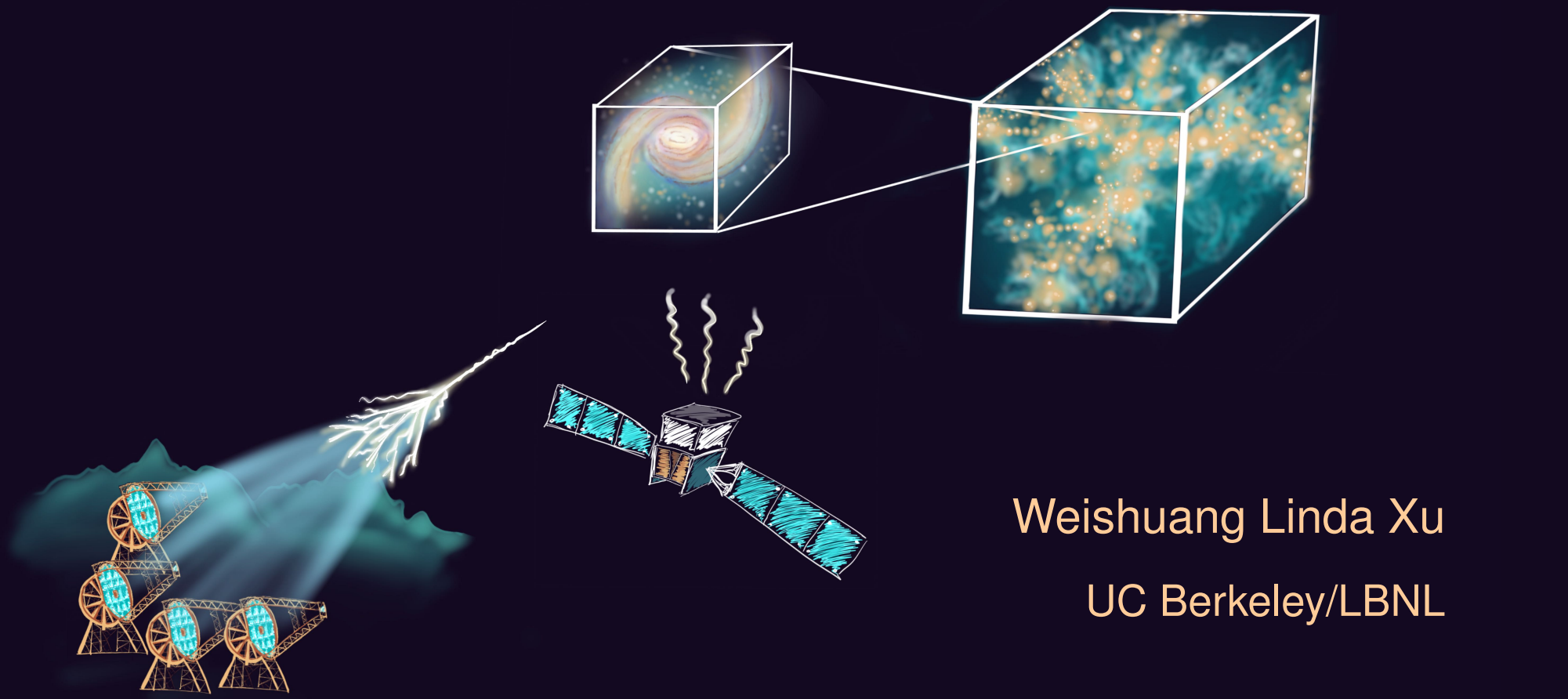
# In Search of a Higgsino

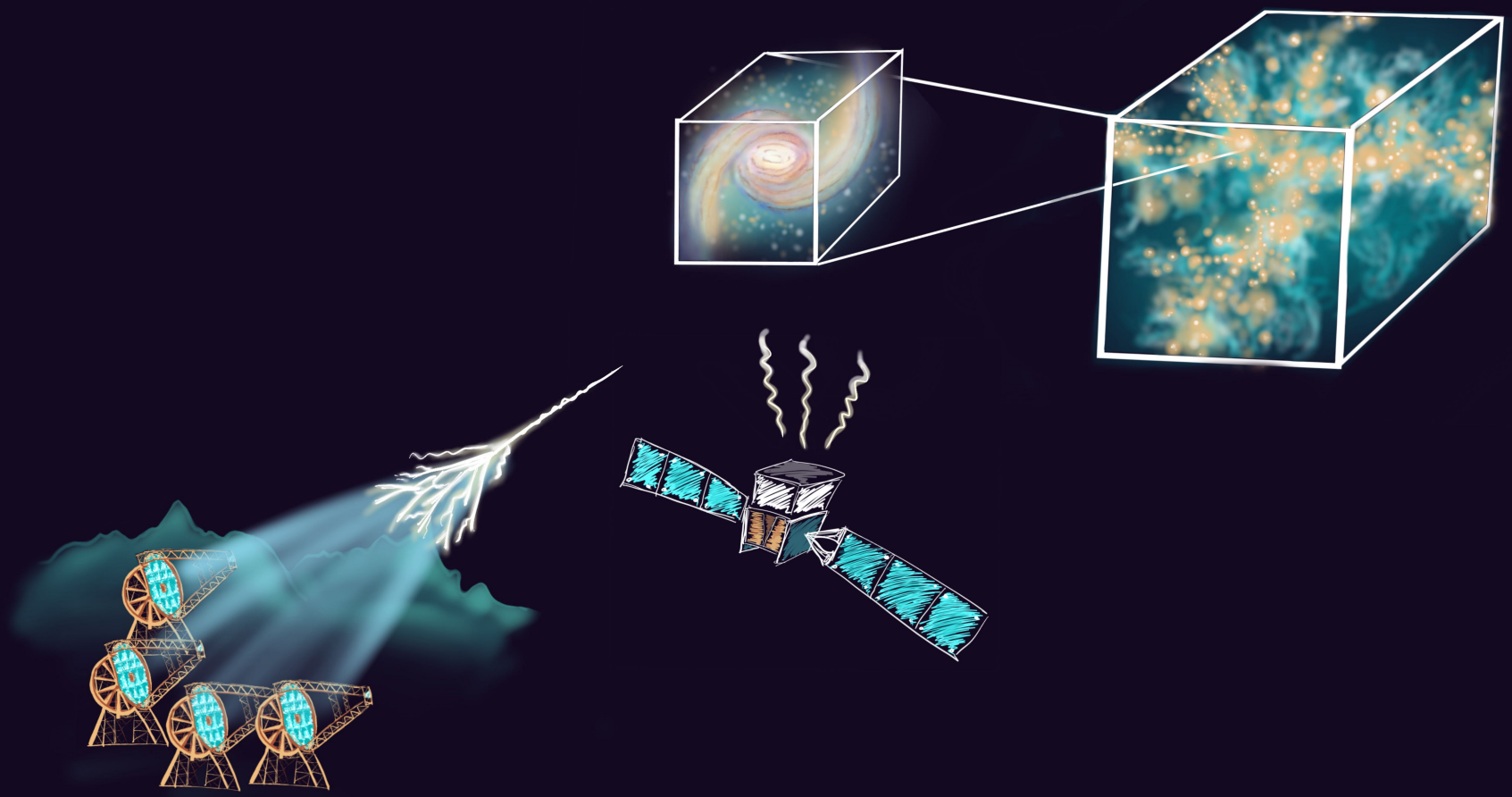
University of Tokyo, Berkeley Week 2024

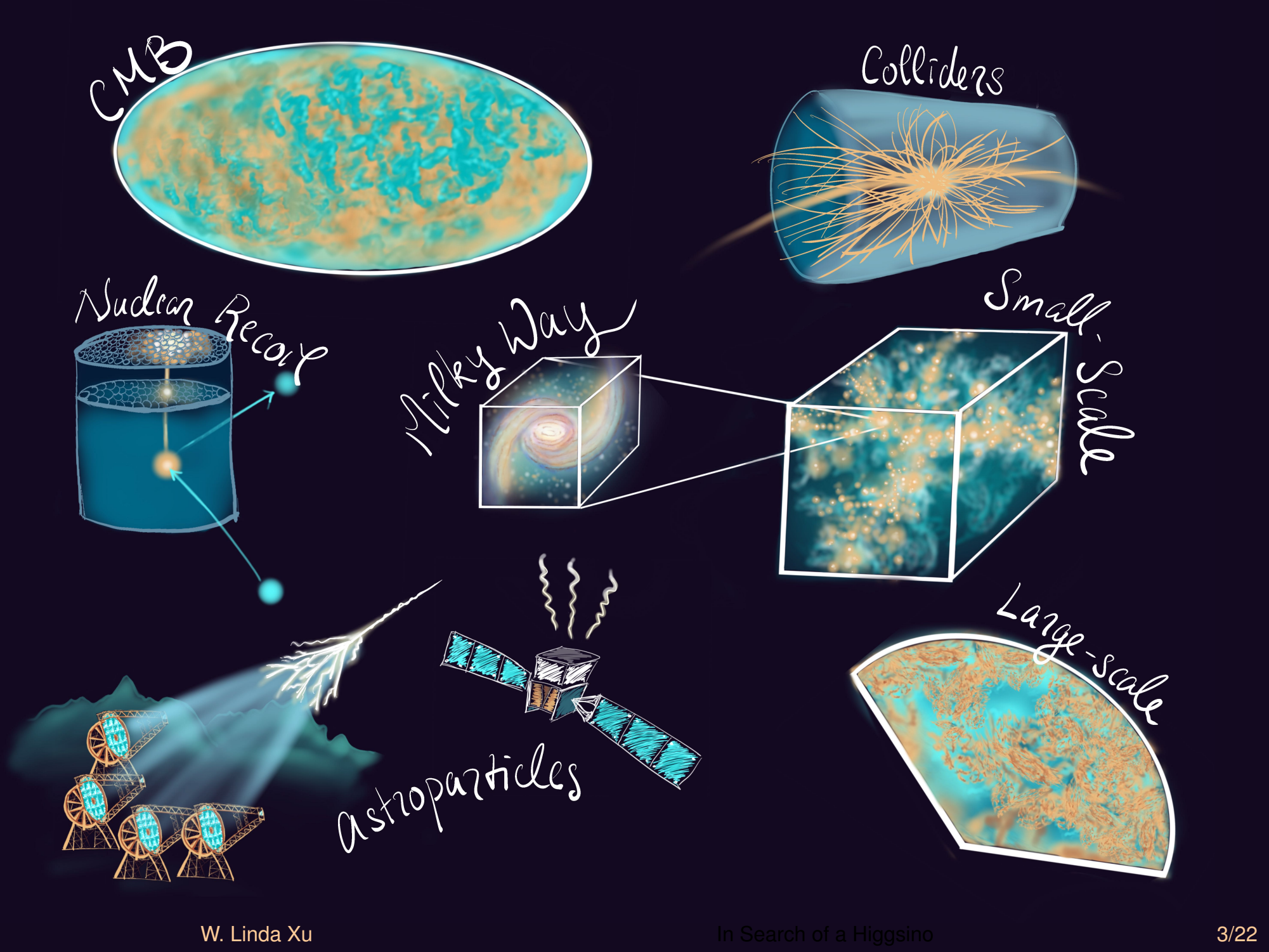


Weishuang Linda Xu

UC Berkeley/LBNL

We don’t know what dark matter is.
(we’re trying very hard to change that)




CMB
Colliders
Nuclear Recoil
Milky Way
Small-Scale
Large-scale
Astroparticles

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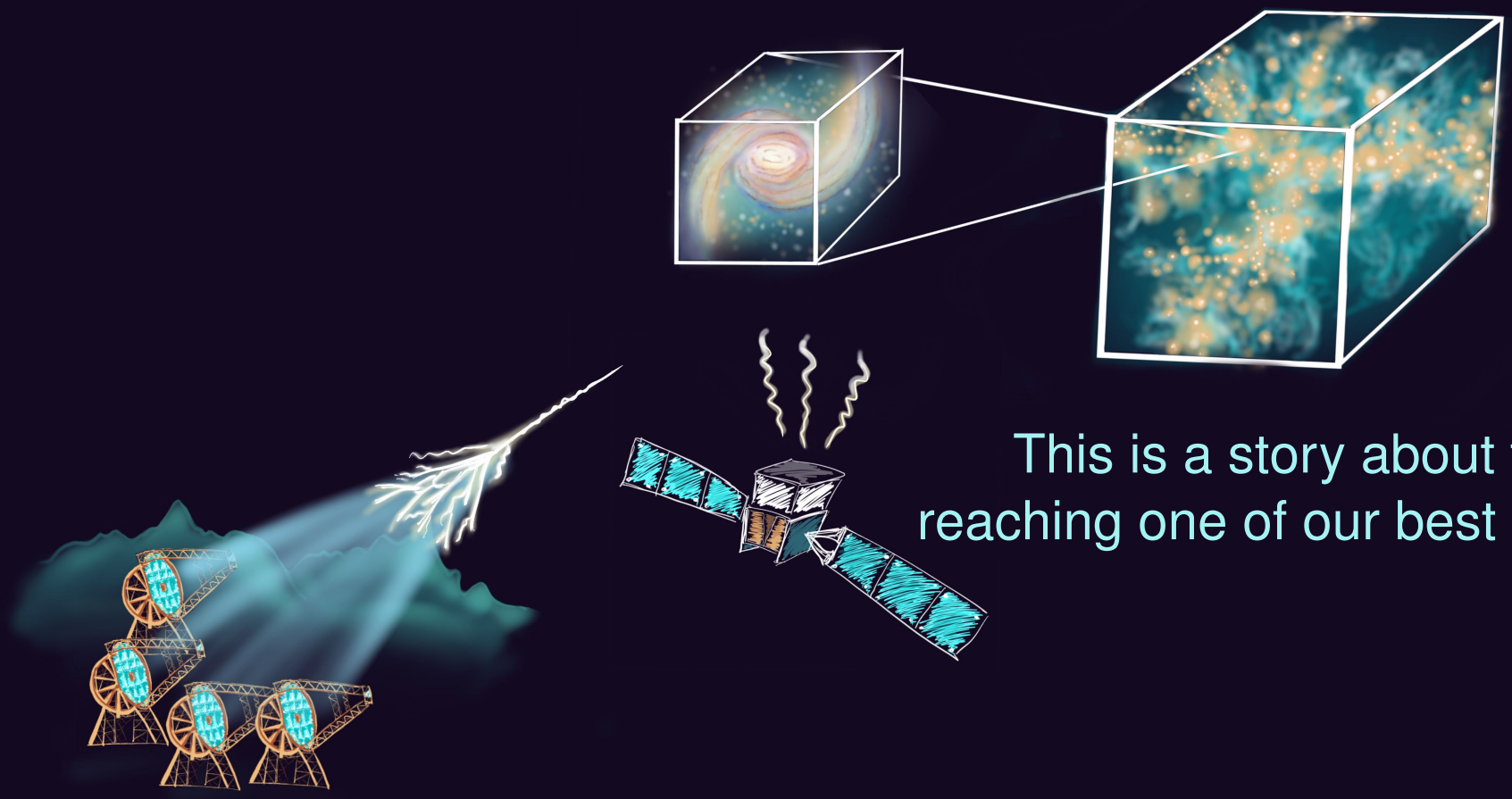
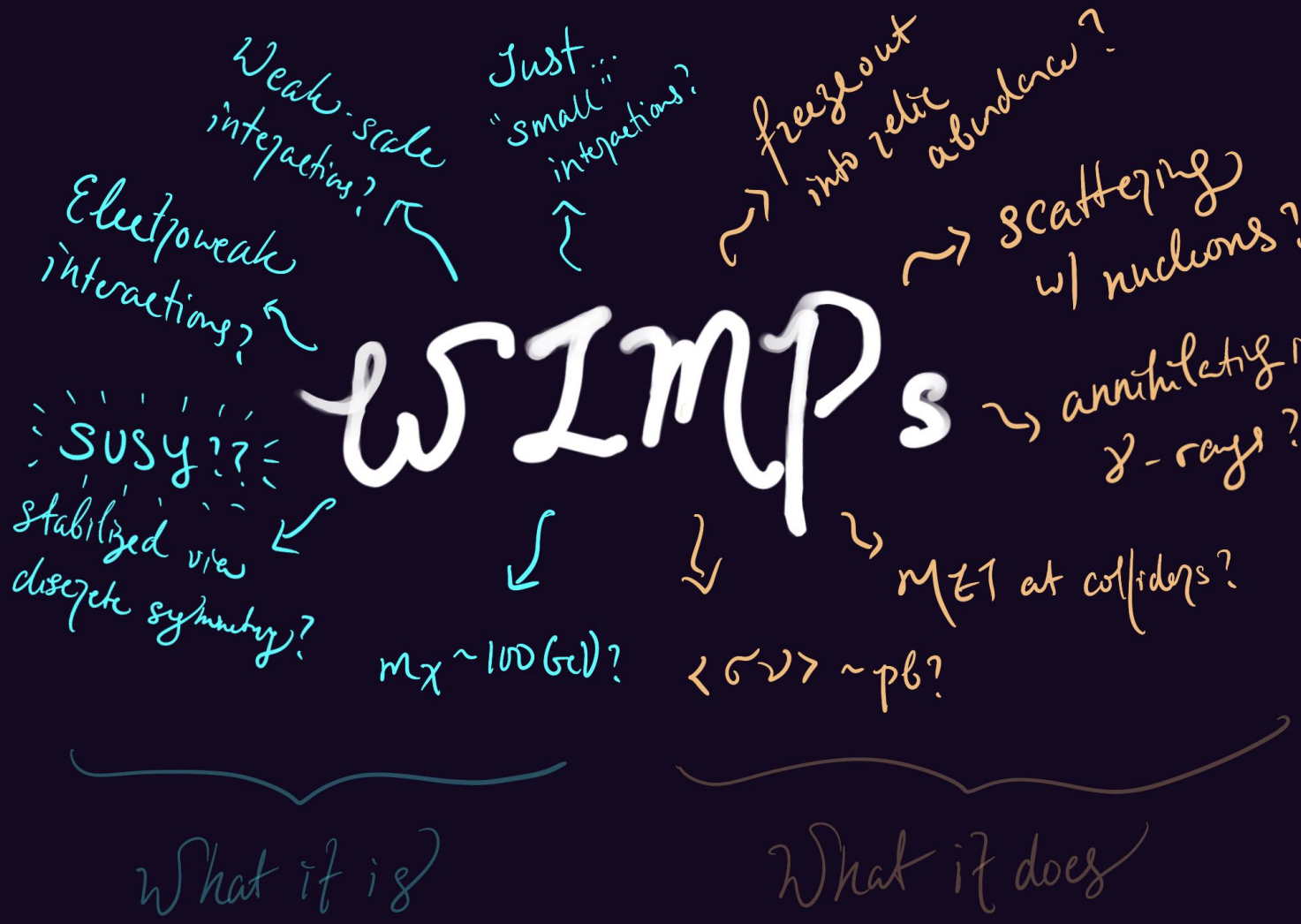
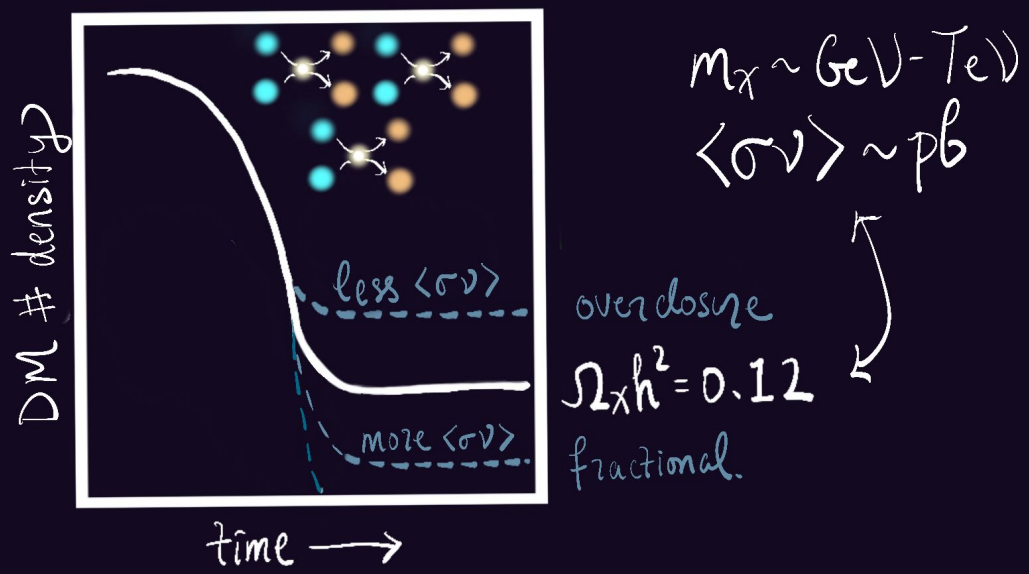


This is a story about finally
reaching one of our best ideas


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

# WIMPs: the pragmatics

- Theoretically (and empirically) motivated



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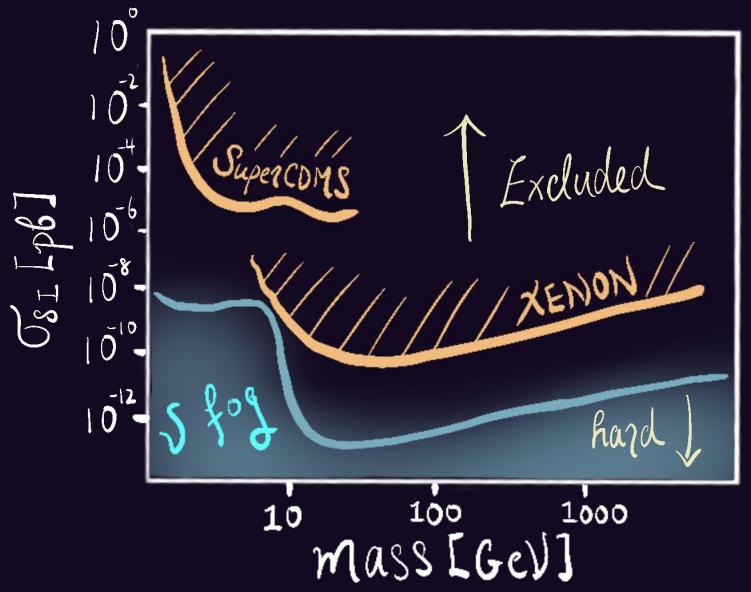

# WIMPs: the pragmatics

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A modern day viable WIMP needs annihilation $\gg$ scattering

$$\frac{\langle \sigma v \rangle_{\chi\chi \to \mathrm{SM}}}{\sigma_{\chi N \to \chi N}} \gtrsim 10^{10}$$

... but scattering is not what a thermal WIMP promises you

[See JHEP 08 (2023) 091, Phys.Rev.D 107 (2023) 10, 103047 , JHEP 03 (2021) 123, JHEP 05 (2020) 081 for some model-building]

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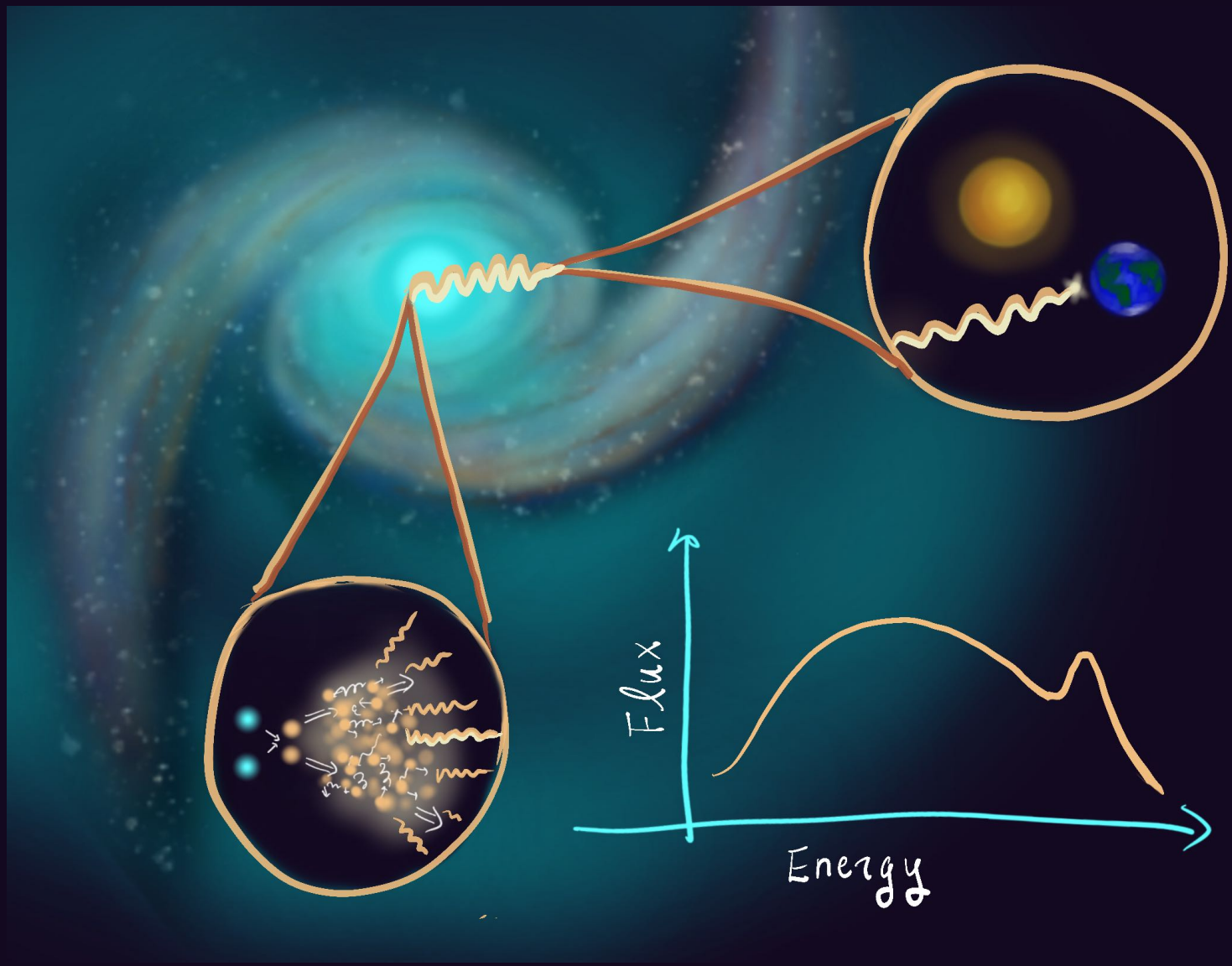
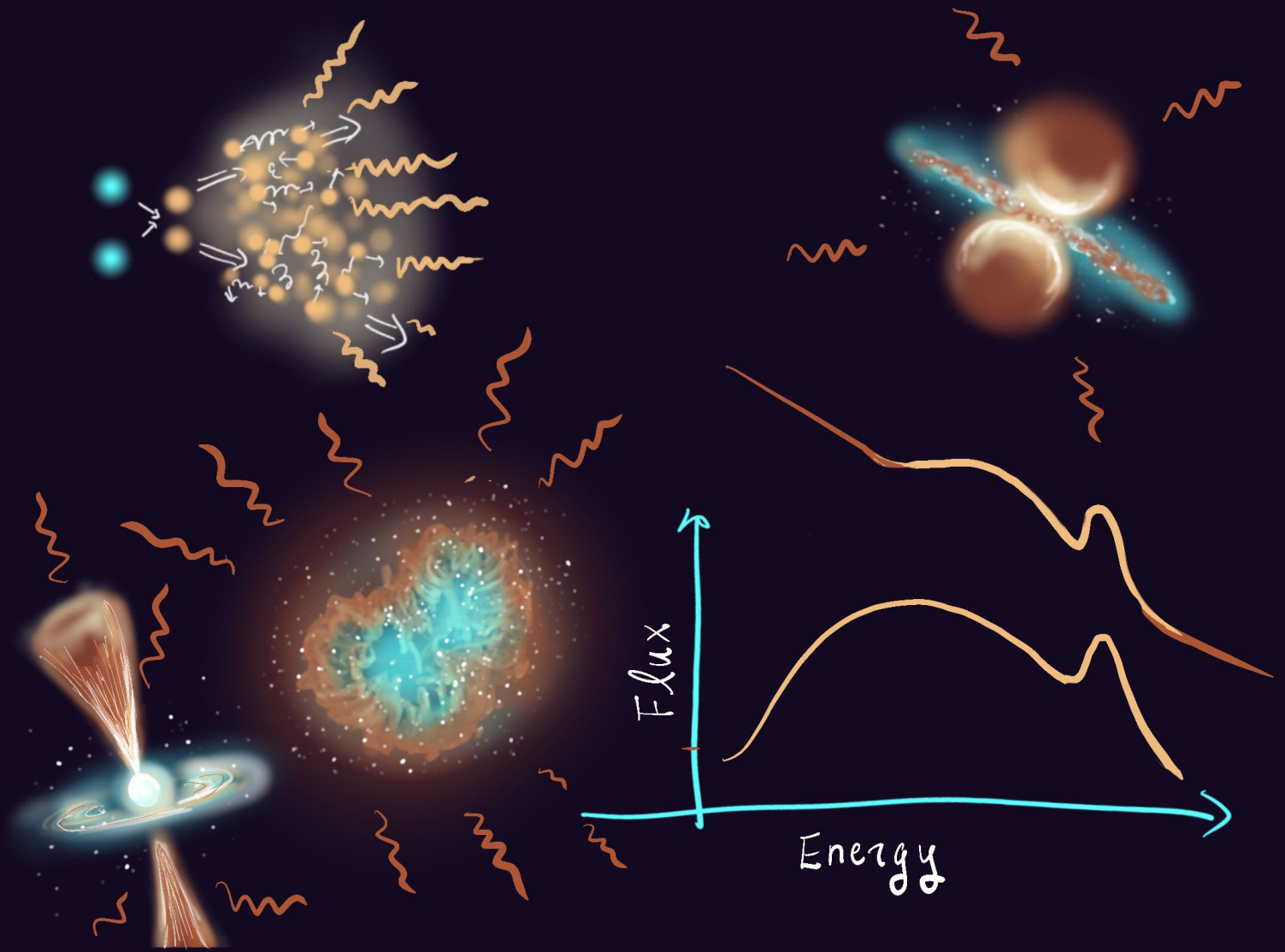
Direct detection will always have blind spots. Indirect detection may be necessary to discover a thermal relic.


Flux
Energy


Flux
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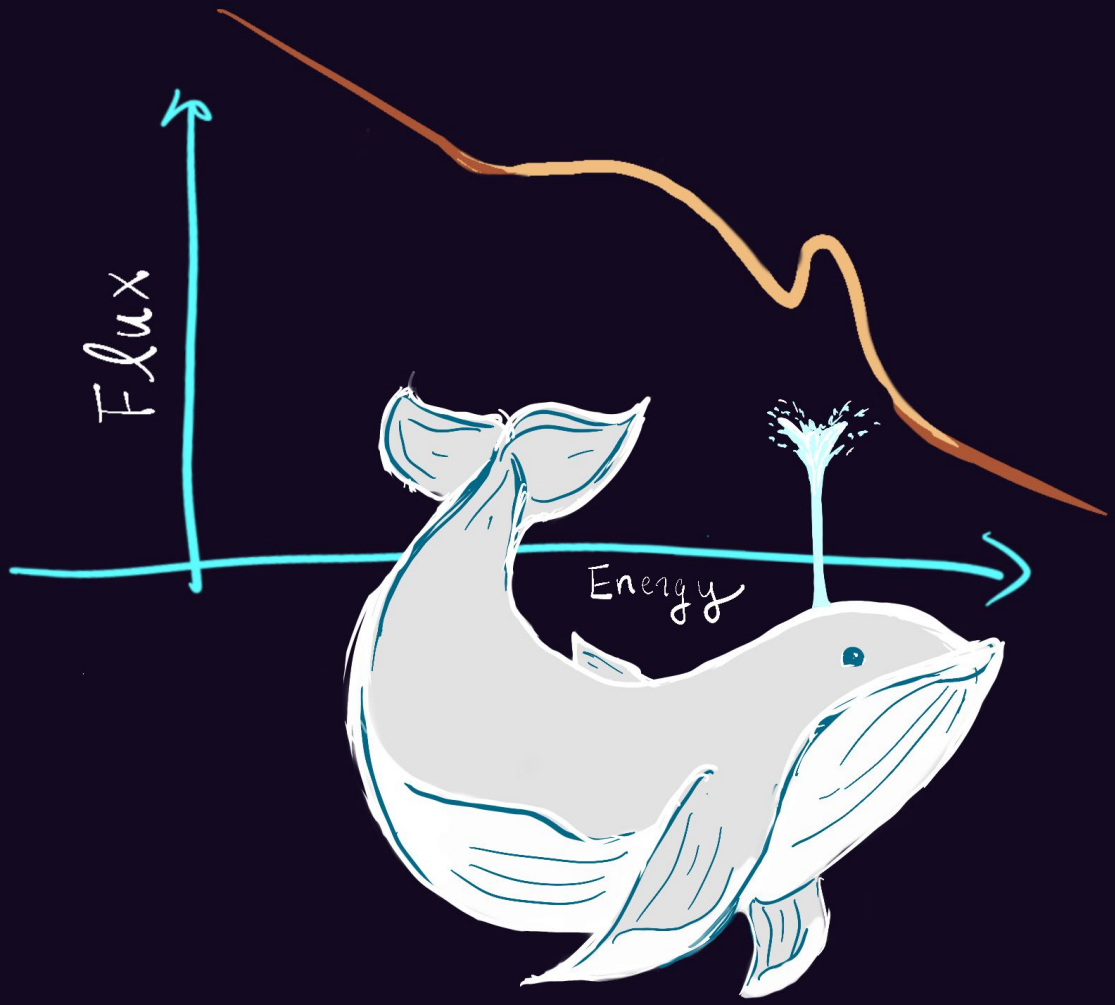
Flux
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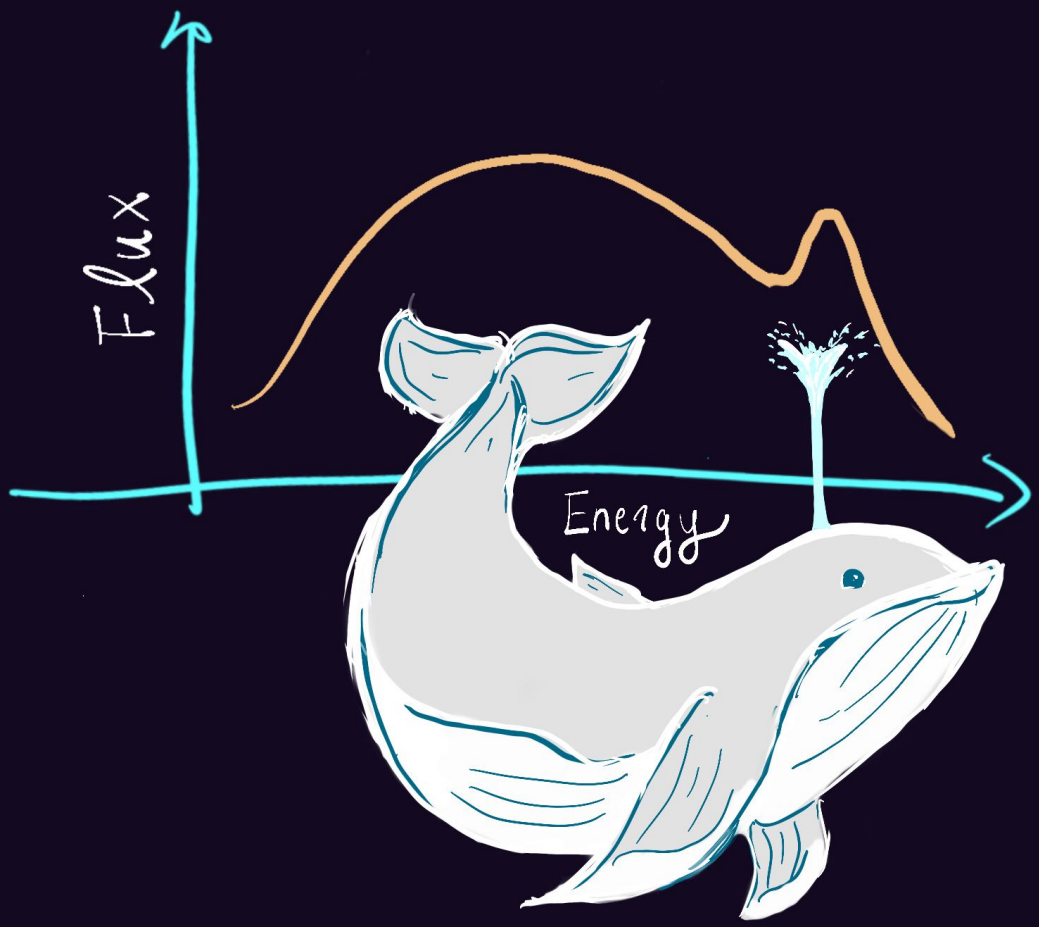
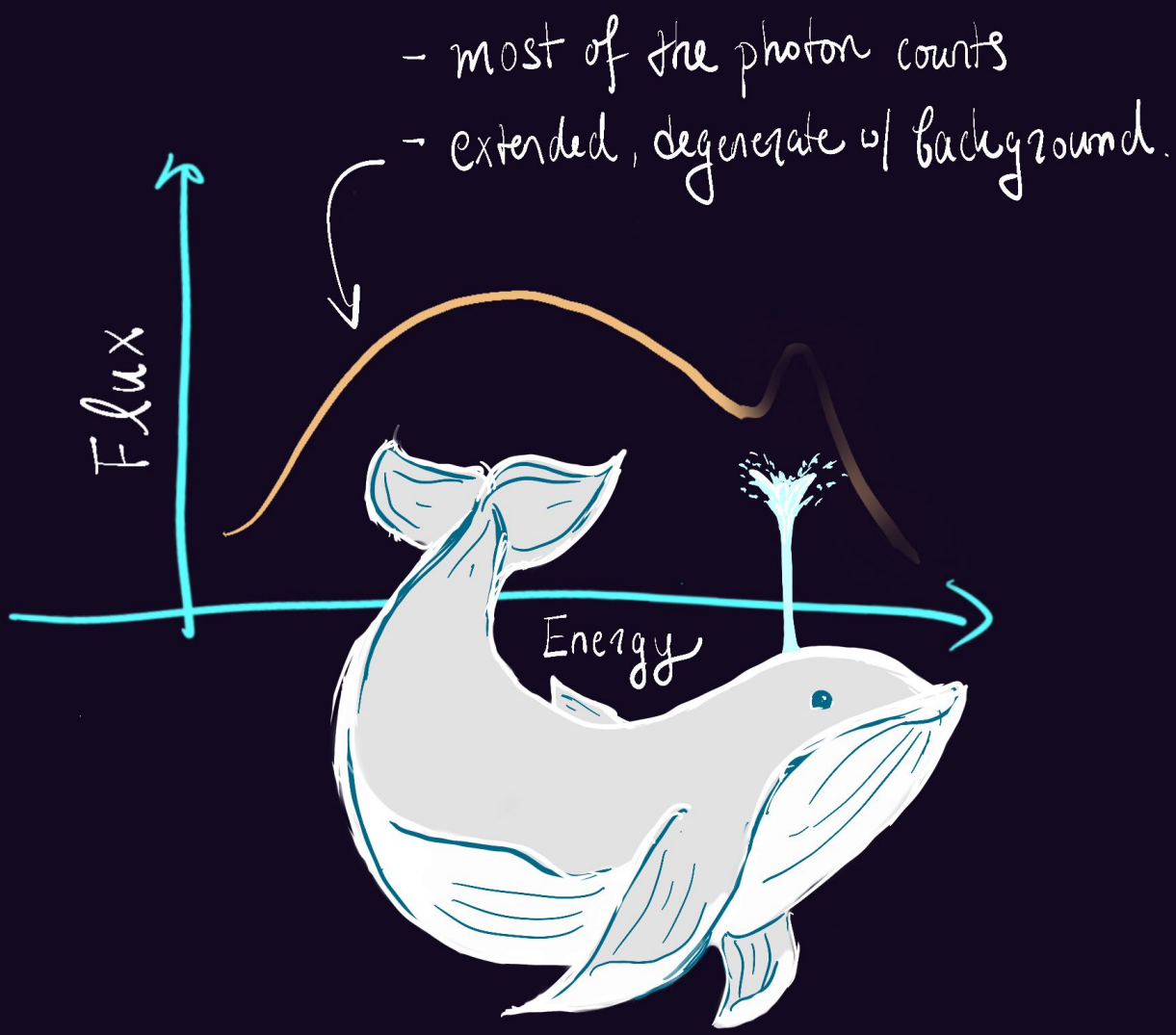
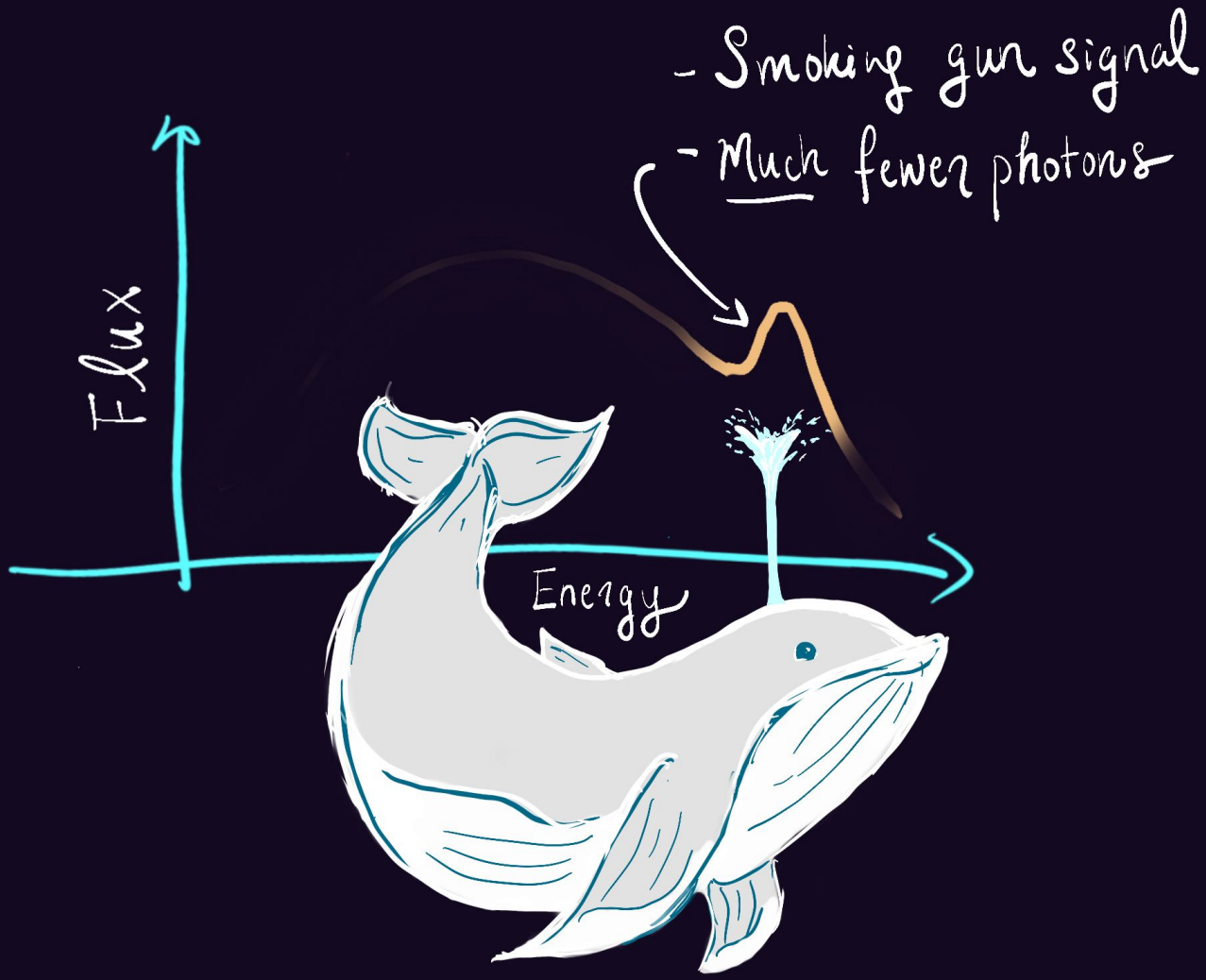
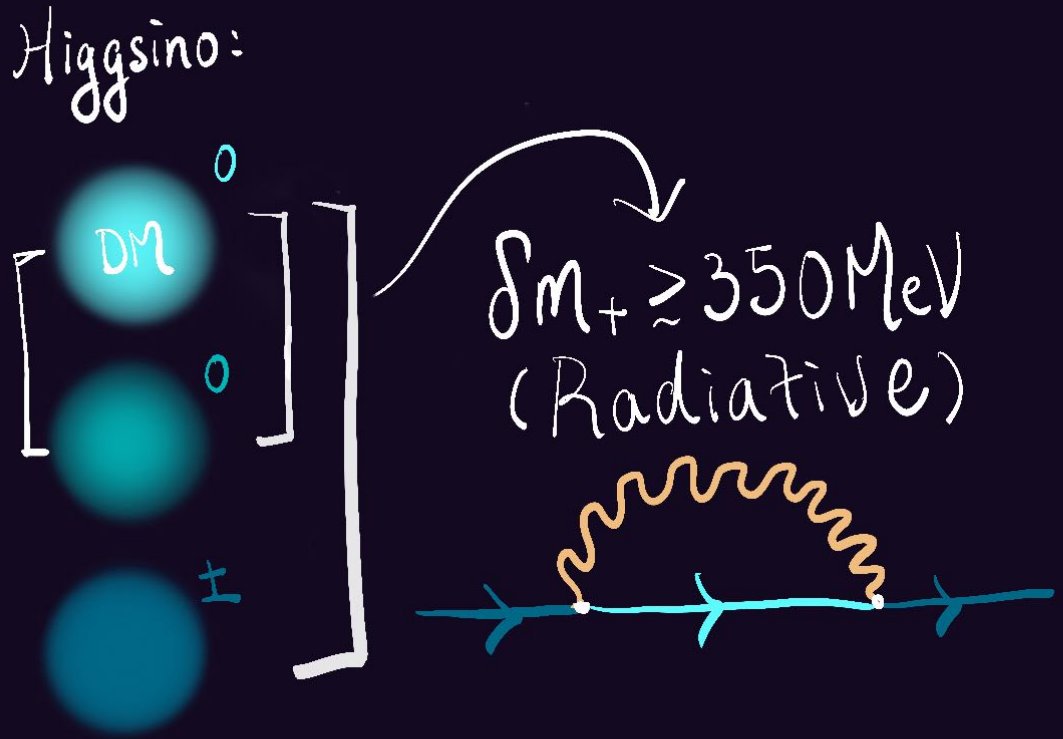

Flux
Energy

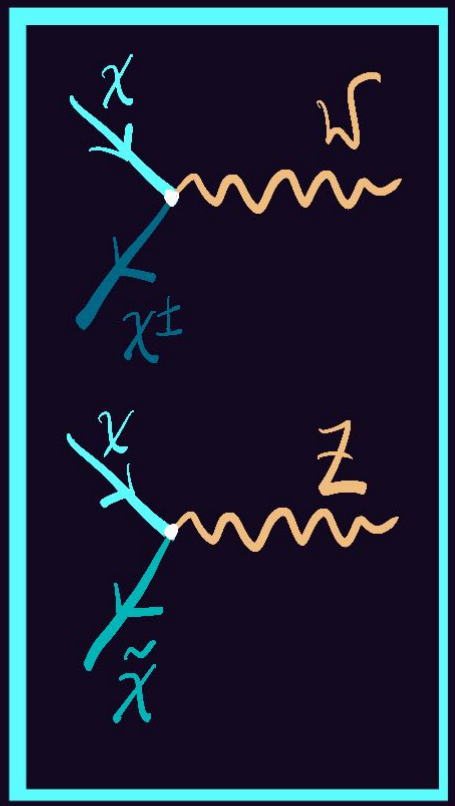

- most of the photon counts
- extended, degenerate w/ background.
Flux
Energy


- Smoking gun signal
- Much fewer photons
Flux
Energy

# Meet the whale

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

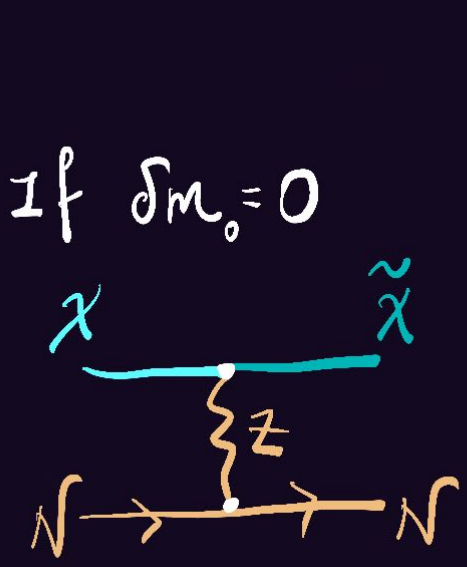


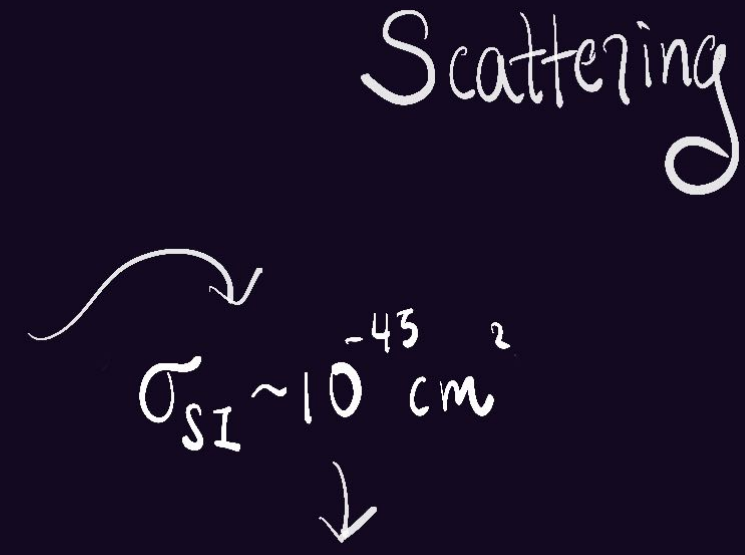




$$\delta m_{0^\sim} \sim \frac{m_Z^2}{M_{1,2}} \text{ (from mixing)}$$

$$\mu \ll M_1, M_2$$

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

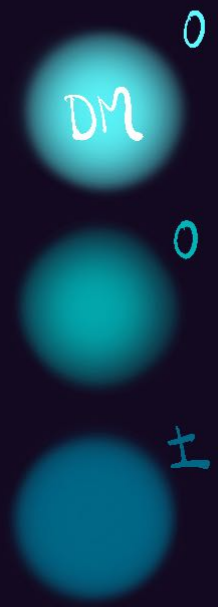



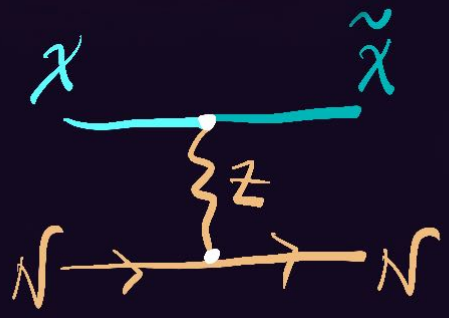

$$M \ll M_1, M_2$$

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

Higgsino:




If $\delta m_0 = 0$




forbidden if

$\delta m_0 \gtrsim 10^{-7} m_\chi$

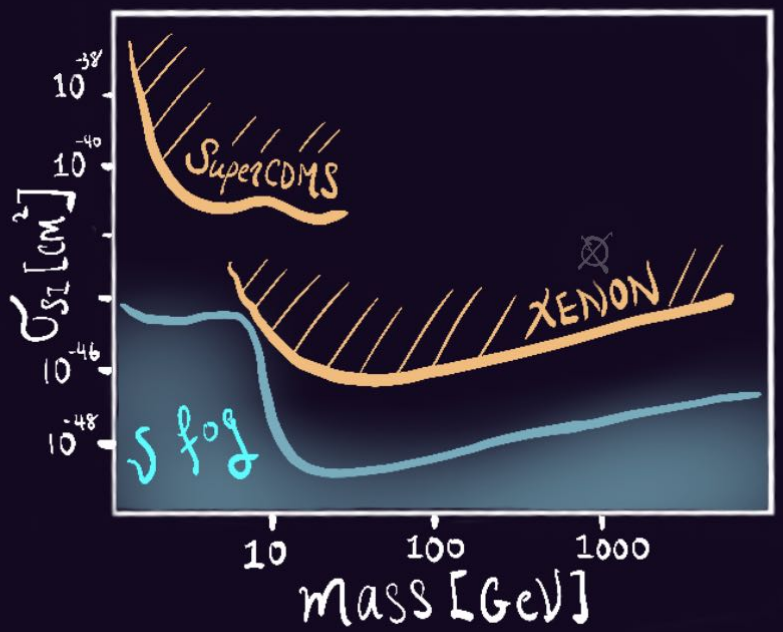
OR, $m_{1,2} \lesssim 10^5 m_\chi$

$M \ll M_1, M_2$

Scattering

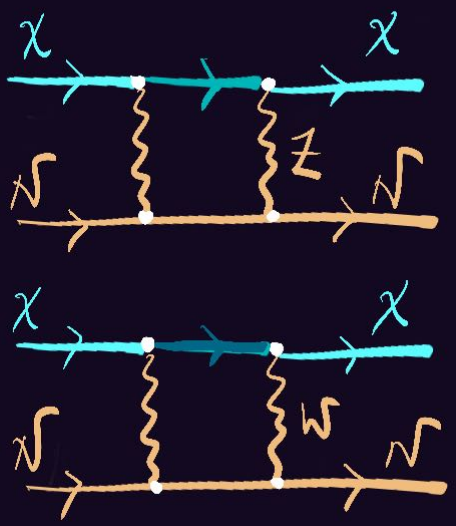
$v_\chi \sim 10^{-6} c$

$\sigma_{SI} \sim 10^{-45}$ cm$^2$



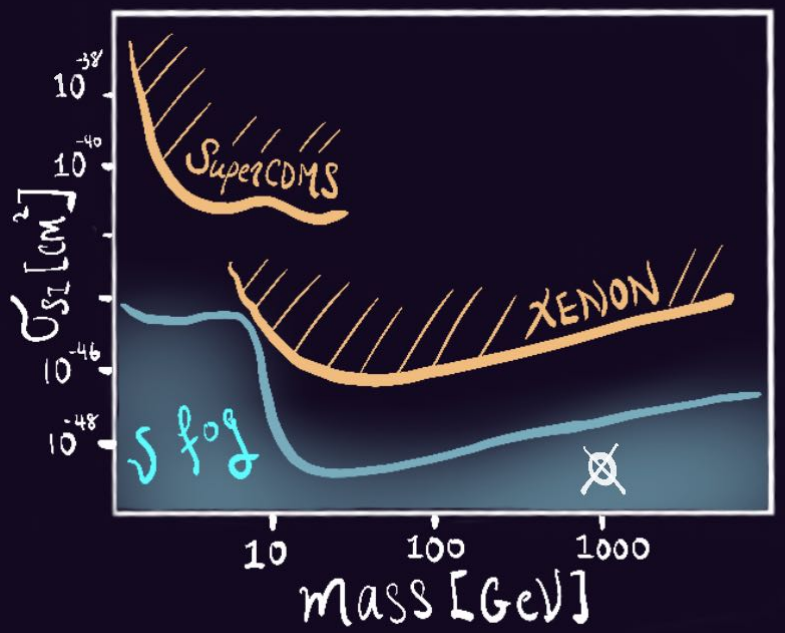
# An SU(2) Doublet (by any other name)

Higgsino:


Scattering

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

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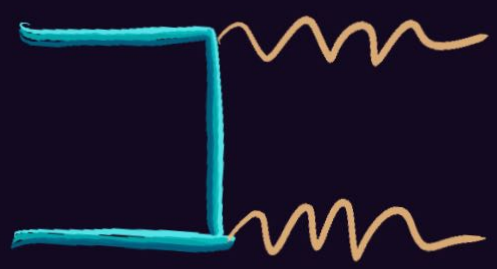
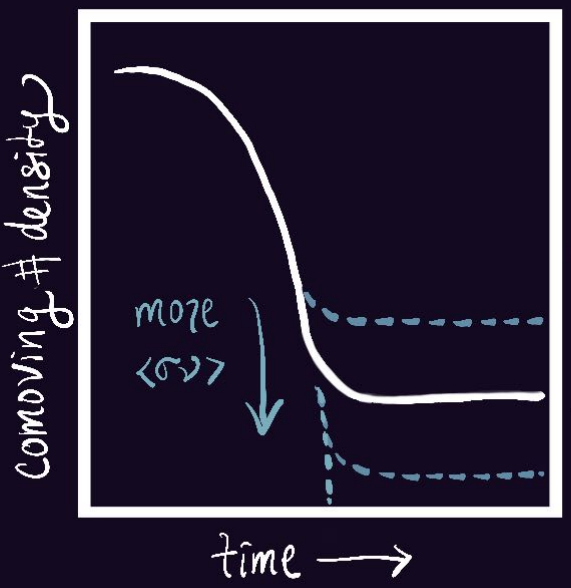


Annihilation (freeze-out)

$\langle \sigma v \rangle_{th} \propto m_\chi^{-2} \approx 1\,\text{pb}$




$m_\chi = 1.1\,\text{TeV}$

$\Omega_\chi h^2 = 0.12$

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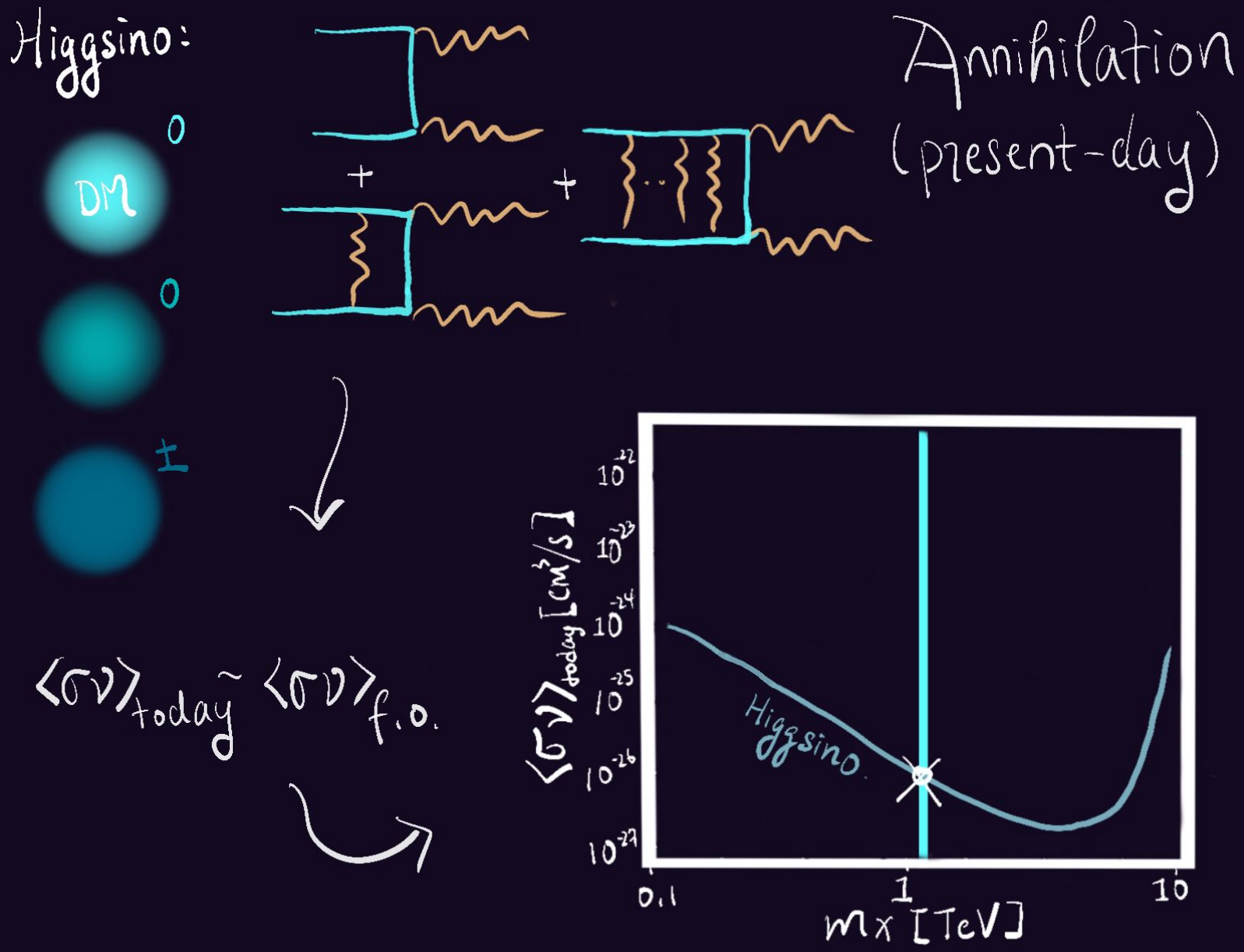

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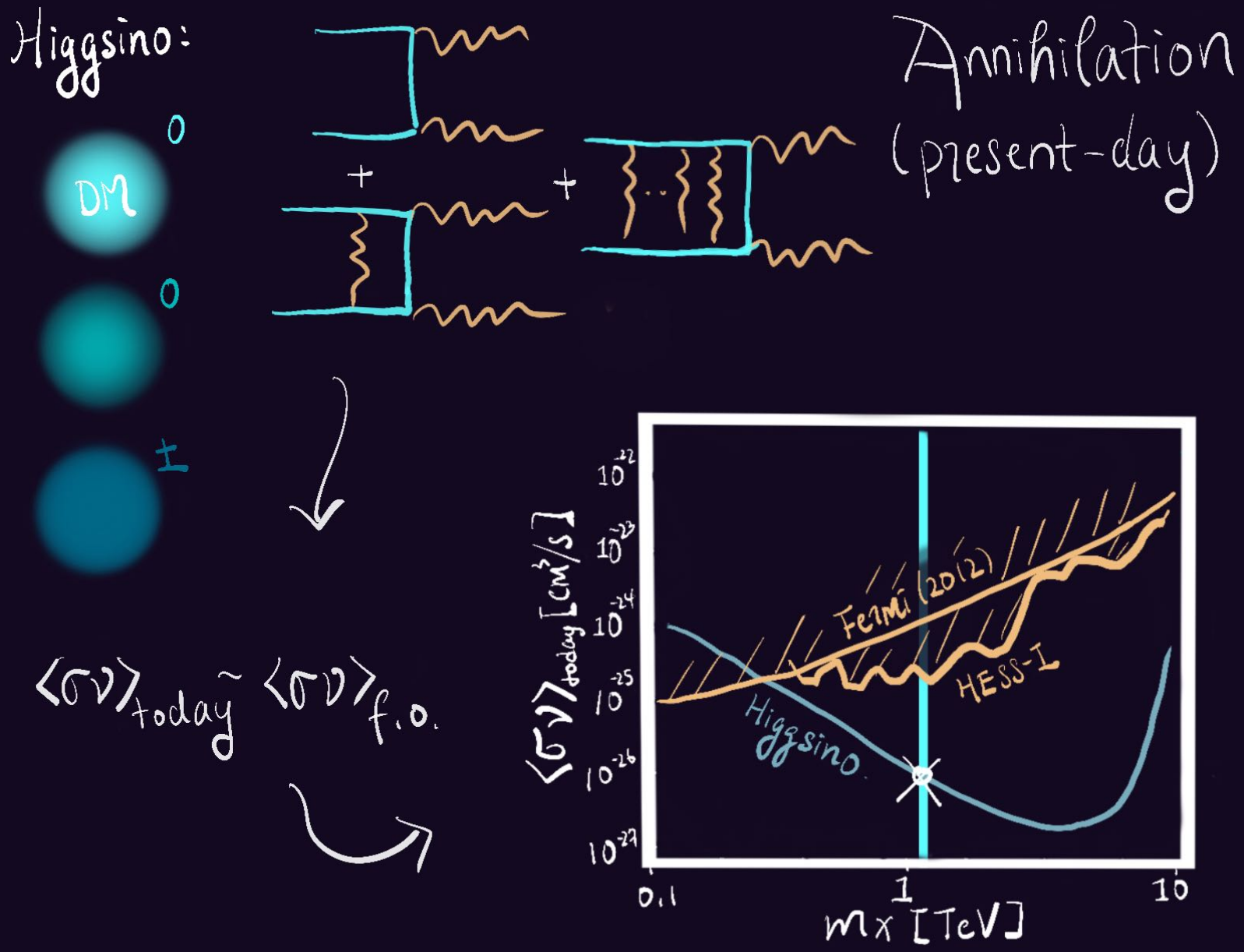
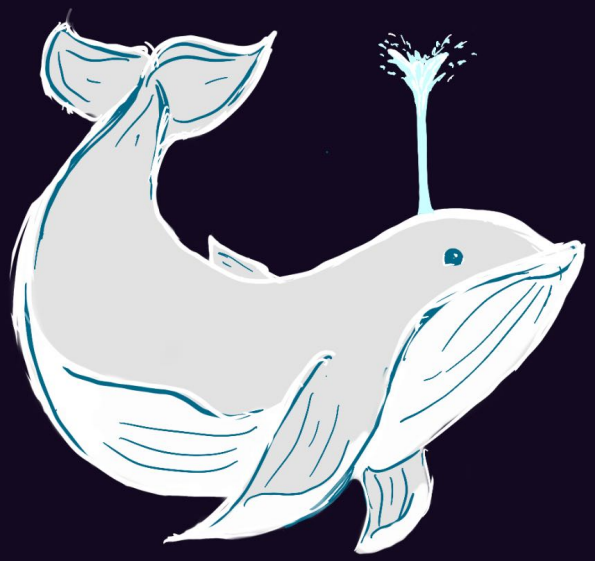


The nearly-pure Higgsino:

- Theoretically motivated
- Viable in minimal realization
- Imminently discoverable



# The Plan

Follow the shortest path to discovery.

- First detectable observable is Higgsino annihilation signal
- First detectable annihilation signal is $\gamma$ rays in the GC
  - Gamma rays are the cleanest signal species
  - Galactic Center dominates the luminosity

# Annihilation signal

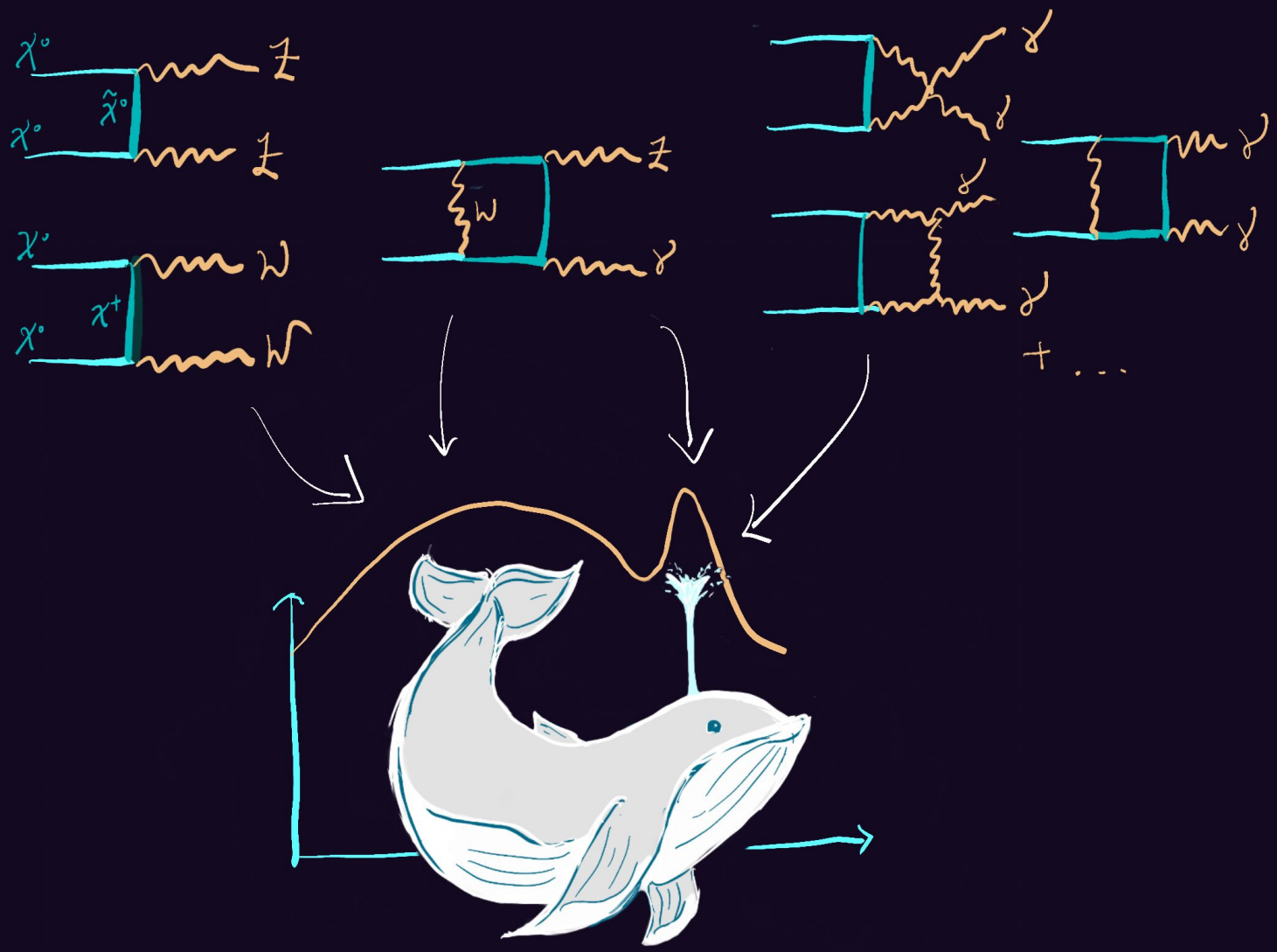
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \left[\frac{\text{Photon Counts}}{\text{Energy} \cdot \text{Area} \cdot \text{Time} \cdot \text{Solid Angle}}\right]$$

# Annihilation signal

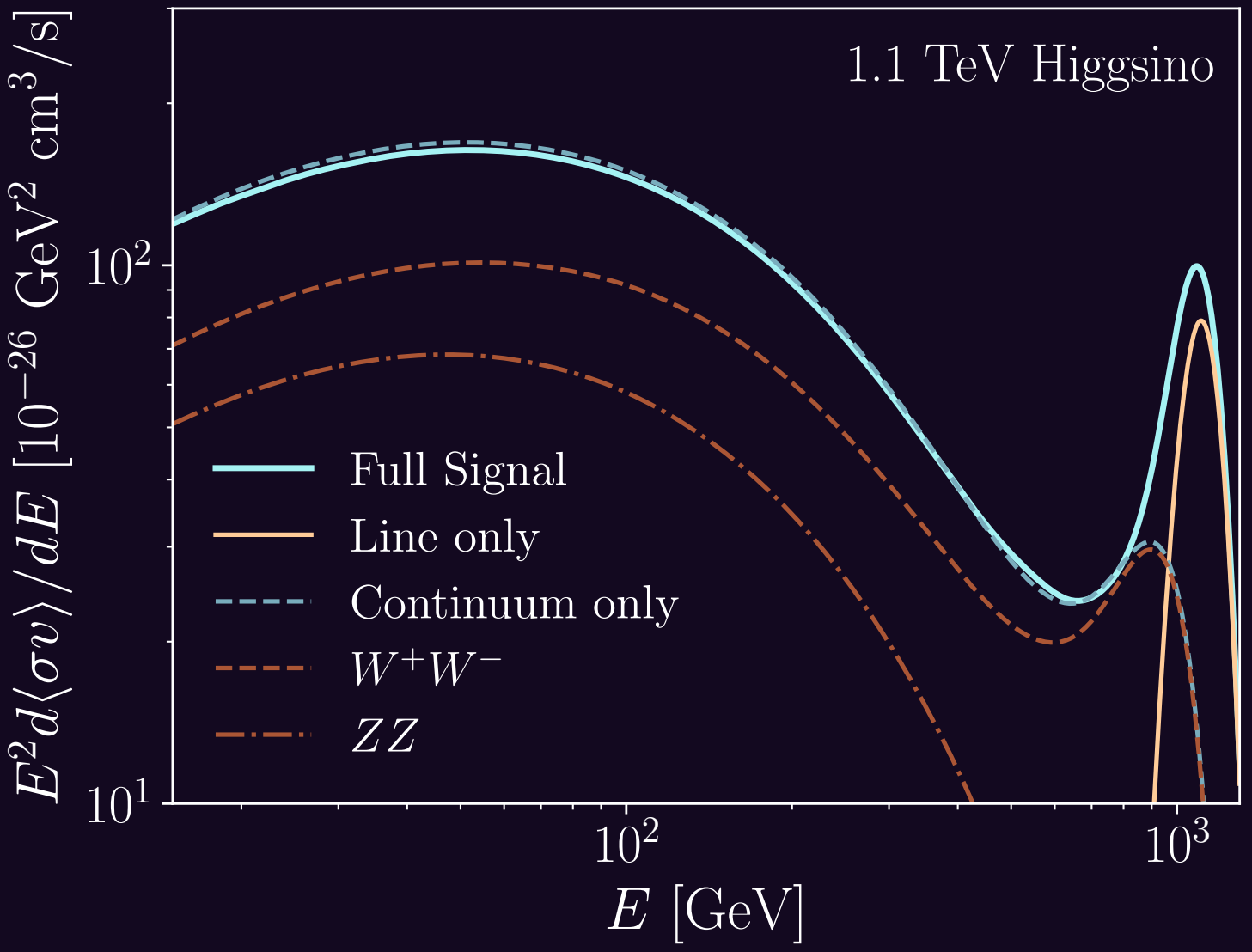
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \left[\frac{\text{Photon Counts}}{\text{Energy} \cdot \text{Area} \cdot \text{Time} \cdot \text{Solid Angle}}\right]$$

$$= \overbrace{\frac{\mathcal{J}}{8\pi m_\chi^2}}^{\text{DM abundance}} \times \underbrace{\sum_X \langle\sigma v\rangle_{\chi\chi\to X} \frac{\mathrm{d}N_{X\to\gamma}}{\mathrm{d}E}}_{\text{What the DM is doing}}$$

# The Higgsino spectral profile



# The Higgsino spectral profile




[Beneke, Urban & Vollmann, 2203.01692]

# The DM spatial profile

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \overbrace{\frac{\mathcal{J}}{8\pi m_\chi^2}}^{\text{DM abundance}} \times \underbrace{\sum_X \langle\sigma v\rangle_{\chi\chi\to XX} \frac{\mathrm{d}N_{X\to\gamma}}{\mathrm{d}E}}_{\text{What the DM is doing}}$$

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

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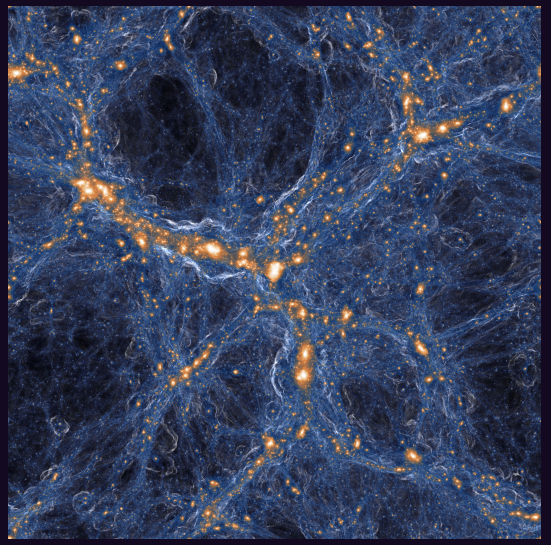
We simply do not know the distribution of DM in our galaxy.

# The DM spatial profile

We simply do not know the distribution of DM in our galaxy.

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

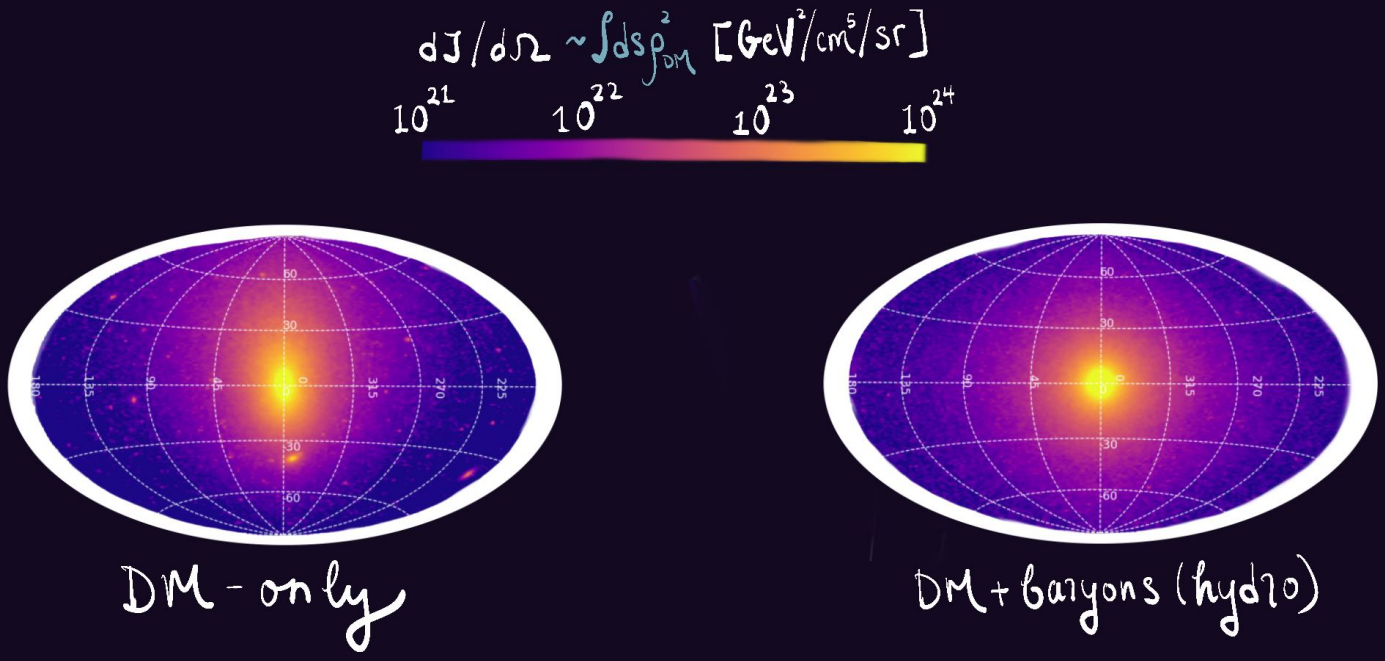


However ...

- Baryons exist and are important
- Especially for the center of the galaxy

[TNG Collaboration]

# The DM spatial profile

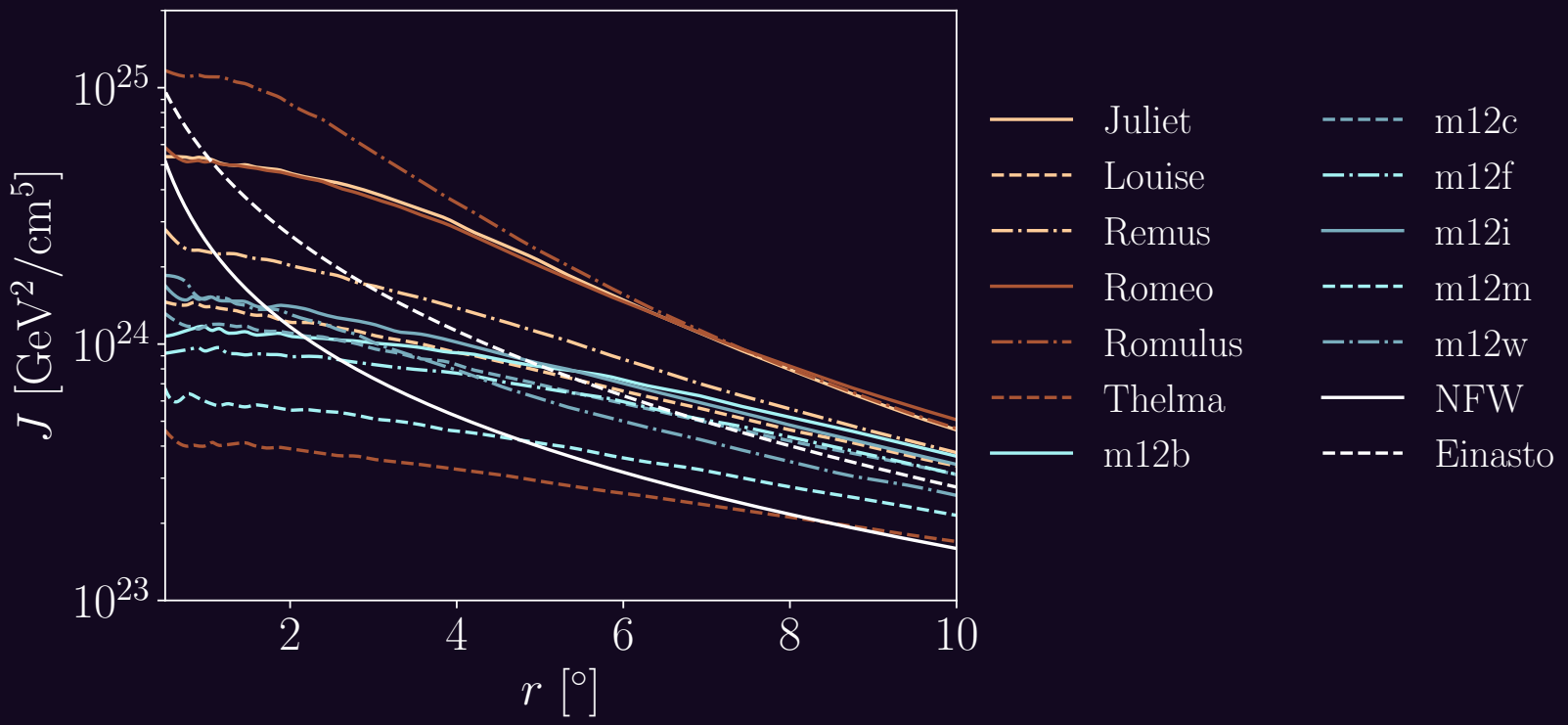



Feedback In Realistic Environments

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

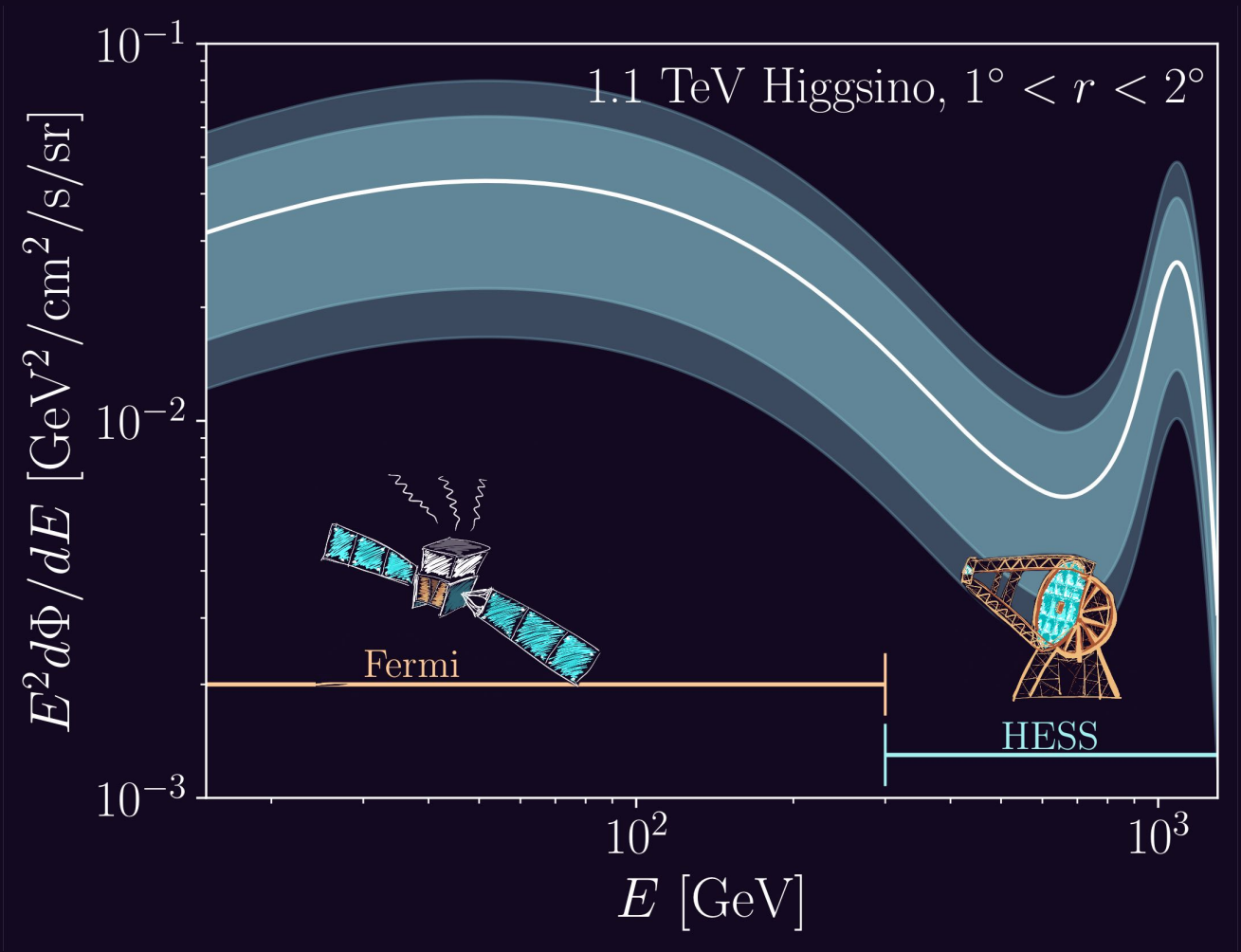
# The DM spatial profile

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



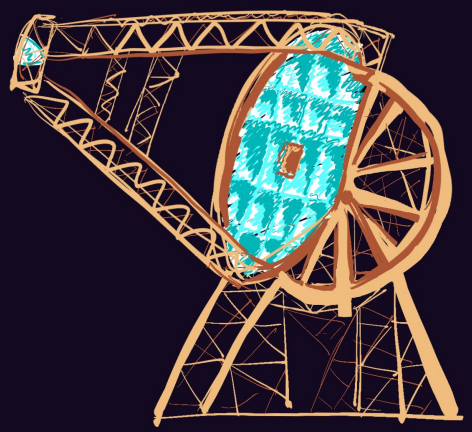

- 6 of these evolved in pairs (à la MW + M31)
- Highest resolution (important for J-factors)

# How it all shakes out




- Spectrally extremely precise
- Spatially extremely uncertain

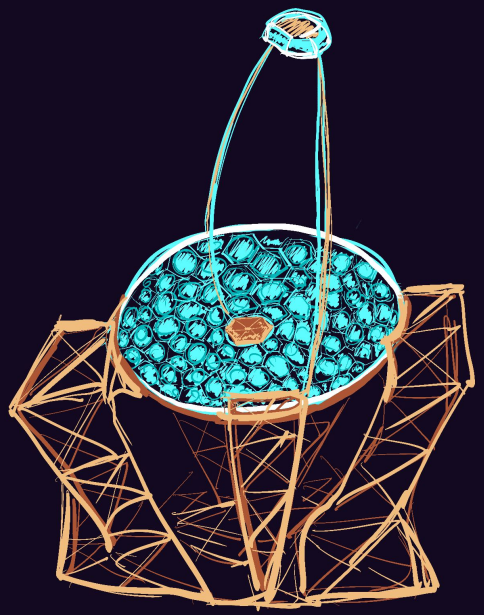
# Meet the Experiment(s)



High Energy Stereoscopic System (HESS):

- 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 presently, $\sim$ 500h more to come

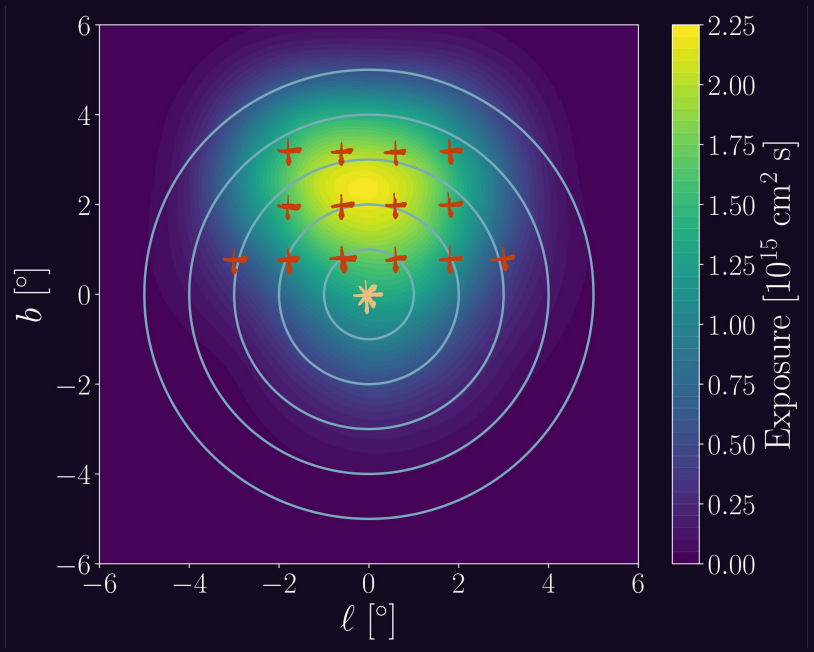
# Meet the Experiment(s)



Cherenkov Telescope Array (CTA):

- 10 GeV - 100 TeV reach
- peak sensitivity at $\sim$ TeV
- $\sim 1\,\mathrm{km}^2$ effective area
- $\sim$ 5% energy resolution
- Projected 500h in inner GC

# Analysis: HESS x Line Search

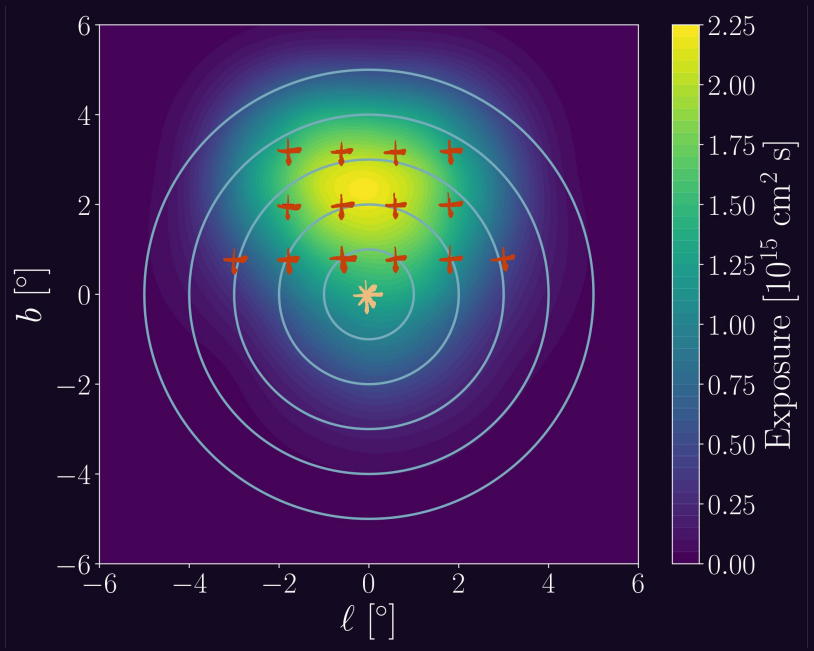



HESS-II Inner Galaxy Survey

- 2014 - 2020
- 546h of exposure
- 14 pointing locations
- Biased slightly north of the galactic center

[HESS Collaboration, Phys.Rev.Lett. 129 (2022) 11, 111101]

# Analysis: HESS x Line Search




HESS-II Inner Galaxy Survey

- 2014 - 2020
- 546h of exposure
- 14 pointing locations
- Biased slightly north of the galactic center

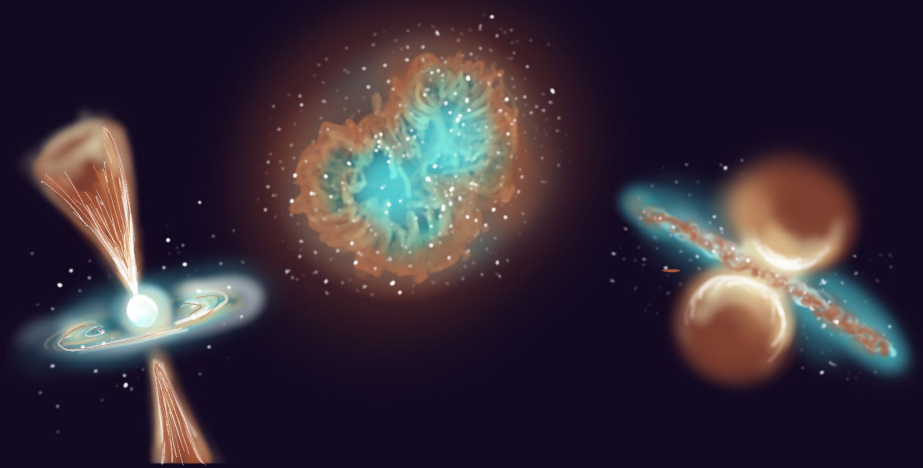
We don't have full public data*, but can think deeply about analysis strategies

[HESS Collaboration, Phys.Rev.Lett. 129 (2022) 11, 111101]

# Analysis: HESS x Line Search

Background components:

- Misidentified Cosmic Rays
  - HESS: $\gtrsim$ 99% CR rejection
- Point Sources
- Diffuse Emission



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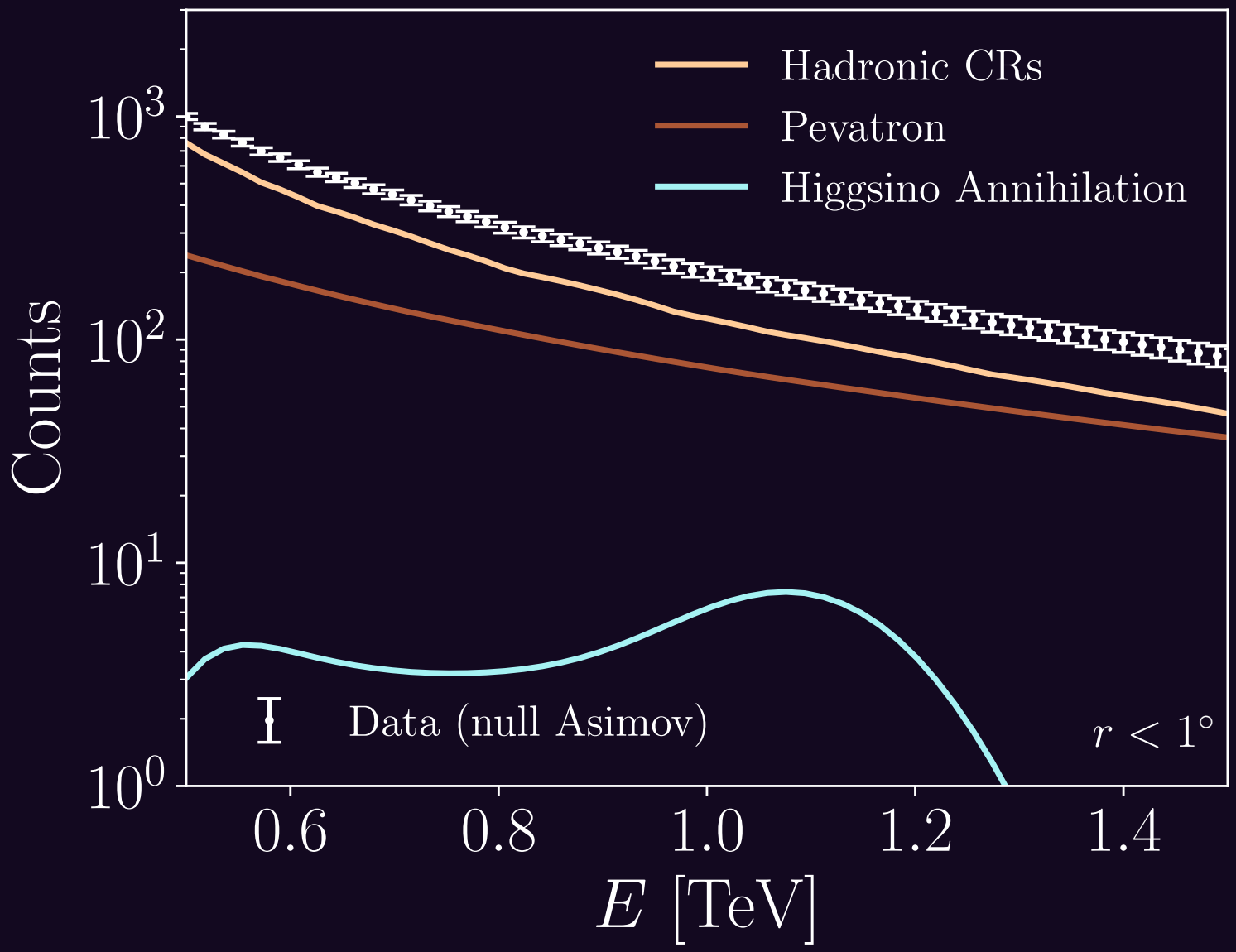
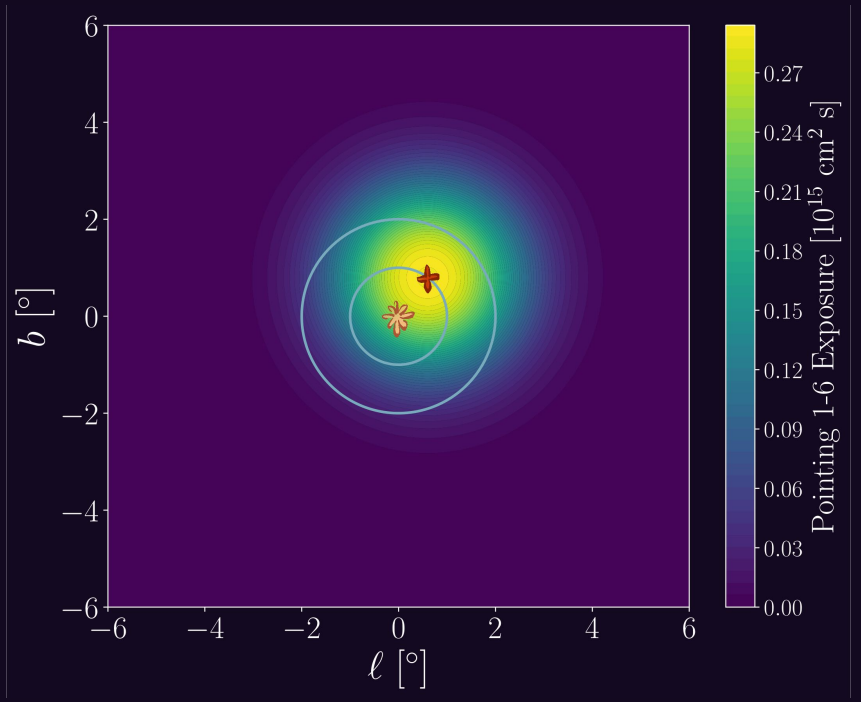


# Analysis: HESS x Line Search

HESS uses a ON/OFF subtraction scheme



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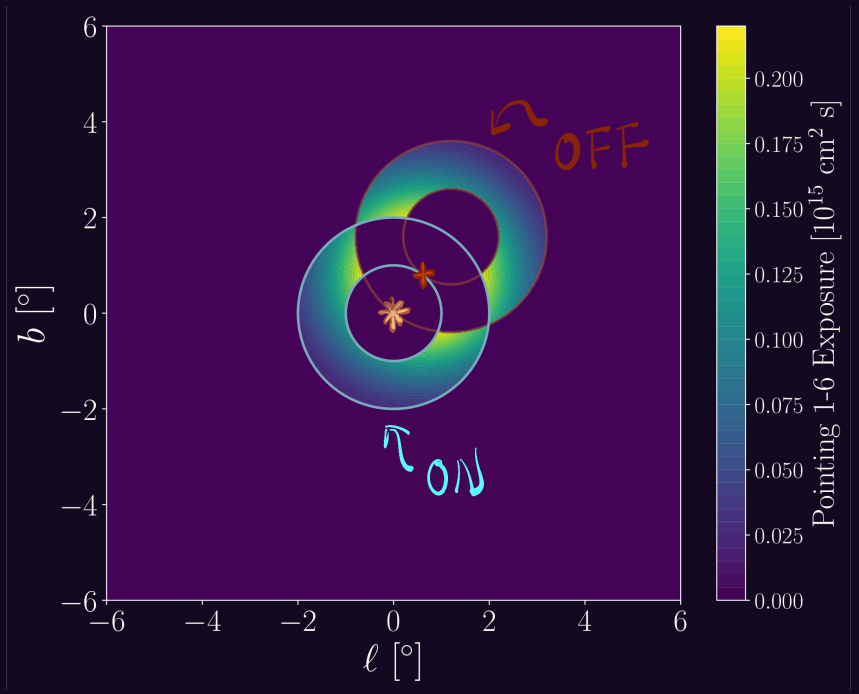

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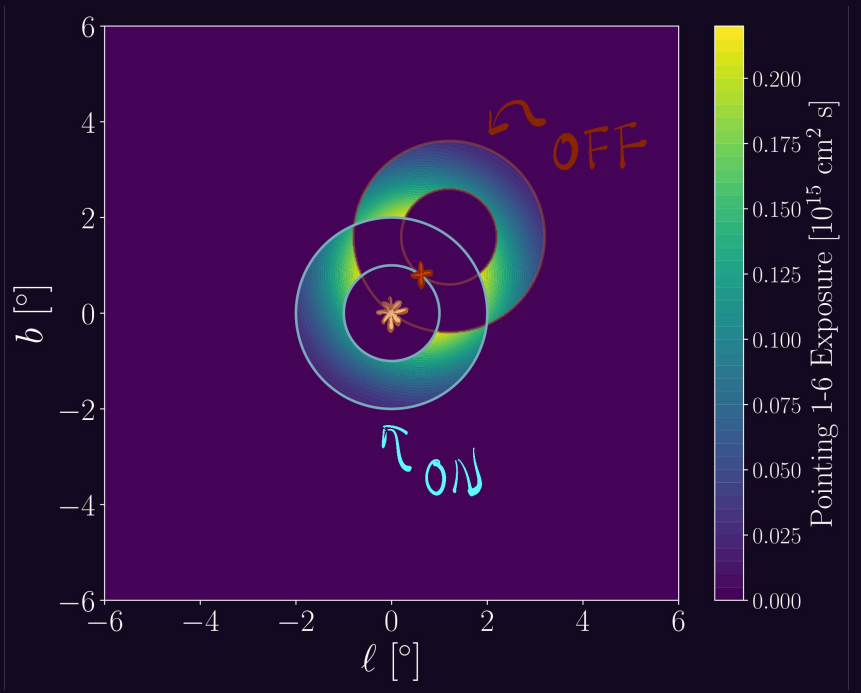
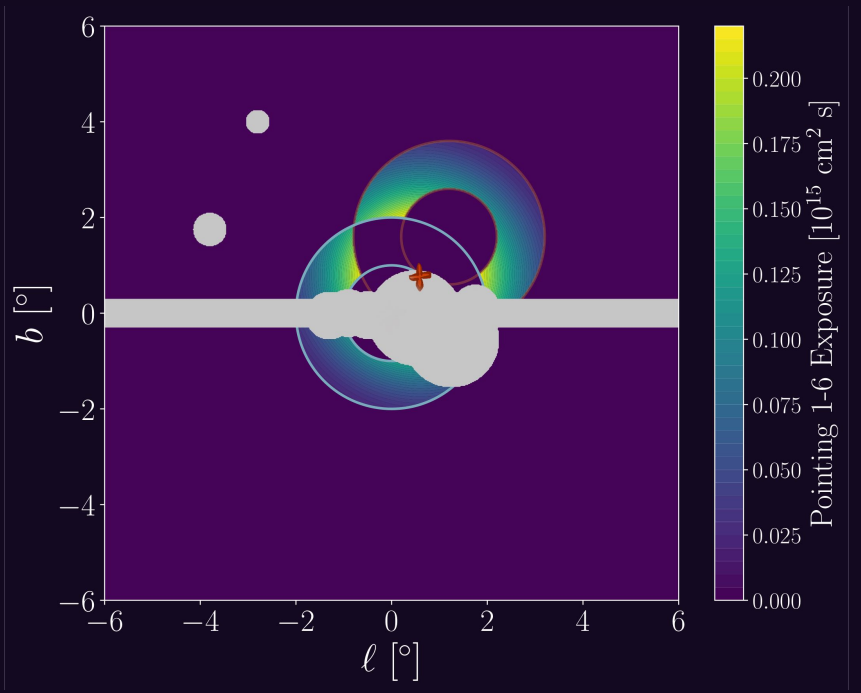



$$-\log p(d|\theta) \approx \sum_{\substack{j\in \\ \text{annuli}}} \sum_{\substack{k\in \\ \text{E bins}}} \frac{(\Delta S_{jk}(\theta) - (N_{jk}^{\text{ON}} - N_{jk}^{\text{OFF}}))^2}{N_{jk}^{\text{ON}} + N_{jk}^{\text{OFF}}}$$

$$\Delta S(\theta) = S_{jk}^{\text{ON}}(\theta) - S_{jk}^{\text{OFF}}(\theta) \qquad \theta = \{\langle\sigma v\rangle_{\text{ann}}\} \qquad \text{fixed } m_\chi$$

# Analysis: HESS x Line Search

HESS uses a *masked* ON/OFF subtraction scheme

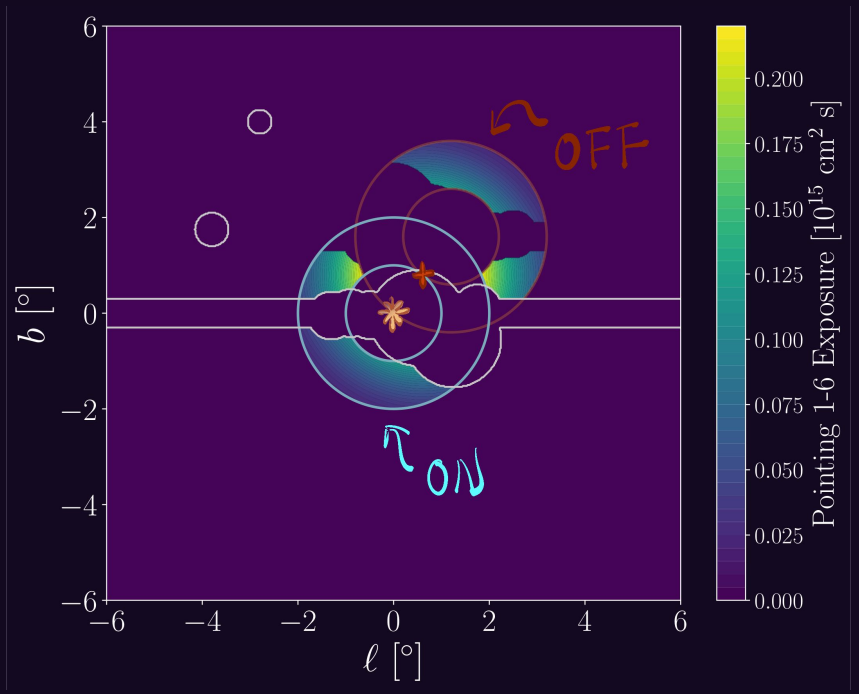



$$-\log p(d|\theta) \approx \sum_{\substack{j\in \\ \text{annuli}}} \sum_{\substack{k\in \\ \text{E bins}}} \frac{(\Delta S_{jk}(\theta) - (N_{jk}^{\text{ON}} - N_{jk}^{\text{OFF}}))^2}{N_{jk}^{\text{ON}} + N_{jk}^{\text{OFF}}}$$

$$\Delta S(\theta) = S_{jk}^{\text{ON}}(\theta) - S_{jk}^{\text{OFF}}(\theta) \qquad \theta = \{\langle\sigma v\rangle_{\text{ann}}\} \qquad \text{fixed } m_\chi$$

# Analysis: HESS x Line Search

HESS uses a *masked* ON/OFF subtraction scheme



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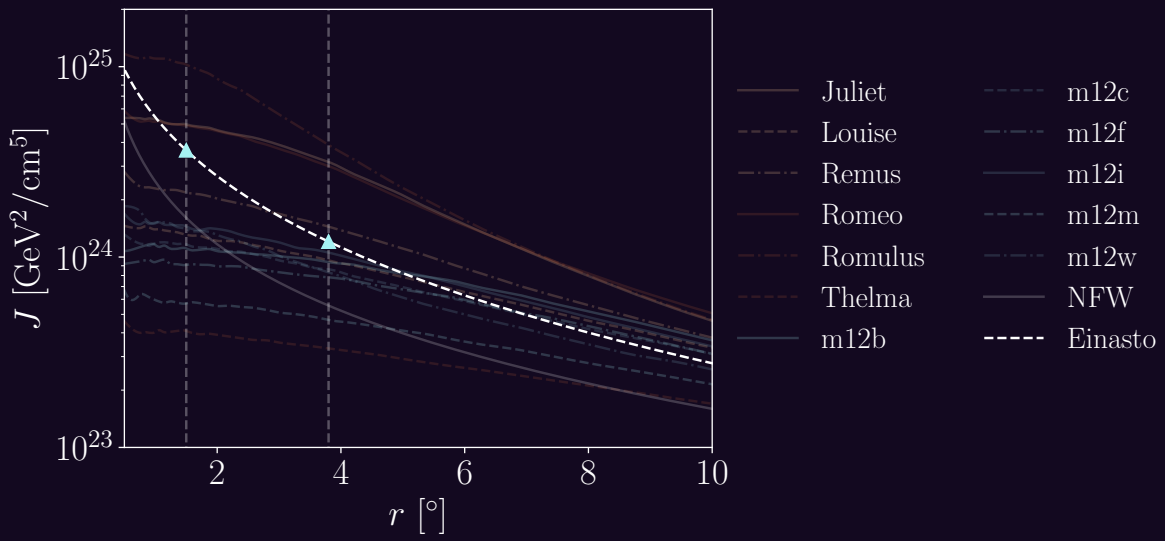


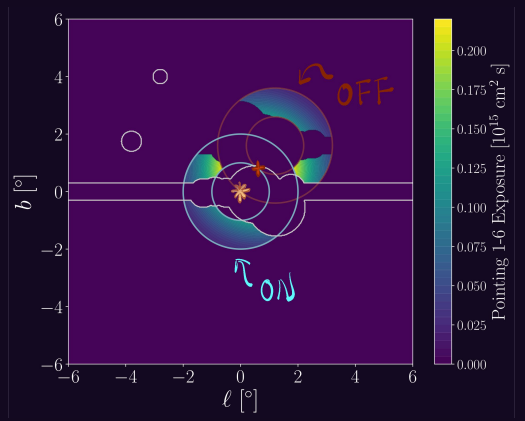

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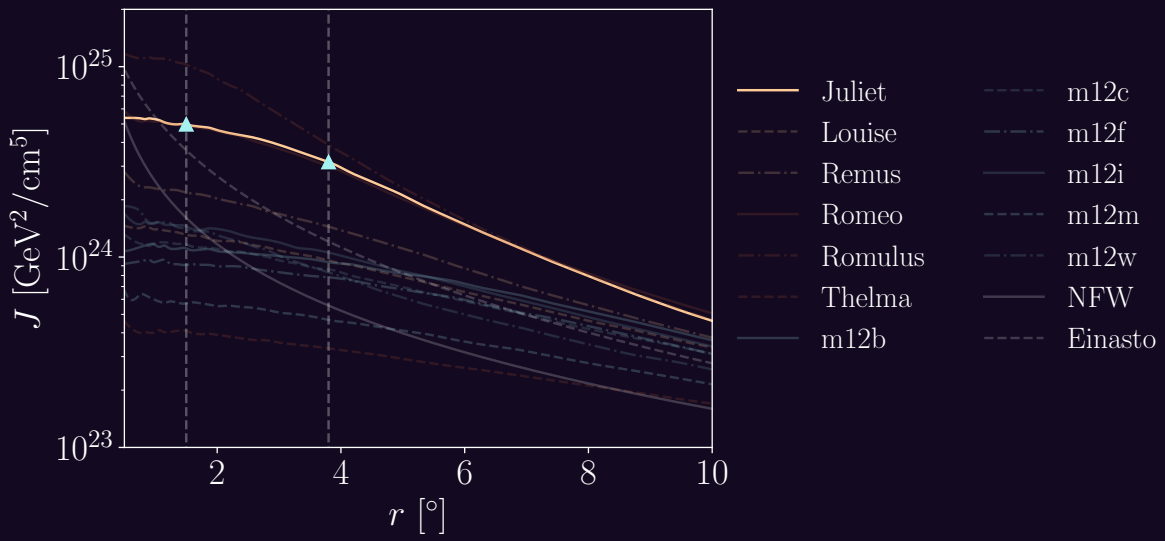
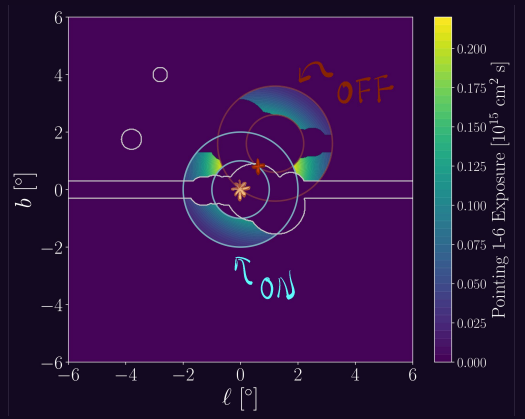
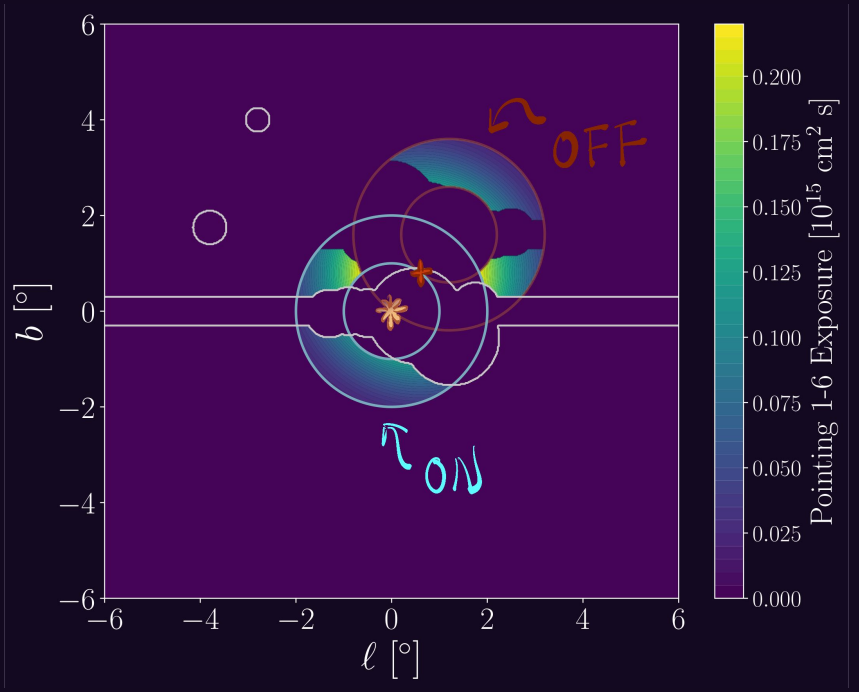


# Analysis: HESS x Line Search

HESS uses a *masked* ON/OFF subtraction scheme

- Robust(er) to systematics
- ...*if* background well-masked & isotropic
- Loses $\sim 60 - 97\%$ of signal counts




- Insensitive to signal shape (the thing we know)
- Very sensitive to DM profile (the thing we don't know)

# Analysis: HESS x Line Search

We propose a Template + Power Law scheme

- Collect dedicated off data to absorb CRs
- Gaussian Process to absorb fluctuations
- Absorb PS + Diffuse with power law
- Takes advantage of the line shape

$$B_{jk} = \alpha_j^{\mathrm{Temp}} b_{jk}^{\mathrm{Temp}} + \alpha_j^{\mathrm{PL}} \left(\frac{E_k}{E_*}\right)^{\beta_j^{\mathrm{PL}}}$$

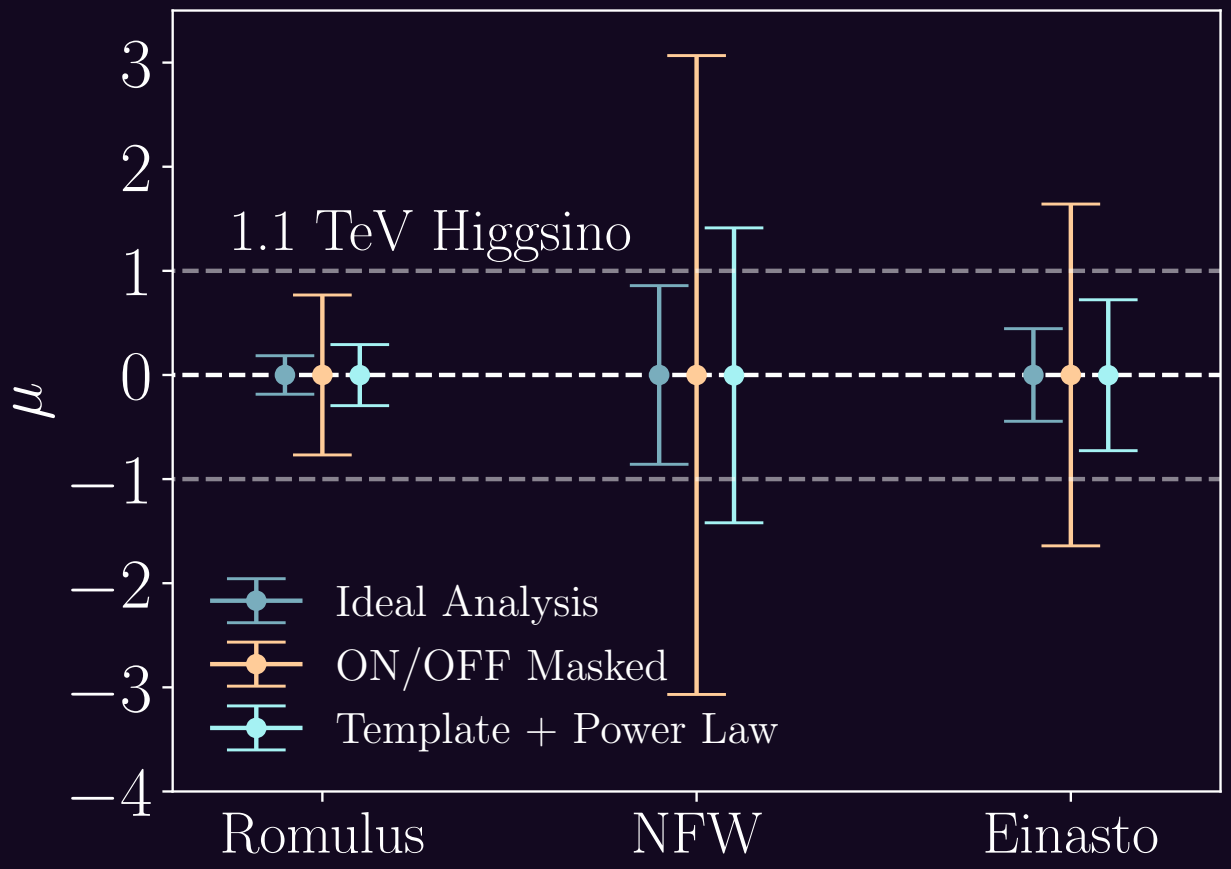
$$\mu_{jk} = S_{jk} + B_{jk}$$

$$p(\mathbf{d}|\theta) = \prod_{\substack{j\in \\ \text{annuli}}} \prod_{\substack{k\in \\ \text{E bins}}} \frac{\mu_{jk}(\theta)^{\mathbf{d}_{jk}} e^{-\mu_{jk}(\theta)}}{\mathbf{d}_{jk}!}$$

$$\theta = \{\langle\sigma v\rangle_{\mathrm{ann}},\ \alpha_j^{\mathrm{Temp}}, \alpha_j^{\mathrm{PL}}, \beta_j^{\mathrm{PL}}\}$$

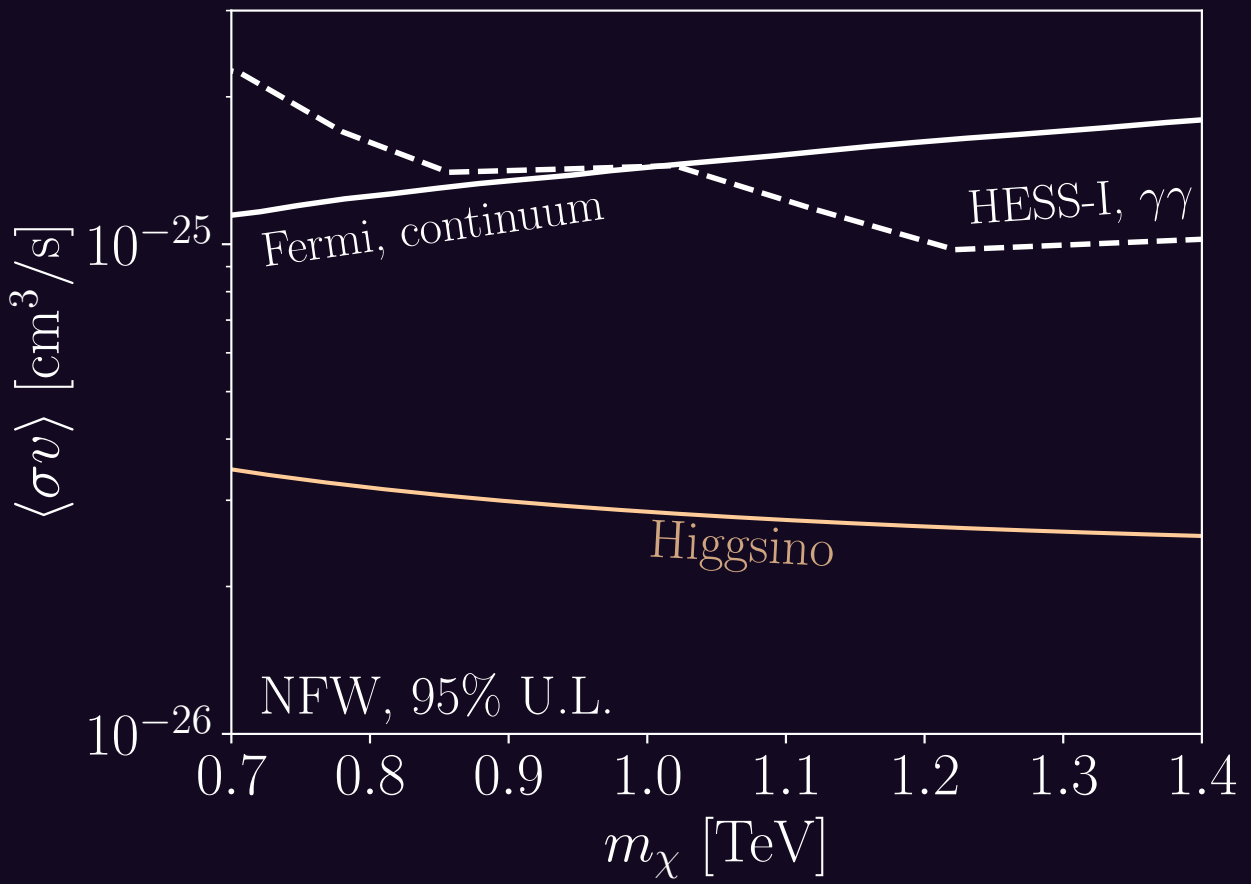
fixed $m_\chi$

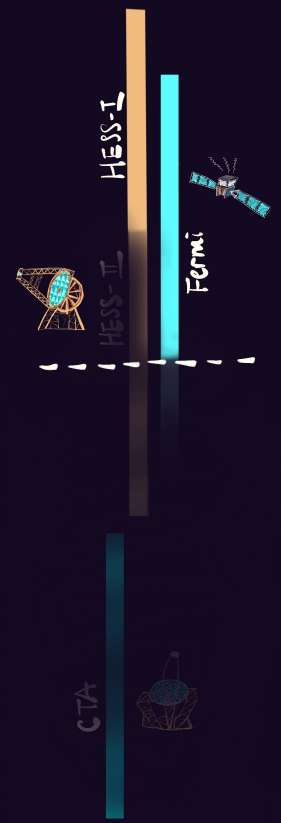
# Analysis: HESS x Line Search



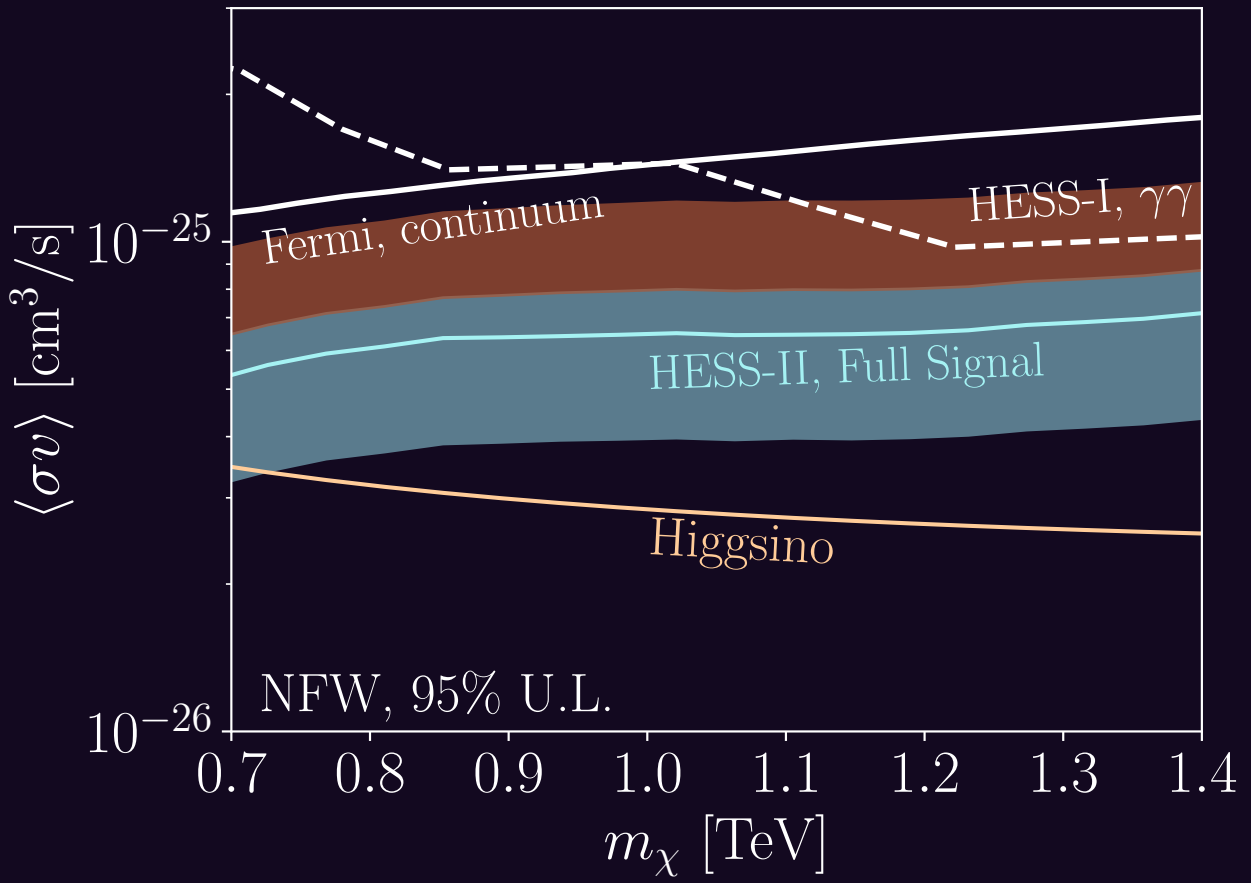

Our ability to discover or rule out the higgsino will hinge on our analysis strategy.

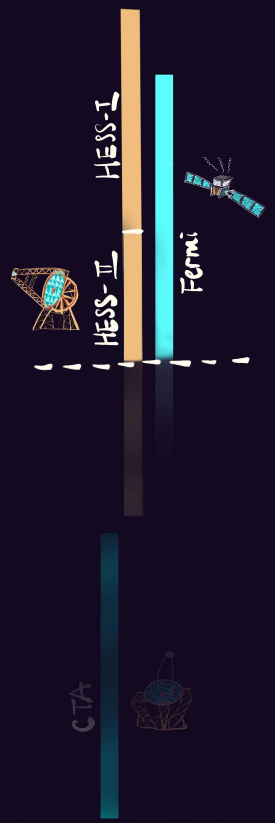
# Results [Projected]: HESS/CTA x Line Search



# Results [Projected]: HESS/CTA x Line Search



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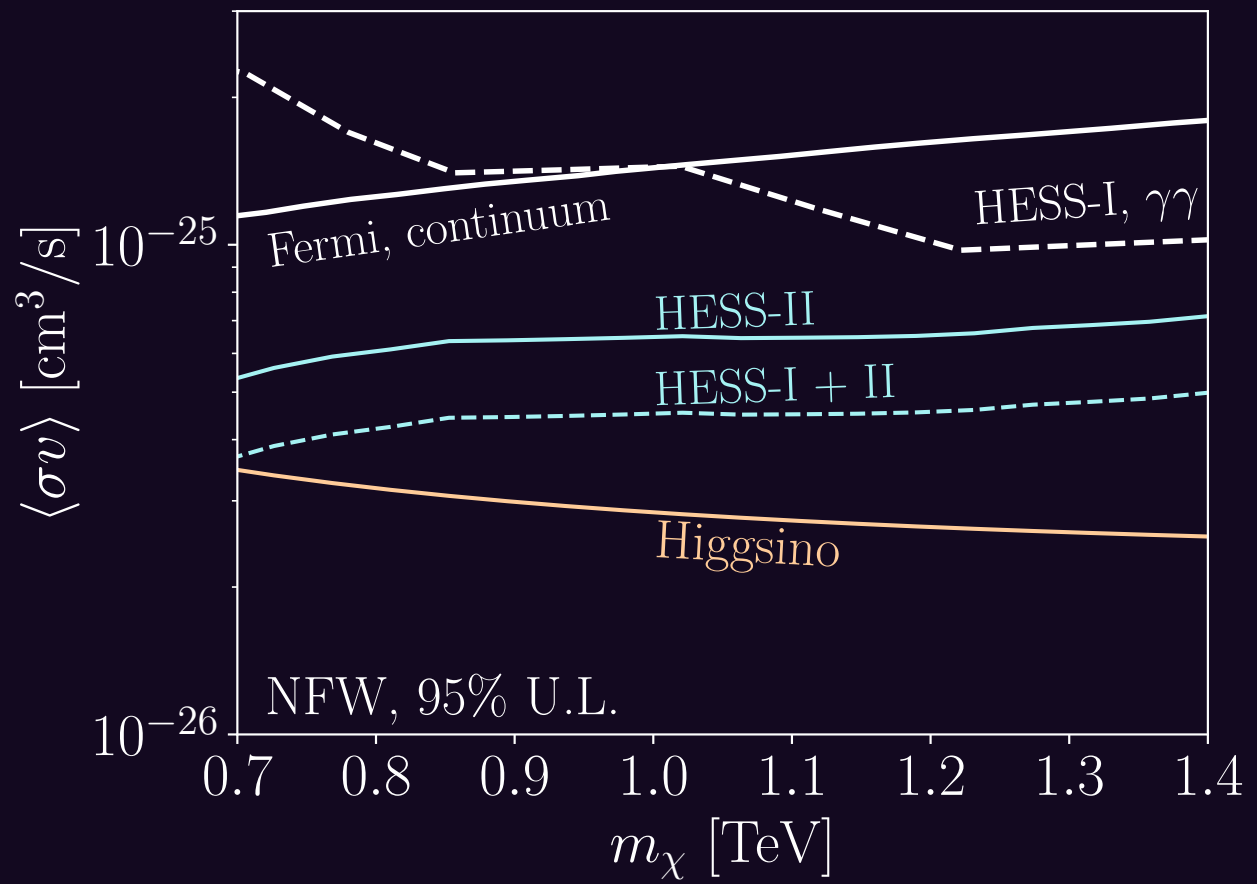


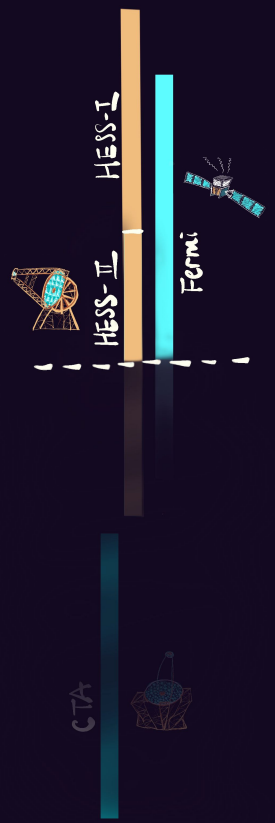

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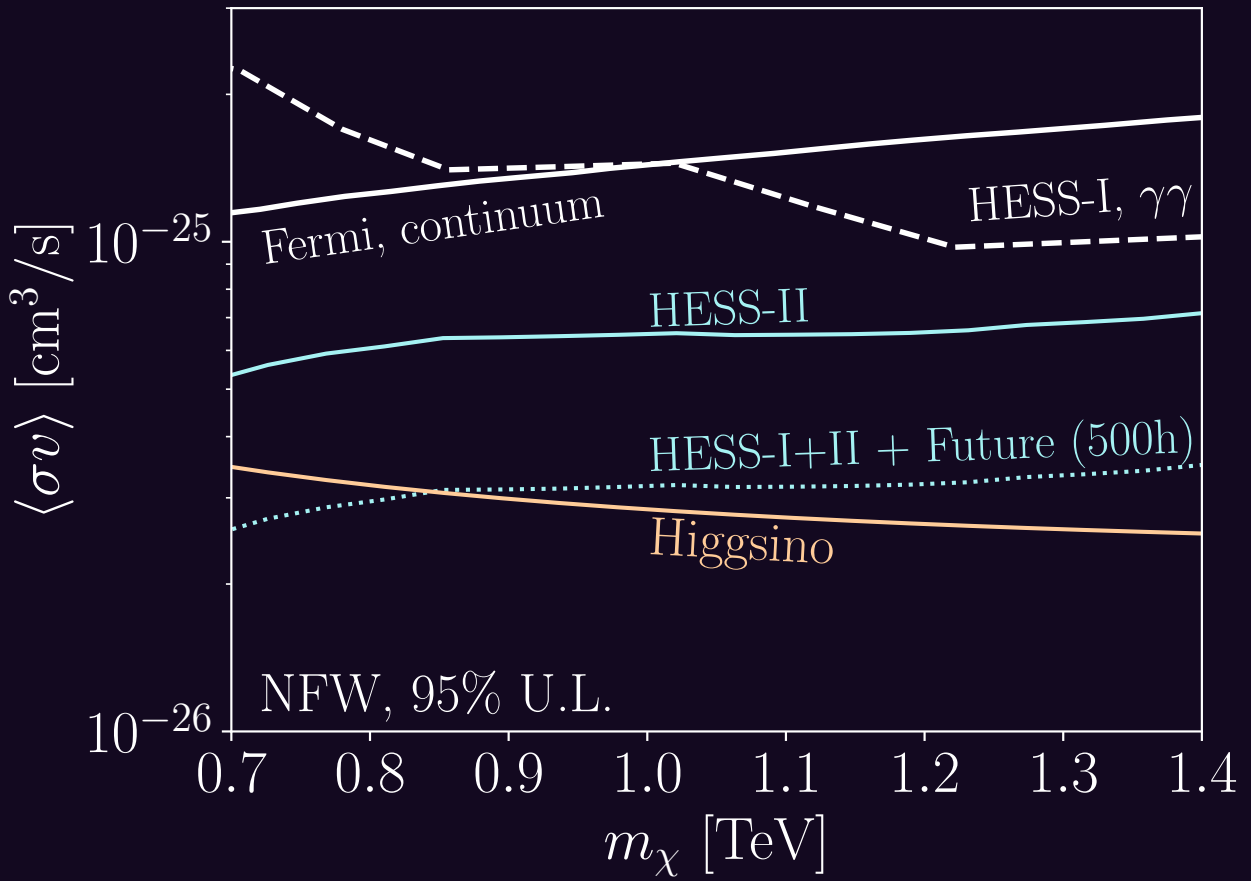


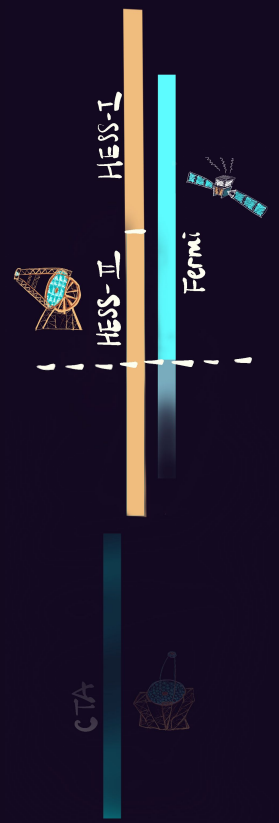

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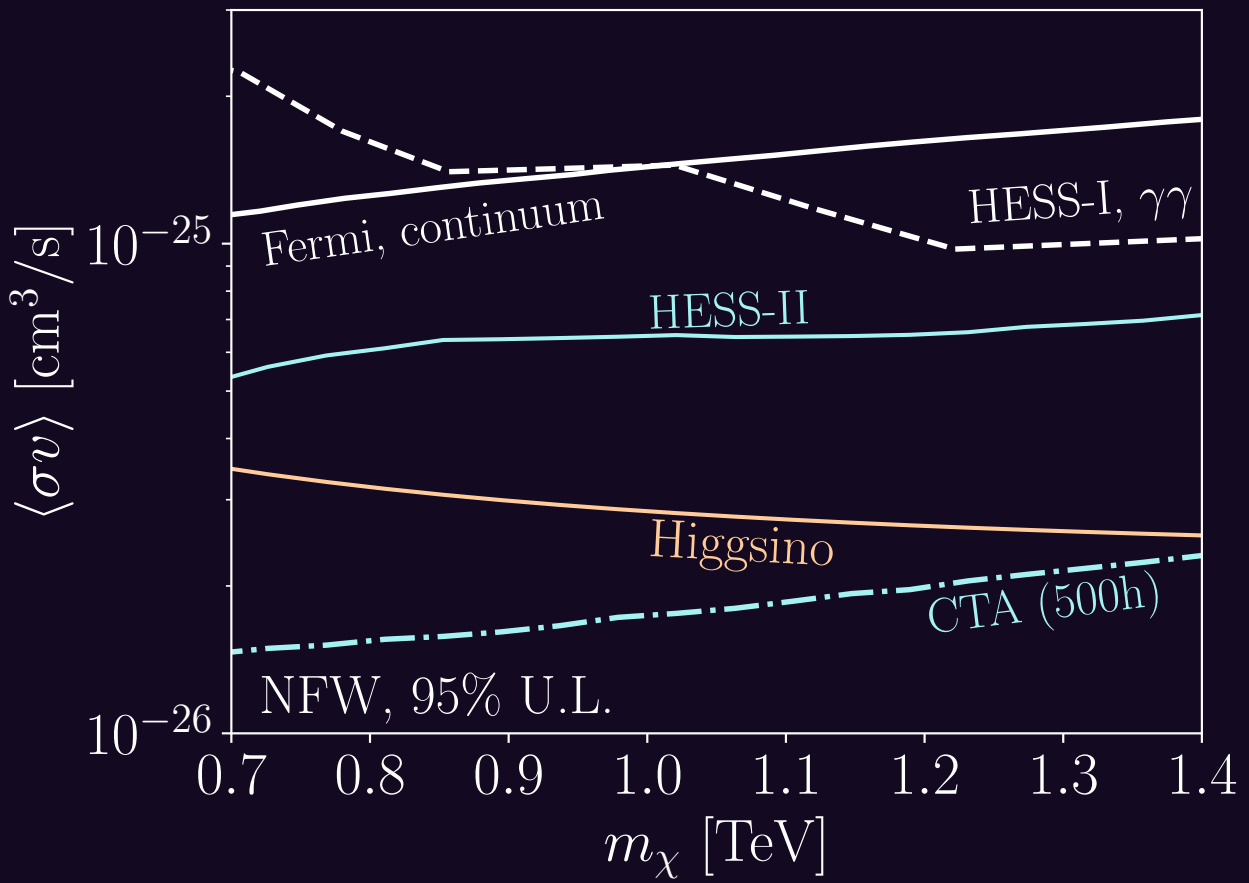


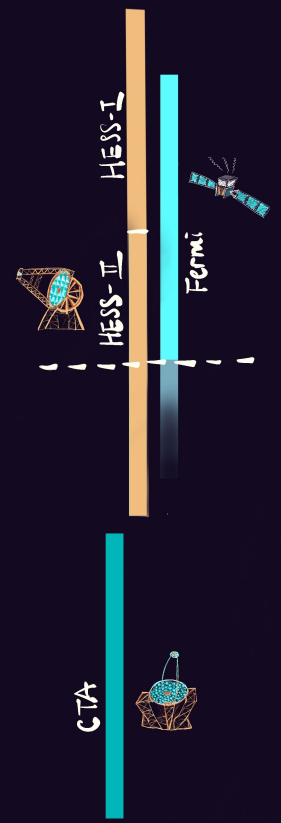

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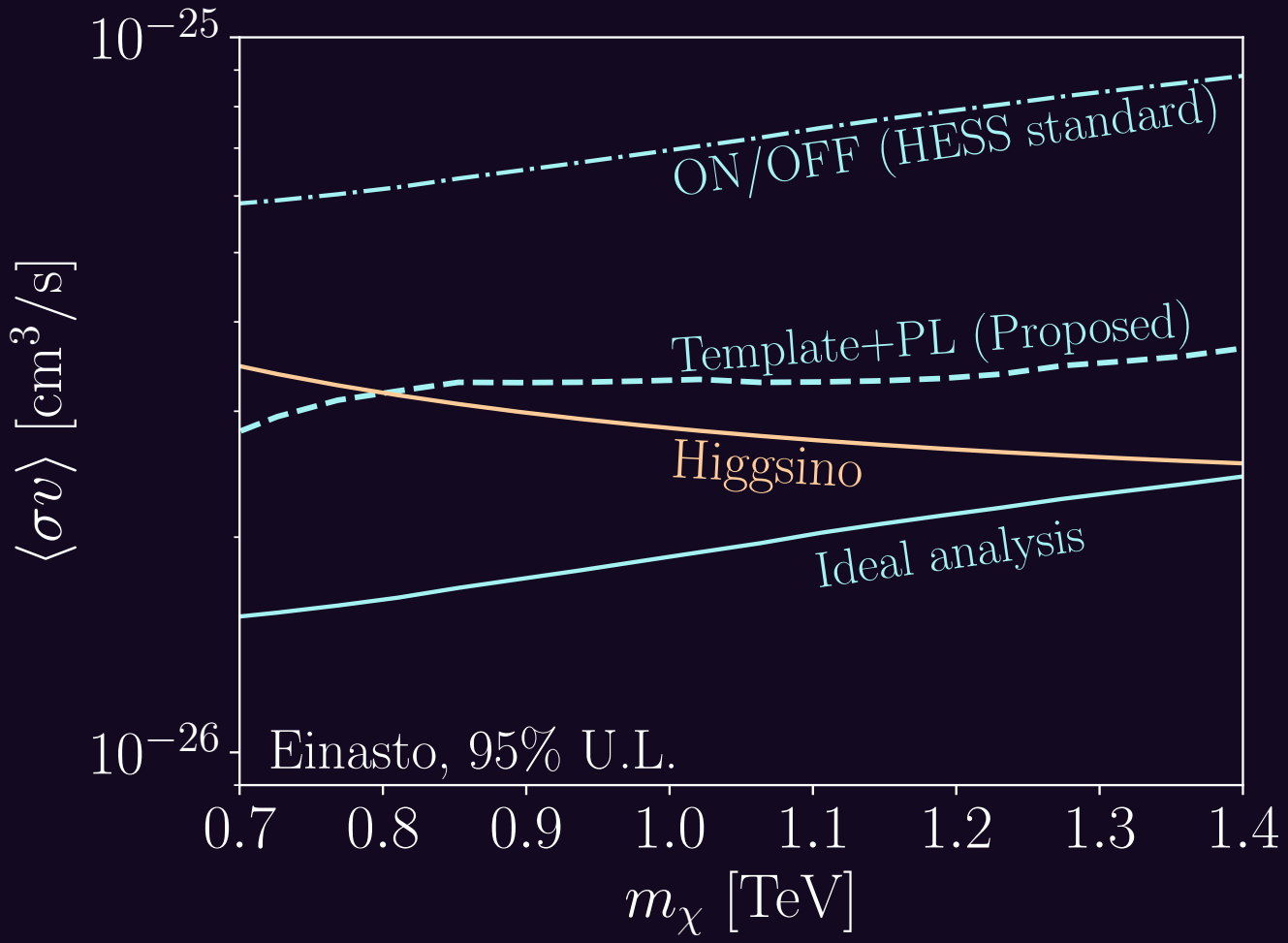

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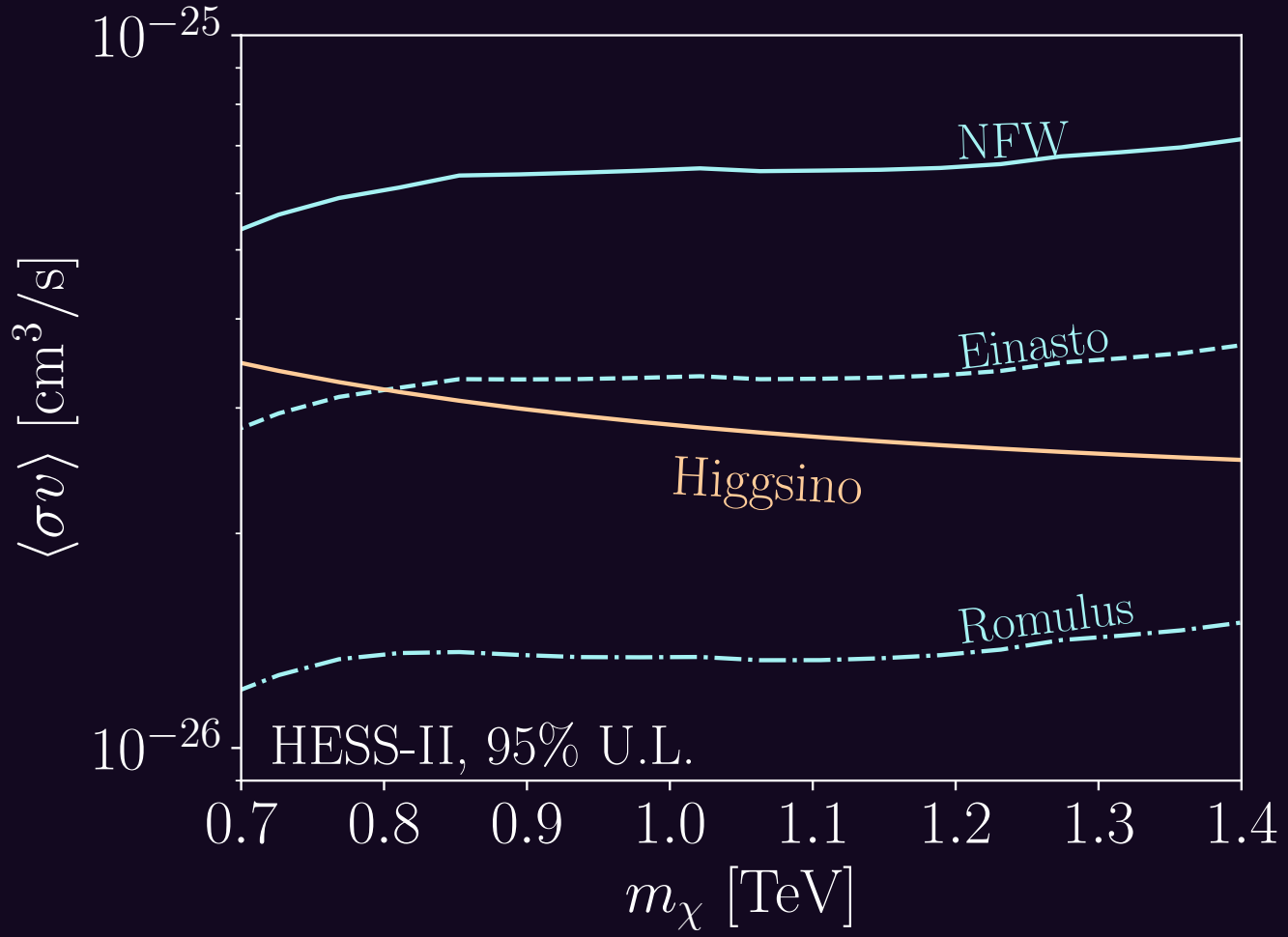

# Results [Projected]: Time to Discovery

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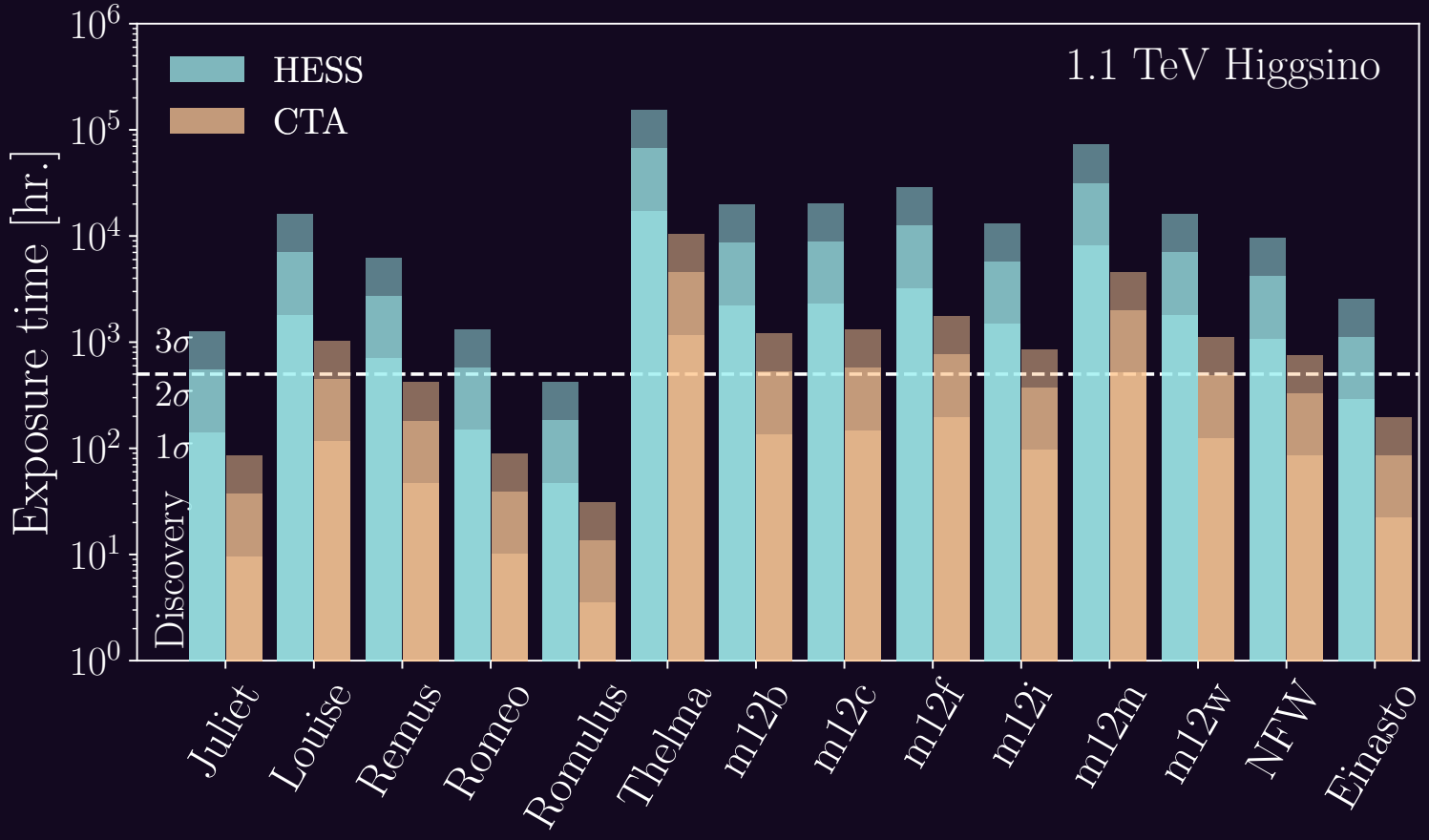


- HESS *could have* discovered a few profile scenarios
- Baseline CTA will cover *almost* all our bases

# What's next, and what to take home

- For the Higgsino:

  We could have a discovery on disk *right now*

# What's next, and what to take home

- For the Higgsino:

  We could have a discovery on disk *right now*
- For gamma-ray searches: Make sure we aren't leaving sensitivity on the table
- For DM indirect detection: Look for signals in other places
- For supporting theory: Updated look at the EW neutralino space, complementarity w/ colliders & didt
- For DM science: How do we tackle our ignorance of the local DM distribution?