



A Joint Gamma-ray Search for Dark Matter in Dwarf Spheroidal Galaxies with Fermi-LAT, HAWC, H.E.S.S., MAGIC and VERITAS

Javier Rico

Institut de Física d'Altes Energies, Barcelona (Spain)

C. Armand, E. Charles, M. Di Mauro, C. Giuri, J. P. Harding, D. Kerszberg, T. Miener, E. Moulin, L. Oakes, V. Poireau, E. Pueschel, L. Rinchuso, D. Salazar-Gallegos and K. A. Tollefson

On behalf of the Fermi-LAT, H.E.S.S., MAGIC, VERITAS and HAWC Collaborations

Introduction/context

★ DM general properties:

- * ~25% of all the energy/matter; ~85% of all the matter
- * Non-baryonic and electrically neutral → so far, only gravitational effects observed
- * Cold → seed of structures, we know where it accumulates
- * Stable (on cosmological scales) → we know how much there is

★ WIMPs:

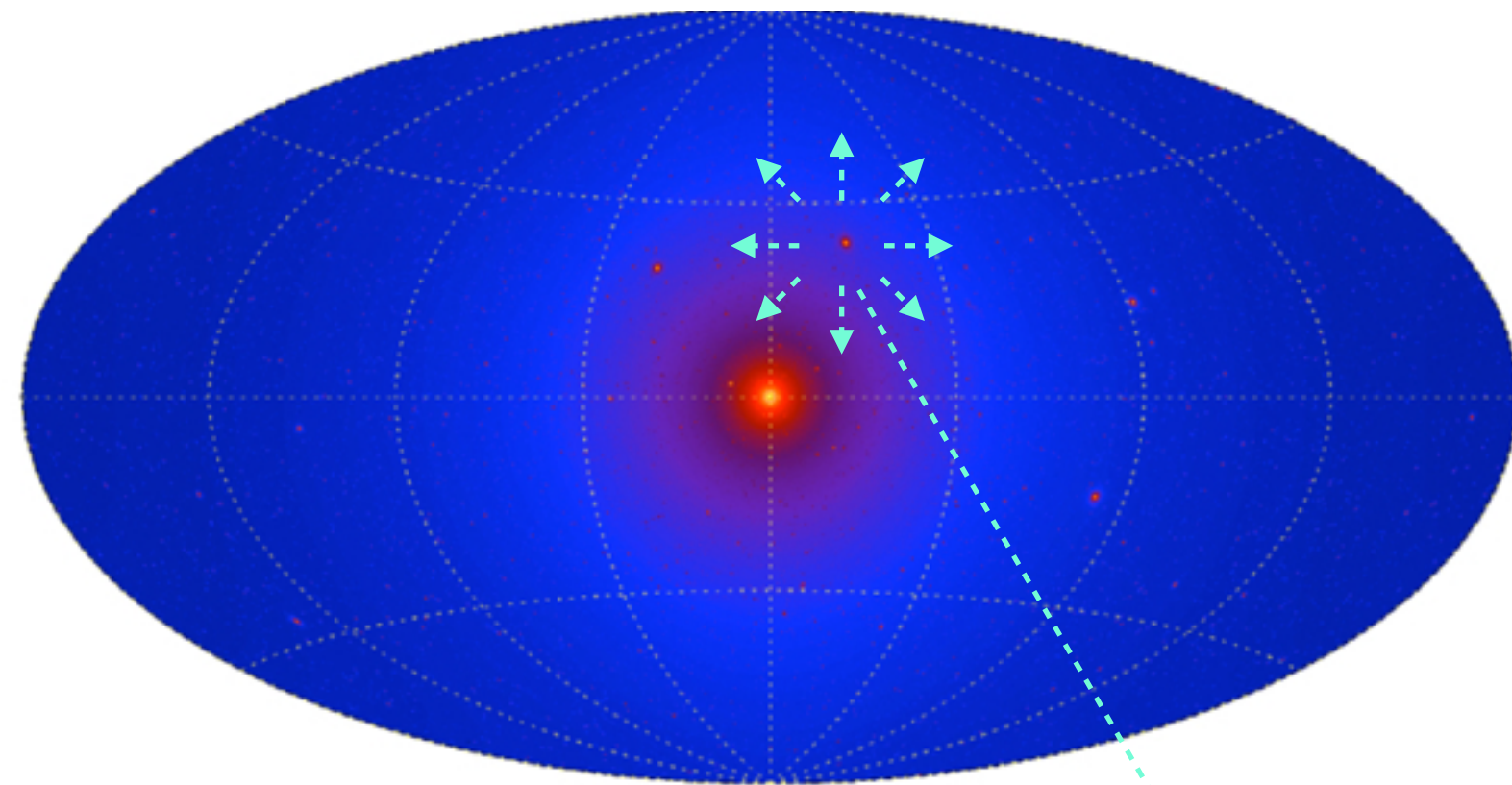
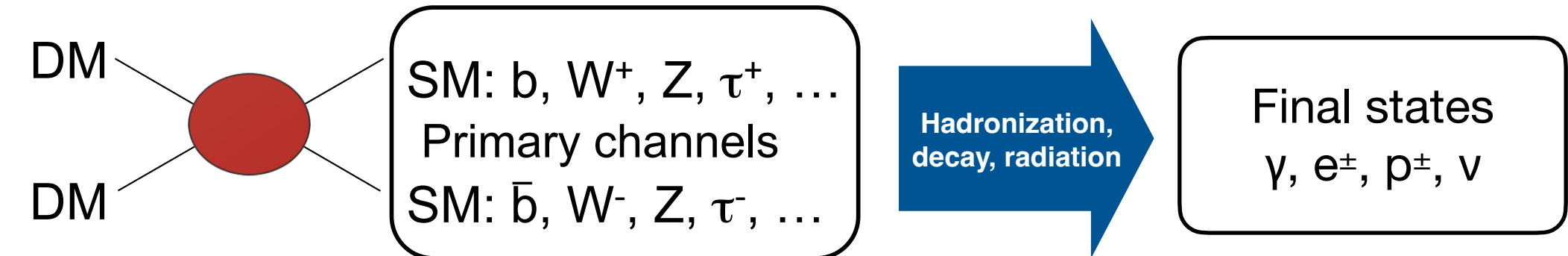
- * Thermal relic → interacts (weakly) with regular matter
- * Mass ~TeV → SM particles in the GeV-TeV regime expected from DM annihilation/decay
- * Annihilation cross section $\langle\sigma v\rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$ → relic density → reference for expected SM signal intensities

★ ~20 years of observations by current generation of high-energy gamma-ray instruments:

- * All try to measure/constrain the same fundamental quantities (DM mass, interaction cross section...)
- * Published results cannot be trivially combined

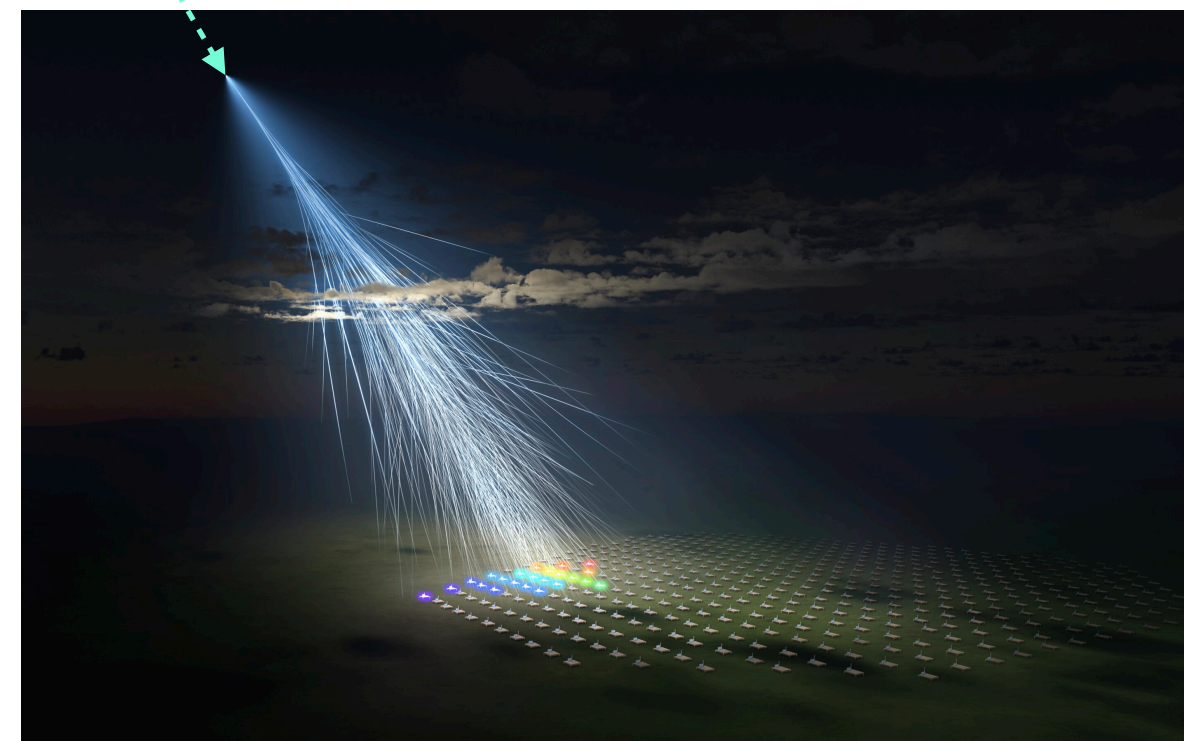
Indirect dark matter detection

- ★ Search the extra-terrestrial fluxes of SM particles for **spectral and spatial signatures** of dark matter



★ HE Messengers

- ★ Gamma-rays
- ★ Neutrinos
- ★ Electron/positrons
- ★ Anti-matter



★ Spectral features:

- ★ Separation from background
- ★ Mass, cross-section / lifetime

★ Spatial features

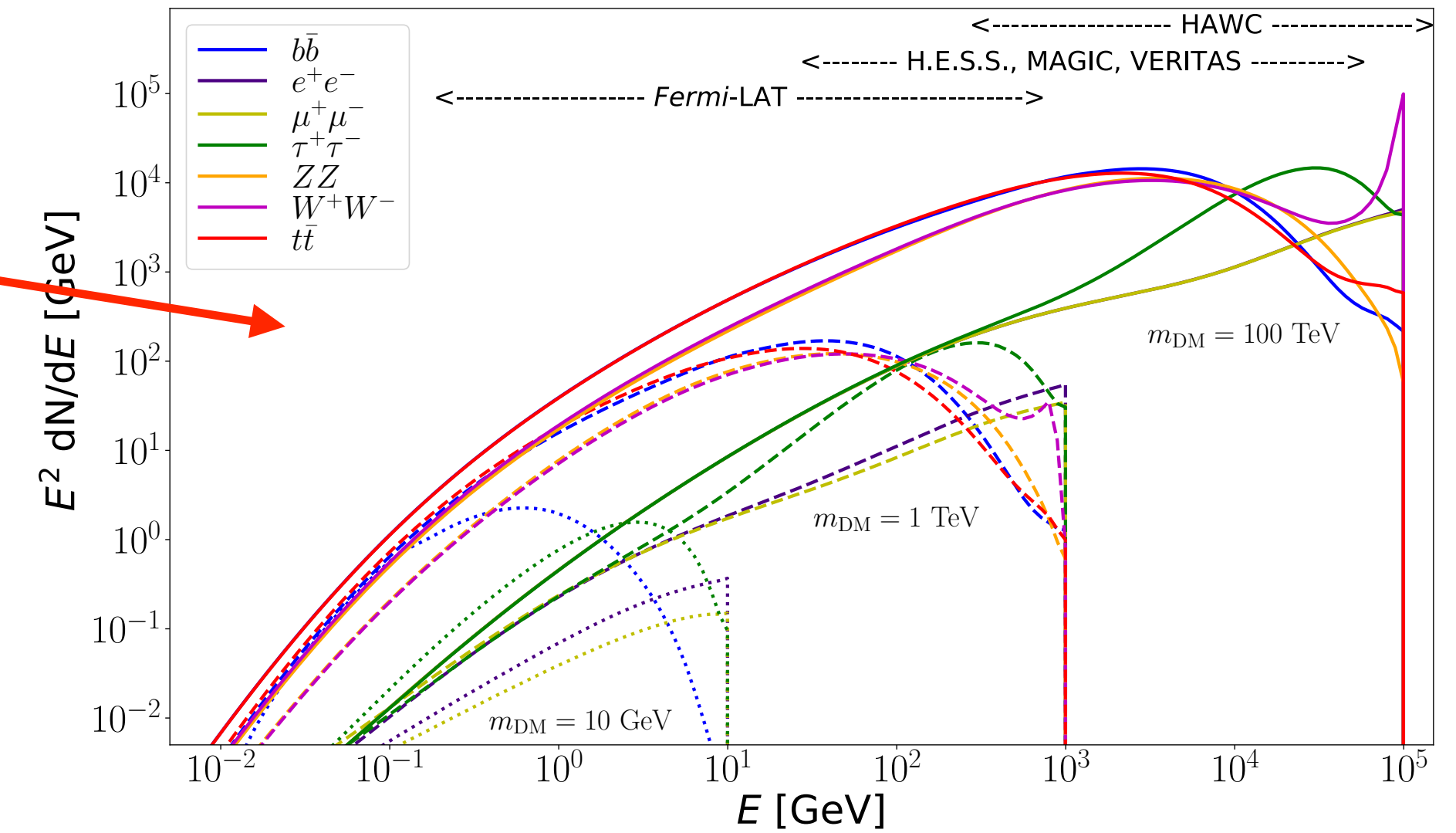
- ★ Coarse and energy-dependent for charged final states
- ★ **Gamma-rays or neutrinos do not suffer from propagation effects:**
 - ★ Exploit spatial features known from N-body simulations and measurements
 - ★ Can determine DM abundance and distribution in the Universe

DM [annihilation] gamma-ray flux

$$\frac{d\Phi_\gamma}{dE} \propto \langle \sigma v \rangle \times \frac{J}{m_{\text{DM}}^2} \times \frac{dN_\gamma}{dE}$$

DM [annihilation] gamma-ray flux

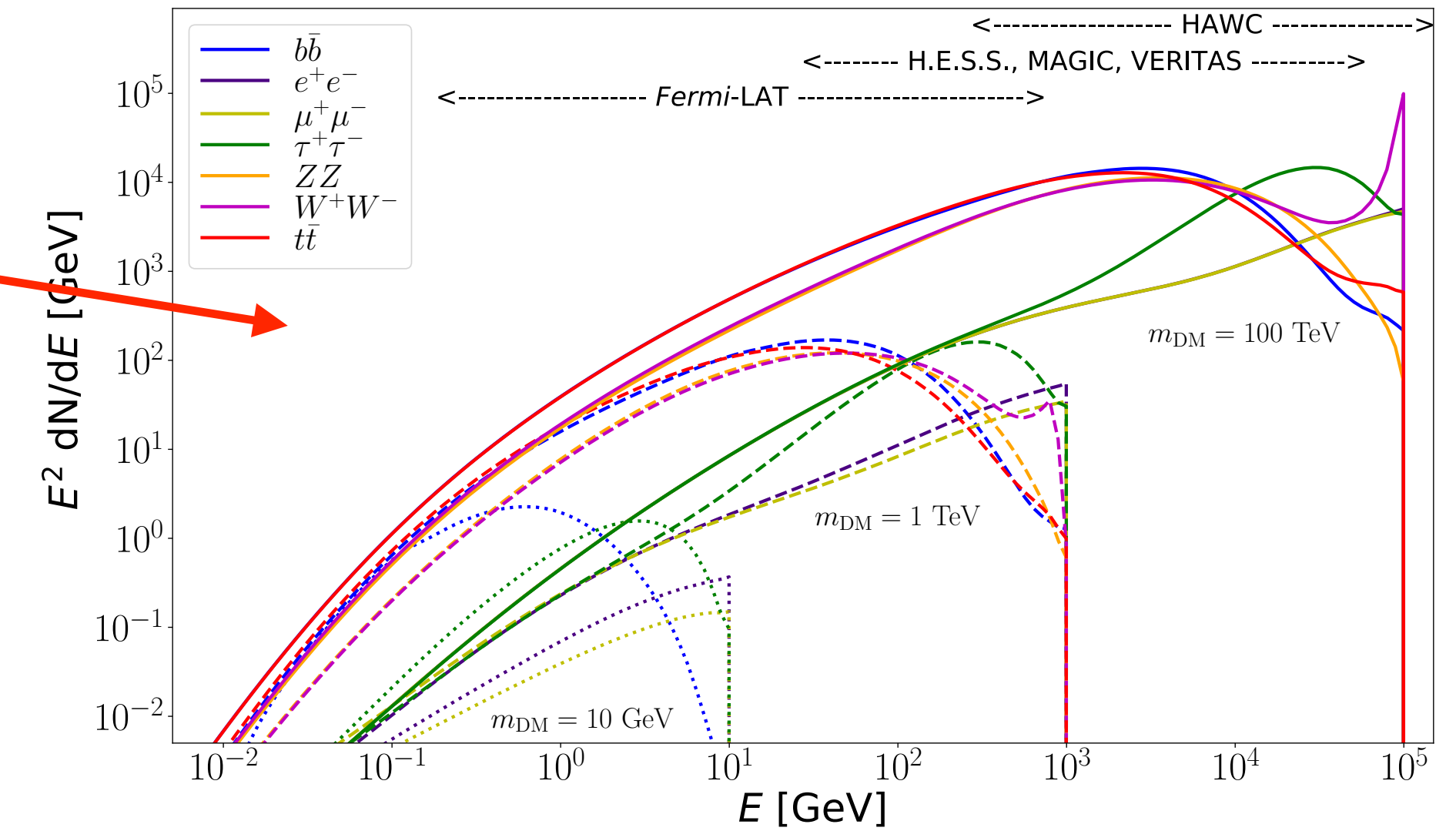
$$\frac{d\Phi_\gamma}{dE} \propto \langle \sigma v \rangle \times \frac{J}{m_{\text{DM}}^2} \times \frac{dN_\gamma}{dE}$$



DM [annihilation] gamma-ray flux

$$\frac{d\Phi_\gamma}{dE} \propto \langle \sigma v \rangle \times \frac{J}{m_{\text{DM}}^2} \times \frac{dN_\gamma}{dE}$$

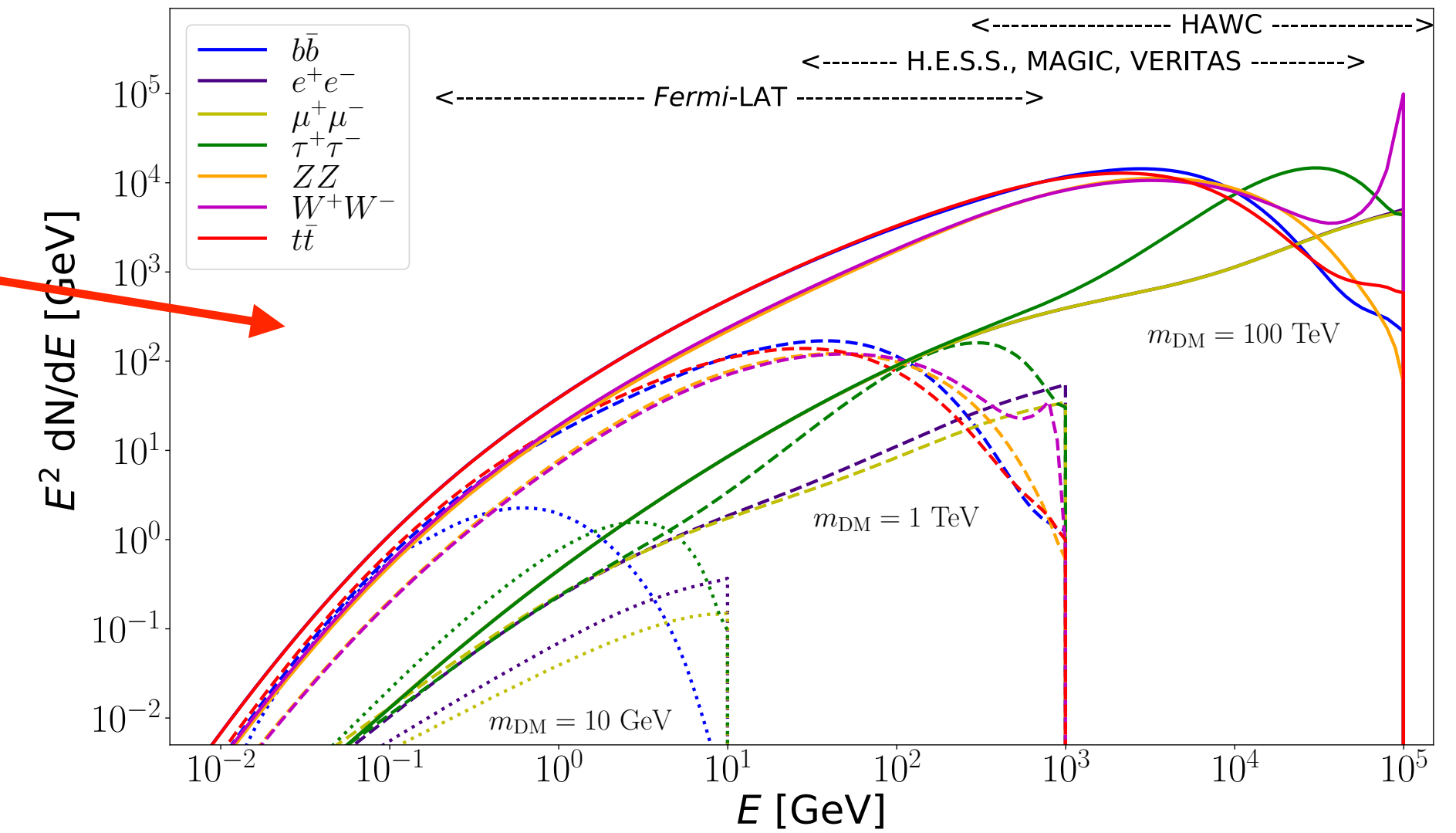
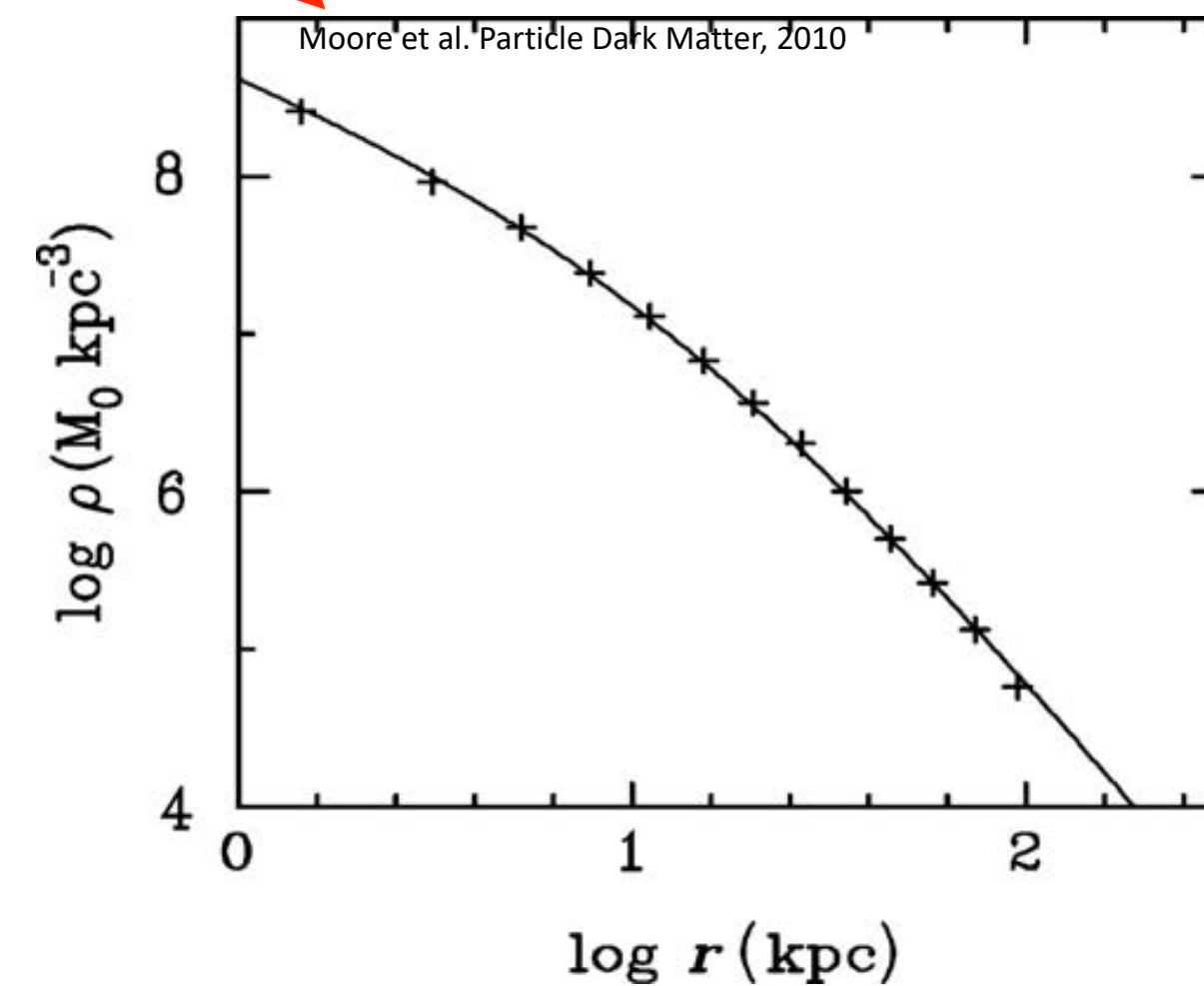
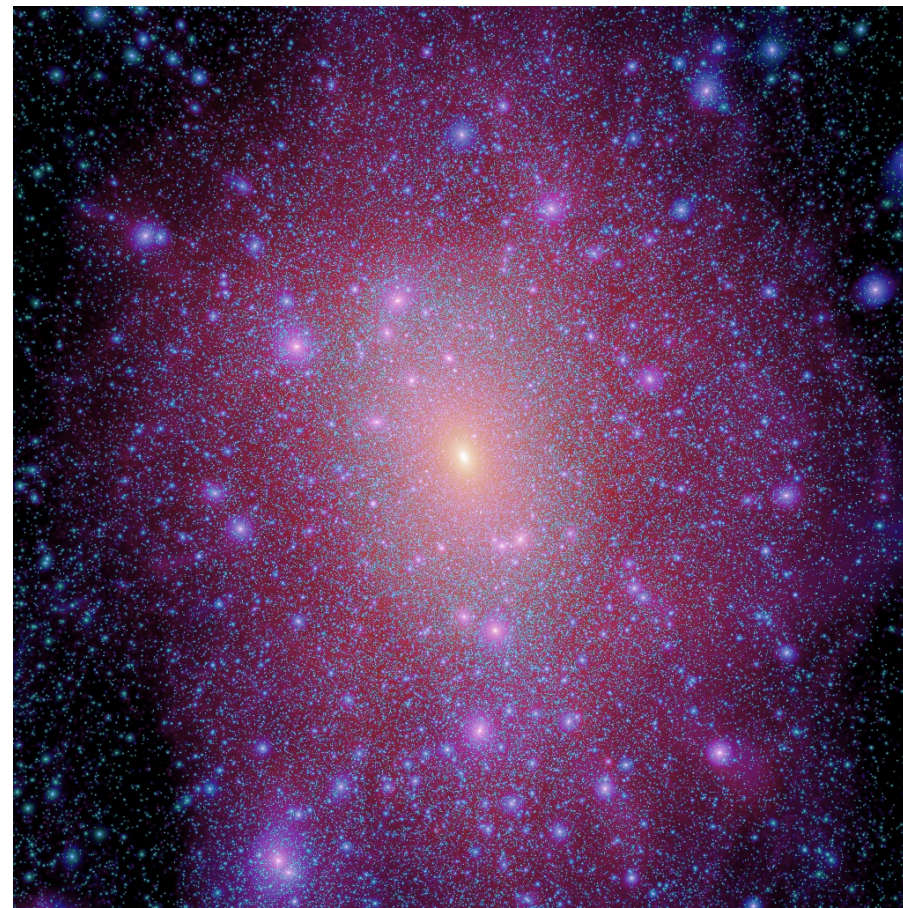
$$J = \int d\Omega \, dl \, \rho_{\text{DM}}^2$$



DM [annihilation] gamma-ray flux

$$\frac{d\Phi_\gamma}{dE} \propto \langle \sigma v \rangle \times \frac{J}{m_{\text{DM}}^2} \times \frac{dN_\gamma}{dE}$$

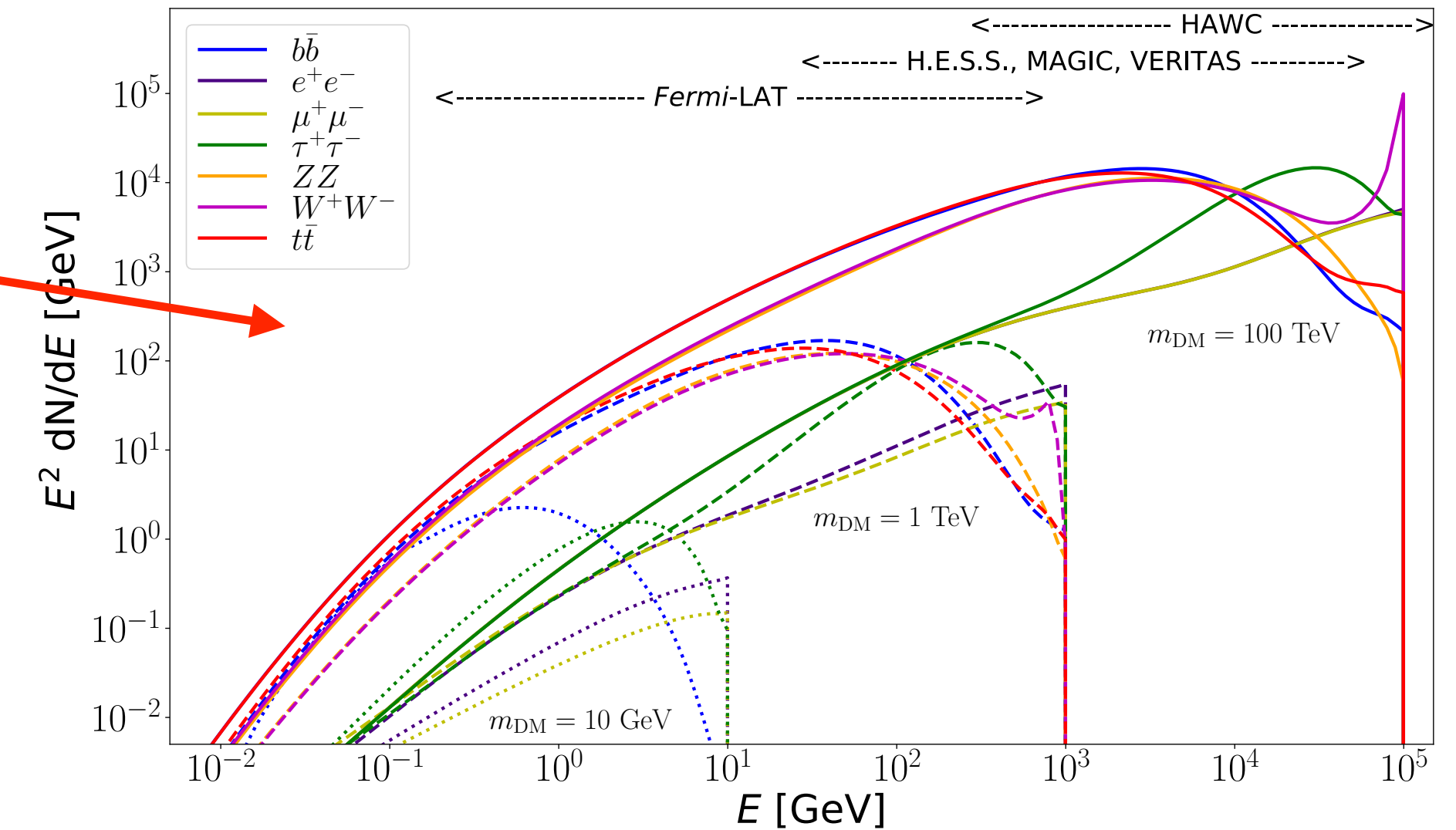
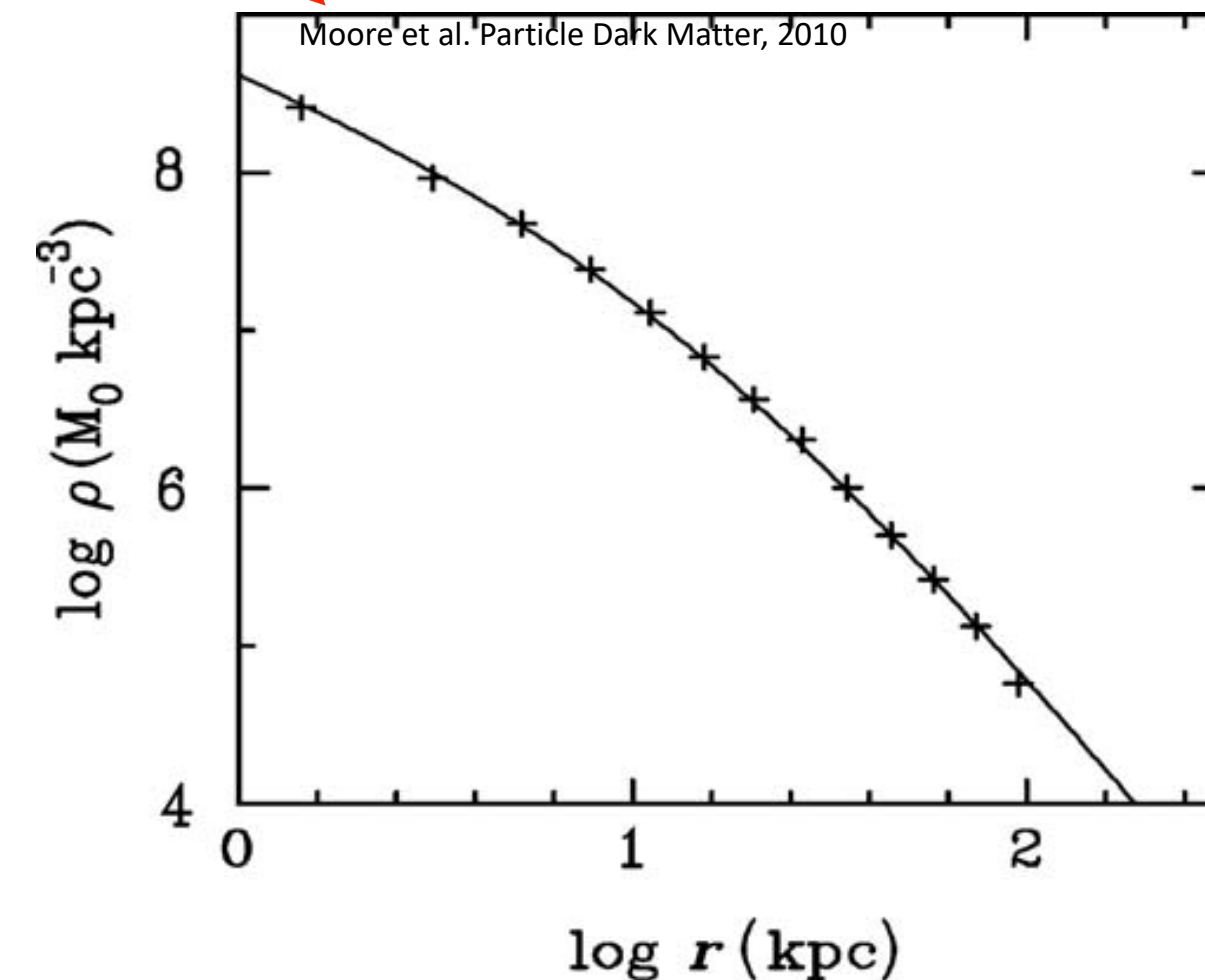
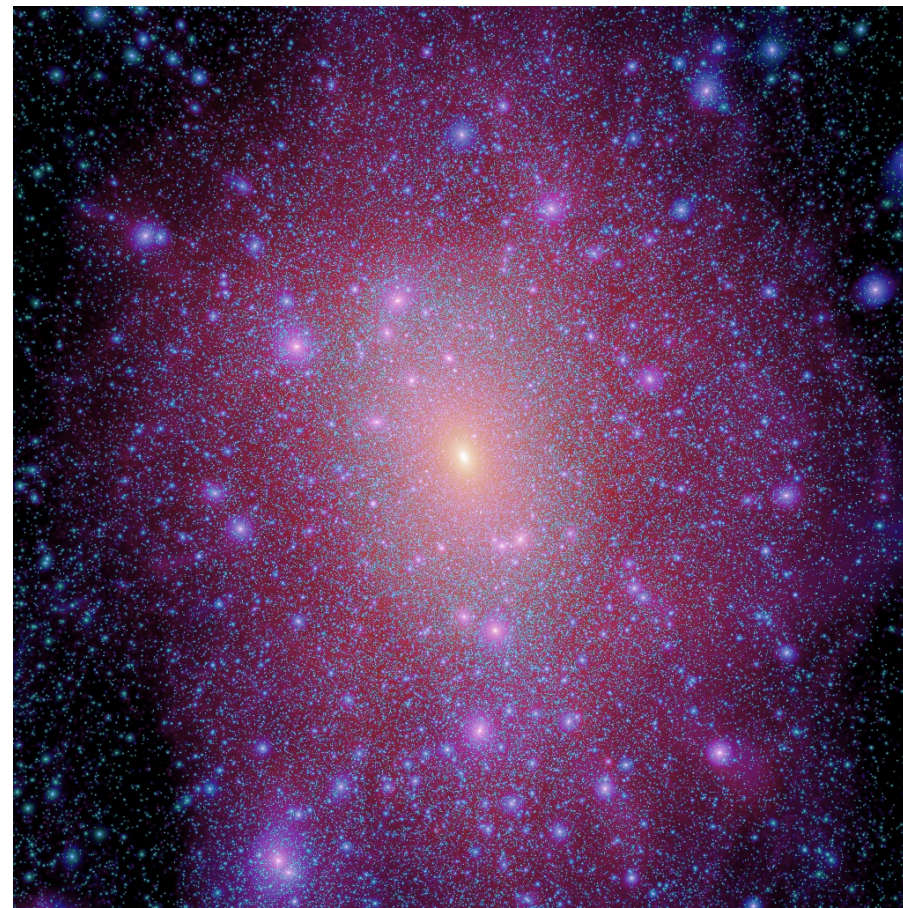
$$J = \int d\Omega \, dl \, \rho_{\text{DM}}^2$$



DM [annihilation] gamma-ray flux

$$\frac{d\Phi_\gamma}{dE} \propto \langle \sigma v \rangle \times \frac{J}{m_{\text{DM}}^2} \times \frac{dN_\gamma}{dE}$$

$$J = \int d\Omega \, dl \, \rho_{\text{DM}}^2$$



Work-flow:

$d\Phi_\gamma/dE$ measurement/limit
 +
 measured J
 +
 assumed m_{DM} and ann. channel
 =
 $\langle \sigma v \rangle$ measurement/limit

Observational targets

Dwarf spheroidal galaxies

Gravitationally bound ~ spherical group of stars

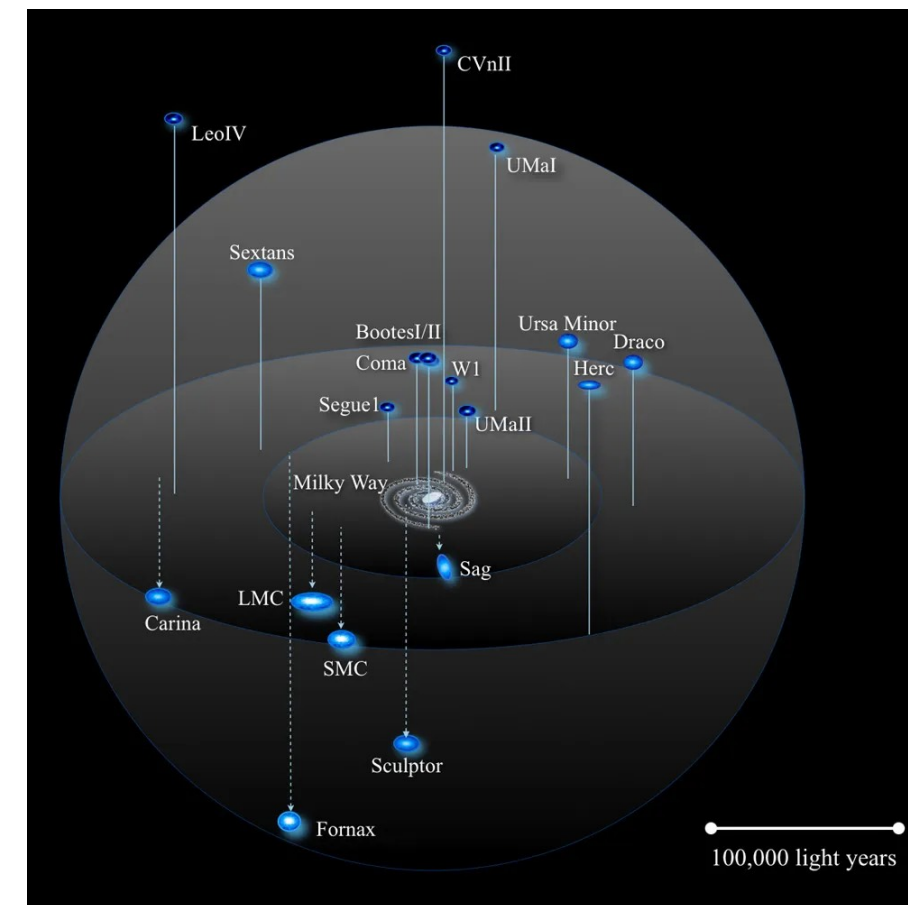
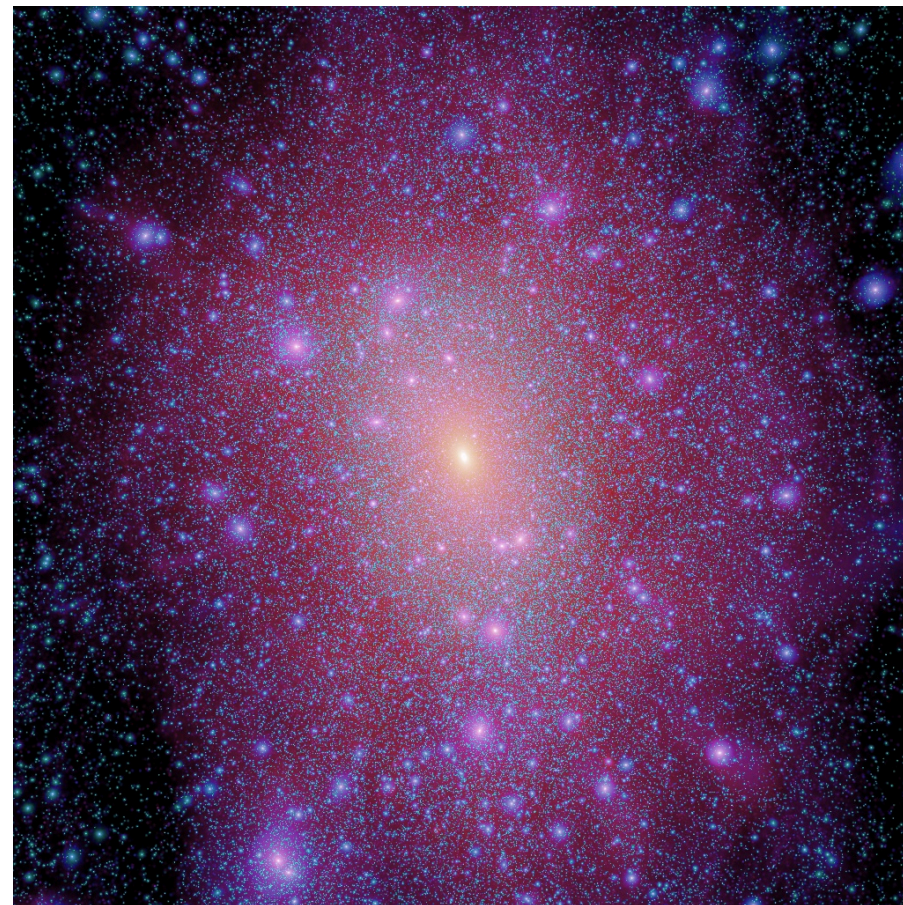
Low luminosity ~ $10^2 - 10^6 L_{\odot}$

Mass ~ $10^7 M_{\odot}$

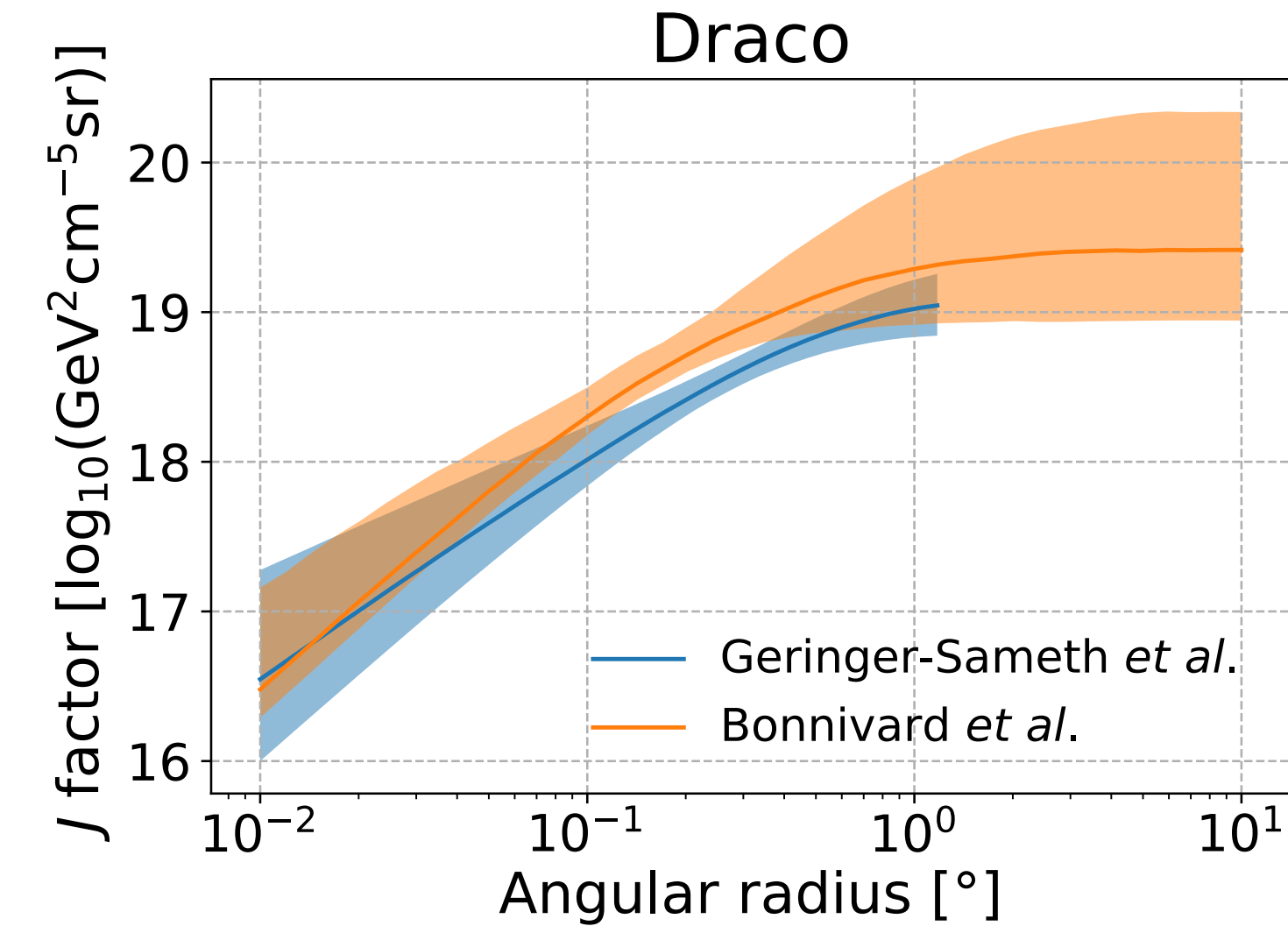
Very low gas/dust content → “primordial”

Stellar kinematics allow to derive $\rho_{\text{DM}} \rightarrow J$

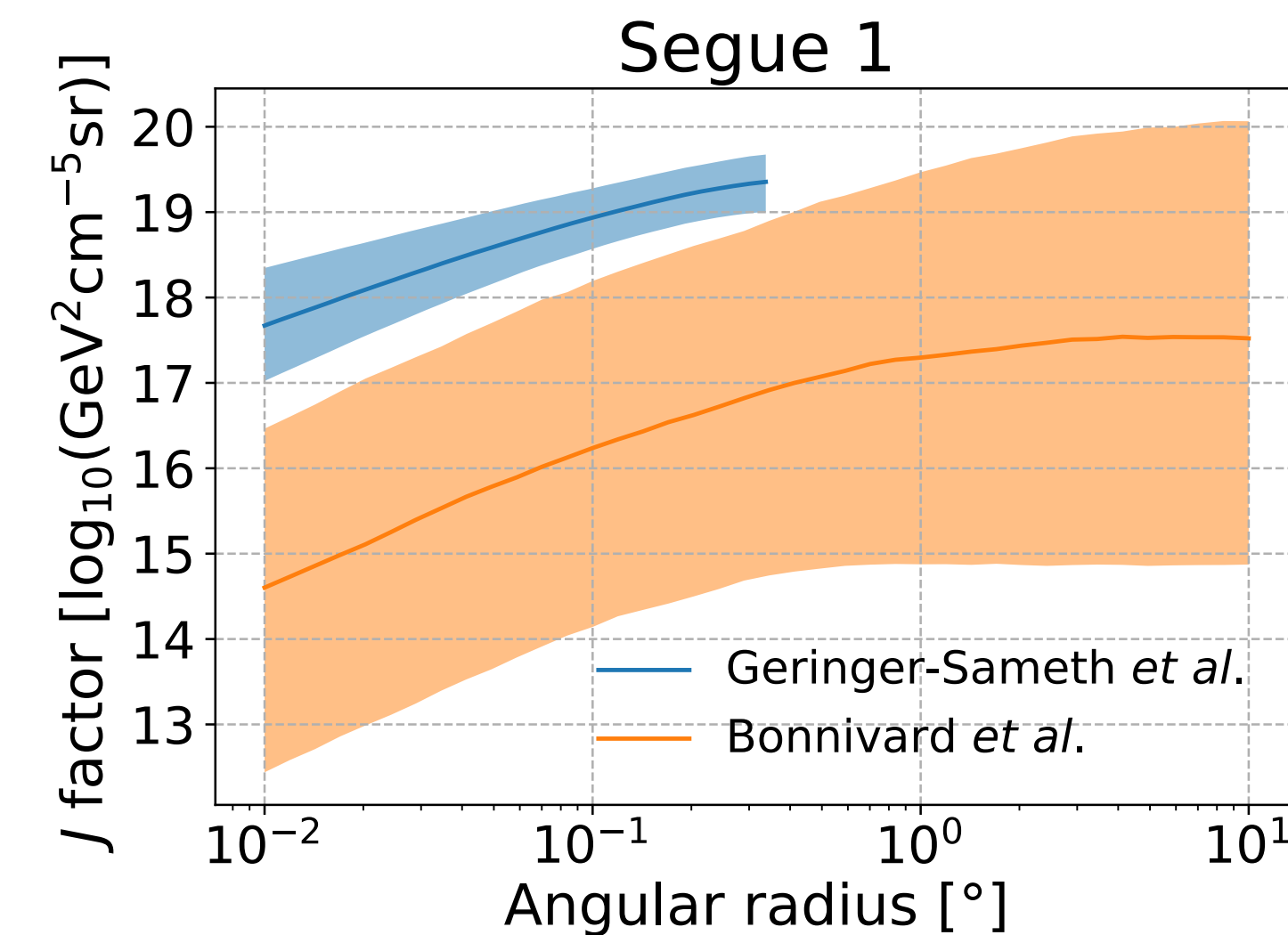
No astrophysical background



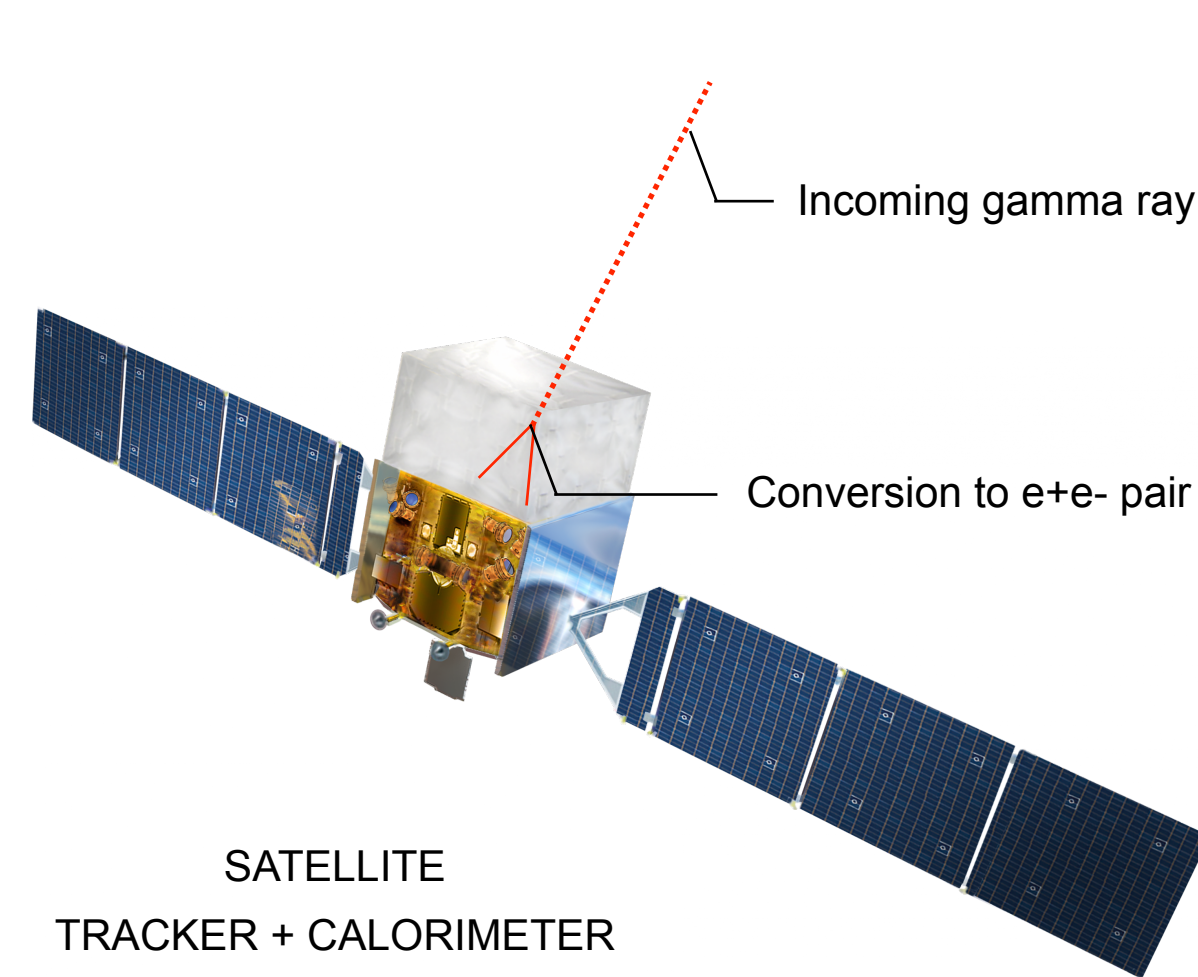
Classical



Ultra-faint



Gamma-ray detection



Key features

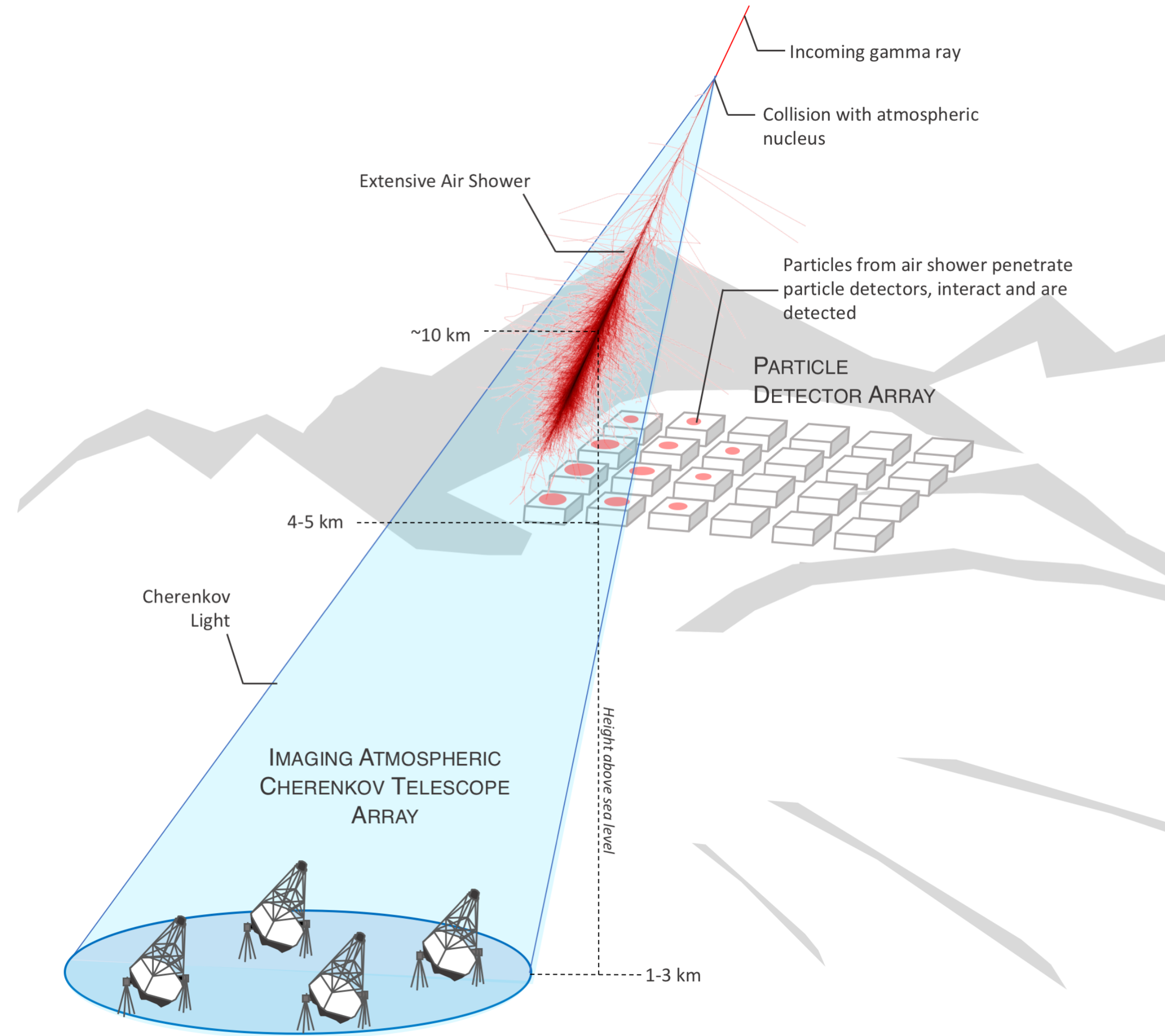
Duty cycle

Field of view

Background intensity

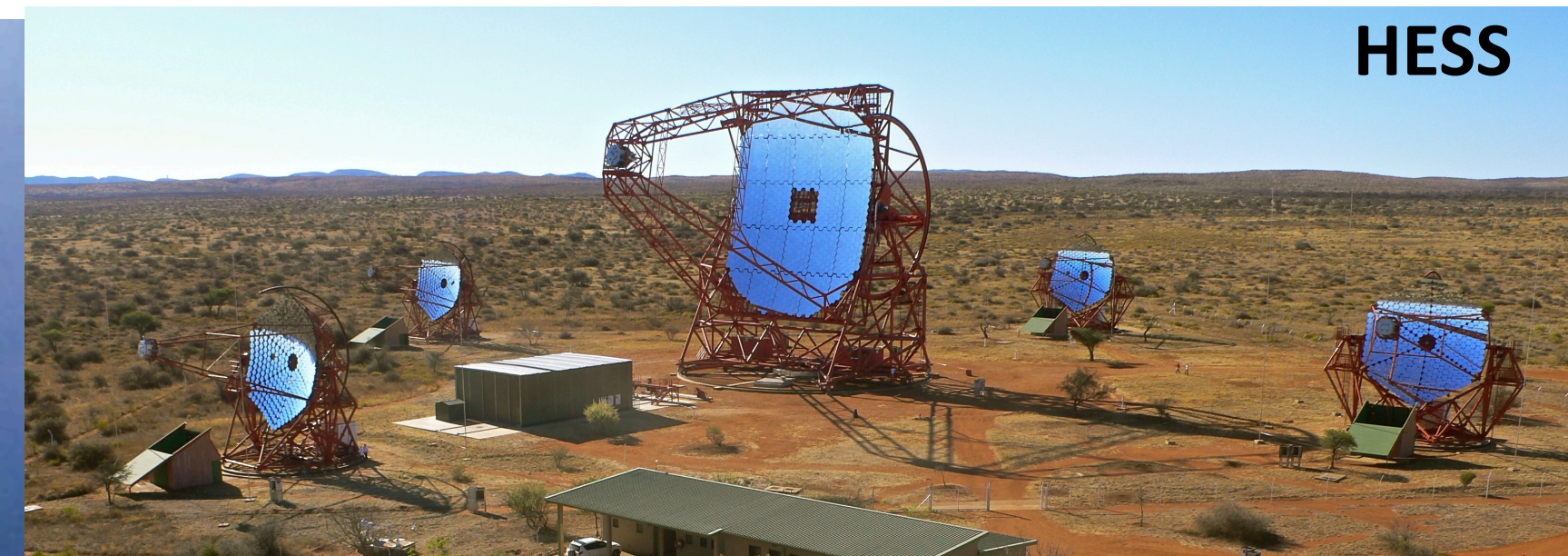
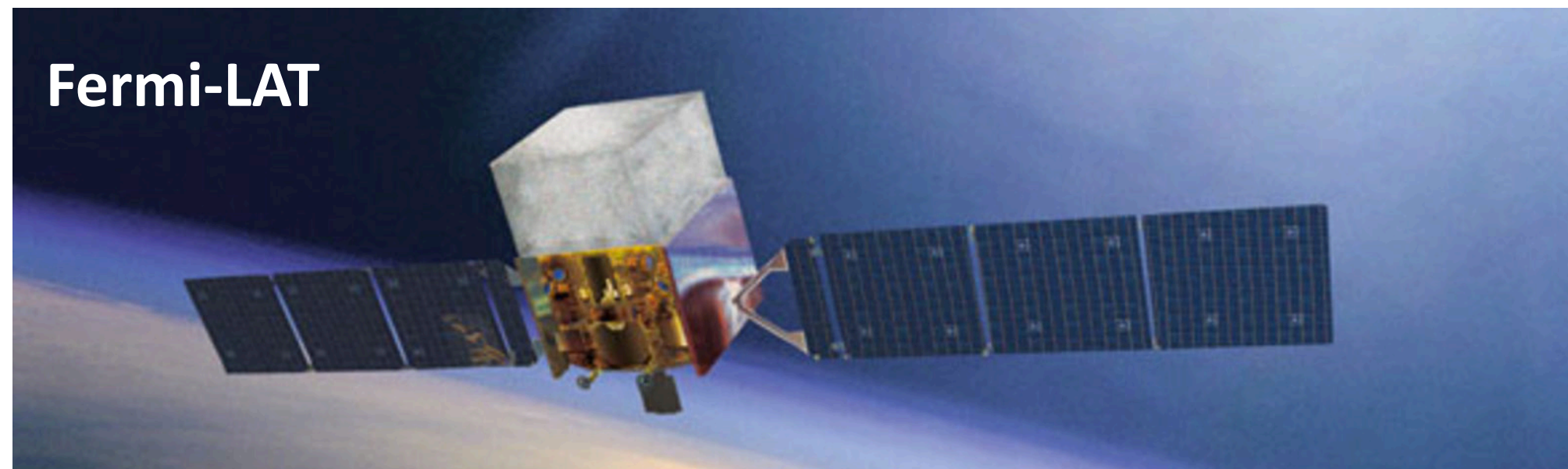
Angular resolution

Energy resolution



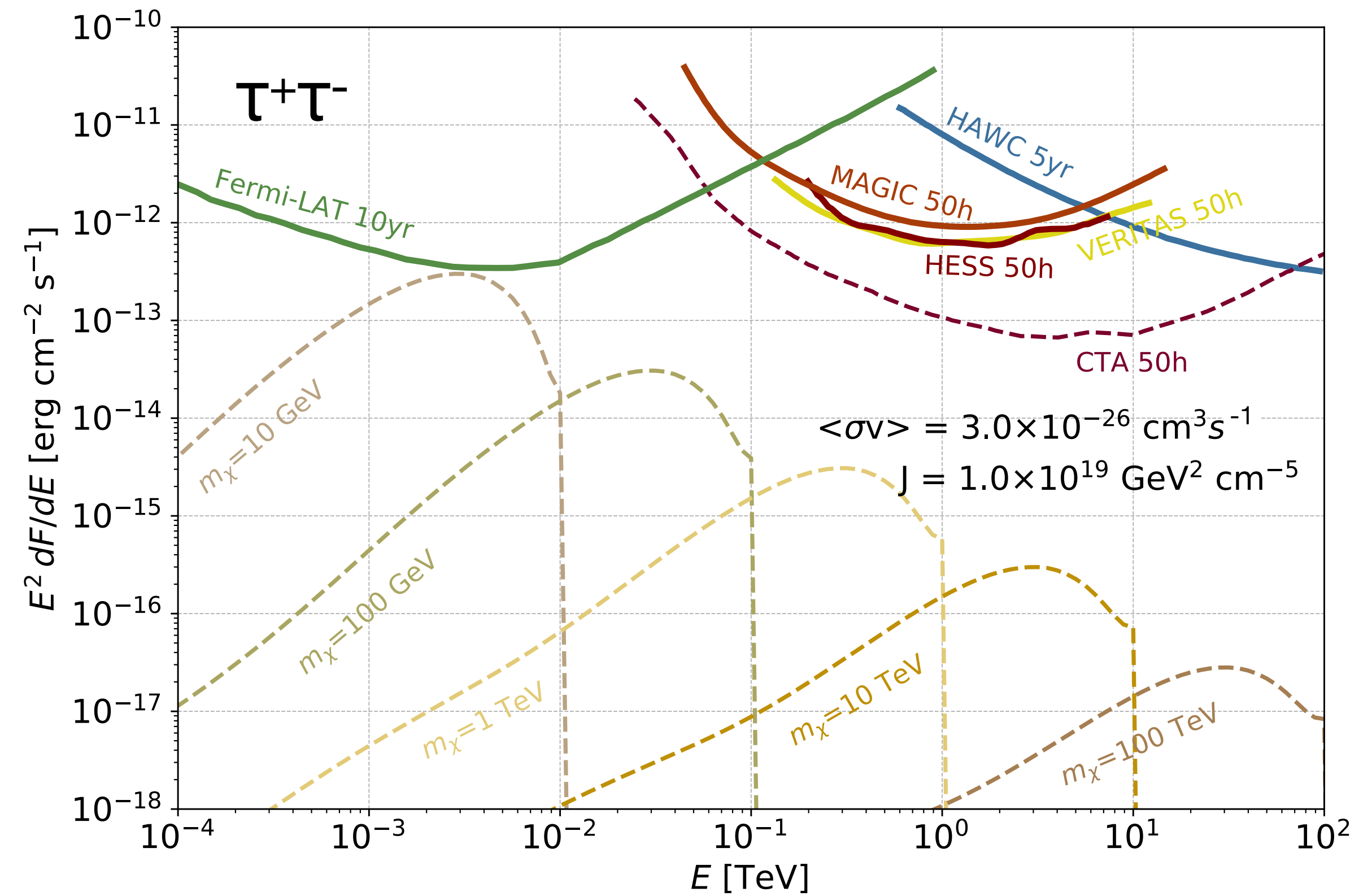
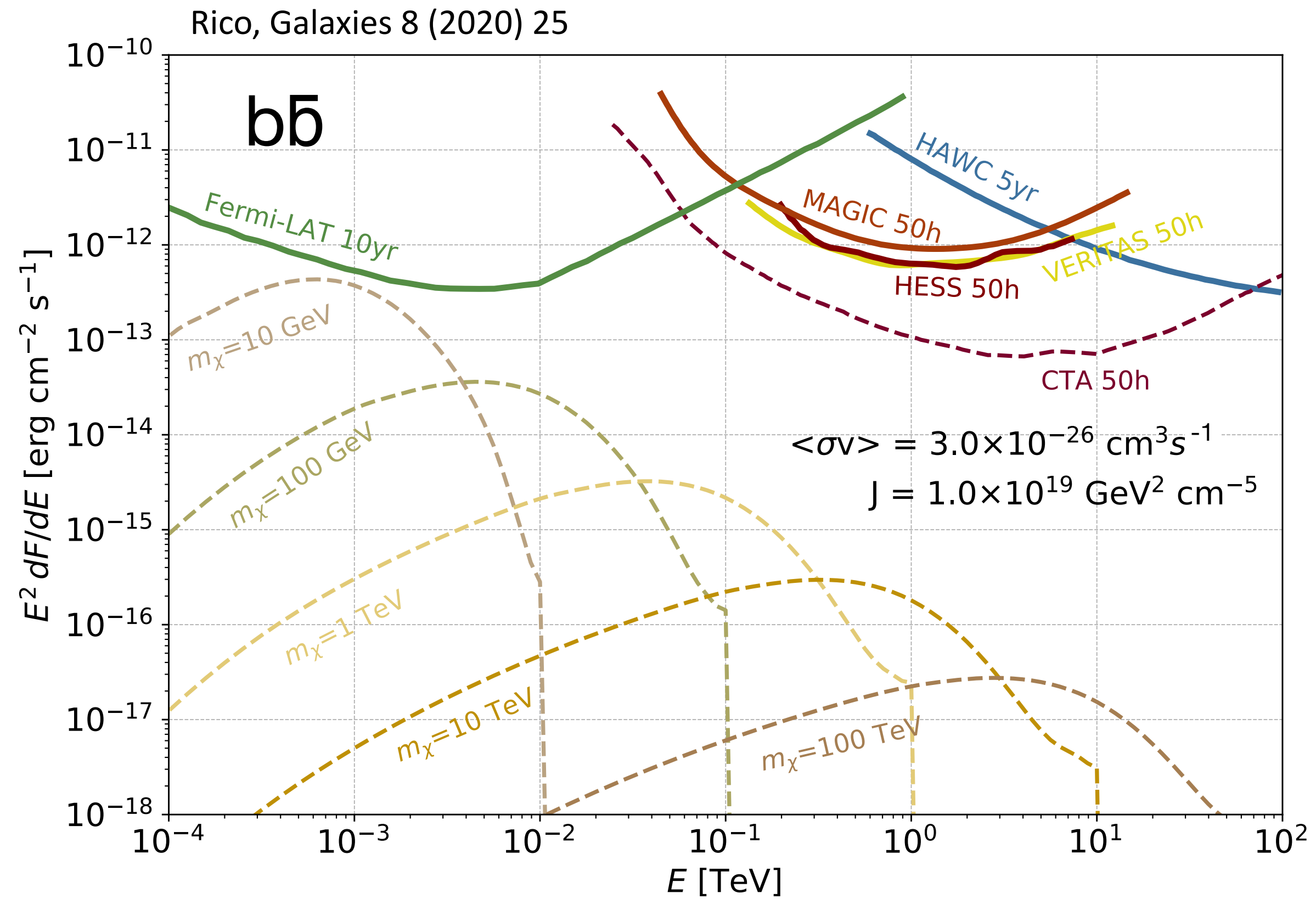
Not to scale

Instruments



- ★ 5 Collaborations
- ★ ~600 authors
- ★ 120 research institutions

Wide energy coverage

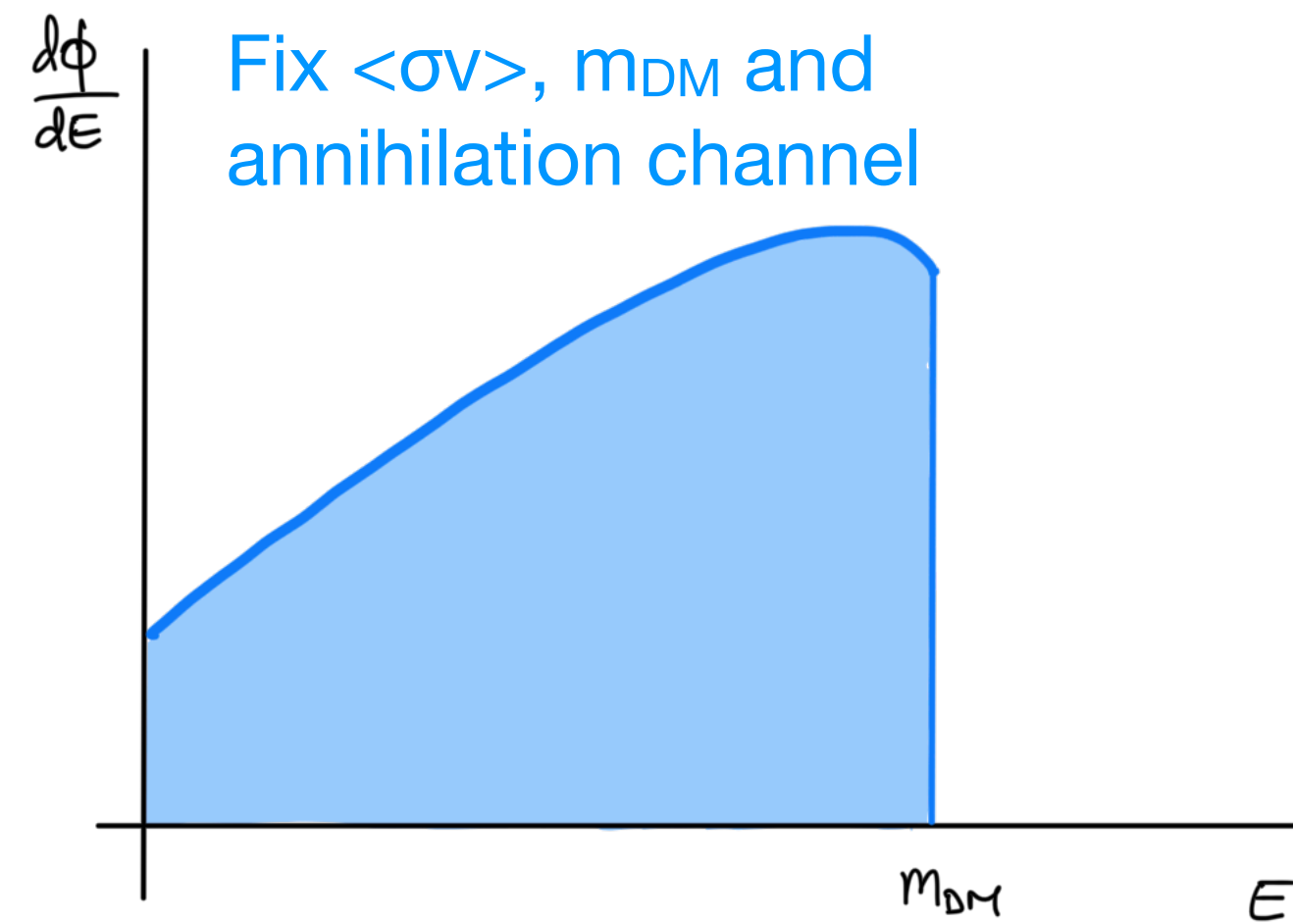


Observations

10 years 1038 days

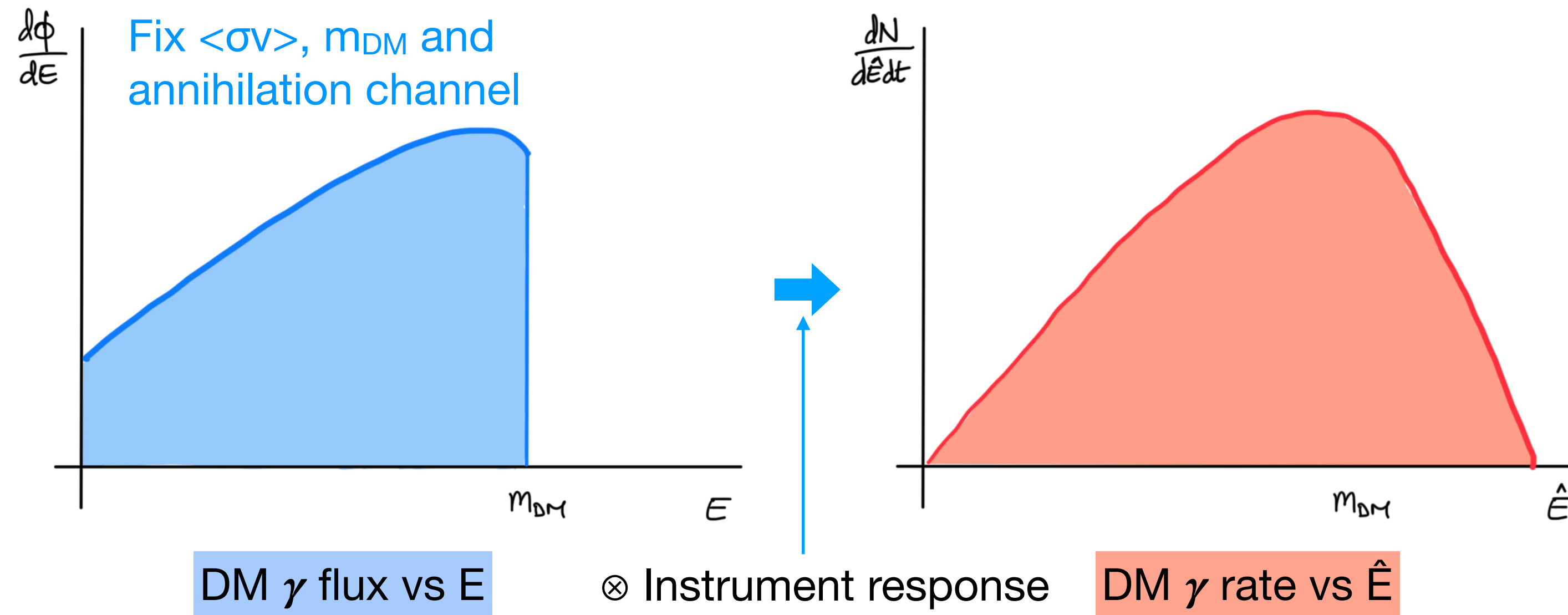
	<i>Fermi</i> -LAT	HAWC	H.E.S.S., MAGIC, VERITAS						
Source name	Exposure (10^{11} s cm ²)	$ \Delta\phi $ (°)	IACTs	Zenith (°)	Time exposure (h)	Energy range (TeV)	θ_{sig} (°)	τ	S (σ)
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0	0.10 – 41	0.17	8.6	−1.0
Canes Venatici I	2.9	14.6	—	—	—	—	—	—	—
Canes Venatici II	2.9	15.3	—	—	—	—	—	—	—
Carina	3.1	—	H.E.S.S.	27 – 46	23.7	0.31 – 70	0.10	18.0	−0.3
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4	0.55 – 70	0.10	14.4	−0.4
			MAGIC	5 – 37	49.5	0.06 – 10	0.17	1.0	0.8
Draco	3.8	38.1	MAGIC	29 – 45	52.1	0.07 – 10	0.22	1.0	−0.7
			VERITAS	25 – 40	49.8	0.12 – 70	0.17	9.0	−1.0
Fornax	2.7	—	H.E.S.S.	11 – 25	6.8	0.23 – 70	0.10	45.5	−1.5
Hercules	2.8	6.3	—	—	—	—	—	—	—
Leo I	2.5	6.7	—	—	—	—	—	—	—
Leo II	2.6	3.1	—	—	—	—	—	—	—
Leo IV	2.4	19.5	—	—	—	—	—	—	—
Leo V	2.4	—	—	—	—	—	—	—	—
Leo T	2.6	—	—	—	—	—	—	—	—
Sculptor	2.7	—	H.E.S.S.	10 – 46	11.8	0.20 – 70	0.10	19.8	−2.2
Segue 1	2.5	2.9	MAGIC	13 – 37	158.0	0.06 – 10	0.12	1.0	−0.5
			VERITAS	15 – 35	92.0	0.08 – 50	0.17	7.6	0.7
Segue 2	2.7	—	—	—	—	—	—	—	—
Sextans	2.4	20.6	—	—	—	—	—	—	—
Ursa Major I	3.4	32.9	—	—	—	—	—	—	—
Ursa Major II	4.0	44.1	MAGIC	35 – 45	94.8	0.12 – 10	0.30	1.0	−2.1
Ursa Minor	4.1	—	VERITAS	35 – 45	60.4	0.16 – 93	0.17	8.4	−0.1

Likelihood analysis

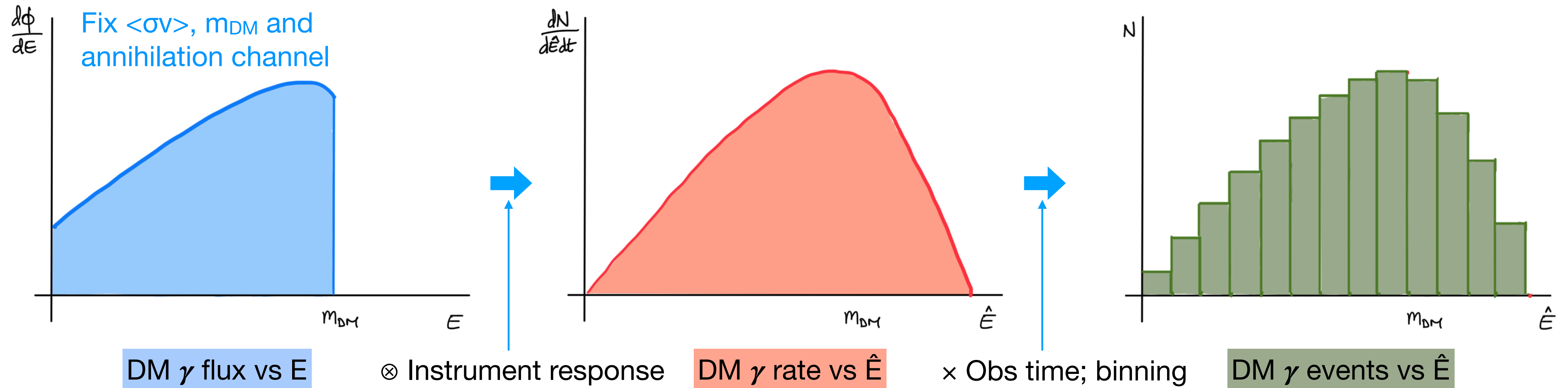


DM γ flux vs E

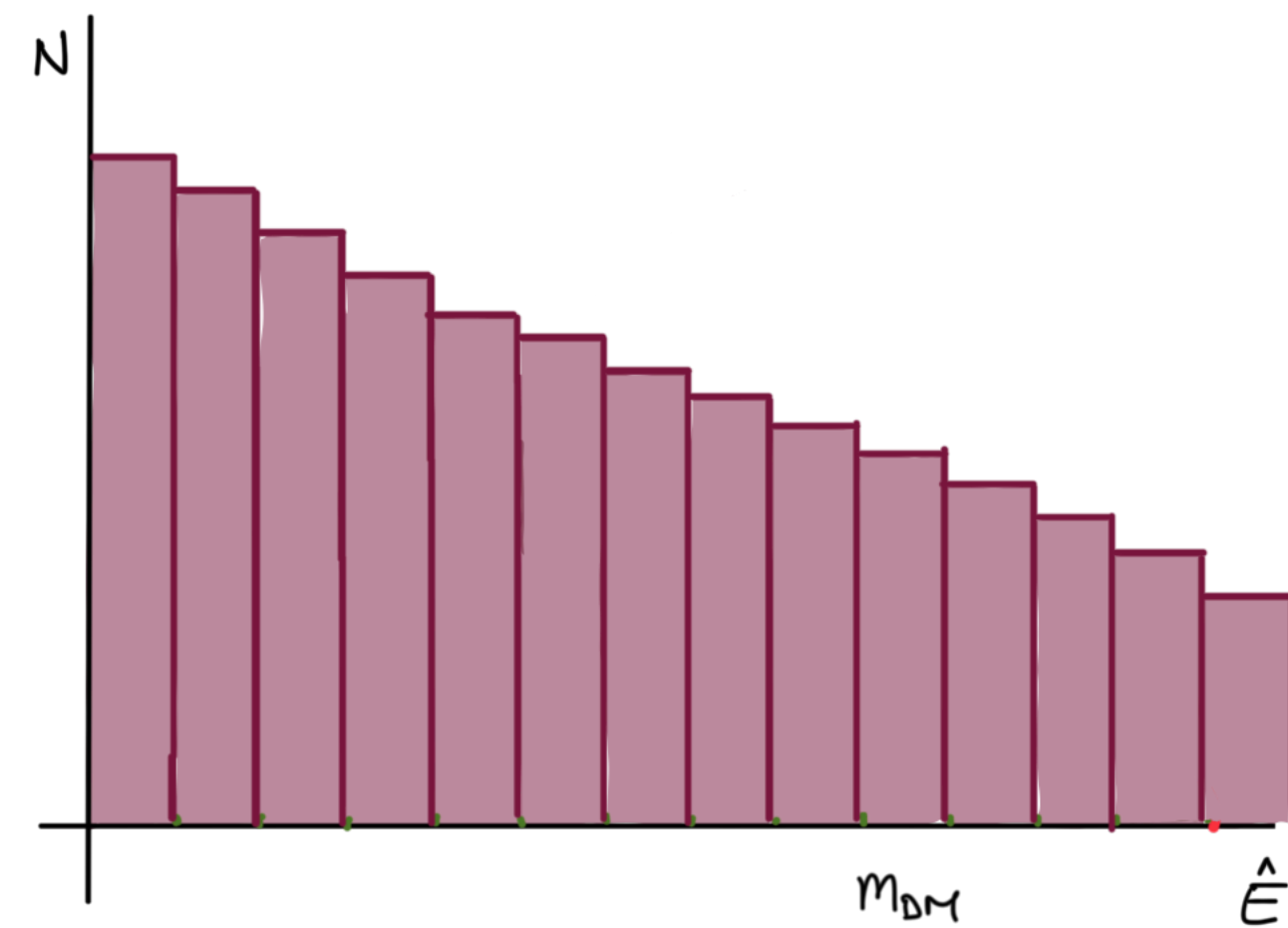
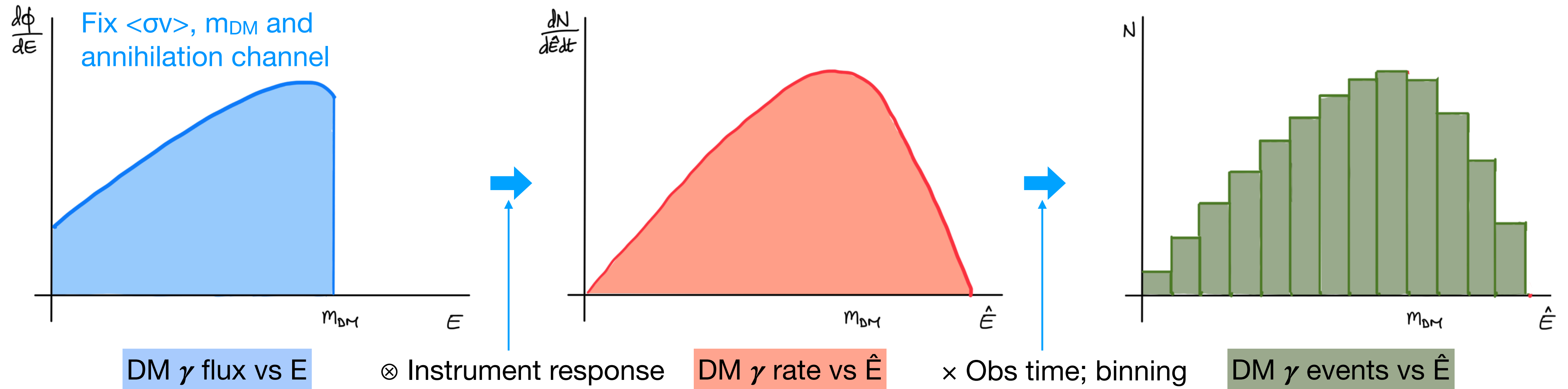
Likelihood analysis



Likelihood analysis

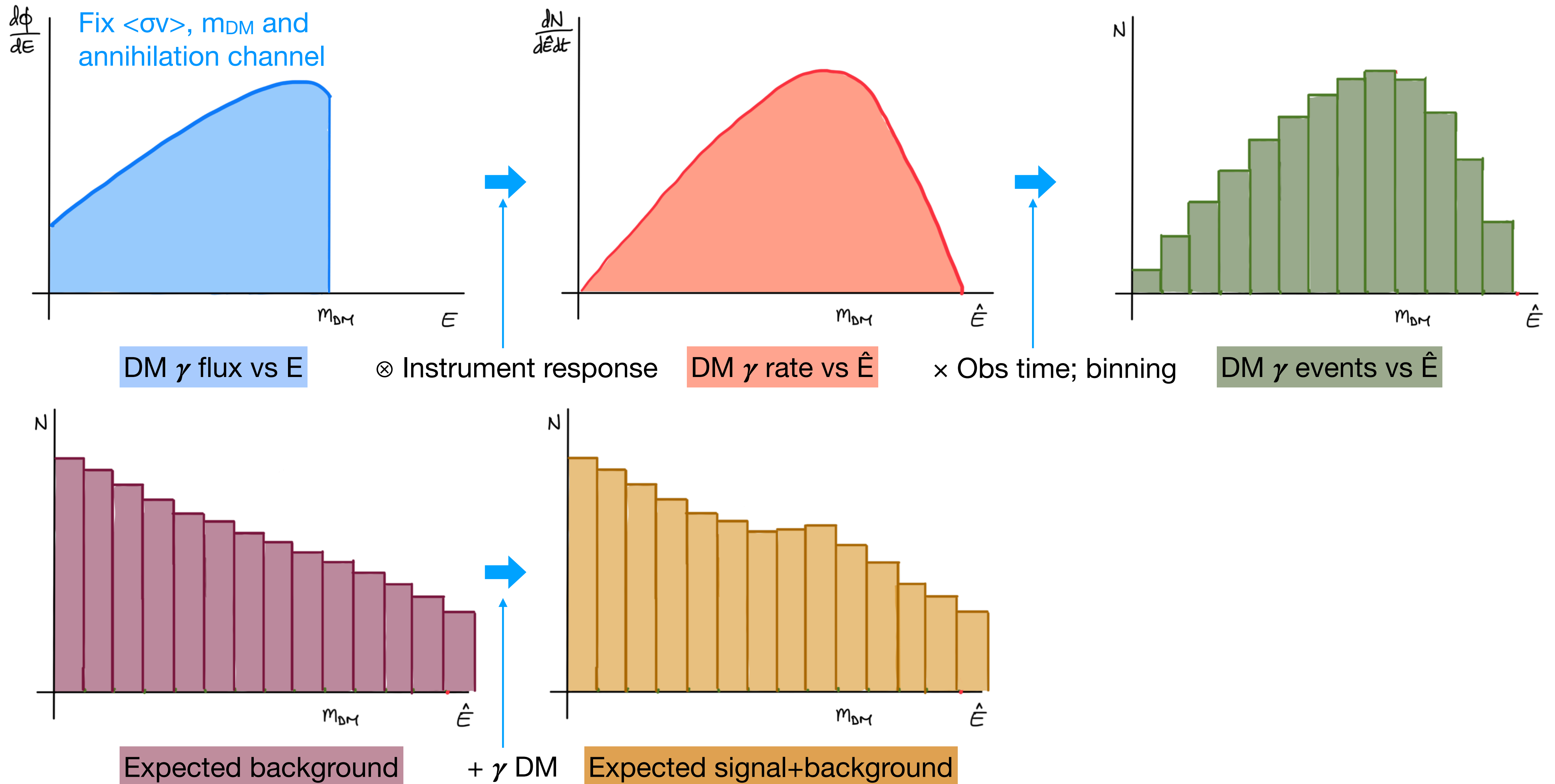


Likelihood analysis

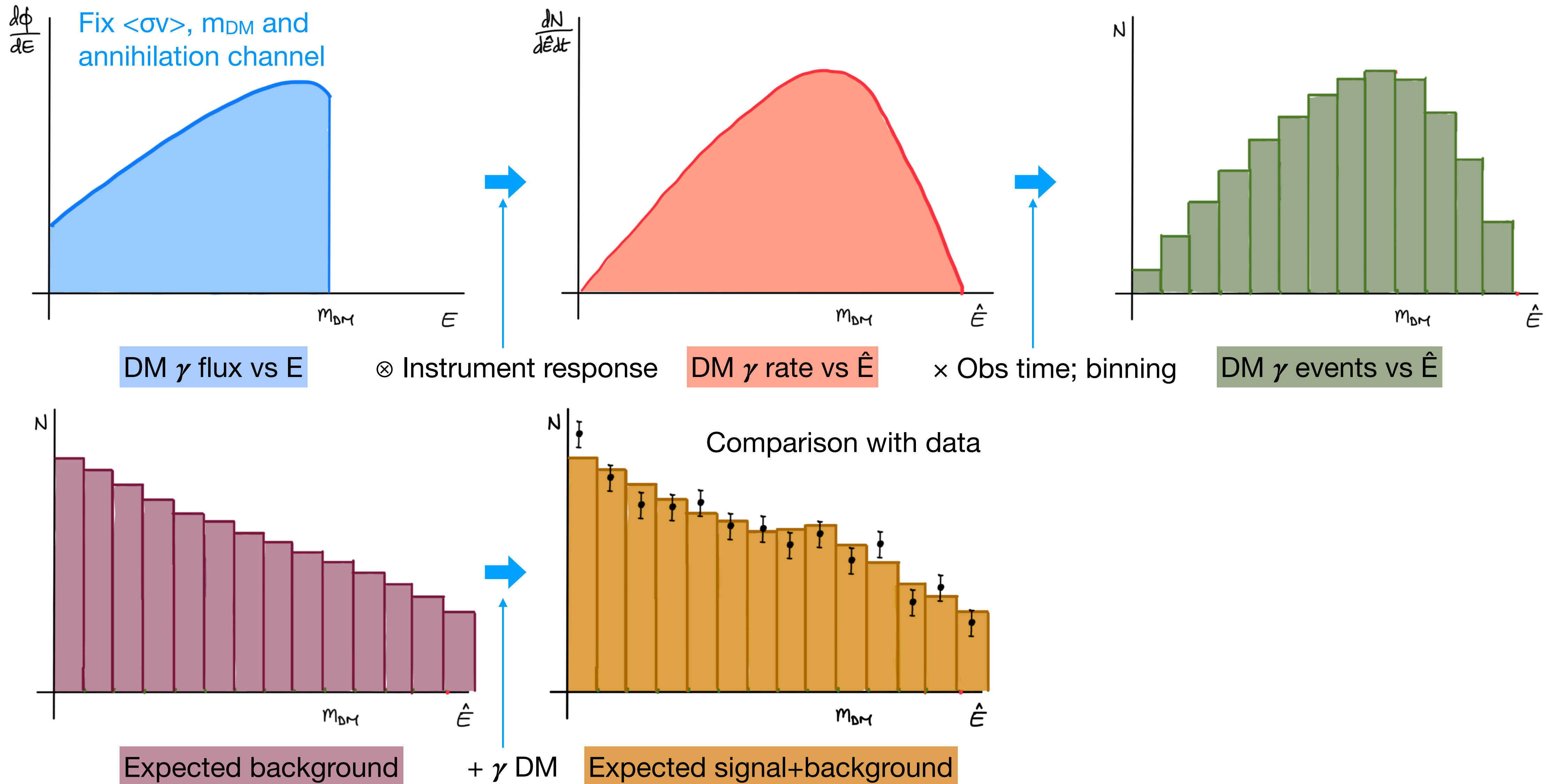


Expected background

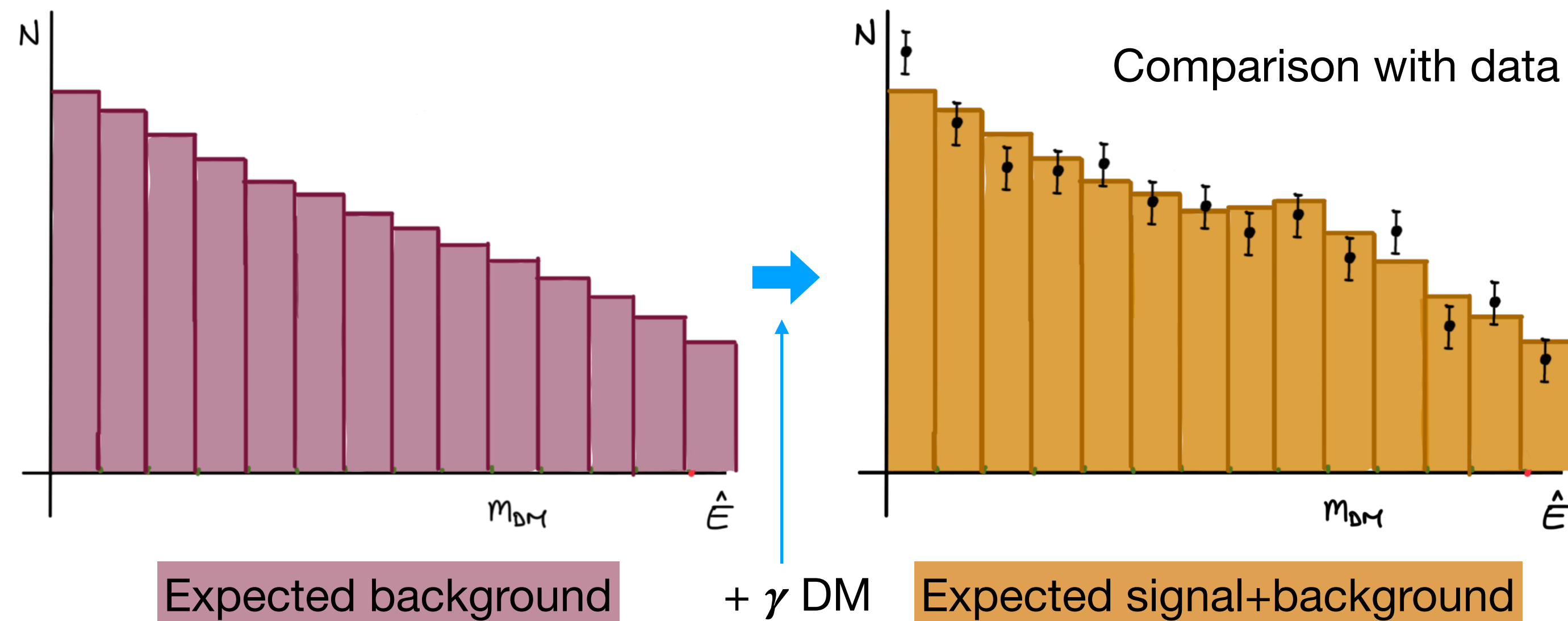
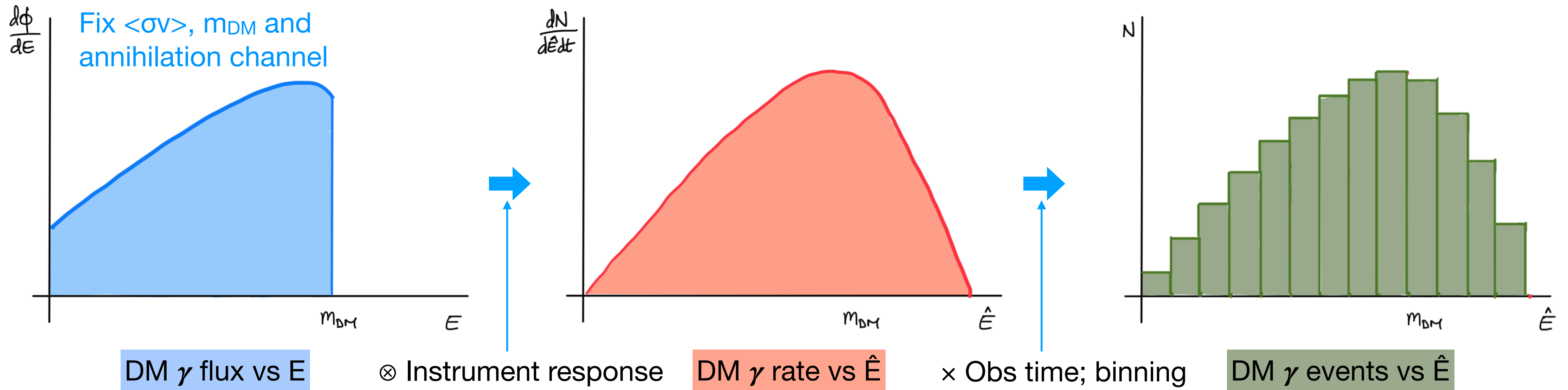
Likelihood analysis



Likelihood analysis



Likelihood analysis



$$\mathcal{L}(\langle\sigma v\rangle; \mathbf{b} | \mathcal{D}) = \prod_{i=1}^{N_{\hat{E}}} \prod_{j=1}^{N_{\hat{p}}} P(s_{ij}(\langle\sigma v\rangle) + b_{ij} | N_{ij})$$

Combined likelihood

$$\begin{aligned} & \mathcal{L}_{\text{Segue1,LAT}}(\langle\sigma\nu\rangle J_S; \mathbf{b}_{\text{SL}} | \mathcal{D}_{\text{SL}}) \\ & \times \mathcal{L}_{\text{Segue1,MAGIC}}(\langle\sigma\nu\rangle J_S; \mathbf{b}_{\text{SM}} | \mathcal{D}_{\text{SM}}) \\ & \times \mathcal{L}_{\text{Segue1,HAWC}}(\langle\sigma\nu\rangle J_S; \mathbf{b}_{\text{SHa}} | \mathcal{D}_{\text{SHa}}) \end{aligned}$$

Profile background uncertainties

Combined likelihood

$$\begin{aligned}
 & \mathcal{L}_{\text{Segue1,LAT}}(\langle\sigma v\rangle J_S; \mathbf{b}_{\text{SL}} | \mathcal{D}_{\text{SL}}) \\
 & \times \mathcal{L}_{\text{Segue1,MAGIC}}(\langle\sigma v\rangle J_S; \mathbf{b}_{\text{SM}} | \mathcal{D}_{\text{SM}}) \\
 & \times \mathcal{L}_{\text{Segue1,HAWC}}(\langle\sigma v\rangle J_S; \mathbf{b}_{\text{SHa}} | \mathcal{D}_{\text{SHa}})
 \end{aligned}
 \times \mathcal{L}_{\text{Segue1}}(J_S)$$

Profile background uncertainties

Profile J uncertainties

Combined likelihood

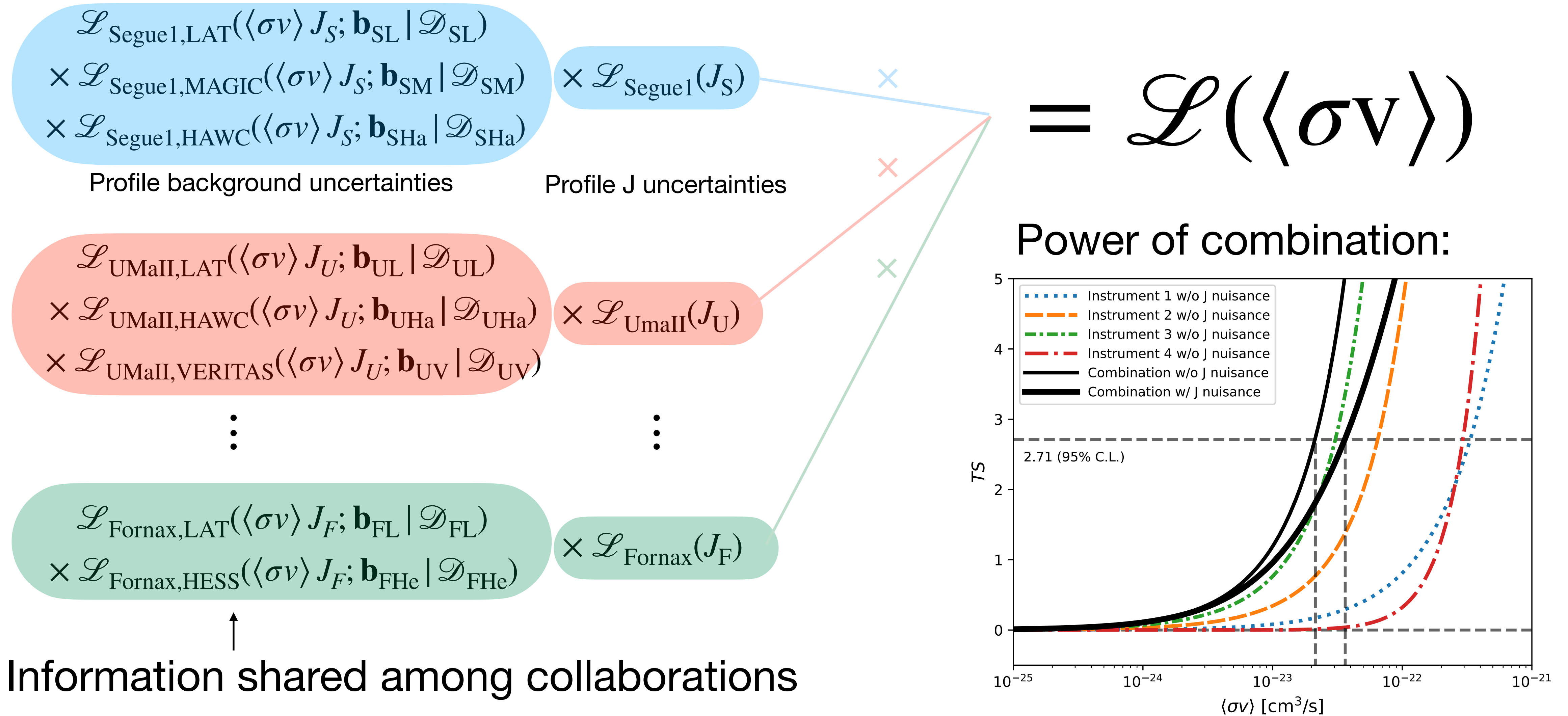
$$\begin{aligned}
 & \mathcal{L}_{\text{Segue1,LAT}}(\langle\sigma\nu\rangle J_S; \mathbf{b}_{\text{SL}} | \mathcal{D}_{\text{SL}}) \\
 & \times \mathcal{L}_{\text{Segue1,MAGIC}}(\langle\sigma\nu\rangle J_S; \mathbf{b}_{\text{SM}} | \mathcal{D}_{\text{SM}}) \\
 & \times \mathcal{L}_{\text{Segue1,HAWC}}(\langle\sigma\nu\rangle J_S; \mathbf{b}_{\text{SHa}} | \mathcal{D}_{\text{SHa}})
 \end{aligned}
 \times \mathcal{L}_{\text{Segue1}}(J_S)$$

Profile background uncertainties

Profile J uncertainties

$$\begin{aligned}
 & \mathcal{L}_{\text{UMaII,LAT}}(\langle\sigma\nu\rangle J_U; \mathbf{b}_{\text{UL}} | \mathcal{D}_{\text{UL}}) \\
 & \times \mathcal{L}_{\text{UMaII,HAWC}}(\langle\sigma\nu\rangle J_U; \mathbf{b}_{\text{UHa}} | \mathcal{D}_{\text{UHa}}) \\
 & \times \mathcal{L}_{\text{UMaII,VERITAS}}(\langle\sigma\nu\rangle J_U; \mathbf{b}_{\text{UV}} | \mathcal{D}_{\text{UV}})
 \end{aligned}
 \times \mathcal{L}_{\text{UmaII}}(J_U)$$

Combined likelihood

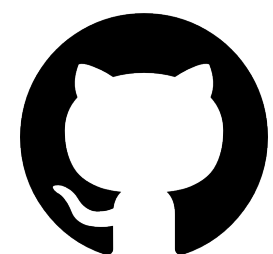


gLike

- ★ ROOT-based code for **generic maximum likelihood analysis**
- ★ Basic features:
 - ✧ One free parameter + arbitrary number of nuisance parameters
 - ✧ Two main classes:
 - ✧ **Lk1** (abstract): Likelihood computation, maximization and profiling of nuisance parameters
 - ✧ **JointLk1**: Joint likelihood computation (multiplies **Lk1** terms + inherits from **Lk1** → recursive); conversion of common free parameter to particular observables

This enables full modularity, allowing:

- ✧ **Arbitrarily complex likelihood computation** method (from LUT to full data analysis)
- ✧ **Arbitrarily complex likelihood nesting schemes** (including of nuisance parameters)
- ★ **Publicly available and documented** at gitHub (developers) and Zenodo (stable releases)



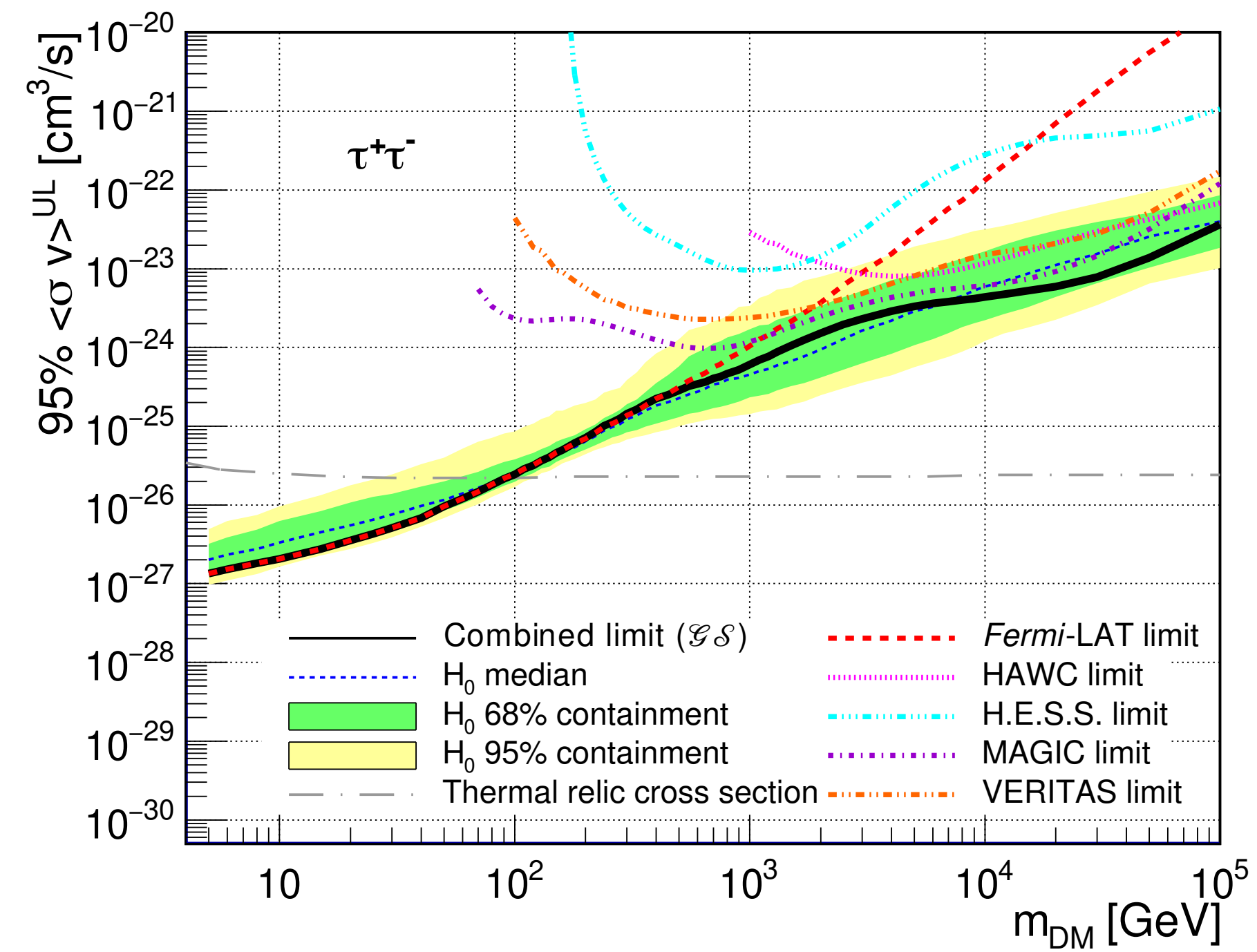
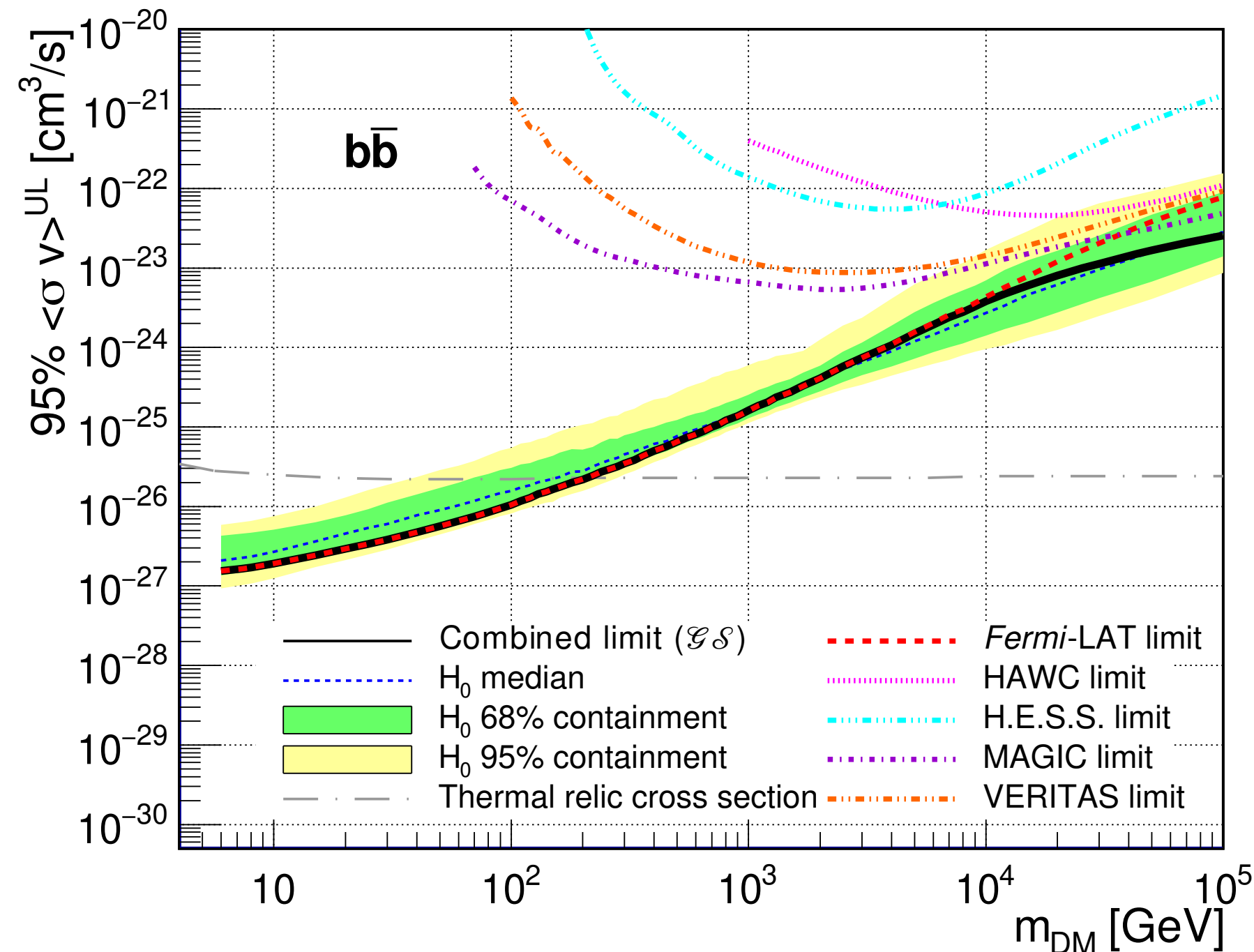
<https://github.com/javierrico/gLike>

zenodo

DOI 10.5281/zenodo.3967385

Results (1/2)

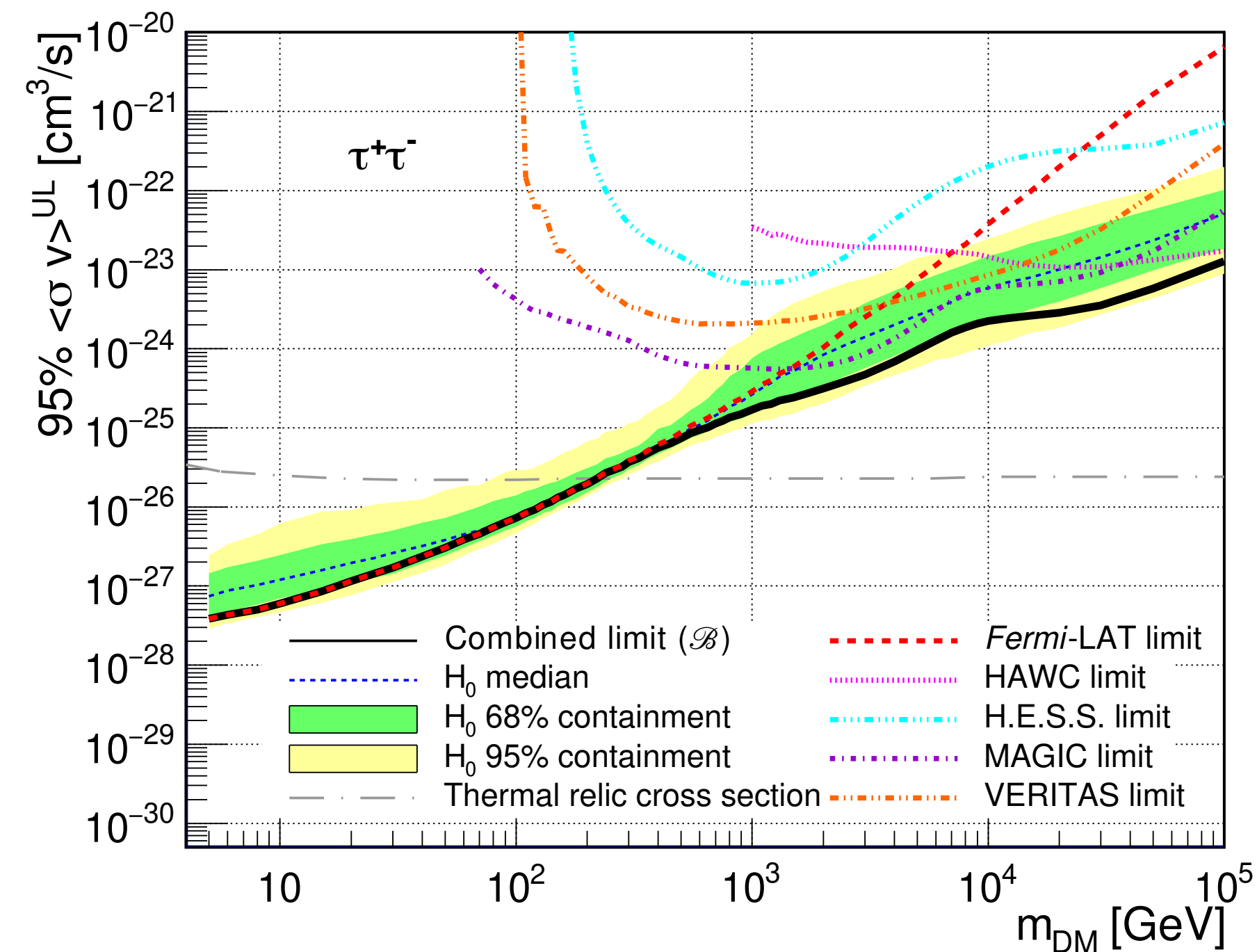
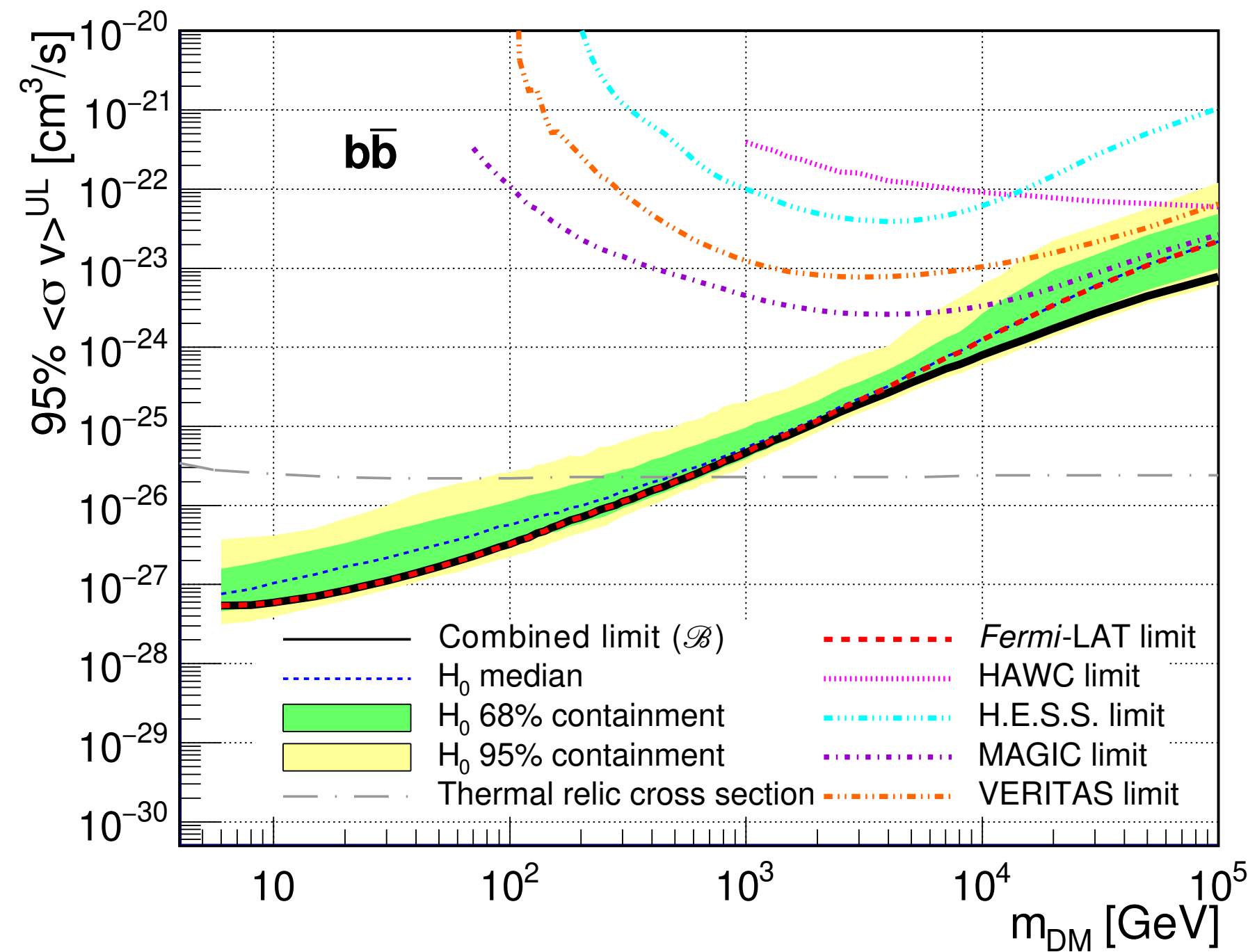
Geringer-Sameth et al. 2015



- ★ Scanned **WIMP mass** between 5 GeV and 100 TeV
- ★ **Annihilation channels:** $b\bar{b}$, $t\bar{t}$, W^+W^- , ZZ , e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$
- ★ Two different **J-factor parameterizations**
- ★ **Median, 68% and 95% containment** expected values/regions from simulations/measurements of no-signal regions
- ★ **No positive signal for any dSph individually or altogether** → upper limits to cross-section

Results (2/2)

Bonnivard et al. 2015



- ★ Scanned **WIMP mass** between 5 GeV and 100 TeV
- ★ **Annihilation channels:** $b\bar{b}$, $t\bar{t}$, W^+W^- , ZZ , e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$
- ★ Two different **J-factor parameterizations**
- ★ **Median, 68% and 95% containment** expected values/regions from simulations/measurements of no-signal regions
- ★ **No positive signal for any dSph individually or altogether** → upper limits to cross-section

Concluding remarks

★ **Publication** finally out [Abdollahi et al. JCAP 03 (2026) 035] after 8 years of work!

★ **Relevance of the results:**

- * Search spans a **wide WIMP mass range**
- * More **constraining limits**: factor 2-3 improvement wrt best limits in the overlapping region
- * More **robust limits**: independent uncertainties tend to balance
- * **Uncertainty from J-factor determination dominates**: effect gauged using two independent computations
- * **Legacy result** from the current generation of gamma-ray instrument

★ **Relevance of developed methodology:**

- * Can be used to **extend the DM search to multi-messenger context** adding neutrino observations (relatively trivial)
- * Broader **potential in gamma-ray astronomy** (e.g. axion searches, Lorentz Invariance tests, ...), and beyond
- * Byproduct: **gLike public software** ready to be used in these scenarios

★ **Remaining bottle-neck**: overhead of **coordinating five international collaborations**