[A global fit of the gamma-ray galactic center](https://indico.desy.de/abstractDisplay.py?abstractId=14&confId=11832) [excess within the scalar Higgs portal model](https://indico.desy.de/abstractDisplay.py?abstractId=14&confId=11832) [A. Cuoco, B. Eiteneuer, JH, M. Krämer; JCAP 1606 (2016),1603.08228]

Jan Heisig (RWTH Aachen)

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Fermi GeV Galactic Center Excess

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

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Fermi GeV Galactic Center Excess GITTIN SCA GARACTIC CENTER FYCESS

Millisecond Pulsars

dark matter only point s

Figure 17. Spectrum of the GCE emission, together with statistical and systematical errors, for Jan Heisig (Aachen University). We emphasize the GCE with various spectral models. We emphasize that \mathcal{L}

Fermi GeV Galactic Center Excess GITTIN SCA GARACTIC CENTER FYCESS

Millisecond Pulsars **WIMP Dark Matter**

Figure 17. Spectrum of the GCE emission, together with statistical and systematical errors, for Jan Heisig (Aachen University). We show fits the GCE with various spectral models. We emphasize that 2

Fermi GeV Galactic Center Excess

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

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 $m_\chi[\text{GeV}]$

gg σ *m*^χ − σ*v* Fermi GeV Galactic Center Excess

→ Excess over the known foregrounds in *Fermi*-LAT data σ*v*

Figure 17. Spectrum of the GCE emission, together with statistical and systematical errors, for model F (cf. figure 14). We show fits to the GCE with various spectral models. We emphasize that Jan Heisig (Aachen University) 2 DSU 2016, Bergen July 28th

This work: d*N*FS

E Very simple Dark Matter model (singlet scalar Higgs portal) dΩd*E* $\sqrt{\epsilon}$ *y* simple Dark Matter mod :
11 FS

- **Detailed numerical fit involving further constraints** (invisible Higgs width, LUX, relic density,...) FS invo d*E* ving f ng further constraints
- **Allow for additional non-WIMP DM component** (PBHs, axions,...) to a discussed matter and discussed in the integral over the integral over the line of sight in the line of sight in section 3.4. The integral over the line of sight in section 3.4. The integral over the line of sight in s $\sum_{i=1}^n \frac{1}{i}$
	- \rightarrow Interesting implications on WIMP DM fraction

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

Scalar Singlet Higgs Portal Model Scalar Singlet Higgs Port

can be searched for at colliders and through direct and through direct and indirect detection experiments and i
The search direct detection experiments in direct detection experiments in the search of the search of the sea [Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Veldhuis: '01; ...]

- \bullet Higgs bilinear $H^\dagger H$ unique (renormalizable) way to directly couple DM to the SM and all SM gauge groups. Imposing an additional *Z2* symmetry, would be seen as a symmetry, $\frac{1}{2}$ $\mathbf{f}_{\mathbf{q}}$ is the singlet Higgs portal model $\mathbf{f}_{\mathbf{q}}$
- Add Singlet Scalar *S* with *Z*2-symmetry: **E** Add Singlet Scalar S with Z_{as} cymmetry:

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

Scalar Singlet Higgs Portal Model under all SM gauge groups. Imposing an additional *Z*² symmetry, *S* → −*S*, the scalar particle model comprises the Standard Model and a real scalar field, *S*, which is a singlet under all SM

can be searched for at colliders and through direct and through direct and indirect detection experiments and i
The search direct detection experiments in direct detection experiments in the search of the search of the sea \overline{a} [Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Veldhuis: '01; ...]

- \blacksquare Higgs bilinear $H^\dagger H$ unique (renormalizable) way to directly couple DM to the SM and the dark matter would be couple DM to the SM and the above Lagrangian become the above L *L* = *L*SM + \overline{c} *y*₁, Durgess, 1 Osper
− 2020 0 1:00 le l o l $\overline{1}$ *S,*0*S*² [−] ¹ $\overline{=}$ ^λ*SS*⁴ [−] ¹ **L** Higgs bi $\mathsf{linear}\,H^\dagger H$ un iqu *S* \bullet (renormalizable) way to directly 2
- Add Singlet Scalar *S* with *Z*2-symmetry: contribute to the invisible to the invisible to the indirect \sim 2 *m*² *n* metry A dd Singlet Scalar S with Z_2 -symmetry

\n- Add Singlet Scalar S with Z₂-symmetry:\n
$$
\mathcal{L} \supset -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{HS} h^2 S^2 - \frac{1}{2} \lambda_{HS} v h S^2,
$$
\n where $m_S^2 = m_{S,0}^2 + \lambda_{HS} v^2 / 2.$ \n*(after EWSB)*\n
\n

Scalar Singlet Higgs Portal Model

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

- \blacksquare Higgs bilinear $H^\dagger H$ unique (renormalizable) way to directly couple DM to the SM
- Add Singlet Scalar *S* with *Z*₂-symmetry:

Dark Matter annihilation

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Dark Matter annihilation

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Gamma-ray spectrum

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

A -computation for the GCE \sim atio $\frac{1}{2}$ computation for the CCC *rections are Relevant for Dark Matter Indirect Detection)]* γ^2 -computation for the GCF 8.20 χ^2 -computation χ^2 d₁ d*E* **for the GCE** λ compaction io. the cost χ^2 -comput α ation for the GCE

- \blacksquare Take measured spectrum d_i and covariance matrix **from [Calore, Cholis, Weniger: 1409.0042] interval matter and development of the data matter of the data matter of** $\lim_{i \to \infty} d_i$ and covariance matrix \sum_{ij} **Take measured spectrum** d_i and covariance matrix Σ_{ij} λ*HS* = 0*.*01 (right panel). Below *m^S* = *m^h* the contributions are independent of λ*HS*. $F = \frac{1}{2}$ fig. 2 $\frac{1}{2}$ for $\frac{1}{2}$ and $\frac{1}{2}$ for $\frac{1}{2}$ and $\frac{1}{2}$ for $\frac{1}{$ $\begin{array}{ccc} & & & & & 10^{-5} & \textcolor{red}{\textbf{1}} & \textcolor{red}{$ \blacksquare iake ineasured spect **Reference to Fig. 2.** $\mathsf{Im}\ \mathcal{C}$
- **Example 3 Additional uncertainty on the theoretical prediction**

of the spectrum $\Sigma_{ij} \rightarrow \Sigma_{ij} + \Sigma_{ij} \delta_{ij} t^2 \sigma^2$, $\sigma_t = 10^{\circ}$ **Additional uncertainty on the theoretical prediction**
 of the spectrum $\sum_{ij} \rightarrow \sum_{ij} + \sum_{ij} \delta_{ij} t_i^2 \sigma_t^2$, $\sigma_t = 10\%$ [Achterberg et al. 1502.05703] $\sum_{ij} + \sum_{ij} \delta_{ij} t_i^2 \sigma_t^2$, α ^{*f*} the spectrum</sub> p **Incertainty o** \sum $\begin{array}{rcl} \textsf{ty} \textsf{ on the the}\ \textsf{m}\ \textsf{b} \ \textsf{c} \ \textsf{c} \ \textsf{d} \ \textsf{c} \end{array} \begin{array}{rcl} \textsf{c} \ \textsf{c$ aratir $\zeta_{\cdot\cdot}$ $\Sigma_{ij} \rightarrow \Sigma_{ij} + \Sigma_{ij} \delta_{ij} t_i^2 \sigma_t^2$, $\sigma_t = 10\%$ $\textbf{prediction}$ $\frac{10^{-8}}{10^{9}}$ Achterberg et al. 1502.05703]

- Large theoretical uncertainties on DM distribution in galaxy: ■ Large theoretical uncertainties on DM distribution in galaxy: ^σ*^v* composed in this way are shown exem-In the previous section, we found that the previous section, we found that the \mathbf{r} \textsf{of} the spectrum $\Sigma_{ij} \rightarrow$ and \textsf{Large} theoretical unce
- **Compute** χ^2 : $\frac{1}{2}$ [−]1(*d^j* [−] ¹⁰ξ*m^j*) + ^ξ² $\begin{picture}(180,10) \put(0,0){\line(1,0){10}} \put(10,0){\line(1,0){10}} \put(10,0){\line($ i,j 0 0.2 0.4 0.6 0.8 1 1.2 0 0.5 1 1.5 2 2.5 3 $PDF(\bar J)$ \bar{J}/\bar{J}_{nom} $\mu = 0.0144901$
 $\sigma = 0.426307$ $\sigma = 0.426307$ $40^{\circ} \times 40^{\circ}$ Lognormal $(x; \mu, \sigma)$ **Take NFWc profile** $1.2 \sqrt{40^\circ \times 4}$ ■ Vary around best fit parameters with MC [from Calore, Cholis, Weniger: 1409.0042] + Distribution for *J*-factor $\overline{}$ Determine σ_{ξ} for from Calore, Cholis, Weniger: 1409.0042]

→ Distribution for *I*-factor $(\int_{a}^{1}$ (e^{i}) = $\frac{1}{2}$ (d_{0}^{1}) = $\sum_{i,j}$ $\langle x_i \rangle$ $\langle x_j \rangle$ $\langle x_j \rangle$ $\langle x_j \rangle$ 40◦ × 40◦ Lognormal(*x*; *µ,* σ) **3.3** Take NFWc profile $1.2 \frac{1}{\sqrt{100 \times 100}}$ our treatment of the *J*_{-ale}ssandro (1409.0042)

(*δ*)² ζ^2 $\chi^2 = \sum (d_i - e^{\xi} t_i)(\Sigma_{ij})^{-1}(d_j - e^{\xi} t_j) + \frac{\xi^2}{\sqrt{2\pi}}$ \mathcal{L} . ake N -
Wc prof $\frac{1}{2}$ **b** $\frac{1}{2}$ $\frac{1}{2$ σ_{ξ} for $\xi = \ln (\bar{J}/\bar{J}_{\rm nom})$ Our treatment of the *J*-factor. → Benedikt, Alessandro $\mathbf{y} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$ and $\mathbf{y} = \begin{bmatrix} 40^{\circ} \times 40^{\circ} & \text{Lognormal}(x; \mu, \sigma) & \text{Lognormal}(x; \mu, \sigma) \\ & \text{Lognormal}(x; \mu, \sigma) & \text{Lognormal}(x; \mu, \sigma) \end{bmatrix}$ $\overline{1}$ **Compute** χ ⁻: λ **Place NFWc profile** $1.2 \frac{1}{\left(\frac{40^{\circ} \times 40^{\circ}}{40^{\circ} \times 40^{\circ}} \right) \frac{1}{\text{1}} \cdot \text{1}}$ $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ *i*fe χ^2 : $\chi^2 = \sum$ i,j $(d_i - e^{\xi}t_i)(\Sigma_{ij})^{-1}(d_j - e^{\xi}t_j) + \frac{\xi^2}{(\sigma_i)^2}$ $(\sigma_{\xi})^2$ $1.2 \frac{1}{40^{\circ} \times 40^{\circ}}$ \circ $\begin{array}{c|c|c} 1 & 1 & 1 & 1 \ \hline \circ \times 40^{\circ} & \text{Lognormal}(x;\mu,\sigma) & \overline{\hspace{2cm}} \end{array}$ $\frac{1}{2}$ We will hence adopt the following *strategy*: We will use the GCE spectrum and associated statistical errors from model F only, which gives formally the best-fit to the *Fermi*-LAT systematics, and neglect the theoretical ones. Given the small scatter for the small scatter for the GCE species \mathcal{L} $\sigma = 0.426307$ | \mathbb{U} different GDE model as starting point in the spectral fits would not alter our results would not alt significantly (see appendix C.2). Hence, we consider our approach as statistically sound and \Box robust to derive meaningful results. We will introduce general aspects of fits with correlated errors in subsection \mathcal{A} then test then test the most common interpretations of the GCE emission in terms of \mathbb{R} and as transmitted in subsection \mathbb{R} . Vary around best fit parameters with MC

[from Calore, Cholis, Weniger: 1409.0042]
 $\begin{bmatrix} 1 & 1 \ 0 & 8 \end{bmatrix}$ $\begin{bmatrix} \mu = 0.0144901 \\ \sigma = 0.426307 \end{bmatrix}$ **n** Determine σ_{ξ} for $\xi = \ln(\bar{J}/\bar{J}_{\text{nom}})$ and $\begin{bmatrix} 1 & 1 \ 0 & 0.6 \end{bmatrix}$ **Performed on the Compute** χ^2 :

 \mathcal{L} would like to thank Kerstin Hoepfner, Alexander Knochel, Manfred Krauss, Lennart Oy- \mathcal{L} Heisig (<mark>Aachen</mark> Reference to Fig. 3. 40◦ × 40◦ Lognormal(*x*; *µ,* σ) Jan Heisig (Aachen University) 7 DSU 2016, Bergen July 28th

Constraints on the parameter space

Sign on the Fløien Mountain, Bergen

Constraints on the parameter space

Dark matter annihilation in the scalar Higgs portal model proceeds through *s*-channel Higgs, Constraints on the parameter space

 $J_{40\degree\times40\degree}/J_{40\degree\times40\degree}$, nom \sim 40 $\,\times$ 40 $\,\degree$ \sim 40 $\,\times$ 40 $\,\degree$ and \sim 40 $\,\degree$

Fit parameters and tools plarily in Fig. (ref to Spectra). Here, *R* denotes the fraction of annihilating dark matter to the total dark matter content which is discussed in section 3.4. The integral over the line of sight is discussed function Γ in section 3.3.1.

- u_i for additional unconcified $\mathsf{DM}_{\mathsf{component}}$ \blacksquare is discussed in section \blacksquare If $E = \mu$ **Allow for additional unspecified DM component** \rightarrow WIMP fraction: $R = \rho_{\mathrm{WIMP}}/\rho_{\mathrm{DM, total}}$
- 4 scan parameters:

 $m_S\text{: } \quad 5 \ldots 220 \,\mathrm{GeV}$ λ_{HS} : 3 × 10^{-5} \dots 4π $\ln(\bar{J}/\bar{J}_{\rm nom})$: $-4\sigma_{\xi} \dots 4\sigma_{\xi}$ *R*: 10^{−3} ...1 $m_S: 5...220 \text{ GeV}$
 $\frac{1}{2} \times 10^{-5}$

- **Exampling algorithm)** [Feroz et al. '13]
- **EXAGOMETAL EXAGOMEGAS EXAGOMEGAS** [Bélanger *et al.* '14]
- **Example 1 Frequentist interpretation**

Results

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

- $p_{\text{max}} D \neq 1$ \blacksquare For $R < 1$:
	- \rightarrow Relic density: $\varOmega_{\rm DM,\, total} =$ Ω_{WIMP} \overline{R} ∝ 1 $R\,\langle\sigma v\rangle_{\rm f.o.}$

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

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Summary

- **E** GCE: Astrophysics of WIMPs?
- **EXTERGHEEVICES Higgs Portal: Unique coupling to minimal DM**
- Singlet Scalar Model: Good fit!
- **After constraints: Only Higgs-resonance remains**
- **E** Allow for additional non-WIMP DM component
- **EXECT:** 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

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Back-up III: Table with best-fit points