# Wino DM Constraints from $\gamma$-ray Obs of dSphs

**Koji Ichikawa**

with

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S. Matsumoto (IPMU) and K. Nishiyama (IPMU)

(JHEP 07(2014)080 [arXiv: 1405.4914])

**PPP2014, Kyoto, Japan, July 2014**

# Outline

- Introduction
  - Indirect Detection
  - Dwarf Spheroidal Galaxies
  - Case Study: Wino DM
- Analysis
  - Signal Flux
  - Background Flux
  - Detector Capabilities
- Result
  - Future Sensitivity Line
- Summary

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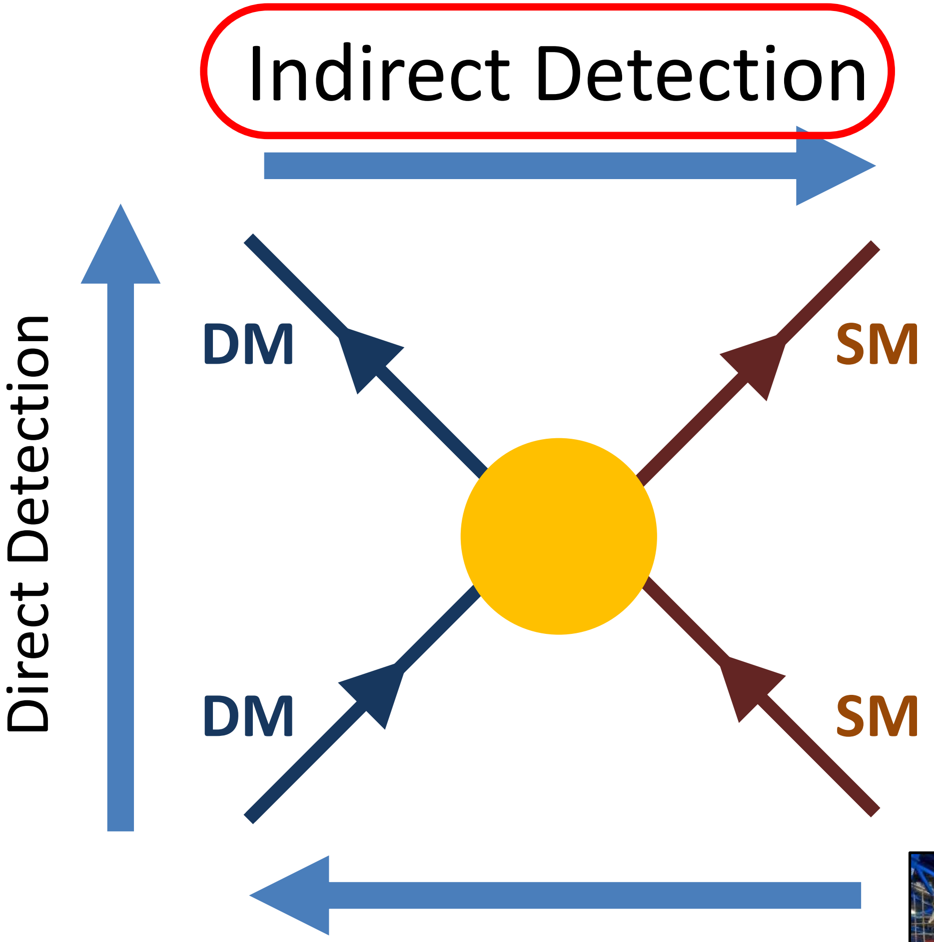
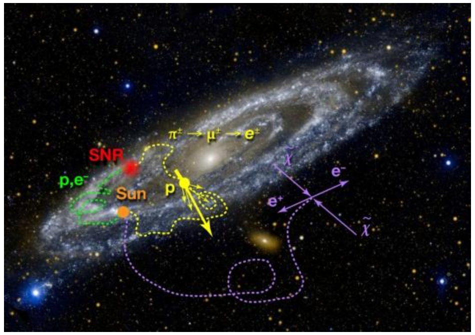
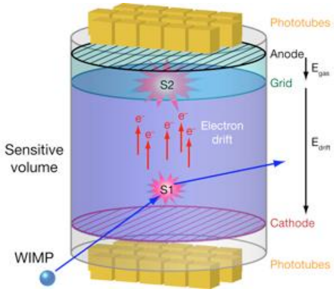
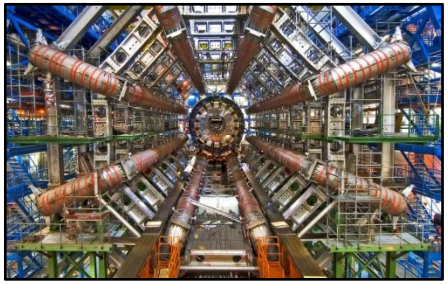
# Dark Matter Search



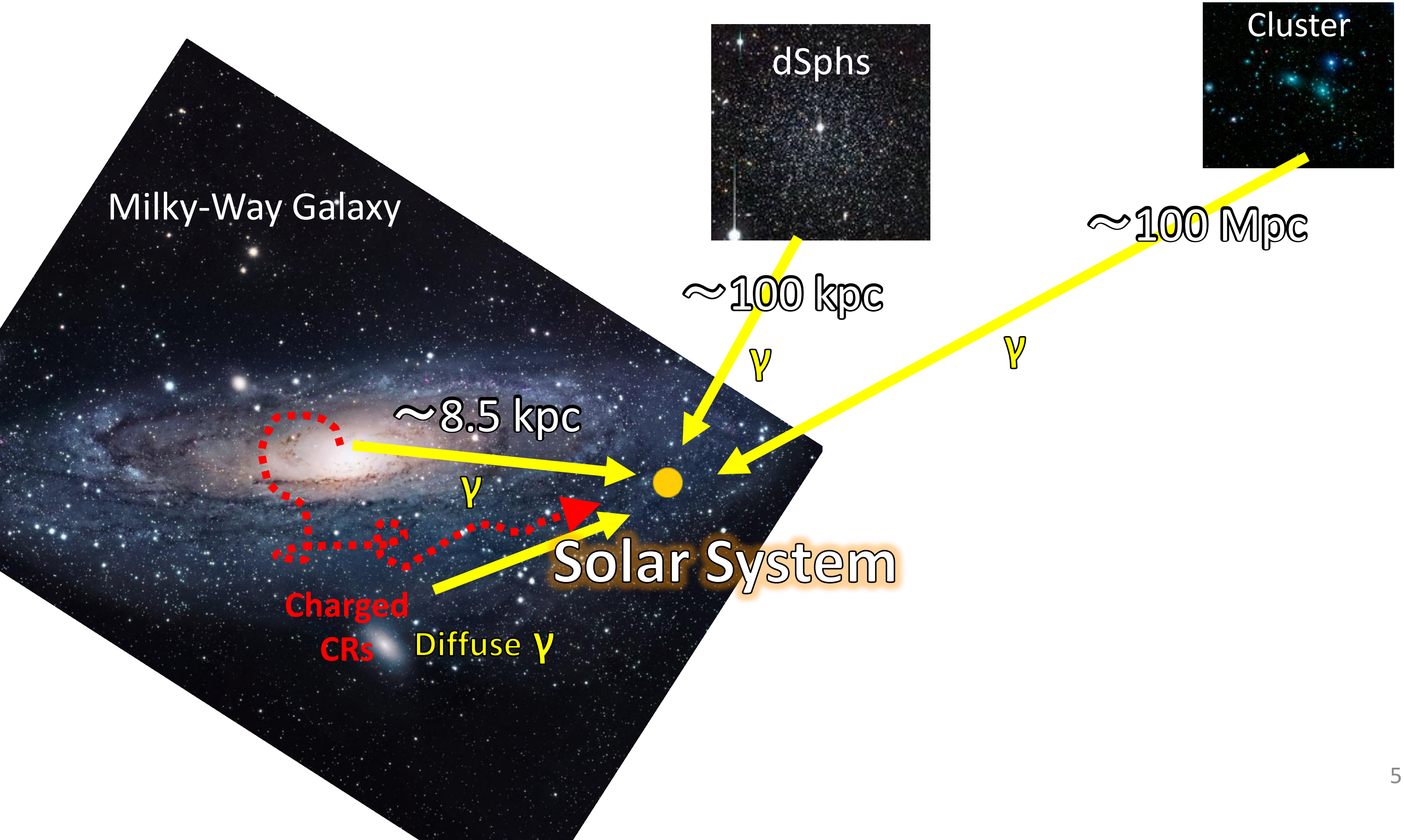
Collider Production







# Signal Target



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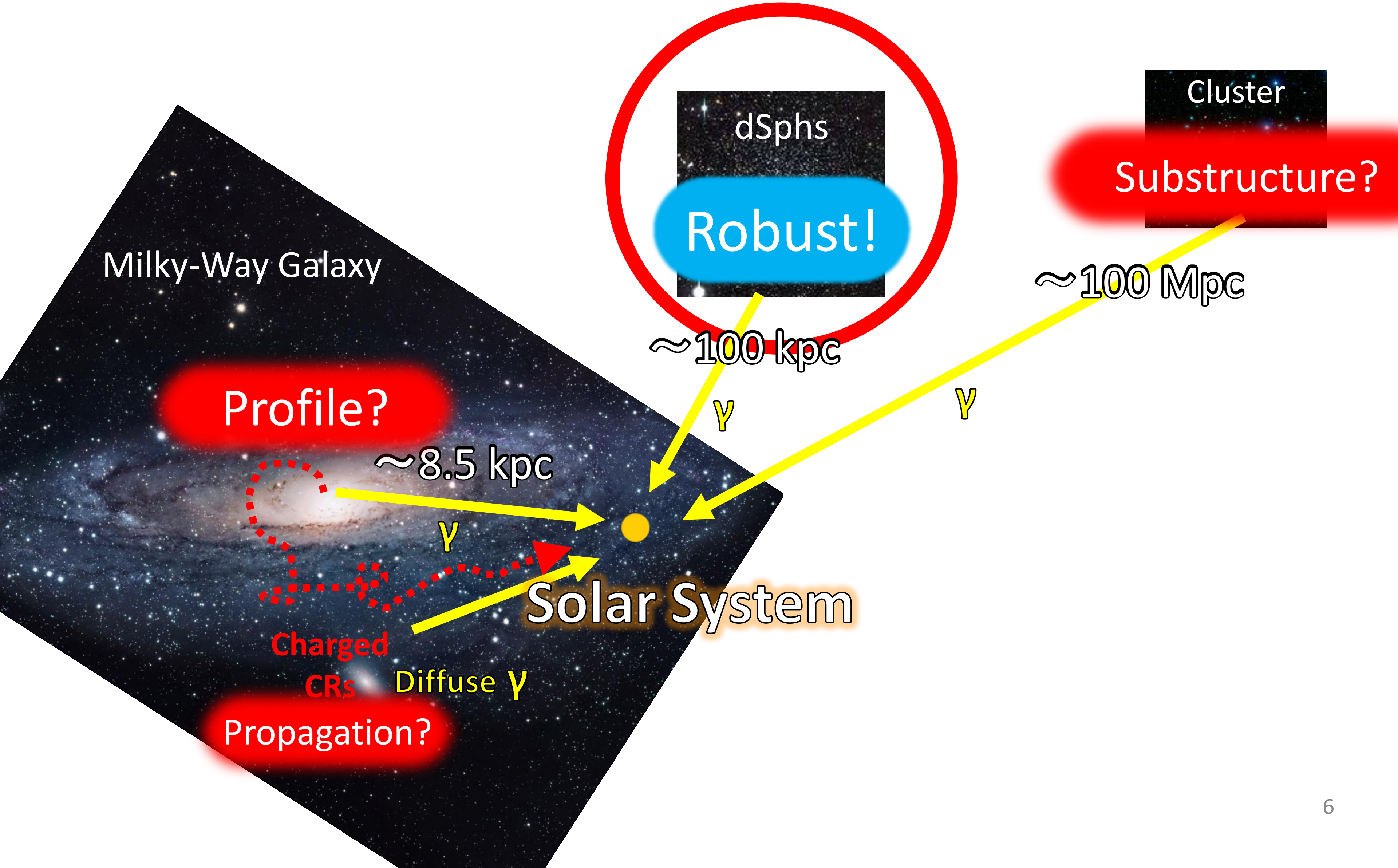
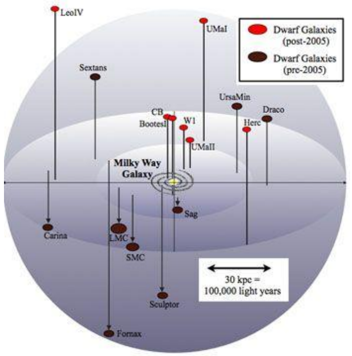
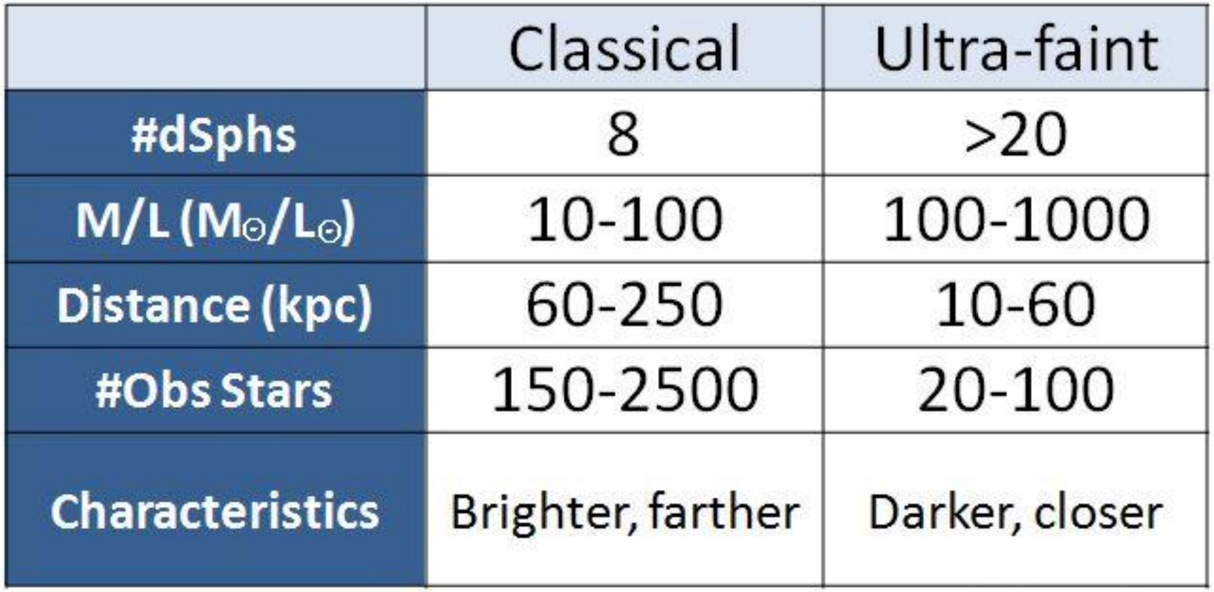


# Dwarf spheroidal galaxies

dSphs:

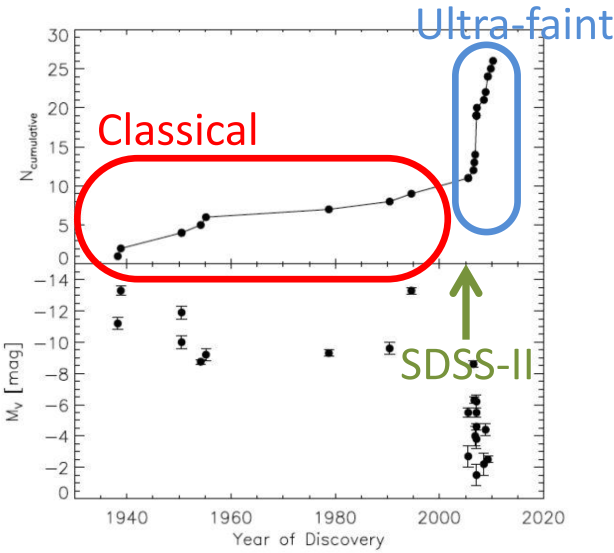
1. Neighbor galaxies: 10~100kpc
2. Large Mass to Luminosity ratio = **DM rich**
3. Fewer gas containment





| | Classical | Ultra-faint |
|---|---|---|
| **#dSphs** | 8 | >20 |
| **M/L ($M_\odot/L_\odot$)** | 10-100 | 100-1000 |
| **Distance (kpc)** | 60-250 | 10-60 |
| **#Obs Stars** | 150-2500 | 20-100 |
| **Characteristics** | Brighter, farther | Darker, closer |

See, e.g. Wolf et al (2010)



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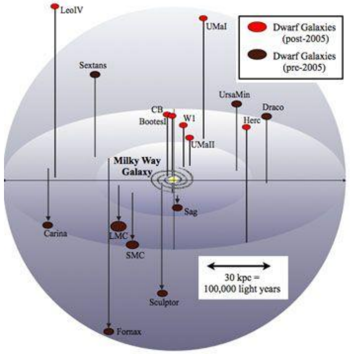

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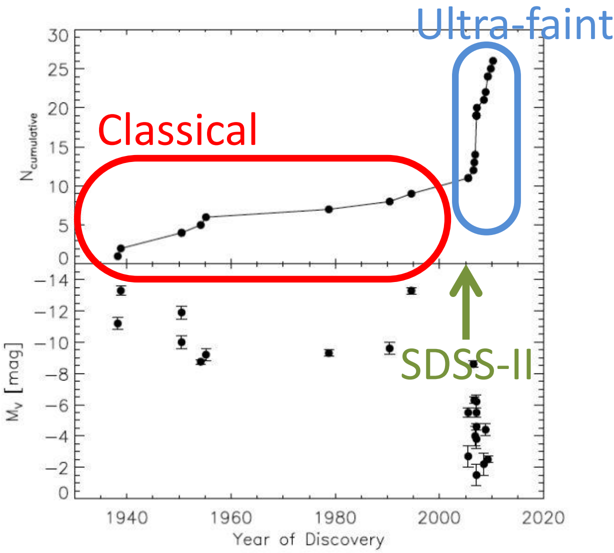


# Case Study: Wino DM

SUSY

- Higgs UV divergence
- Dark matter candidates
- Gauge Unification

A. **Higgs Radiative Correction**
B. **DM Relic Abundance**

Heavy sfermion + (relatively) light DM seems to be favored…

AMSB → Wino DM

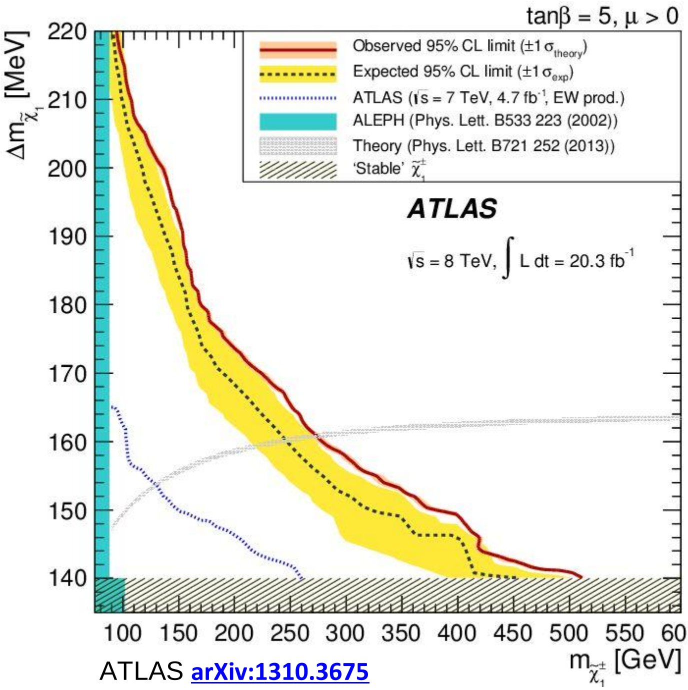
# Wino DM: Current observational limit

- Collider: LHC bound
- DM relic abundance
- Astro: γ-ray observation from the milky way satellite galaxies

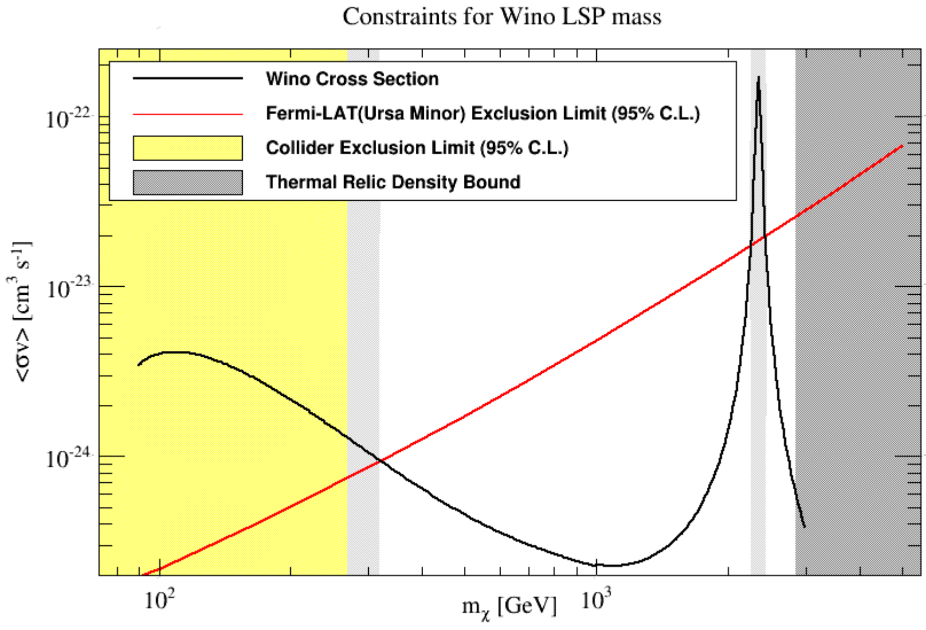
$M_{\mathrm{Wino}} \geq 270\,\mathrm{GeV}$ (ATLAS 95% C.L)

$M_{\mathrm{Wino}} \leq 2.9\,\mathrm{TeV}$ (M. Ibe, et al, PLB709, 2012)

$M_{\mathrm{Wino}} \geq 320\,\mathrm{GeV}$ (Fermi-LAT 95% C.L)

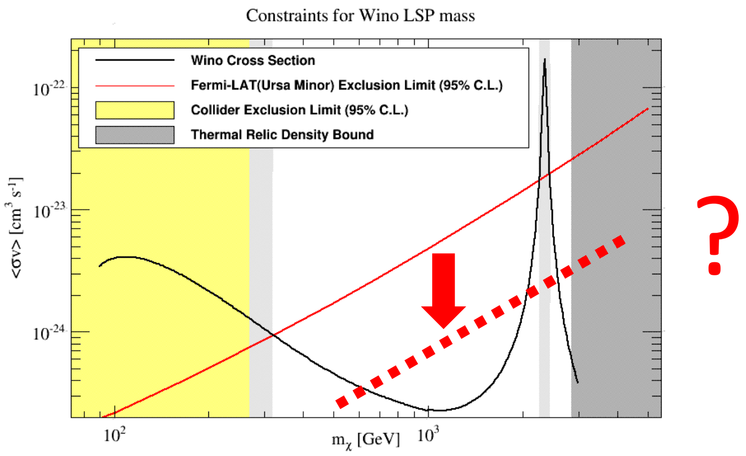


ATLAS arXiv:1310.3675



Data: Fermi-LAT arXiv:1310.0828

# Questions…



## 1.

What will the future exclusion region be like?

## 2.

What should we do to improve the sensitivity line efficiently?

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# Observed Events

Signal: $$S_{ai} = t_{\text{obs}} \times \int_{\Delta E_i} dE\, \mathcal{F}_a^{(\mathrm{S})}(E, \Delta\Omega_i)\, A_{\text{eff}}(E)$$

Background: $$B_{ai} = t_{\text{obs}} \times \int_{\Delta E_i} dE\, \mathcal{F}_a^{(\mathrm{B})}(E, \Delta\Omega_i)\, A_{\text{eff}}(E)$$

a: dSph
i: Energy Bin

Energy Bin

ROI

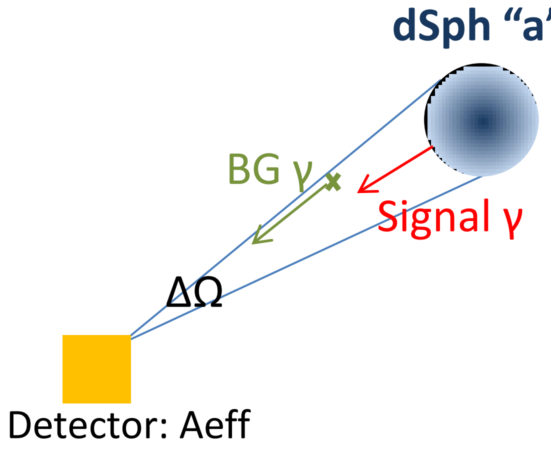
Effective Area

Signal Flux: $F^{(S)}$

Particle Factor
Astrophysical Factor

BG Flux: $F^{(B)}$

Galactic Diffuse
Isotropic Diffuse
Point-like Source



# Signal Flux

$$\Phi(E,\Delta\Omega) = \left[\frac{\langle\sigma v\rangle}{8\pi m_{\tilde{w}}^2}\sum_f \mathrm{Br}(\tilde{w}^0\tilde{w}^0\to f)\left(\frac{dN_\gamma}{dE}\right)_f\right]\left[\int_{\Delta\Omega} d\Omega\int_{l.o.s.} dl\,\rho^2(l,\Omega)\right]$$

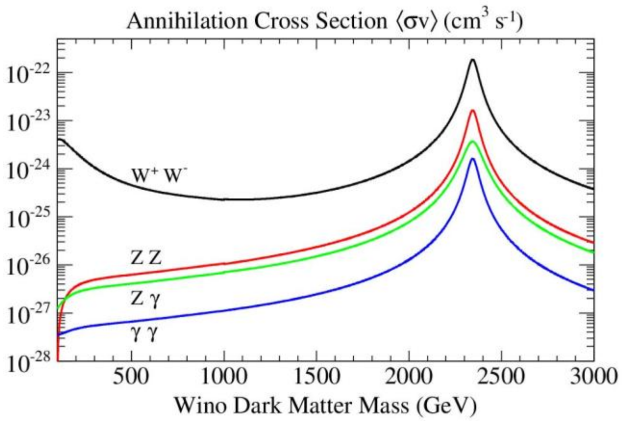
**Particle Physics Factor**

**Astrophysics Factor (J-factor)**

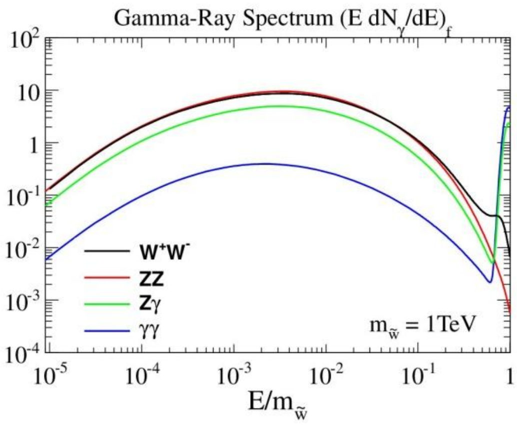
$f = WW, ZZ, \gamma\gamma, Z\gamma$ Error: 1-10 % level

Large uncertainty:
Next Slide

$$J \simeq \frac{1}{D^2}\int_{\mathrm{Vol}} r^2\rho^2(r)\mathrm{d}r$$

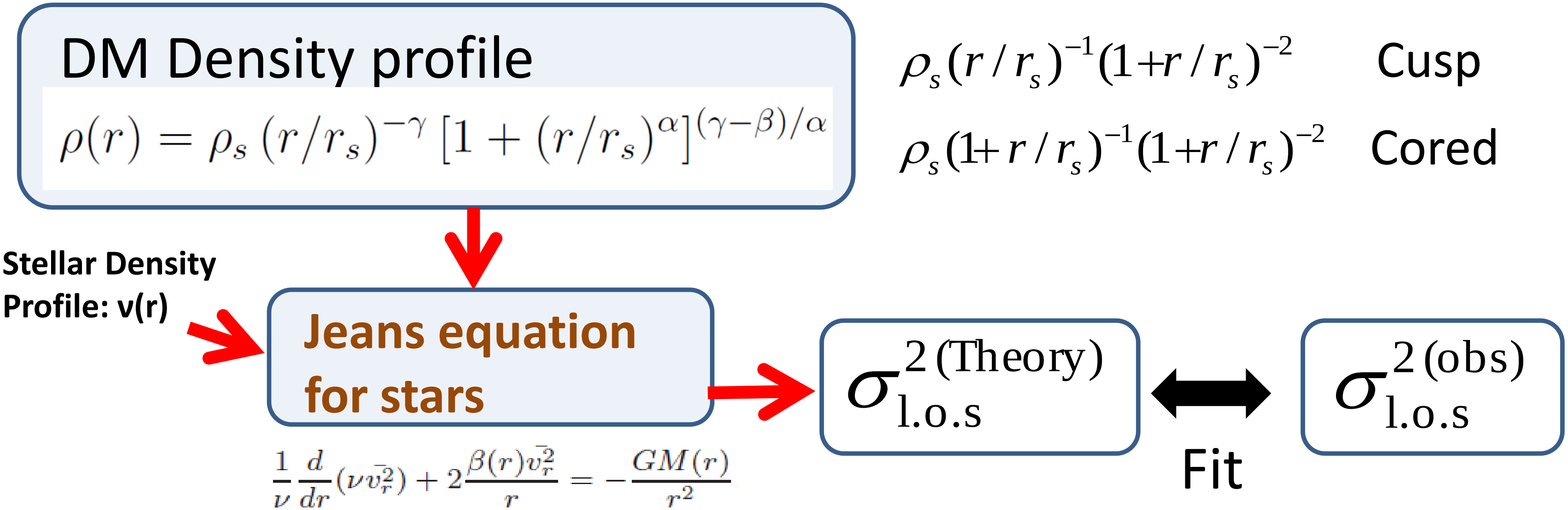


Hryczuk and Iengo (2012)



Cirelli et al (2012)

# Astrophysical Factor



DM Density profile

$$\rho(r) = \rho_s\,(r/r_s)^{-\gamma}\,[1 + (r/r_s)^{\alpha}]^{(\gamma-\beta)/\alpha}$$

$\rho_s (r/r_s)^{-1}(1+r/r_s)^{-2}$ Cusp

$\rho_s (1+r/r_s)^{-1}(1+r/r_s)^{-2}$ Cored

**Stellar Density Profile: ν(r)**

**Jeans equation for stars**

$$\frac{1}{\nu}\frac{d}{dr}(\nu \bar{v_r^2}) + 2\frac{\beta(r)\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

$\sigma^{2\,(\mathrm{Theory})}_{\mathrm{l.o.s}}$

$\sigma^{2\,(\mathrm{obs})}_{\mathrm{l.o.s}}$

Fit

| | | long. (deg.) | lat. (deg.) | dist. (kpc) | $\alpha_s$ (deg.) | $\log_{10}[J(0.5°)/(\mathrm{GeV^2cm^{-5}sr})]$ |
|---|---|---|---|---|---|---|
| Classical:<br>Well-determined | Draco | 86.4 | 34.7 | 76 | $0.25^{+0.15}_{-0.09}$ | $18.8 \pm 0.16$ |
| | Ursa Min. | 105.0 | 44.8 | 76 | $0.32^{+0.18}_{-0.12}$ | $18.8 \pm 0.19$ |
| | Sculptor | 287.5 | -83.2 | 86 | $0.25^{+0.25}_{-0.13}$ | $18.6 \pm 0.18$ |
| | Sextans | 243.5 | 42.3 | 86 | $0.13^{+0.07}_{-0.05}$ | $18.4 \pm 0.27$ |
| Ultra-faint:<br>Not well-determined.<br>Prior dependence | Segue 1 | 220.5 | 50.4 | 23 | $0.40^{+0.86}_{-0.27}$ | *$19.5 \pm 0.29$* |
| | Ursa Maj. II | 152.5 | 37.4 | 32 | $0.32^{+0.48}_{-0.19}$ | *$19.3 \pm 0.28$* |
| | Willman 1 | 158.6 | 56.8 | 38 | $0.25^{+0.54}_{-0.17}$ | *$19.1 \pm 0.31$* |
| | Coma B. | 241.9 | 83.6 | 44 | $0.25^{+0.54}_{-0.17}$ | *$19.0 \pm 0.25$* |

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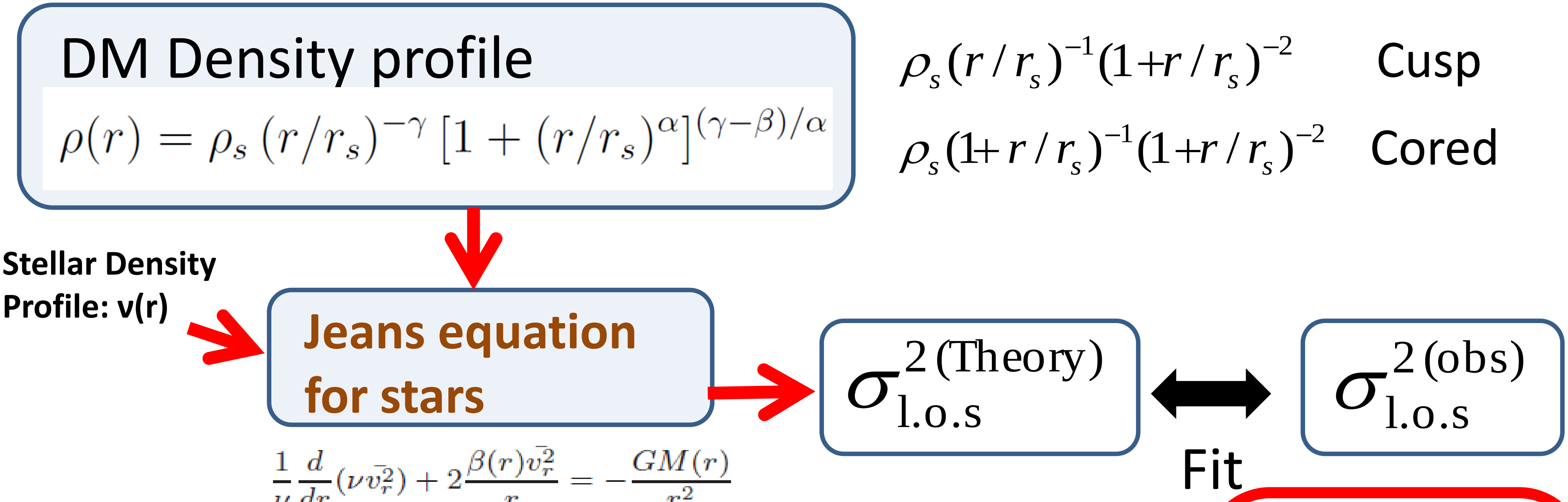

**DM Density profile**

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$\rho_s (r/r_s)^{-1}(1+r/r_s)^{-2}$ Cusp

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# Background Flux

### 1. Galactic Diffuse

CR + ISM, Brems of CRe, IC (CRe + Interstellar radiation field)

→ Simulation (e.g. GALPROP) with ISM, ISRF, Large Scale Structure.

### 2. Isotropic Diffuse

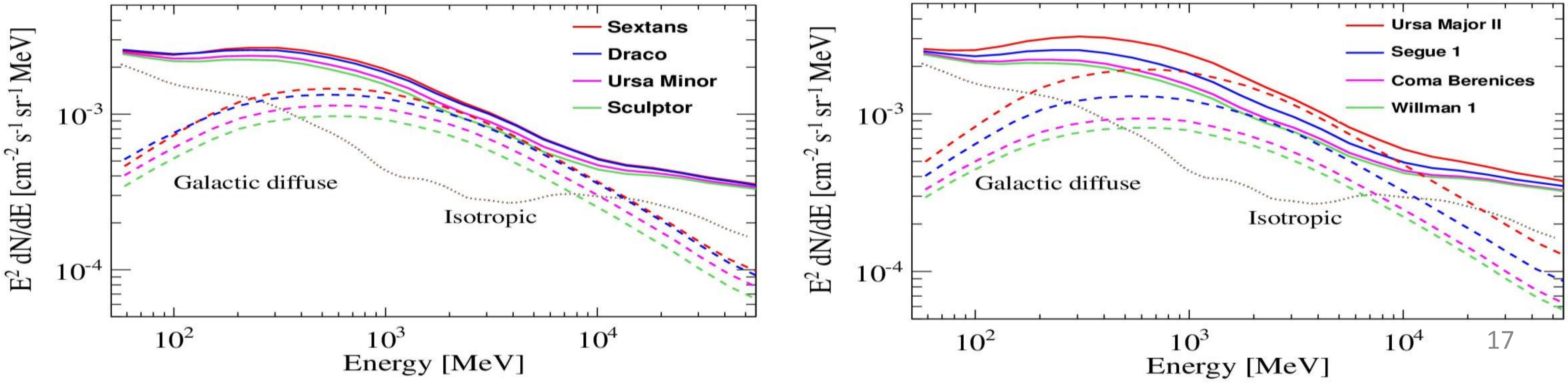
AGN, Starburst, γ-Ray burst, unknown sources

→ Evaluated from |b| > 30° sky data

### 3. Point-like Source

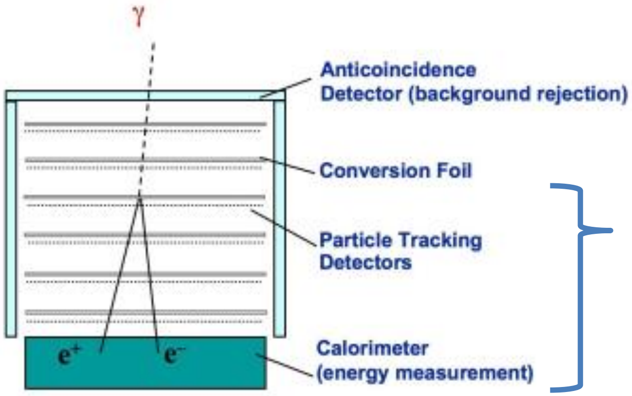
AGN, SNR, Pulsars, Unidentified

→ Mask/Model

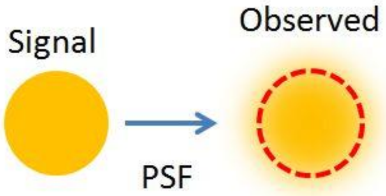


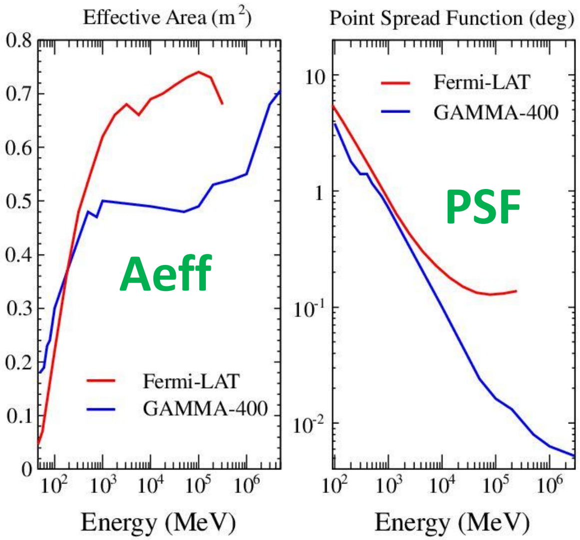
# Detector Capabilities

Satellite- type Obs



Direction Reconstruction

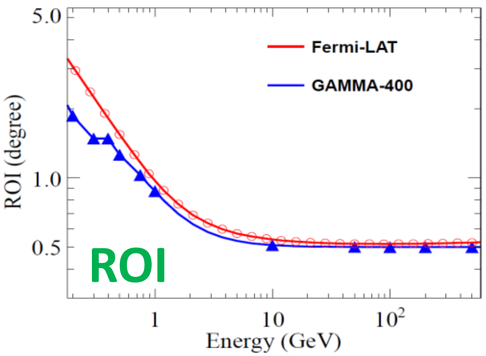


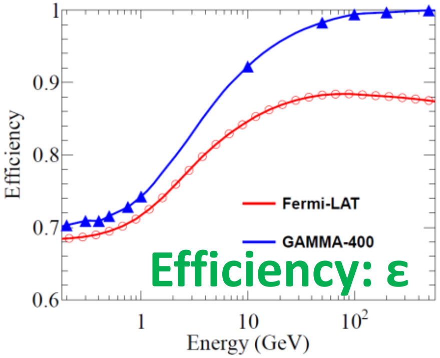


**ROI:** $\Delta\Omega_i = 2\pi(1 - \cos\alpha_i)$

$$\alpha_i = [(0.5^\circ)^2 + \psi_{68}^2(E_i)]^{1/2}$$

Typical dSphs Size PSF (68 % containment angle)





Signal Flux

$$\mathcal{F}_a^{(\mathrm{S})}(E, \Delta\Omega_i) = \epsilon(\Delta\Omega_i)\,\Phi_a(E, \Delta\Omega_i)$$

PSF effect -> efficiency ε

Background Flux

$$\mathcal{F}_a^{(\mathrm{B})}(E, \Delta\Omega_i) = \Delta\Omega_i\,(d\Phi_a^{\mathrm{B}}(E)/d\Omega)$$

Large ΔΩ -> Large Background

# Sensitivity Line

## Profile Likelihood

J-factor error is included

$$\mathcal{L}[\langle\sigma v\rangle, \{J_a\}] \equiv \prod_{a,i} \frac{P\left(N_{ai}; S_{ai}[\langle\sigma v\rangle, J_a] + B_{ai}\right)}{P\left(N_{ai}; N_{ai}\right)} G\left(J_a; \log_{10} J_a^{(\mathrm{obs})}, \delta(\log_{10} J_a^{(\mathrm{obs})})\right)$$

P(N:λ): Poisson
G(x: μ, σ): Log Gaussian
$N_{ai}$: Observed Events

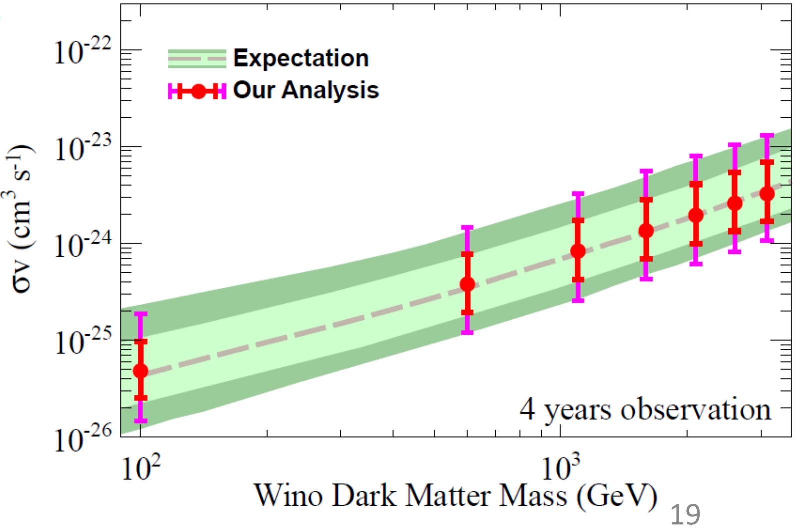
## Test (95% C.L)

$$-2\ln\mathcal{L}(\langle\sigma v\rangle, \{J_{\min}\}) + 2\ln\mathcal{L}(0, \{J_{\min}\}) = 2.71$$

2000 Pseudo Experiments for $N_{ai}$ ($\{N^{(1)}_{ai}, N^{(2)}_{ai}, N^{(3)}_{ai}\ldots\}$)
(Poisson with the mean of $B_{ai}$)

Each $N^{(i)}_{ai} \rightarrow \langle\sigma v\rangle^{(i)}$

Right Figure:
Mean and 68 (95) % band
for the set $\{\langle\sigma v\rangle^{(1)}, \langle\sigma v\rangle^{(2)}, \langle\sigma v\rangle^{(3)}, \ldots\}$



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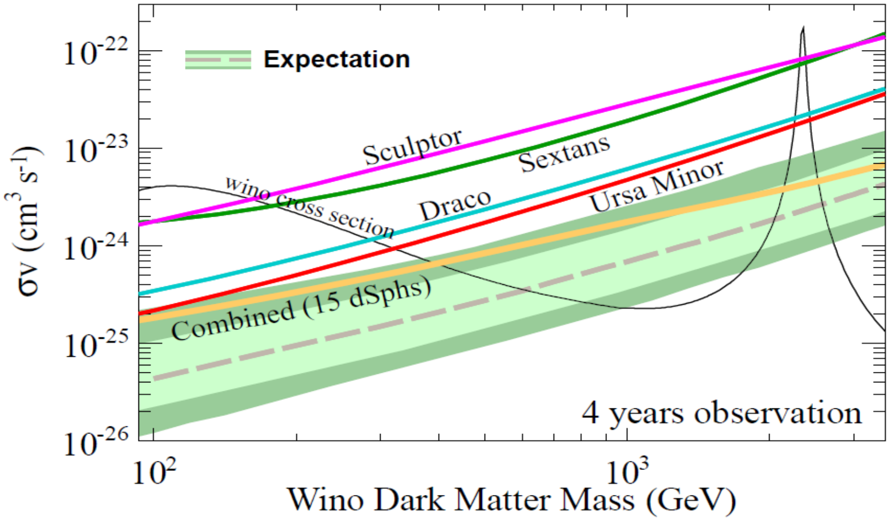
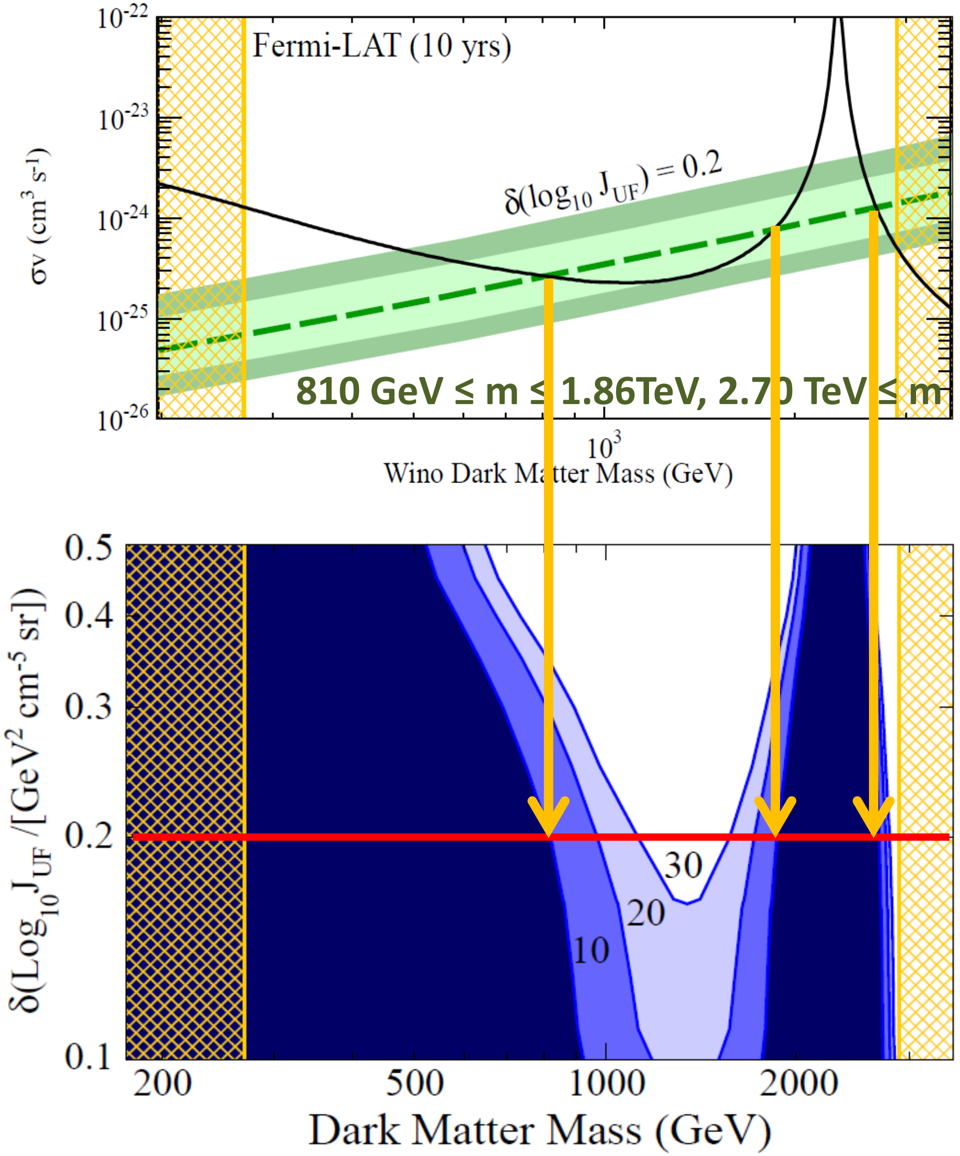
# Current Limit



Ursa Minor
320 GeV ≤ m ≤ 2.25TeV and 2.43 TeV ≤ m

Combined (15 dSphs) <- Aggressive
390 GeV ≤ m ≤ 2.14TeV and 2.53 TeV ≤ m

# Future Prospects



810 GeV ≤ m ≤ 1.86TeV, 2.70 TeV ≤ m

# Summary

- Indirect detection is essential for the heavy DM search.
- Gamma-ray observation of dSph can give robust constraints on the DM annihilation cross section.
- Investigation of Ultra-faint’s stellar kinematics dramatically affects the sensitivity lines.

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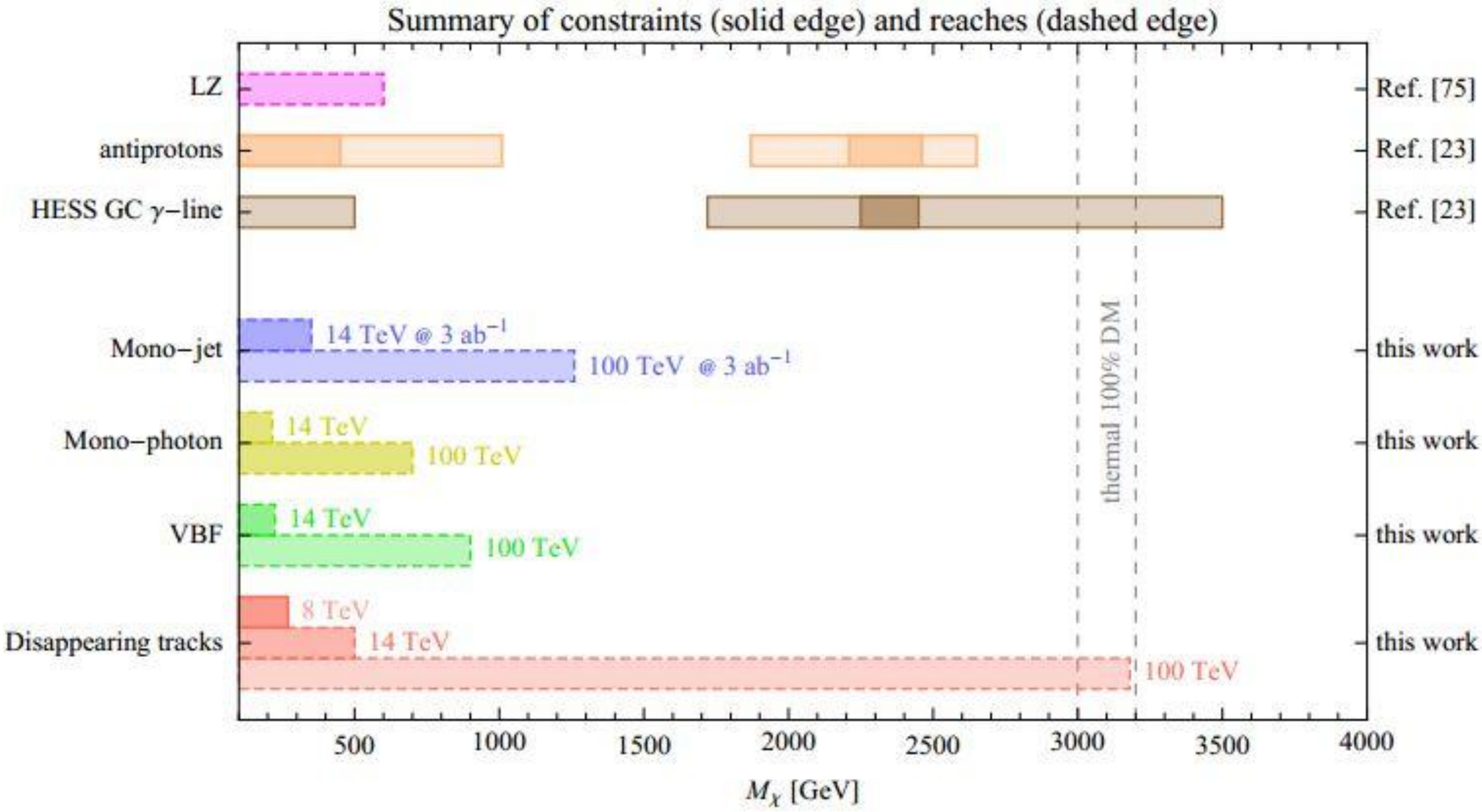

Cirelli et al:1407.7058

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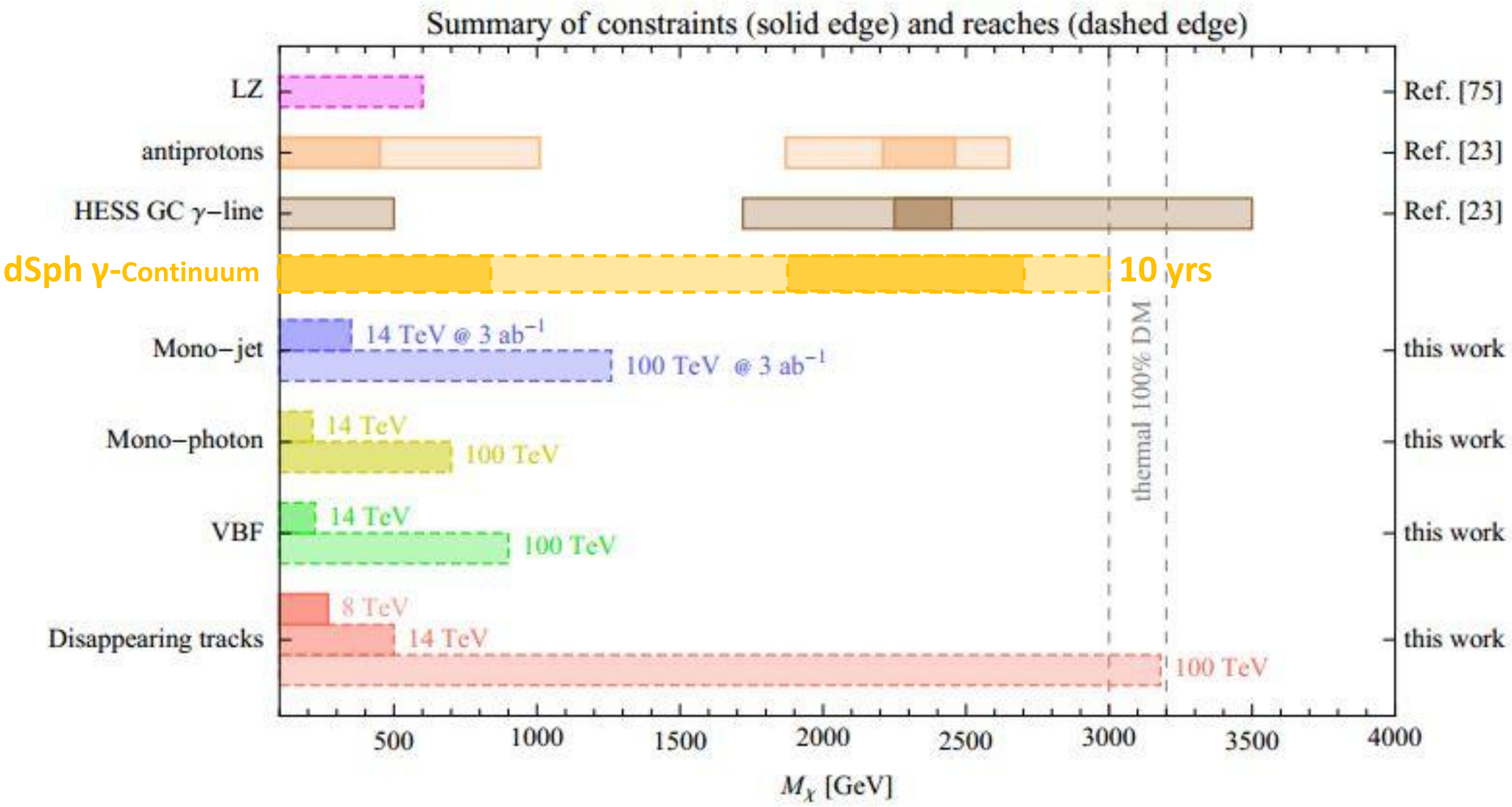

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