

# TeV dark matter search at the Galactic centre with the CTA



**Gabrijela Zaharijas**

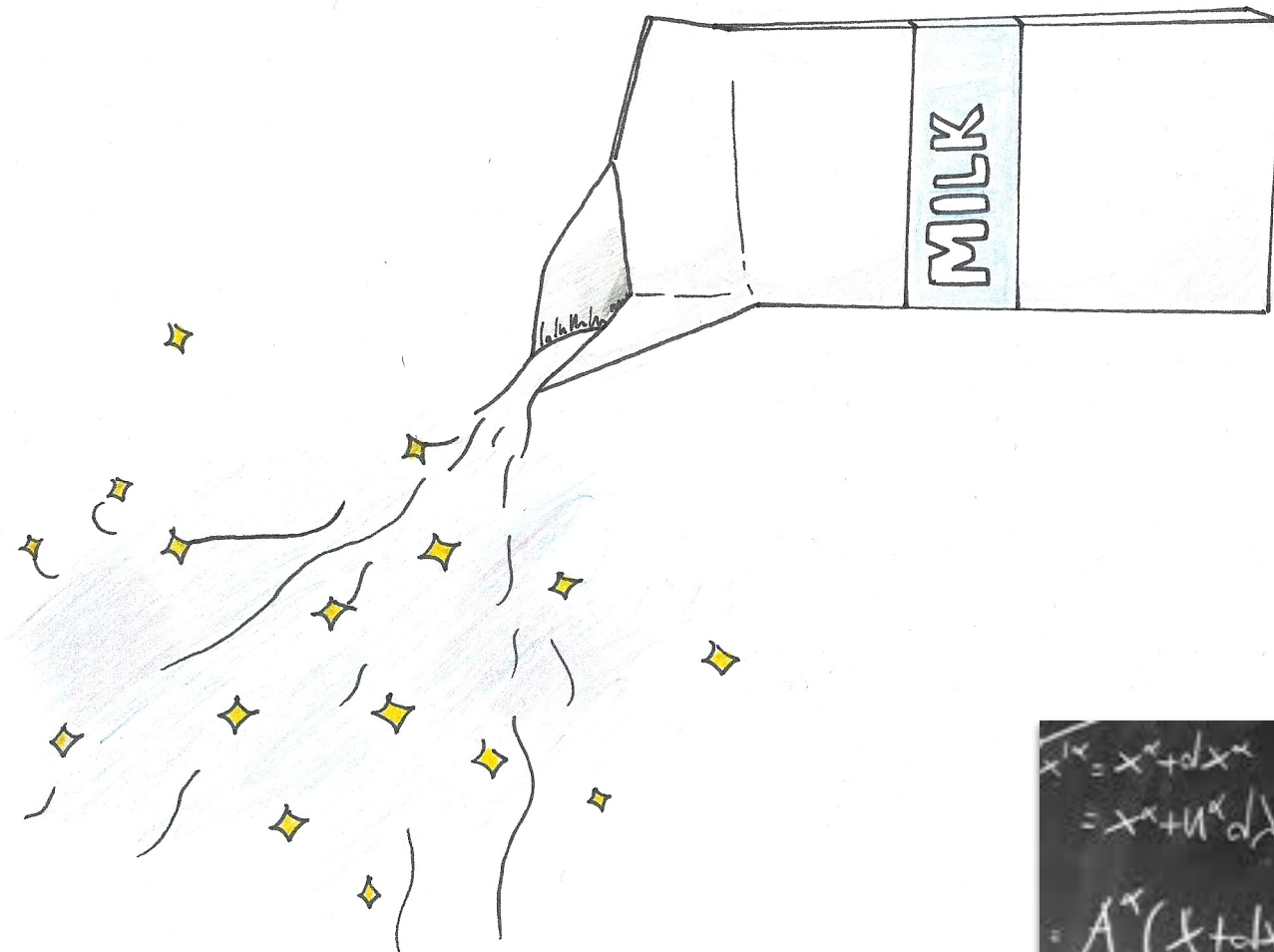
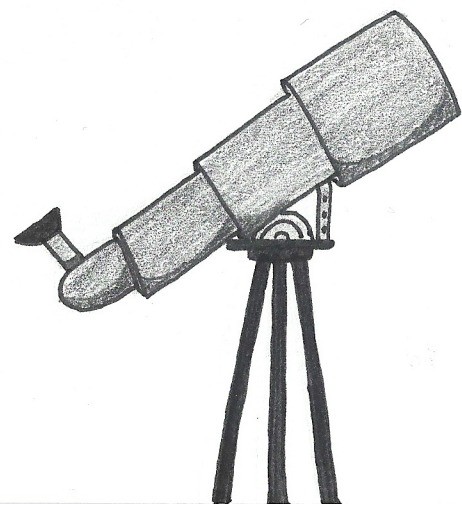
**for the CTA consortium**

*Un. of Nova Gorica*

work within the **CTA DM working group** (with T. Bringmann, C. Eckner, A. Sokolenko, L. Yang)



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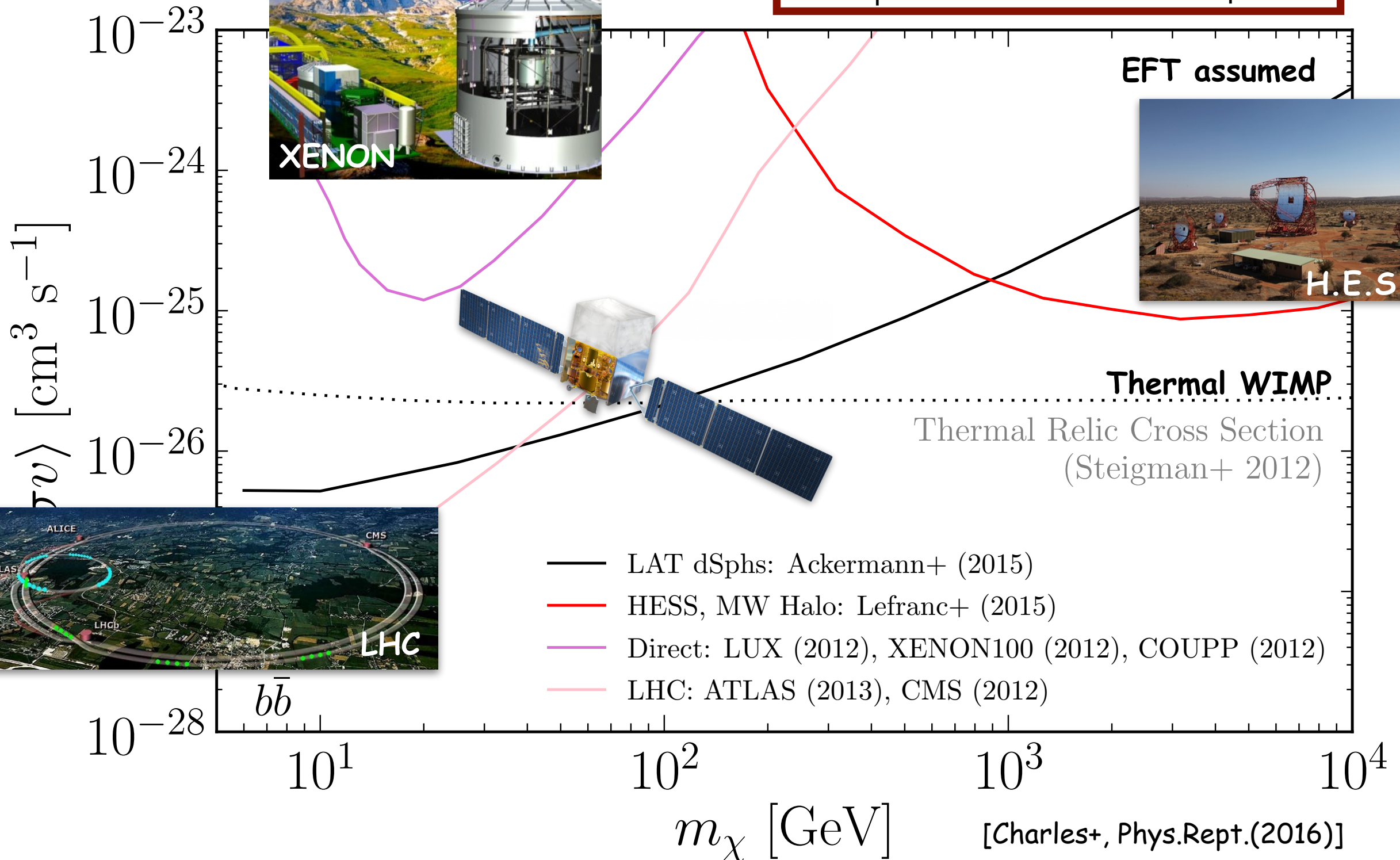
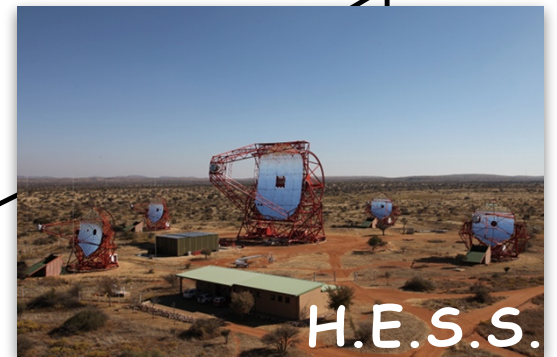
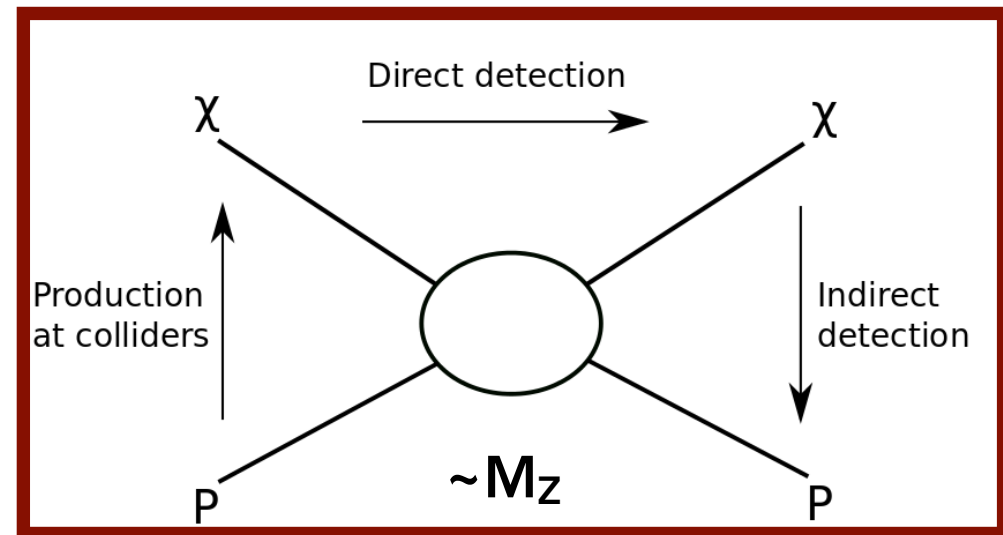
# Thermal DM ?

- Minimal assumptions about DM origin (thermal decoupling(s) responsible for most of the Early history of the Universe)
- In vanilla scenario, gives a *prediction* for mass ( $\sim M_Z$ ) & annihilation cross section  $\rightarrow$  thermal WIMPs
- Motivated from particle physics ('weak charged' DM models)

Monday talks  
(Matsumoto+)?

# Cornering the WIMP

Pani's talk (+...)!

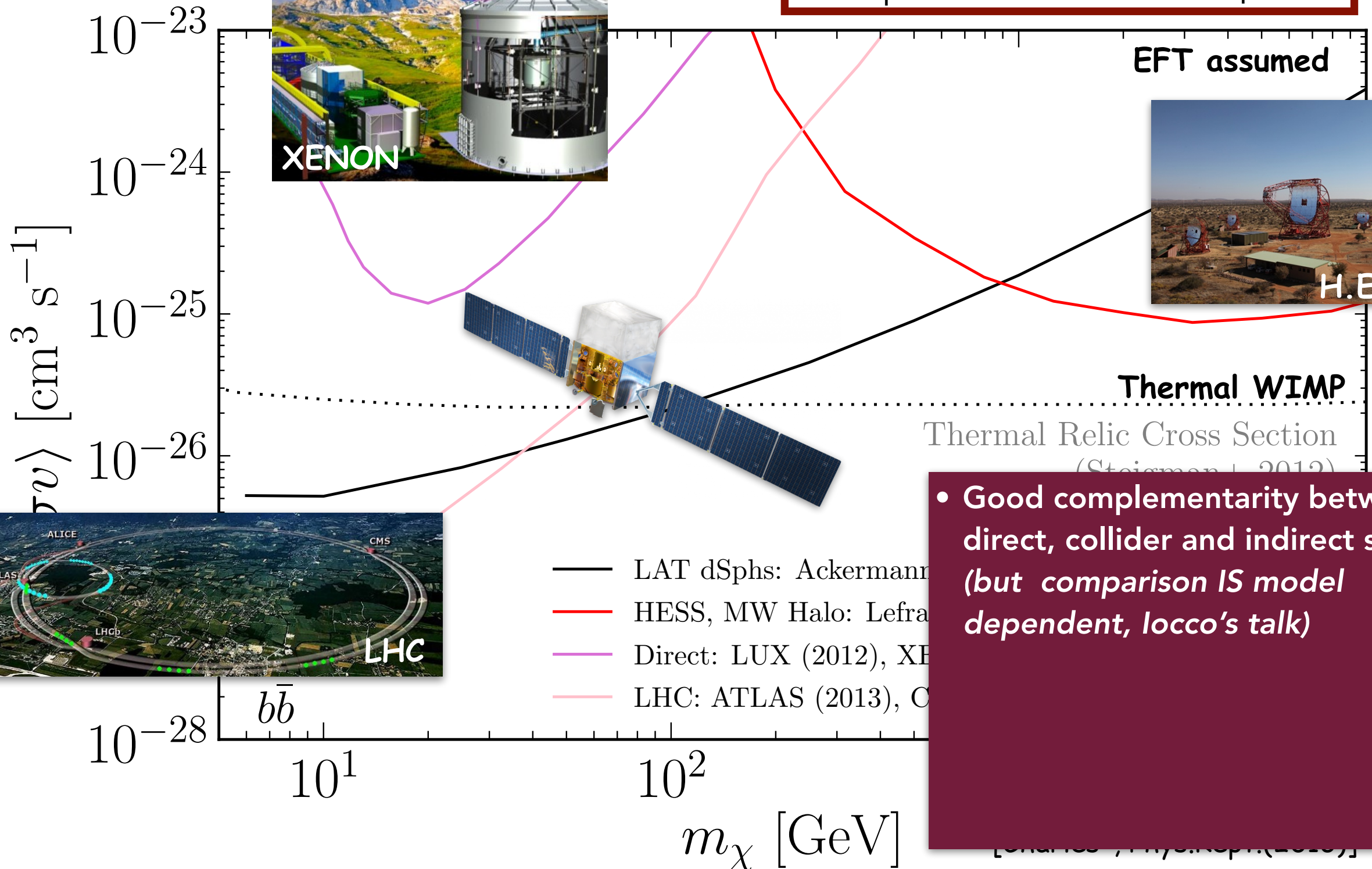
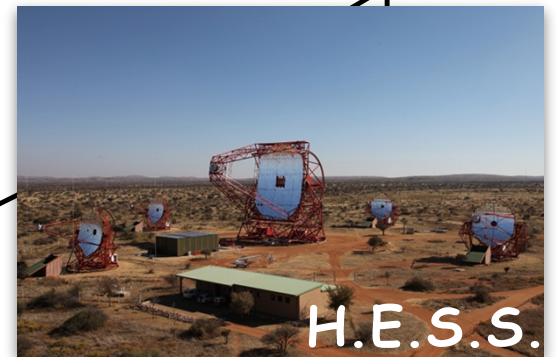
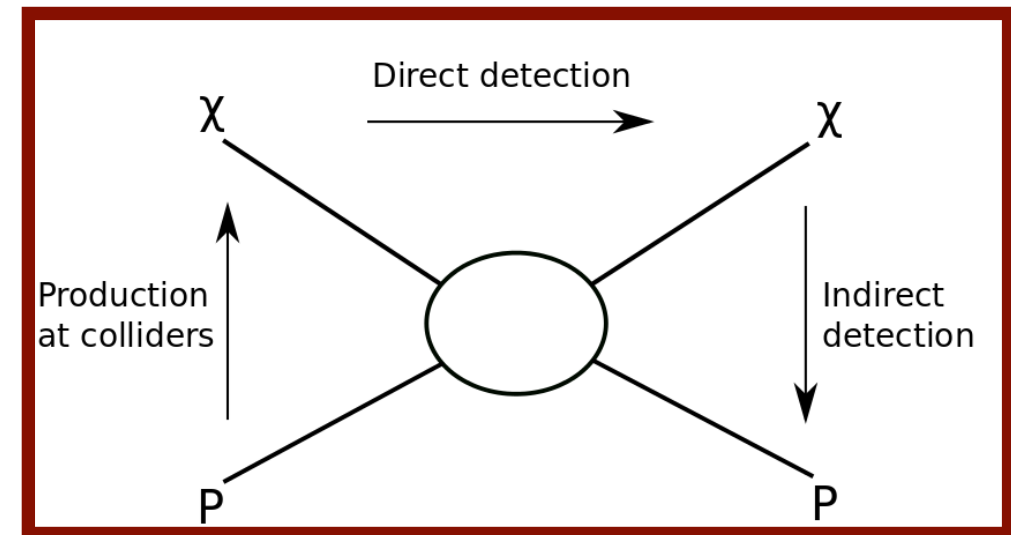


- LAT dSphs: Ackermann+ (2015)
- HESS, MW Halo: Lefranc+ (2015)
- Direct: LUX (2012), XENON100 (2012), COUPP (2012)
- LHC: ATLAS (2013), CMS (2012)

[Charles+, Phys.Rept.(2016)]



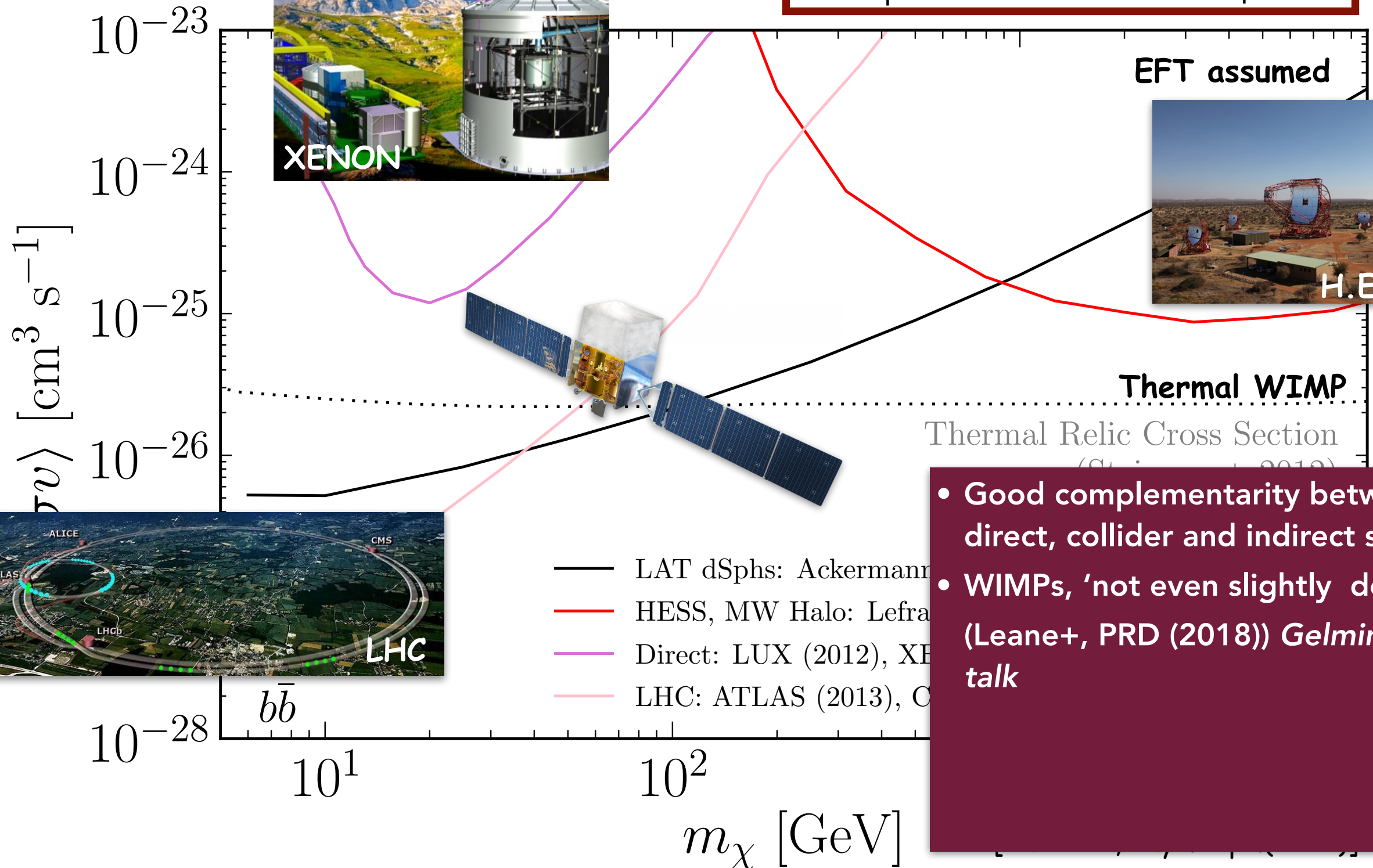
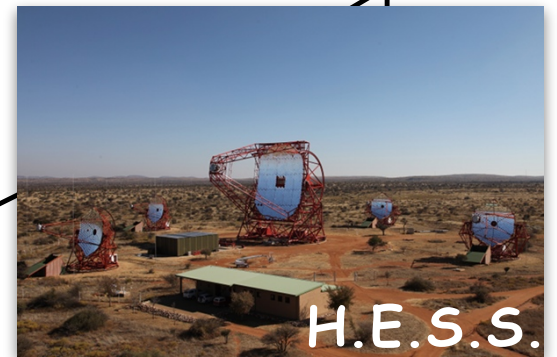
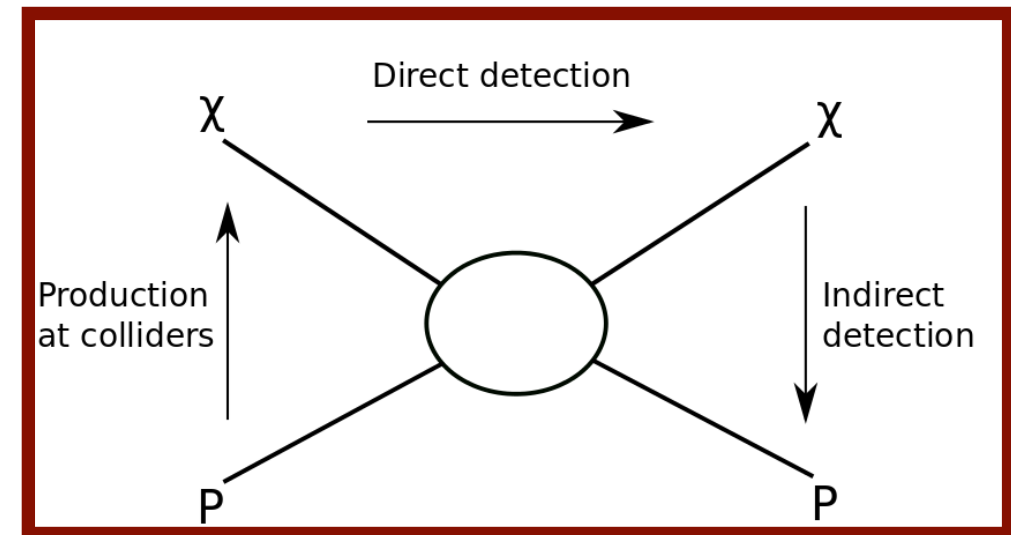
# Cornering the WIMP



- Good complementarity between direct, collider and indirect search (but comparison IS model dependent, locco's talk)



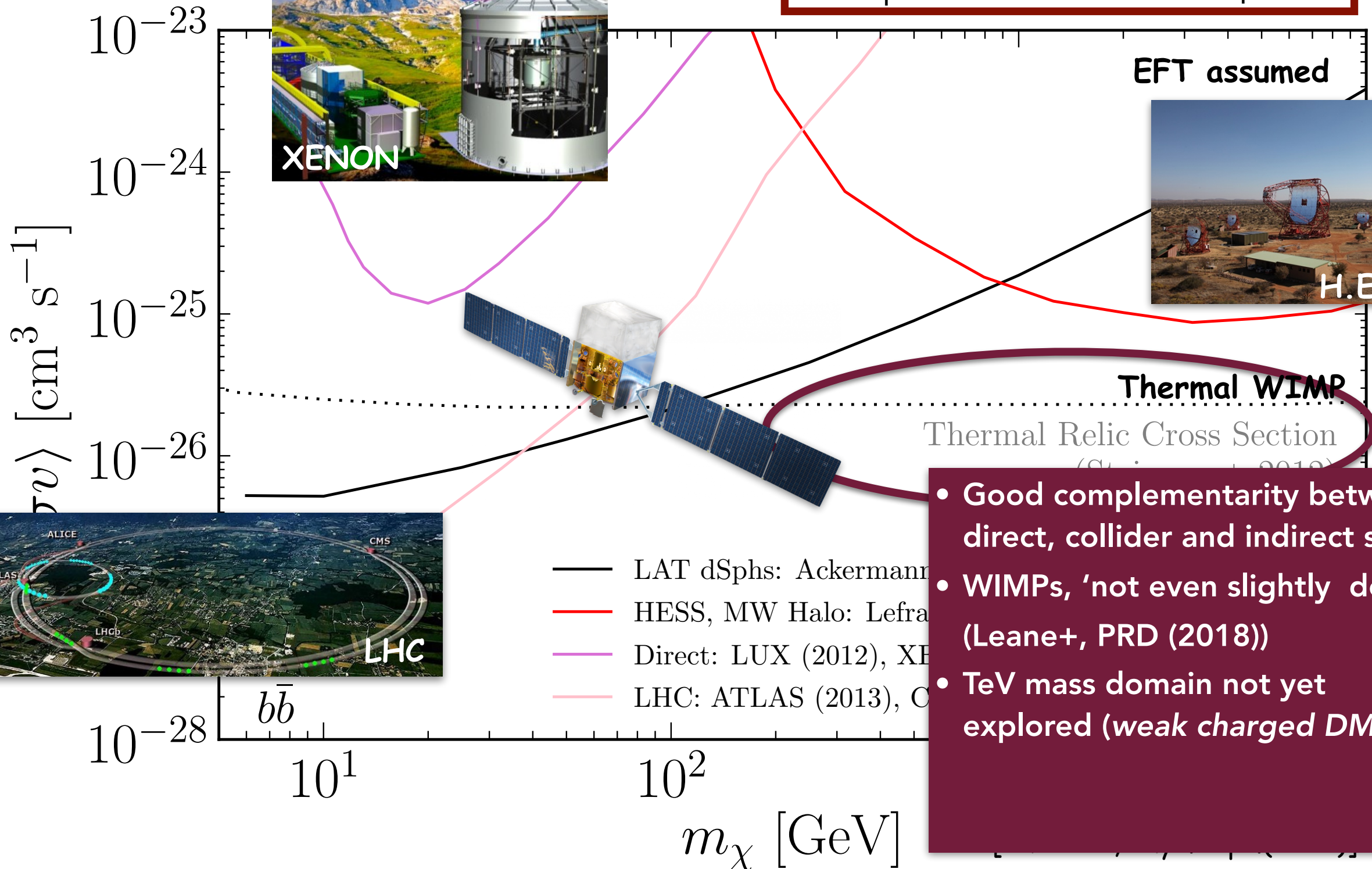
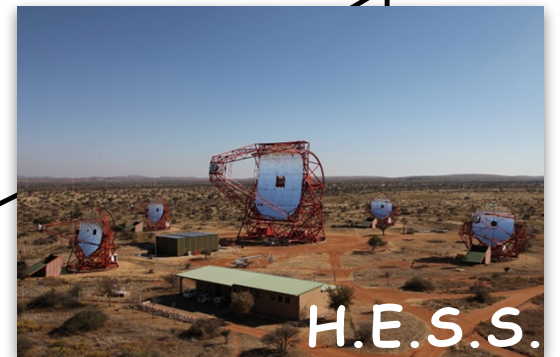
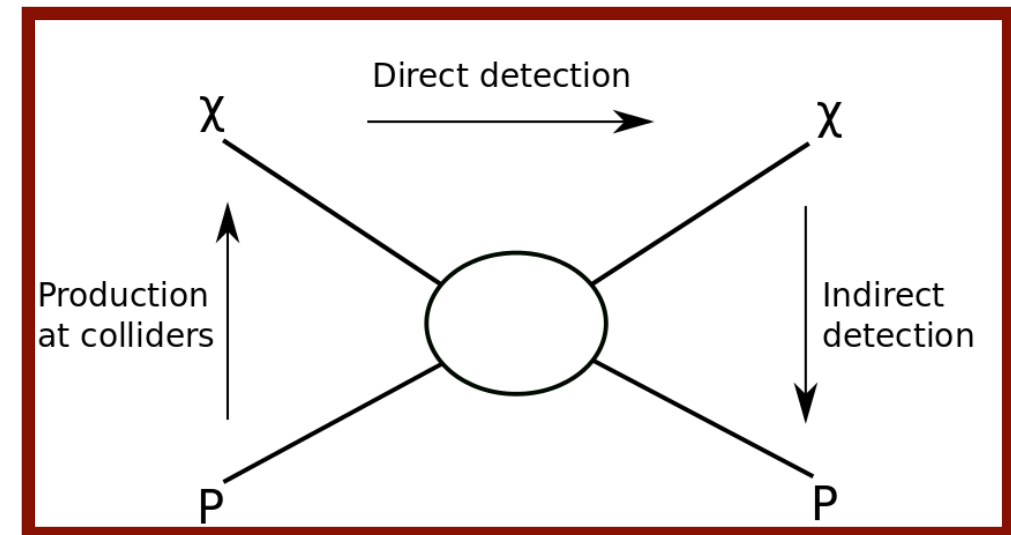
# Cornering the WIMP



- LAT dSphs: Ackermann et al. (2015)
- HESS, MW Halo: Lefrandt et al. (2017)
- Direct: LUX (2012), XENON1T (2017)
- LHC: ATLAS (2013), CMS (2014)

- Good complementarity between direct, collider and indirect search
- WIMPs, 'not even slightly dead' (Leane+, PRD (2018)) *Gelmini's talk*

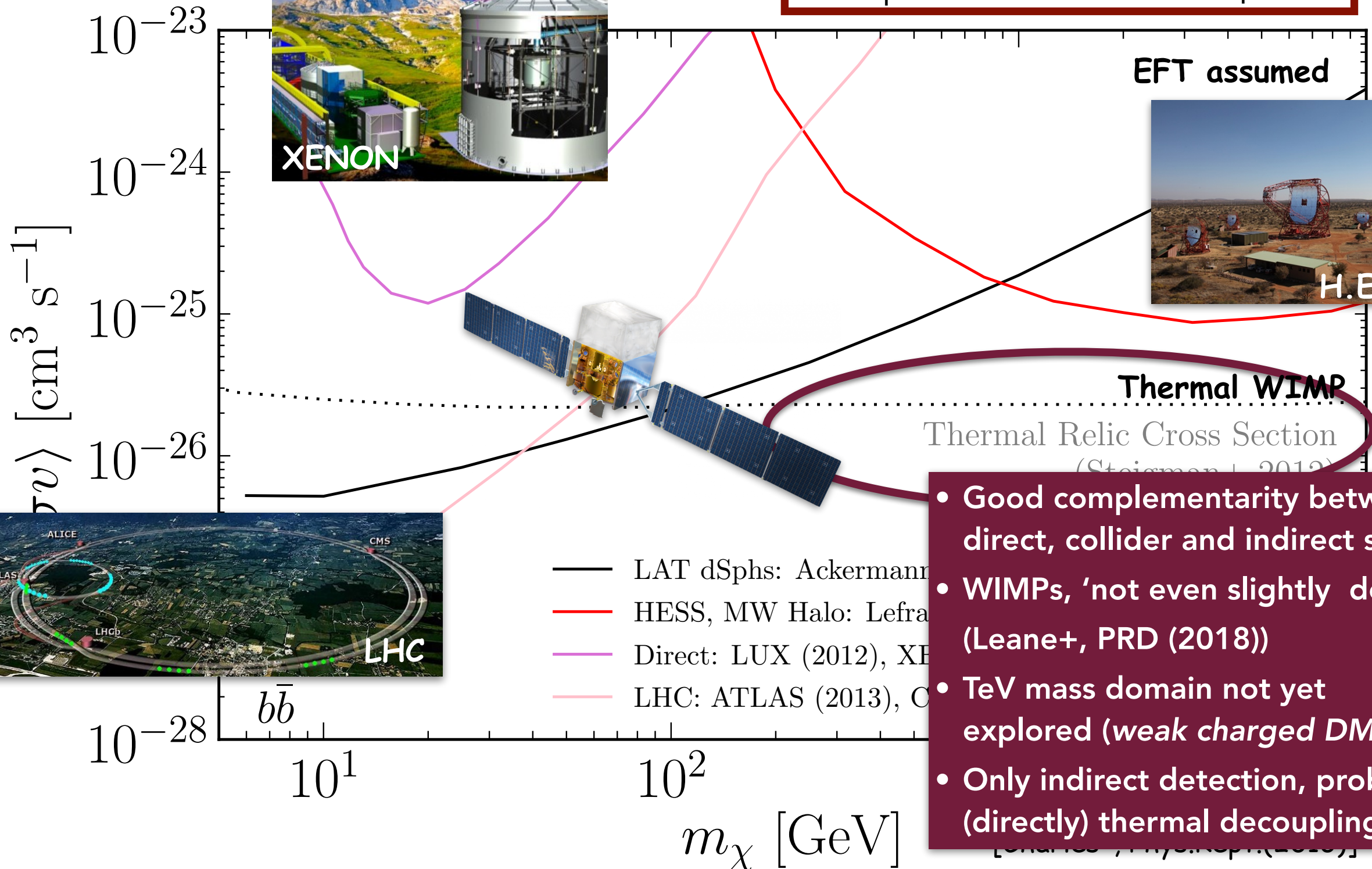
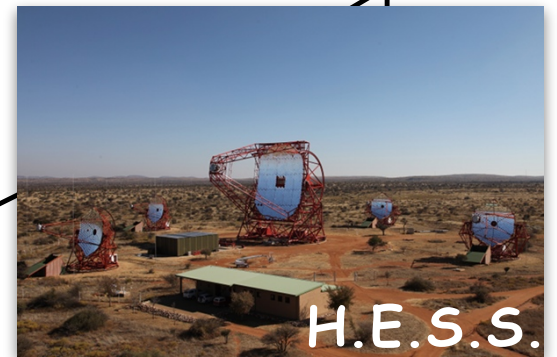
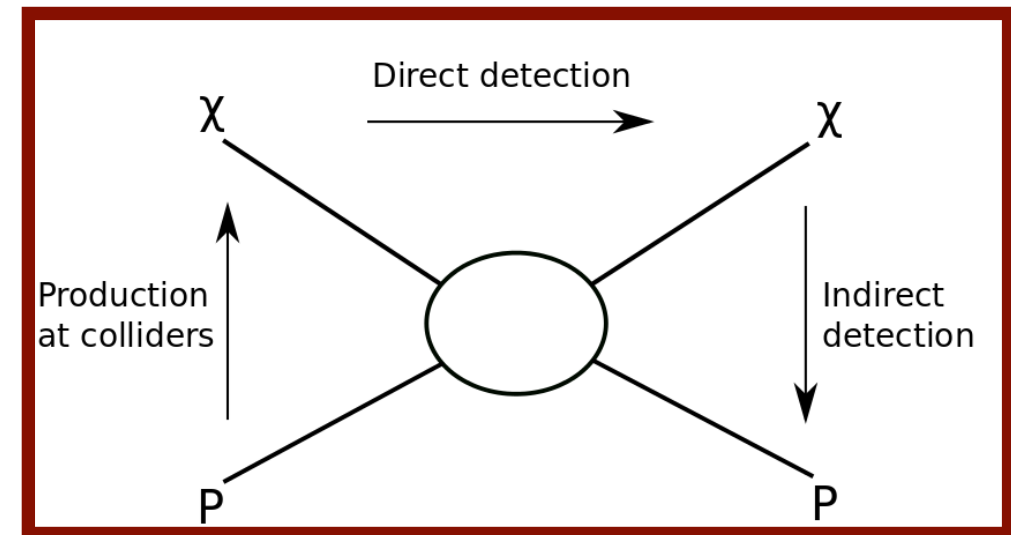
# Cornering the WIMP



- Good complementarity between direct, collider and indirect search
- WIMPs, 'not even slightly dead' (Leane+, PRD (2018))
- TeV mass domain not yet explored (*weak charged DM*)



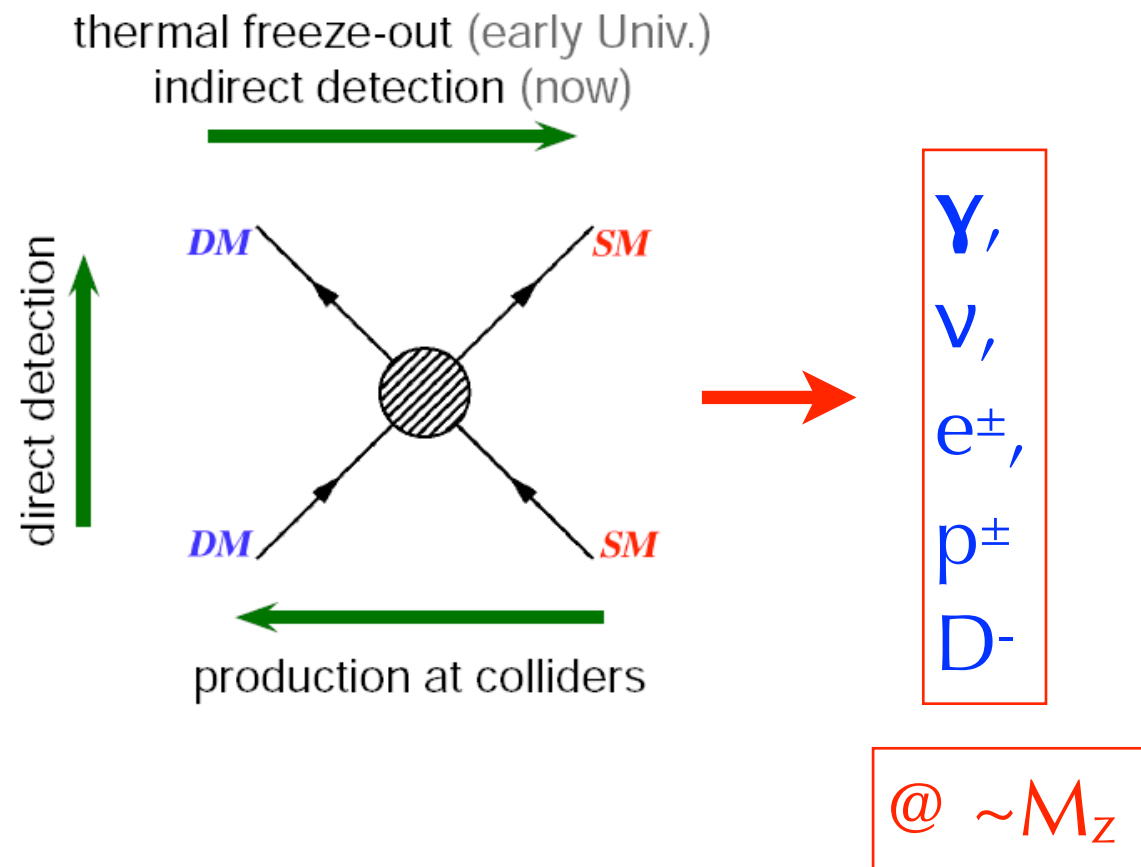
# Cornering the WIMP



- LAT dSphs: Ackermann et al. (2012)
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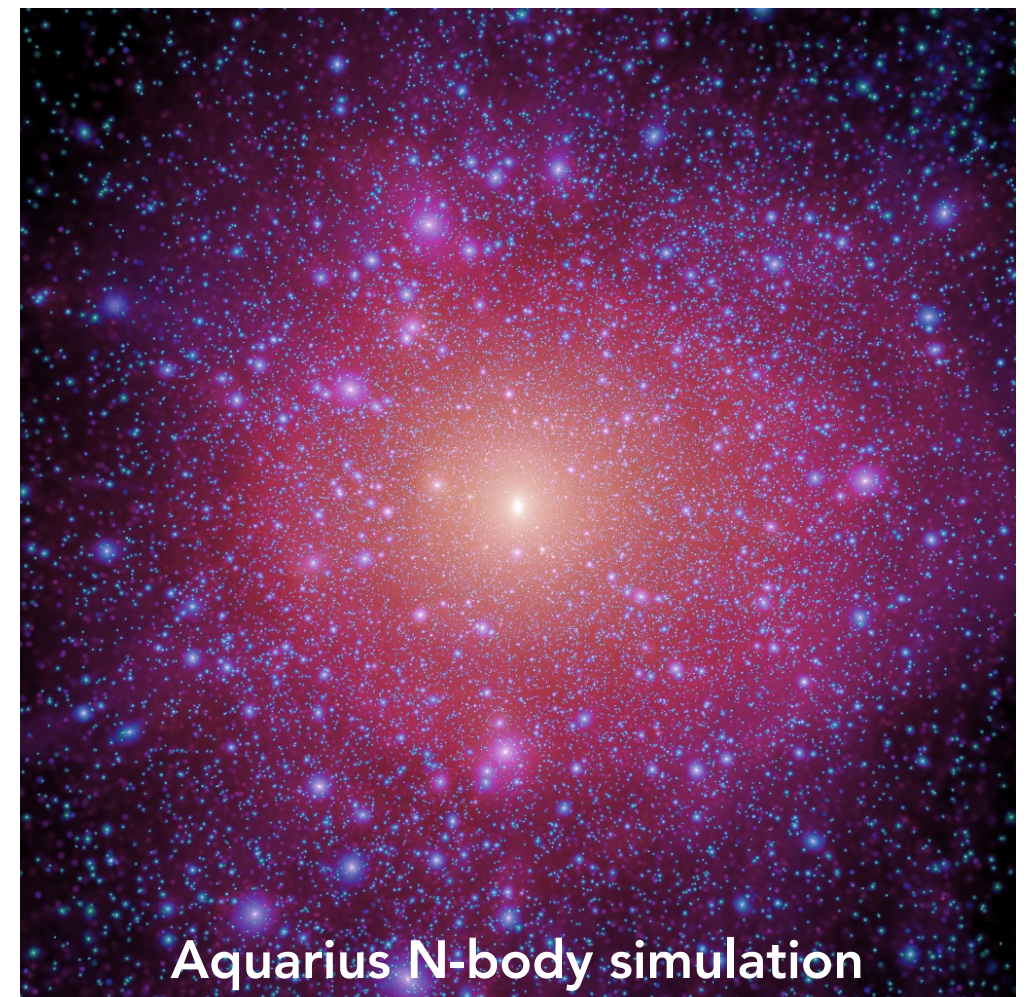
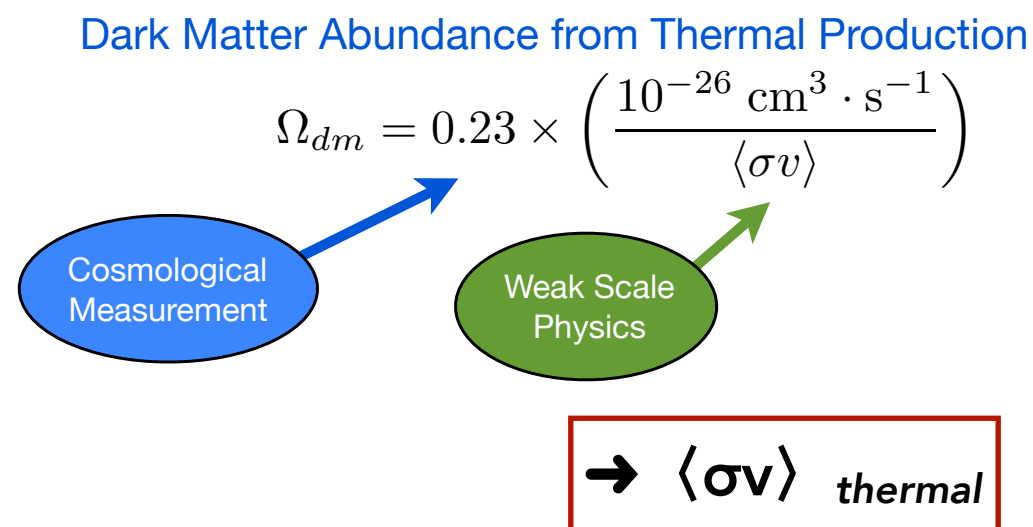
- Good complementarity between direct, collider and indirect search
- WIMPs, 'not even slightly dead' (Leane+, PRD (2018))
- TeV mass domain not yet explored (*weak charged DM*)
- Only indirect detection, probes (directly) thermal decoupling

# Serach in astro data



**In the Early Universe:** DM kept in equilibrium w SM by self-annihilations  $\langle \sigma v \rangle_{\text{thermal}}$ .

**Today,** DM expected to annihilate with the same  $\langle \sigma v \rangle_{\text{thermal}}$ , in places where its **density is enhanced!**



Aquarius N-body simulation

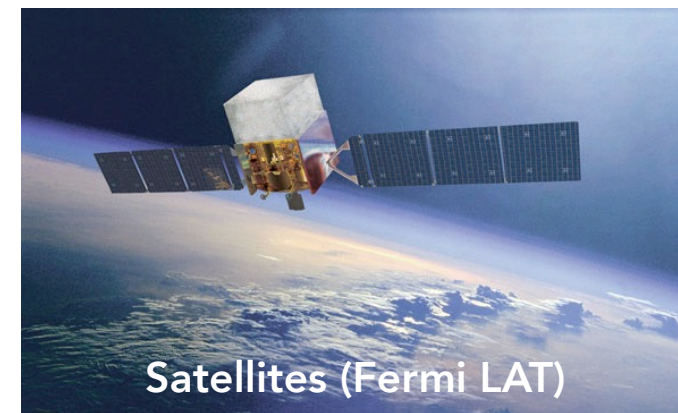


# Gamma rays?

Especially powerful astrophysical messenger:

- ▶ energy range  $> \sim \text{GeV}$
- ▶ Travel in straight lines (morphology)
- ▶ Easier to catch than neutrinos (higher statistics)

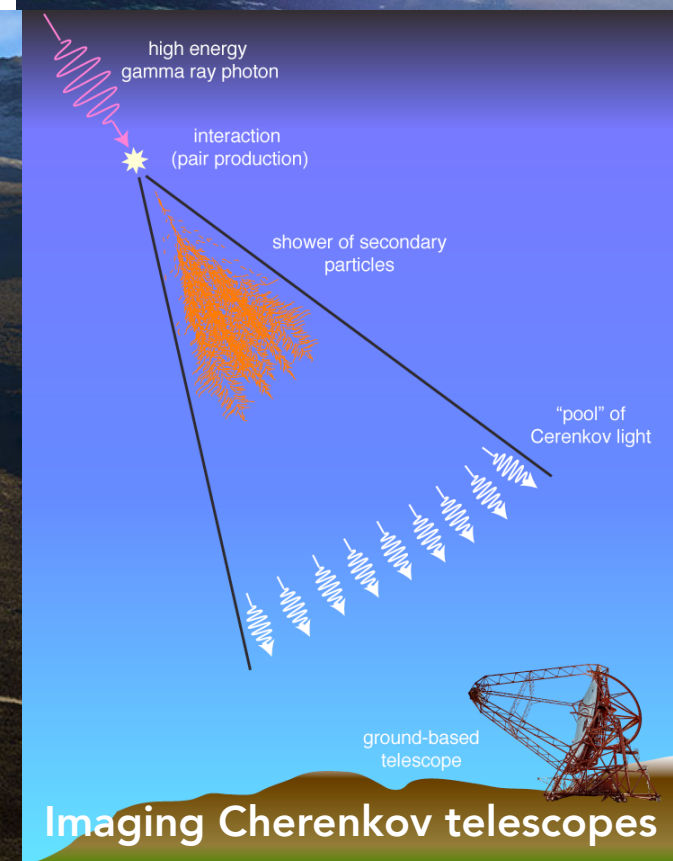
***But this is a lucky time (charged CR + neutrinos competitive too!)***



Satellites (Fermi LAT)

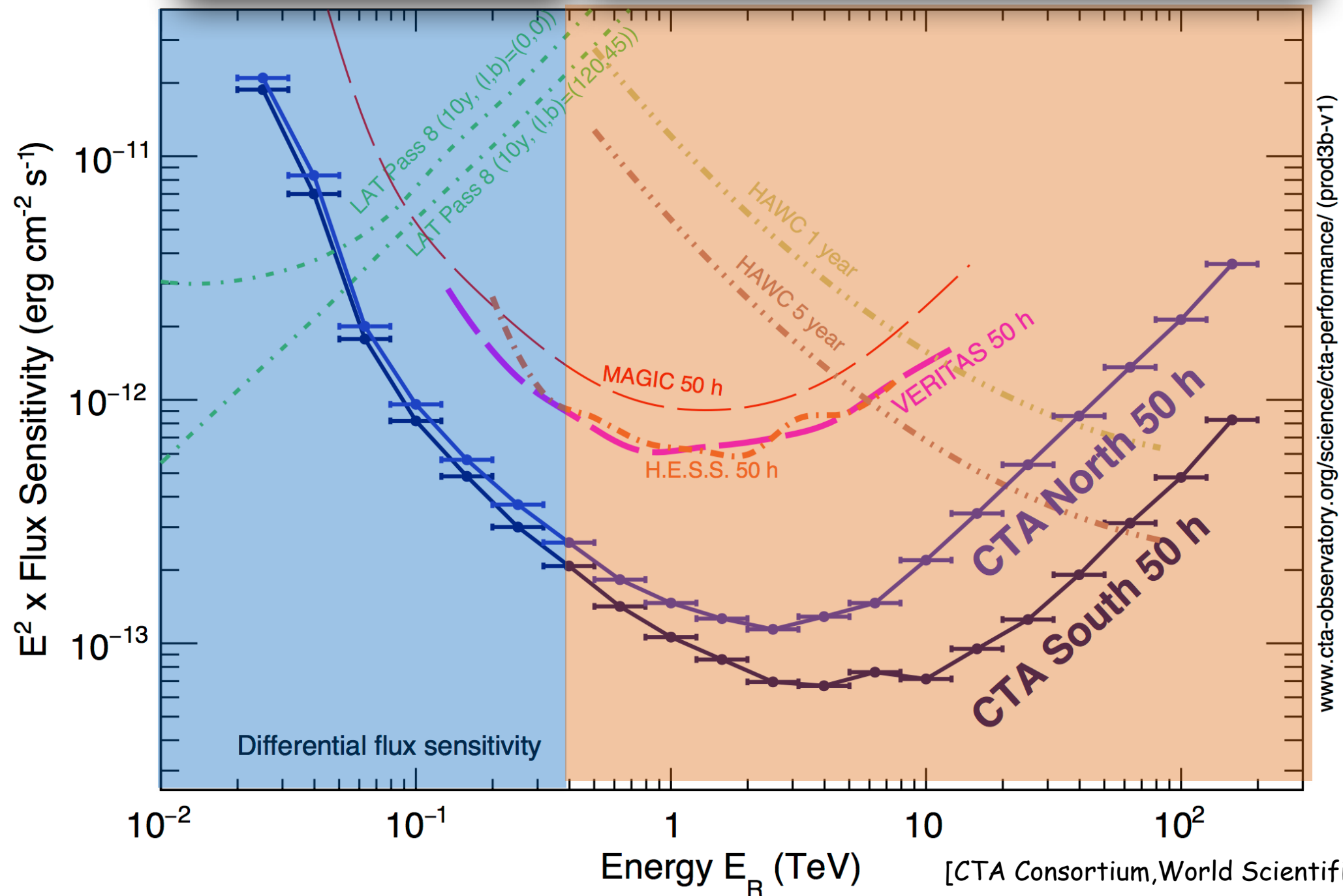


Water Cherenkov detectors (HAWC)



Imaging Cherenkov telescopes

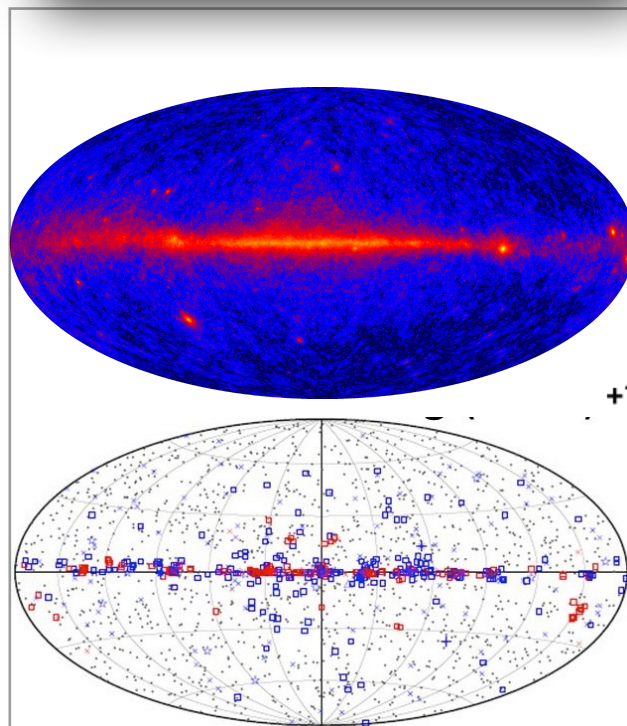
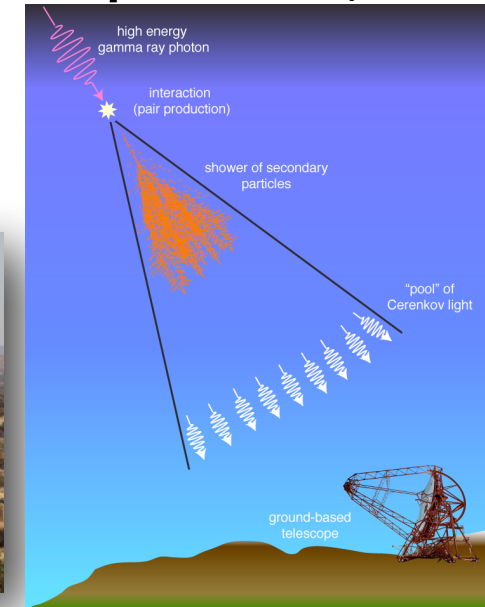
# Satellites vs IACTs





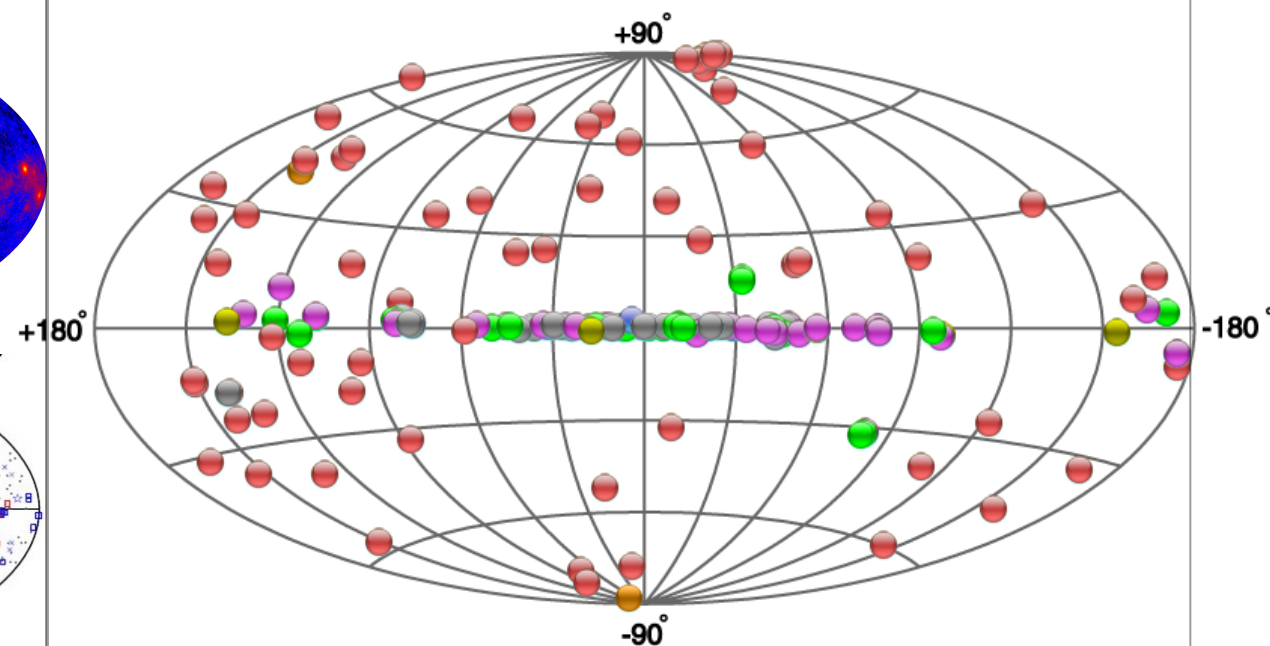
# Satellites vs IACTs

CRp flux  $\gg \gamma$  flux



## Satellites:

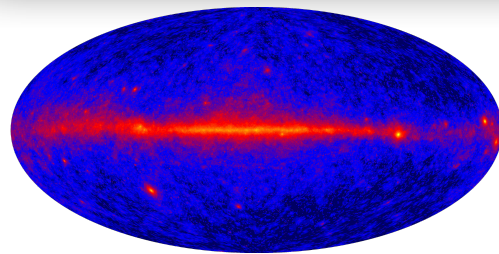
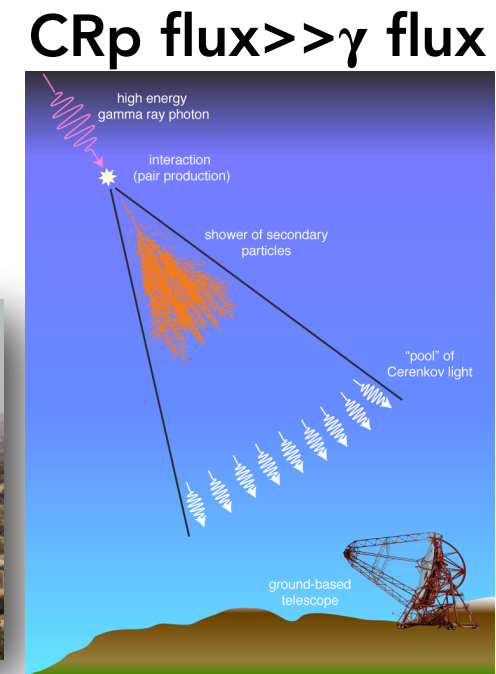
- Large FoV
- Limited CR bckgd



## IACTs are pointing telescopes:

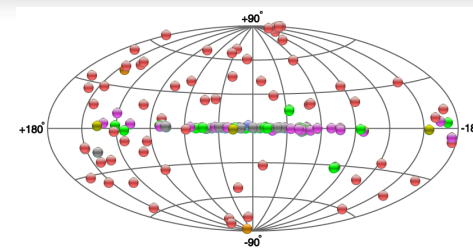
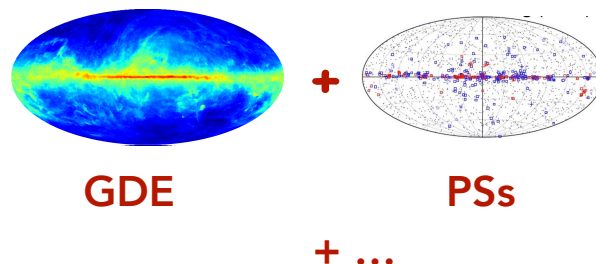
- Small FoV
- Significant CR contamination

# Satellites vs IACTs



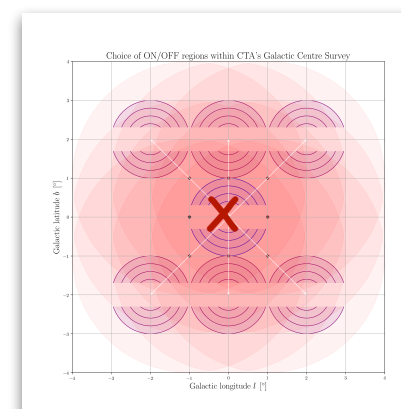
## 'Template' analysis:

- Likelihood fit of the templates of the emission models
- Only as good as the models — **systematic uncertainty** challenging to determine



## 'ON/OFF' analysis:

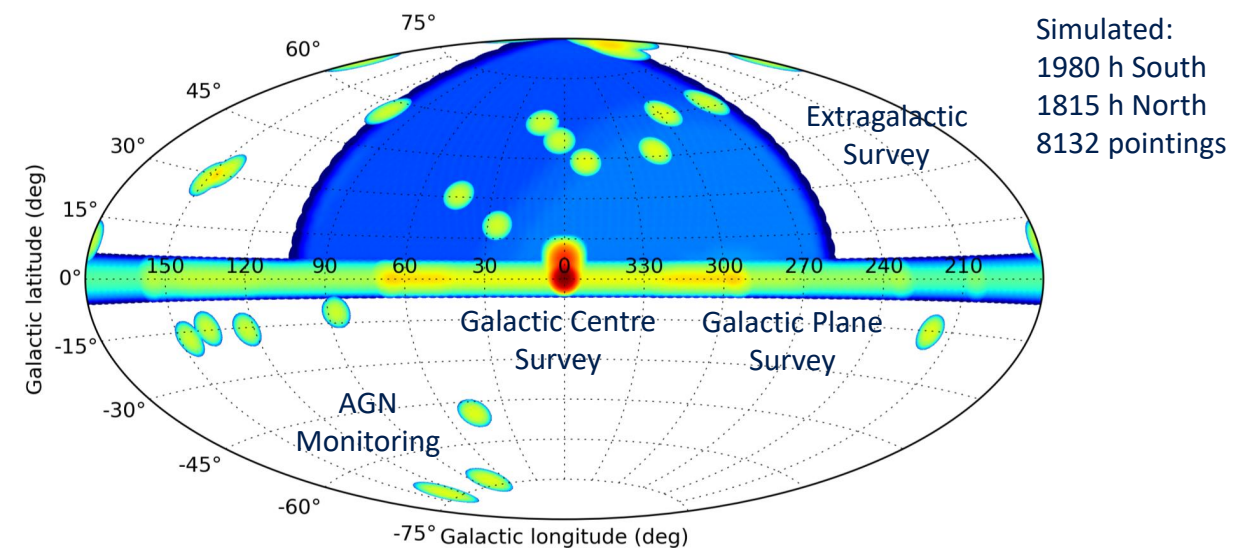
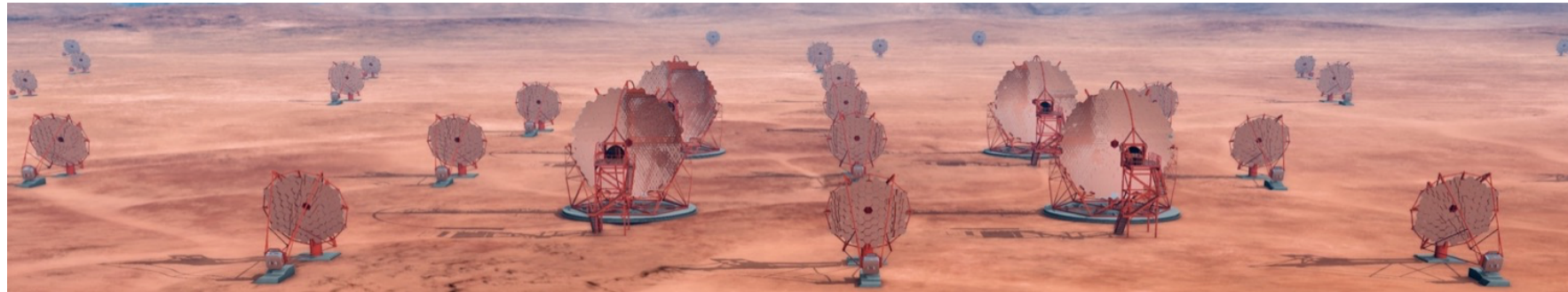
- 'measures' CR background in the OFF region
  - Assumes backgrounds 'flat'
- ➔ **Point sources!**



OFF  
ON



# Future: the CTA



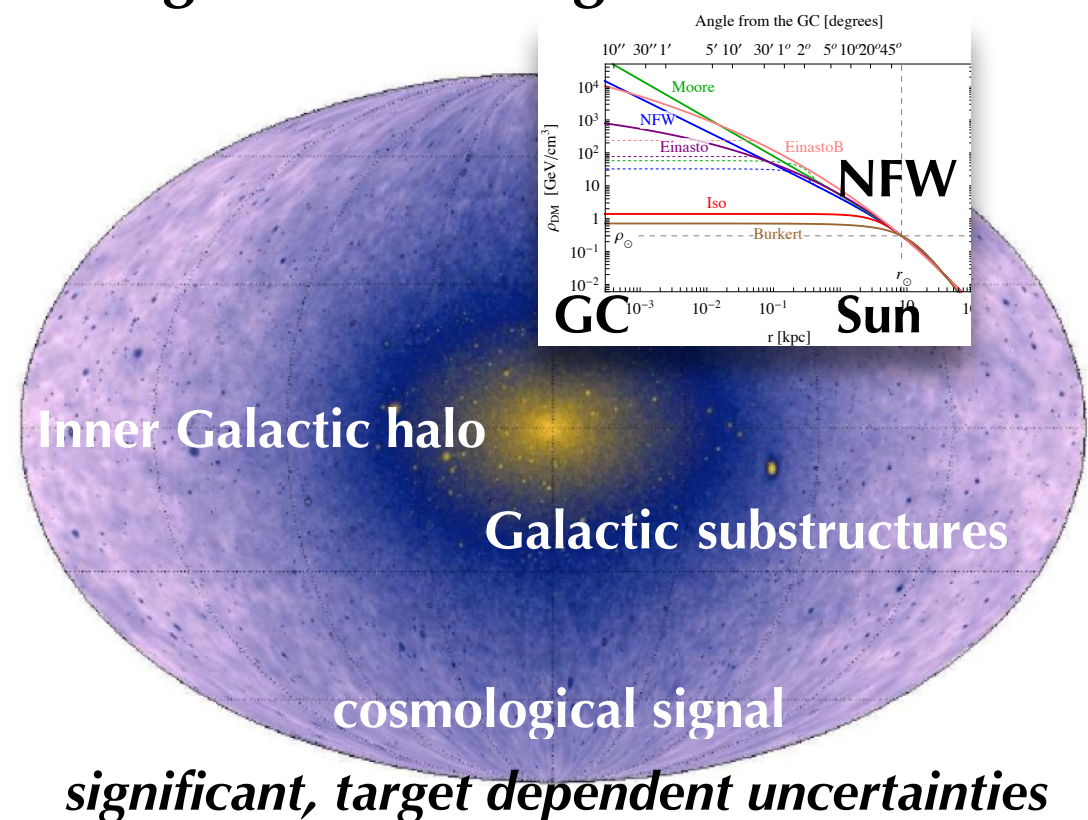
## Bridging the differences with satellite data:

- Unbiased view of the sky (Large survey-like observations)
- Energy threshold  $\sim 20$  GeV
- ➔ Cross-analysis techniques (template analysis motivated)

**Hiroshima's talk!**

**this is what  
we are after!**

**integrated DM density squared  
along the line of sight**





# Where to look?



dSph Galaxies



Galactic Centre



Dark sub halos



# Where to look?



dSph Galaxies



Galactic Centre

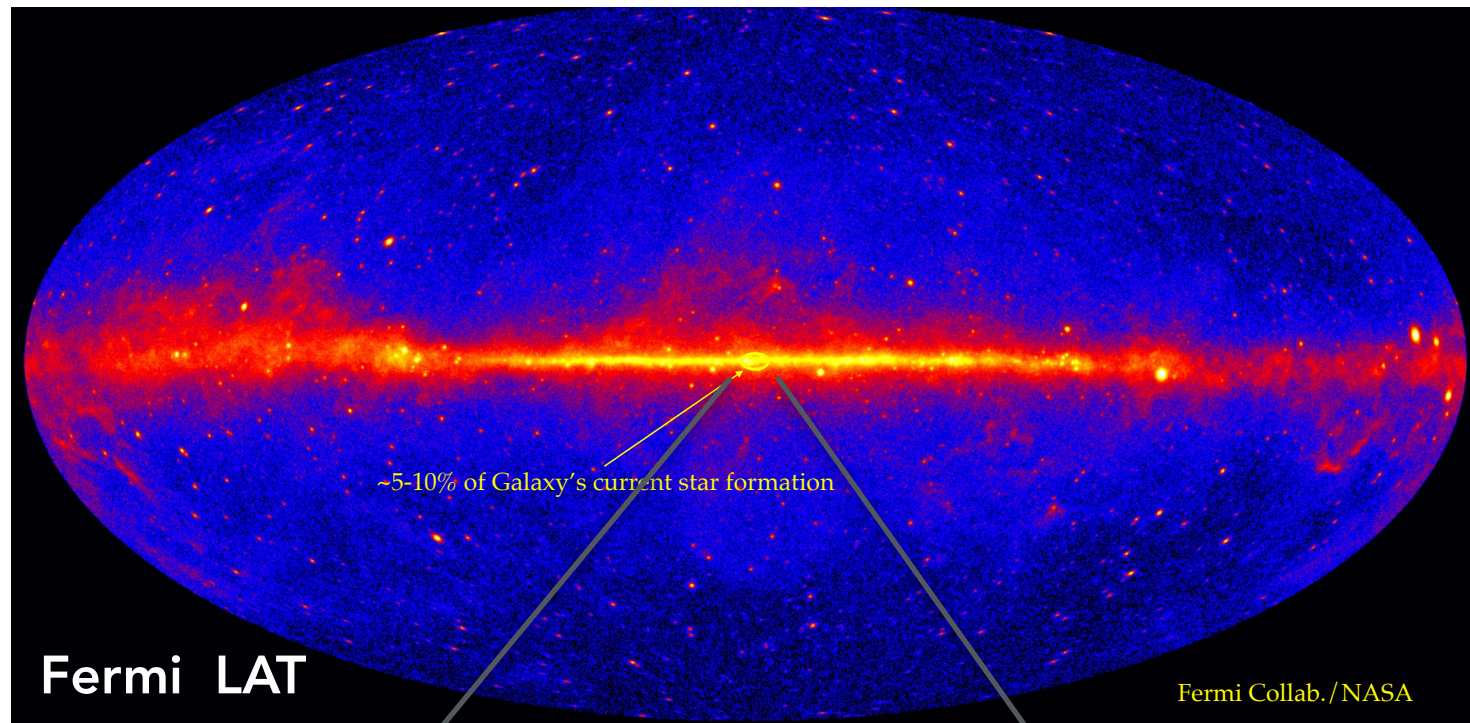


Dark sub halos

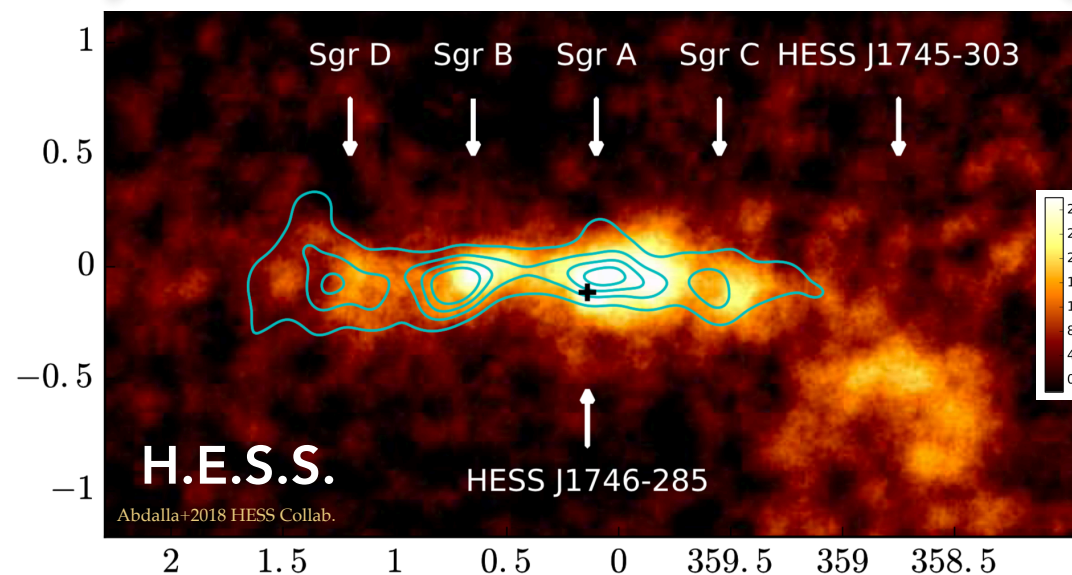
- THIS TALK - Galactic center:
  - Signal the brightest
  - But backgrounds too...
- dSphs, dark sub halos + extragalactic -> Moritz's talk!



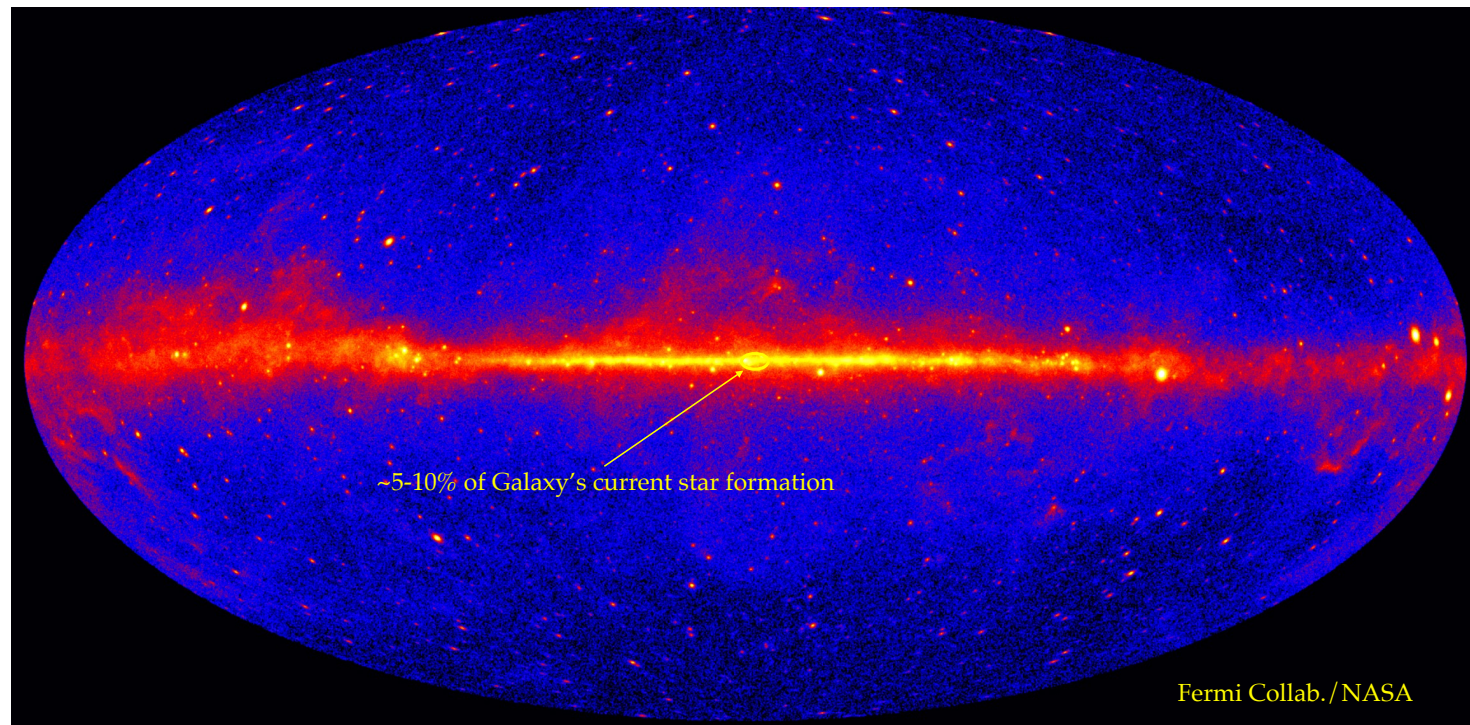
# GC in gamma rays?



- Galactic center gamma-ray emission:
  - Interstellar Emission (CRs + Galactic medium)
  - Point sources:
    - Individually resolved
    - Sub threshold
  - ...



# GC in gamma rays? - many open questions

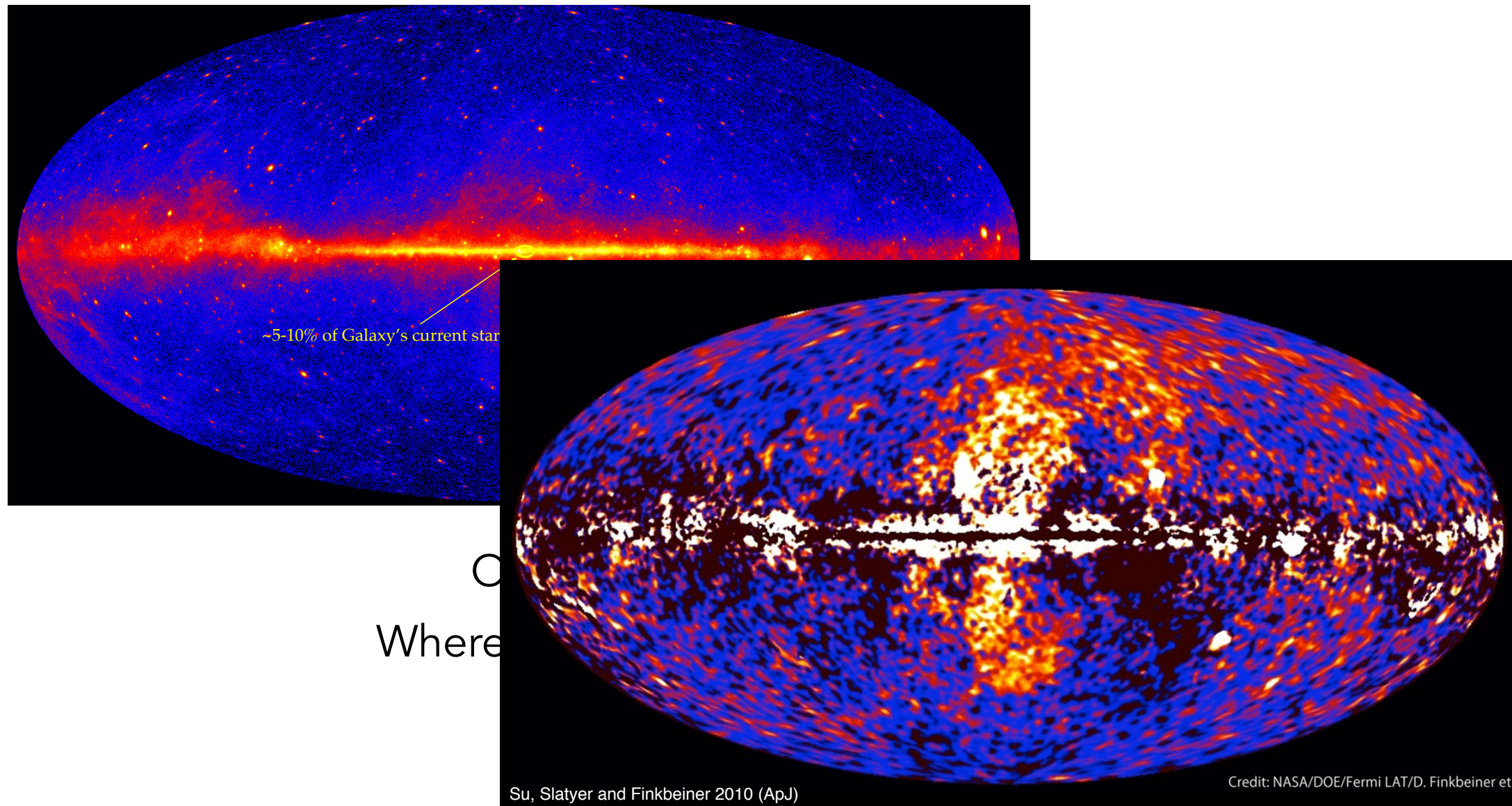


O (1)

Where is GC?



# GC in gamma rays? - many open questions

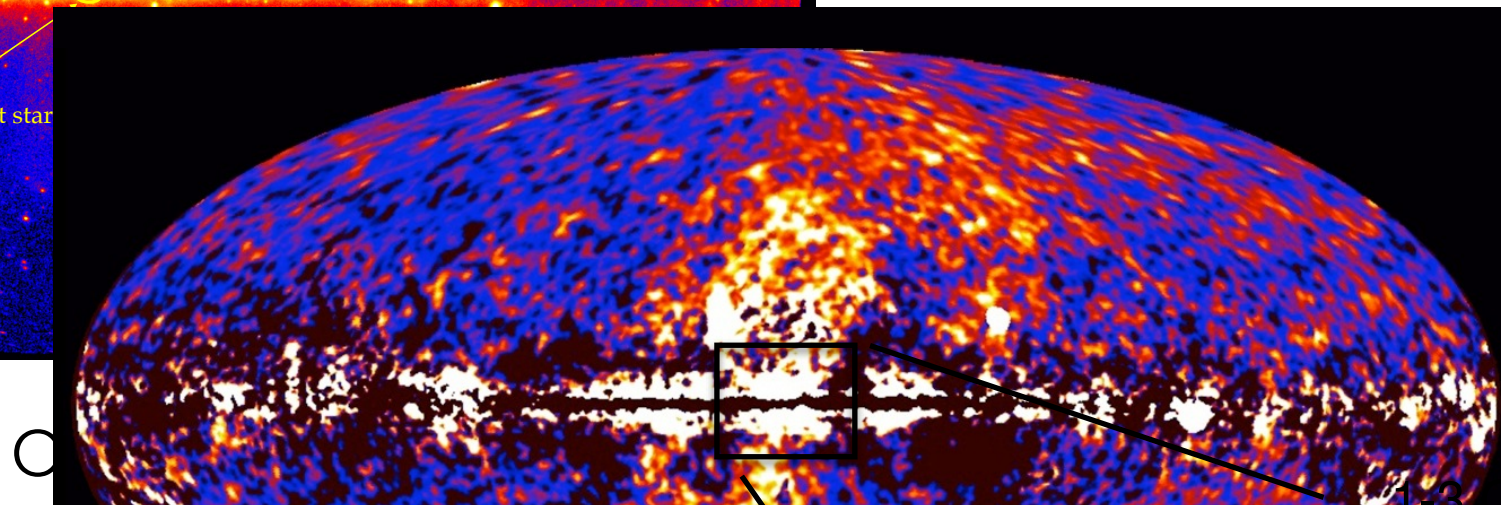
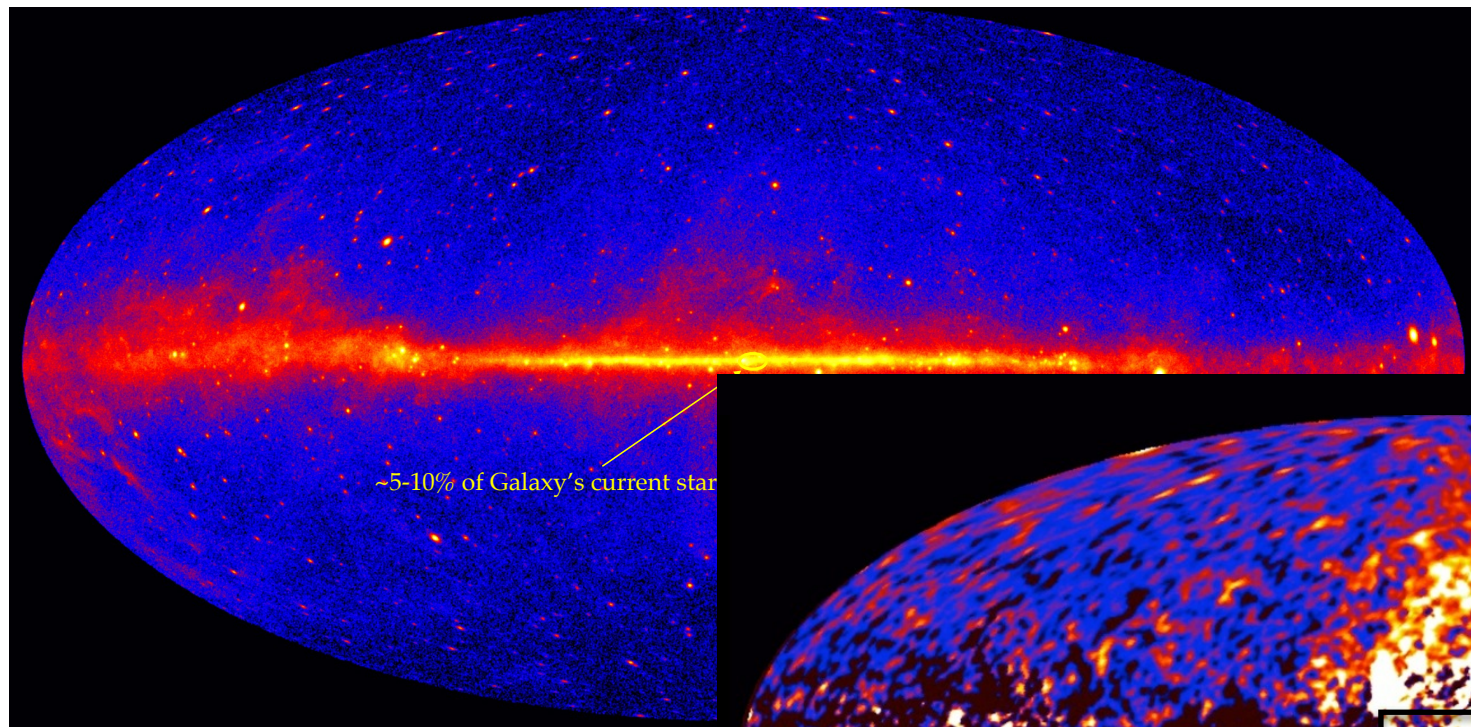


O (2)

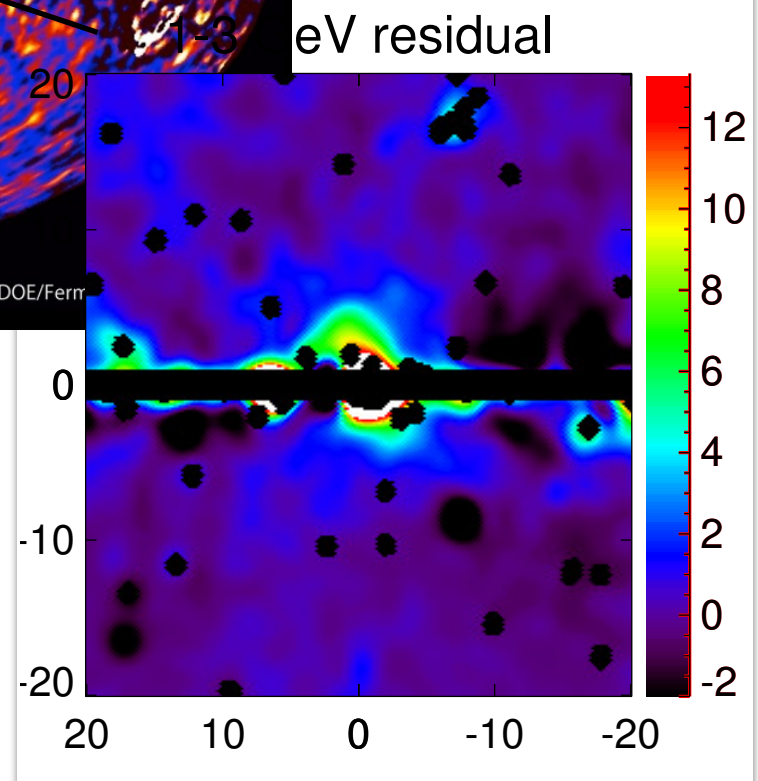
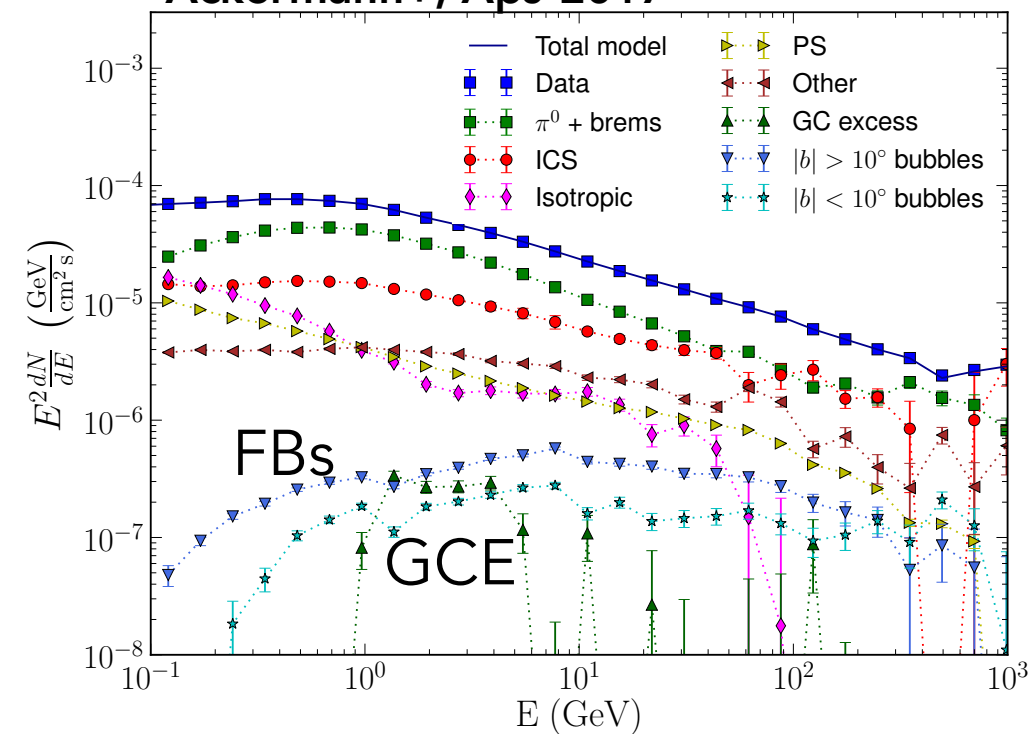
The Fermi bubbles!



# GC in gamma rays? - many open questions



Ackermann+, ApJ 2017



Credit: NASA/DOE/Fermi

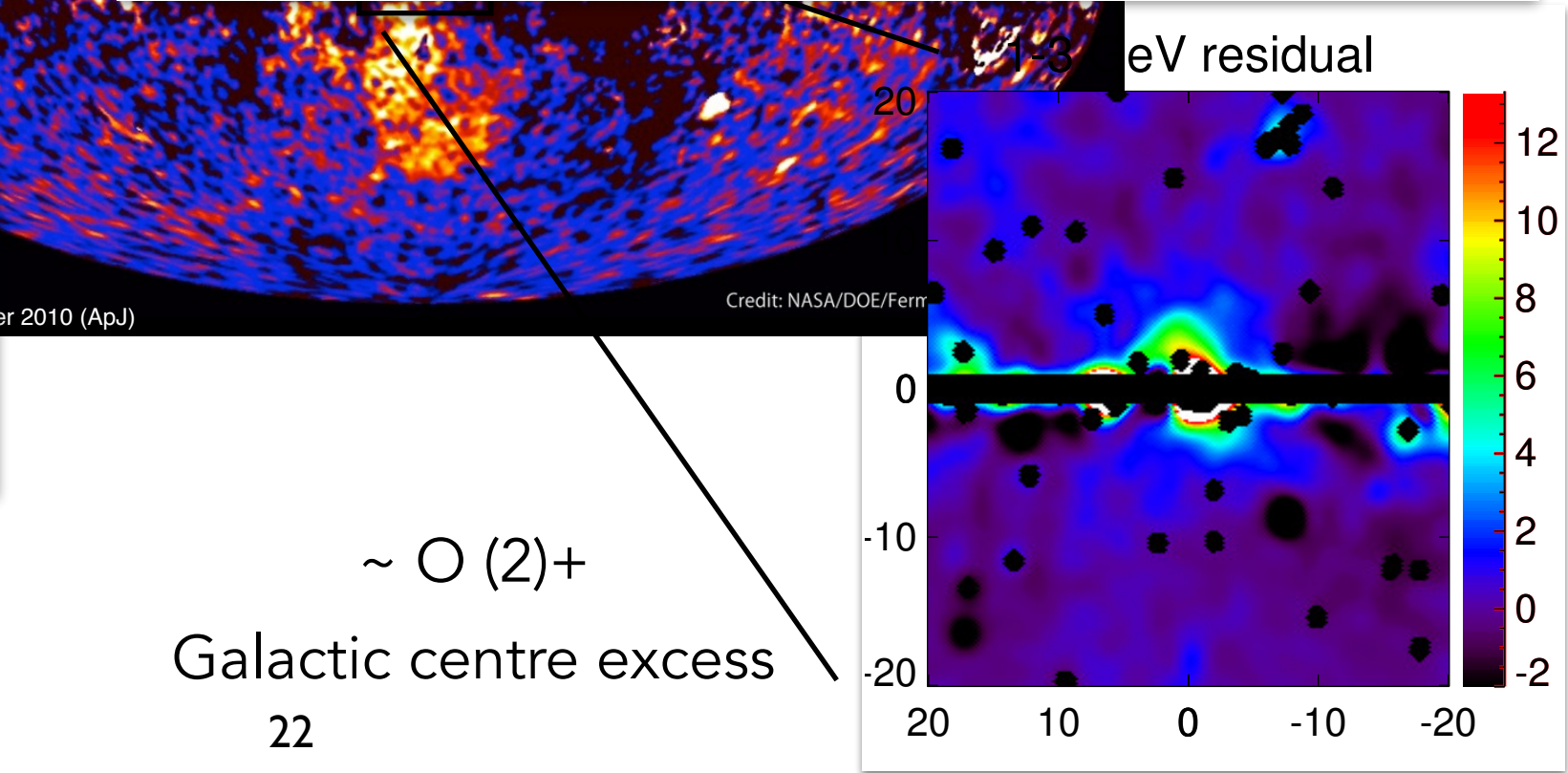
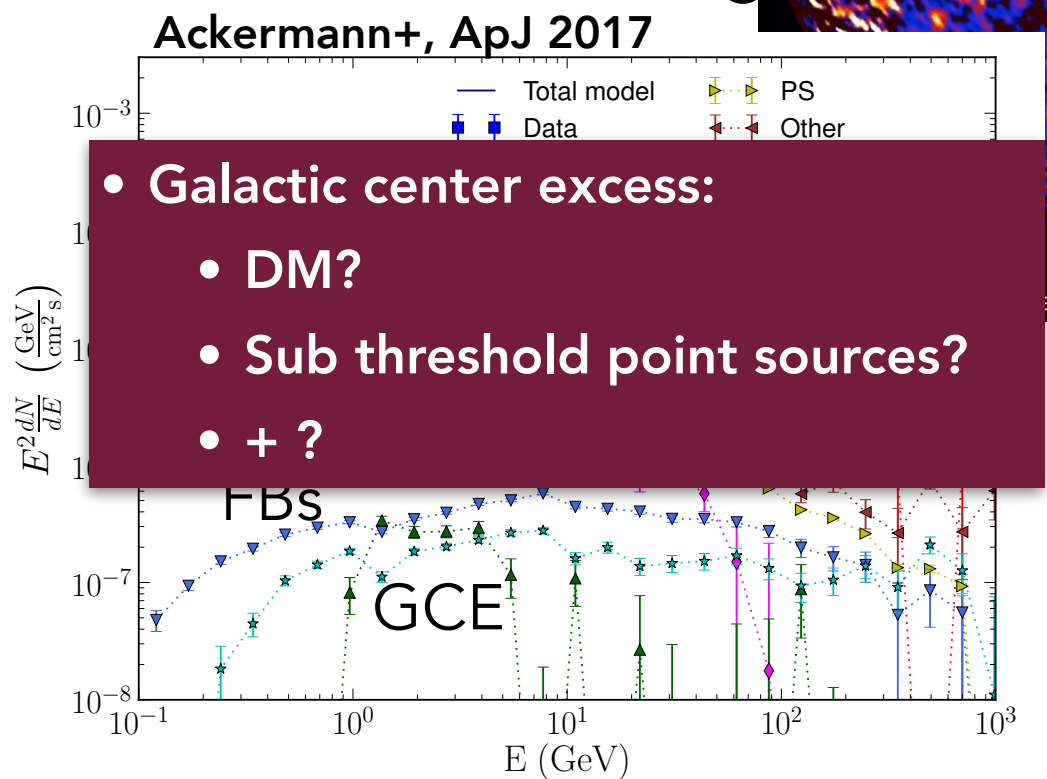
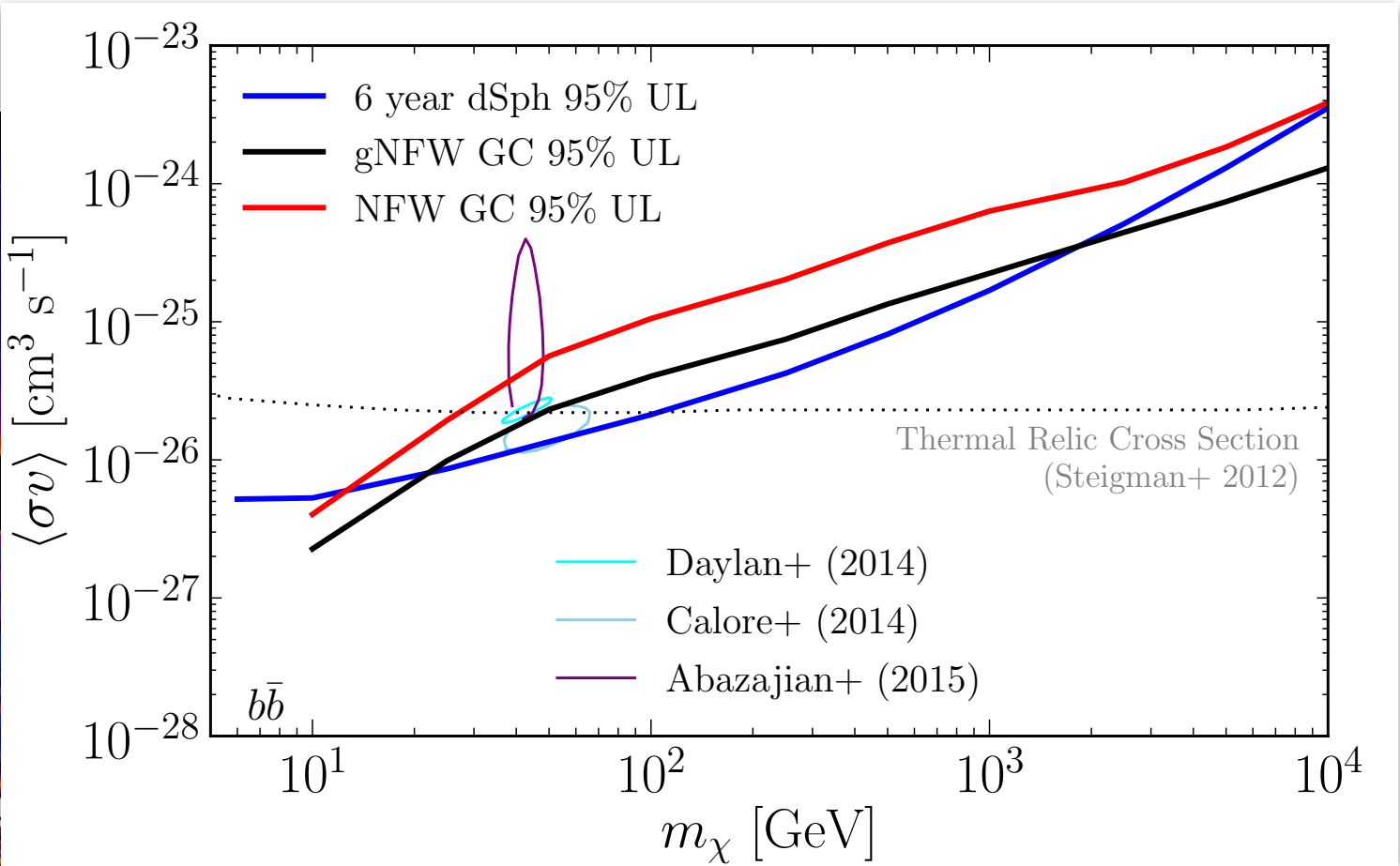
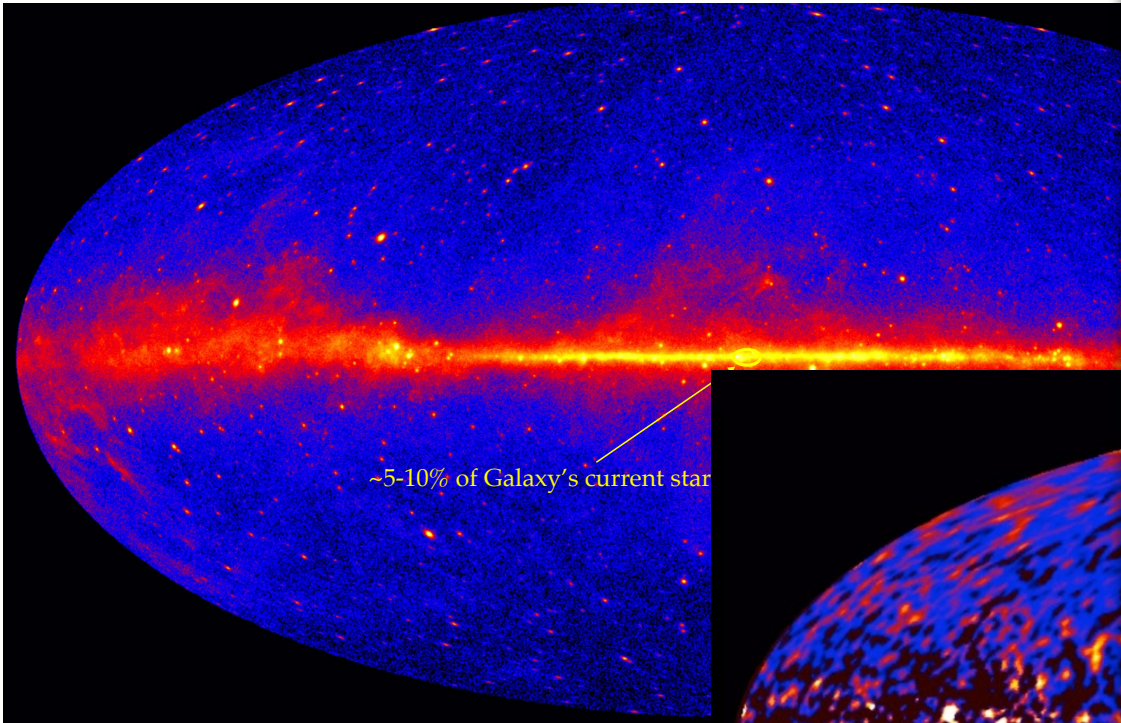
er 2010 (ApJ)

~ O (2)+  
Galactic centre excess

21



# GC in gamma rays? - many open questions





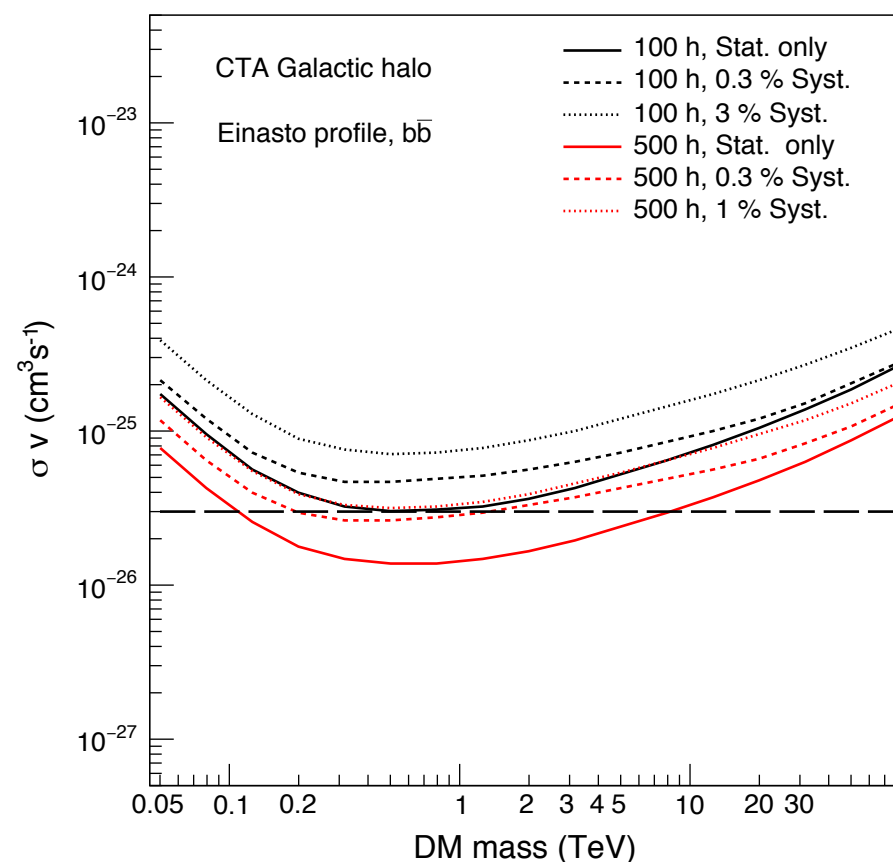
# Looking for DM at the GC with CTA

## Most of the older works:

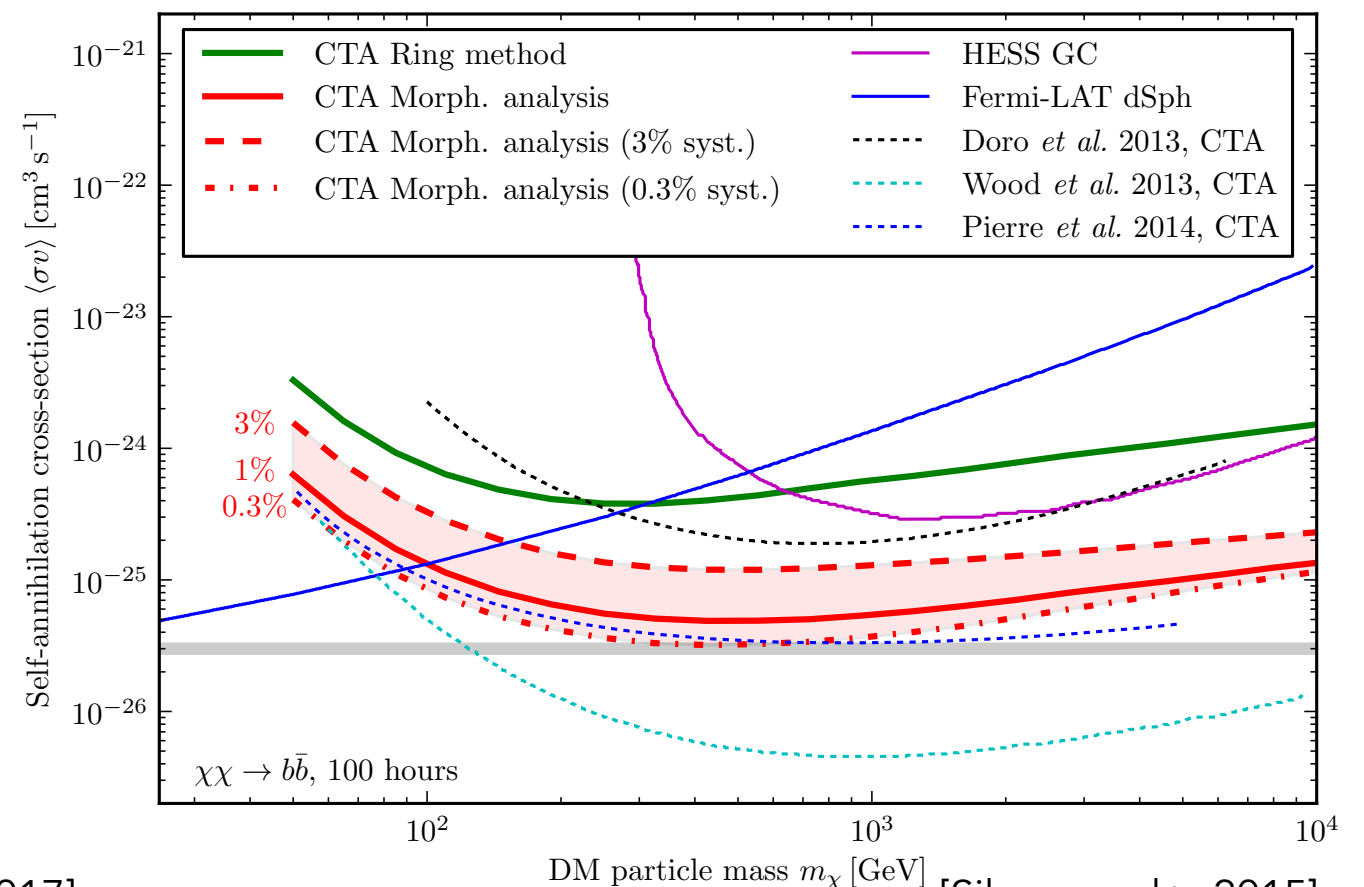
- use ON/OFF type analysis (assumes signal is 'point like' and backgrounds uniform), though indications that template analysis is promising
- do not assume any IE, only CR backgrounds
- When using IE models, outdated ones

## Lets take a closer look:

- What is the realistic DM sensitivity, given state-of-the-art models of IE, Instrumental Response Functions (IRFs) and CTA's observational strategy?



[Science with CTA, 2017]

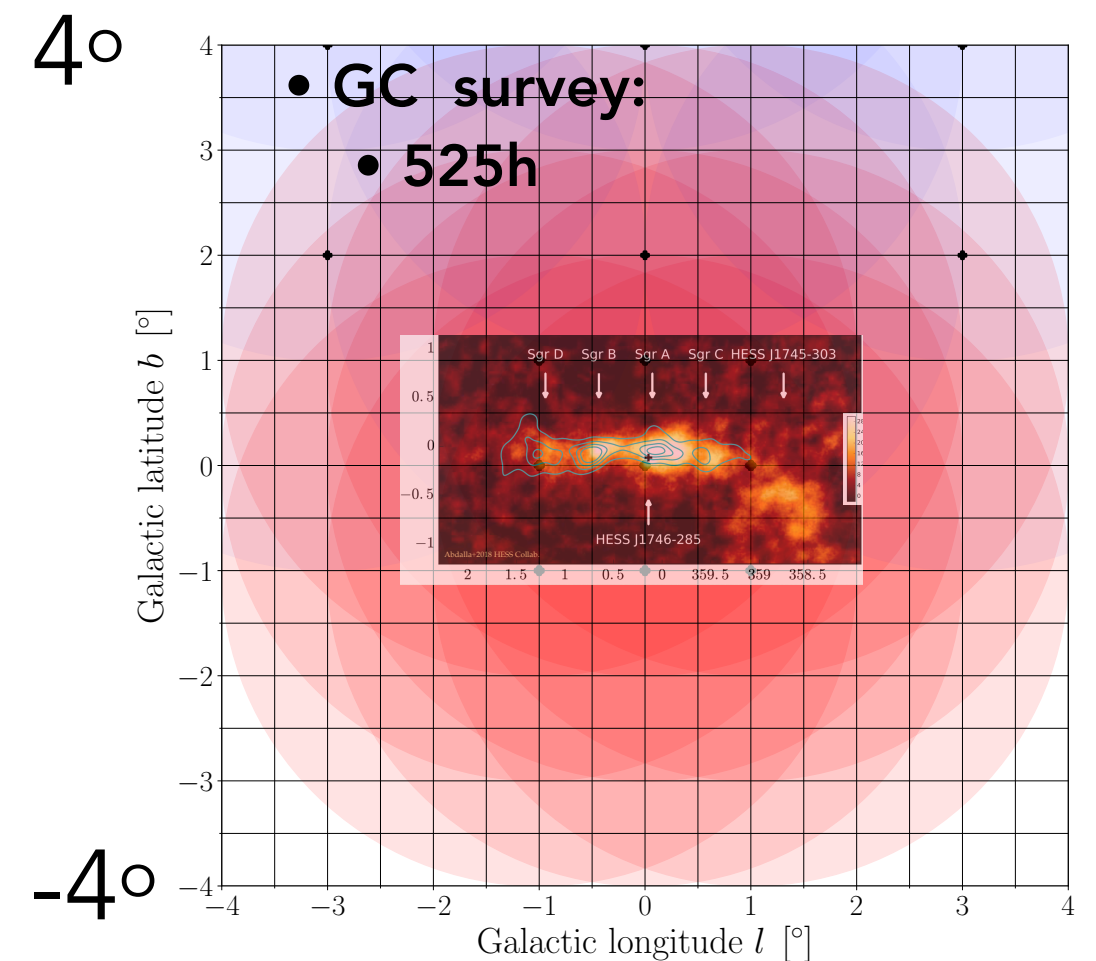
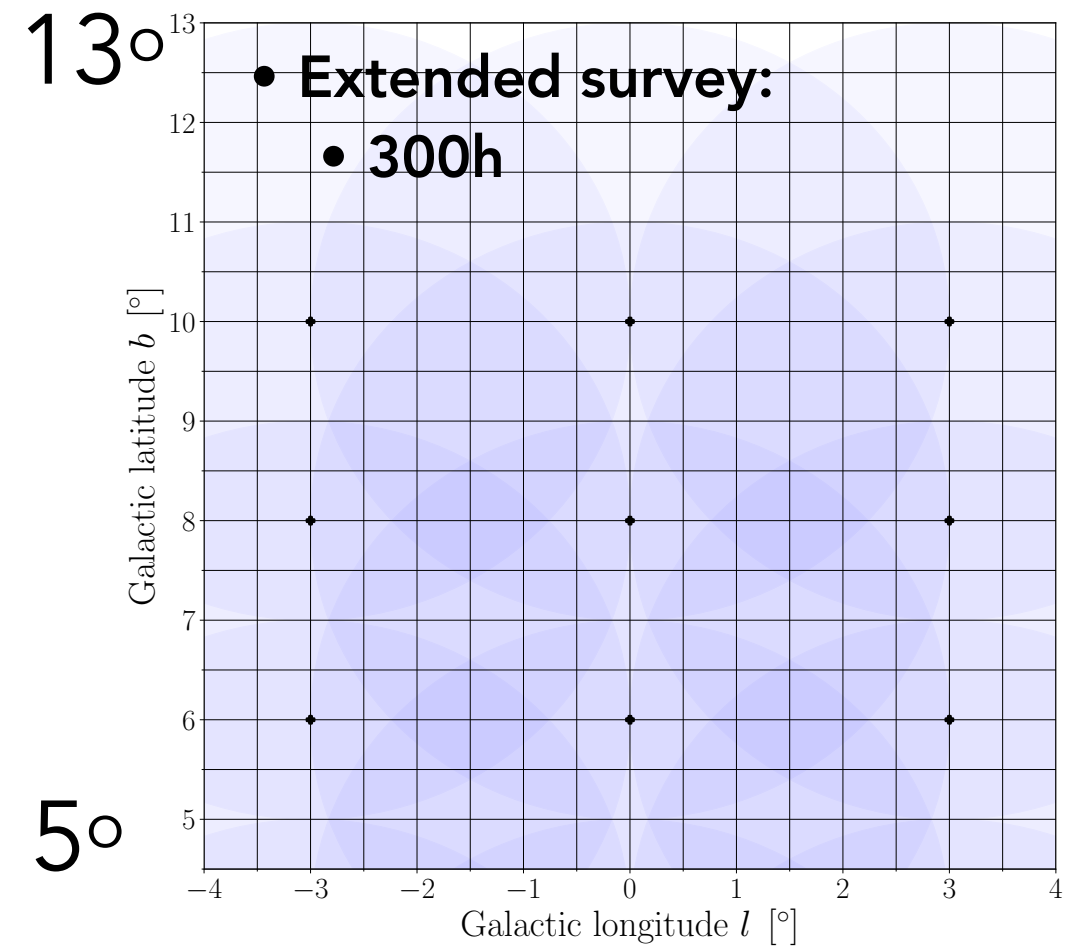


[Silverwood+, 2015]



# CTA @ GC

- Data: **galactic centre and extended surveys**
- Analysis - **template fitting**
  - **PRO**
    - One can distinguish among different emission components (traditionally only CR background, but with CTA more!)
  - **CONs**
    - Works only if emission models reliable
    - Is CR background really isotropic?
    - Do we really know the shape of IE?





# CTA @ GC

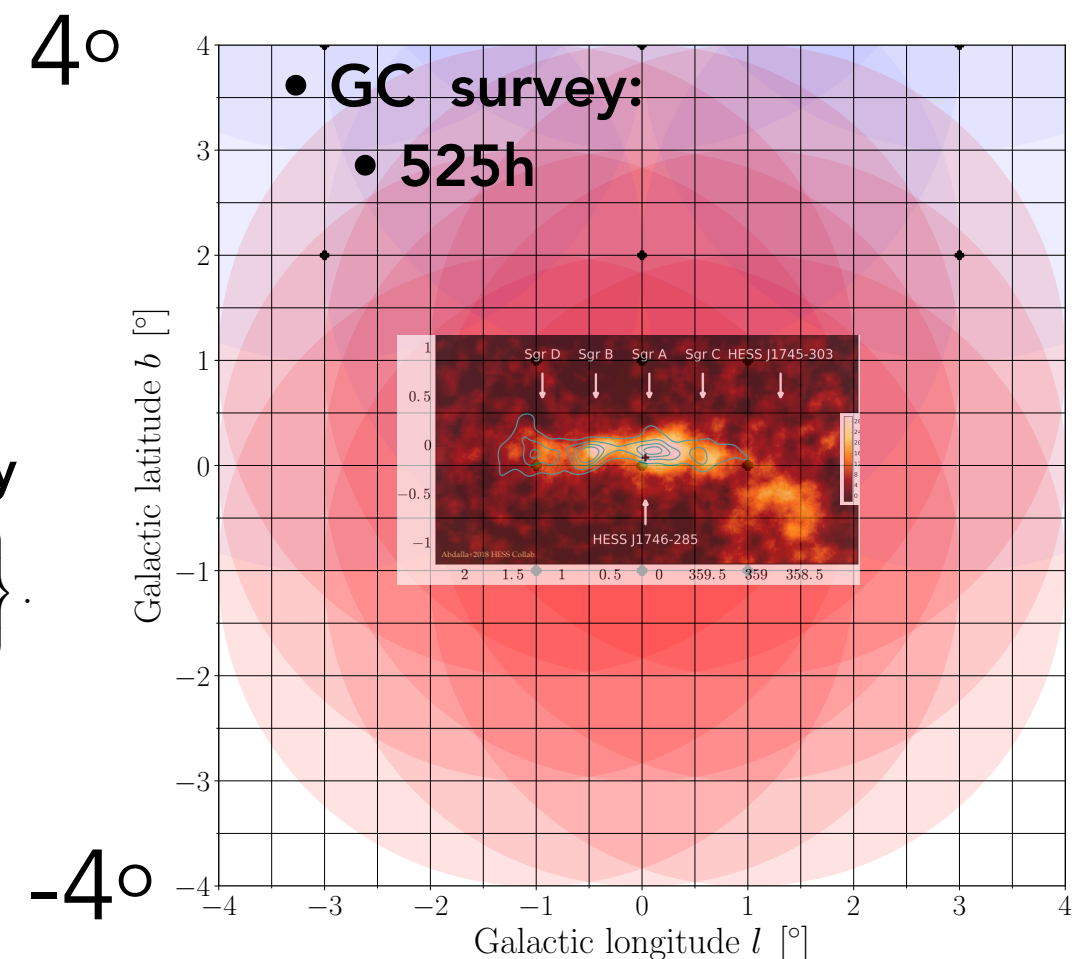
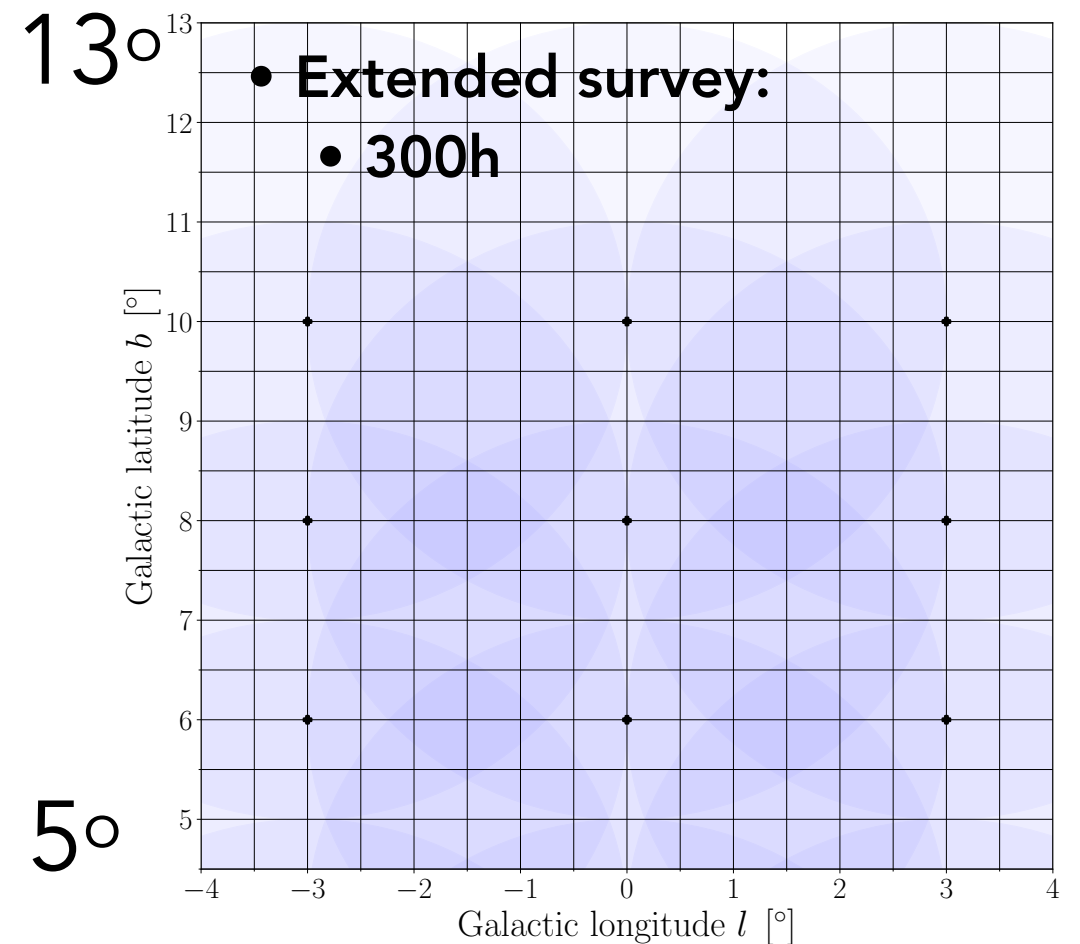
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$$-2 \ln \mathcal{L}(\boldsymbol{\mu}_K | \boldsymbol{n}) = \min_{\Delta B} \left\{ \sum_{k=1}^{\mathcal{N}} \left[ n_k \ln (\mu_K)_k - (\mu_K)_k \right] - \frac{1}{2} \sum_{k,l=1}^{\mathcal{N}} \left[ \Delta B_k (K^{-1})_{kl} \Delta B_l \right] \right\}.$$

Standard Poisson Likelihood

Systematic uncertainty

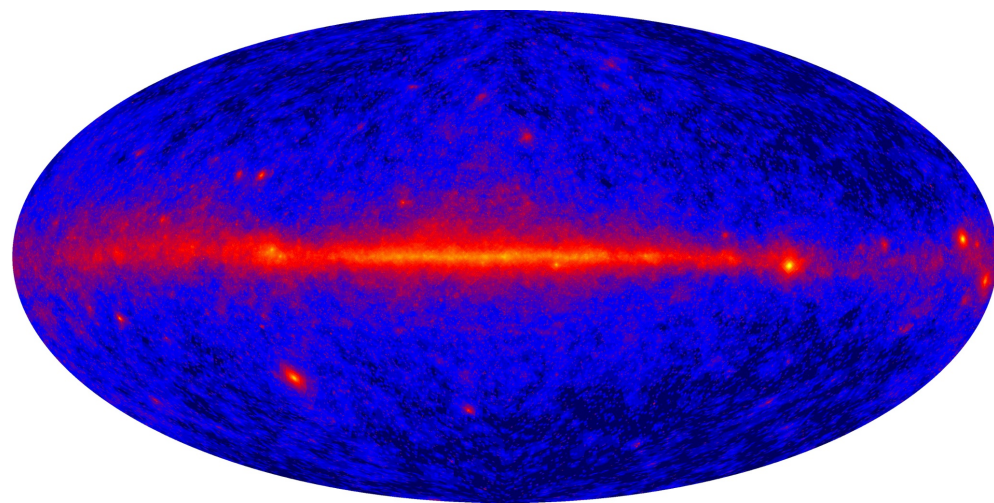
[Swordfish (Edwards&Weniger, 2017)]



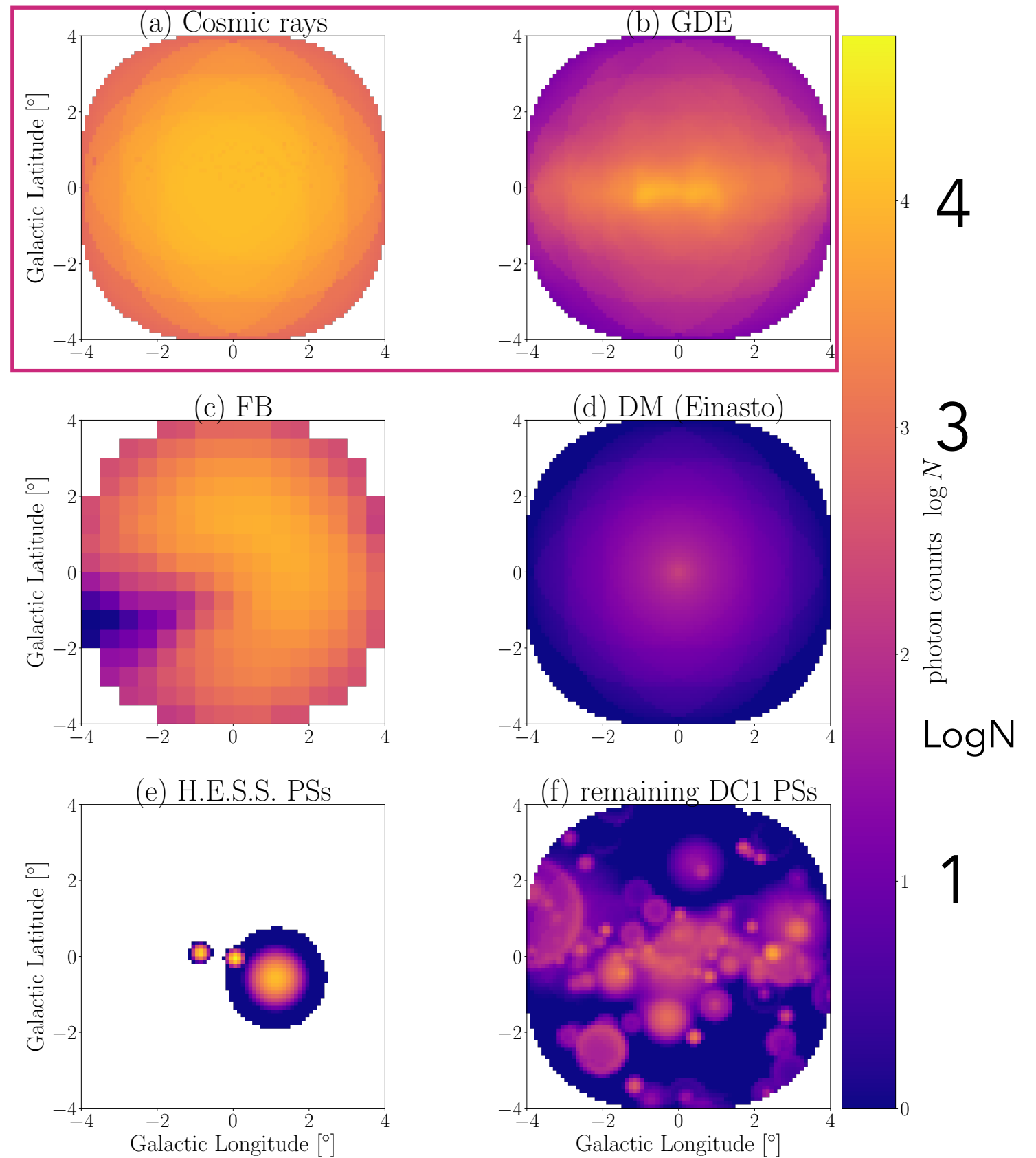


# Emission at the GC

- Focus on the GC survey:
  - **CR backgrounds**
  - Interstellar Emission (**IE**)
    - Fermi LAT inspired models



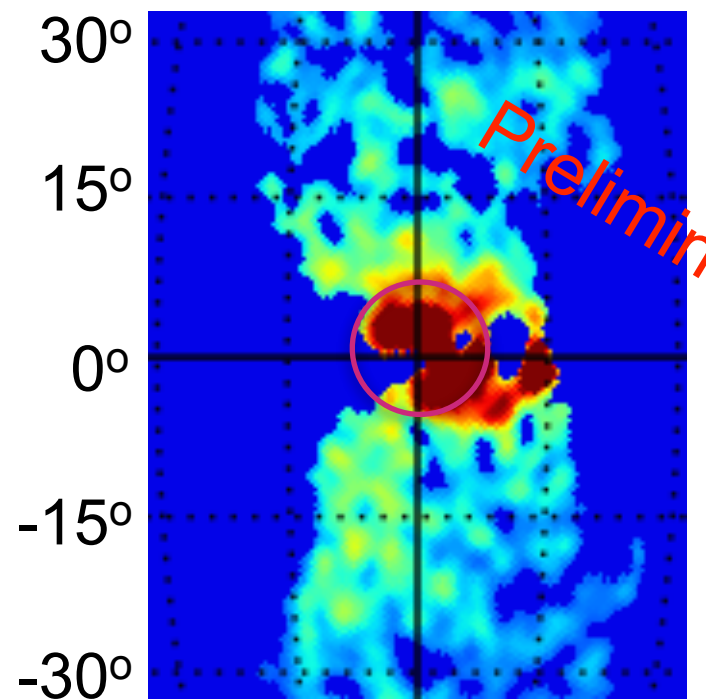
[Fermi LAT sky]



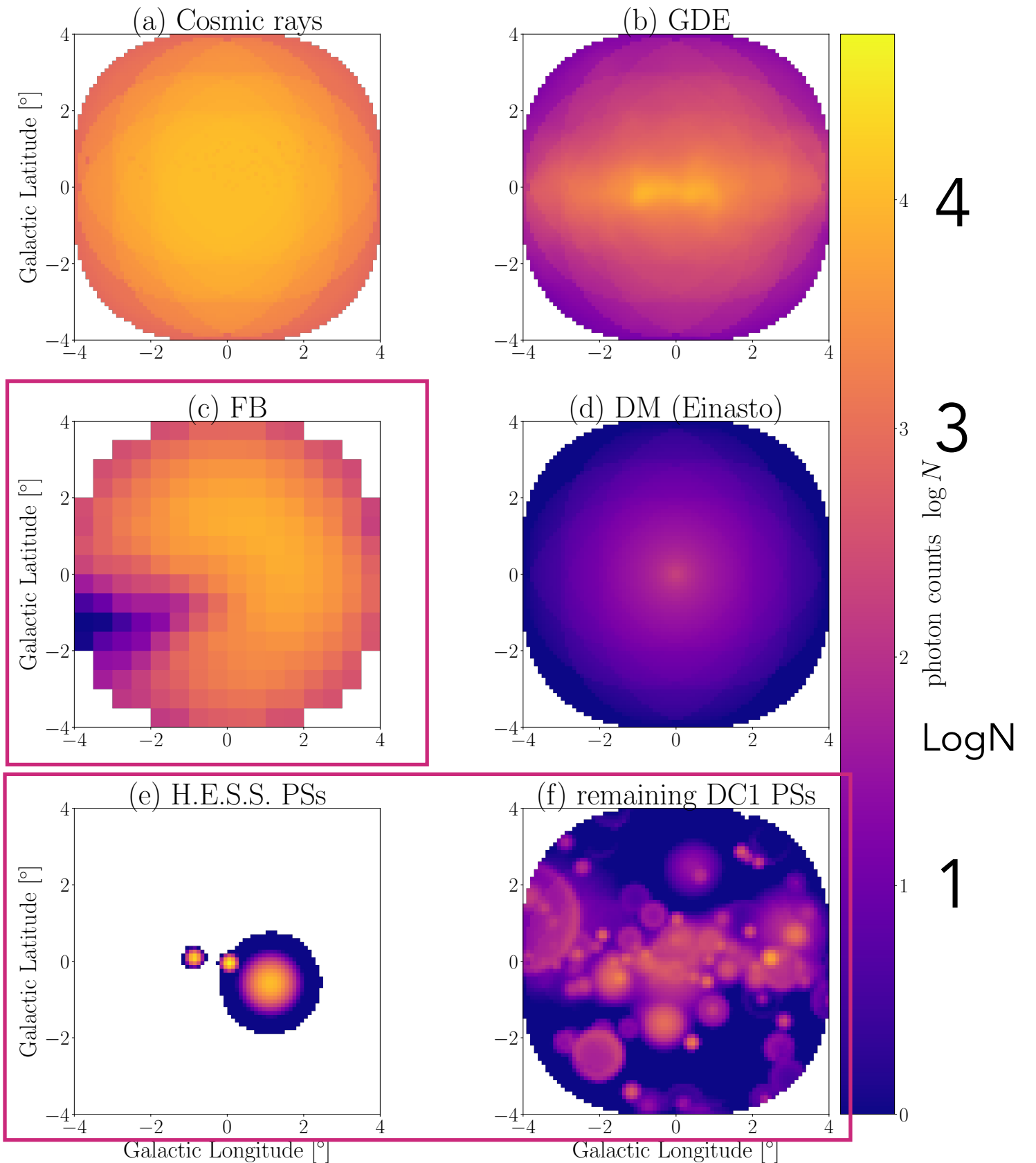


# Emission at the GC

- Focus on the GC survey:
  - **CR backgrounds**
  - Interstellar Emission (**IE**)
    - Fermi LAT inspired models
  - **Fermi Bubbles** (FB),  
studies the base, based on the LAT
  - **Point Sources** (PSs)  
detected by H.E.S.S. and  
sub-threshold ones



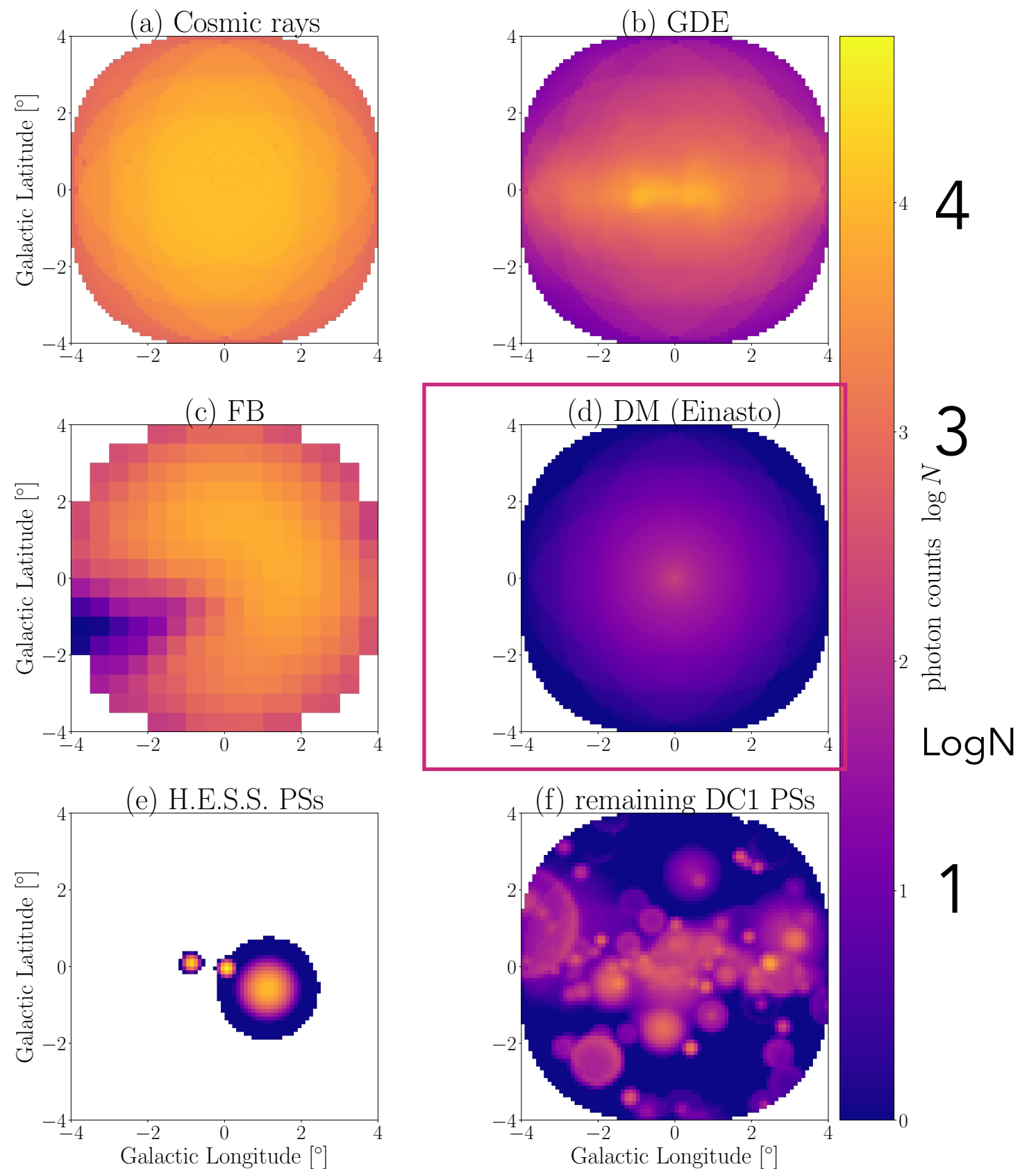
[FB LAT template, Herold & Malyshev, 2019]





# Emission at the GC

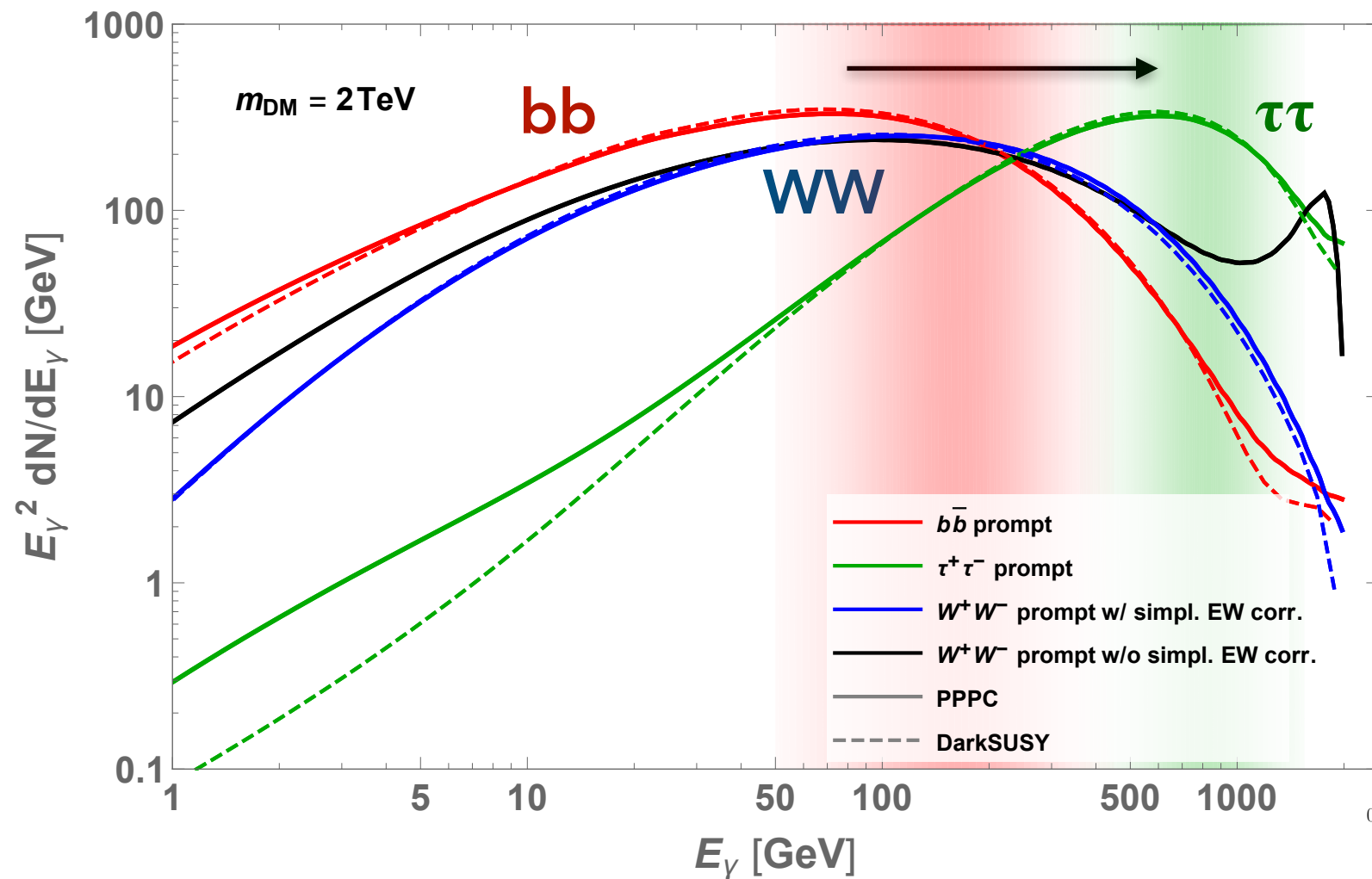
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sub-threshold ones
  - **+ DM**



# DM signal

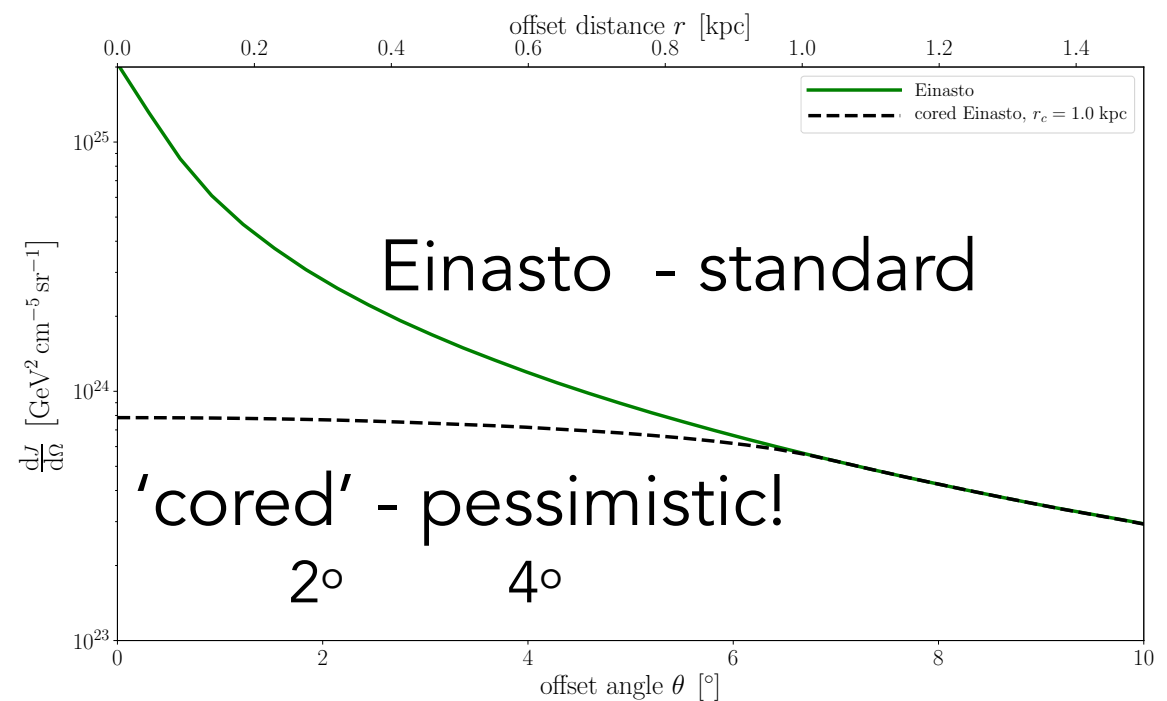
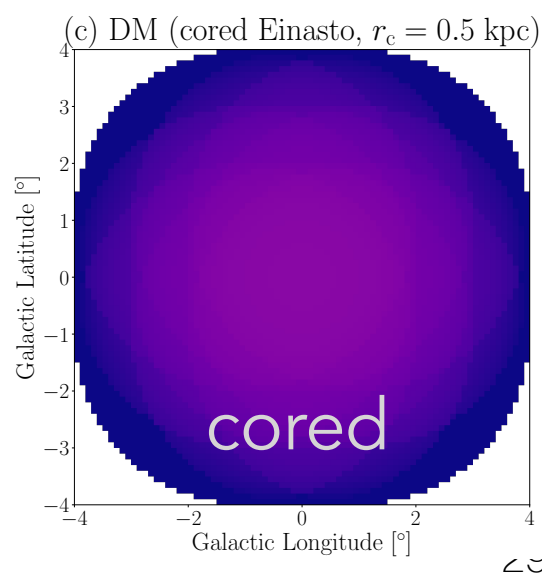
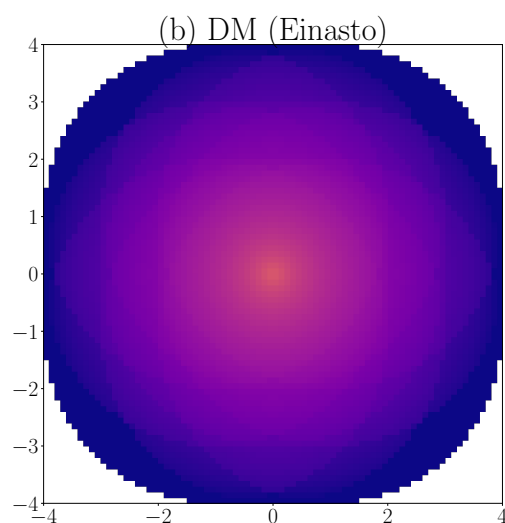
locco & Salucci's talks!

## Spectrum: Different DM annihilation channels



- Harder spectrum, increased CTA sensitivity
- Note: 'standard/vanilla' DM models, no perturbative signals
- Models consistent with the 'DM conventions' document

## Morphology: DM density profile





# Generic setup

- **Template fitting (3D analysis)**

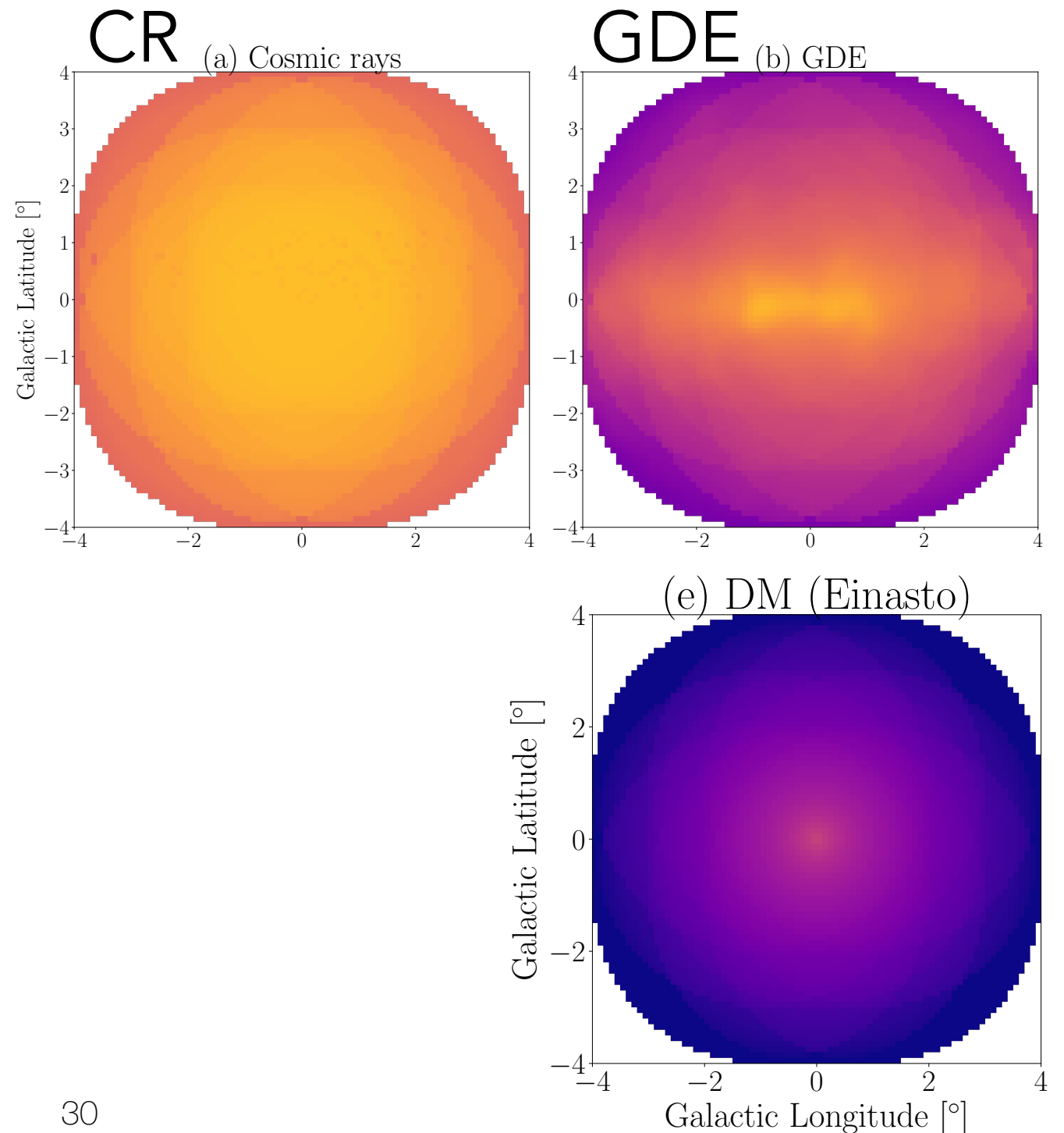
$$(\mu_K)_k = \mu_k^{\text{CR}} + \mu_k^{\text{GDE}} + \Delta B_k + A^{\text{DM}} \mu_k^{\text{DM}}.$$

## Data:

- an Asimov data set
- **CR + IE** templates (FB and PS added in some cases)
- **Binning 0.1 deg**
- **No mask**

## Models:

- CR+IE (+DM)



$$K_S = \sum_{k,l=1}^{\mathcal{N}_S} \sigma_S^2 \exp \left( -\frac{1}{2} \frac{\|\vec{r}_k - \vec{r}_l\|^2}{\ell_S^2} \right),$$

# Generic setup

## • Template fitting (3D analysis)

$$(\mu_K)_k = \mu_k^{\text{CR}} + \mu_k^{\text{GDE}} + \Delta B_k + A^{\text{DM}} \mu_k^{\text{DM}}.$$

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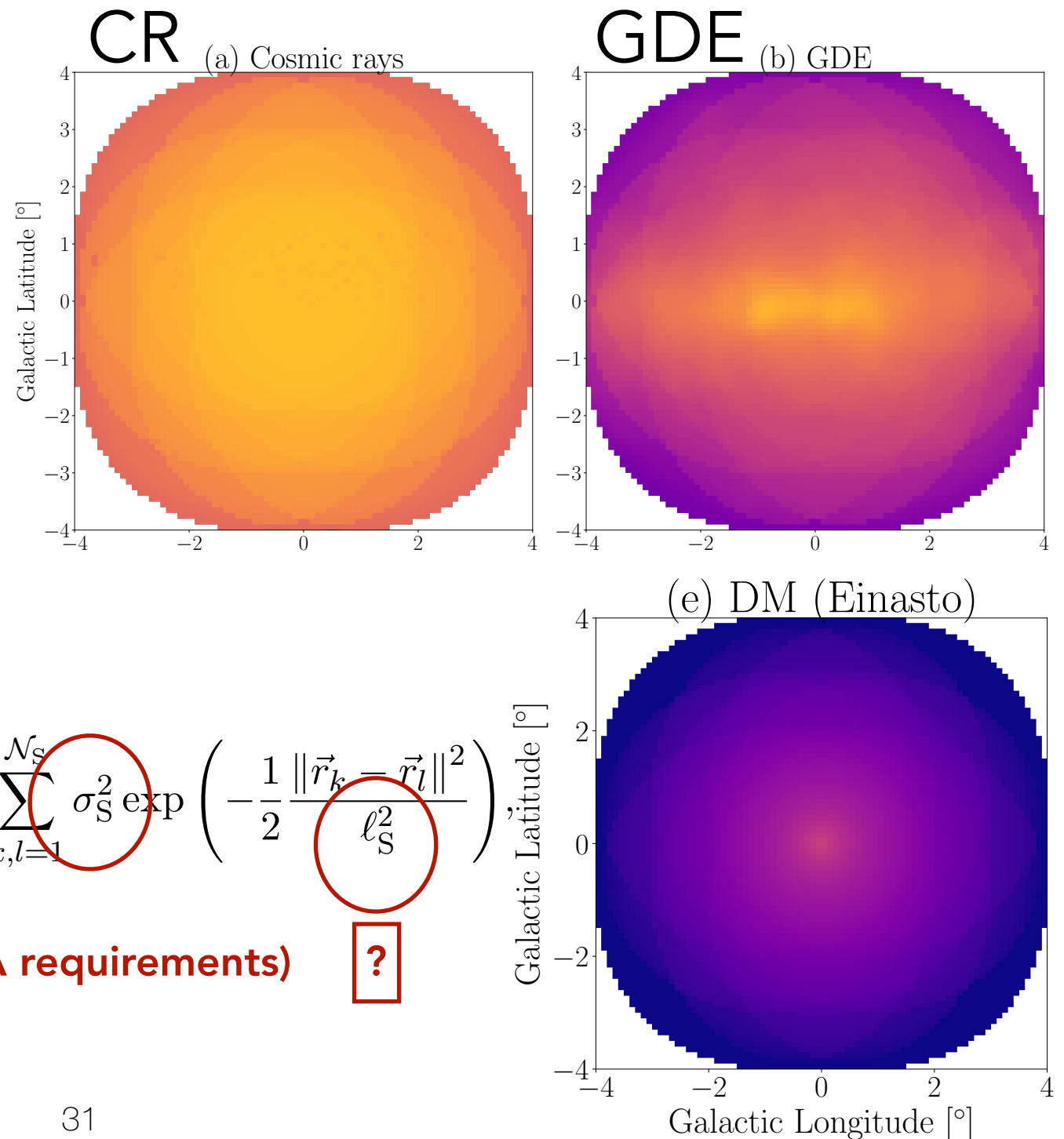
- an Asimov data set
- **CR + IE** templates (FB and PS added in some cases)
- **Binning 0.1 deg**
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### Models:

- CR+IE (+DM)

### Systematic uncertainty:

- added via covariance matrix



$$K_S = \sum_{k,l=1}^{\mathcal{N}_S} \sigma_S^2 \exp \left( -\frac{1}{2} \frac{\|\vec{r}_k - \vec{r}_l\|^2}{\ell_S^2} \right),$$

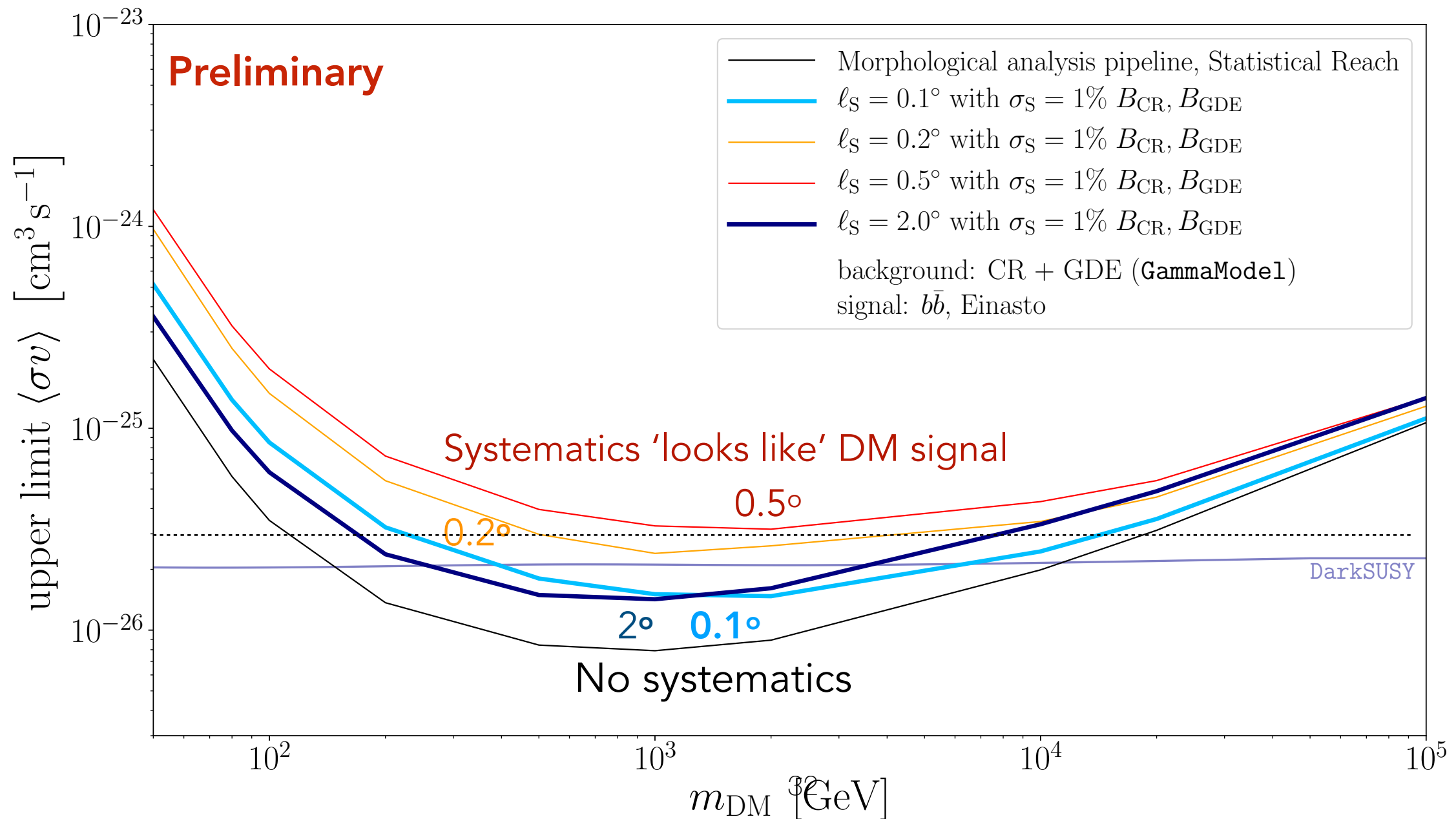
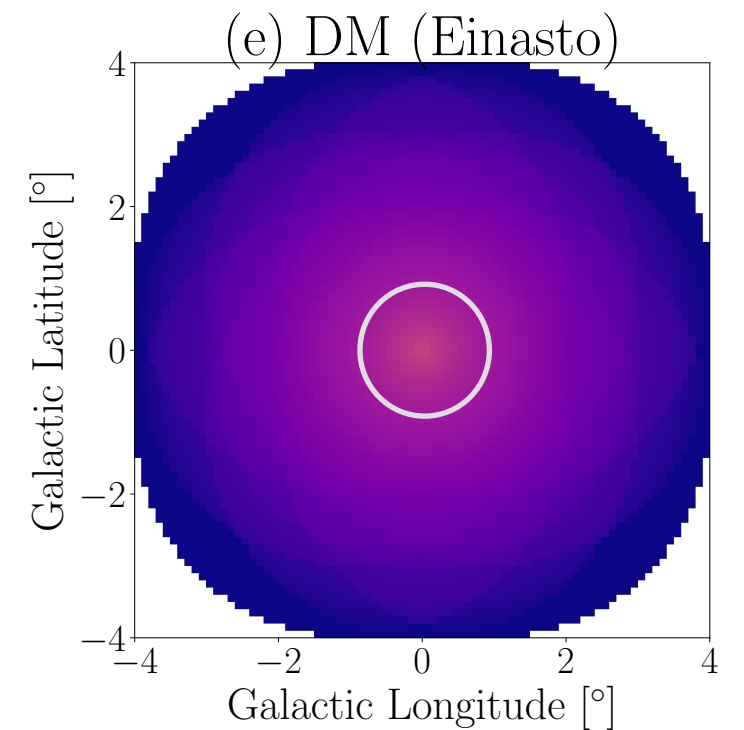
~1% (CTA requirements) ?



But what **systematics**?

- **Impact of different systematics correlation lengths on the DM sensitivity:**

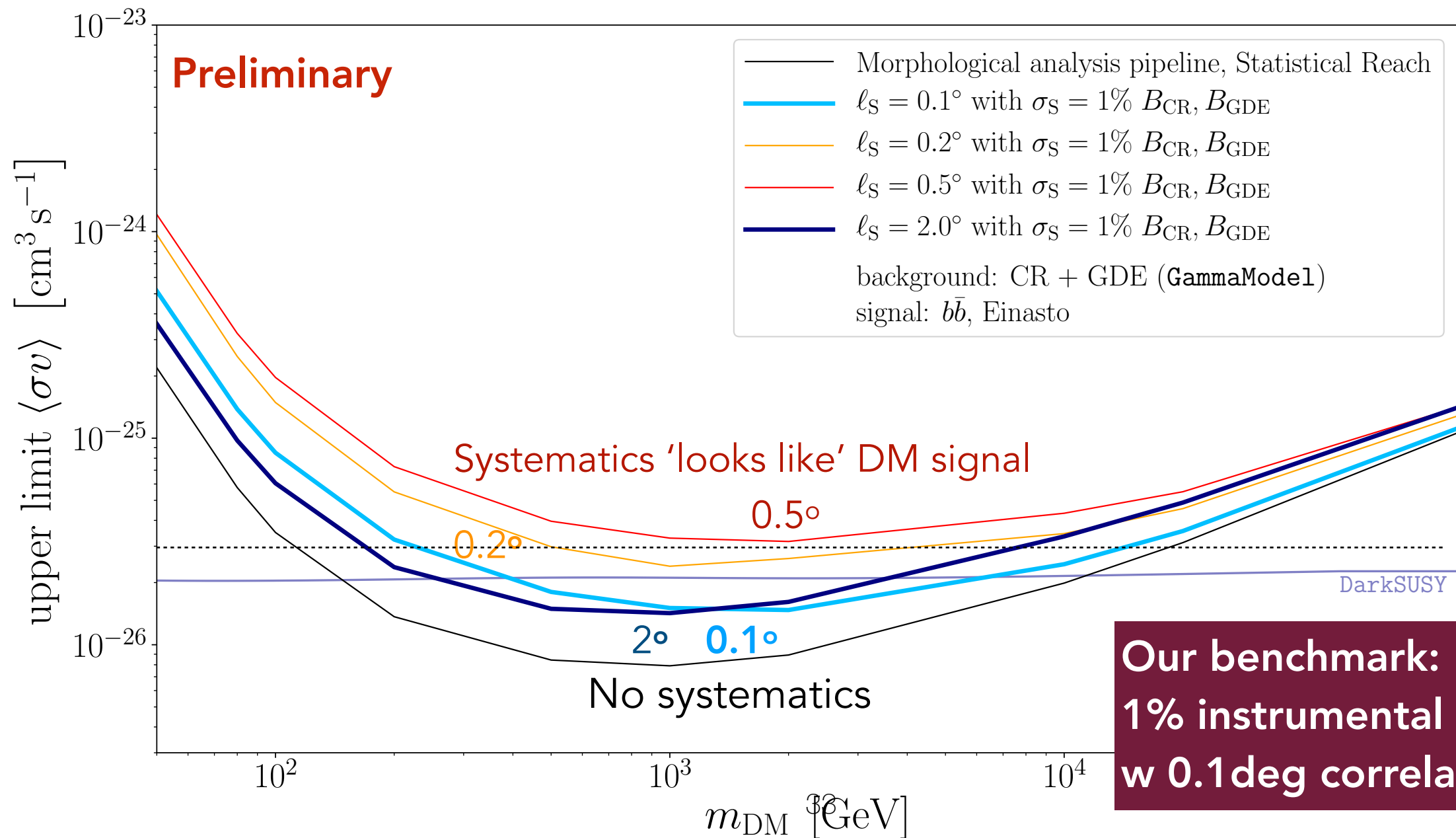
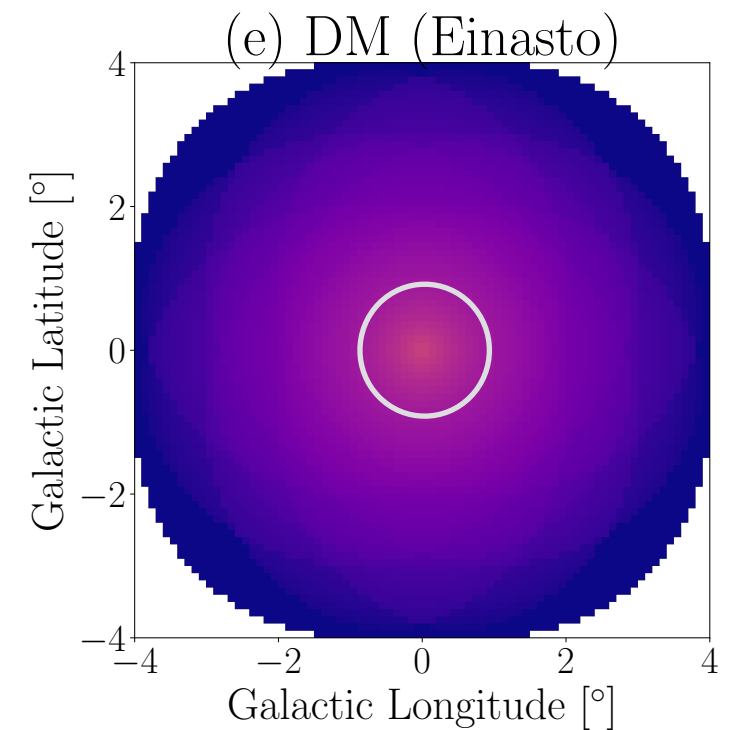
- ➔ Limited unless background fluctuate at 0.5 deg scale ( $\sim$ DM signal)
- ➔ Note - very important to include this term, significant impact!



But what **systematics**?

- **Impact of different systematics correlation lengths on the DM sensitivity:**

- ➔ Limited unless background fluctuate at 0.5 deg scale ( $\sim$ DM signal)
- ➔ Note - very important to include this term, significant impact!



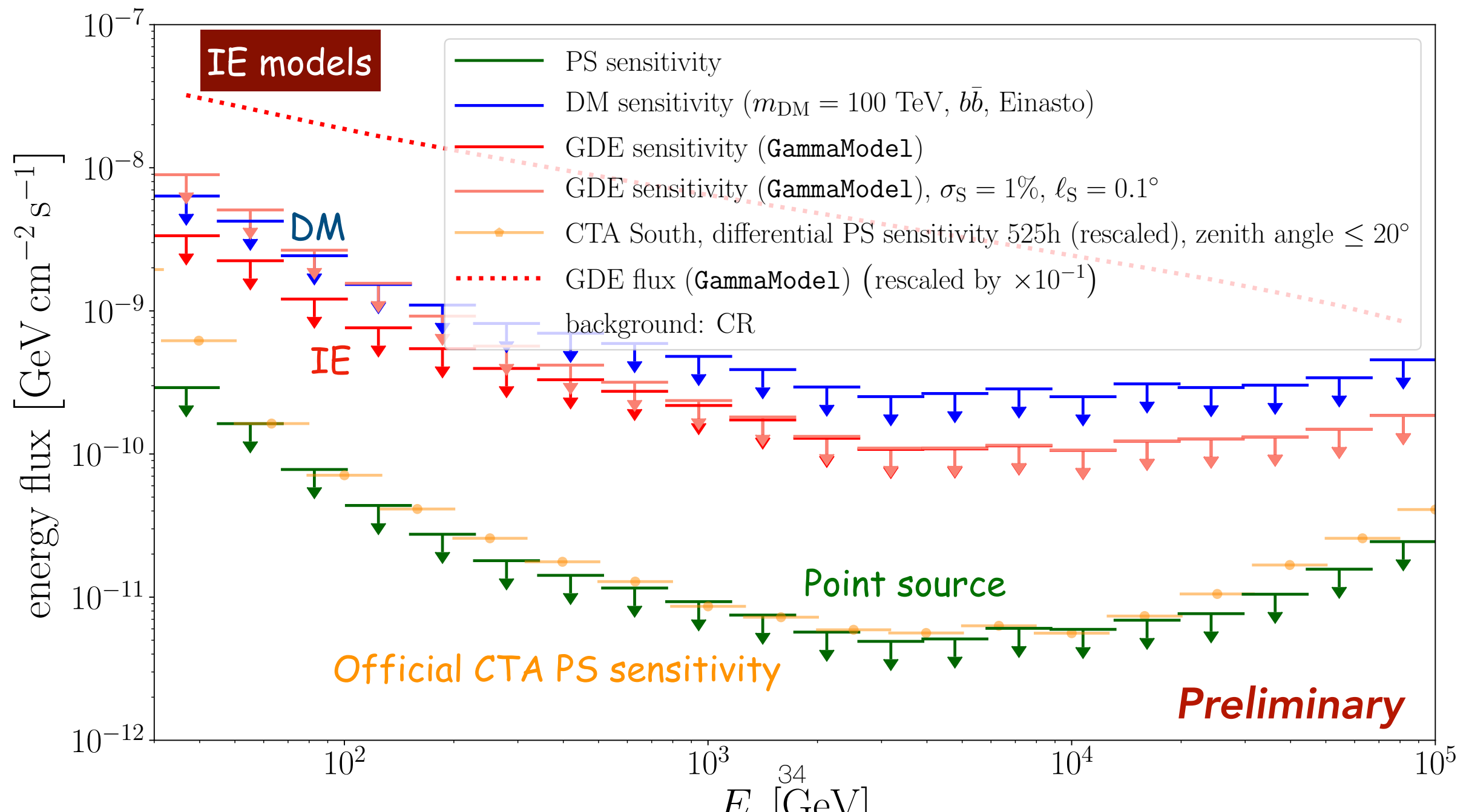
**Our benchmark:**  
1% instrumental systematics  
w 0.1deg correlations



# Flux sensitivity

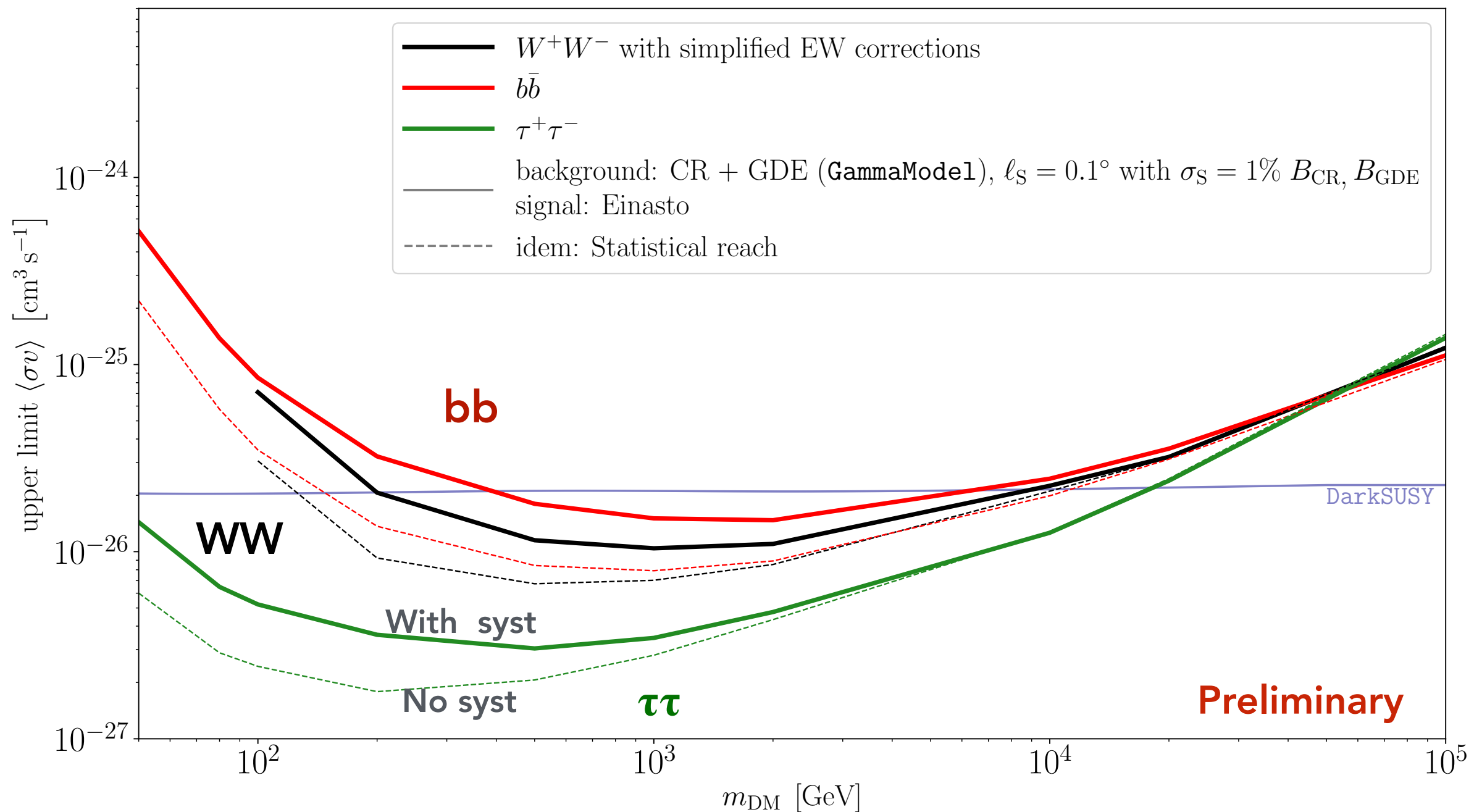
Having all ingredients, it is straightforward to explore the flux sensitivity to different templates

- shows that **CTA should be sensitive to the large scale Interstellar emission (huge discovery on its own) !**



# Results

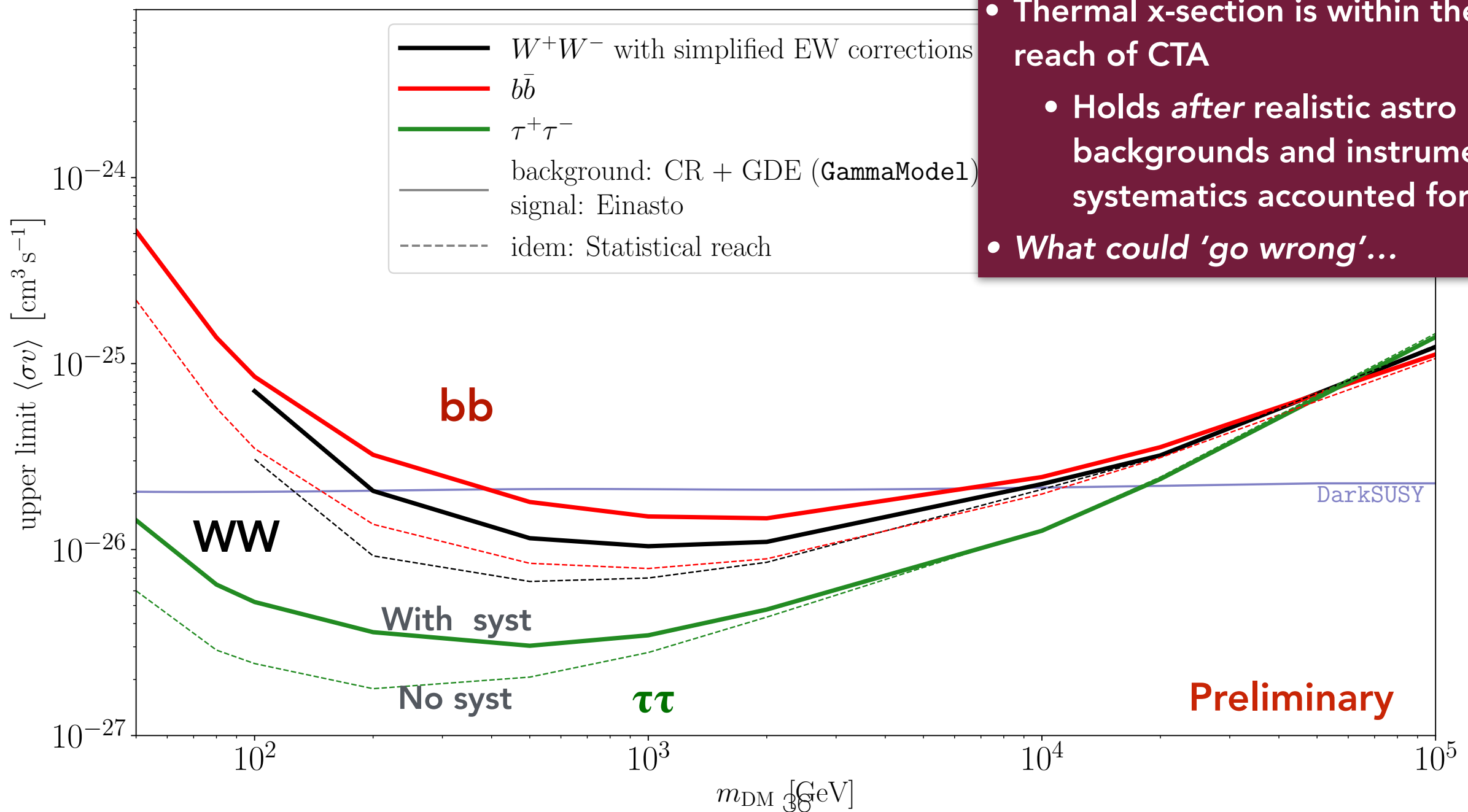
- Sensitivity to various DM annihilation channels
  - **systematics** worsens the sensitivity by a factor of  $\sim 2$





# Results

- Sensitivity to various DM annihilation channels
  - **systematics** worsens the sensitivity by a factor of  $\sim 2$

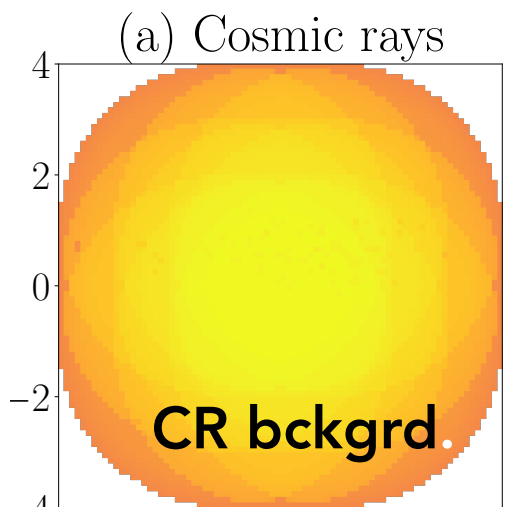
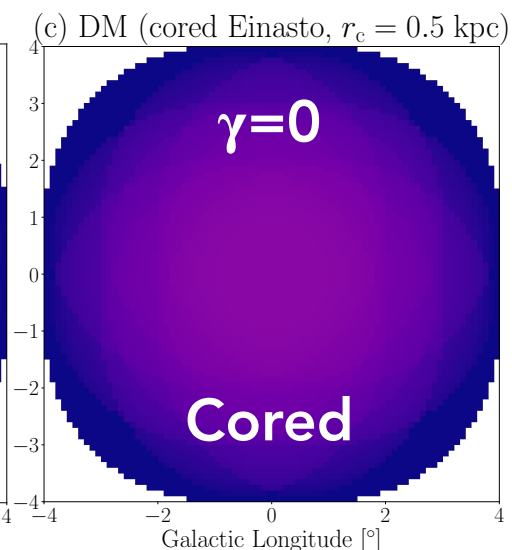
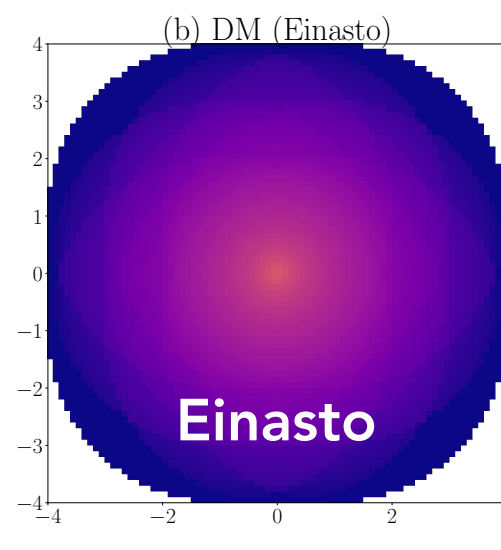
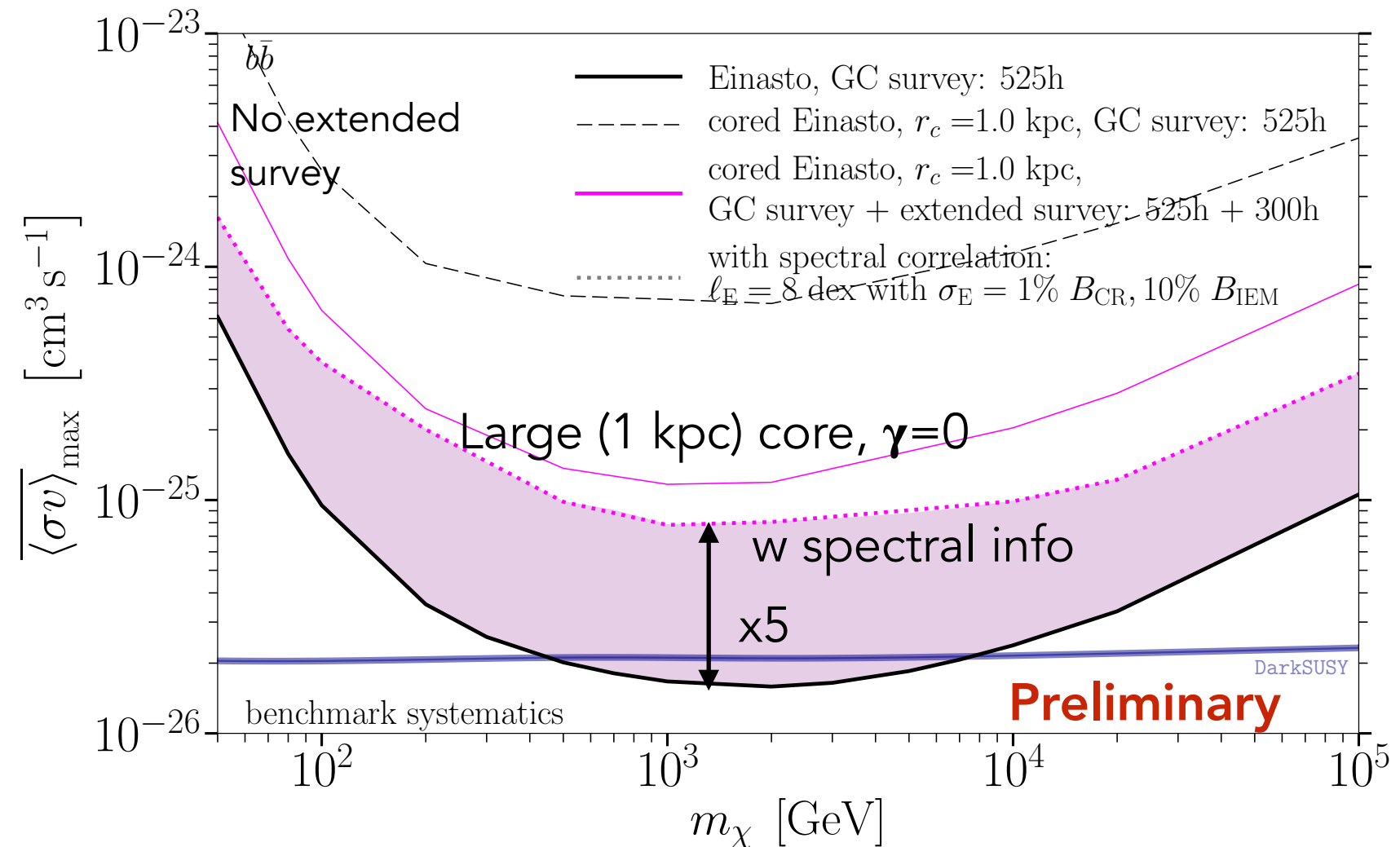
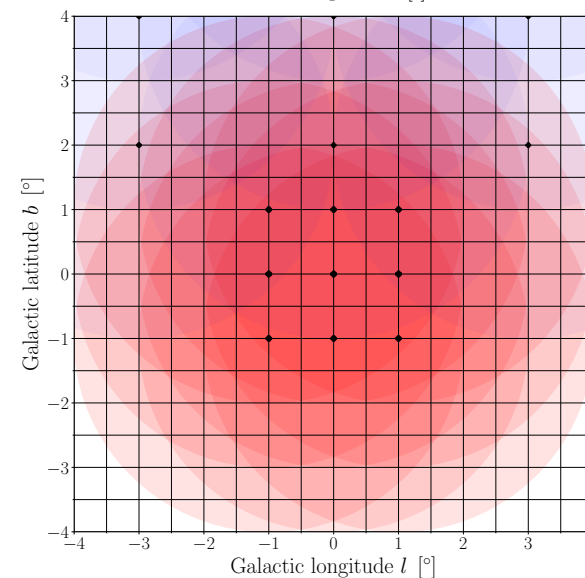
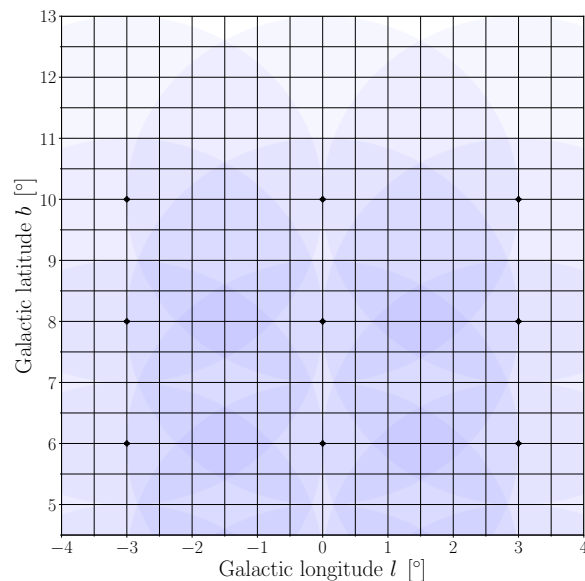


- Thermal x-section is within the reach of CTA
  - Holds *after* realistic astro backgrounds and instrumental systematics accounted for
  - *What could 'go wrong'...*

# Uncertainties - DM profile

- **Different DM density profiles:**

- Consider  $\gamma=0$  (worse case scenario)
- **Extended observation survey** helps to break degeneracy (survey extends to 800 kpc)
- Using **spectral information** adds discriminating power

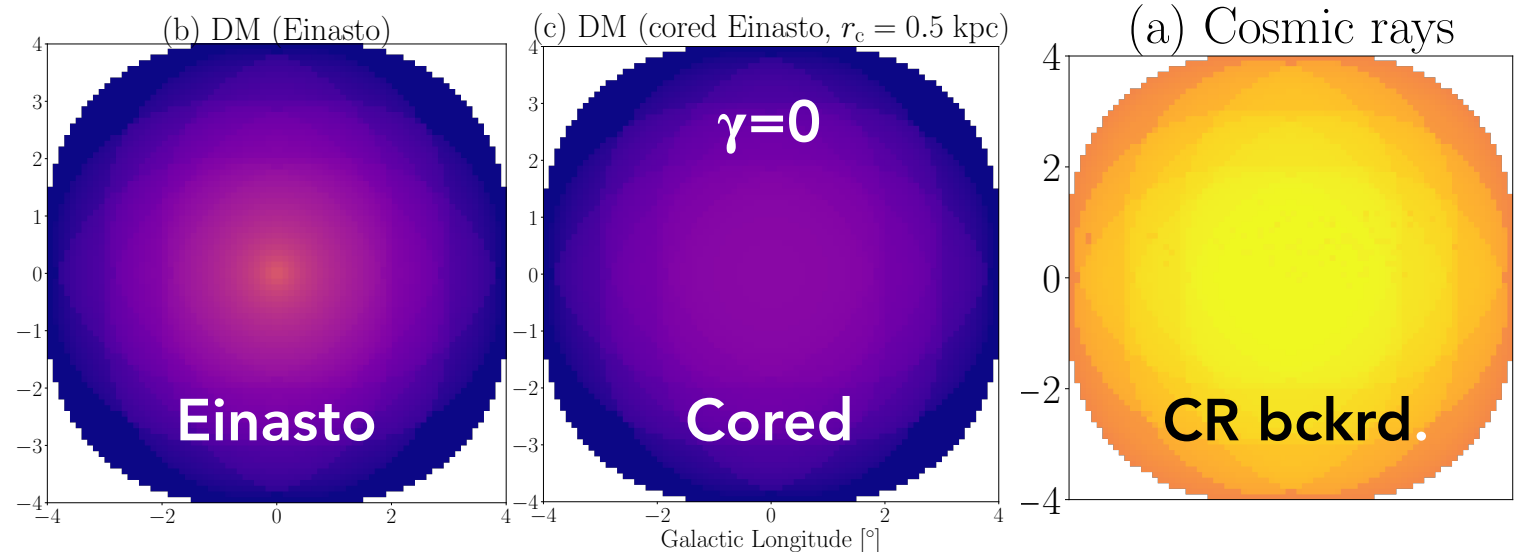
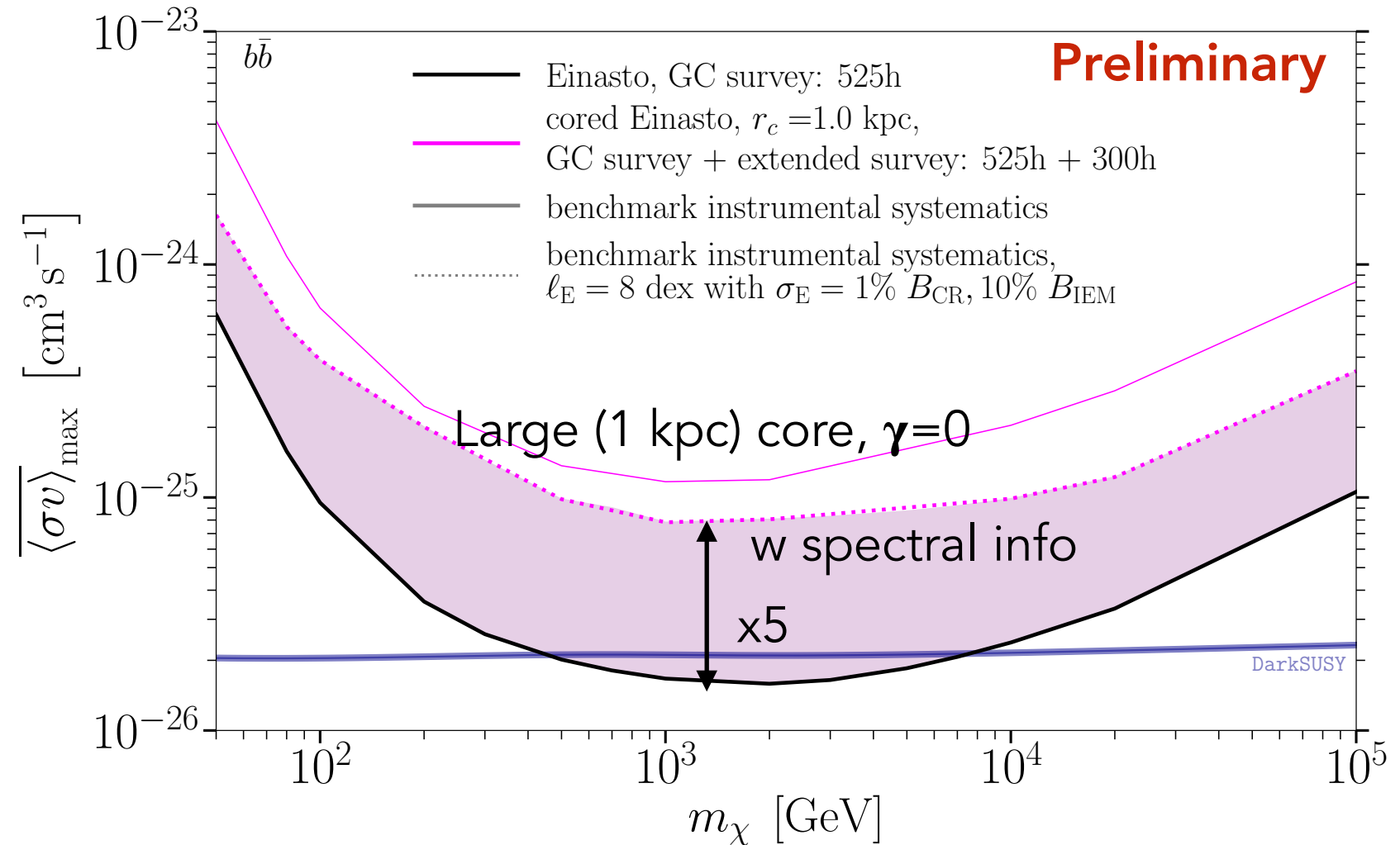
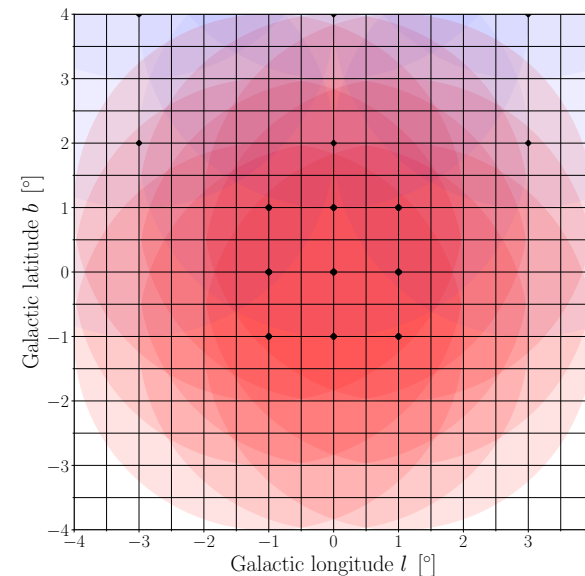
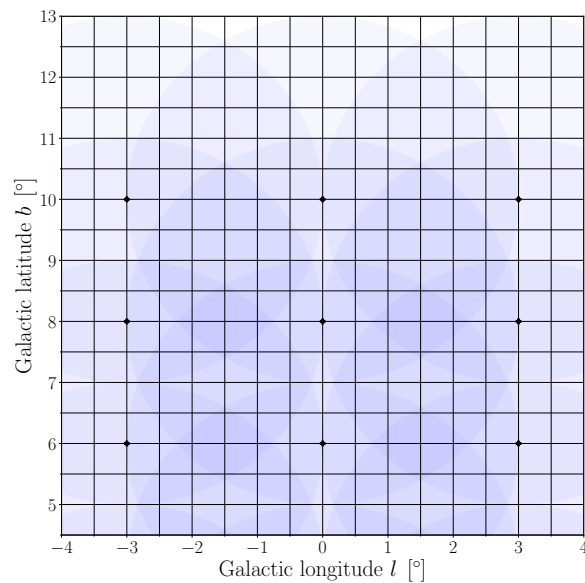




# Uncertainties - DM profile

- **Different DM density profiles:**

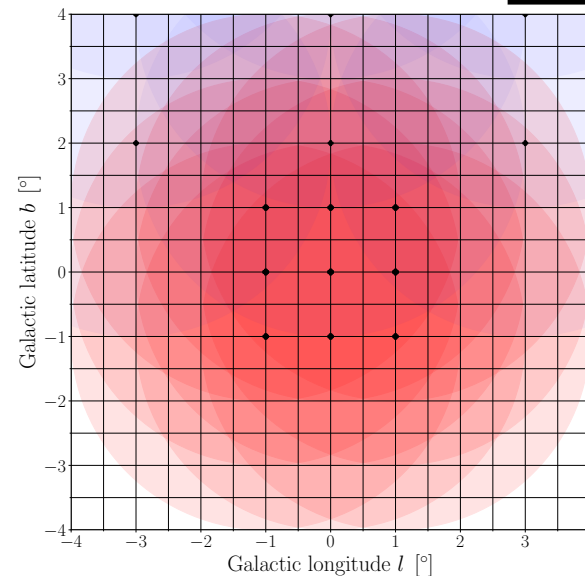
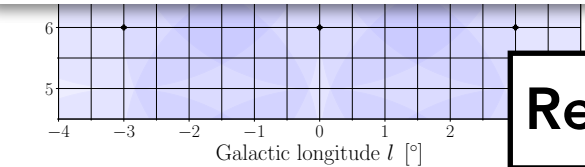
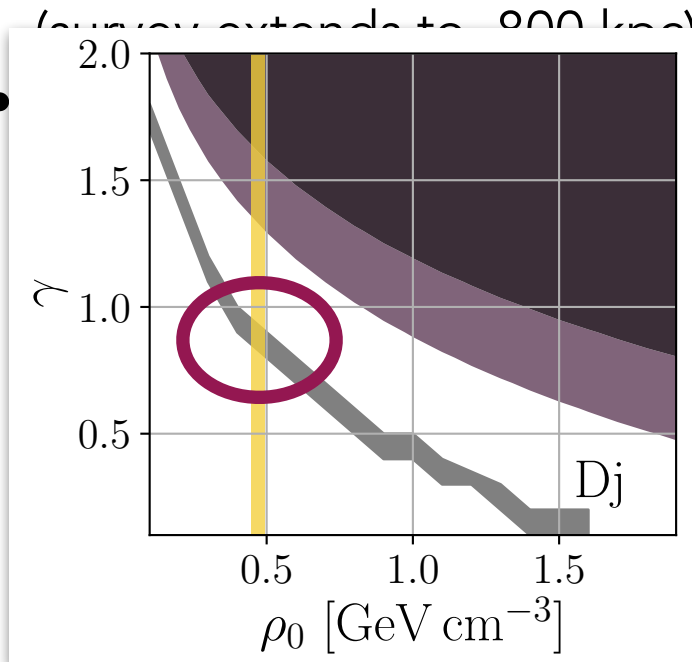
- Consider  $\gamma=0$  (worse case scenario)
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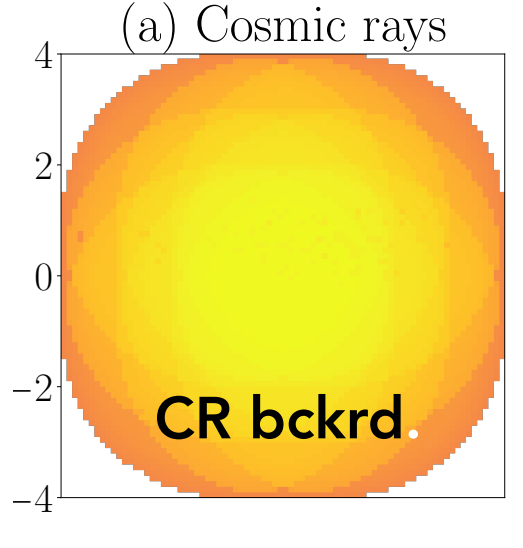
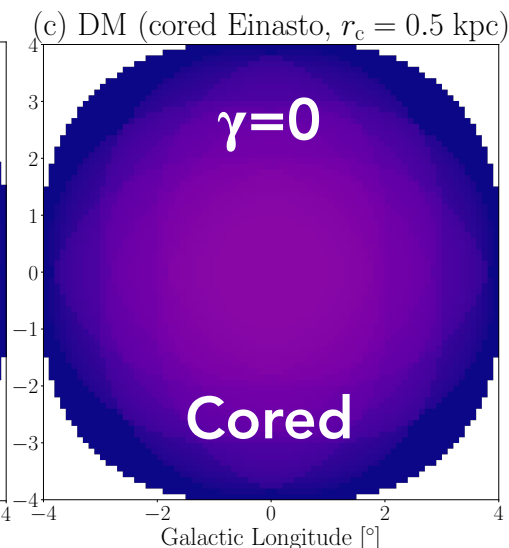
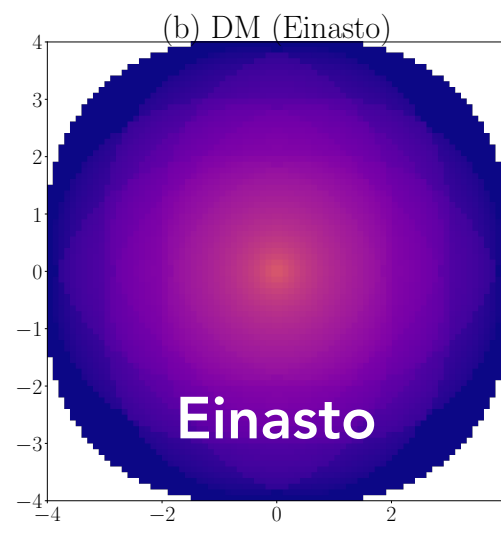
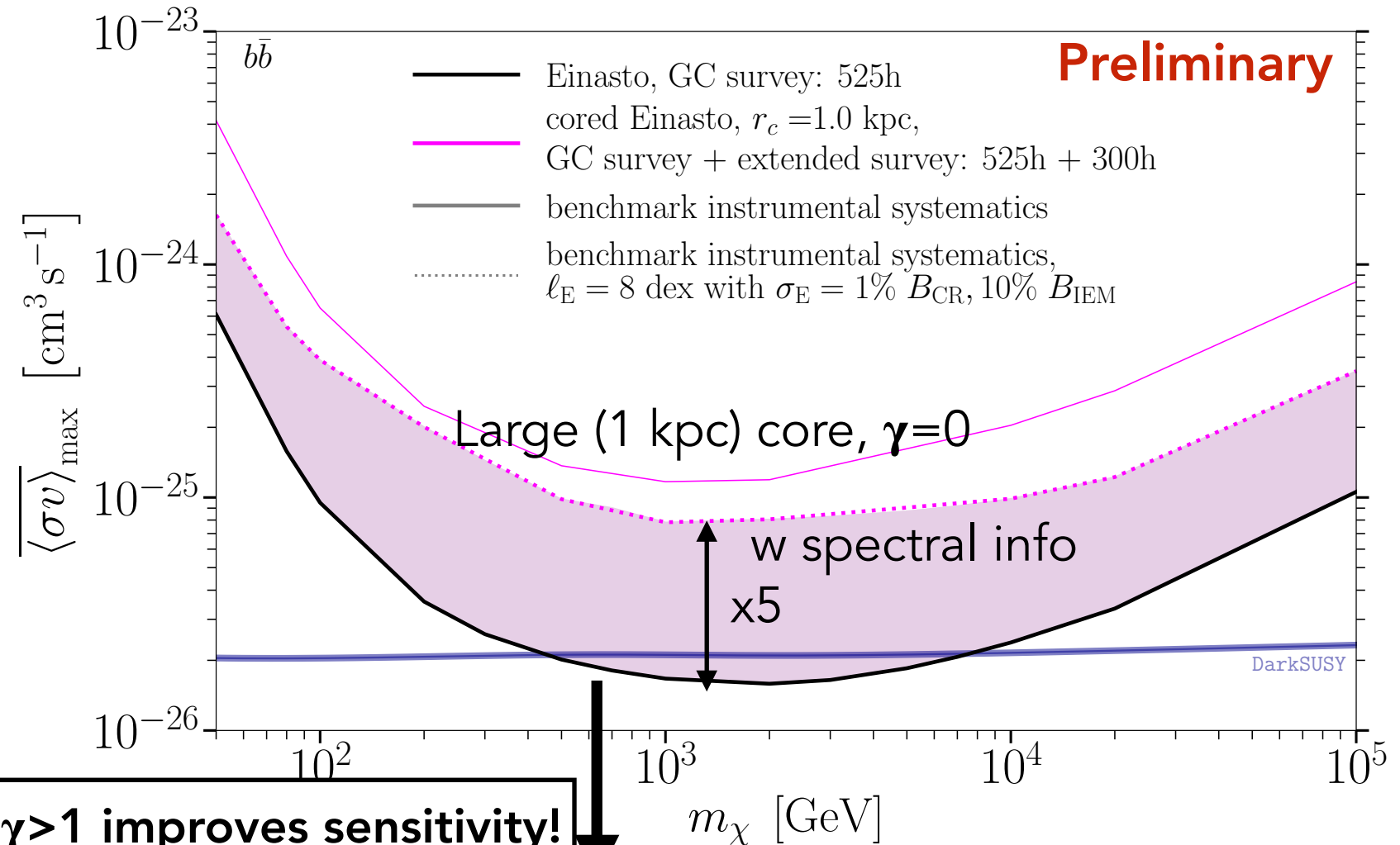
# Uncertainties - DM profile

- **Different DM density profiles:**

- Consider  $\gamma=0$  (worse case scenario)
- **Extended observation survey** helps to break degeneracy



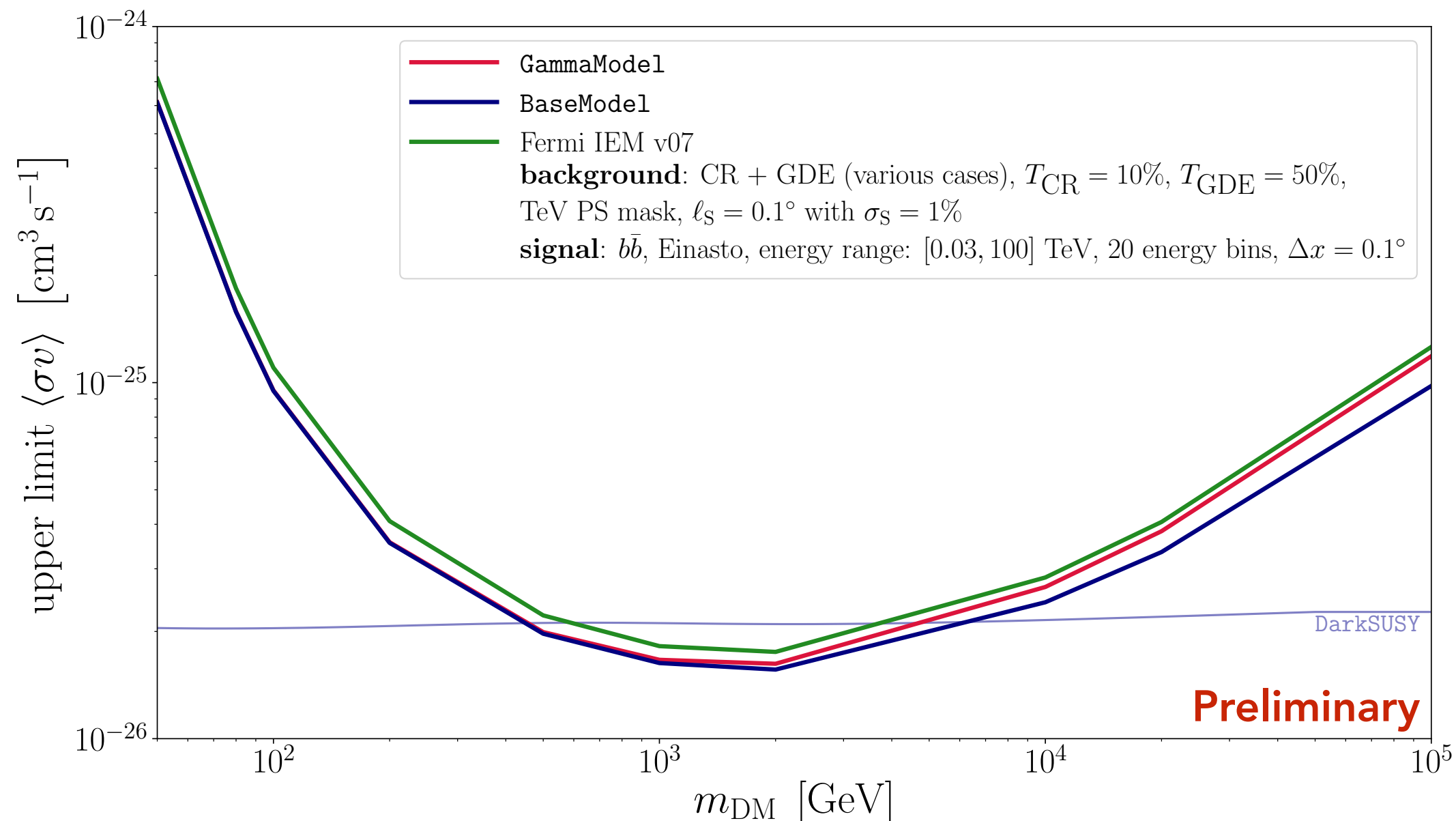
**Remember  $\gamma > 1$  improves sensitivity!**





# Uncertainties - on IEM

- Impact of different IE models
  - Limited
  - If having a good IE model



# Uncertainties - on IEM

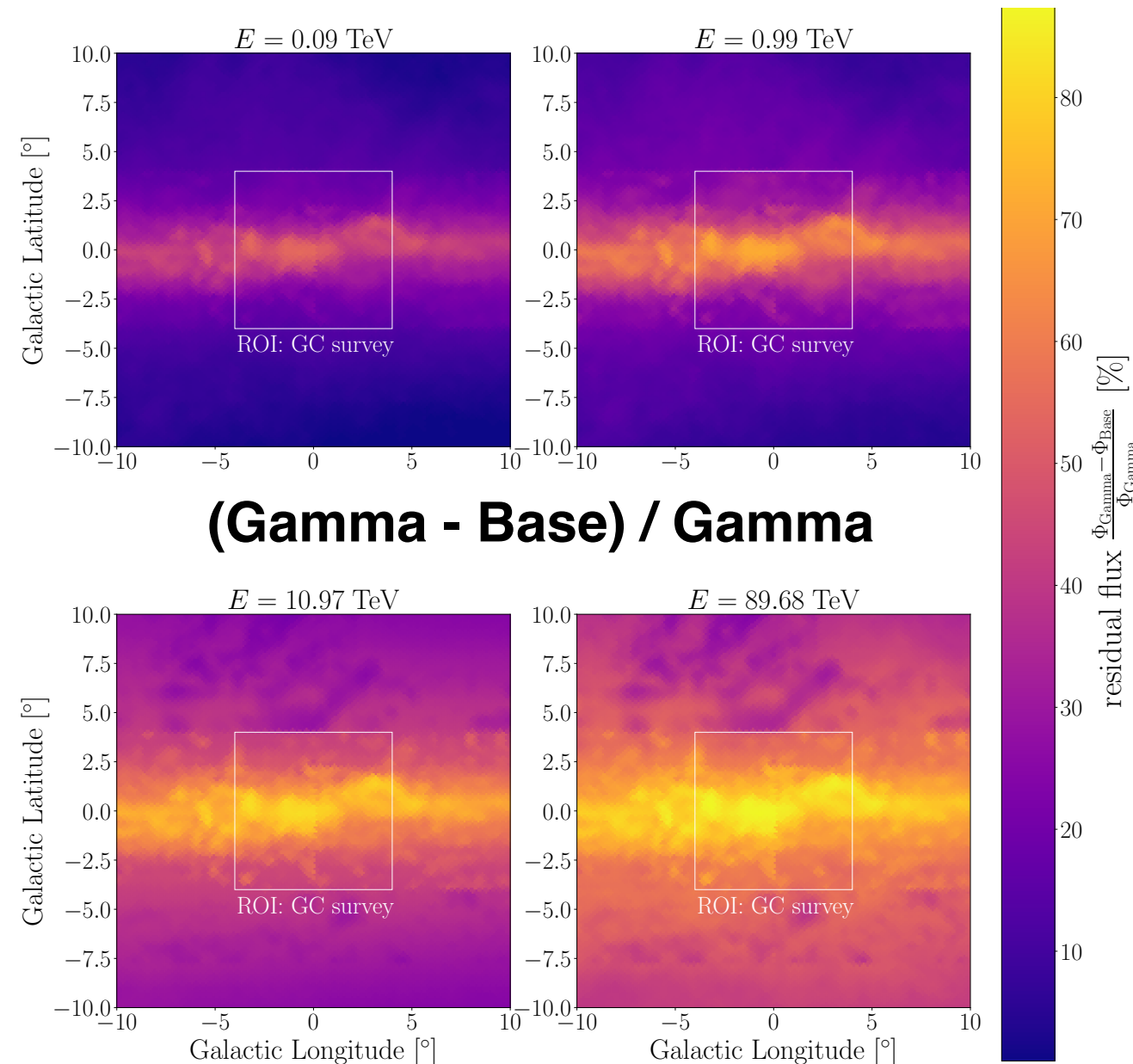
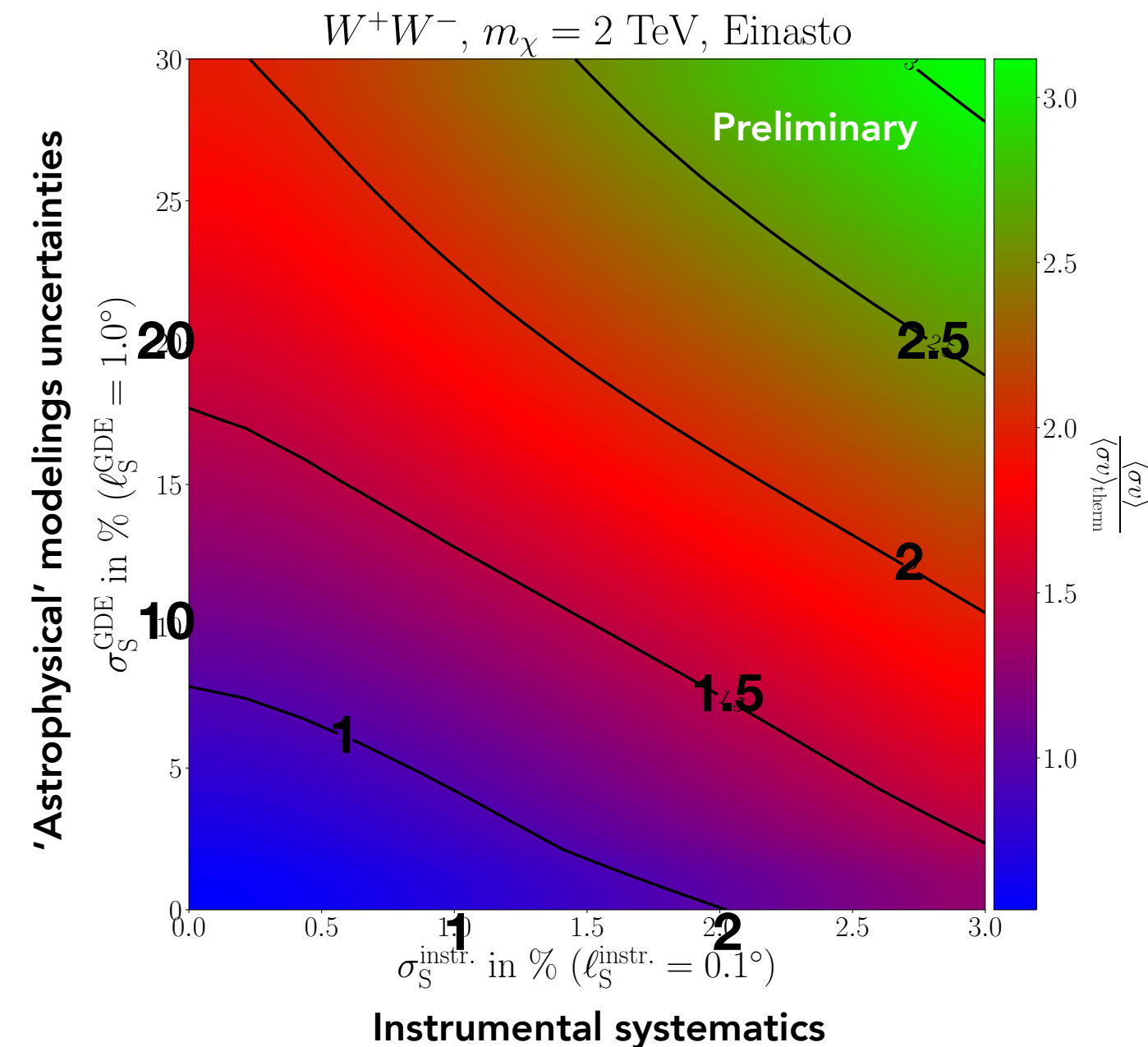
- Impact of different IE models

- Limited

- If having a good IE model

→ relaxing that assumption — ~10% of knowledge of IEM needed

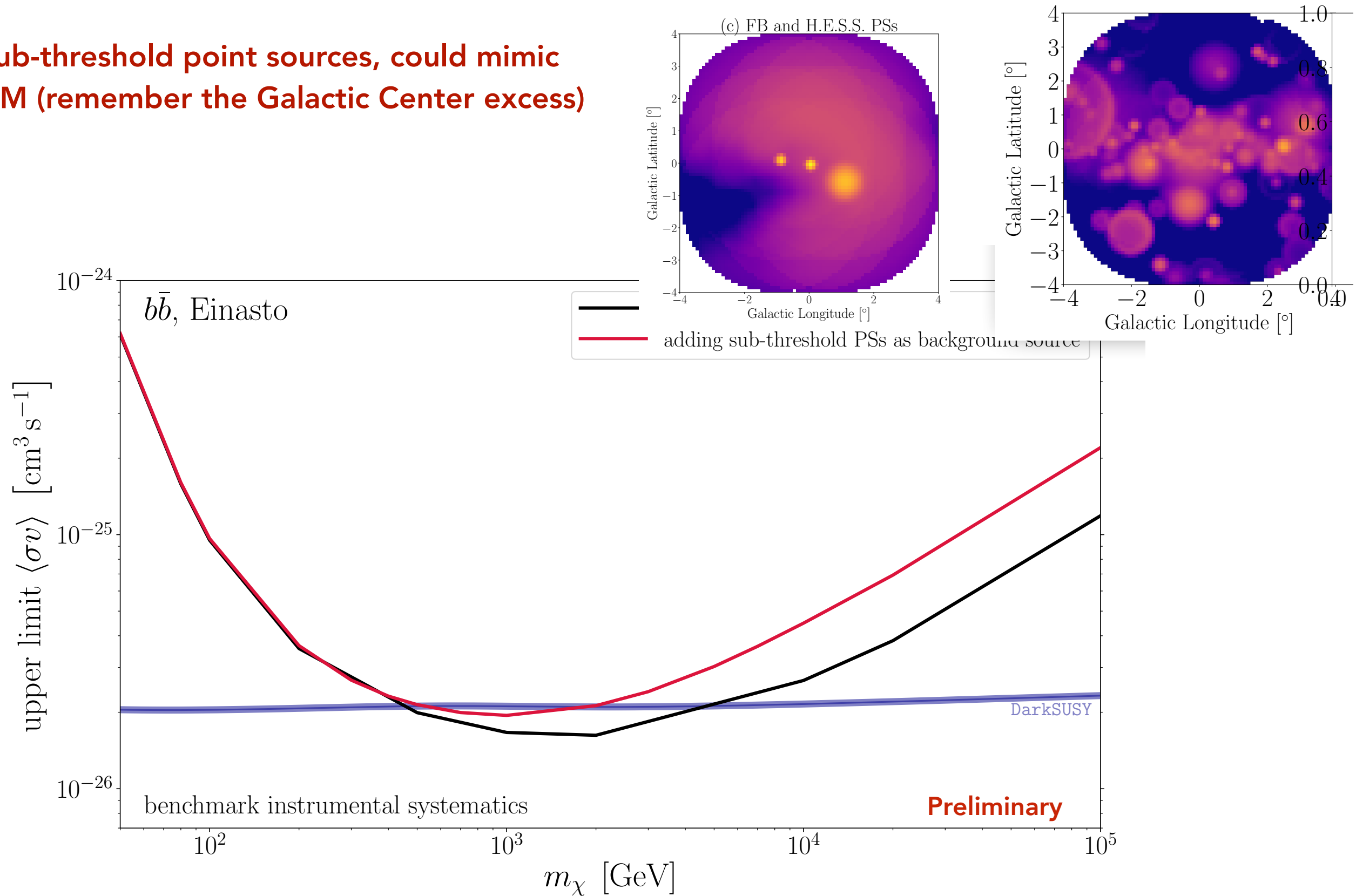
Remember: we expect to measure the IEM



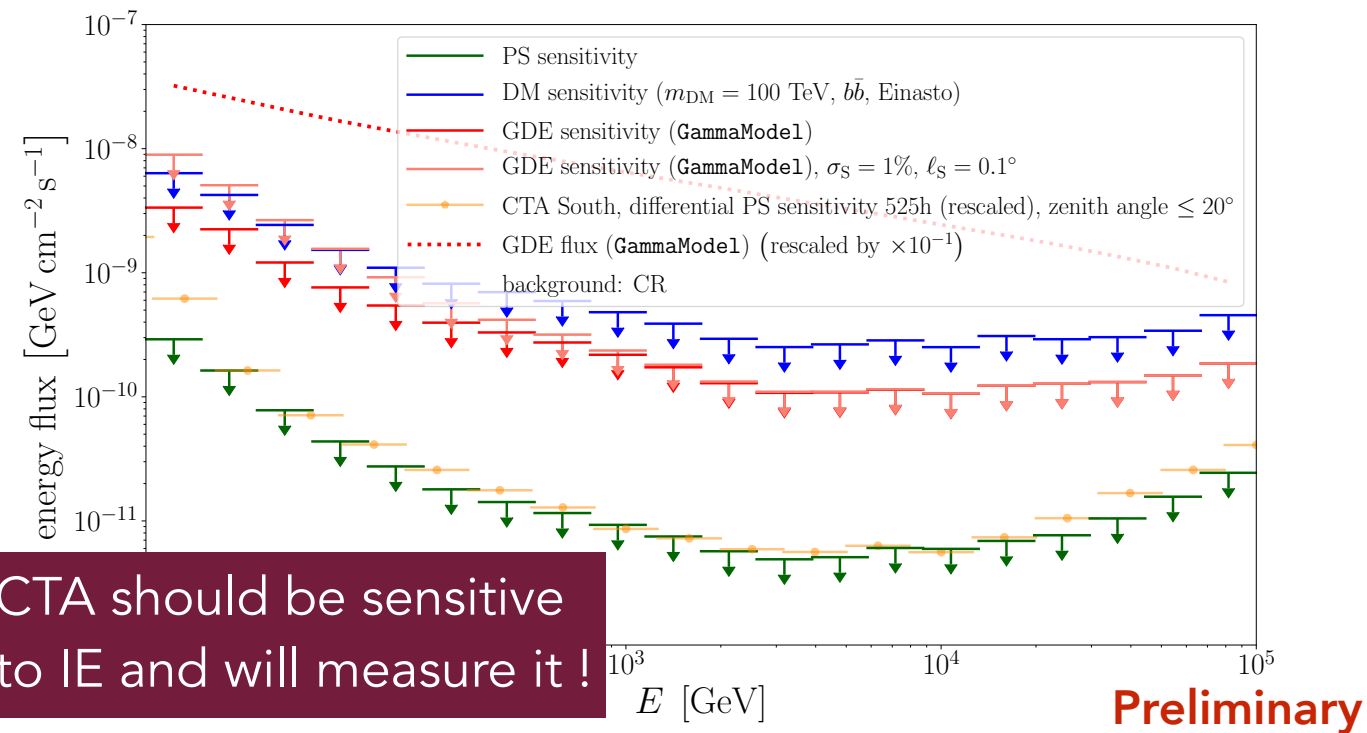


# Uncertainties - impact of sub threshold PSs

- **Sub-threshold point sources, could mimic DM (remember the Galactic Center excess)**

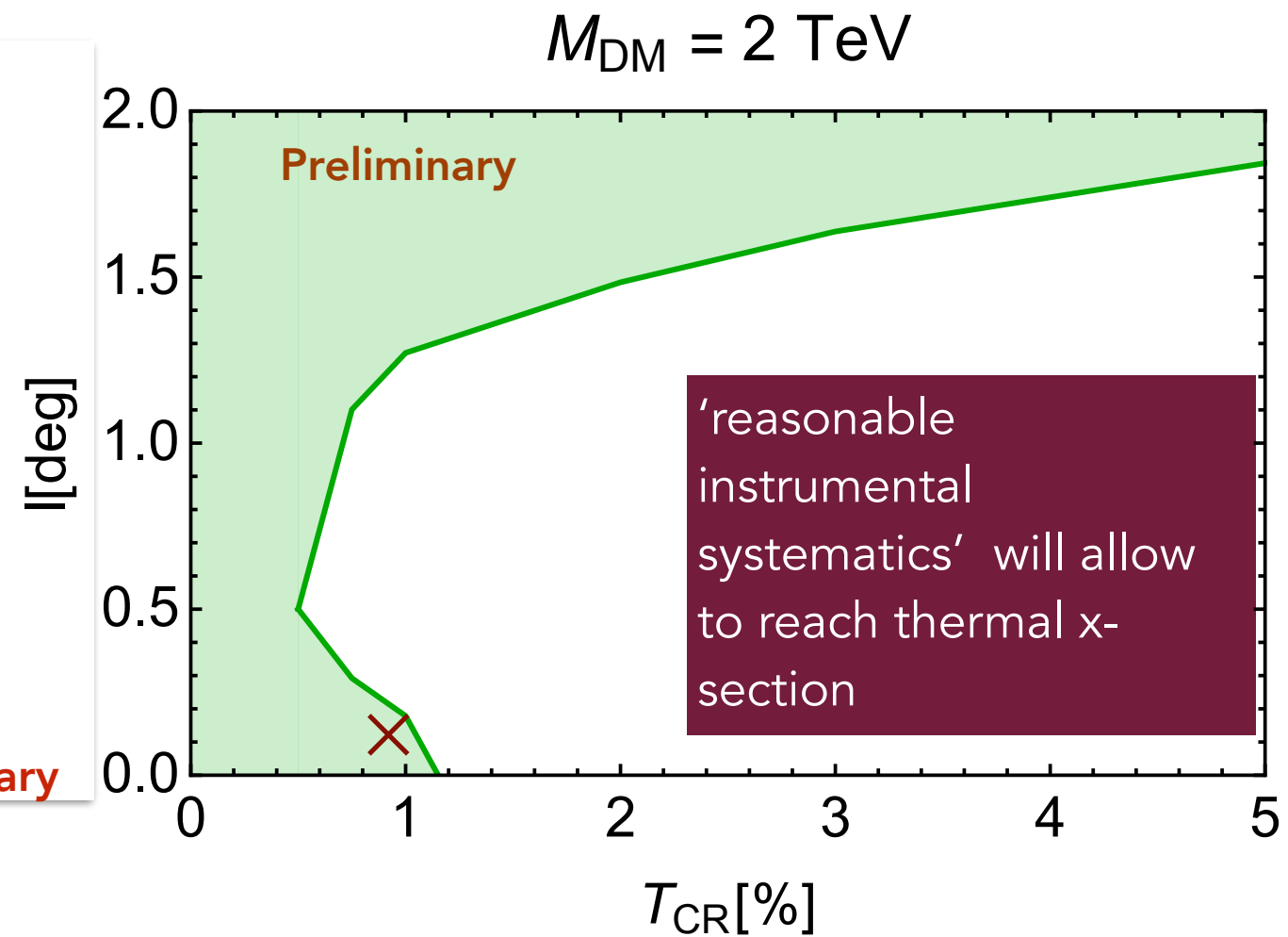
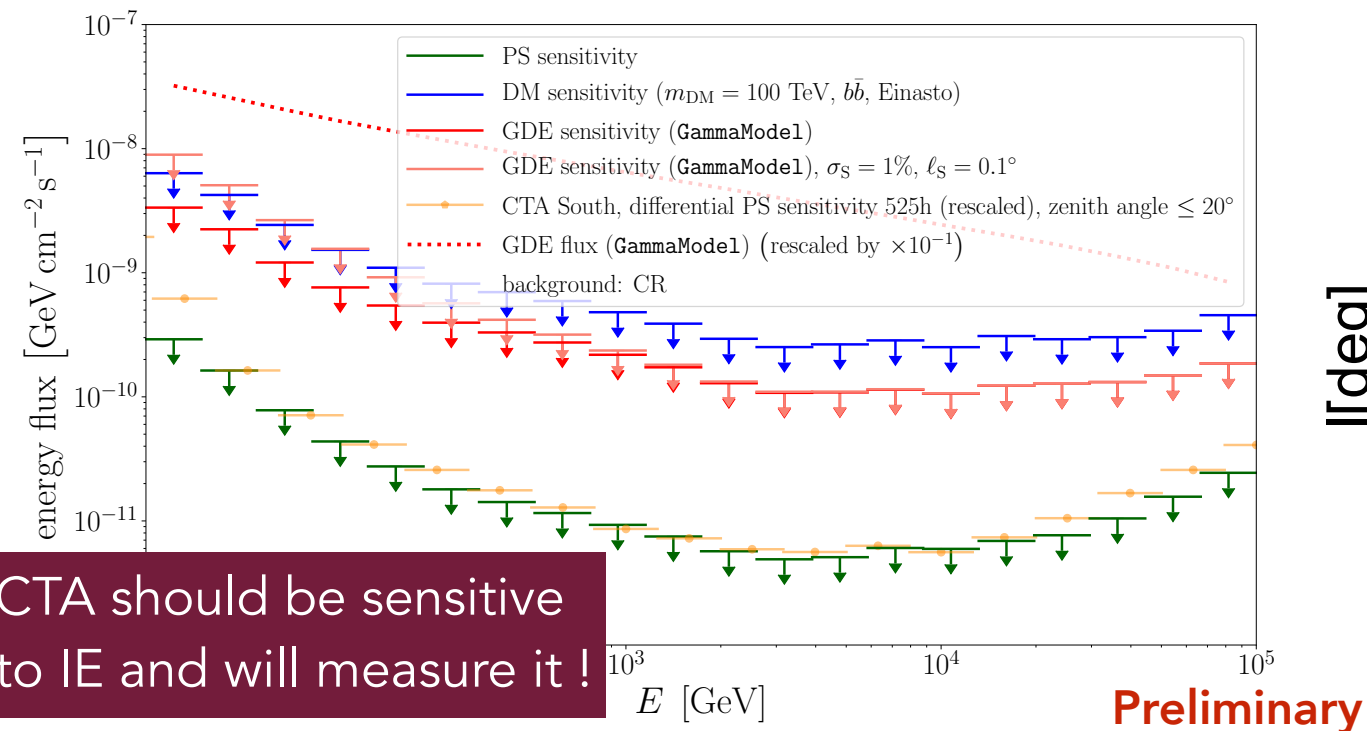


# Summary

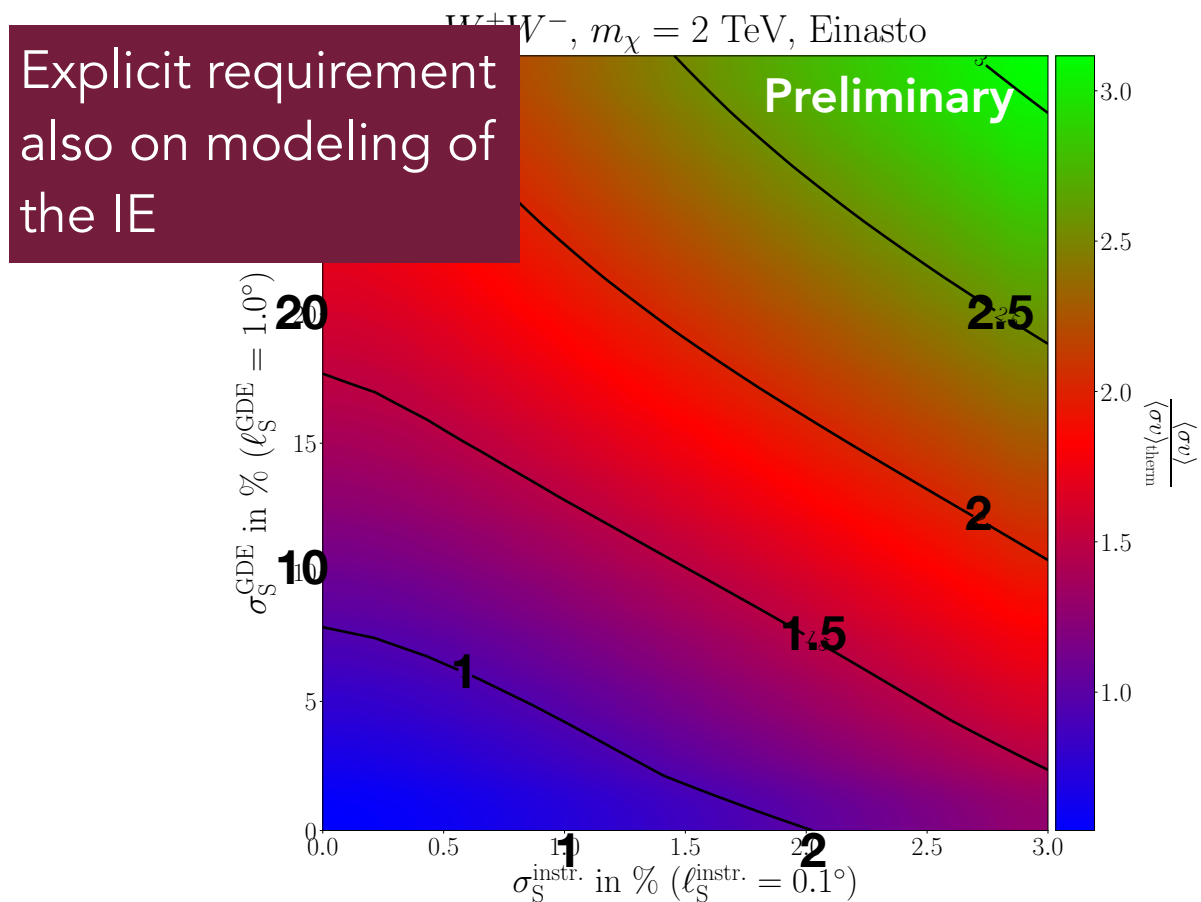
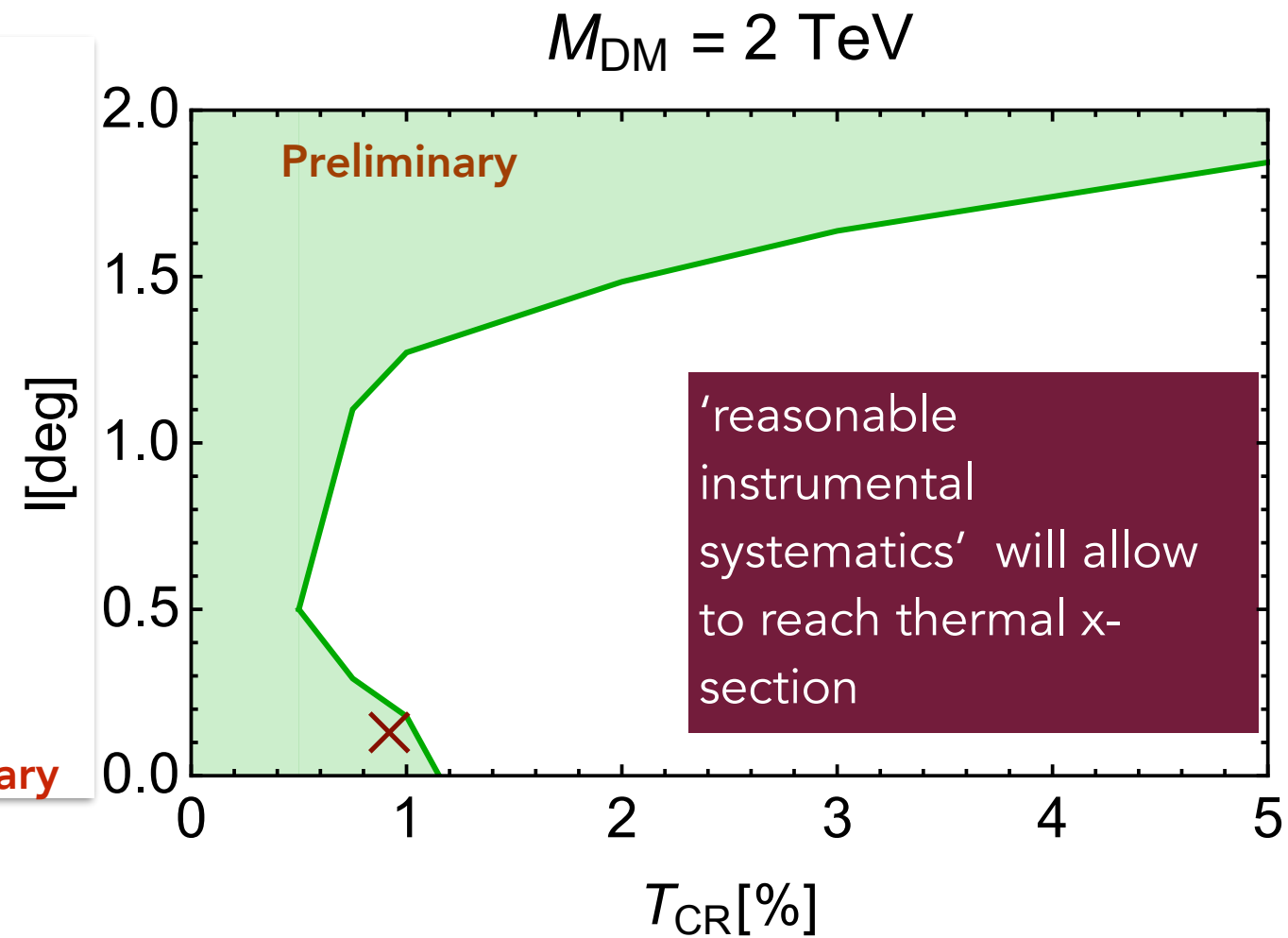
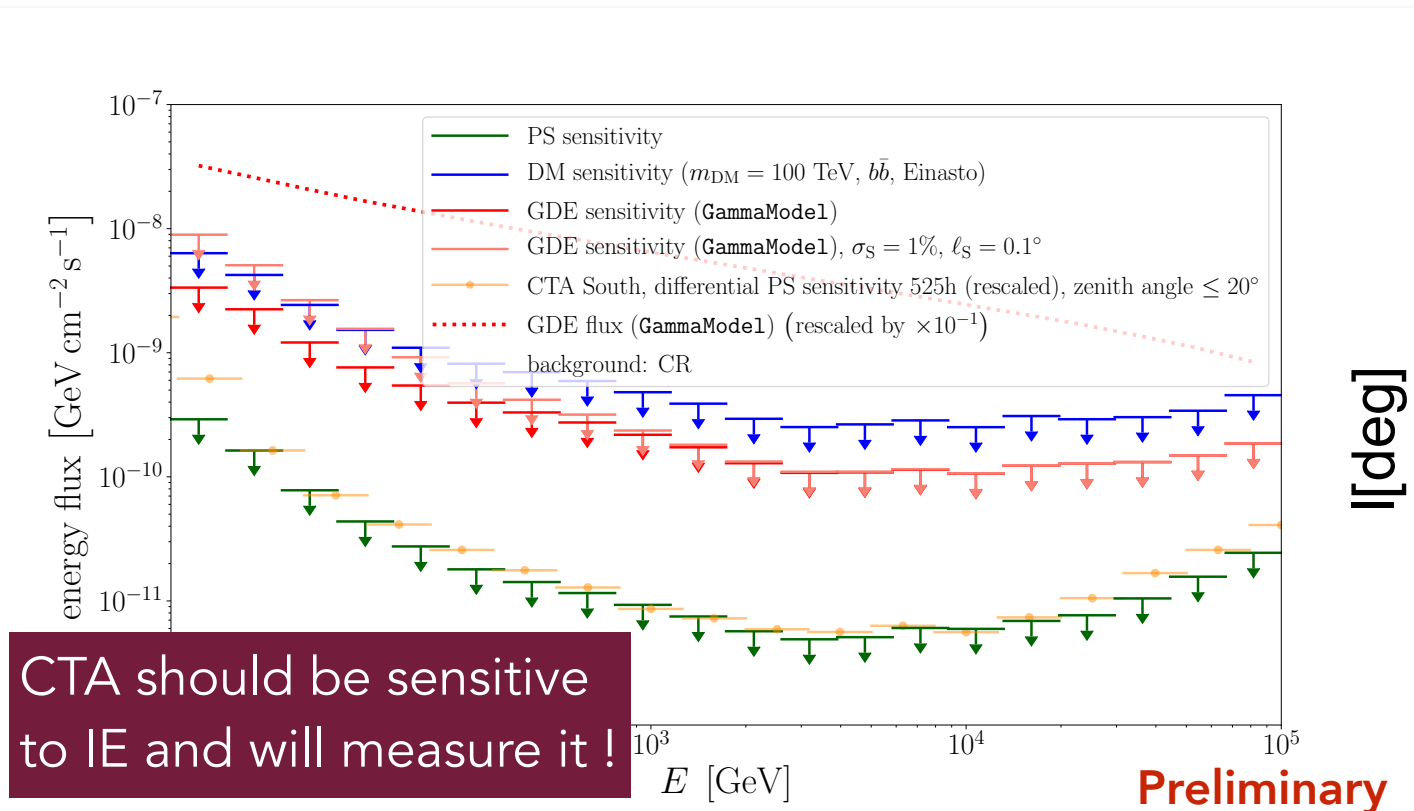




# Summary

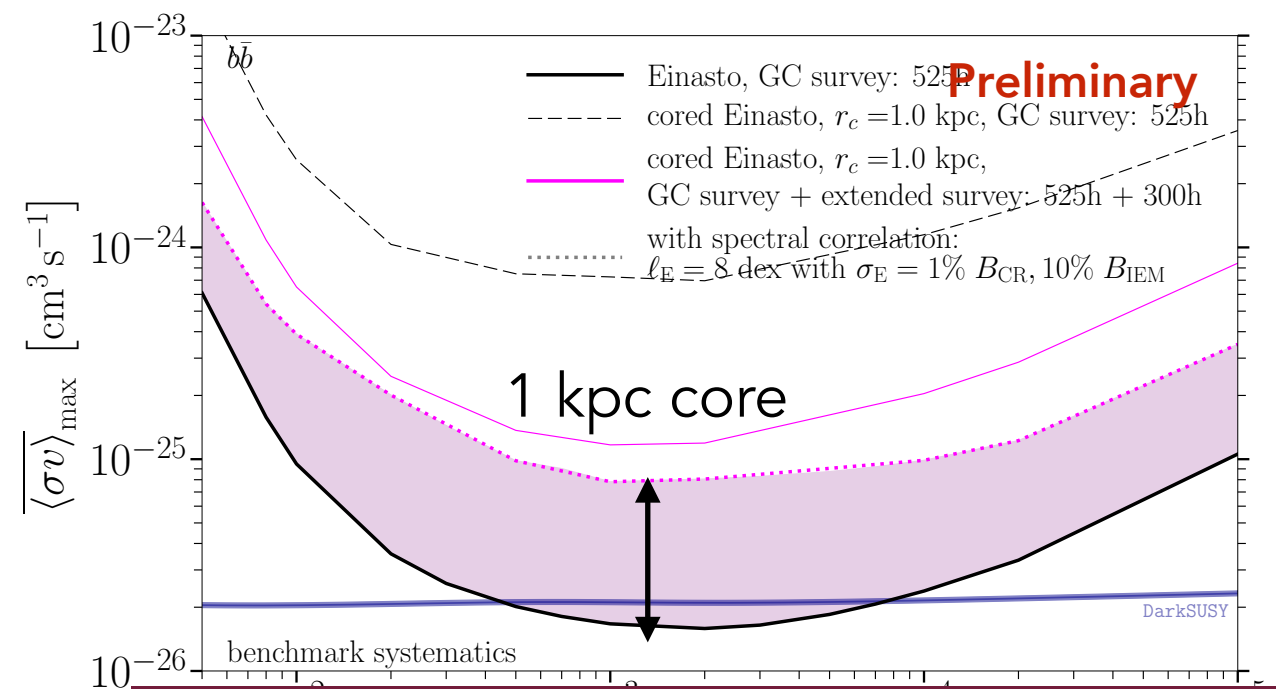
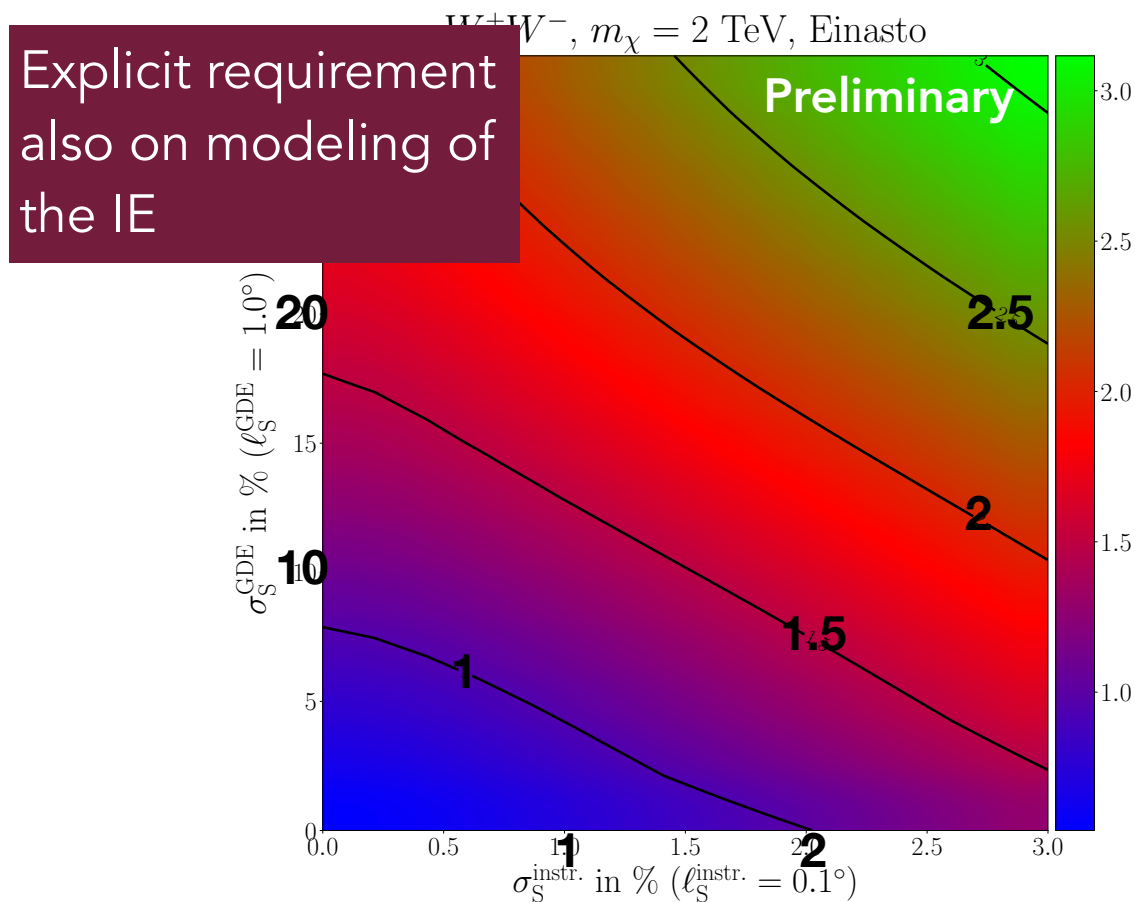
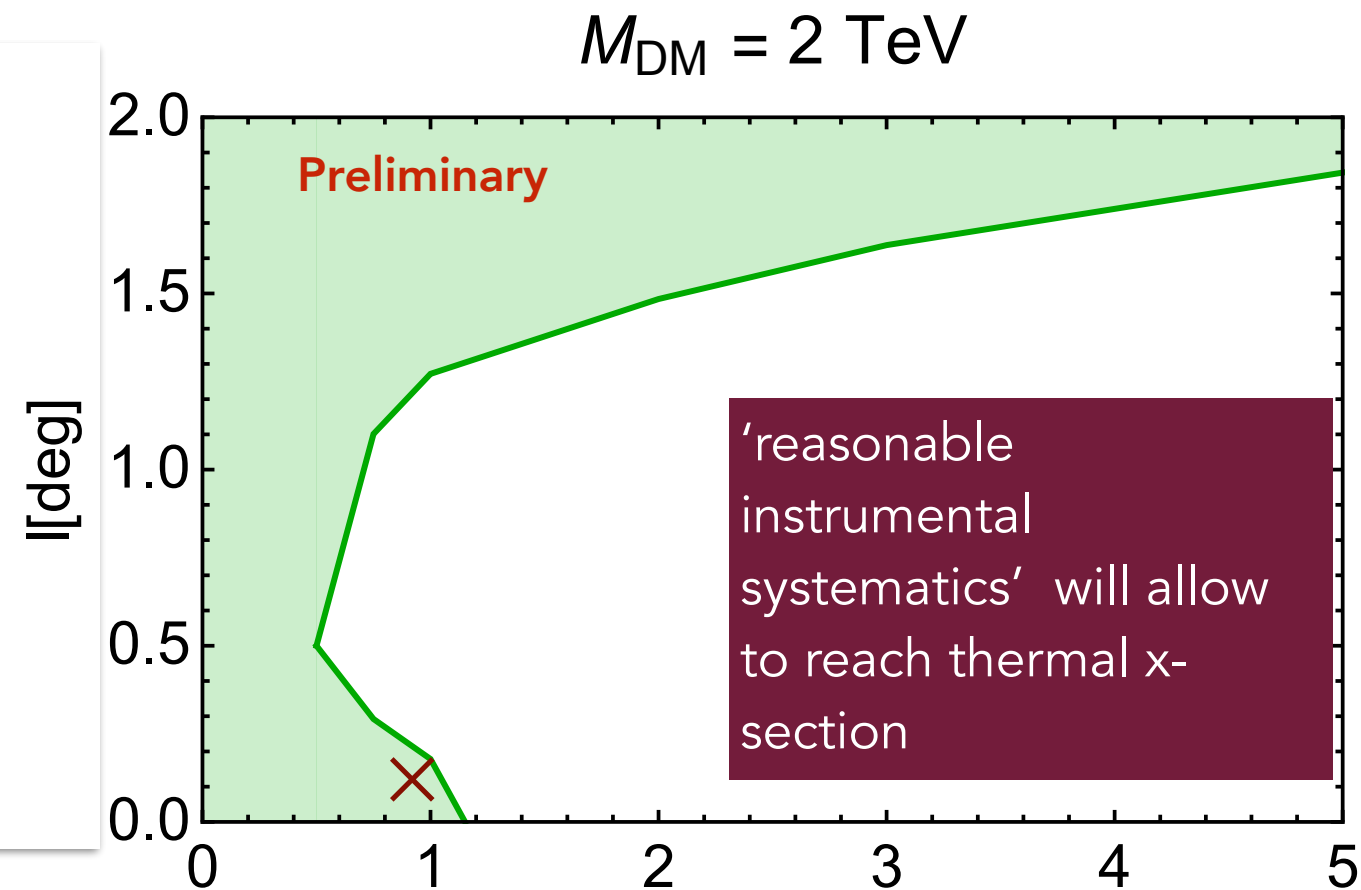
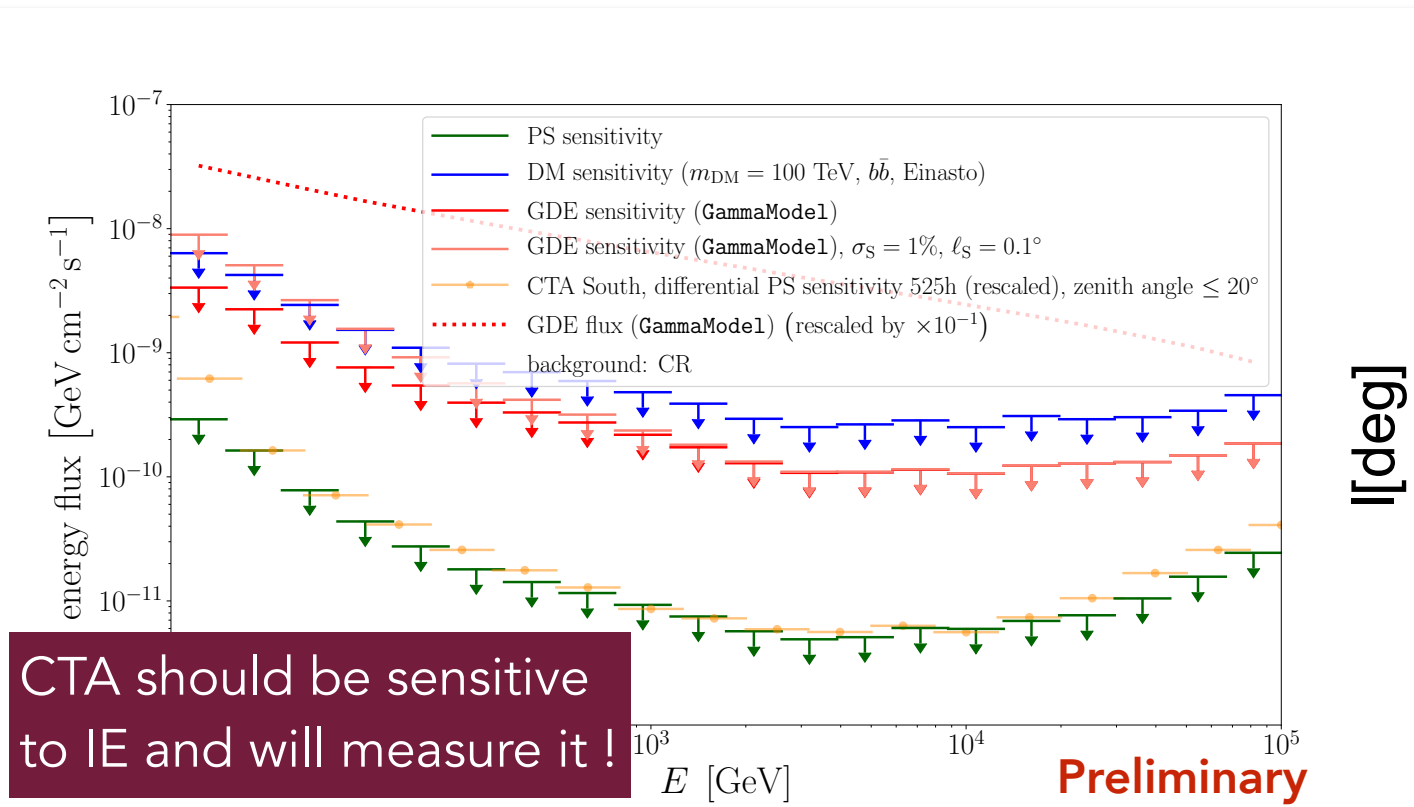


# Summary





# Summary



If profile has a **large core**, limits worsen by a factor of  $\sim 5$ . Note: up to one order of magnitude 'enhanced' annihilation motivated for TeV DM: Sommerfeld enhancement, resonances

# Summary

**Good chance** to test thermal WIMP models in the TeV range (and for some models **CTA is the only chance of testing!**)

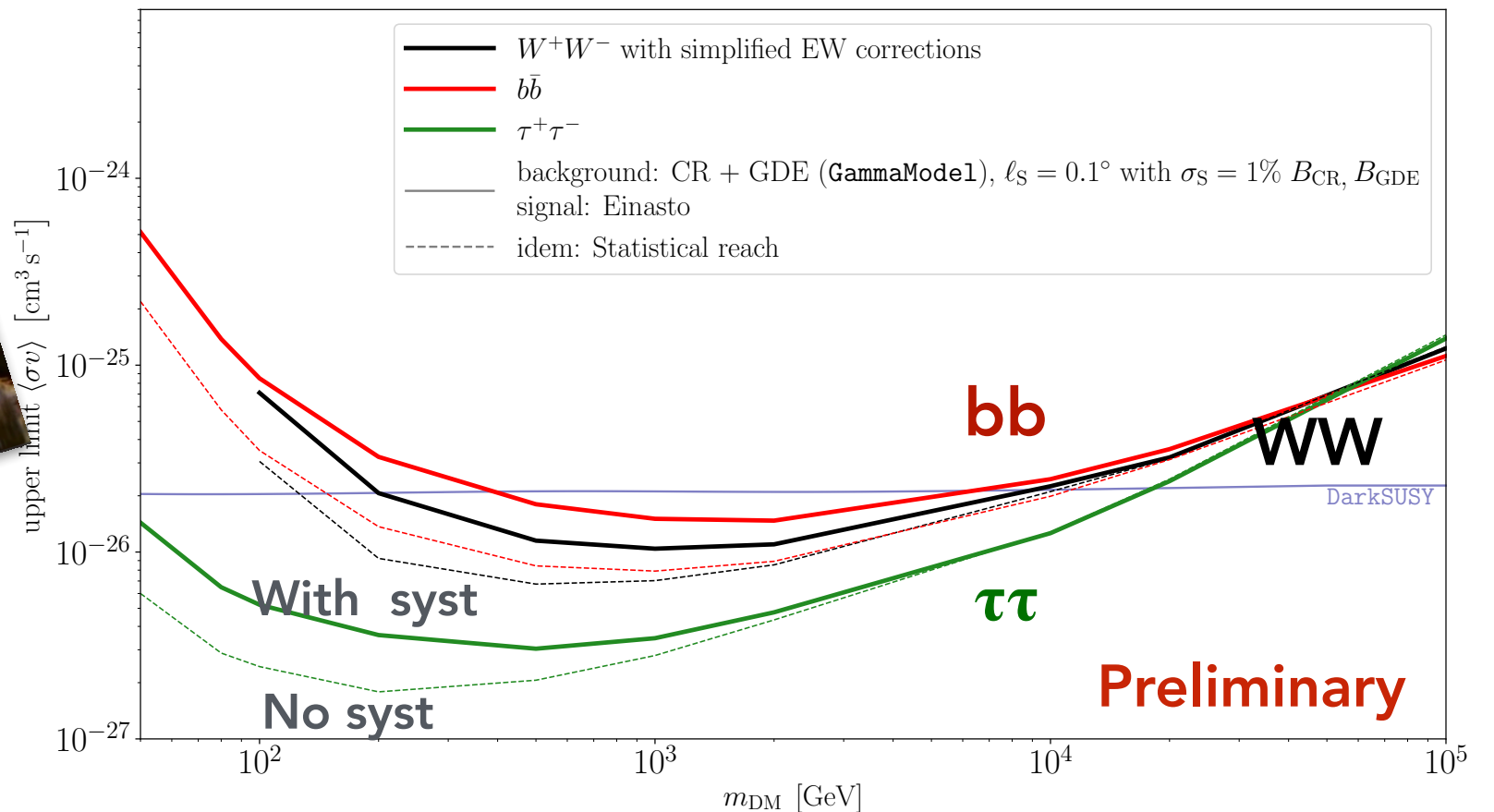
- Even when including up-to-date **astro and instrumental backgrounds**
- And **systematic uncertainties!**

Detection **not guaranteed**:

- Large cores
- Unpredicted astro backgrounds (in any case discovery!)

Still **a good bet !**

- DM density slope can go both ways!
- + Sommerfield enhancements, resonances etc motivated for TeV DM



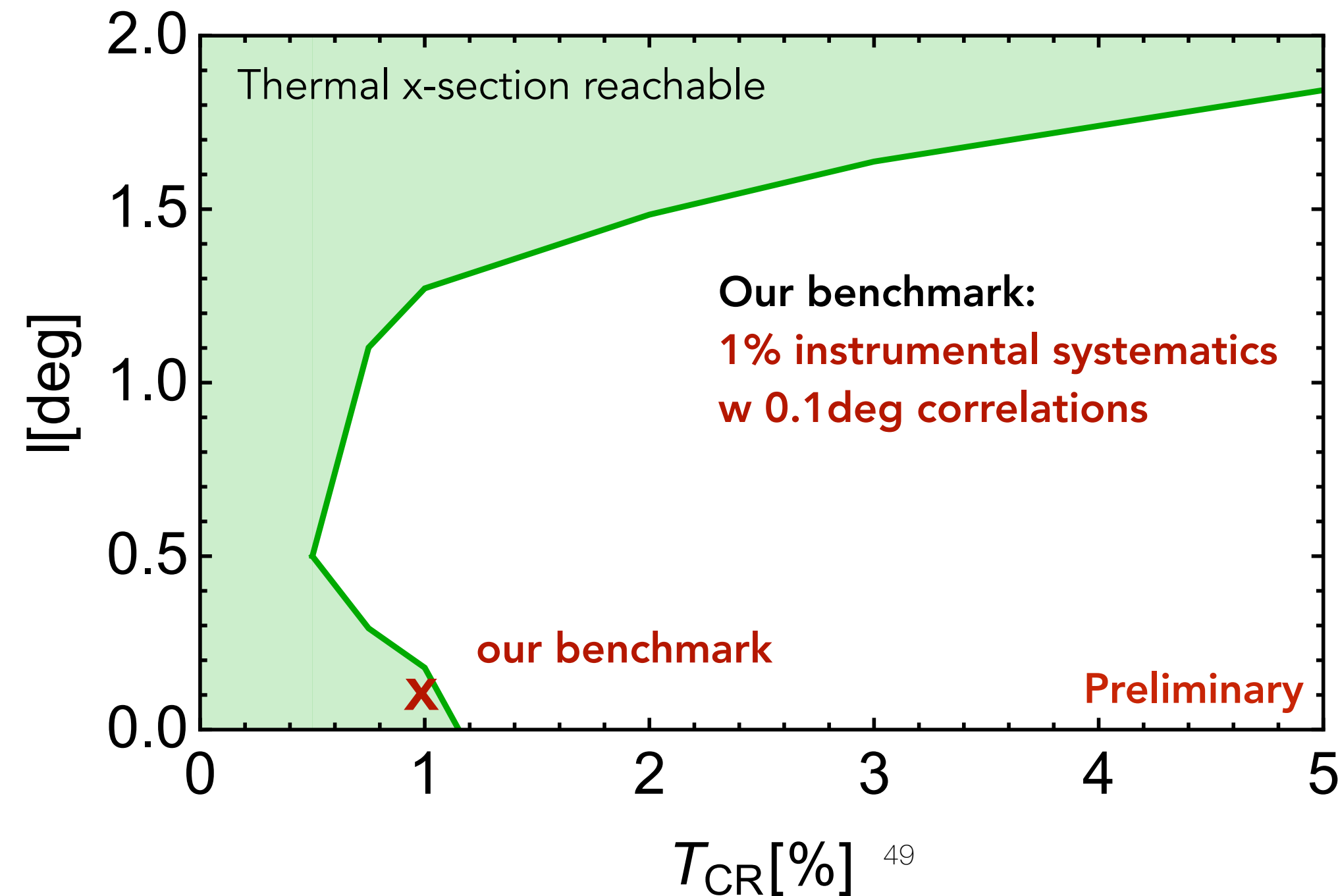
# Extra Slides



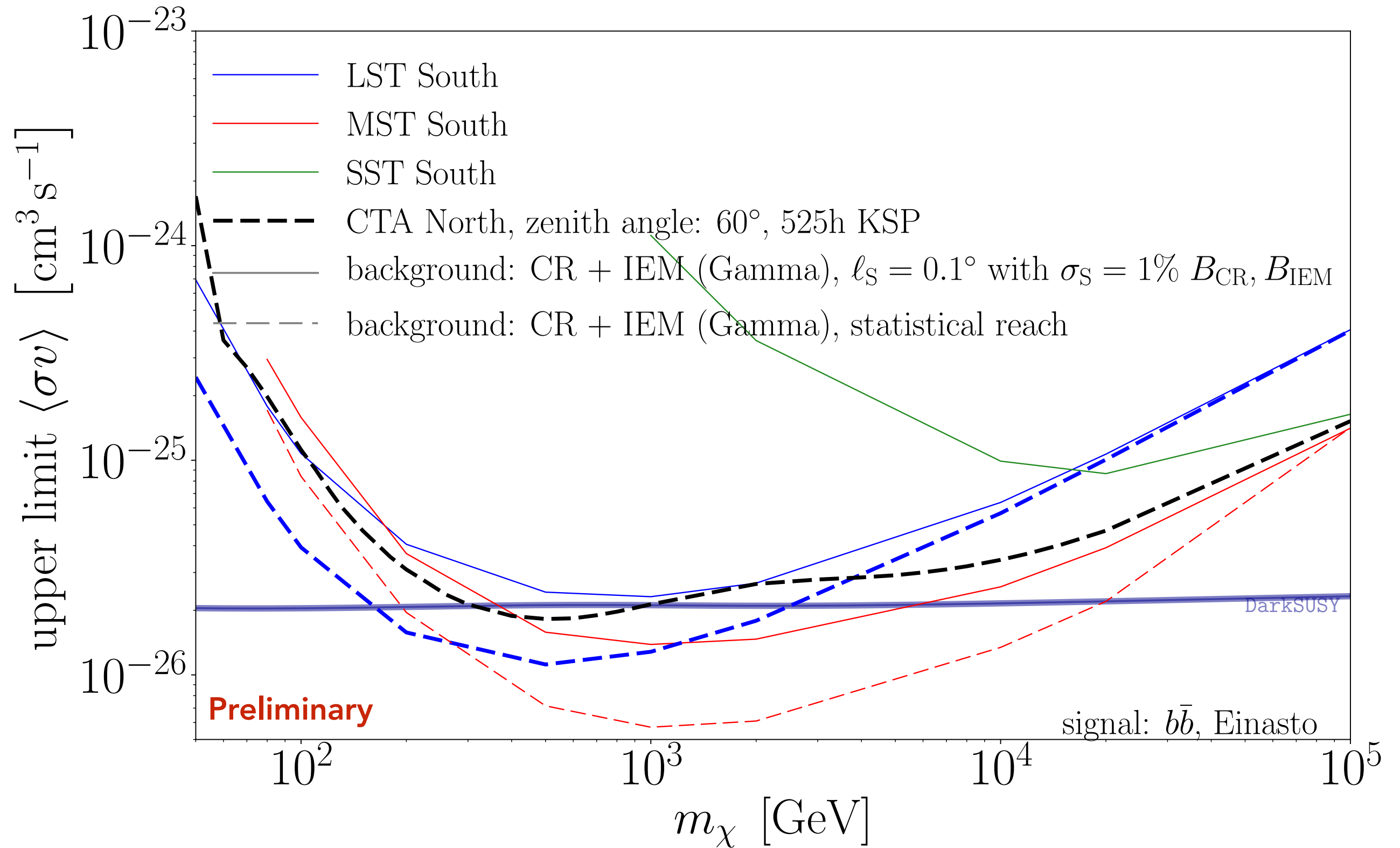
# Results

- Turn the issue around - what systematics can we tolerate and still reach thermal cross section (test WIMP hypothesis) ?
  - Our benchmark point 'reasonable' (~PSF size) and not an 'isolated' case
  - When real data available, could produce a subset of events (event class) to satisfy this criteria

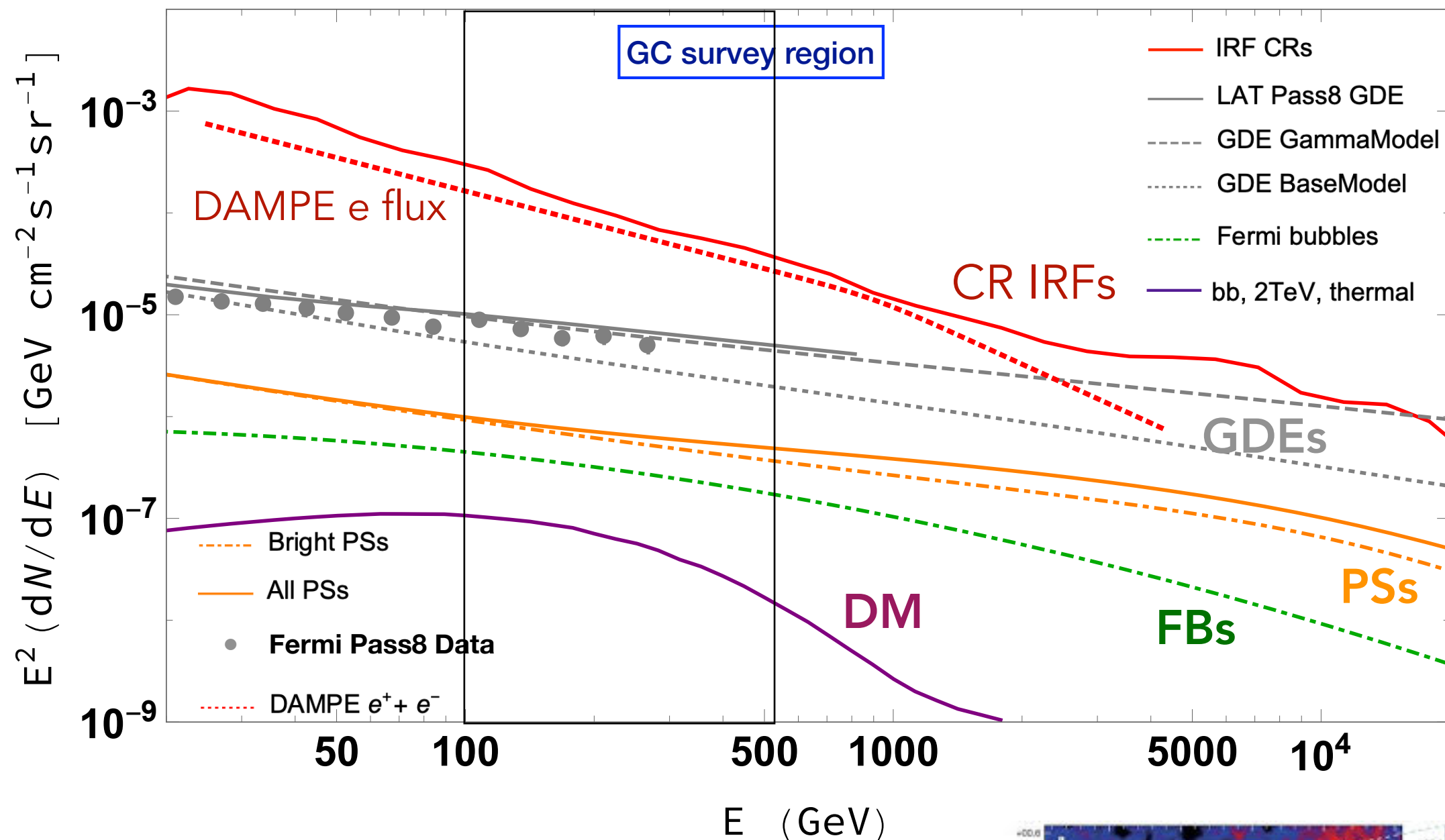
$$M_{\text{DM}} = 2 \text{ TeV}$$



# Sensitivity per telescope type



# A closer look - spectral fluxes



## Diffuse emission

- **Galactic Ridge** emission measured by H.E.S.S.
- **Larger scale emission** ( $b > 0.3$  deg) not probed at TeV energies
  - **Gamma model** (Gaggero+, PRL 2017)
  - **Base model** (Gaggero+, PRL 2017)
  - **Pass-8 Fermi diffuse model** ('safe' to extrapolate  $< \sim$  TeV)

