BOOKS AND ARTS · 12 JUNE 2018 nature

How the belief in beauty has triggered a crisis in physics

Anil Ananthaswamy parses Sabine Hossenfelder's analysis of why the field is at an impasse.

Natural SUSY's last stand

symmetry

40,394 views | Feb 12, 2019, 02:00am Forbes

Why Supersymmetry May Be The Greatest Failed Prediction In Particle Physics History

Are Physicists Ready To Give Up The Chase For SUSY? SCIENTIFIC AMERICAN

SUSY, are you dead yet?

Melissa van Beekveld - Nikhef Jamboree 2019

Supersymmetry Dealt Another Blow By LHC

Charming SUSY: running out of places to hide

Pushing the limits on supersymmetry

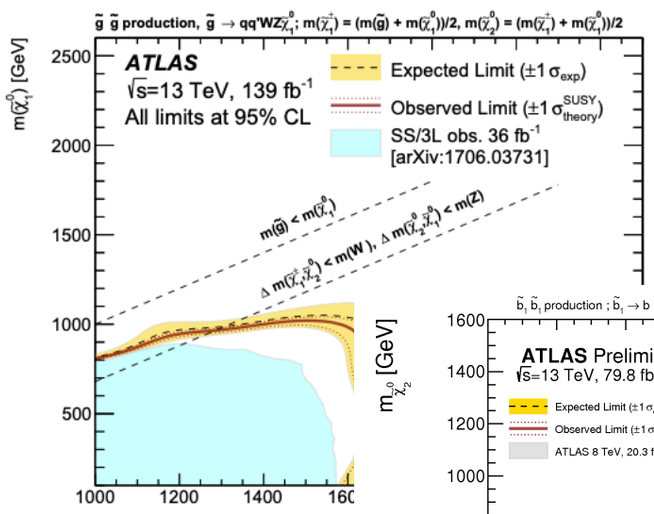
8 May 2019 CERNCOURIER

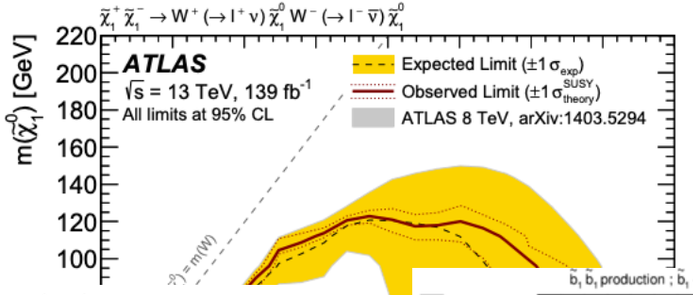
Is een mooie theorie wel echt beter dan een lelijke?

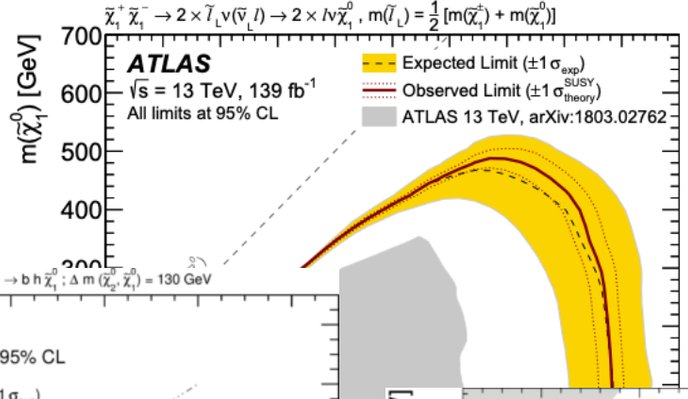
Martijn van Calmthout 15 juni 2018, 15:00 deVolkskrant

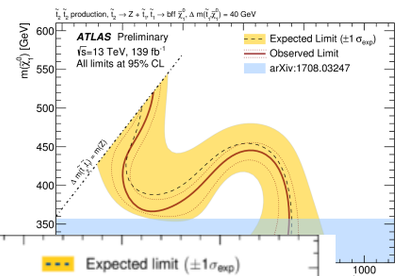
Where Are All the 'Sparticles' That Could Explain What's Wrong with the Universe?

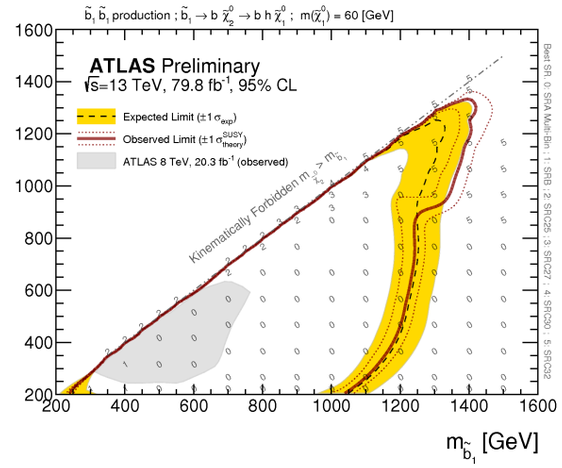
By Paul Sutter March 01, 2019 Strange News

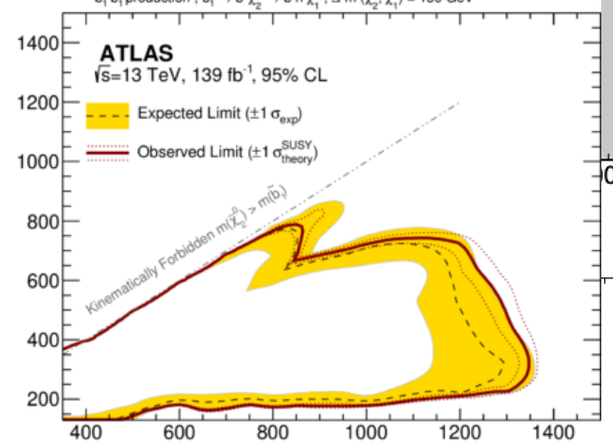

g̃ g̃ production, g̃ → qq'WZχ̃₁⁰; m(χ̃₁±) = (m(g̃) + m(χ̃₁⁰))/2, m(χ̃₂⁰) = (m(χ̃₁±) + m(χ̃₁⁰))/2
ATLAS
√s=13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
SS/3L obs. 36 fb⁻¹ [arXiv:1706.03731]
m(g̃) < m(χ̃₁⁰)
Δ m(χ̃₂⁰, χ̃₁⁰) < m(W), Δ m(χ̃₂⁰, χ̃₁⁰) < m(Z)
m(χ̃₁⁰) [GeV]

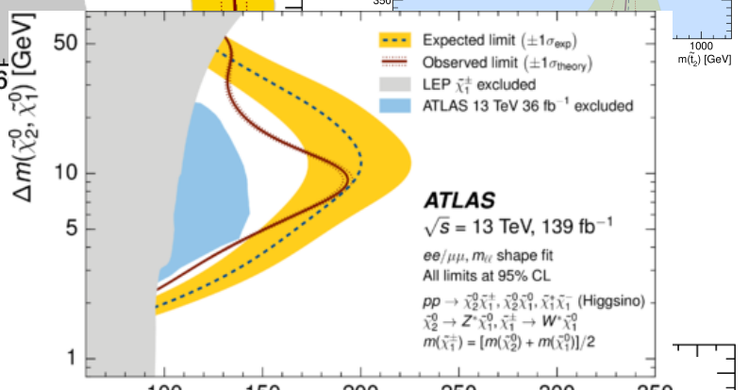

χ̃₁⁺ χ̃₁⁻ → W⁺ (→ l⁺ ν) χ̃₁⁰ W⁻ (→ l⁻ ν̄) χ̃₁⁰
ATLAS
√s = 13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
ATLAS 8 TeV, arXiv:1403.5294
m(χ̃₁⁰) = m(W)
m(χ̃₁⁰) [GeV]

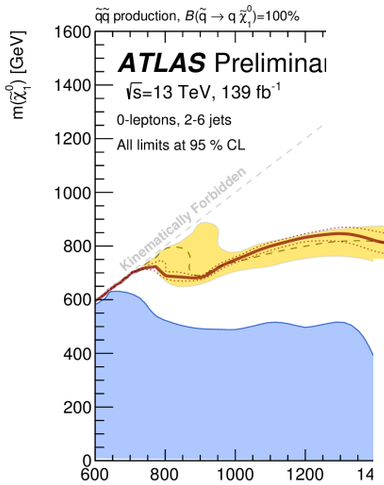

χ̃₁⁺ χ̃₁⁻ → 2 × l̃L ν(ν̄L l) → 2 × l ν χ̃₁⁰, m(l̃L) = ½ [m(χ̃₁⁰) + m(χ̃₁⁰)]
ATLAS
√s = 13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
ATLAS 13 TeV, arXiv:1803.02762
m(χ̃₁⁰) [GeV]

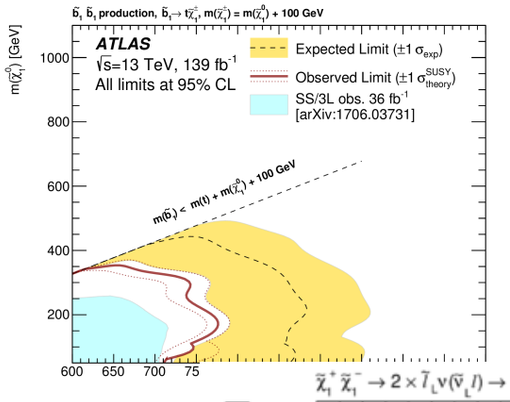

b̃₁ b̃₁ production, b̃₁ → b χ̃₂⁰ → b h χ̃₁⁰
ATLAS Preliminary
√s=13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit
arXiv:1708.03247
m(b̃₁) [GeV]

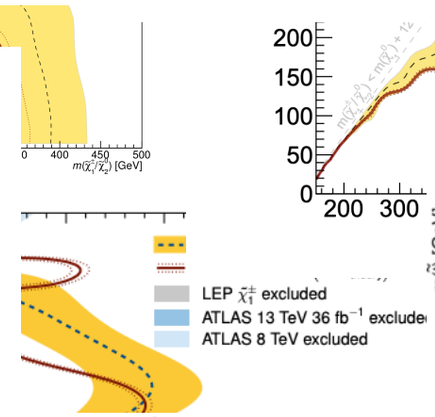

b̃₁ b̃₁ production ; b̃₁ → b χ̃₂⁰ → b h χ̃₁⁰ ; m(χ̃₁⁰) = 60 [GeV]
ATLAS Preliminary
√s=13 TeV, 79.8 fb⁻¹, 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
ATLAS 8 TeV, 20.3 fb⁻¹ (observed)
Kinematically Forbidden m(χ̃₂⁰) > m(b̃₁)
m(χ̃₂⁰) [GeV]
m(b̃₁) [GeV]

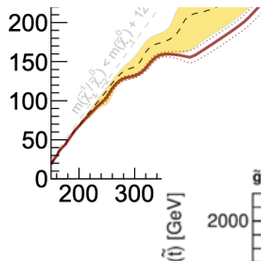

b̃₁ b̃₁ production ; b̃₁ → b χ̃₂⁰ → b h χ̃₁⁰ ; Δ m (χ̃₂⁰, χ̃₁⁰) = 130 GeV
ATLAS
√s=13 TeV, 139 fb⁻¹, 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
Kinematically Forbidden m(χ̃₂⁰) > m(b̃₁)
m(χ̃₂⁰) [GeV]
m(b̃₁) [GeV]

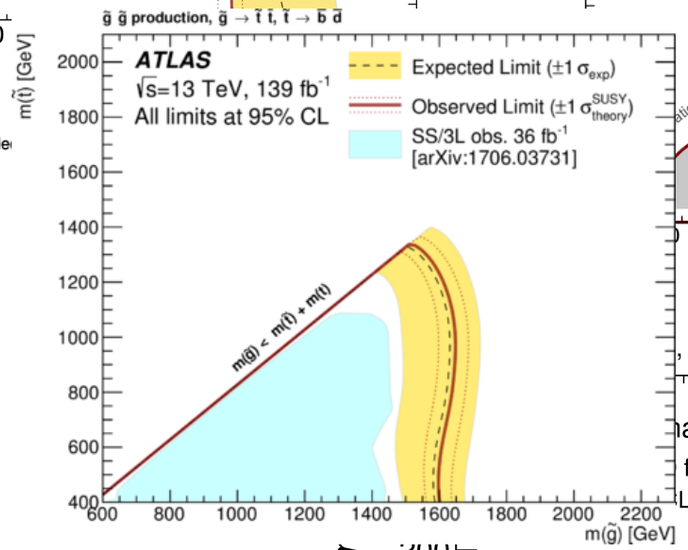

ATLAS
√s = 13 TeV, 139 fb⁻¹
ee/μμ, mℓℓ shape fit
All limits at 95% CL
pp → χ̃₂⁰χ̃₁±, χ̃₂⁰χ̃₁⁰, χ̃₁±χ̃₁∓ (Higgsino)
χ̃₂⁰ → Z*χ̃₁⁰, χ̃₁± → W*χ̃₁⁰
m(χ̃₁±) = [m(χ̃₂⁰) + m(χ̃₁⁰)]/2
Expected limit (±1 σexp)
Observed limit (±1 σtheory)
LEP χ̃₁± excluded
ATLAS 13 TeV 36 fb⁻¹ excluded
Δm(χ̃₂⁰, χ̃₁⁰) [GeV]

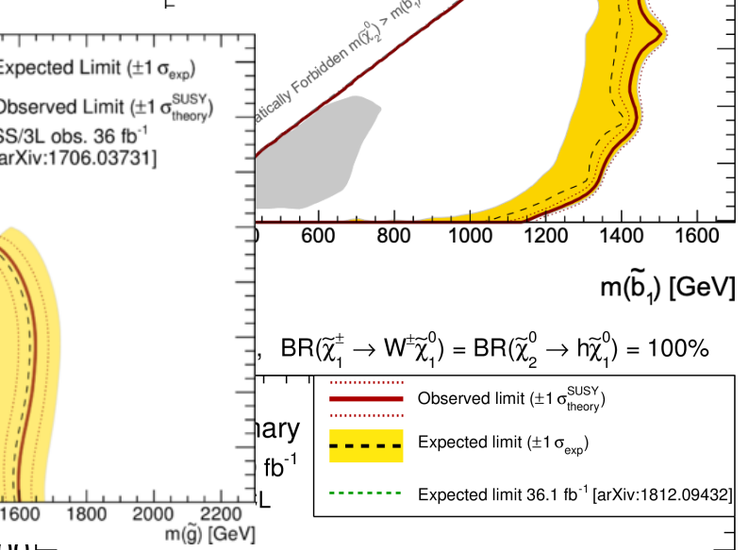

q̃q̃ production, B(q̃ → q χ̃₁⁰)=100%
ATLAS Preliminar
√s=13 TeV, 139 fb⁻¹
0-leptons, 2-6 jets
All limits at 95 % CL
Kinematically Forbidden
m(χ̃₁⁰) [GeV]

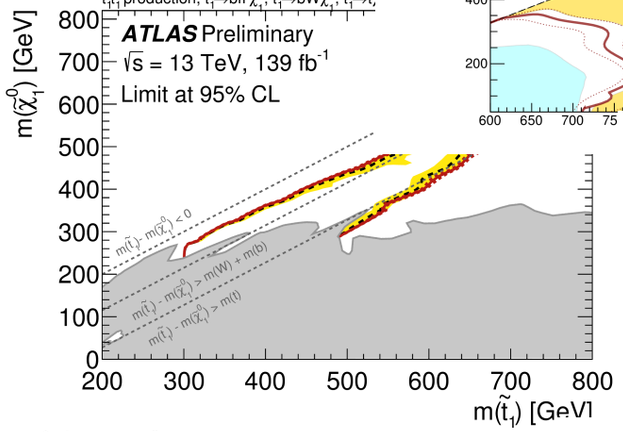

b̃₁ b̃₁ production, b̃₁→ t χ̃₁±, m(χ̃₁±) = m(χ̃₁⁰) + 100 GeV
ATLAS
√s=13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
SS/3L obs. 36 fb⁻¹ [arXiv:1706.03731]
m(b̃₁) < m(t) + m(χ̃₁⁰) + 100 GeV
m(χ̃₁⁰) [GeV]

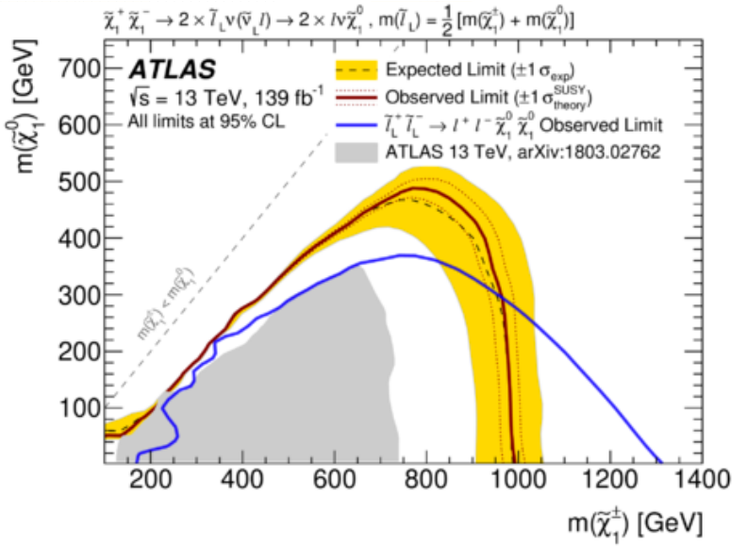

LEP χ̃₁± excluded
ATLAS 13 TeV 36 fb⁻¹ excluded
ATLAS 8 TeV excluded


m(χ̃₂⁰) > m(χ̃₁⁰) + mZ


g̃ g̃ production, g̃ → t̄ t, t → b̄ d
ATLAS
√s=13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
SS/3L obs. 36 fb⁻¹ [arXiv:1706.03731]
m(g̃) < m(t̃) + m(t)
m(t̃) [GeV]
m(g̃) [GeV]

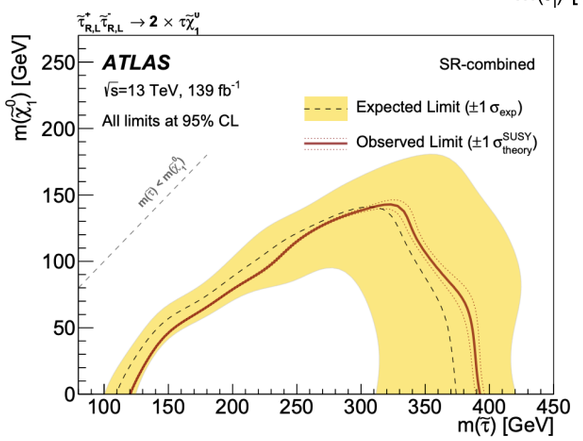

Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
ATLAS 8 TeV, 20.3 fb⁻¹ (observed)
Kinematically Forbidden m(χ̃₂⁰) > m(b̃₁)
m(χ̃₂⁰) [GeV]
m(b̃₁) [GeV]

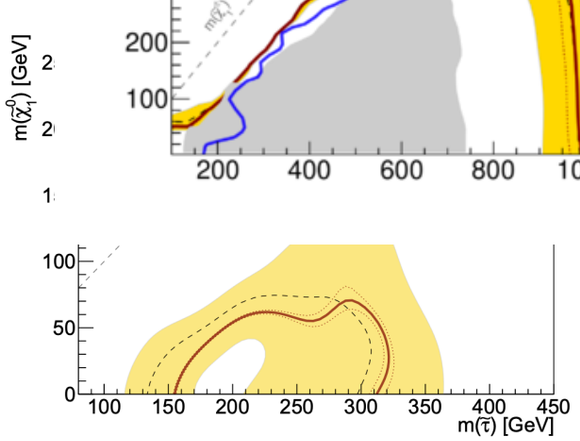

t̃₁t̃₁ production, t̃₁→bff'χ̃₁⁰, t̃₁→bWχ̃₁⁰, t̃₁→tχ̃₁⁰
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
Limit at 95% CL
m(t̃₁) - m(χ̃₁⁰) < 0
m(t̃₁) - m(χ̃₁⁰) > m(W) + m(b)
m(t̃₁) - m(χ̃₁⁰) > m(t)
m(χ̃₁⁰) [GeV]
m(t̃₁) [GeV]

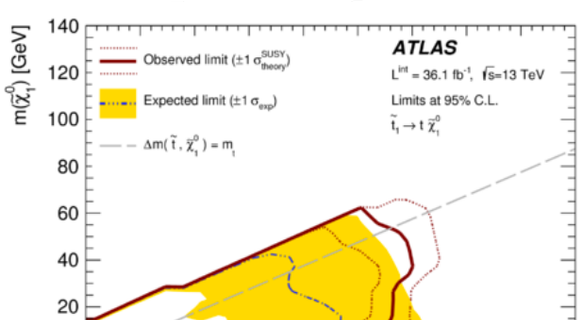

χ̃₁⁺ χ̃₁⁻ → 2 × l̃L ν(ν̄L l) → 2 × l ν χ̃₁⁰, m(l̃L) = ½ [m(χ̃₁⁰) + m(χ̃₁⁰)]
ATLAS
√s = 13 TeV, 139 fb⁻¹
All limits at 95% CL
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
l̃L⁺ l̃L⁻ → l⁺ l⁻ χ̃₁⁰ χ̃₁⁰ Observed Limit
ATLAS 13 TeV, arXiv:1803.02762
m(χ̃₁⁰) < m(χ̃₁±)
m(χ̃₁⁰) [GeV]
m(χ̃₁±) [GeV]

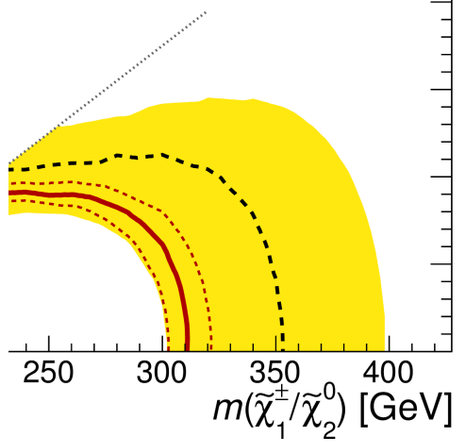
m(g̃) < m(t̃) + m(t)
m(g̃) [GeV]

BR(χ̃₁± → W±χ̃₁⁰) = BR(χ̃₂⁰ → hχ̃₁⁰) = 100%
Observed limit (±1 σtheory SUSY)
Expected limit (±1 σexp)
Expected limit 36.1 fb⁻¹ [arXiv:1812.09432]
m(b̃₁) [GeV]


ATLAS
√s=13 TeV, 139 fb⁻¹
All limits at 95% CL
SR-combined
Expected Limit (±1 σexp)
Observed Limit (±1 σtheory SUSY)
m(χ̃₁⁰) < m(τ̃)
m(χ̃₁⁰) [GeV]
m(τ̃) [GeV]


m(τ̃) [GeV]


Observed limit (±1 σtheory SUSY)
Expected limit (±1 σexp)
Δm(t̃, χ̃₁⁰) = m_t
ATLAS
L^int = 36.1 fb⁻¹, √s=13 TeV
Limits at 95% C.L.
t̃₁ → t χ̃₁⁰
m(χ̃₁⁰) [GeV]


m(χ̃₁±/χ̃₂⁰) [GeV]

High SUSY masses are assumed to be bad…

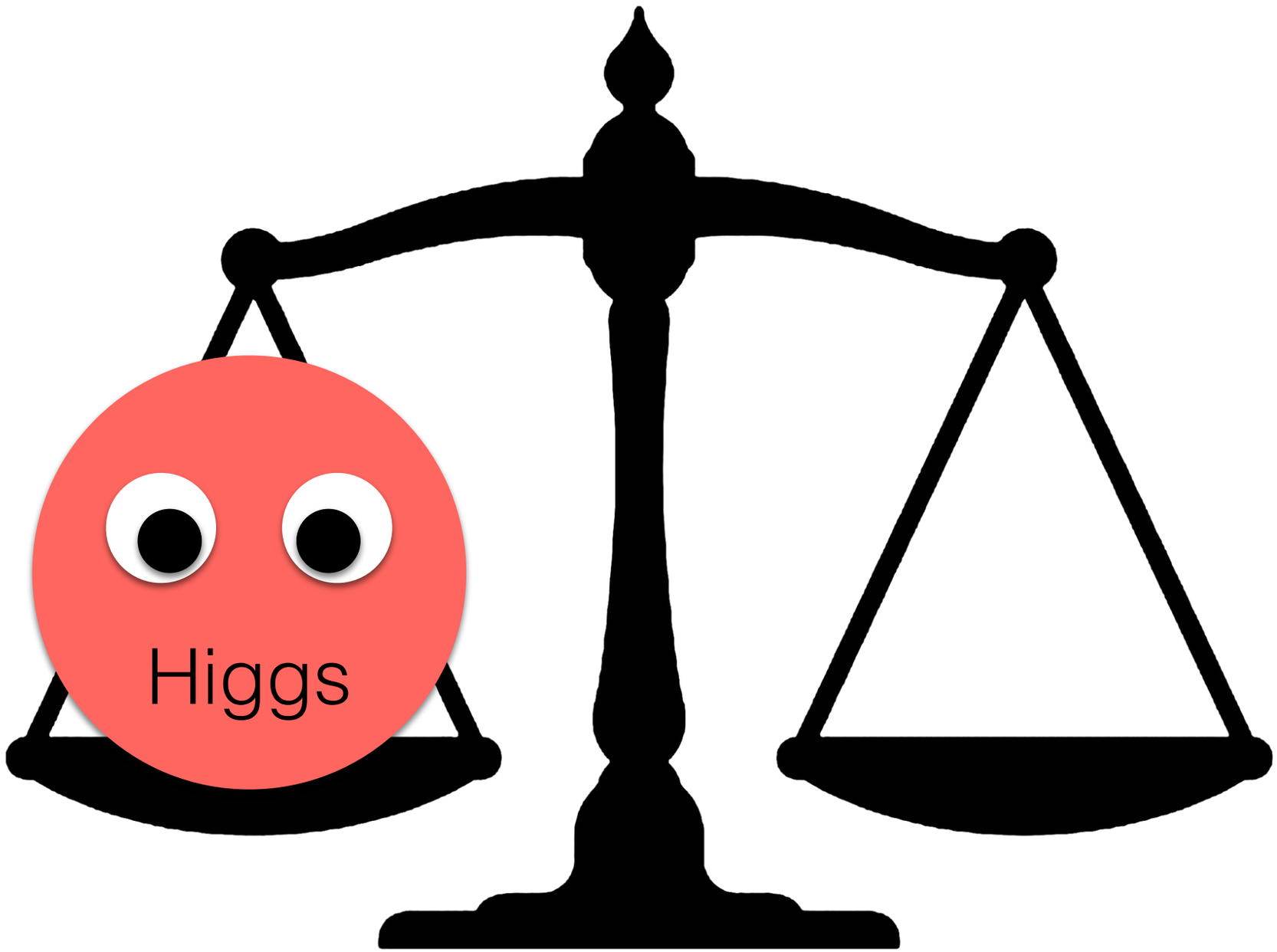
Why?

High SUSY masses are assumed to be bad…

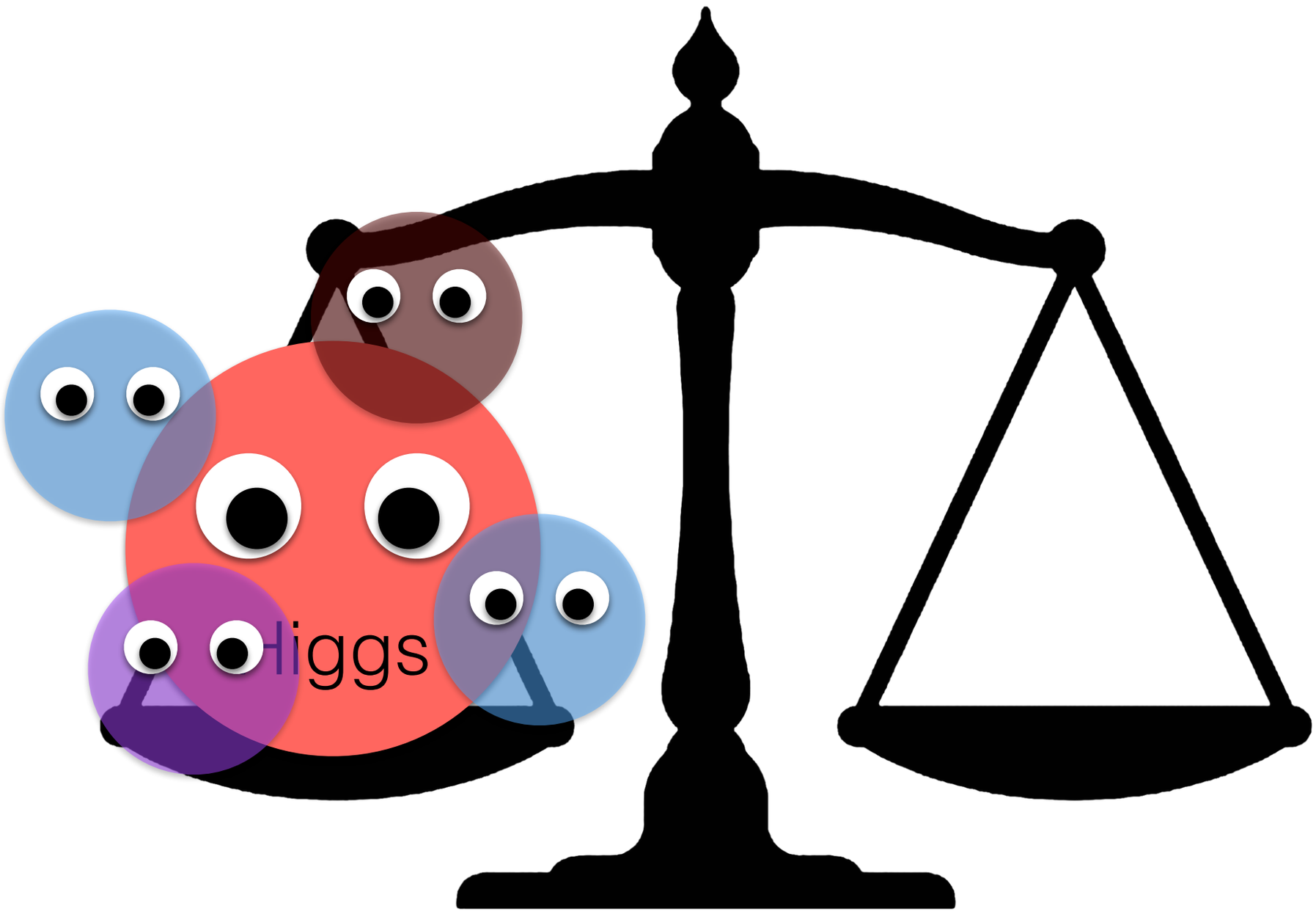
Why?

The fine-tuning problem

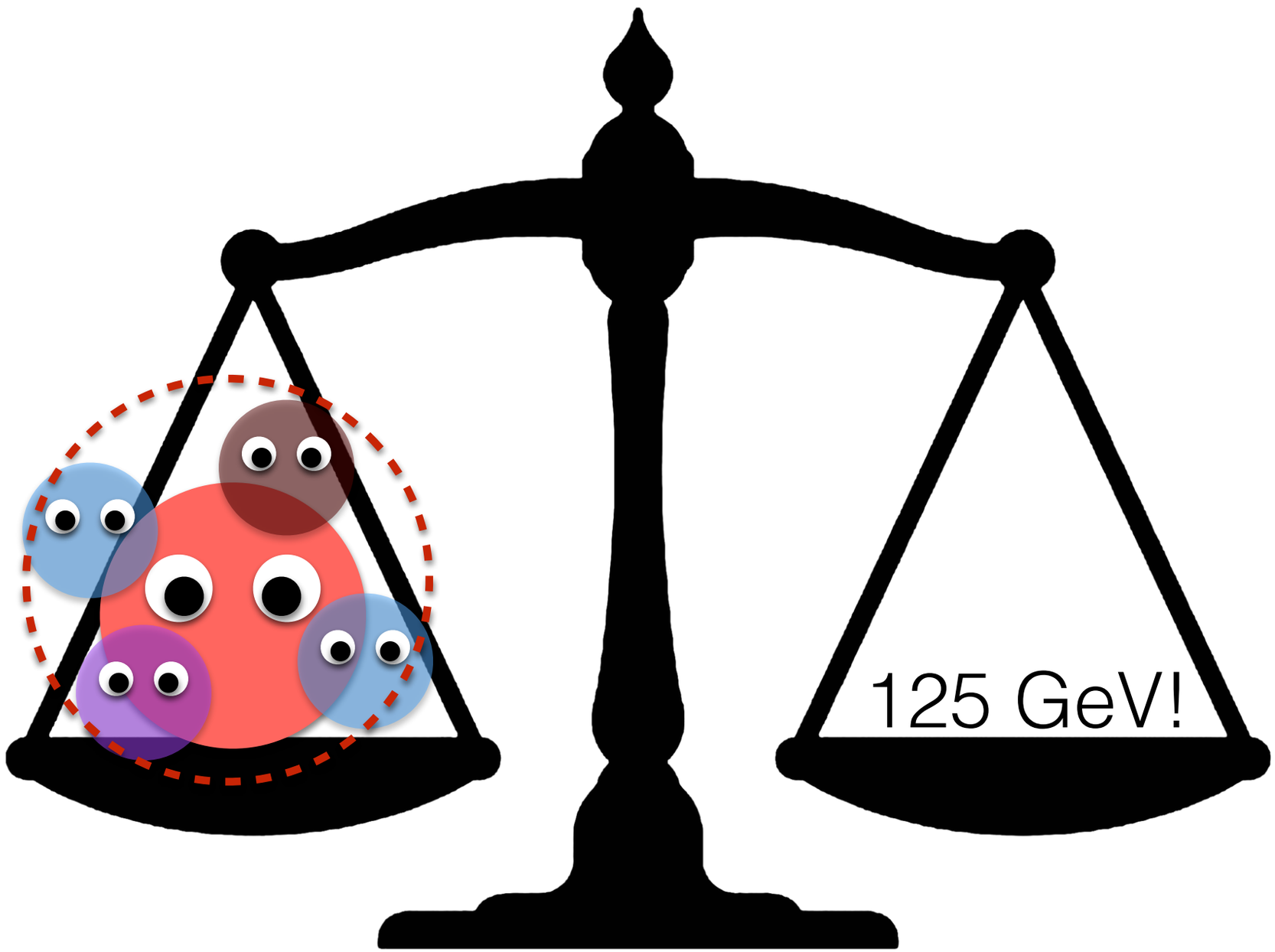
What do we measure?

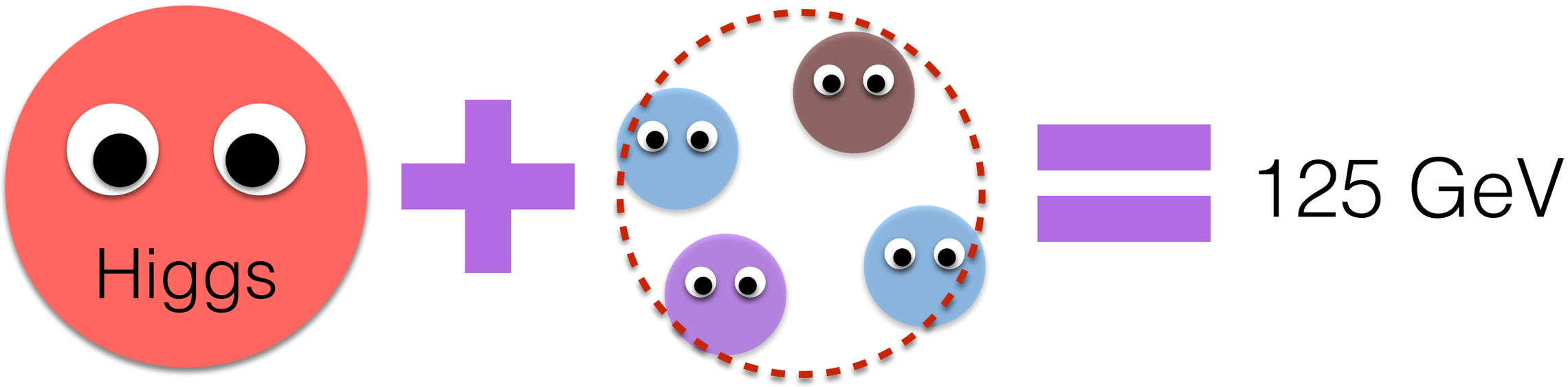


What do we measure?

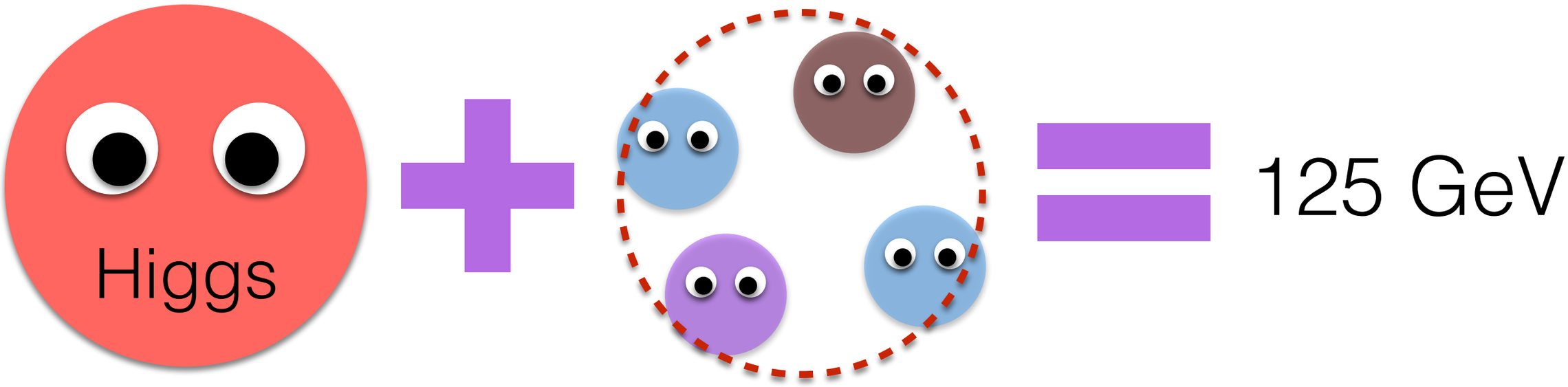


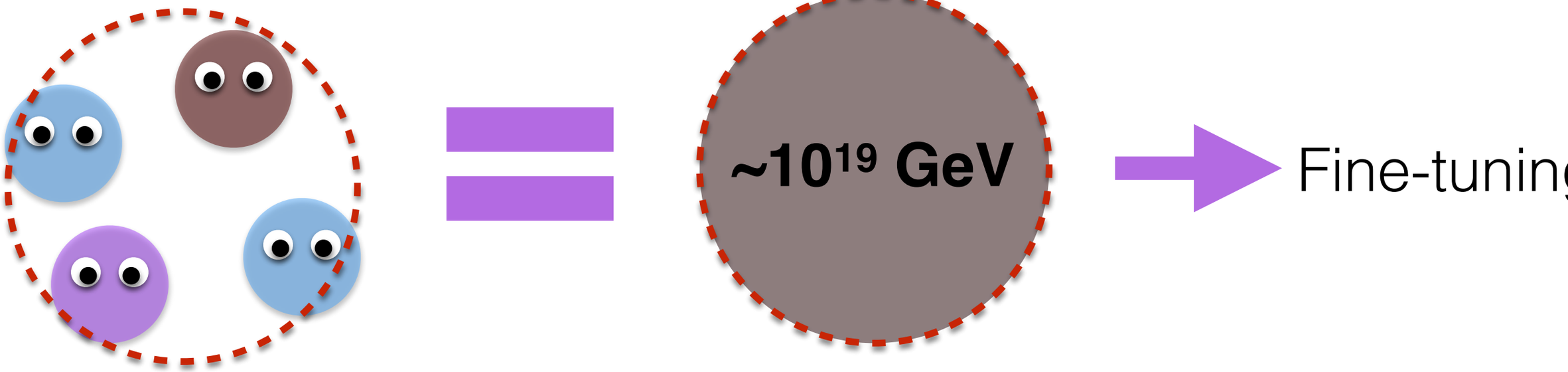
What do we measure?



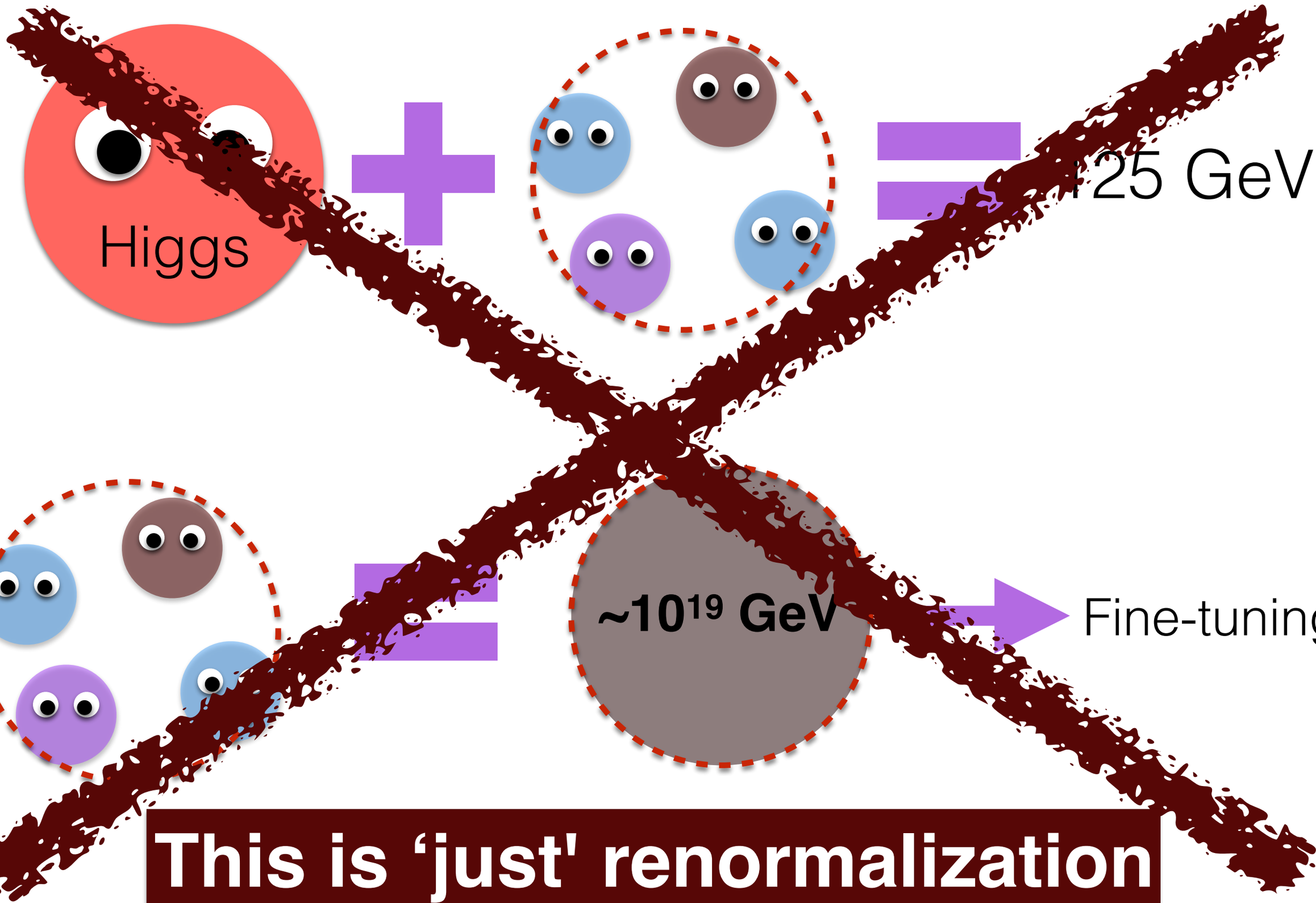

Higgs
125 GeV

Usual story:



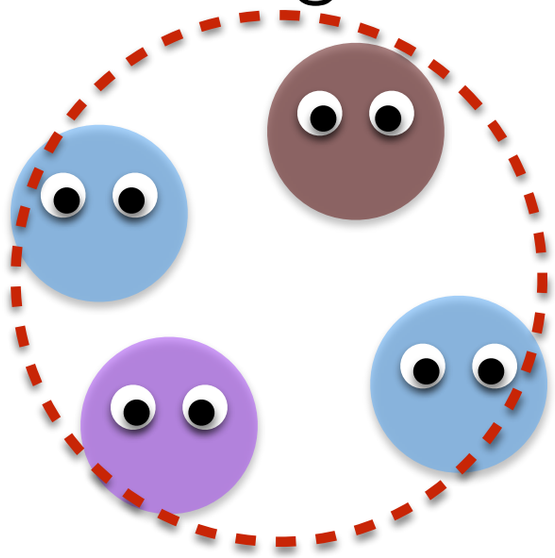


Usual story:



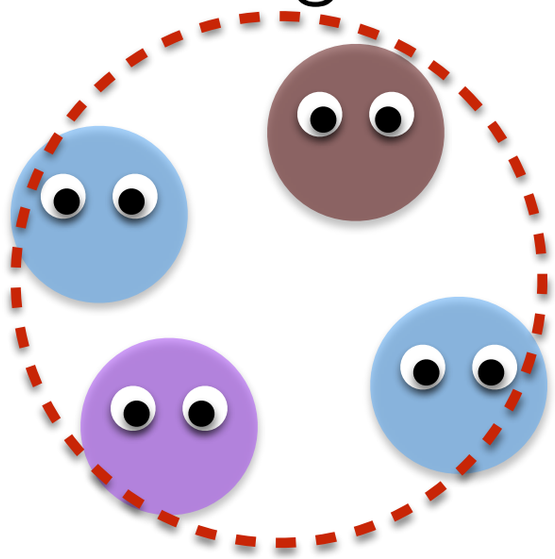
This is ‘just' renormalization

Only if the ingredients of



are observable, you **could** have fine-tuning

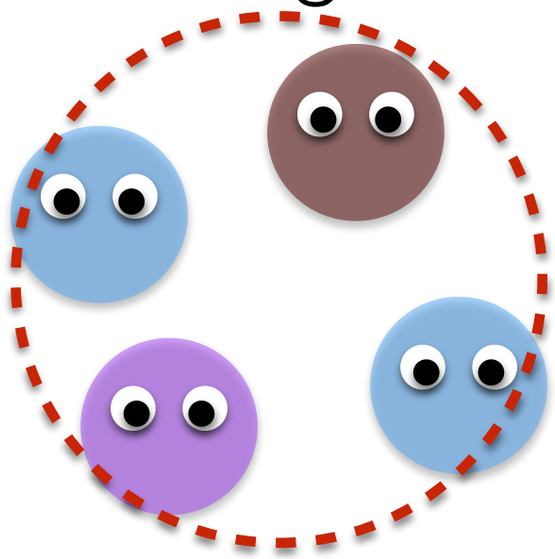
Only if the ingredients of



are observable, you **could** have fine-tuning

e.g. new physics at Planck scale…

Only if the ingredients of



are observable, you **could** have fine-tuning

e.g. new physics at Planck scale…

…or new SUSY particles

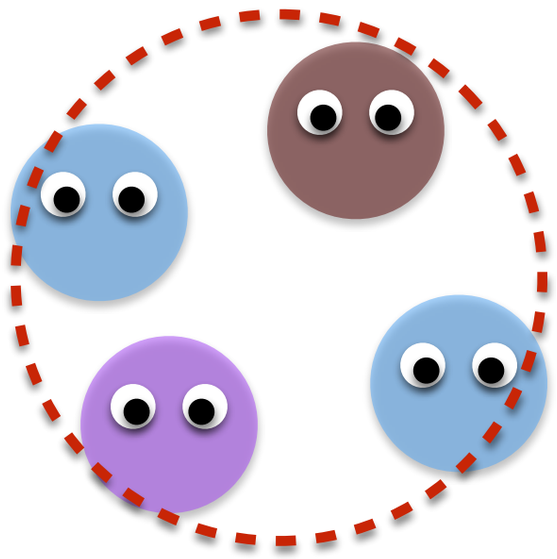
Fine-tuning is…

…when one observable changes a lot as a consequence of a tiny change in other observables

Fine-tuning is…

…when one observable changes a lot as a consequence of a tiny change in other observables

The Higgs boson ‘feels’
the presence of a new scale



Fine-tuning is…

…when one observable changes a lot as a consequence of a tiny change in other observables

The Higgs boson ‘feels’
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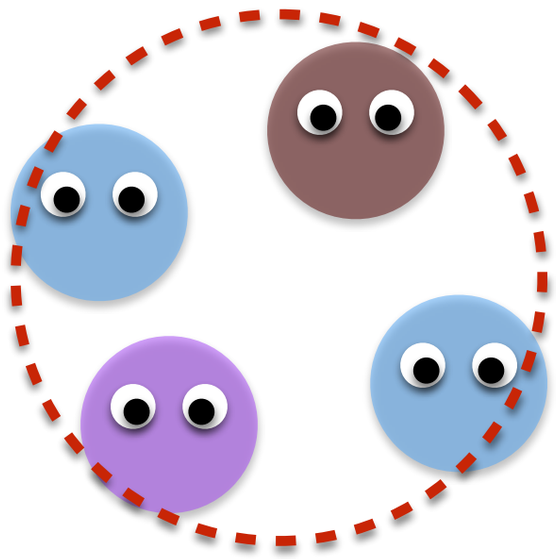

Either in the form of:

1. A high scale model (GUT)
2. An effective theory (EFT)

We want to know:

1. Is SUSY fine-tuned?
   Should we be worried about the LHC limits?
2. Where and how should we look next?
   Fine-tuning aside, are there holes in the experimental coverage?

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1. Is SUSY fine-tuned?
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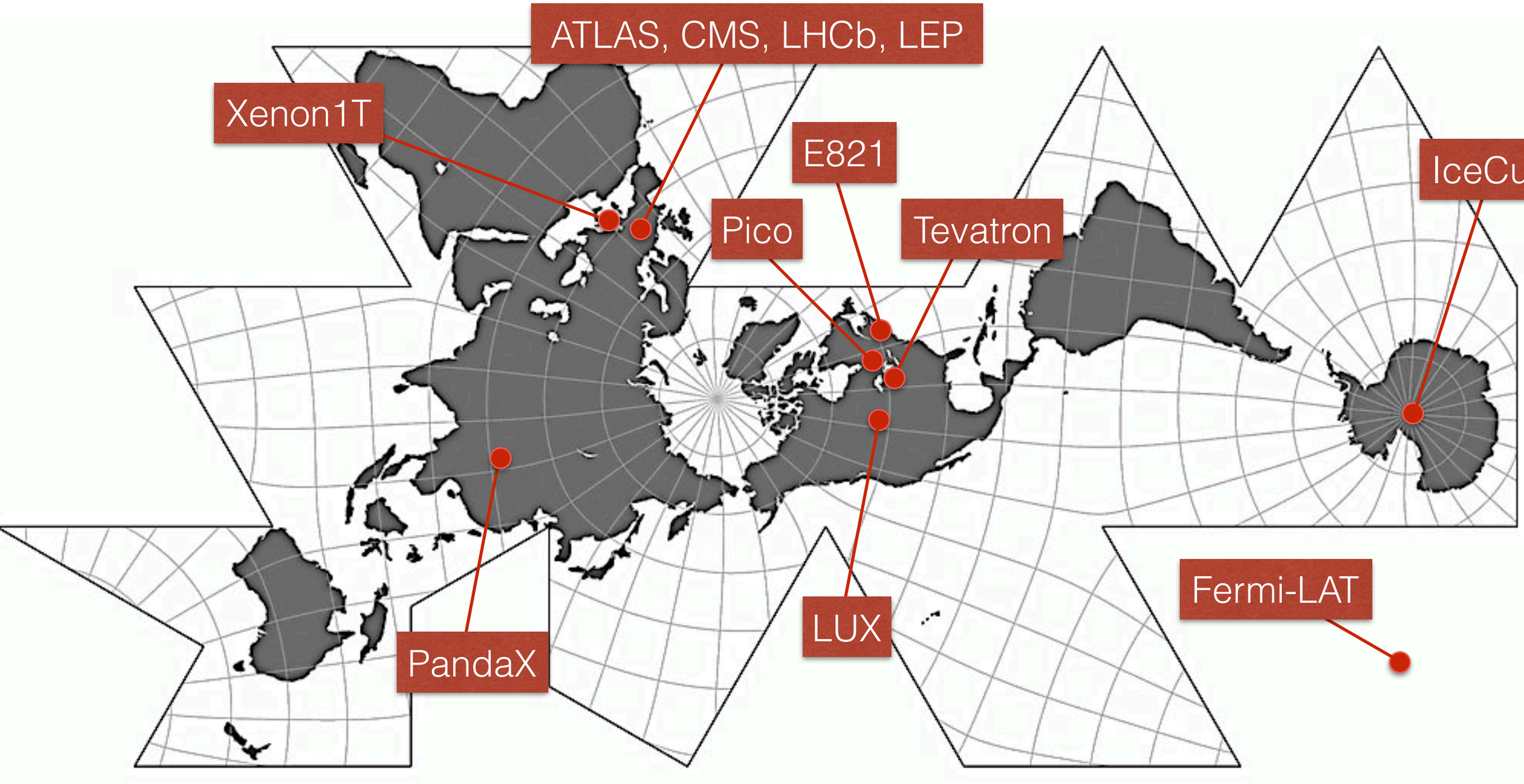
   Fine-tuning aside, are there holes in the experimental coverage?

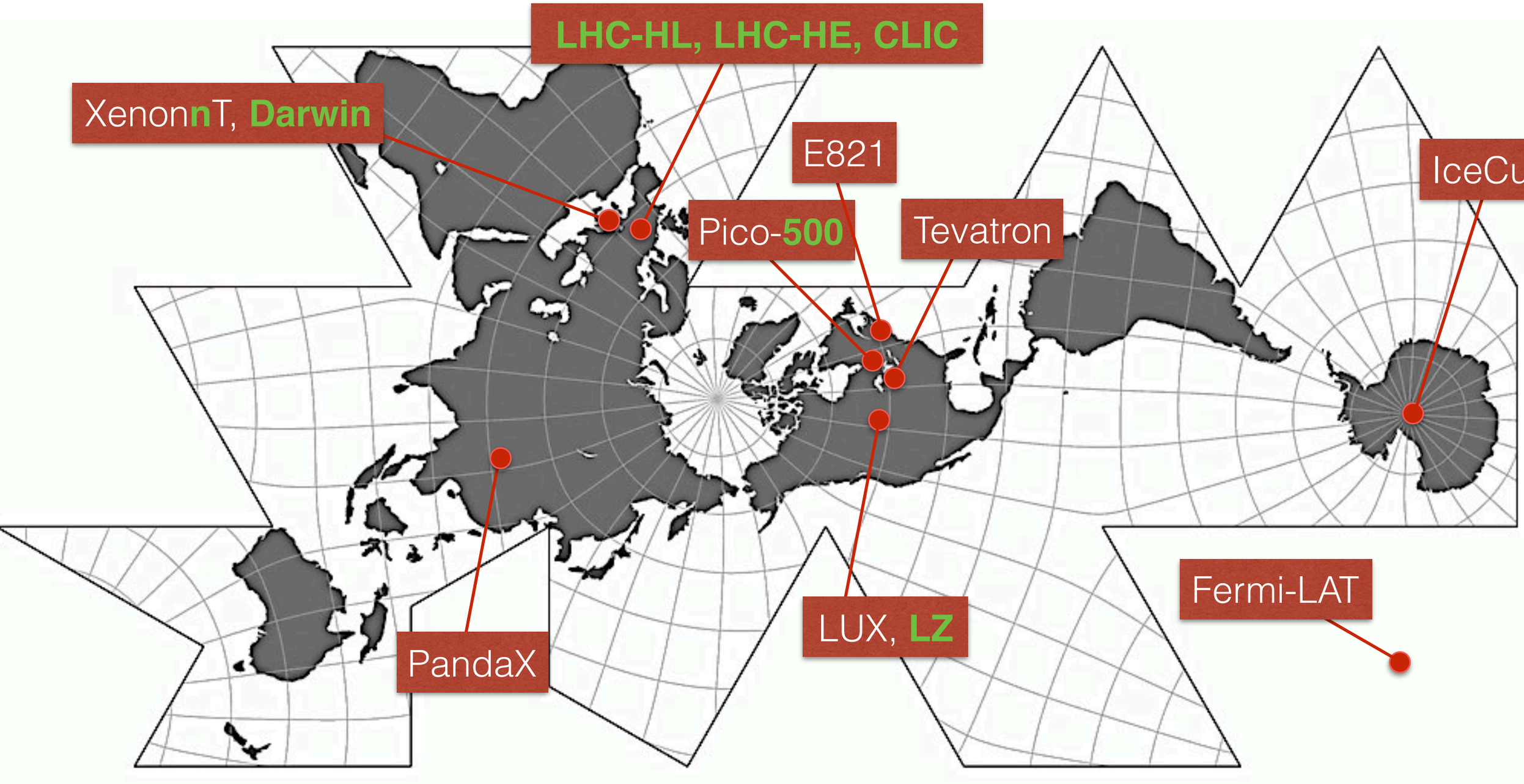
How do we do it? [1612.06333,1906.10706] with W. Beenakker, S. Caron
R. Peeters, R. Ruiz de Austri

1. Consider SUSY GUTs and EFTs
2. Combine the data
3. *Minimize* the possible amount of fine-tuning

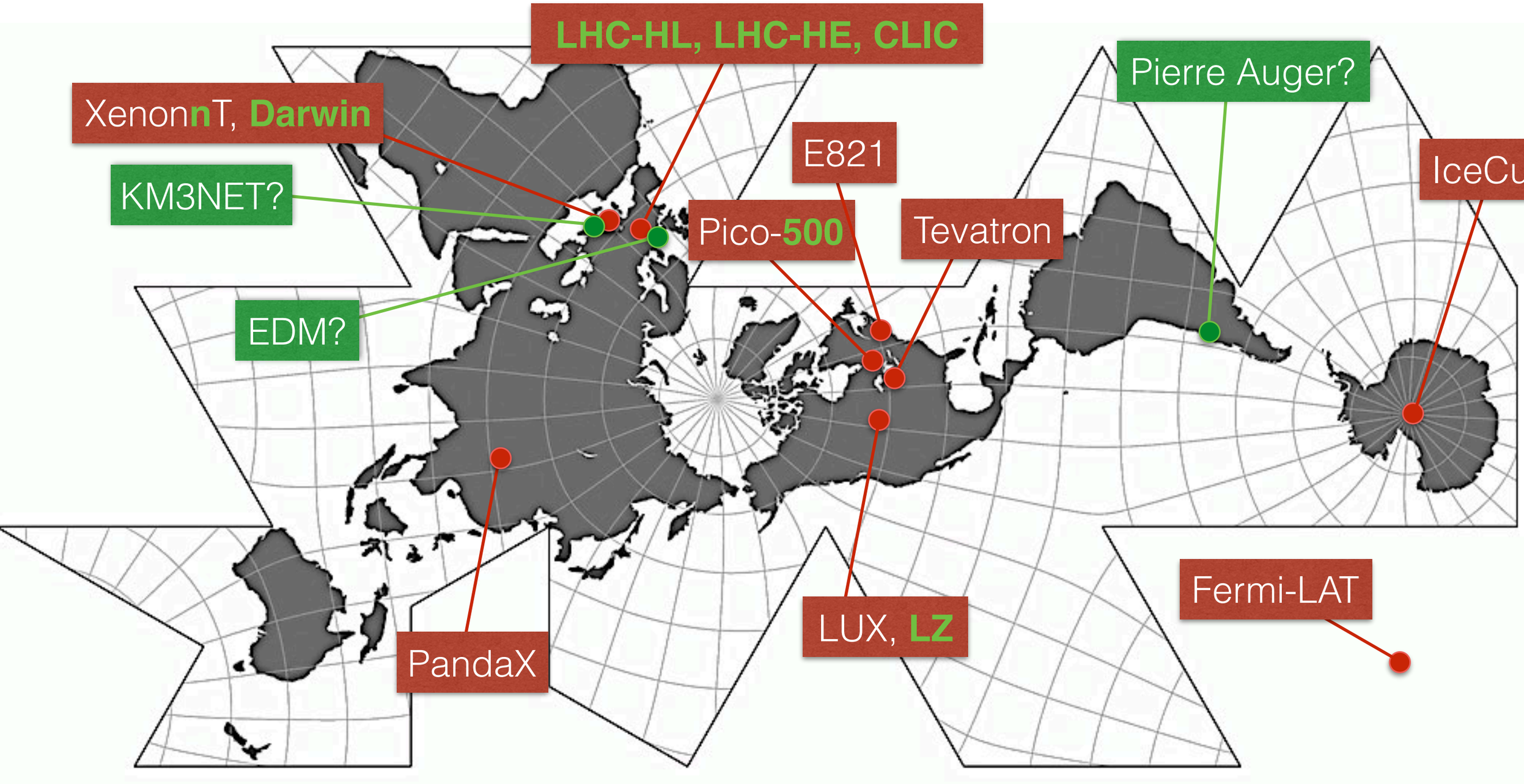
Combine data!



Combine data!

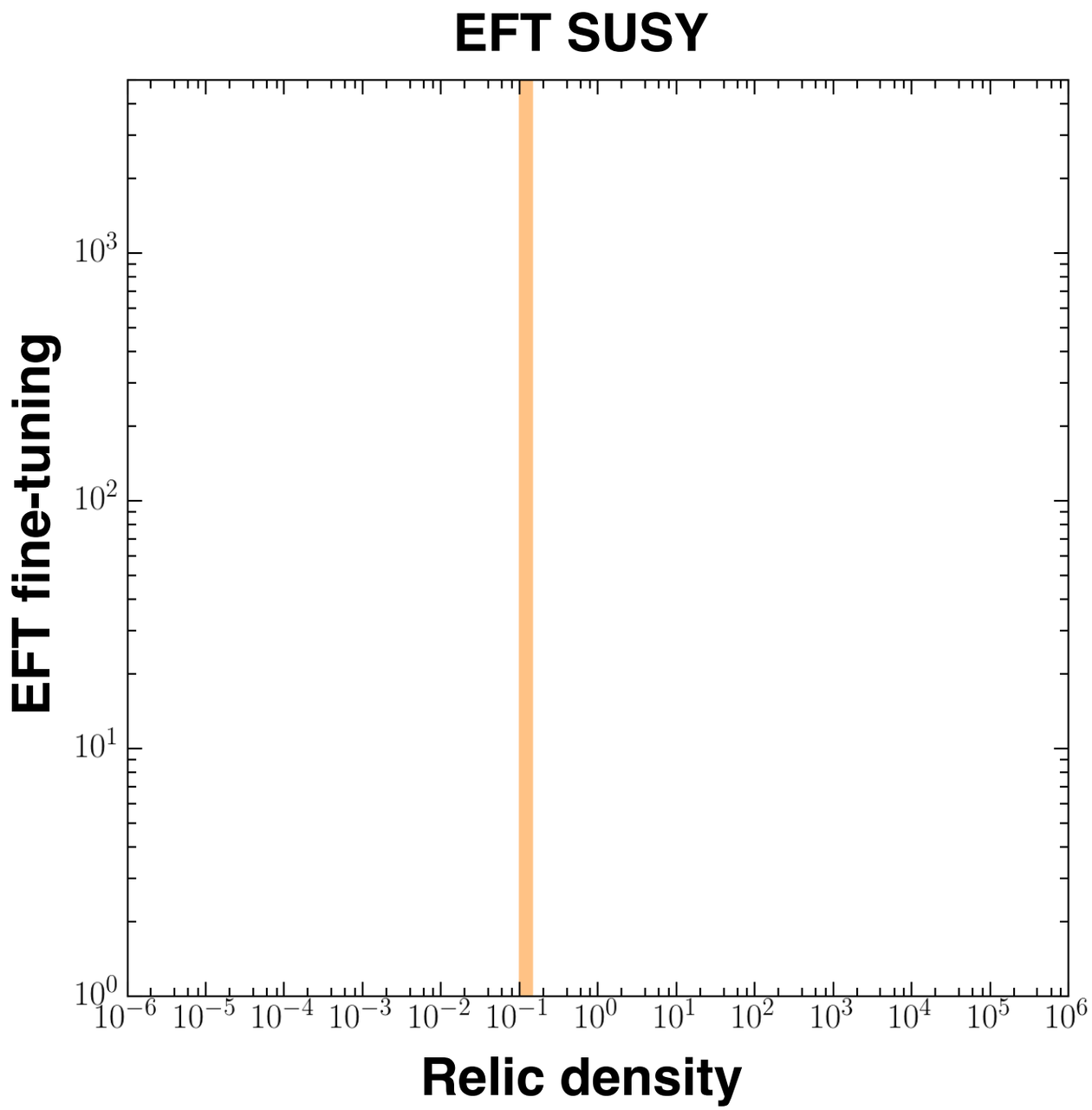


Combine data!

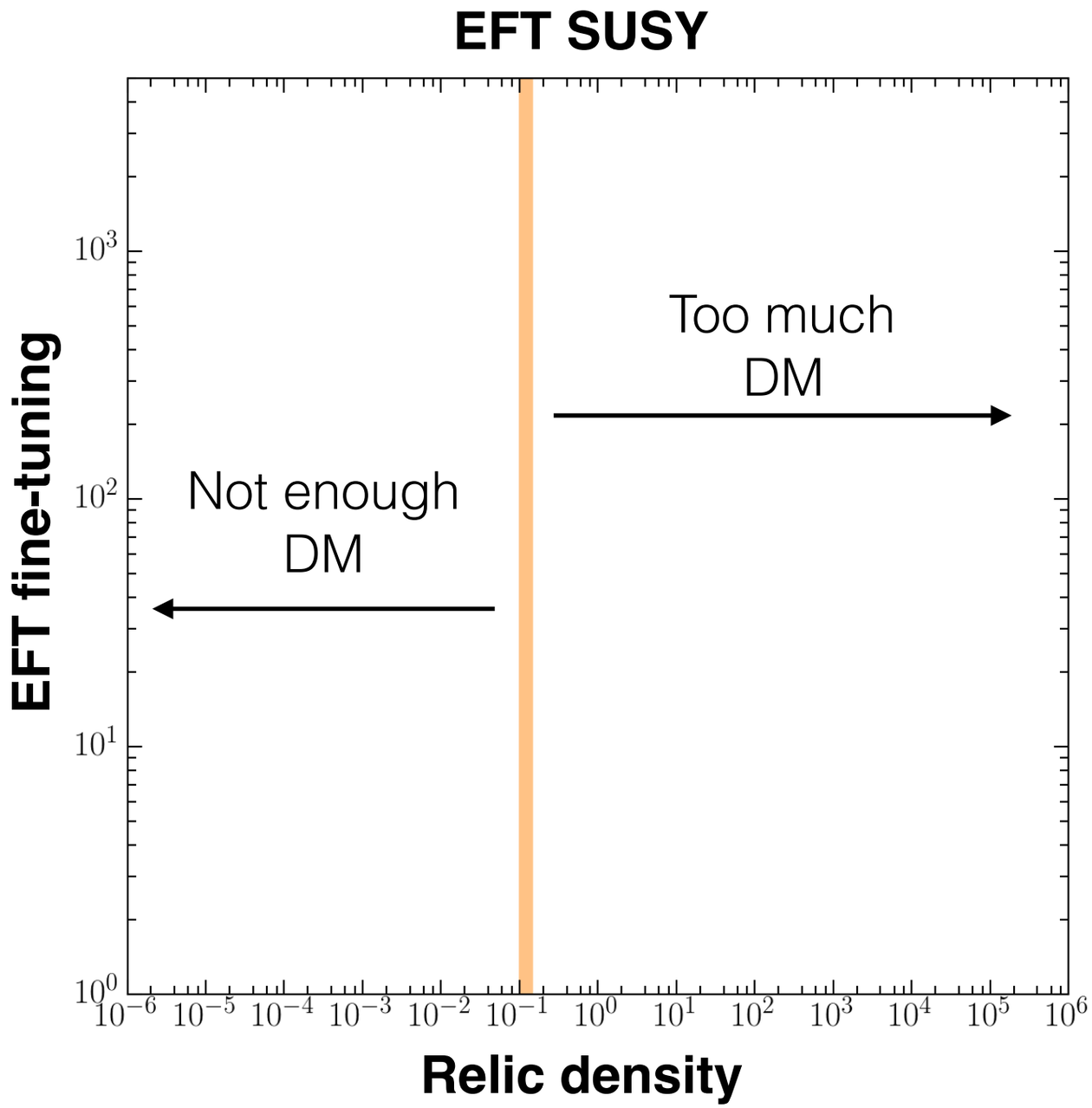


Relic density vs fine-tuning

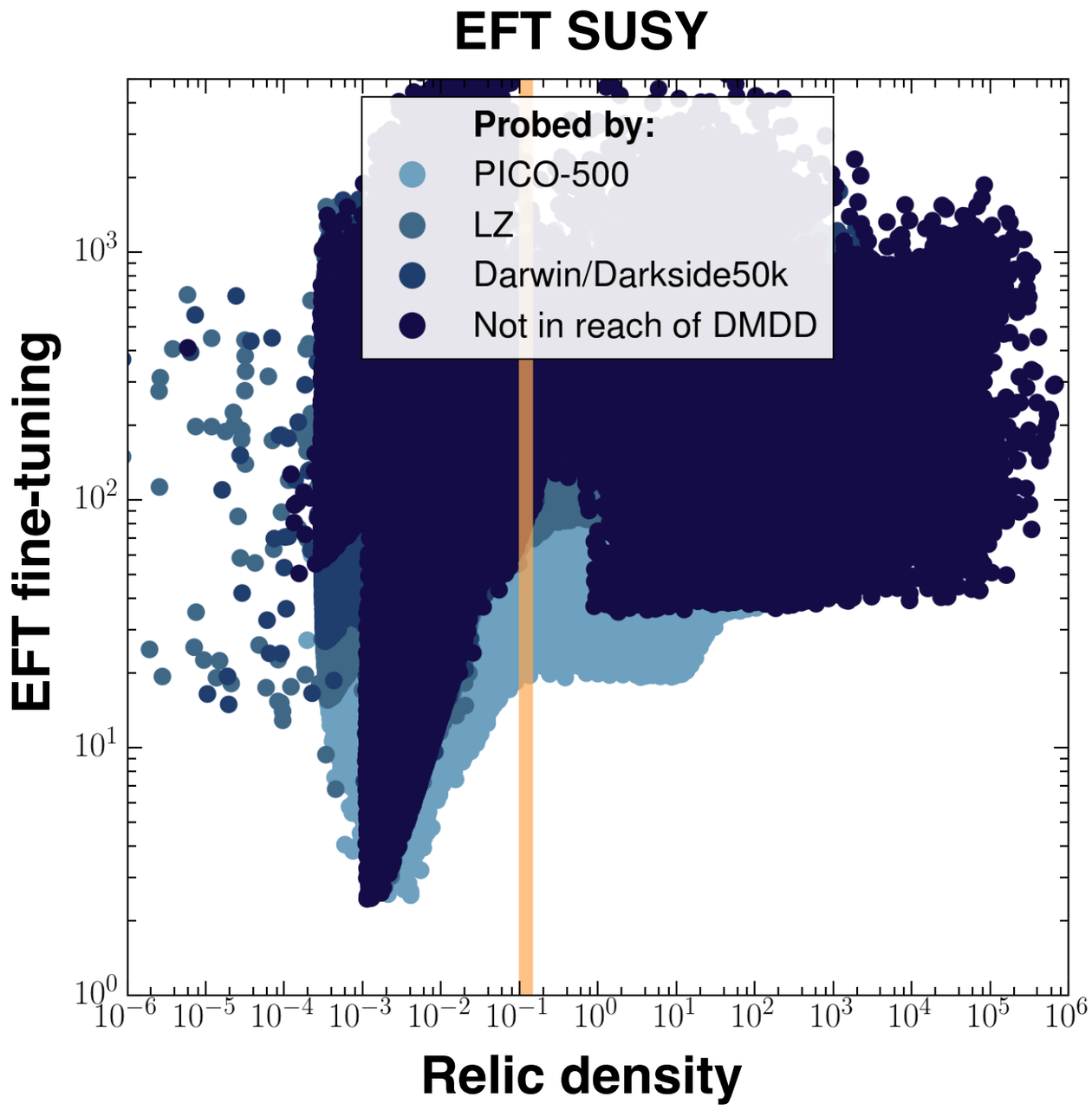
Lower
=
Better



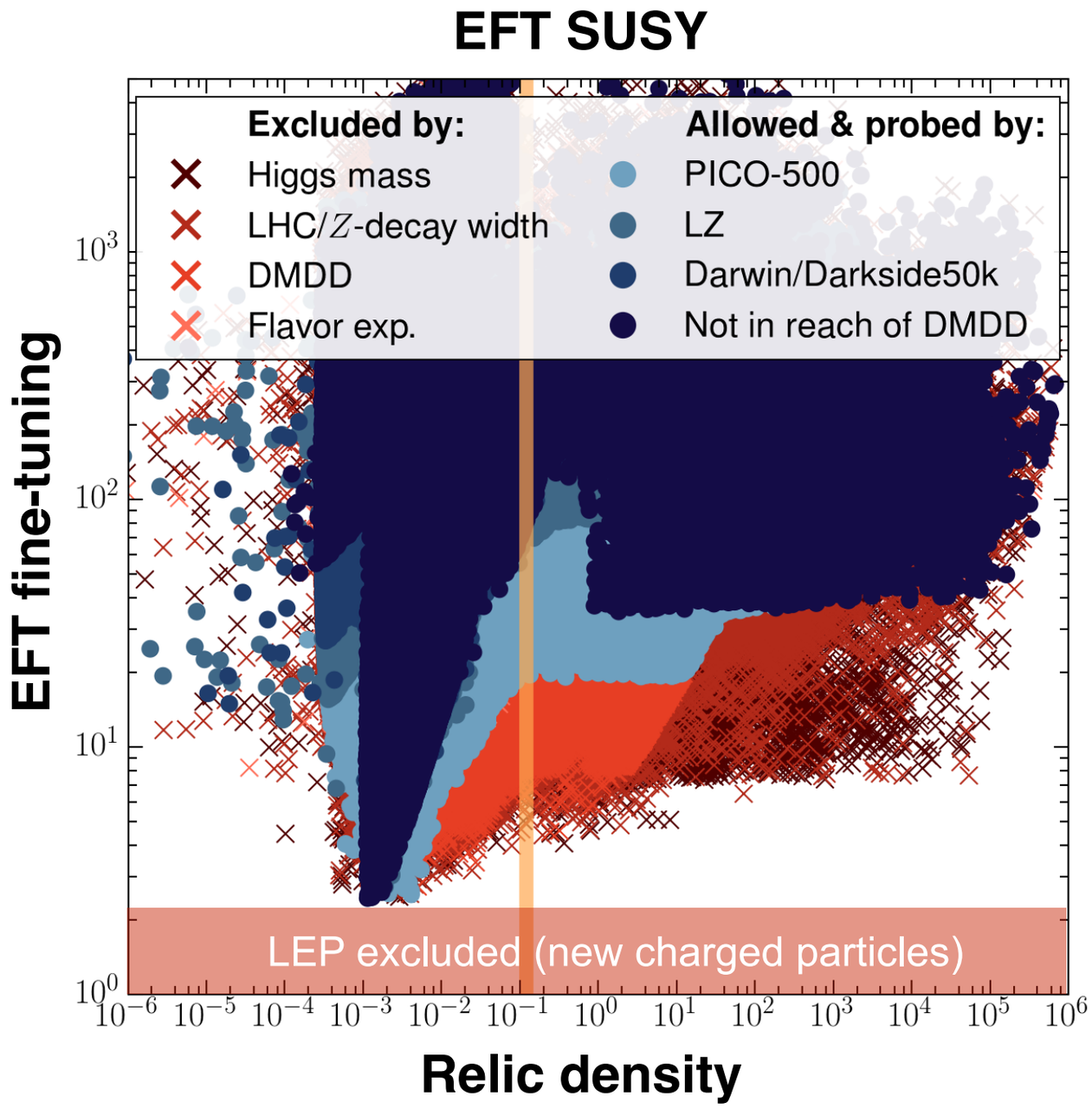
Relic density vs fine-tuning



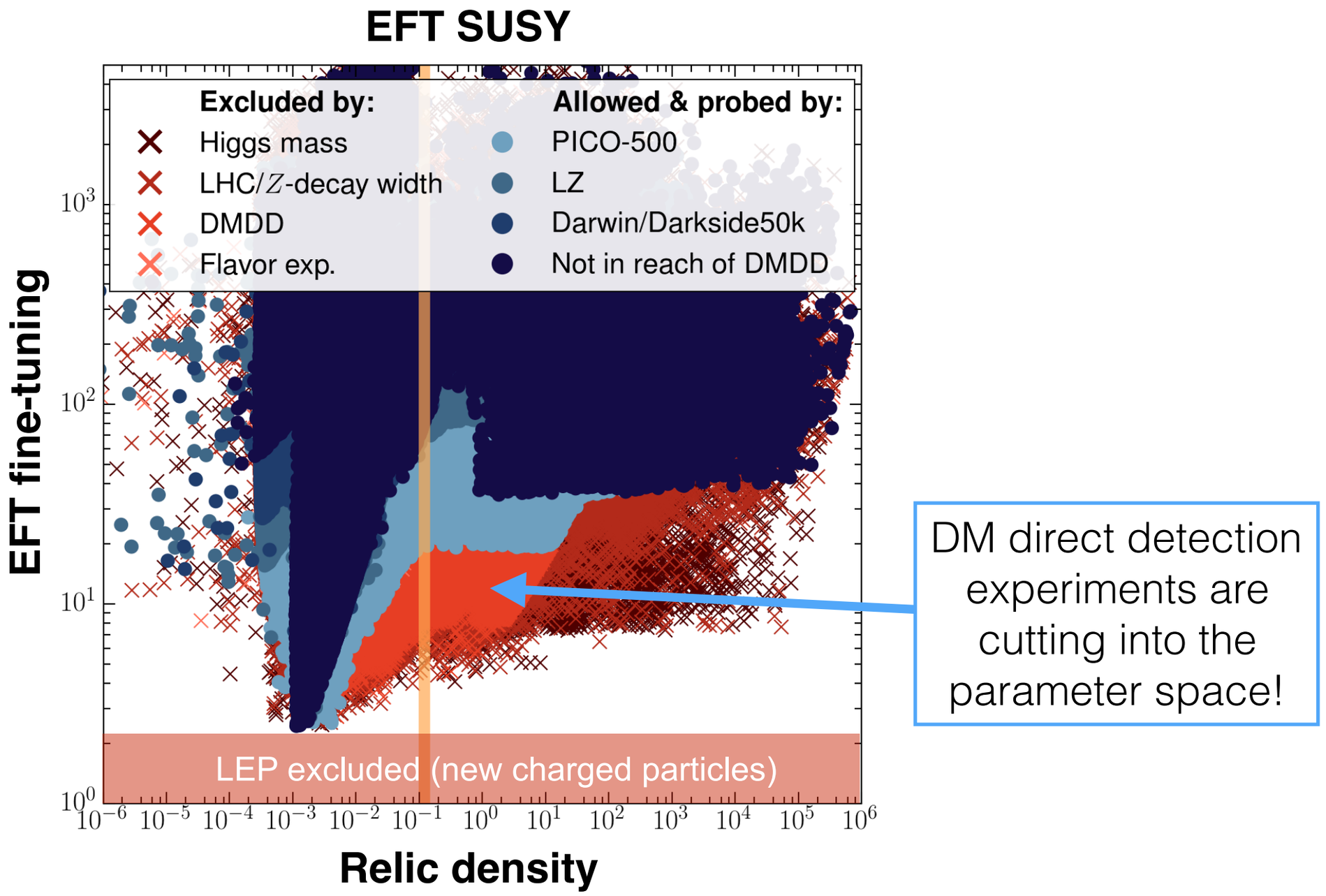
Relic density vs fine-tuning



Relic density vs fine-tuning

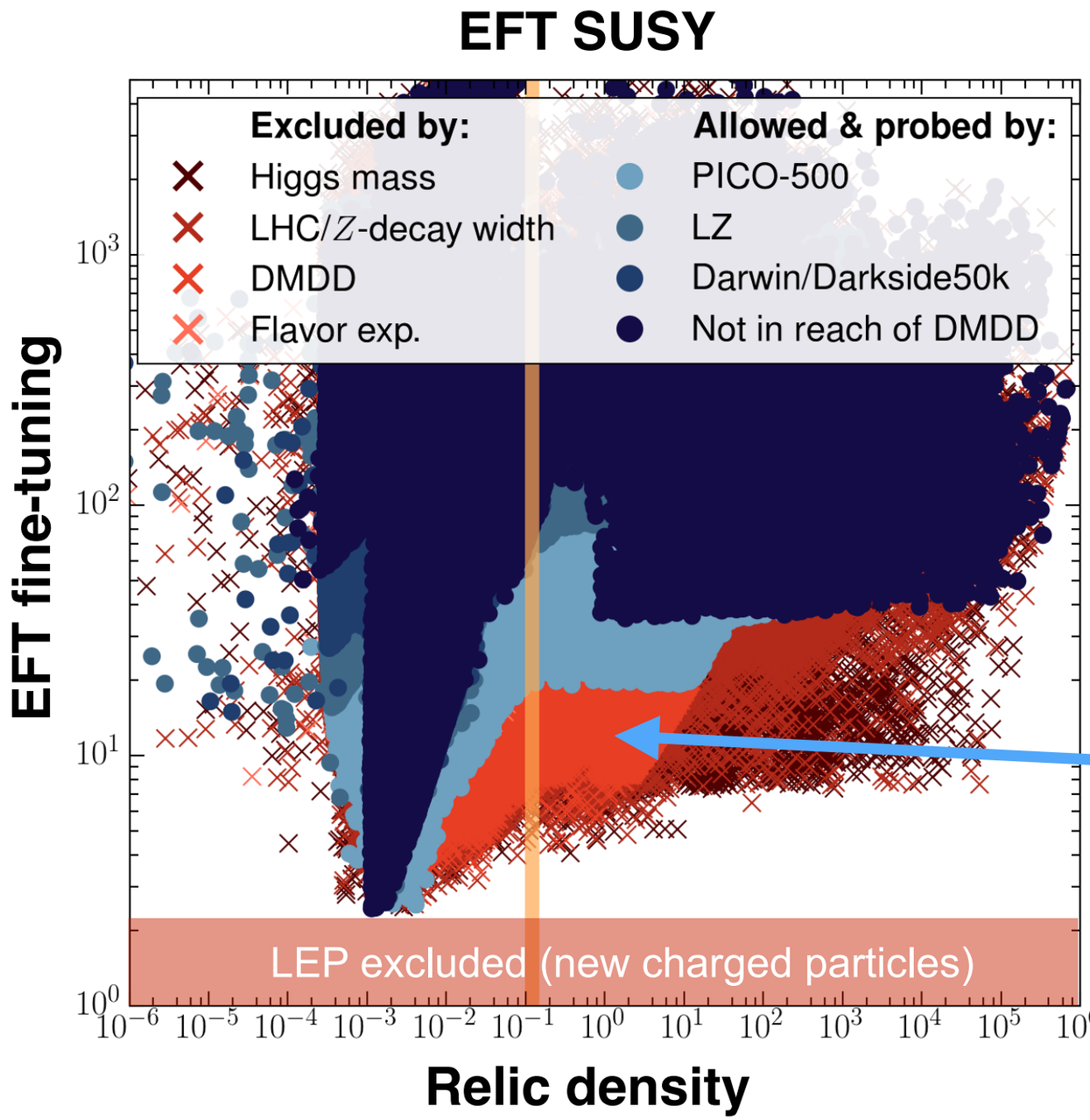


Relic density vs fine-tuning



DM direct detection experiments are cutting into the parameter space!

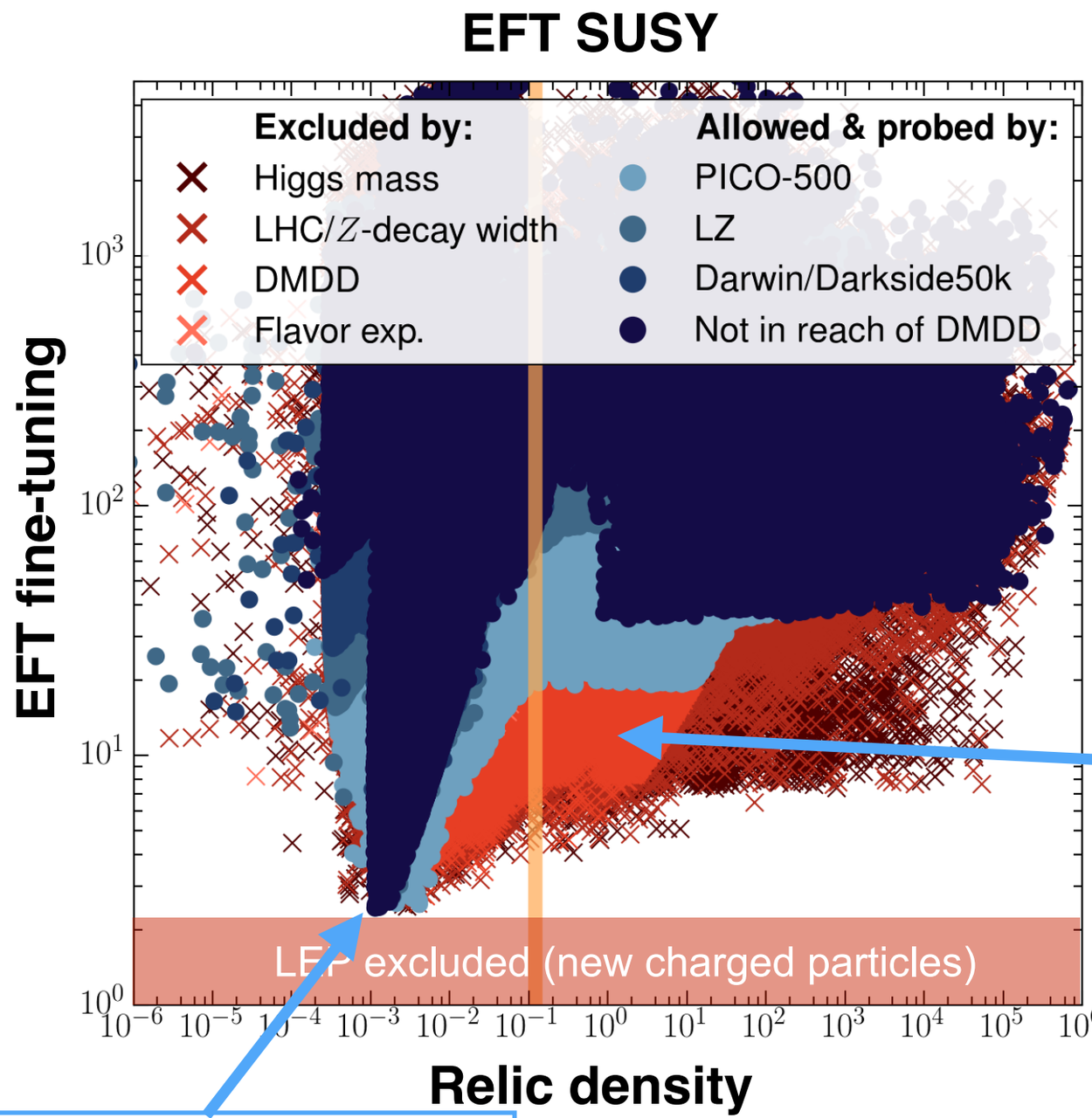
Relic density vs fine-tuning



DM direct detection experiments are cutting into the parameter space!

It is important to combine data

Relic density vs fine-tuning

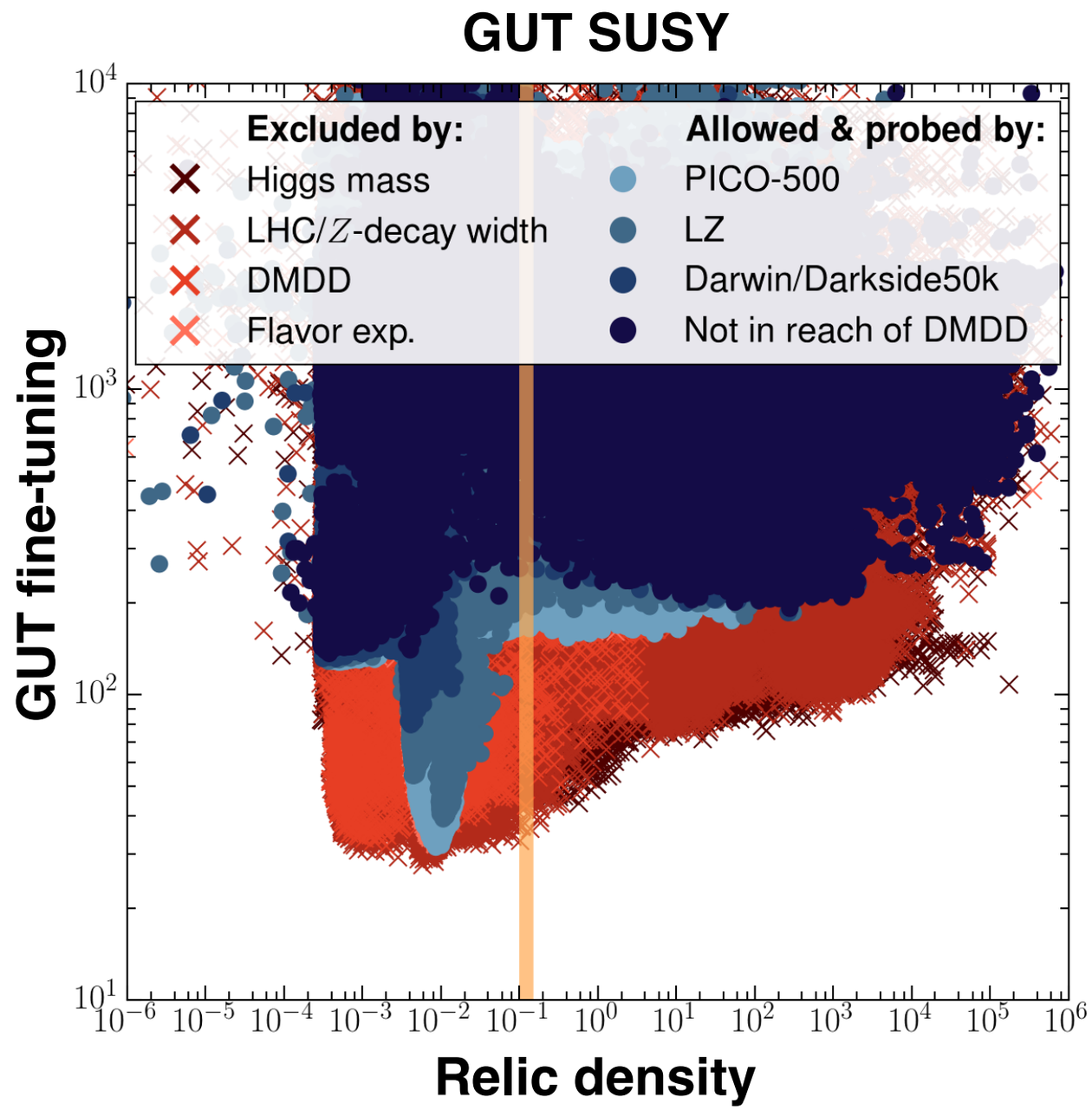


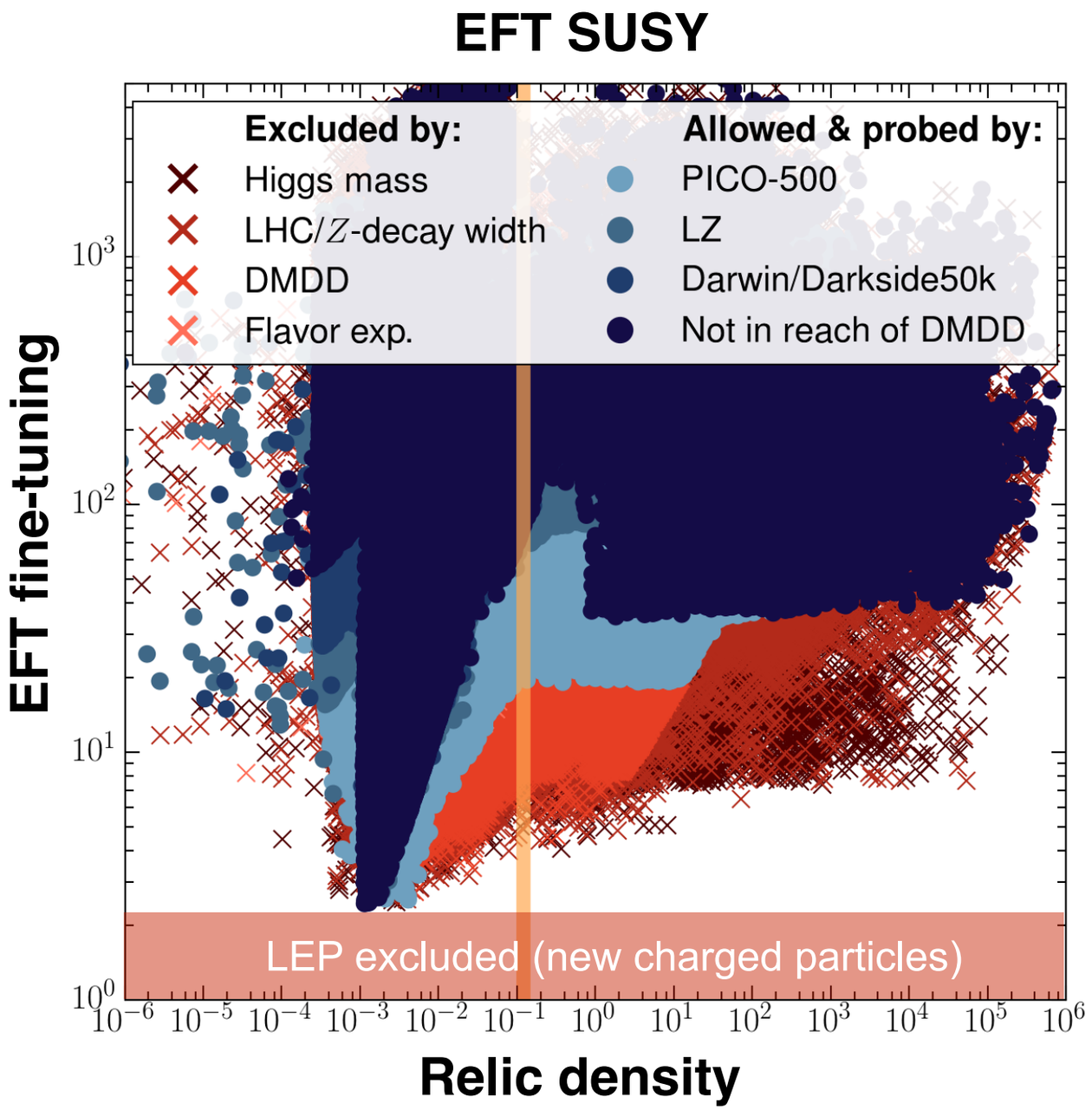
DM direct detection experiments are cutting into the parameter space!

It is important to combine data

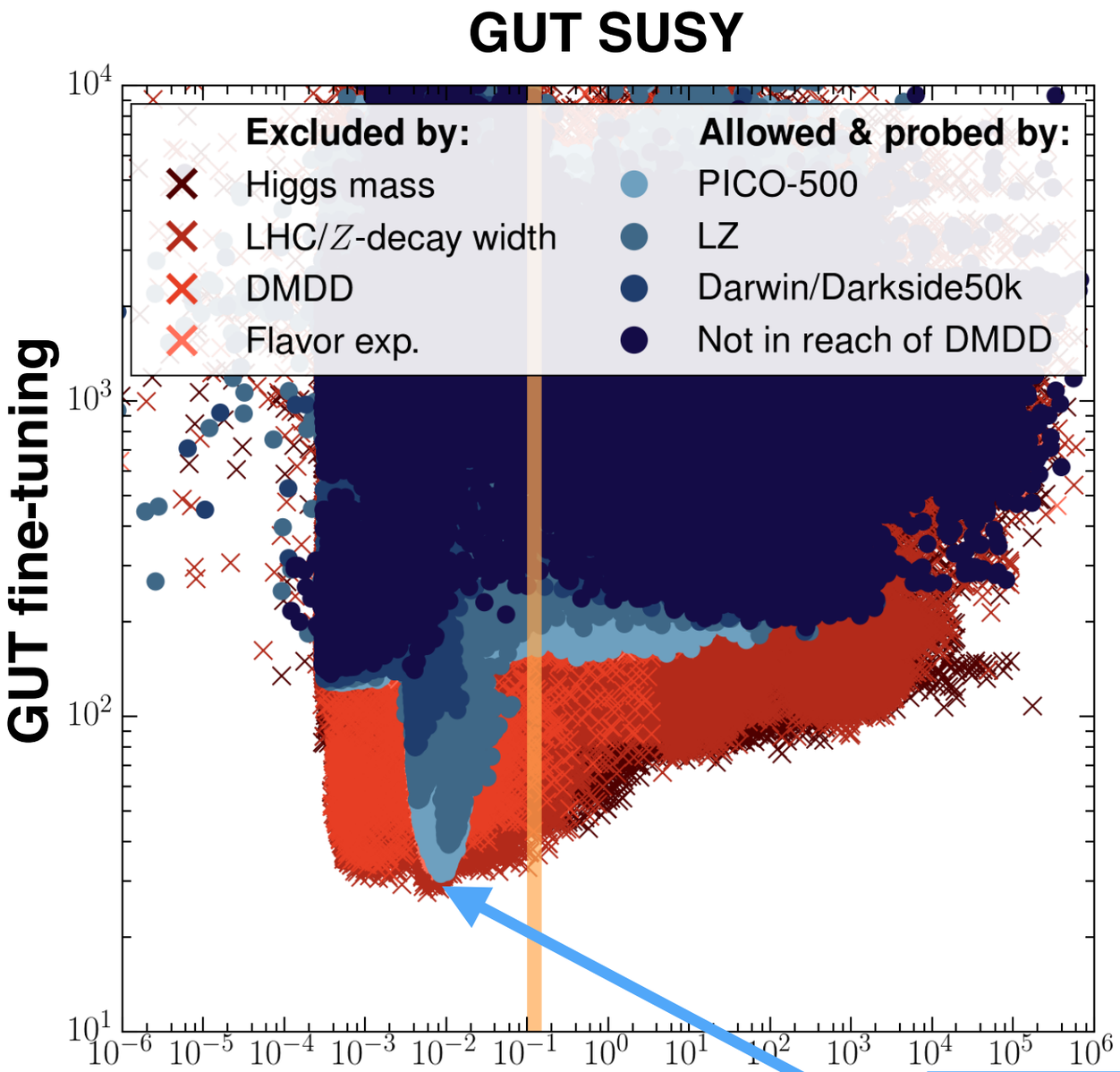
The status of the points with the lowest FT has not changed since LEP!

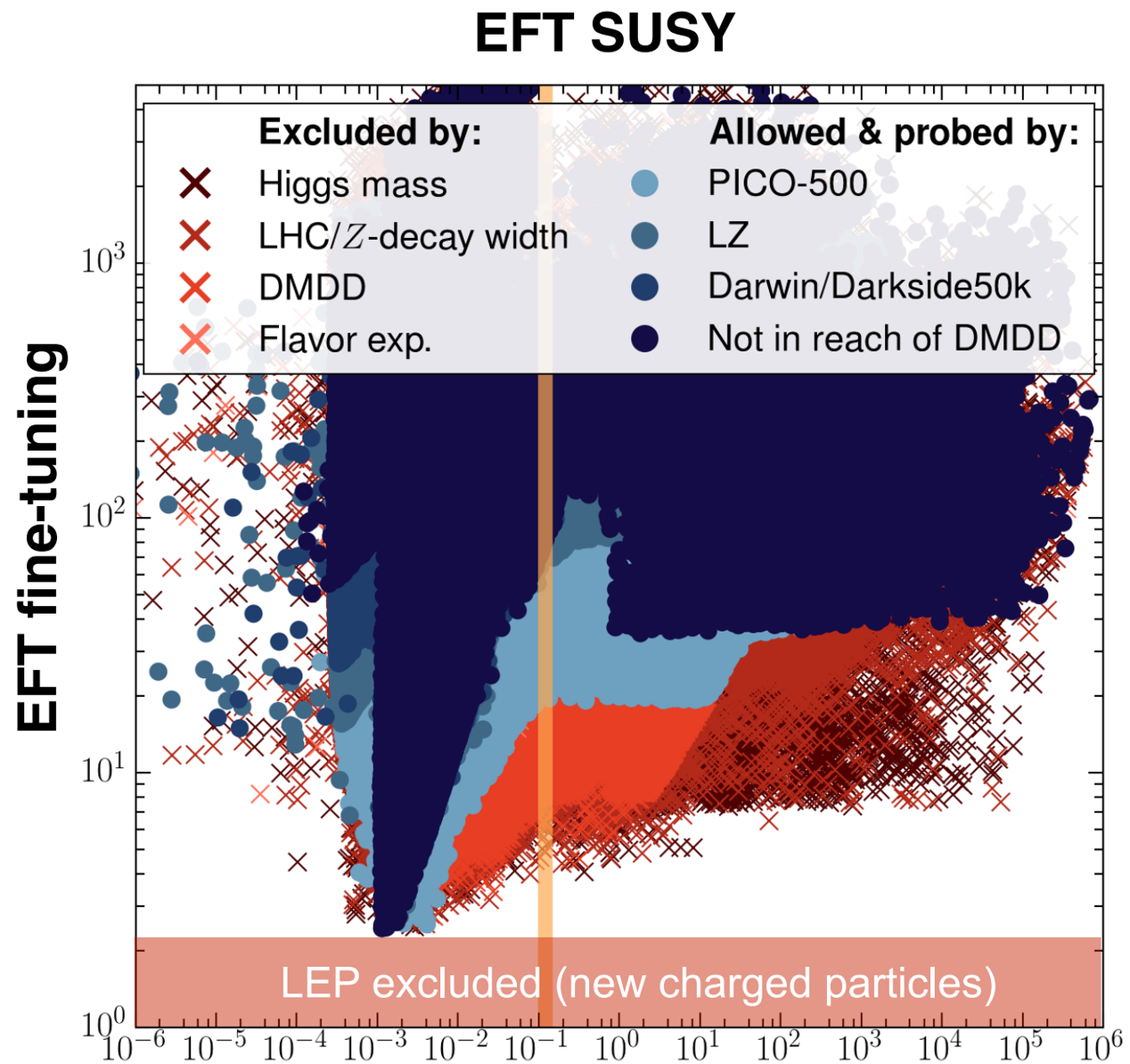
Relic density vs fine-tuning





Relic density vs fine-tuning





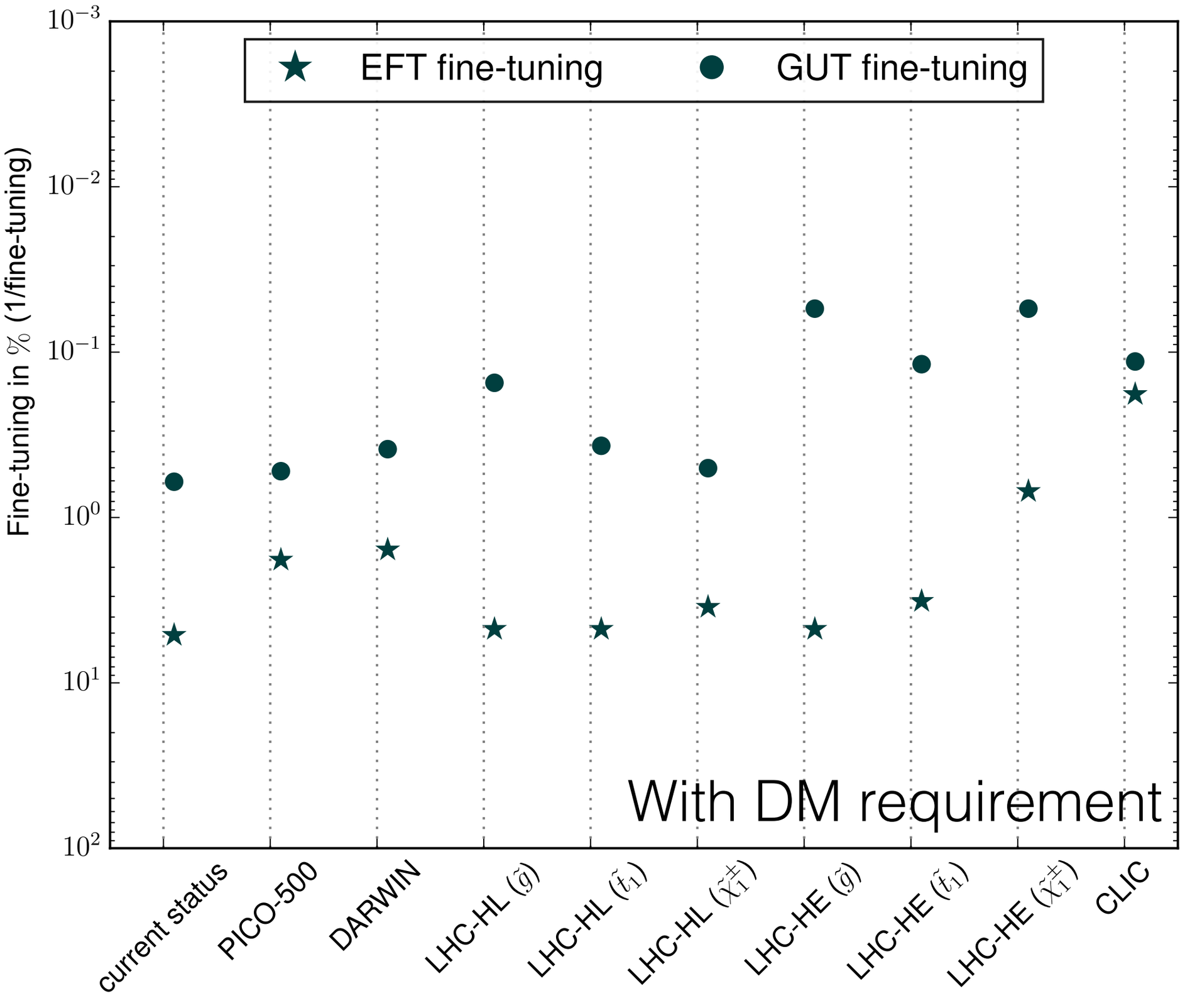
Stop/sbottom searches are constraining this

Conclusions

- The increased ATLAS/CMS limits on SUSY are no reason to worry
- Light SUSY is alive and we should not give up the chase for SUSY
- We need dedicated searches to increase coverage
- Combining data is crucial

Extra slides

Which future experiment to build?



The Hierarchy problem

Proton mass
1 GeV

Planck scale
10^{19} GeV

100 GeV
W,Z, higgs mass

Why this huge energy gap?

Beta functions

- Standard model:

$$\beta_{m_H^2} = \frac{m_H^2}{16\pi^2}\left[6y_t^2 - \frac{9}{4}g^2 - \frac{3}{4}g'^2 - 6\lambda\right]$$

- No issue! The beta function is proportional with the bare higgs mass!

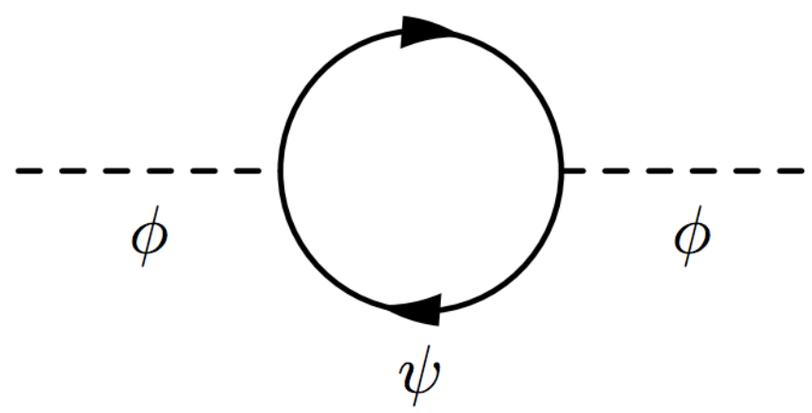
$$\delta m_H^2 \sim \frac{6y_t^2}{16\pi^2} m_H^2 \log(\mu_1/\mu_2)$$

Fine-tuning, the real story

- Pick scalar coupled to fermion

$$\mathcal{L} = -\frac{1}{2}\phi(\Box + m^2)\phi + \lambda\phi\bar{\psi}\psi + \bar{\psi}(i\ \not{\partial} - M)\psi$$

- Compute self energy diagram



$$i\Sigma_2(p^2) \overset{\text{(squared missing)}}{=} -4\lambda \int \frac{d^4k}{(2\pi)^4} \int_0^1 dx \left[\frac{1}{k^2 - \Delta} + \frac{2\Delta}{[k^2 - \Delta]^2}\right]$$

$$\Delta = M^2 - p^2 x(1-x)$$

Regulating the integral

- Cut off regulator:

$$\Sigma_2(p^2) = \frac{3\lambda^2}{4\pi^2}\int_0^1 dx \left([M^2 - p^2 x(1-x)] \log\left(\frac{M^2 - p^2 x(1-x)}{\Lambda^2}\right) + \Lambda^2 \right) + \text{finite}$$

- Dim reg:

$$\Sigma_2(p^2) = \frac{3\lambda^2}{4\pi^2}\left(-\frac{2M^2}{\varepsilon} + \frac{p^2}{3\varepsilon} + \int_0^1 dx \left([M^2 - p^2 x(1-x)] \log\left(\frac{M^2 - p^2 x(1-x)}{4\pi\mu^2 e^{-\Gamma_E}}\right)\right)\right)$$

EW fine-tuning

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

$$\Delta_{\rm EW} \equiv \max_i \left| \frac{C_i}{M_Z^2/2} \right|$$

$$C_{m_{H_d}} = \frac{m_{H_d}^2}{\tan^2\beta - 1}, \quad C_{m_{H_u}} = \frac{-m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}, \quad C_\mu = -\mu^2,$$

$$C_{\Sigma_d^d} = \frac{\max(\Sigma_d^d)}{\tan^2\beta - 1}, \quad C_{\Sigma_u^u} = \frac{-\max(\Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1}.$$

BG fine-tuning

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

$$\Delta_{\rm BG} \equiv \max|\Delta_p|$$

$$\Delta_p \equiv \frac{\partial \ln M_Z^2}{\partial \ln p_i}$$

p_i is one of the independent input parameters of the SUSY model

Requirements

- LEP limits on the masses of the chargino ($m_{\tilde{\chi}_1^\pm} > 103.5$ GeV) and light sleptons ($m_{\tilde{l}} > 90$ GeV) [127]. For the staus we use a limit of $m_{\tilde{\tau}} > 85$ GeV. We do not save any spectra that have sparticle masses below these limits.

- Constraints on the invisible and total width of the Z-boson ($\Gamma_{Z,\mathrm{inv}} = 499.0 \pm 1.5$ MeV and $\Gamma_Z = 2.4952 \pm 0.0023$ GeV) [128].

- The lightest Higgs boson is required to be in the mass range of 122 GeV $\leq m_{h_0} \leq 128$ GeV.

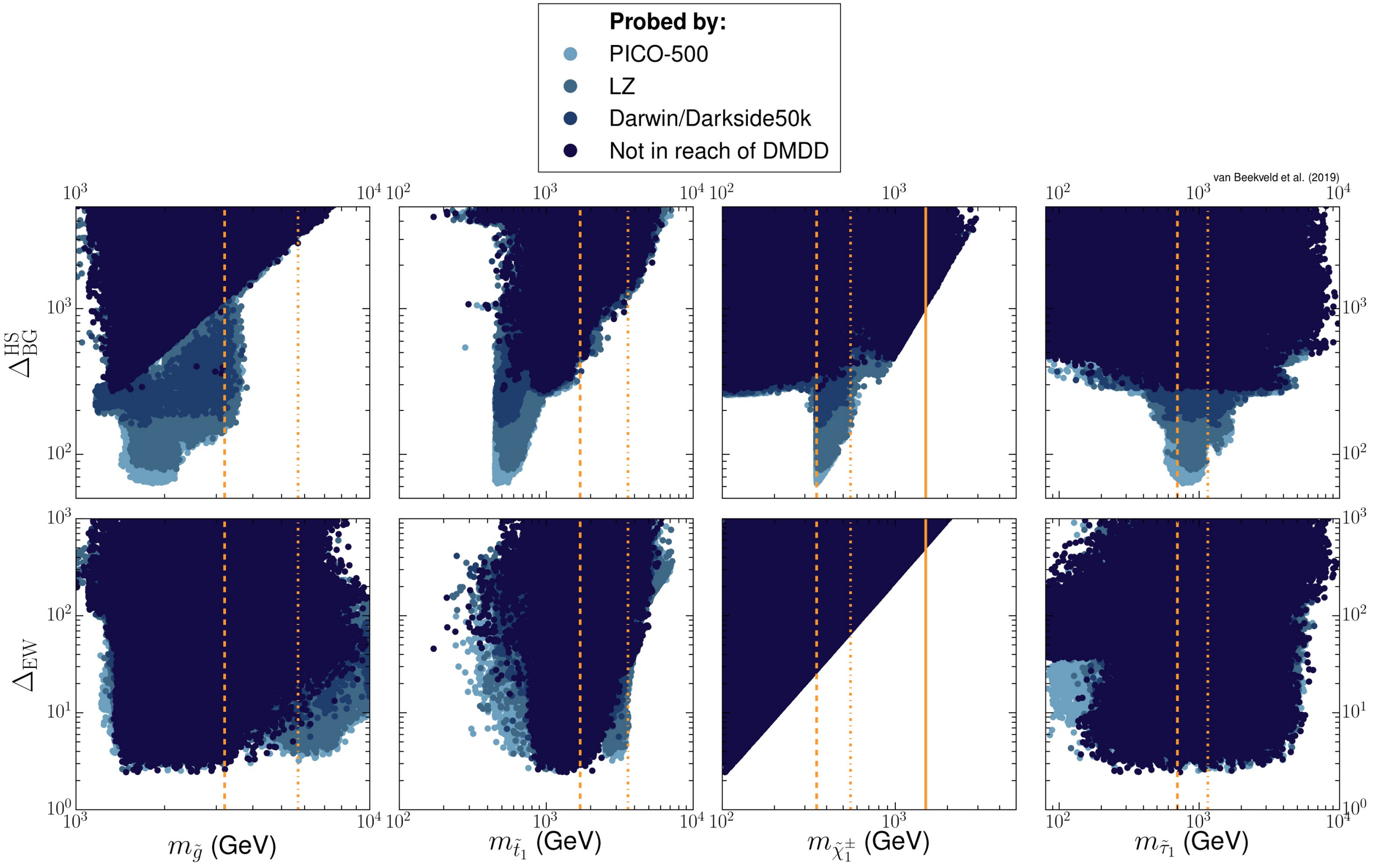
- Taking into account the fact that the SM prediction lies well outside the experimentally obtained value with a discrepancy of $\Delta(g-2)_\mu = (24.9 \pm 6.3) \times 10^{-10}$ [129], we allow for spectra that predict $\Delta(g-2)_\mu < 40 \times 10^{-10}$.

- Measurements of the B/D-meson branching fractions $\mathrm{Br}(B_s^0 \to \mu^+\mu^-)$ [130], $\mathrm{Br}(\bar{B} \to X_s\,\gamma)$ [131, 132], $\mathrm{Br}(B^+ \to \tau^+\,\nu_\tau)$ [133], $\mathrm{Br}(D_s^+ \to \mu^+\,\nu_\mu)$ [134] and $\mathrm{Br}(D_s^+ \to \tau^+\,\nu_\tau)$ [135].

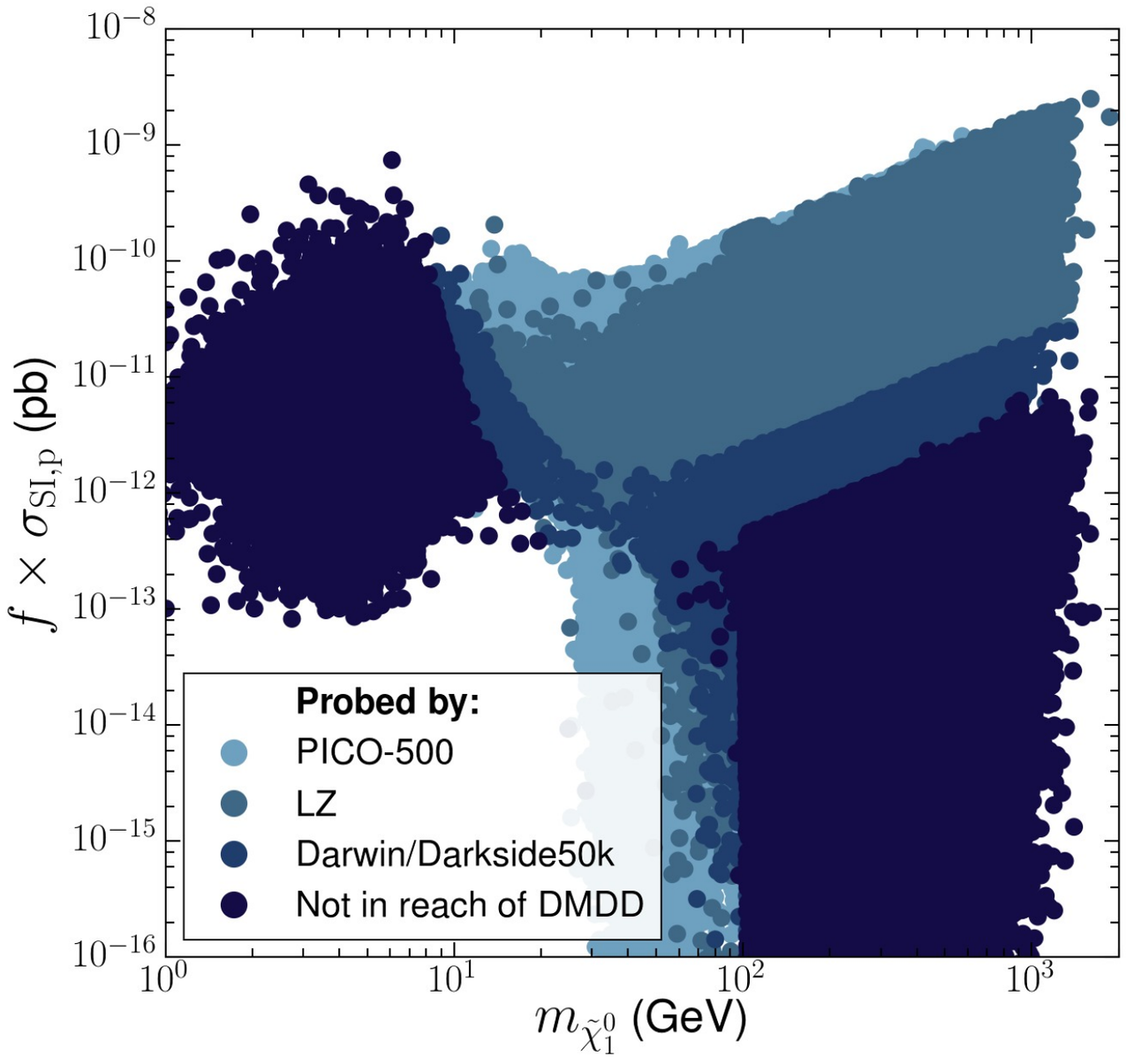
Future collider experiments

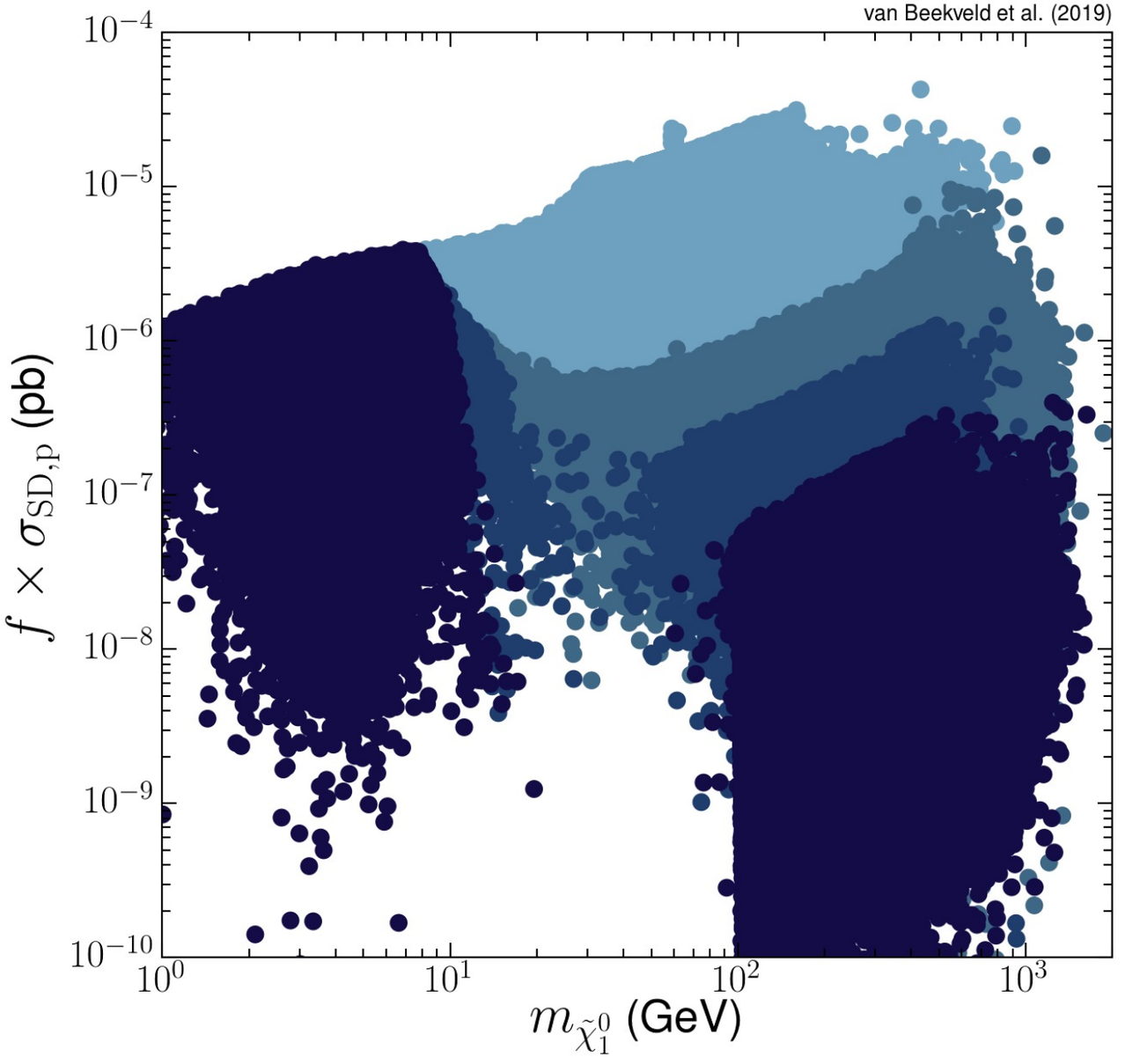
Particle	Mass cut (HL-LHC)	Mass cut (HE-LHC)	Mass cut (CLIC)
$\tilde{g}$	3.2 TeV	5.7 TeV	-
$\tilde{t}_1$	1.7 TeV	3.6 TeV	-
$\tilde{\chi}_1^{\pm}$ (higgsino)	350 GeV	550 GeV	1.5 TeV
$\tilde{\tau}_1$	730 GeV	1.15 TeV	-

Masses of SUSY particles

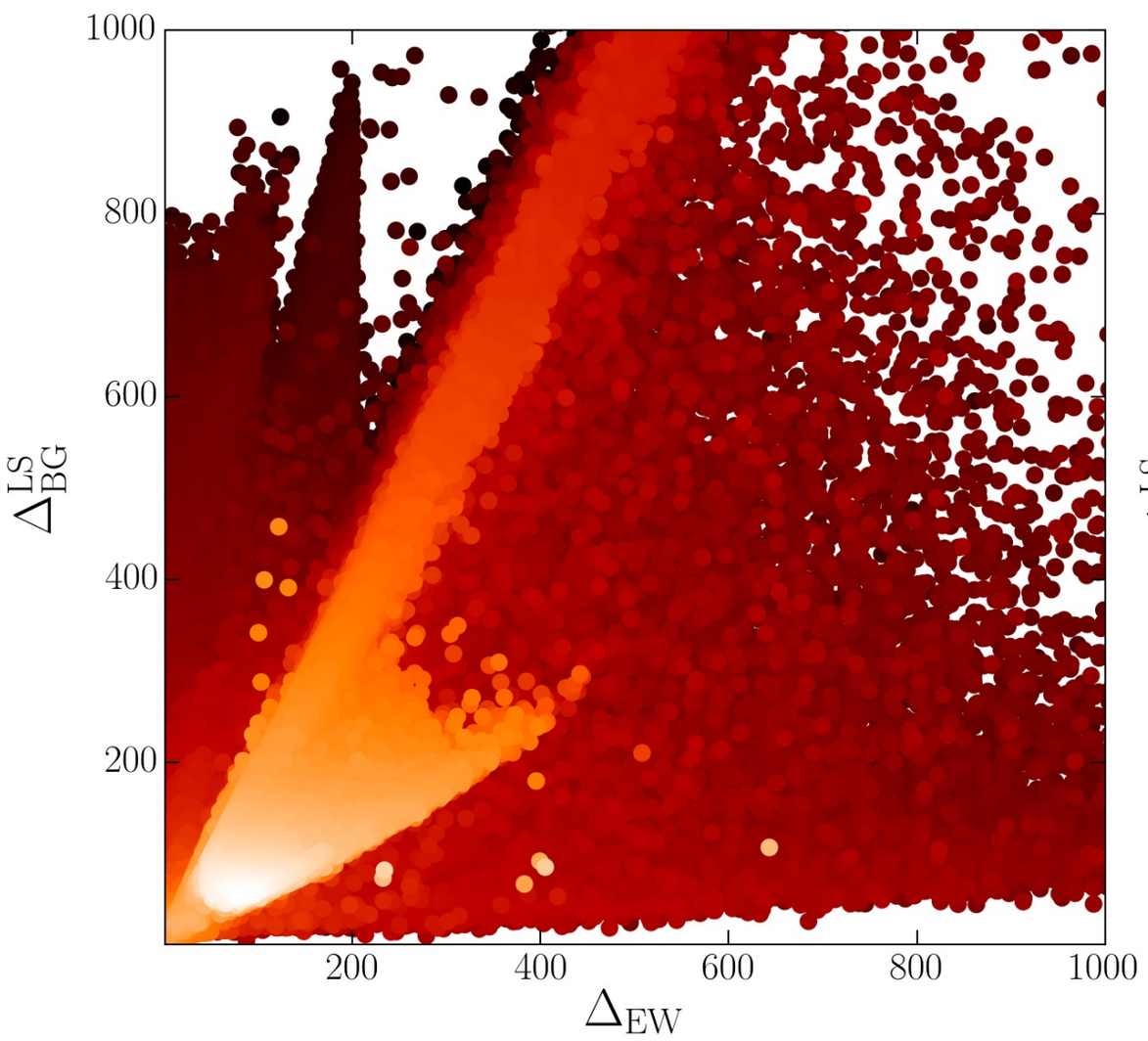


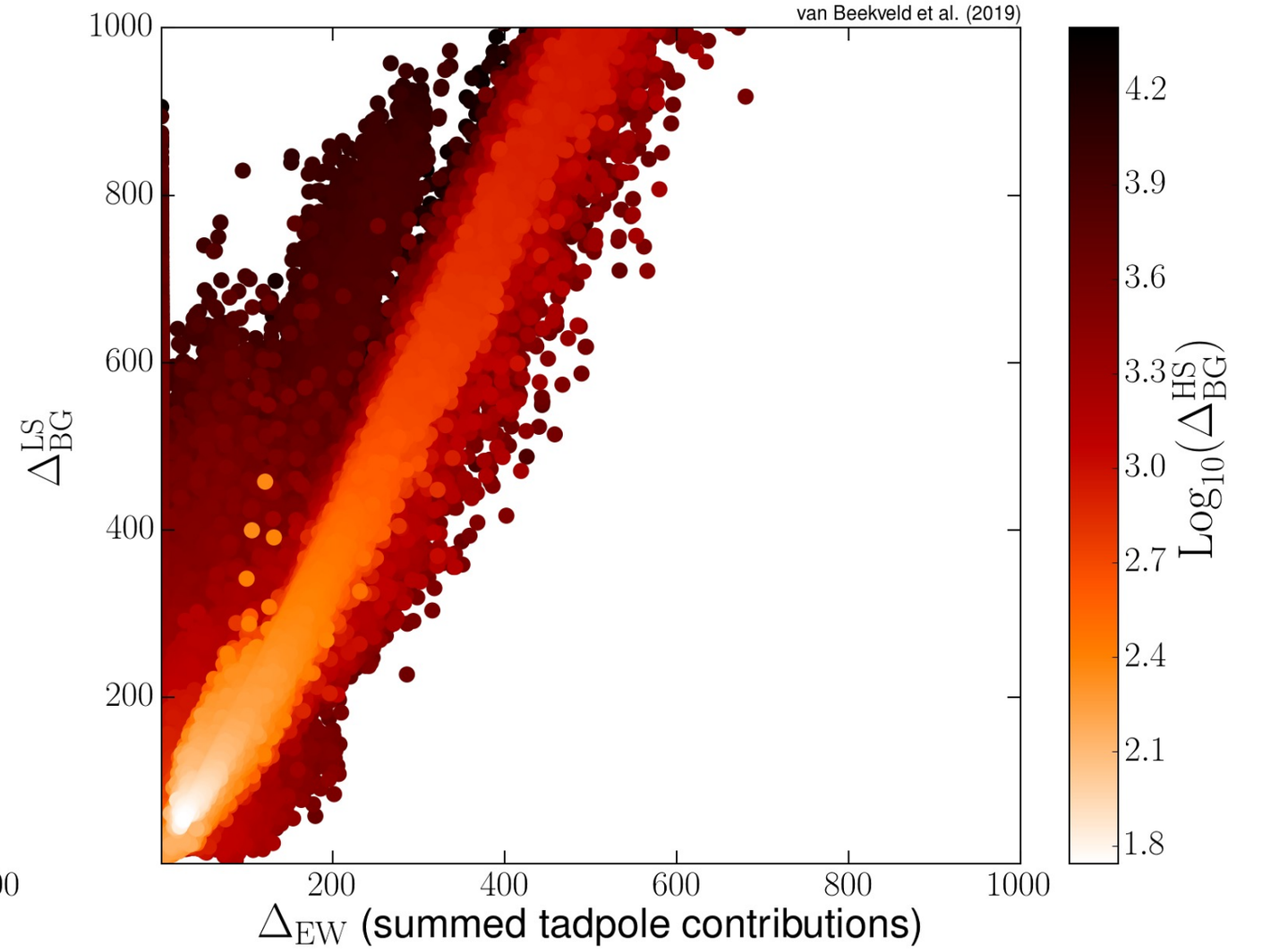
Spin-(in-)dependent cross sections



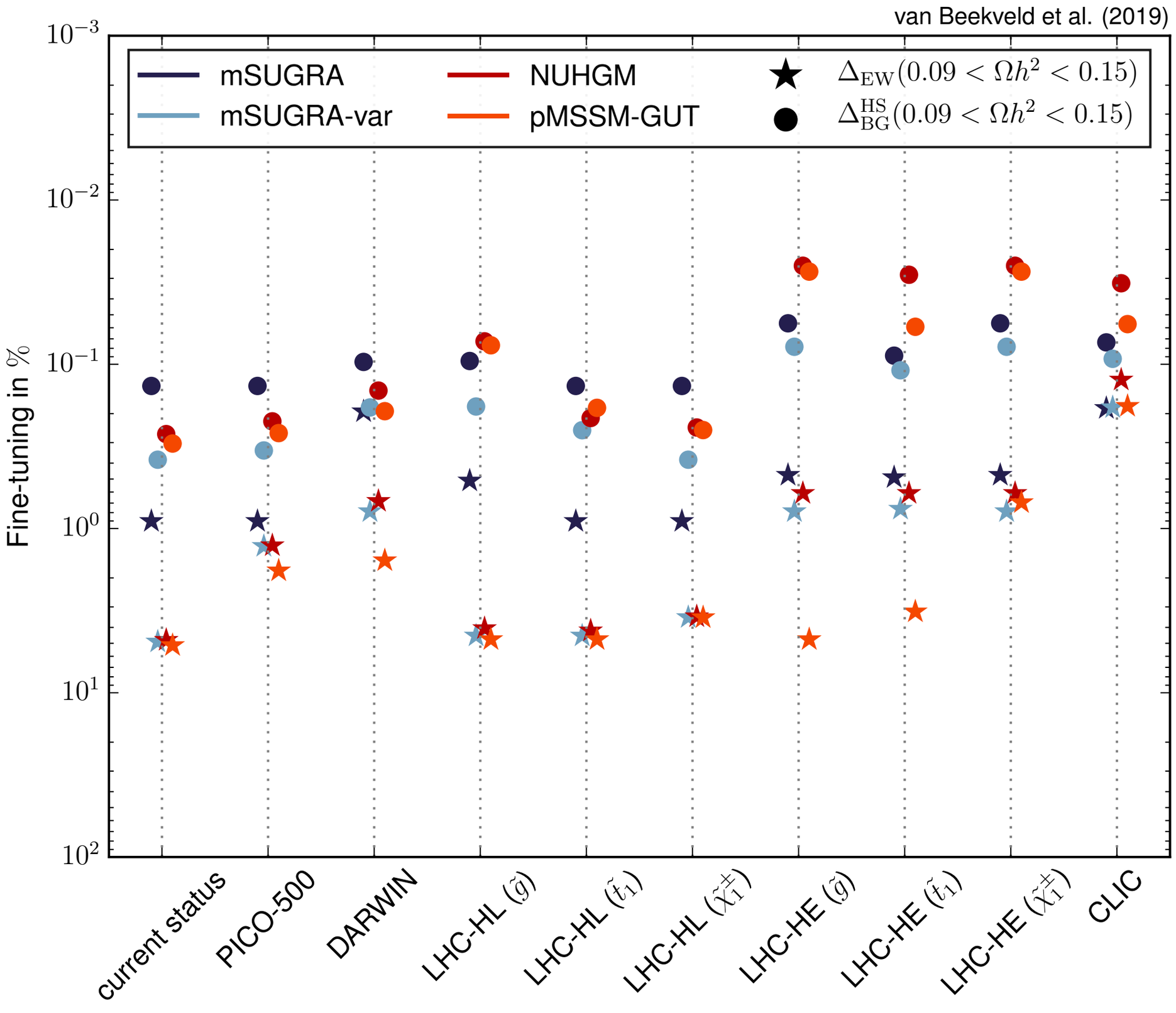


FT measure comparisons





With DM requirement



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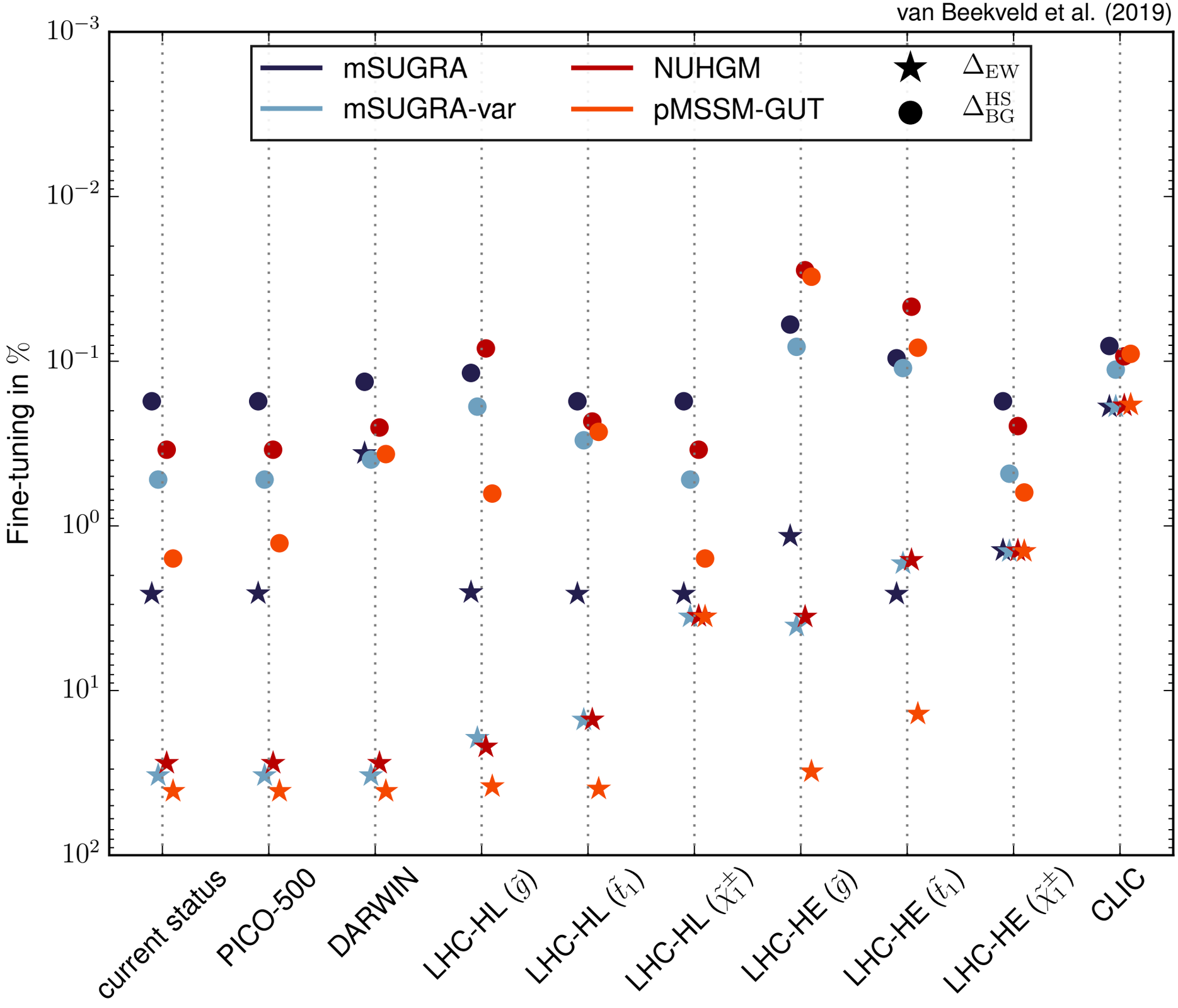
van Beekveld et al. (2019)