The challenge for TeV-scale WIMP Dark Matter

by observing Very-High-Energy Gamma rays around the Galactic Centre with the MAGIC telescopes

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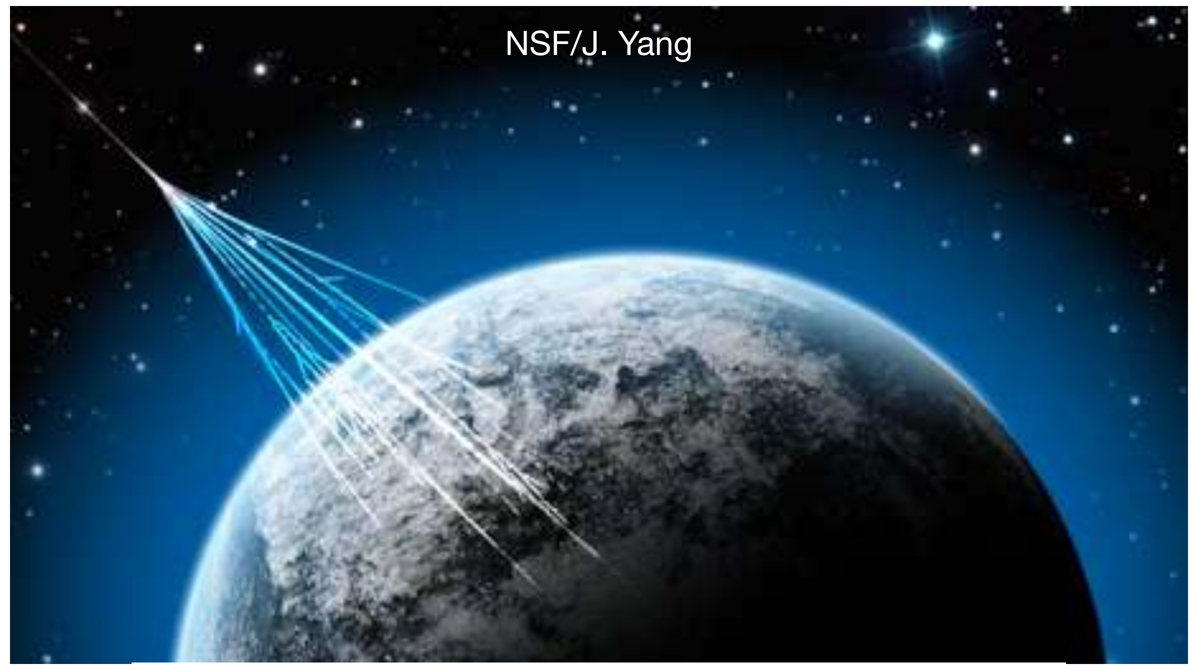
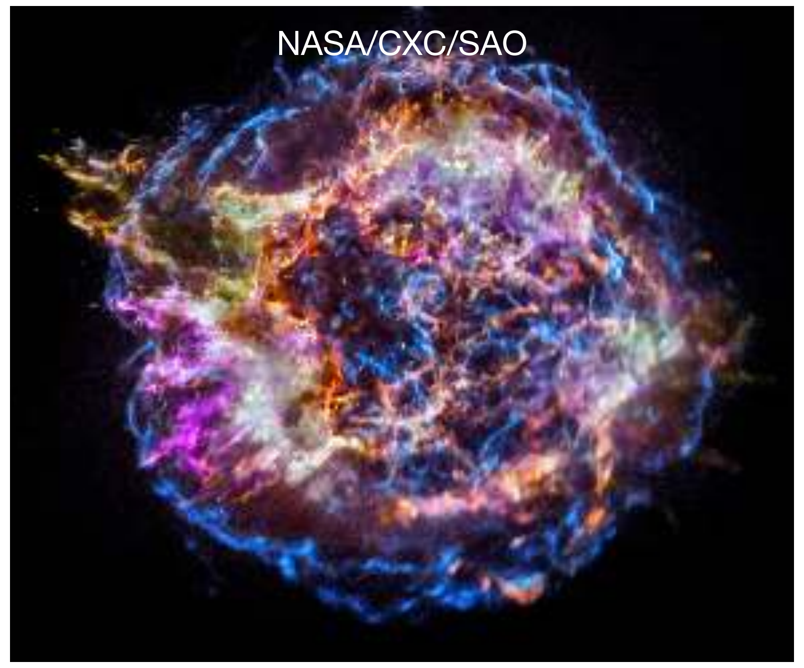
© Urs Leutenegger 2021 Nightscape Photography

High energy phenomena in the universe


NSF/J. Yang

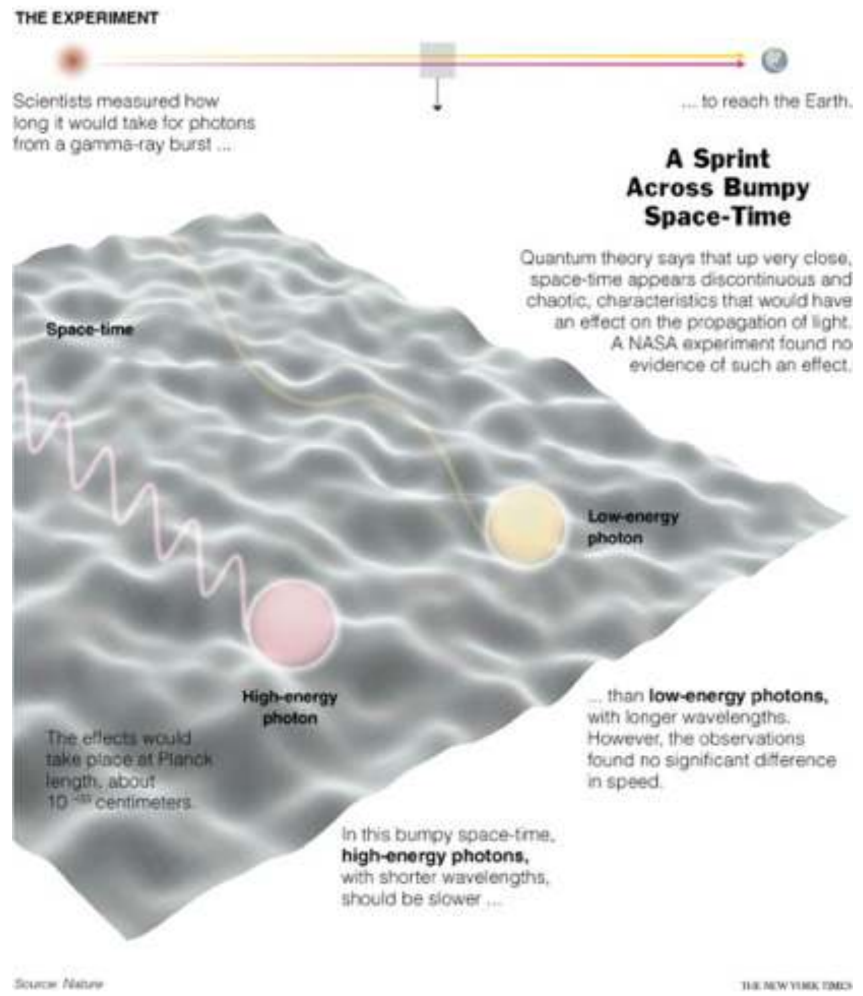
Origin of Cosmic Rays


NASA/CXC/SAO

Supernova Remnant


NASA

Supermassive Black Hole



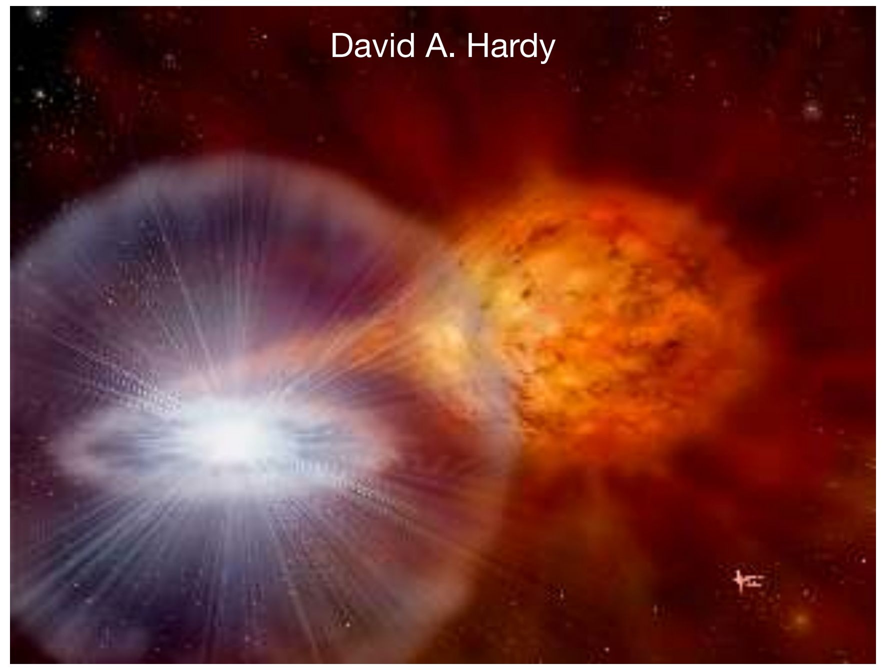
Bounds on Lorentz Invariance Violation


NASA/ESA/M. Kornmesser

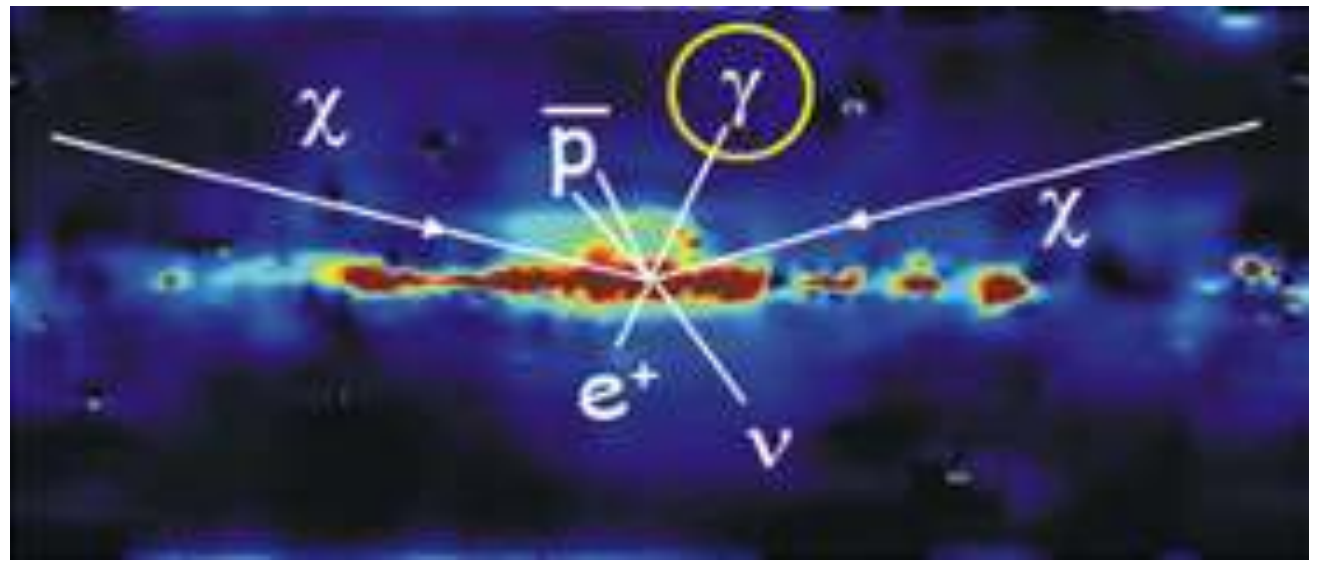
Gamma Ray Burst


NASA/CXC/CfA

Active Galactic Nuclei


David A. Hardy

Binary / Nova

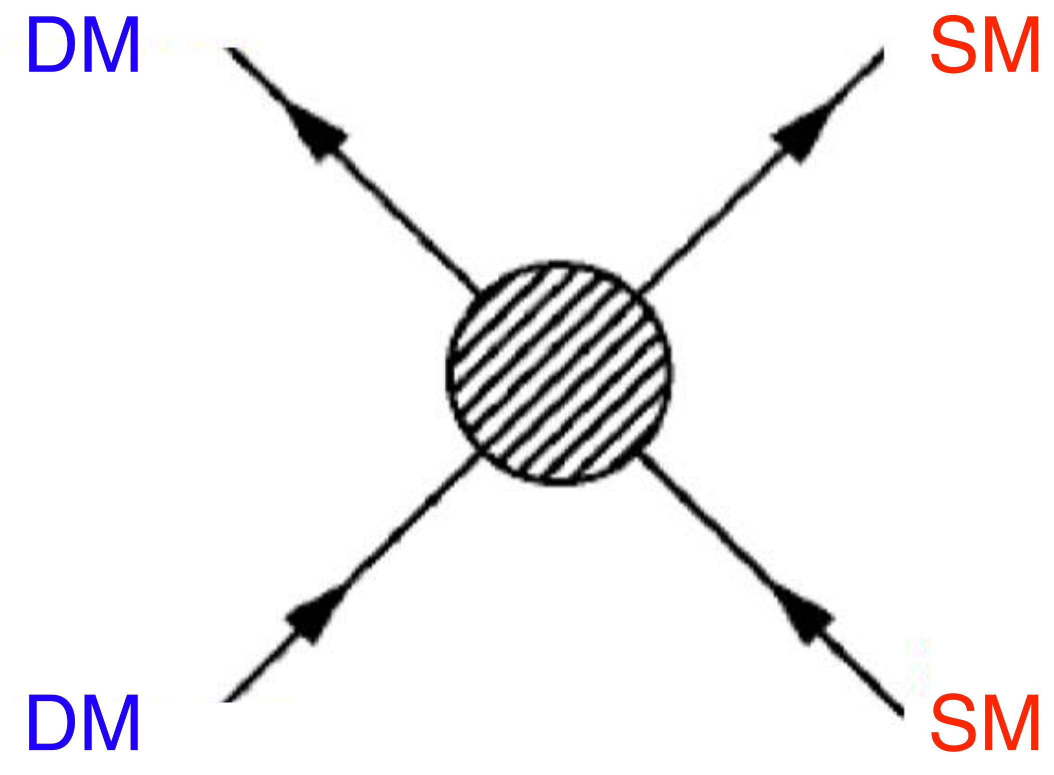


Dark Matter Search

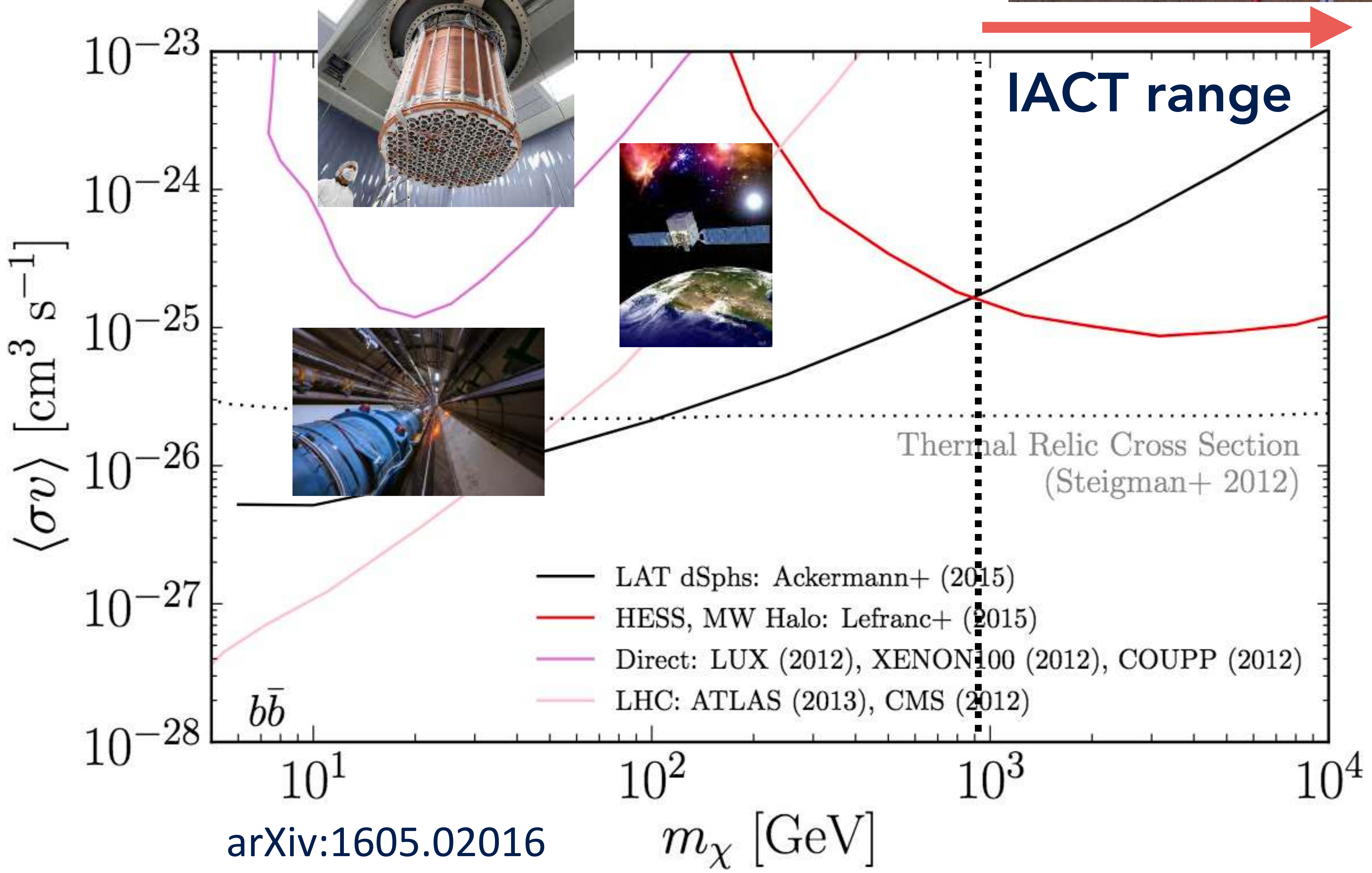
There are plenty of interesting topics in High Energy Universe

Why do we search for dark matter?

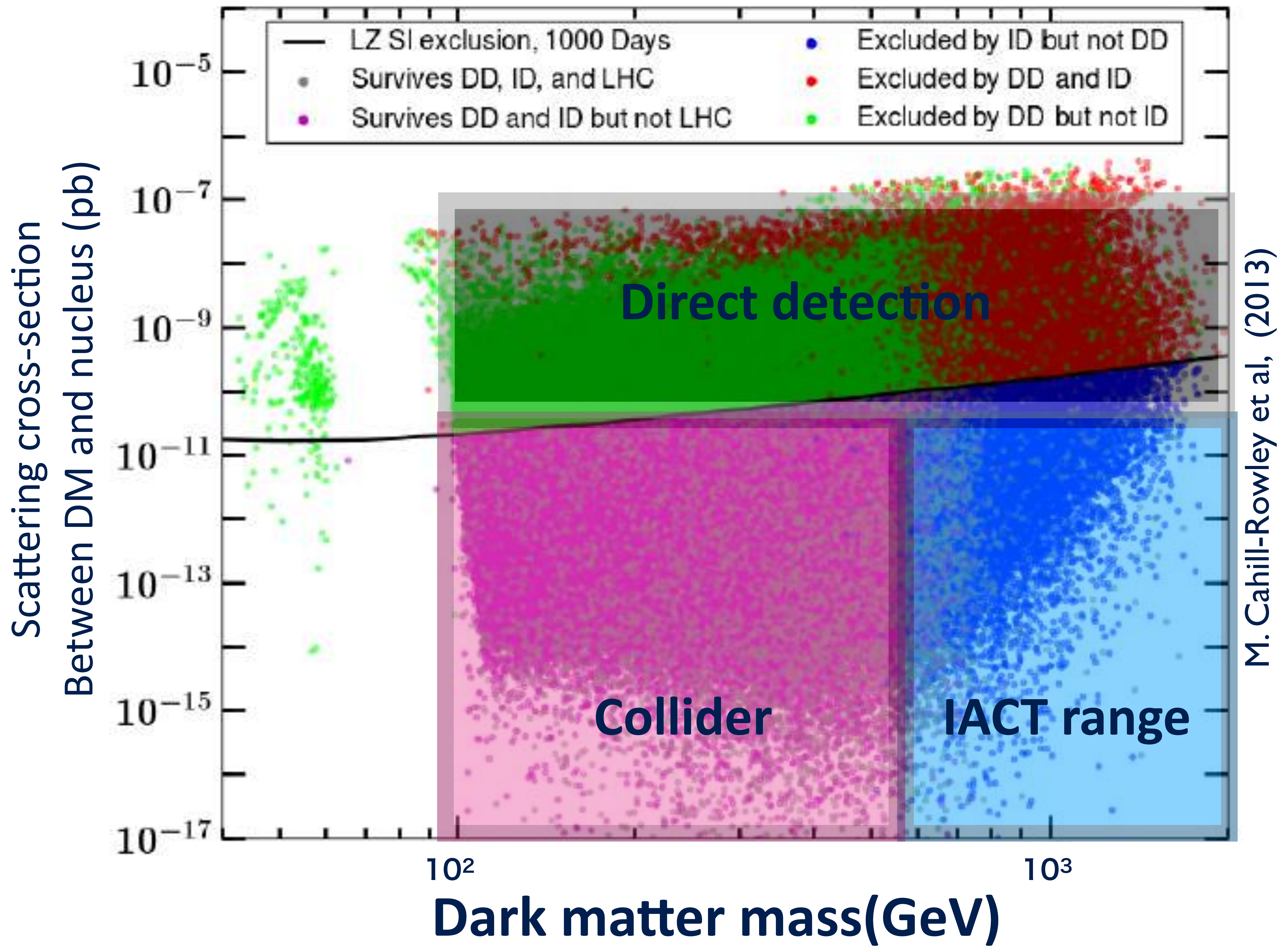
Complementarity of WIMP DM Searches



Various experiments covers huge DM parameter space
→ TeV-scale: well-covered by IACTs



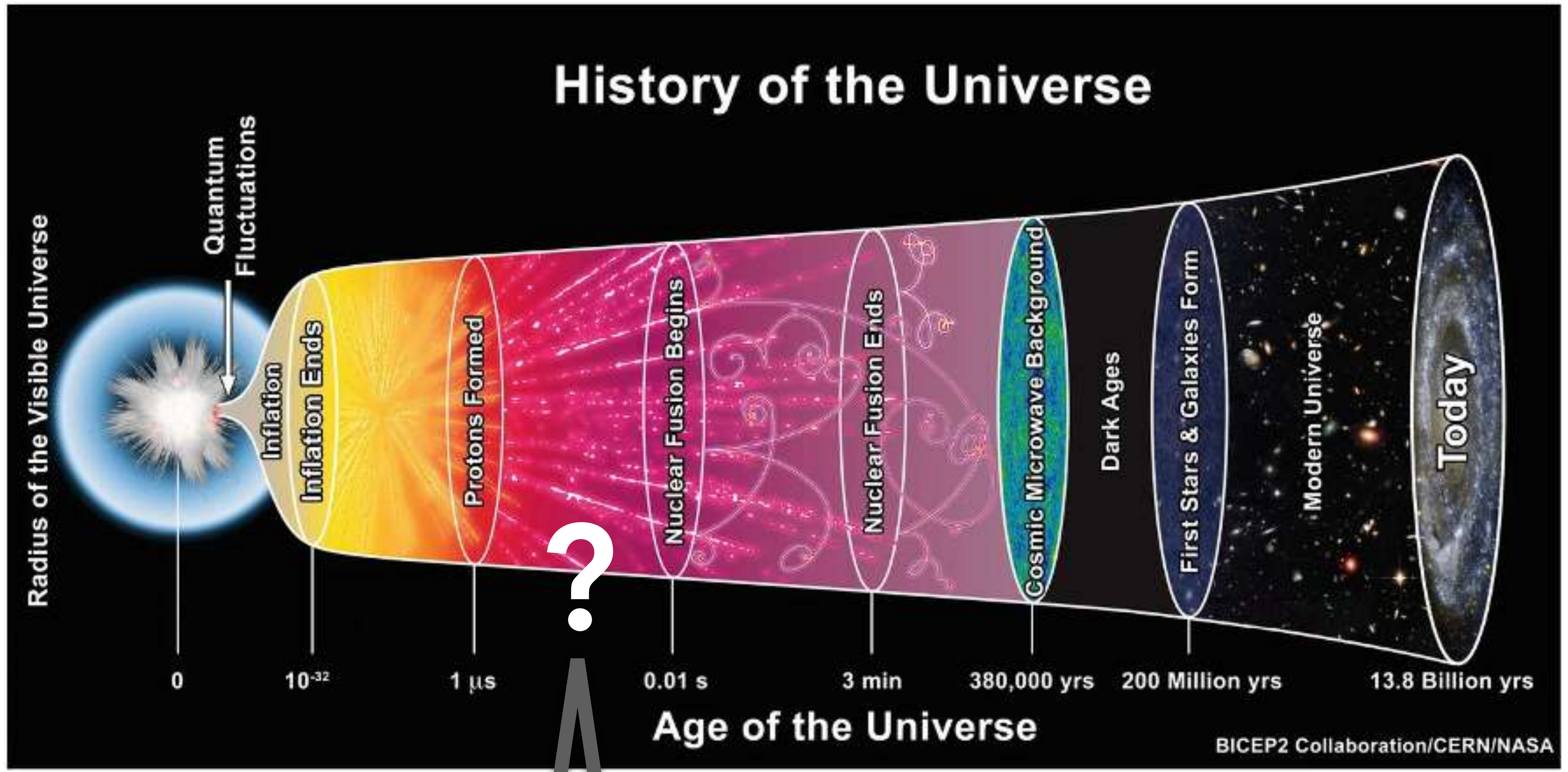
arXiv:1605.02016



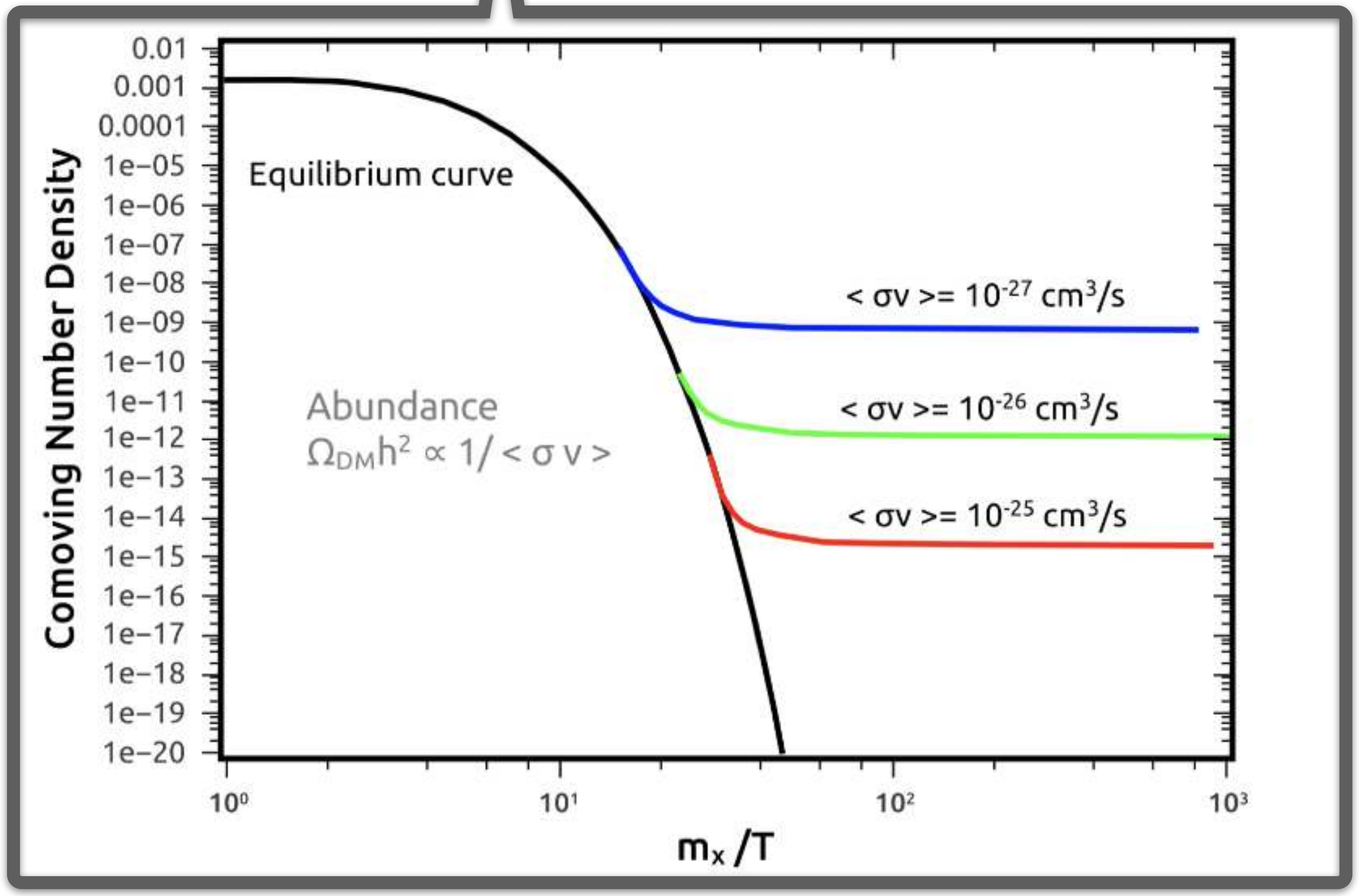
M. Cahill-Rowley et al, (2013)

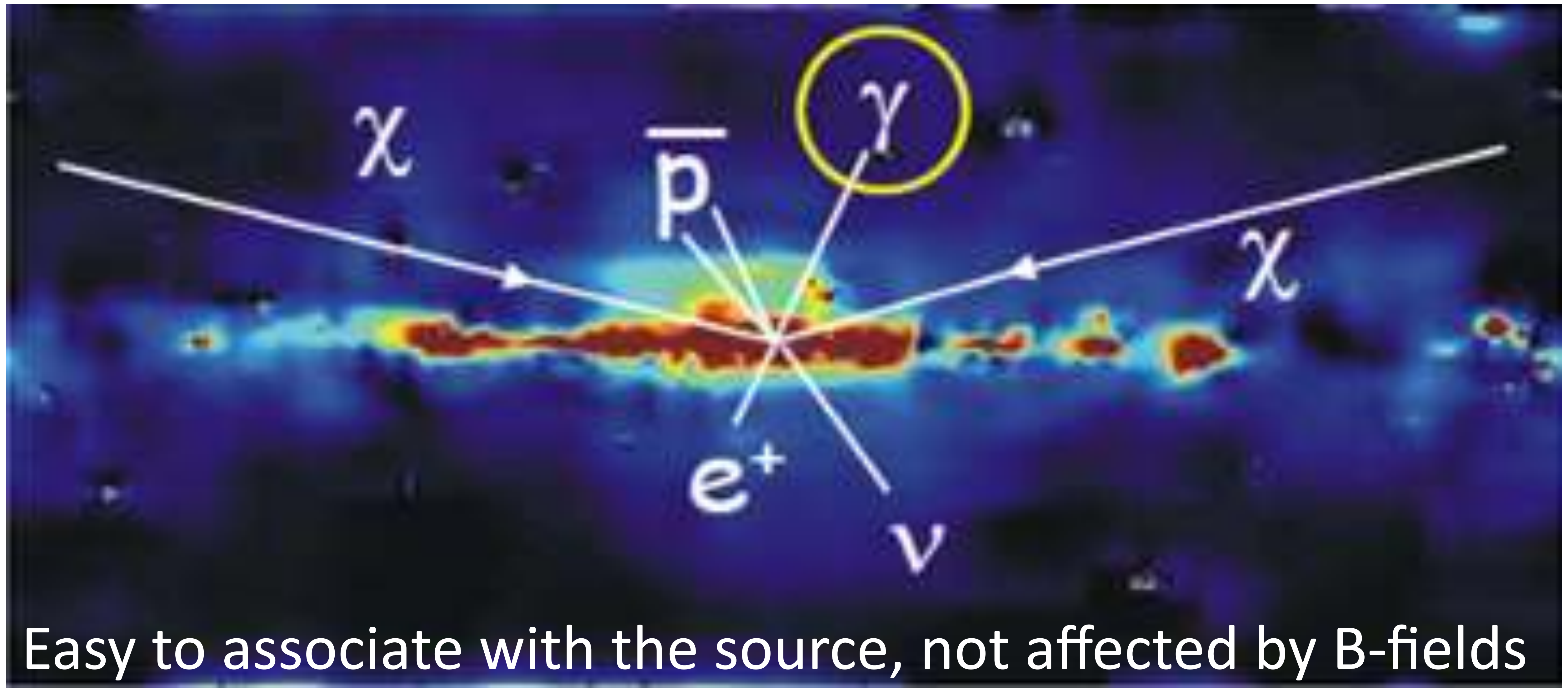
Why indirect and gamma-ray?

- **Test of particle DM**
  - DM mass, a coupling constant… particle information
- **Test of DM production mechanism**
  - When produced? Thermally freeze-out or not
  - Measure annihilation cross-section
    - Benchmark: $\langle\sigma v\rangle \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$
    - So-called **"thermal relic" cross-section**



BICEP2 Collaboration/CERN/NASA



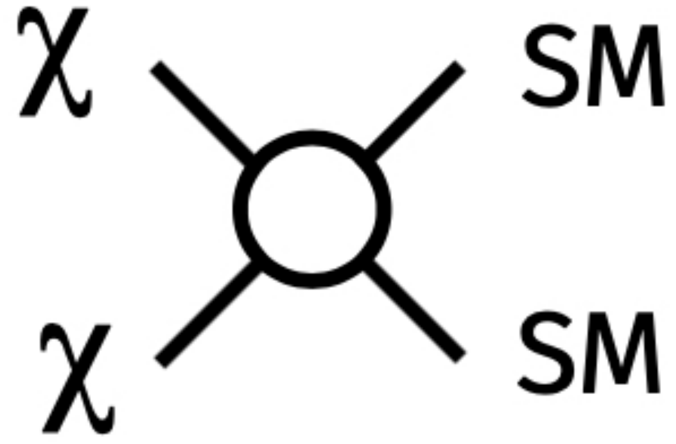


Easy to associate with the source, not affected by B-fields

Expected gamma-ray flux from DM annihilation/decay

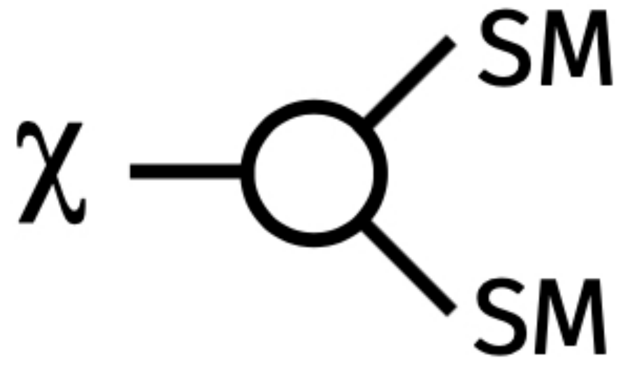
Annihilation

$$\frac{d\Phi^{ann.}}{dE_\gamma} = \frac{1}{4\pi}\frac{\boxed{\sigma v}}{2m_\chi^2} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho^2(s,\ \Omega)$$



Decay

$$\frac{d\Phi^{dec.}}{dE_\gamma} = \frac{1}{4\pi}\frac{1}{m_\chi \boxed{\tau_\chi}} \times \sum_i Br_i \frac{dN_\gamma^i}{dE} \times \int_{\Delta\Omega}\int_{los} ds\ \rho(s,\ \Omega)$$



Particle physics term

σv : annihilation cross-section, τ : lifetime

$m\chi$: Mass of DM particle

BR_i : branching ratio of each channel

dN^i/dE : differential gamma-ray yield of each channel

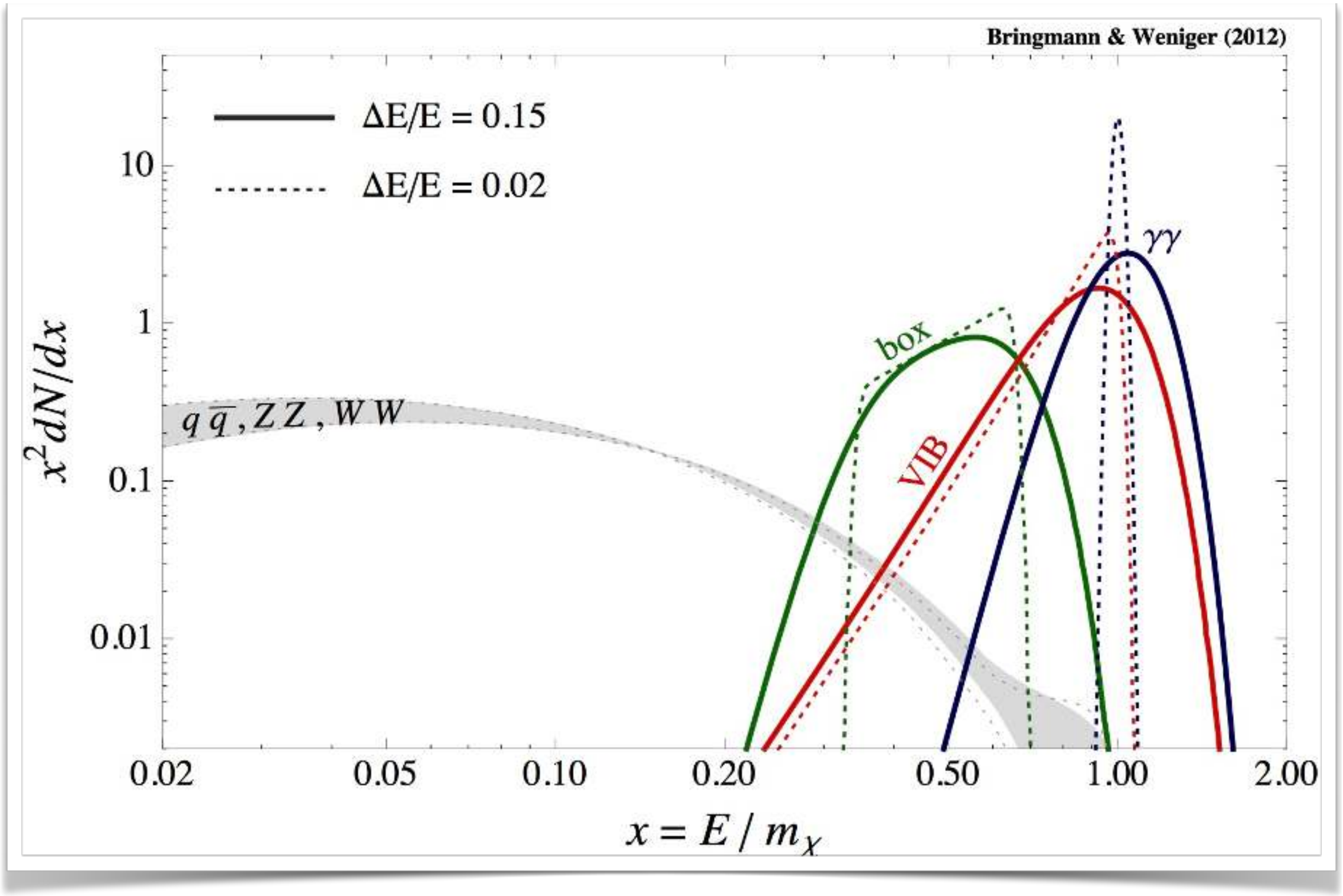
Astrophysics term

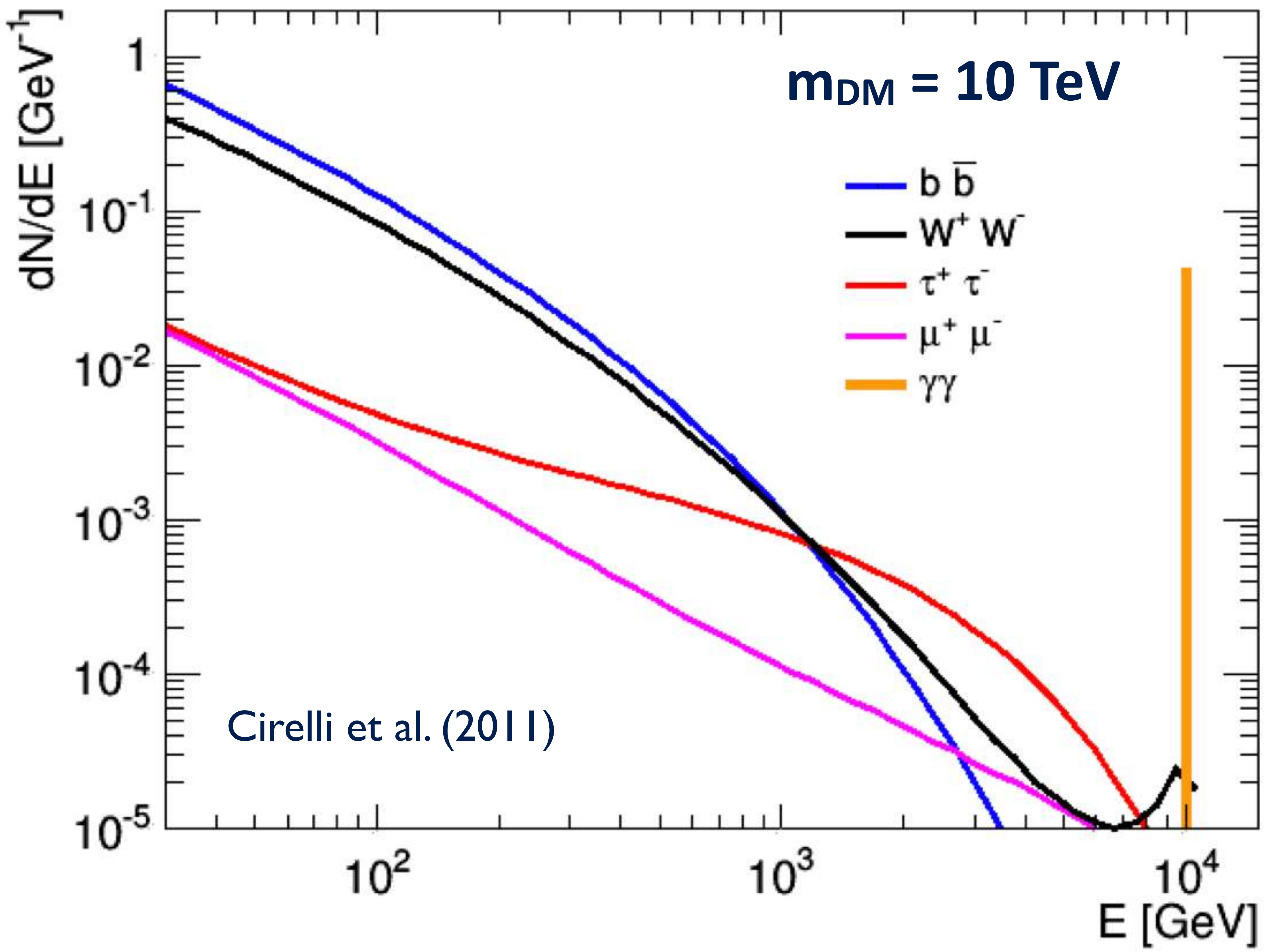
ρ : dark matter density

J-factor : Integrated DM density along the line of sight

(in case of decay. Called “D-factor”)

Gamma-ray spectra from DM





Continuum spectra

- Sharp cut off at DM masses

Line-like emission

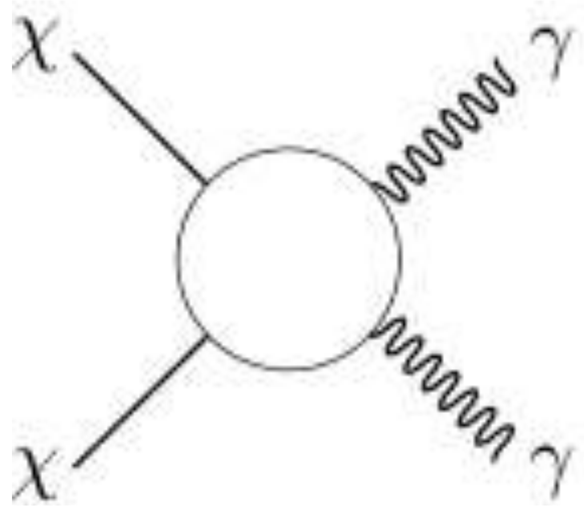
- clear peak, no contamination astrophysical component

TeV DM particles: most energy deposited in **GeV-TeV final state** particles:

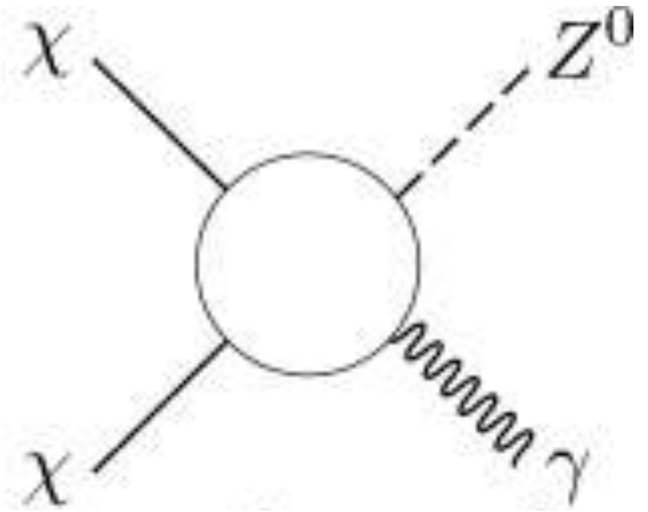
→High energy astronomy regime

Motivation for Gamma-ray Line search

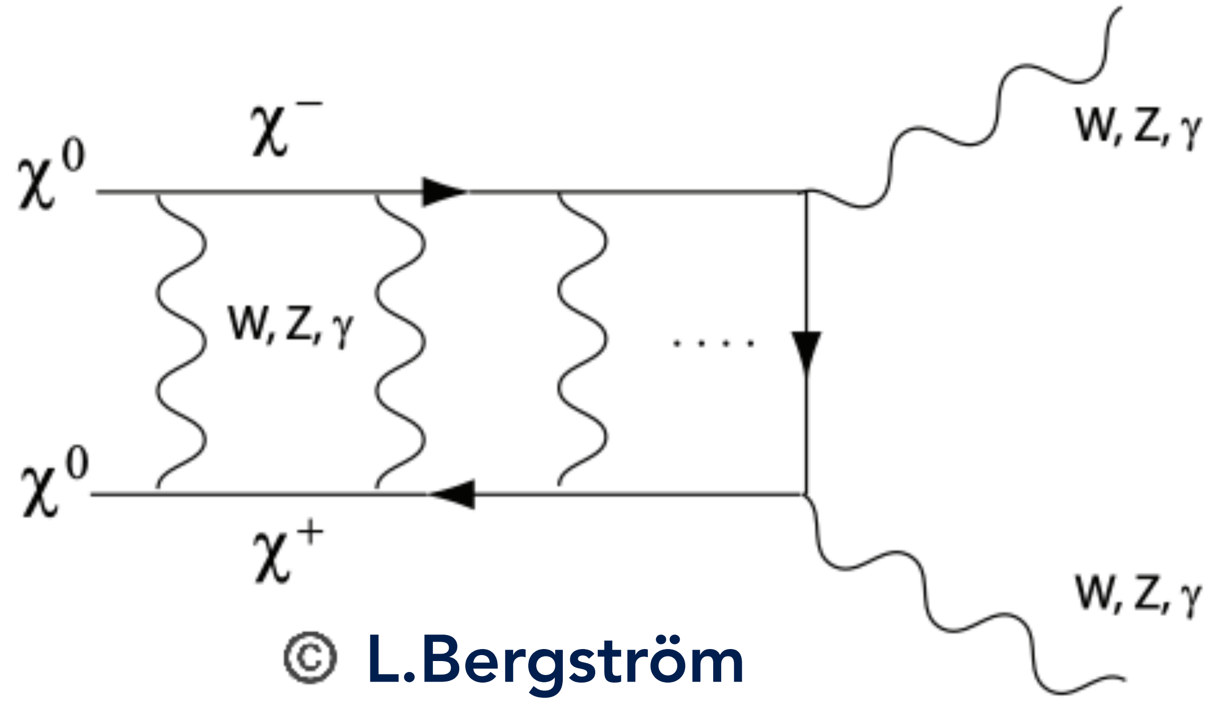
- **Clear peak at DM mass:** No astrophysical contamination
- Loop-suppressed by α^2 (i.e. the fine-structure constant)
- Some heavy DM (e.g. SUSY) models enhance their annihilation rate, called **Sommerfeld enhancement**



$\chi\chi \rightarrow \gamma\gamma$

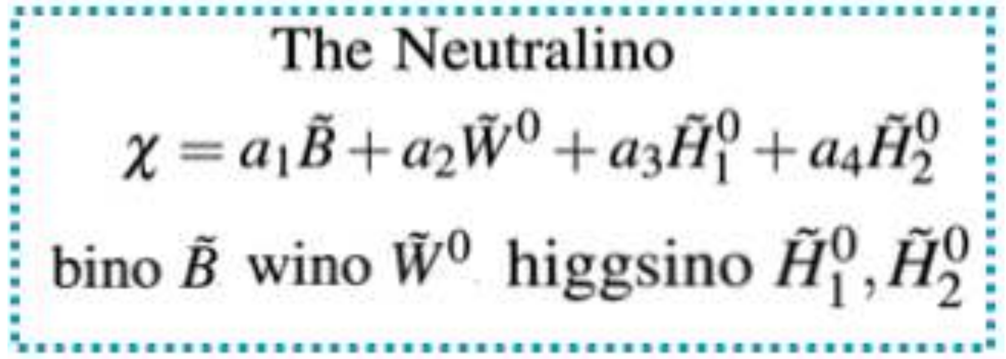


$\chi\chi \rightarrow Z\gamma$



© L.Bergström

One of good DM candidates in SUSY (Lightest SUSY Particles, LSPs)



The Neutralino

$\chi = a_1\tilde{B} + a_2\tilde{W}^0 + a_3\tilde{H}_1^0 + a_4\tilde{H}_2^0$

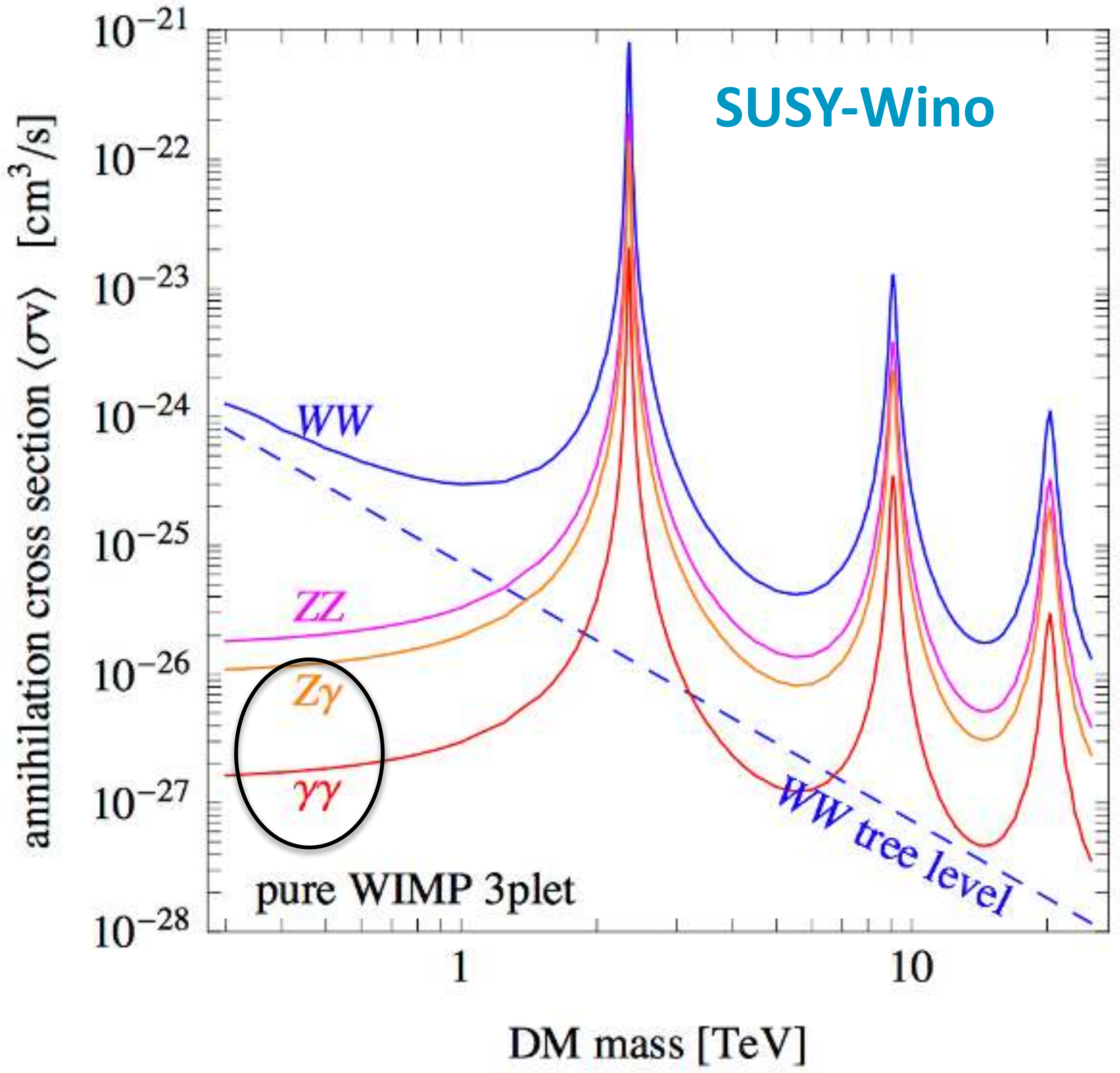
bino $\tilde{B}$ wino $\tilde{W}^0$ higgsino $\tilde{H}_1^0, \tilde{H}_2^0$

DM relic density constraints: $\Omega h^2 < 0.1$

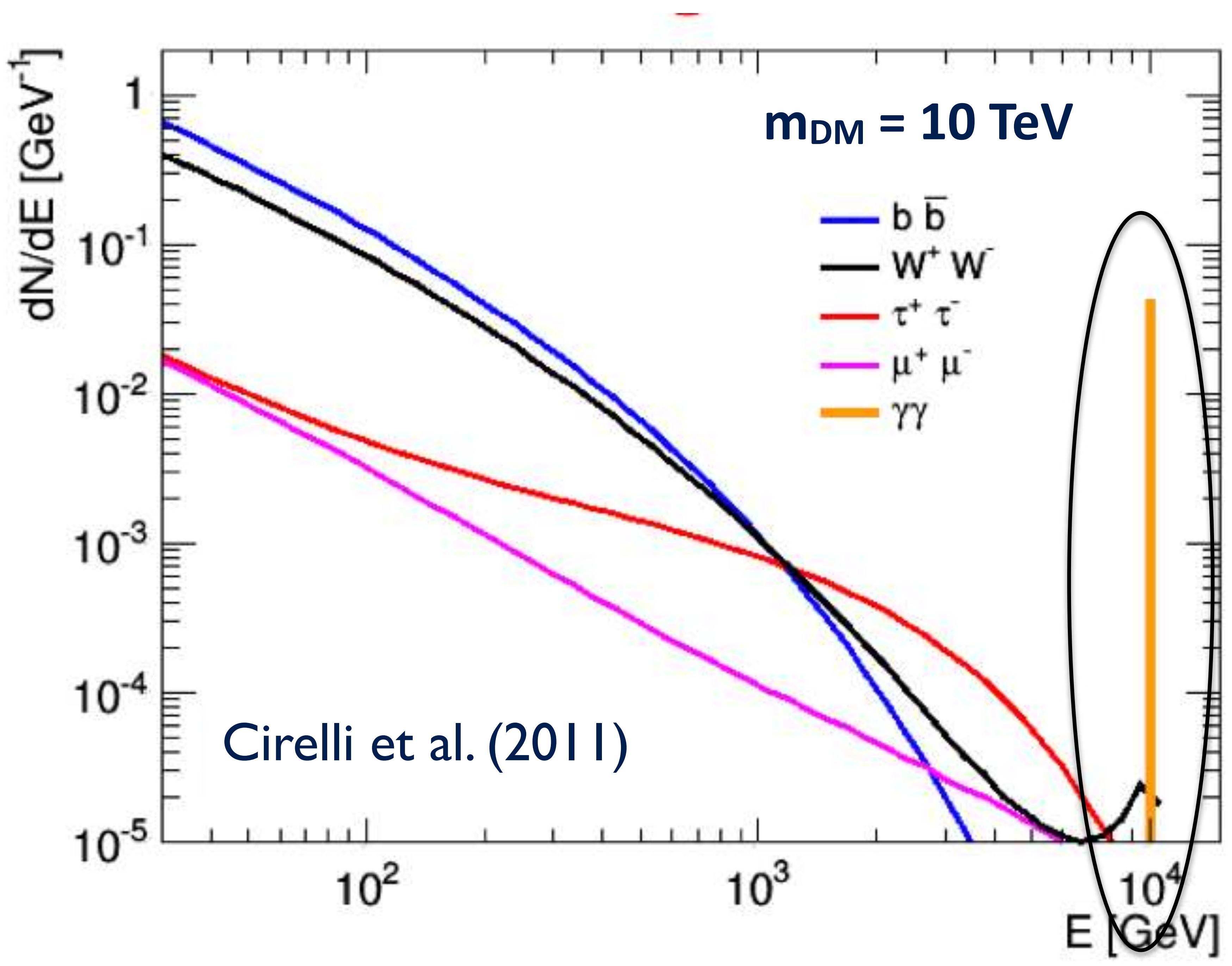
If **Wino is < 3 TeV**, it can explain the DM relic density perfectly.

→makes sense to search for TeV-scale DM

Ref.
J. Hisano, et al.,2005
M. Cirelli, N. Fornengo and A. Strumia (2006)
H.E.S.S. collaboration JCAP11(2018)



SUSY-Wino



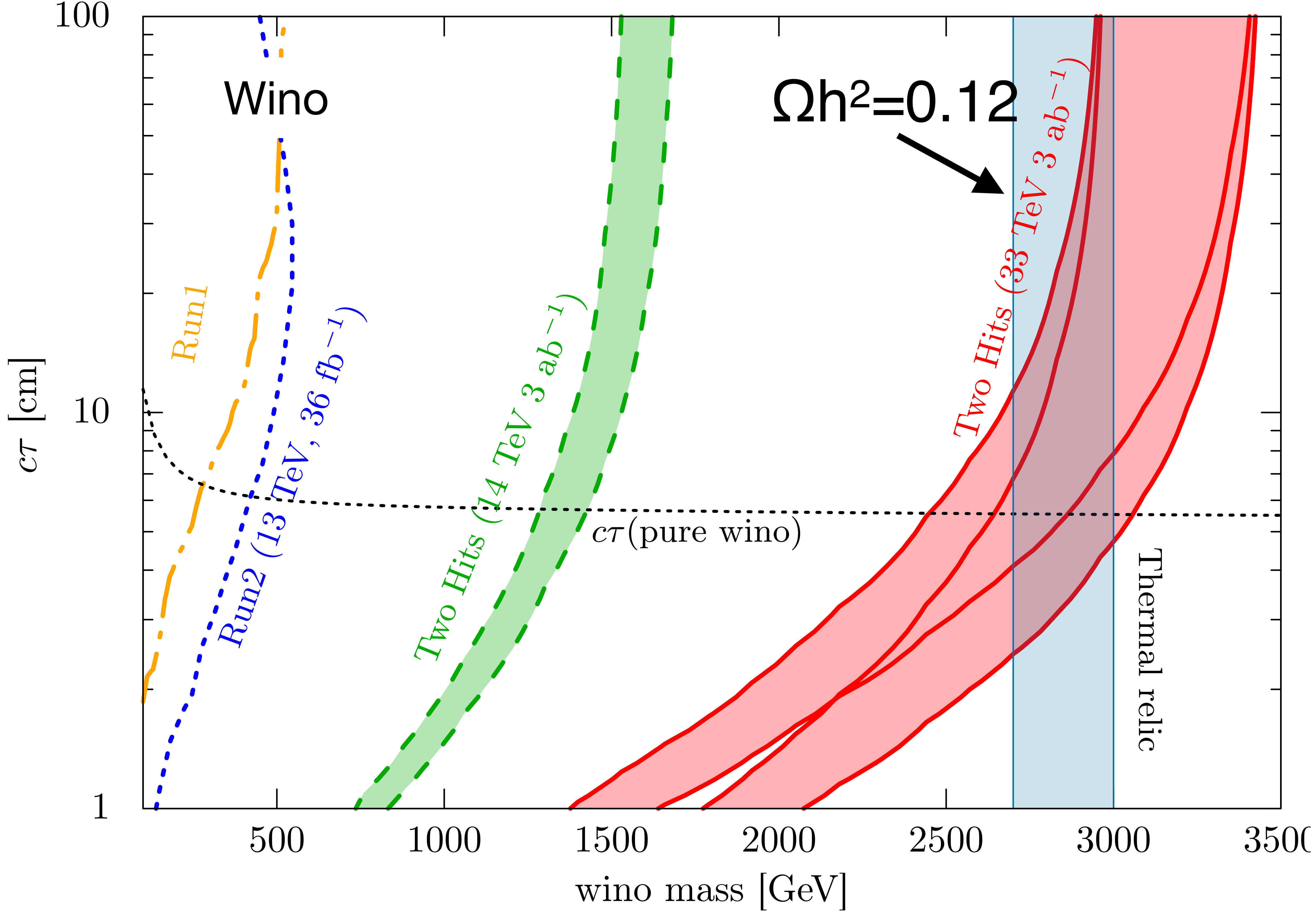
m_{DM} = 10 TeV

Cirelli et al. (2011)

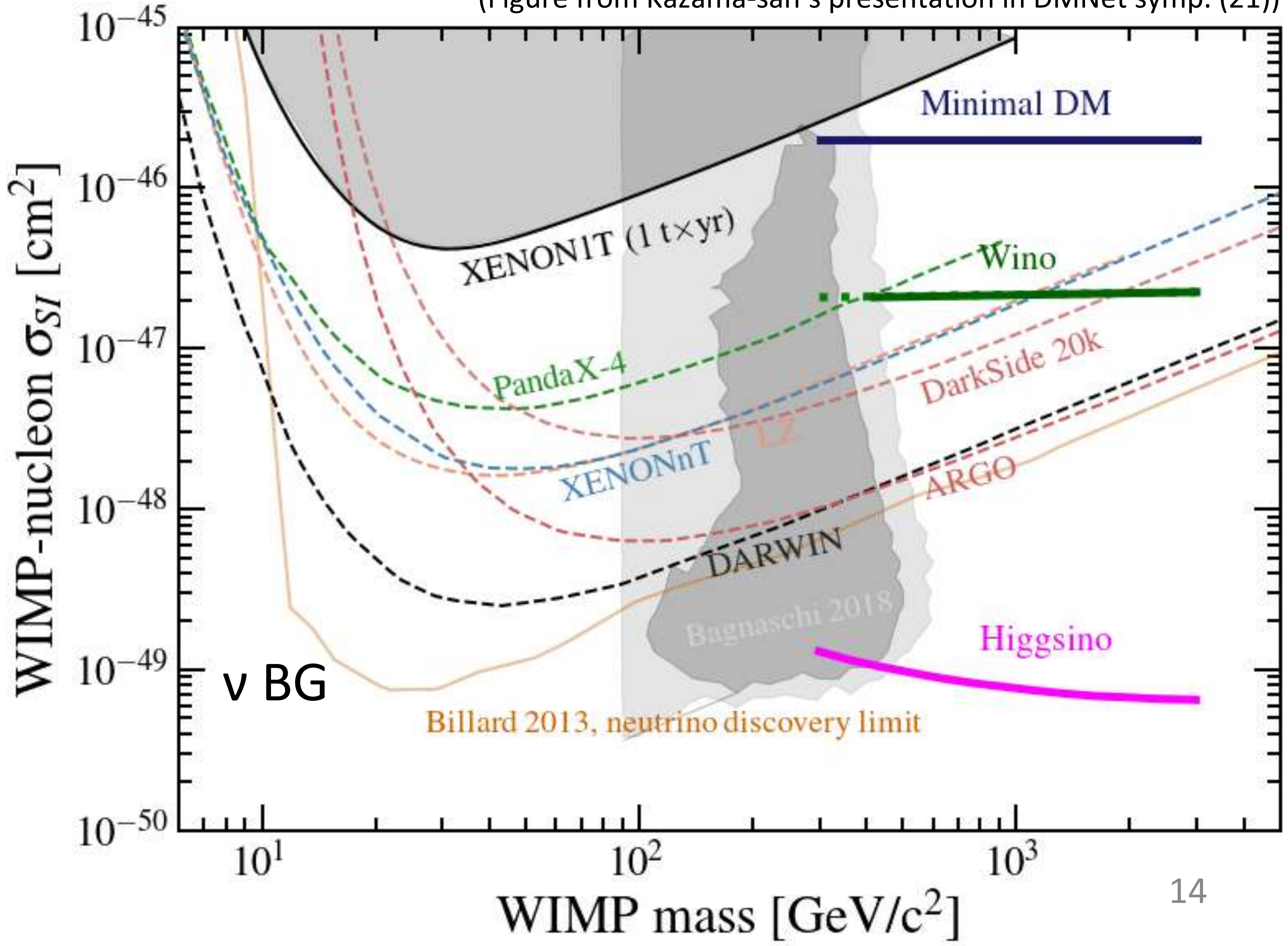
Complementary Searches for SUSY-Wino

- **SUSY-Wino: a kind of common targets in various experiments with many efforts!**
- **Comprehensive understanding with different techniques are essential.**

HL-LHC projections 1703.09675

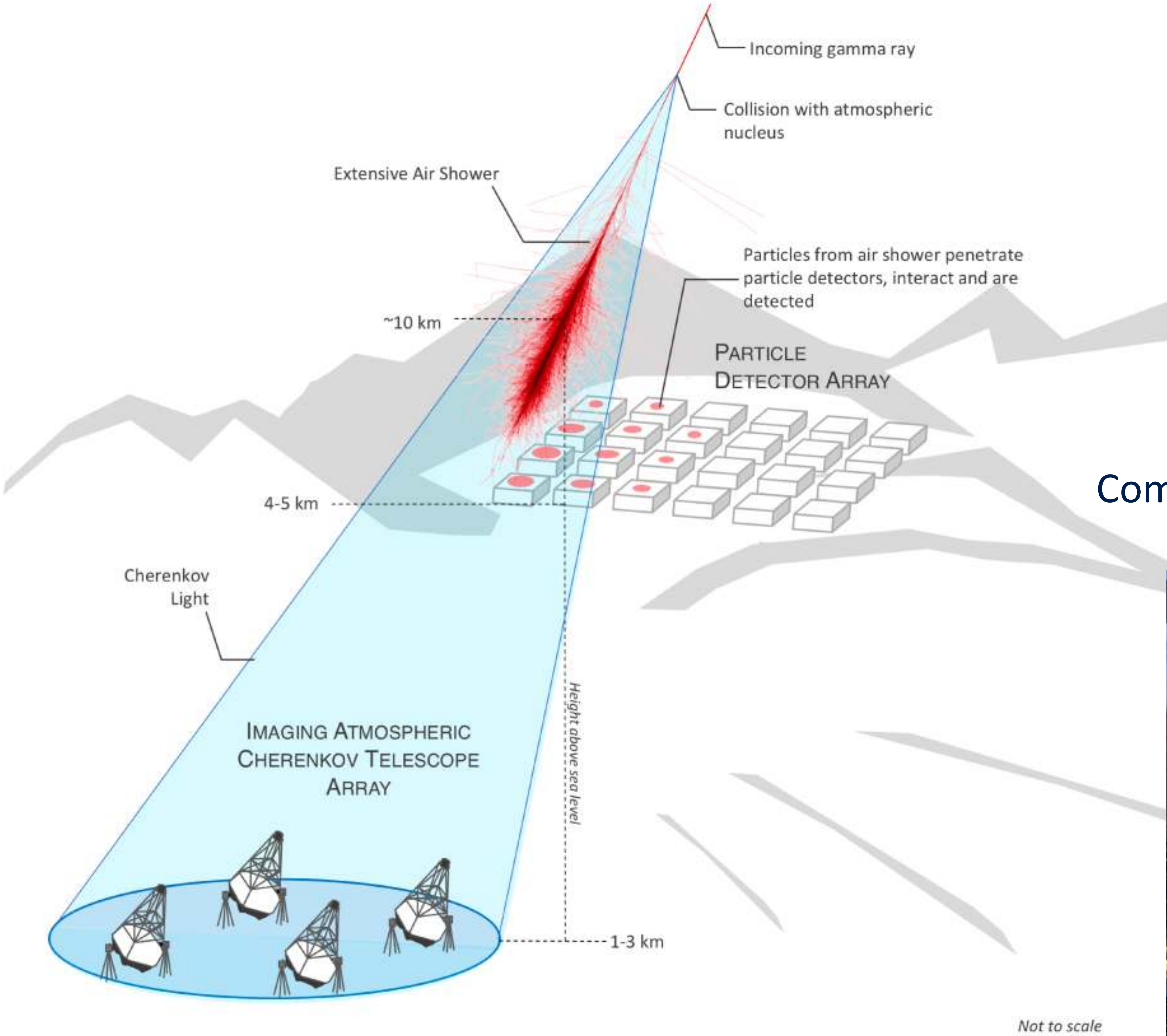


(Figure from Kazama-san's presentation in DMNet symp. (21))



Imaging Atmospheric Cherenkov Telescopes

Gamma-ray detectors

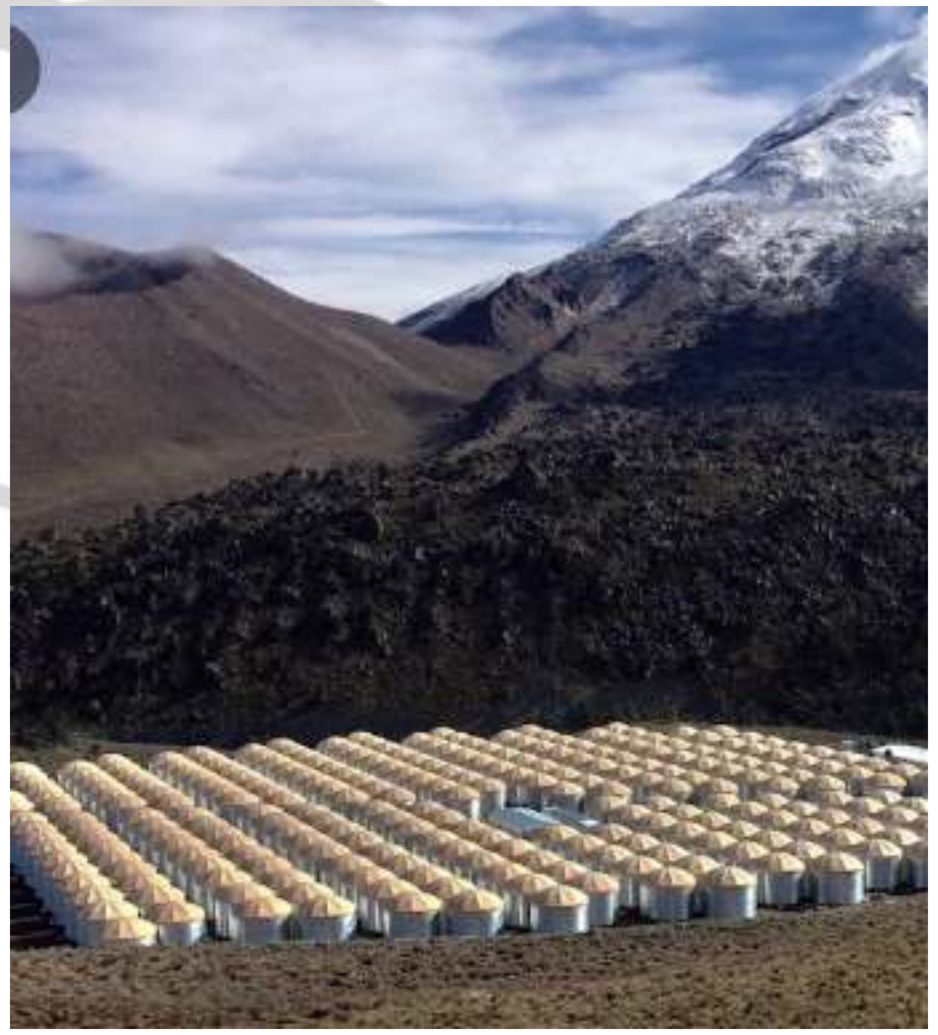


credit: Richard White, MPIK

MeV-GeV range
Satellite-borne detectors

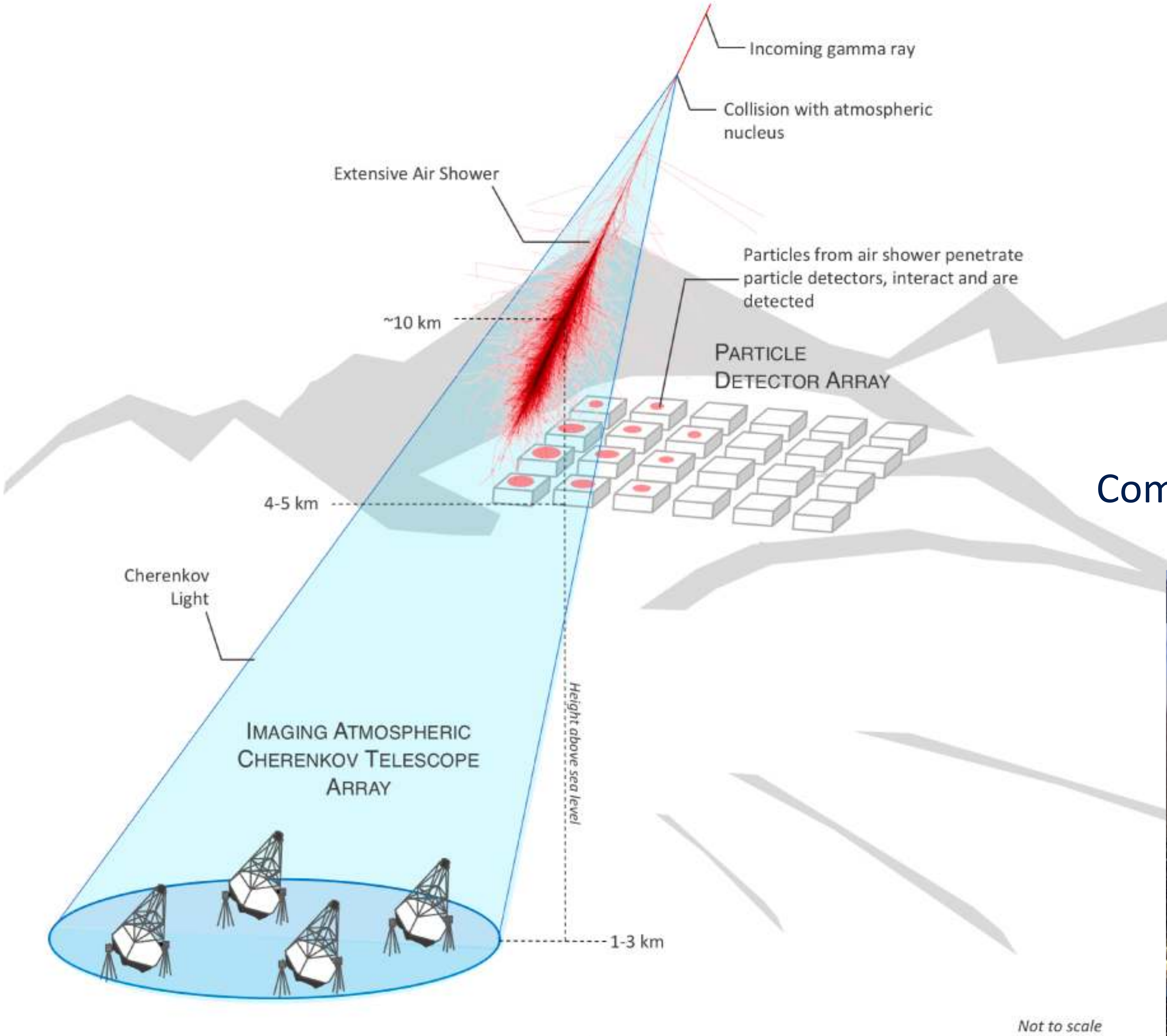
TeV range
Ground-based detectors (light)

TeV-PeV range
Compact Ground based detectors (particles)



>PeV range
Wide Ground-based detectors (particles)

Gamma-ray detectors



credit: Richard White, MPIK

MeV-GeV range

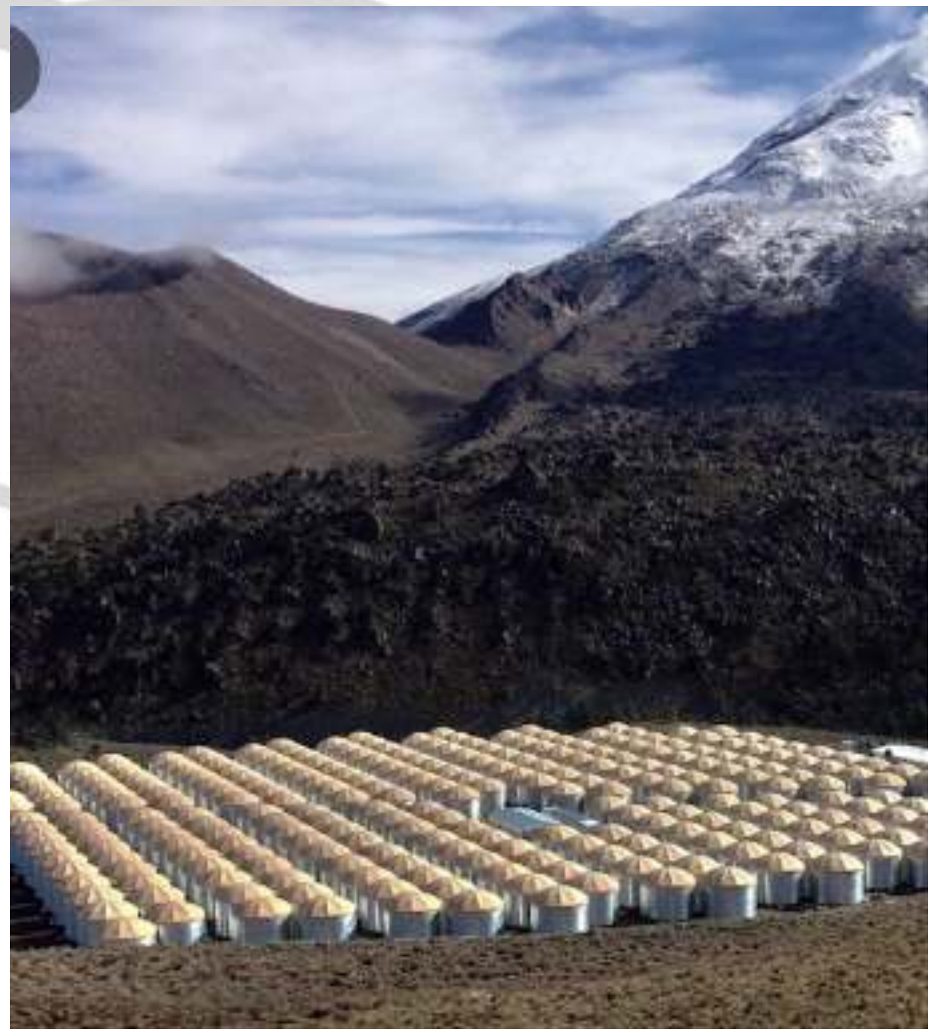
Satellite-borne detectors

TeV range

Ground-based detectors (light)

TeV-PeV range

Compact Ground based detectors (particles)



>PeV range

Wide Ground-based detectors (particles)

Imaging Atmospheric Cherenkov Telescopes (IACTs)

VERITAS
Dia. 12m × 4 tels.

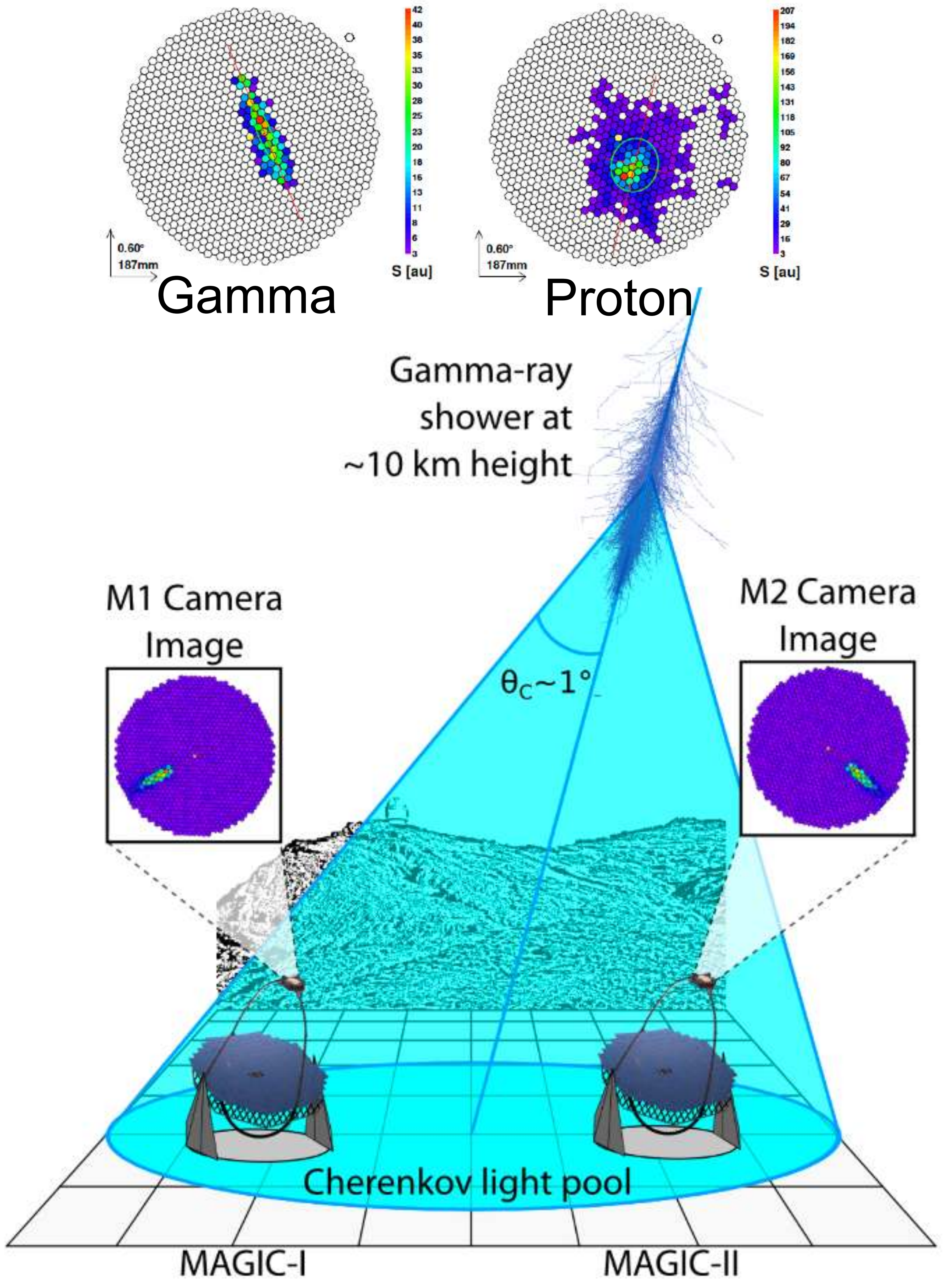
MAGIC
Dia. 17m × 2 tels.

CTA-LST
Dia. 23m × 4 (1) tels.

H.E.S.S. II
Dia. 12m × 4 tels.
+
Dia. 28m tel

The MAGIC telescopes

- Observatorio del Roque de los Muchachos (ORM)
  - ~ 2200 m a.s.l., La Palma, Canary Islands, Spain
  - 2-telescope stereoscopic system
    - 17m diameter
- Energy : 50 GeV - 50 TeV (Low Zd ~20°)
- FoV : 3.5°
- Angular resolution : 0.06° @ 1 TeV
- Energy resolution : 15 % - 25 %



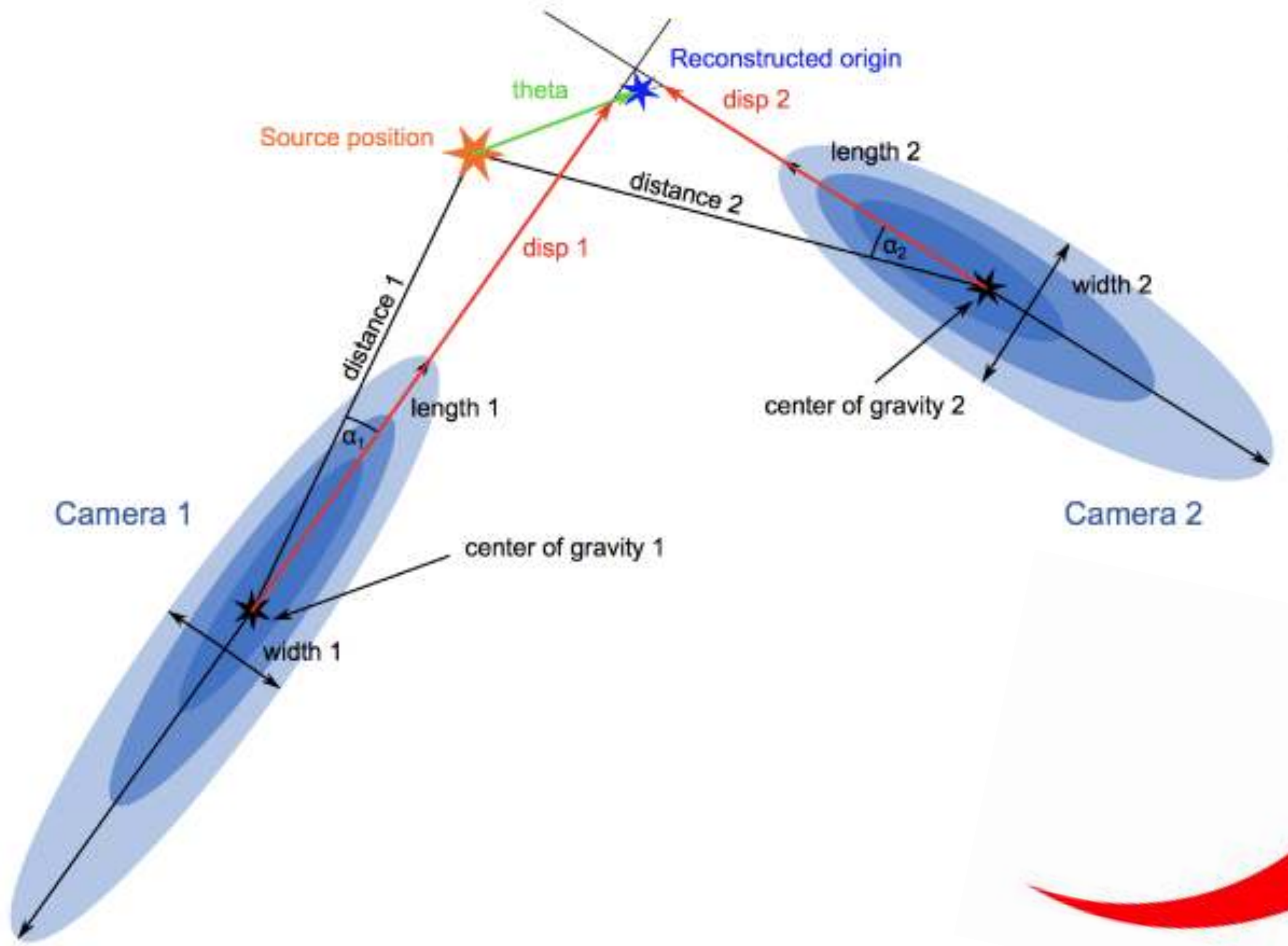
The IACT techniques

Image analysis with shower images

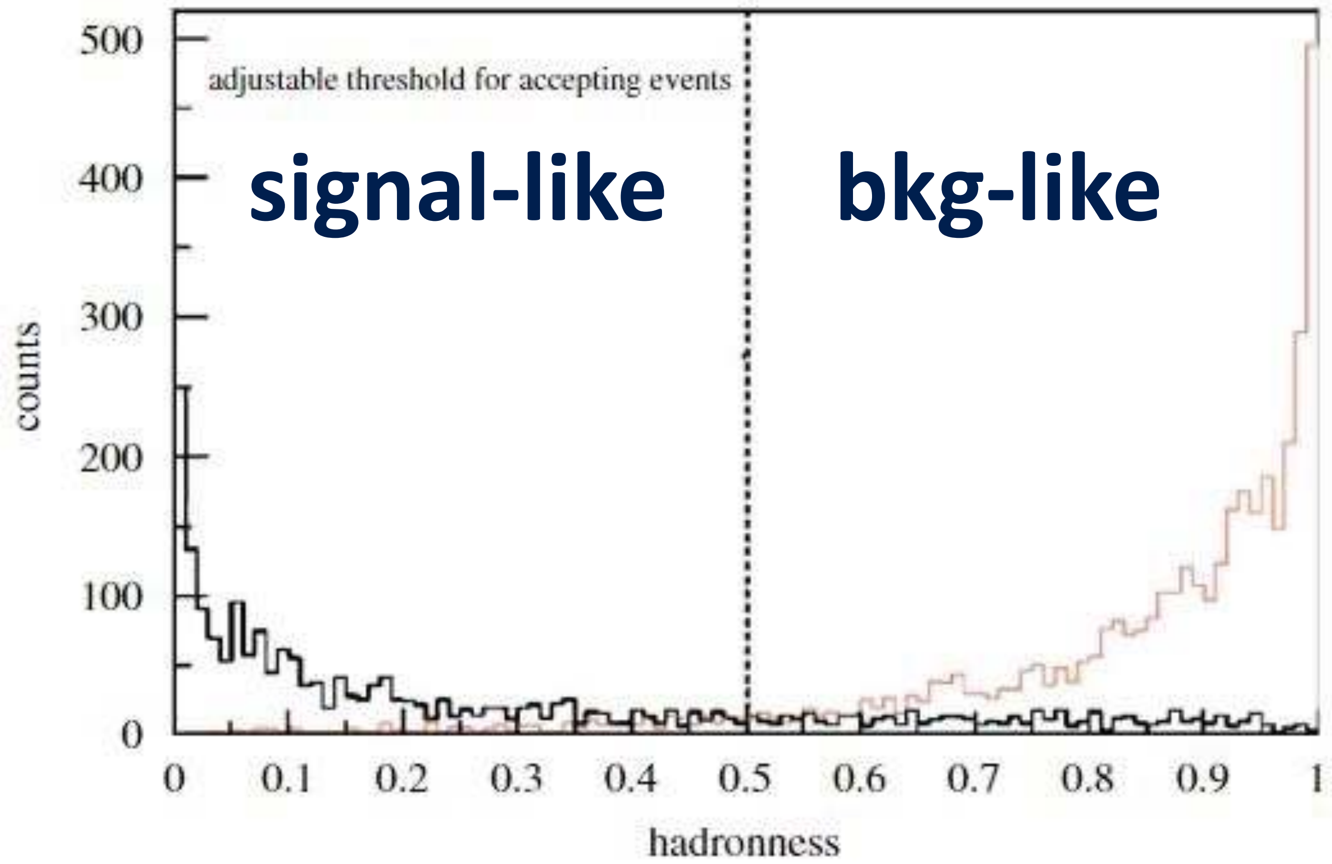
- Orientation
- Size/length/width
- Time gradient

Output on primary particles info

- Energy, direction, arrival time
- Types of particles



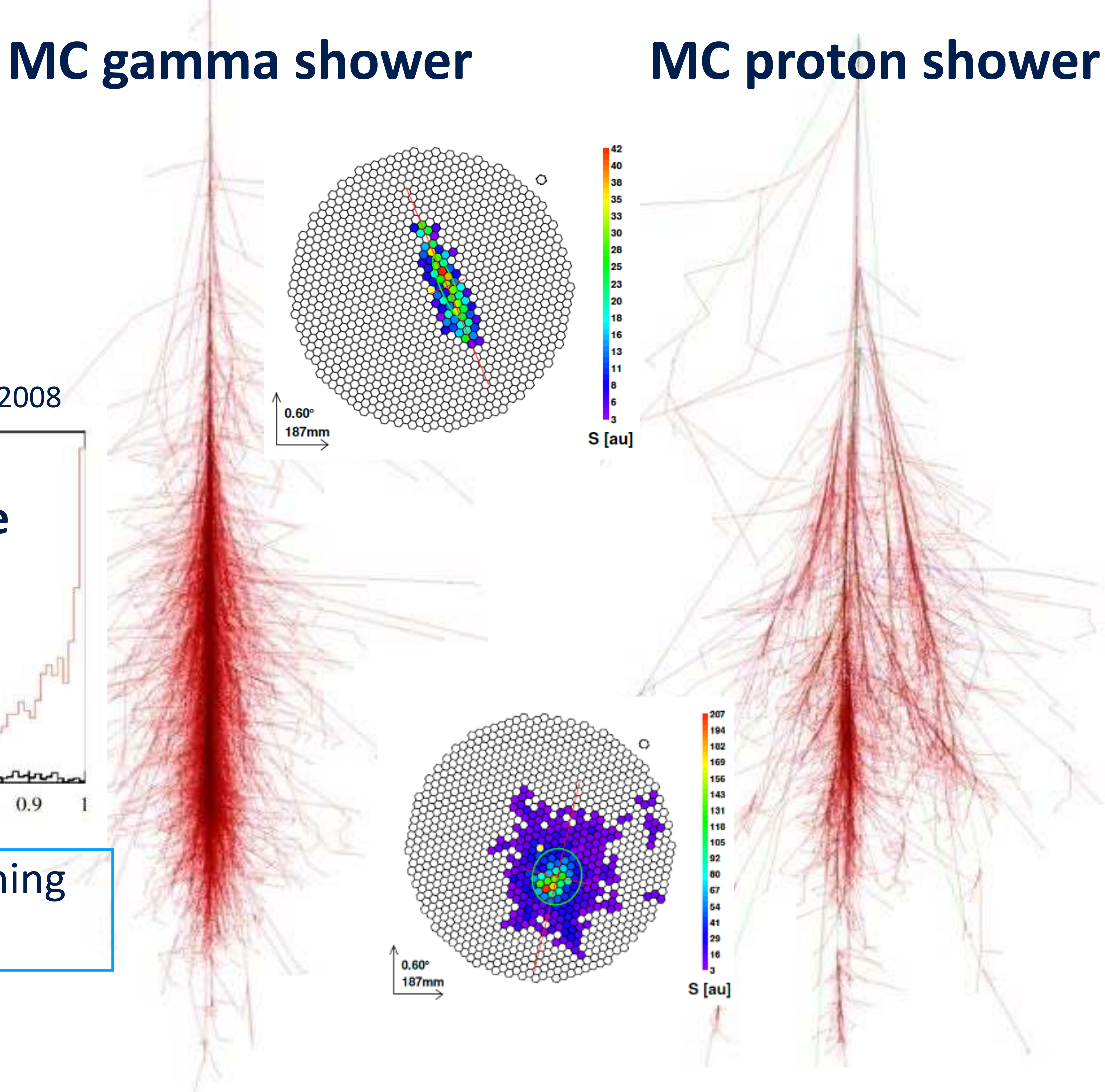
Nucl.Instrum.Meth.A588:424-432,2008



Apply Machine learning based classification

Gamma (signal)

Hadron(background)



CORSIKA simulation

The Galactic Centre observation with MAGIC

The Galactic Centre

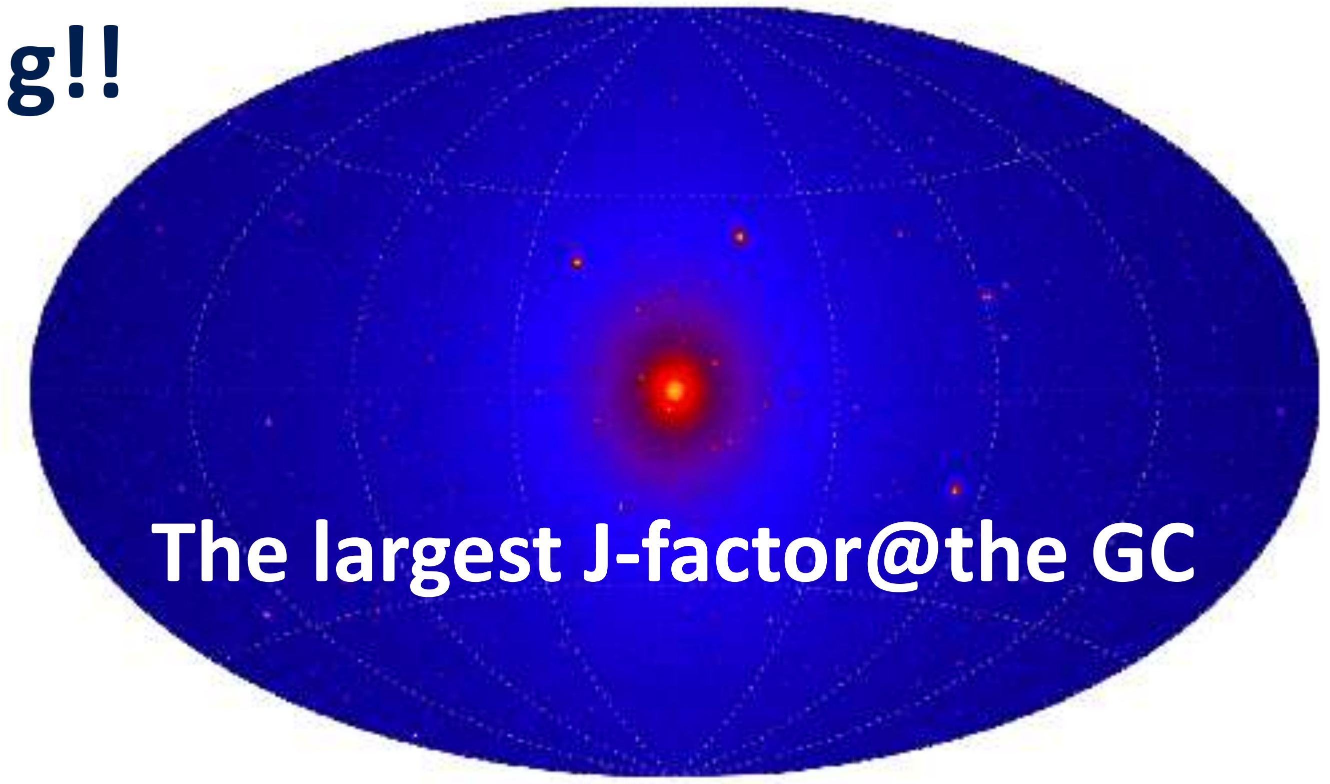
😀Pros: **The largest J-factor** → **the most promising!!**

🤔Cons: Extended, src confusion, diffuse bkg

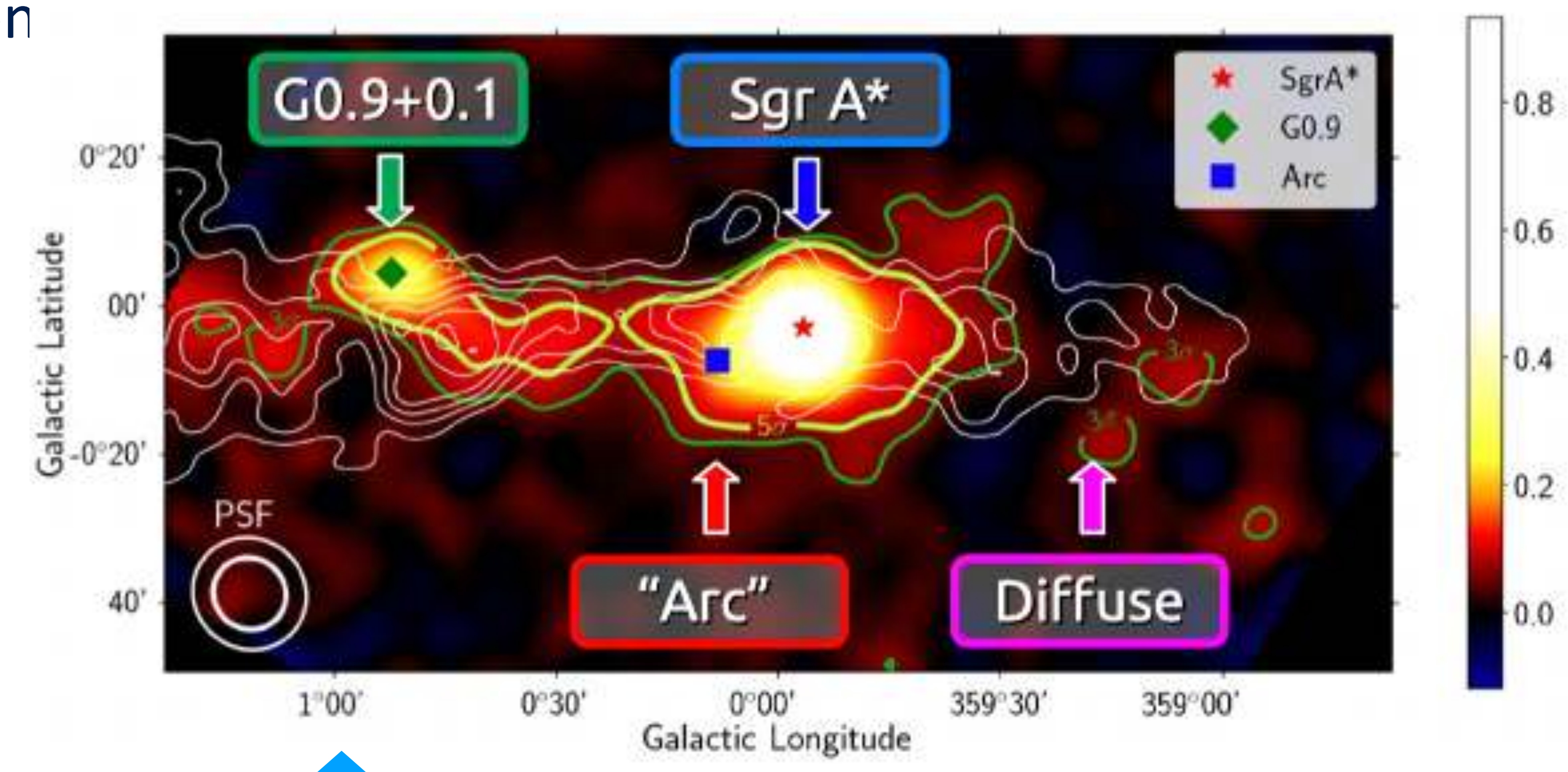
Cuspy/core differences in DM profiles

Both scenario should be taken into account to compare with other exp.

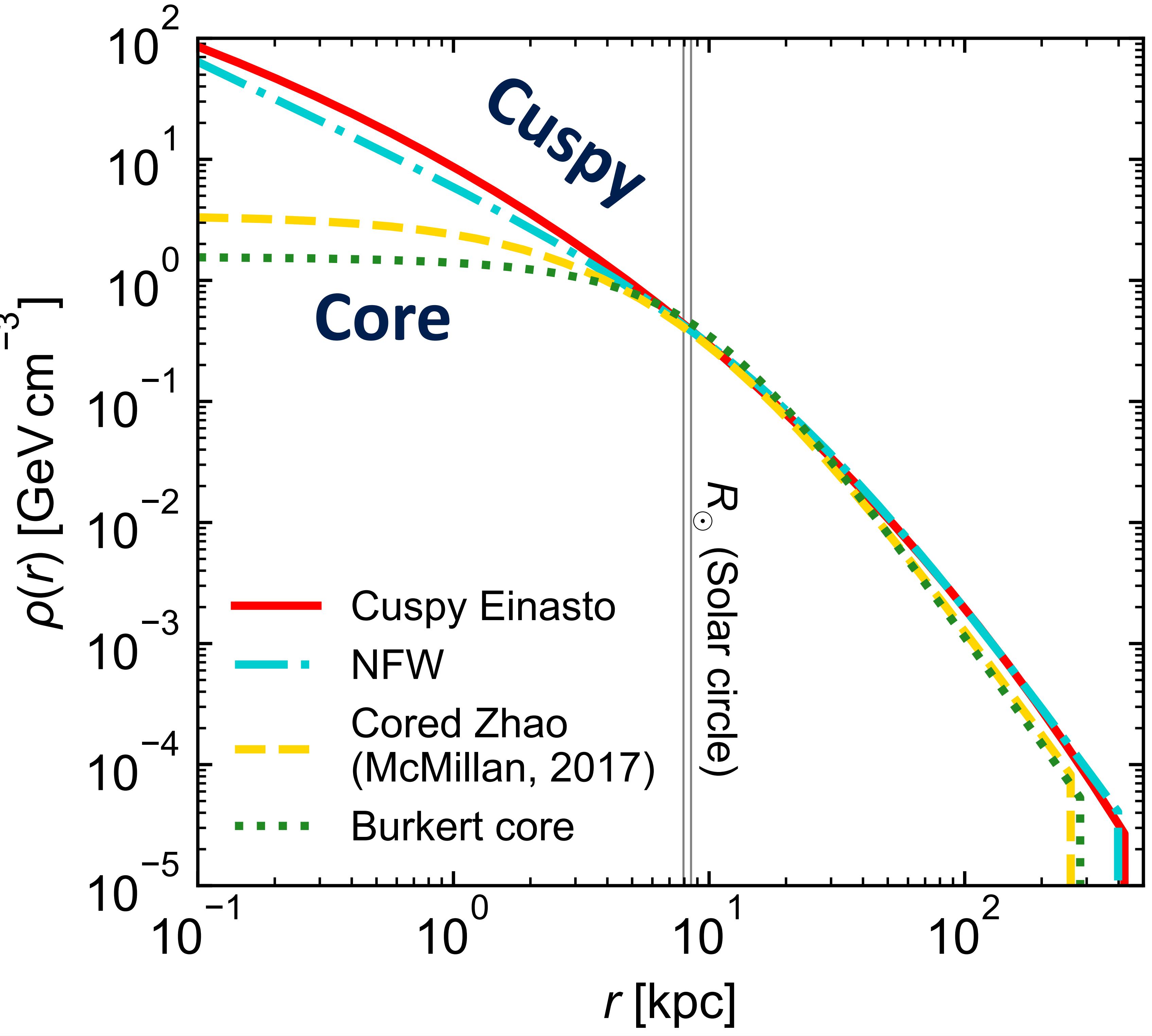
Simulated all-sky map of gamma-rays from DM annihilation (Galactic coordinates) PRD 83, 023518 (2011)

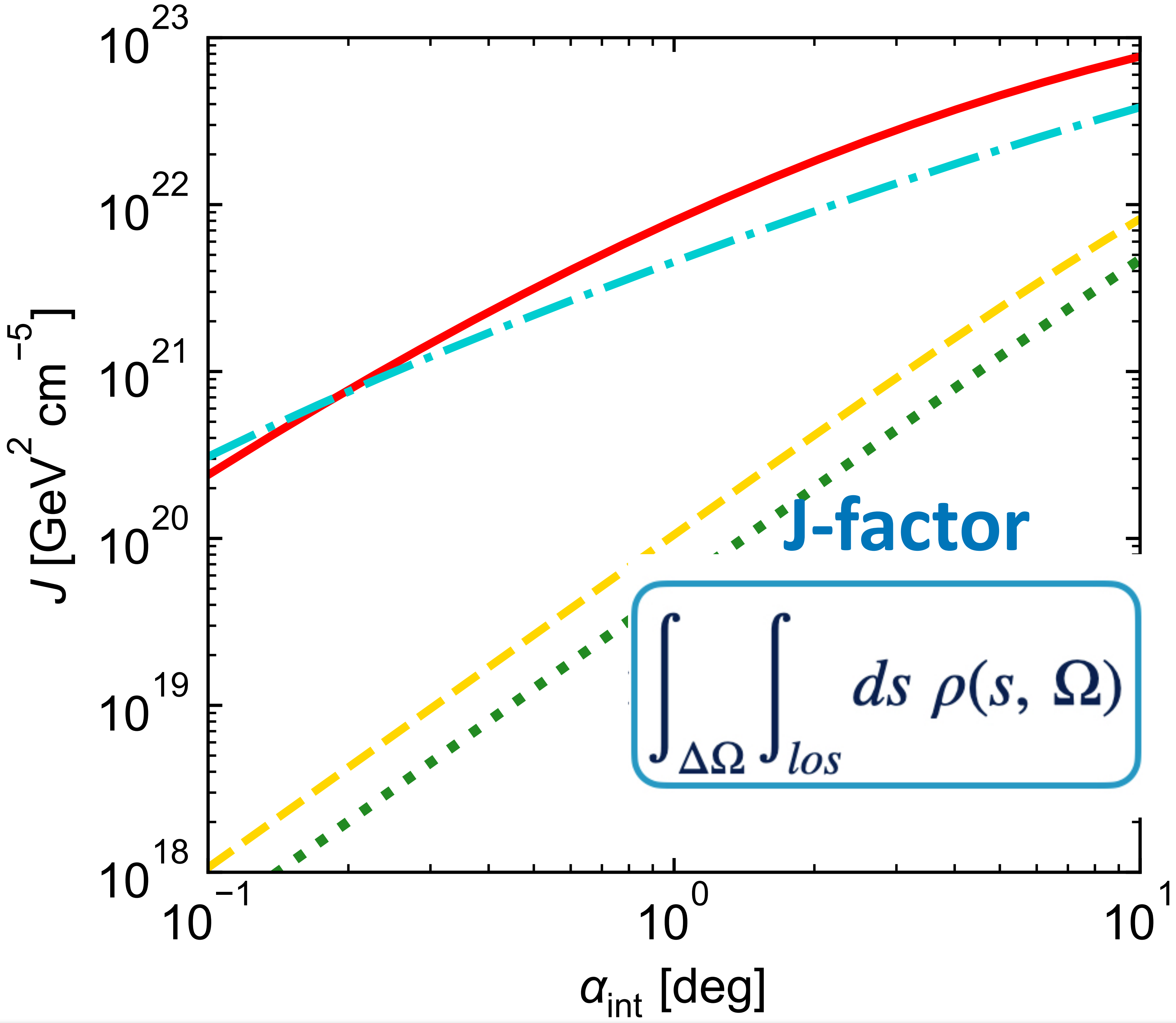


A&A 642. A190 (2020)

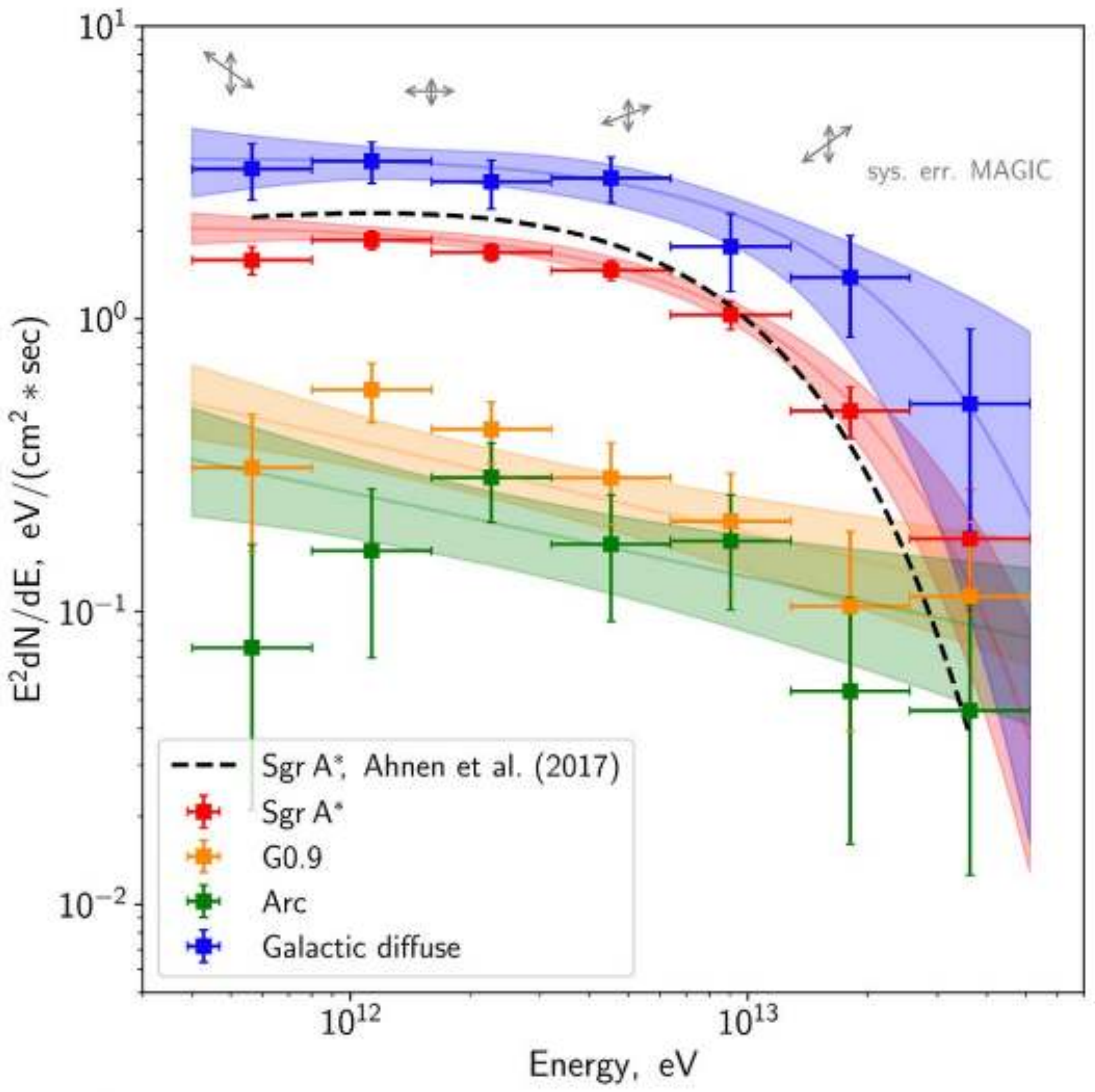


Astrophysical "contamination"





$$\int_{\Delta\Omega}\int_{los} ds\ \rho(s,\,\Omega)$$

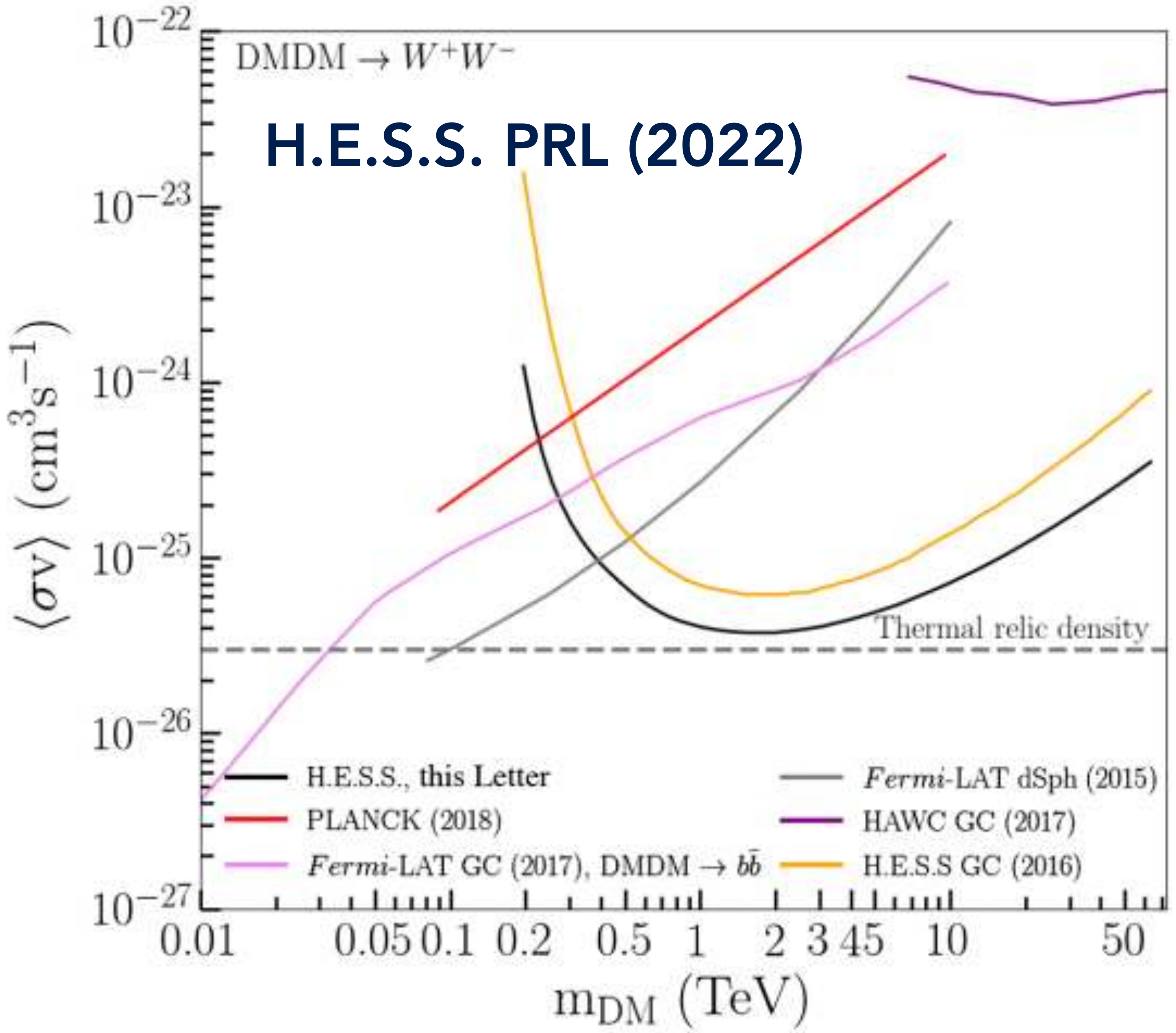


The Dark Side of the Galactic Centre

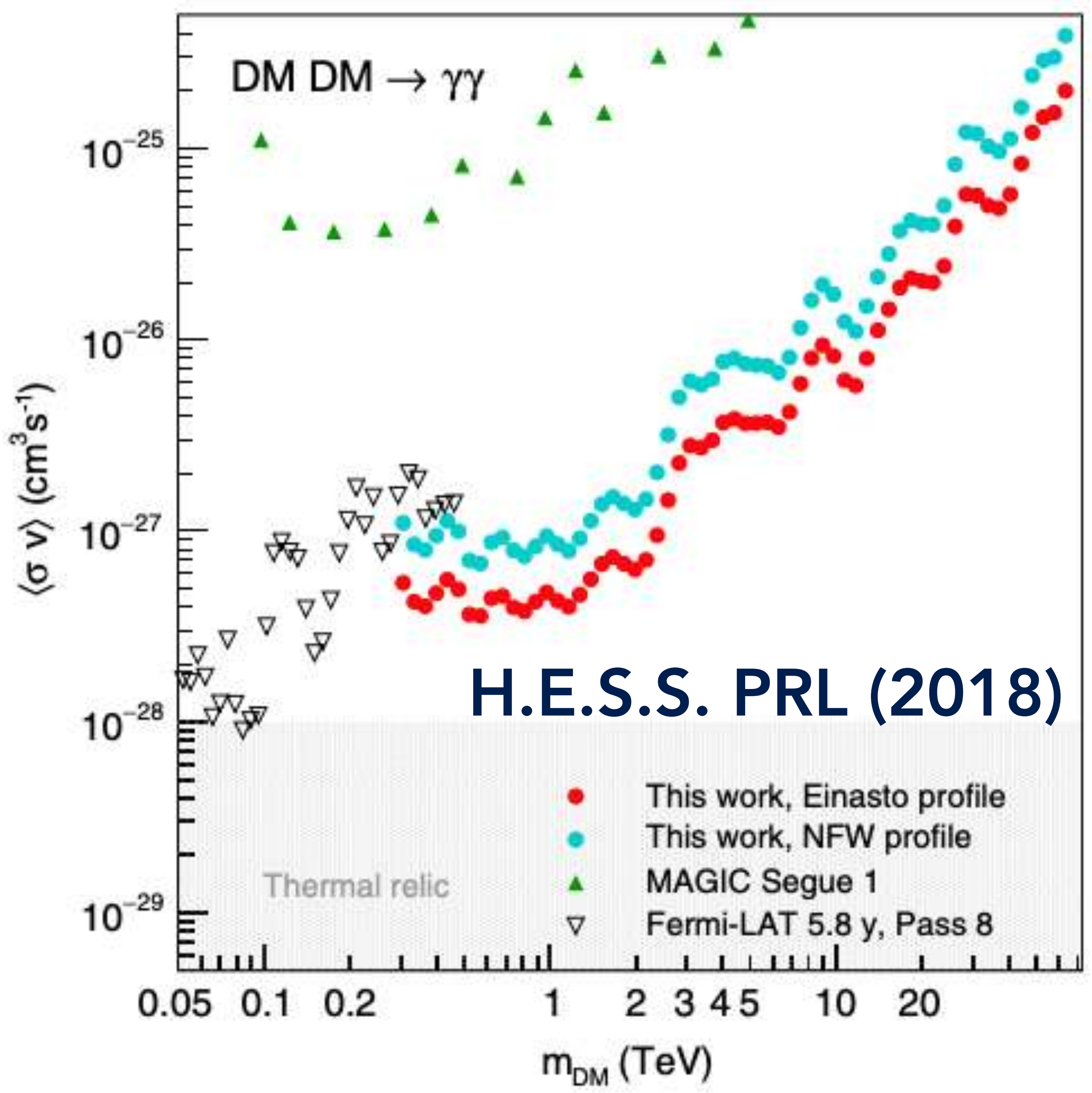
https://arxiv.org/abs/2111.01198

Dark Matter searches at the Galactic Centre

- Full of excellent results from H.E.S.S. collaboration
  - **No results** during about **15 years** from **Northern telescopes**
- The GC observation is “a home game” for Southern telescopes

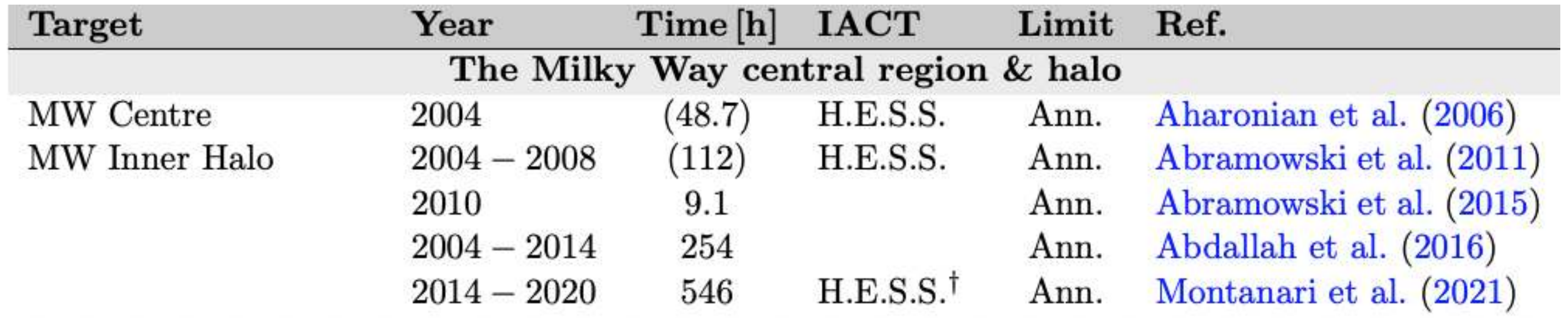


H.E.S.S. PRL (2022)



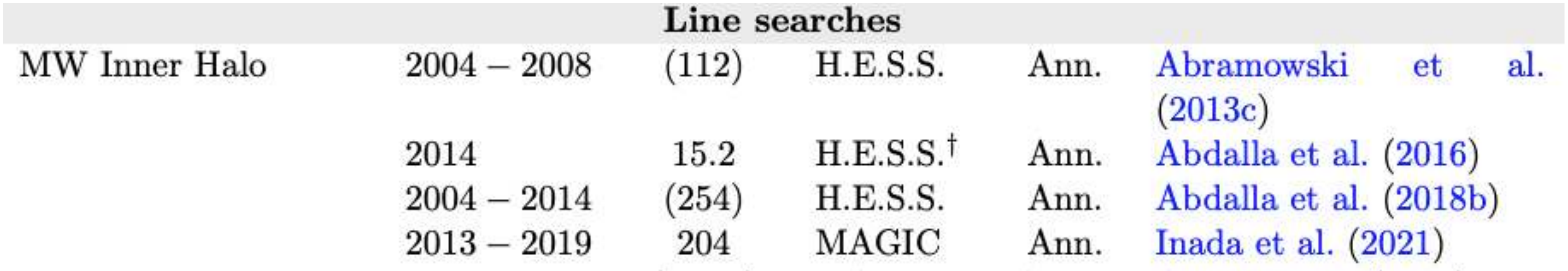
H.E.S.S. PRL (2018)

Continuum spectra searches

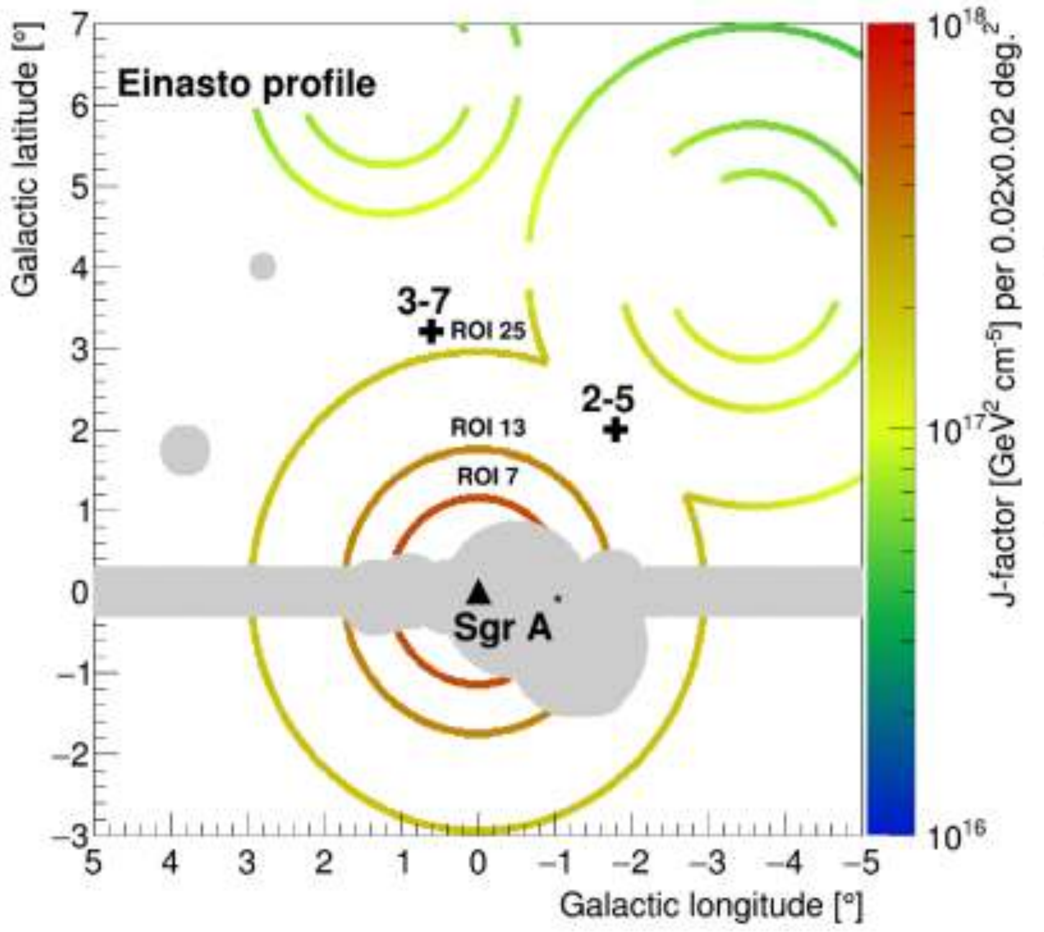


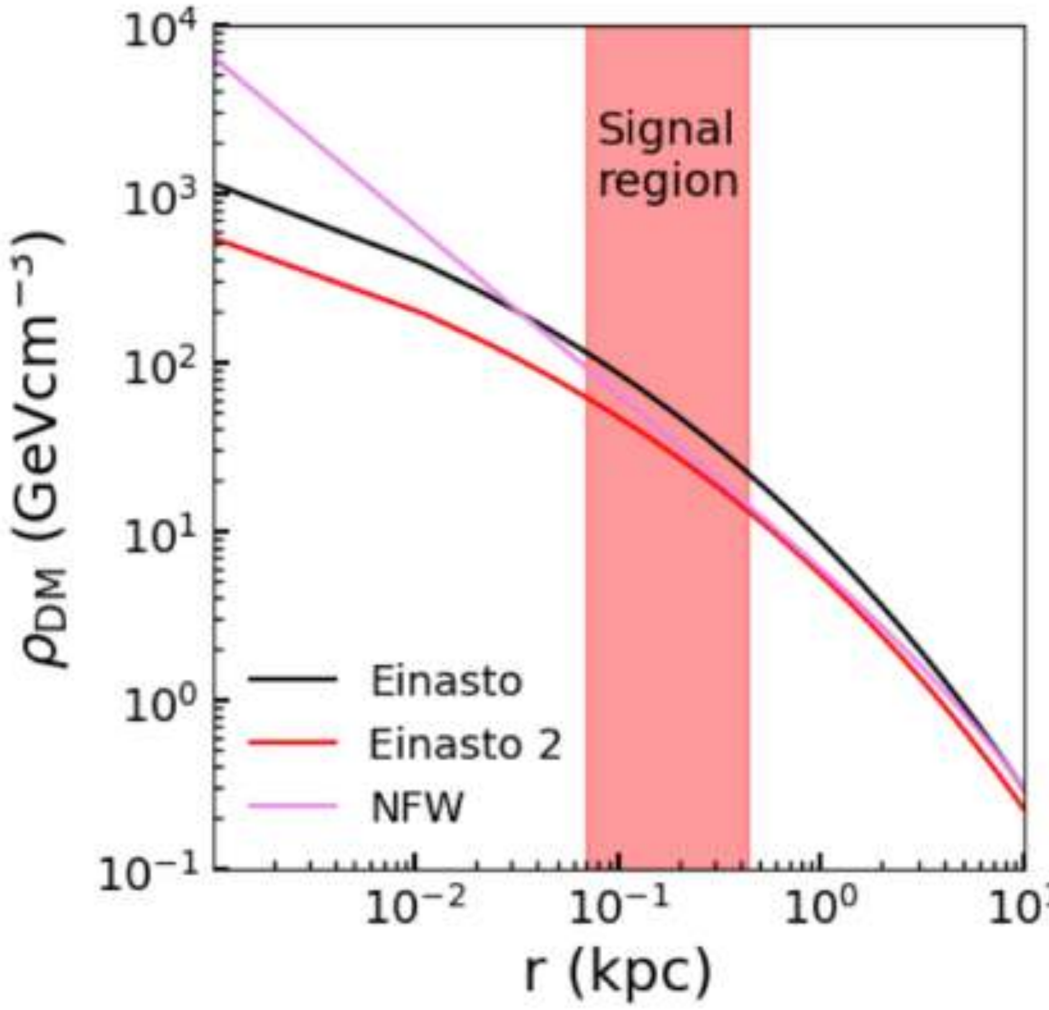
Target	Year	Time [h]	IACT	Limit	Ref.
The Milky Way central region & halo					
MW Centre	2004	(48.7)	H.E.S.S.	Ann.	Aharonian et al. (2006)
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2011)
	2010	9.1		Ann.	Abramowski et al. (2015)
	2004 – 2014	254		Ann.	Abdallah et al. (2016)
	2014 – 2020	546	H.E.S.S.†	Ann.	Montanari et al. (2021)

Line searches



Line searches					
MW Inner Halo	2004 – 2008	(112)	H.E.S.S.	Ann.	Abramowski et al. (2013c)
	2014	15.2	H.E.S.S.†	Ann.	Abdalla et al. (2016)
	2004 – 2014	(254)	H.E.S.S.	Ann.	Abdalla et al. (2018b)
	2013 – 2019	204	MAGIC	Ann.	Inada et al. (2021)



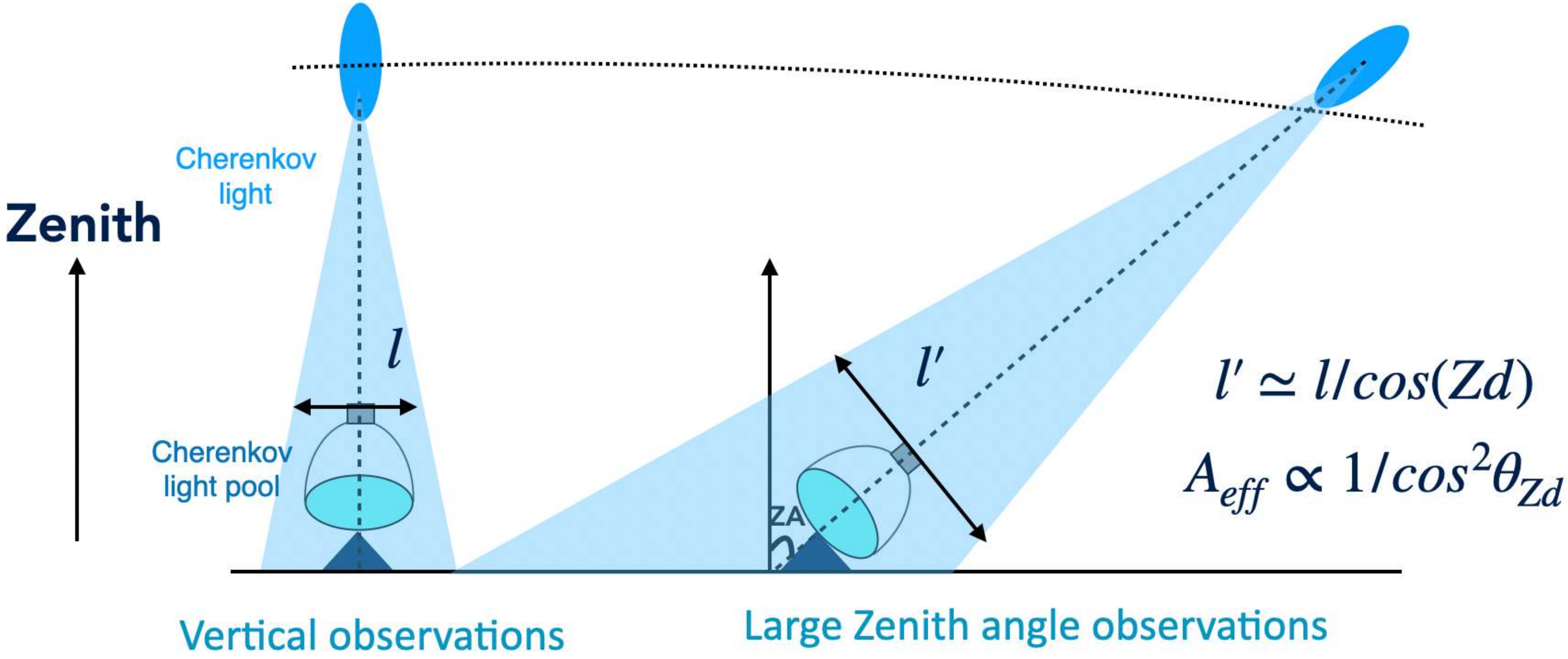


The GC observation with MAGIC

- Nominal IACT setup: vertical observation

Key experimental fact:

- IACT performance depends on zenith angles
  - because of difference in a shower distance



$$l' \simeq l/cos(Zd)$$

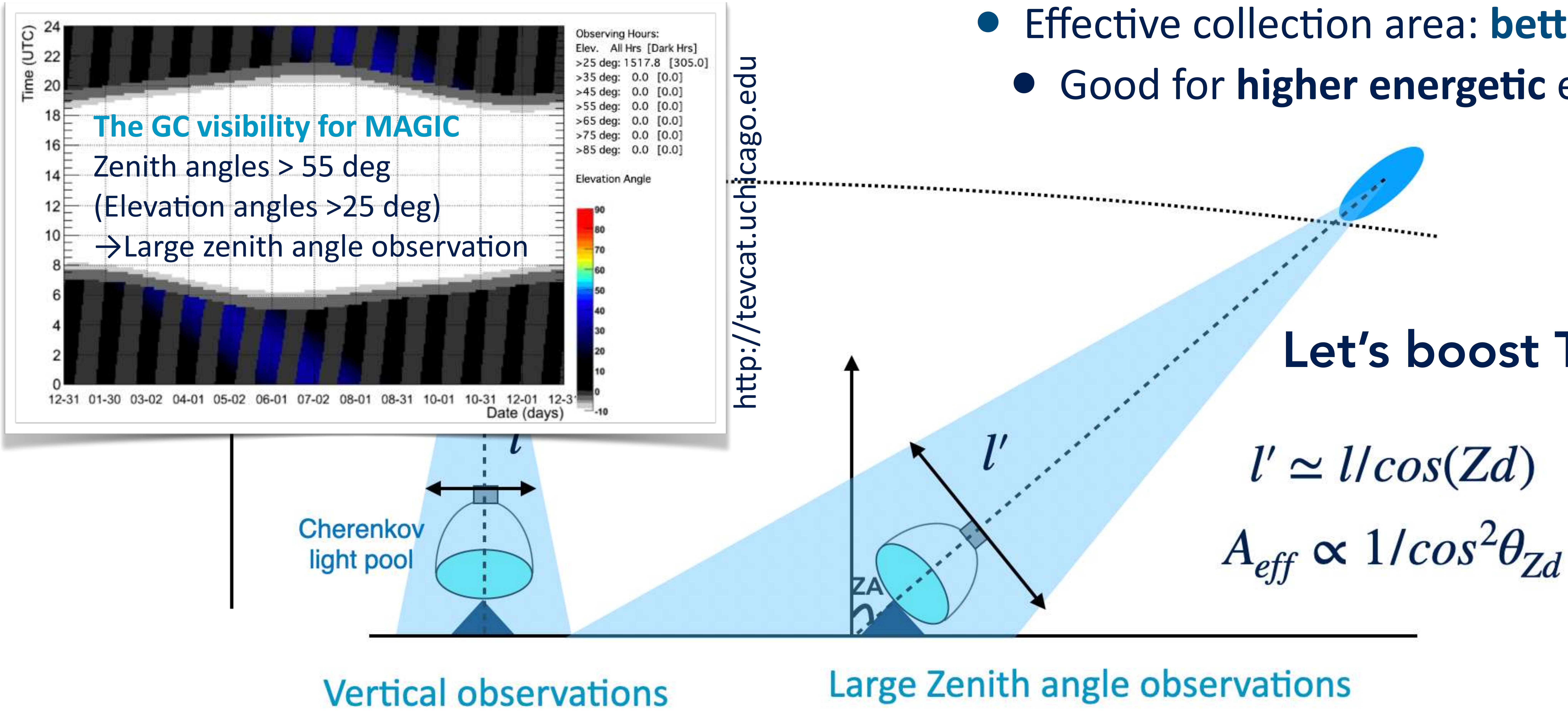
$$A_{eff} \propto 1/cos^2\theta_{Zd}$$

The GC observation with MAGIC

Key experimental fact:

- IACT performance depends on zenith angles
  - because of difference in a shower distance

- ~~Nominal IACT setup: vertical observation~~
- **Large zenith angle observation**
  - Energy threshold: worse
  - Energy resolution: worse
  - Effective collection area: **better**
    - Good for **higher energetic** events



The GC visibility for MAGIC

Zenith angles > 55 deg

(Elevation angles >25 deg)

→Large zenith angle observation

http://tevcat.uchicago.edu

Let's boost TeV range!

$$l' \simeq l/cos(Zd)$$

$$A_{eff} \propto 1/cos^2\theta_{Zd}$$

Data set for analysis

Data : March 2013 - August 2020

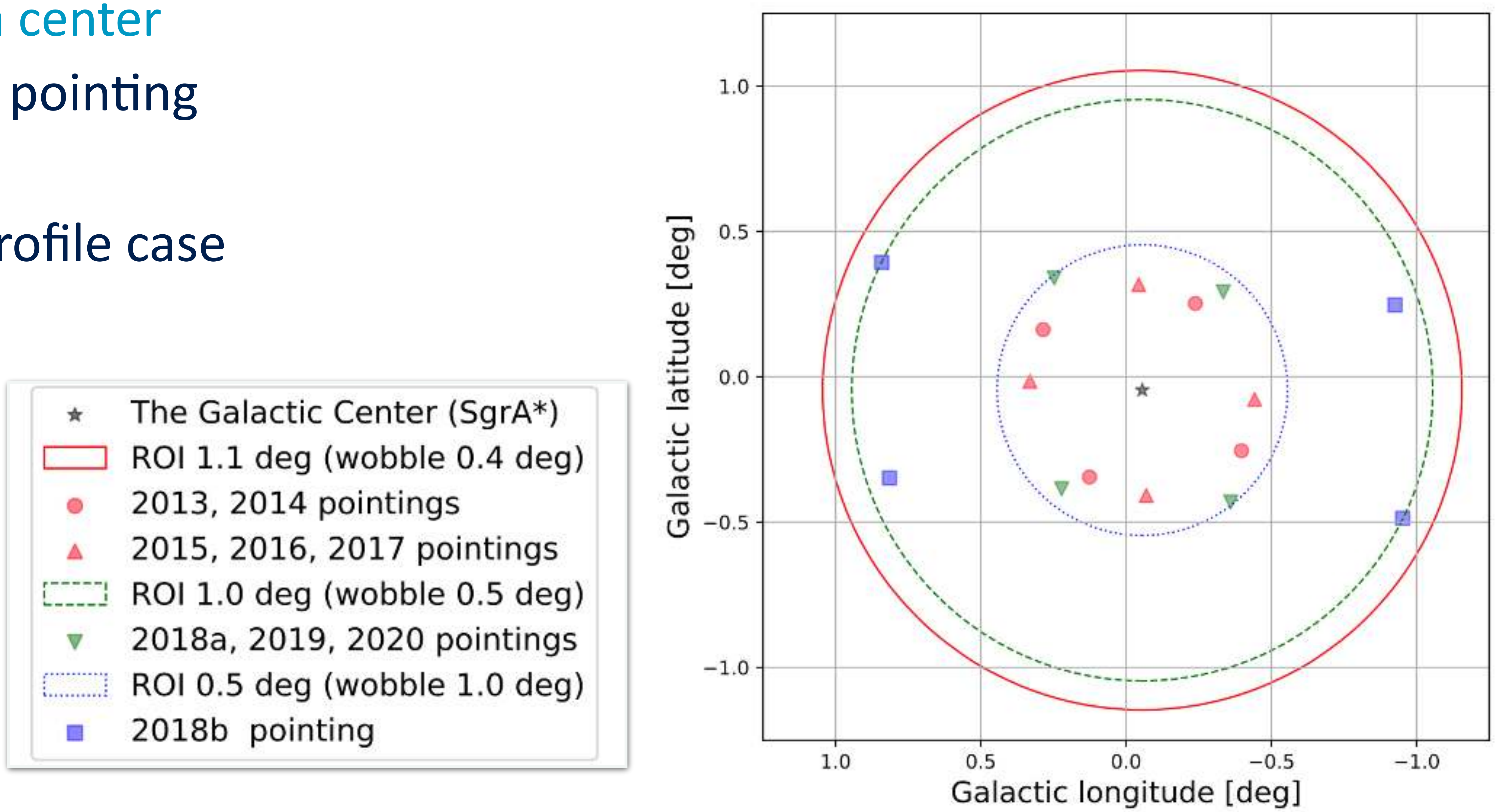
- Zd range : 58° < Zd < 70°
- total observation time (after cuts) : 223 h

Dates	Label	Total observation time [h] (before quality cuts)	Effective live time [h] (after quality cuts)
2013/03/10 – 2013/07/18	2013	47.1	38.8
2014/03/01 – 2014/07/07	2014	37.3	30.1
2015/03/29 – 2016/04/13	2015	27.0	18.9
2016/05/02 – 2016/08/05	2016	24.8	17.3
2017/03/26 – 2017/06/24	2017	26.0	22.1
2018/02/19 – 2018/09/30	2018a	26.3	19.1
	2018b	7.0	5.8
2019/03/11 – 2019/08/04	2019	54.4	52.0
2020/06/19 – 2020/08/21	2020	22.9	19.1
Total		272.8	223.2

Analysis region (ROI)

- Fixed Regions within 1.5° away from the camera center
- Different ROI sizes used due to the variation in pointing directions
- J-factors are computed in each assumed DM profile case

Profile name	$J(0.5^\circ)$	$J(1.0^\circ)$	$J(1.1^\circ)$
Cuspy Einasto	3.14×10^{21}	8.01×10^{21}	9.03×10^{21}
NFW	2.18×10^{21}	4.55×10^{21}	5.02×10^{21}
Cored Zhao	2.66×10^{19}	1.06×10^{20}	1.28×10^{20}
Burkert core	1.26×10^{19}	5.04×10^{19}	6.10×10^{19}



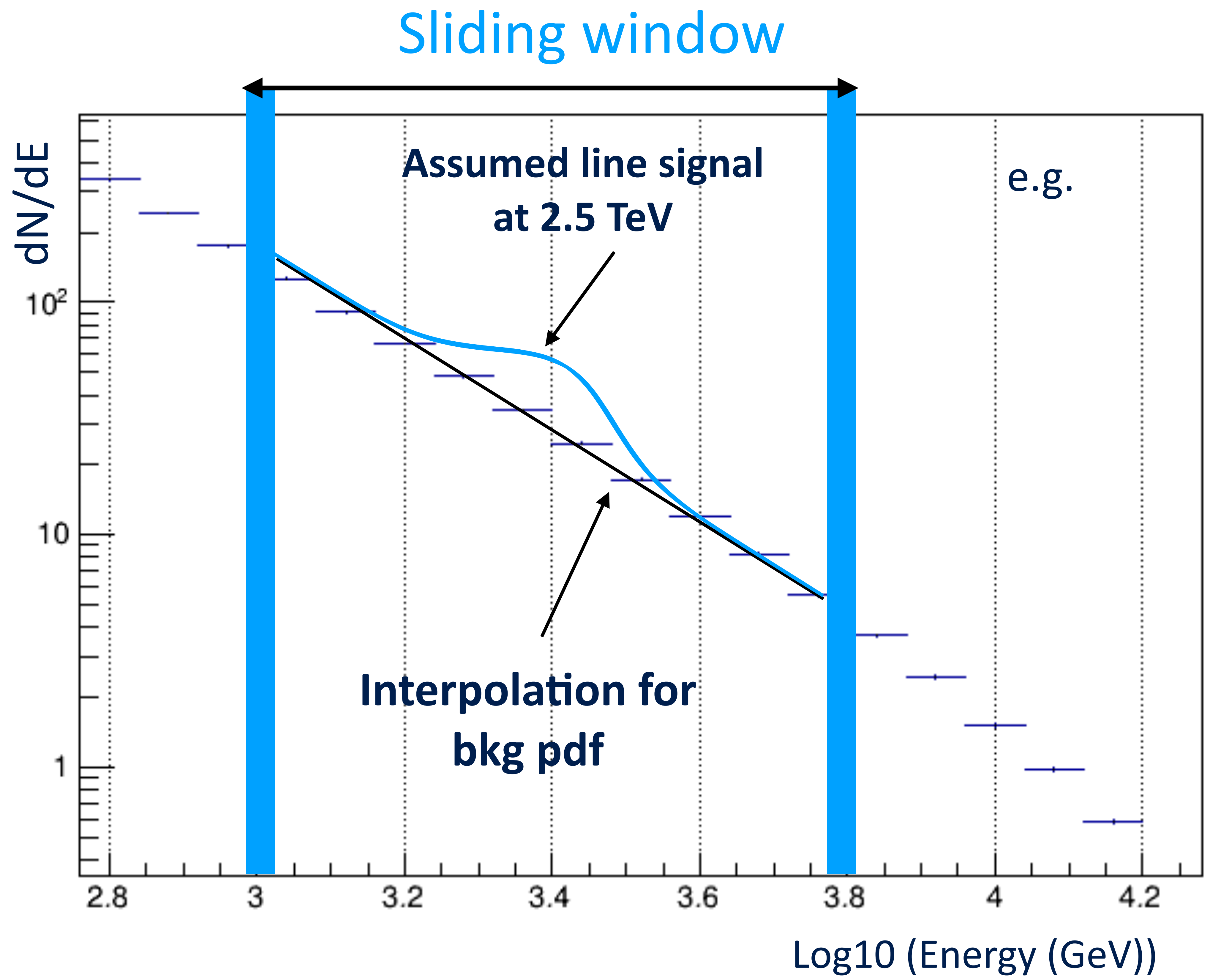
Likelihood analysis for line search

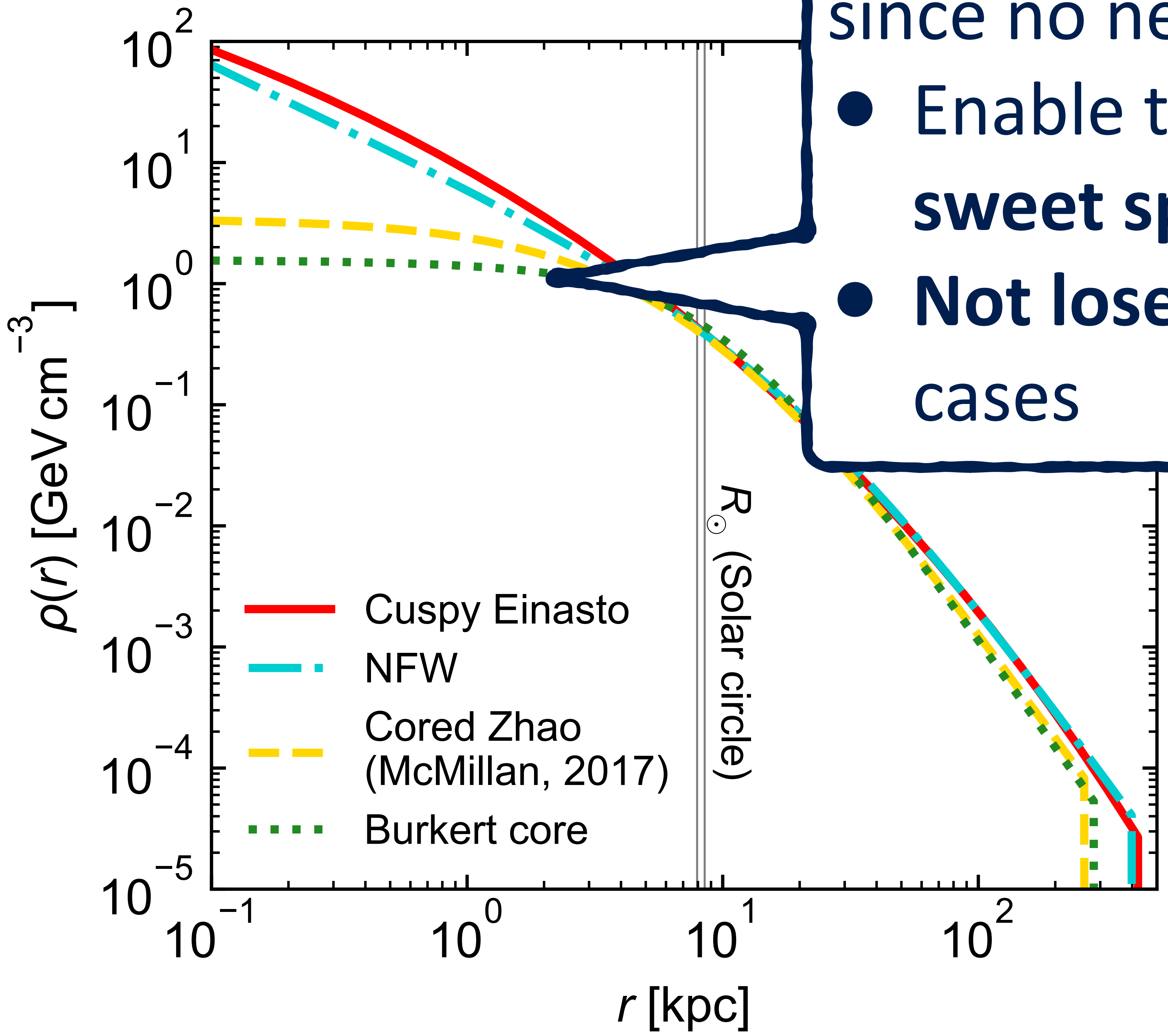
The term for dealing with a systematic uncertainty of a bkg model

Unbinned likelihood analysis with a sliding window

$\mathcal{L}$ $\mathcal{L}_i(g_i; \nu_i \,|\mathcal{D}_i) = \mathcal{L}_i(g_i; b_i, \tau_i \,|\{E'_j\}_{j=1,\ldots,N_{\mathrm{ON},i}}, N_{\mathrm{ON},i})$)

$$= \frac{(g_i + \tau_i b_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!} e^{-(g_i+\tau_i b_i)} \times \frac{1}{g_i + \tau_i b_i} \prod_{j=1}^{N_{\mathrm{ON}}} (g_i f_g(E'_j) + \tau_i b_i f_b(E'_j)) \times \mathcal{T}(\tau_i | \tau_{\mathrm{obs},i}, \sigma_{\tau,i})$$





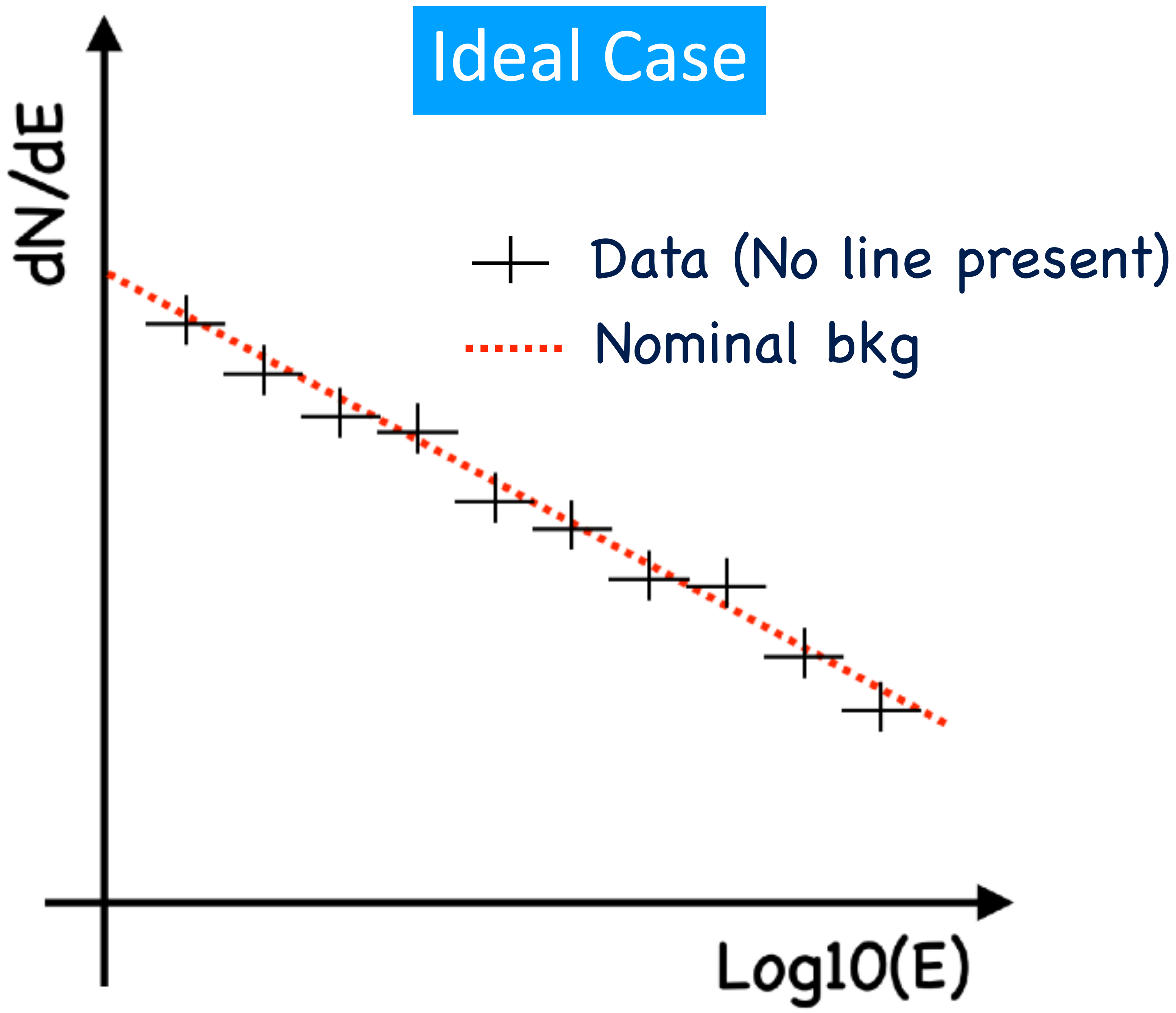
Sliding window gives us **two good things** since no need to **ON-OFF subtraction**

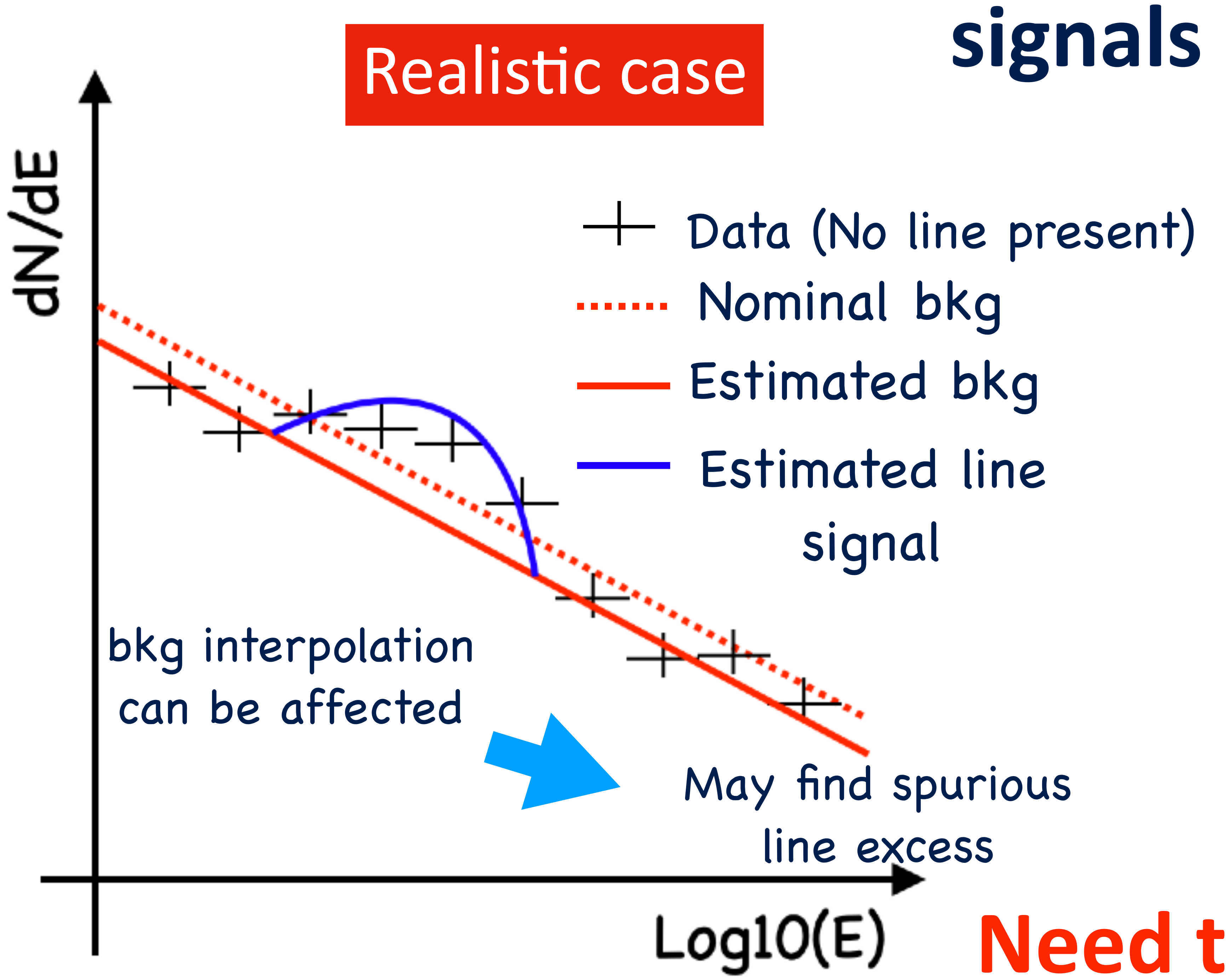
- Enable to include **the center region, sweet spot of J-factor**
- **Not lose sensitivity** to **cored** profile' cases

Background model uncertainty?

Potential to **under/overestimation** number of signals by the systematic uncertainty of bkg model

Systematical bump could mimic **fake-line signals**


Ideal Case


Realistic case

bkg interpolation can be affected

May find spurious line excess

Need to estimate potential fake-line cause

$\tau = 1$

$\tau = \mathrm{Gaus}(\tau_{\mathrm{obs}}, \sigma_\tau)$

$\sigma_\tau^2 = \sigma_{\tau,\mathrm{stat}}^2 + (\tau\sigma_{syst})^2$

$$\mathcal{L}_i(g_i;\nu_i\,|\mathcal{D}_i) = \mathcal{L}_i(g_i;b_i,\boxed{\tau_i}\,|\{E'_j\}_{j=1,\ldots,N_{\mathrm{ON},i}}, N_{\mathrm{ON},i})$$

$$= \frac{(g_i+\boxed{\tau_i}b_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!}e^{-(g_i+\boxed{\tau_i}b_i)} \times \frac{1}{g_i+\boxed{\tau_i}b_i}\prod_{j=1}^{N_{\mathrm{ON}}}(g_i f_g(E'_j)+\boxed{\tau_i}b_i f_b(E'_j)) \times \boxed{\mathcal{T}(\tau_i|\tau_{obs,i},\sigma_{\tau,i})}$$

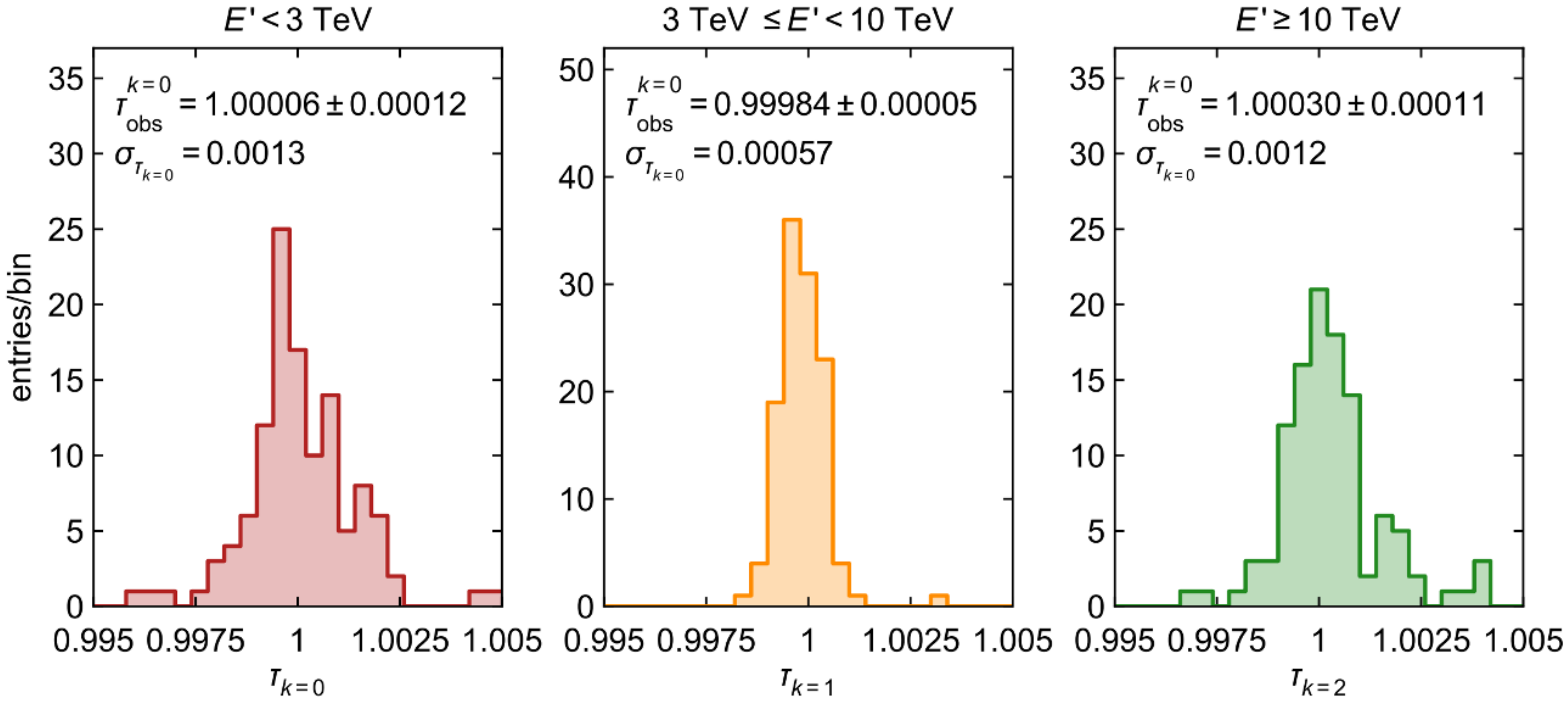
Study for systematic uncertainty

$$\tau = \frac{N_{\mathrm{ON}} - N_{\mathrm{sig}}}{N_{\mathrm{ON}}}$$

Estimated systematic uncertainty in a bkg pdf determination

- Applied the **line search** analysis to data without DM target sources with 120 samples
- Divided into 3 energy categories
  - E < 3 TeV, 3 TeV < E < 10 TeV, E > 10 TeV

$$\sigma^2_{\tau,\mathrm{stat}} = \left(\frac{\partial\tau}{\partial N_{\mathrm{sig}}} \times \sigma_{N_{\mathrm{sig}}}\right)^2 + \left(\frac{\partial\tau}{\partial N_{\mathrm{ON}}} \times \sigma_{N_{\mathrm{ON}}}\right)^2$$



τ^k_{obs} is the mean of the distribution, which is included as the bias to likelihood eq.

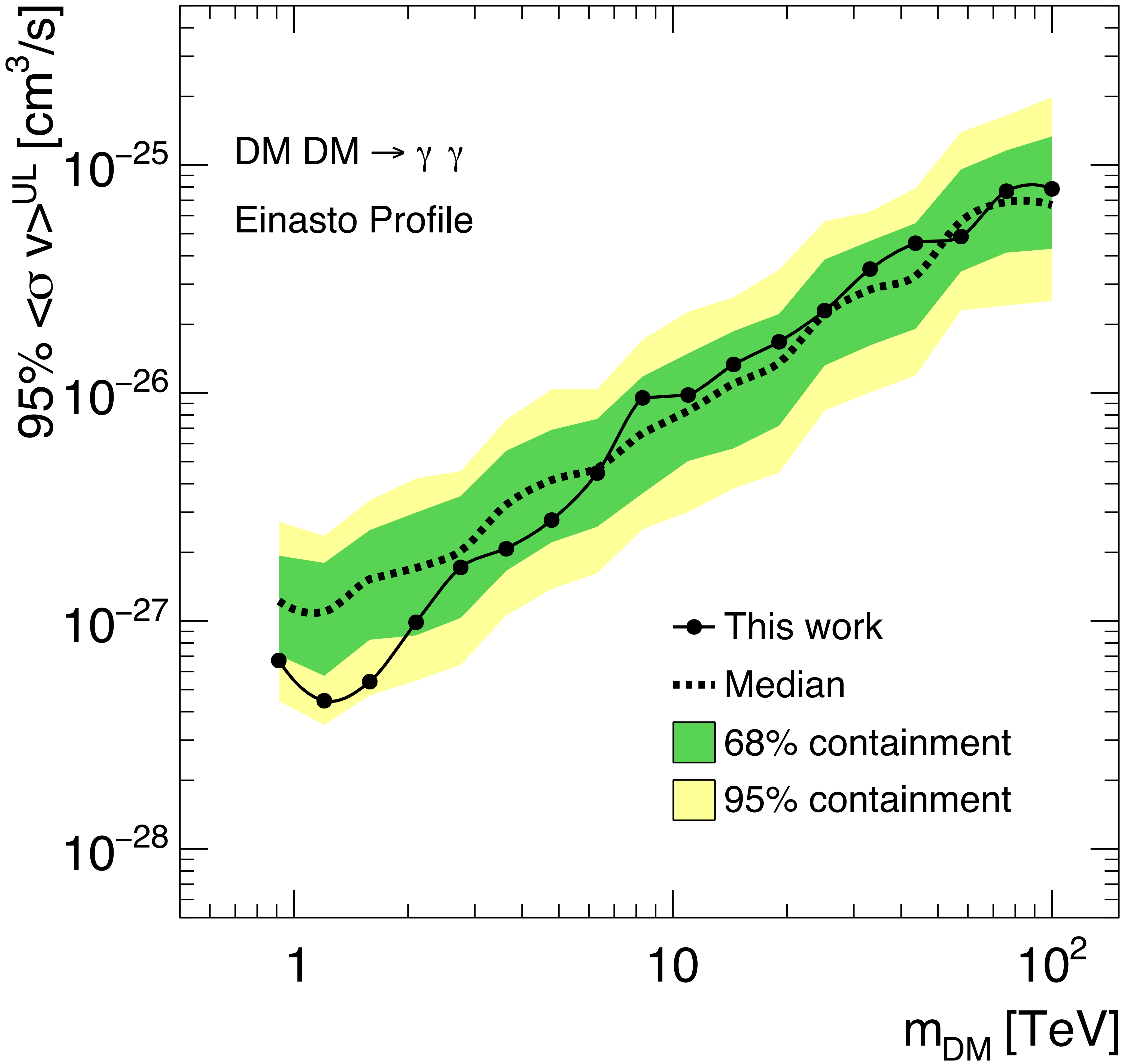
$$\sigma^2_{\tau^k} = \sigma^2_{\tau^k,\mathrm{stat}} + \sigma^2_{\tau^k,\mathrm{syst}}$$

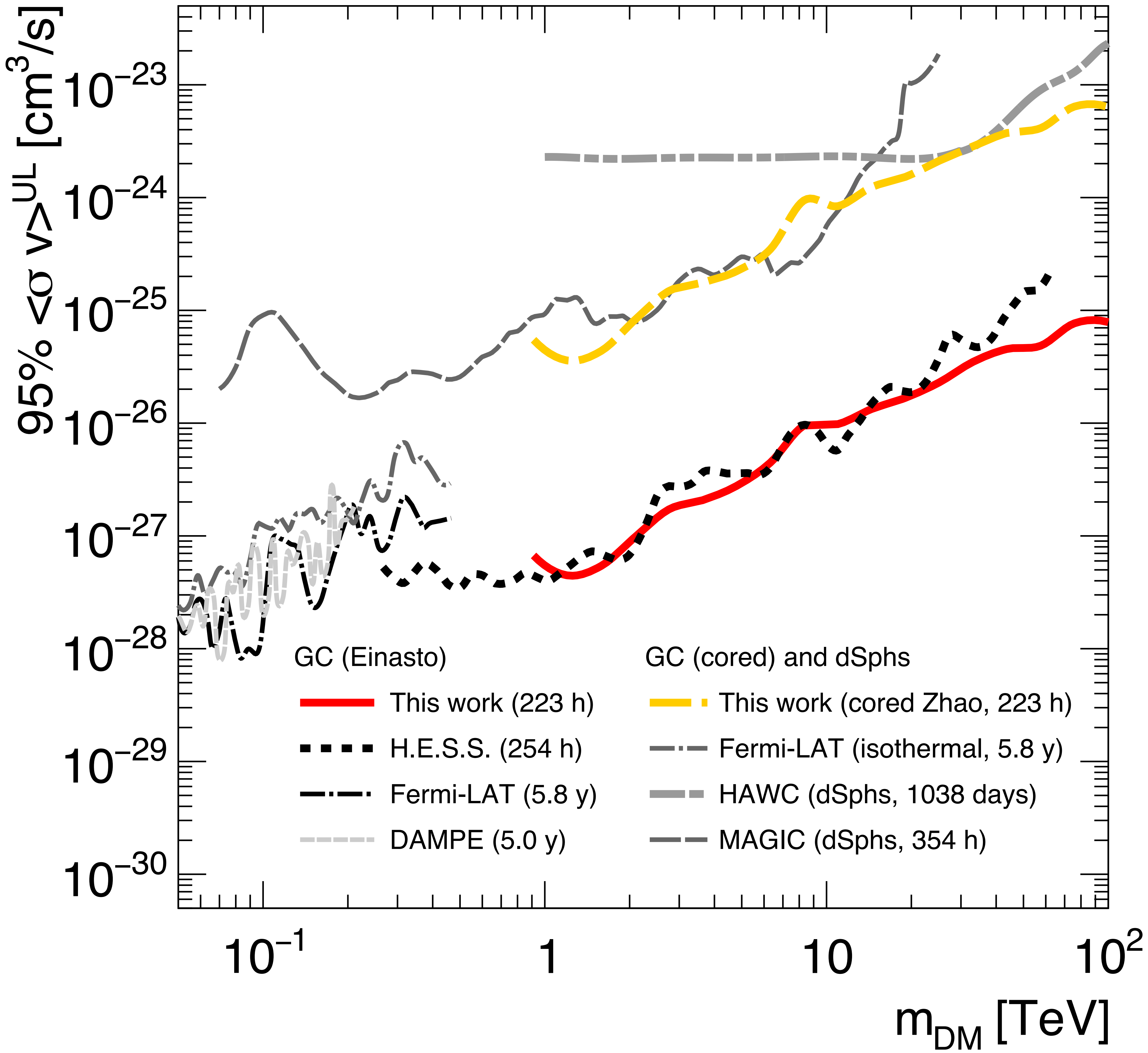
$$\sigma_{\tau^k,\mathrm{syst}} < 1\ \%$$

Less than 1% contribution to the line shape signals

Results

Results



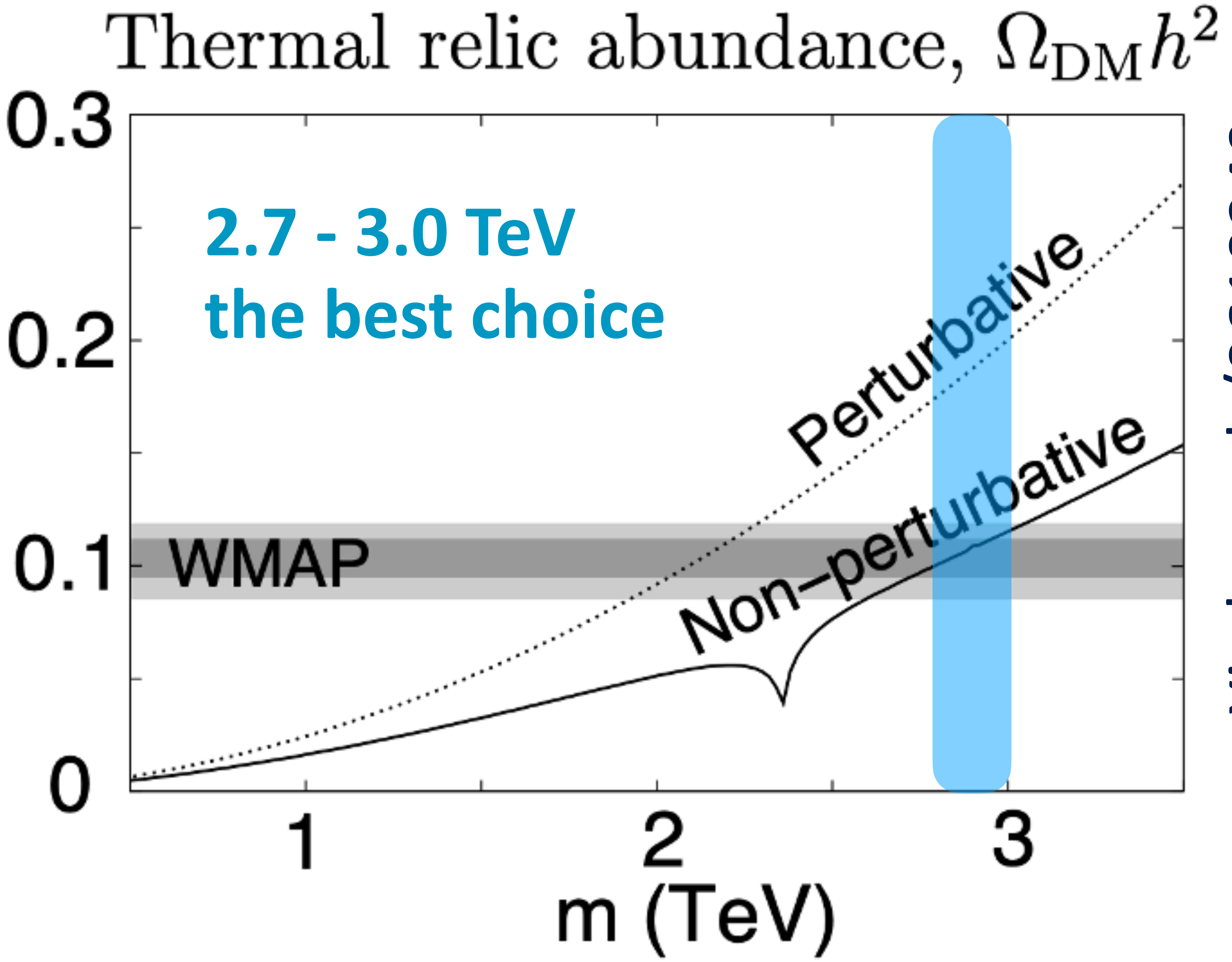


No significant line-like excess found

- Set upper limits at 95% C.L. on 18 masses in the range **0.9 TeV - 100 TeV**

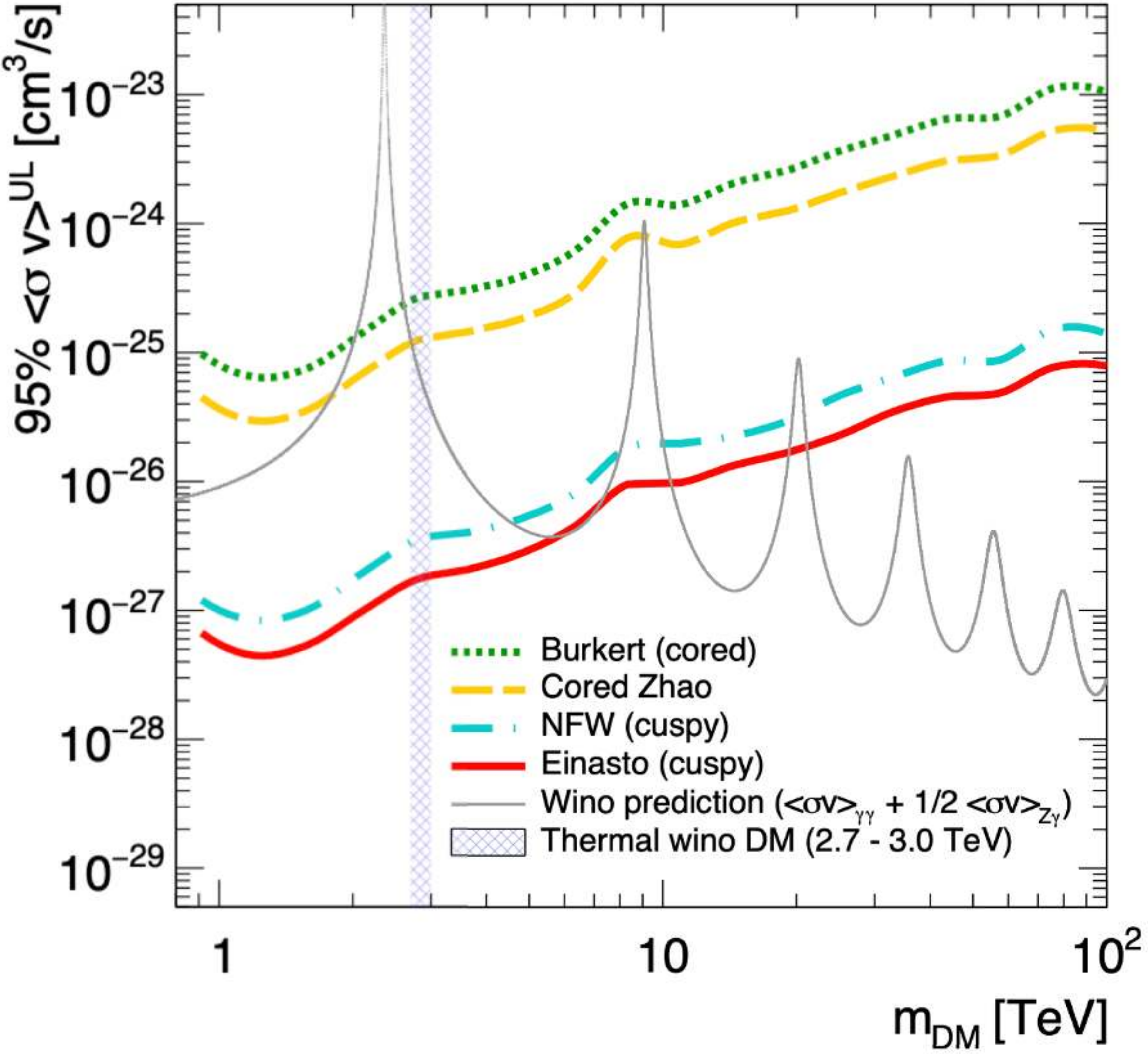
- **Einasto : the best limits above 20 TeV**
- **Cored** : competitive with **dSph** results

Testing SUSY-Wino with various DM profiles



2.7 - 3.0 TeV
the best choice

arXiv:hep-ph/0610249



Up to 2.8 TeV rejected by **Cored Zhao** (the reasonable cored profile), **Einasto and NFW**

The first time to constrain **SUSY-wino DM** with **both cuspy** and **cored** profiles!

Future prospects

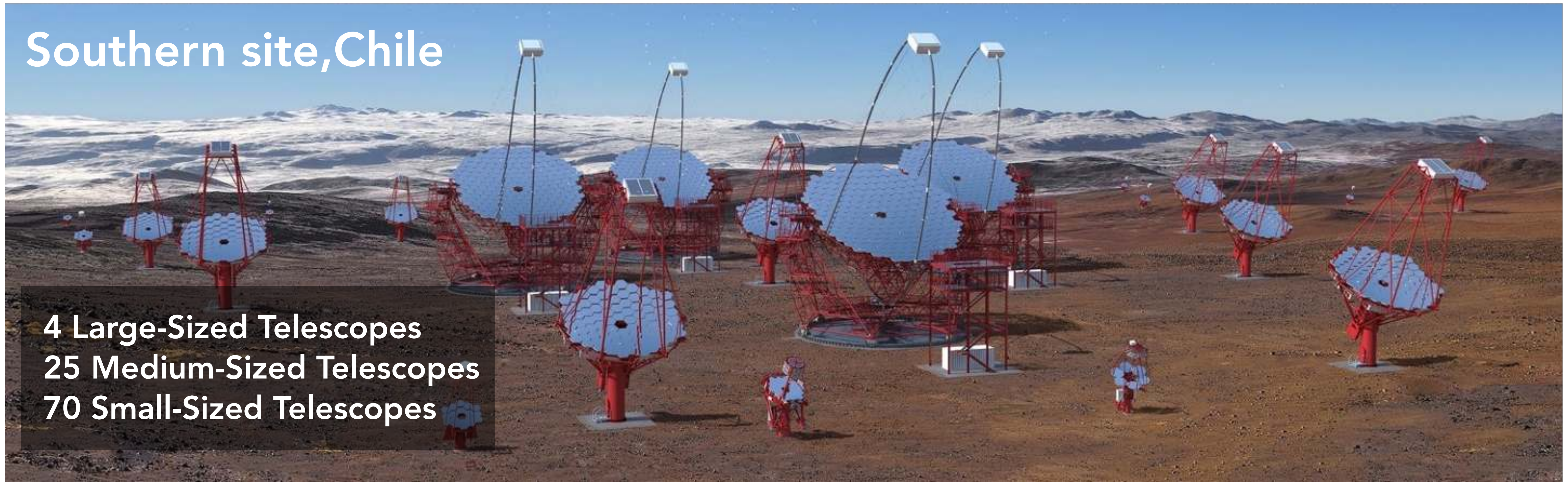
Cherenkov Telescope Array

North site, La Palma

4 Large-Sized Telescopes
15 Medium-Sized Telescopes

in operation

CTA, G. Pérez, IAC, SMM



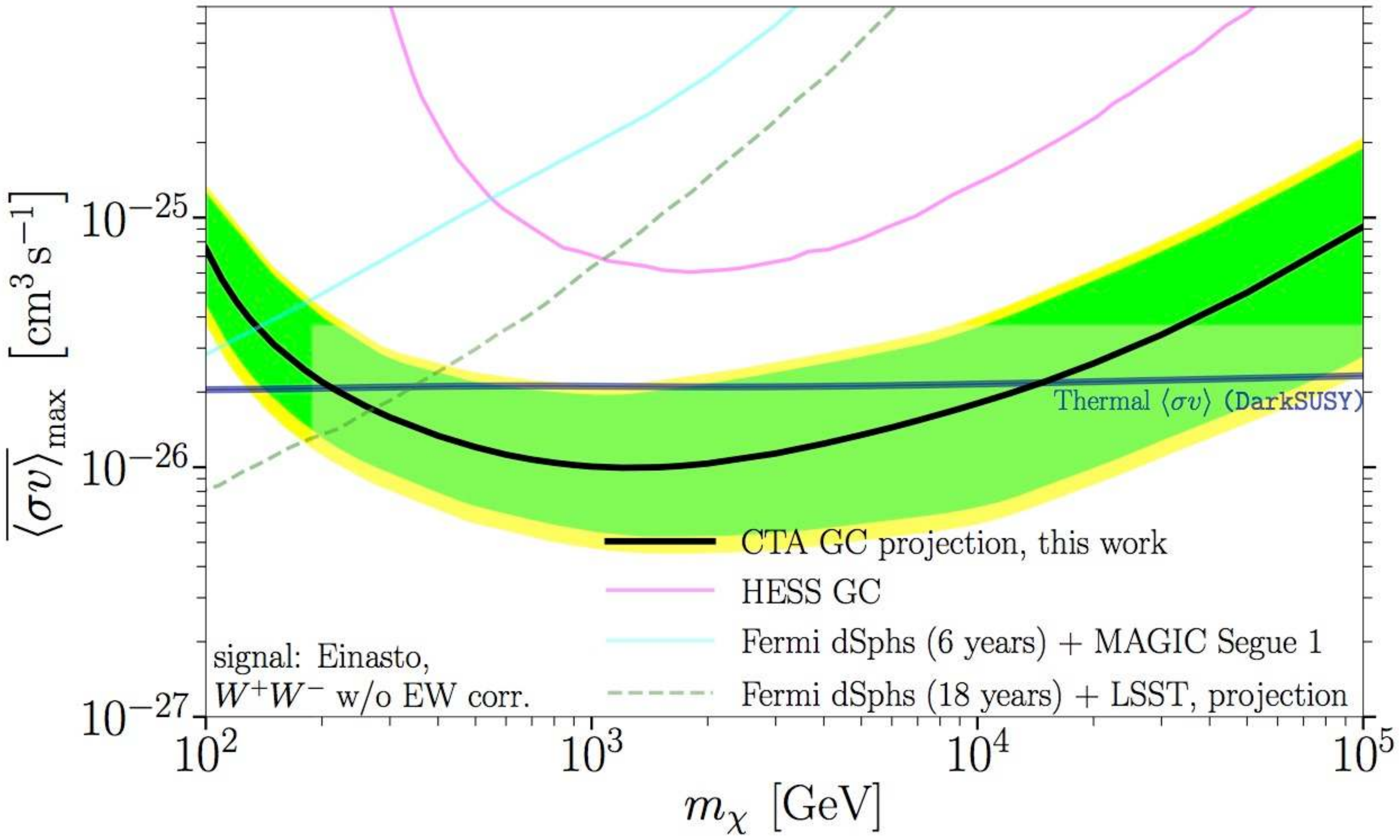
Southern site,Chile

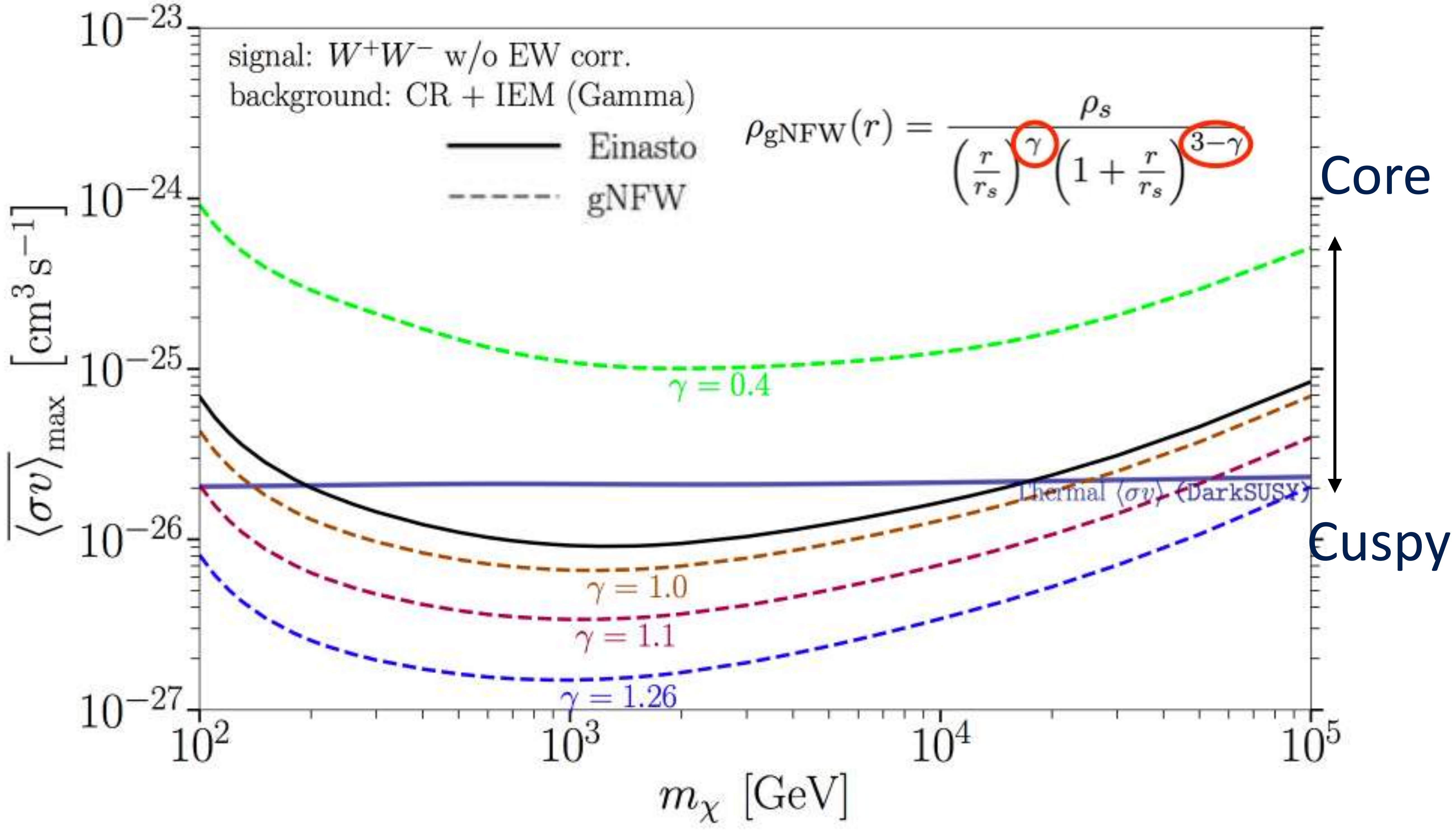
4 Large-Sized Telescopes
25 Medium-Sized Telescopes
70 Small-Sized Telescopes

Next generation ground-based gamma-ray telescope: Two arrays of Cherenkov telescopes in **Chile/ La Palma**

- Over 100 telescopes
- About 1500 scientists and engineers
- About 200 institutes

CTA: Sensitivity to DM signal from Galactic Center





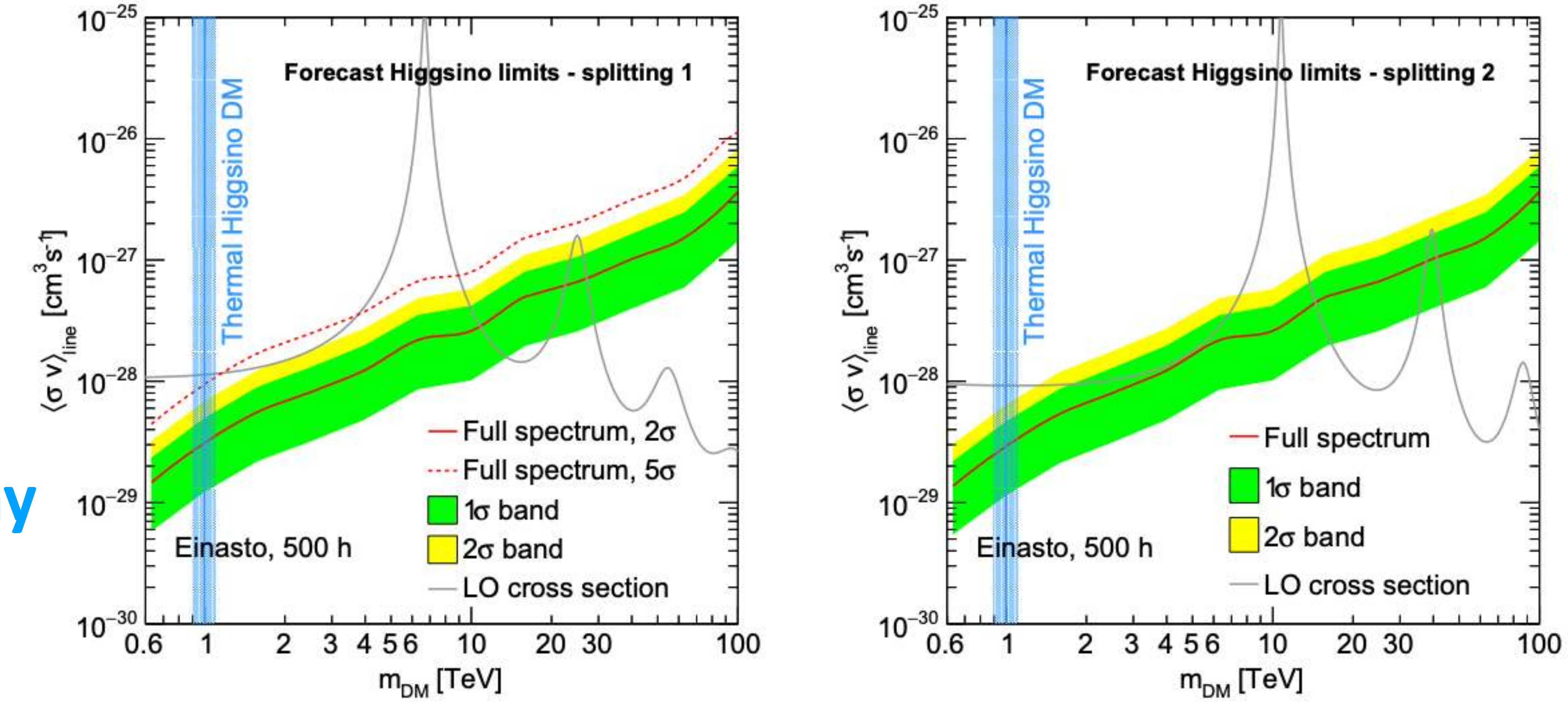
Galactic center observations with CTA can
test the thermal relic cross section of **500 GeV - 10 TeV WIMPs**

CTA: Sensitivity to popular SUSY models with the GC

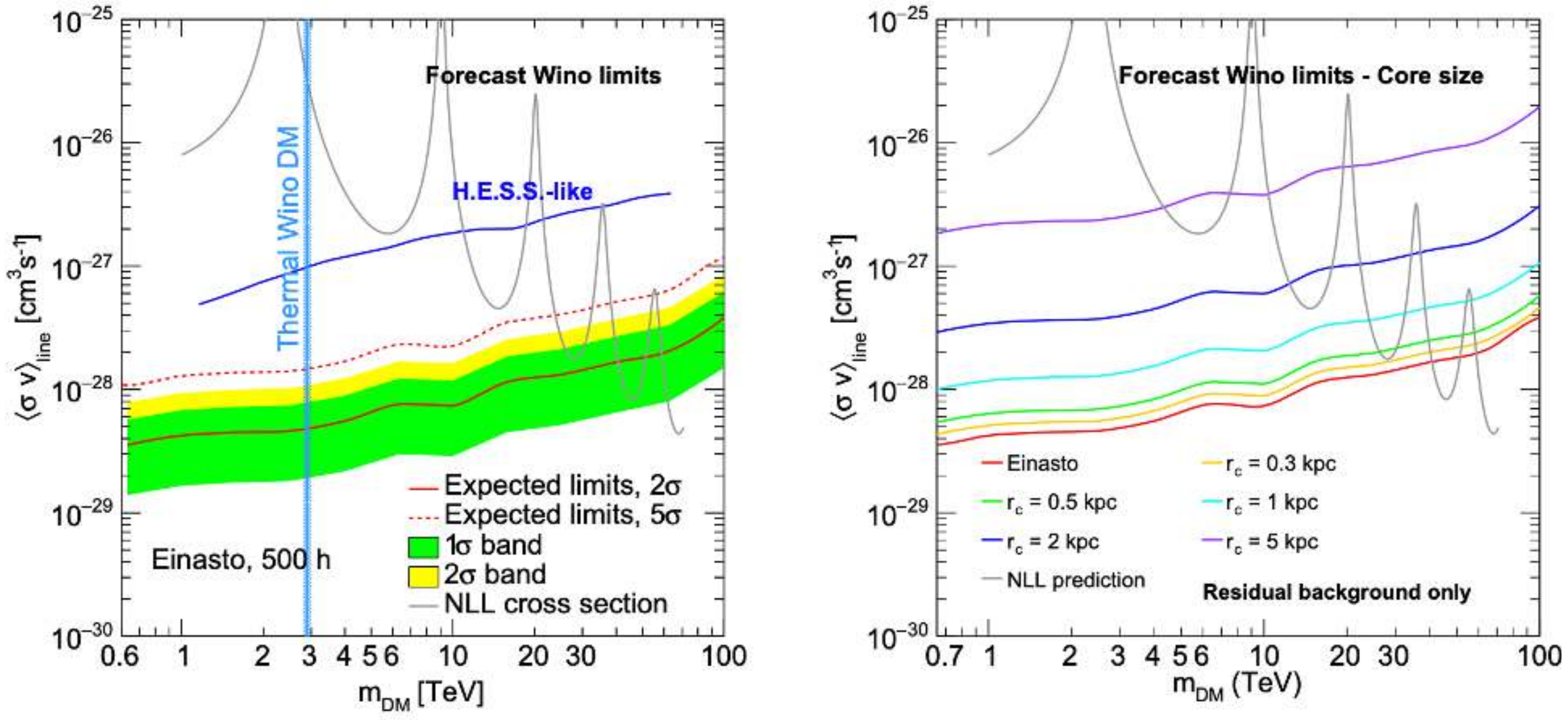
Phys. Rev. D 103, 023011 (2021)

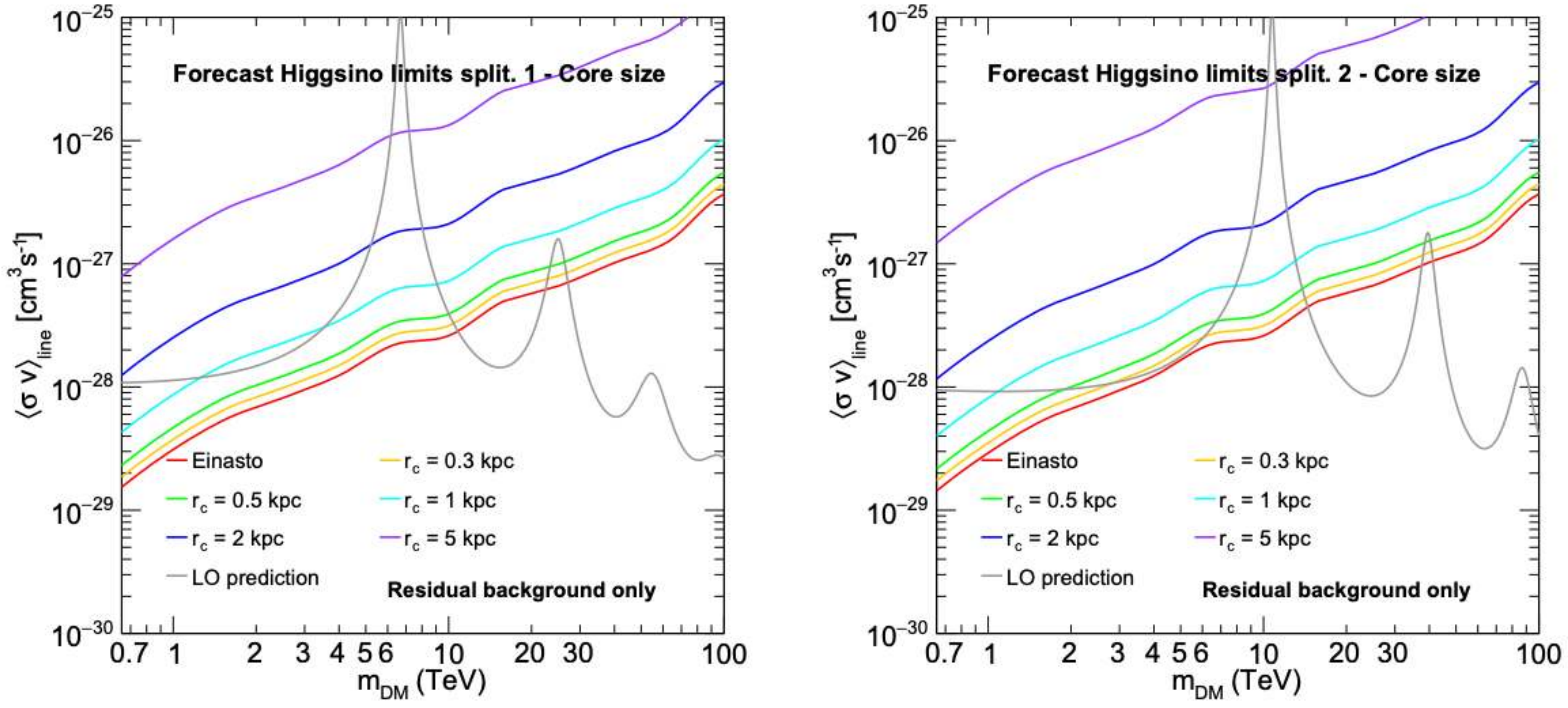
- CTA with the GC can constrain **SUSY-Wino, Higgsino**
  - **Wino@3 TeV: with both core and cuspy**
  - **Higgsino@1 TeV: with up to 1kpc core size**
  - The channel considered, mainly
    - **line emission** + **continuum spectra from W, Z decay**

Higgsino



Wino





Summary

- Indirect DM searches with gamma-ray is complementary with other WIMP searches
  - In particular, good tool to access **heavy DM models**

- **Ground-based Gamma-ray telescopes (IACTs)** has a good sensitivity on TeV gamma-ray
  - constrain WIMPs with variety of targets
    - **the Galactic Centre**: one of the most promising
    - MAGIC introduced the large zenith angle observation
      - Boosted the sensitivity at TeV energies
    - constrain on **SUSY-Wino** with **different DM density profiles**

- Next generation: **Cherenkov Telescope Array**
  - The first **Large-Sized Telescope** in **La Palma** is in operation
  - **The Galactic Centre** analysis with **CTA-LST** is ongoing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ASTRONOMÍA

Estrellas dobles: Aries

Esta constelación alberga algunas estrellas dobles de gran belleza

Rafael Benavides

Aplicaciones de la tecnología astrofísica en medicina

La astrofísica genera desarrollos tecnológicos que pueden utilizarse en otros campos, como la medicina

Alejandra Rueda

El universo cíclico de los antiguos egipcios

¿Cómo trató la cosmogonía egipcia la cuestión del origen y el fin del cosmos?

José Lull

CTA: explorando el universo más energético

El *Cherenkov Telescope Array Observatory* observará todo el cielo de rayos gamma con una precisión sin precedentes

Alba Fernández