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Multiple dark matter signatures

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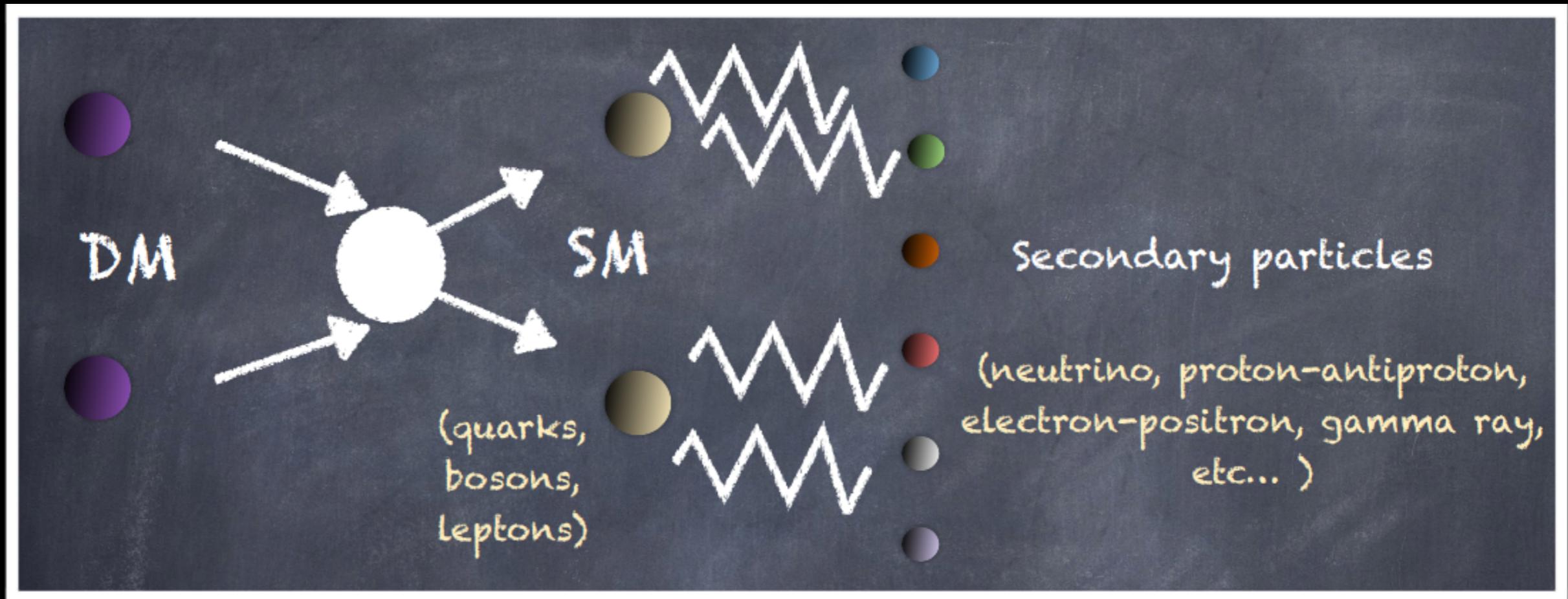
**Vulcano Workshop 2022 - Frontier Objects in Astrophysics and Particle Physics,
September 29th, 2022 to October 1, Elba Island (Tuscany, Italy)**

Outline

- Context: indirect searches for Dark Matter (DM), here Weakly Interactive Massive Particle (WIMP)
- Multi-messenger and multi-wavelength DM signatures
- DM signature and Monte Carlo event generator softwares
 - Model independent and model dependent approaches
 - Phenomenological approach for Machine Learning
- Conclusions

Context: indirect detection of DM

DM Candidate: Weakly Interactive Massive Particles (WIMPs)



$$J(\Delta\Omega, l.o.s) \times P(E) = \underbrace{d\phi_{sp}}_{\text{Astrophysics}}(E, \Delta\Omega, l.o.s) \underbrace{\frac{dE}{dE}}_{\text{Particle Physics}} \underbrace{\text{Expected DM signature}}$$

Indirect detection of WIMPs

$$\frac{\eta_{\text{sp}}}{4\pi} \sum_{a=1}^2 \kappa_{\text{sp}}^{(a)} \cdot \underbrace{\sum_i \text{SM channels}}_{\text{Astrophysical factor}} \frac{\zeta_i^{(a)}}{\delta m_{DM-\chi}^a} \frac{dN_i^{(\text{sp})}}{dE} = \underbrace{\frac{d\Phi_{\text{sp-DM}}}{dE}}_{\text{Expected DM signature}}$$

Astrophysical factor
 $\kappa_{\text{sp}}^{(a)} \propto \rho_{DM}(r)^{a=1,2}$

Secondary particle (sp) propagation

$$\eta_\gamma = 1 ; \eta_\nu \sum_{p=1}^3 ; \nu_{\bar{p}} \propto v_{\bar{p}},$$

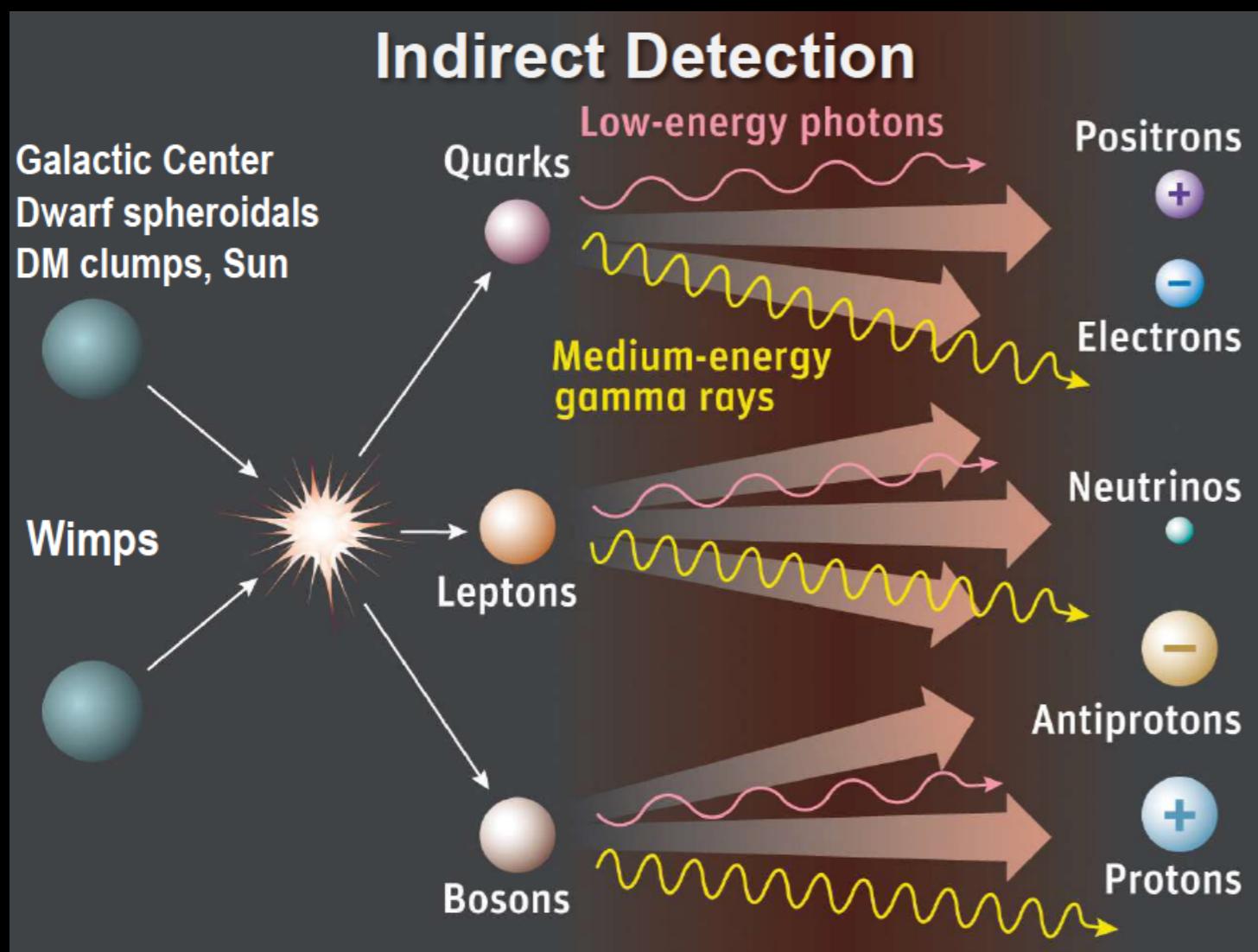
Particle physics factor:

Decay $a = 1 \rightarrow \zeta_i^{(1)} = 1/\tau_i^{\text{decay}}$,

Annihilation $a = 2 \rightarrow \zeta_i^{(2)} = \langle \sigma_i v \rangle$

Majorana ($\delta = 2$) vs Dirac($\delta = 1$) particle
model dependent or model independent
($\rightarrow i 100\%$) analysis

Multi-messenger DM signature

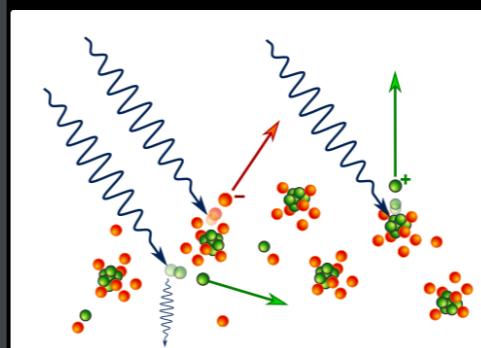
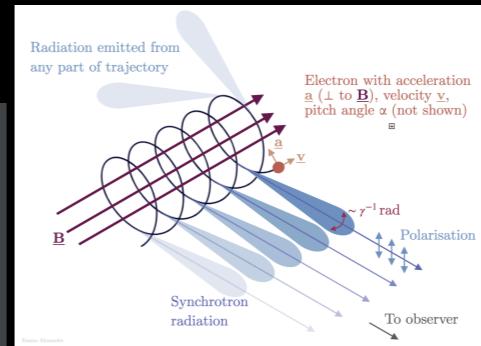
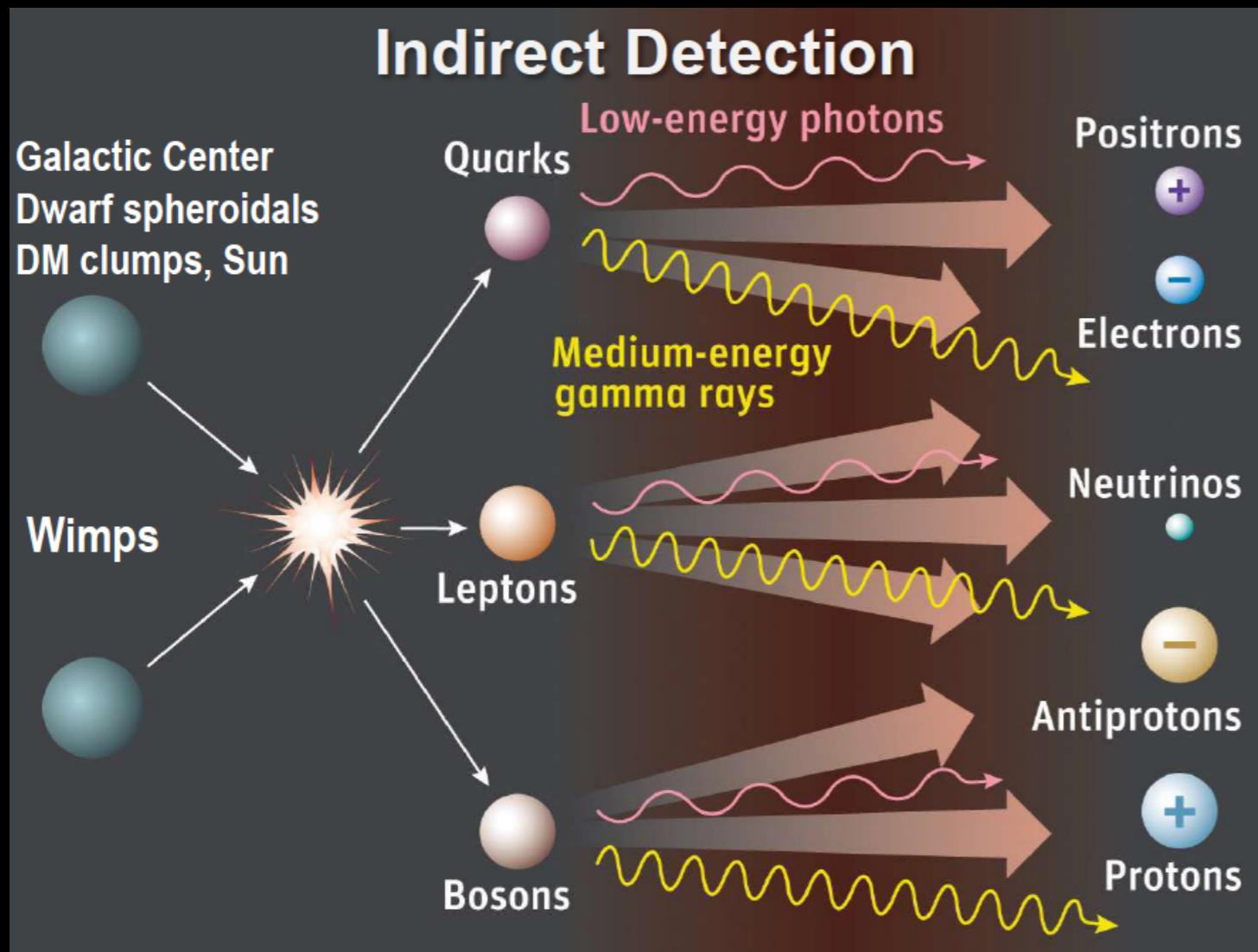


$$\frac{\eta_{\text{sp}}}{4\pi} \sum_{a=1}^2 \kappa_{\text{sp}}^{(a)} \cdot \sum_i \text{SM channels} \frac{\zeta_i^{(a)}}{\delta m_{DM-\chi}^a} \frac{dN_i^{(\text{sp})}}{dE} = \frac{d\Phi_{\text{sp-DM}}}{dE}$$

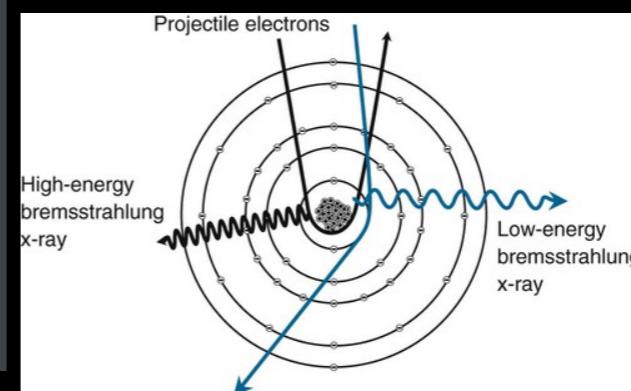
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Multi-wavelength DM signature

Synchrotron emission



Inverse Compton



Bremsstrahlung

$$-\nabla \cdot [D(\mathbf{r}, E) \nabla \psi] - \frac{\partial}{\partial E} [b(\mathbf{r}, E) \psi] = Q_e(\mathbf{r}, E)$$

Multi-wavelength DM signature

Let's assume the e^+/e^- secondary particles produced by the WIMP candidate annihilating into W^+W^- channel. After injection the e^+/e^- follow the diffusion equation:

Diffusion coefficient:

$$D(\mathbf{r}, E) \sim D(E) = D_0 E^\delta$$

Energy loss term:

Source term:

$$-\nabla \cdot [D(\mathbf{r}, E) \nabla \psi] - \frac{\partial}{\partial E} [b(\mathbf{r}, E) \psi] = Q_e(\mathbf{r}, E)$$

Number density after propagation

$$\psi(\mathbf{r}, E) = \frac{1}{b(\mathbf{r}, E)} \int_E^M dE_s G(r, E, E_s) Q_e(\mathbf{r}, E)$$

Source term ($\alpha=2$):

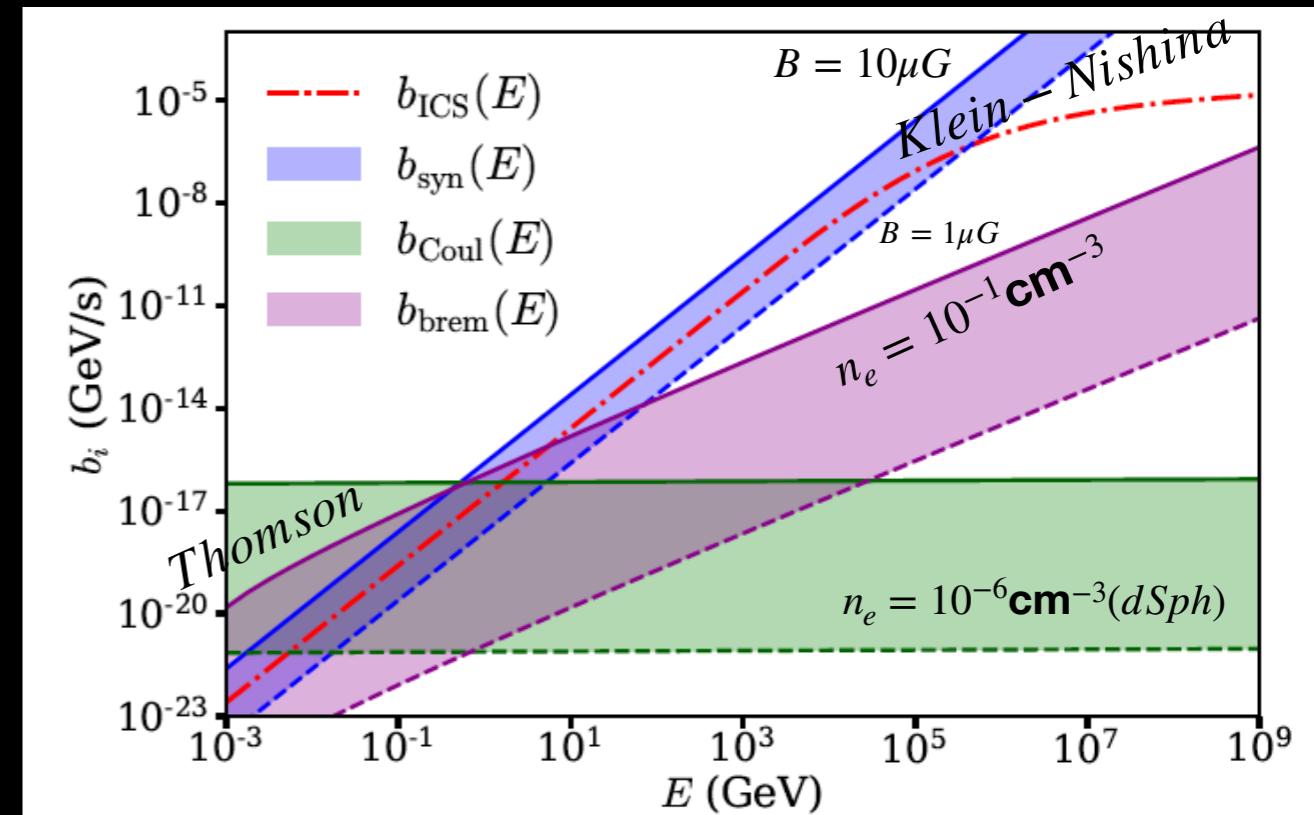
$$Q_e(\mathbf{r}, E) = \frac{1}{2} \langle \sigma v \rangle \left(\frac{\rho_{DM}(\mathbf{r})}{M} \right)^2 \sum_j \beta_j \frac{dN_e^j}{dE}$$

$$b(\mathbf{r}, E) = b_{\text{brem}}(E) + b_{\text{Coul}}(E) + b_{\text{ICS}}(E) + b_{\text{syn}}(\mathbf{r}, E)$$

$$b_{\text{brem}}(E) = 1.51 \cdot 10^{-16} n_e E [\log(E/m_e) + 0.36]$$

$$b_{\text{syn}}(\mathbf{r}, E) = 0.0254 \cdot 10^{-4} B^2(\mathbf{r}) E^2$$

$$b_{\text{Coul}}(E) = 6.13 \cdot 10^{-16} n_e [1 + \log(E/n_e m_e)/75]$$



Detectors and telescopes

- Cherenkov telescopes:

Atmospheric Cherenkov: e.g CTA, HESS.

Water Cherenkov: e.g. HAWC

Ice Cherenkov: e.g. IceCube



- Satellites: e.g Fermi-LAT, Pamela, AMS-02.



- Interferometers:
e.g. SKA radio telescope



Indirect detection of WIMPs

Multi-messenger DM signatures

$$\frac{n_{\text{sp}}}{4\pi} \sum_{a=1}^2 \kappa_{\text{sp}}^{(a)} \cdot \underbrace{\sum_i \text{SM channels}}_{\text{Astrophysical factor and Secondary particle (sp) propagation}} \underbrace{\frac{\zeta_i^{(a)}}{\delta m_{DM-\chi}^a} \frac{dN_i^{(\text{sp})}}{dE}}_{\text{Particle physics factor:}} = \underbrace{\frac{d\Phi_{\text{sp-DM}}}{dE}}_{\text{Expected DM signature}}$$

Multi-wavelength DM signatures

$$-\nabla \cdot [D(\mathbf{r}, E) \nabla \psi] - \frac{\partial}{\partial E} [b(\mathbf{r}, E) \psi] = Q_e(\mathbf{r}, E)$$

$$Q_e(\mathbf{r}, E) = \frac{1}{2} \langle \sigma v \rangle \left(\frac{\rho_{\text{DM}}(\mathbf{r})}{M} \right)^2 \sum_j \beta_j \frac{dN_e^j}{dE}$$

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Monte Carlo event generator software

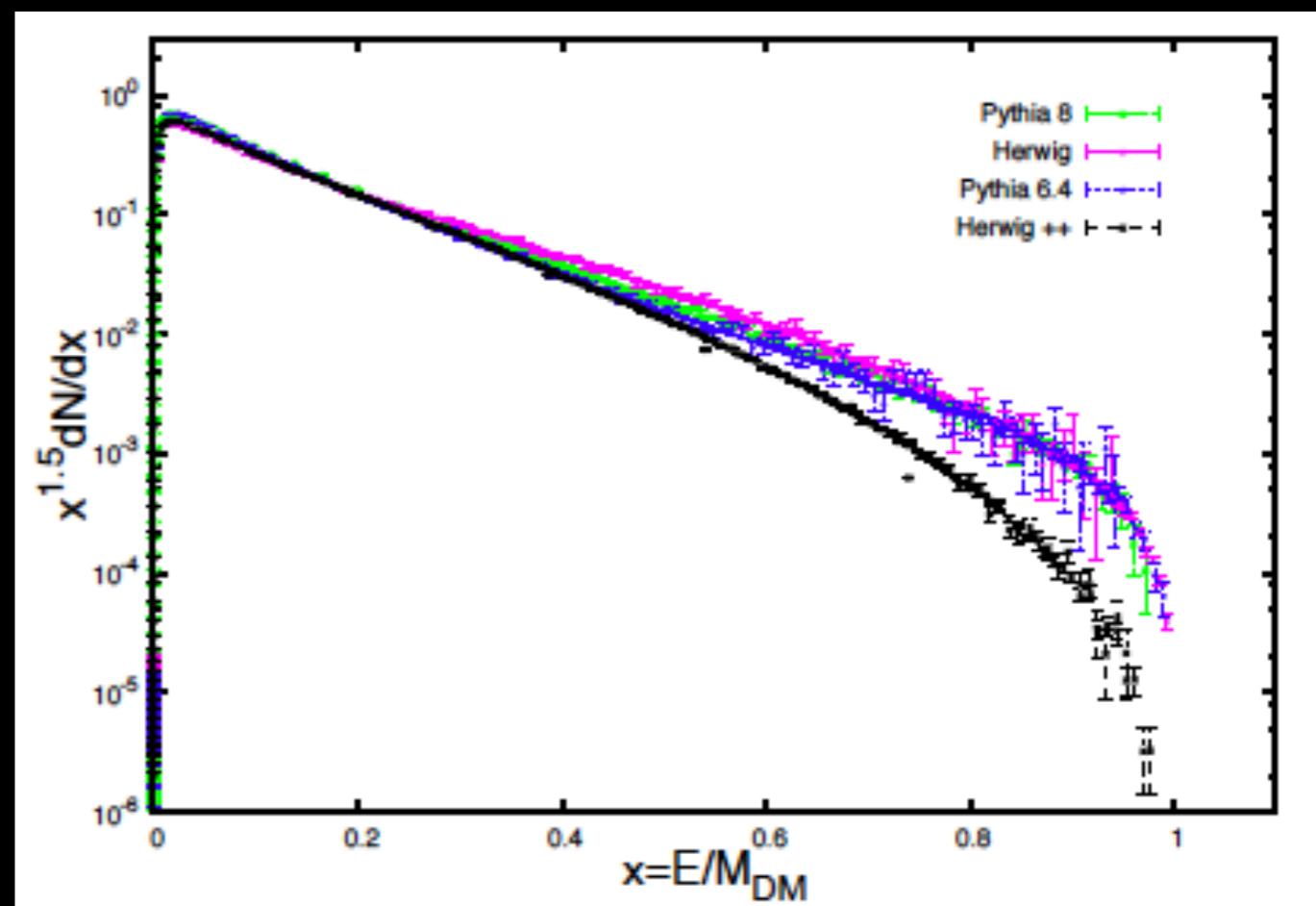
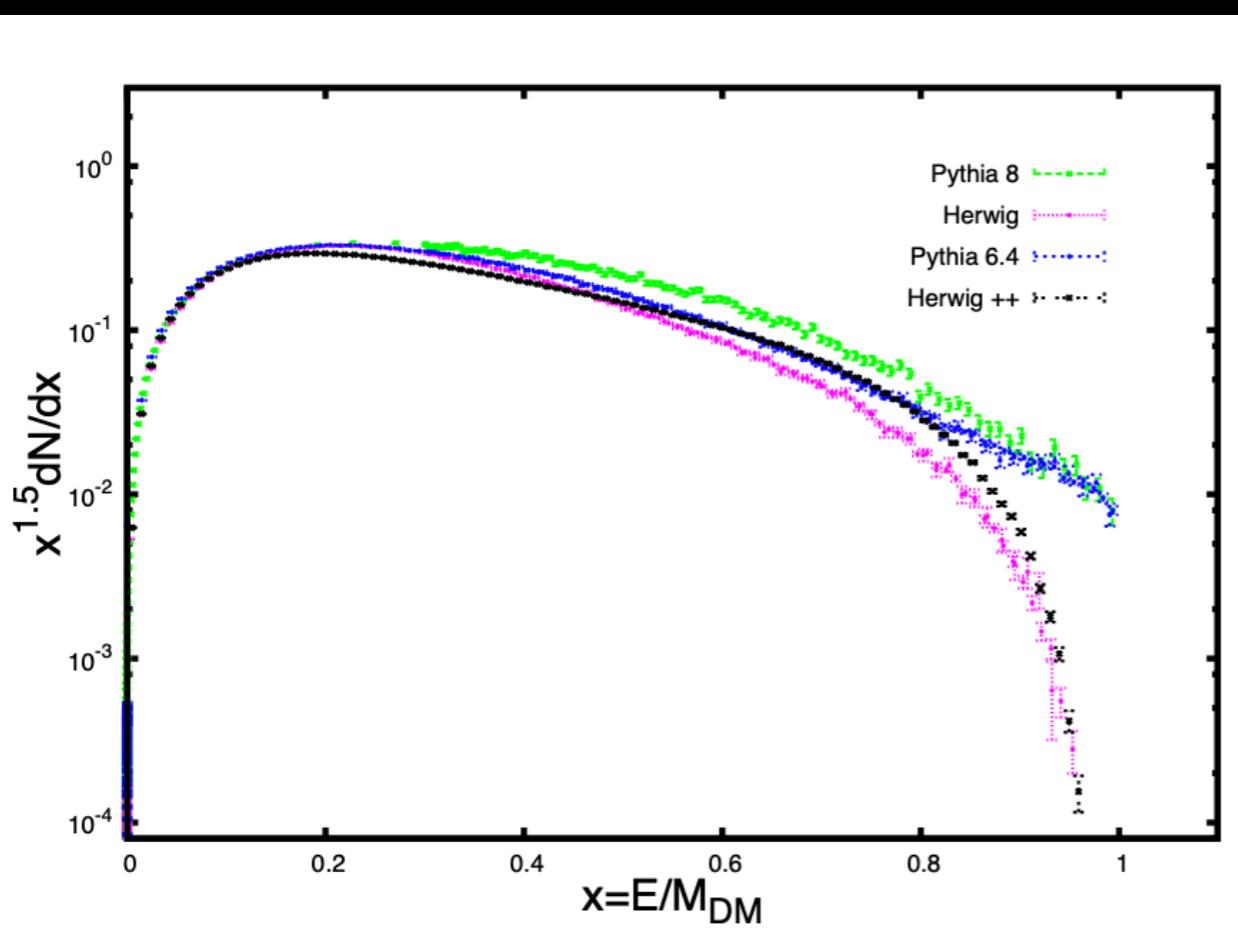
Monte Carlo event generator softwares (e.g. Pythia 8, Herwig) simulate the spectra of secondary particles produced by WIMP candidates of different masses (energy event E) annihilating (or decay) in different Standard Model (SM) channels, by using only SM physics (e.g. QCD, hadronization, QED).



E.g. gamma-ray spectra of m_{DM}= 100 GeV annihilating in $i = \tau^+\tau^-$

$$\frac{dN_i^{(SP)}}{dE}$$

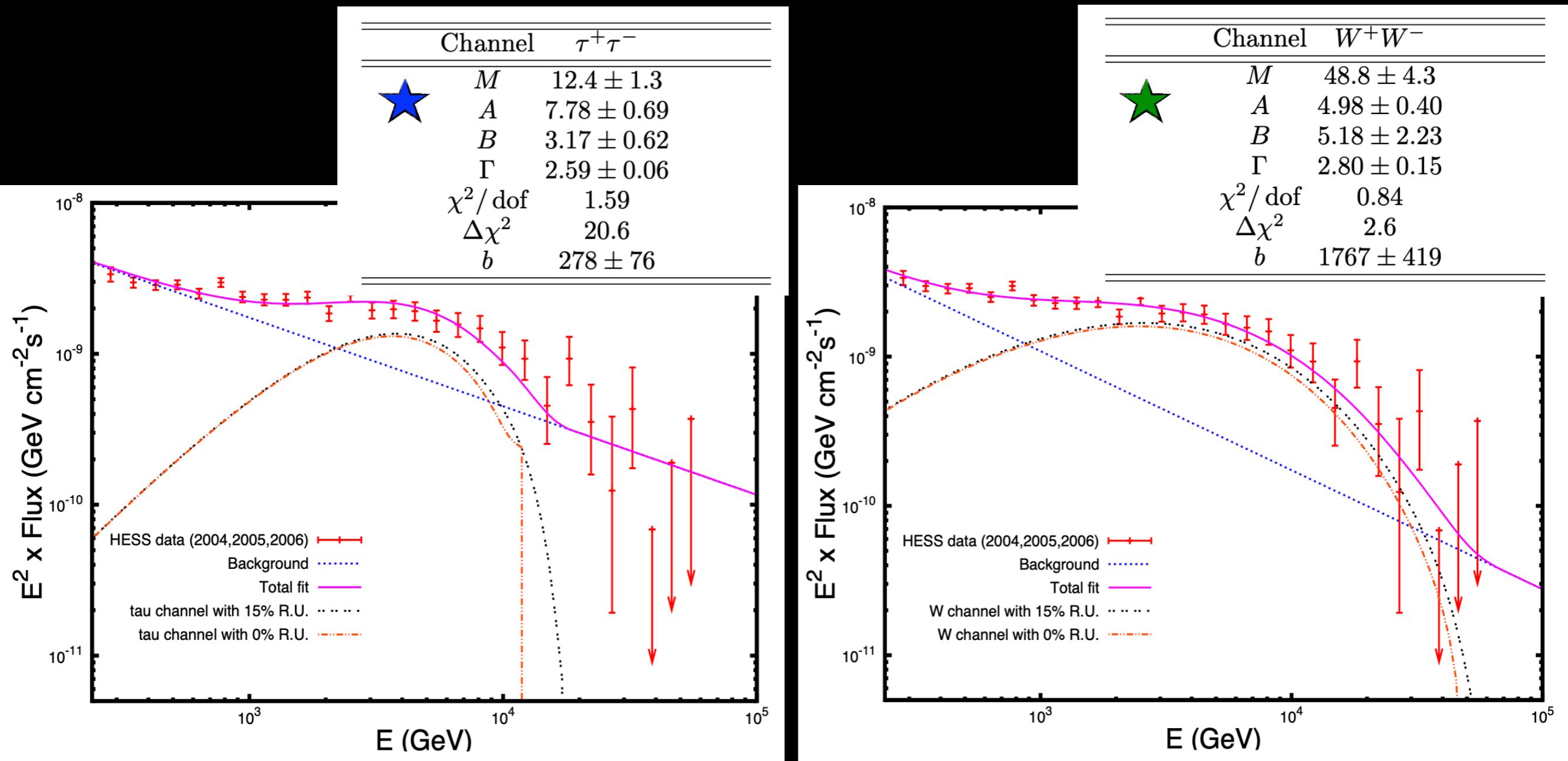
E.g. gamma-ray spectra of m_{DM}= 1 TeV annihilating in $i = W^+W^-$



Model independent DM signatures

Model independent DM candidate: A WIMP particle with a given mass can annihilate in only one SM channel with 100% of probability.

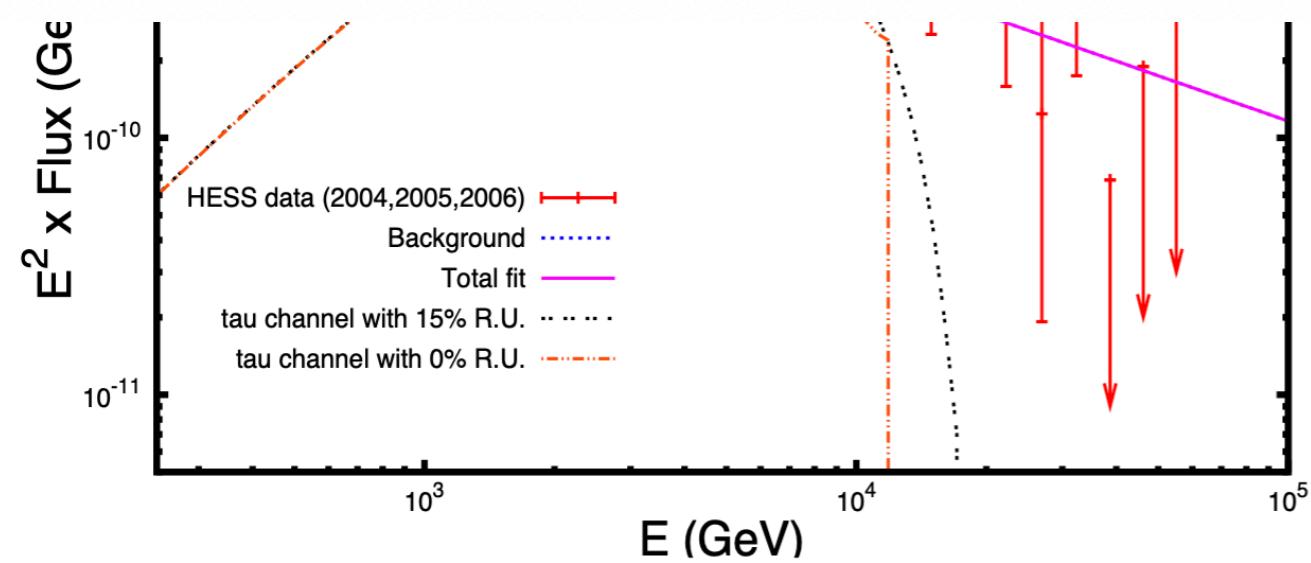
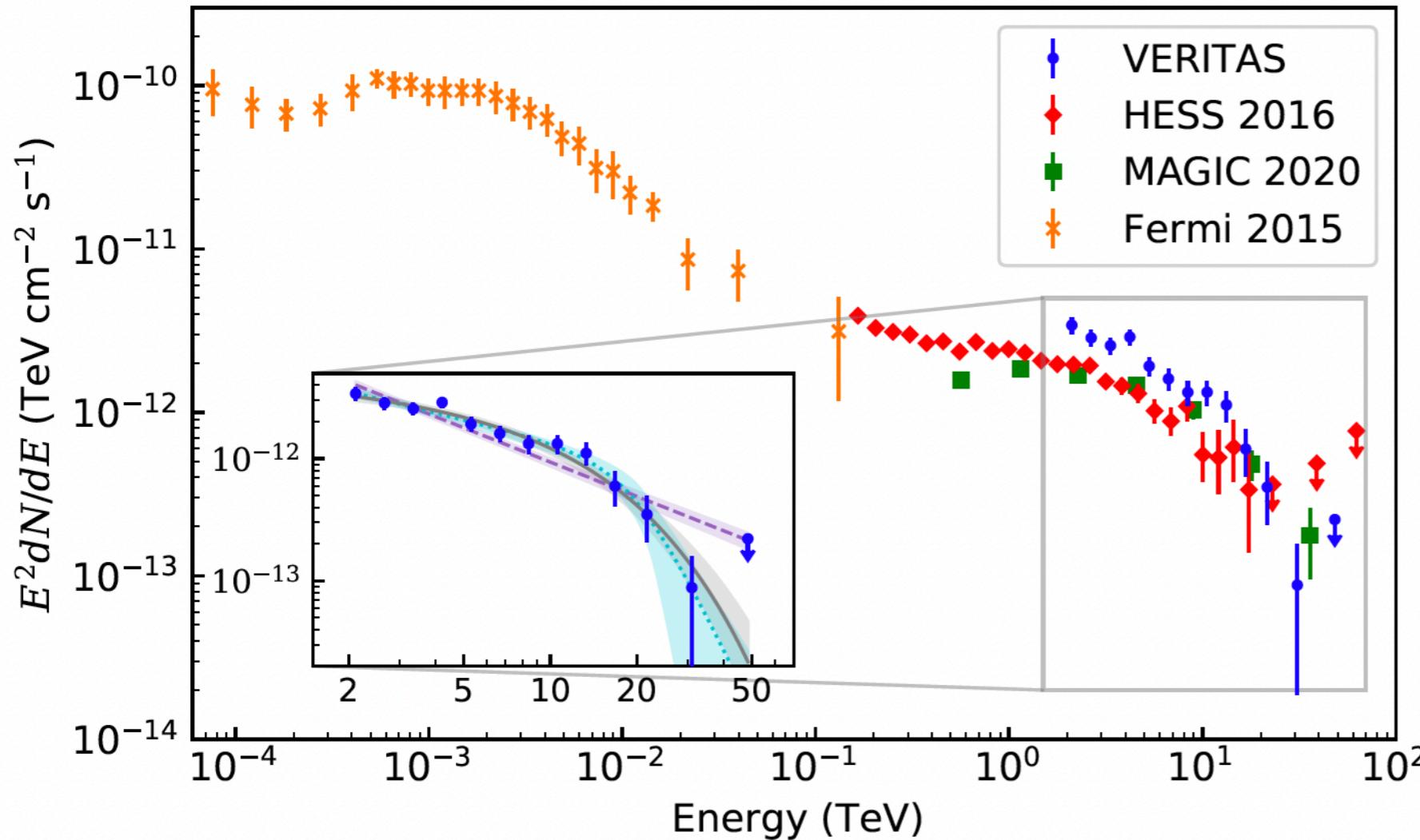
As an example, a multi-TeV WIMP candidate well fits the GC cut-off detected by HESS at TeV energy scale.



Model independent DM signatures

C. B. Adams *et al* 2021 *ApJ* 913 115

Still open issue



Channel	W^+W^-
M	48.8 ± 4.3
A	4.98 ± 0.40
B	5.18 ± 2.23
Γ	2.80 ± 0.15
χ^2/dof	0.84
$\Delta\chi^2$	2.6
b	1767 ± 419

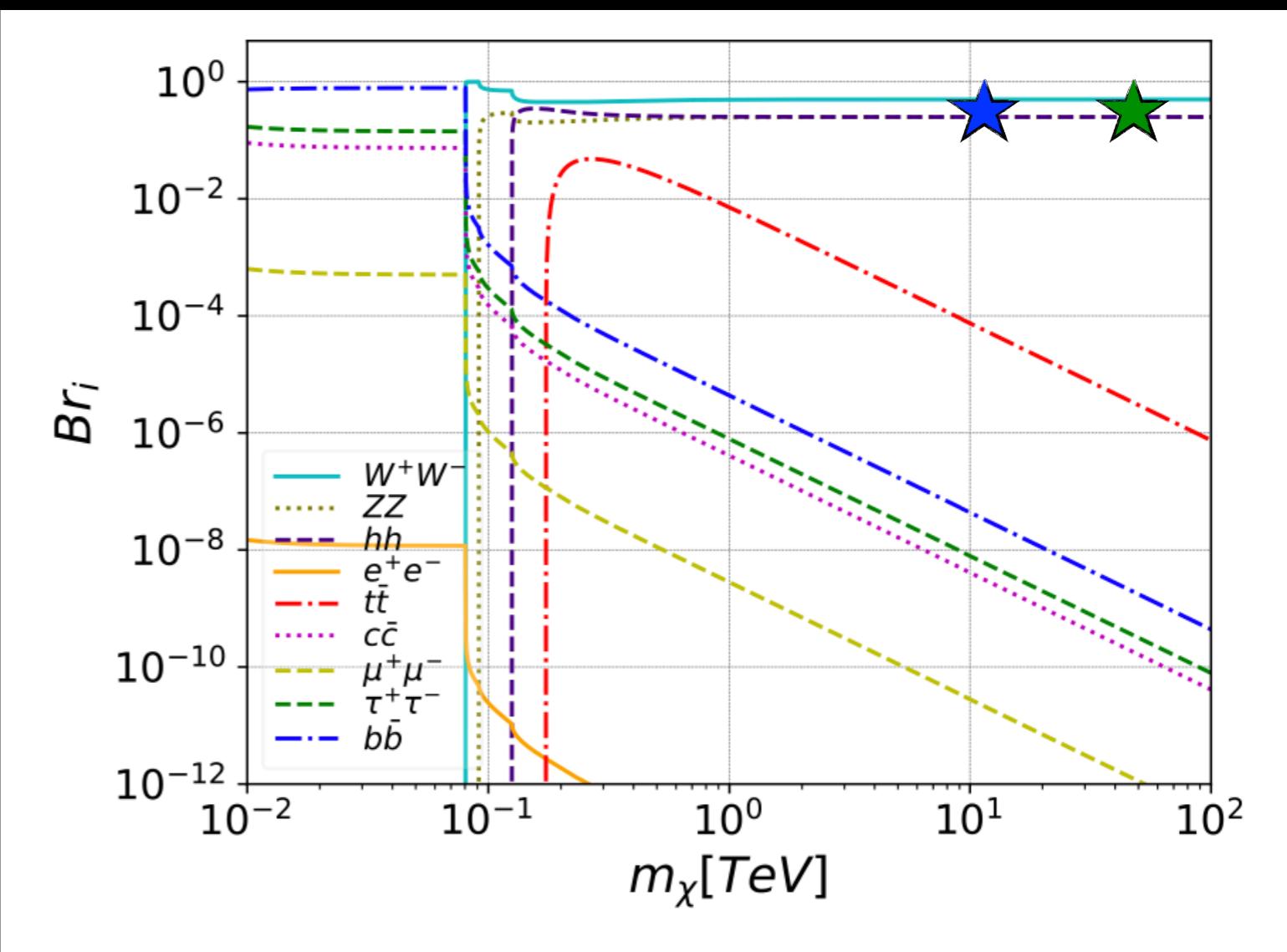
Model dependent DM signatures

Model dependent DM candidate: A WIMP particle with a given mass can annihilate into a combination of SM channels with a given probability (branching ratio).

E.g.: extra-dimensional WIMP candidate: branons

branching ratios

$$\text{SM channels} \sum_i \frac{dN_i^{(\text{SP})}}{dE}$$



Multi-messenger DM signature

A WIMP particle with a $\sim 50\text{ TeV}$ mass annihilating 100% into W^+W^- well fits the gamma-ray spectra detected by HESS at the GC. If such a particle exists, I would expect fluxes of several cosmic rays, e.g. both neutrinos and antiprotons. These fluxes can also be simulated and compared with the data of IceCube or PAMELA, respectively.

$$\text{Thermal DM } \langle \sigma v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$$

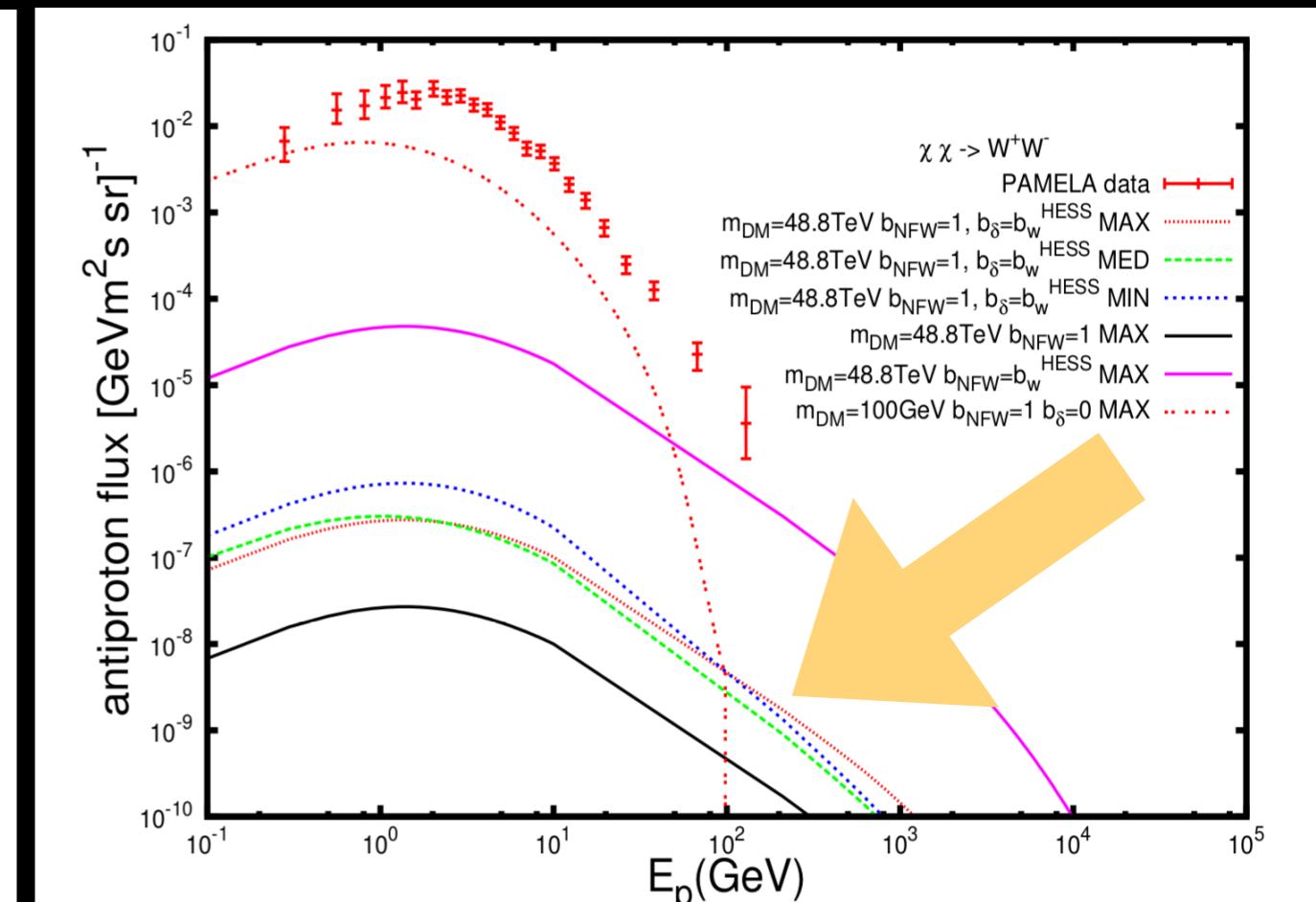
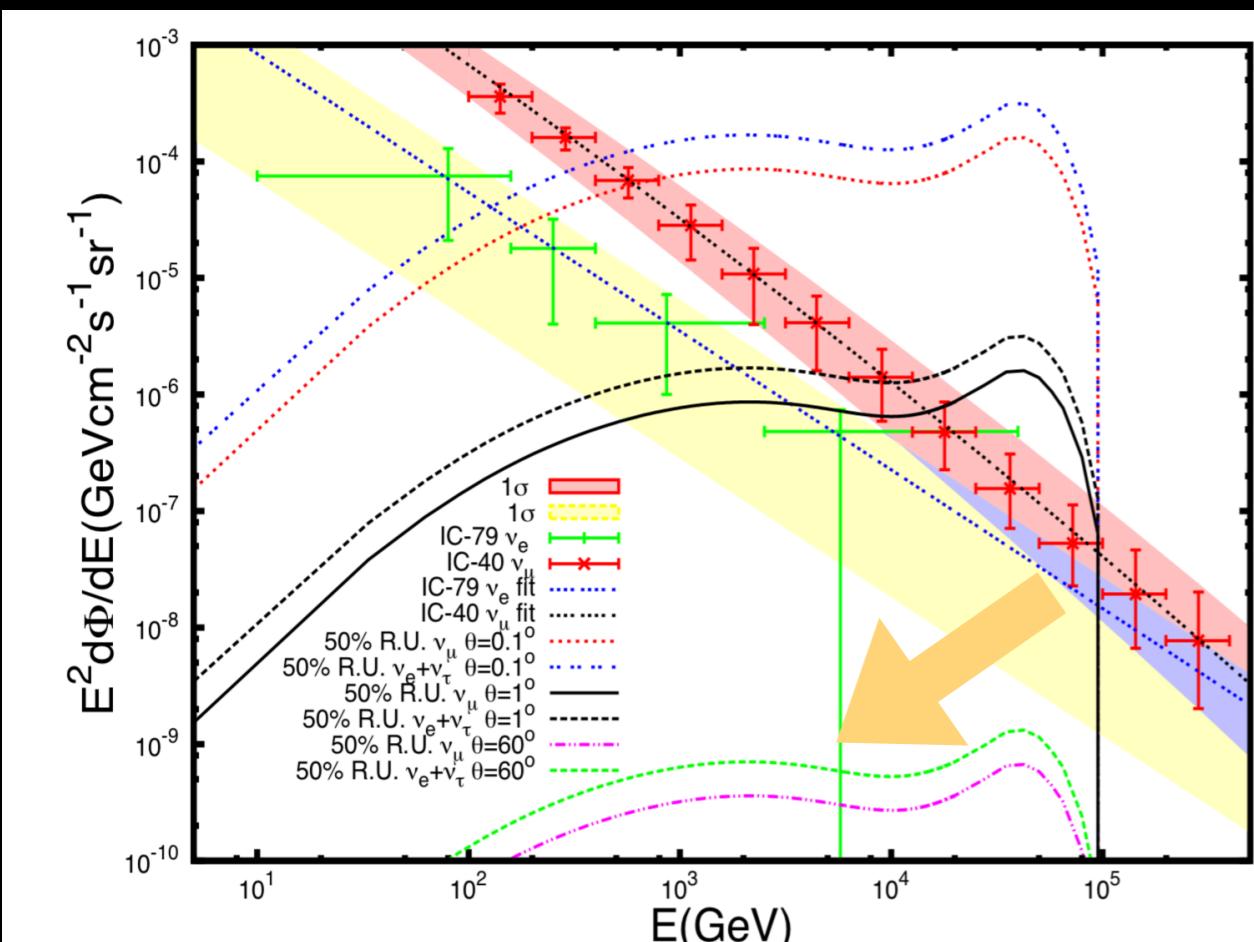
$$\text{NFW density distribution profile } J \approx 2.80 \times 10^{25} \text{ GeV}^2 \text{cm}^{-5}$$

Boost required
 $\sim 10^3 (\theta \sim 0.1^\circ)$

neutrinos

V.G., Front. Astron. Space Sci., 05 April 2019

antiprotons

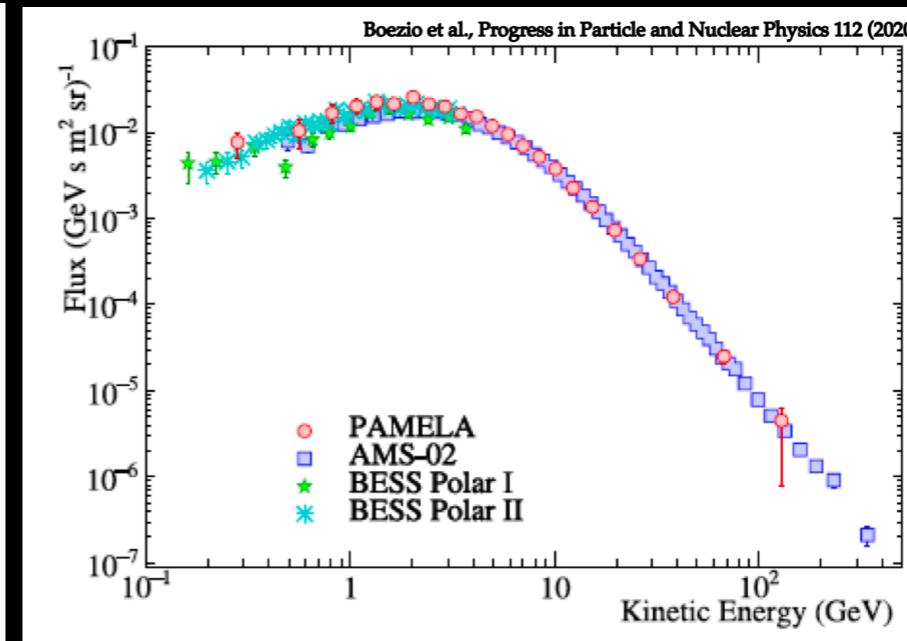
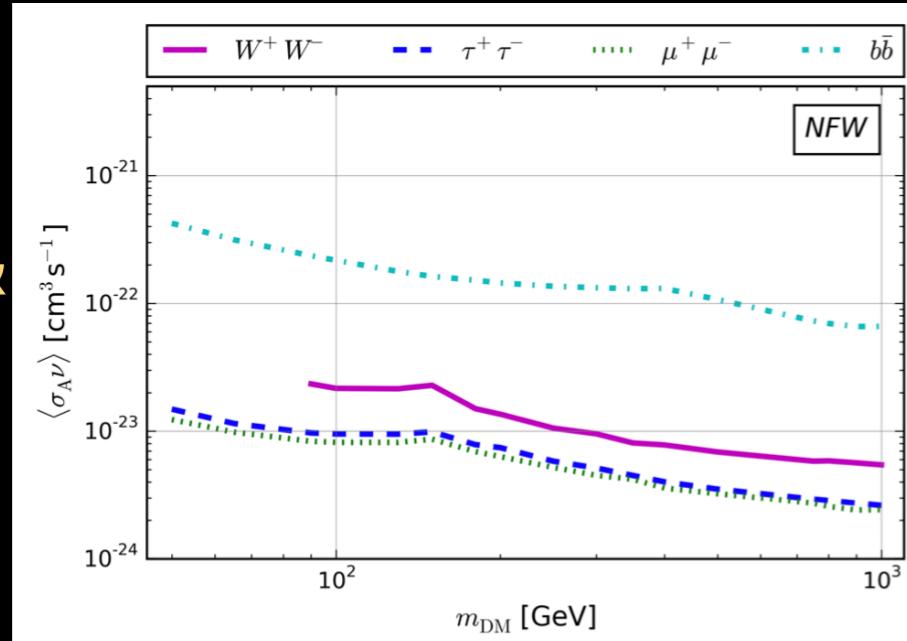


Multi-messenger DM signature

ANTARES Collaboration, Phys. Rev. D 102, 082002 (2020)

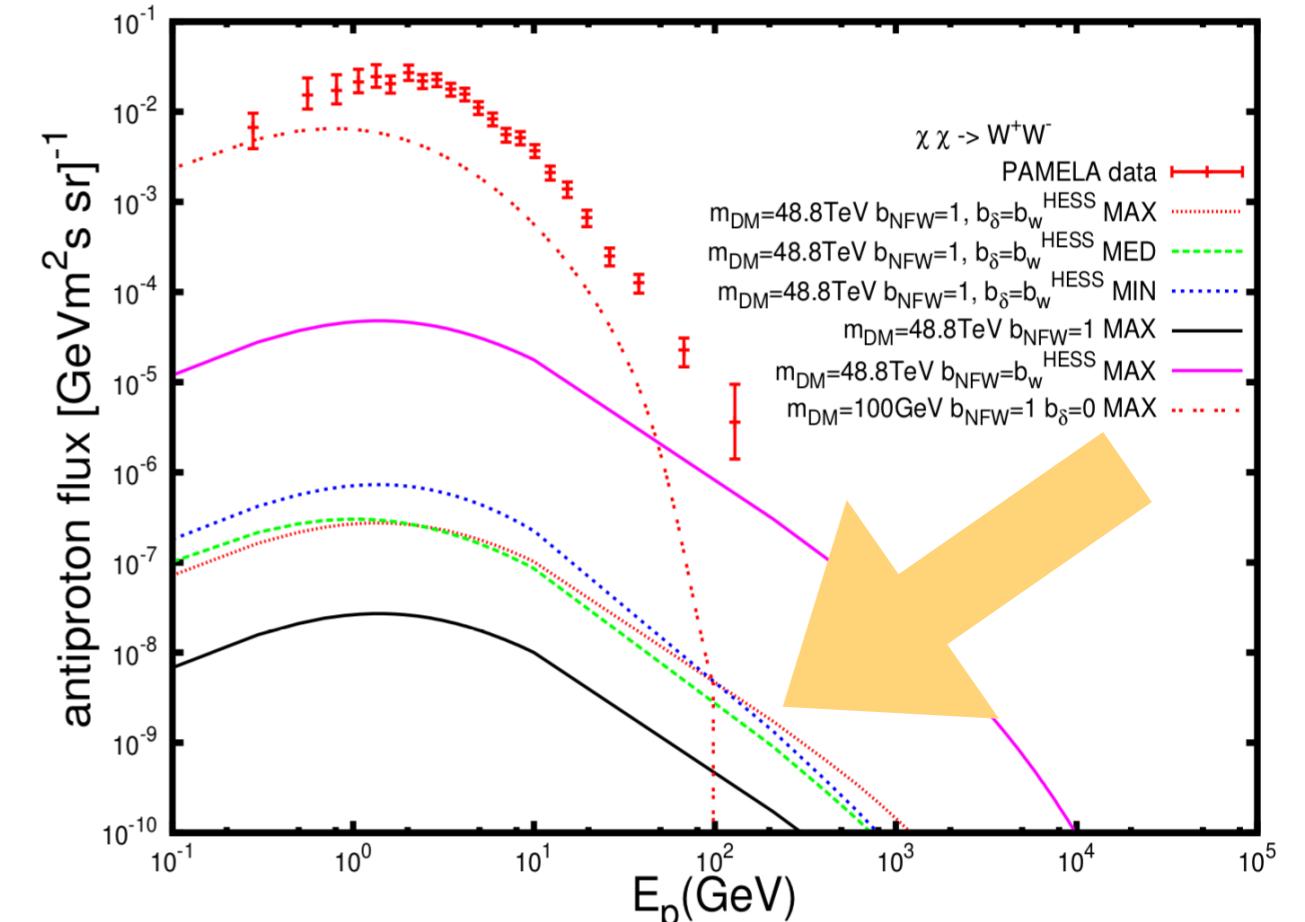
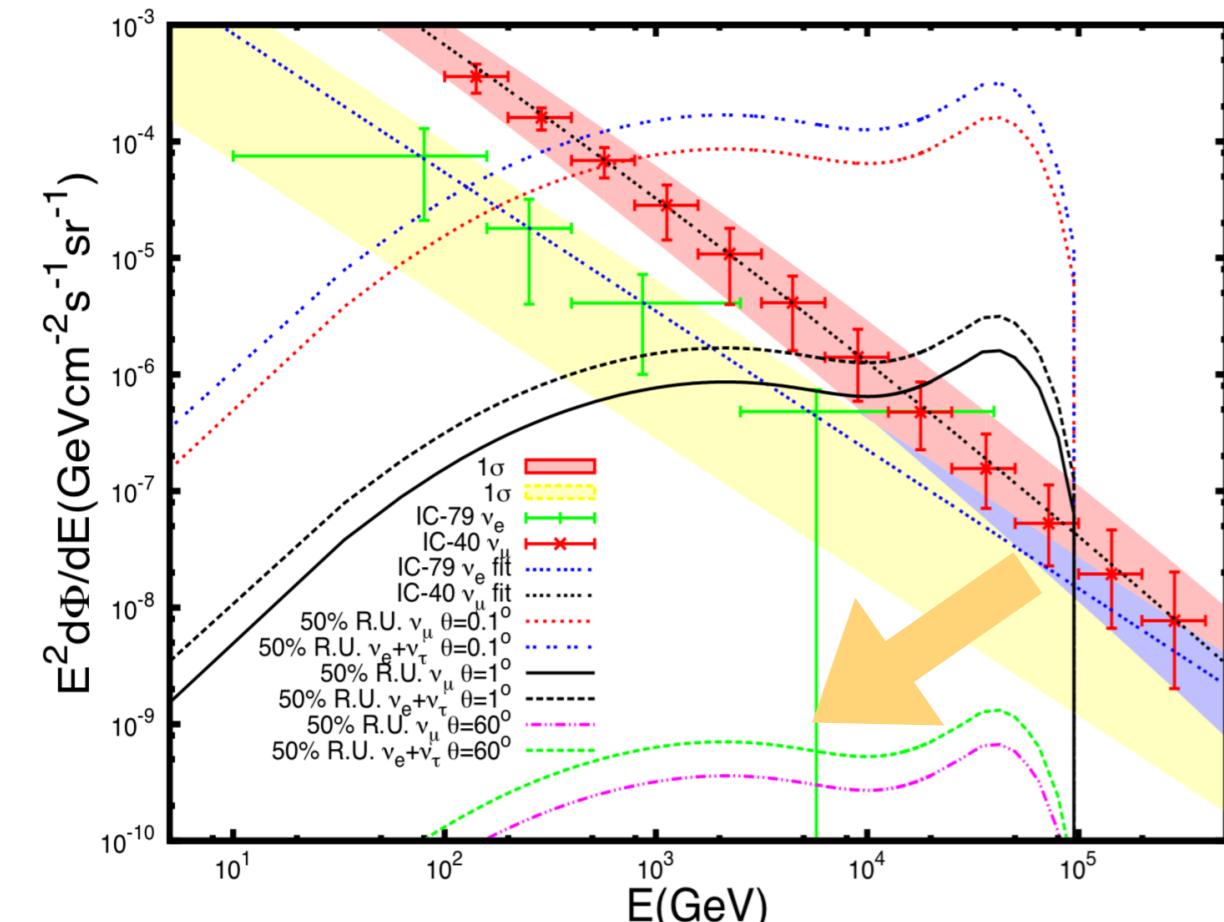
Combined
ANTARES &
IceCube

neutrinos



Latest data

antiprotons



Cembranos, VG, Maroto, Phys. Rev. D 90, 043004 (2014)

V.G., Front. Astron. Space Sci., 05 April 2019

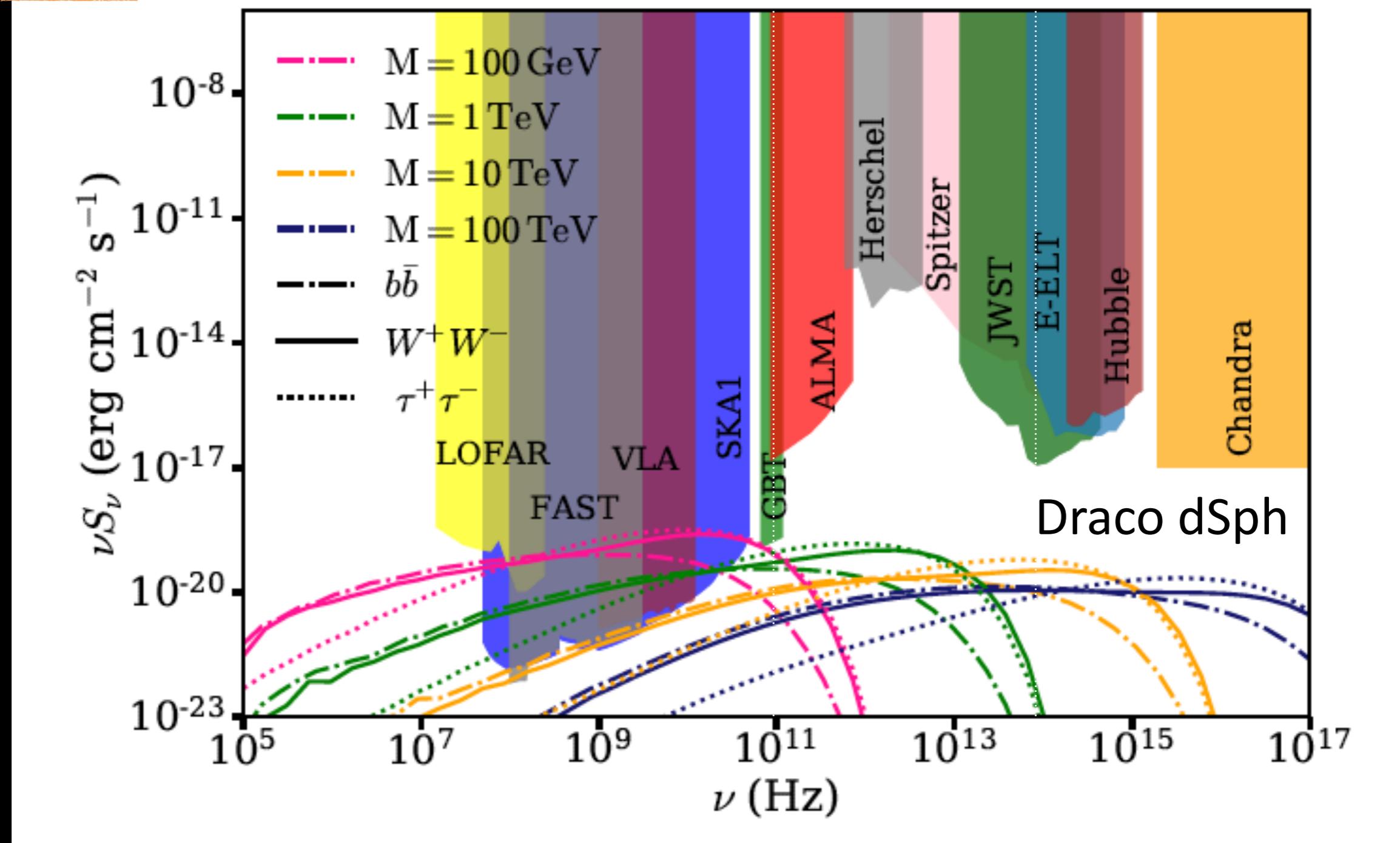
Cembranos, VG, Maroto, JCAP03(2015)041

Multi-wavelength DM signature

Flux density

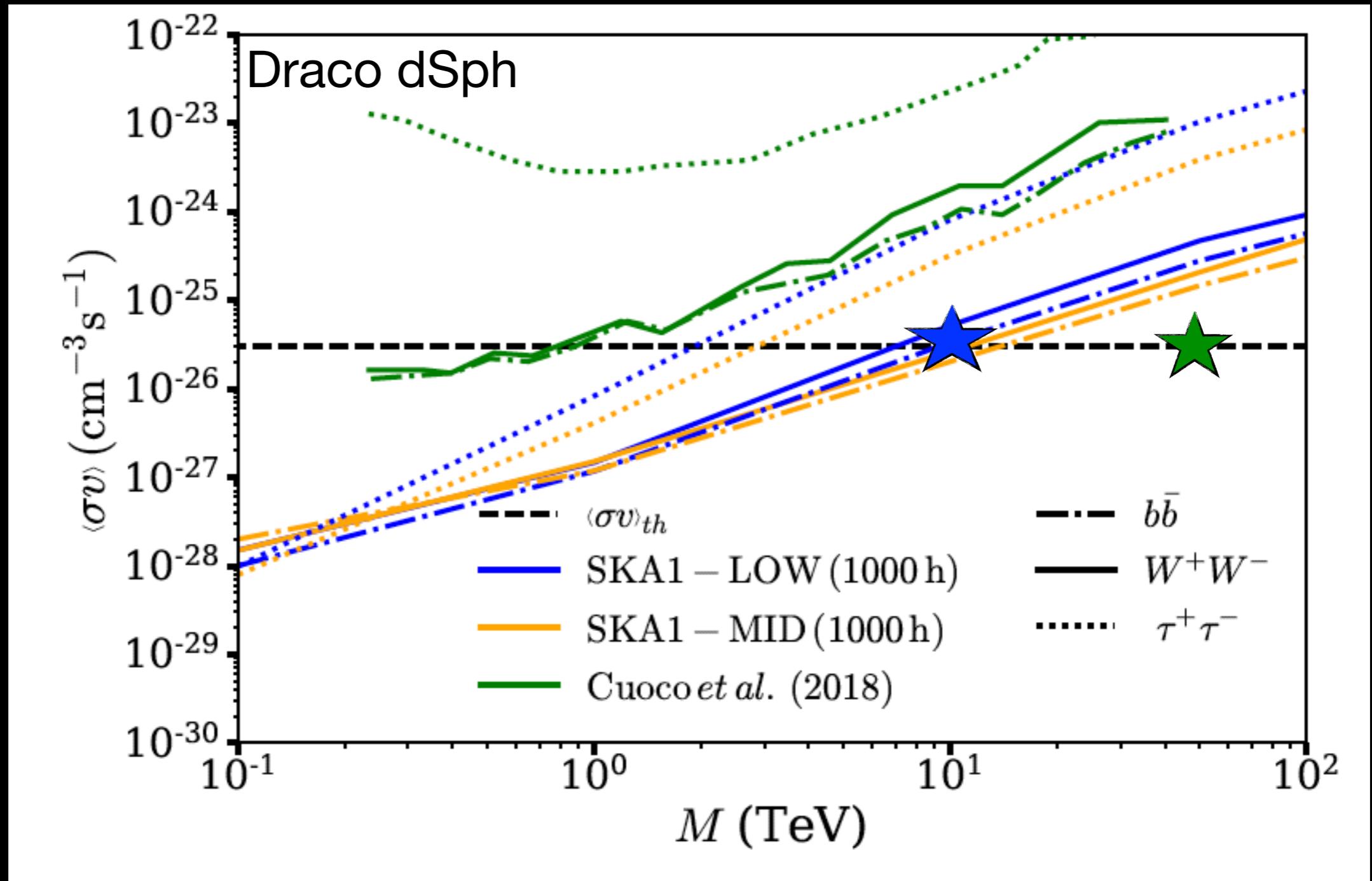
$$S_\nu(z) = \int_{\Omega} d\Omega I_\nu(\theta, z)$$

Model independent synchrotron emission



Multi-wavelength exclusion limits

In absence of a detected signal we can set constraints on the WIMP mass and annihilation cross section.



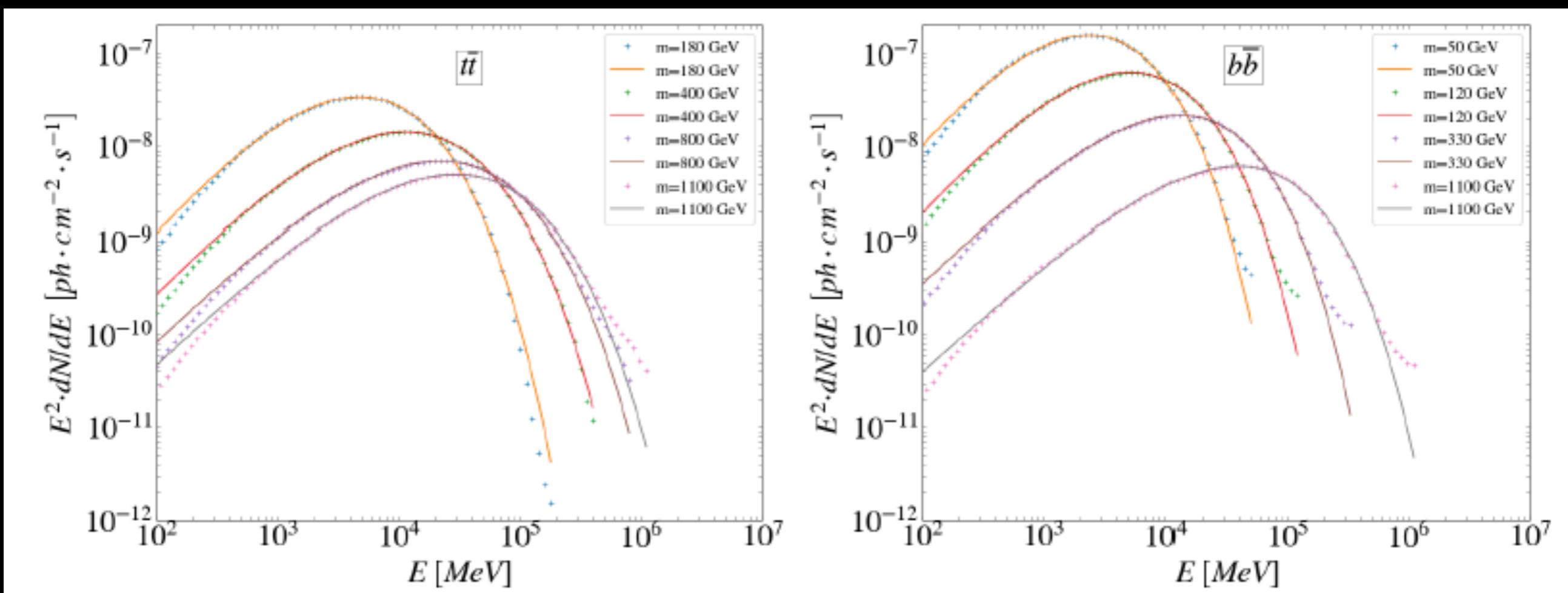
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Approach for Machine Learning

Monte Carlo event generator softwares (e.g. Pythia 8) allow to simulate fluxes of astroparticles expected by WIMP candidates of different masses annihilating in different SM channels. By fitting e.g. the simulated gamma-ray flux with a log-parabola we get:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha - \beta \cdot \log(E/E_0)}, \quad E_{peak} = E_0 \cdot e^{\frac{2-\alpha}{2\beta}}$$



New approach for Machine Learning (phenomenologically motivated)

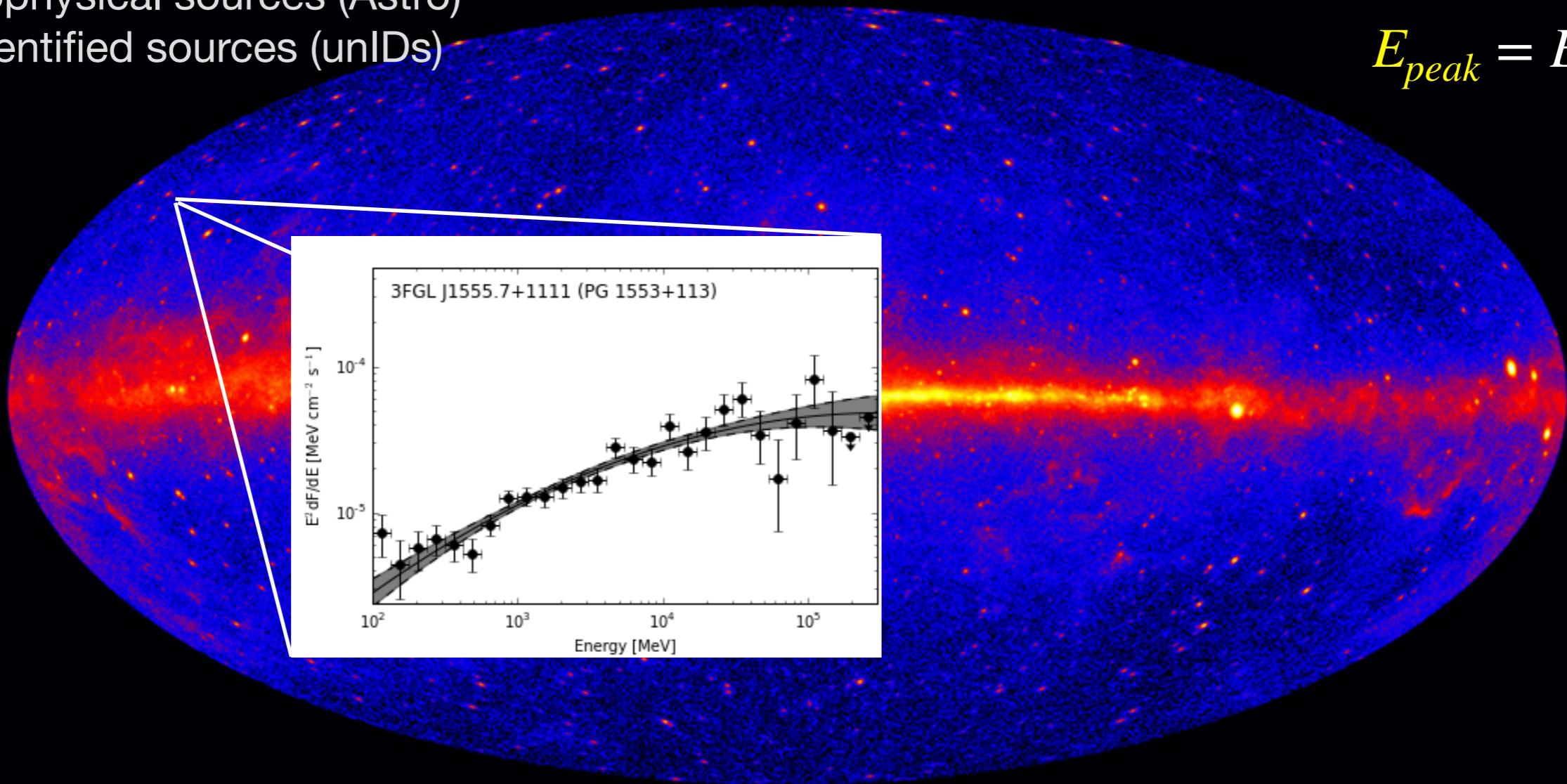
Fermi-LAT data:

Astrophysical sources (Astro)

Unidentified sources (unIDs)

Log-Parabola:
$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha - \beta \cdot \log(E/E_0)},$$

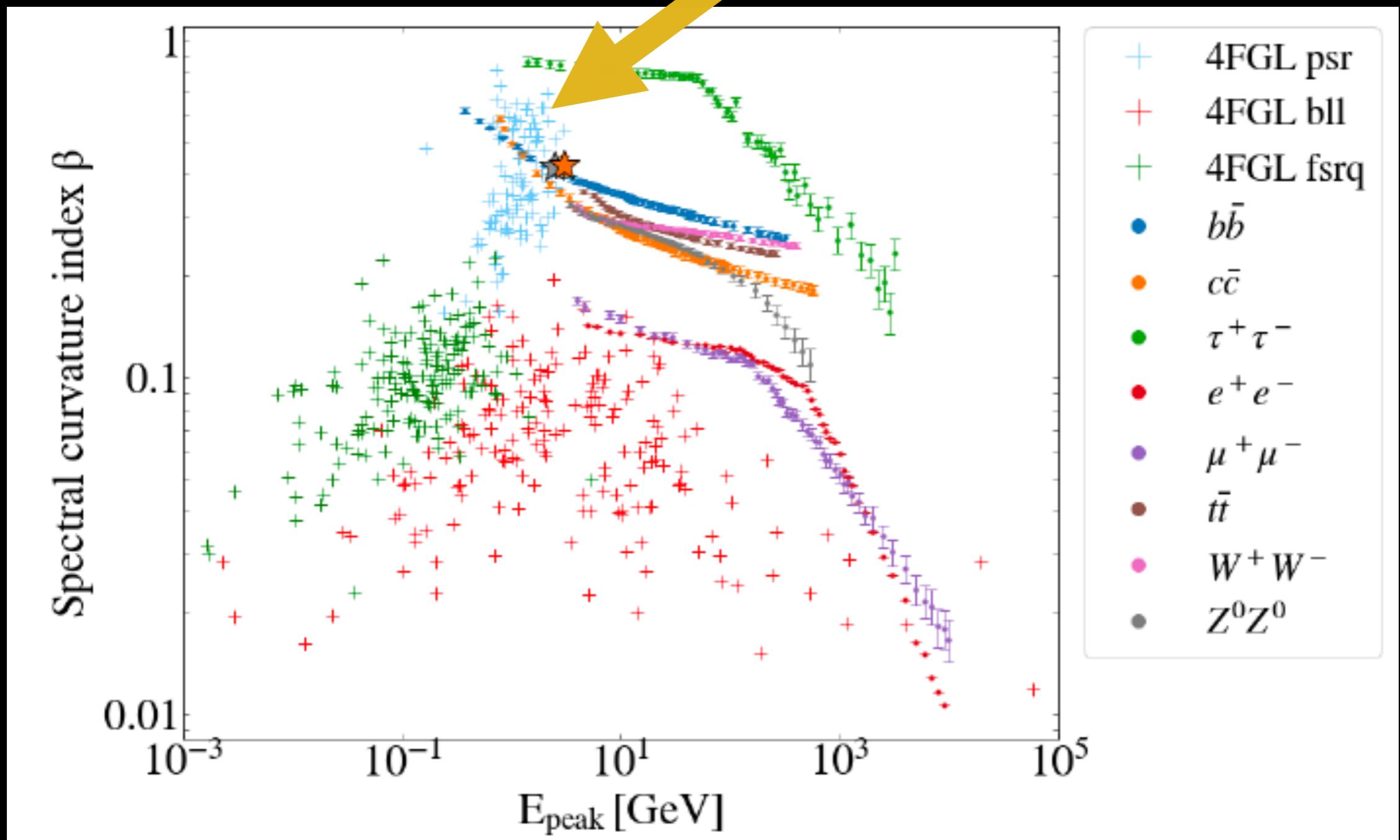
$$E_{peak} = E_0 \cdot e^{\frac{2-\alpha}{2\beta}}$$



New approach for Machine Learning

Model independent

Well-known degeneracy between pulsar and DM signature (e.g. GC)

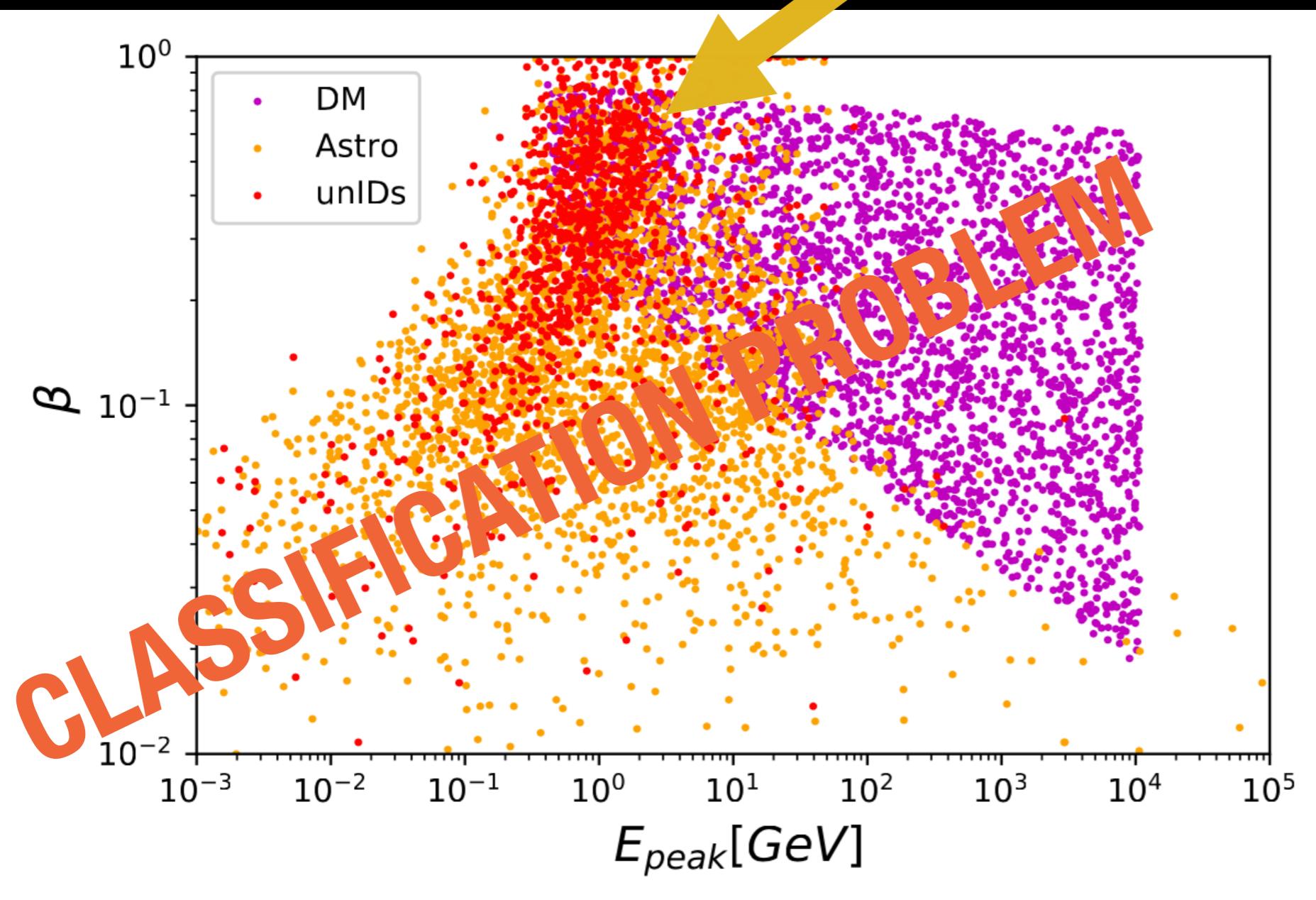


New approach for Machine Learning

Broadly-based model dependent

$$\frac{dN}{dE} = B_r \left(\frac{dN}{dE} \right)_{C_1} + (1 - B_r) \left(\frac{dN}{dE} \right)_{C_2}$$

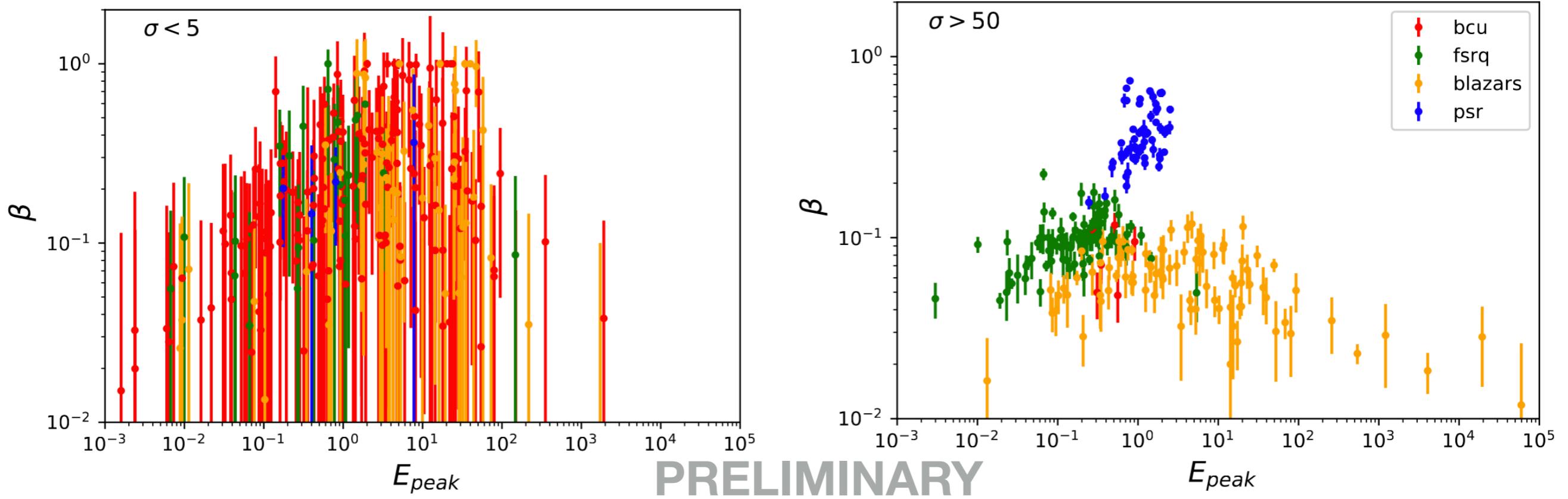
Well-known degeneracy between pulsar and DM signature (e.g. GC)



This methodology represents a more general approach in order to search for different DM signatures at the same time among a set of experimental data set (here, unidentified sources);

Systematic uncertainty

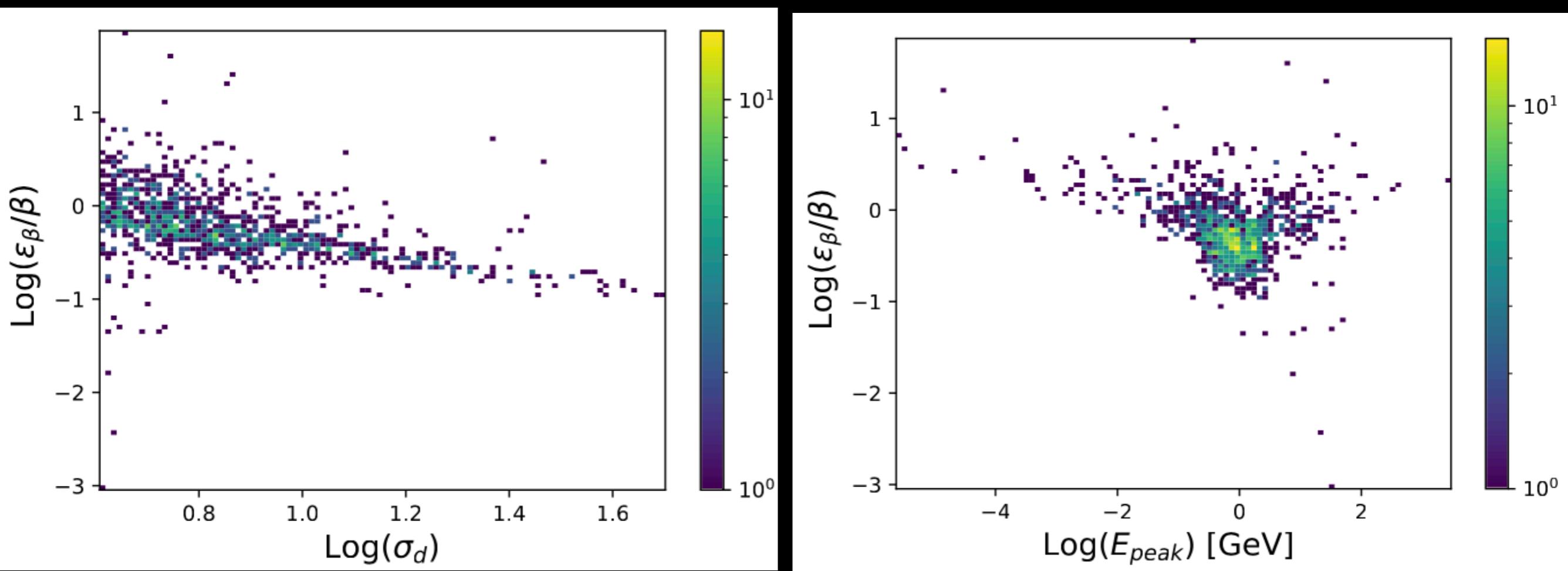
Both the detection significance and uncertainty in spectral parameters affect the classification of unidentified sources.



V.G. et al. arXiv: 2207.09307

Systematic uncertainty

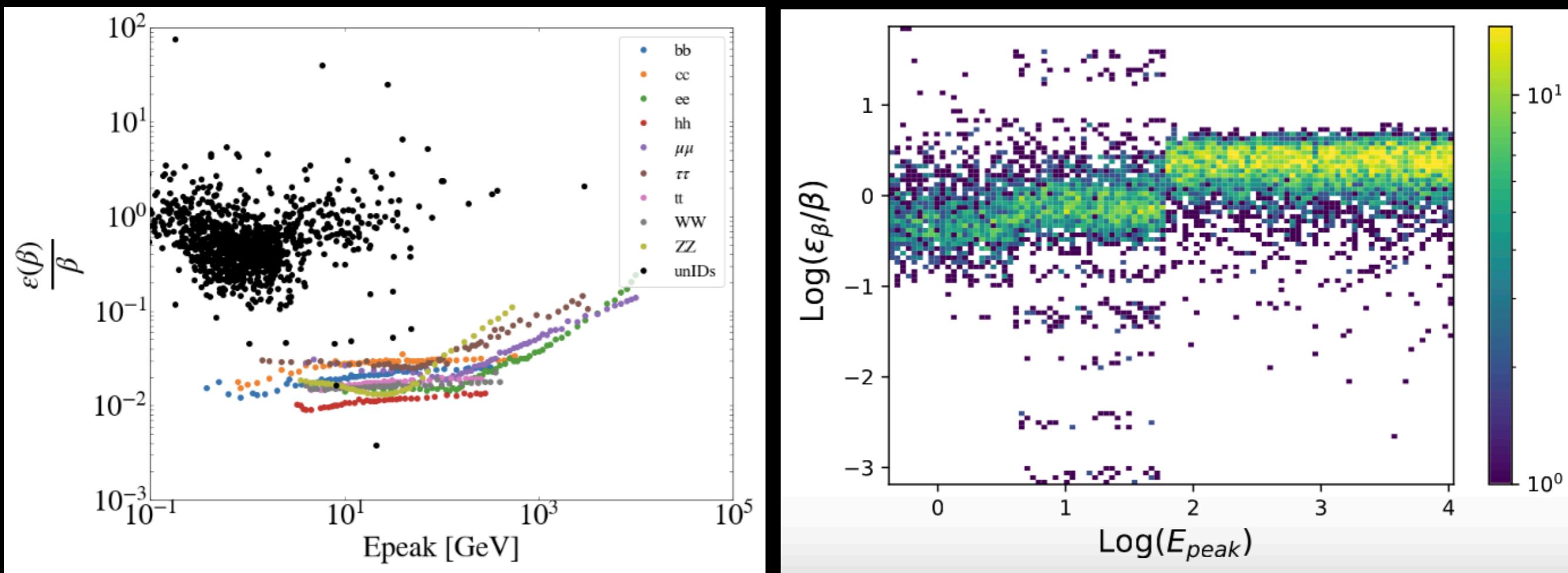
Both the detection significance and uncertainty in spectral parameters are strictly related with the instrumental systematic uncertainty.



V.G. et al. arXiv: 2207.09307

Systematic features

We determine the systematic uncertainty for the theoretical DM data set.



V.G. et al. arXiv: 2207.09307

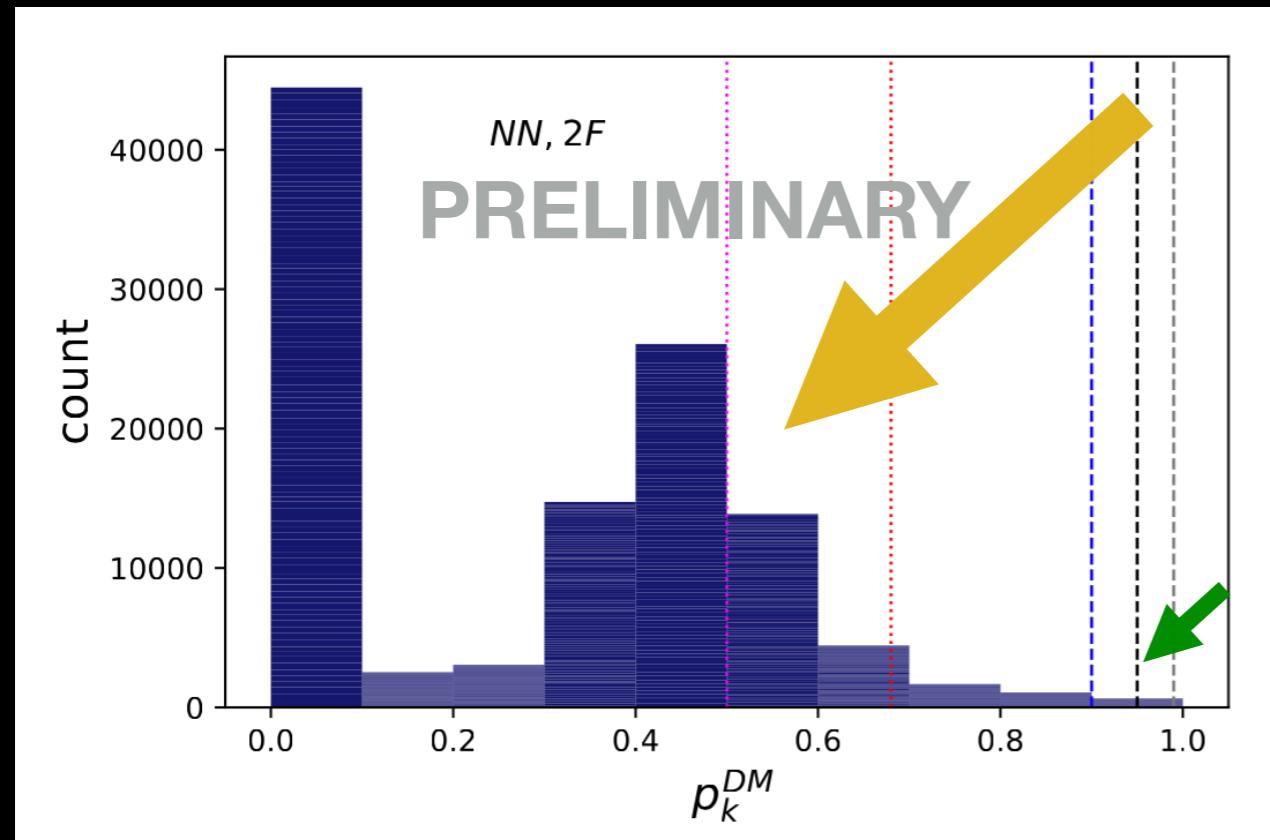
This methodology represents a more general approach in order to:

- 1) search for different DM signatures at the same time among a set of experimental data set (here, unidentified sources);
- 2) improve the classification accuracy by taking into account the experimental systematic uncertainty for the prospective detection of any theoretical DM candidate.

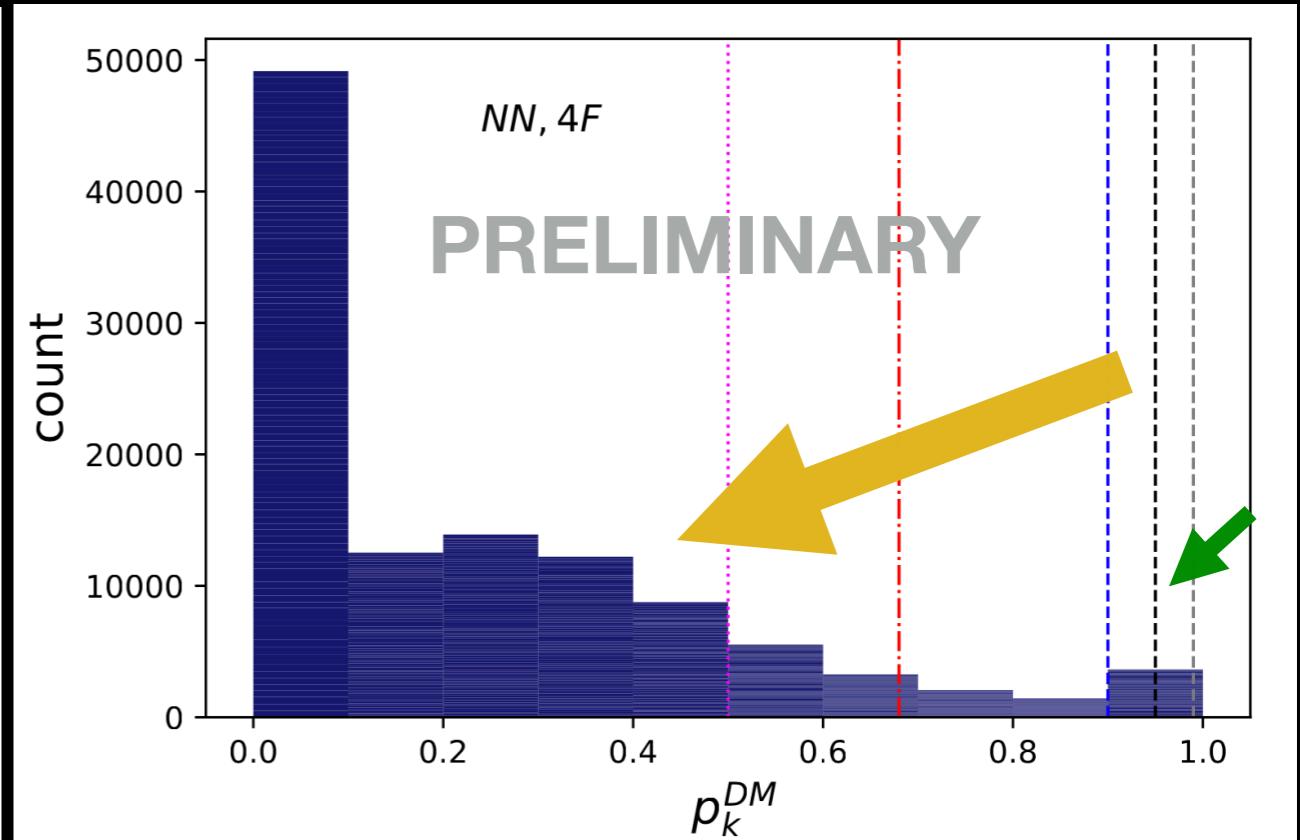
unIDs classification with Neural Network

Probability distribution for the full sample of 1125 Fermi-AT unIDs
(100 classification runs)

2-FEATURES CLASSIFICATION
 (E_{peak}, β)



4-FEATURES CLASSIFICATION
 $(E_{peak}, \beta, \sigma_{det}, \beta_{rel})$



The degeneracy between pulsar and DM signatures is partially solved
We cannot claim for any robust DM candidate among the Fermi-LAT unIDs sources

Conclusions

- Any possible claim of detected DM signature needs an observed counterpart in multi-messenger or multi-wavelength telescopes (and/or direct detection and/or detection at colliders);
- Such a counterpart depends on the DM nature;
- In the model independent approach for WIMP searches (first approximation), the expected counterpart depends on the SM model physics;
- In the model dependent approach, the WIMP signature (e.g. its mass, annihilation cross-section, annihilation channels...) allows to distinguish between different theoretical models for WIMP candidates;
- In the phenomenologically based machine learning approach, we can search for multiple WIMP signatures in an observed data set at the same time.
- Including systematic features, we can partially solve the degeneracy between the signature of WIMP candidates and astrophysical sources.



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Than you for your attention

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 @Gammaldiv

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BACK UP SLIDES

Model independent DM signatures

$$\frac{d\phi_\gamma}{dE}(E, \Delta\Omega, l.o.s) = \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{\delta m_\chi^2} \frac{dN_\gamma}{dE}(E) \times J(\Delta\Omega, l.o.s)$$

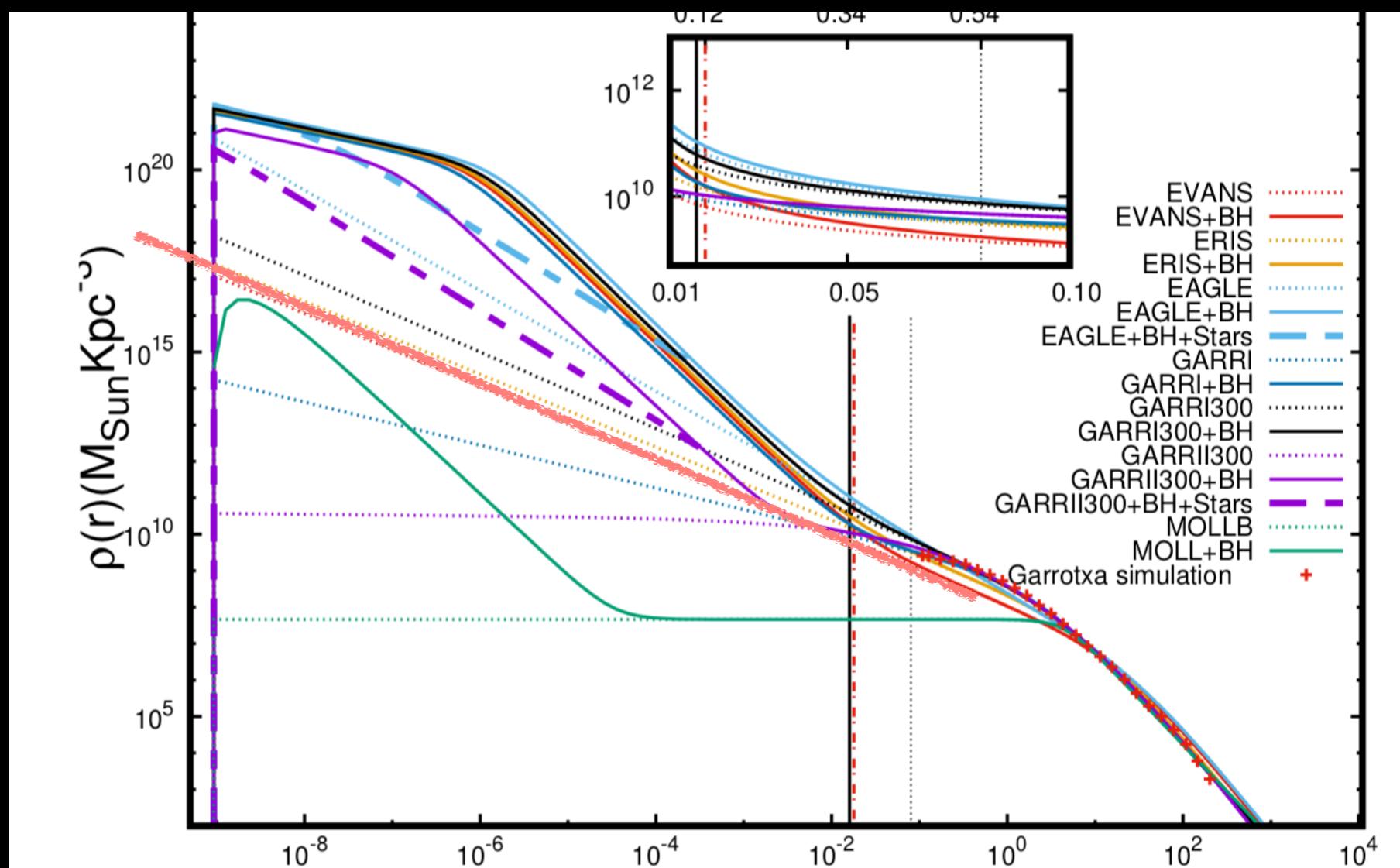
Thermal DM $\langle\sigma v\rangle \approx 3 \times 10^{-26} \text{cm}^3\text{s}^{-1}$

NFW density distribution profile $J \approx 2.80 \times 10^{25} \text{ GeV}^2\text{cm}^{-5}$

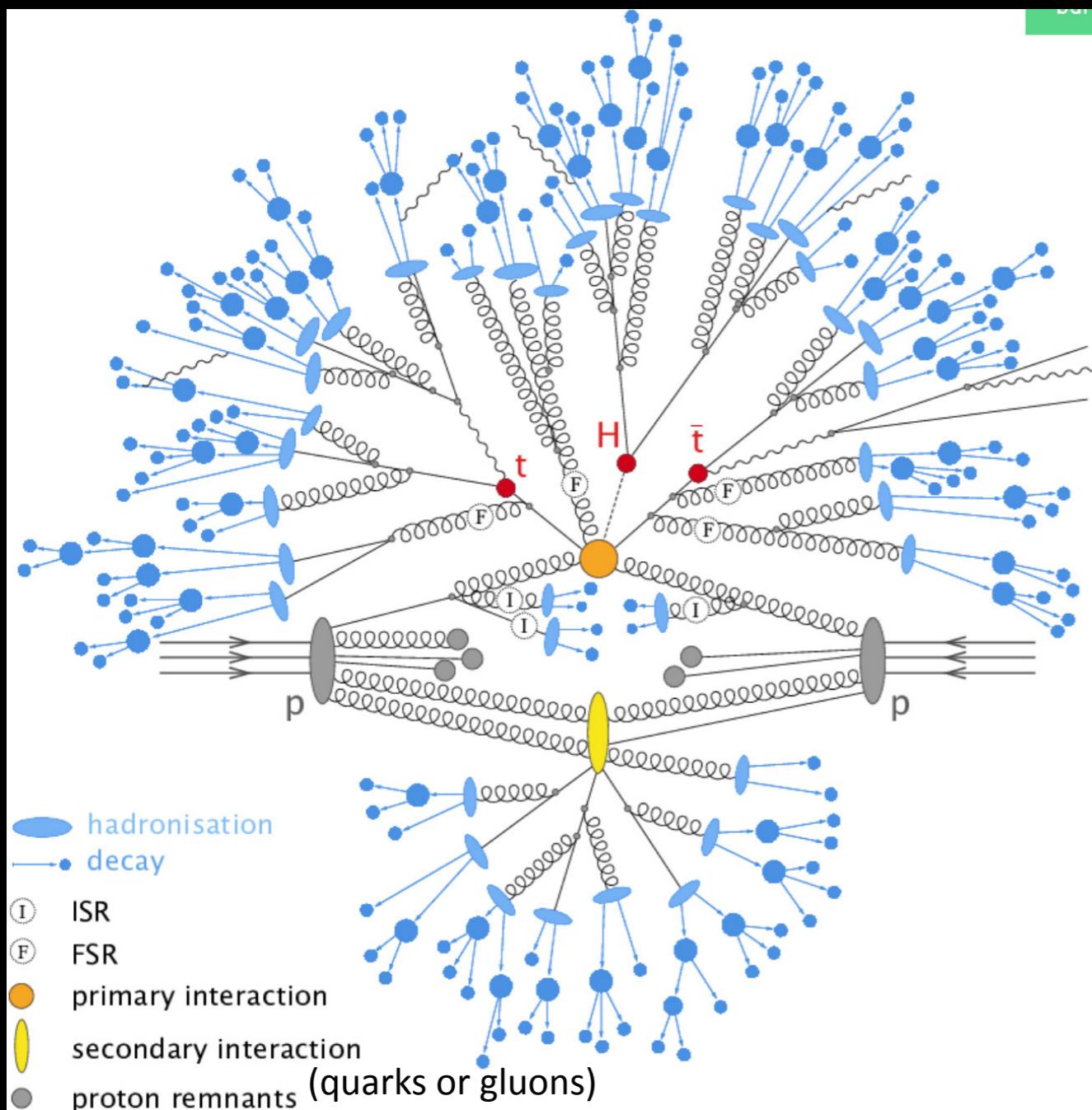
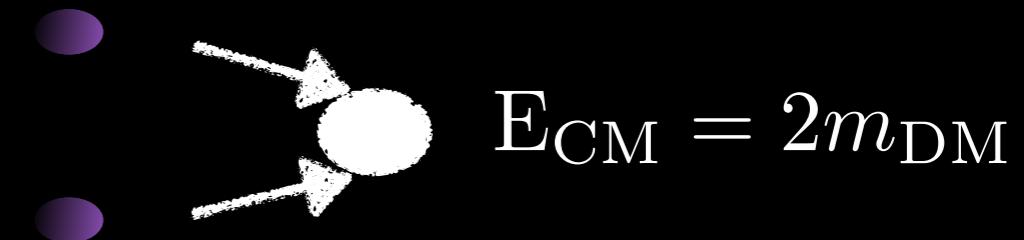
DM density distribution

Boost required
 $\sim 10^3 (\theta \sim 0.1^\circ)$

(FERMI-LAT Data)		W^+W^-
m_{DM}	★	51.7 ± 5.2
$A^{(\gamma)}$		4.44 ± 0.34
$B^{(\gamma)}$		3.29 ± 1.03
Γ		2.63 ± 0.02
χ^2/dof		0.75



Monte Carlo event generator software



Fortran Code:

PYTHIA 6.4 and HERWIG

C++ Code:

PYTHIA 8 and HERWIG++

Intrinsic differences:

- 1) QCD Parton Shower Evolution
Variable: probability to radiate partons from the incoming protons
- 2) Hadronization Model (String in PYTHIAs o Cluster in HERWIGs)
produces mainly leptons -> tuned on colliders
- 3) QED Final State Radiation: 2->2 EW Processes and Bremsstrahlung
- 4) Top decay

Multi-wavelength DM detection

Source term ($\alpha=2$): $Q_e(\mathbf{r}, E) = \frac{1}{2} \langle \sigma v \rangle \left(\frac{\rho_{\text{DM}}(\mathbf{r})}{M} \right)^2 \sum_j \beta_j \frac{dN_e^j}{dE}$

$$\psi(\mathbf{r}, E) = \frac{1}{b(\mathbf{r}, E)} \int_E^M dE_s G(r, E, E_s) Q_e(\mathbf{r}, E)$$


Green's function

Power of emission:

$$B(r) = B_0 \exp(-r/r_c)$$

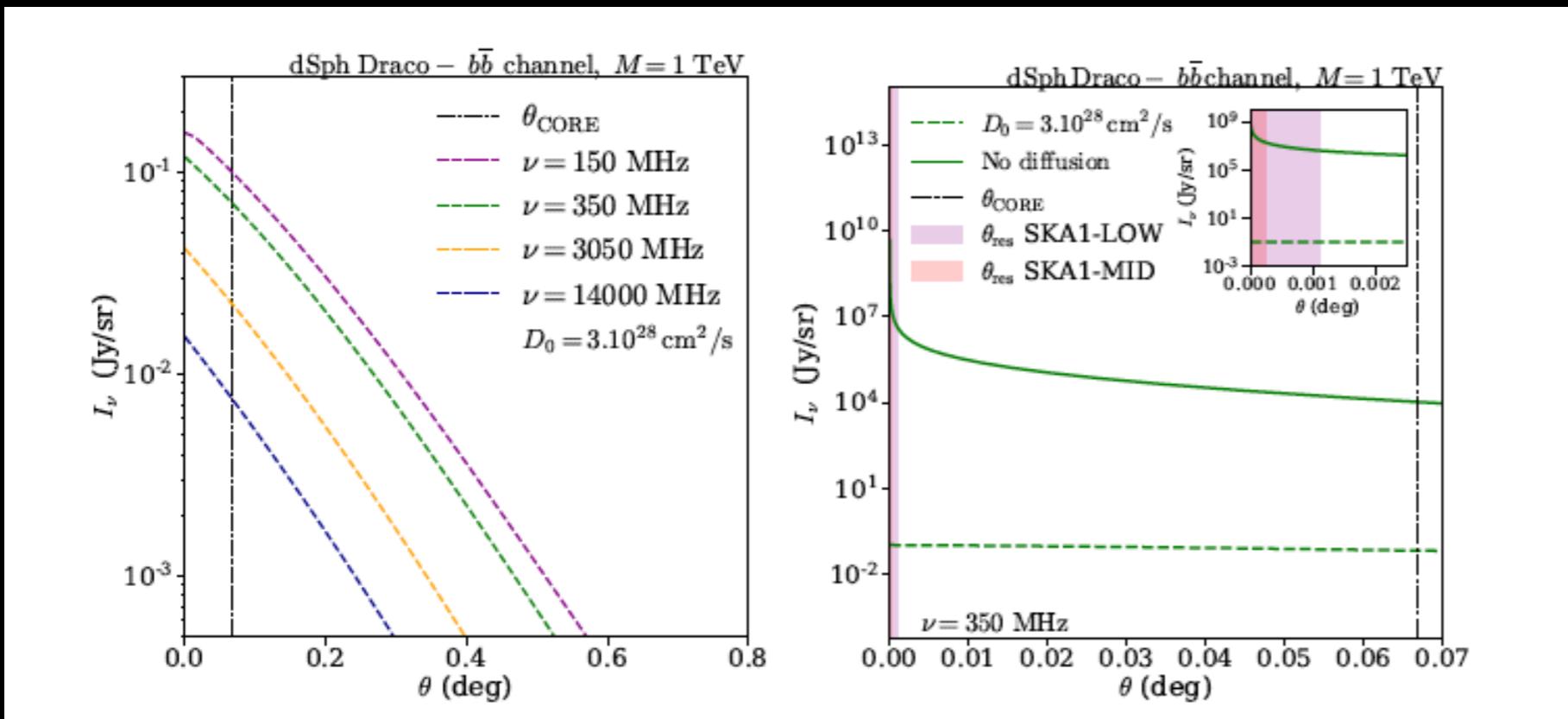
$$\nu_c(\mathbf{r}, E) = \frac{3eB(\mathbf{r})}{4\pi m_e} \gamma^2(E)$$

Emissivity

$$P_{\text{syn}}(\nu, \mathbf{r}, E, z) = \int_0^\pi d\alpha \frac{\sin^2 \alpha}{4\pi \epsilon_0} \frac{\sqrt{3} e^3 B(\mathbf{r})}{m_e c} F_i \left(\frac{\nu(1+z)}{\nu_c(\mathbf{r}, E) \sin \alpha} \right)$$

$$F_i(s) = s \int_s^\infty d\xi K_{\frac{5}{3}}(\xi) \simeq \frac{5}{4} s^{\frac{1}{3}} \exp(-s) (648 + s^2)^{1/12}$$

$$j_\nu(\mathbf{r}, z) = \int_E^M dE (\psi_{e^+} + \psi_{e^-}) P_{\text{syn}}(\nu, \mathbf{r}, E, z) 2 \int_E^M dE \psi(\mathbf{r}, E) P_{\text{syn}}(\nu, \mathbf{r}, E, z)$$

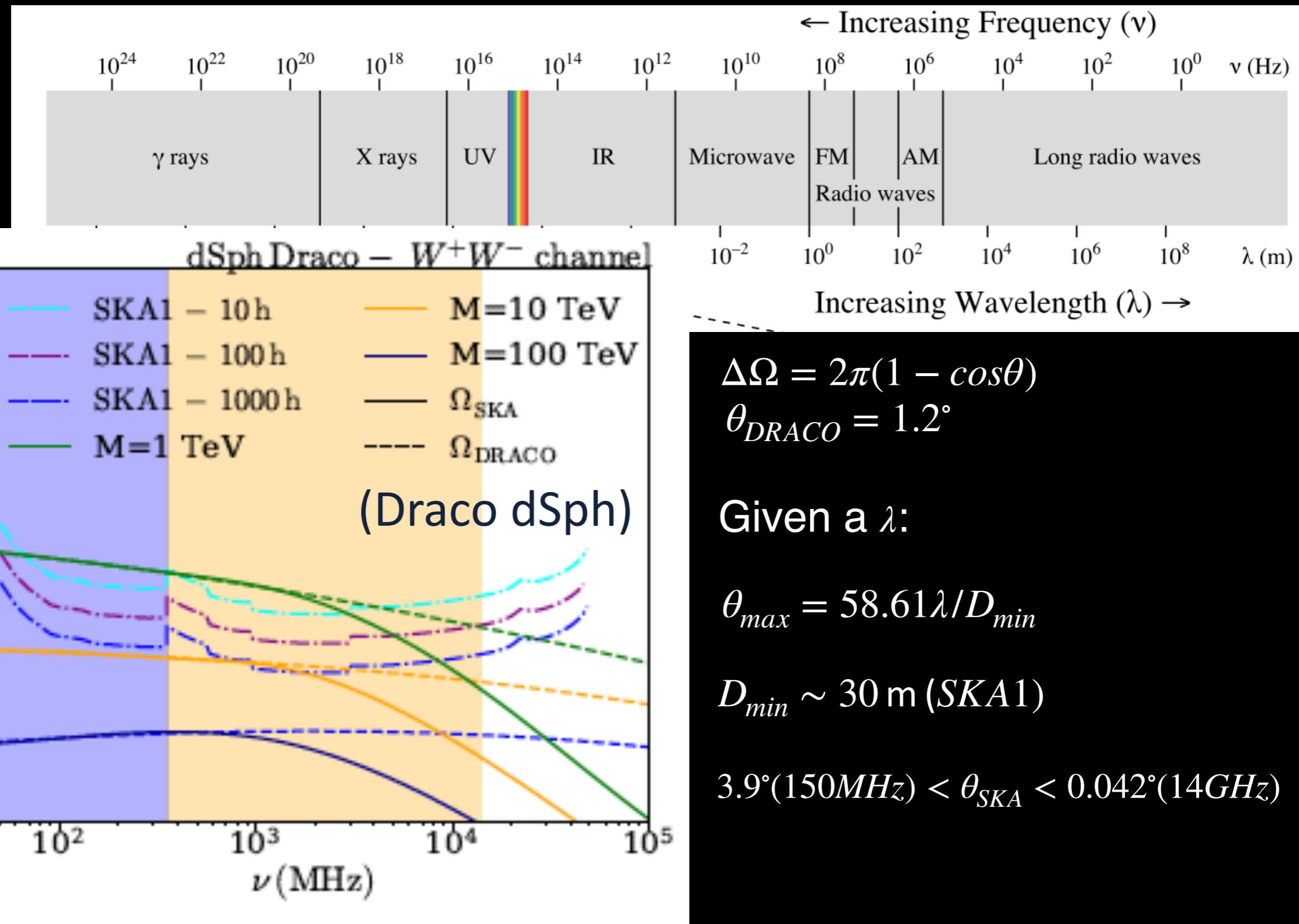


Specific Intensity

$$I_\nu(\theta, z) = \int_{\text{l.o.s.}} dl \frac{j_\nu(l, \theta, z)}{4\pi}$$

(Draco dSph)

Model independent DM signatures



Multi-TeV DM candidates

- Brane-world dark matter
(e.g. J. A. R. Cembranos, A. Dobado and A. L. Maroto , Phys.Rev.D68:103505,2003)
- Heavy Minimal Dark Matter
(e.g. C. Garcia-Cely, A. Ibarra, A. S. Lamperstorfer, M. H.G. Tytgat, JCAP 1510 (2015) no.10, 058;
A. Cuoco, J. Heisig, M. Korsmeier, M. Krämer, JCAP 1804 (2018) no.04, 004)
- Inverse Seesaw and Portal Dark Matter
(e.g. C. Pongkitivanichkul, N. Thongyoi, P. Uttayarat, arXiv:1905.13224)

The branon DM candidate

$\alpha = 1 \dots N$

$$\mathcal{L}_{Br} = \frac{1}{2}g^{\mu\nu}\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - \frac{1}{2}m_{DM}^2\pi^\alpha\pi^\alpha + \frac{1}{8f^4}(4\partial_\mu\pi^\alpha\partial_\nu\pi^\alpha - m_{DM}^2\pi^\alpha\pi^\alpha g_{\mu\nu})T^{\mu\nu}$$

- ✓ Branons are mass eigenstates of the fluctuations in the extra-space directions

-> massive particles

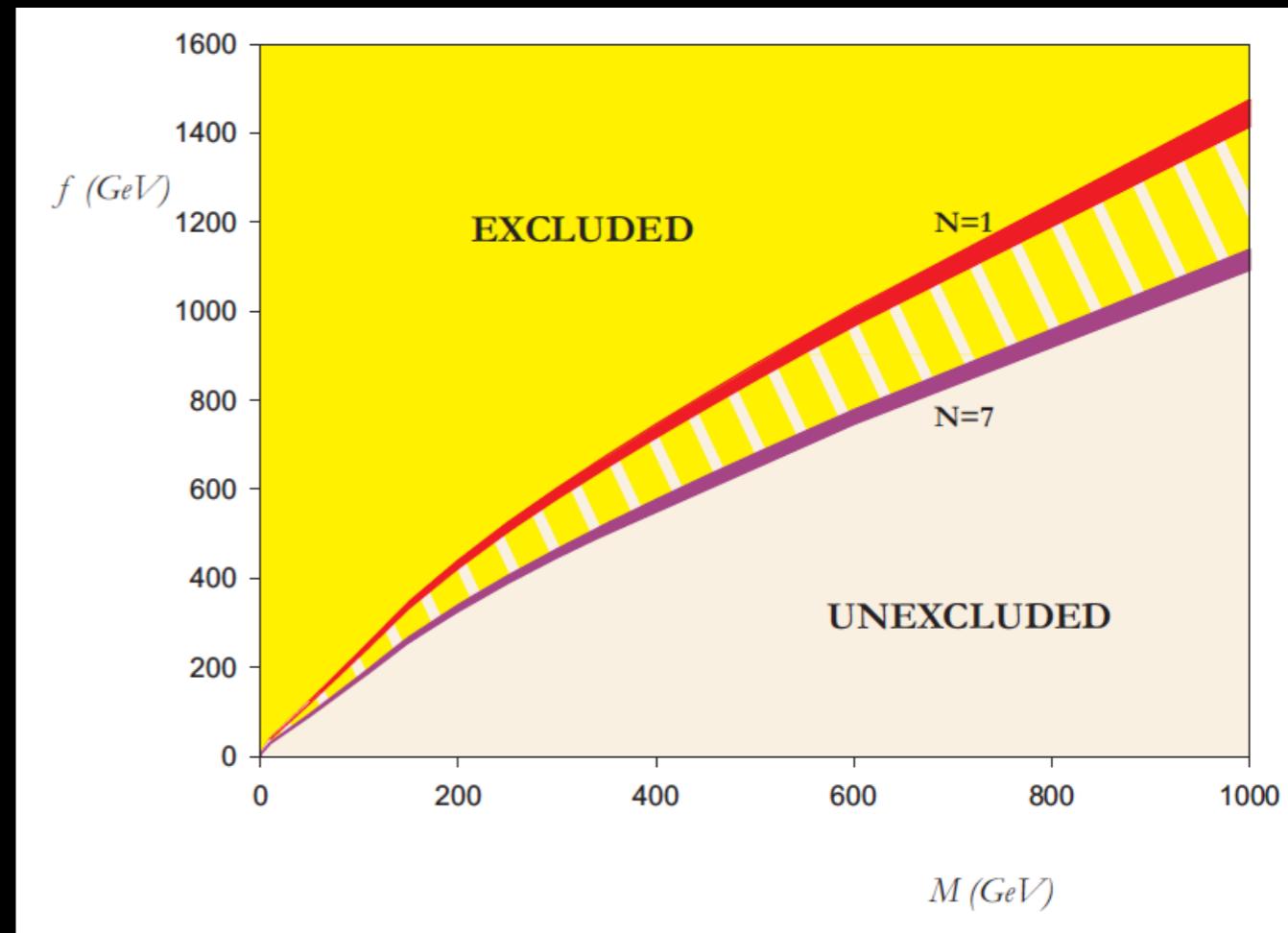
- ✓ Their couplings are suppressed by the tension f^4

-> weakly interacting

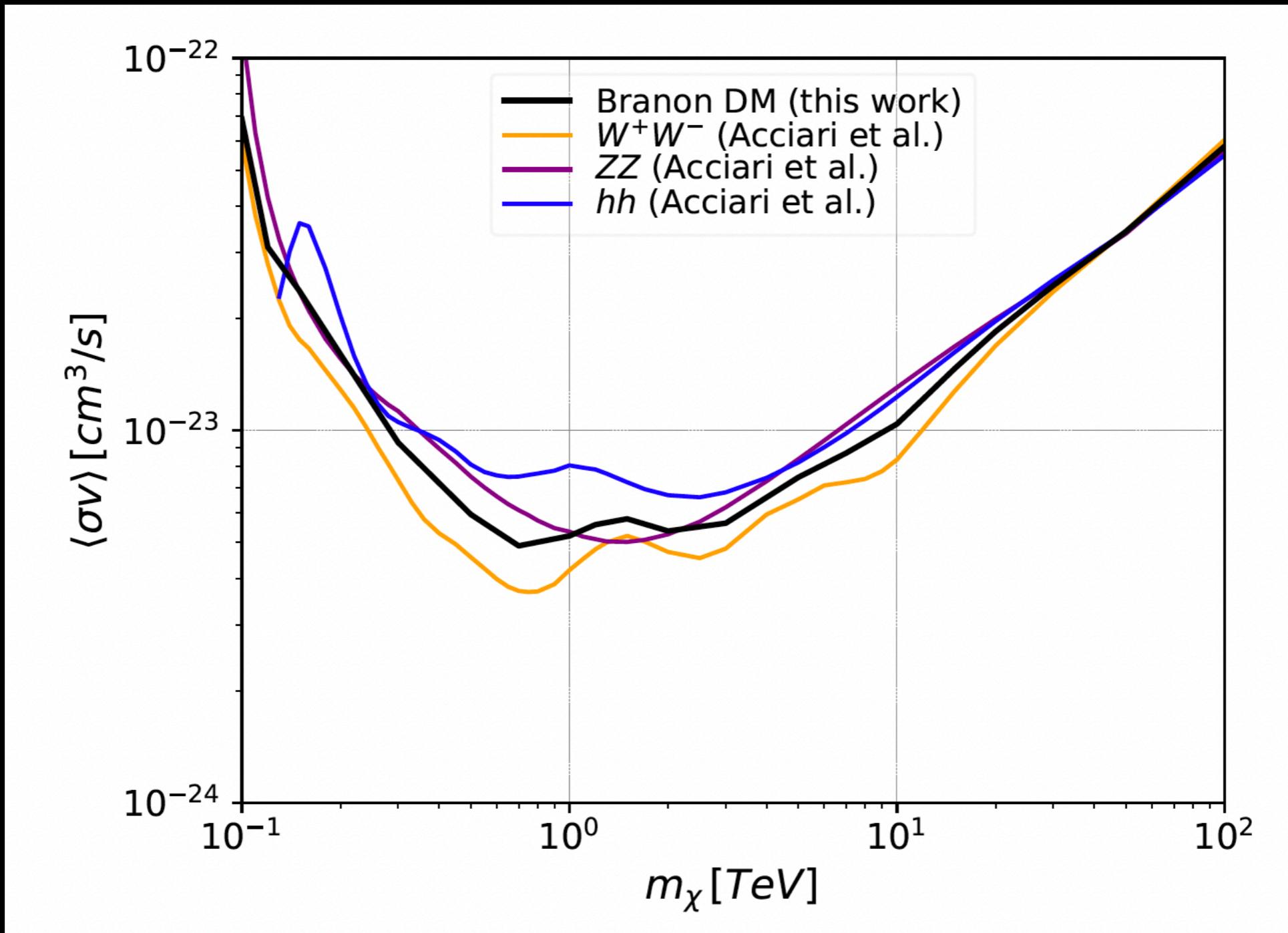
Natural
WIMP
candidate

Thermal candidate

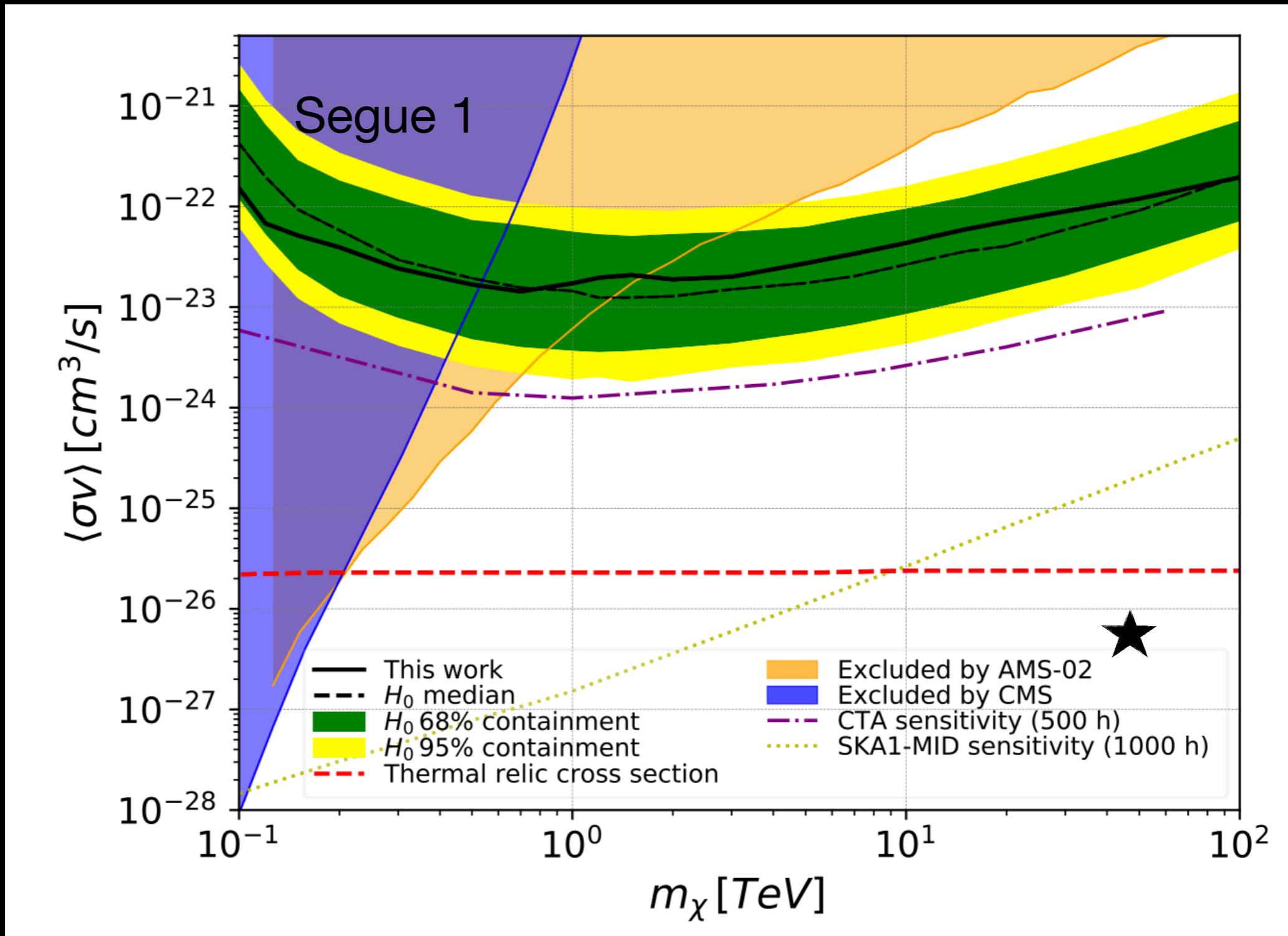
J.A.R. Cembranos, A. Dobado. A.L. Maroto, Phys.Rev.D68:103505,2003



Model dependent DM signatures

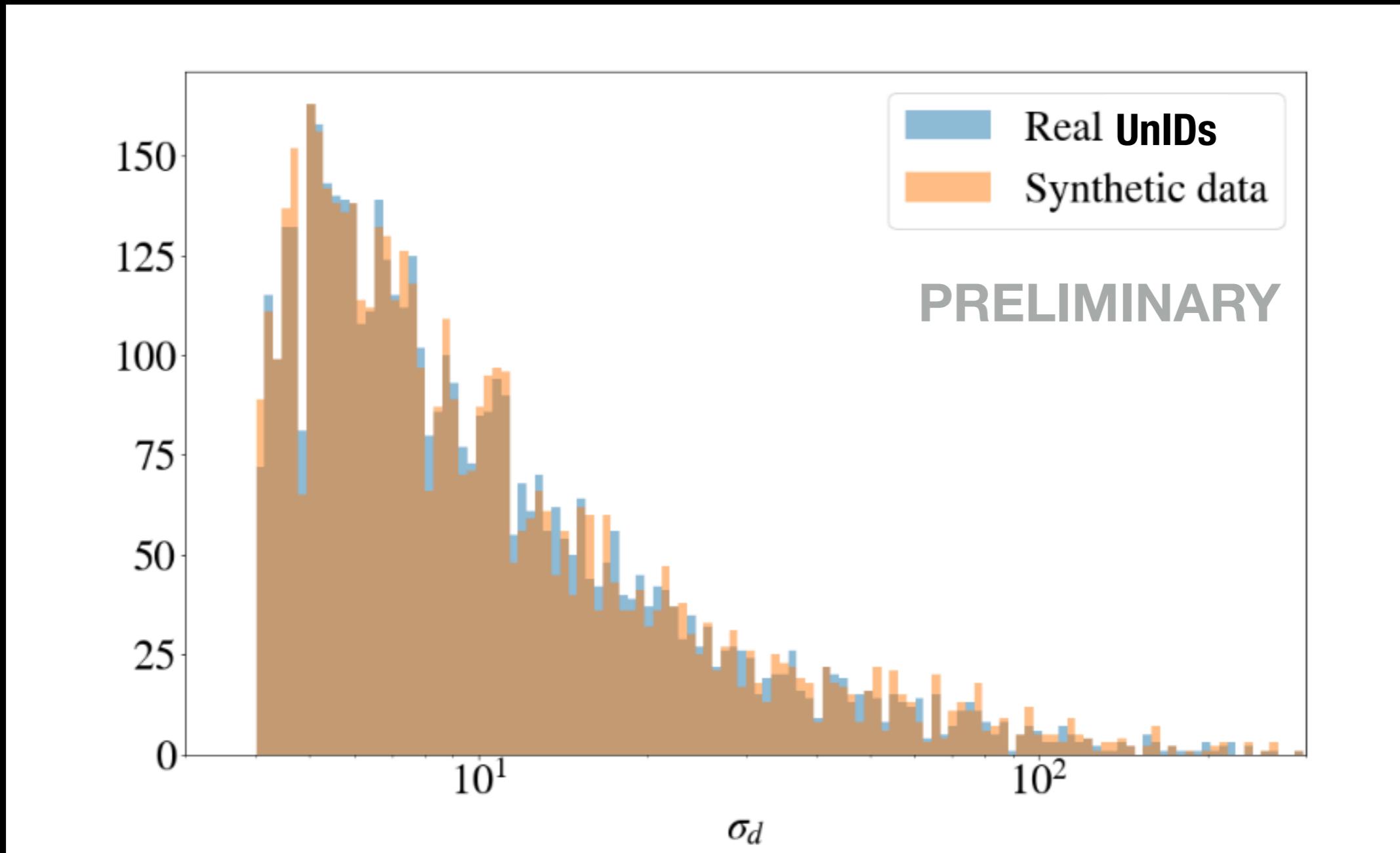


Model dependent DM signatures

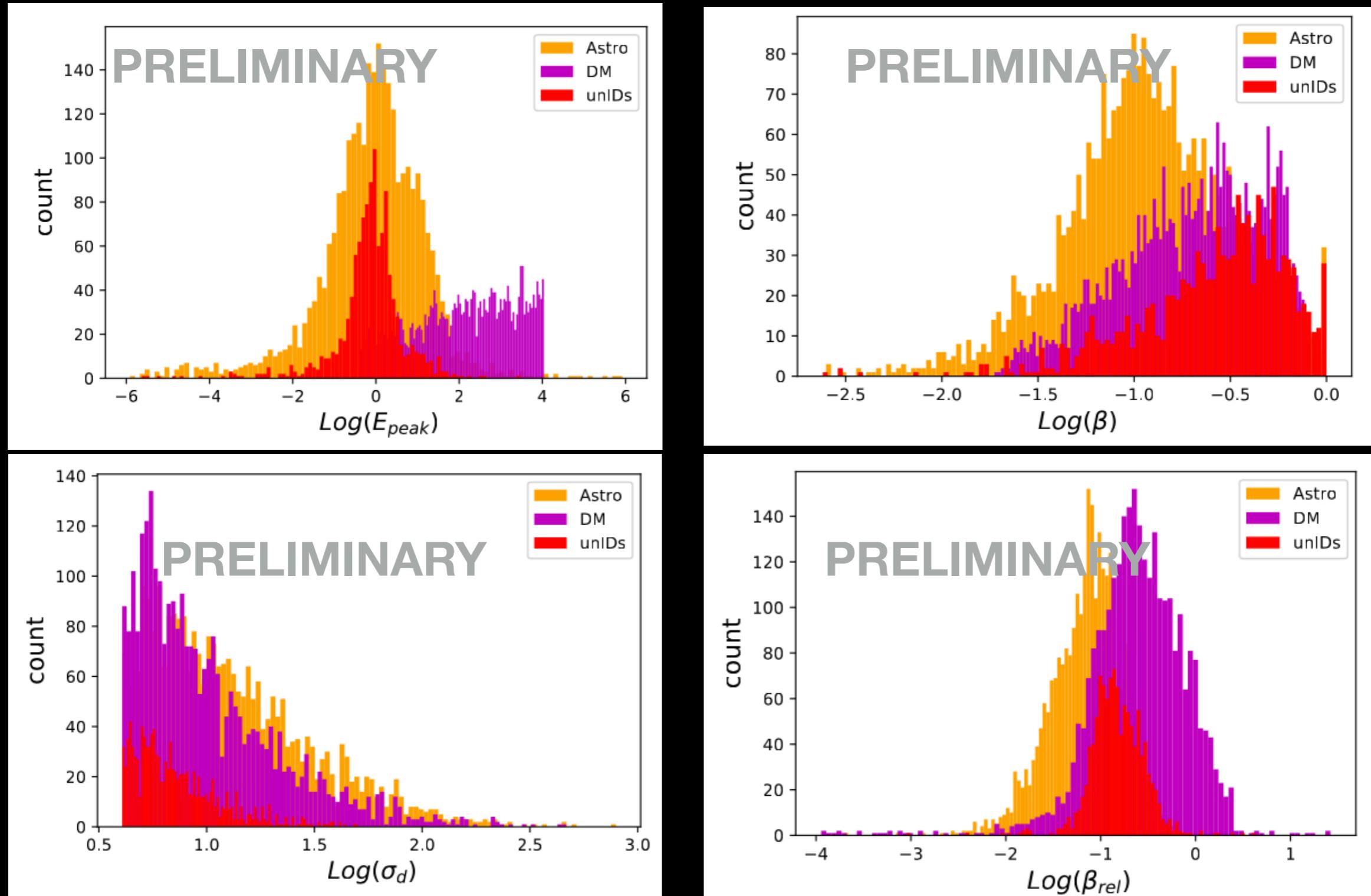


DETECTION SIGNIFICANCE

We assume that all the DM candidates are unIDs



From Two to four FEATURES



RESULTS

V.G. et al. arXiv: 2207.09307

- ▶ **OVERALL ACCURACY:** PERCENTAGE OF WELL CLASSIFIED DATA SET

$$\text{Overall accuracy (OA)}(y, \hat{y}) = \frac{1}{n_{\text{samples}}} \sum_{i=0}^{n_{\text{samples}}-1} 1(\hat{y}_i = y_i)$$

- ▶ **TRUE NEGATIVE (TN):** PERCENTAGE OF WELL CLASSIFIED ASTRO SOURCES (NORMALISED TO THE TOTAL NUMBER OF ASTRO SOURCES)
- ▶ **TRUE POSITIVE (TP):** PERCENTAGE OF WELL CLASSIFIED DARK MATTER SOURCES (NORMALISED TO THE TOTAL NUMBER OF DM SOURCES)

THE OVERALL CLASSIFICATION ACCURACY IMPROVES WITH THE INTRODUCTION OF SYSTEMATIC FEATURES FOR ALL THE TRAINED ALGORITHMS.

	OA(%)	TN (%)	TP (%)
LR			
2F	84.9 ± 0.8	85.4 ± 1.5	84.4 ± 1.4
3F-A	83.0 ± 0.1	85.0 ± 0.2	$81.0 \pm .2$
4F	86.0 ± 0.9	86.7 ± 1.5	85.2 ± 1.3
NN			
2F	86.2 ± 0.8	86.1 ± 3.0	86.4 ± 3.4
3F-A	85.0 ± 0.2	87.9 ± 1.8	$82.3 \pm .1.8$
4F	93.3 ± 0.7	94.7 ± 1.7	91.8 ± 1.5
NB			
2F	82.4 ± 1.5	83.9 ± 1.9	80.5 ± 2.5
3F-A	82.5 ± 0.3	83.7 ± 0.4	81.6 ± 0.3
4F	83.5 ± 1.0	86.2 ± 1.2	81.7 ± 1.2
GP			
3F-B	88.1 ± 0.2	89.6 ± 0.3	84.9 ± 0.2