A global fit of the gamma-ray galactic center excess within the scalar Higgs portal model

[A. Cuoco, B. Eiteneuer, JH, M. Krämer; JCAP 1606 (2016), 1603.08228]

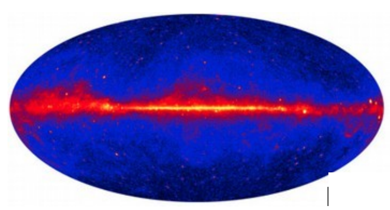
Jan Heisig (RWTH Aachen)

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Dark Side of the Universe 2016

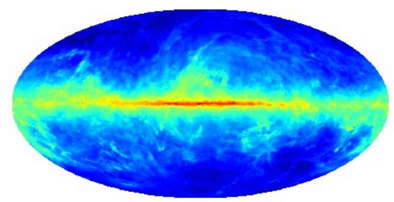
July 25-29, Bergen, Norway

Fermi GeV Galactic Center Excess



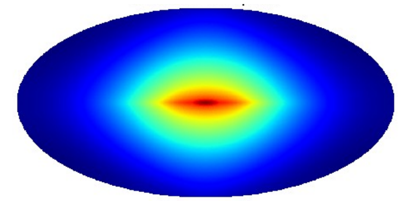
Fermi gamma-ray sky

=



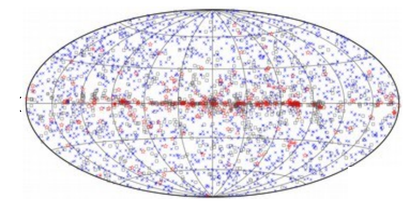
Pion decay/Bremsst.

+



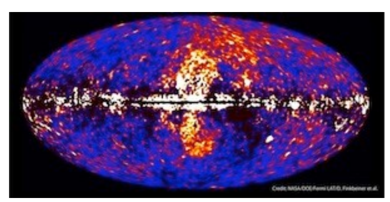
Inverse Compton

+



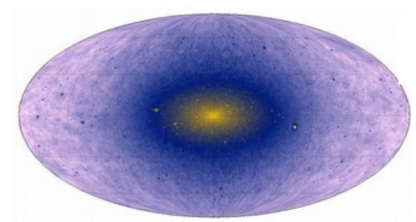
Point sources

+



Fermi bubbles

+

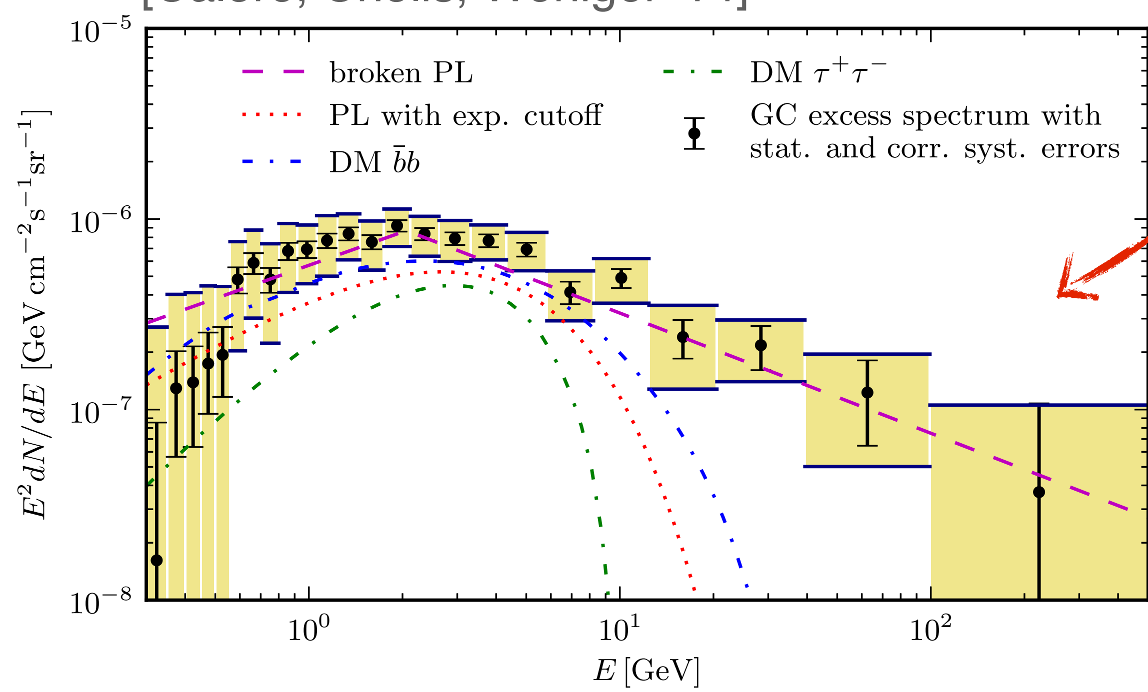


Excess

⇒ Christoph's talk on Monday

⇒ Aldo's, Gabrijela's talks today

[Calore, Cholis, Weniger '14]

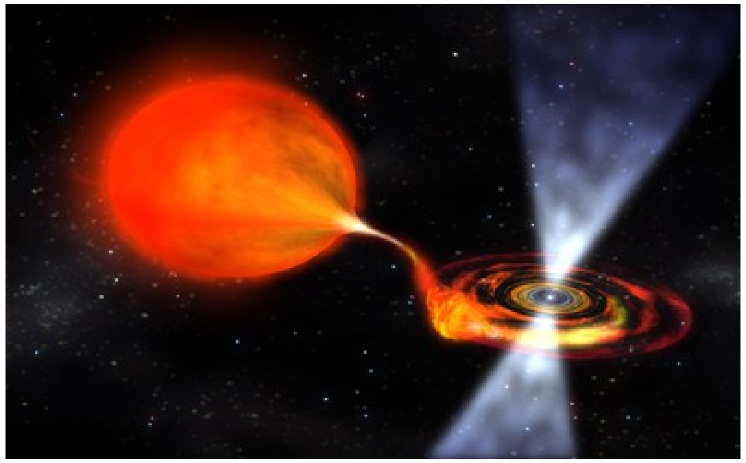


[Goodenough, Hooper '09, '10; Vitale, Morselli '09; Hooper, Linden '11; Abazajian, Kaplinghat '12; Hooper, Slatyer '13; Macias, Gordan '13; Huang *et al*. '13; Abazajian *et al*. '14; Daylan *et al*. '14; Zhou *et al*. '14; Calore *et al*. '14; Gaggero *et al*. '15; Cholis *et al*. '15; Bartels *et al*.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

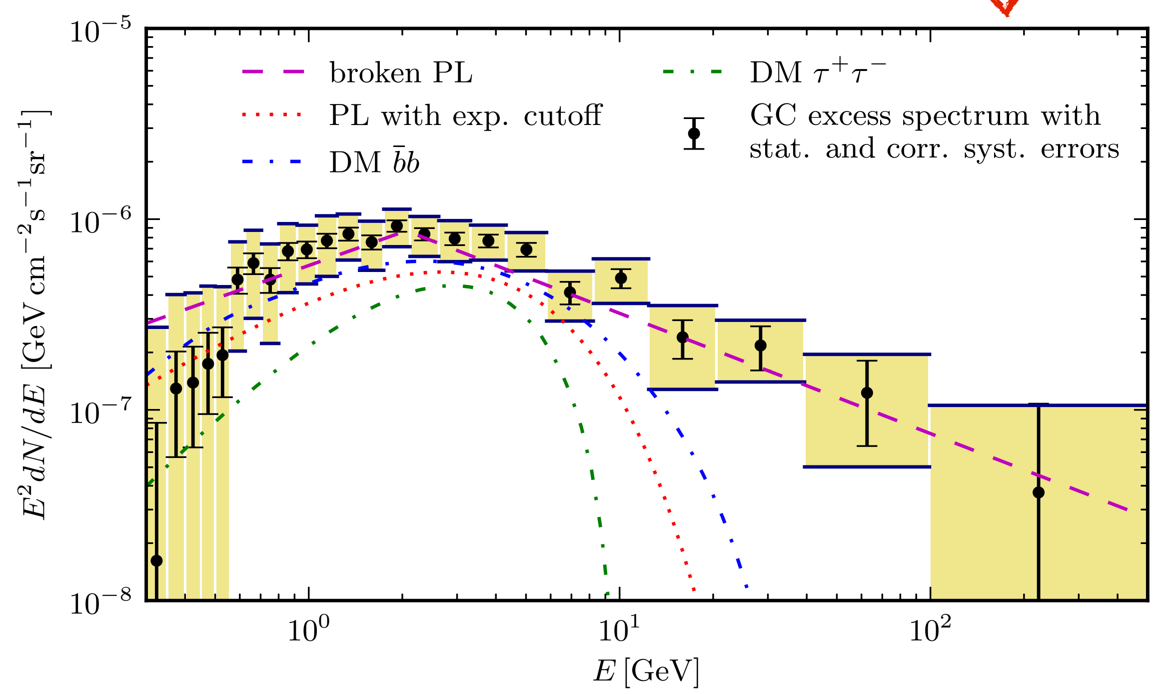
⇒ Excess over the known foregrounds in *Fermi*-LAT data

Fermi GeV Galactic Center Excess

Millisecond Pulsars



?

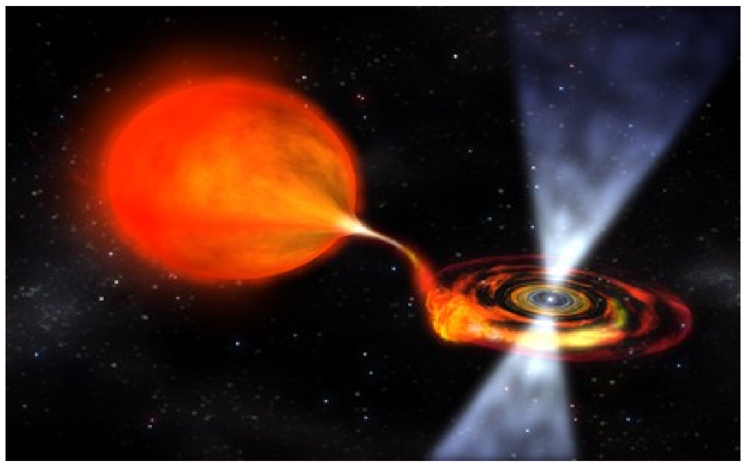


[Calore, Cholis, Weniger '14]

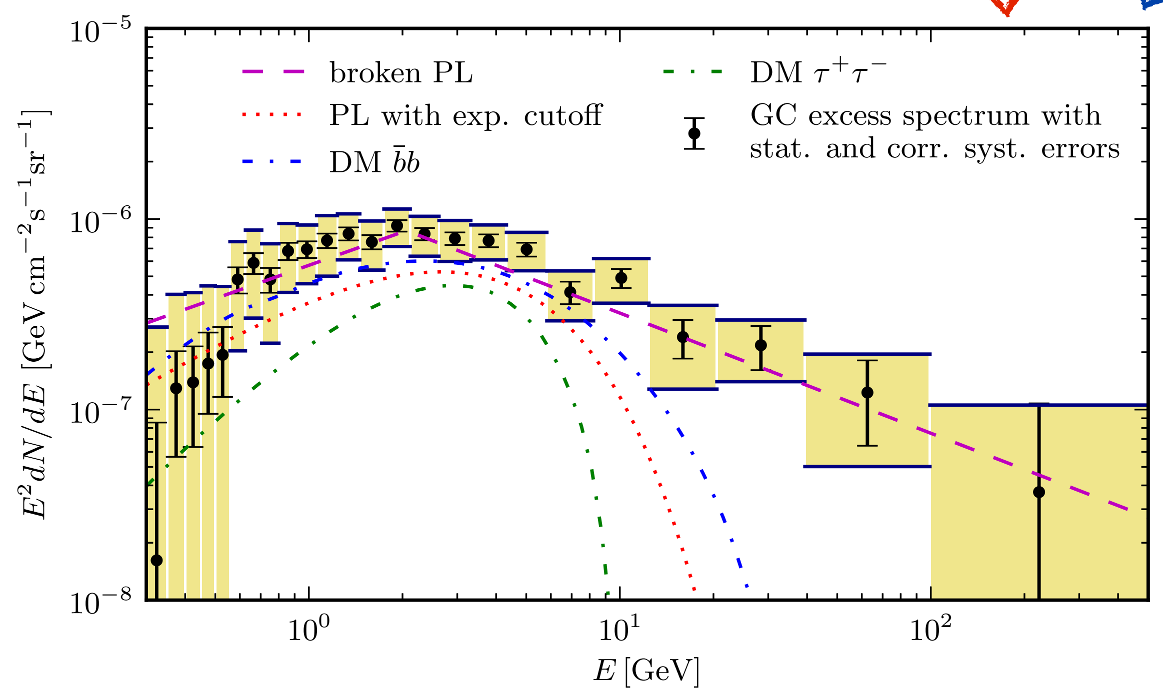
⇒ Excess over the known foregrounds in *Fermi*-LAT data

Fermi GeV Galactic Center Excess

Millisecond Pulsars



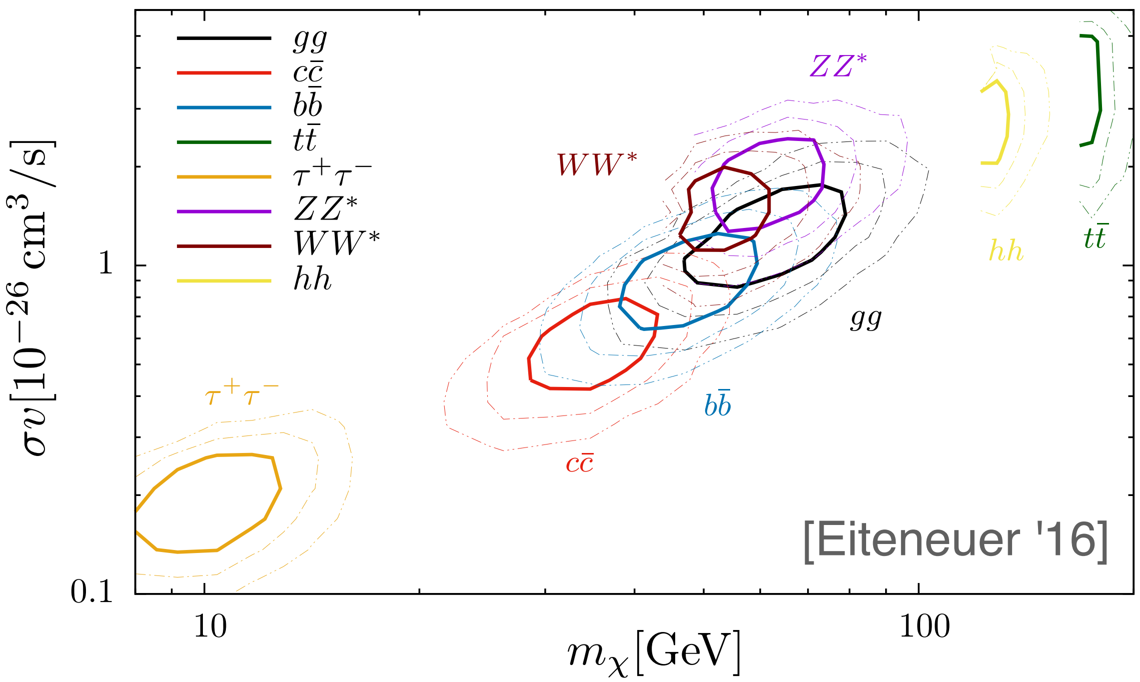
WIMP Dark Matter

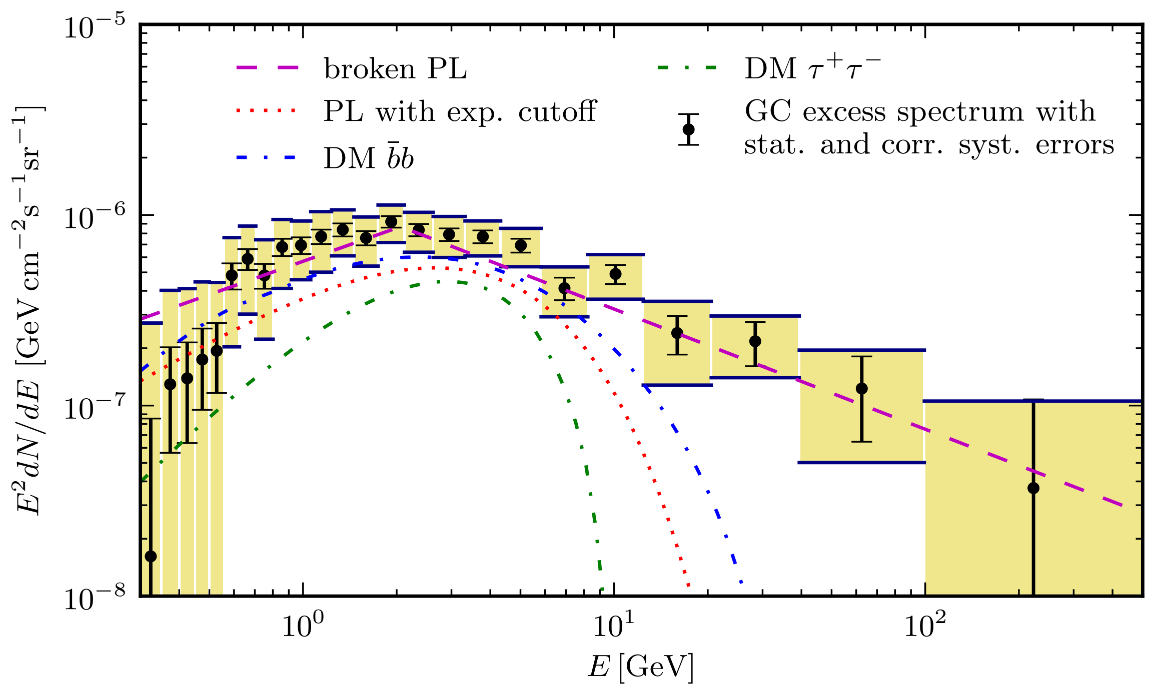


[Calore, Cholis, Weniger '14]

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

Fermi GeV Galactic Center Excess



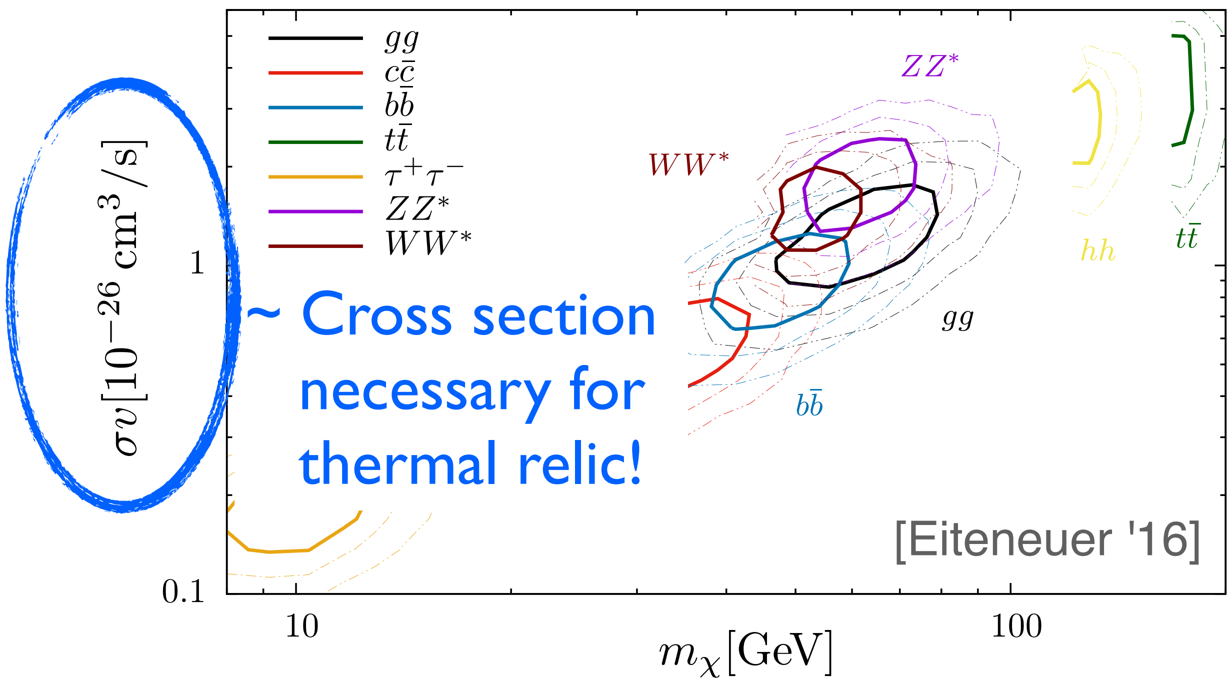


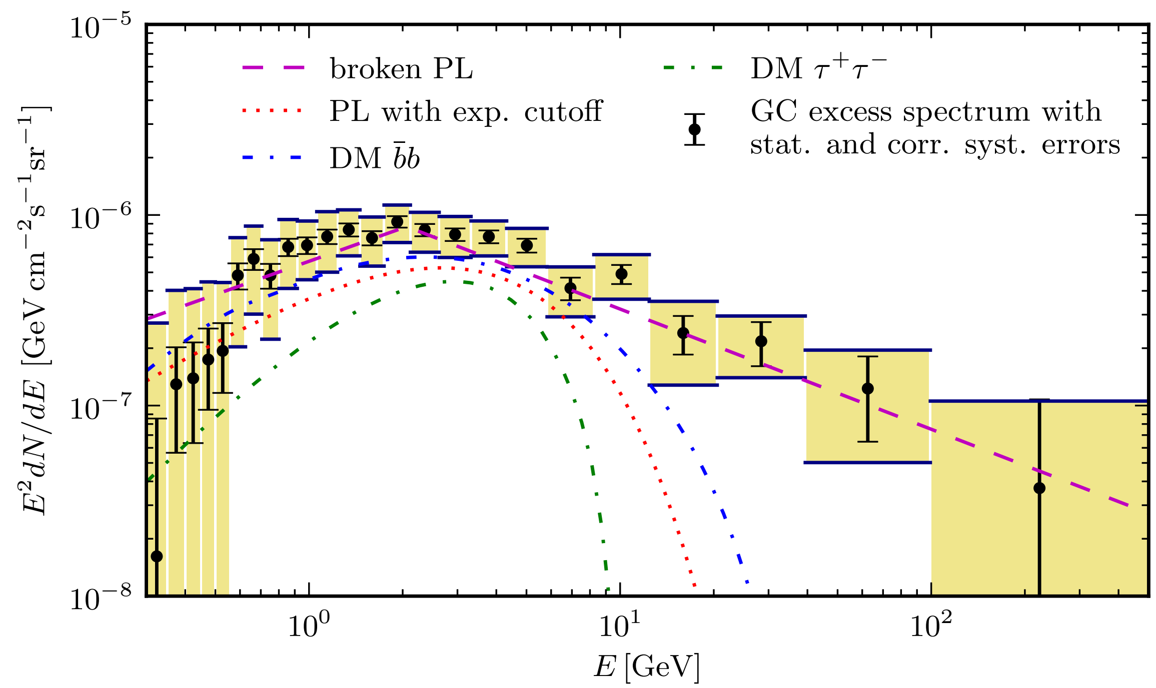
[Calore, Cholis, Weniger '14]

WIMP Dark Matter

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

Fermi GeV Galactic Center Excess





[Calore, Cholis, Weniger '14]

WIMP Dark Matter

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

This work:

- Very simple Dark Matter model (singlet scalar Higgs portal)
- Detailed numerical fit involving further constraints (invisible Higgs width, LUX, relic density,...)
- Allow for additional non-WIMP DM component (PBHs, axions,...)

➔ Interesting implications on WIMP DM fraction

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

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

[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:

$$\mathcal{L} \supset -\frac{1}{2}m_S^2\, S^2 - \frac{1}{4}\lambda_S\, S^4 - \frac{1}{4}\lambda_{HS}\, h^2 S^2 - \frac{1}{2}\lambda_{HS}\, vhS^2\,,$$

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

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:

$$\mathcal{L} \supset -\frac{1}{2} m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HS} h^2 S^2 - \frac{1}{2}\lambda_{HS} v h S^2 ,$$

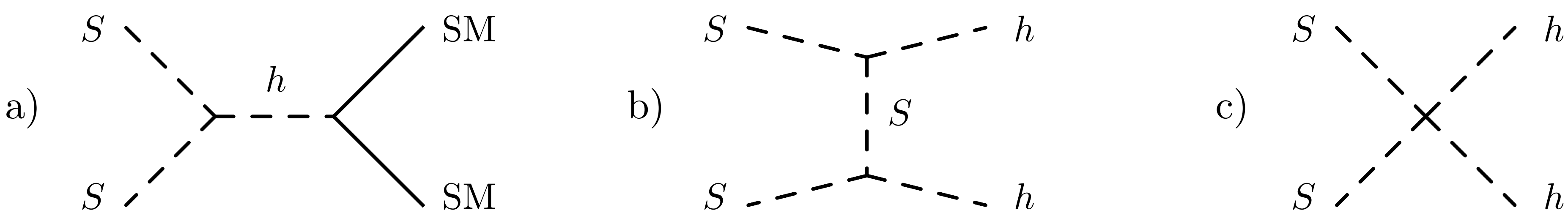
where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2/2.$ (after EWSB)

Important for this work

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

Dark Matter annihilation

- Annihilation processes:

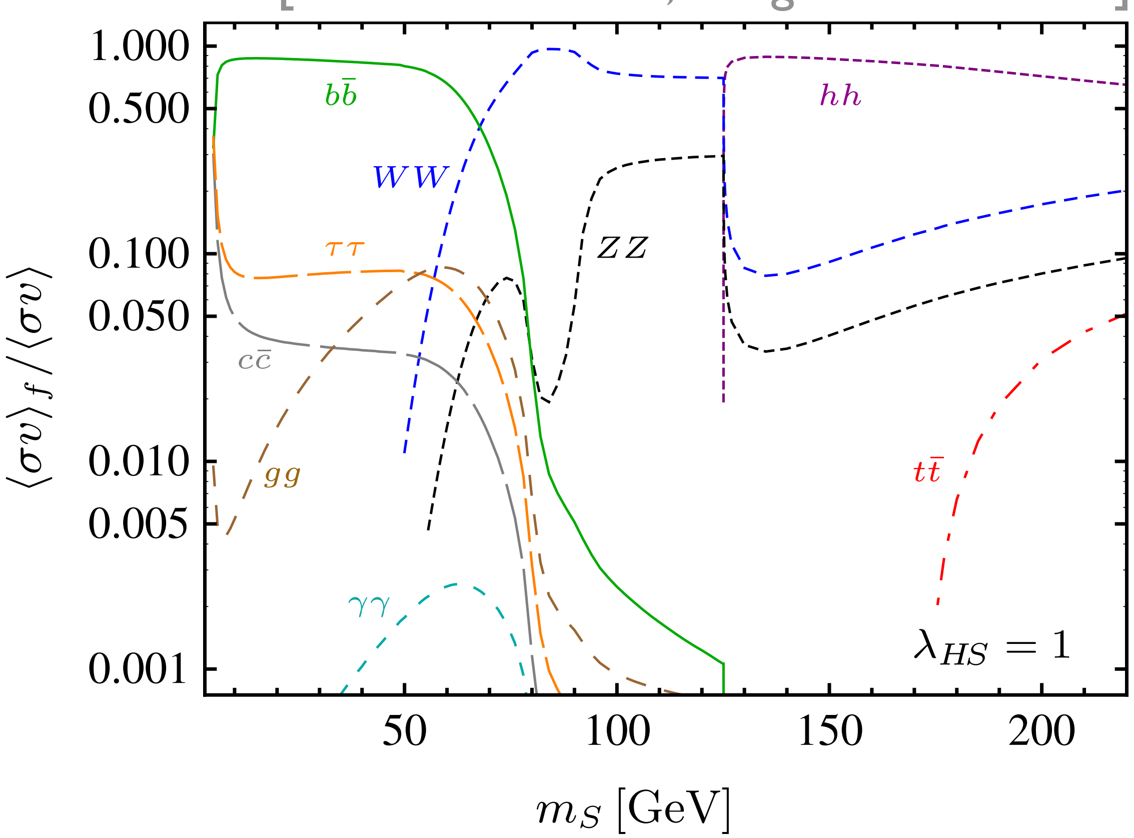


$\propto v\lambda_{HS}$ $\propto (v\lambda_{HS})^2$ $\propto \lambda_{HS}$

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

Only present above Higgs threshold

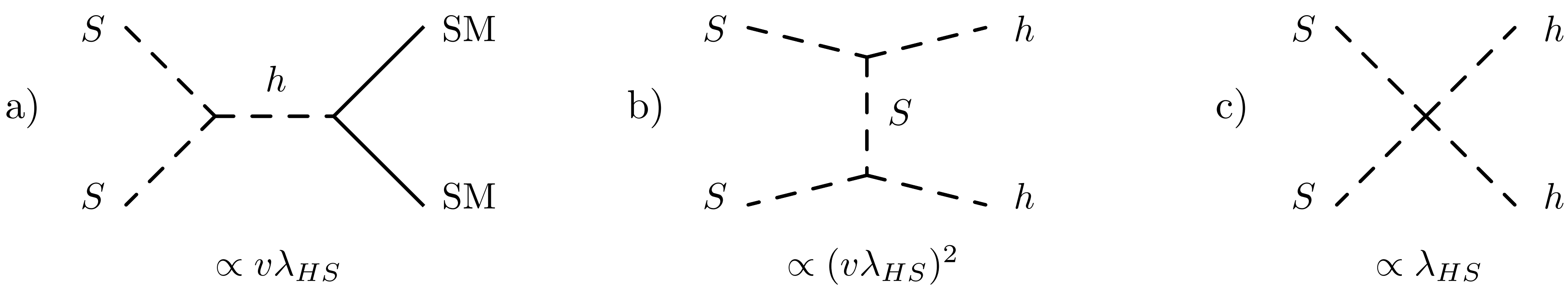
[from 1603.08228, using micrOMEGAs]



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

Dark Matter annihilation

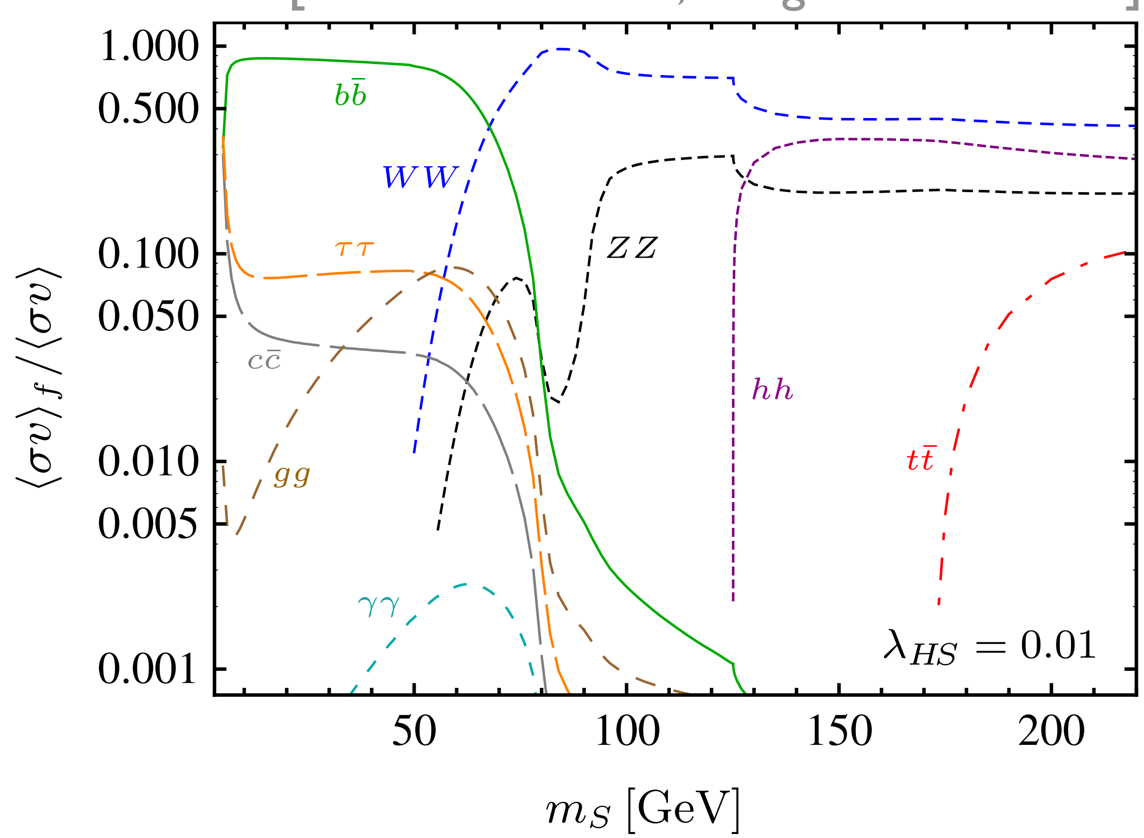
- Annihilation processes:



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

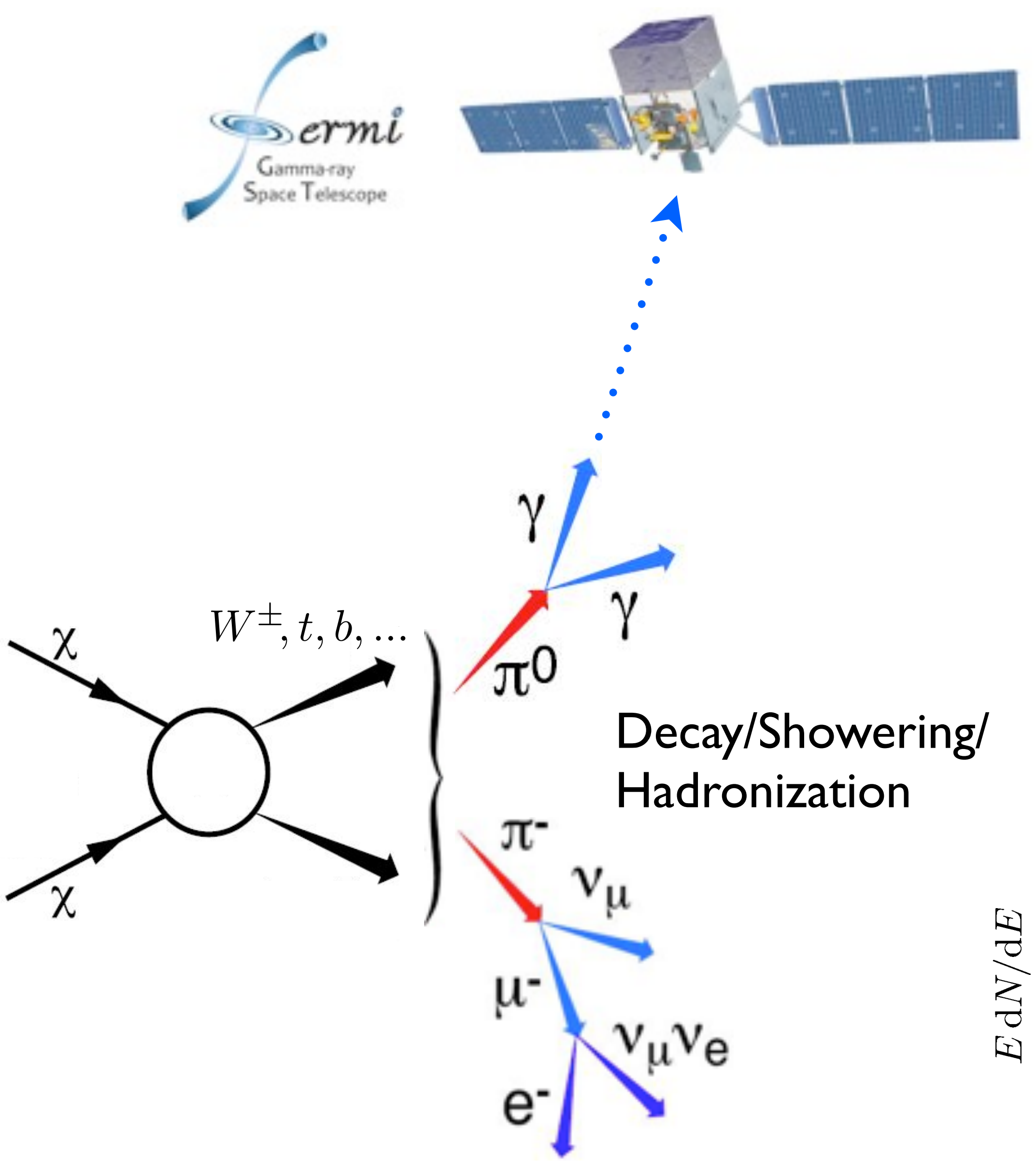
Only present above Higgs threshold

[from 1603.08228, using micrOMEGAs]



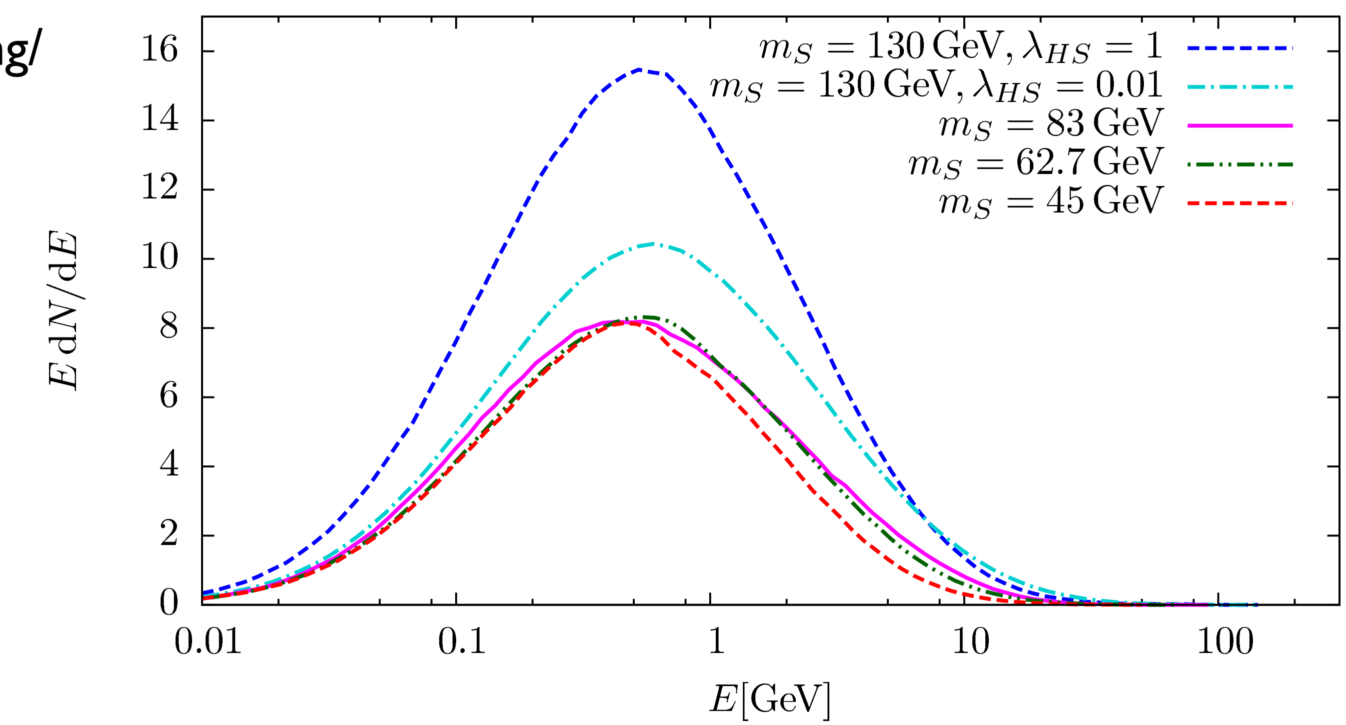
[see also e.g.
Cline, Scott, Kainulainen, Weniger '13;
Duerr, Pérez, Smirnov '15;
Beniwal *et al.* '15]

Gamma-ray spectrum

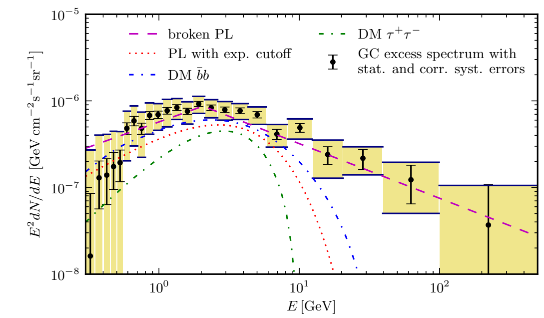


- Continuous photon spectrum
- Slow in fit
  ⇒ Precompute spectra for all channels with MadGraph/Pythia 8
- During fit: Combine spectra according to contribution

Photon spectra for several masses/couplings:

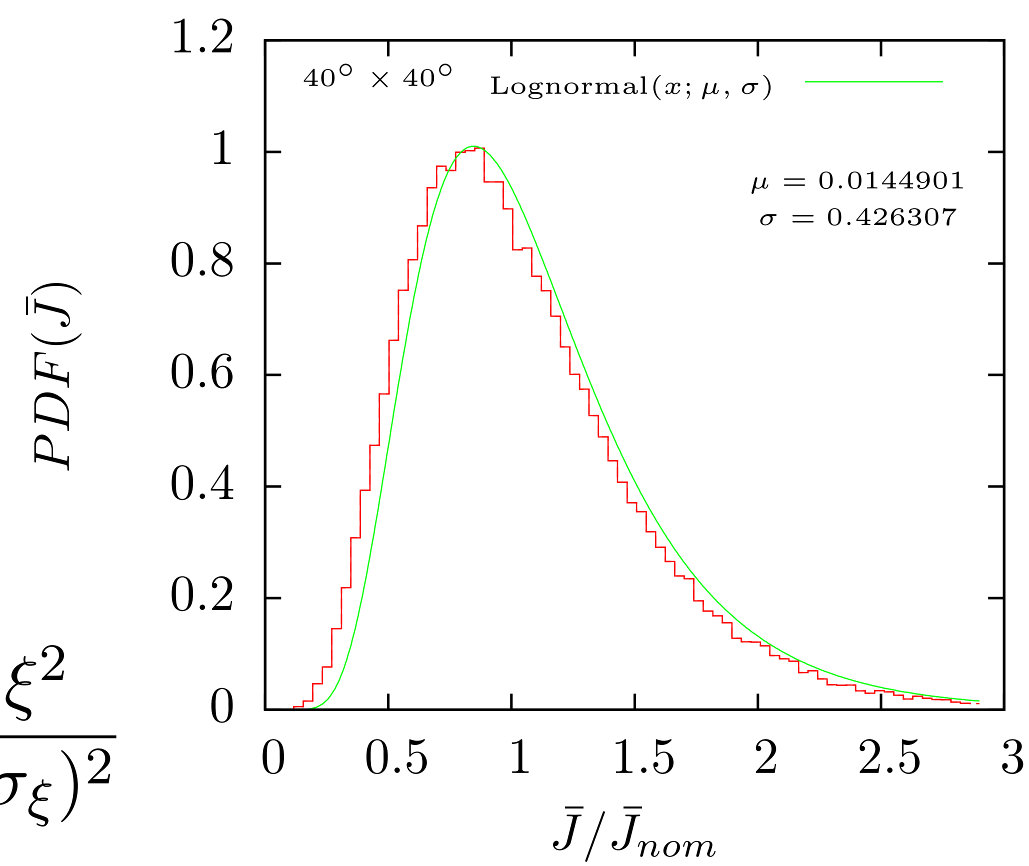


χ^2-computation for the GCE



- 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]

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



- Compute χ^2:

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

Constraints on the parameter space

Sign on the Fløien Mountain, Bergen

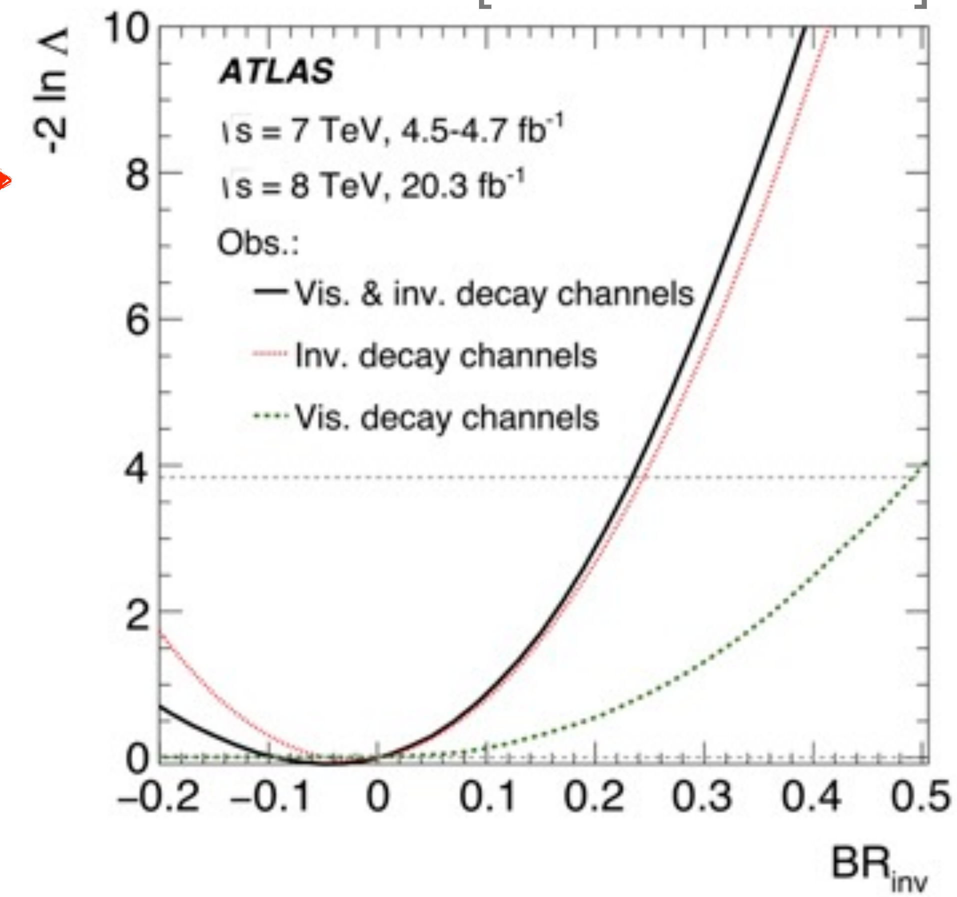
Constraints on the parameter space

(i) Collider constraints: Higgs invisible BR

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

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

[ATLAS: 1509.00672]



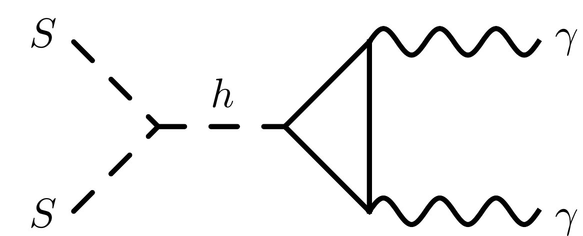
Constraints on the parameter space

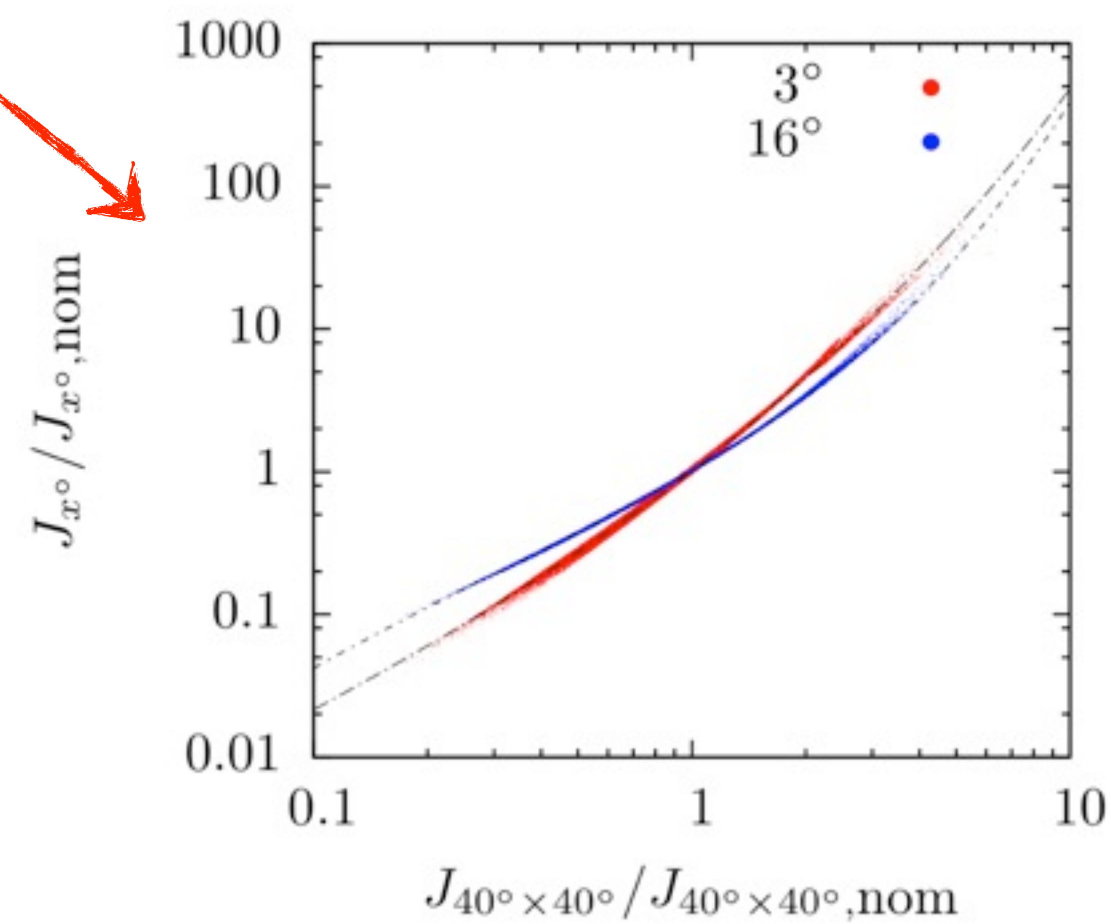
(iv) Gamma-lines:

[*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]

Fit parameters and tools

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

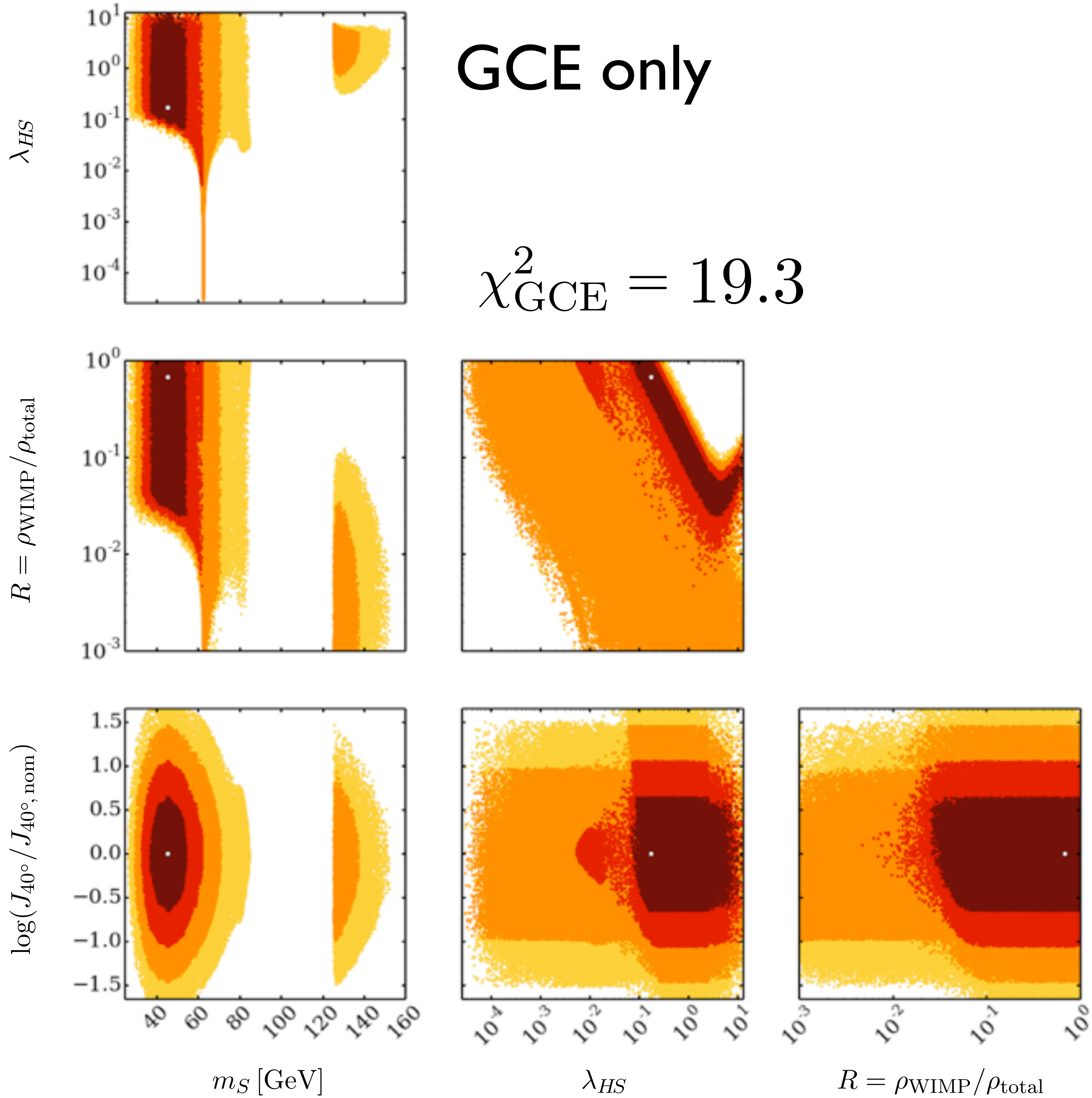
$$\begin{aligned} m_S\!: &\quad 5\ldots 220\,\text{GeV} \\ \lambda_{HS}\!: &\quad 3\times 10^{-5}\ldots 4\pi \\ \ln(\bar{J}/\bar{J}_{\text{nom}})\!: &\quad -4\sigma_\xi \ldots 4\sigma_\xi \\ R\!: &\quad 10^{-3}\ldots 1 \end{aligned}$$

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

Results

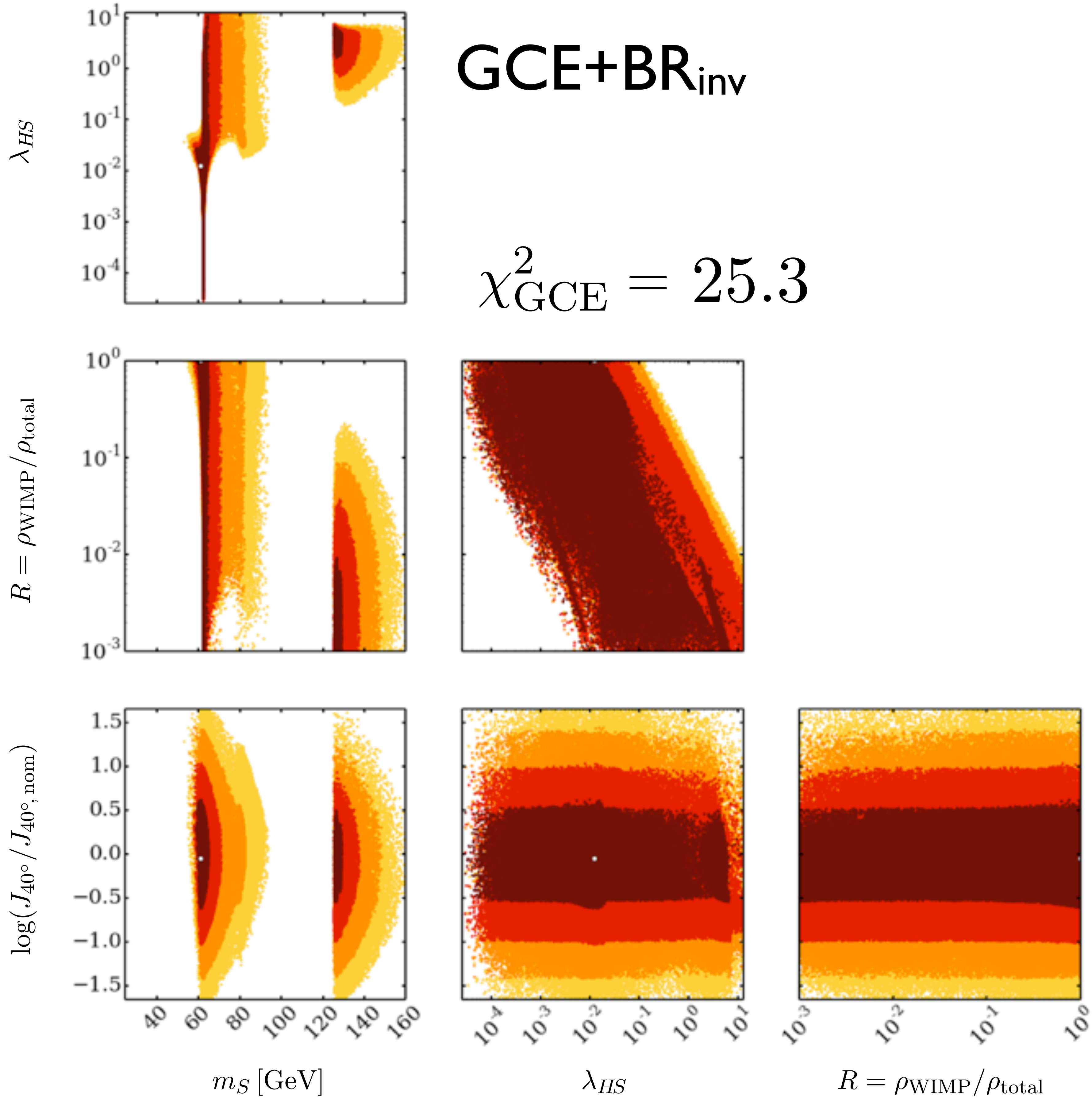
GCE only

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



GCE+BR$_{inv}$

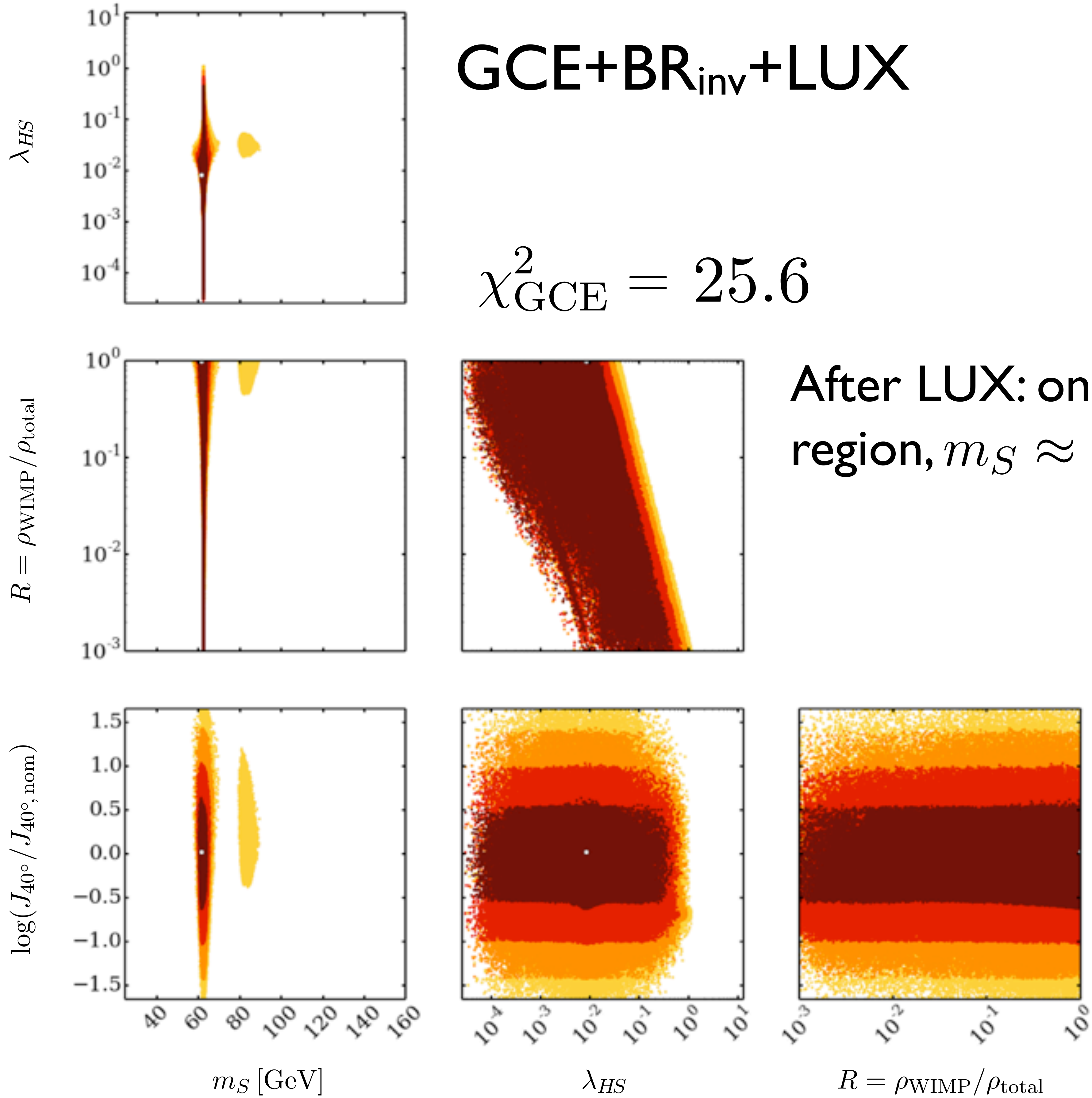
$$\chi^2_{\rm GCE} = 25.3$$



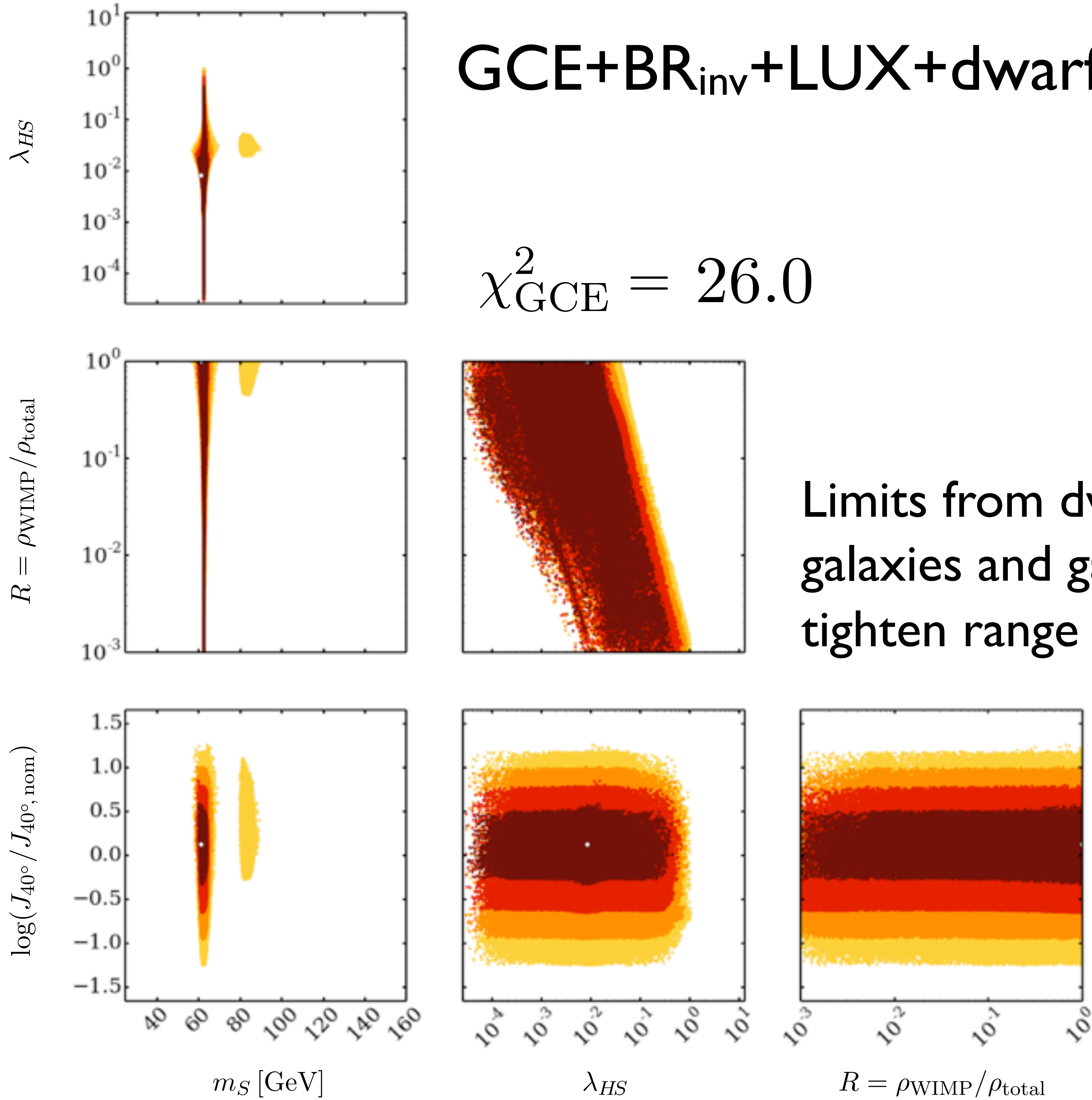
GCE+BR$_{inv}$+LUX

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

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



GCE+BR$_{\rm inv}$+LUX+dwarfs+γ-lines

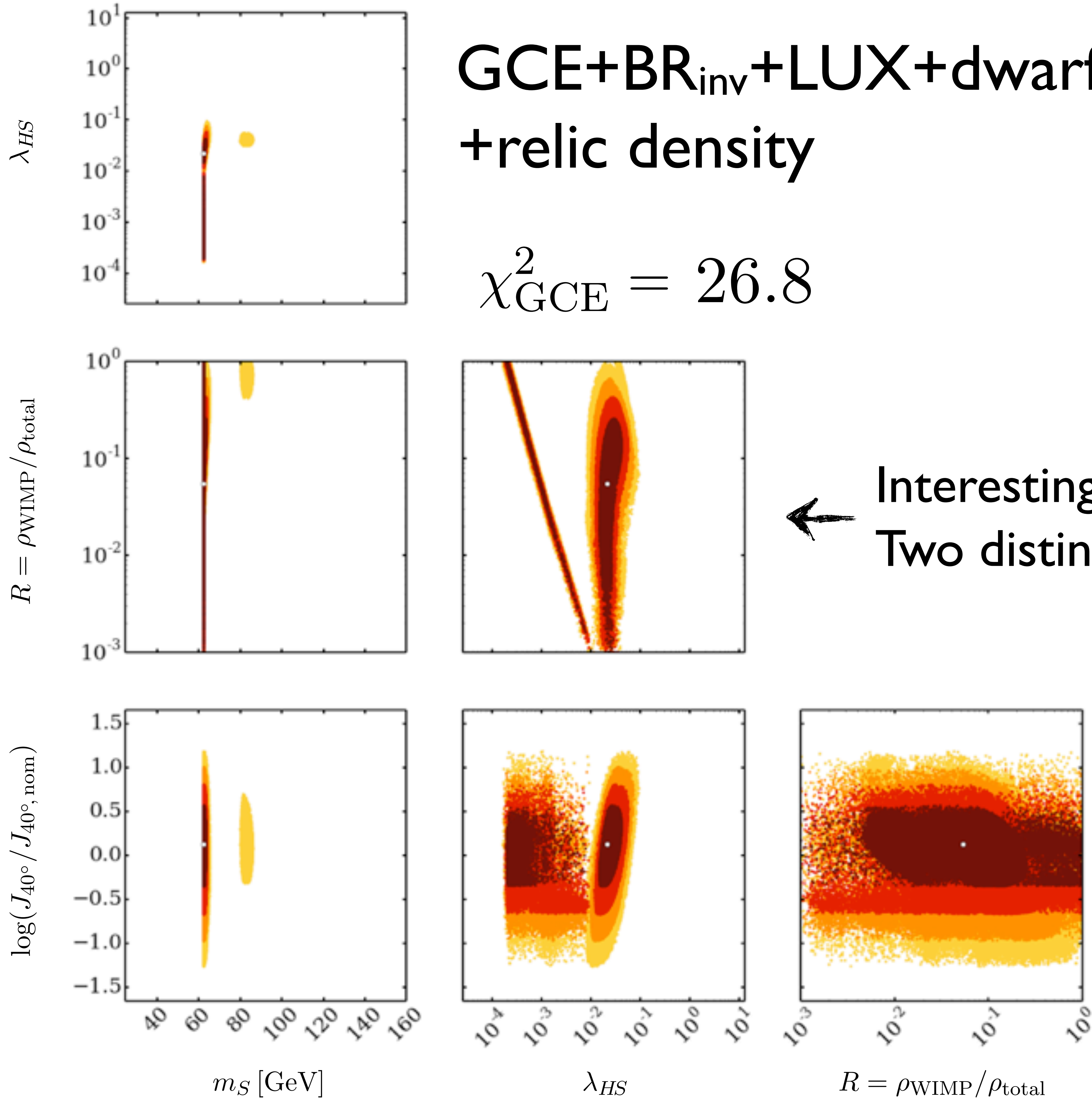


$$\chi^2_{\rm GCE} = 26.0$$

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

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

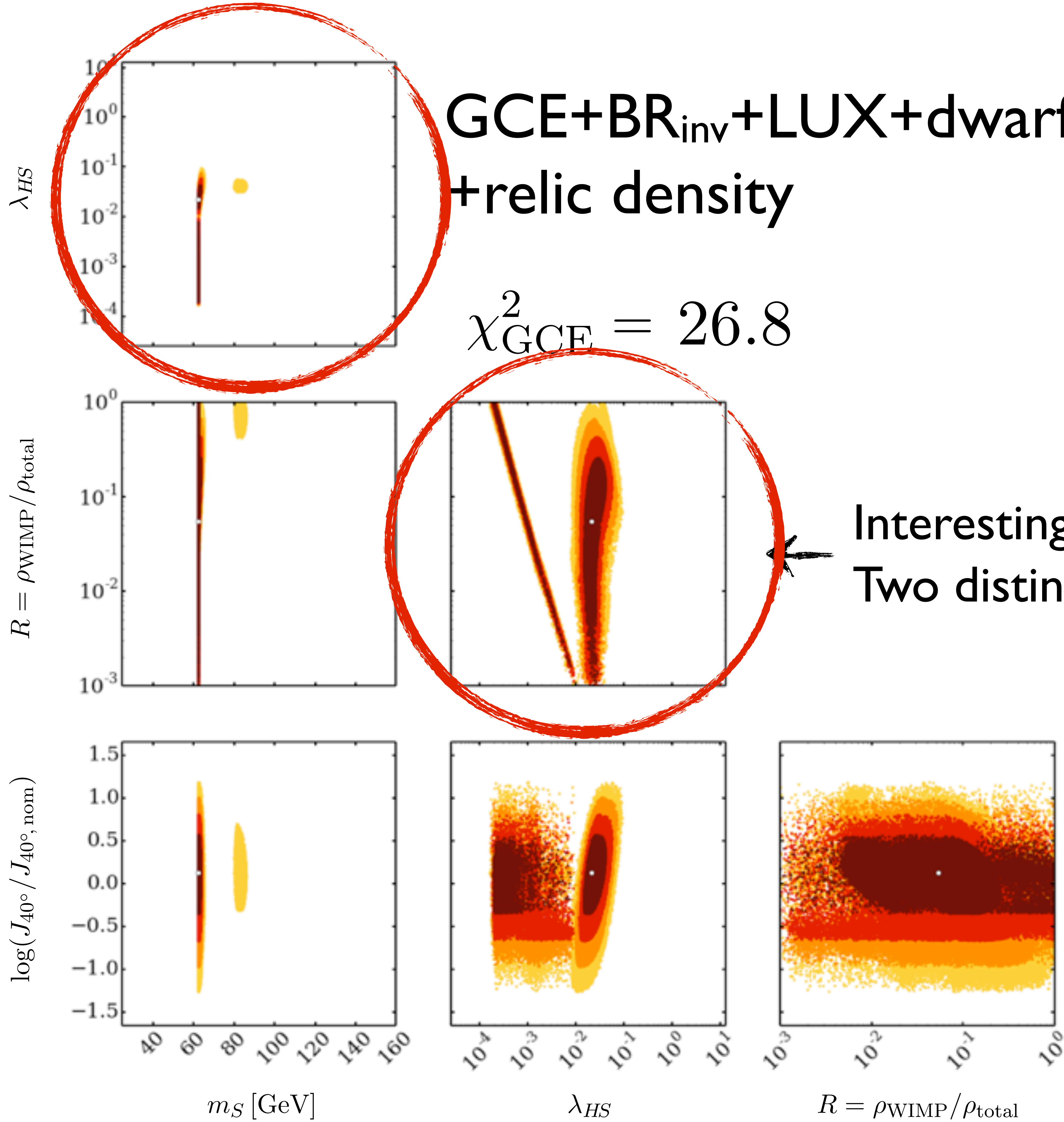
$$\chi^2_{\rm GCE} = 26.8$$



Interesting structure in *R*
Two distinct regions

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

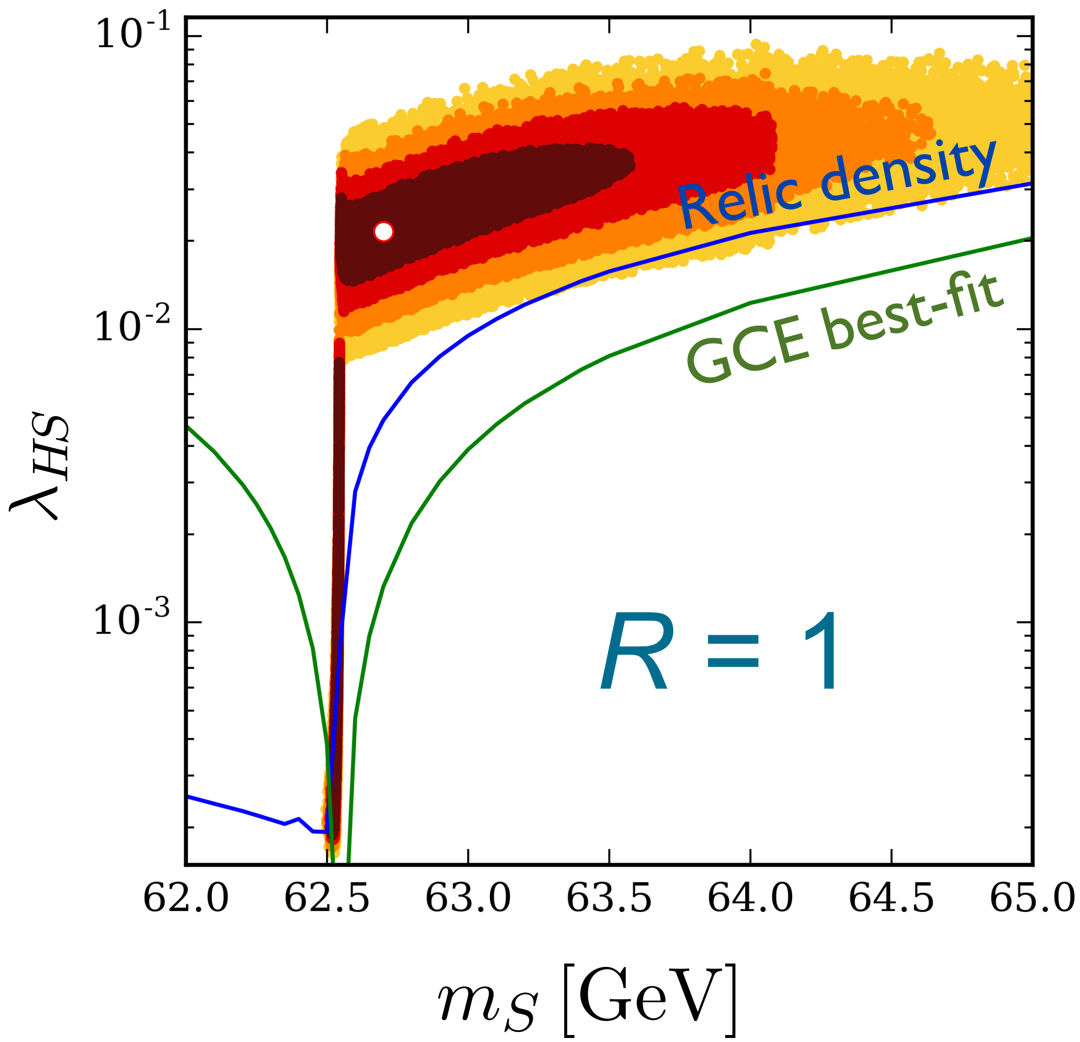
$$\chi^2_{\rm GCE} = 26.8$$

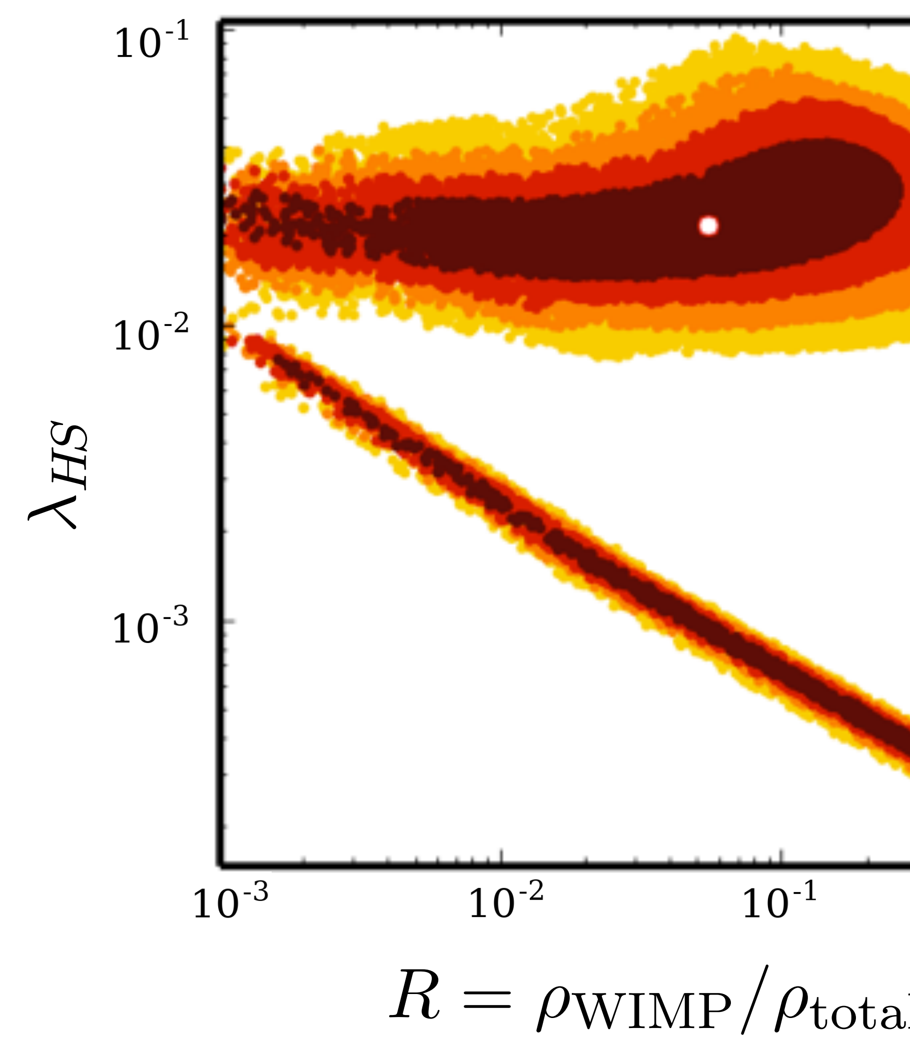


Interesting structure in *R*
Two distinct regions

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

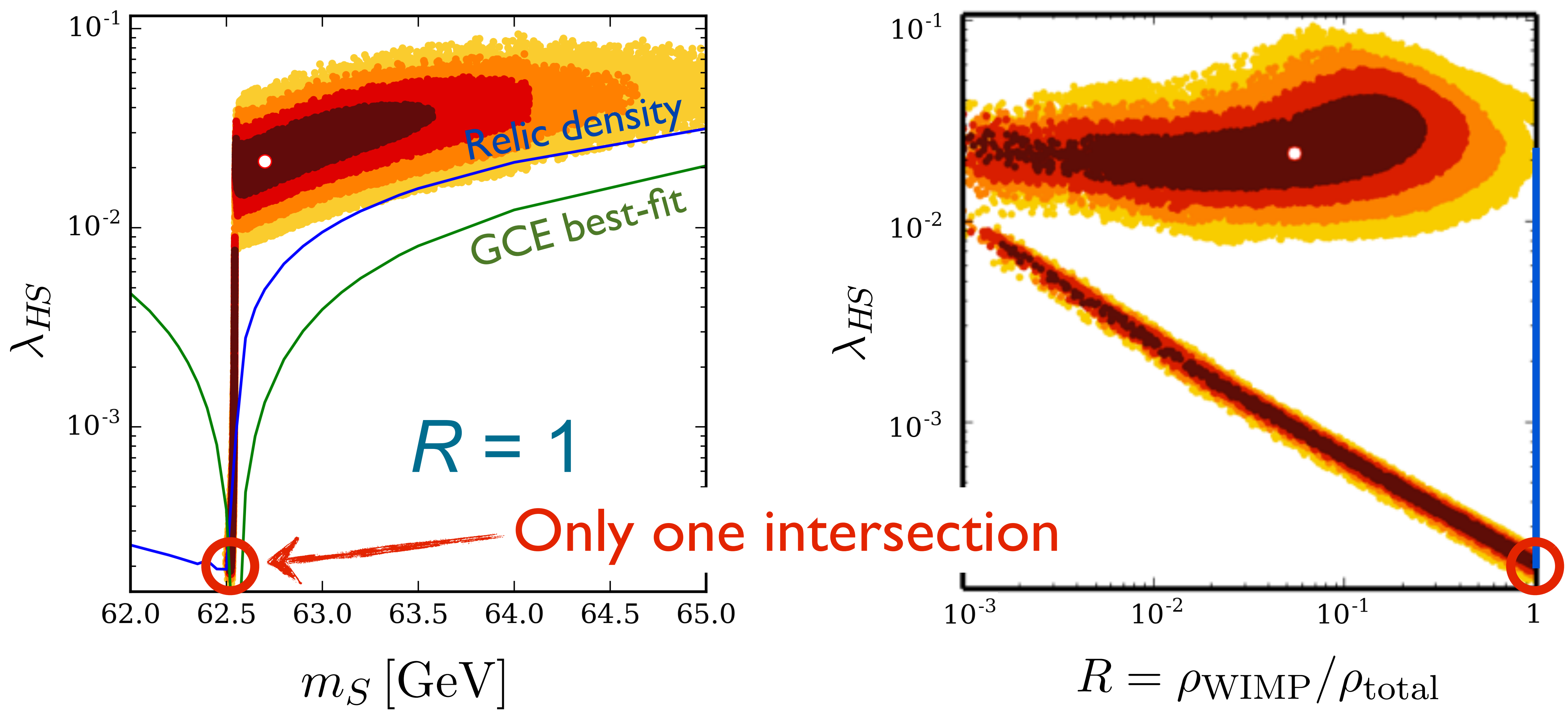
- Large velocity dependence around Higgs resonance
- $\sigma v \propto \frac{1}{(m_h^2 - s)^2 + m_h^2 \Gamma_h^2} \simeq \frac{1/m_h^2}{(\delta^2 - v_{\text{rel}}^2)^2 + \Gamma_h^2}, \quad \delta^2 \equiv \frac{m_h^2 - 4m_S^2}{m_h^2}$
- annihilation today: $v_{\text{rel}} \simeq 10^{-3}$, freeze-out: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





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

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

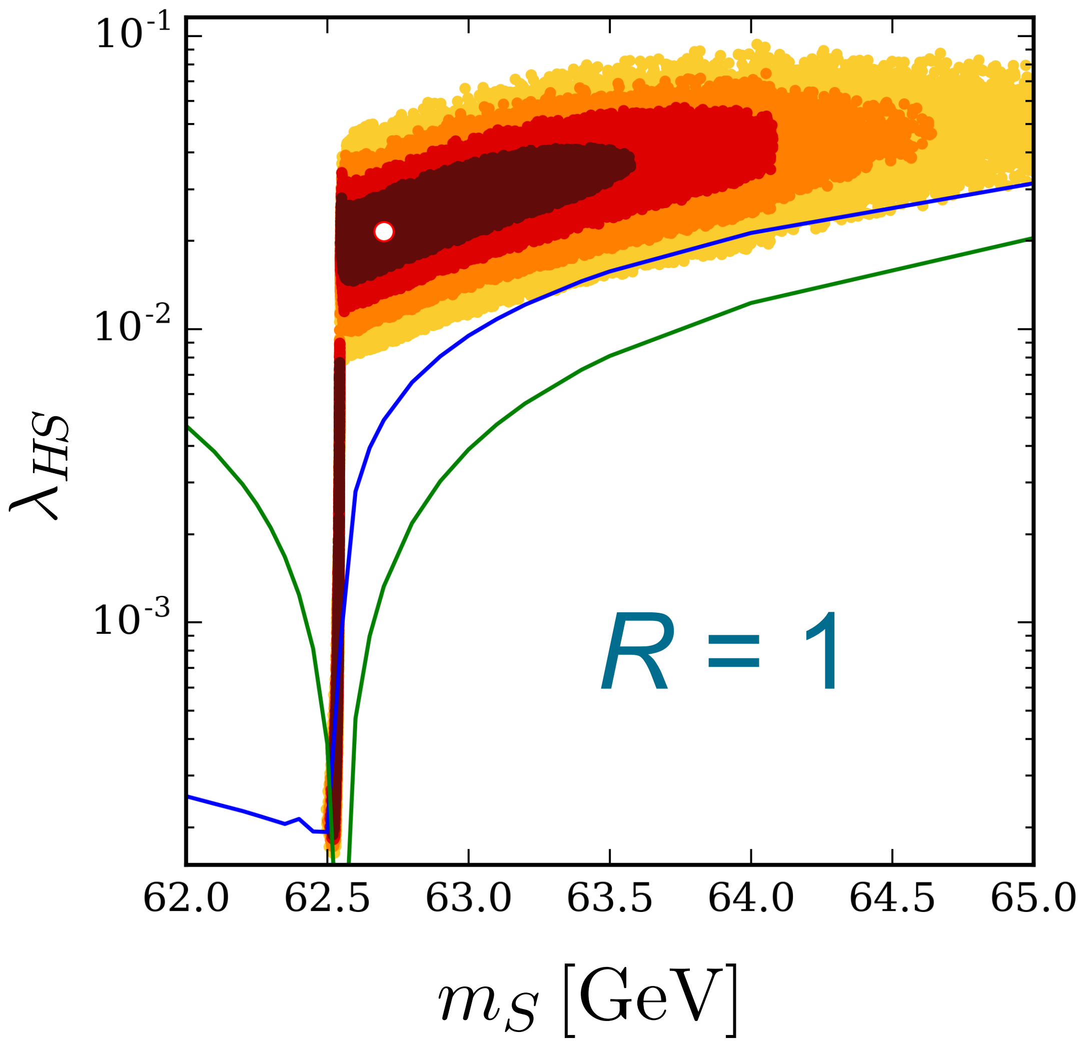


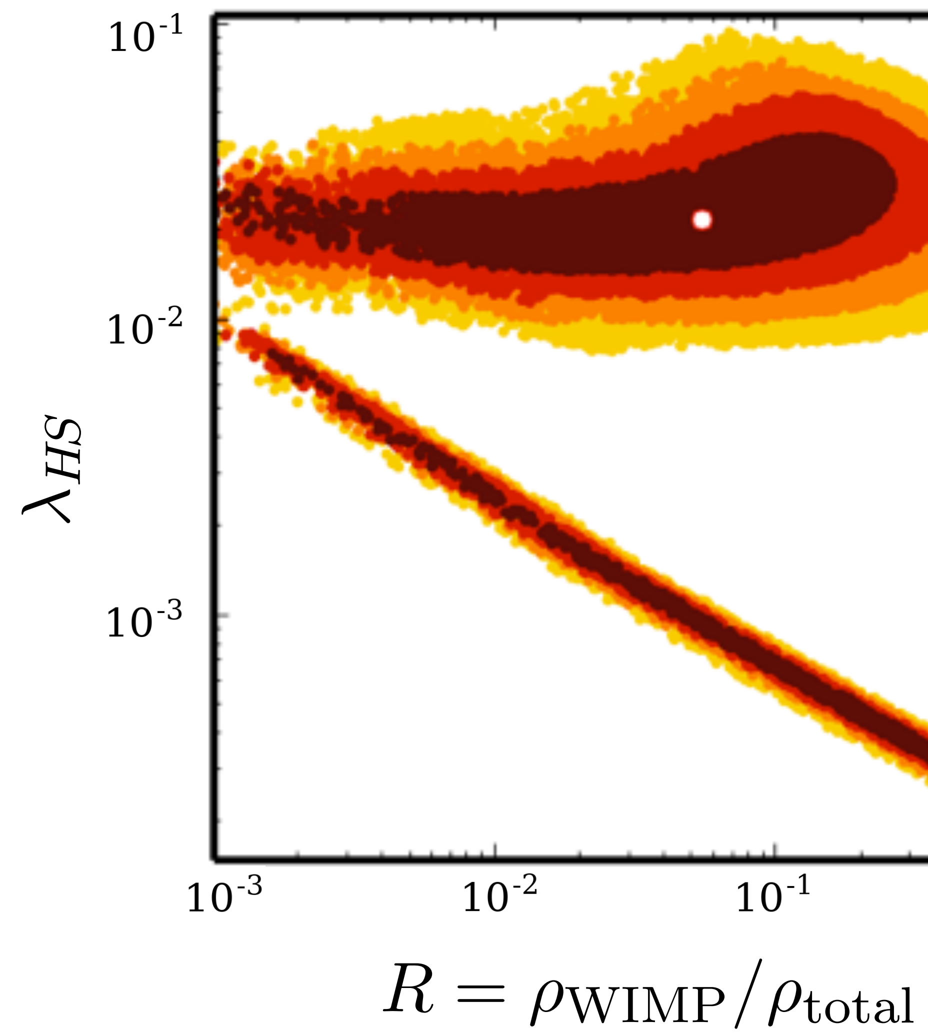
GCE+BR_{inv}+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:

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

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



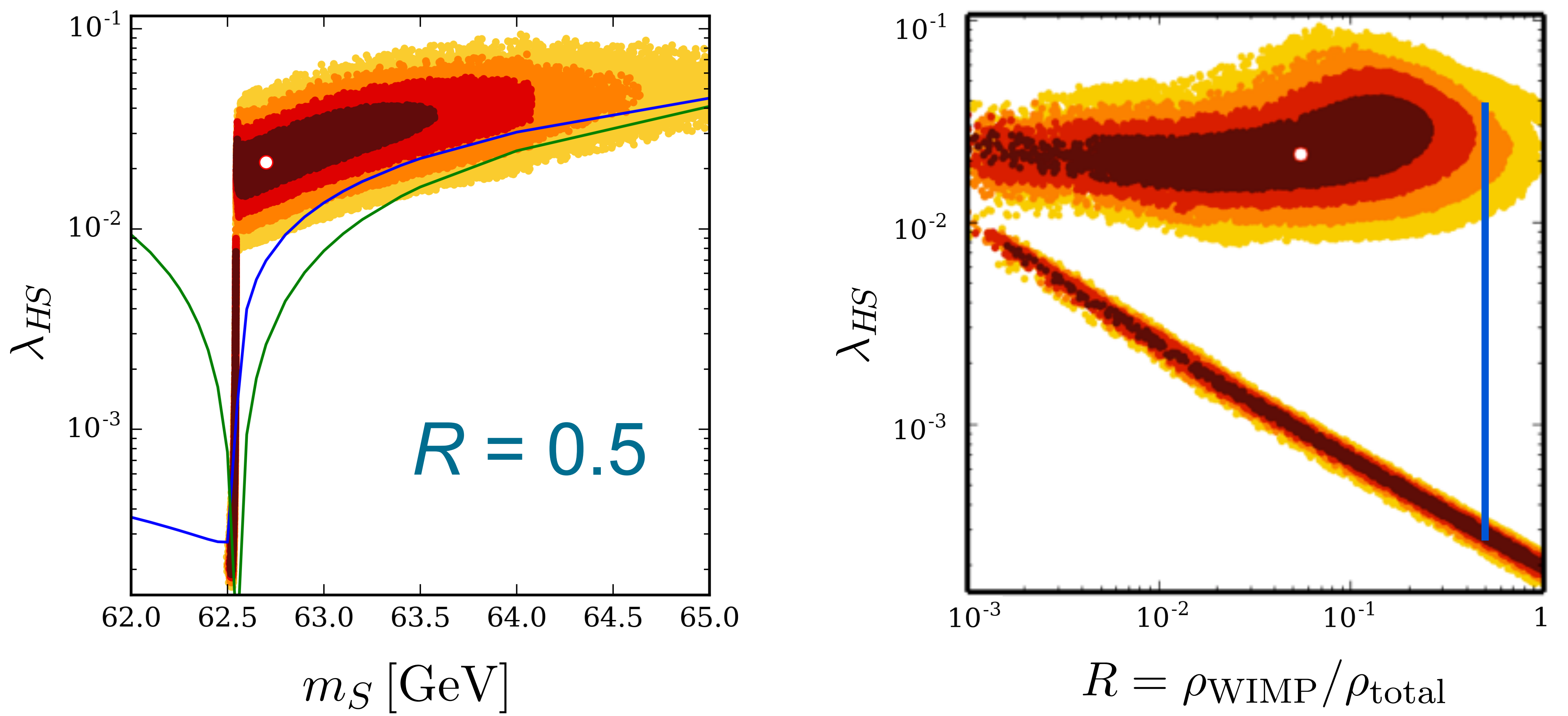


GCE+BR$_{inv}$+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:

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

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

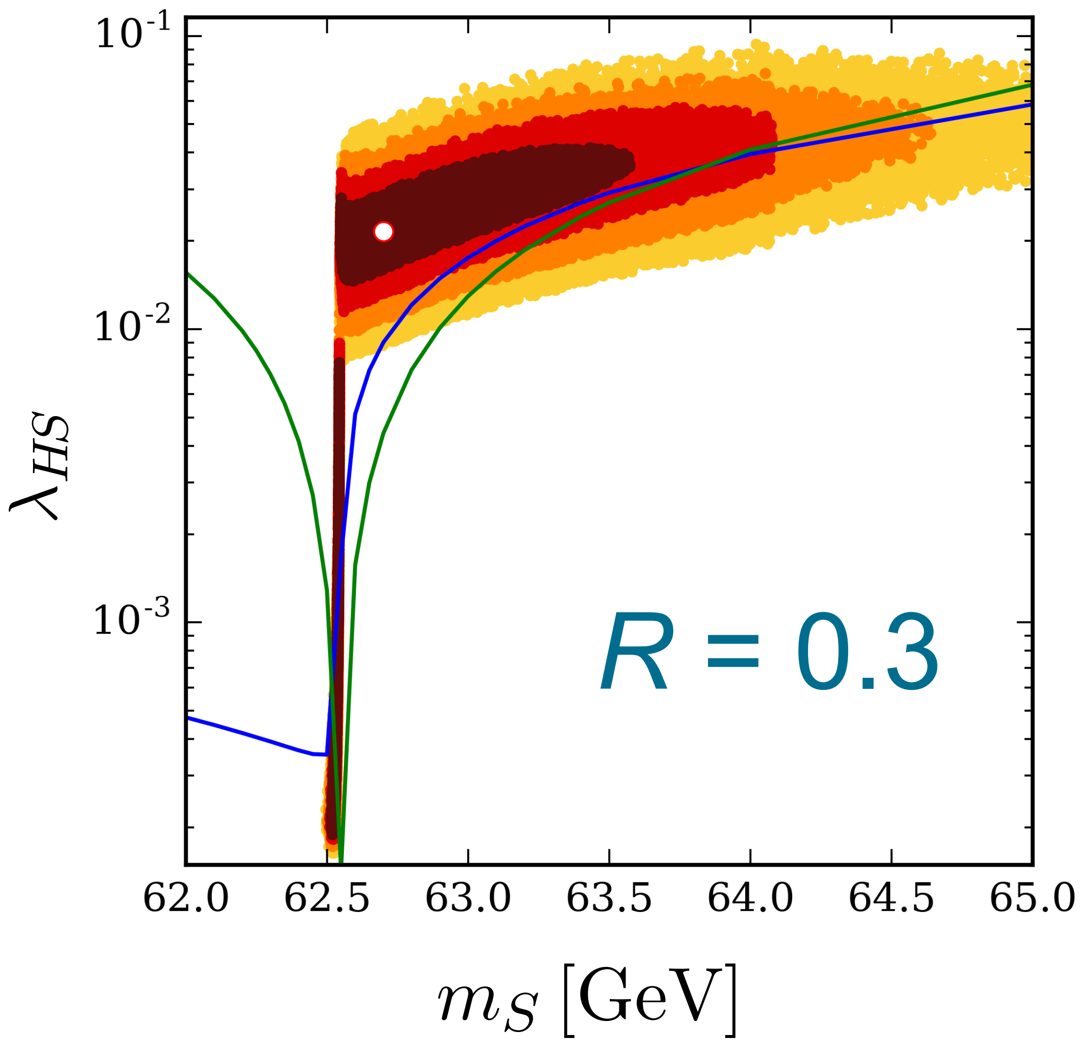


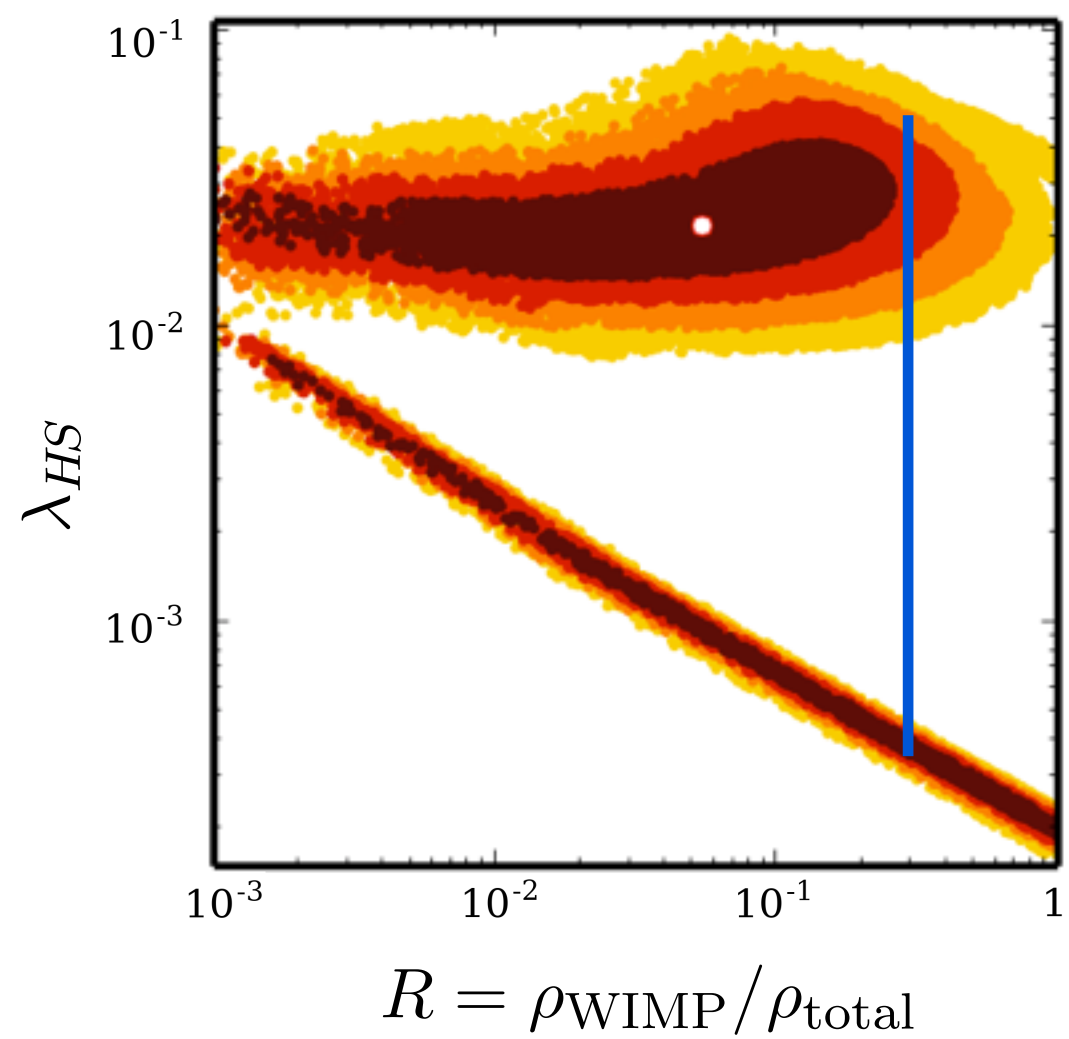
GCE+BR$_{inv}$+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:

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

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



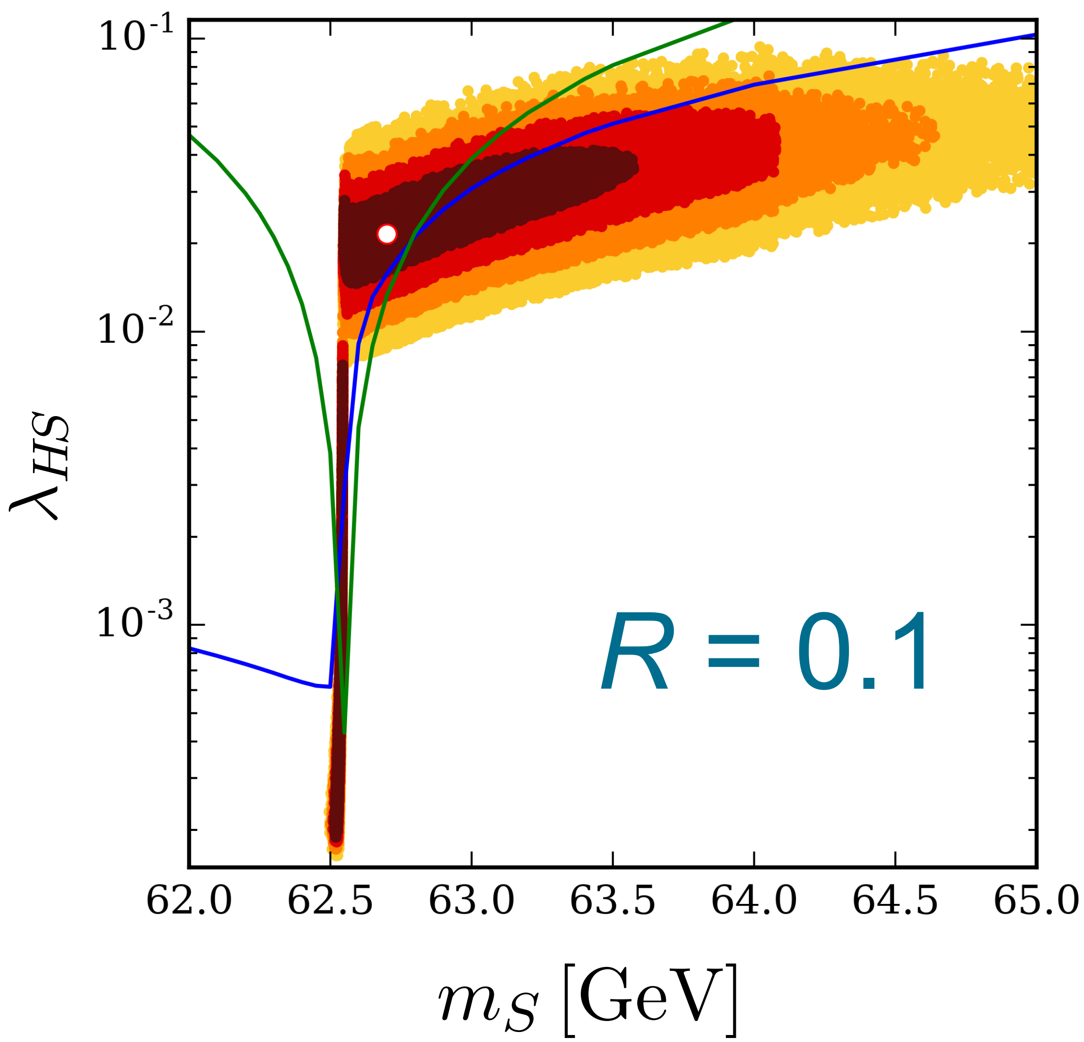


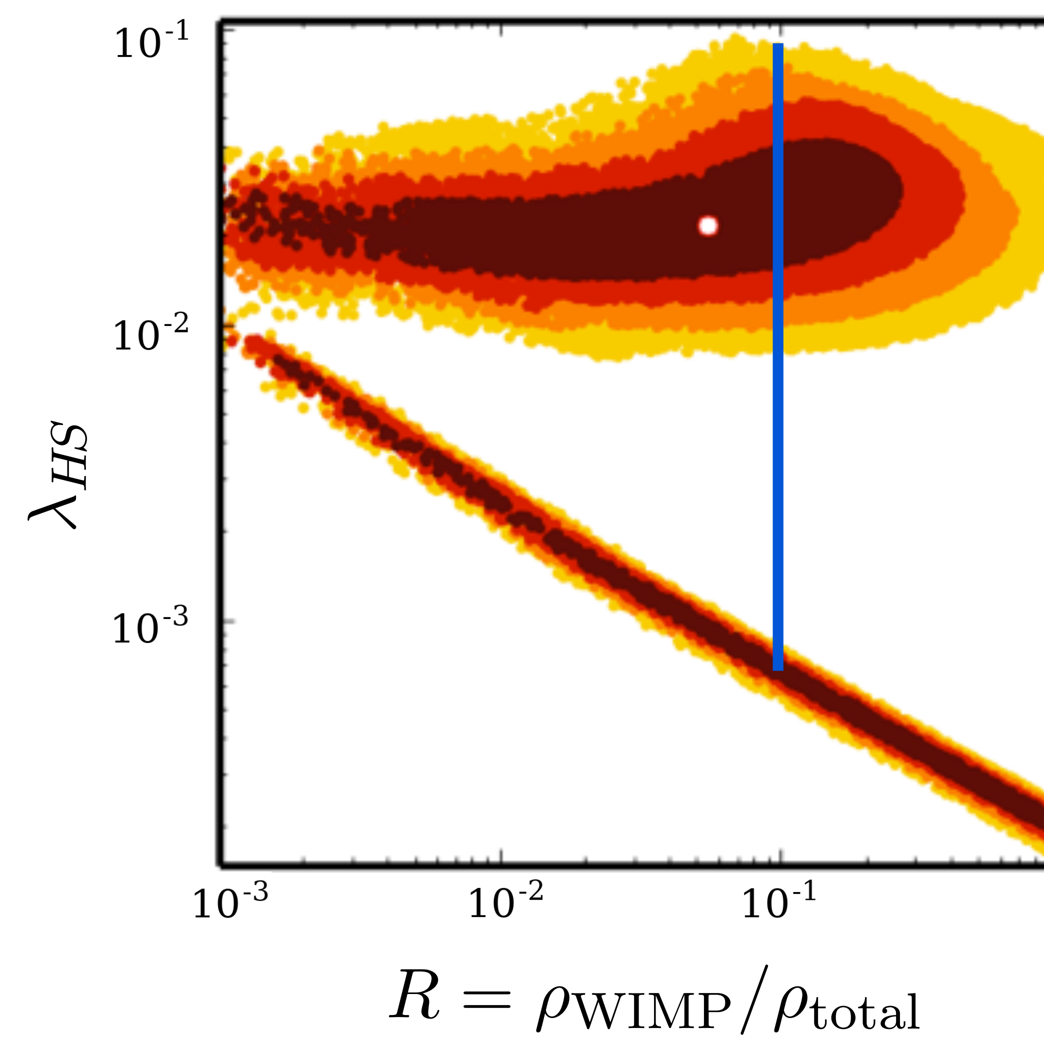
GCE+BR$_{inv}$+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:

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

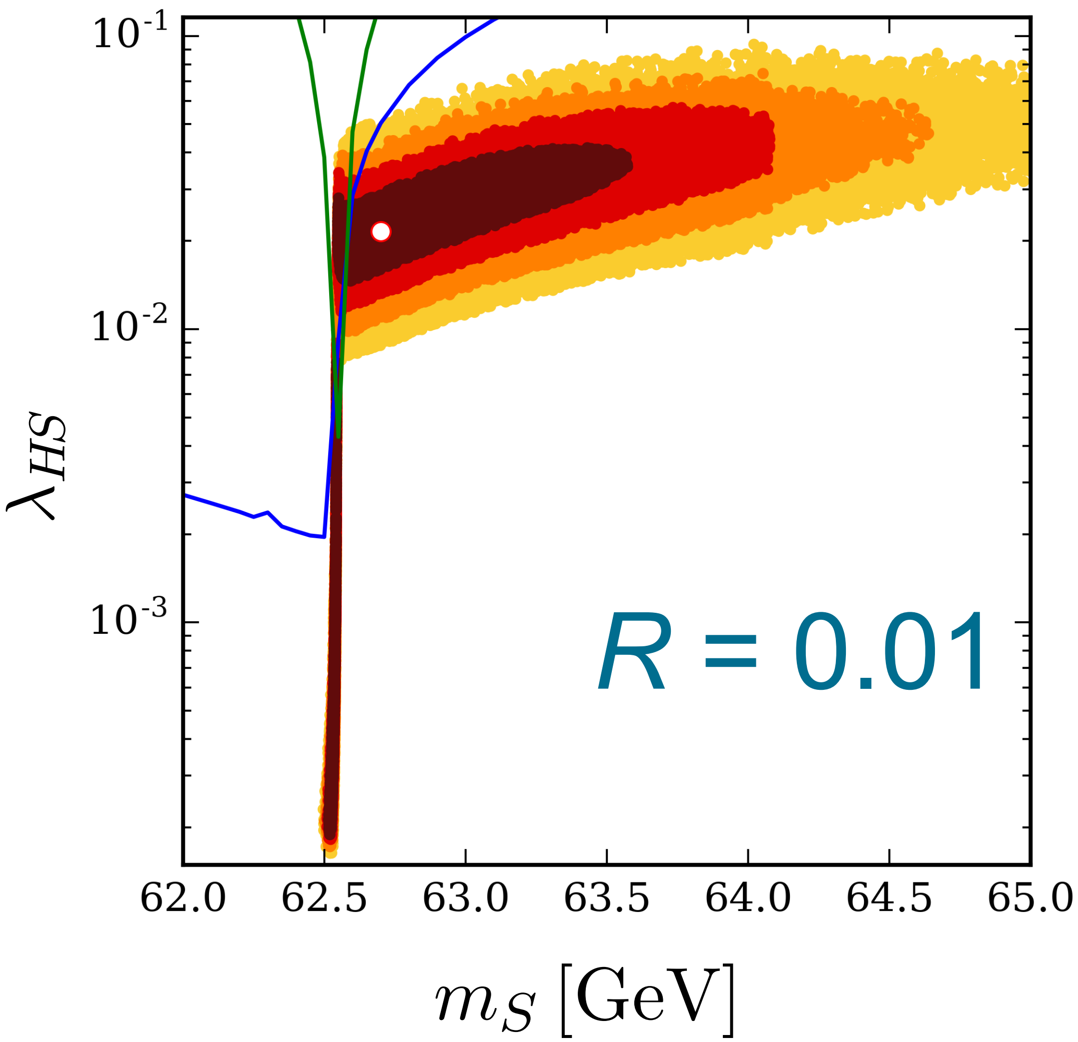
➔ GCE flux: $\phi \propto R^2 \langle\sigma v\rangle_{\mathrm{today}}$

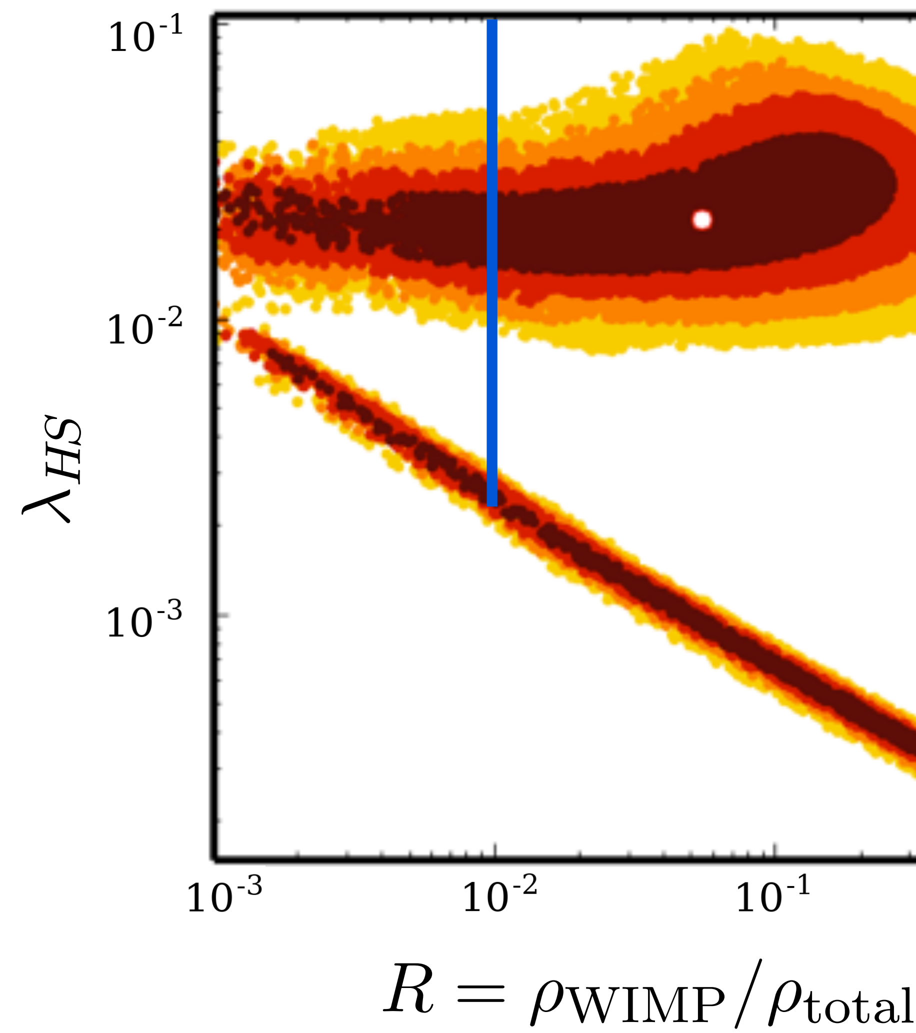




GCE+BR$_{inv}$+LUX+dwarfs+γ-lines+relic density

- For $R < 1$:
  - ➔ Relic density: $\Omega_{\mathrm{DM,\,total}} = \frac{\Omega_{\mathrm{WIMP}}}{R} \propto \frac{1}{R\,\langle\sigma v\rangle_{\mathrm{f.o.}}}$
  - ➔ GCE flux: $\phi \propto R^2 \langle\sigma v\rangle_{\mathrm{today}}$



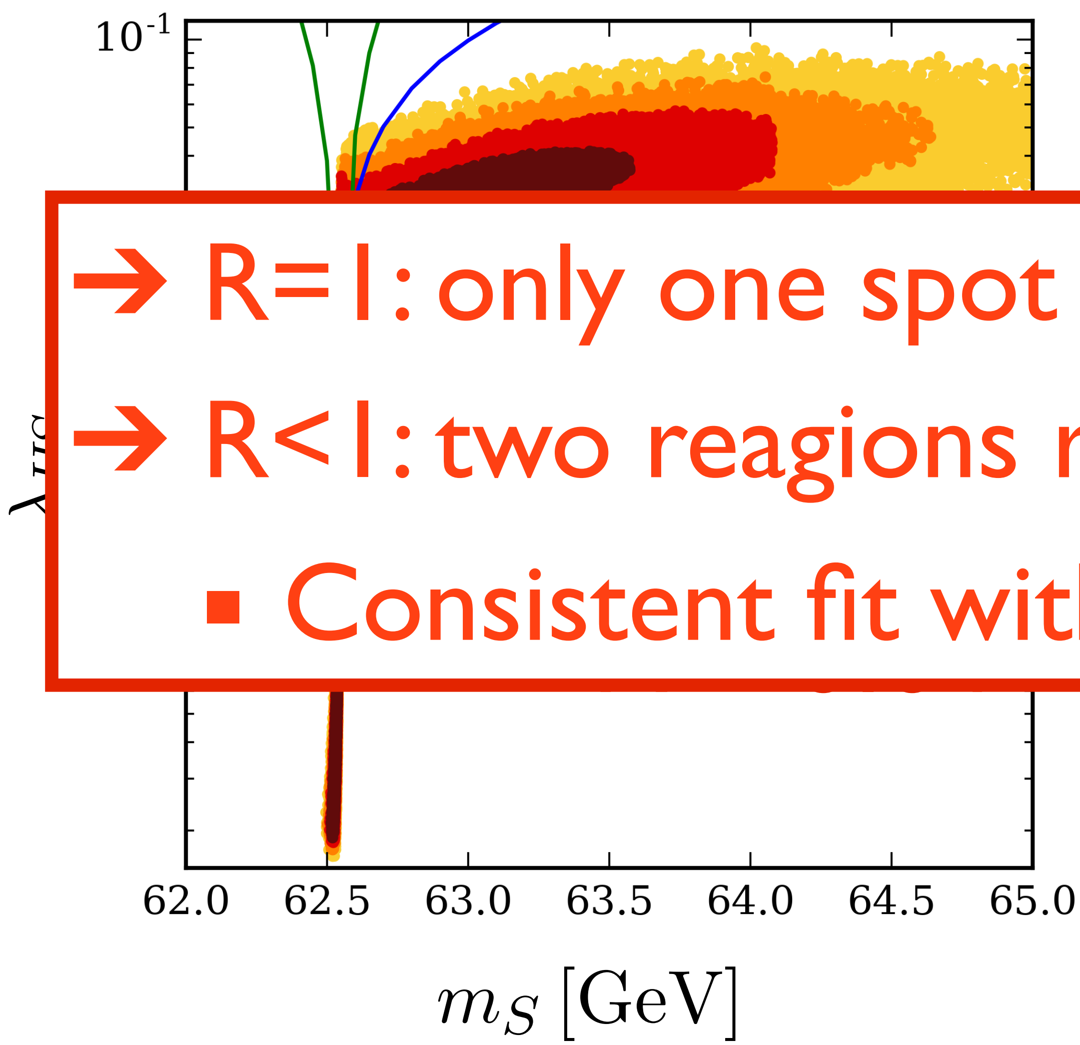


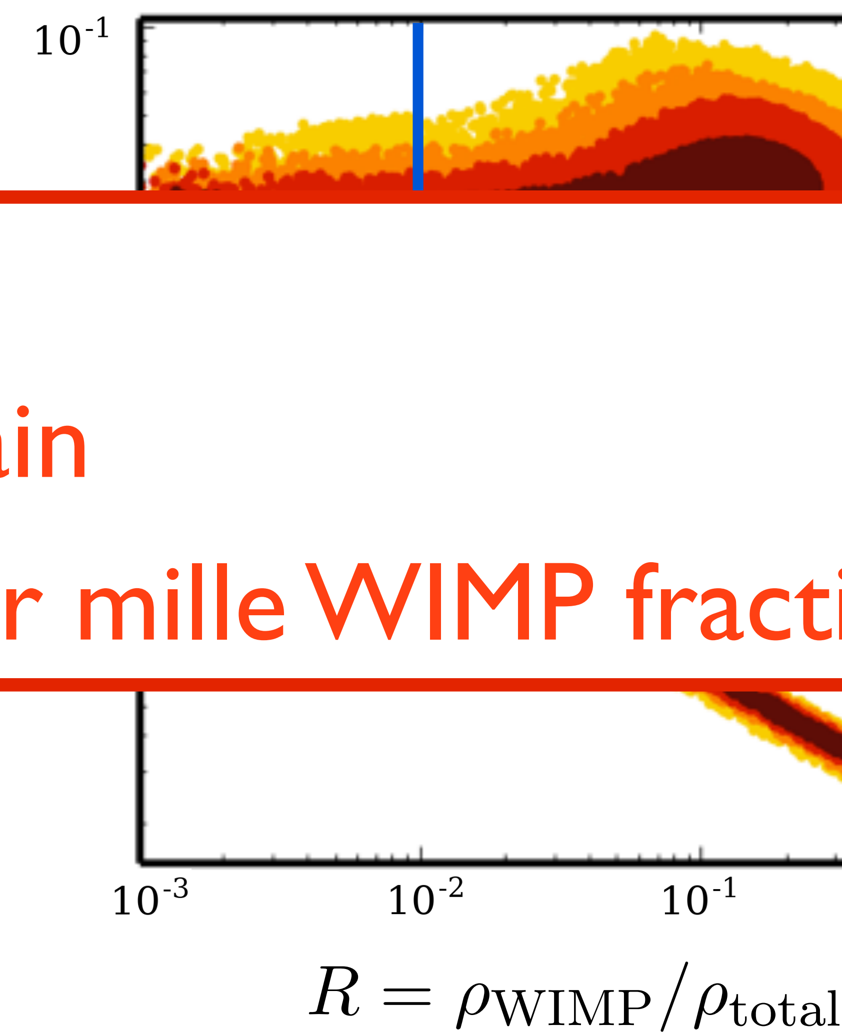
GCE+BR$_{\text{inv}}$+LUX+dwarfs+γ-lines+relic density

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





➔ R=1: only one spot

➔ R<1: two reagions remain

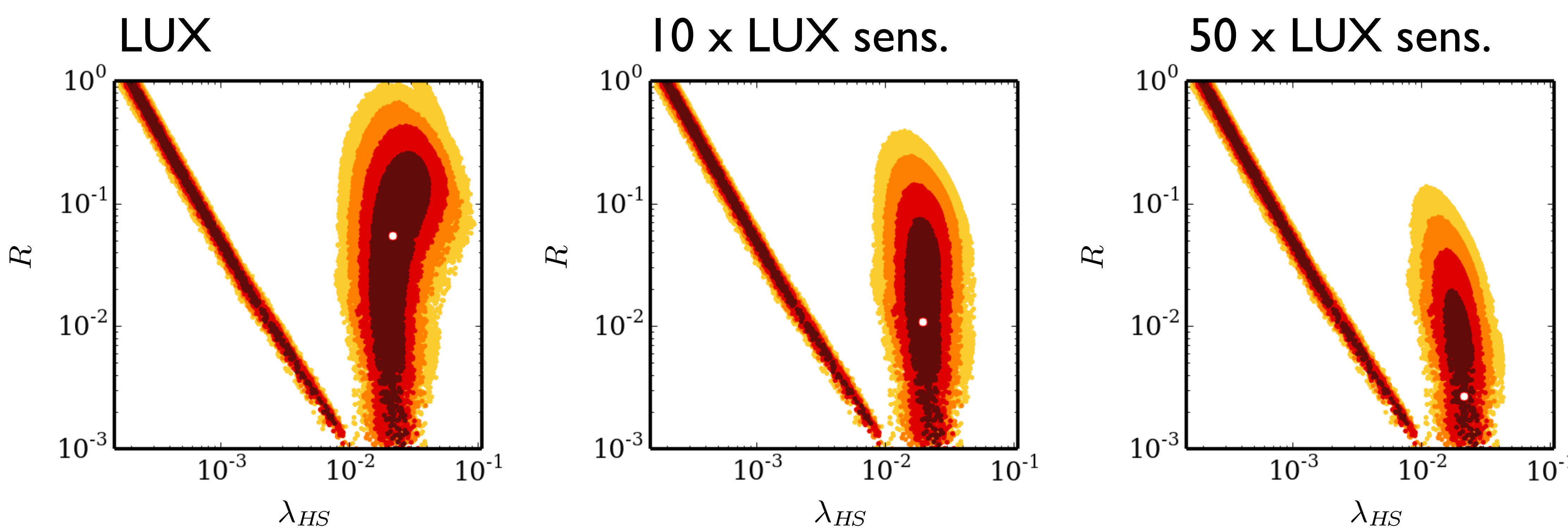
- Consistent fit with per mille WIMP fraction!

Summary

- GCE: Astrophysics of WIMPs?
- Higgs Portal: Unique coupling to minimal DM
- 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 (large velocity dependence)

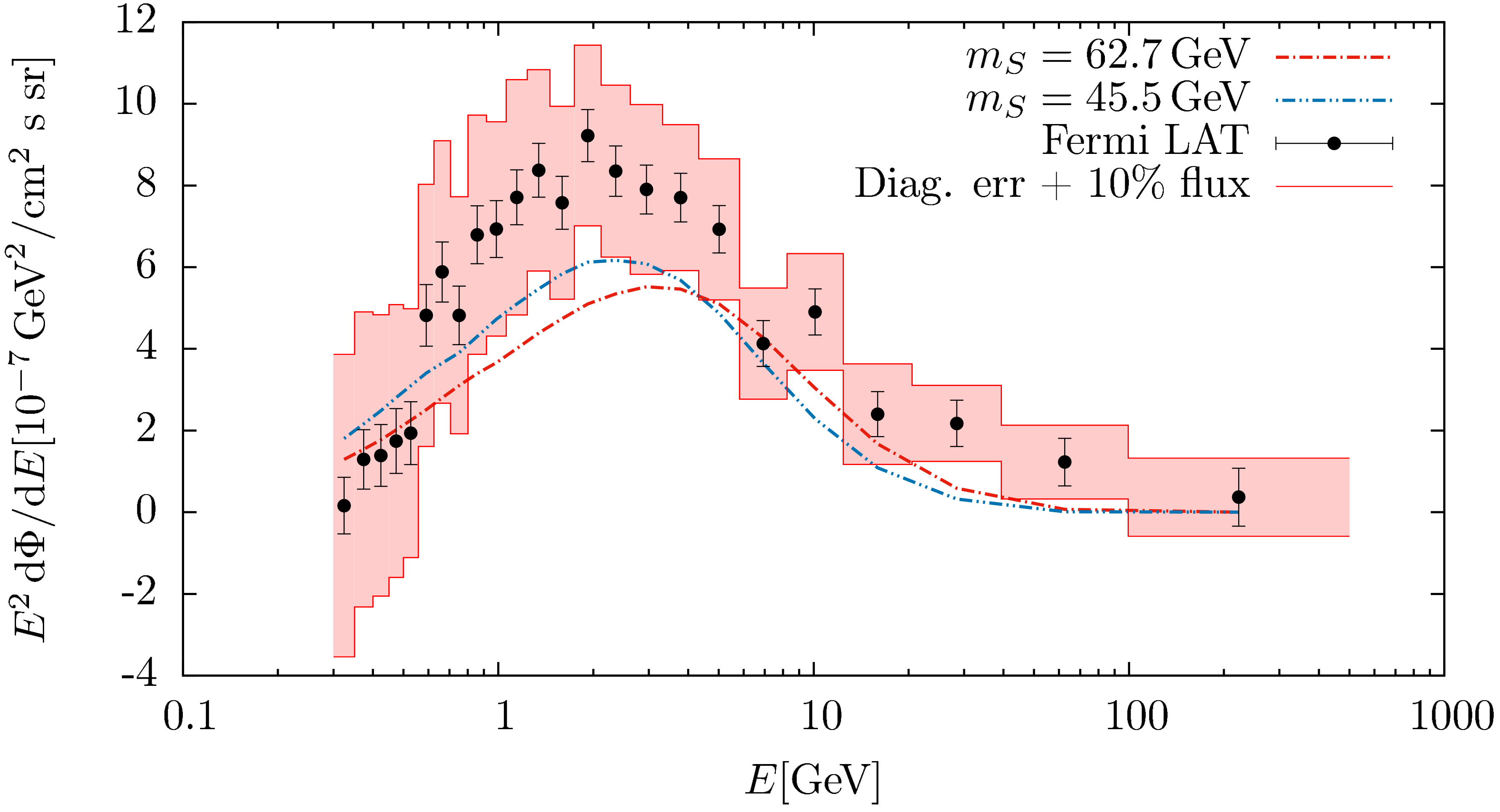
Back-up I: Future experimental prospects

- Collider constraints: virtually unchallanged
- Constraints from dwarfs: General challenge for GCE
- Direct detection projections:



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

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



Back-up III: 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	$0.68^{+0.32}_{-0.65}$	$1.0^{+0.0}_{-1.0}$	$0.99^{+0.01}_{-0.99}$	$1.0^{+0.0}_{-1.0}$	$1.0^{+0.0}_{-1.0}$	$0.054^{+0.141}_{-0.053}$	$0.498^{+0.502}_{-0.496}$
$\log J/J_{\mathrm{nom}}$	$0.0^{+0.44}_{-0.44}$	$-0.05^{+0.48}_{-0.36}$	$0.02^{+0.42}_{-0.43}$	$0.22^{+0.36}_{-0.35}$	$0.12^{+0.31}_{-0.29}$	$0.13^{+0.30}_{-0.32}$	$0.13^{+0.32}_{-0.31}$
$\sigma v\,[10^{-26}\,\mathrm{cm^3/s}]$	$1.97^{+1034}_{-1.38}$	$1.28^{+4.1e6}_{-0.61}$	$1.23^{+1.7e6}_{-0.55}$	$0.96^{+1.3e6}_{-0.37}$	$1.04^{+1.3e6}_{-0.42}$	$359^{+9.7e5}_{-327}$	$4.3^{+1.6e5}_{-0.9}$
$\sigma v\,R^2\,[10^{-26}\,\mathrm{cm^3/s}]$	$0.91^{+0.53}_{-0.35}$	$1.28^{+2.02}_{-0.53}$	$1.21^{+0.68}_{-0.45}$	$0.96^{+0.43}_{-0.31}$	$1.04^{+0.39}_{-0.32}$	$1.06^{+0.42}_{-0.32}$	$1.06^{+0.43}_{-0.31}$
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