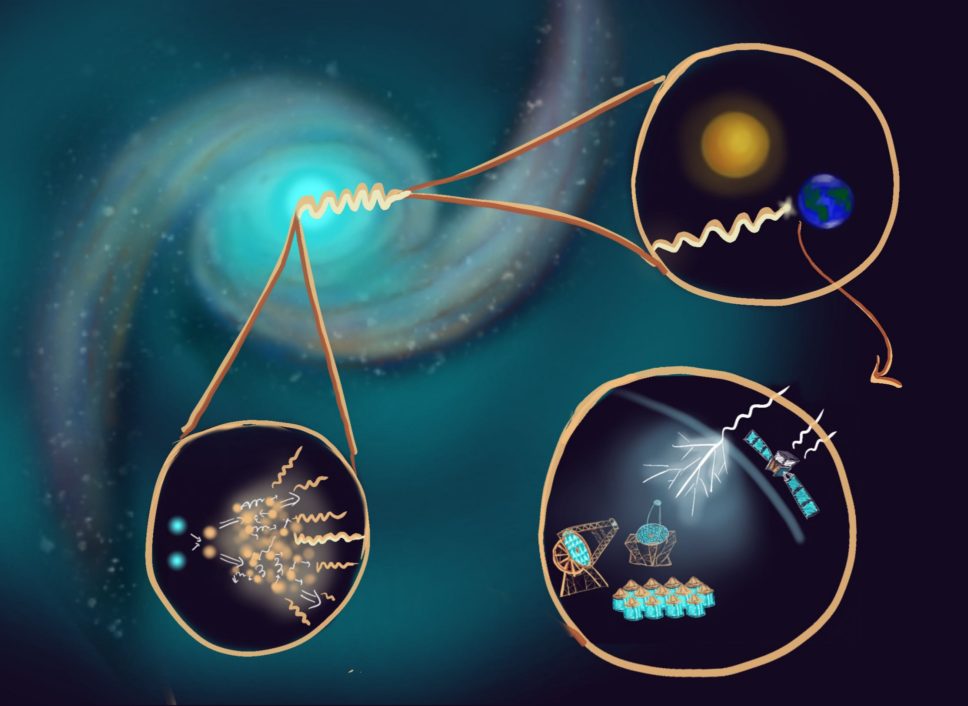
$$\sigma_{SI} \sim 10^{-48}\ \mathrm{cm}^2$$




Higgsino (SU(2) Doublet)
0
DM
0
±
χ
W
χ±
χ
Z
χ̃
Direct Detection
SuperCDMS
XENON
ν fog
σSI [cm²]
mχ [GeV]
10
100
1000
Indirect Detection
Fermi (2012)
HESS-I
Higgsino
⟨σv⟩today [cm³/s]
mχ [TeV]
0.1
1
10
Collider Production
ATLAS
√s = 13 TeV
139 fb⁻¹
m+ - mχ [GeV]
mχ [GeV]
0
10
20
30
40
50
60
100
300
500
700
900
1100

Conclusions

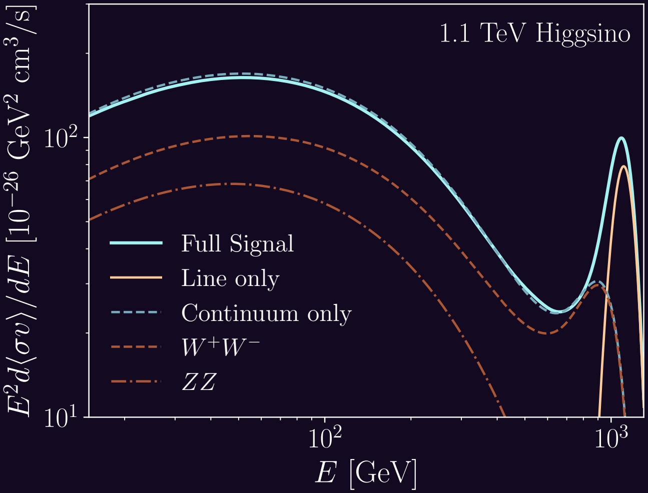
1. The nearly-pure higgsino is one of our best DM theories
2. The shortest path to discovery is in indirect detection
3.
4.
5.



$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E\,\mathrm{d}\Omega} = \frac{\overbrace{\mathcal{J}}^{\text{Spatial behavior}}}{8\pi m_\chi^2} \times \underbrace{\sum_X \langle \sigma v \rangle_{\chi\chi\to XX} \frac{\mathrm{d}N_{X\to\gamma}}{\mathrm{d}E}}_{\text{Spectral behavior}}$$

$$\mathcal{J} \equiv \int_{\mathrm{l.o.s.}} \mathrm{d}s\,\rho_\chi^2(s,\Omega)$$

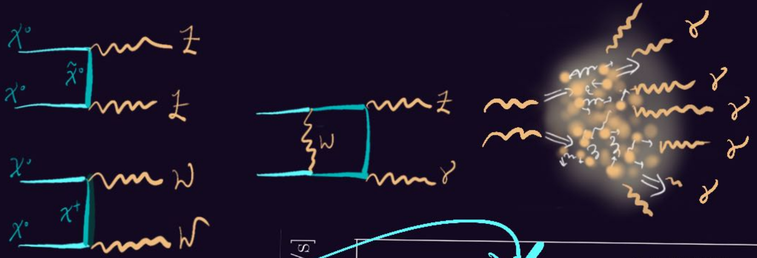
Spectral signal (Well known)

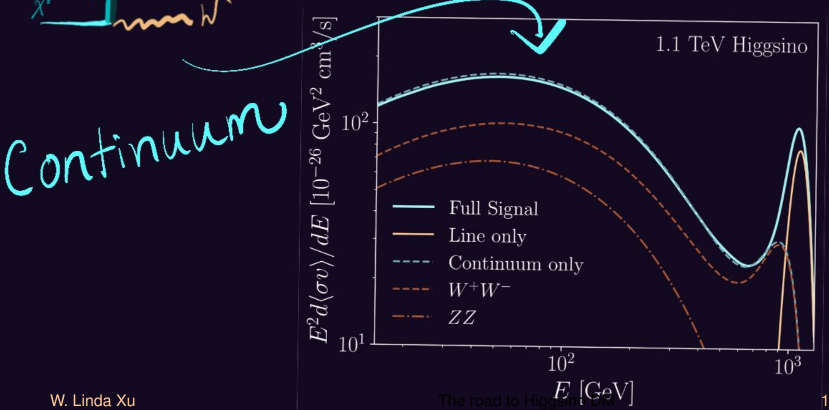


[Beneke, Urban & Vollmann, 2203.01692]

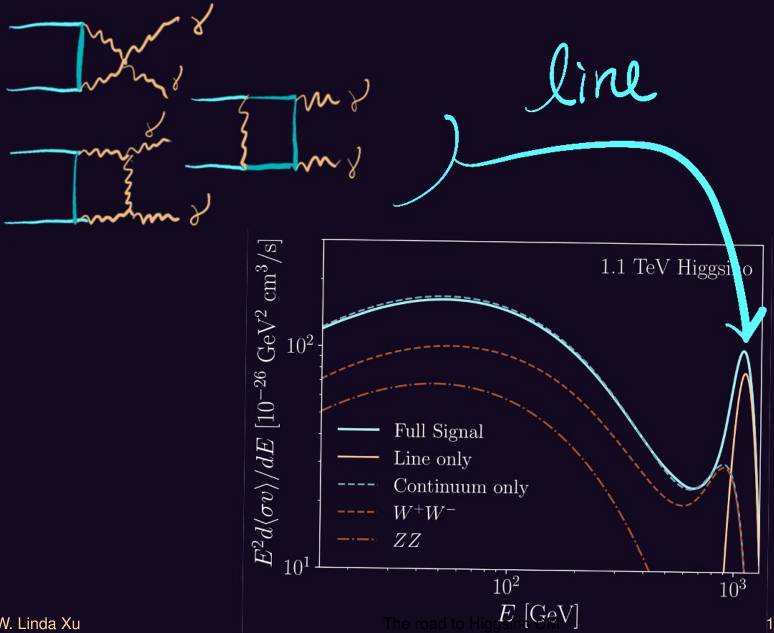
See Martin's talk on Friday!

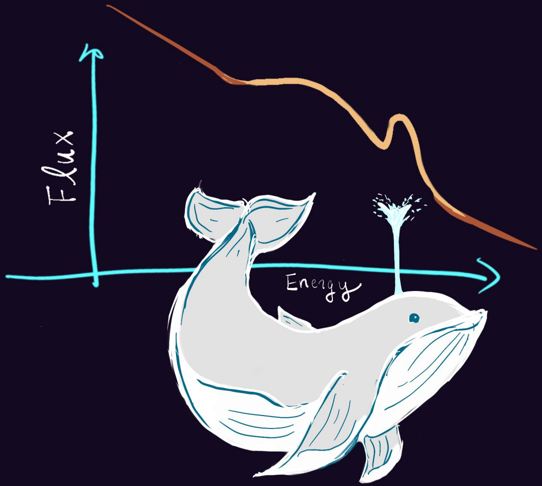
Spectral signal (Well known)

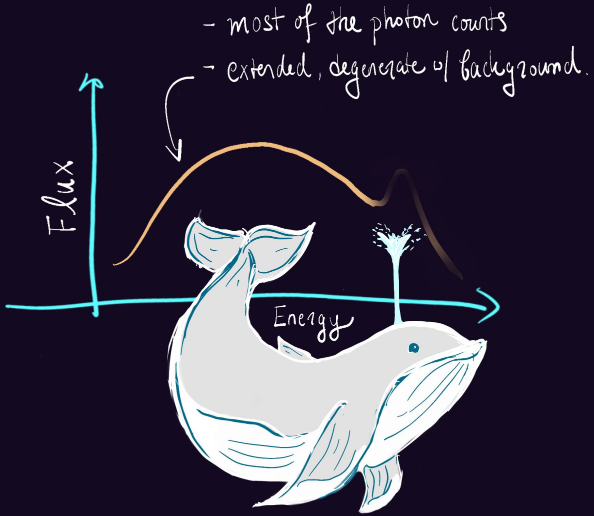


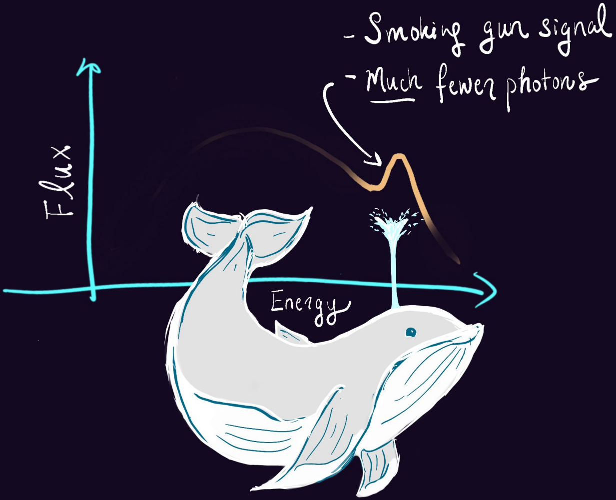


Spectral signal (Well known)




Flux
Energy


- most of the photon counts
- extended, degenerate w/ background.
Flux
Energy

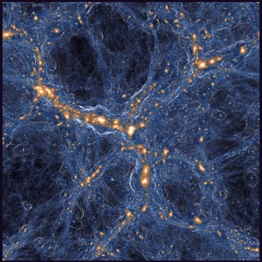

- Smoking gun signal
- Much fewer photons
Flux
Energy

Spatial signal (Very not well known)

We don't know how to directly measure (or predict) the distribution of DM in our galaxy

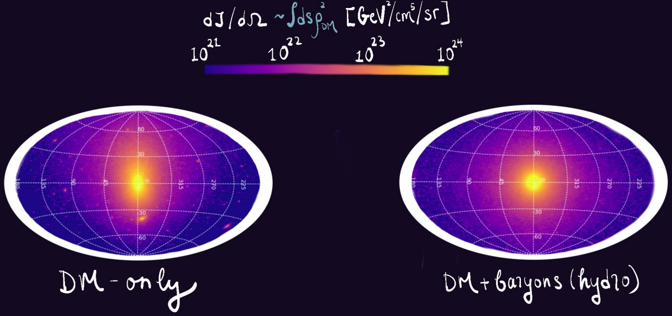
CDM-only n-body sims give a fairly universal behavior

$$\rho_{\chi,NFW} = \frac{\rho_s}{(r/r_s)(1+r/r_s)^3}$$



...However, baryons exist ($> 5\sigma$) & are important for the Galactic center

Spatial signal (Very not well known)

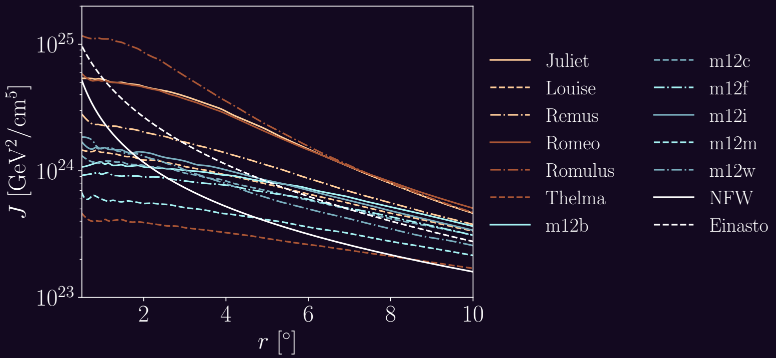


Feedback In Realistic Environments

[FIRE-2 collab., McKeown et. al. MNRAS 513 1 pp.55-70]

Spatial signal (Very not well known)

12 MW-like hydro sims, each giving a different profile and $\mathcal{J}$-factor



[FIRE-2 collab., McKeown et. al. MNRAS 513 1 pp.55-70]

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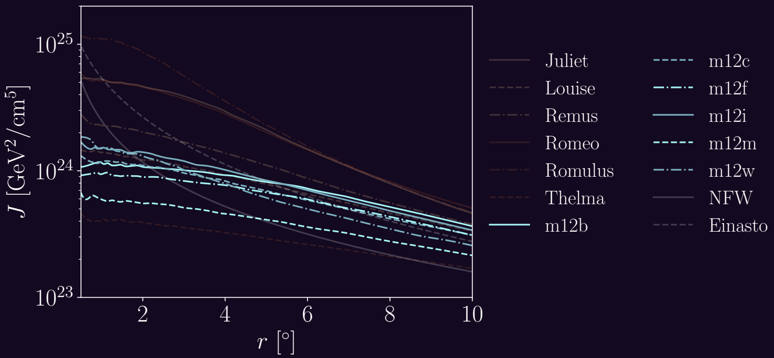

[FIRE-2 collab., McKeown et. al. MNRAS 513 1 pp.55-70]

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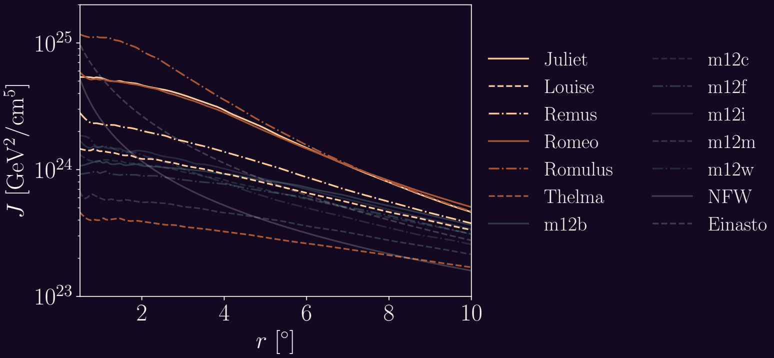

6 of these evolved in pairs (à la MW + M31)

[FIRE-2 collab., McKeown et. al, MNRAS 513 1 pp.55-70]

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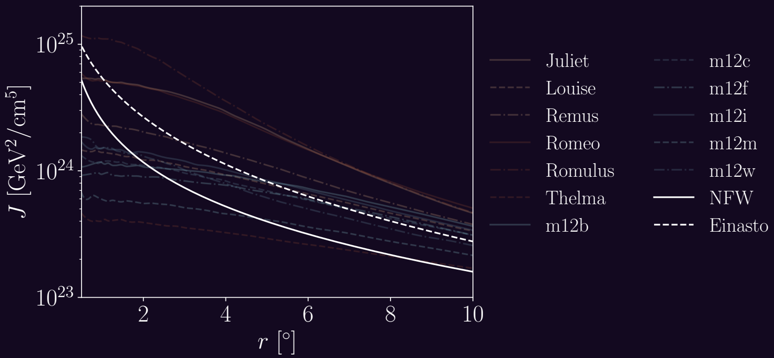

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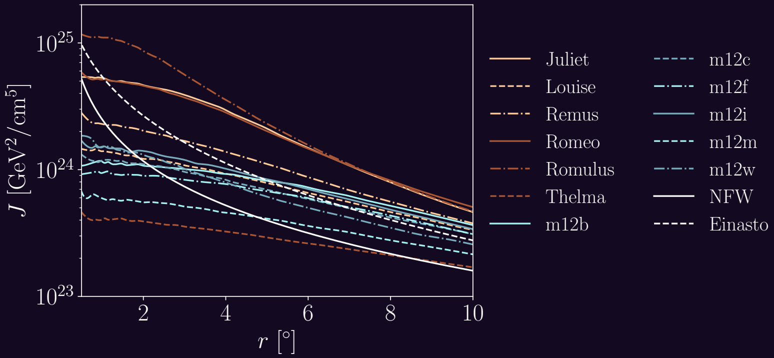
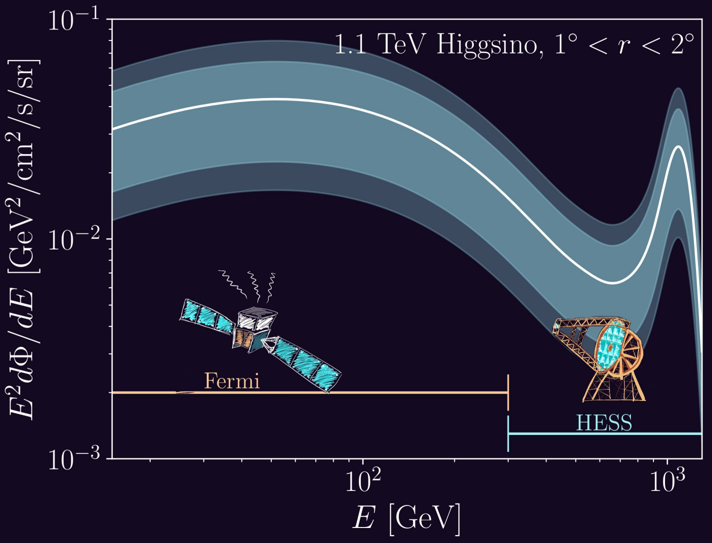


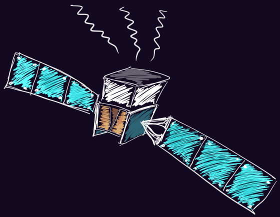
- Systematically more cored (but not less abundant)
- Giant variation between sims

Conclusions

1. The nearly-pure higgsino is one of our best DM theories
2. The shortest path to discovery is in indirect detection
   - We critically need better understanding of local/galactic distributions
3.
4.
5.

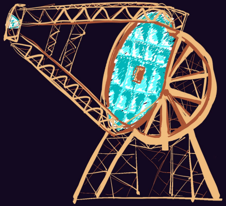
Let's start with what we have





Fermi - Large Area Telescope (LAT):

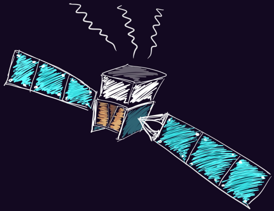
- 100 MeV - TeV reach
- peak sensitivity at ~ 10 GeV
- $\sim \mathrm{m}^2$ Effective area
- $\sim 10\%$ energy resolution
- 15 years of data scanning the sky



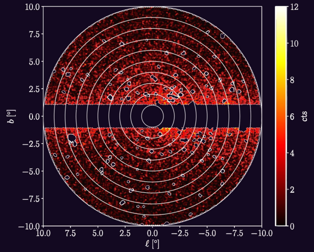
High Energy Stereoscopic System (H. E. S. S.):

- 100 GeV - 100 TeV reach
- peak sensitivity at $\sim$ 10 TeV
- $\sim 0.1\,\mathrm{km}^2$ effective area
- $\sim$ 10% energy resolution
- 800h of data pointed at the GC, $\sim$ 500h more to come

Part I: A continuum search with Fermi



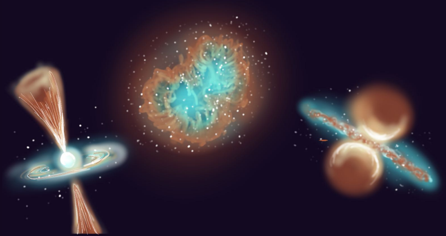
[w/ Chris Dessert & Josh Foster, 2207.10090]

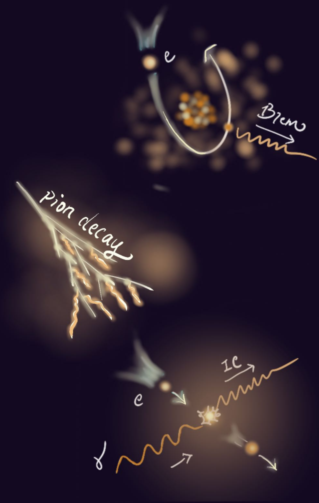


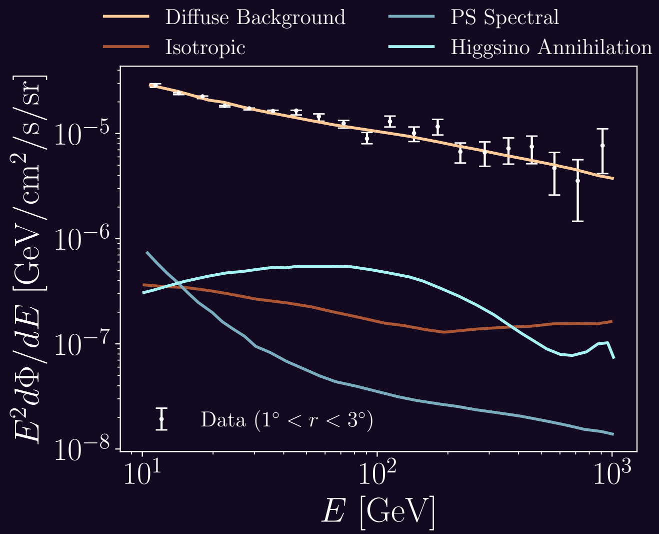
- Masked GP $|b| \leq 1°$, pt sources
- ROI: 9 concentric annuli, each $1°$
  - forgiving of under-masking, template mismatch
  - follow spatial profile of signal
- 21 bins, $E \in [10\text{GeV},\ 2\text{TeV}]$
  - Avoids most of diffuse background, + the GCE

Background components

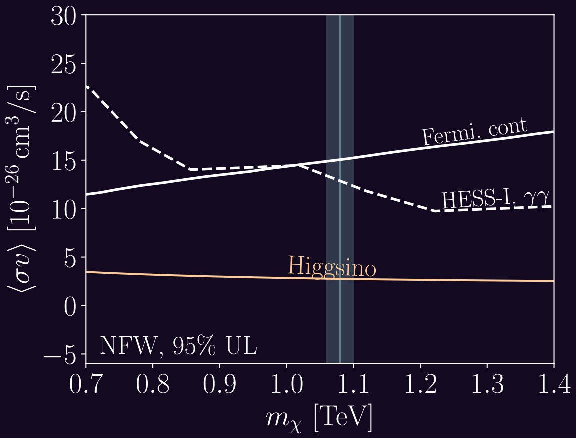
- `p8r3` diffuse Galactic emission
- + associated isotropic flux
- 4FGL point source spectral



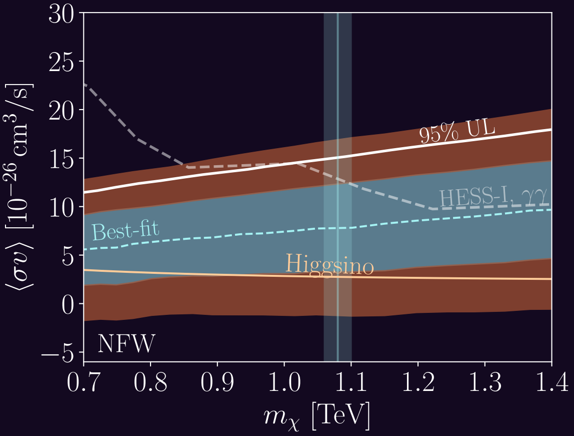




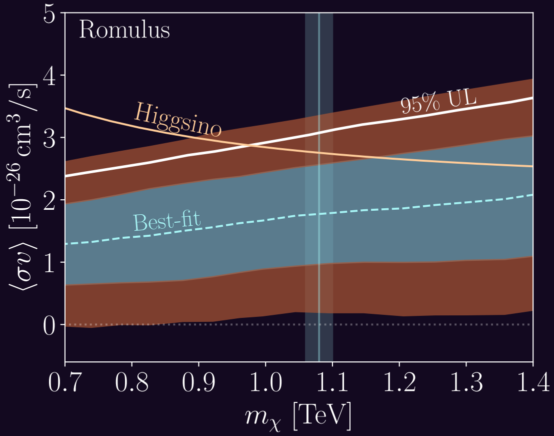
Diffuse Background
Isotropic
PS Spectral
Higgsino Annihilation
Data (1° < r < 3°)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
$E^2 d\Phi/dE$ [GeV/cm^2/s/sr]
10^1
10^2
10^3
E [GeV]



[Phys.Rev.Lett. 130 (2023) 20, 201001]



[Phys.Rev.Lett. 130 (2023) 20, 201001]



- $\sim 2\sigma$ excess at $\sim$ TeV masses in most FIRE profiles
- Limited by ability to model background

[Phys.Rev.Lett. 130 (2023) 20, 201001]

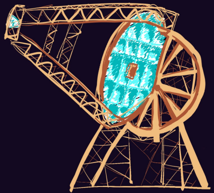
Conclusions

1. The nearly-pure higgsino is one of our best DM theories
2. The shortest path to discovery is in indirect detection
   - We critically need better understanding of local/galactic distributions
3. There are intriguing hints at lower energies ...
4.
5.

Conclusions

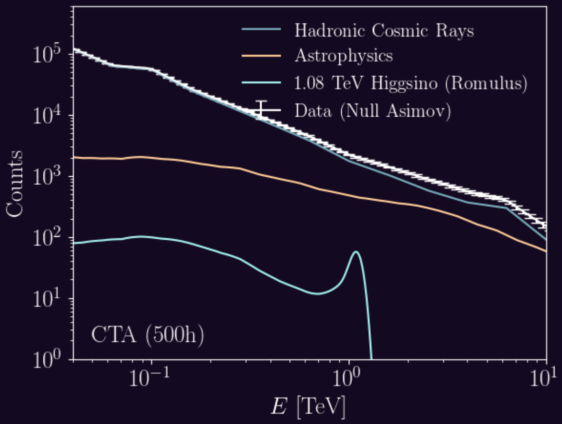
1. The nearly-pure higgsino is one of our best DM theories
2. The shortest path to discovery is in indirect detection
   - We critically need better understanding of local/galactic distributions
3. There are intriguing hints at lower energies ...
4. ... but smoking gun discoveries will need to come at the TeV scale
5.

Part II: A deep dive into line searches with H.E.S.S.

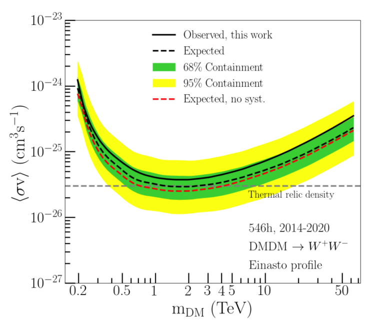


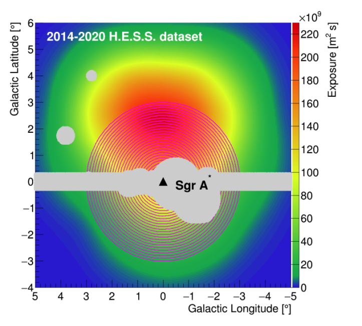
Background components:

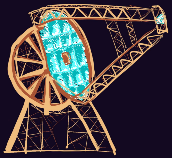
- Misidentified Cosmic Rays
  - Isotropic, extragalactic
  - $\sim$ 99% rejection
- Point Sources
- Diffuse Emission



Search for dark matter annihilation signals in the H.E.S.S. Inner Galaxy Survey







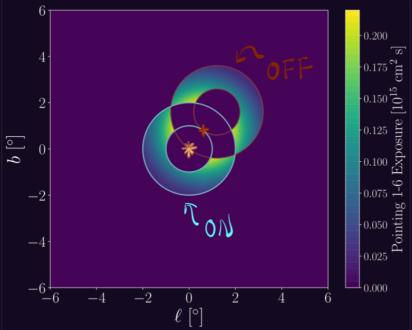
[2207.10471, Phys. Rev. Lett. 129, 111101 (2022)]

We do not have access to the data, but there is a lot to learn from what's been released.

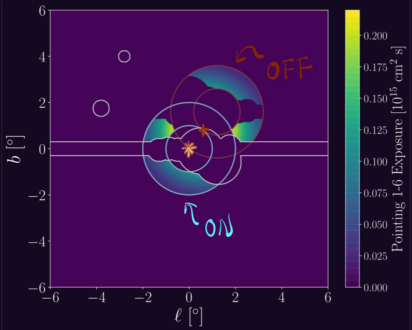
There are two, independent, key points here.

- This study uses a suboptimal analysis strategy for the Galactic center
-

HESS uses a ON/OFF subtraction scheme

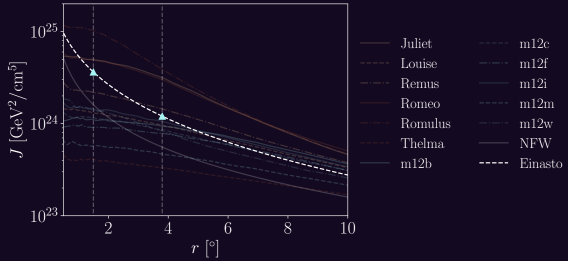


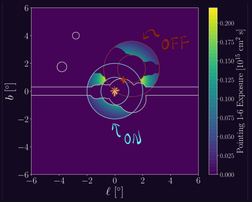
HESS uses a *masked* ON/OFF subtraction scheme



$$N^{ON} - N^{OFF} = N^{\text{Signal}} \sim \langle \sigma v \rangle \left(\mathcal{J}^{ON} - \mathcal{J}^{OFF} \right)$$

HESS uses a *masked* ON/OFF subtraction scheme





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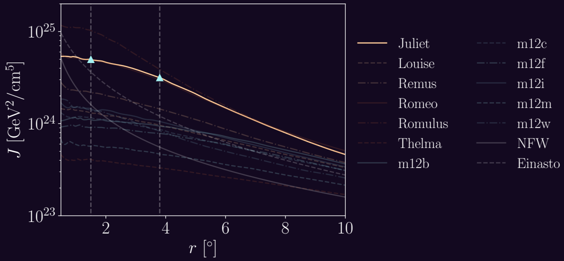
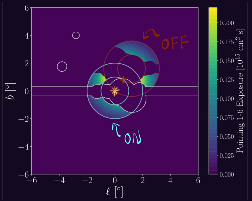
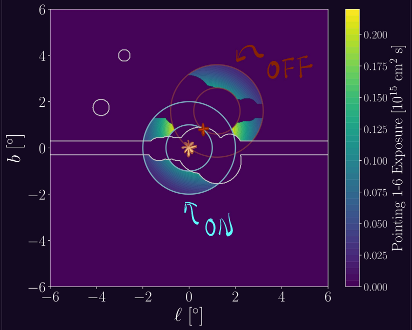




$$N^{ON} - N^{OFF} = N^{\text{Signal}} \sim \langle \sigma v \rangle \left(\mathcal{J}^{ON} - \mathcal{J}^{OFF} \right)$$

HESS uses a masked ON/OFF subtraction scheme

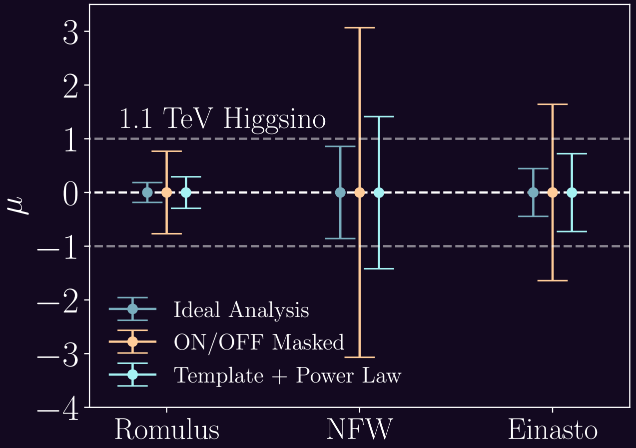
- Optimized for point sources
- Not robust for diffuse background
- Loses 60 - 95 % of signal counts in the GC
- Highly sensitive to DM profile



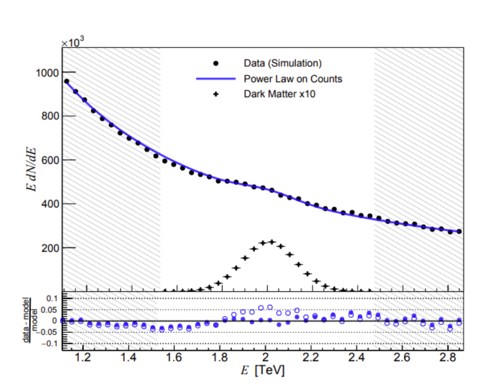
The wrong analysis strategy can leave *a lot* of sensitivity on the table

We advocate for a template analysis

- Use all inner Galaxy data for signal
- Model CR bkg with high-statistics data-driven template
  - Every point source observation contains blank sky footage
  - A lot of opportunity to stress-test this
- + Fermi diffuse model or Power law for astro component



1.1 TeV Higgsino
μ
3
2
1
0
−1
−2
−3
−4
Ideal Analysis
ON/OFF Masked
Template + Power Law
Romulus
NFW
Einasto



See [Torsten et al, 2403.04857]! Line search w/ sliding window

N.B. :

- Power law / sliding window techniques trade bias/sensitivity
- Neglecting the continuum for us can lower TS by factor ~ 2

We do not have access to the data, but there is a lot to learn from what's been released.

There are two, independent, key points here.

- This study uses a suboptimal analysis strategy for the Galactic center
- We think H.E.S.S. mischaracterizes their sensitivity by a factor of ~ 8

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$\left.\frac{d\Phi}{dE}\right|_{\text{DM Annihilation}}$

Known by hypothesis

$\left.\frac{d\Phi}{dE}\right|_{\text{Galactic diffuse}}$

Known from Fermi-LAT

$\left.\frac{d\Phi}{dE}\right|_{\text{CR background}}$

Known from AMS-02

$\times$ rejection

$\rightarrow$ [Instrument response

Observation strategy] $\rightarrow$

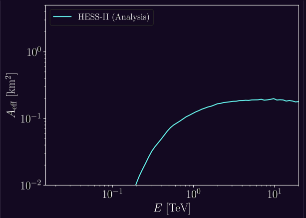
$N_{\text{DM}}^{ON}, N_{\text{DM}}^{OFF}$

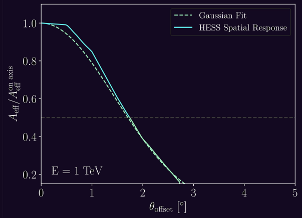
$N_{\text{diff}}^{ON}, N_{\text{diff}}^{OFF}$

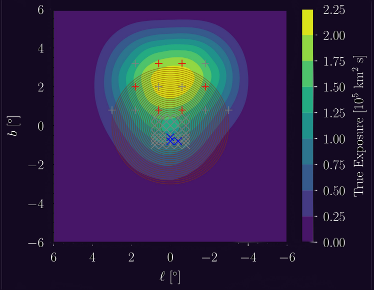
$\approx N_{\text{tot}}^{ON}, N_{\text{tot}}^{OFF}$

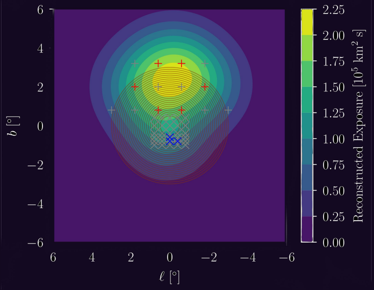
Instrument response

Observation strategy







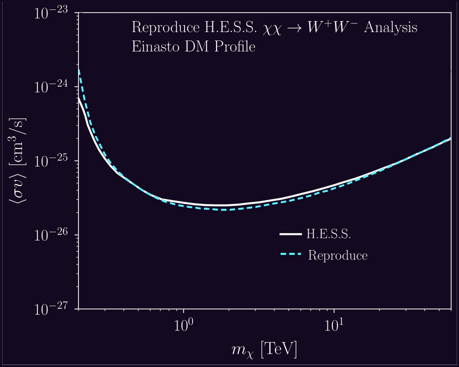


$\left.\frac{d\Phi}{dE}\right|_{\text{DM Annihilation}}$

Known by hypothesis

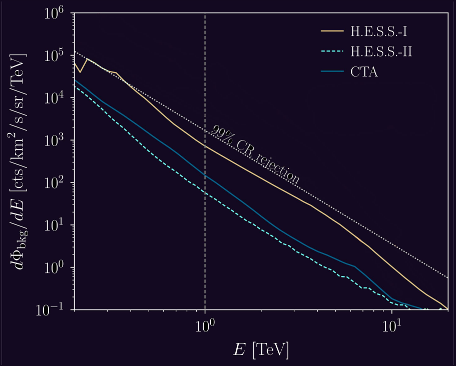
$\rightarrow$ [Instrument response / Observation strategy] $\rightarrow$

$\rightarrow$



$$\left.\frac{d\Phi}{dE}\right|_{\text{CR background}} = \epsilon_{\text{rej.}} \times 9.6 \times 10^4 \left[\frac{E}{\text{TeV}}\right]^{-2.7} \text{cts/s/sr/TeV/km}^2 \Bigg\} \rightarrow$$

$$\rightarrow \left[\begin{array}{r} \text{Instrument} \\ \text{response} \\ \\ \text{Observation} \\ \text{strategy} \end{array}\right] \rightarrow \left\{ \begin{array}{l} \approx \text{Total reported} \\ \quad N^{ON} + N^{OFF} \end{array}\right.$$



Rejection Efficiency $\gtrsim 99.95\%$ → [Instrument response / Observation strategy] → { ≈ Total reported $N^{ON} + N^{OFF}$

$\left.\frac{d\Phi}{dE}\right|_{\text{Galactic diffuse}}$

Known from Fermi-LAT

Between 200 GeV - 2 TeV,

same energies, same sky

$\rightarrow$ [Instrument response

Observation strategy] $\rightarrow$

$$\rightarrow \left\{ \; N_{\text{tot}}^{ON} - N_{\text{tot}}^{OFF} \approx N_{\text{diff}}^{ON} - N_{\text{diff}}^{OFF} \right.$$

$\frac{d\Phi}{dE}\Big|_{\text{Galactic diffuse}}$

Known from Fermi-LAT

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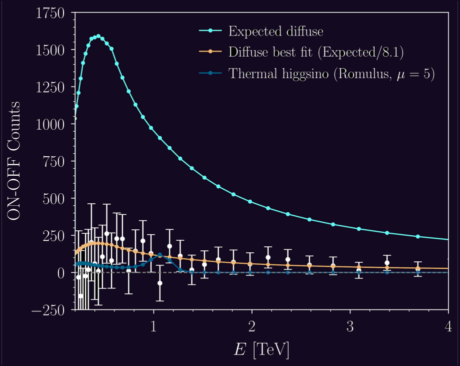
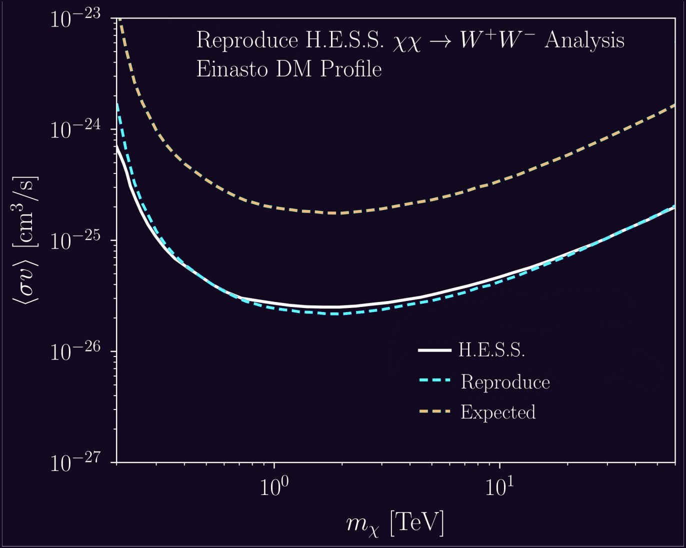
$\rightarrow$



$$N_{\text{tot}}^{ON} - N_{\text{tot}}^{OFF} \approx N_{\text{diff}}^{ON} - N_{\text{diff}}^{OFF}$$

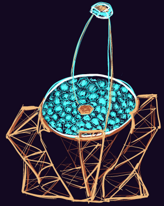


[Genuinely welcome any feedback, would be exciting to be wrong!]

Conclusions

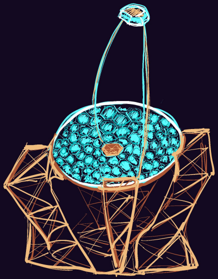
1. The nearly-pure higgsino is one of our best DM theories
2. The shortest path to discovery is in indirect detection
   - We critically need better understanding of local/galactic distributions
3. There are intriguing hints at lower energies ...
4. ... but smoking gun discoveries will need to come at the TeV scale
   - The analysis strategy can make or miss a discovery
   - There are some concerns with what we currently have
5.

Part III: A look into future with CTA and SWGO



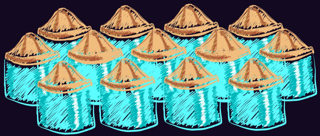
CTA (-South*):

- peak sensitivity $\sim$ TeV
- $\sim 1\,\mathrm{km}^2$ effective area
- $\sim$ 5% energy resolution
- $\sim$ 500h in inner GC
- $\sim 4^\circ$ FOV

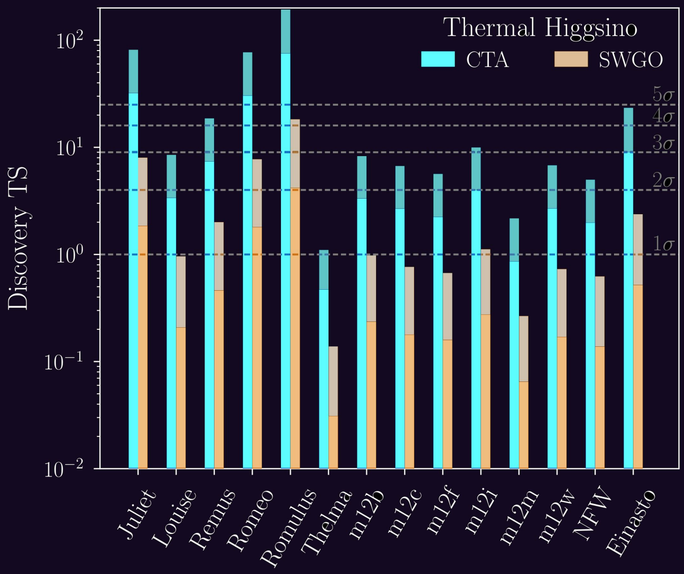


SWGO:

- peak sensitivity $\sim$ 10 TeV
- $\sim 0.1\,\mathrm{km}^2$ effective area
- $\sim$ 20% energy resolution
- $\sim$ 6 hrs/day for $\sim$ 5 years
- $\sim$ 1 sr FOV



* Also exciting potential with CTA-North!


Thermal Higgsino
CTA
SWGO
Discovery TS
10^2
10^1
10^0
10^{-1}
10^{-2}
5σ
4σ
3σ
2σ
1σ
Juliet
Louise
Remus
Romeo
Romulus
Thelma
m12b
m12c
m12f
m12i
m12m
m12w
NFW
Einasto

Conclusions

1. The nearly-pure higgsino is one of our best DM theories
2. The shortest path to discovery is in indirect detection
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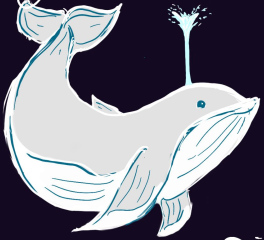
3. There are intriguing hints at lower energies ...
4. ... but smoking gun discoveries will need to come at the TeV scale
   - The analysis strategy can make or miss a discovery
   - There are some concerns with current data
5. We have a very optimistic shot with CTA & SWGO

Thank you!



Wilt thou not chase the white whale?