Higgs Portal Fits to the Galactic Center Excess

[work in progress: Alessandro Cuoco, Benedikt Eiteneuer, JH, Michael Krämer]

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Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Aachen Bonn Heidelberg Mainz

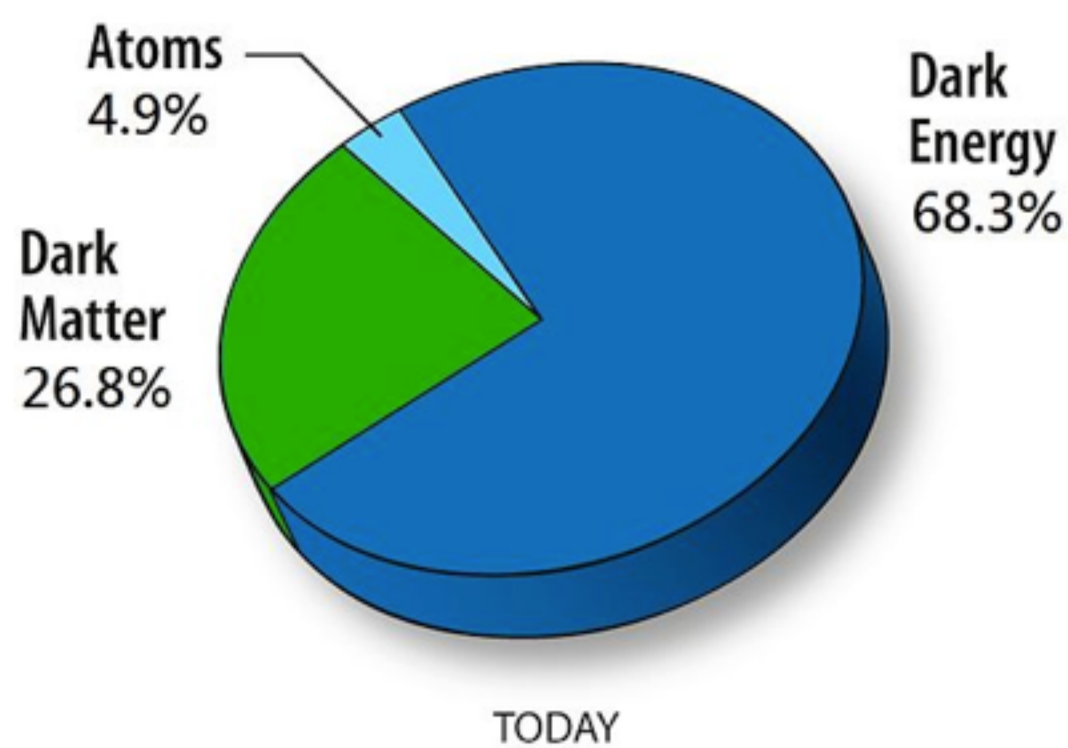
Meeting of the Research Unit

New Physics at the LHC

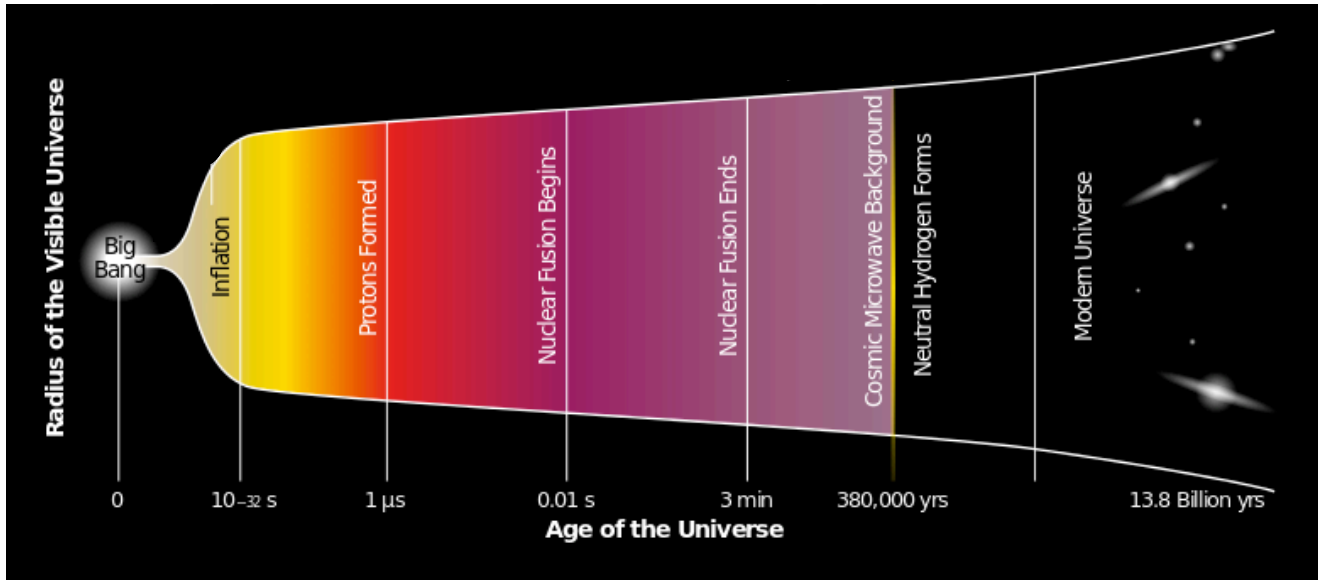
JGU Mainz - March 7th - 2016

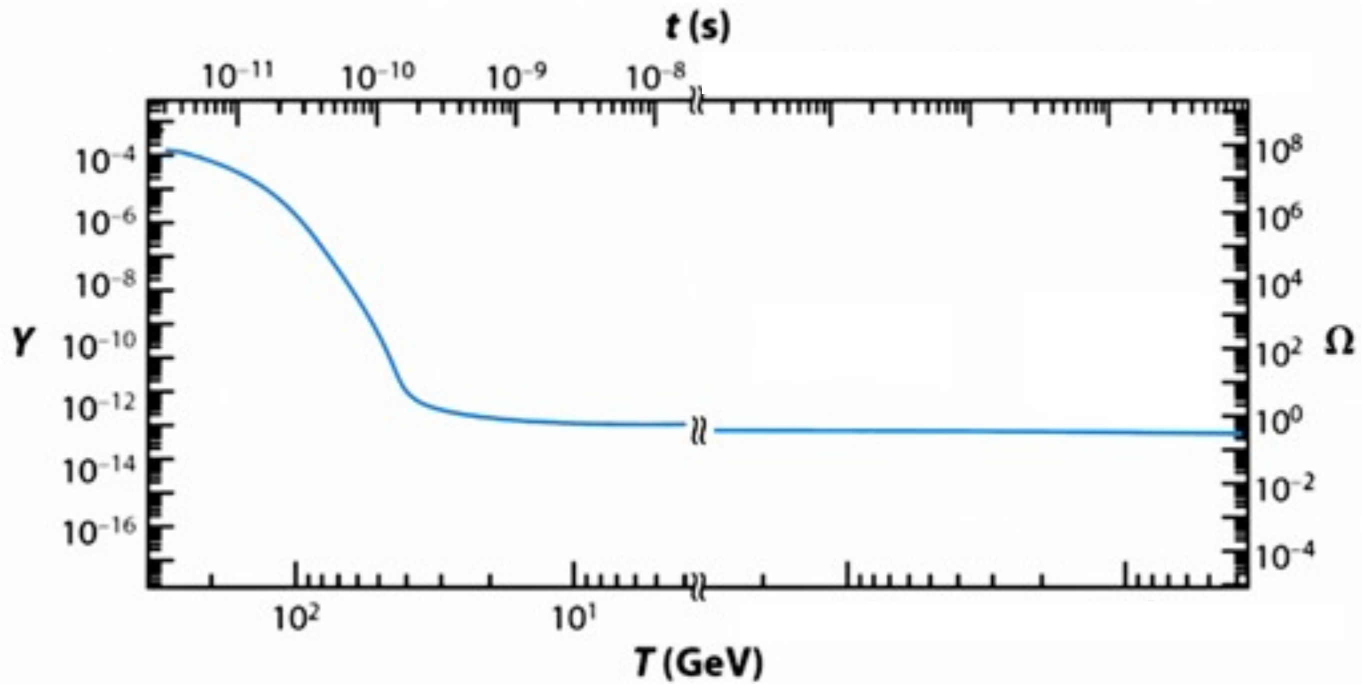
Possible contribution: WIMP Dark Matter

Energy density of the universe:



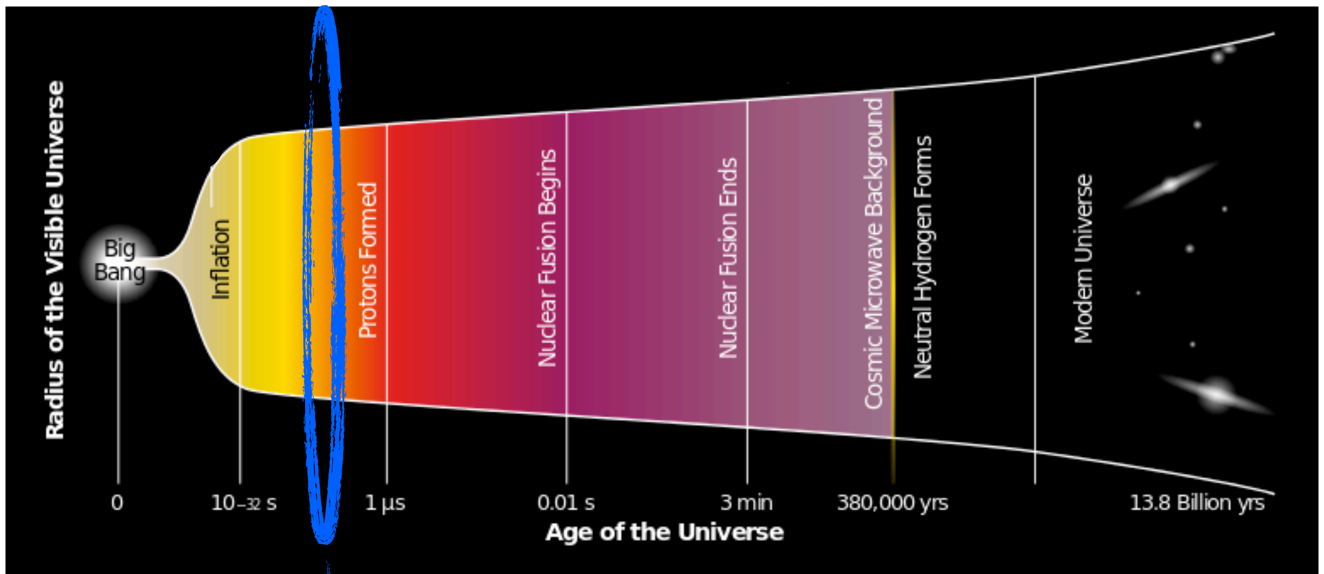
WIMP Dark Matter: freeze-out

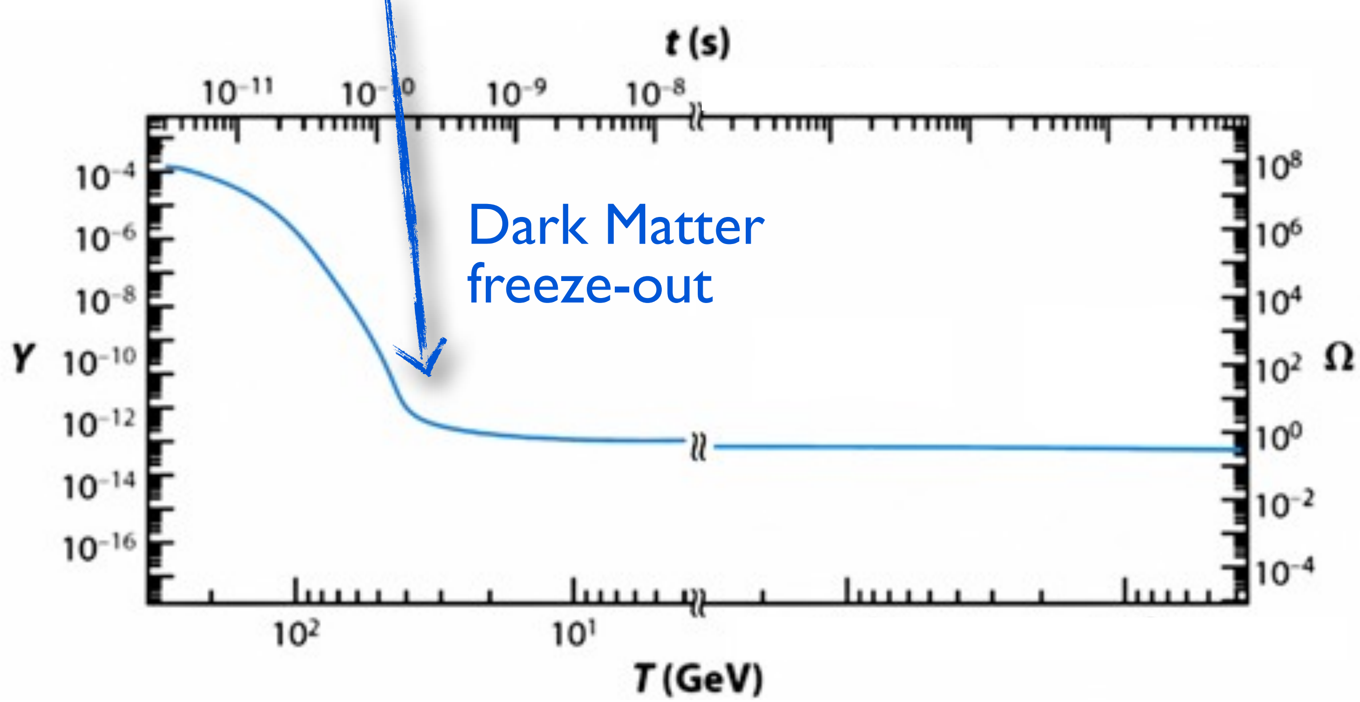




- Standard cosmological history: Well motivated "production" mechanism

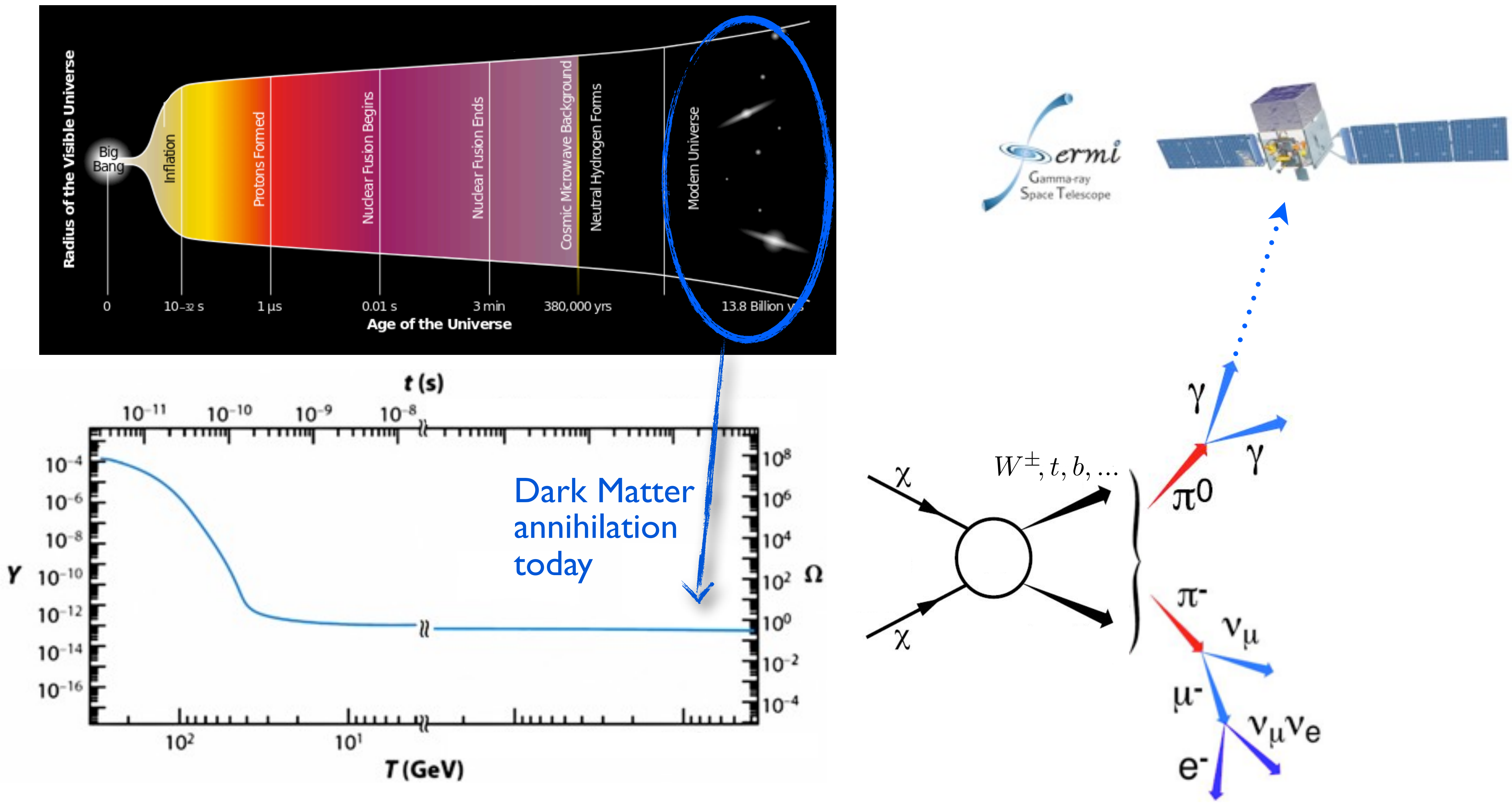
WIMP Dark Matter: freeze-out





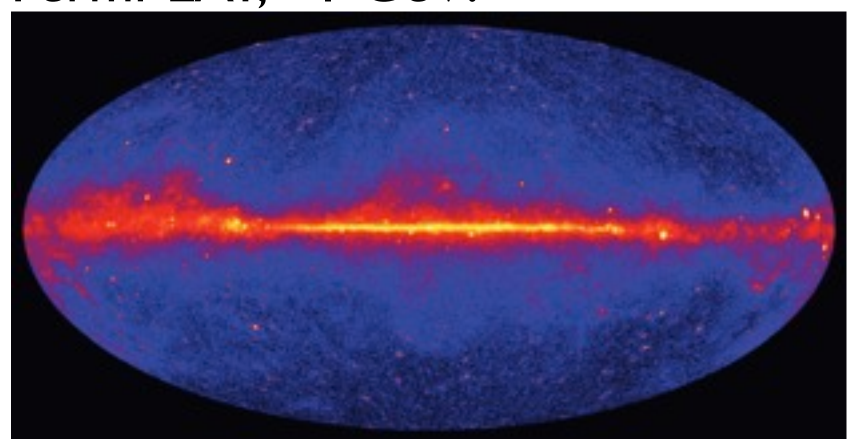
- Standard cosmological history: Well motivated "production" mechanism
- Conection between cosmology and particles

WIMP Dark Matter: annihilation today



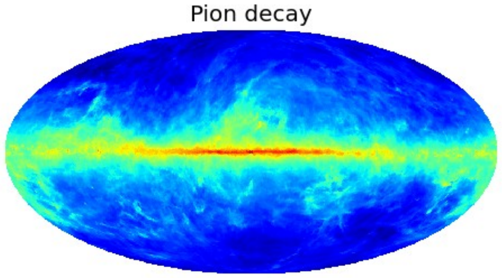
Searches for WIMP Dark Matter annihilation in the inner galactic region

Fermi-LAT, >1 GeV:

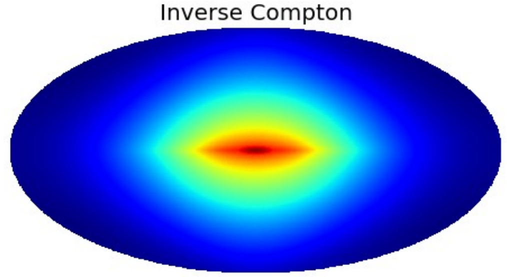


- Subtract: Diffuse foregrounds + Point sources

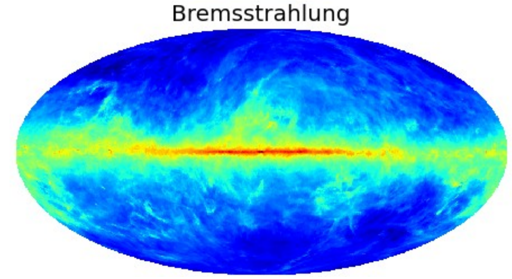
Pion decay



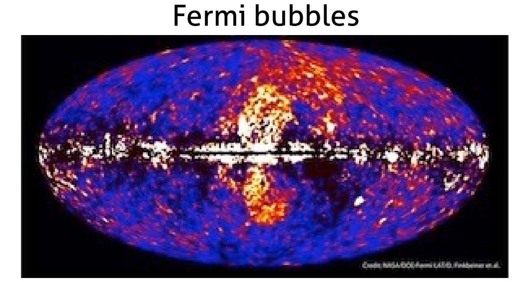
Inverse Compton



Bremsstrahlung



Fermi bubbles



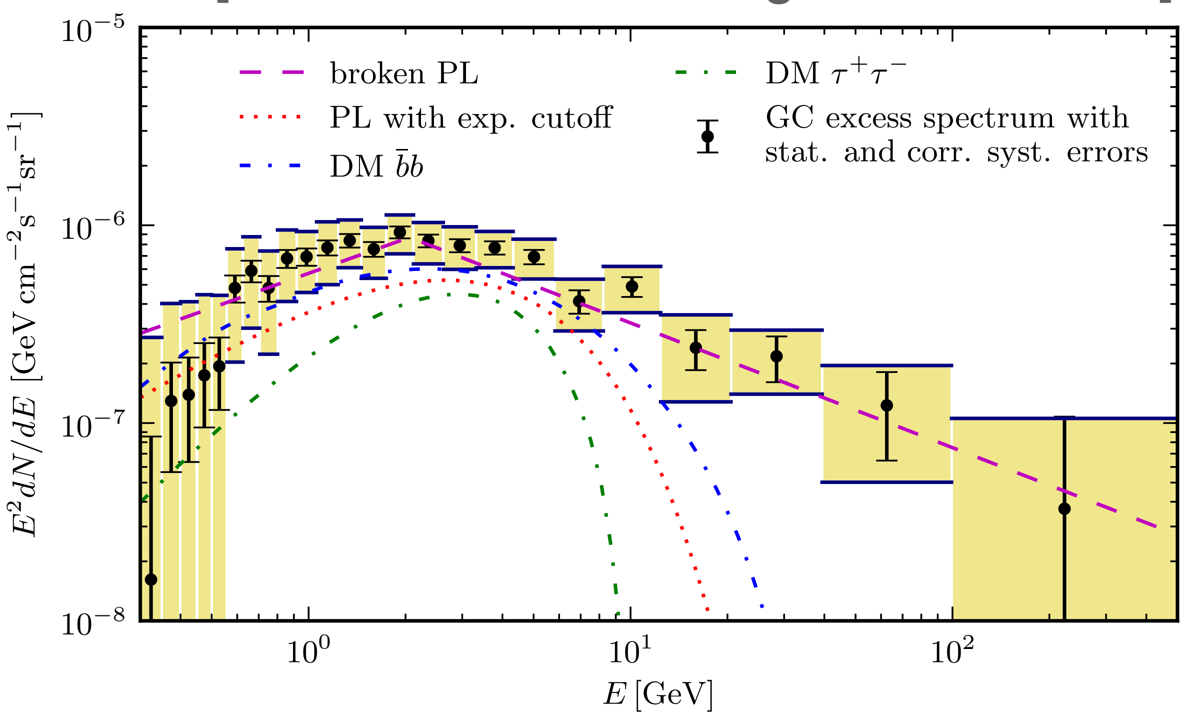
...

[see e.g. Calore, Cholis, Weniger]

Searches for WIMP Dark Matter annihilation in the inner galactic region

⇒ Excess over the known foregrounds:

[Calore, Cholis, Weniger: 1409.0042]



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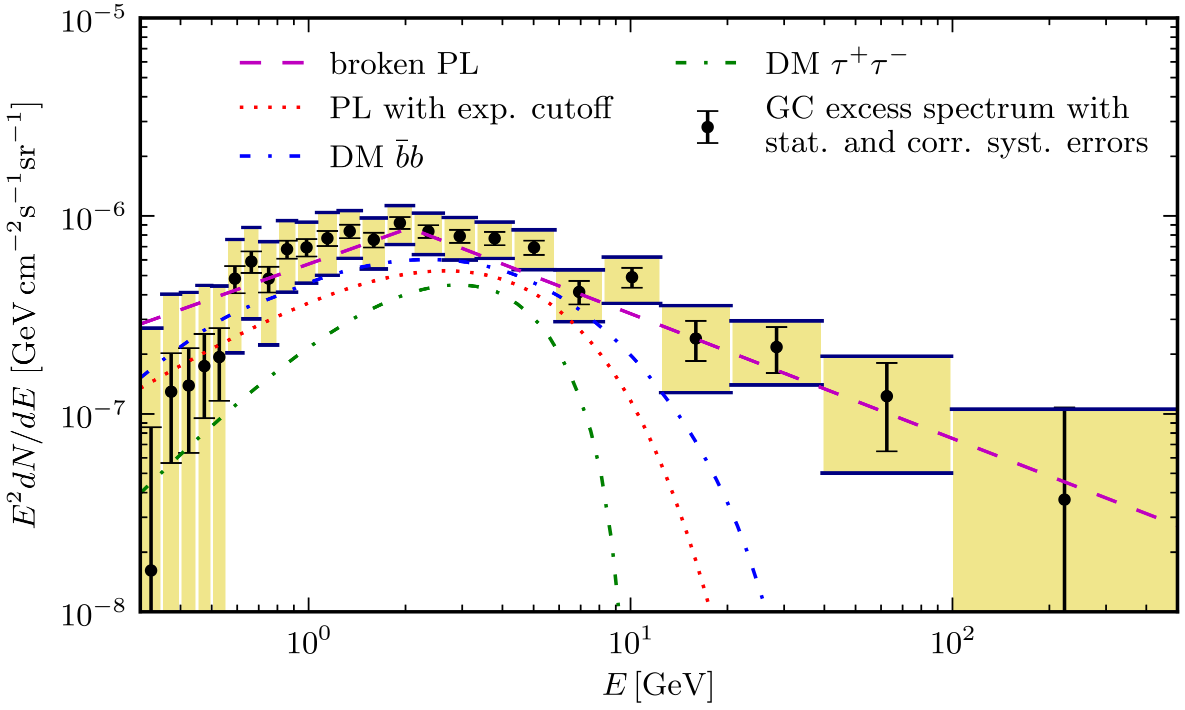

Astrophysical explanation?

[see e.g. 1405.7928, 1411.2980, 1506.05119]

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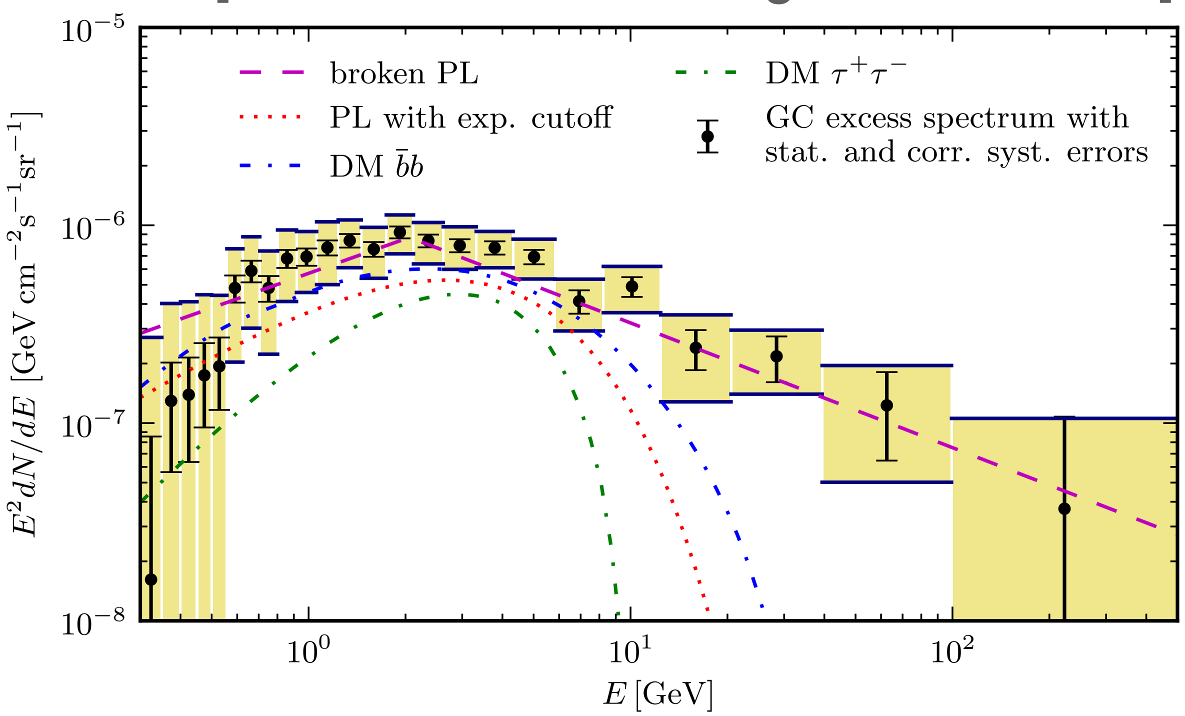

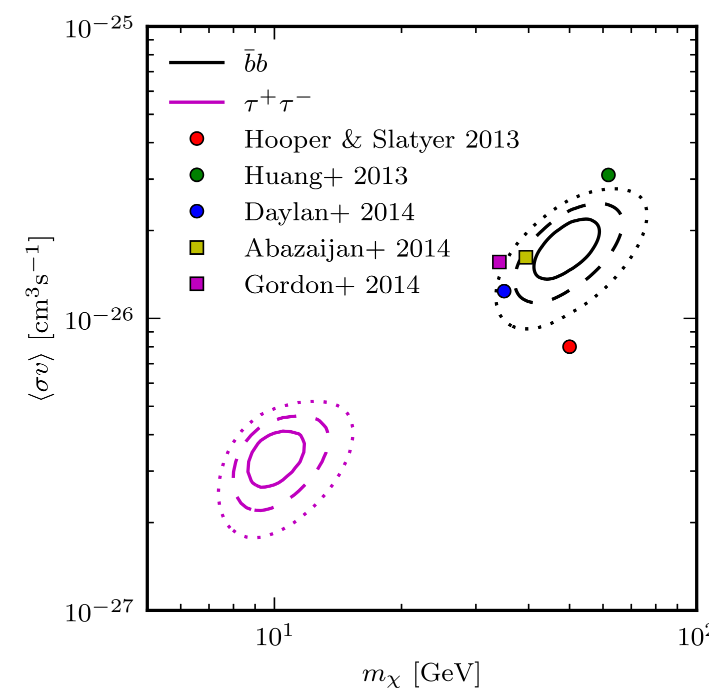

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Or signal of WIMP Dark Matter?

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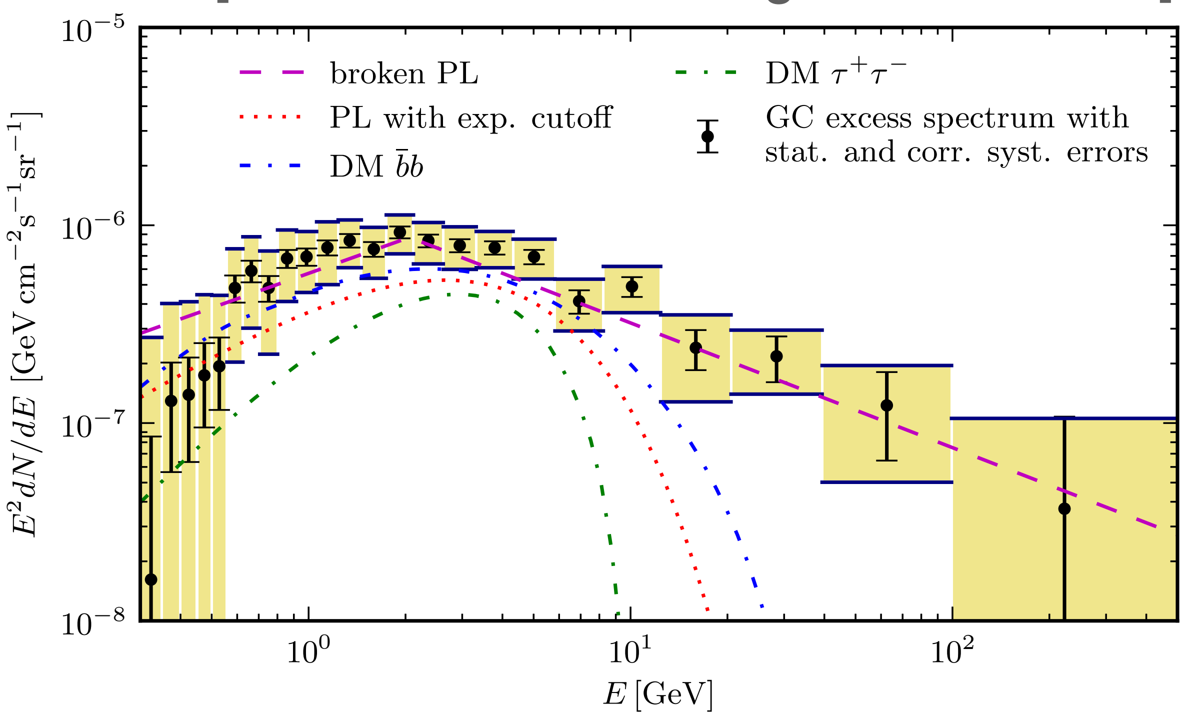

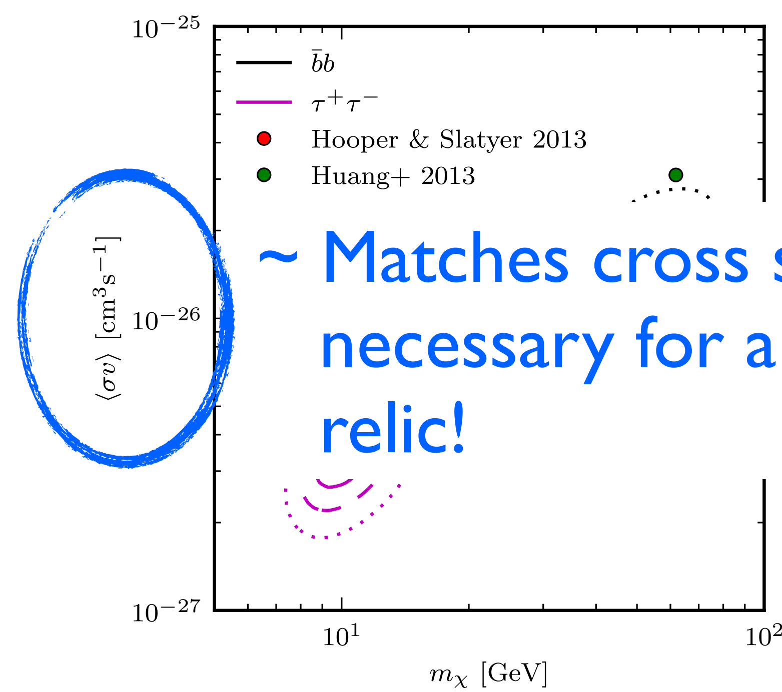

~ Matches cross section necessary for a thermal relic!

Astrophysical explanation?

[see e.g. 1405.7928, 1411.2980, 1506.05119]

Or signal of WIMP Dark Matter?

Can the signal be explained by simple DM models?

(taking into account further constraints)

This talk:

➔ "Simplest" Dark Matter model (Singlet Scalar)

➔ Detailed numerical fit

➔ Allow for additional DM components

Outline

- The Model
- Implementation
  - The galactic center excess
  - Constraints
- Fit Results
- Conclusion

The Model

Scalar Singlet Higgs Portal Model

[Burgess, Pospelov, Veldhuis: hep-ph/0011335, ...]

- Higgs bilinear $H^\dagger H$ unique (renormalizable) way to directly couple DM to the SM
- Add Singlet Scalar *S* with Z_2-symmetry:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_{S,0}^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS}\, S^2 H^\dagger H$$

(before EWSB)

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where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2/2.$ (after EWSB)

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Important for vacuum stability

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Important for this work

⇒ Only two parameters: $m_S,\ \lambda_{HS}$

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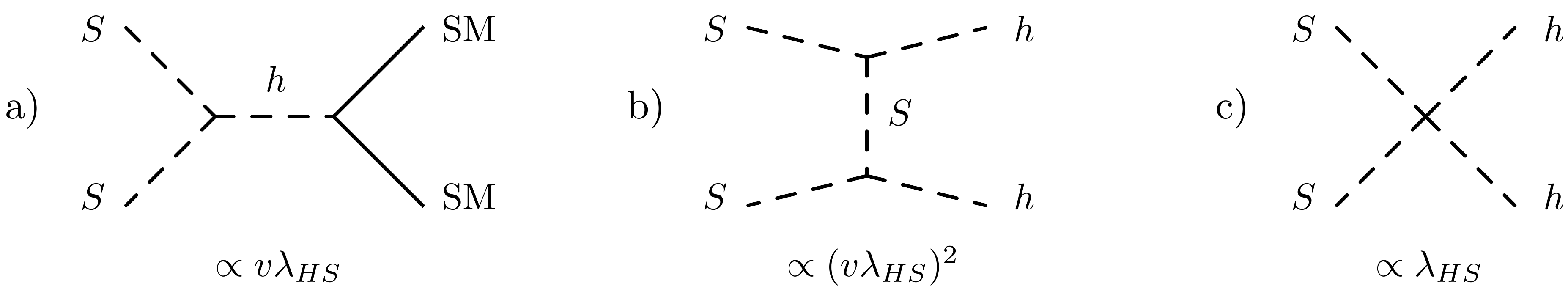
$\Rightarrow$ Only two parameters: $m_S, \, \lambda_{HS}$

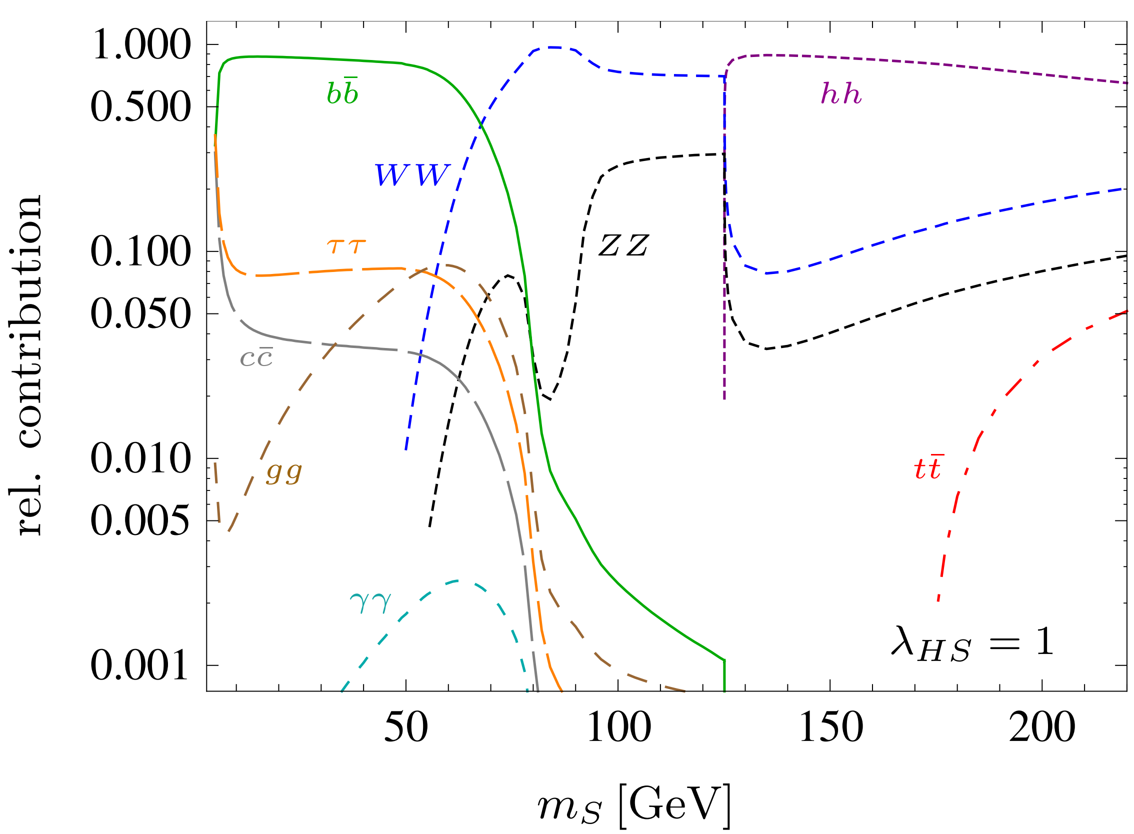
Scalar Singlet Higgs Portal Model

- Annihilation processes:



$\text{SM} = t, h, Z, W, b, \tau, c, g, \gamma$

Only present above Higgs threshold



[Using micrOMEGAs]

Scalar Singlet Higgs Portal Model

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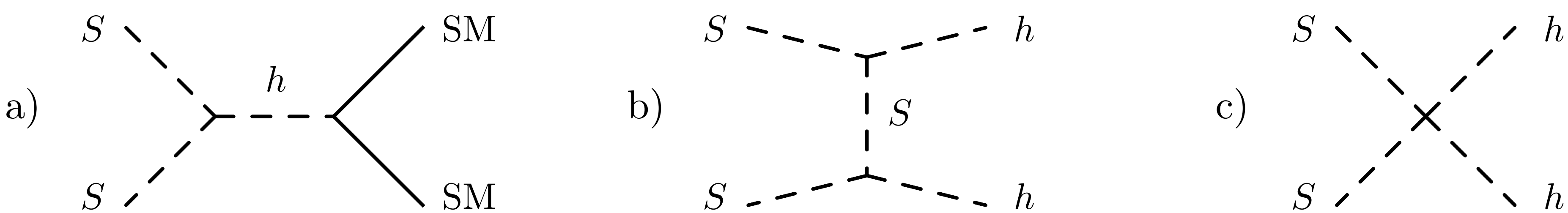

$\propto v\lambda_{HS}$ $\propto (v\lambda_{HS})^2$ $\propto \lambda_{HS}$

$\mathrm{SM} = t, h, Z, W, b, \tau, c, g, \gamma$

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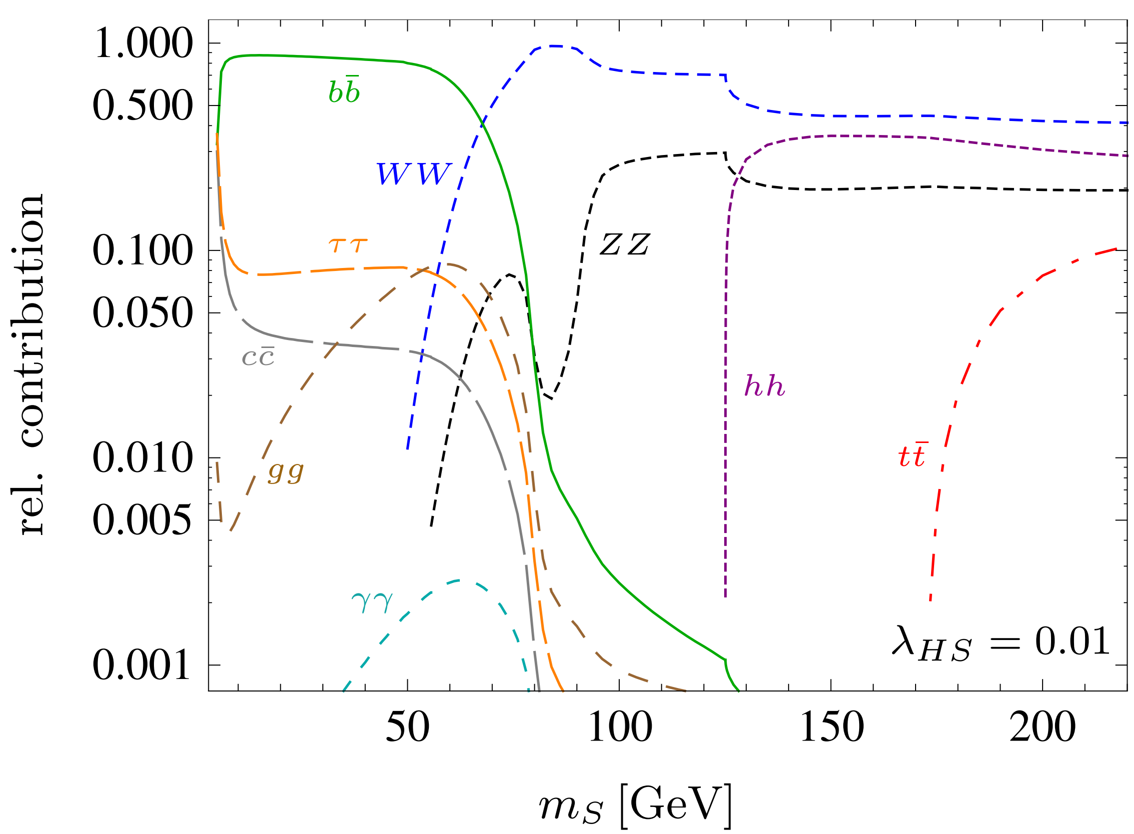


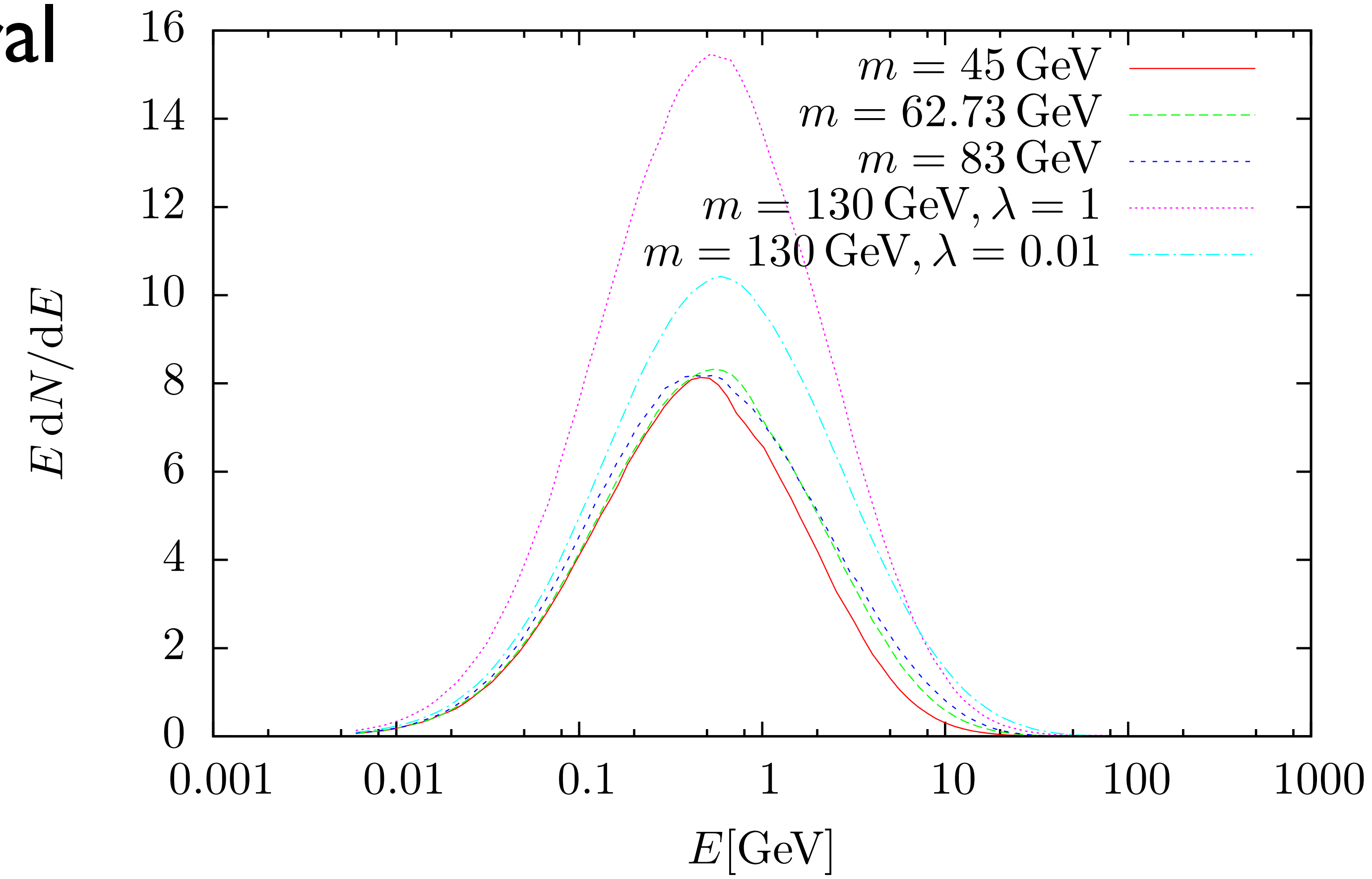
[Using micrOMEGAs]

Implementation

Implementation: Galactic center excess

- Need gamma-ray spectrum
- Slow in fit ⇒ Pre-compute spectra for all channels (as function of DM mass) with MadGraph/Pythia 8
- During fit: Combine spectra according to contribution

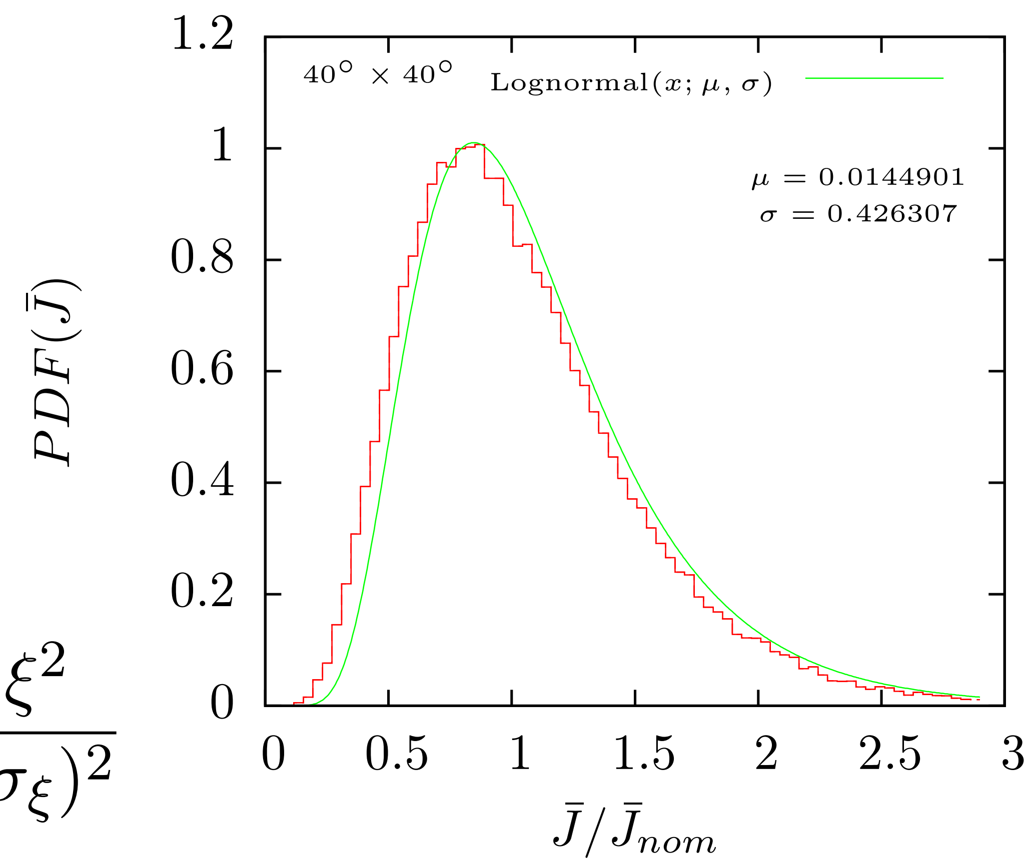
Photon spectra for several masses/couplings:



Implementation: Galactic center excess

- Take measured spectrum d_i and covariance matrix Σ_{ij} from [Calore, Cholis, Weniger: 1409.0042]
- Additional uncertainty on the theoretical prediction of the spectrum $\Sigma_{ij} \to \Sigma_{ij} + \Sigma_{ij}\delta_{ij}t_i^2\sigma_t^2\,, \quad \sigma_t = 10\%$ [Achterberg et al. 1502.05703]
- Large theoretical uncertainties on DM distribution in galaxy:
  - Take NFWc profile
  - Vary around best fit parameters with MC [from Calore, Cholis, Weniger: 1409.0042]

  ⇒ Distribution for *J*-factor
  - Determine σ_ξ for $\xi = \ln(\bar{J}/\bar{J}_{\rm nom})$



- Compute χ^2:

$$\chi^2 = \sum_{i,j}(d_i - e^\xi t_i)(\Sigma_{ij})^{-1}(d_j - e^\xi t_j) + \frac{\xi^2}{(\sigma_\xi)^2}$$

Non-WIMP contribution to Dark Matter

- Allow for additional unspecified DM component
- Fraction of WIMP component:

$$R = \rho_{\mathrm{WIMP}} / \rho_{\mathrm{DM,\,total}}$$

- Assumption: same distribution

⇒ Rescaling of flux:

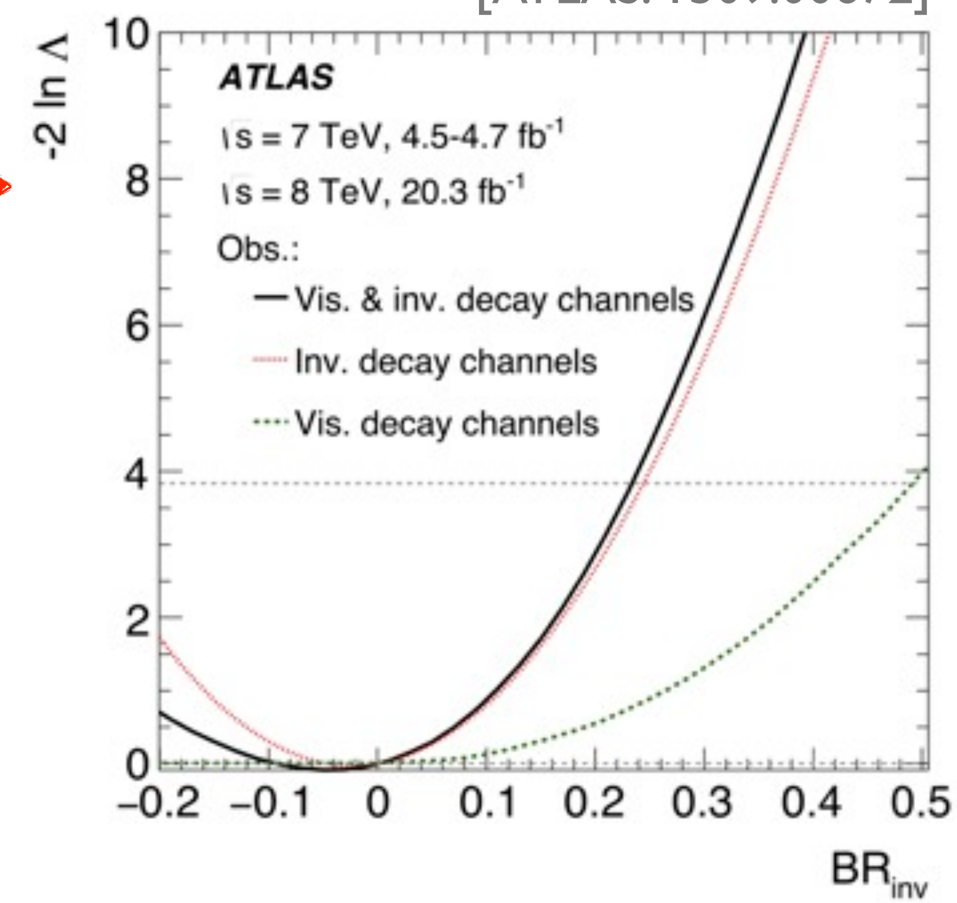
$$\phi \to R^2 \phi$$

← For indirect detection

Implementation: Constraints

[ATLAS: 1509.00672]

(i) Collider constraints:
Higgs invisible BR
(no rescaling with *R*!)



(ii) Direct detection constraints: LUX
[LuxCalc; Savage *et al.* 1502.02667]
(rescals linear in *R*)

(iii) Dwarf Spheroidal Galaxies
[Fermi-LAT: 1503.02641]

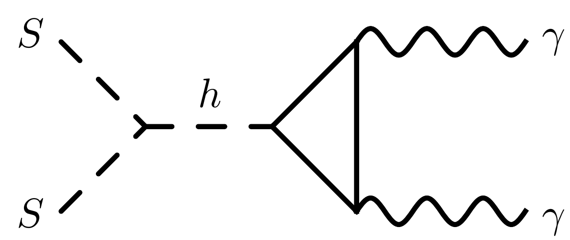
Implementation: Constraints

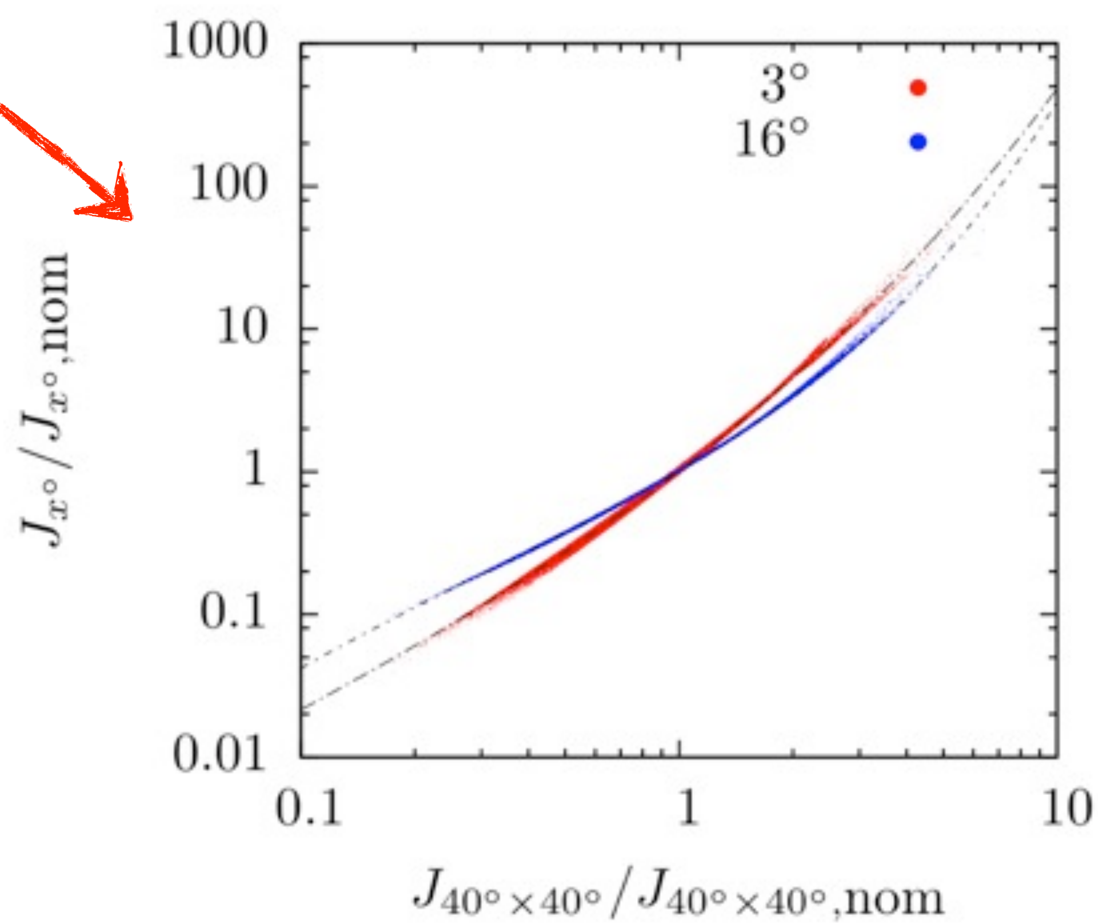
(iv) Gamma-lines:

[Fermi-LAT: 1506.00013]

J-factor different from GCE

almost 100% correlation





(v) Relic density constraint

[Planck: 2013]

Apply 10% theoretical uncertainty

[computed with micrOMEGAs]

Implementation: Fitting tools

- Use MultiNest (nested sampling algorithm)
  [Feroz *et al.* 1306.2144]
- 4 scan parameters:

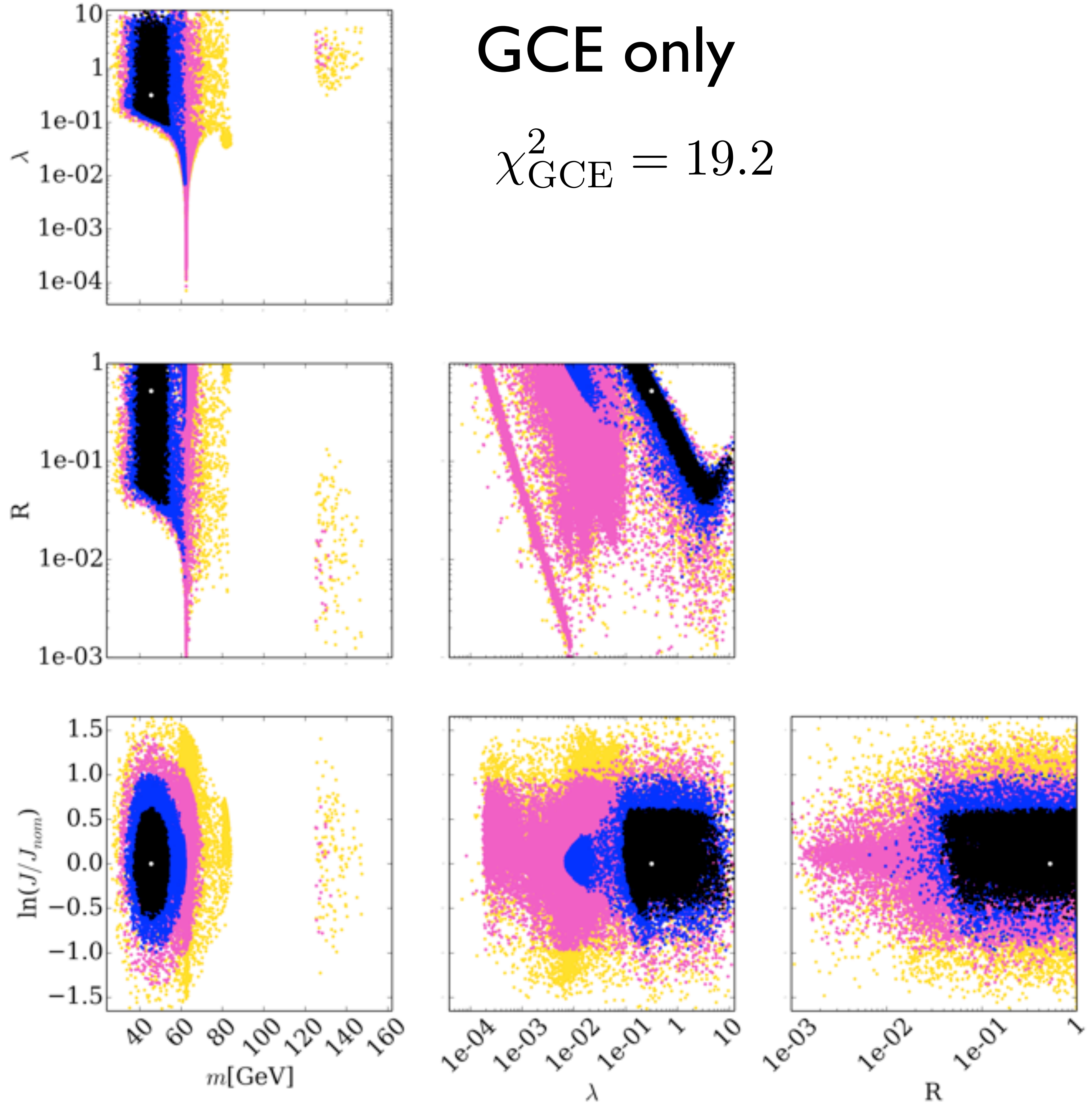
$$
\begin{aligned}
m_S: &\quad 5 \ldots 220\,\mathrm{GeV} \\
\lambda_{HS}: &\quad 3 \times 10^{-5} \ldots 4\pi \\
\ln(\bar{J}/\bar{J}_{\mathrm{nom}}): &\quad -4\sigma_\xi \ldots 4\sigma_\xi \\
R: &\quad 10^{-3} \ldots 1
\end{aligned}
$$

- Cross sections and BRs: micrOMEGAs
- Frequentist interpretation

Fit results

GCE only

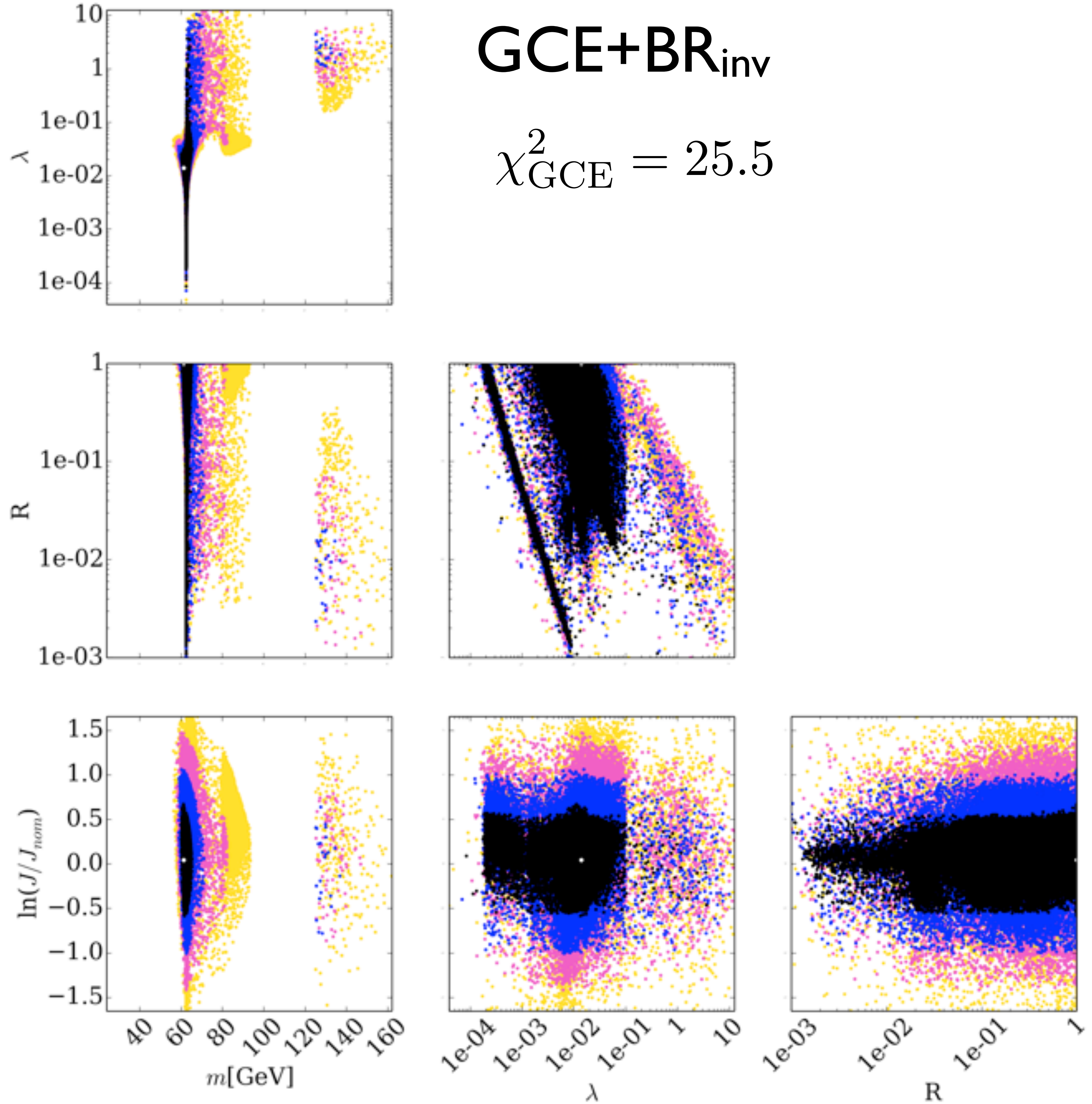
$$\chi^2_{\rm GCE} = 19.2$$



preliminary

GCE+BR_{inv}

$$\chi^2_{\rm GCE} = 25.5$$

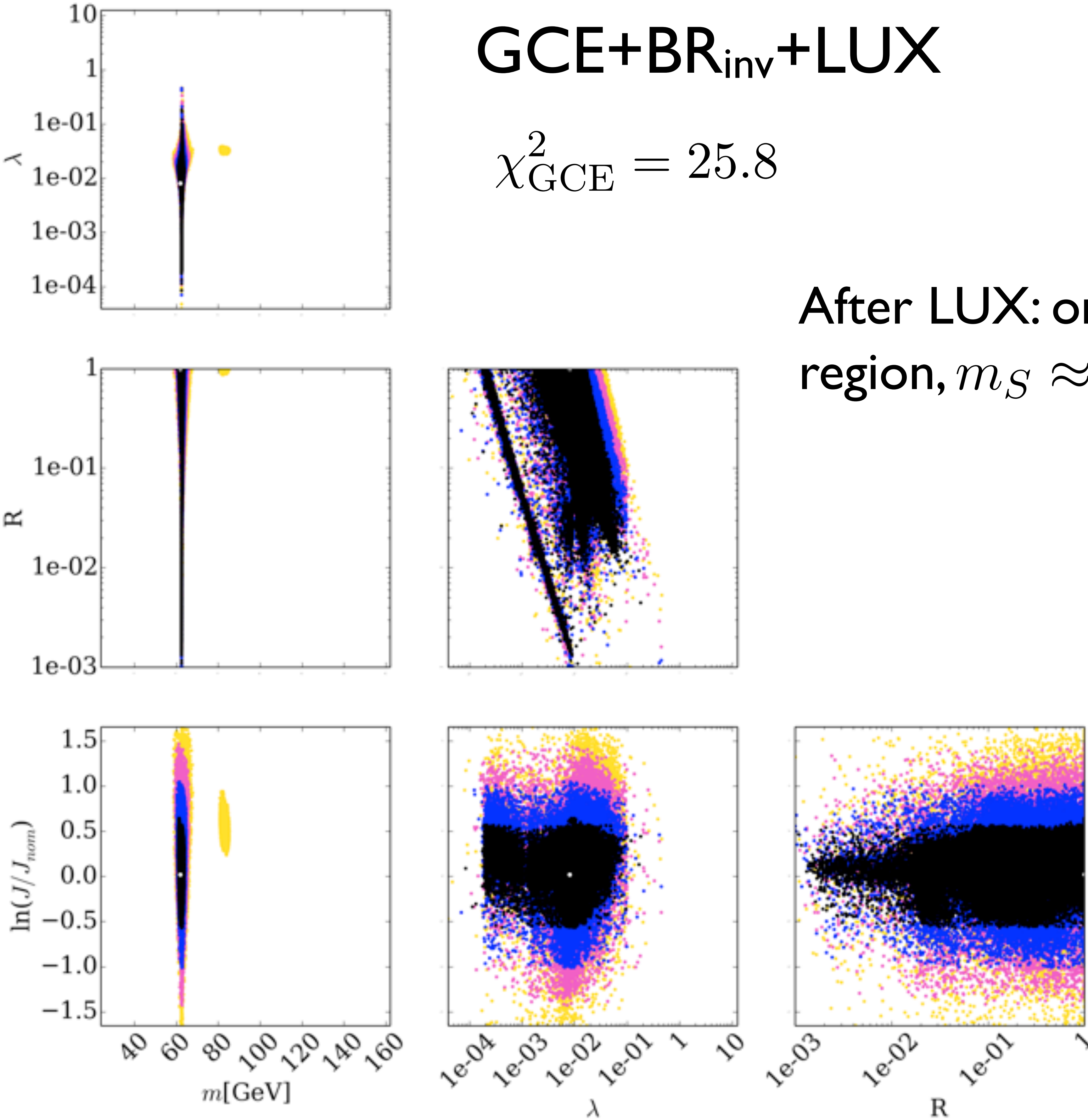


preliminary

GCE+BR_{inv}+LUX

$$\chi^2_{\rm GCE} = 25.8$$

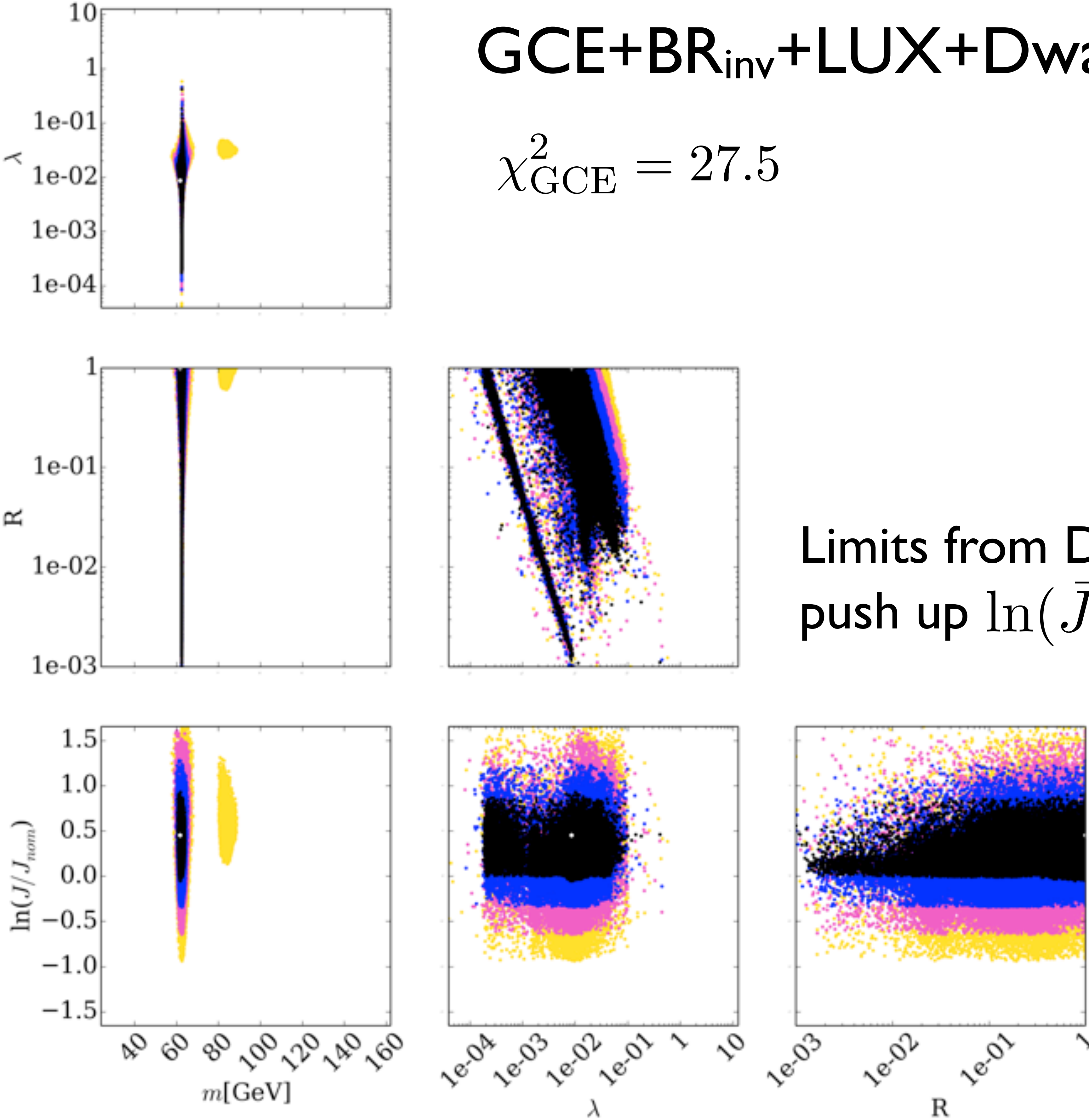
After LUX: only Higgs-resonant region, $m_S \approx m_h/2$, remains



preliminary

GCE+BR_{inv}+LUX+Dwarfs

$$\chi^2_{\rm GCE} = 27.5$$

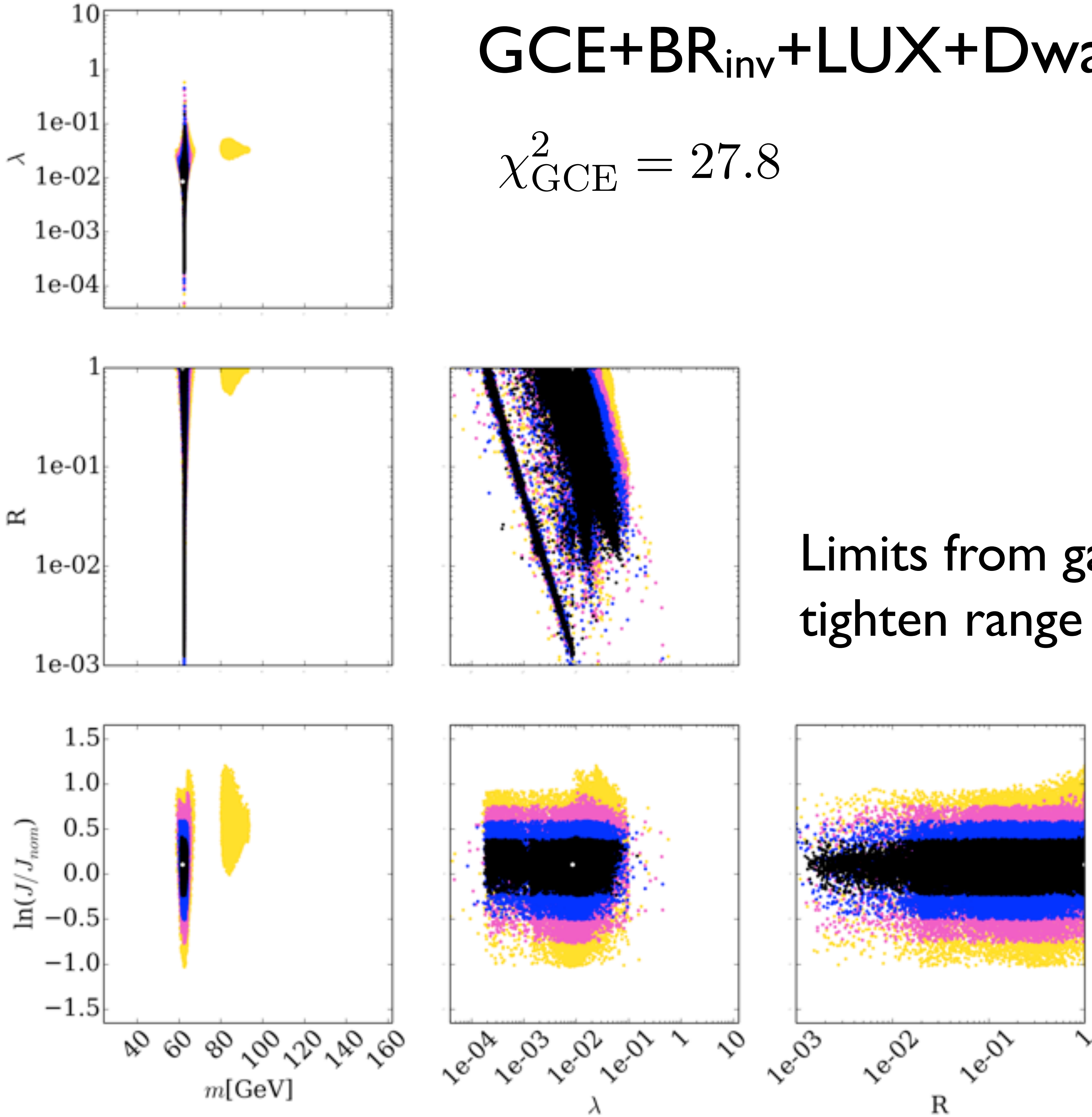


Limits from Dwarf galaxies push up $\ln(\bar{J}/\bar{J}_{\rm nom})$

preliminary

GCE+BR_{inv}+LUX+Dwarfs+Lines

$$\chi^2_{\rm GCE} = 27.8$$

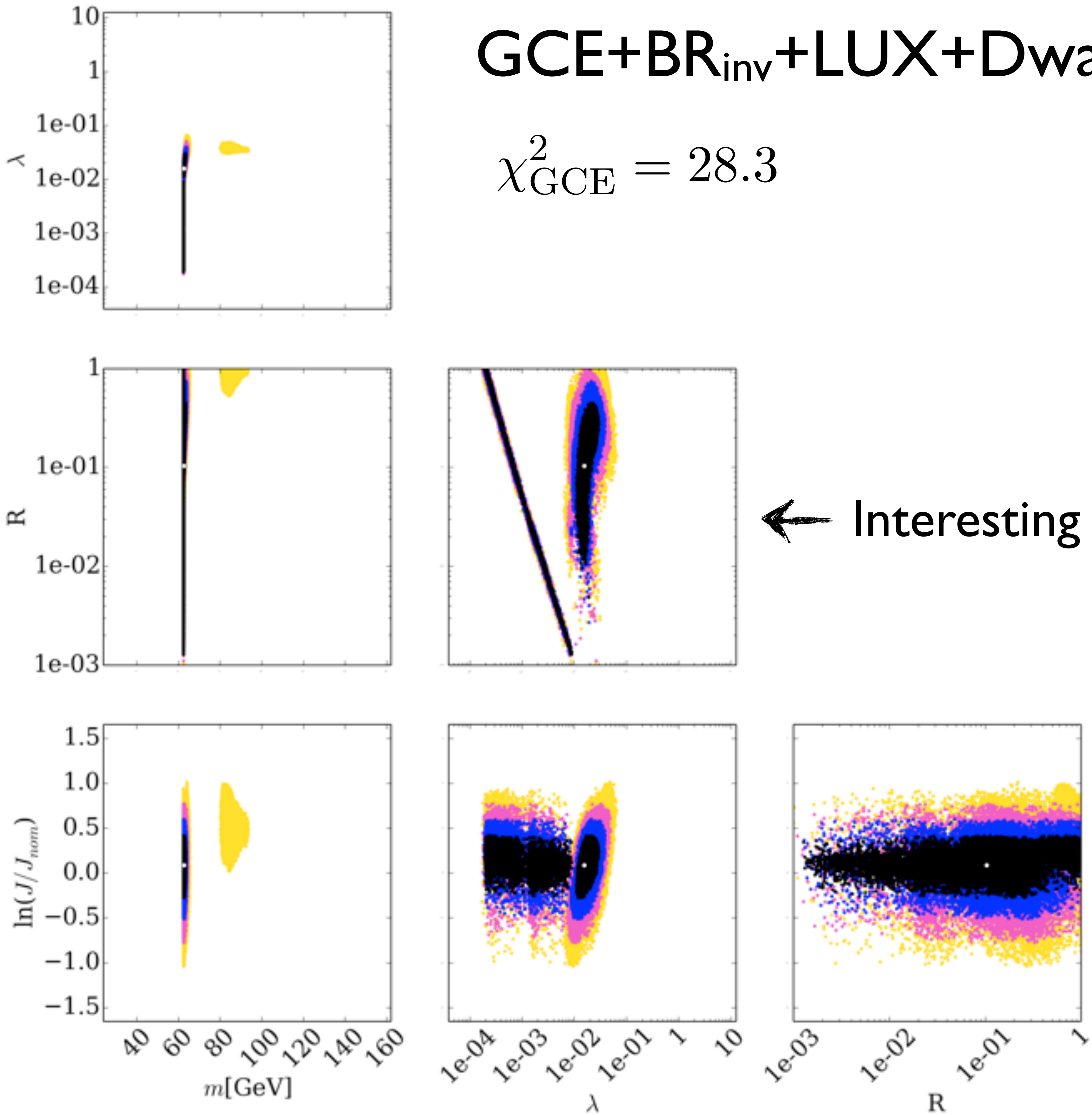


Limits from gamma lines further tighten range for $\ln(\bar{J}/\bar{J}_{\rm nom})$

preliminary

GCE+BR_{inv}+LUX+Dwarfs+Lines+DM

$$\chi^2_{\rm GCE} = 28.3$$

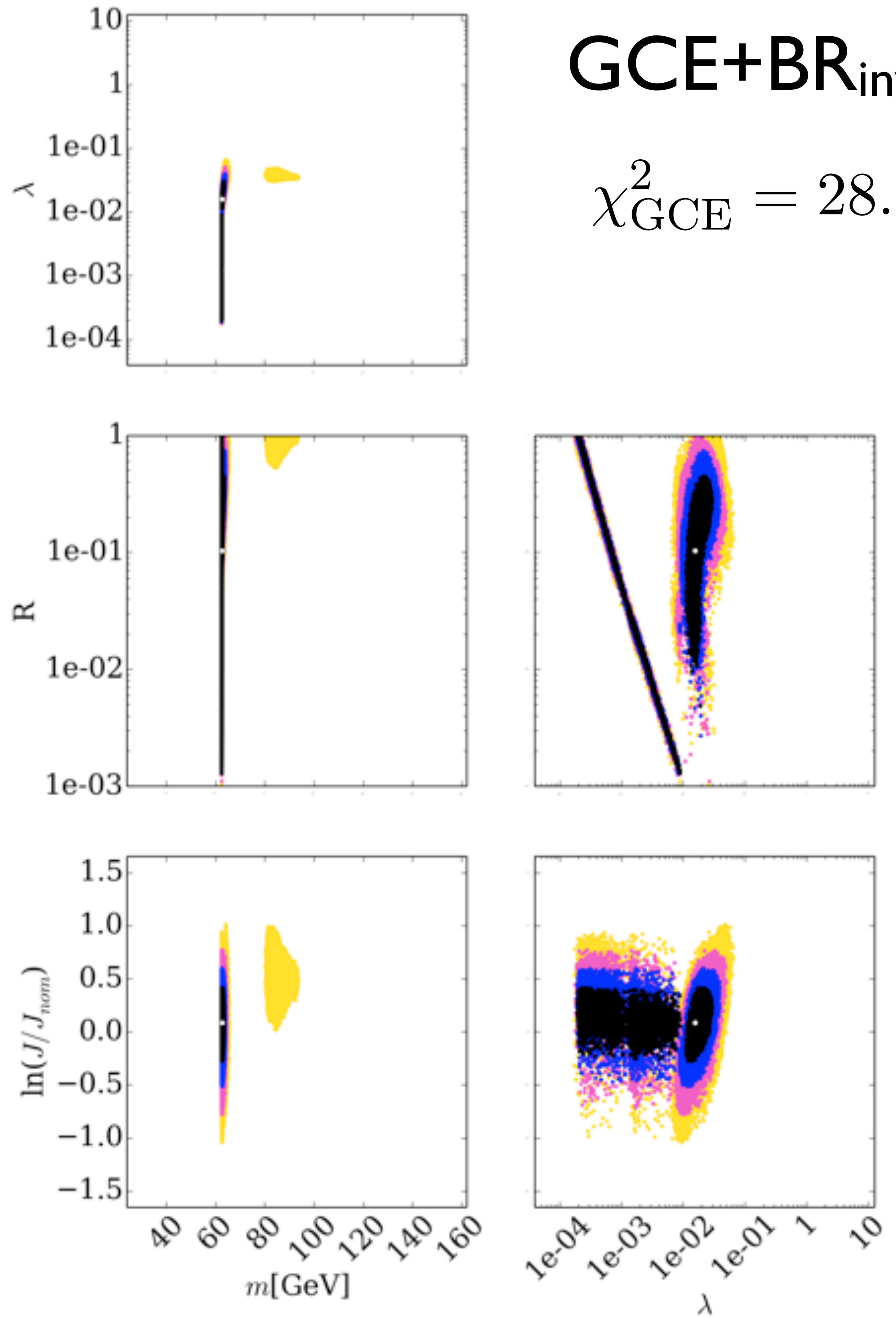


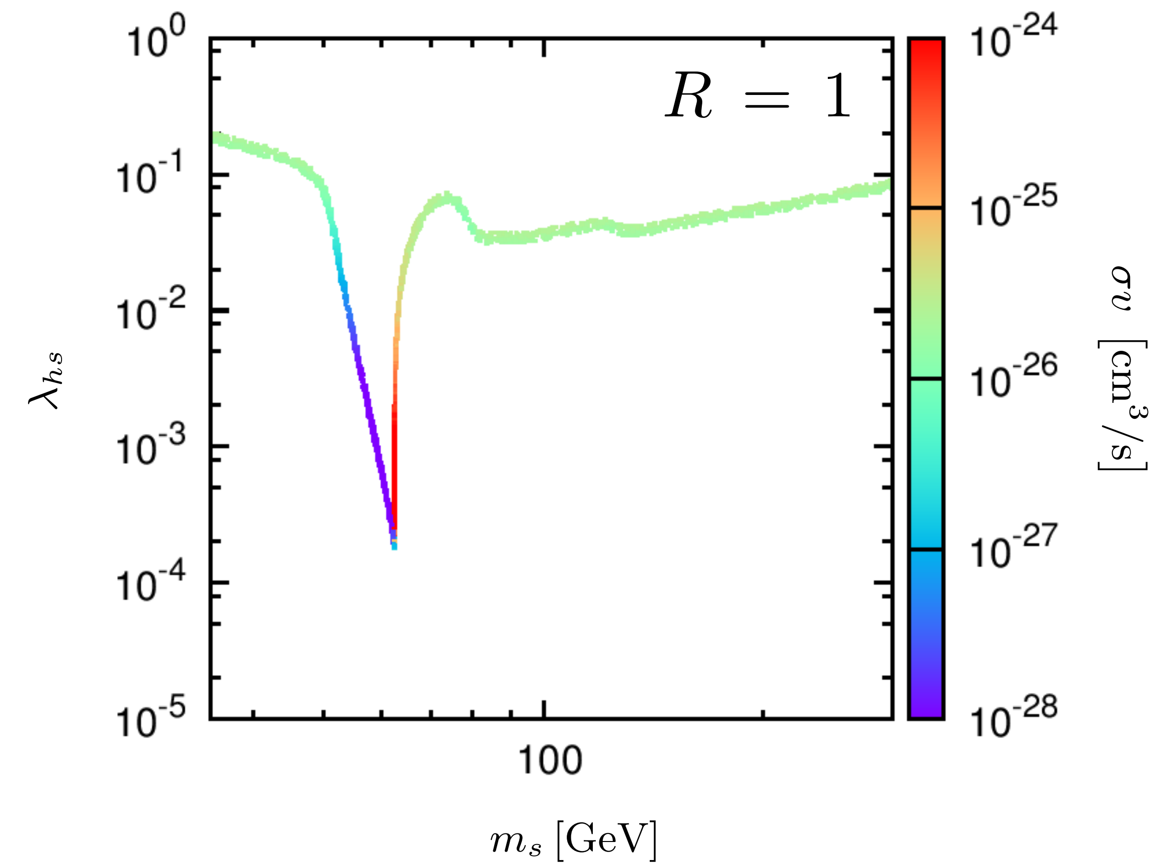
← Interesting structure in *R*

preliminary

GCE+BR$_{\text{inv}}$+LUX+Dwarfs+Lines+DM

$$\chi^2_{\text{GCE}} = 28.3$$





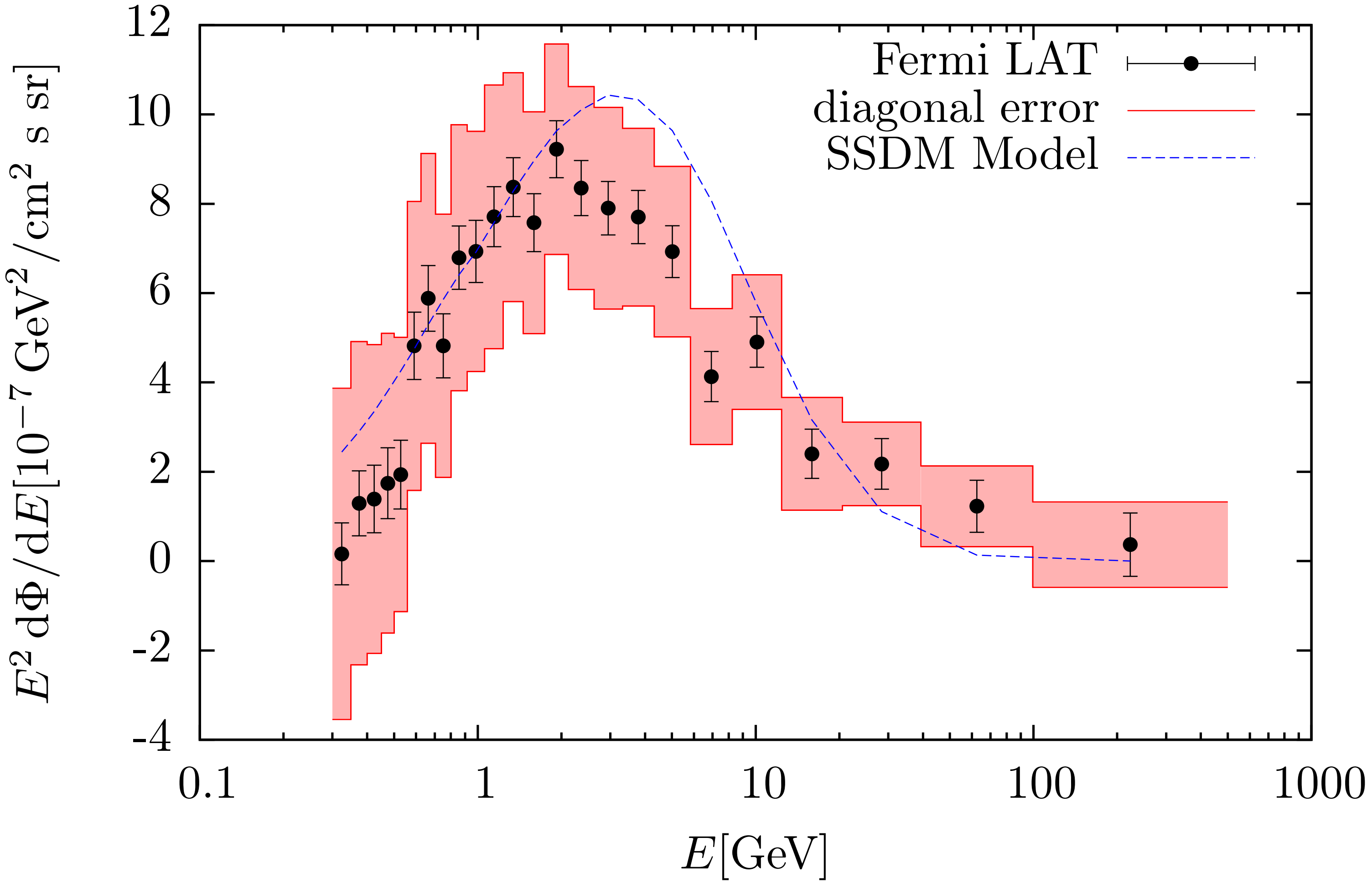
$$\phi \propto R^2 \langle \sigma v \rangle_{\text{today}}$$

$$\Omega_{\text{DM, total}} = \frac{\Omega_{\text{WIMP}}}{R} \propto \frac{1}{R\,\langle \sigma v \rangle_{\text{f.o.}}}$$

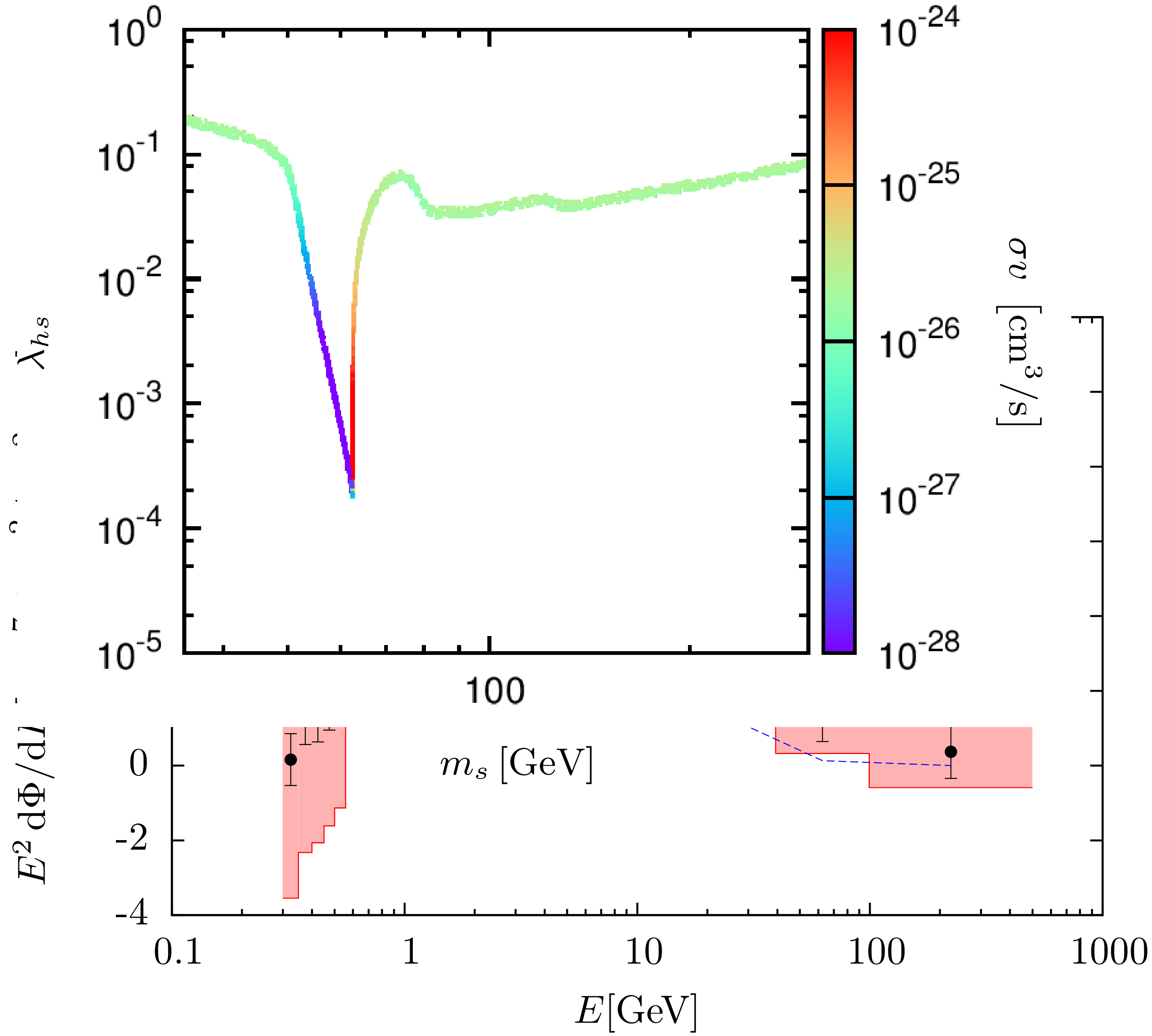
Summary

- WIMP DM intriguing explanation of GCE
- Higgs Portal: Unique coupling to minimal DM models
- Singlet Scalar Model: Good fit!
- After constraints: Only Higgs-resonance remains
- Allow for additional non-WIMP DM component
- Non-trivial implications for WIMP fraction near resonance (for large velocity dependence)

Backup slides:
Spectrum for best-fit point
(after all constraints)



Explain final result and R-factor



ToDo

- Best-fit points raussuchen
-

Parametric fits and theoretical uncertainties

- Take measured spectrum d_i and covariance matrix Σ_{ij} from [Calore, Cholis, Weniger: 1409.0042]
- Additional uncertainty on the theoretical prediction of the spectrum $\Sigma_{ij} \to \Sigma_{ij} + \delta_{ij} d_i^2 \sigma_s^2$, $\sigma_s = 10\%$

[Achterberg et al. 1502.05703]

- Compute χ^2 via:

$$\chi^2 = \sum_{i,j} (d_i - 10^{\xi} m_i)(\Sigma_{ij})^{-1}(d_j - 10^{\xi} m_j) + \frac{\xi^2}{(\log_{10} 2)^2}$$

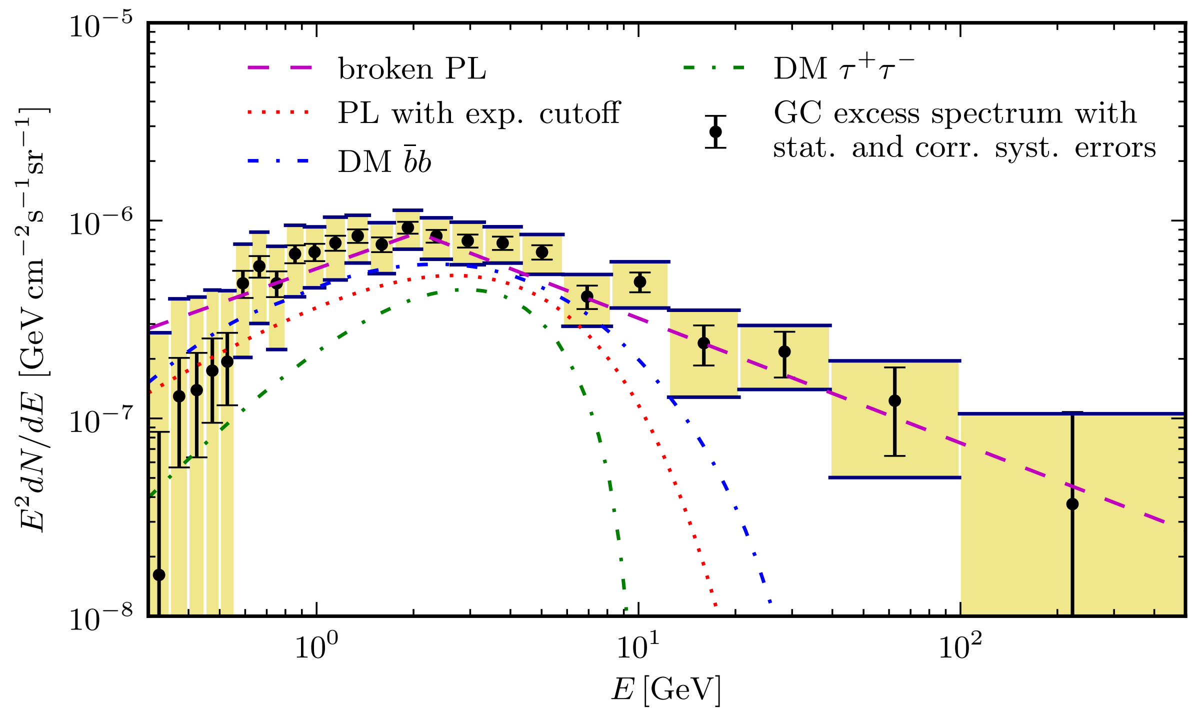
where $\xi = \log_{10}\left(\frac{\bar{J}}{\bar{J}^{\mathrm{NFW}}_{\text{best fit}}}\right)$

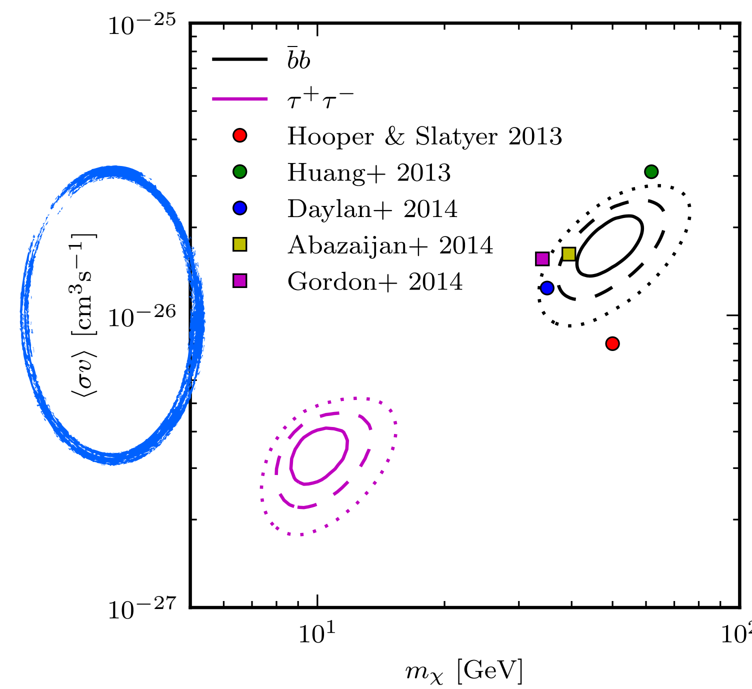
$\bar{J}^{\mathrm{NFW}}_{\text{best fit}}$ from [Calore, Cholis, Weniger: 1409.0042]

Takes into account uncertainties on the *J*-factor

Parametric fits to the Galactic center excess

[Calore, Cholis, Weniger: 1409.0042]





$$\chi^2 = \sum_{i,j}(d_i - m_i)(\Sigma_{ij})^{-1}(d_j - m_j)\ ,\ \Sigma_{ij} = (\sigma_i^{\mathrm{stat.}})^2\delta_{ij} + \Sigma_{ij,\,\mathrm{mod}}^{\mathrm{trunc}} + \Sigma_{ij,\,\mathrm{res}}$$

Spectrum	Parameters	χ^2/dof	p-value
broken PL	$\alpha_1 = 1.42^{+0.22}_{-0.31}$, $\alpha_2 = 2.63^{+0.13}_{-0.095}$, $E_{\mathrm{break}} = 2.06^{+0.23}_{-0.17}$ GeV	1.06	0.47
DM $\chi\chi \to \bar{b}b$	$\langle\sigma v\rangle = 1.76^{+0.28}_{-0.27} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 49^{+6.4}_{-5.4}$ GeV	1.08	0.43
DM $\chi\chi \to \bar{c}c$	$\langle\sigma v\rangle = 1.25^{+0.2}_{-0.18} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 38.2^{+4.6}_{-3.9}$ GeV	1.07	0.44
PL with exp. cutoff	$E_{\mathrm{cut}} = 2.53^{+1.1}_{-0.77}$ GeV, $\alpha = 0.945^{+0.36}_{-0.5}$	1.37	0.16
DM $\chi\chi \to \tau^+\tau^-$	$\langle\sigma v\rangle = 0.337^{+0.047}_{-0.048} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 9.96^{+1.1}_{-0.91}$ GeV	1.52	0.065

Higgs Portal Model

[Burgess, Pospelov, Veldhuis: hep-ph/0011335, ...]

- Extend Higgs sector by a scalar singlet *s*:

$$V(s^2, H^\dagger H) = \lambda_h \left[\left(H^\dagger H \right) - \frac{v^2}{2} \right]^2 + \frac{1}{2}\, \lambda_{hs}\, s^2\, H^\dagger H + \frac{1}{4}\, \lambda_s\, s^4 + \frac{1}{2}\, m_{s_0}^2\, s^2$$

After EW symmetry breaking:

$$V(s^2, h) = V(h) + \frac{1}{2}\, m_s^2\, s^2 + \frac{1}{4}\, \lambda_s\, s^4 + \frac{1}{2}\, \lambda_{hs}\, v\, h\, s^2 + \frac{1}{4}\, \lambda_{hs}\, h^2\, s^2,$$

where $m_s^2 = m_{s_0}^2 + \lambda_{hs}\, v^2/2.$

Important for pheno

[also interesting in the context of WIMP Inflation, see e.g. Kahlhoefer, McDonald: 1507.03600 for a recent analysis]

Implementation: Constraints

- Collider constraints: Higgs invisible BR

Constraints

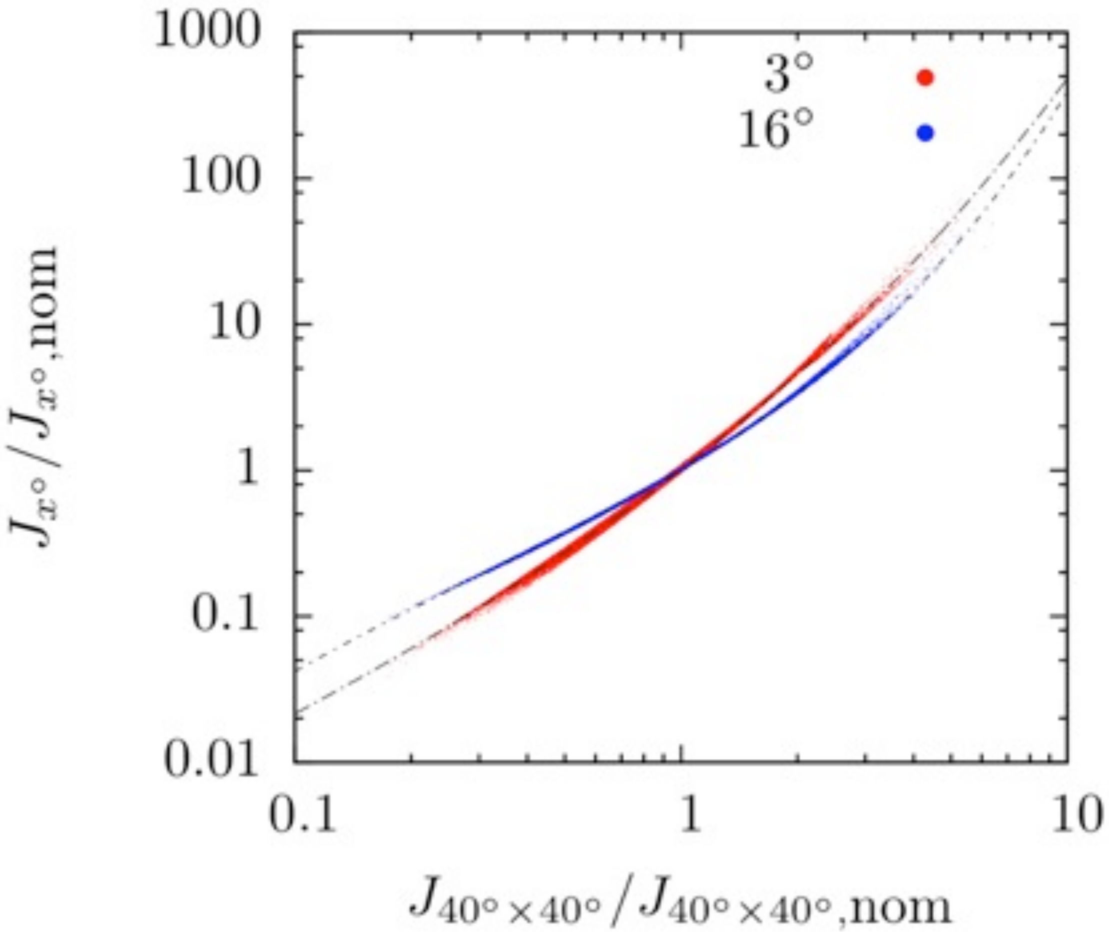
-BRinv (not dep.on R)

-LUX (LuxCalc) ll, p-valu

-Dwarfs

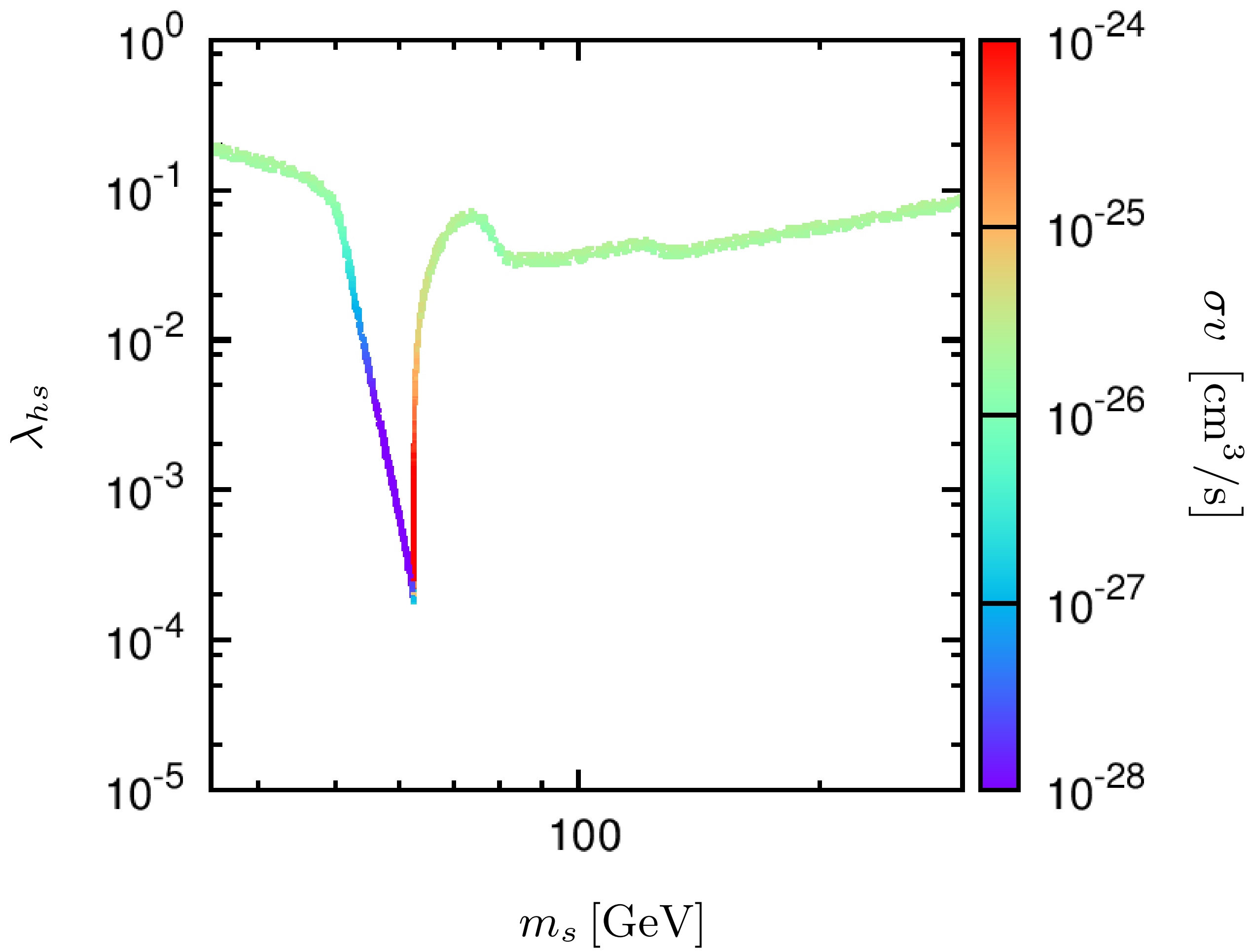
-gamma-lines

-density

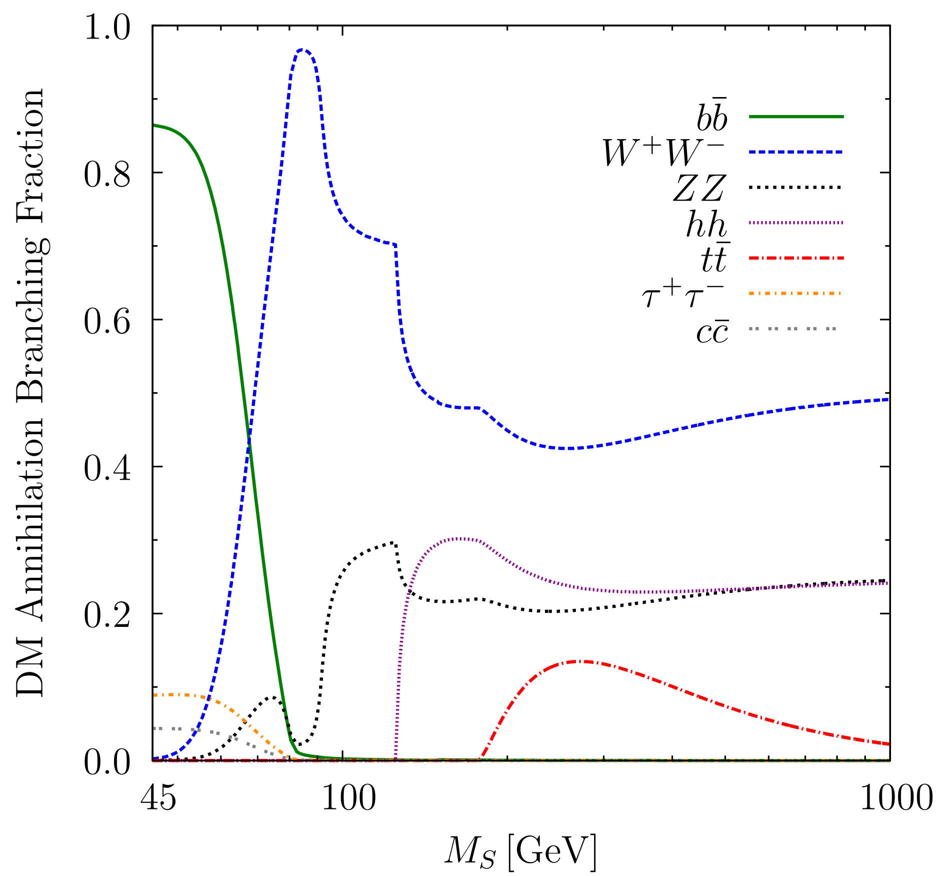


Higgs Portal Model

- Constraints on the parameter space:

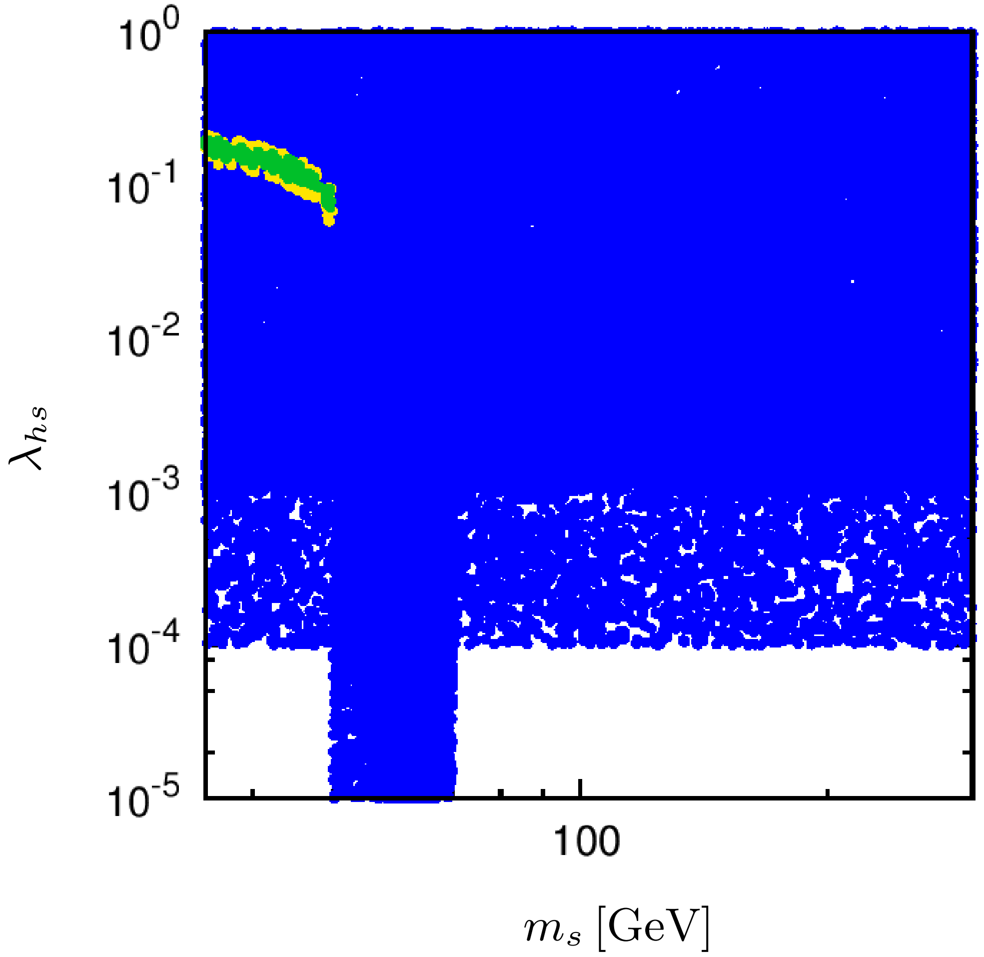


[Duerr, Pérez, Smirnov: 1510.07562]

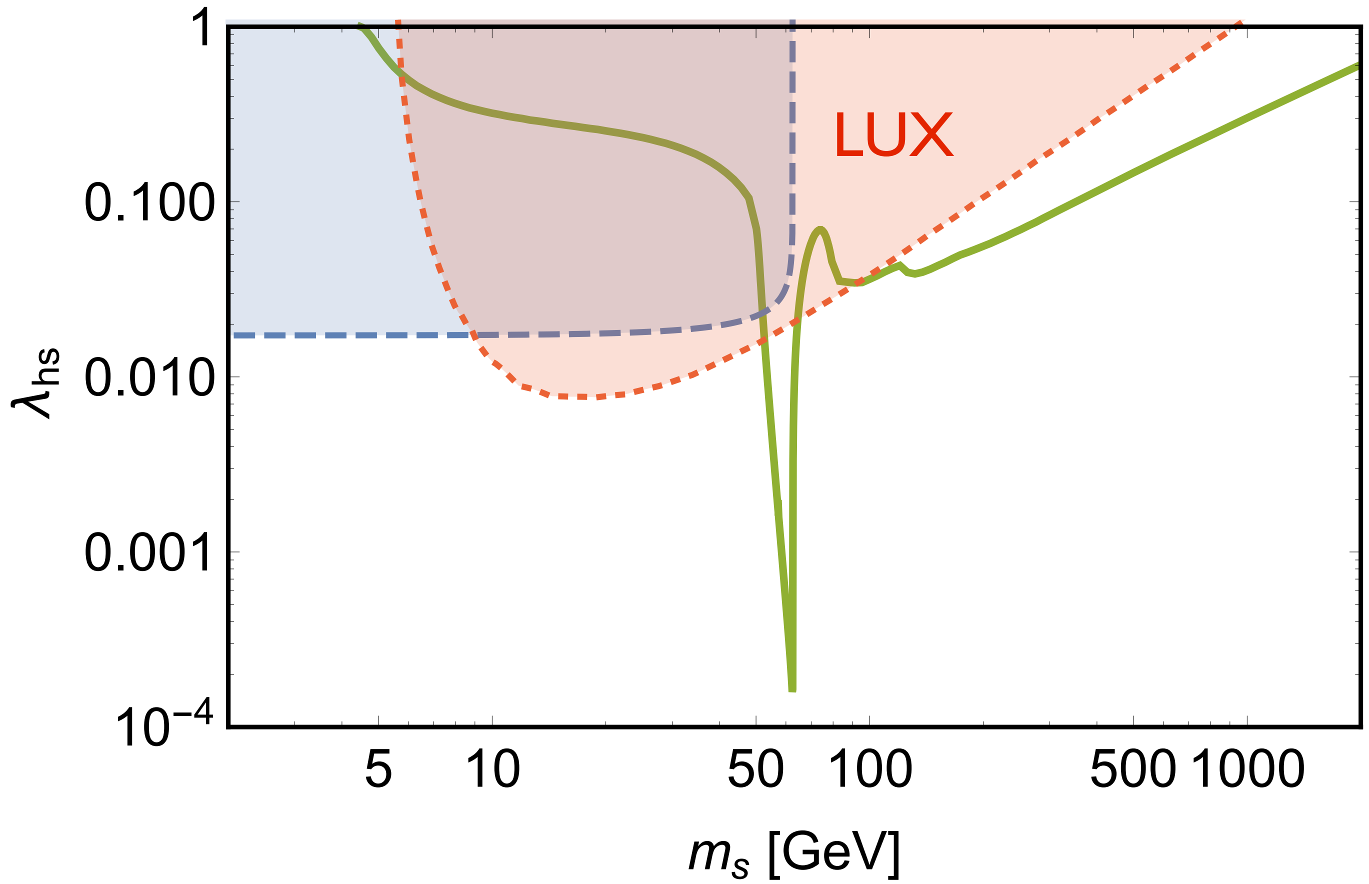


Higgs Portal Model

- GCE fits versus constraints:



[Kahlhoefer, McDonald: 1507.03600]

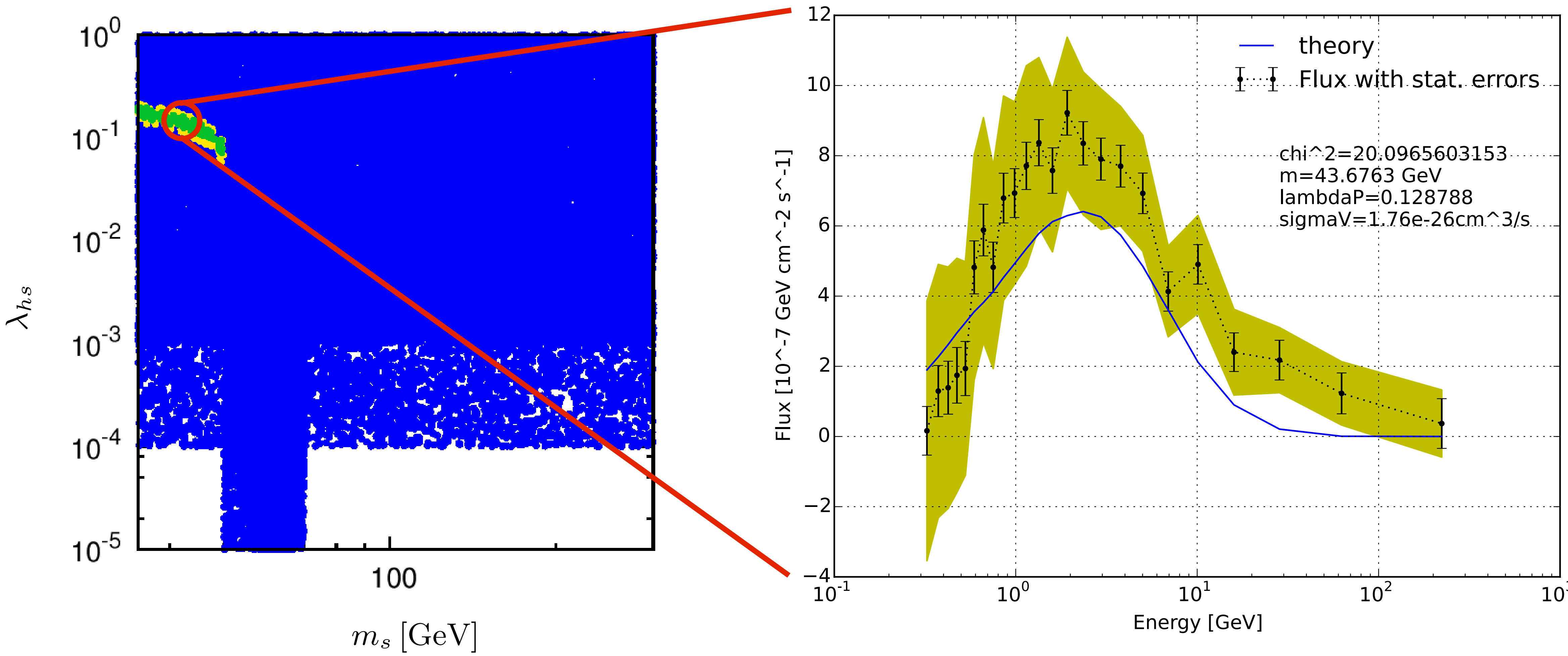


[see also Duerr, Pérez, Smirnov:1509.04282]

Higgs Portal Model

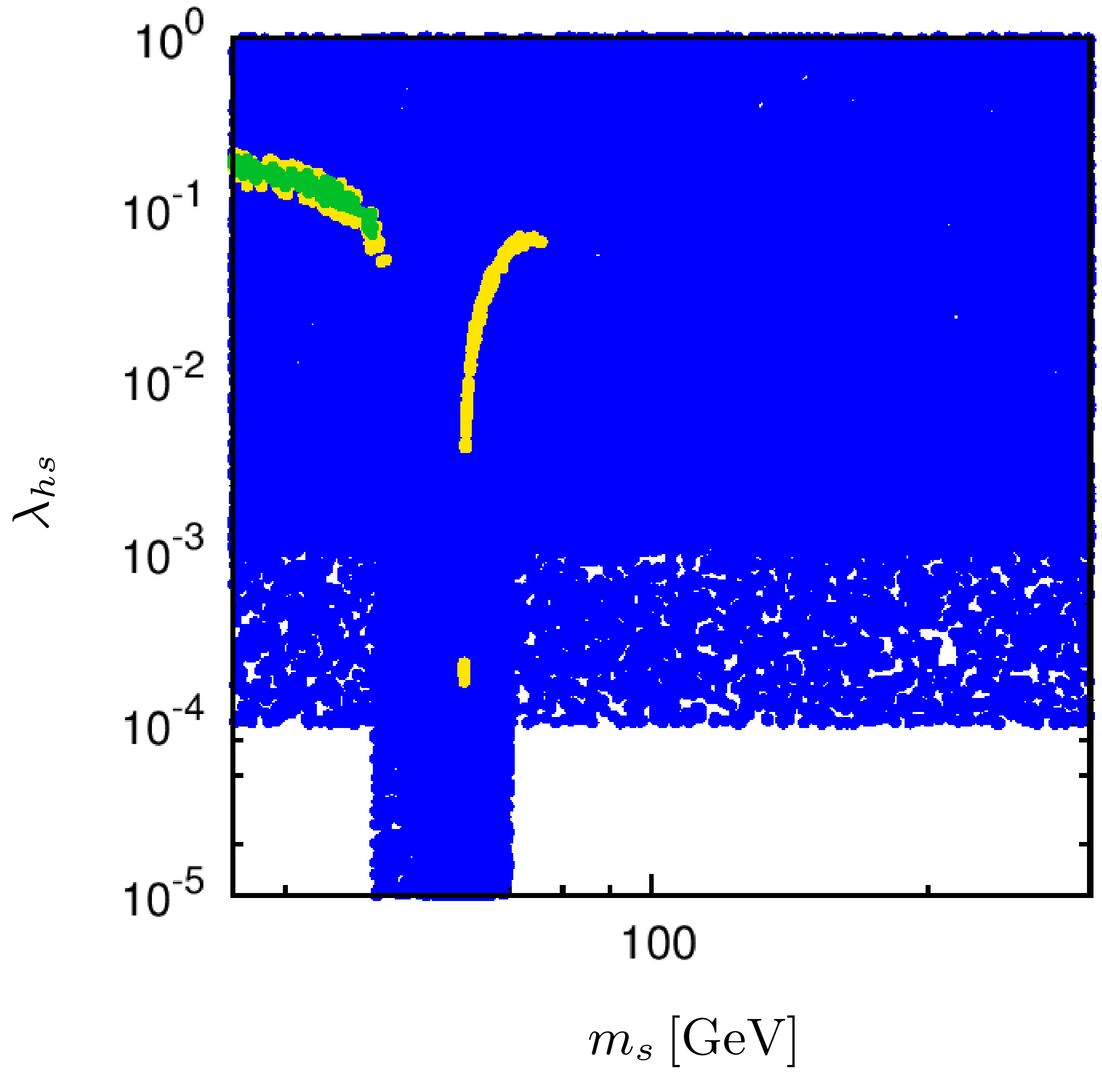
- GCE fits versus constraints:

Best fit point:

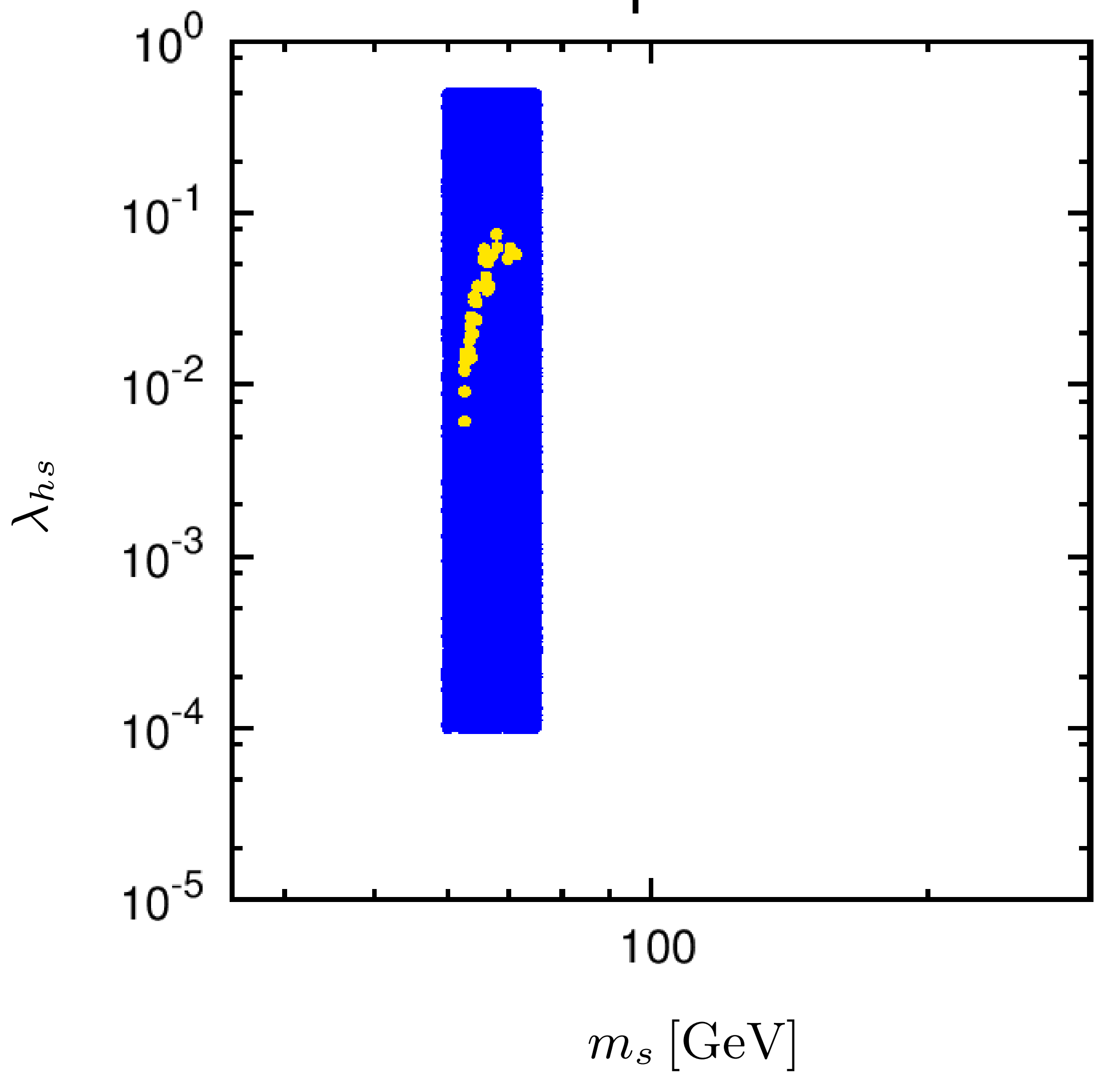


Higgs Portal Model

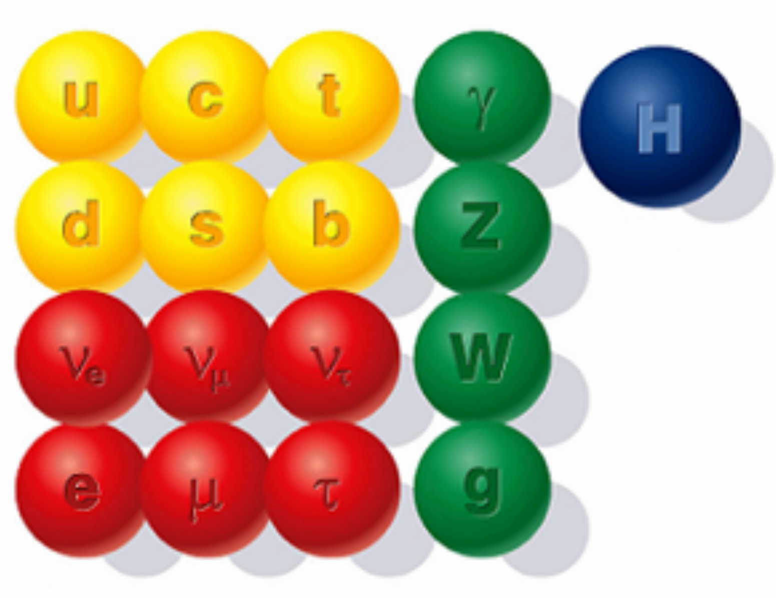
- GCE fits:



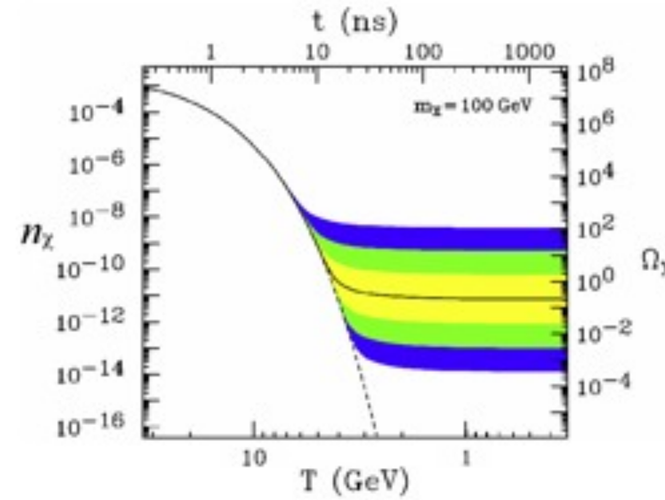
Dropping the assumtion that the WIMP makes up 100% of DM:

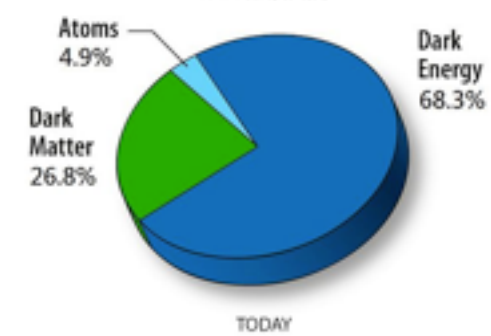


Dark Matter → WIMP



+ X →





Pheno description

- Effective Operators
- Simplified Models

Probe

- Direct detection experiments
- Indirect detection (IceCube)
- Thermal relic density
- DM production@LHC