Stefano Profumo

UC Santa Cruz

The Hunt for Particle Dark Matter

Pheno 2008 Symposium
Madison, WI, April 29 2008

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS

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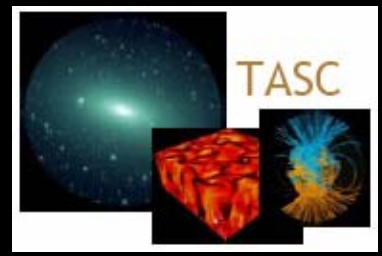
TASC



Hunting WIMP's

Particle Dark Matter might be an **Electro-Weak Scale**

Weakly Interacting Massive Particle (WIMP)

- Predicted in (independently motivated) **Extensions** to the Standard Model

(*e.g. SUSY, UED*)

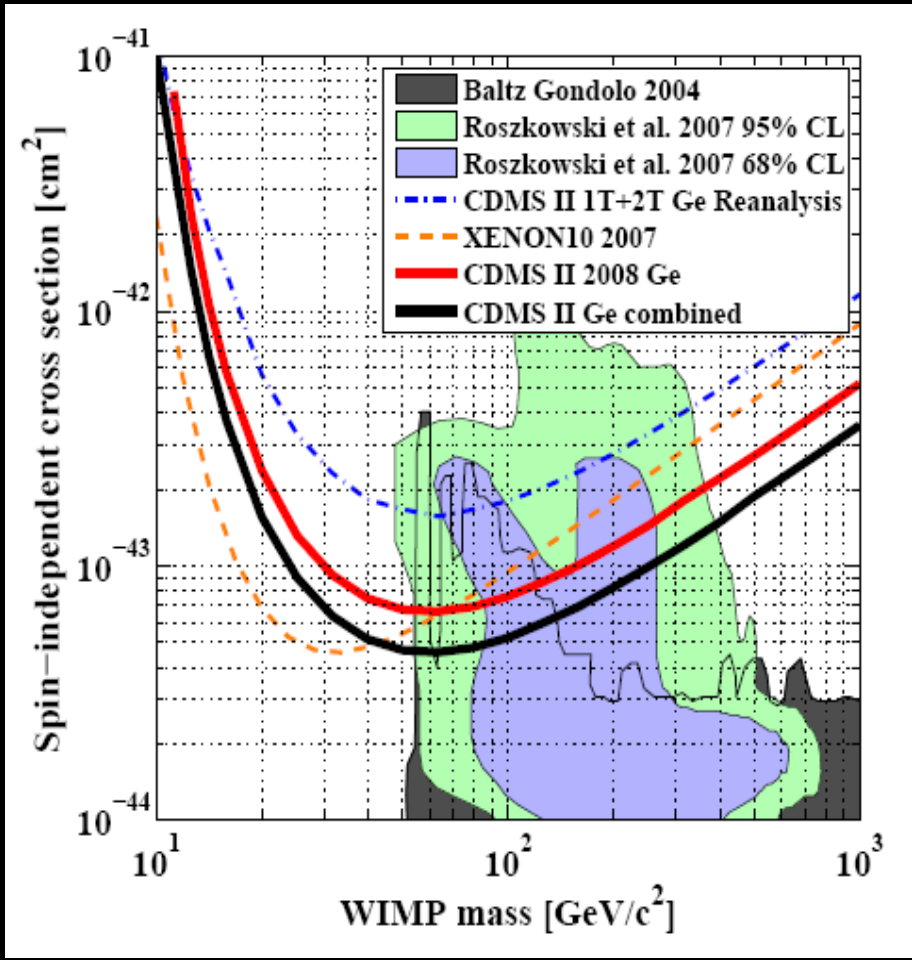
- In a radiation dominated Early Universe, it can be another **thermal relic** leftover

(*e.g. Light Elements (BBN), Cosmic Microwave Bcgk.*)

Exciting Times Lie Ahead!

- **Direct** Detection Expt's:
  - Steady **progress** in sensitivity
  - Exploring parameter space regions where theory predicts plausible **signals**
  - Puzzling result from **DAMA/LIBRA**
- **GLAST**:
  - Opening the 10-100 GeV **Gamma-Ray** window
  - Detect Dark **Sources** – **Lines**
- **PAMELA** (AMS-02):
  - Shed light on **anomalies** in charged CR
  - Understanding the CR & GR **background**

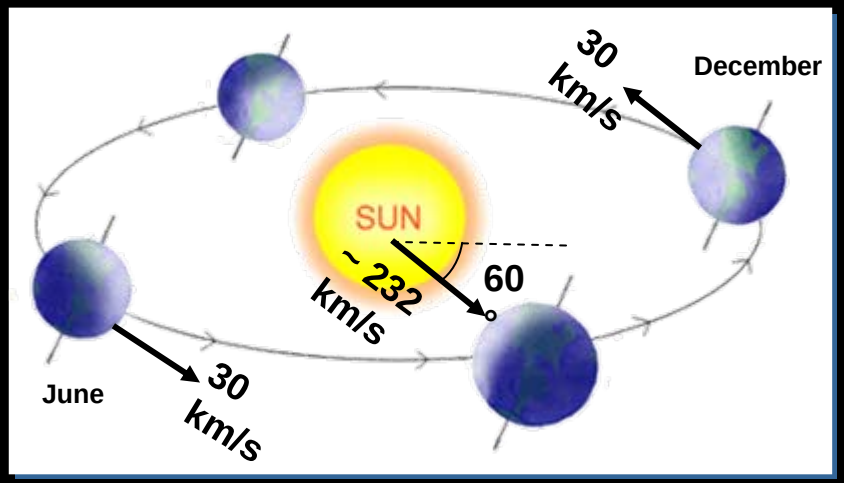
Direct Dark Matter Detection



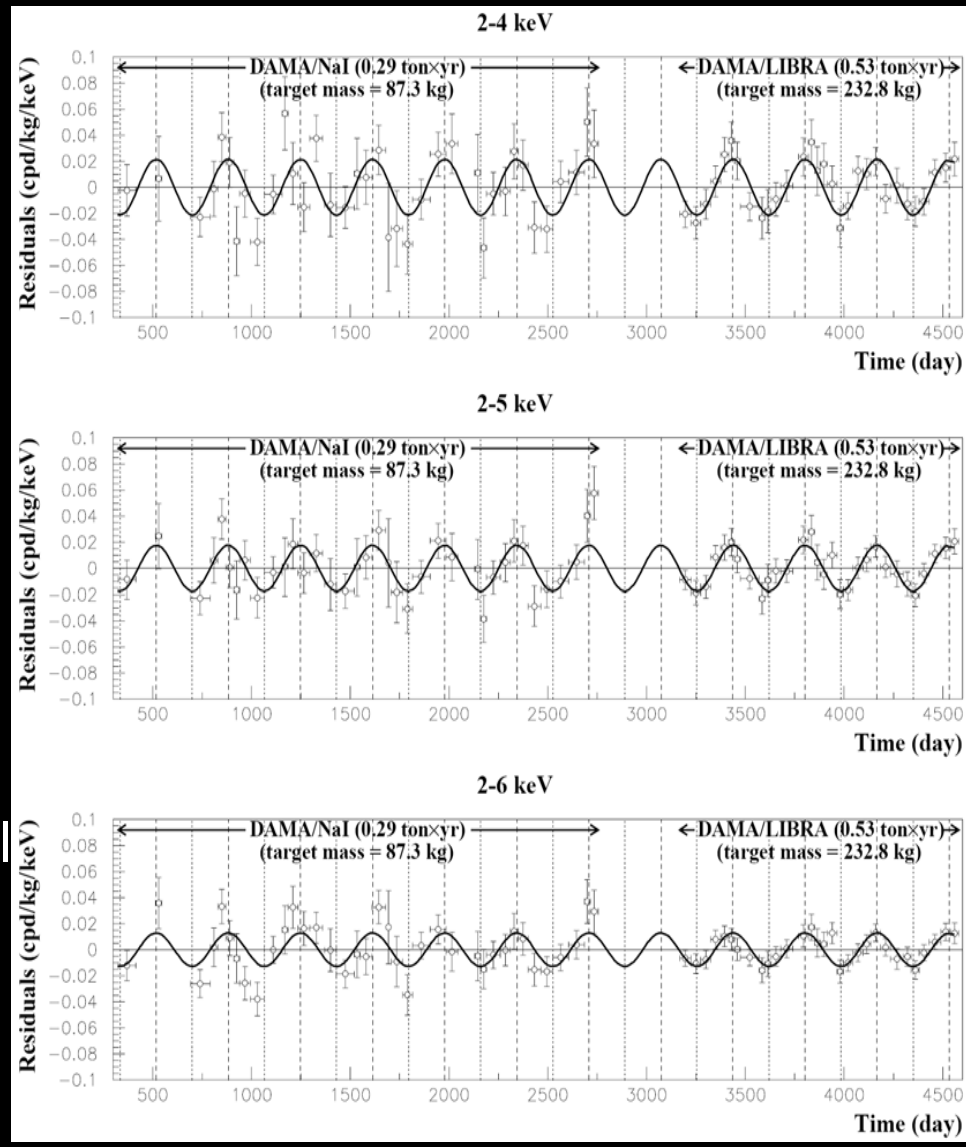
- Steady **progress**, exploring interesting WIMP **parameter space**
- Solid state and noble gas detectors achieving **comparable sensitivities**
- Other, easily scaled-up, **methods** becoming **competitive** or better (**COUPP**, new SD limits)

Ahmed et al, arXiv: 0802.3530

The DAMA/LIBRA result *(ann. April 16)*



- **LIBRA**: scaled up, improved version of DAMA NaI
- **Confirms**, with higher statistical significance (>**8σ**) the DAMA signal
- No modulation in **E>90 keV** band
- No modulation in the **multiple-hits** rate



Bernabei et al, arXiv: 0804.2741

The DAMA/LIBRA result: so what?

- **Unidentified** annually modulated **background** / systematic effect?

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- Is it **compatible** with other (spin-indep.) direct search experiments?

YES, if one goes beyond “vanilla” WIMP paradigms

- dominantly spin-dep. WIMP-nucleon coupling
- inelastic scattering / scattering off electrons
- light dark matter
- non-standard DM velocity distribution

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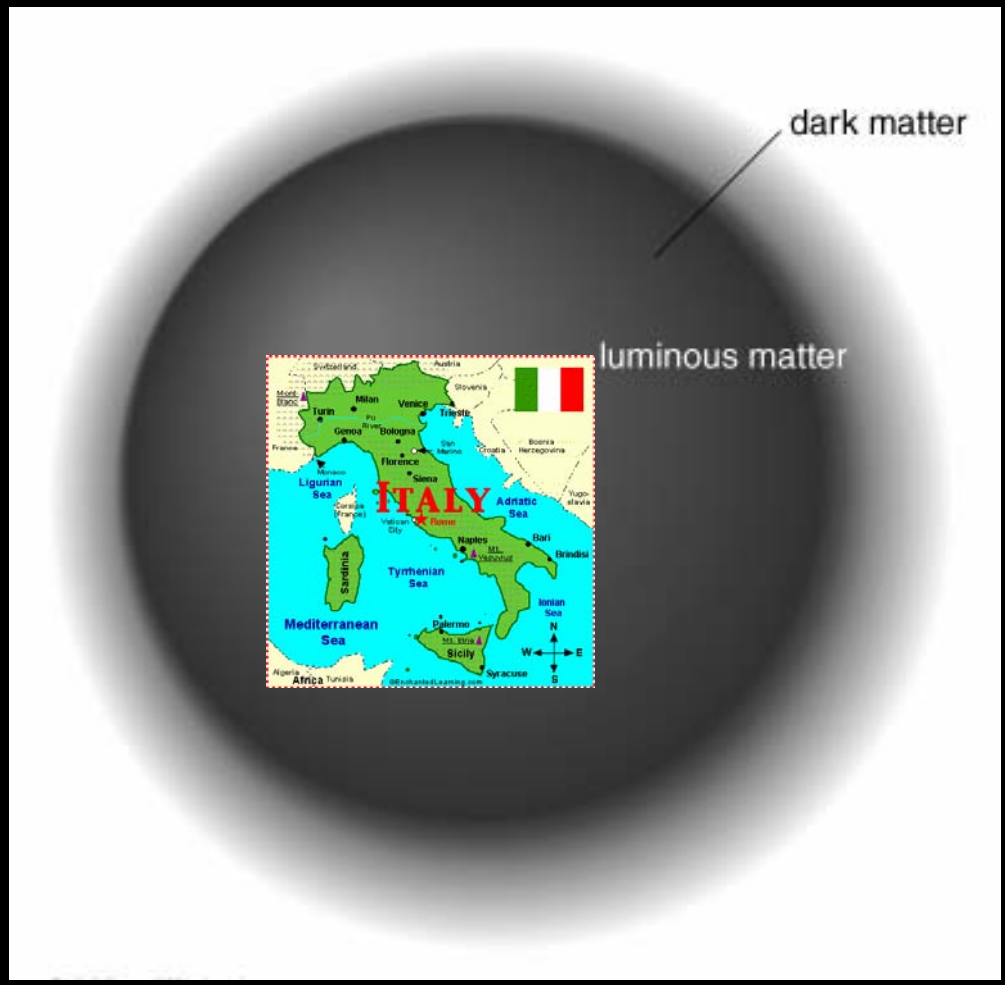
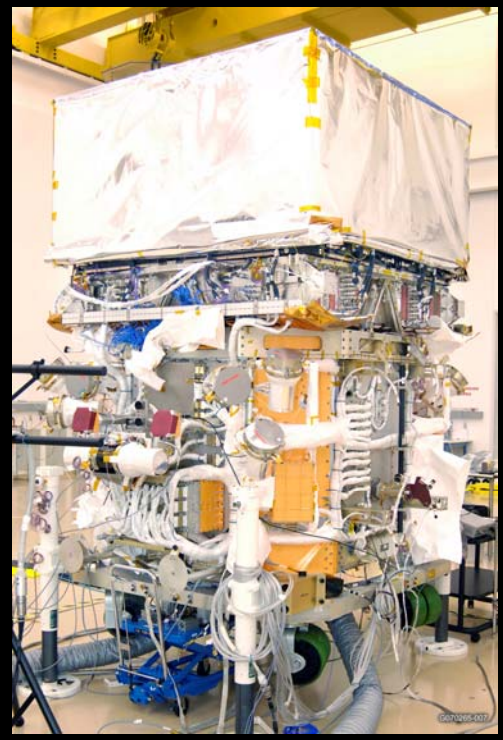
- **Good scientific practice** (see e.g. the LSND / MiniBooNE saga): build similar **experiment**, in a **different lab**, by a different **collaboration**, to explore the detected anomaly!

- **Just to make sure that my country doesn't actually live in a Dark Matter clump…**

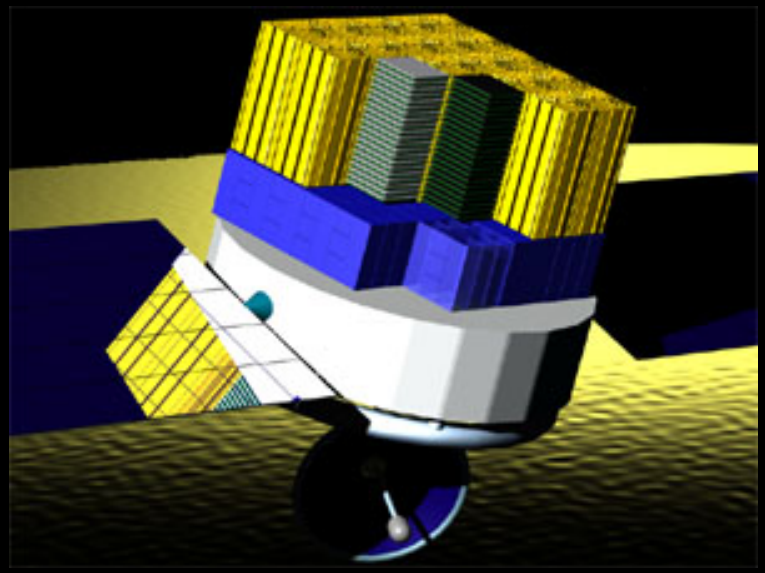


GLAST

- Payload in Florida, **ready** to go
- Launch scheduled for **May 16**
- **Science data** ~ 40 days after launch



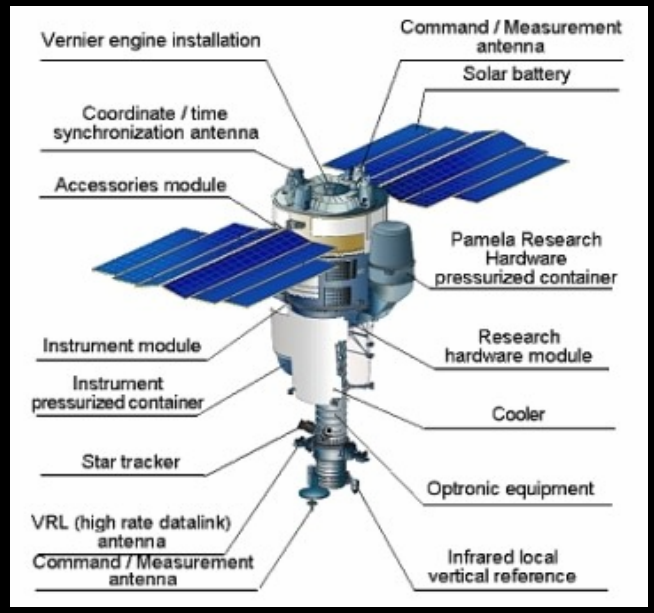
GLAST - LAT



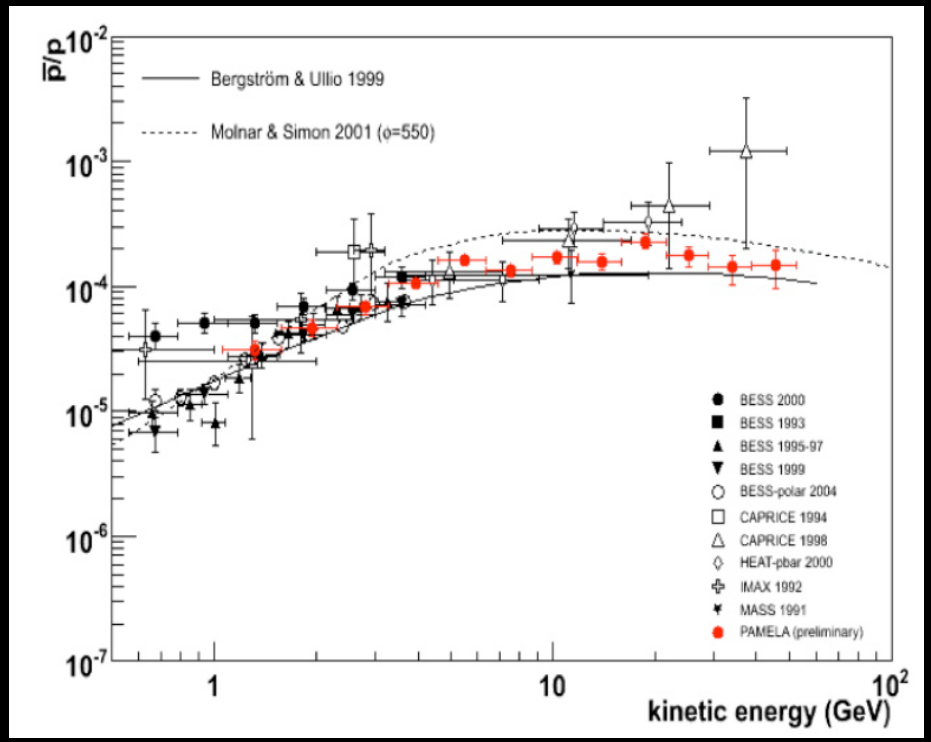
- **Monochromatic** Gamma-Ray **Line** from $\chi\,\chi \rightarrow \gamma\,\gamma$
- Detect DM **substructures**

- **Gamma Rays** from Dark Matter in:
  - **dSph** [no bckg, DM dom.]
  - **Clusters** [largest DM str.]
  - **Galactic Center** [close, conc.]
- **e^+e^-** [20-1000 GeV], promising for:
  - Nearby **Clumps** [spectr. feat.]
  - Models with large prompt e^+e^- BR (e.g. **UED**)

PAMELA



- Steadily **collecting data** (@ 16 Gb/day)
- **No anomalies** in $p\bar{p}$ spectrum
- **e^+e^- data** soon to be released



Addressing Controversial Claims

Important **legacy** of PAMELA and GLAST:

to shed light on anomalies / **claims** of indirect particle DM signatures

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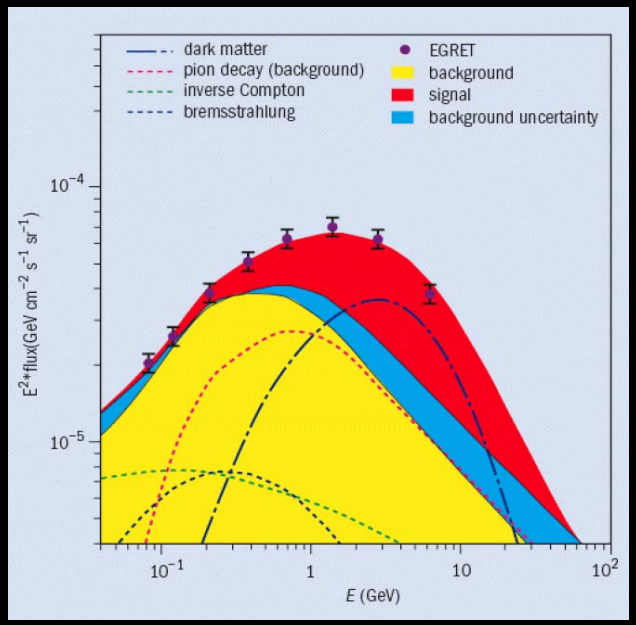

EGRET, galactic

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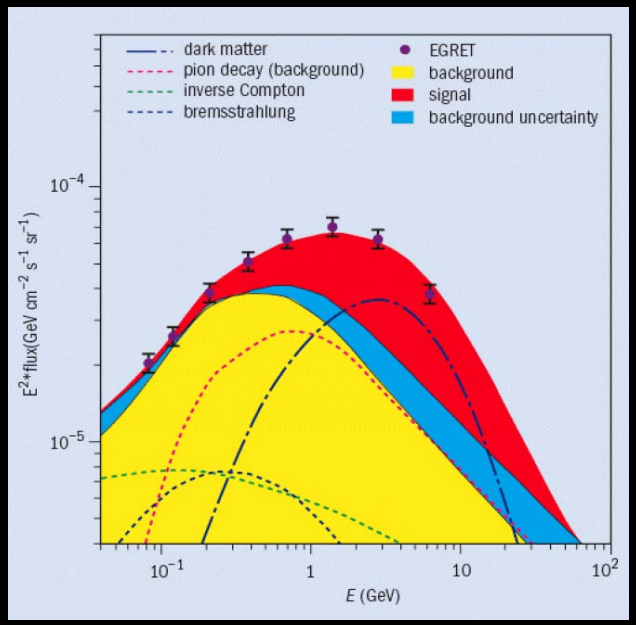

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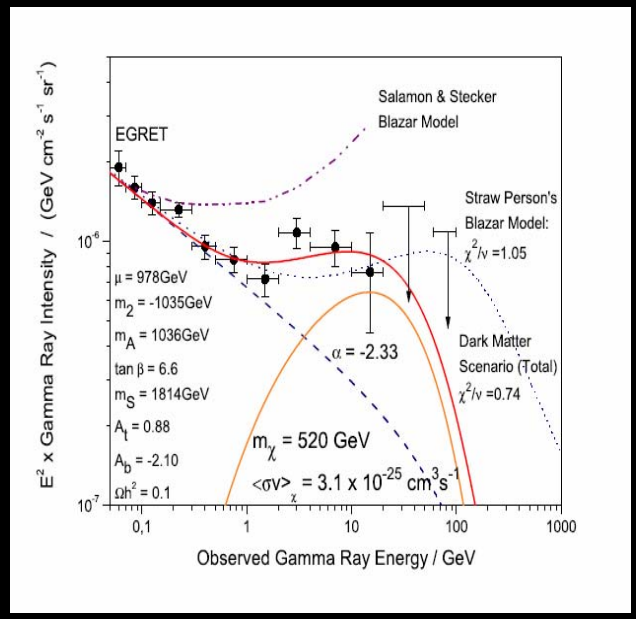

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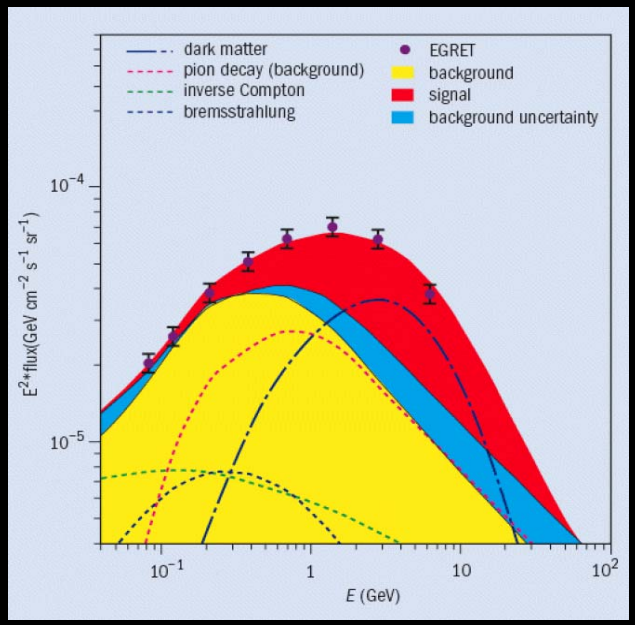

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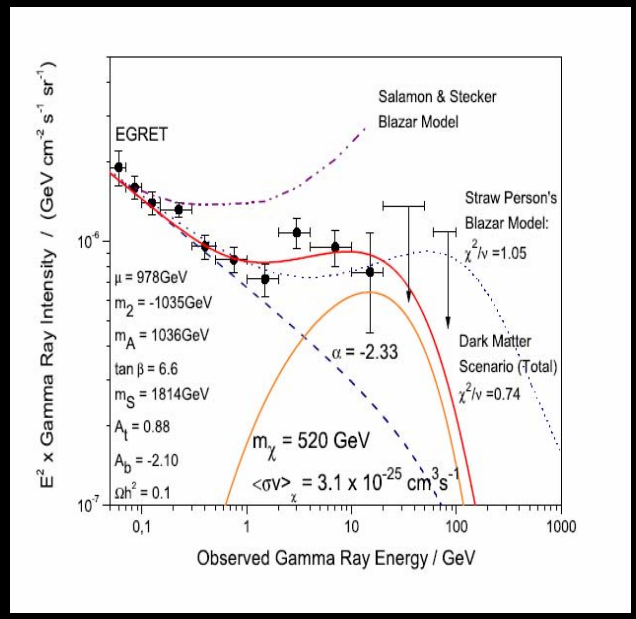

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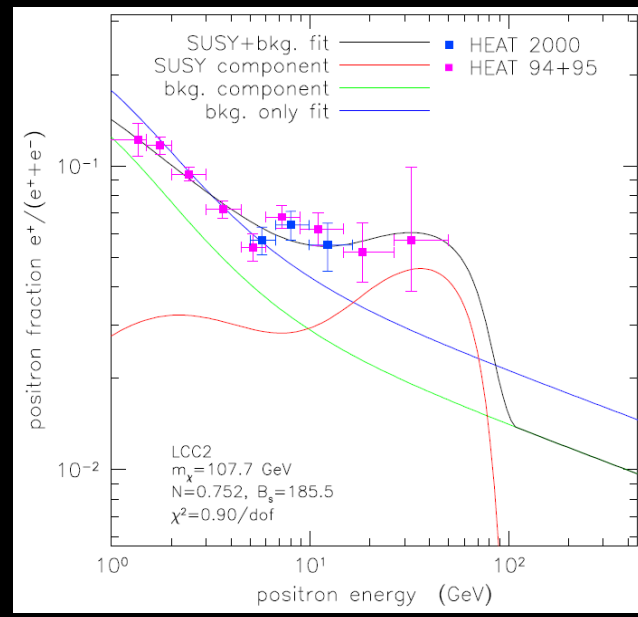

HEAT-AMS01 (e^+e^-)

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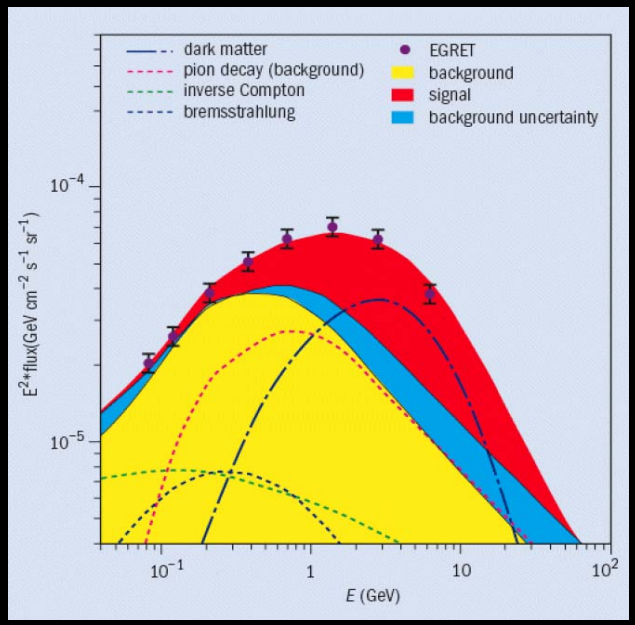

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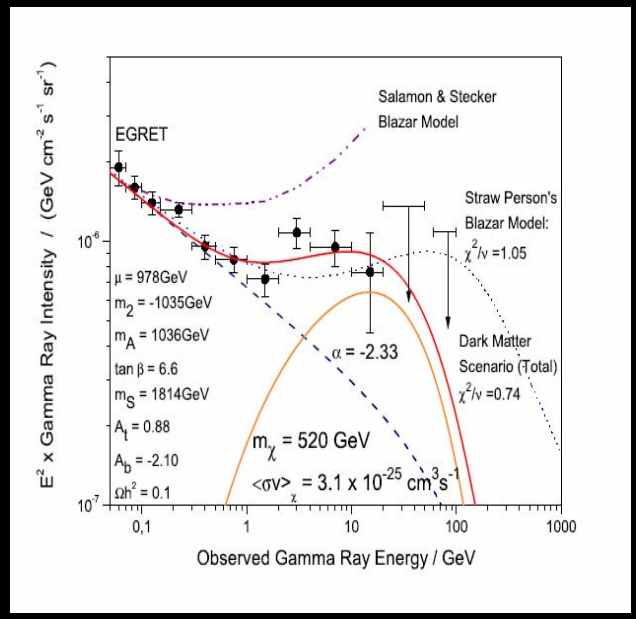

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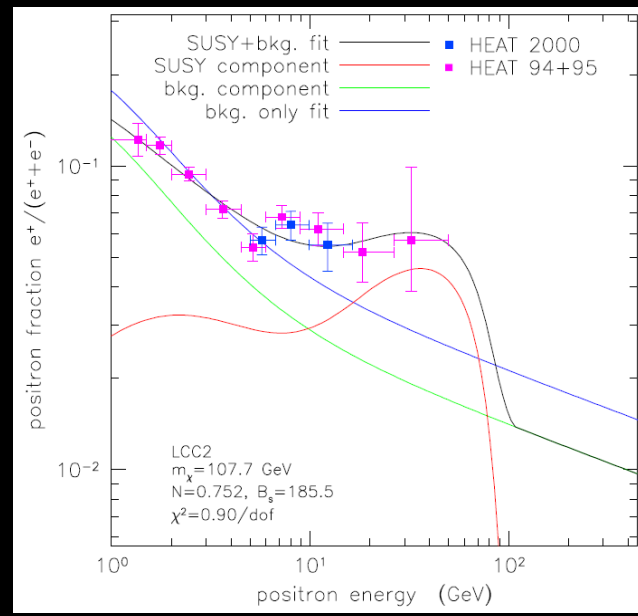

HEAT-AMS01 (e^+e^-)

- Huge **statistics** / **systematics** control improvement
- Accurate modeling of CR **propagation** and Gamma-Rays **Background**

A Multi-Wavelength View

- WIMP Dark Matter annihilation produce **non-thermal**, energetic **e^+e^-**
- e+e- produce **secondary** radiation – Synchrotron, Inv. Compton, Bremsstr
- The entire **multi-wavelength** DM annihilation spectrum can be predicted

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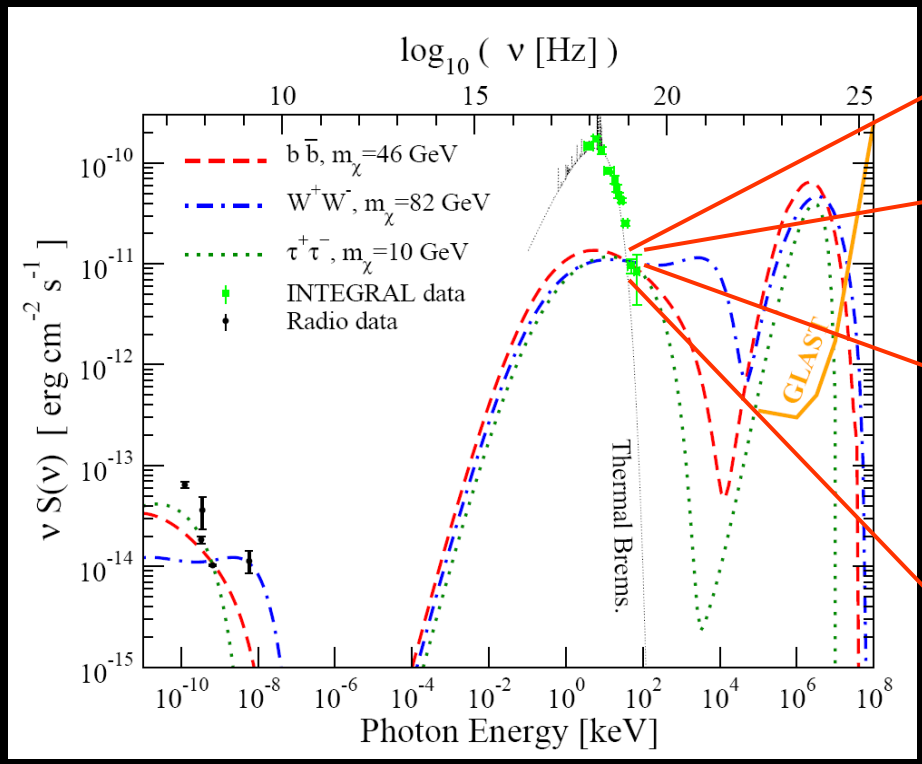

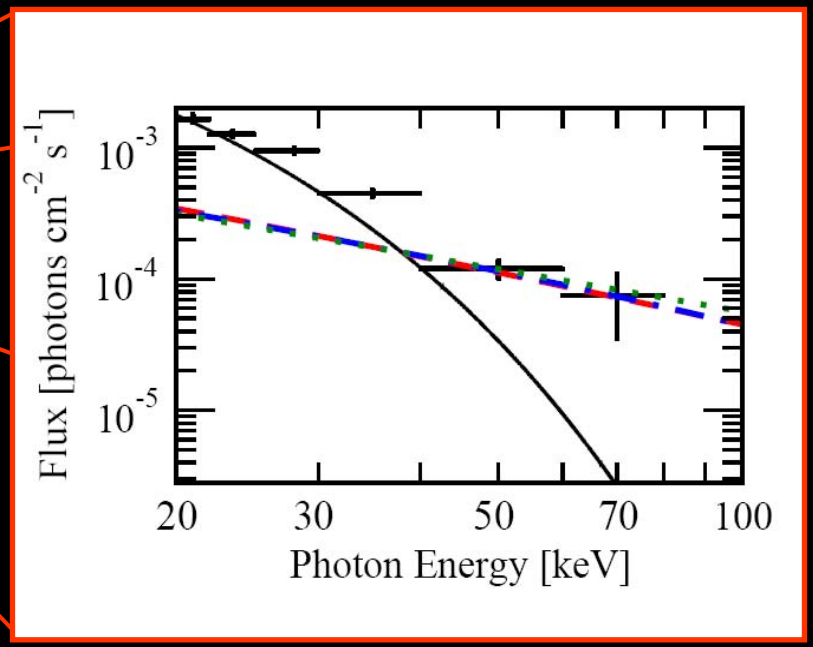

Profumo, arxiv:0801.0740

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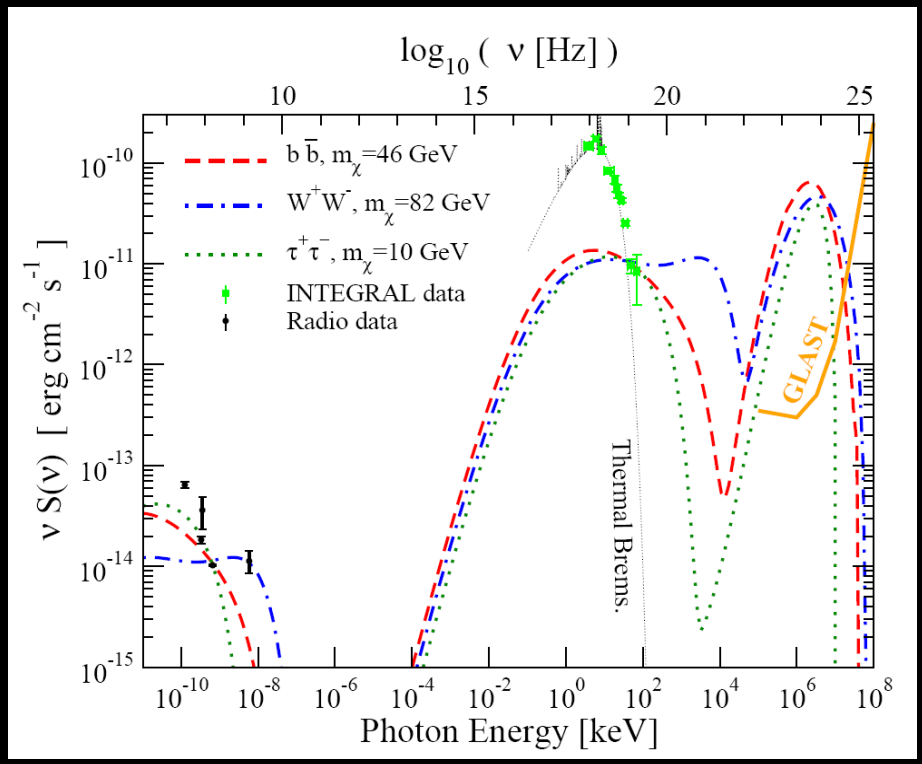

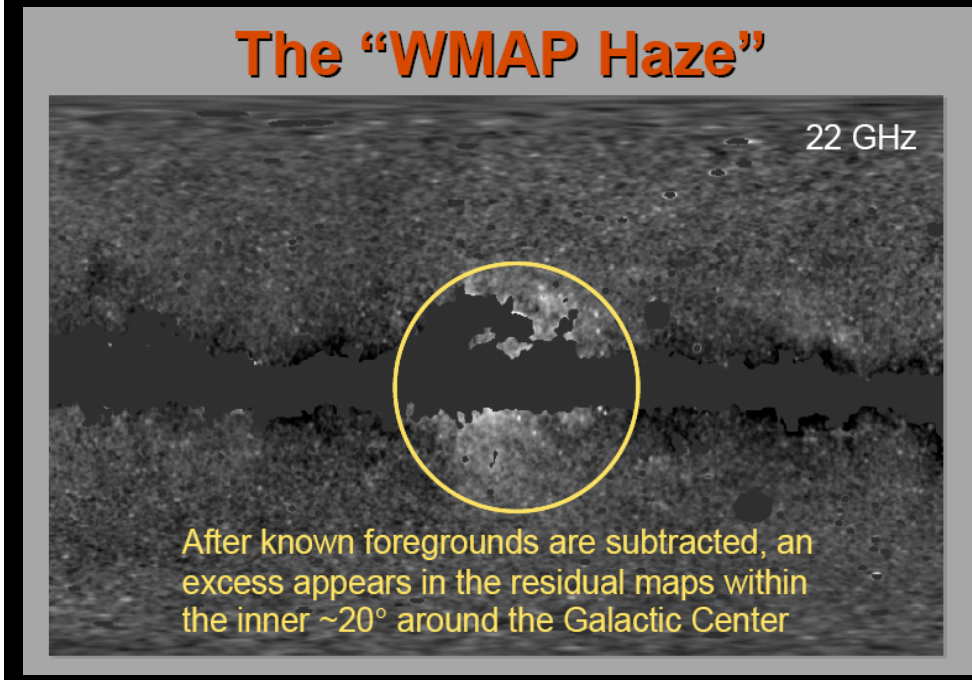

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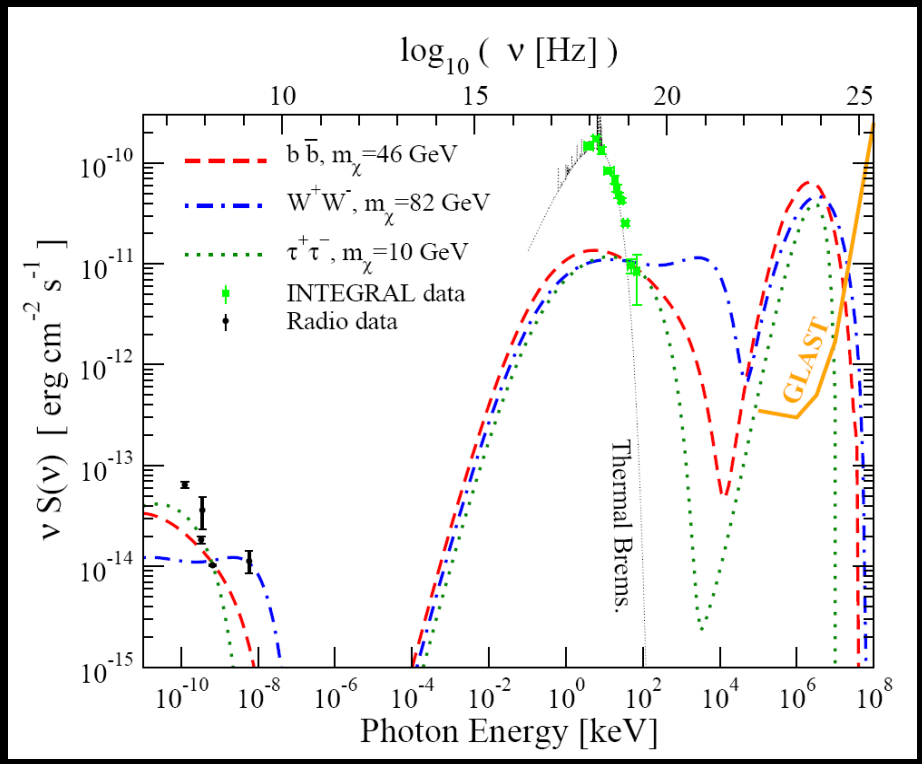

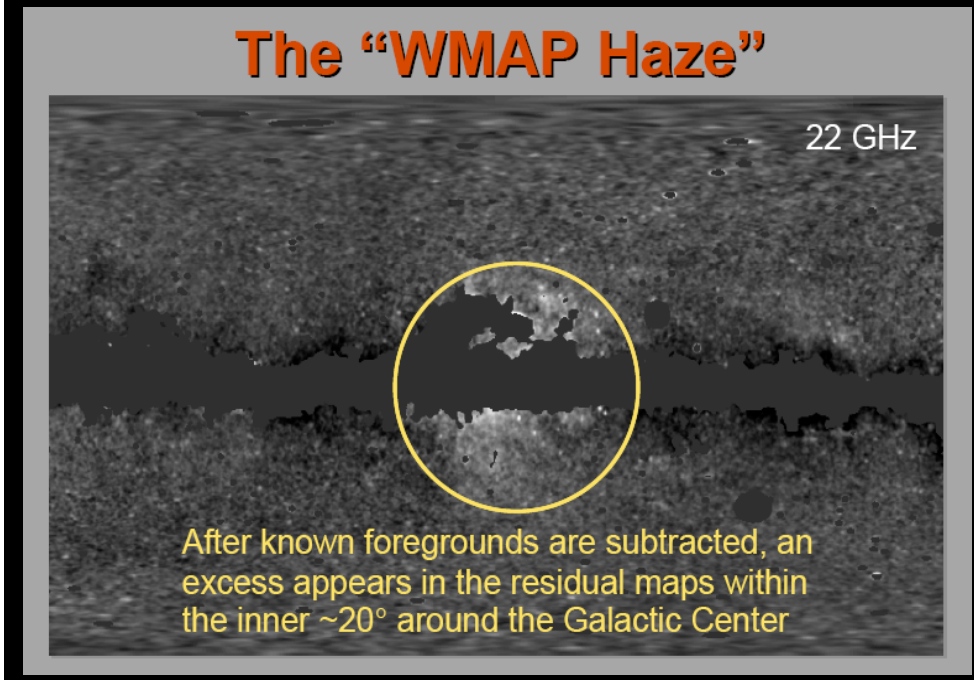

- Both Hypothesis will conclusively be tested by **GLAST**
- Vice-versa, GLAST claims can be **cross-checked** via **multi-wavelength**

Profumo, arxiv:0801.0740; Hooper et al, arXiv:0709.3114, arXiv:0705.3655

Beyond WIMPs?

The **WIMP paradigm** is well motivated – and intensely searched for

In the near future, however, **new data** can point **beyond WIMPs**

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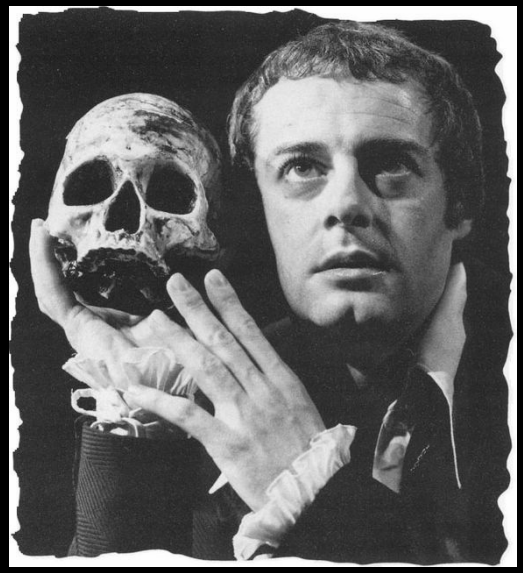
In the words of Shakespeare:



Horatio:
O day and night, but this is wondrous strange!

Hamlet:
And therefore as a stranger give it welcome.
***There are more things in heaven and Earth**, Horatio, **than are dreamt of in your philosophy**.*

Hamlet, Act 1, scene 5, 159-167

We might need a paradigm shift, from Occam ("WIMPs")…

OCCAM

Entia non sunt multiplicanda praeter necessitatem

Entities should not be multiplied beyond necessity
Keep it simple!

…to Scherlock Holmes (“beyond WIMPs”)

HOLMES

“We approached the case with an absolutely blank mind.
We had formed no theories.
We were simply there to observe and to draw inferences from our observations”

DON’T NEGLECT CLUES!

Beyond Occam: Multi-Component Dark Matter

The “**visible world**” is **not** as **simple** as we think the “**dark world**” is

Can we discriminate between single and **multi-component DM** models?

Beyond Occam: Multi-Component Dark Matter

The "**visible world**" is **not** as **simple** as we think the "**dark world**" is

Can we discriminate between single and **multi-component DM** models?

- Assume there are **two**, instead of one, weakly interacting stable **DM particles**

INDIRECT DETECT.

- Search for two (or more) monoch. **annihilation lines** in GR spectrum

DIRECT DETECT.

- **Disentangle two masses**, X-sec in scattering off nucleons

COLLIDERS

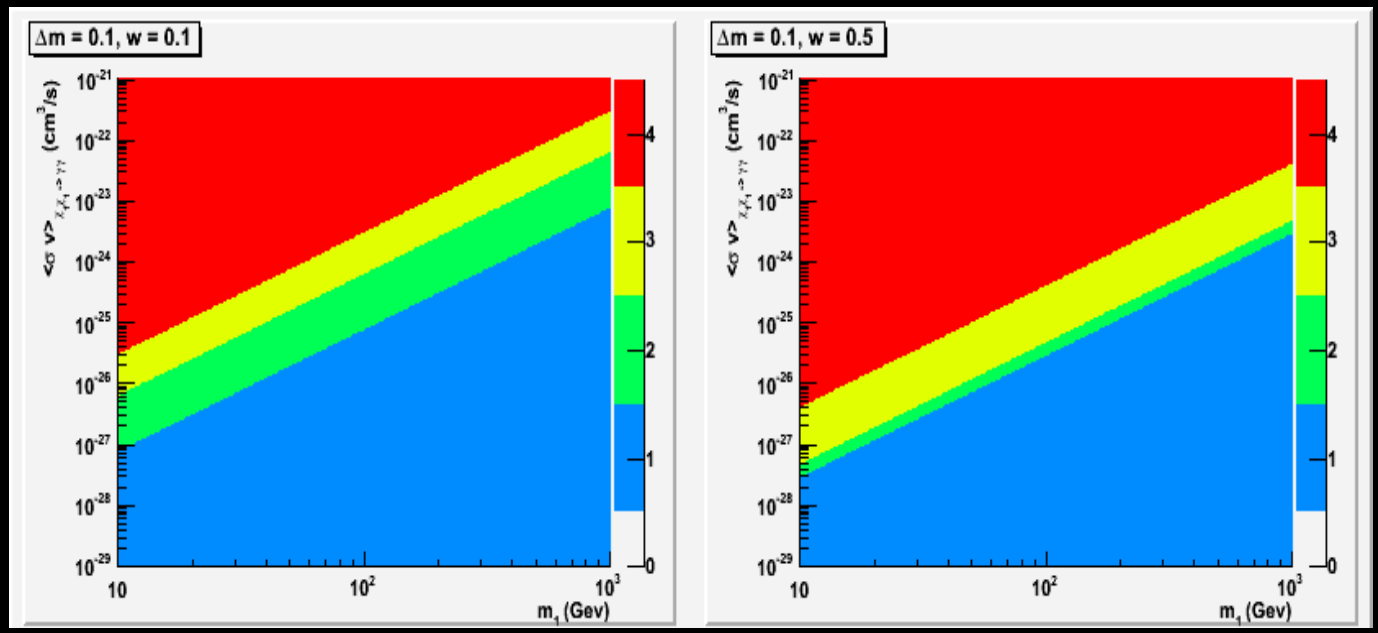
- Infer 2 stable states from **missing energy** events

Profumo, Sigurdson and Ubaldi, in preparation

Beyond Occam: Multi-Component Dark Matter

$$\Delta m = \frac{m_2 - m_1}{m_2}$$

$$w = \frac{\langle \sigma \, \mathrm{v} \rangle_{\gamma\gamma}^{\chi_1\chi_1}}{\langle \sigma \, \mathrm{v} \rangle_{\gamma\gamma}^{\chi_2\chi_2}} \approx \frac{\langle \sigma \, \mathrm{v} \rangle_{\mathrm{tot}}^{\chi_1\chi_1}}{\langle \sigma \, \mathrm{v} \rangle_{\mathrm{tot}}^{\chi_2\chi_2}} \approx \frac{\Omega_{\chi_2}}{\Omega_{\chi_1}}$$



Both det+ discrim.

Det both, but no discrim.

Det only 1

None

- Model **Independent** Analysis
- Make contact with actual **theoretical models** (SUSY +2RP., 2 Extra Dim.)

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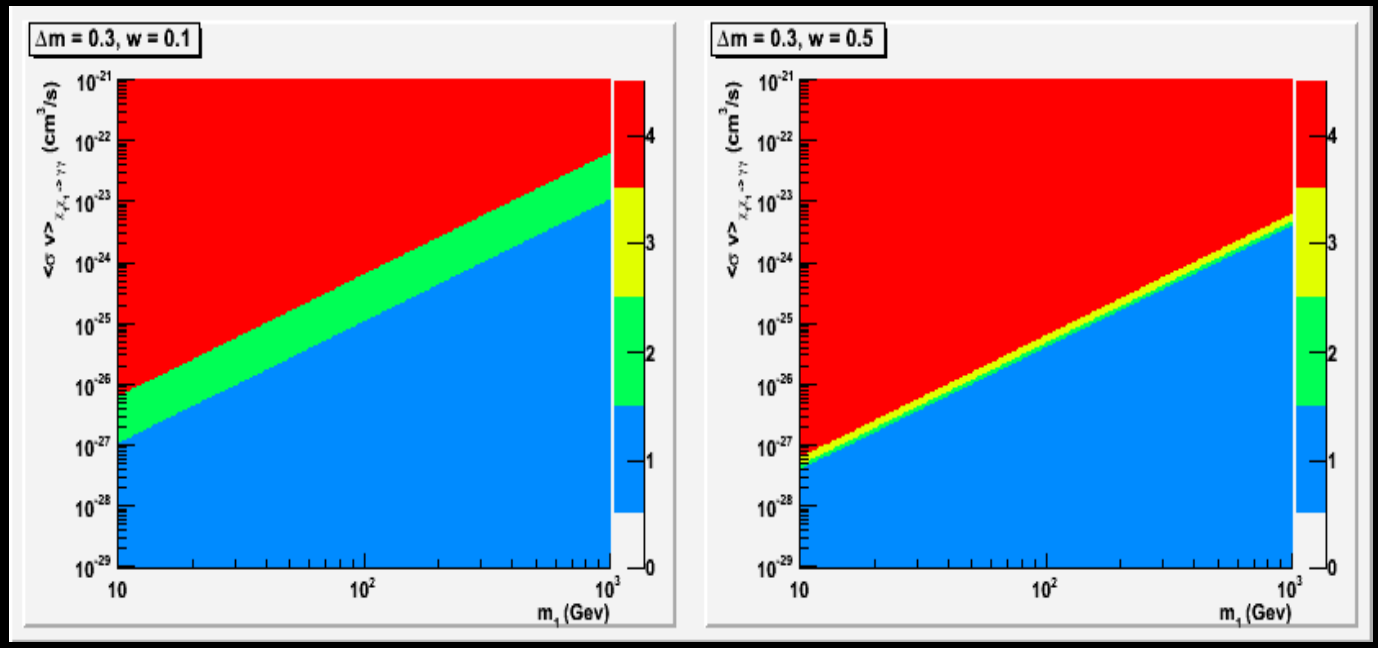

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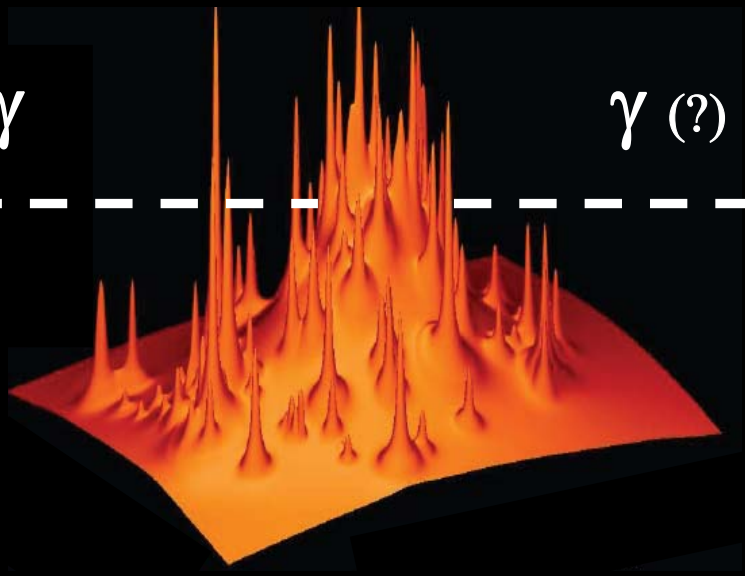
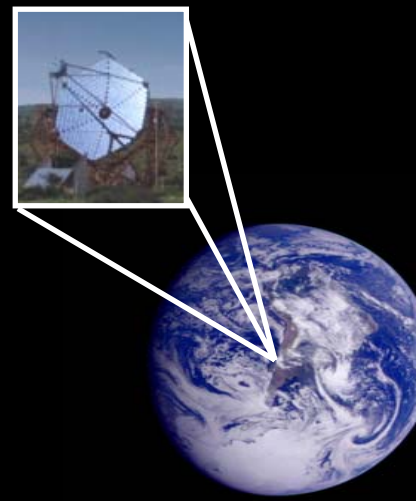
Following Holmes: the Shadow of Dark Matter

?

γ

γ (?)





Background Photon Source

Dark Matter

Observer

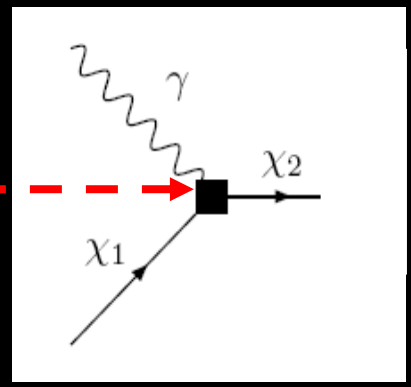
Following Holmes: the Shadow of Dark Matter

Suppose to have

- Two **neutral** particles χ_1 (the DM particle) and χ_2
- An effective **transition dipole moment** coupling $\gamma-\chi_1-\chi_2$

$$\mathcal{L}_{\rm eff} = -\frac{i}{2}\bar{\chi}_2\,\sigma_{\mu\nu}\frac{a+b\gamma_5}{\widetilde{M}}\chi_1\,F^{\mu\nu}$$

$1/M$



Profumo and Sigurdson, Phys.Rev.D75:023521,2007

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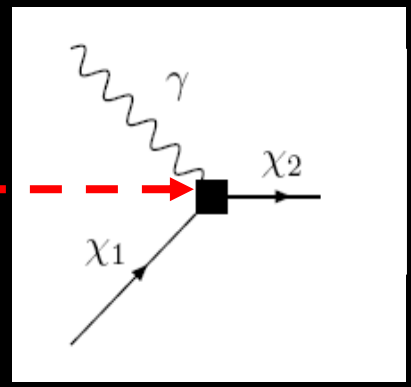

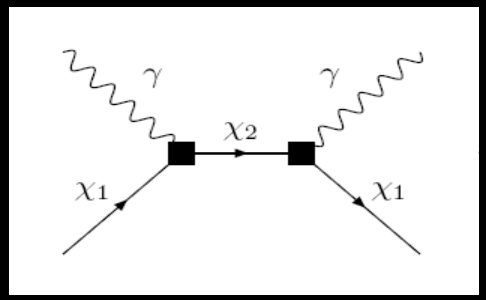

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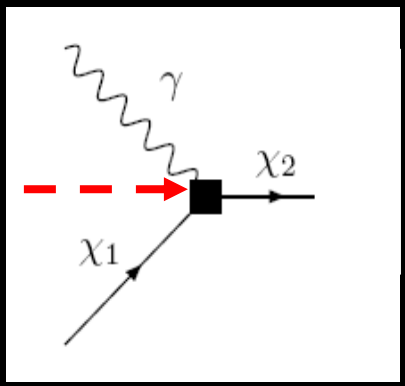

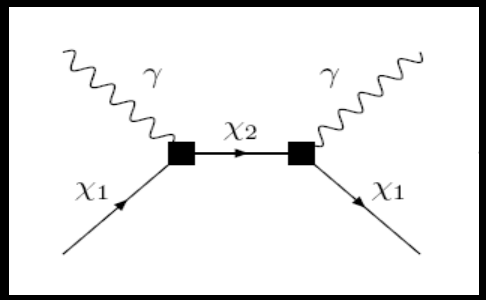

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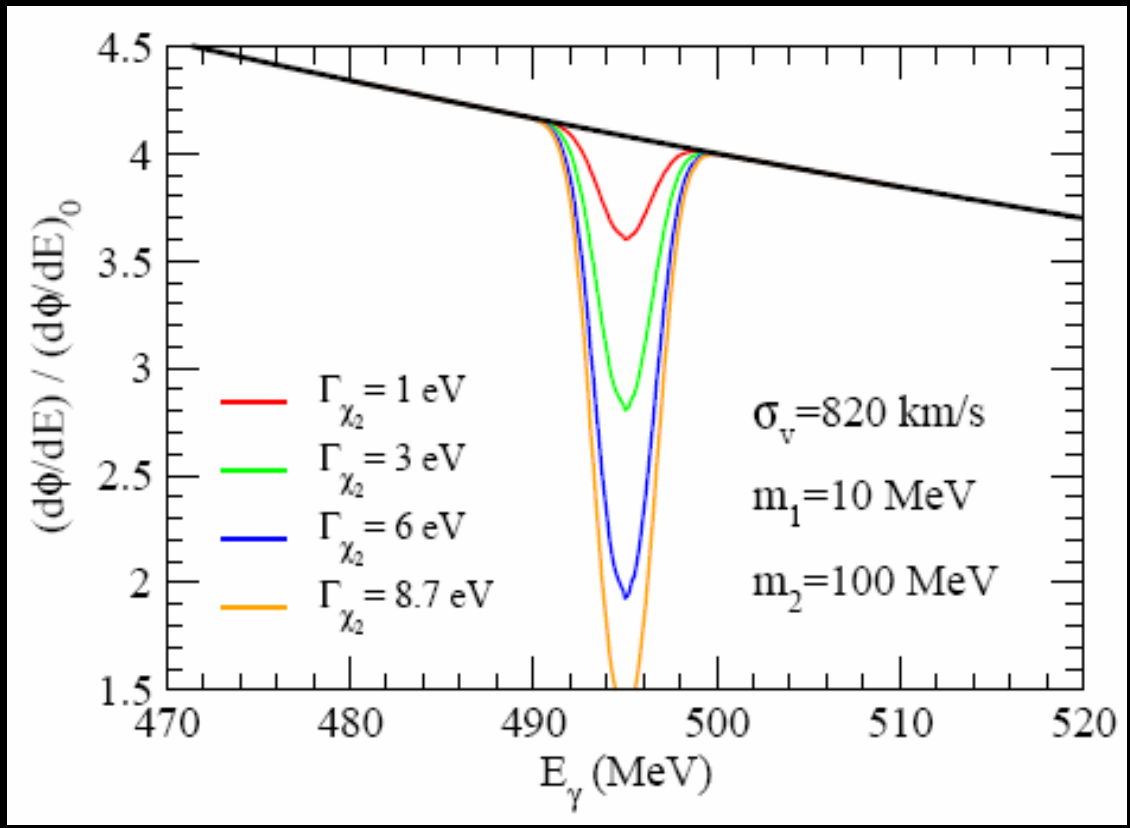
➢ **Absorption** occurs if

$$\tau \approx \frac{\sigma_{\chi_1-\gamma}\,\Sigma_{\rm DM}}{m_1} \geq 1$$

Profumo and Sigurdson, Phys.Rev.D75:023521,2007

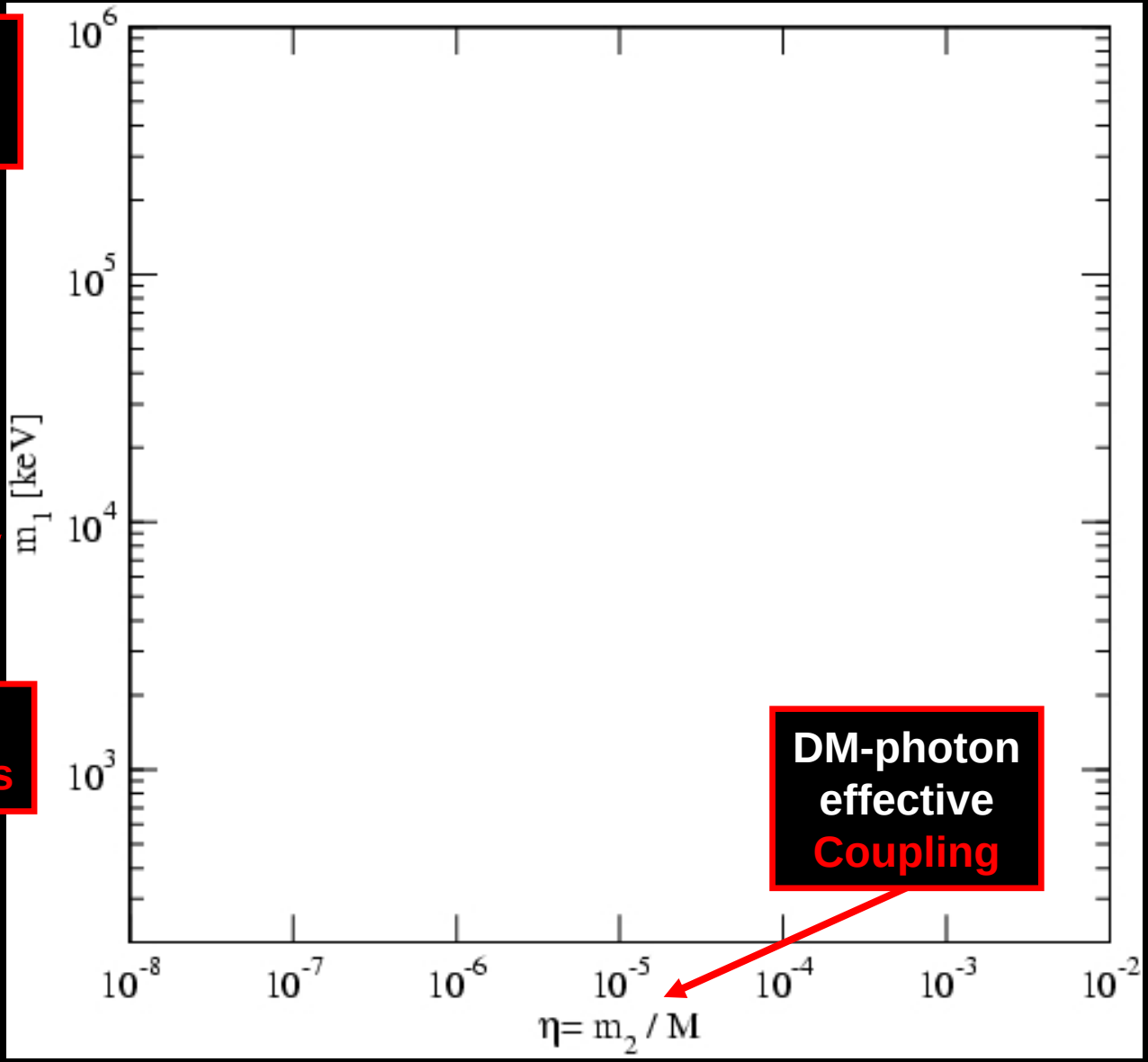
Following Holmes: the Shadow of Dark Matter



Profumo and Sigurdson, Phys.Rev.D75:023521,2007

Following Holmes: the Shadow of Dark Matter

Example with $m_1/m_2=0.1$

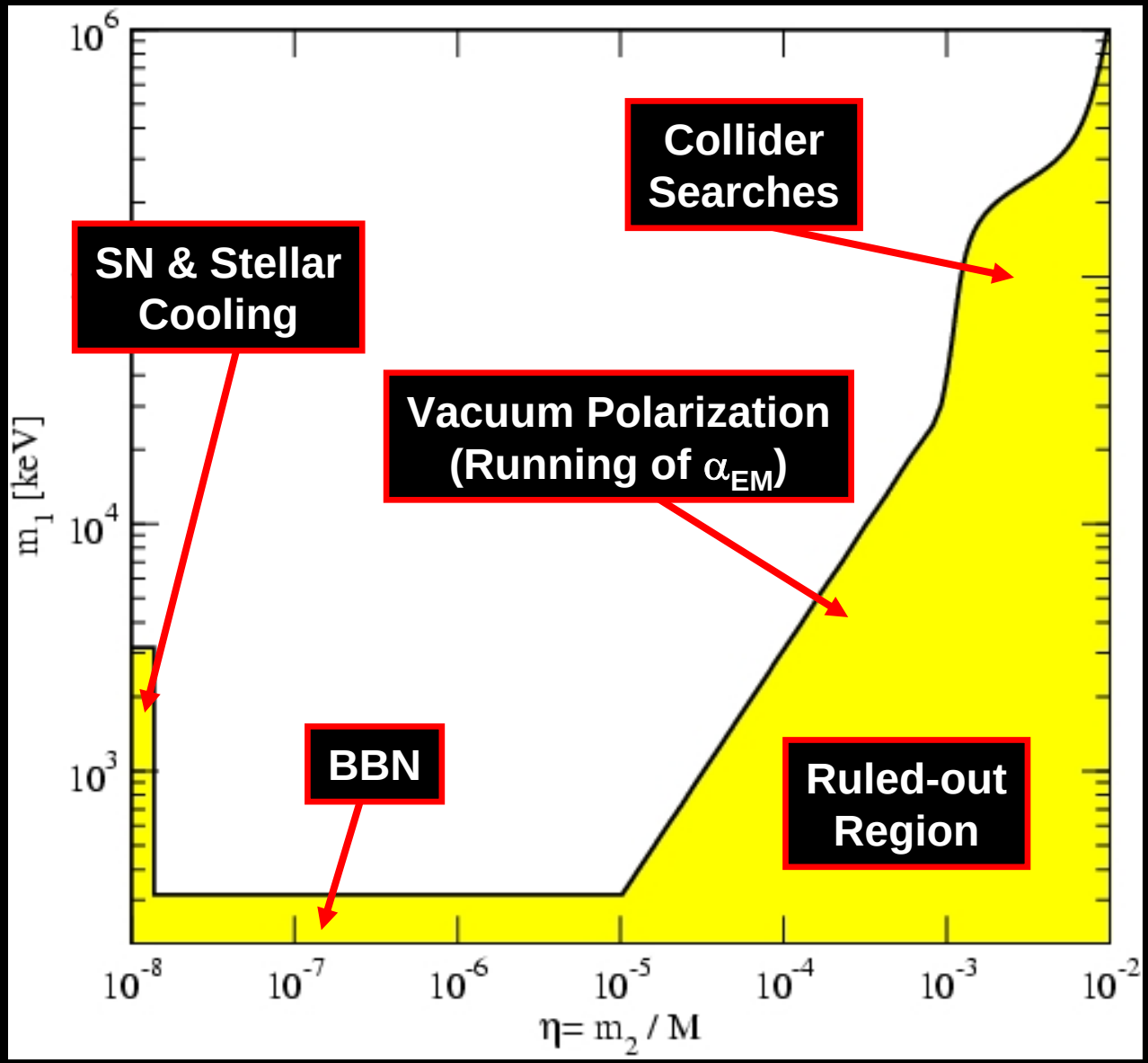


Dark Matter Particle Mass

DM-photon effective Coupling

Profumo and Sigurdson, Phys.Rev.D75:023521,2007

Following Holmes: the Shadow of Dark Matter



Profumo and Sigurdson, Phys.Rev.D75:023521,2007

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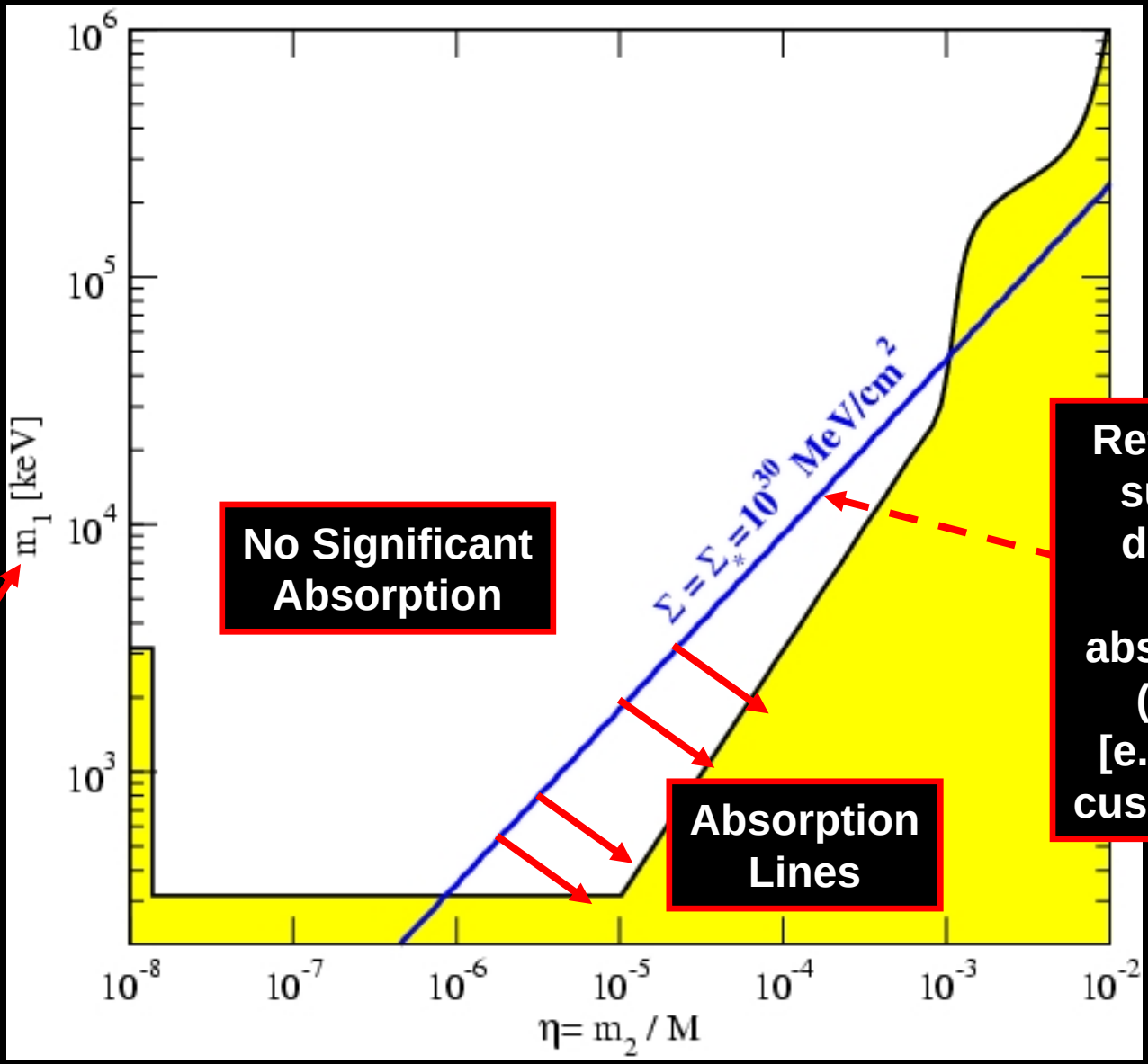

$E_\gamma^{\rm res} \approx 50\, m_1$

Reference surface density for γ absorption ($\tau \sim 1$) [e.g. M87, cuspy prof.]

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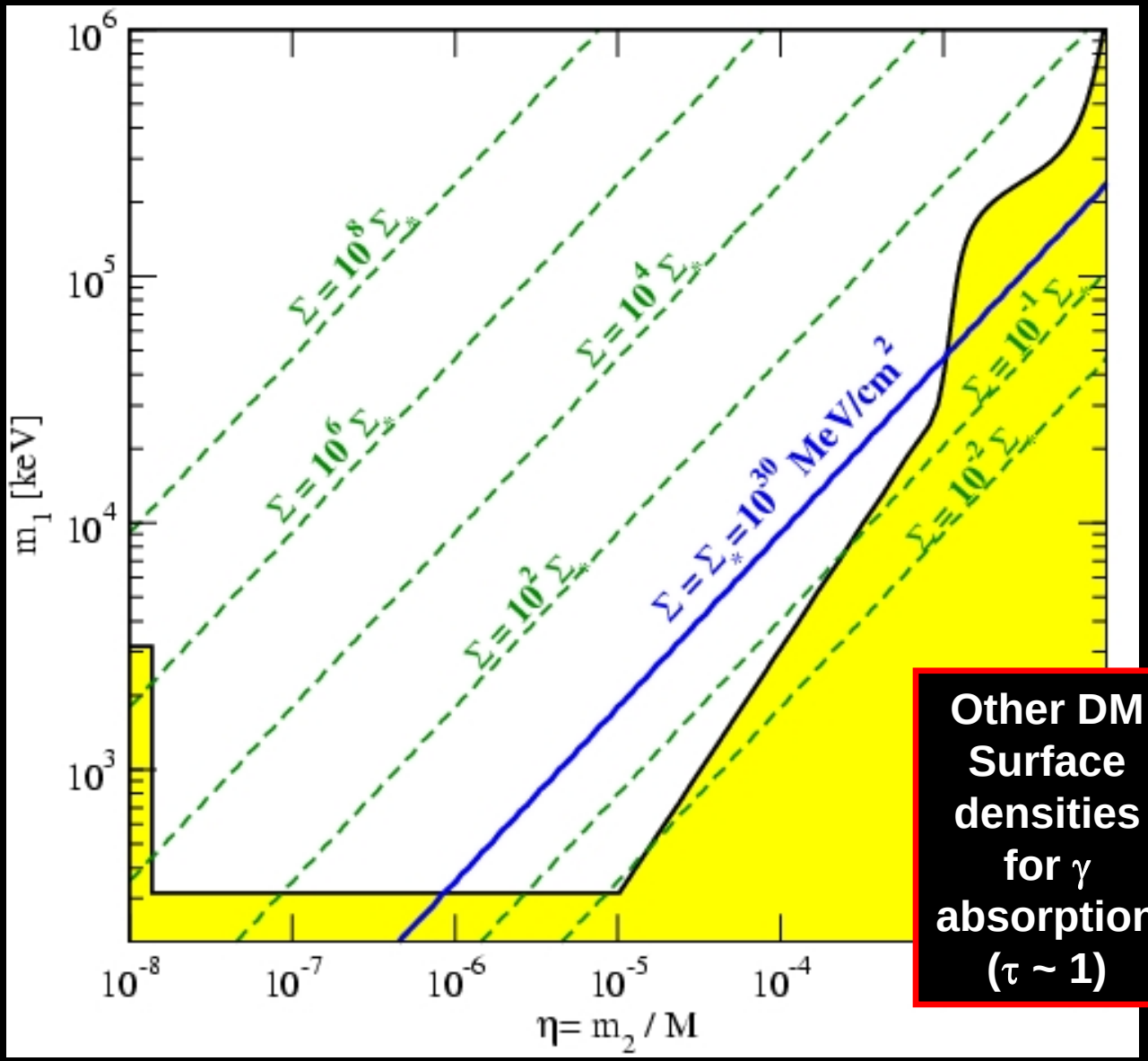

Other DM Surface densities for γ absorption ($\tau \sim 1$)

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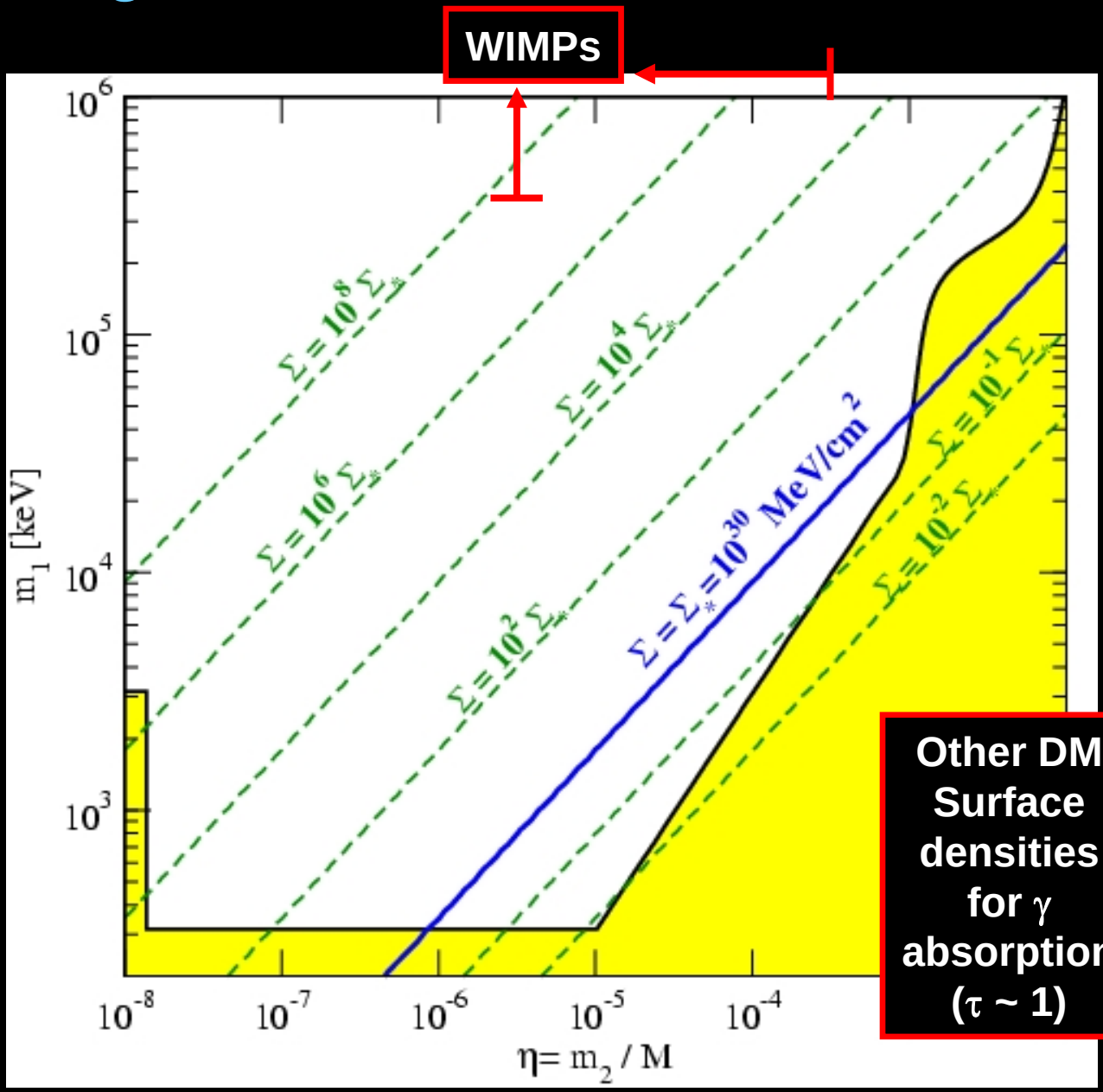

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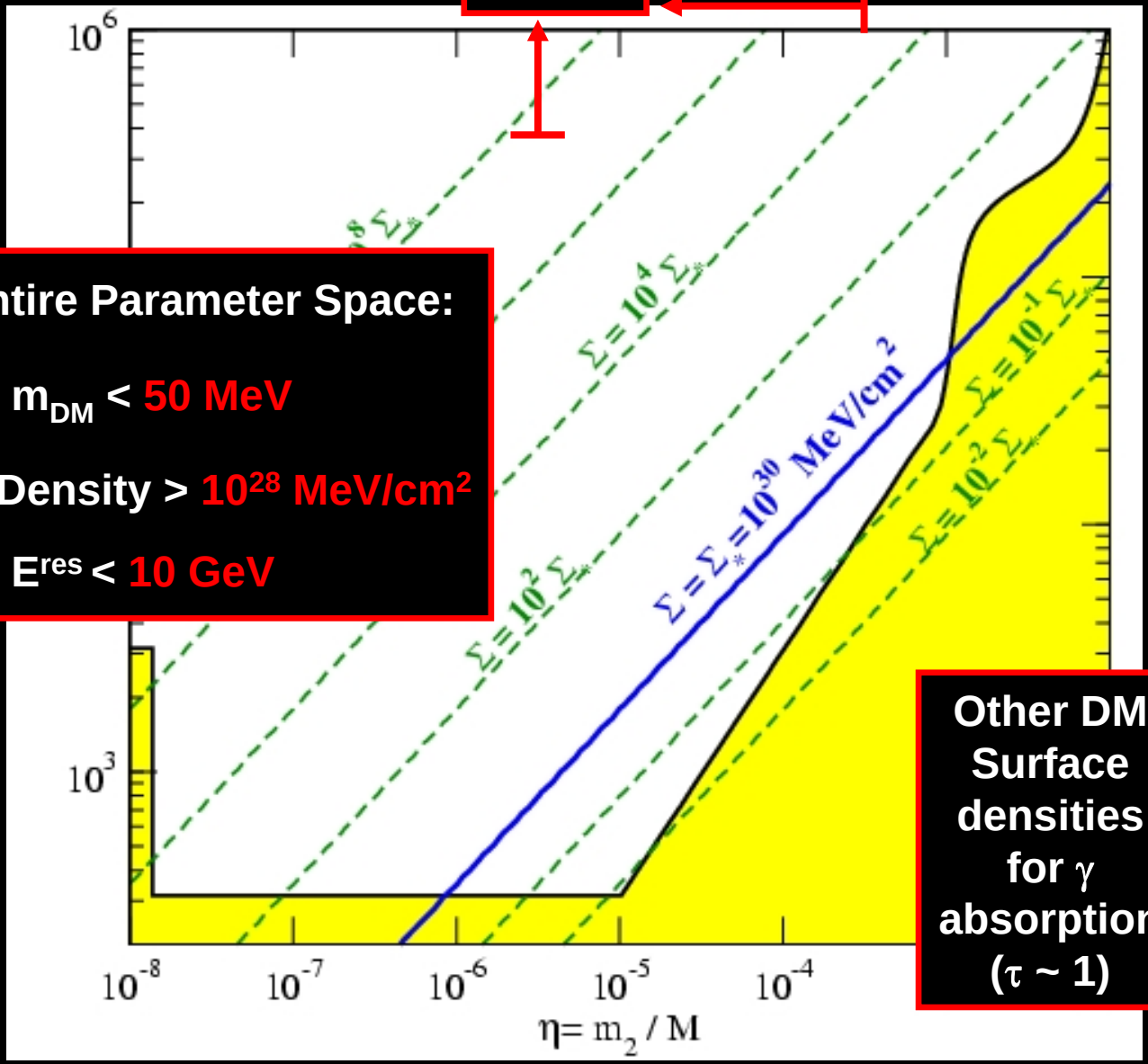

On the Entire Parameter Space:

- ✓ 10 keV < m_{DM} < 50 MeV
- ✓ Surface Density > 10^{28} MeV/cm^2
- ✓ 10 keV < E^{res} < 10 GeV

Other DM Surface densities for γ absorption (τ ~ 1)

Profumo and Sigurdson, Phys.Rev.D75:023521,2007

The Lightest Lightest Neutralino

- The MSSM **neutralino** can be **massless**
  - Cancellations:

$$\det\left(M_{\text{neut}}\right)=0$$

  - “Split-SUSY” limit:

$$M_1 \to 0,\ \ \mu \to \infty$$

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- Extrapolating a **radiation dominated** Universe prior to BBN

$$m_\chi \geq 6\,\text{GeV}$$ (Lee-Weinberg limit for neutralinos)

Bottino et al., Belanger et al., Hooper & Plehn

The Lightest Lightest Neutralino

- Relaxing the assumption of radiation domination (no data prior to BBN!), arbitrarily **high** thermal relic neutralino **abundances** can be brought down to the **CDM density**(*)
  [low rehating models, late decaying species with entropy injection]

(*) Gondolo and Gelmini, 2006; (**) Viel et al., 2005, Seljak et al, 2005

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  [low rehating models, late decaying species with entropy injection]

- Large scale structure data (**Ly-α**) and **CMB** anisotropies force(**)

$$m_\chi \geq \mathrm{O(keV)}$$

(precise number depends on data sets and production mech.)

- Can we **detect sub-GeV** neutralinos?

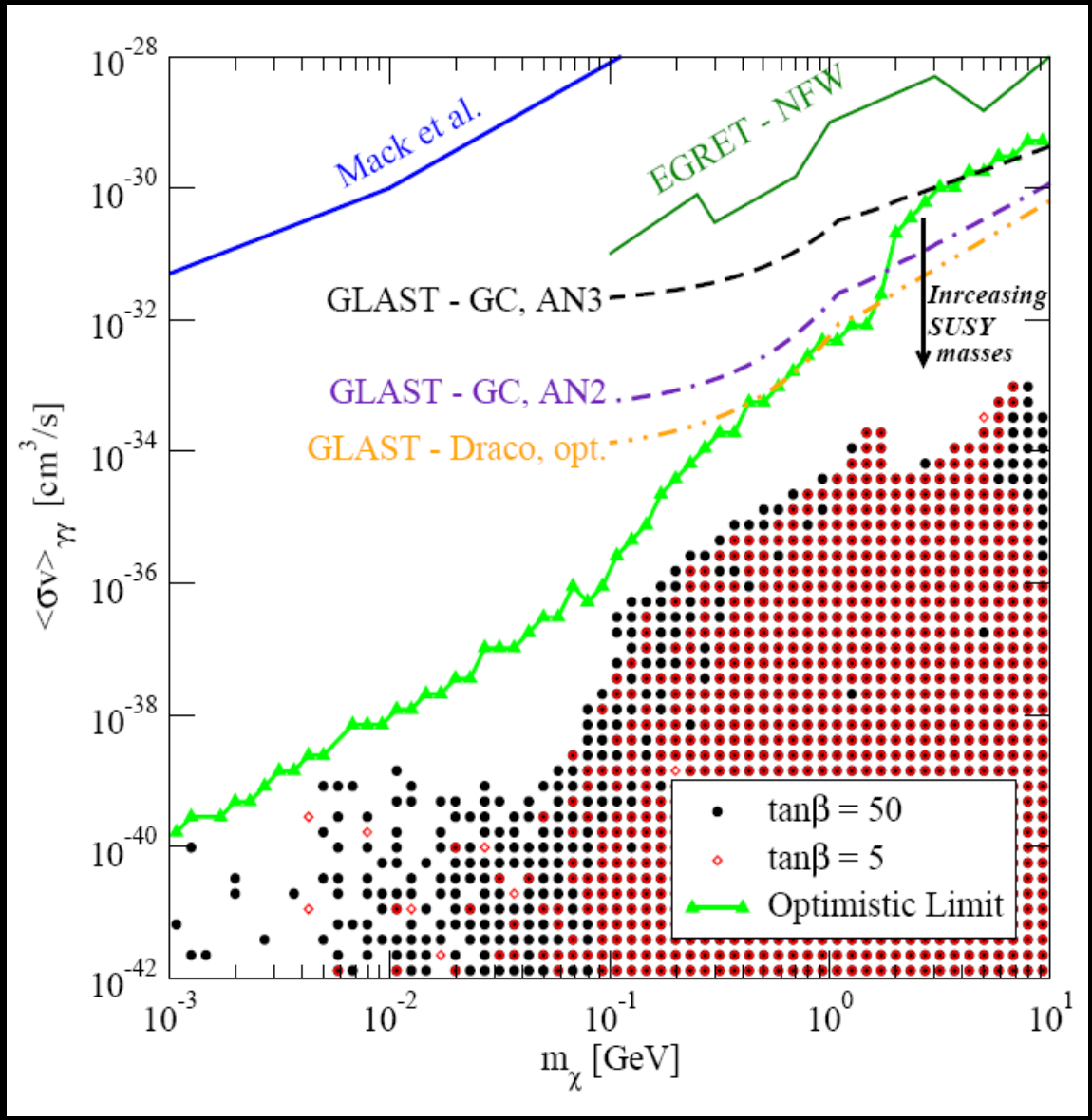
(*) Gondolo and Gelmini, 2006; (**) Viel et al., 2005, Seljak et al, 2005

Hunting the Lightest Lightest Neutralino

- 1 MeV or 1 GeV makes no difference for **LHC** signatures…
- **Indirect** searches:

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

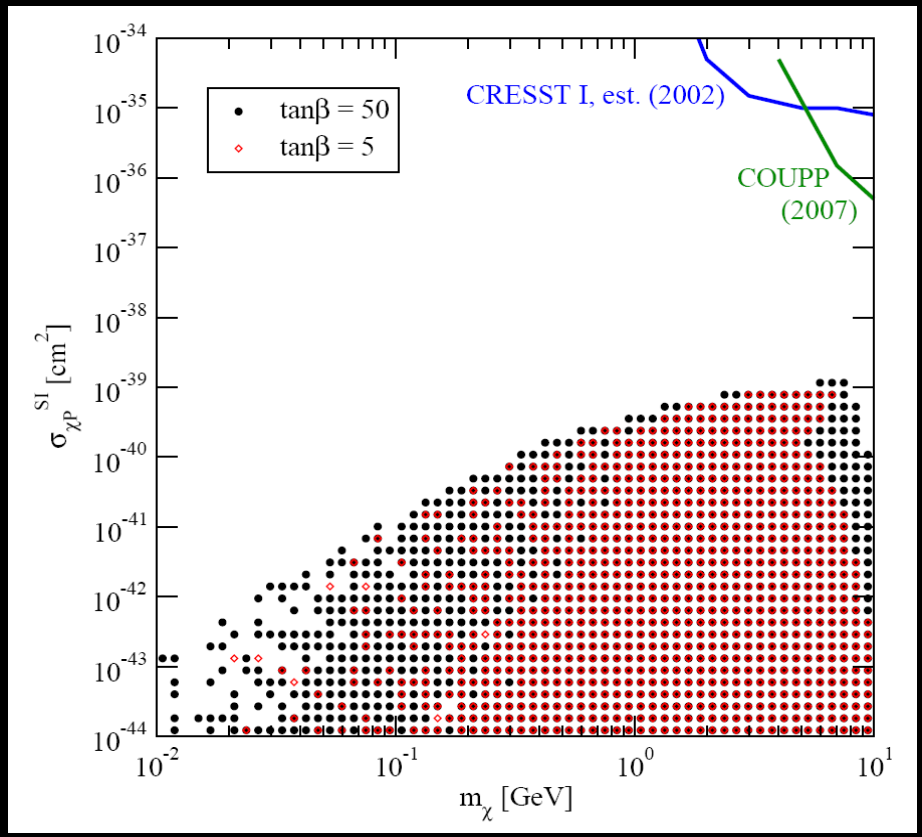
- Hope for **GLAST**



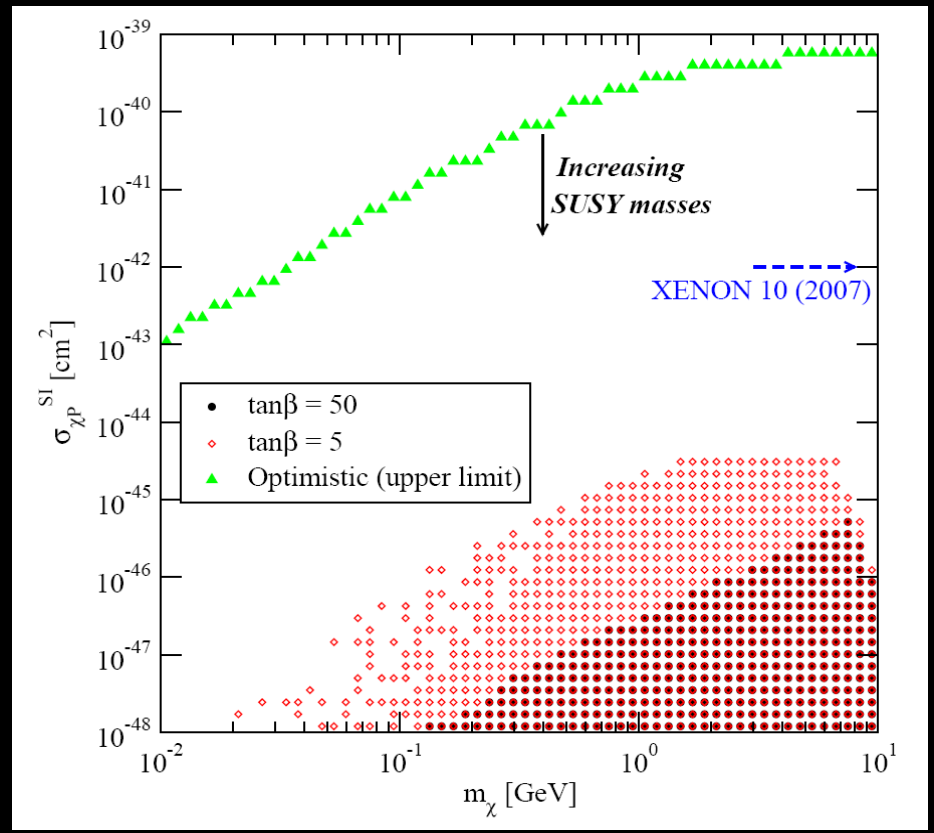
Profumo, 2008

Hunting the Lightest Lightest Neutralino

- Direct Detection: designed for larger masses…



SPIN DEPENDENT



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Profumo, 2008

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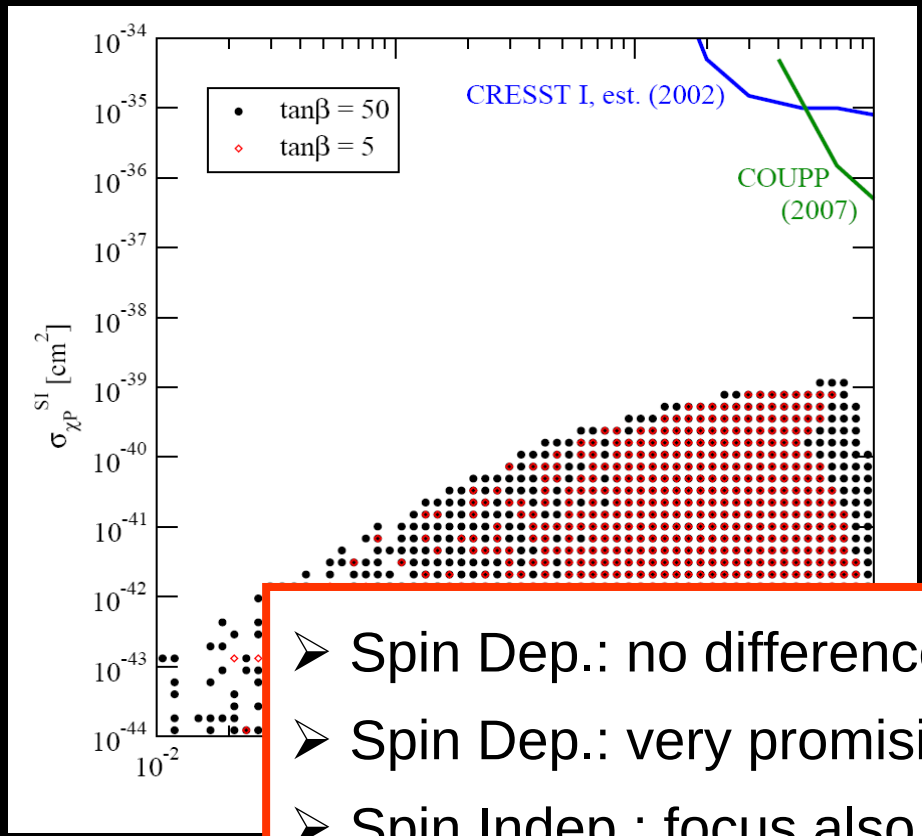
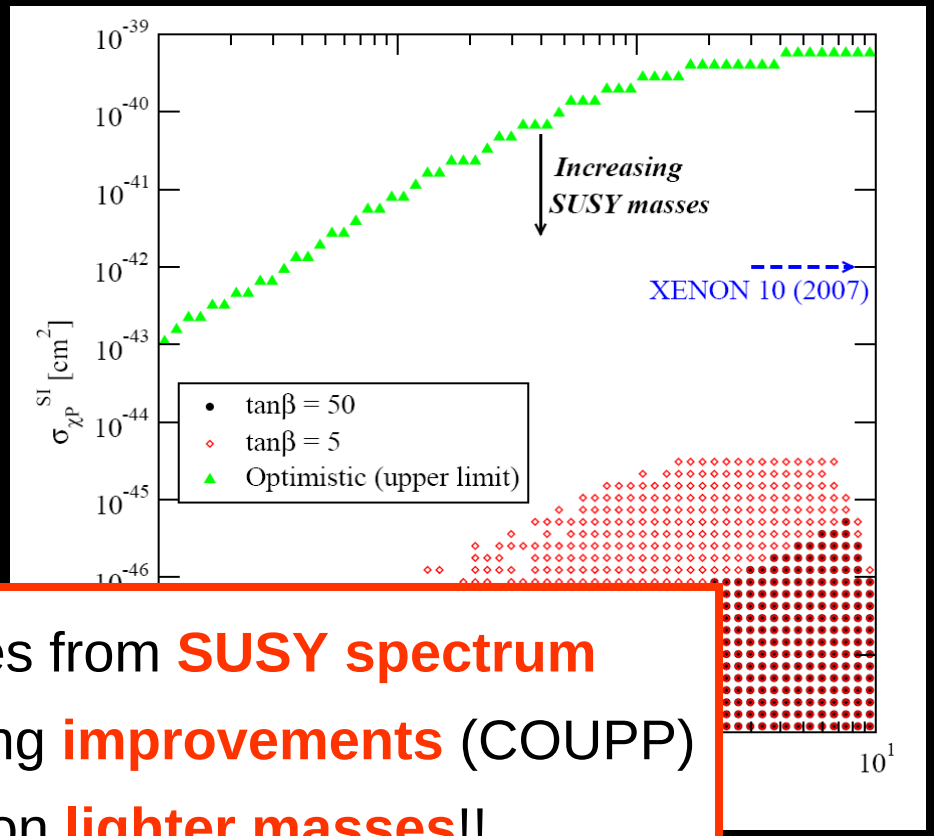




- Spin Dep.: no differences from **SUSY spectrum**
- Spin Dep.: very promising **improvements** (COUPP)
- Spin Indep.: focus also on **lighter masses**!!
- Spin Indep.: **lighter nuclei**: loose on coherence effect, but gain in sensitivity at low masses

Profumo, 2008

Dark Matter and the LHC

- A remark on **cosmological** vs. **collider** time scales:

$$T_{\text{Universe}} \approx 13.7\ \text{Gyr} \approx 4\times10^{17}\ \text{s}$$

$$T_{\text{CMB}} \approx 10^{5}\ \text{yr} \approx 3\times10^{12}\ \text{s}$$

$$T_{\text{BBN}} \approx 1\,\text{s}$$

$$T_{\text{Colliders}} \approx \frac{L_{\text{coll}}}{c} \approx 10^{-7}\ \text{s}$$

- Large $\not{E}_T$ events would be **suggestive** but not **conclusive** proof of a stable WIMP on cosmological scales!

Stretching Inference?

- A possible strategy: **infer** Dark Matter properties **from LHC** results

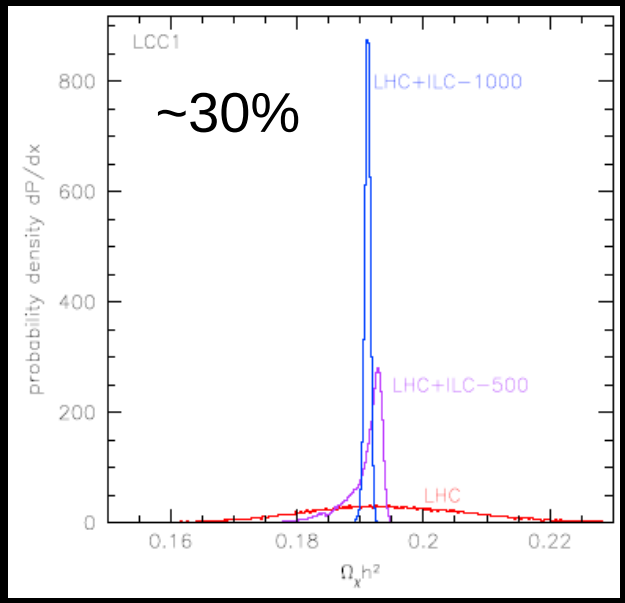
- Assume a particular **theoretical context** for BSM Physics
  [e.g. “constrained” MSSM, “general” MSSM]

- Build **probability distributions** for quantities relevant to DM detection from Markov Chain Monte Carlo scan of the model parameter space

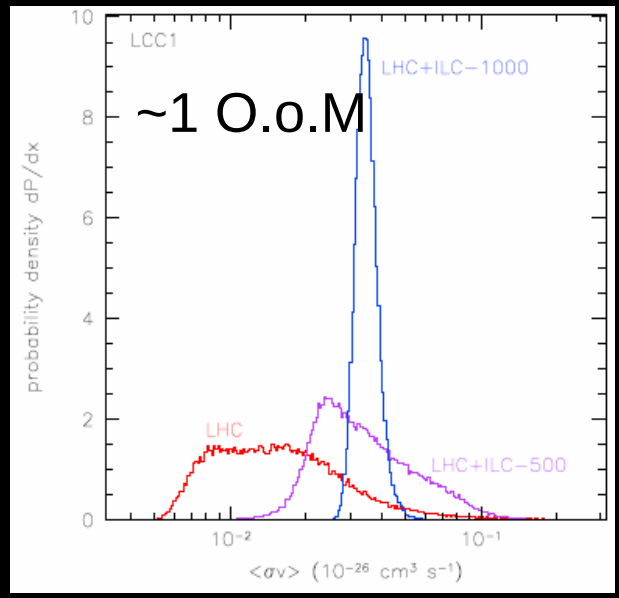
(*) Baltz et al, hep-ph/0602187

Stretching Inference?

RELIC ABUNDANCE



INDIRECT DETECT.



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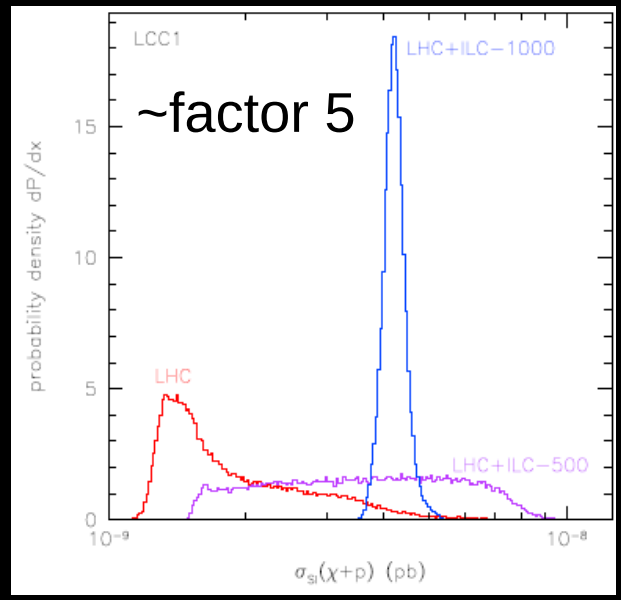

- **LCC1** (SPS1): LHC measures virtually **all** the relevant **particle masses**

  Very optimistic scenario, barely consistent with current constraints

(*) Baltz et al, hep-ph/0602187

Stretching Inference?

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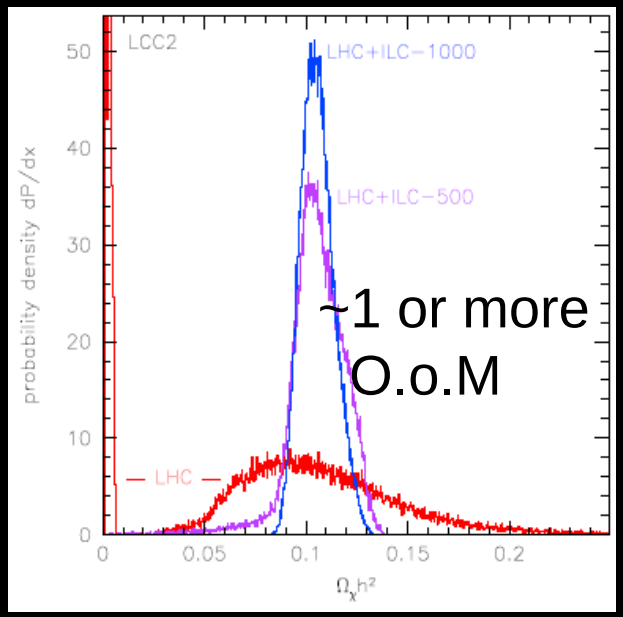

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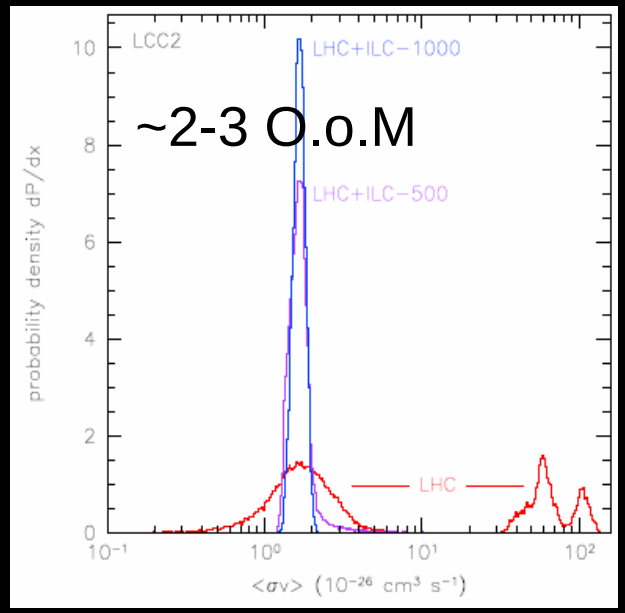

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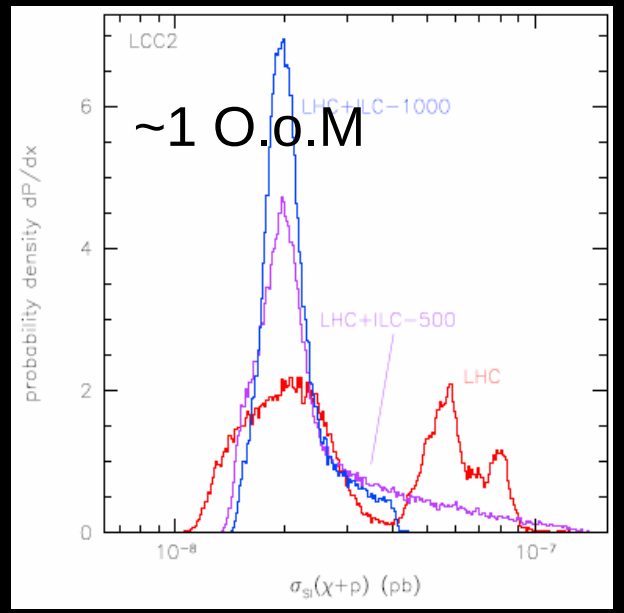

- **LCC2** (FP region): **LHC** measures Neutralinos and Charginos, not Sfermions nor heavy Higgses
- Also **optimistic** scenario; **degenerate** MSSM **solutions**

(*) Baltz et al, hep-ph/0602187

Stretching Inference?

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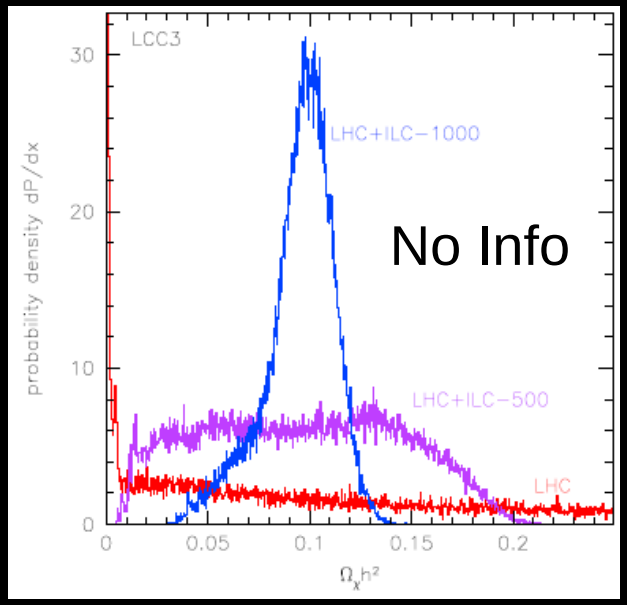

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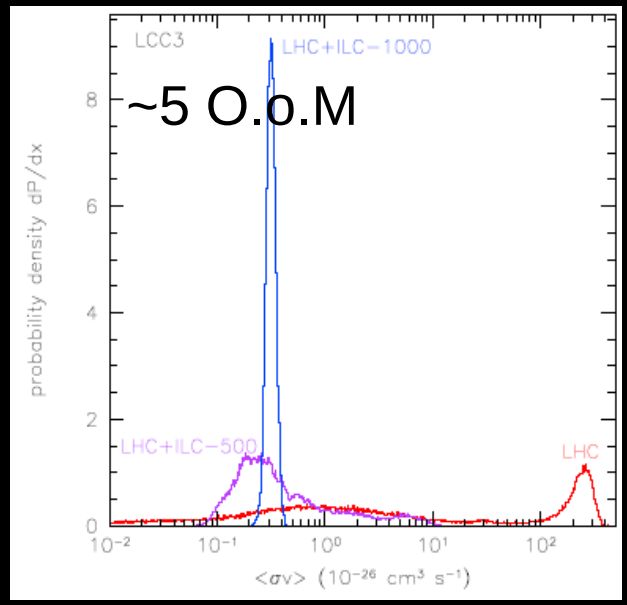

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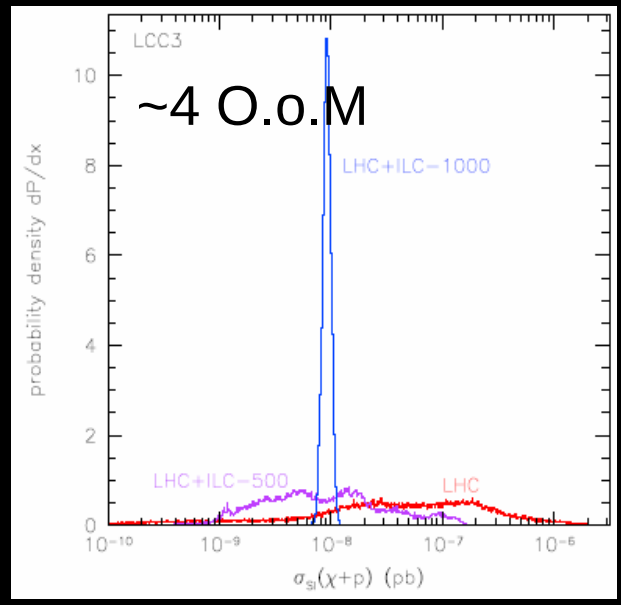

- **LCC3** (Stau Coann): **LHC** measures lightest Neutralinos, charginos and sfermions
- Again optimistic scenario; **degenerate** MSSM solutions; large **spread**…

(*) Baltz et al, hep-ph/0602187

Stretching Inference?

- Even with very optimistic assumptions (mass determination, theory parameter space,…) it is hard with **LHC** results to envision to go beyond vague **guidelines** for particle Dark Matter searches

Stretching Inference?

- Even with very optimistic assumptions (mass determination, theory parameter space,…) it is hard with **LHC** results to envision to go beyond vague **guidelines** for particle Dark Matter searches

- The **LHC will not directly probe** particle **Dark Matter**

- Rather, the LHC will shed light on preferred **BSM frameworks**

Cosmology and the LHC?

- **LHC results** might have a direct impact on **cosmology**

Cosmology and the LHC?

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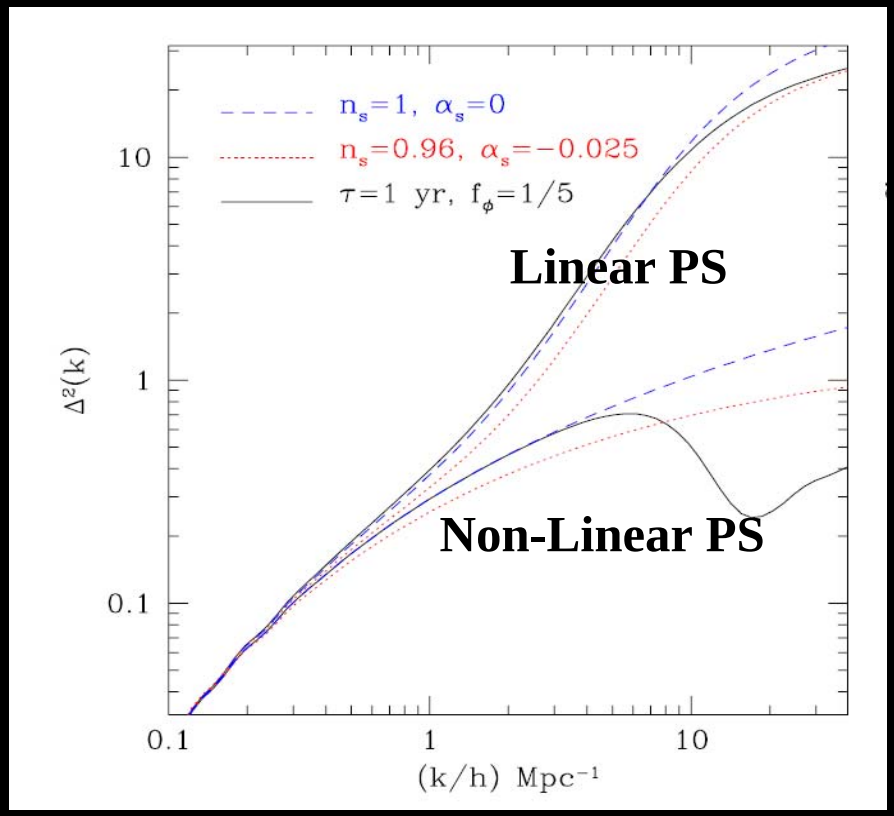
1. **Charged** (long-lived) **particle** (e.g. stau NLSP+gravitino)



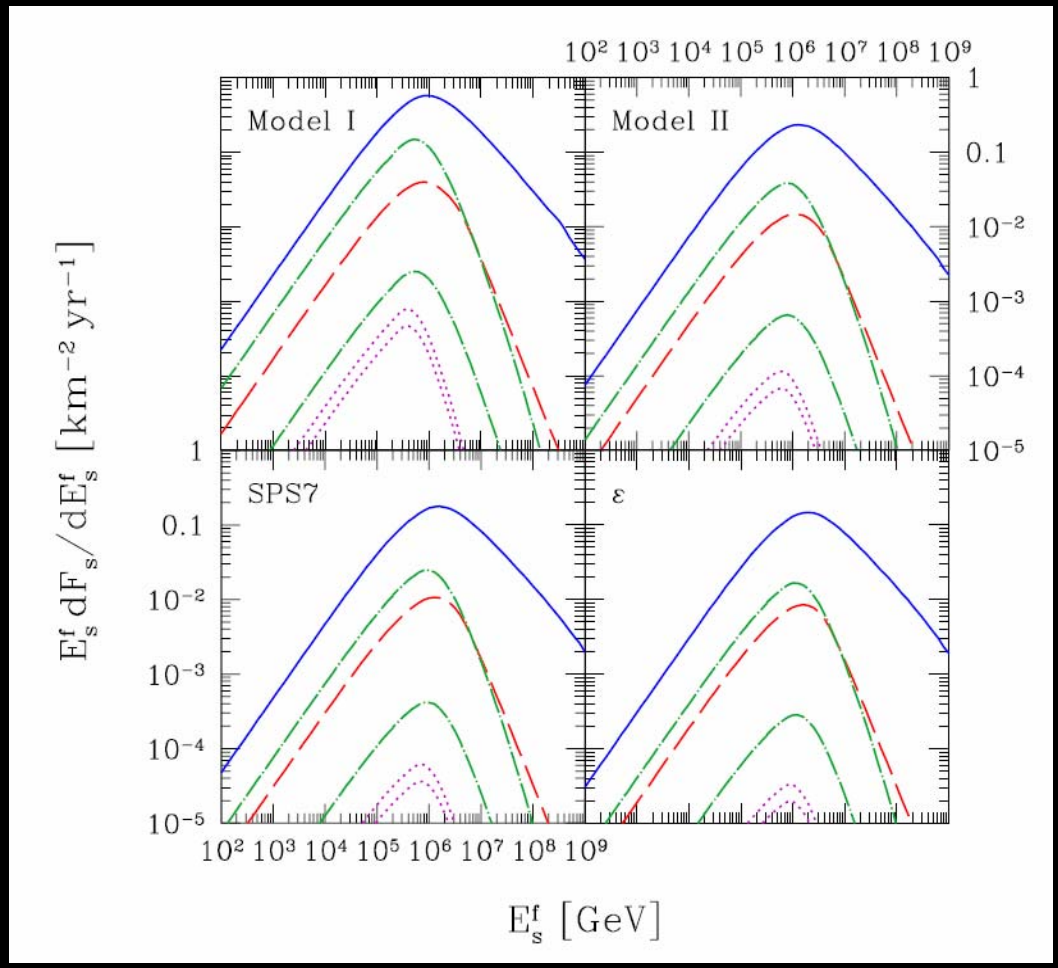
- If lifetime ~ year, profound impact on **structure formation** possible solution to small scale structure problem

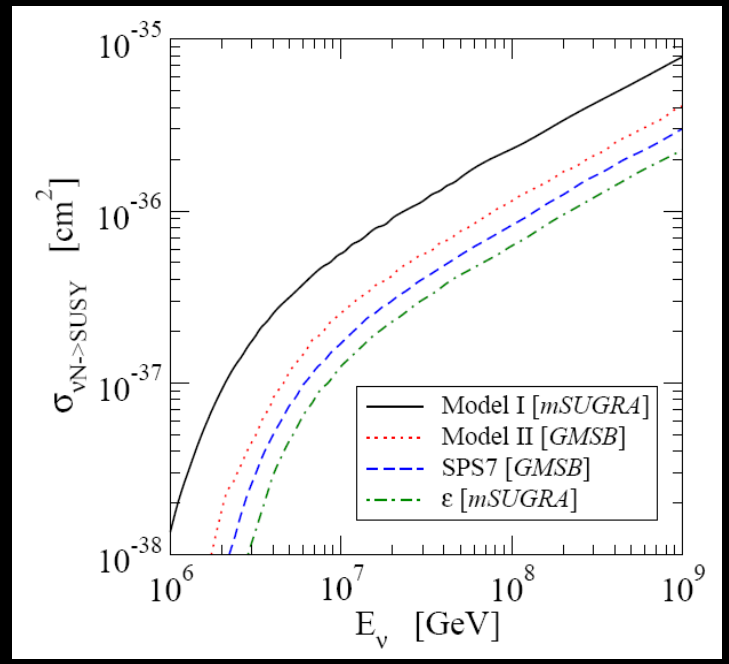
- Mimicks a **running spectral index** in the matter power spectrum

Profumo, Sigurdson, Ullio & Kamionkowski, 2004

Cosmology and the LHC?

2. Charged metastable particle: **neutrino telescopes**





- If $c\tau > R_{Earth}$, staus can be produced by **neutrino interactions** in the Earth and detected at **IceCube**

Ando, Beacom, Profumo and Rainwater, 2007

Cosmology and the LHC?

3. Special, constrained frameworks, e.g.: **Electro-weak Baryogenesis**

- To **work**, need:
  - Light RH **stop**, or extended Higgs sector
  - Light **gaugino** / **higgsino** spectrum
  - **CP** violation

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➢ To **work**, need:
- Light RH **stop**, or extended Higgs sector
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- **CP** violation

➢ Allows for a (conclusive?) **multi-faceted** experimental **search** strategy

➢ **Null results** would point to **other baryogenesis** scenarios (leptogenesis?)

Cirigliano, Profumo, Ramsey-Musolf, 2006, 2008

Cosmology and the LHC?

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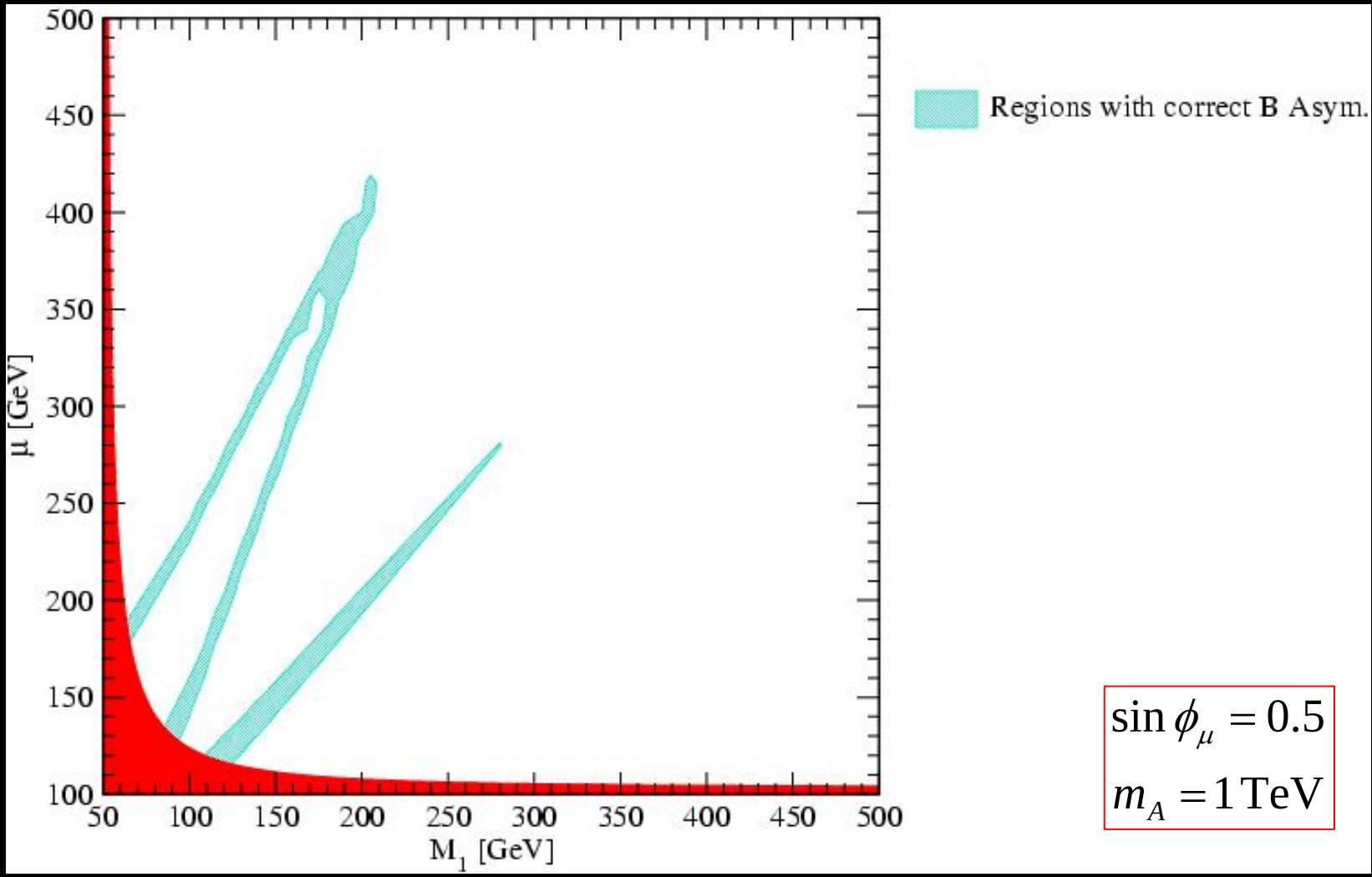

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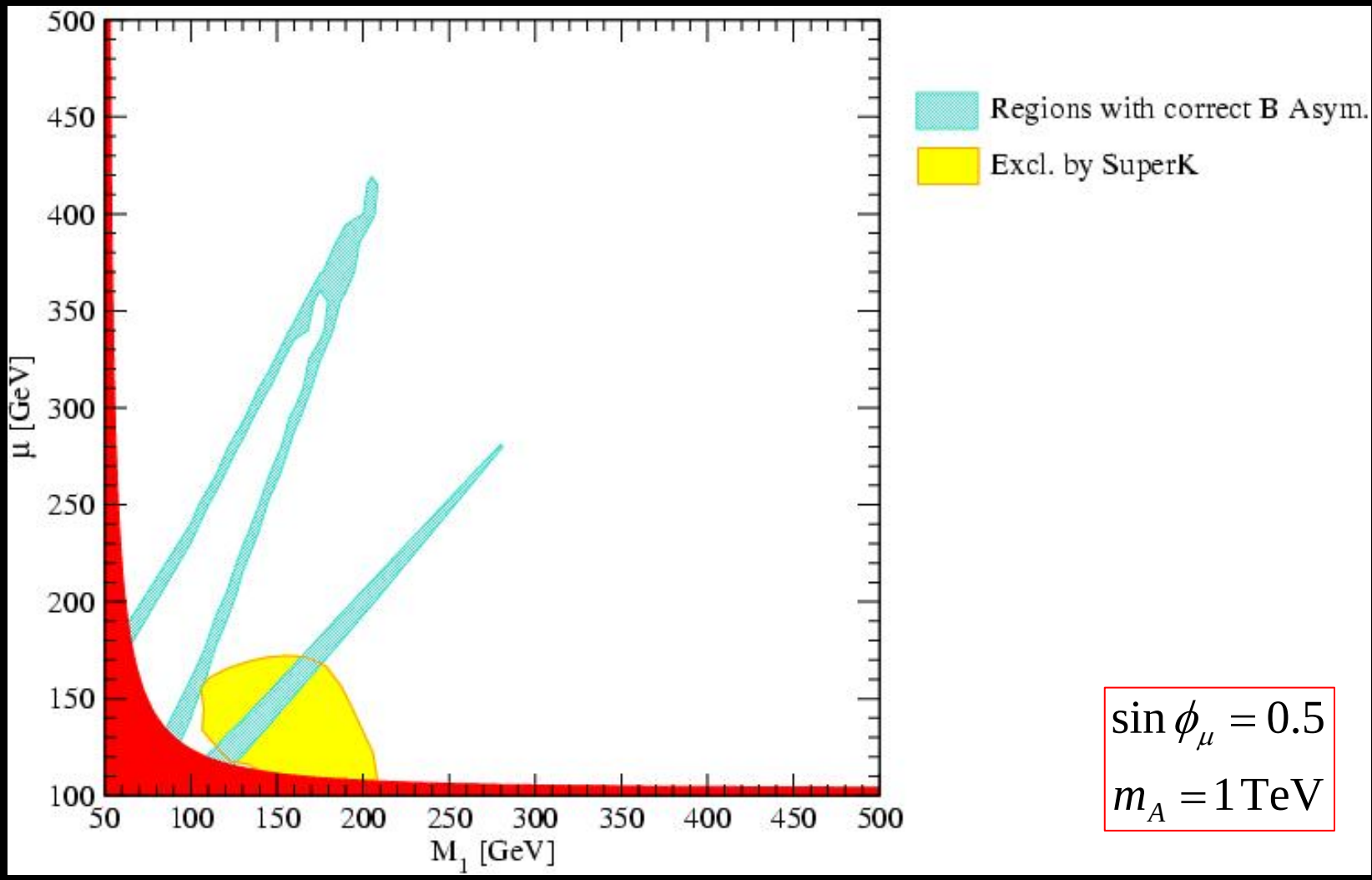

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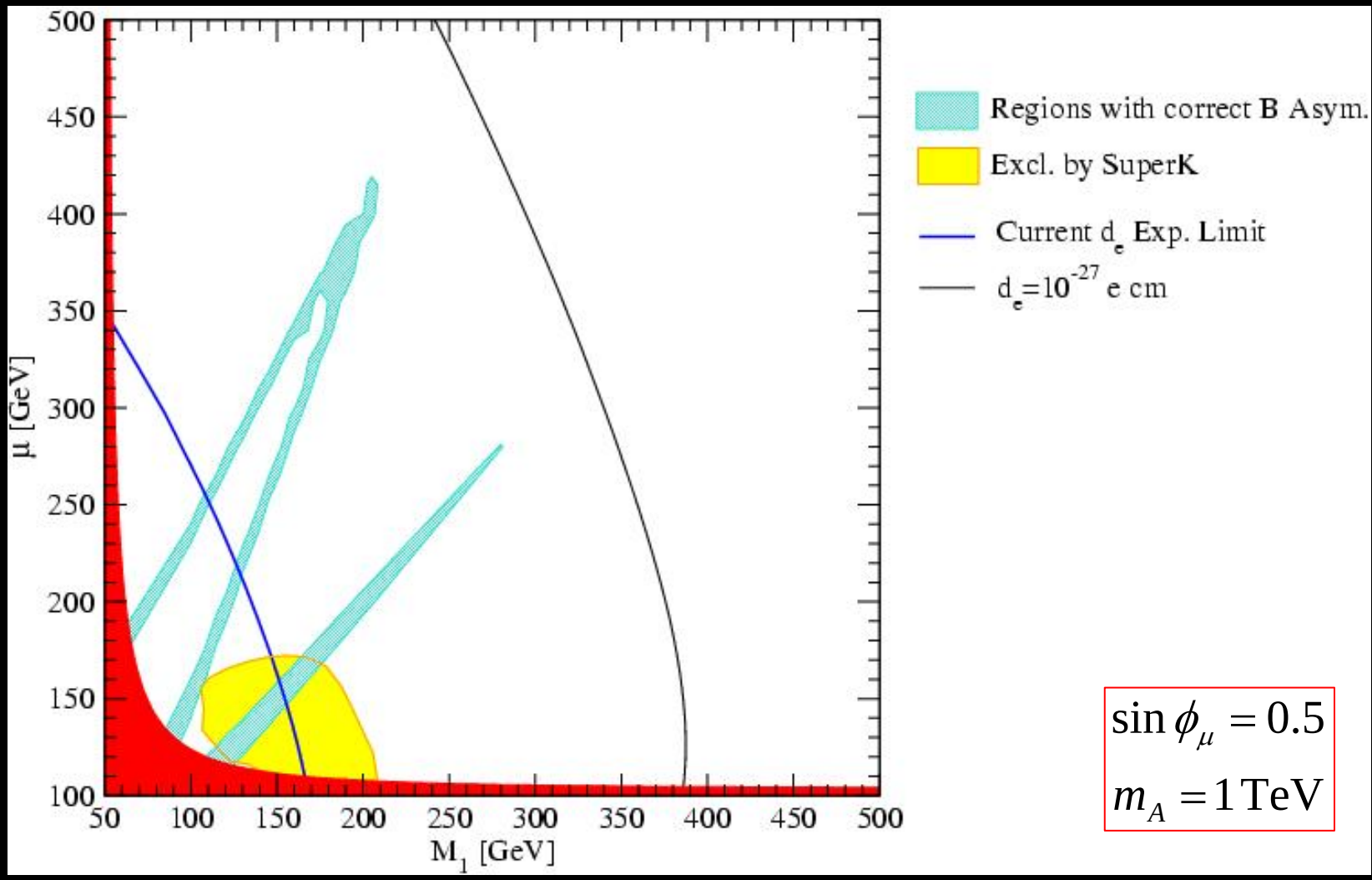

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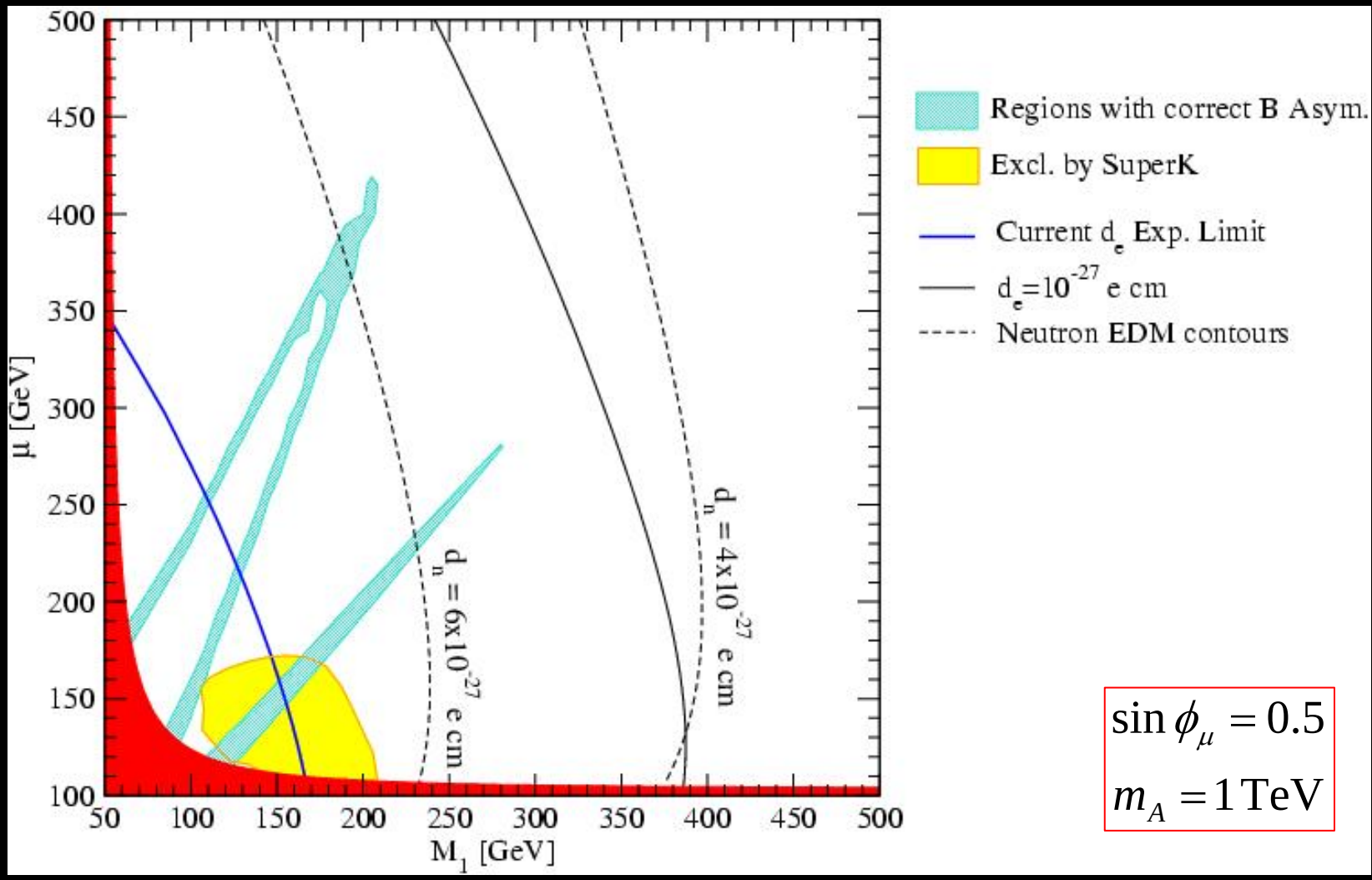

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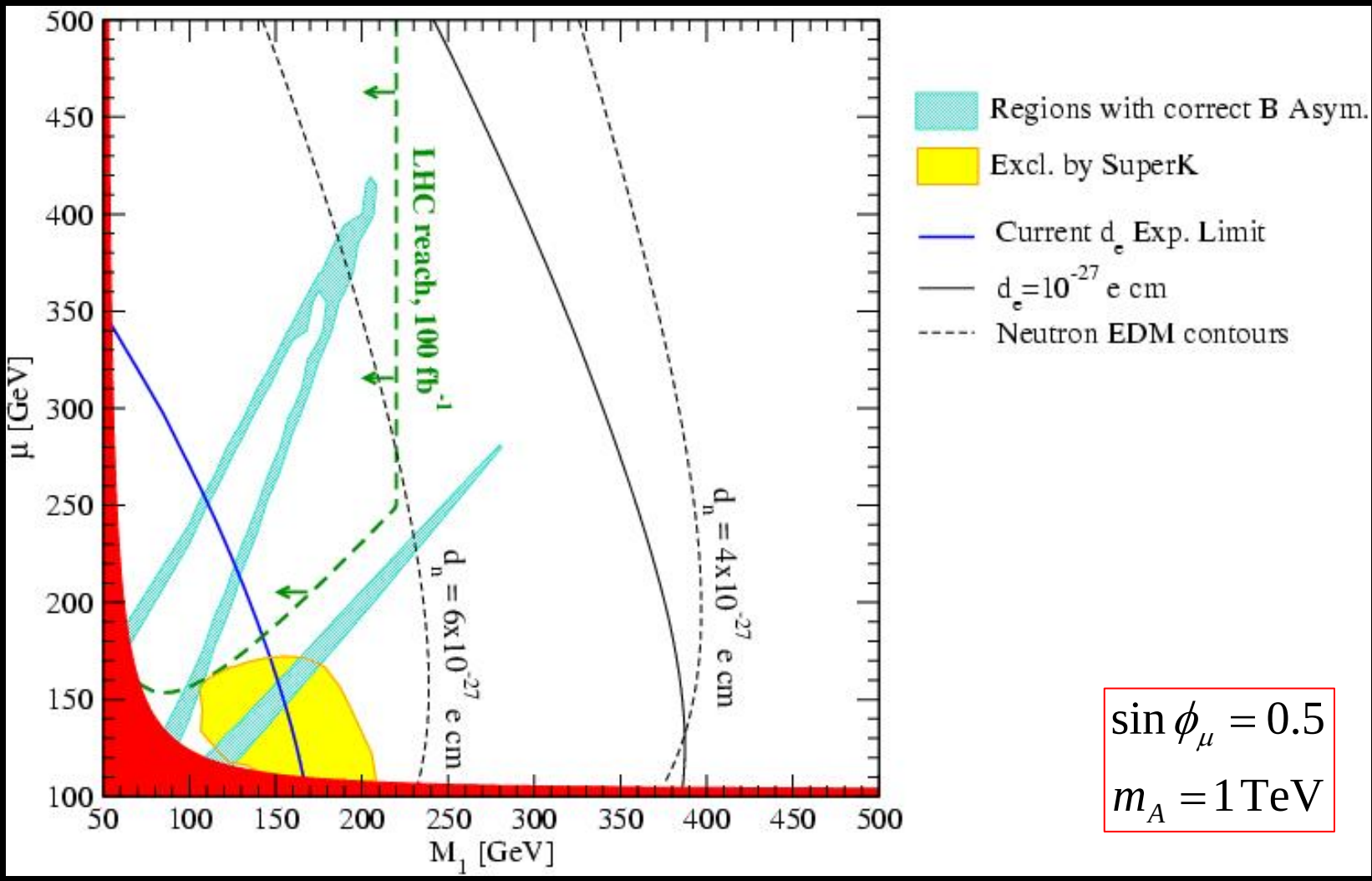

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- Take the **LHC-DM** connection ***cum grano salis***