Global dark matter fits in the light of a possible indirect detection signal

[based on A. Cuoco, B. Eiteneuer, JH, M. Krämer: JCAP 1606 (2016) 050, 1603.08228 and work in progress together with B. Eiteneuer, A. Goudelis]

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Aachen Bonn Heidelberg Mainz

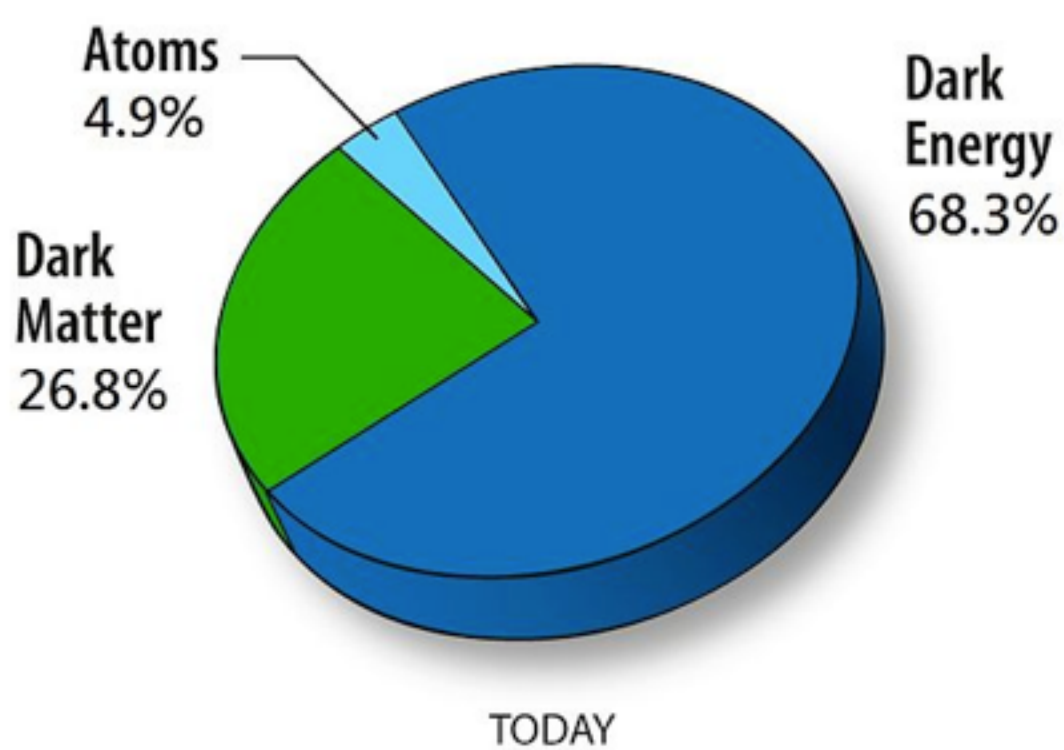
Fit(s) for LHC Run-2 Oct. 2016

Higgs Centre for Theoretical Physics

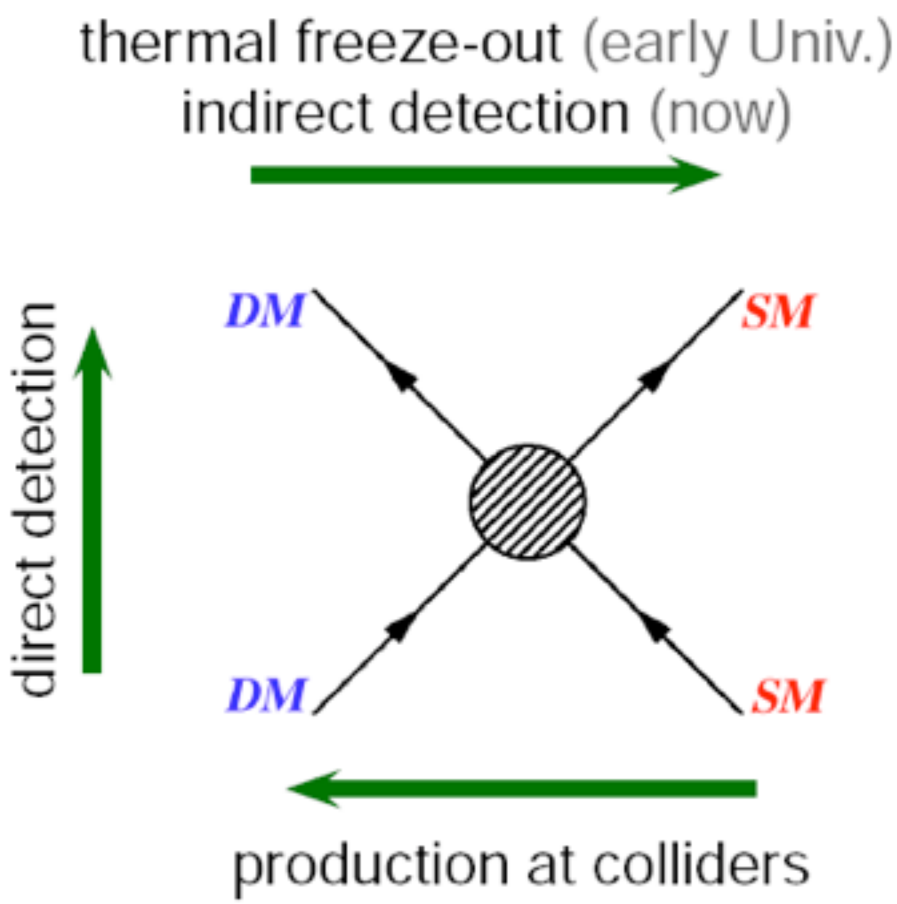
THE UNIVERSITY OF EDINBURGH

Dark Matter at the LHC: WIMP

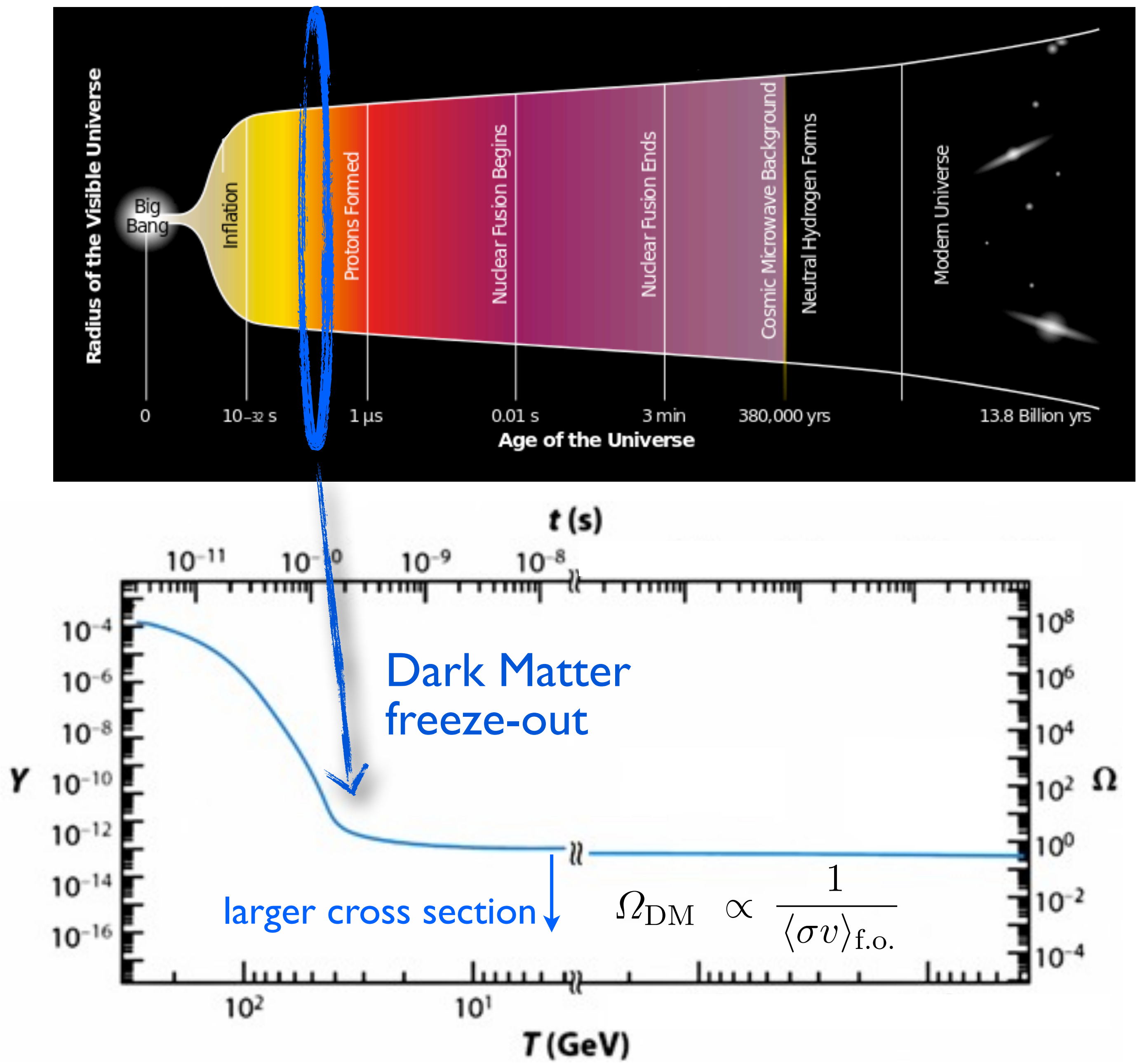
Energy density of the universe:



Dark Matter at the LHC: WIMP

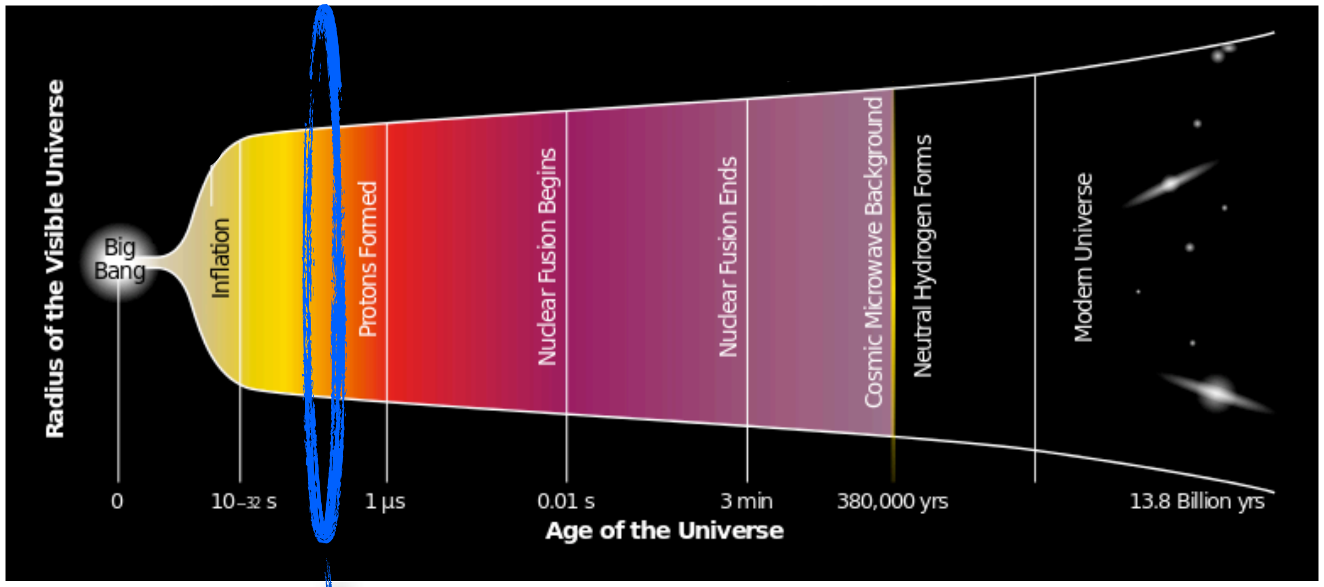


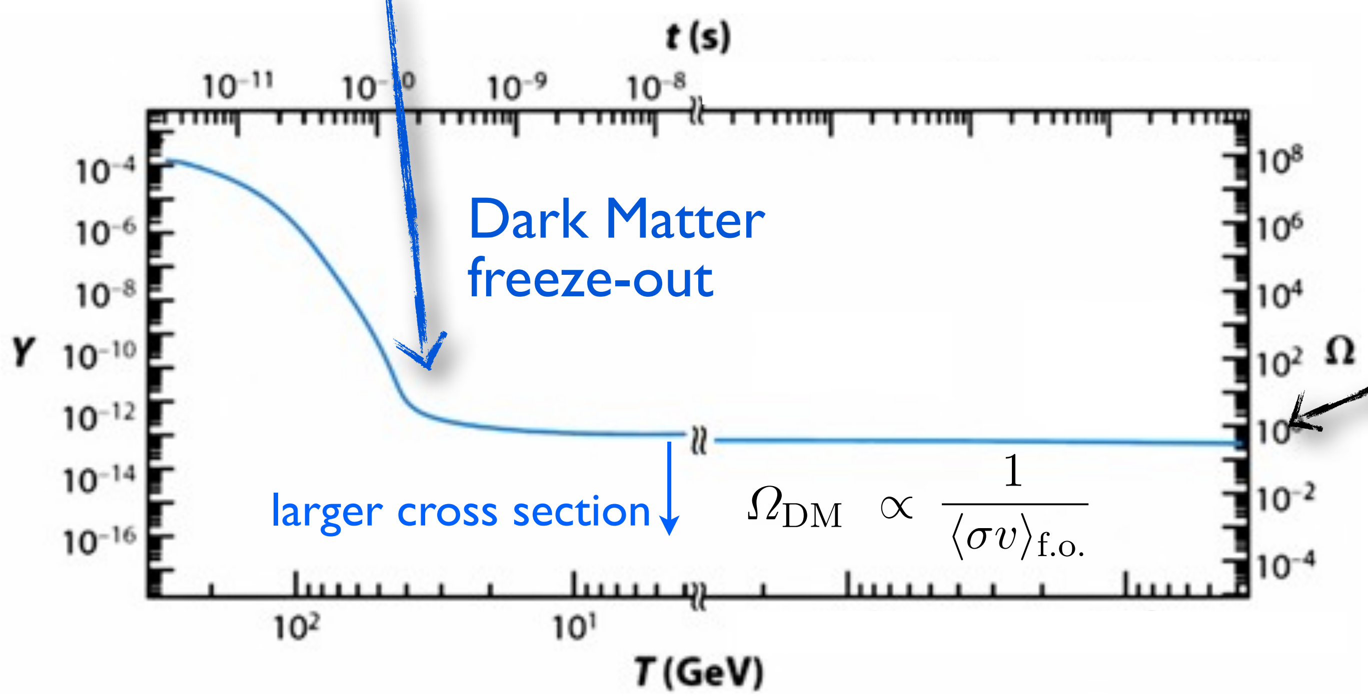
WIMP Dark Matter: freeze-out



- Plausible "production" mechanism
- Computable prediction for relic density

WIMP Dark Matter: freeze-out

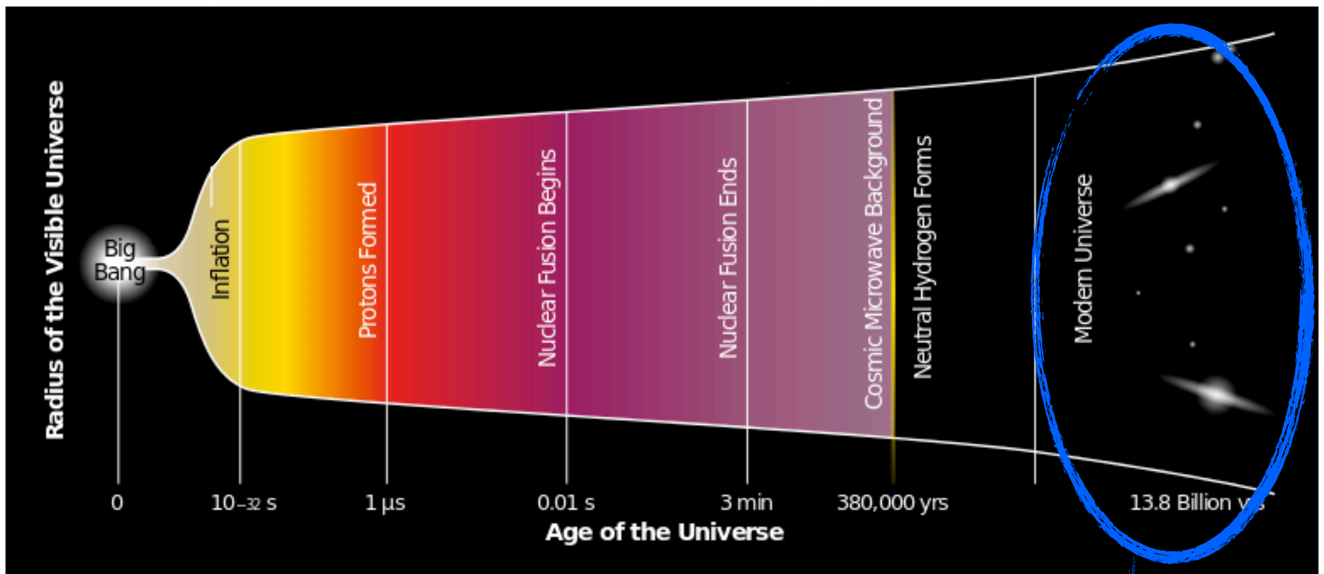


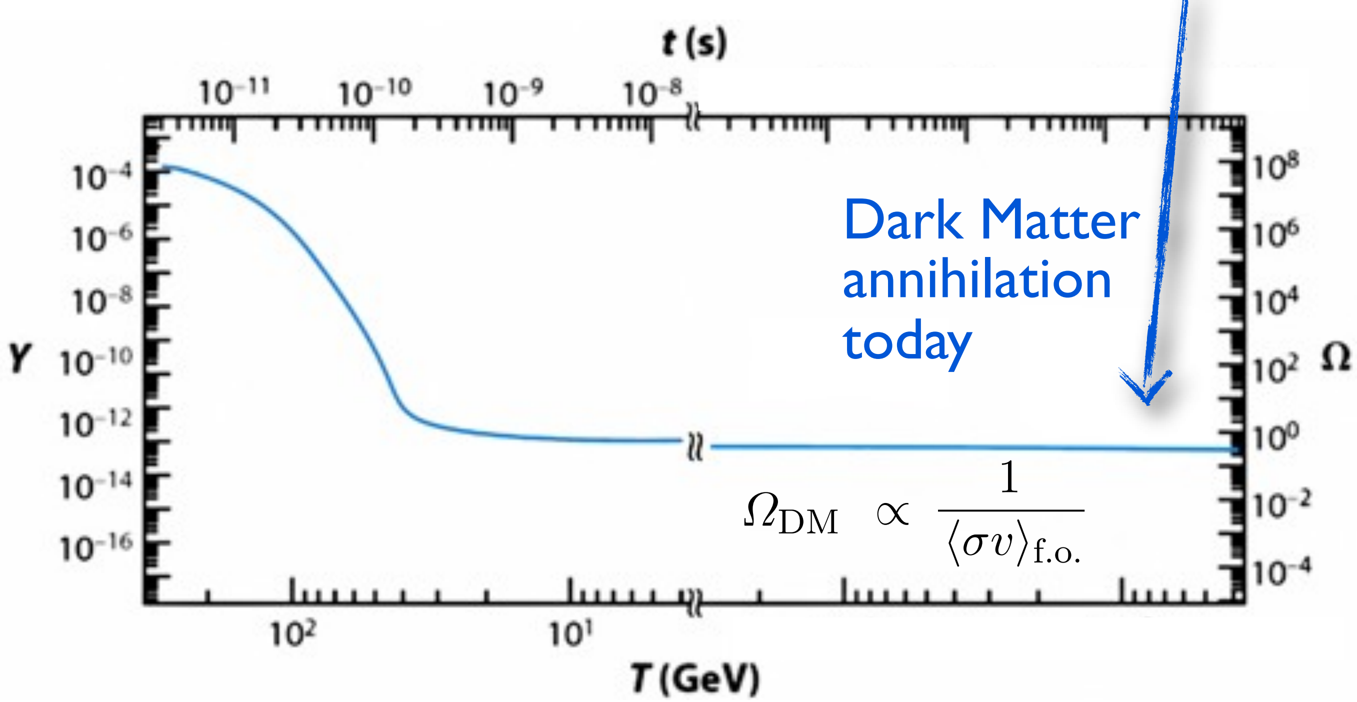


- Plausible "production" mechanism
- Computable prediction for relic density
- Planck measurement:

$$\Omega h^2|_{\rm Planck} = 0.1198 \pm 0.0015$$

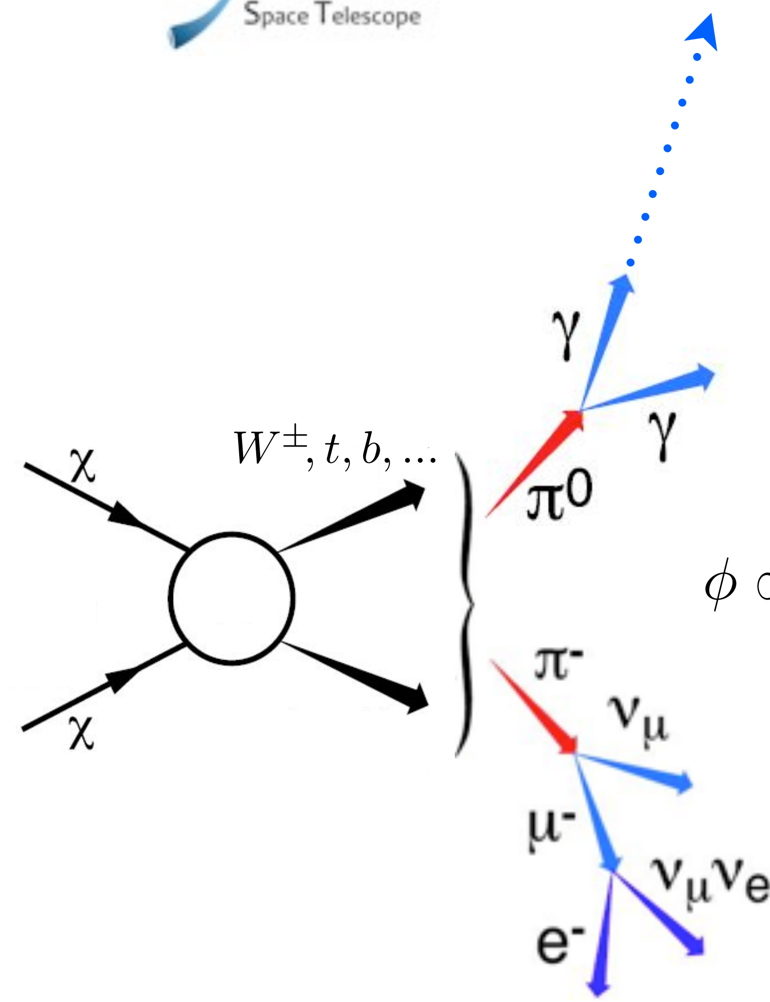
WIMP Dark Matter: annihilation today





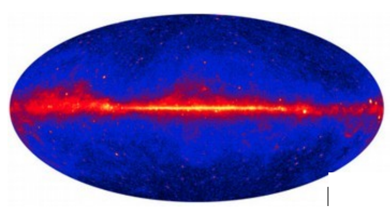
Indirect detection:

Fermi Gamma-ray Space Telescope

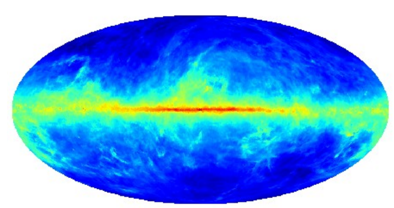


$$\phi \propto \langle\sigma v\rangle_{\rm today}$$

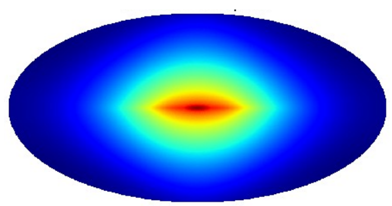
Fermi GeV Galactic Center Excess


Fermi gamma-ray sky

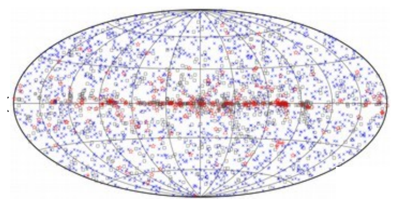
=


Pion decay/Bremsst.

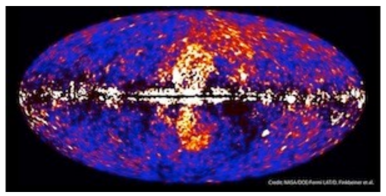
+


Inverse Compton

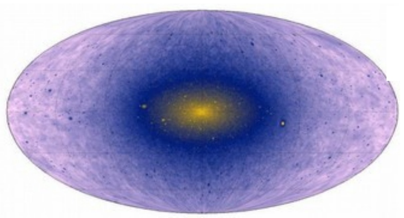
+


Point sources

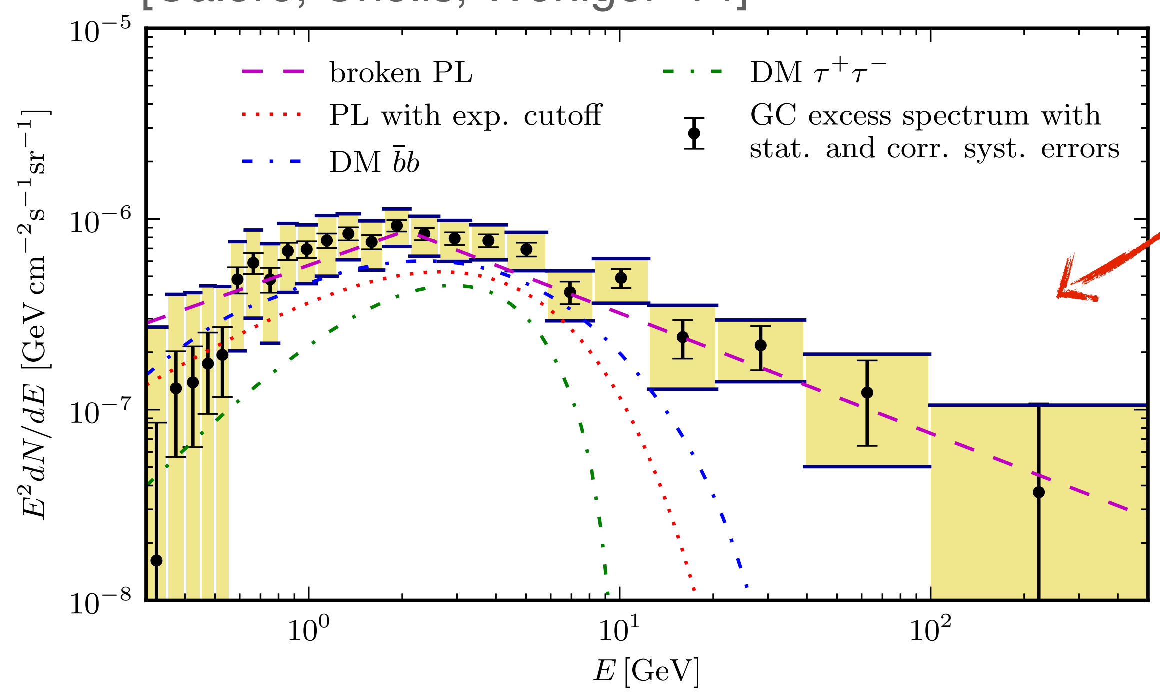
+


Fermi bubbles

+


Galactic buldge emission (excess)

[Calore, Cholis, Weniger '14]

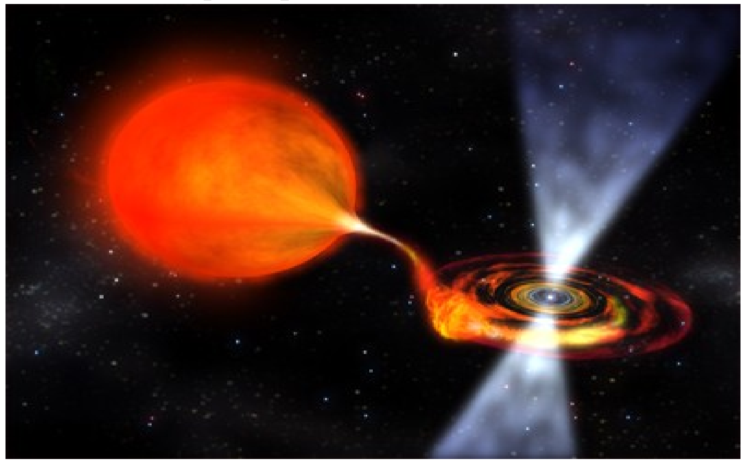


[Goodenough, Hooper '09, '10; Vitale, Morselli '09; Hooper, Linden '11; Abazajian, Kaplinghat '12; Hooper, Slatyer '13; Macias, Gordan '13; Huang *et al.* '13; Abazajian *et al.* '14; Daylan *et al.* '14; Zhou *et al.* '14; Calore *et al.* '14; Gaggero *et al.* '15; Cholis *et al.* '15; Bartels *et al.* '15; Lee *et al.* '15; Ajello *et al.* (*Fermi*-LAT) '15; ...]

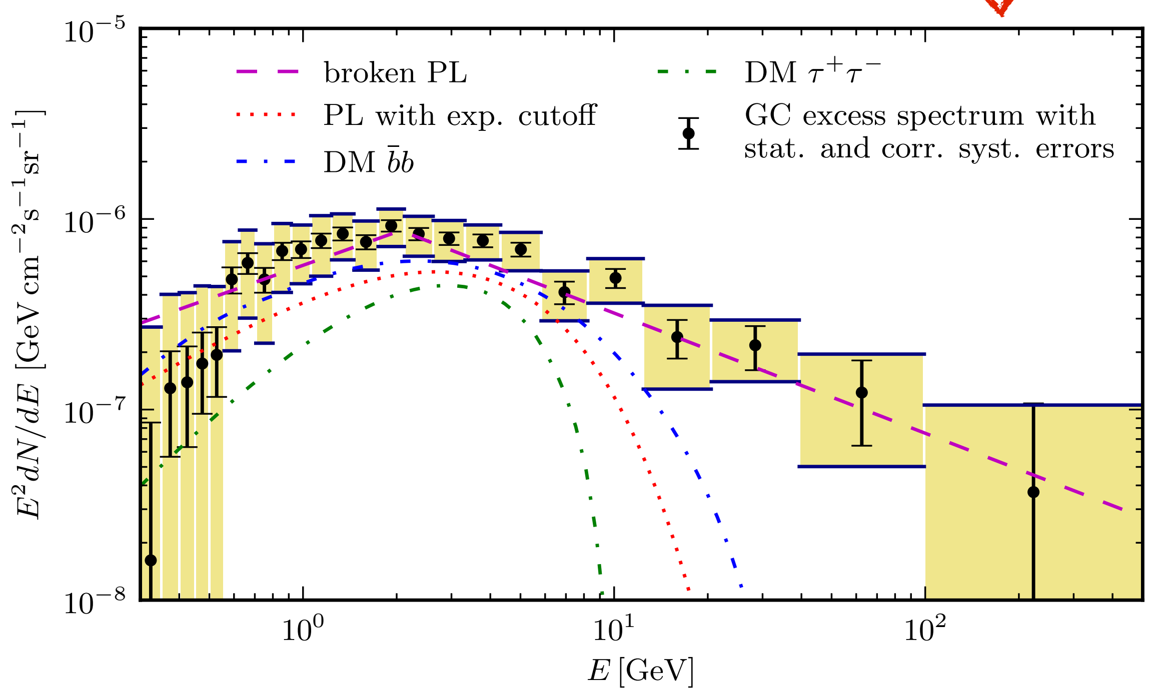
⇒ Excess over the known foregrounds in *Fermi*-LAT data

Fermi GeV Galactic Center Excess

Astrophysical sources



?



[Calore, Cholis, Weniger '14]

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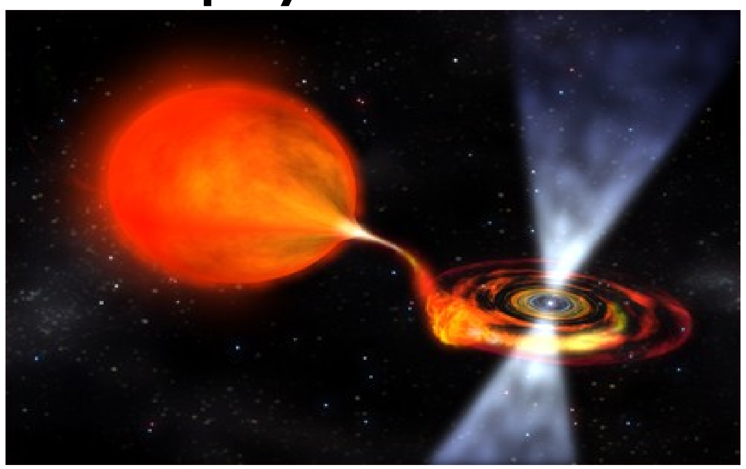
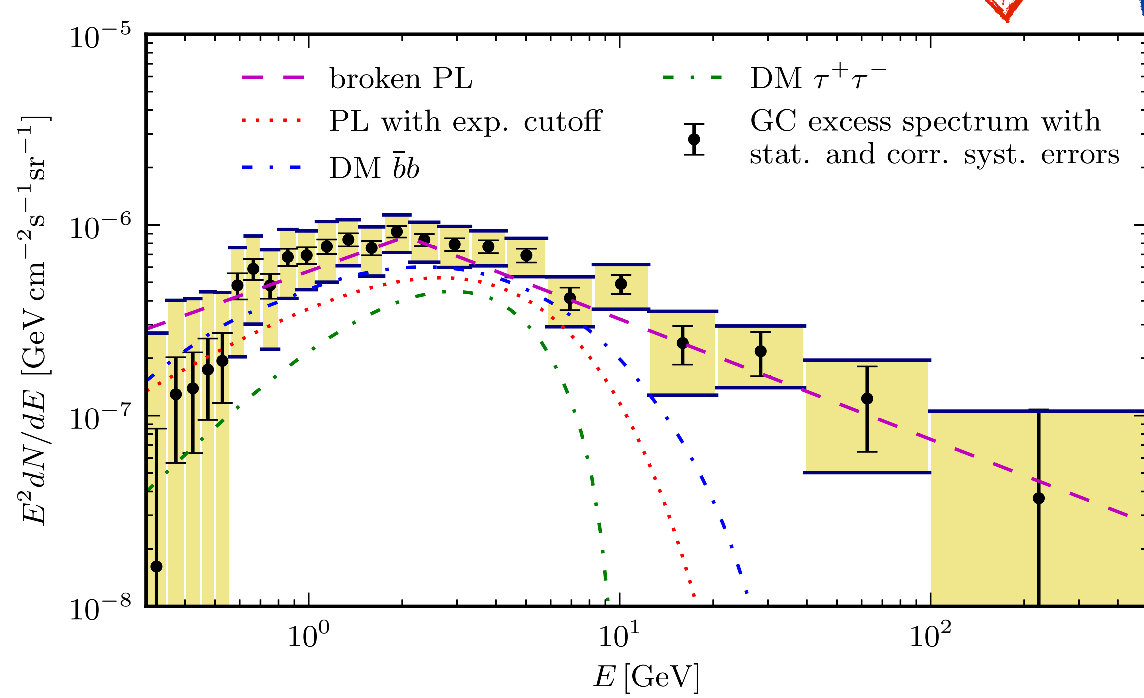


WIMP Dark Matter



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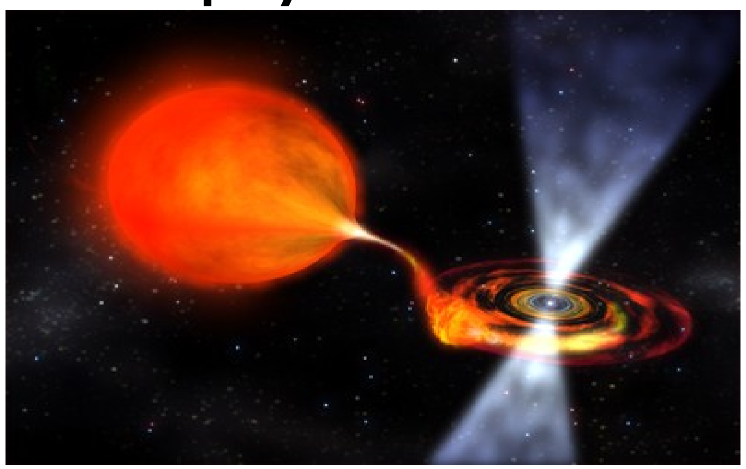
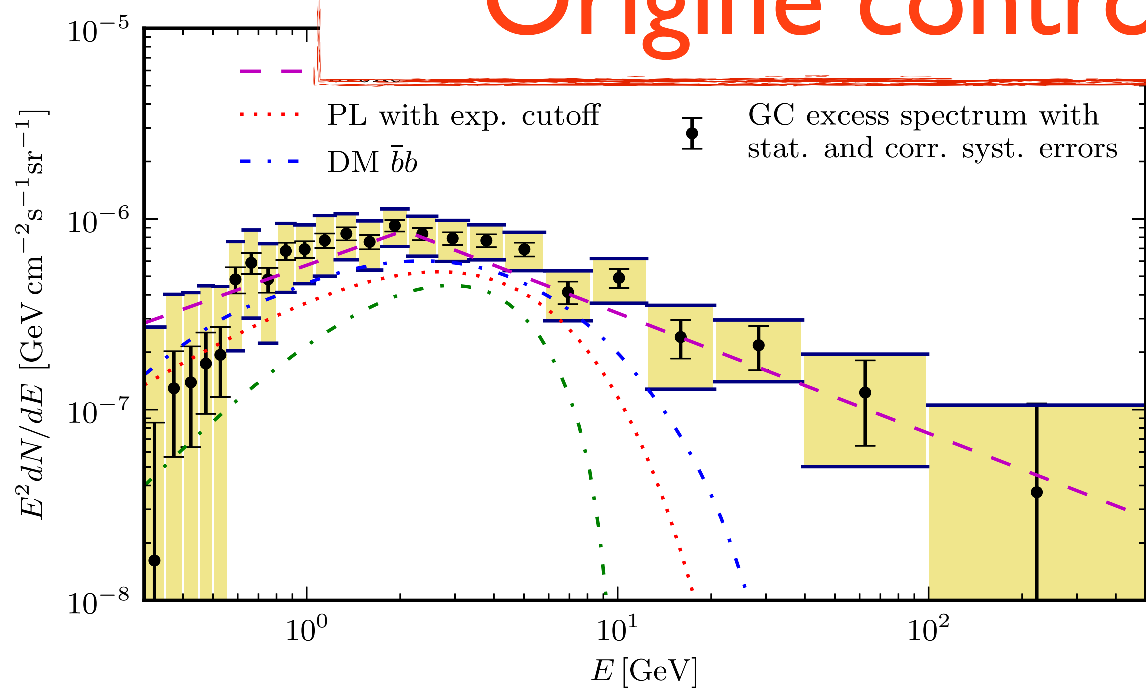


WIMP Dark Matter

? ?

Origine controversially discussed



alore, Cholis, Weniger '14]

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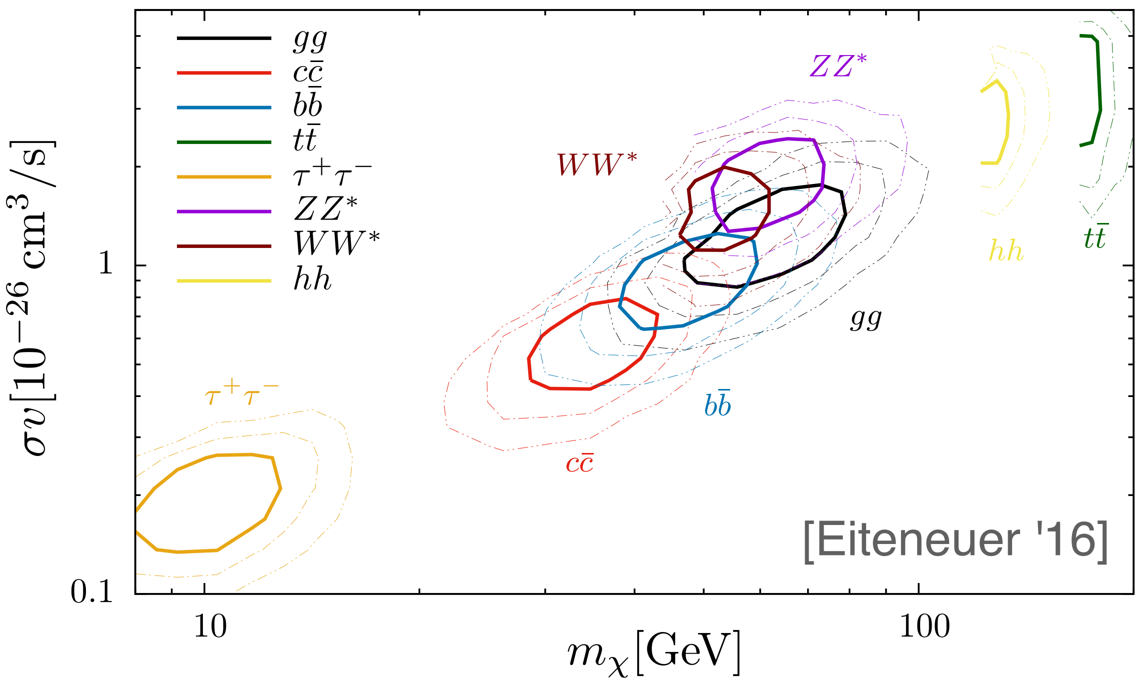

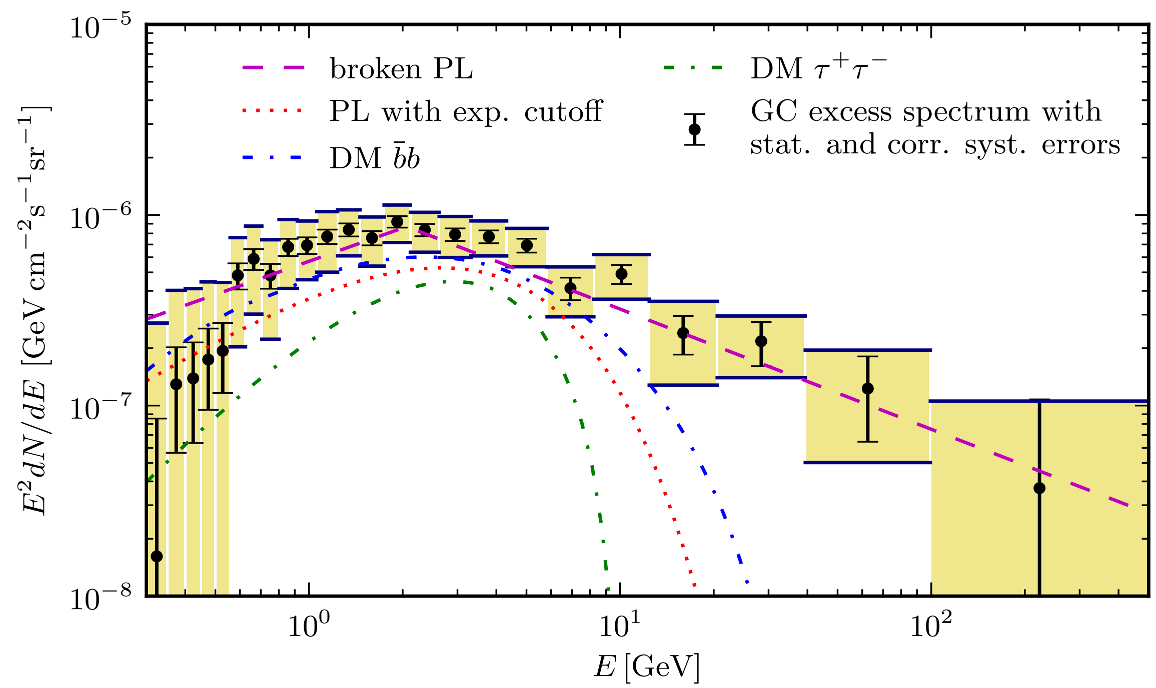

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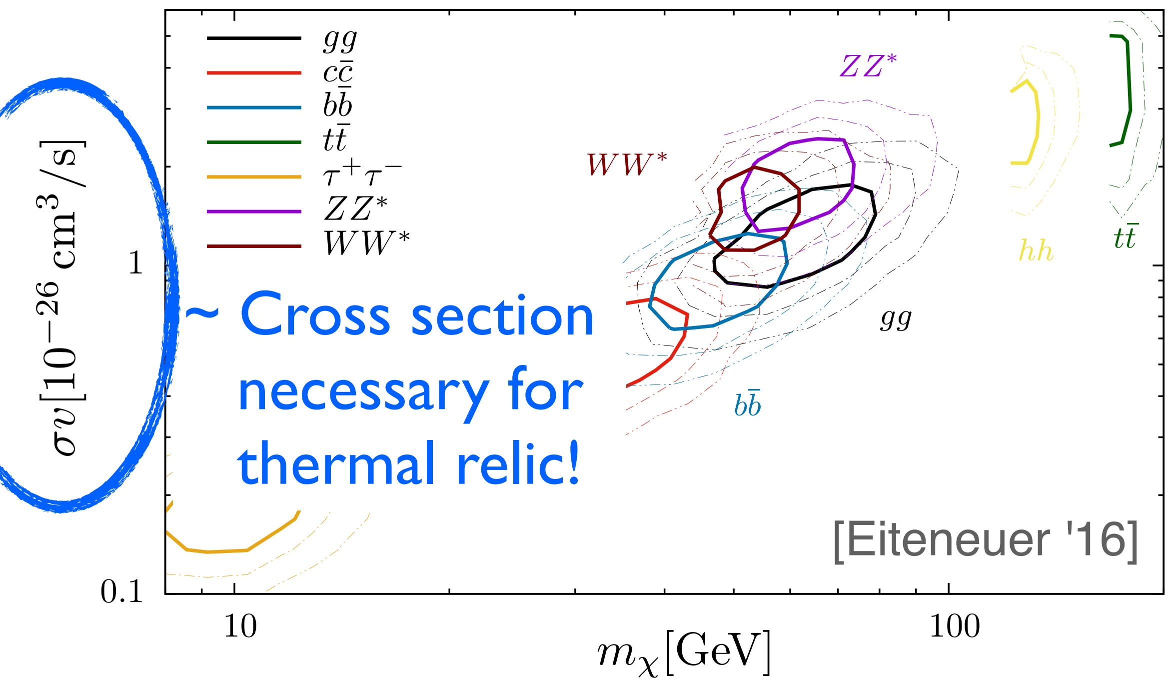
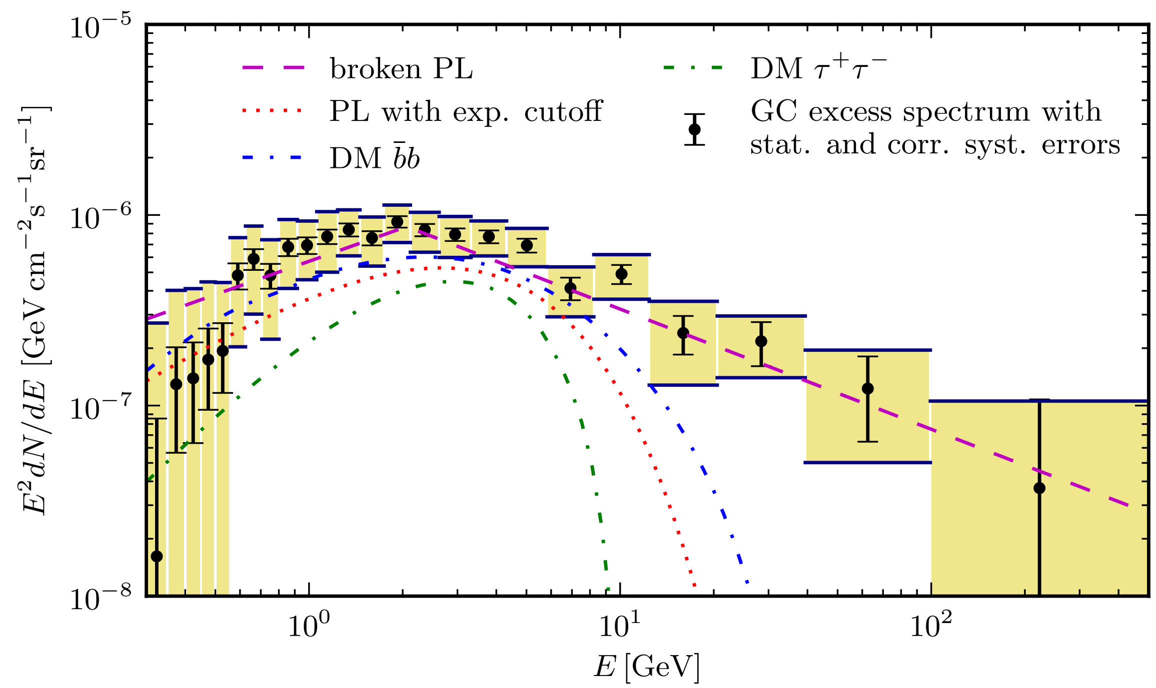


~ Cross section necessary for thermal relic!



[Calore, Cholis, Weniger '14]

WIMP Dark Matter

⇒ Excess over the known foregrounds in *Fermi*-LAT data

This work:

- Include signal in global fits (LHC, LUX, relic density,...)
- Simple but *realistic* DM models:
  - Scalar Singlet Higgs Portal Model
  - Inert Doublet Model
- Allow for additional non-WIMP DM component (PBHs, axions,...)

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

➔ Interesting implications

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➔ Interesting implications

Outline

- Scalar Singlet Higgs Portal Model
  - The model
  - Dark Matter annihilation and GCE fit
  - Constraints on the parameter space
  - Fit Results
  - Future experimental prospects
- Inert Doublet Model
- Conclusions

Scalar Singlet Higgs Portal Model

Scalar Singlet Higgs Portal Model

[Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Veldhuis: '01; ...]

- 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)

Scalar Singlet Higgs Portal Model

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

Scalar Singlet Higgs Portal Model

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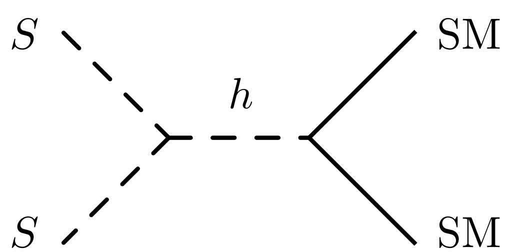
Important for this work

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

Dark Matter annihilation

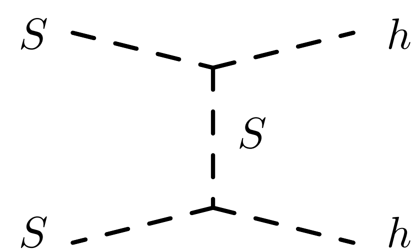
- Annihilation processes:

a)



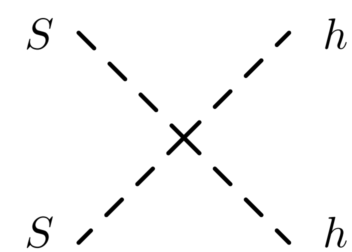
$\propto v\lambda_{HS}$

b)



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

c)

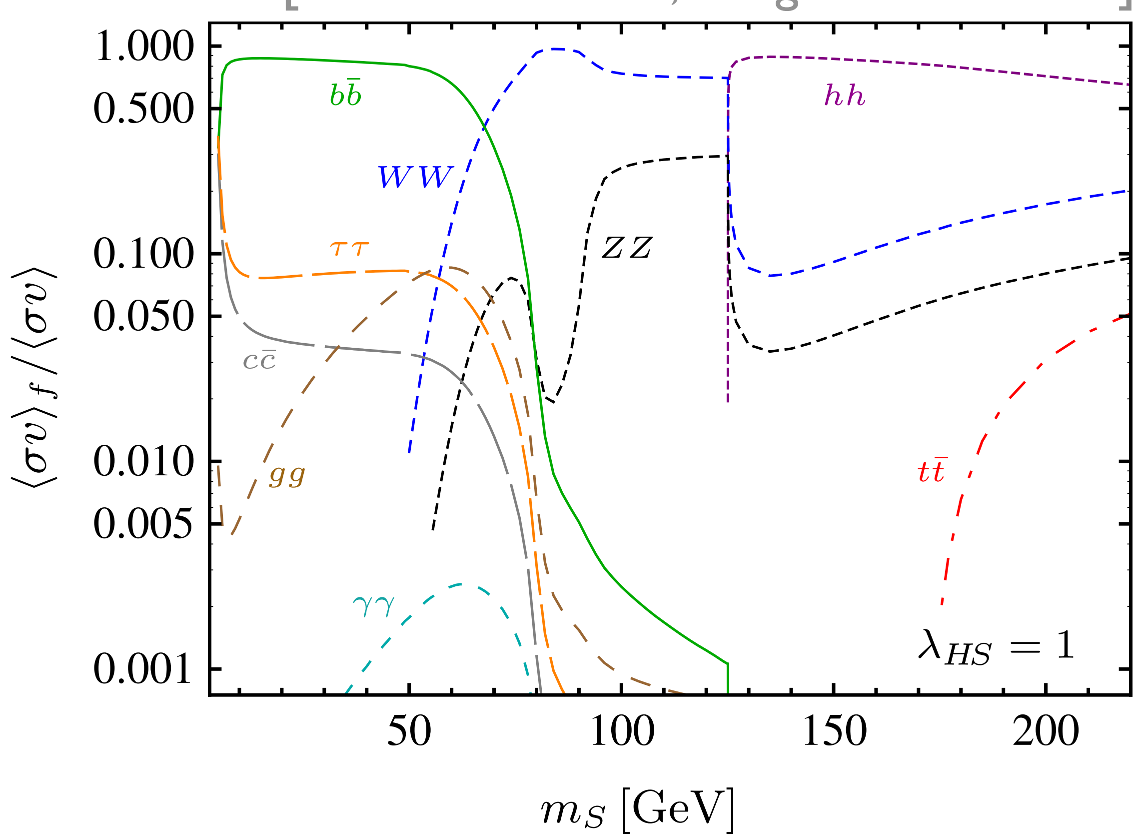


$\propto \lambda_{HS}$

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

Only present above Higgs threshold

[from 1603.08228, using micrOMEGAs]



[see also e.g.
Cline, Scott, Kainulainen, Weniger '13;
Duerr, Pérez, Smirnov '15;
Beniwal *et al.* '15]

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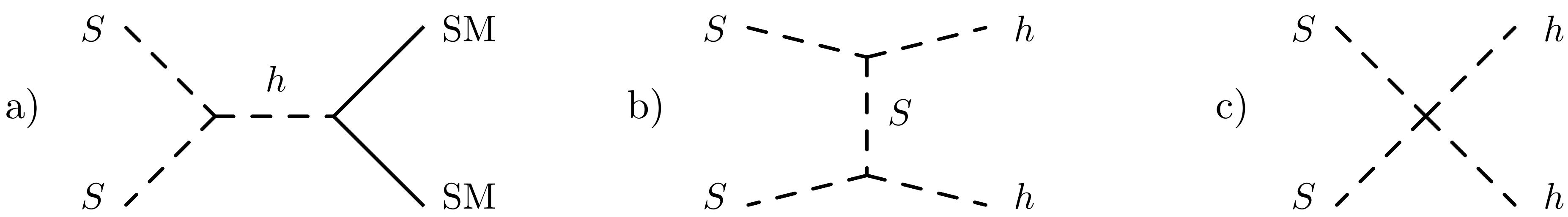

$\propto v\lambda_{HS}$ $\propto (v\lambda_{HS})^2$ $\propto \lambda_{HS}$

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

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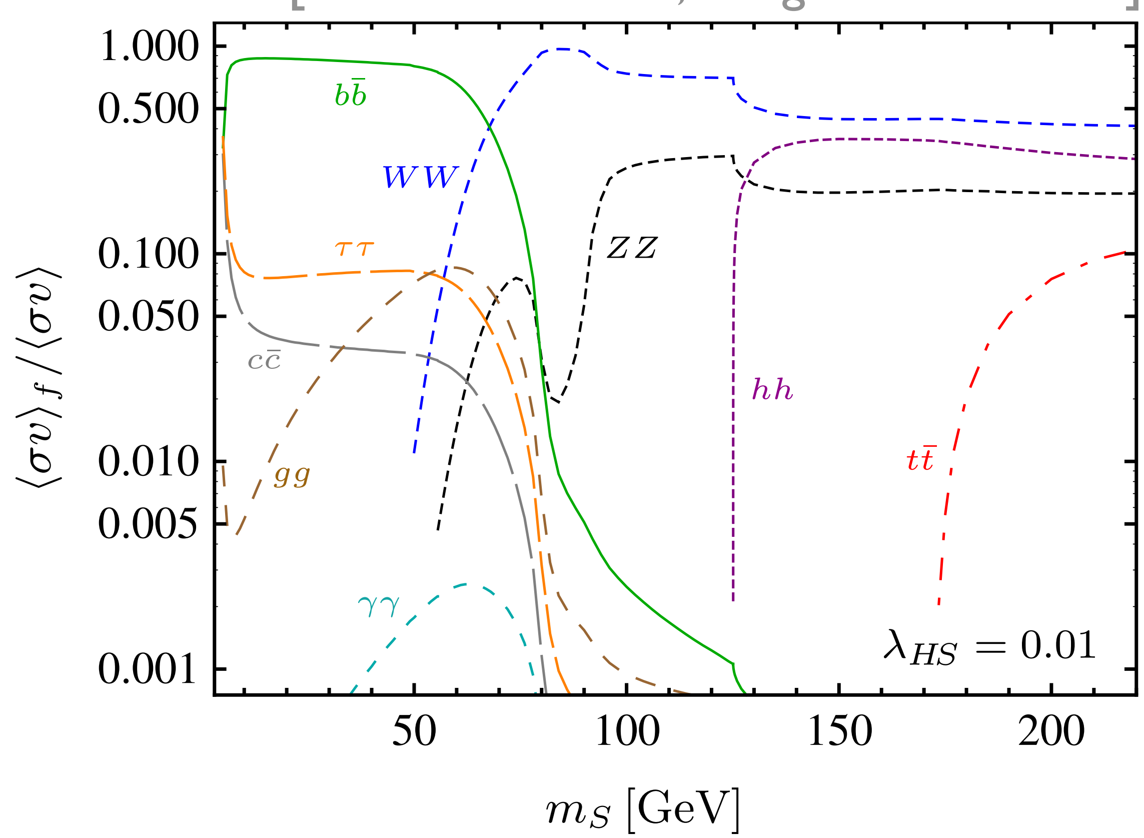

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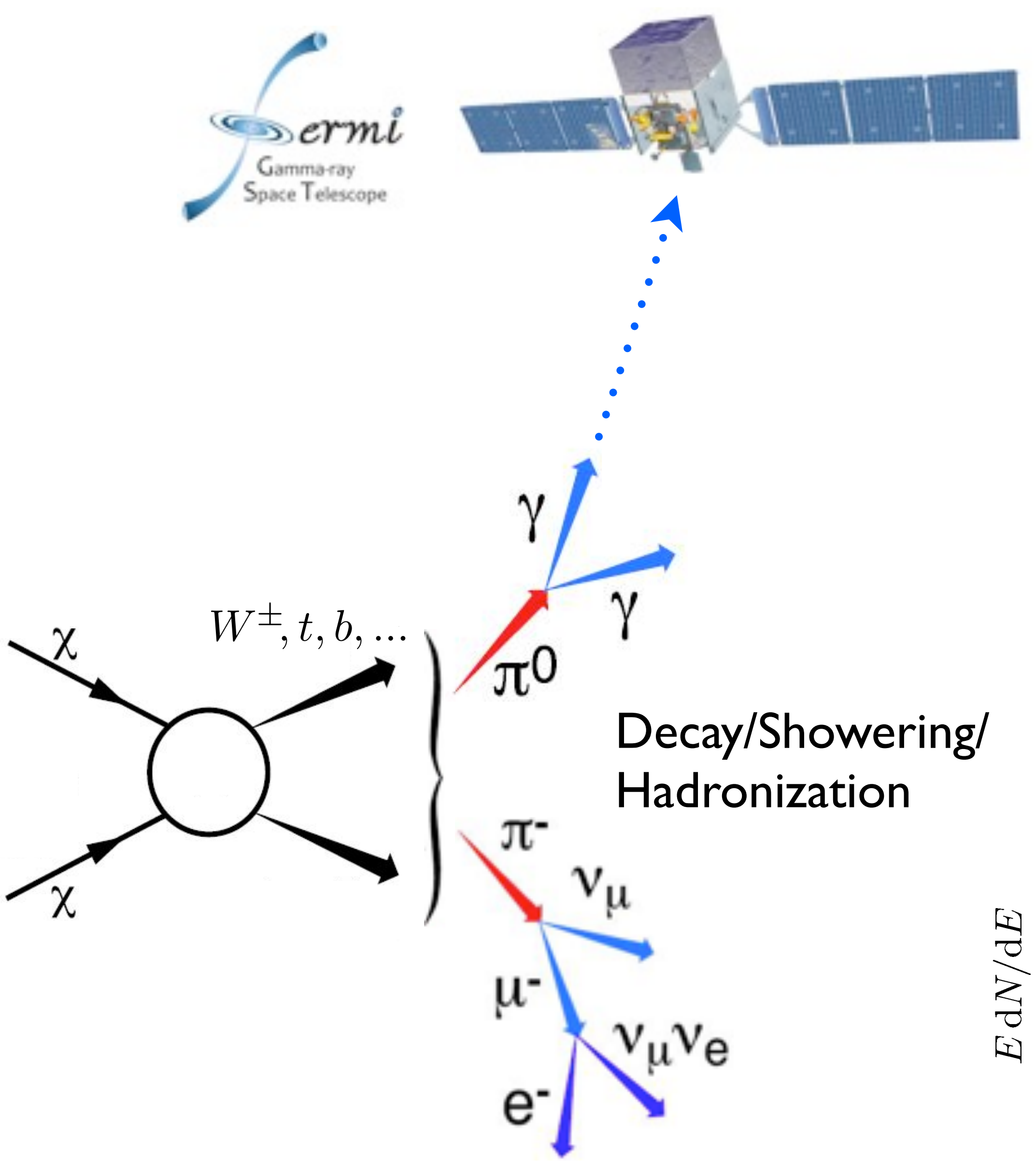
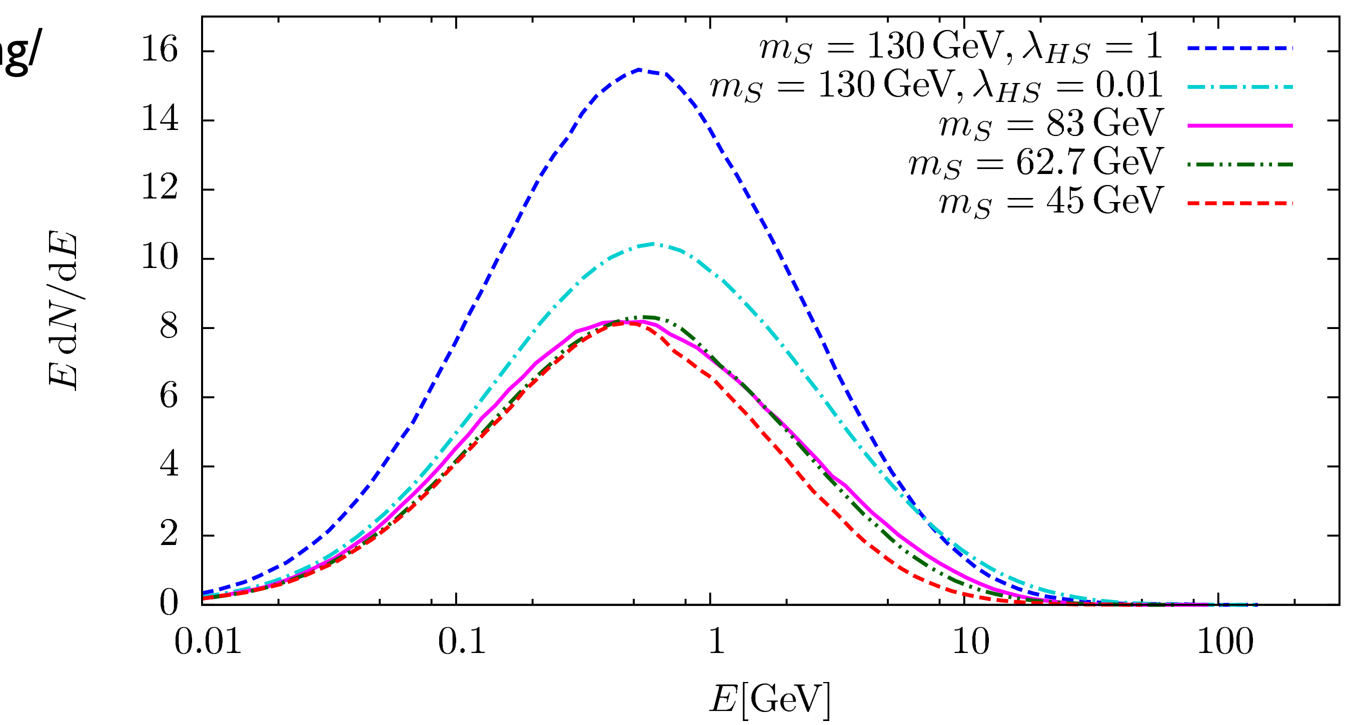
Gamma-ray spectrum

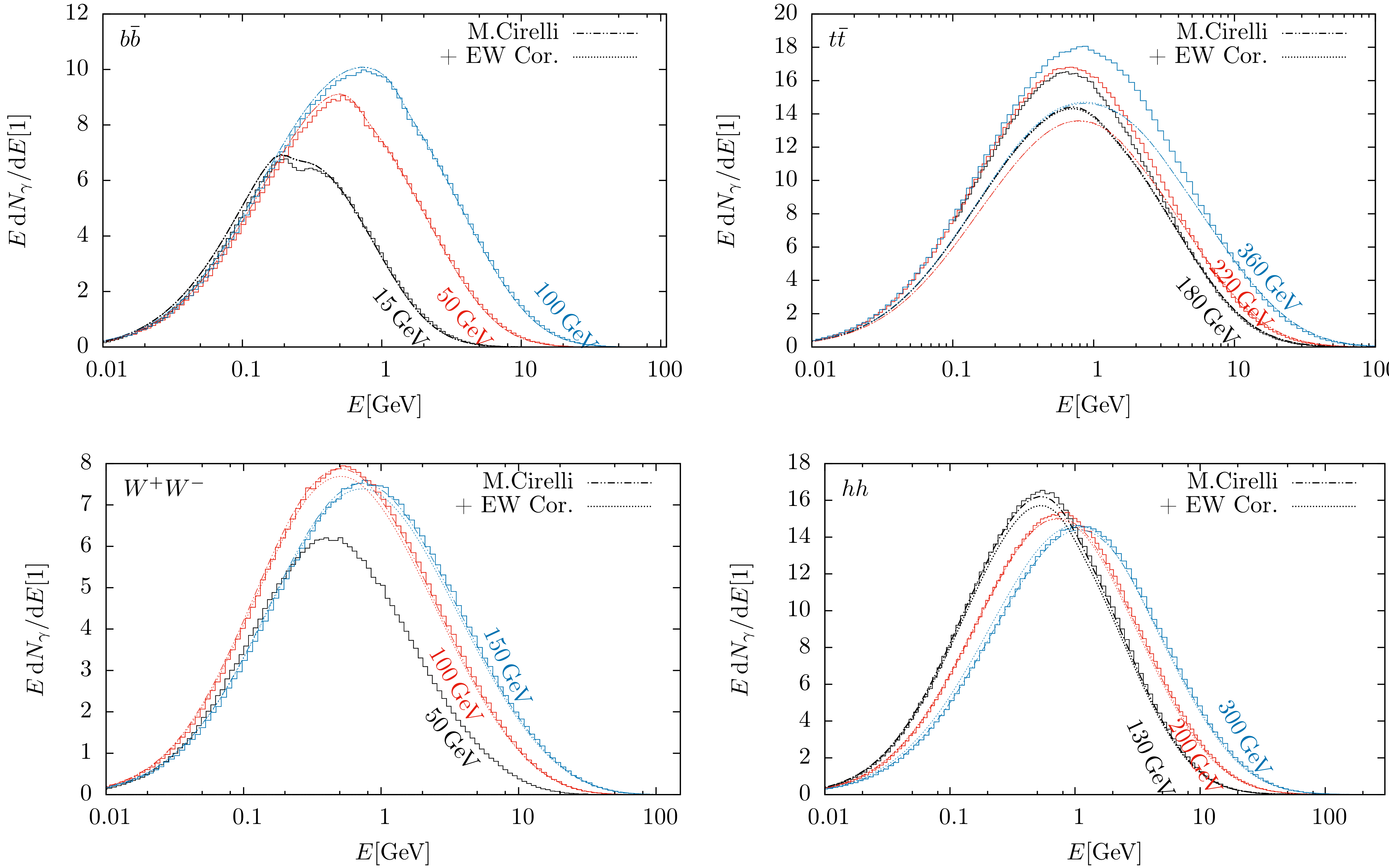


- Continuous photon spectrum
- Slow in fit
  ⇒ Precompute spectra for all channels with MadGraph/Pythia 8
- During fit: Combine spectra according to contribution

Photon spectra for several masses/couplings:



Gamma-ray spectrum

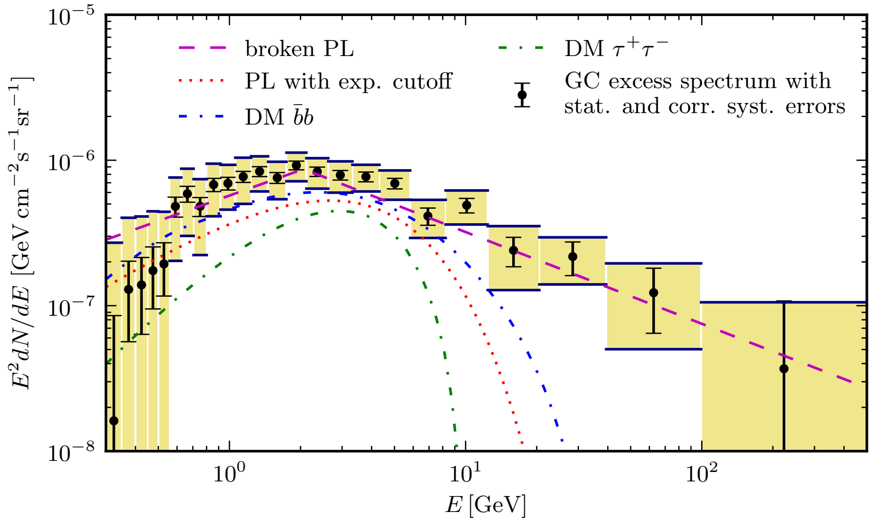


[*cf.* Cirelli *et al.* 1012.4515]

χ^2-computation for the GCE

- Take measured spectrum d_i in 24 bins and covariance matrix Σ_{ij} from [Calore, Cholis, Weniger: 1409.0042]

$$\Sigma_{ij} = (\sigma_i^{\text{stat.}})^2 \delta_{ij} + \Sigma_{ij,\,\text{mod}}^{\text{trunc}} + \Sigma_{ij,\,\text{res}}$$



- 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]

χ^2-computation for the GCE

- Large theoretical uncertainties on DM distribution in galaxy:
  - Consider generalized Navarro-Frenk-White (NFW) profile:

$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{-3+\gamma}$$

  - Compute *J*-factor (integrate $\rho(r)$ over line of sight and region of interest):

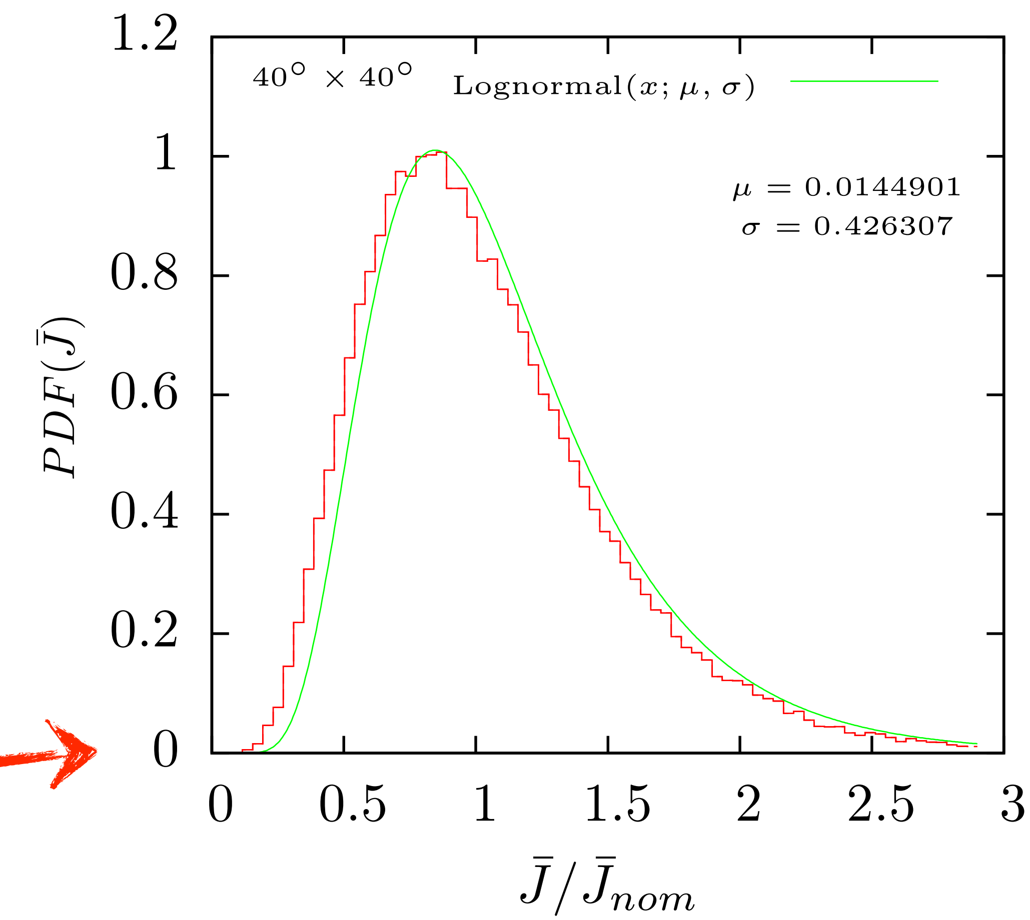
$$J_{40^\circ} = \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s}} \mathrm{d}s \rho^2(r(s,\theta))$$

  - Vary around best fit parameters with MC

    $\gamma = 1.2 \pm 0.08$ [from Calore, Cholis, Weniger]

    ρ_s-r_s from rotation curves [Nesti *et al.* 1304.5127]

    $\Rightarrow$ Distribution for *J*-factor



  - Determine $\sigma_{\log J}$ for $\log(J_{40^\circ}/J_{40^\circ,\,\mathrm{nom}})$

$$\chi^2_{\mathrm{GCE}} = \sum_{i,j} (d_i - t_i) \left(\Sigma_{ij} + \delta_{ij}(\sigma_{\mathrm{rel}}\; t_i)^2\right)^{-1} (d_j - t_j) + \frac{(\log J_{40^\circ} - \log J_{40^\circ,\,\mathrm{nom}})^2}{(\sigma_{\log J})^2}$$

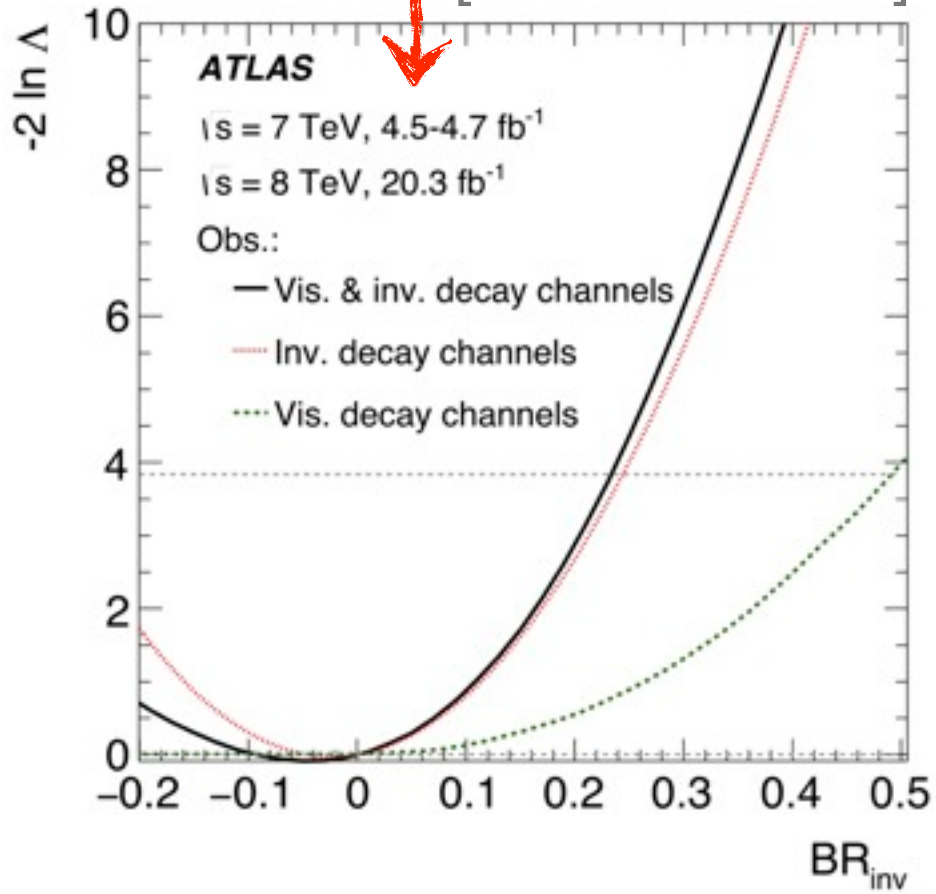
Constraints on the parameter space

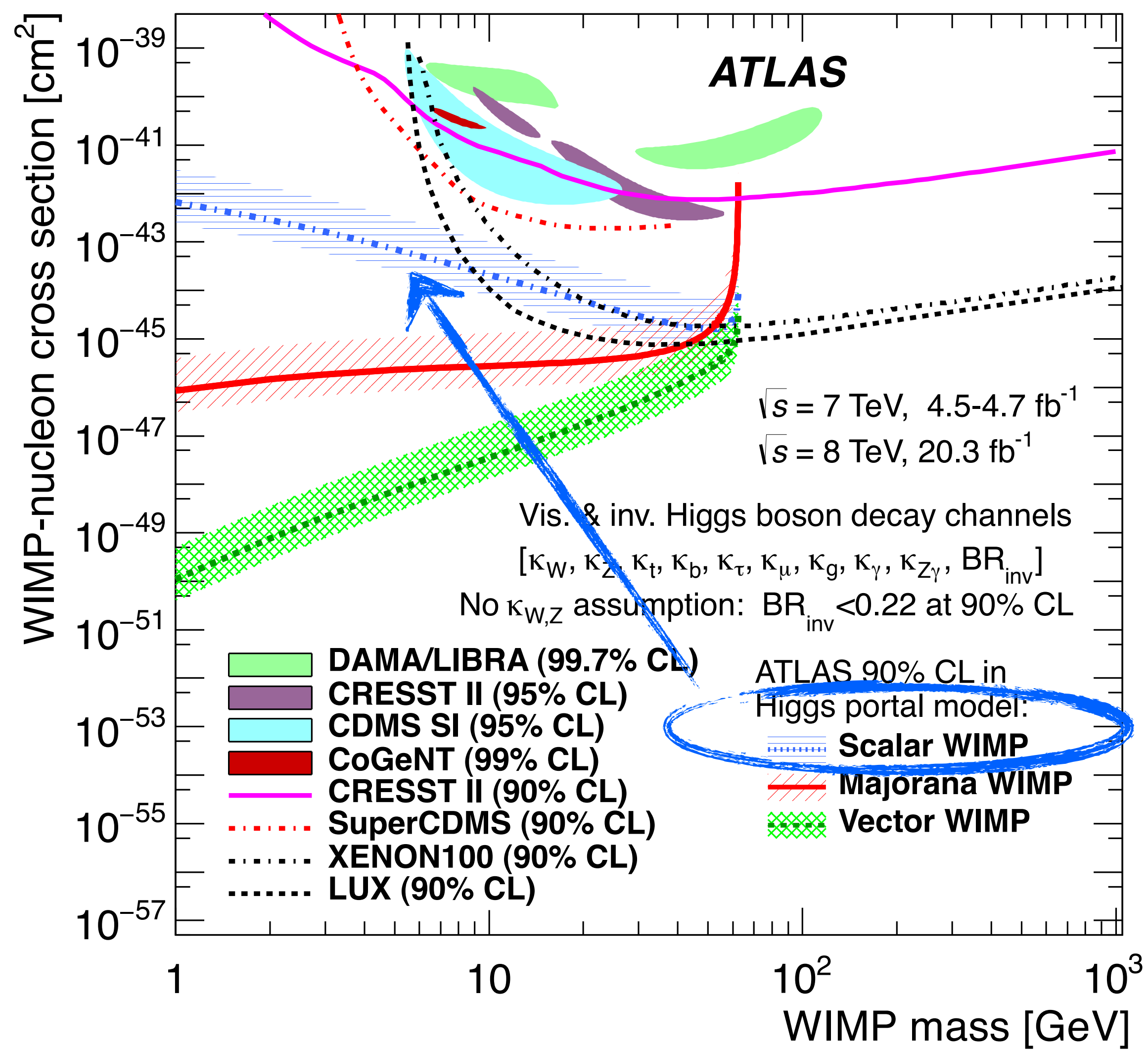
Constraints on the parameter space

(i) Collider constraints:

Higgs invisible BR

[ATLAS: 1509.00672]



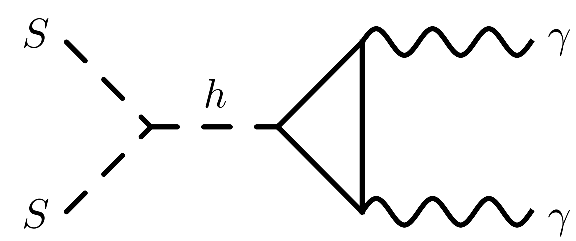


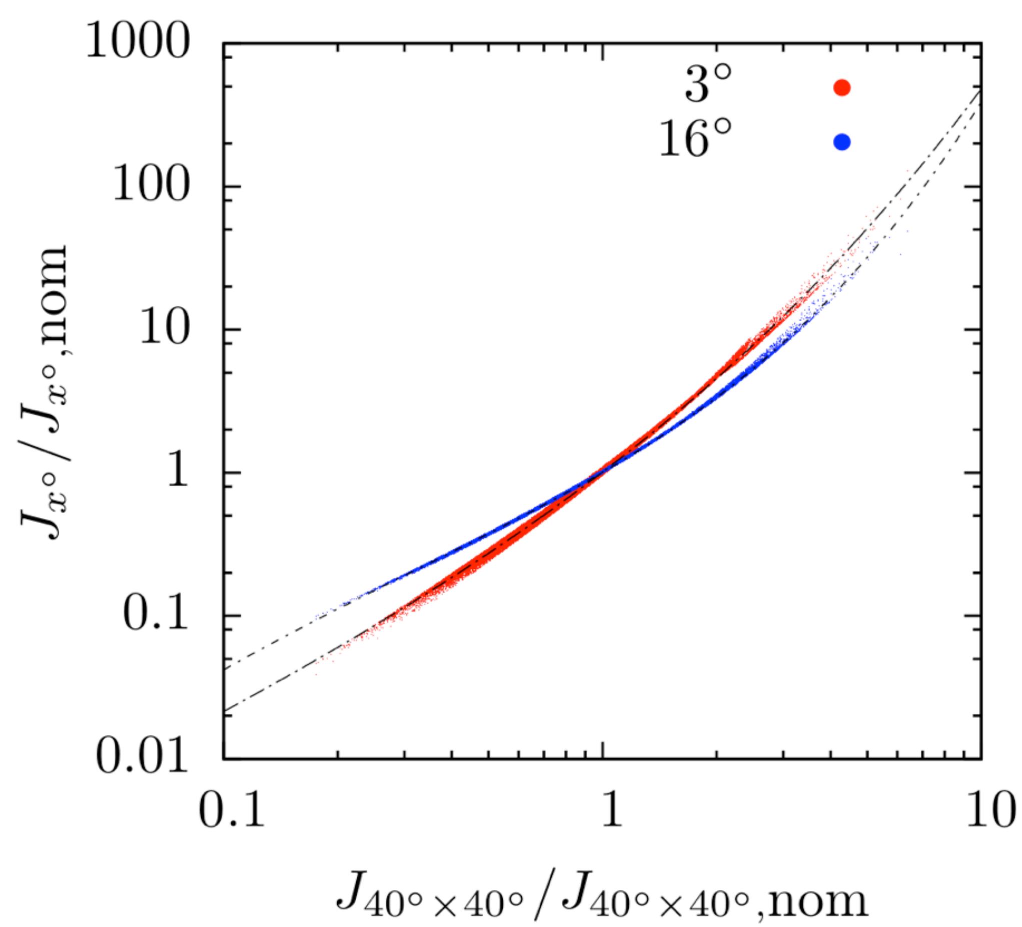
Constraints on the parameter space

(ii) Direct detection constraints: LUX '13 log-likelihood from LUXCalc [Savage *et al.* 1502.02667]

(iii) Dwarf Spheroidal Galaxies log-likelihood 7 dwarfs [*Fermi*-LAT: 1503.02641]

(iv) Gamma-lines: [*Fermi*-LAT: 1506.00013]
J-factor different from GCE almost 100% correlation





Constraints on the parameter space

(v) Relic density constraint [Planck: 2013]

$$\Omega h^2|_{\text{Planck}} = 0.1198 \pm 0.0015$$

Estimate 10% theoretical uncertainty [see e.g. Arroyo *et al.* 1608.00791]
[computed with micrOMEGAs]

$$\chi^2_\Omega = \frac{\left(\Omega h^2|_{\text{DM, total}} - \Omega h^2|_{\text{Planck}}\right)^2}{\left(\sigma_{\text{rel}} \times \Omega h^2|_{\text{DM, total}}\right)^2}$$

Fit parameters and tools

- Allow for additional unspecified DM component
  ➔ WIMP fraction: $R = \rho_{\mathrm{WIMP}}/\rho_{\mathrm{DM,\,total}}$
- 4 scan parameters:

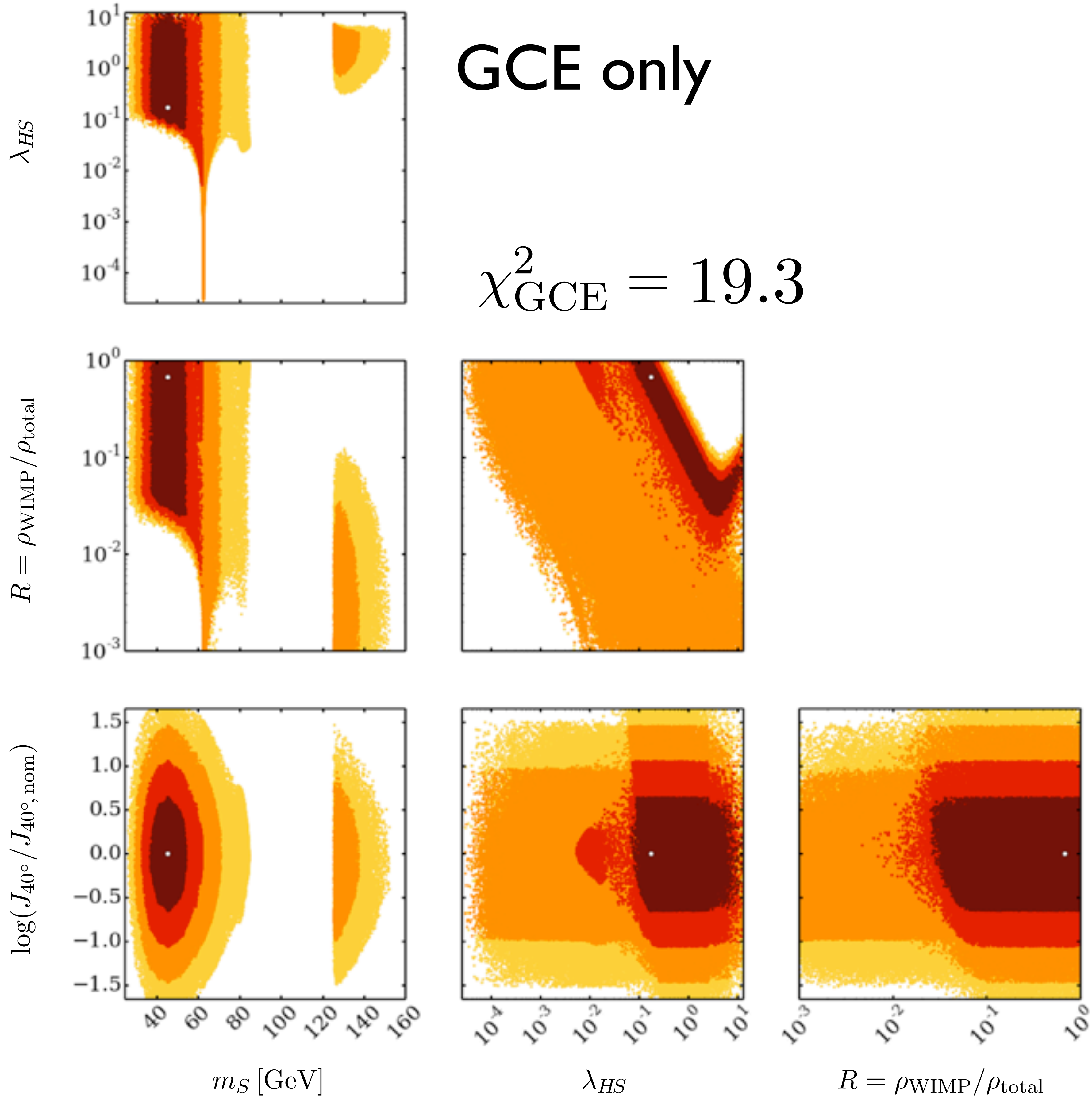
$$\begin{aligned} m_S&: \quad 5\ldots 220\,\mathrm{GeV}\\ \lambda_{HS}&: \quad 3\times 10^{-5}\ldots 4\pi\\ \ln(\bar{J}/\bar{J}_{\mathrm{nom}})&: \quad -4\sigma_\xi\ldots 4\sigma_\xi\\ R&: \quad 10^{-3}\ldots 1 \end{aligned}$$

- Use MultiNest (nested sampling algorithm) [Feroz *et al.* '13]
- Annihilation cross sections and BRs: micrOMEGAs
  [Bélanger *et al.* '14]
- Frequentist interpretation, combination of scans

Fit Results

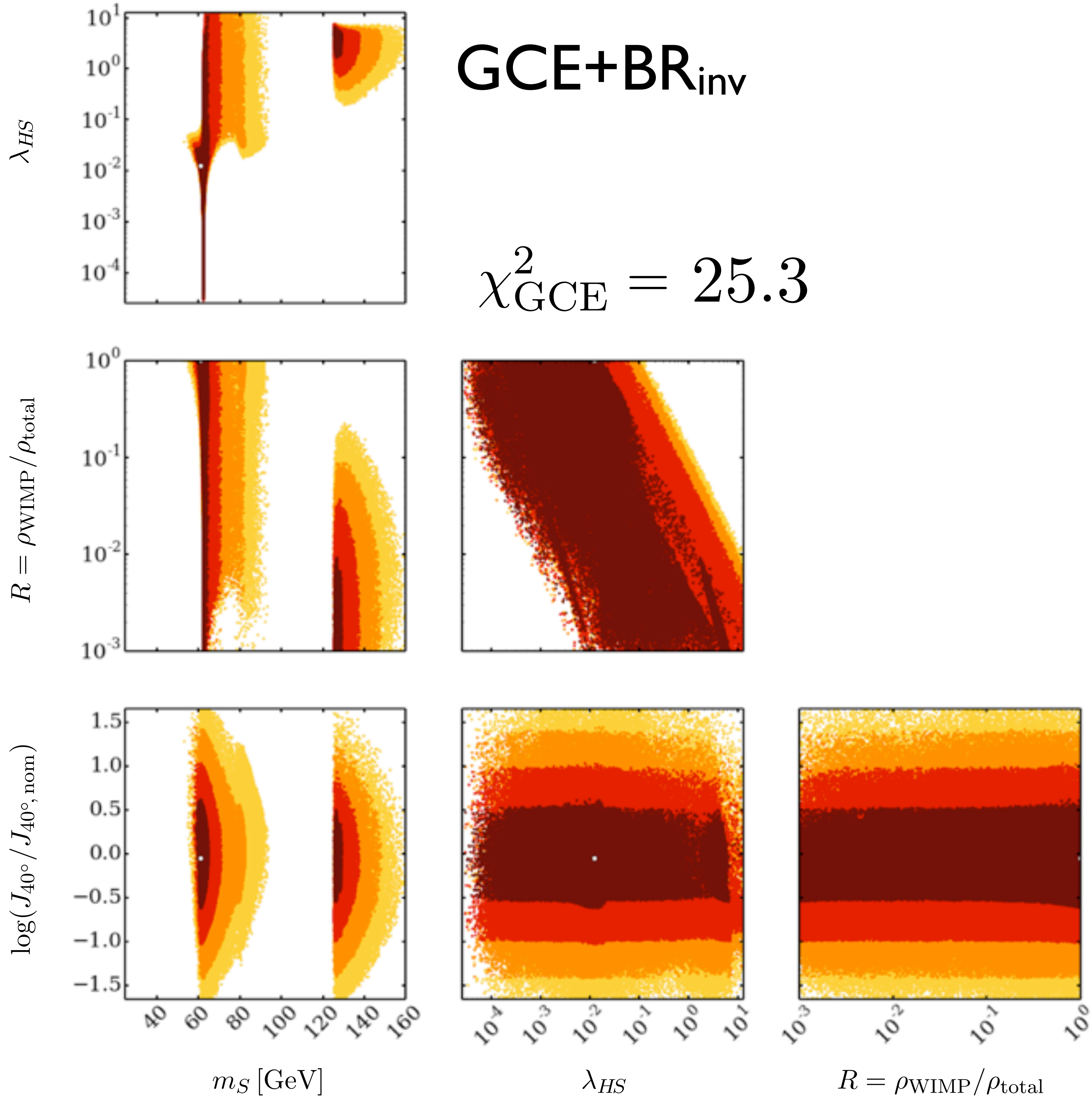
GCE only

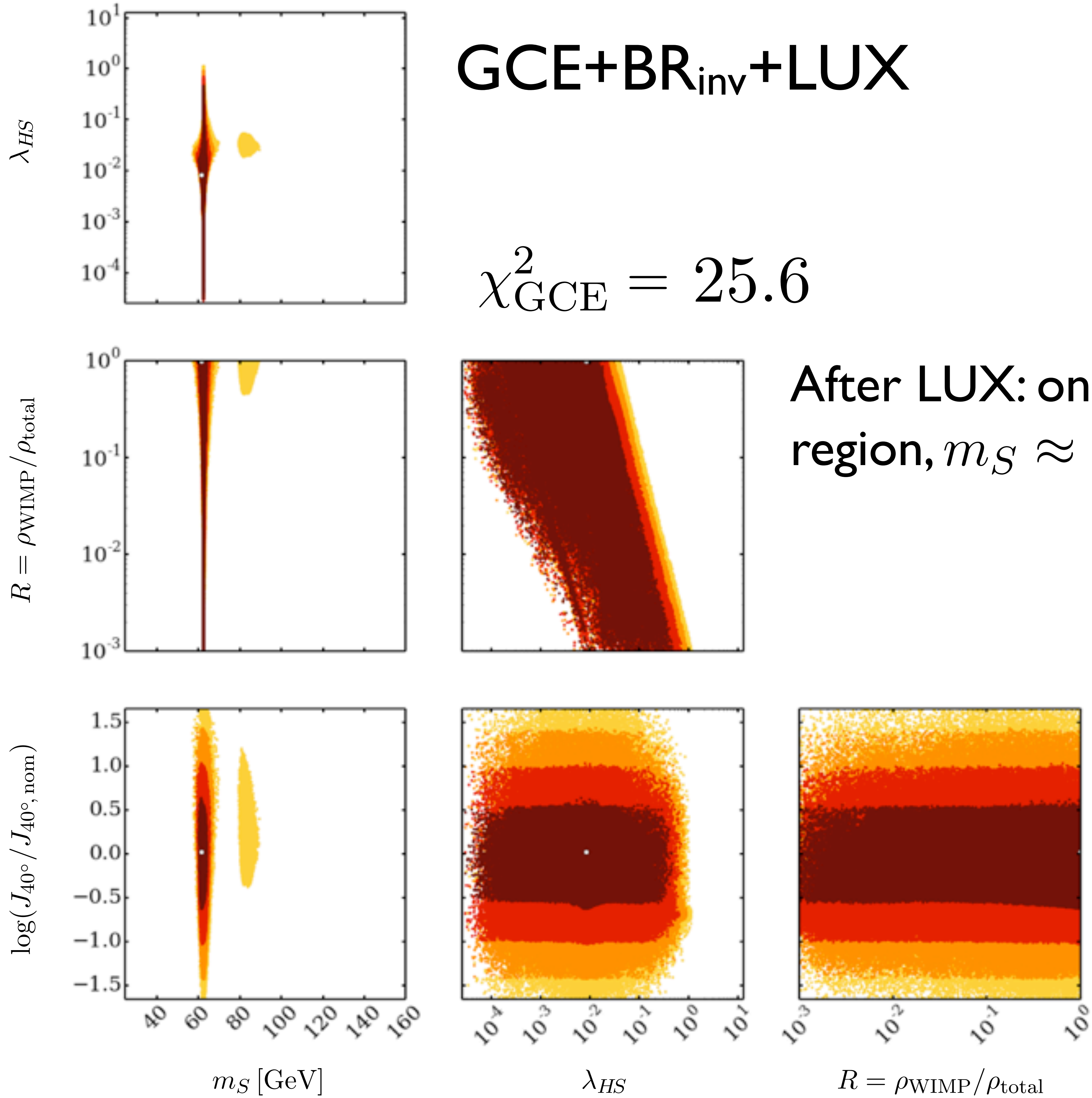
$$\chi^2_{\rm GCE} = 19.3$$



GCE+BR$_{\rm inv}$

$$\chi^2_{\rm GCE} = 25.3$$





GCE+BR_{inv}+LUX

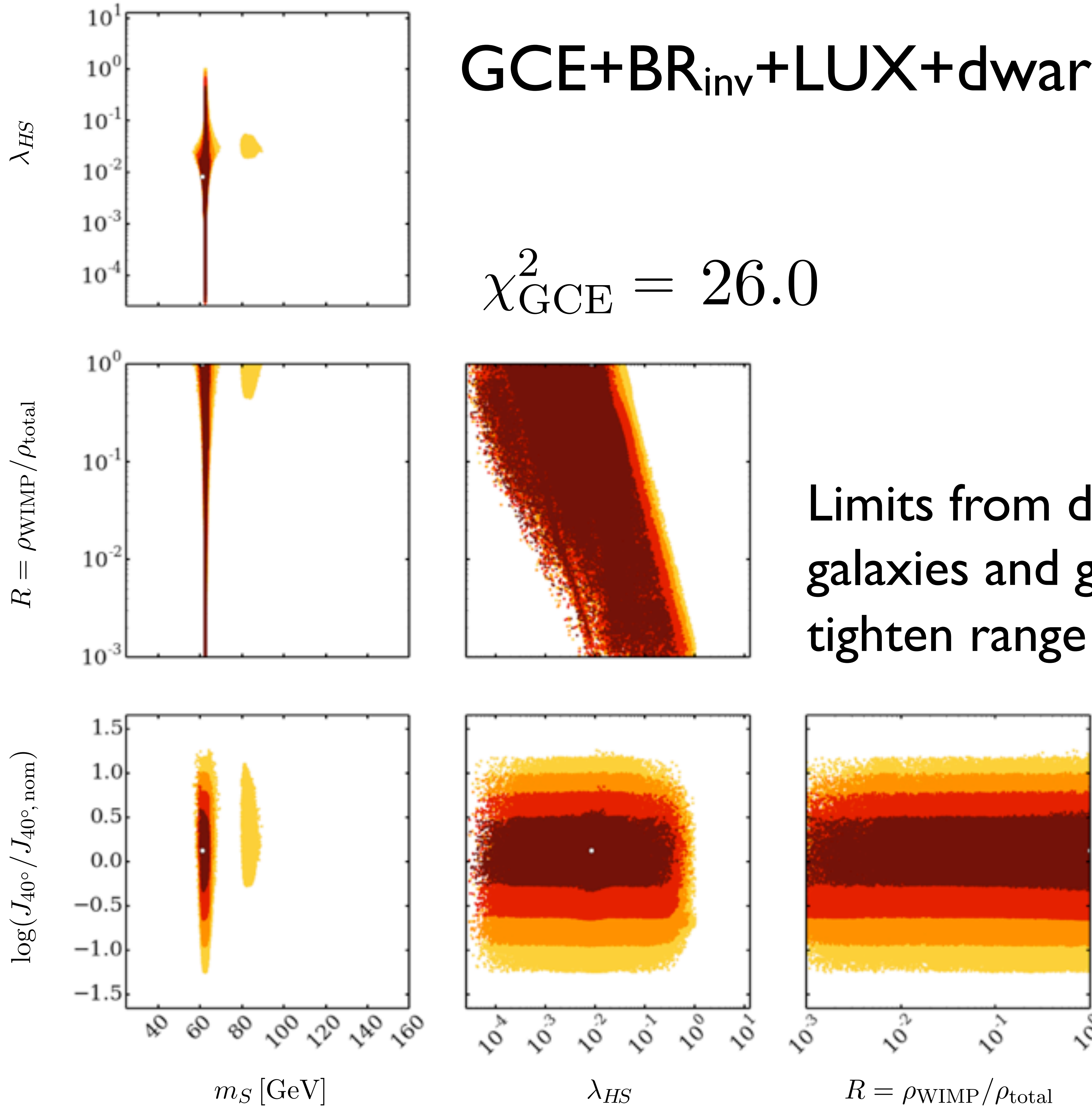
$$\chi^2_{\rm GCE} = 25.6$$

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

GCE+$\mathrm{BR_{inv}}$+LUX+dwarfs+γ-lines

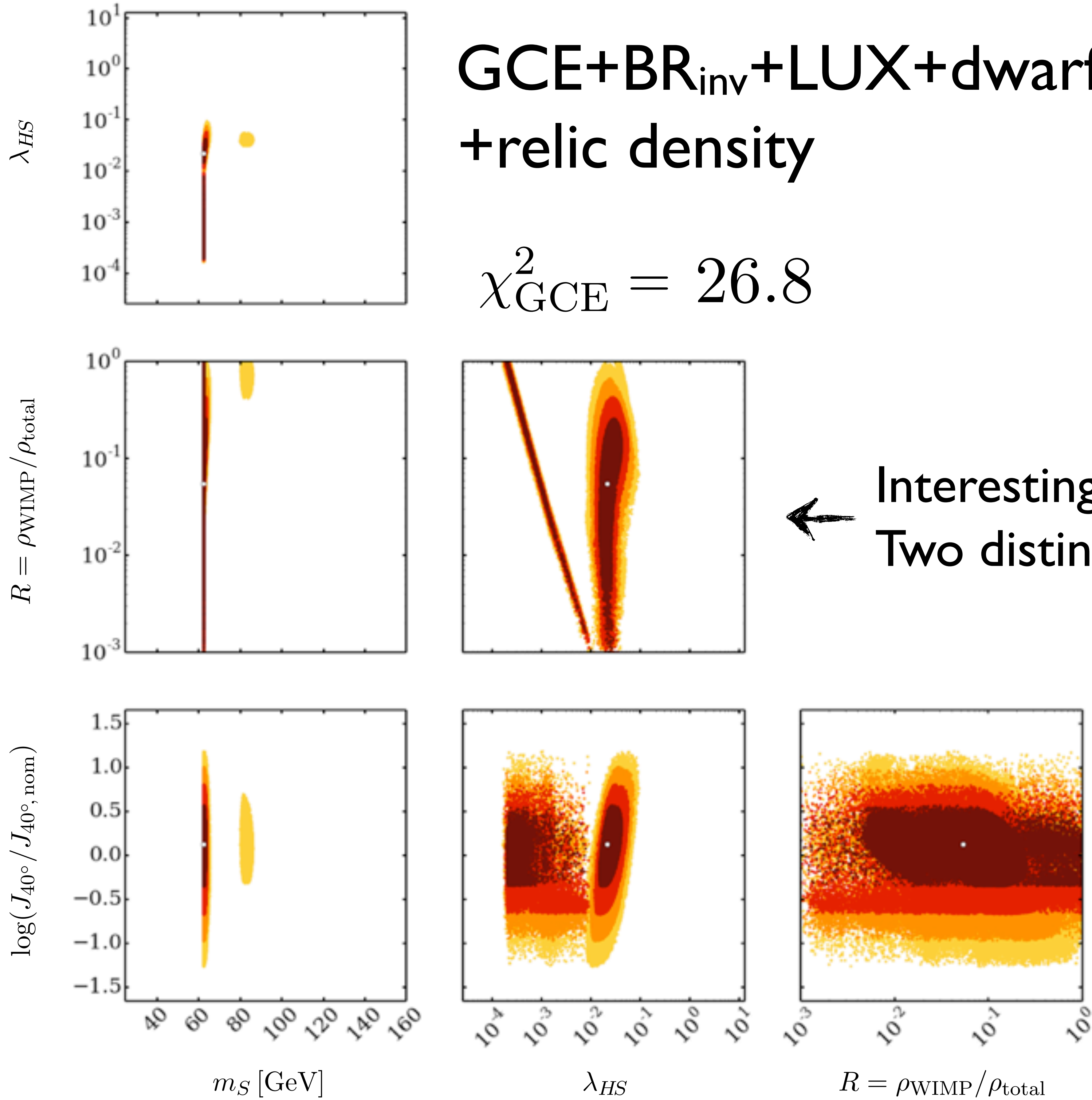
$$\chi^2_{\mathrm{GCE}} = 26.0$$

Limits from dwarf spheroidal galaxies and gamma lines tighten range for $\ln(\bar{J}/\bar{J}_{\mathrm{nom}})$



GCE+$\mathrm{BR_{inv}}$+LUX+dwarfs+γ-lines +relic density

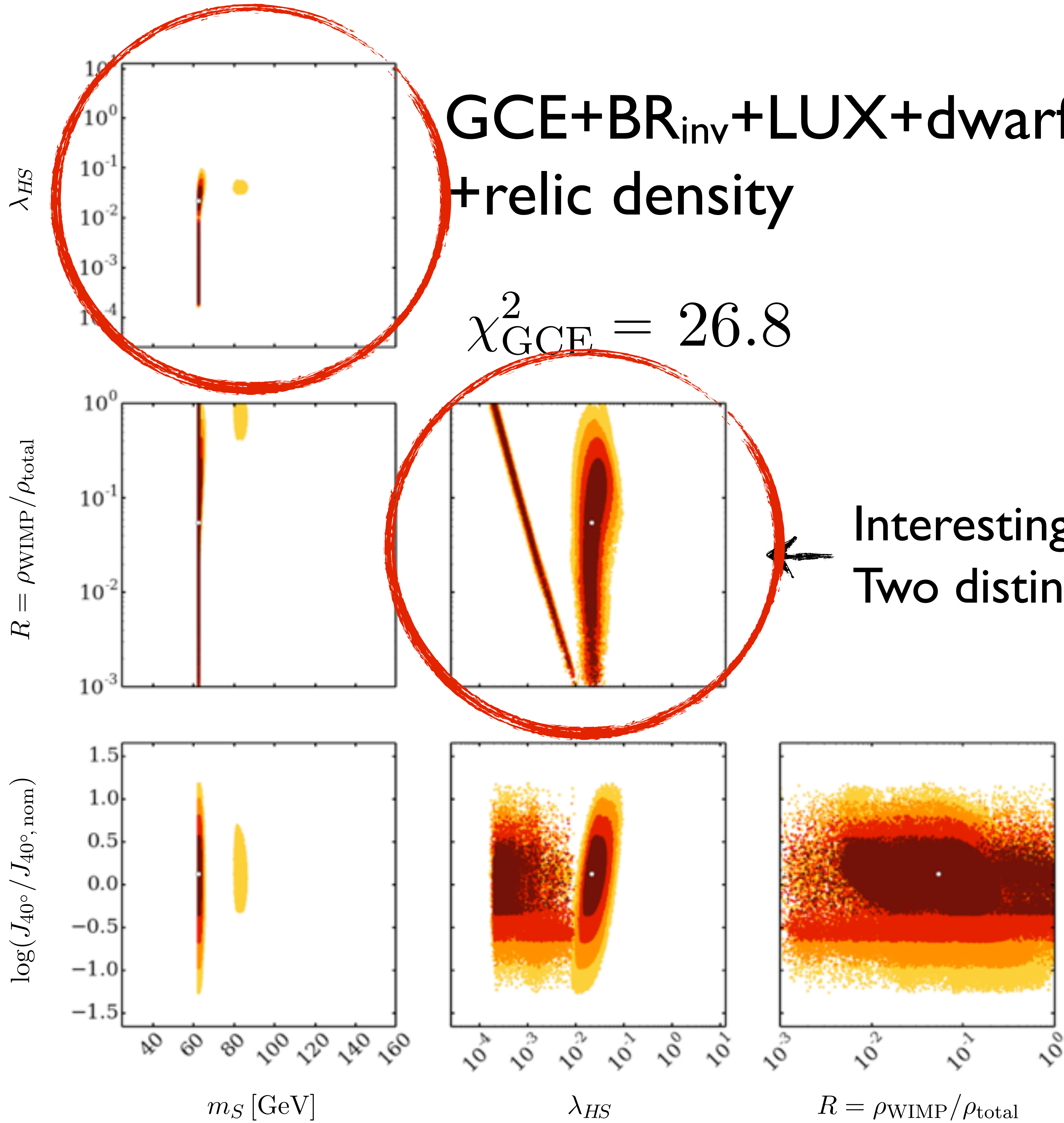
$$\chi^2_{\mathrm{GCE}} = 26.8$$



Interesting structure in R
Two distinct regions

GCE+$\mathrm{BR_{inv}}$+LUX+dwarfs+γ-lines
+relic density

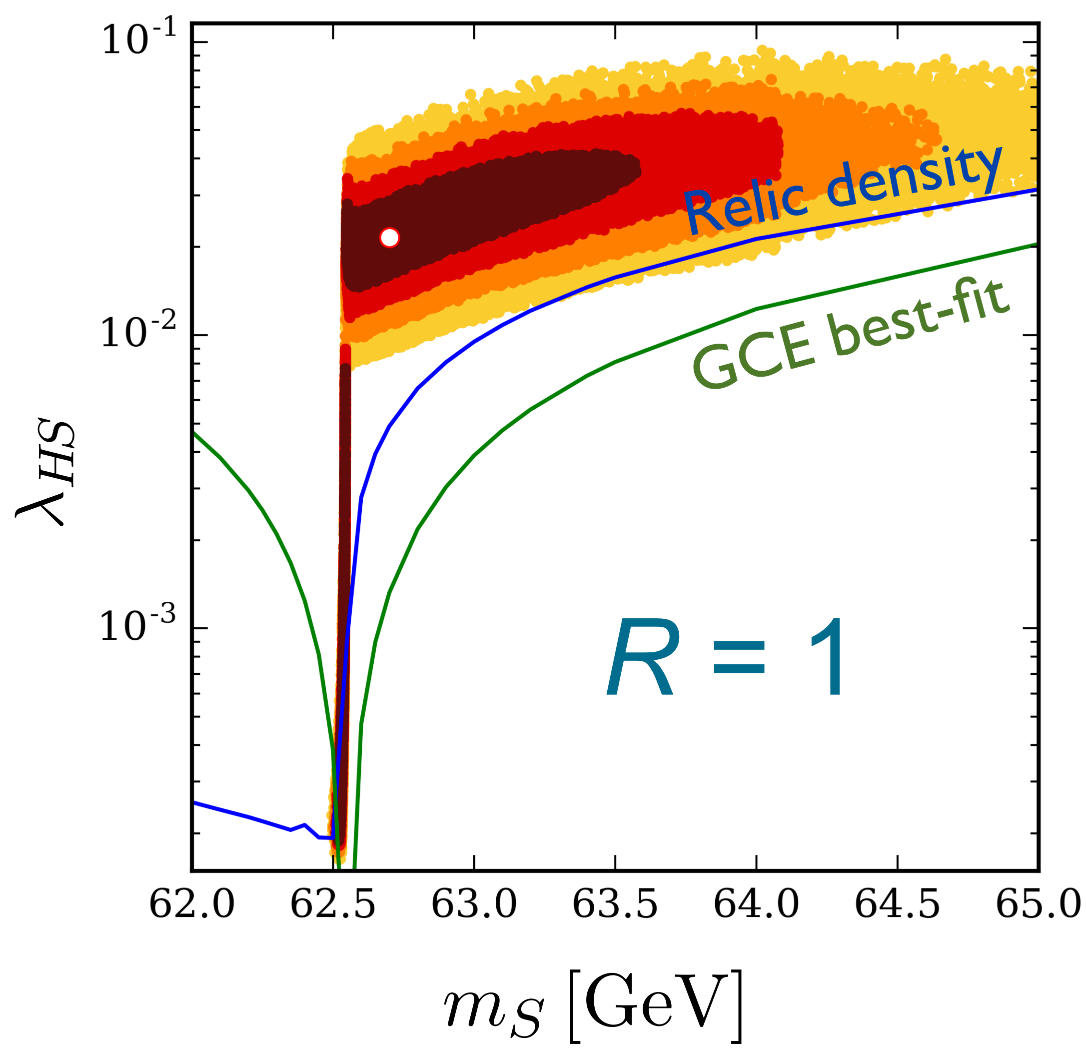
$$\chi^2_{\mathrm{GCE}} = 26.8$$

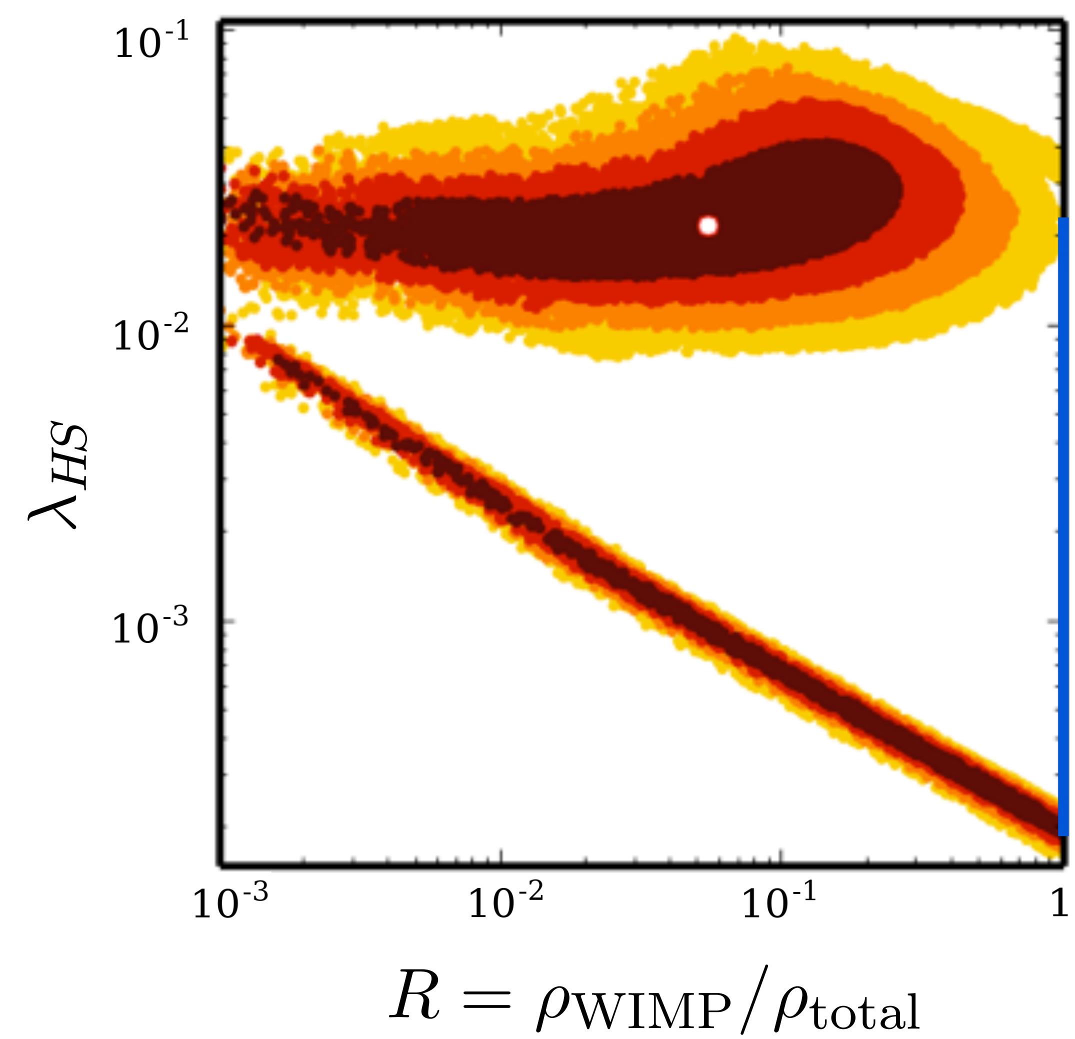


Interesting structure in *R*
Two distinct regions

GCE+BR$_{\text{inv}}$+LUX+dwarfs+γ-lines+relic density

- Large velocity dependence around Higgs resonance
- $\sigma v \propto \frac{1}{(m_h^2 - s)^2 + m_h^2 \Gamma_h^2} \simeq \frac{1/m_h^2}{(\delta^2 - v_{\text{rel}}^2)^2 + \Gamma_h^2}, \quad \delta^2 \equiv \frac{m_h^2 - 4m_S^2}{m_h^2}$
- annihilation today: $v_{\text{rel}} \simeq 10^{-3}$, freeze-out: $v_{\text{rel}} \lesssim 0.3$





GCE+BR$_{\text{inv}}$+LUX+dwarfs+γ-lines+relic density

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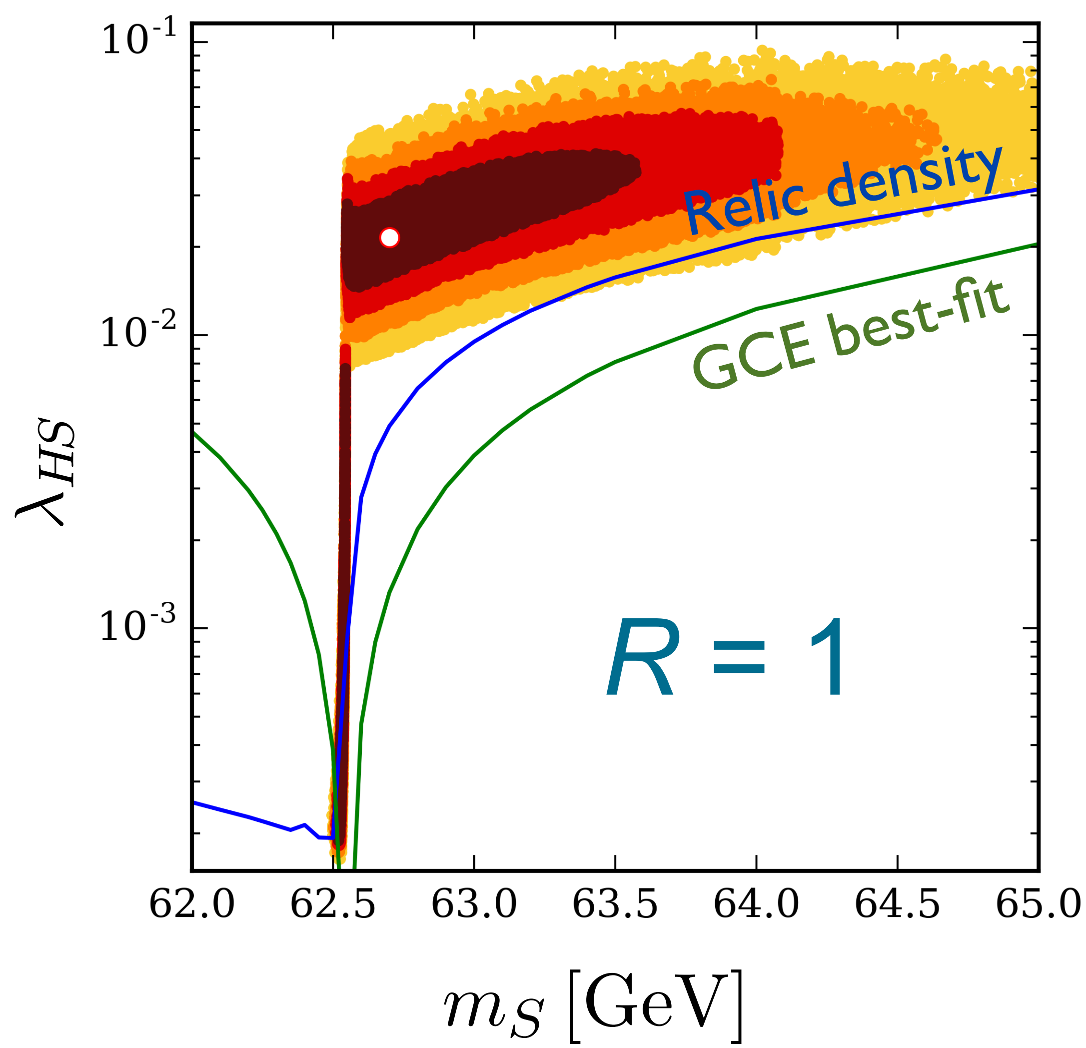

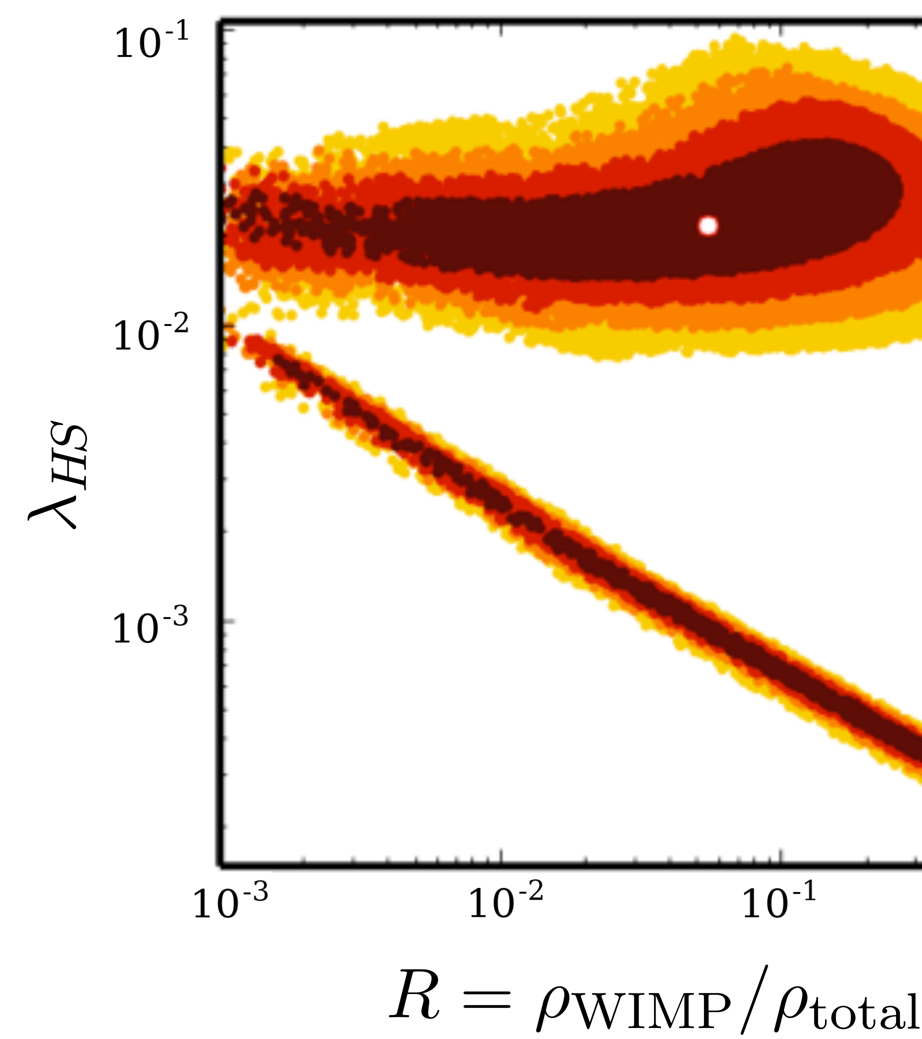

GCE+BR_{inv}+LUX+dwarfs+γ-lines+relic density

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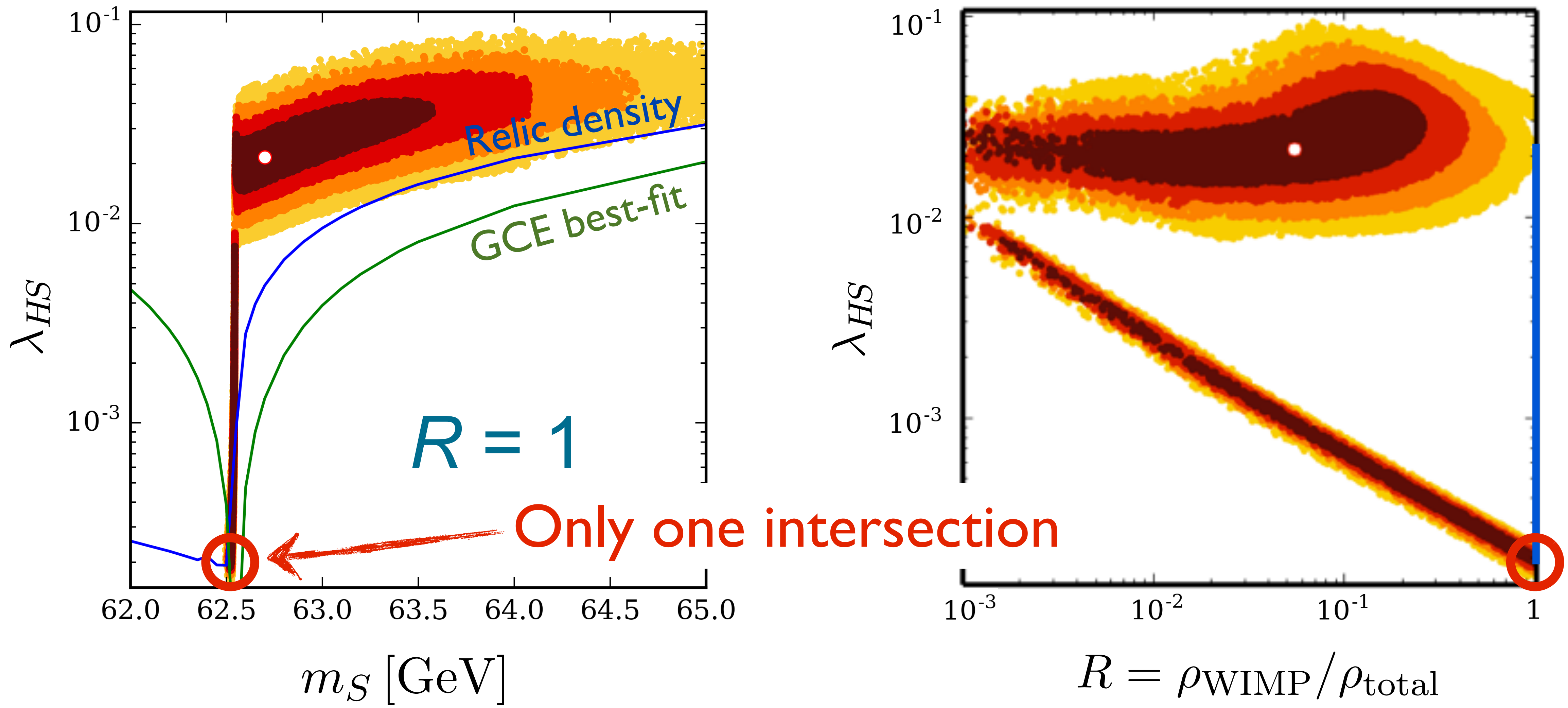
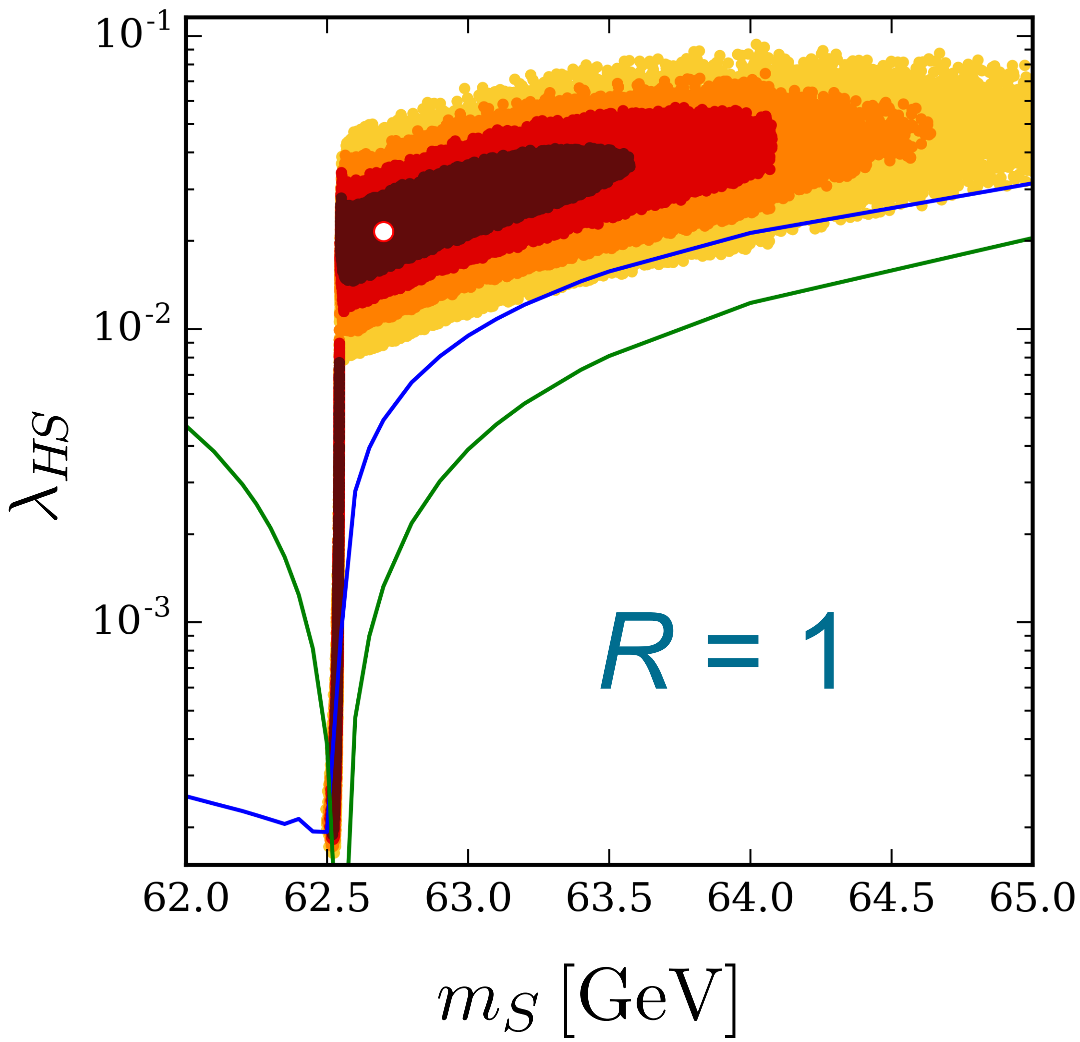


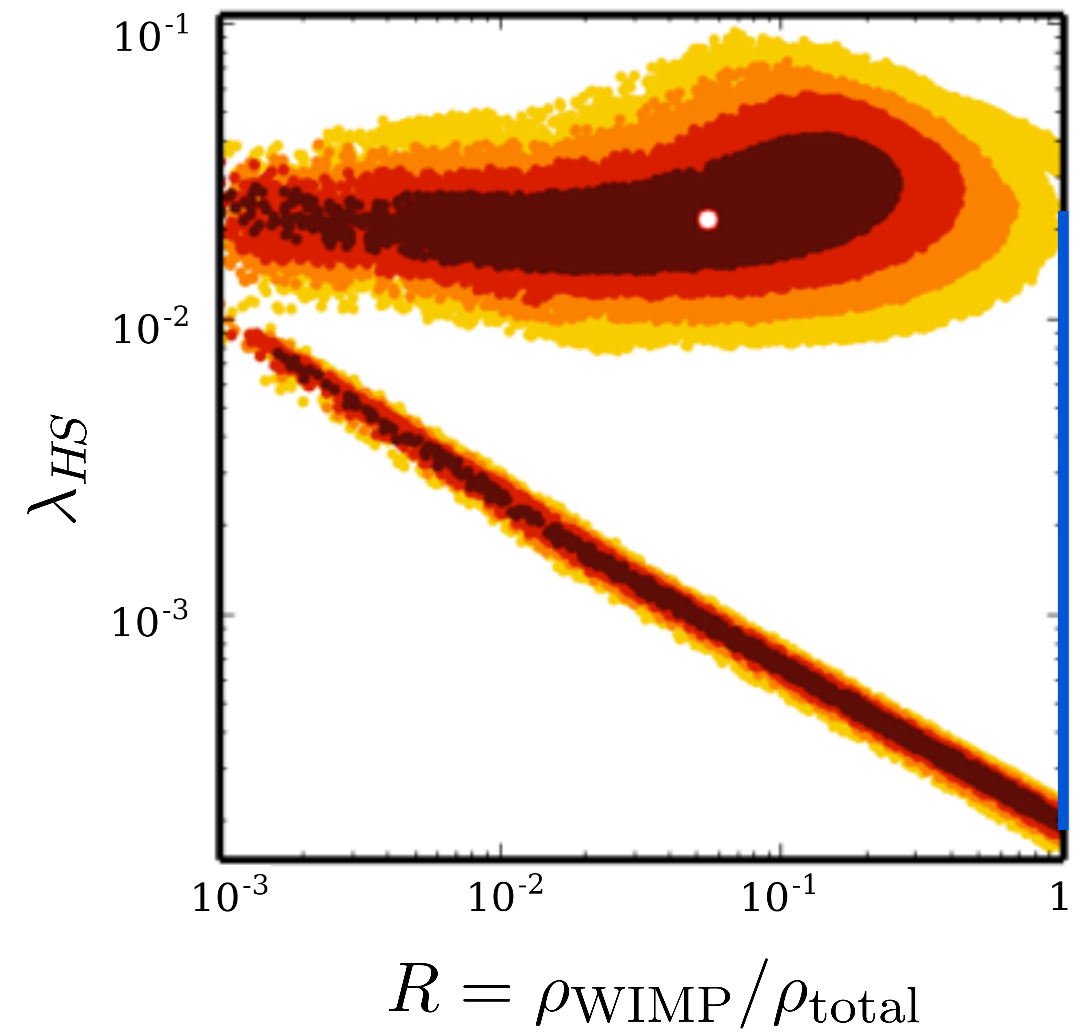
GCE+BR$_{\text{inv}}$+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:

➔ Relic density: $\Omega_{\text{DM, total}} = \dfrac{\Omega_{\text{WIMP}}}{R} \propto \dfrac{1}{R\,\langle\sigma v\rangle_{\text{f.o.}}}$

➔ GCE flux: $\phi \propto R^2 \langle\sigma v\rangle_{\text{today}}$





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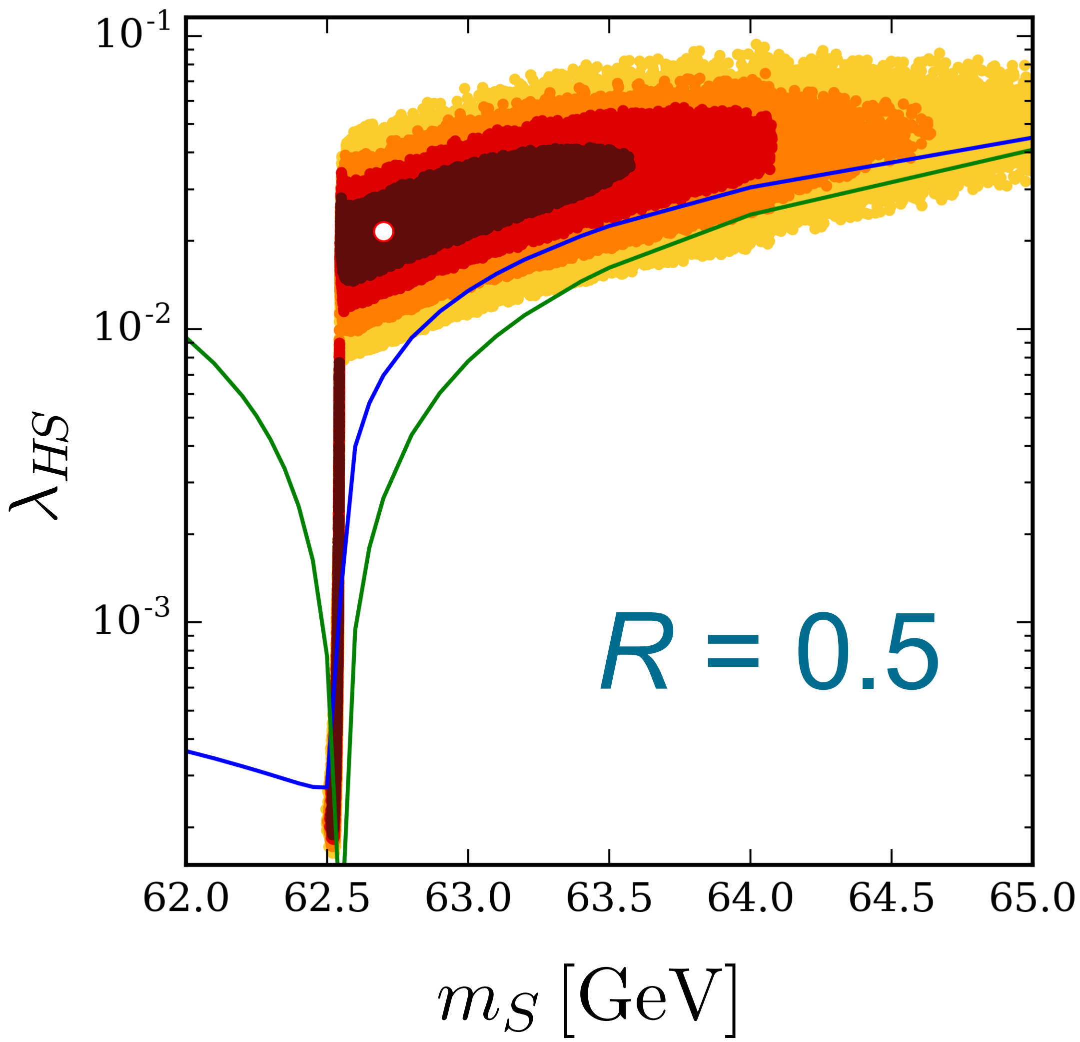

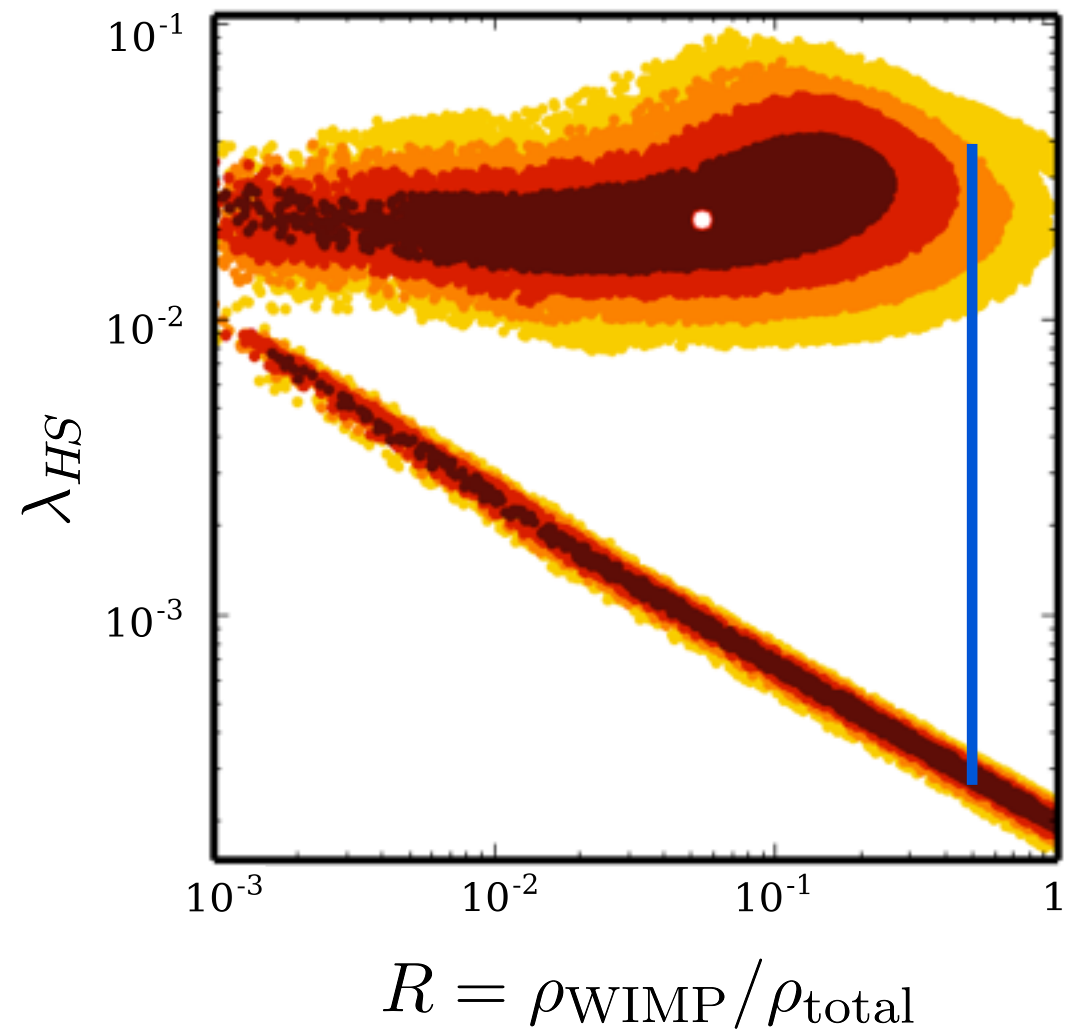

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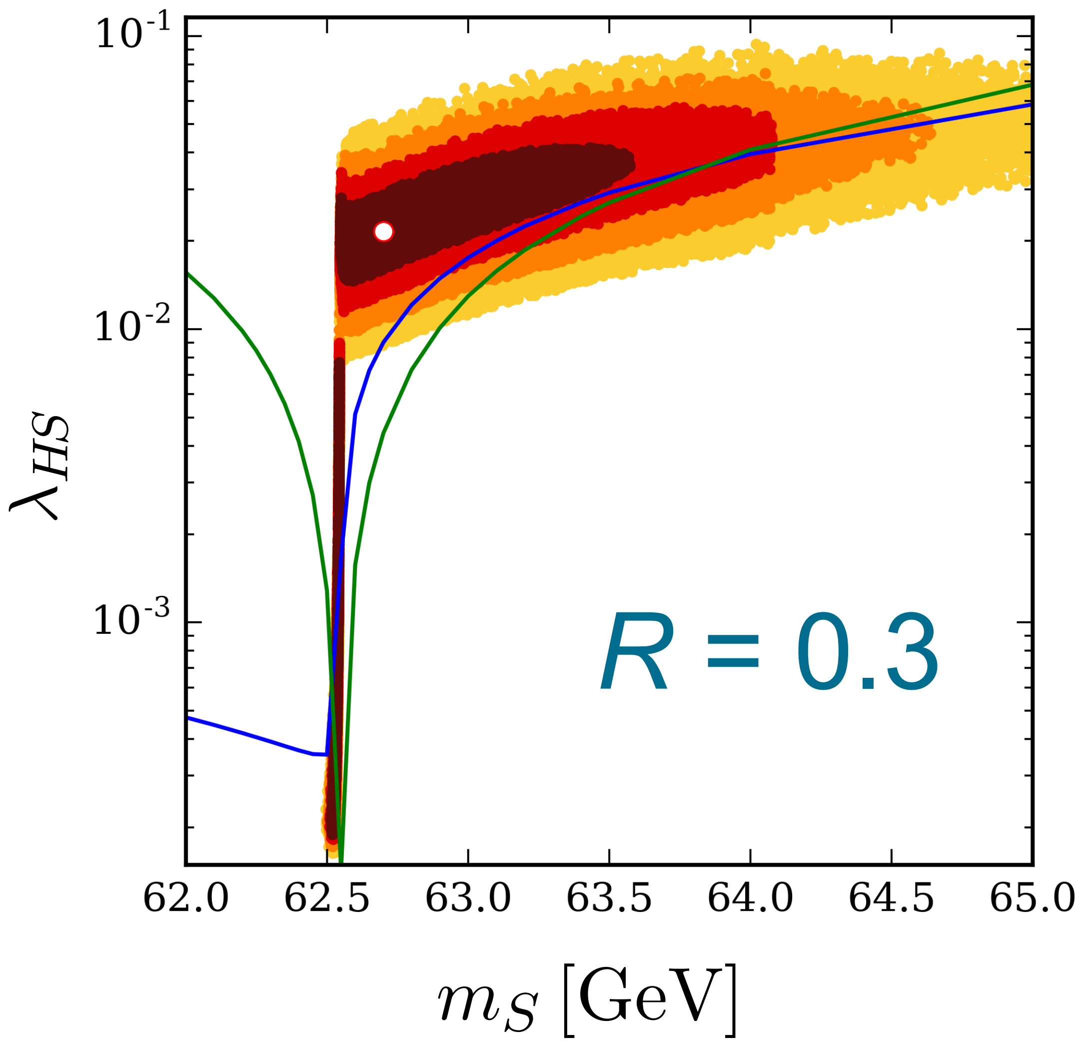

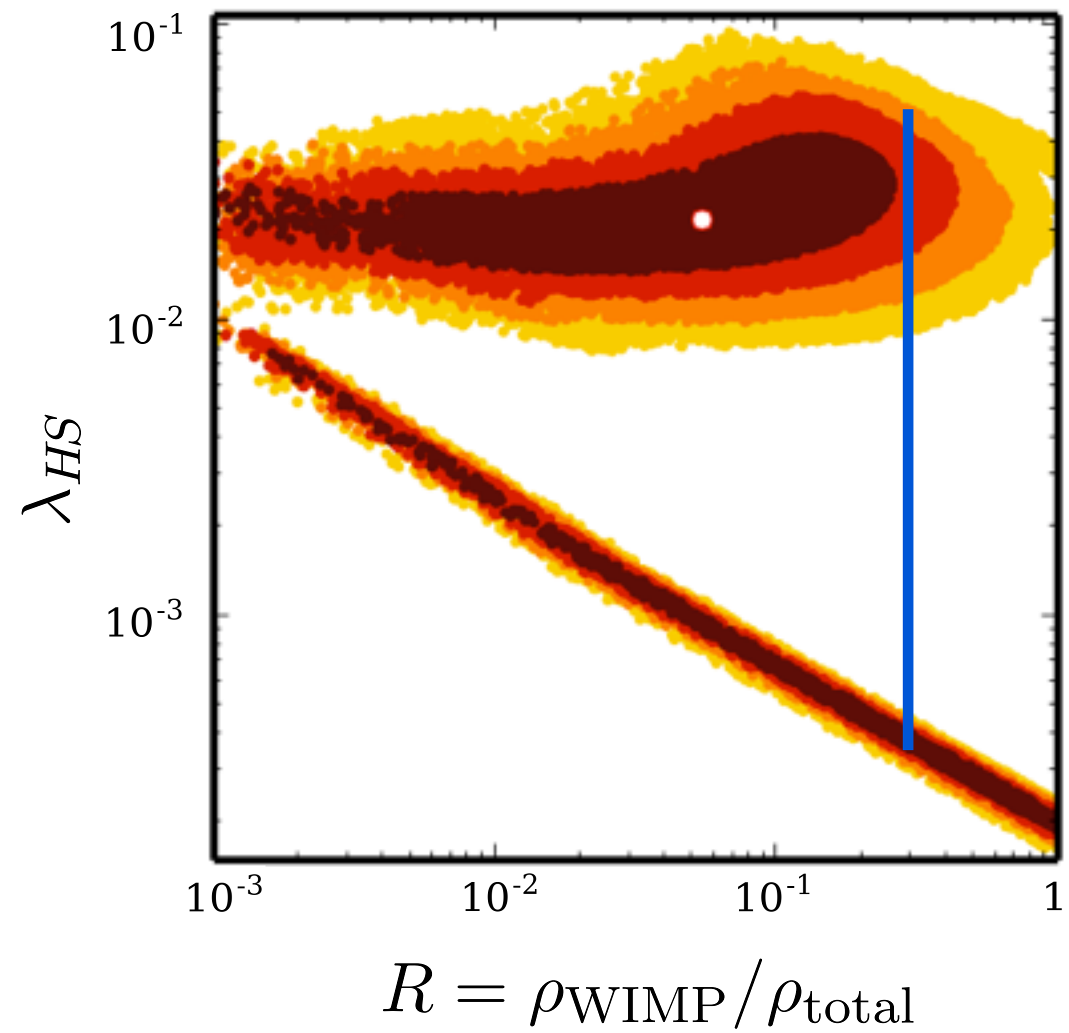

GCE+BR$_{\text{inv}}$+LUX+dwarfs+γ-lines+relic density

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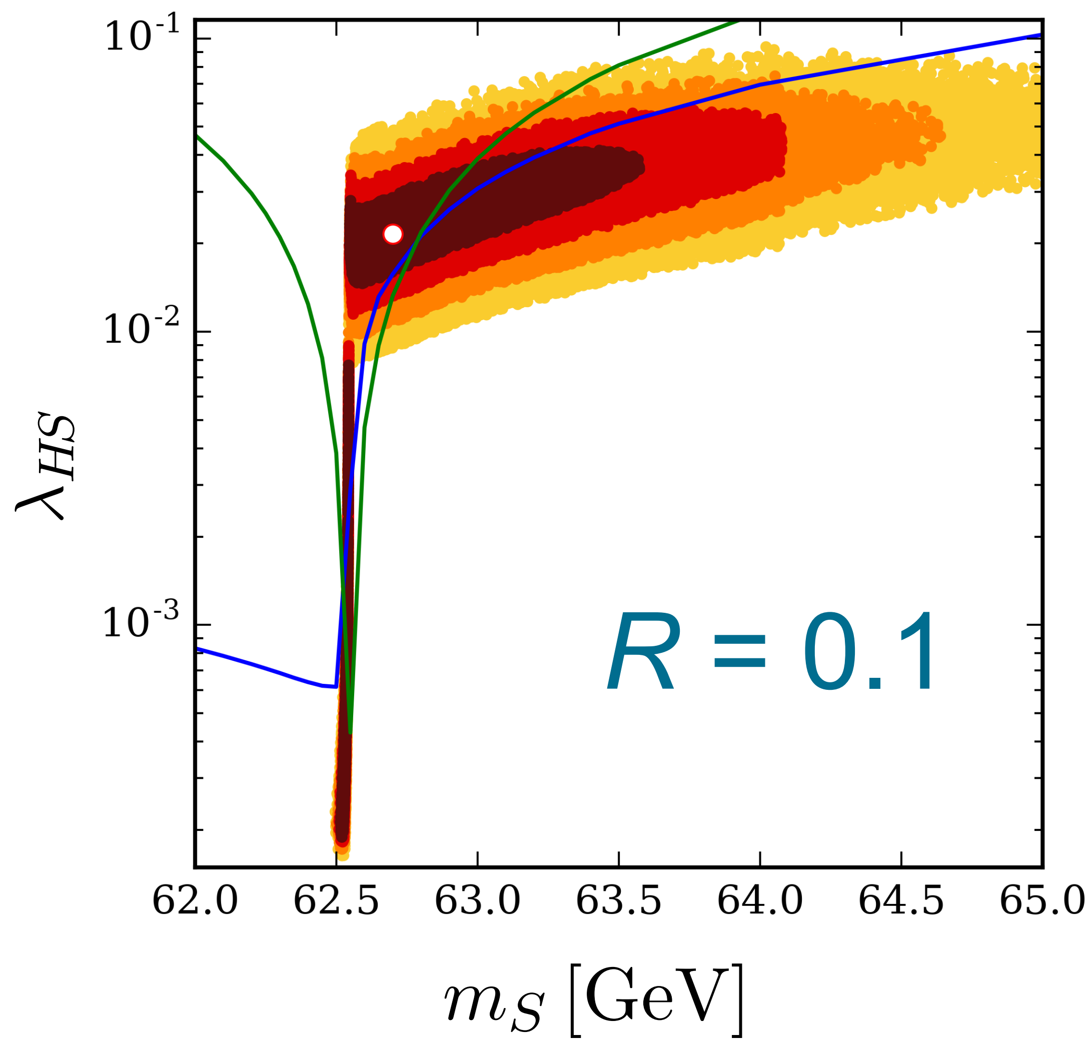

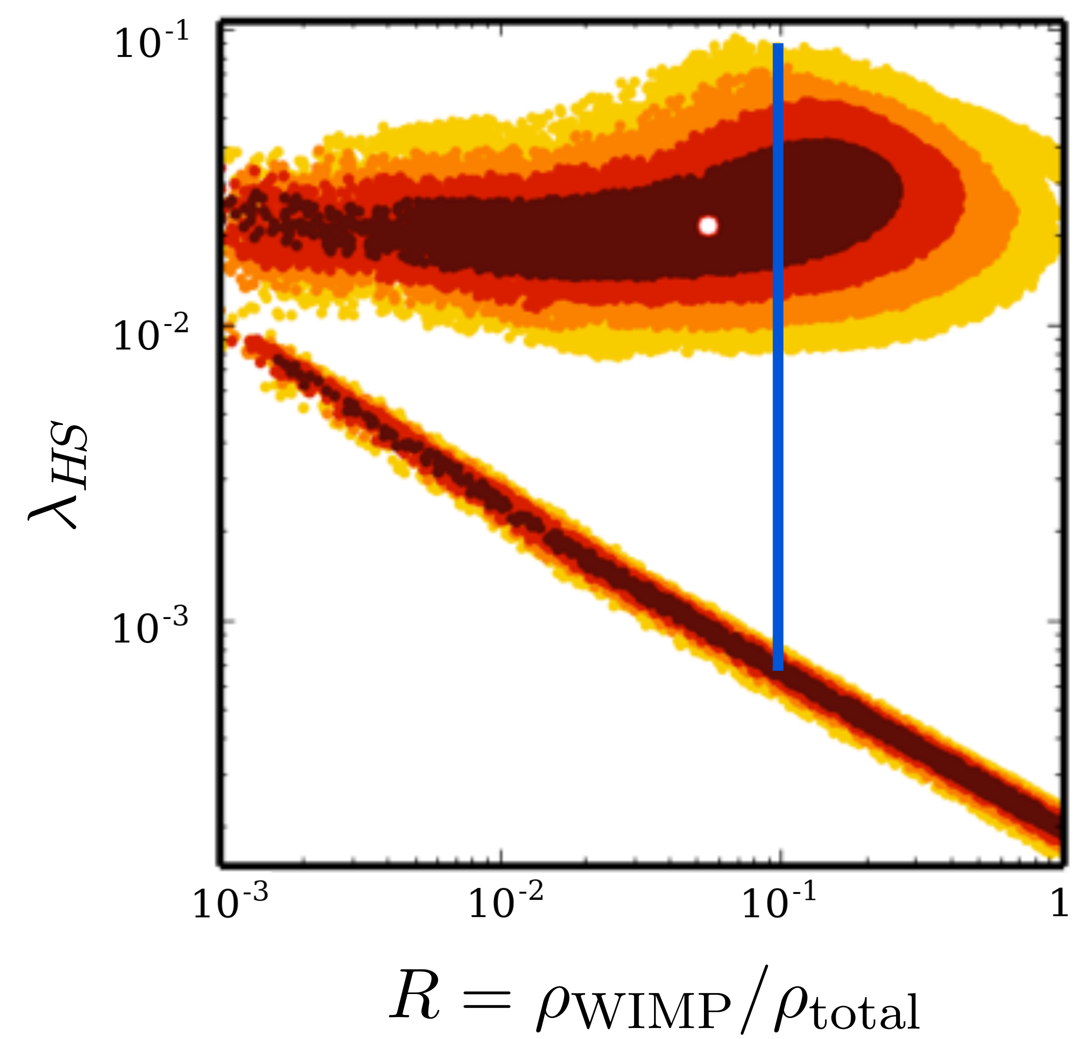

GCE+BR$_{\rm inv}$+LUX+dwarfs+γ-lines+relic density

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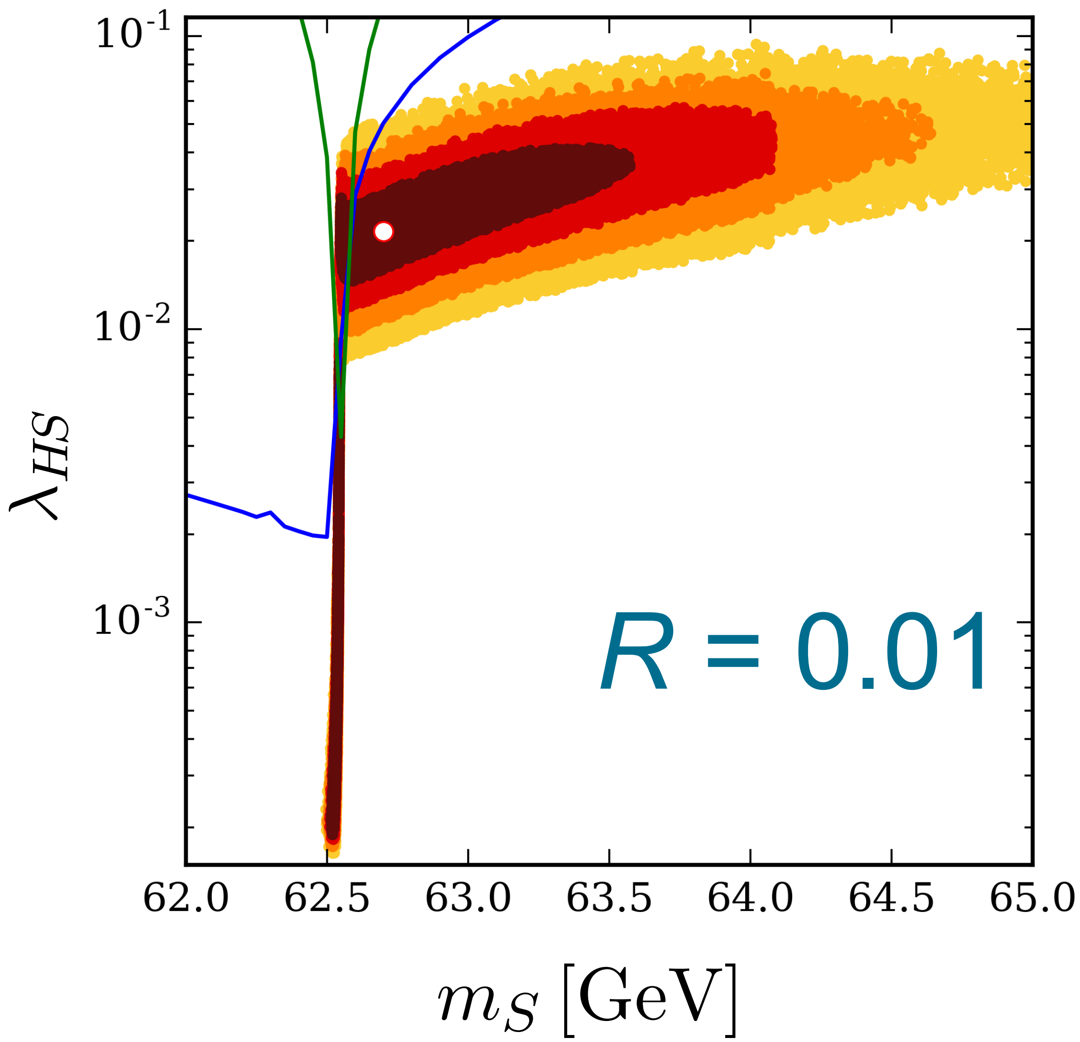

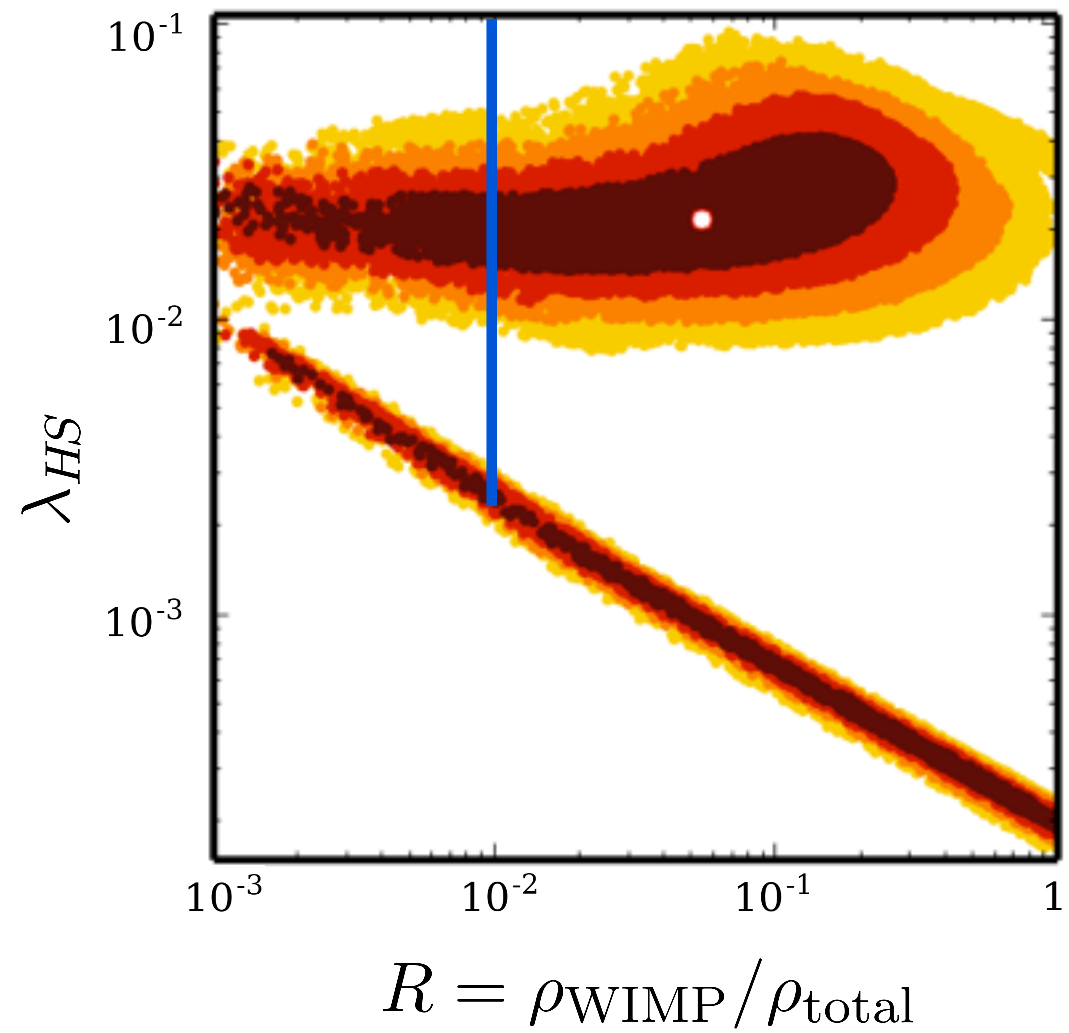

GCE+BR$_{\text{inv}}$+LUX+dwarfs+γ-lines+relic density

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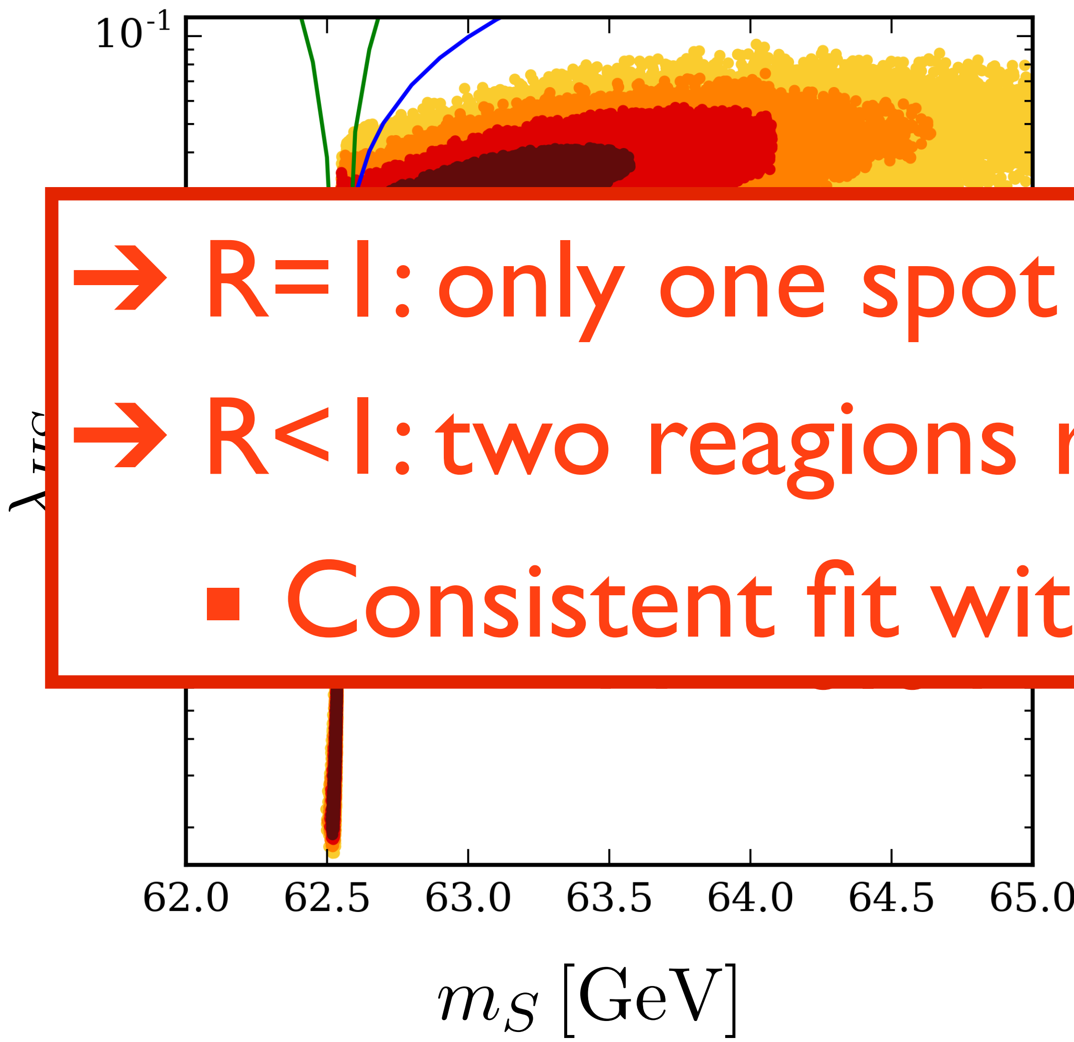
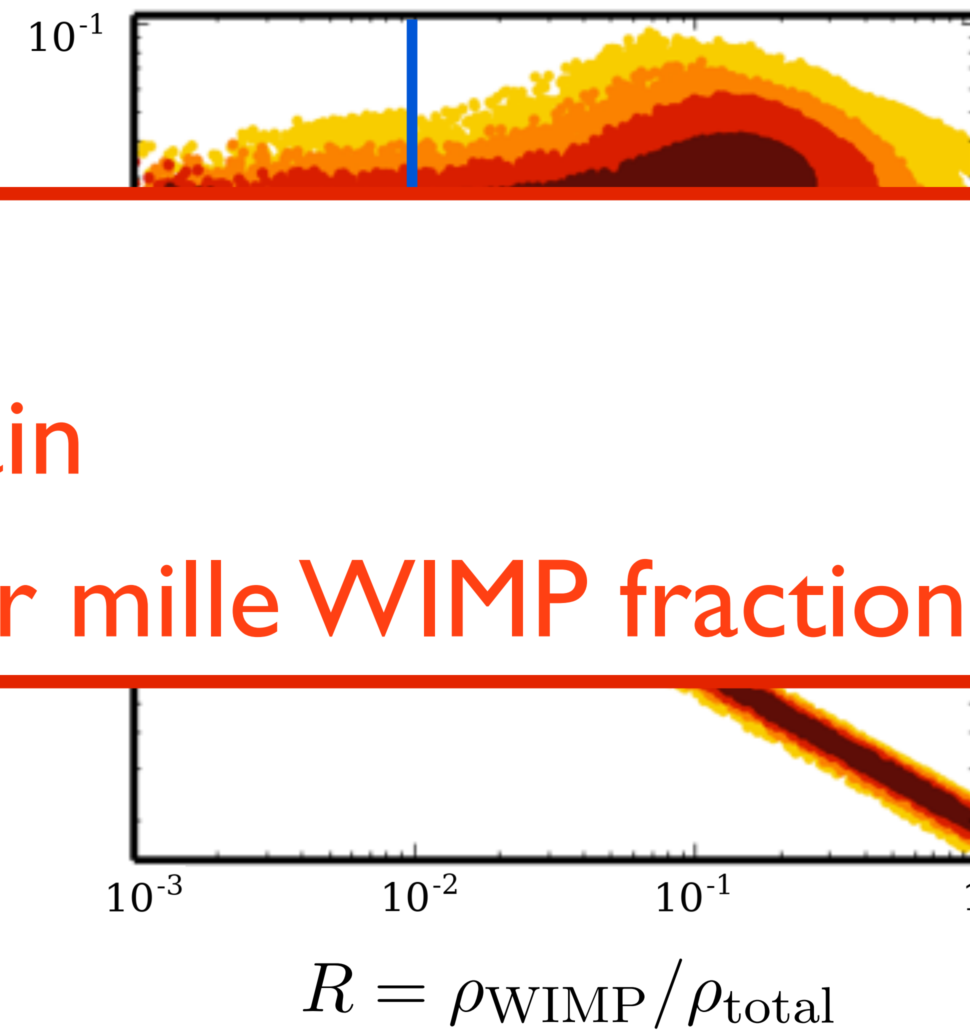




➔ R=1: only one spot

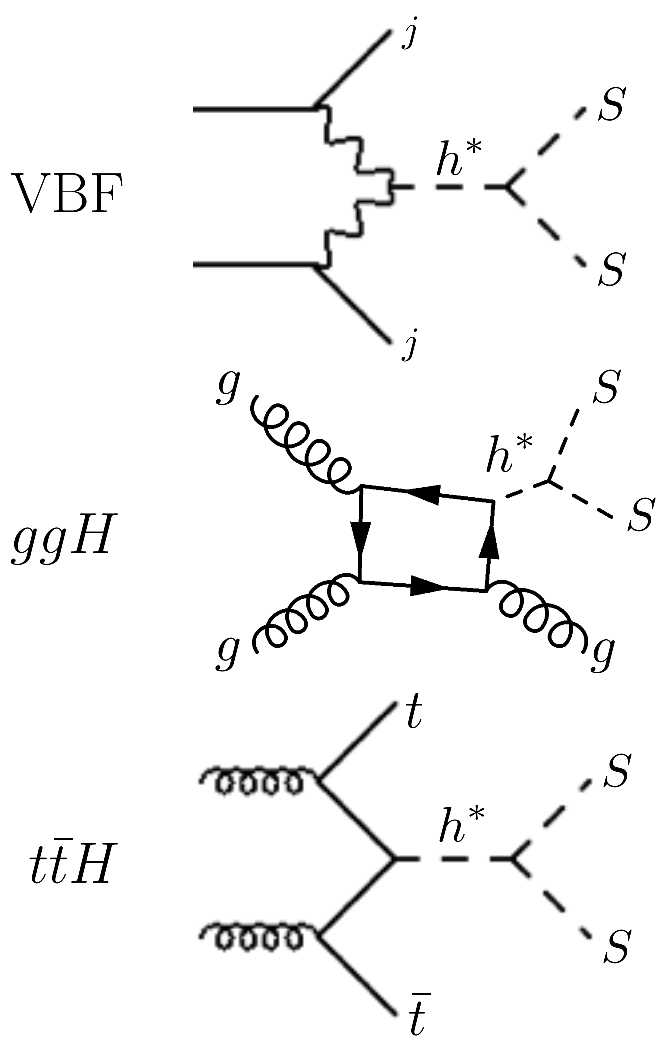
➔ R<1: two reagions remain

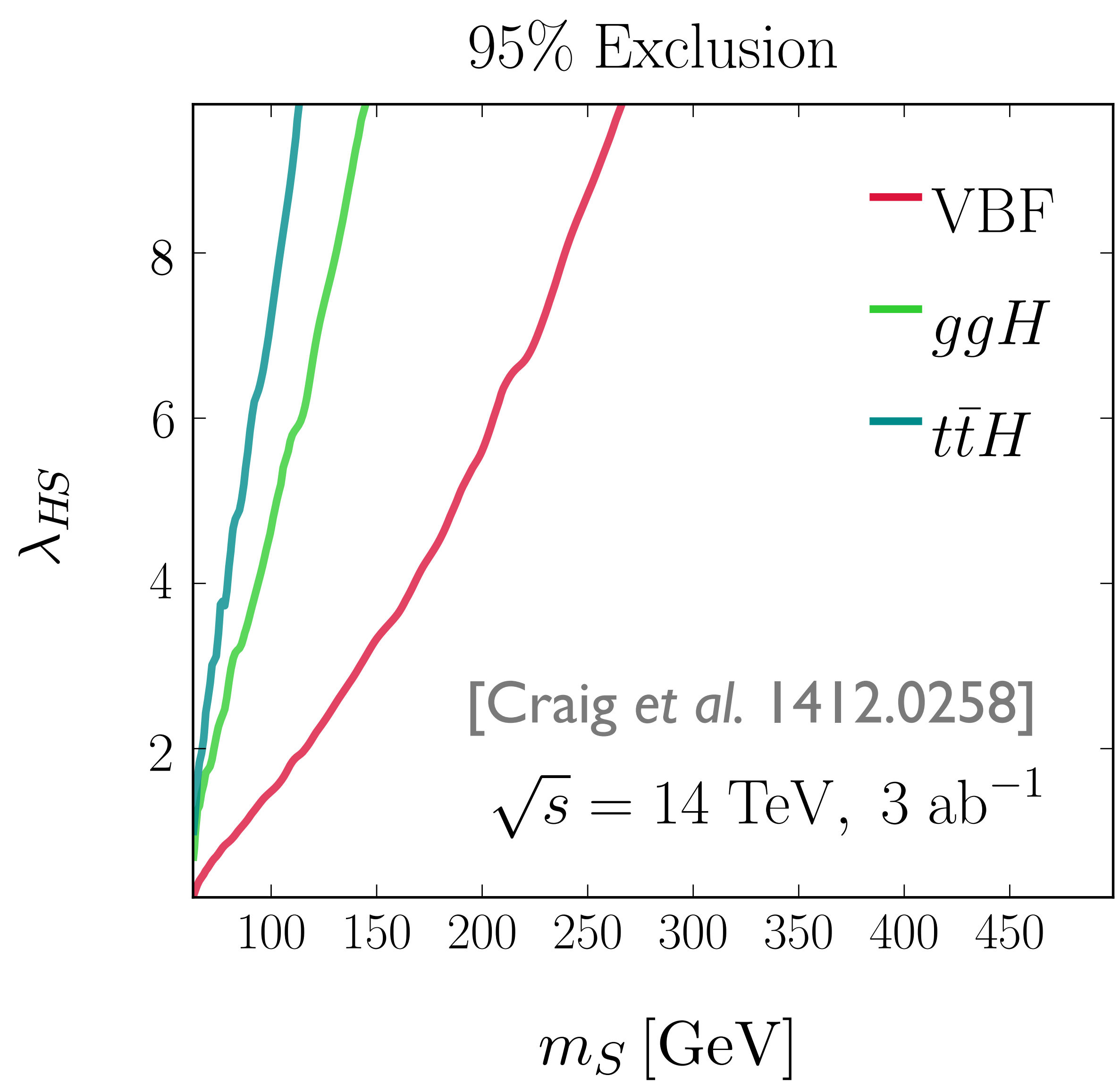
- Consistent fit with per mille WIMP fraction!

Future experimental prospects

Future experimental prospects

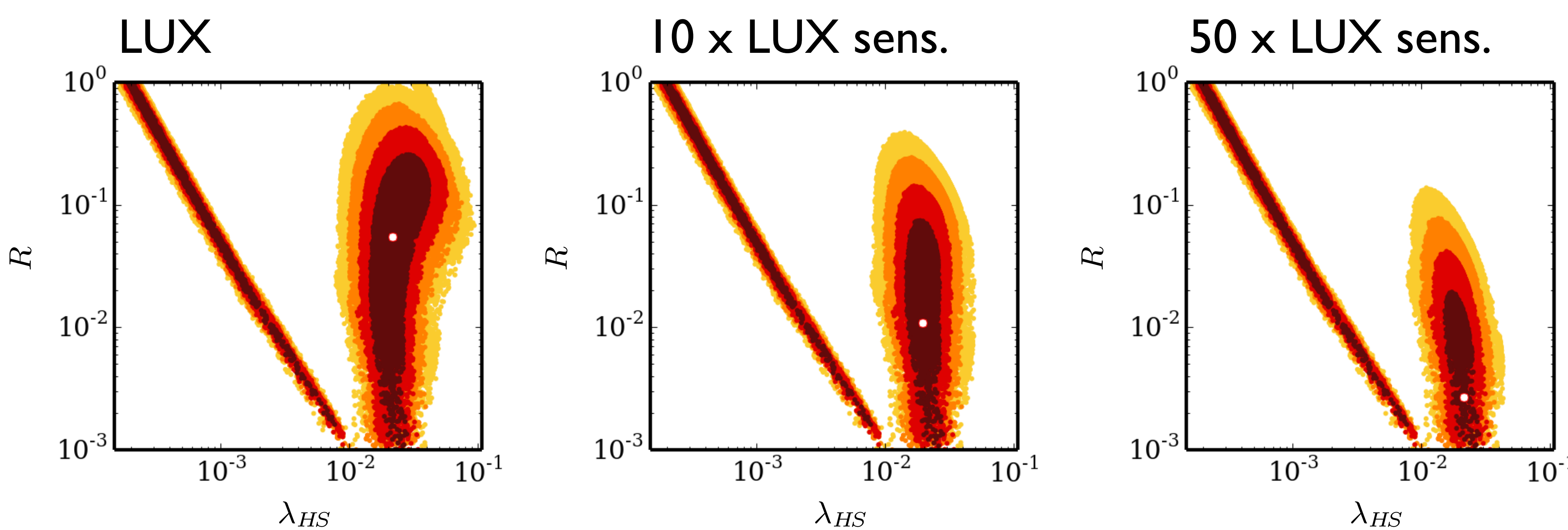
- LHC constraints: off-shell region $m_S \gtrsim m_h/2$ difficult





Future experimental prospects

- LHC constraints: off-shell region $m_S \gtrsim m_h/2$ difficult
- Constraints from dwarfs: General challenge for GCE
- Direct detection projections:



Inert Doublet Model

The Inert Doublet Model (IDM)

[Deshpande, Ma '78; Ma '06; Barbieri, Hall, Rychkov: '06; ...]

- Add second Higgs doublet Φ and Z_2-symmetry:

$$V = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \mathrm{h.c.}\right]$$

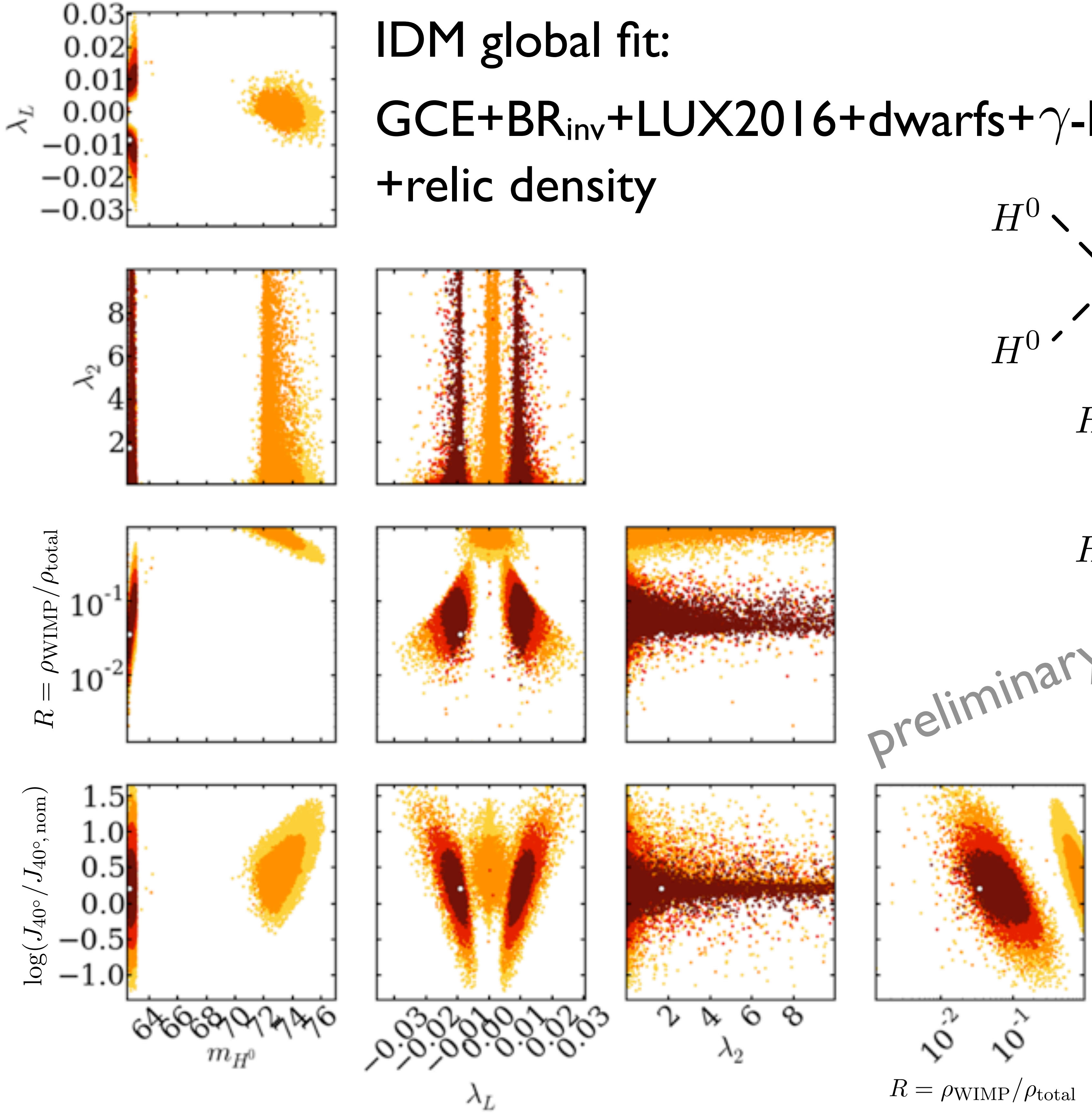
- five free parameters:

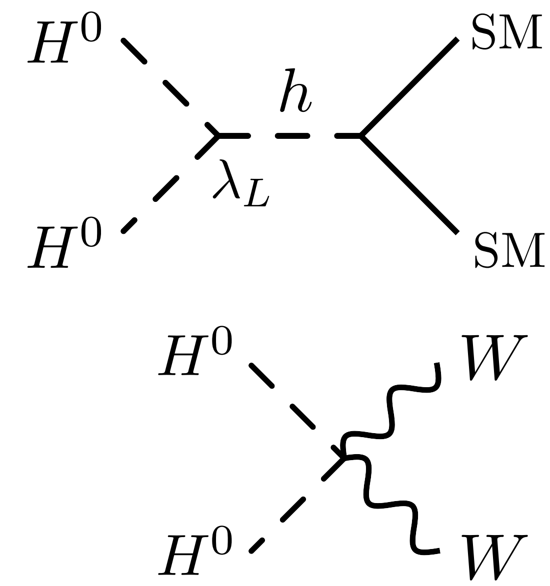
$$m_{H^0}, \quad m_{A^0}, \quad m_{H^\pm}, \quad \lambda_L, \quad \lambda_2$$

IDM global fit:

GCE+BR_{inv}+LUX2016+dwarfs+γ-lines

+relic density





Global fit in the IDM

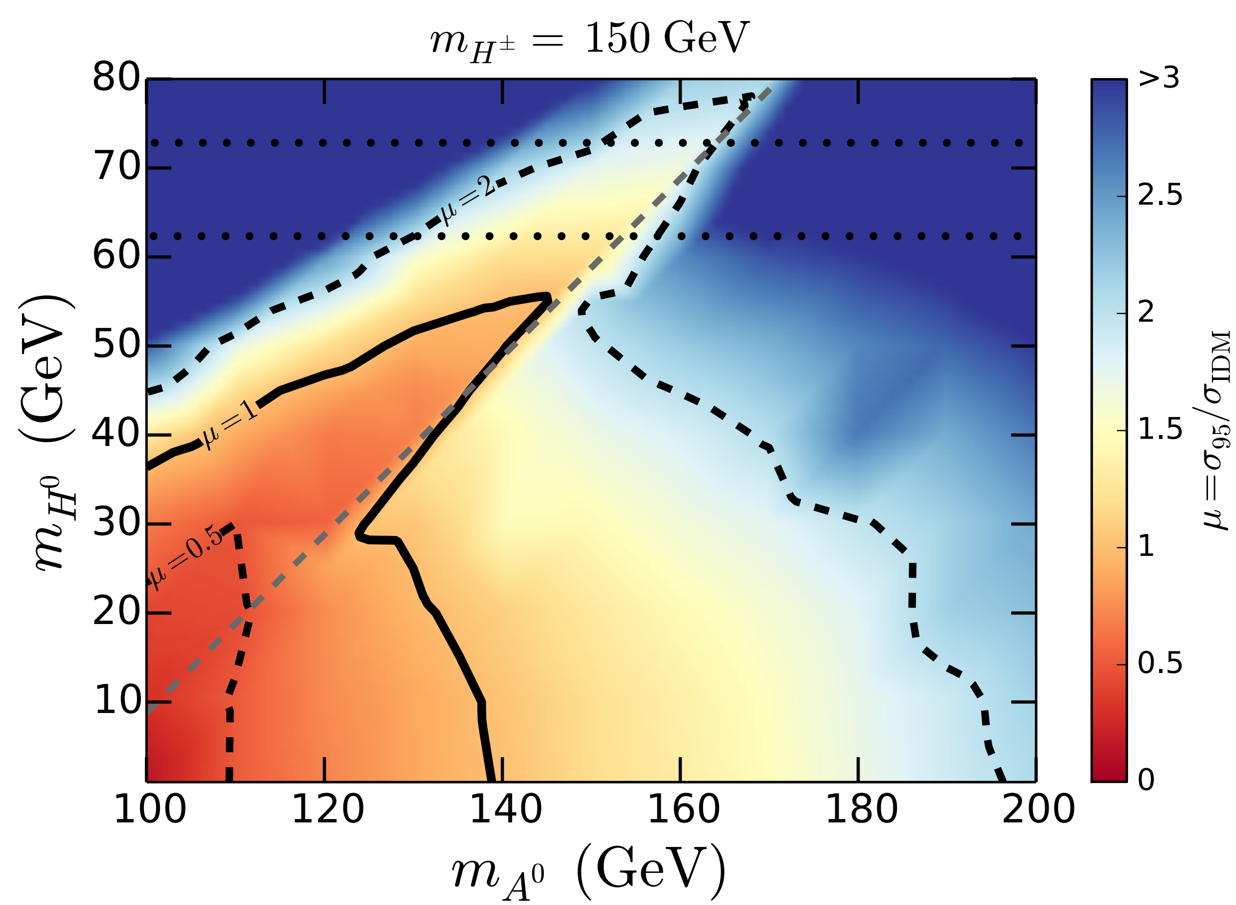
- Similar astrophysical phenomenology
- Additional region around 72 GeV:
  $H^0 H^0 \rightarrow WW$ (4-vertex) yields the right cross section
- Constraints from *S,T,U* parameters, vacuum stability, ...
  with 2HDMC [Eriksson *et al.* 0902.0851]
- Different implications for LHC

LHC constraints on the IDM

- Reinterpretation of ATLAS Di-lepton+MET searches

[ATLAS 1403.5294 (EW SUSY search); ATLAS 1402.3244 (inv. Higgs decay)]

$$q\bar{q} \to Z \to A^0 H^0 \to Z^{(*)} H^0 H^0 \to \ell^+ \ell^- H^0 H^0,$$
$$q\bar{q} \to Z \to H^\pm H^\mp \to W^{\pm(*)} H^0 W^{\mp(*)} H^0$$
$$\to \nu \ell^+ H^0 \nu \ell^- H^0,$$
$$q\bar{q} \to Z \to Z h^{(*)} \to \ell^+ \ell^- H^0 H^0,$$
$$q\bar{q} \to Z \to Z H^0 H^0 \to \ell^+ \ell^- H^0 H^0.$$



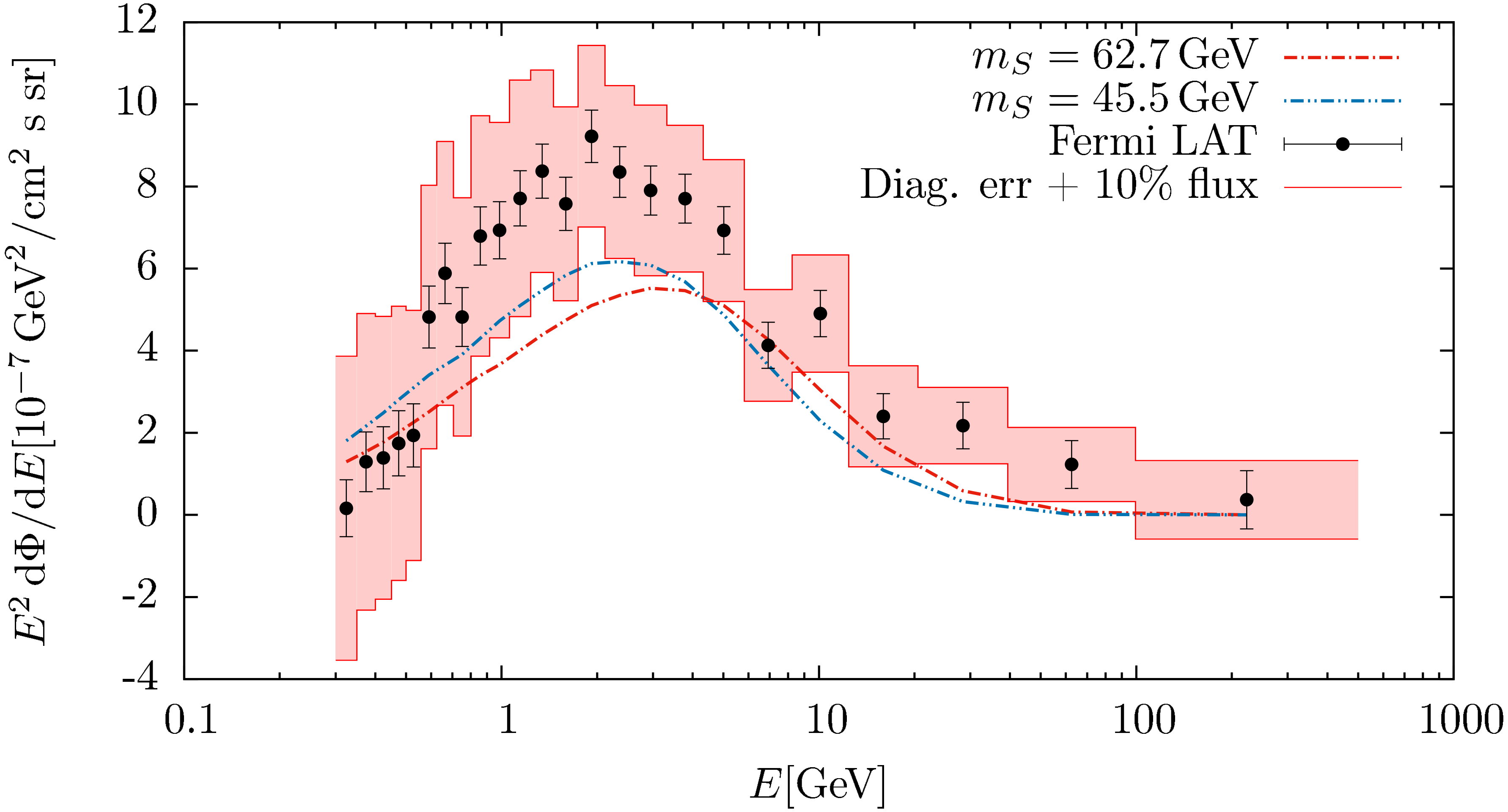
[Bélanger, Dumont, Goudelis, Herrmann, Kraml, Sengupta 1503.07367]

Summary

- GCE: Astrophysics or WIMPs?
- Singlet Scalar Higgs Portal Model: Good fit!
- After constraints: Only Higgs-resonance remains
- Allow for additional non-WIMP DM component
- Non-trivial implications for WIMP fraction near resonance (large velocity dependence)
- Inert Doublet Model: Interesting interplay with LHC

Back-up I: Photon spectra for best-fit points

GCE only (blue) and after all constraints (red):



Back-up II: Table with best-fit points

$\log L$ contribution	GCE	$+\mathrm{BR_{inv}}$	+LUX	+dwarfs	+lines	+relic den.	2nd region
m_S [GeV]	$45.50^{+5.98}_{-5.36}$	$61.07^{+2.65}_{-1.98}$	$61.55^{+1.78}_{-0.85}$	$61.35^{+1.90}_{-0.79}$	$61.46^{+1.87}_{-0.85}$	$62.70^{+0.57}_{-0.18}$	$62.52^{+0.02}_{-0.01}$
λ_{HS}	$0.17^{+11.67}_{-0.09}$	$0.0125^{+7.31}_{-0.0125}$	$0.0082^{+0.317}_{-0.0082}$	$0.0087^{+0.312}_{-0.0087}$	$0.0082^{+0.315}_{-0.0082}$	$0.022^{+0.015}_{-0.013}$	$0.00029^{+0.0078}_{-0.00010}$
R	$0.68^{+0.32}_{-0.65}$	$1.0^{+0.0}_{-1.0}$	$0.99^{+0.01}_{-0.99}$	$1.0^{+0.0}_{-1.0}$	$1.0^{+0.0}_{-1.0}$	$0.054^{+0.141}_{-0.053}$	$0.498^{+0.502}_{-0.496}$
$\log J/J_{\mathrm{nom}}$	$0.0^{+0.44}_{-0.44}$	$-0.05^{+0.48}_{-0.36}$	$0.02^{+0.42}_{-0.43}$	$0.22^{+0.36}_{-0.35}$	$0.12^{+0.31}_{-0.29}$	$0.13^{+0.30}_{-0.32}$	$0.13^{+0.32}_{-0.31}$
$\sigma v\,[10^{-26}\,\mathrm{cm}^3/\mathrm{s}]$	$1.97^{+1034}_{-1.38}$	$1.28^{+4.1e6}_{-0.61}$	$1.23^{+1.7e6}_{-0.55}$	$0.96^{+1.3e6}_{-0.37}$	$1.04^{+1.3e6}_{-0.42}$	$359^{+9.7e5}_{-327}$	$4.3^{+1.6e5}_{-0.9}$
$\sigma v\,R^2\,[10^{-26}\,\mathrm{cm}^3/\mathrm{s}]$	$0.91^{+0.53}_{-0.35}$	$1.28^{+2.02}_{-0.53}$	$1.21^{+0.68}_{-0.45}$	$0.96^{+0.43}_{-0.31}$	$1.04^{+0.39}_{-0.32}$	$1.06^{+0.42}_{-0.32}$	$1.06^{+0.43}_{-0.31}$
χ^2_{GCE}	19.3	25.3	25.6	26.0	26.0	26.8	26.7
$p(\chi^2_{\mathrm{GCE}})$	0.57	0.20	0.24	0.22	0.21	0.18	0.18
$p(\mathrm{BR_{inv}})$	0.0	0.90	0.97	0.97	0.97	1.0	1.0
p(LUX)	0.0	0.32	0.62	0.58	0.62	0.84	1.0
p(dwarfs)	0.18	0.16	0.18	0.24	0.22	0.22	0.22
p(lines R3)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
p(relic den.)	0.03	0.0	0.0	0.0	0.0	0.99	1.0