Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Collaborative Research Center TRR 257

P H

Particle Physics Phenomenology after the Higgs Discovery

Constraining Flavored Dark Matter: A Systematic Study in the DMFV Framework

Lena Rathmann

In collaboration with B. Belfatto, M. Blanke, J. Heisig, M. Krämer and F. Wilsch

CRC Young Scientist Meeting 2025

22.07.2025

Evidence for Dark Matter

[Zwicky 1933]
[PLANCK collaboration 2018]

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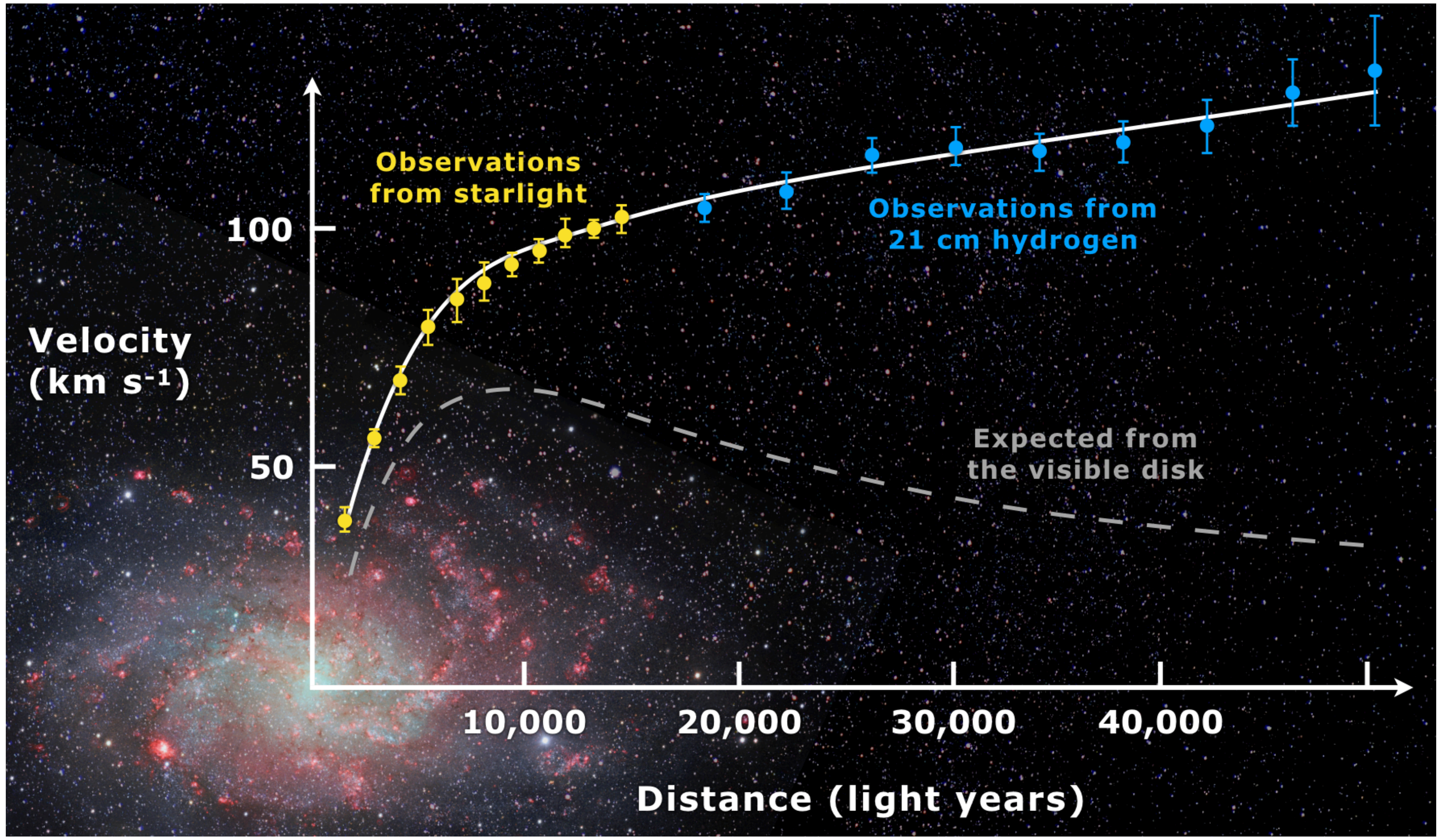
Galaxy rotation curves



[Wikipedia]

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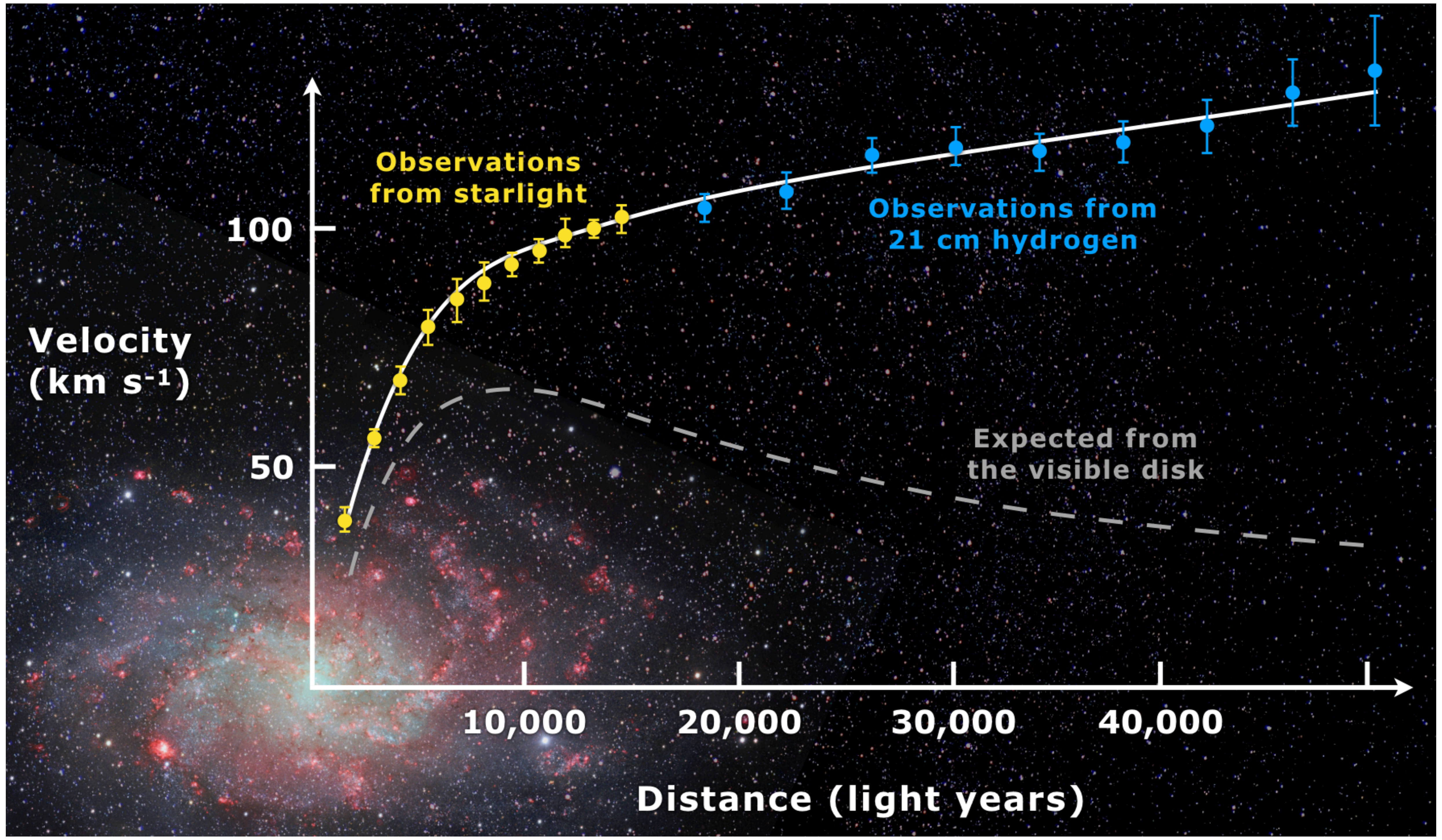

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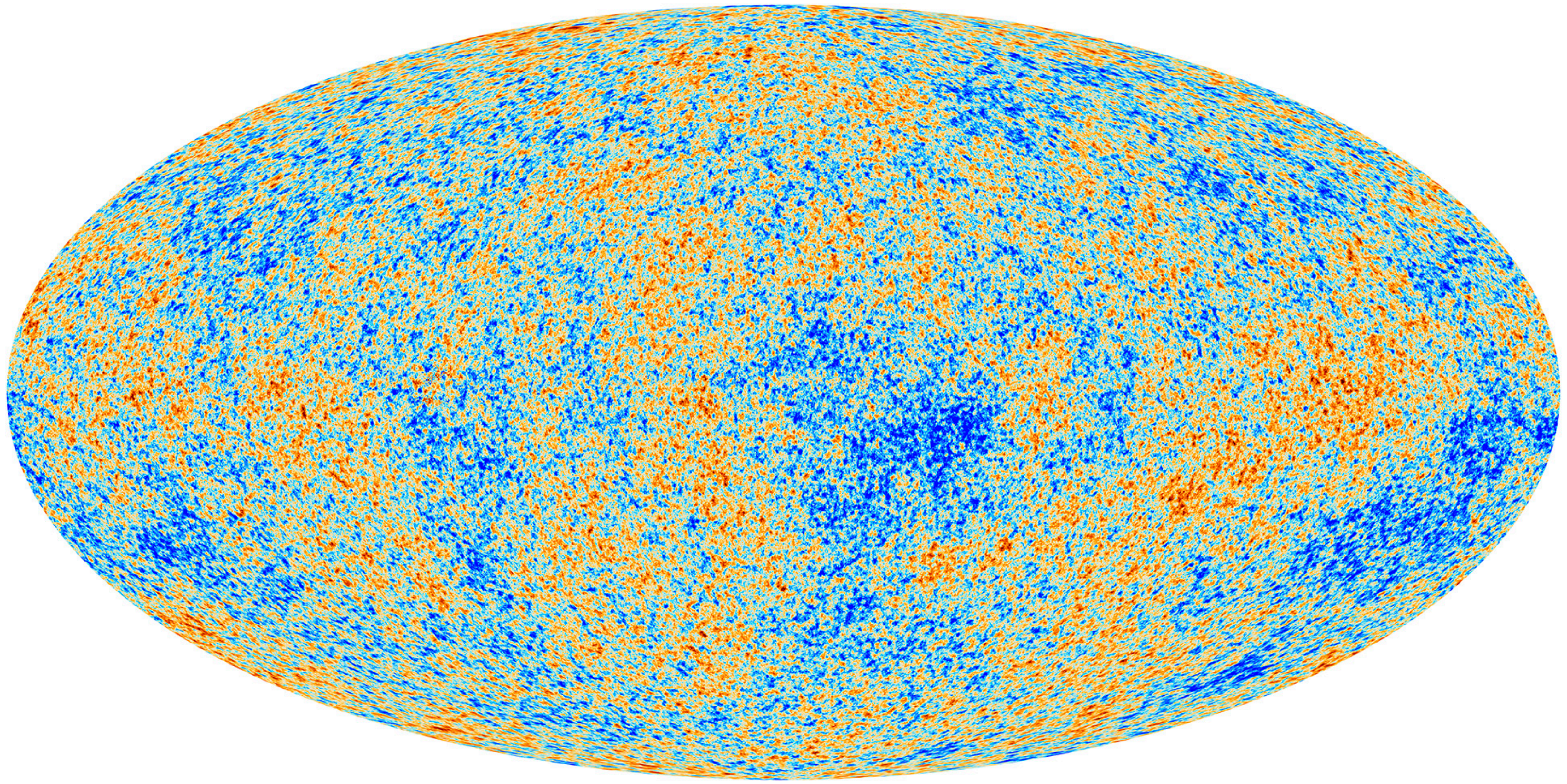
CMB anisotropies



[ESA]

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What is Dark Matter (DM)?

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We have no idea

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We have no idea

→ Study different models for DM, here flavoured DM

Why Flavoured Dark Matter?

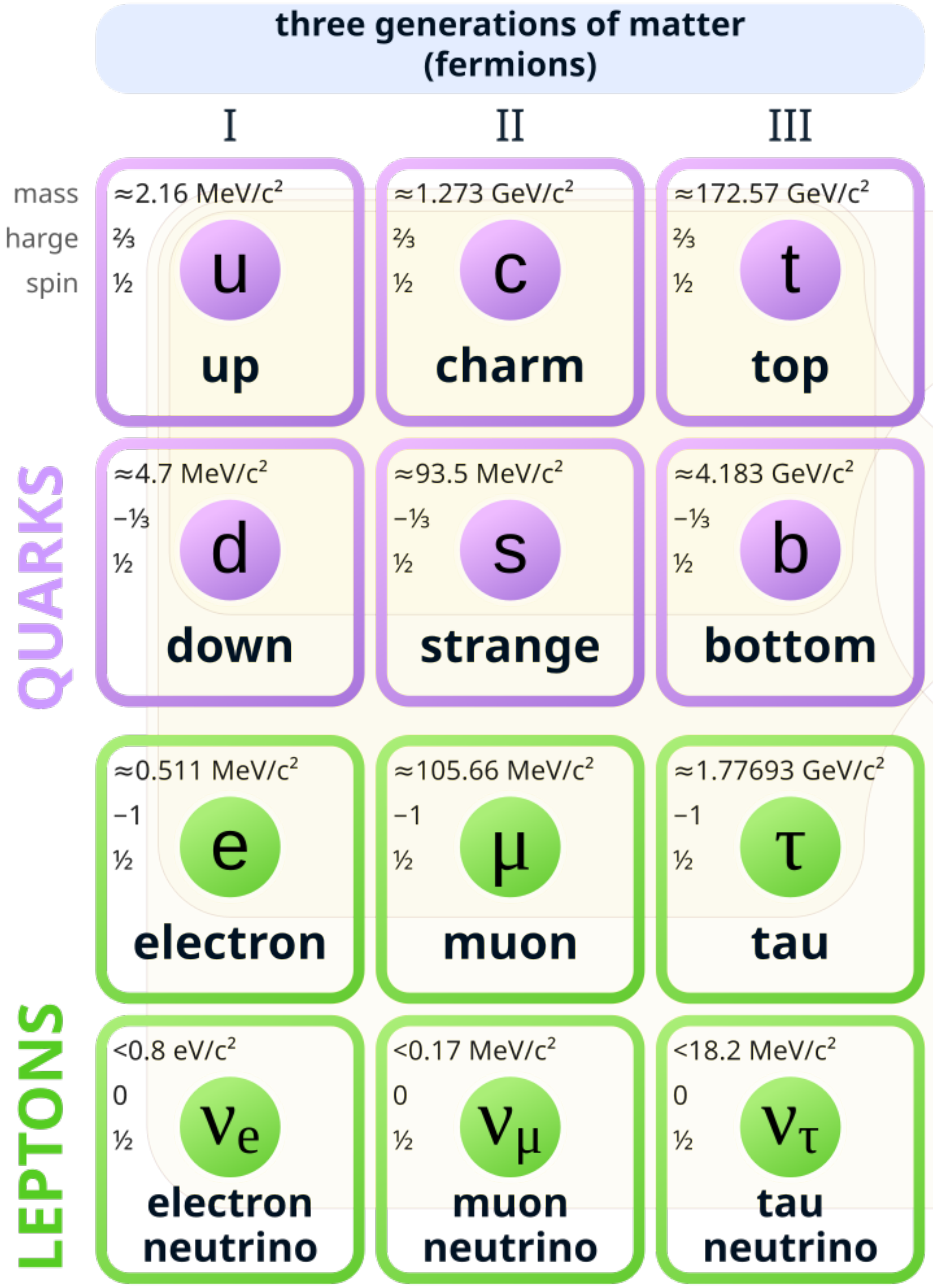
- Traditional weakly interacting massive particle (WIMP) models under severe pressure

  → Assume DM has non-trivial flavour structure like SM

- New source of flavour and CP violation

  → Different phenomenology

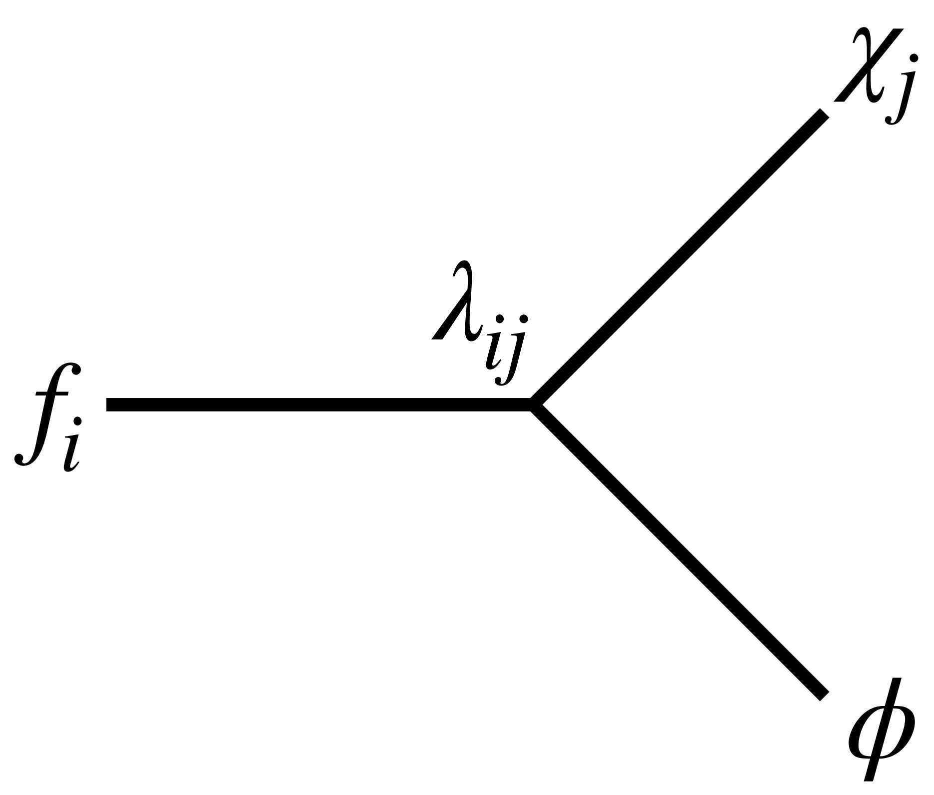
- Introduce dark minimal flavor violation (DMFV) concept to keep parameters minimal



[Wikipedia]

Dark Minimal Flavour Violation [Agrawal, Blanke, Gemmler 2014]

- Extend SM by single new flavour symmetry and new fields (DM flavour triplet $X = (X_1, X_2, X_3)^T$ and mediator Y)
- Couple to SM fermions f through complex 3×3 matrix λ
- Mass matrix M_X expanded in powers of λ



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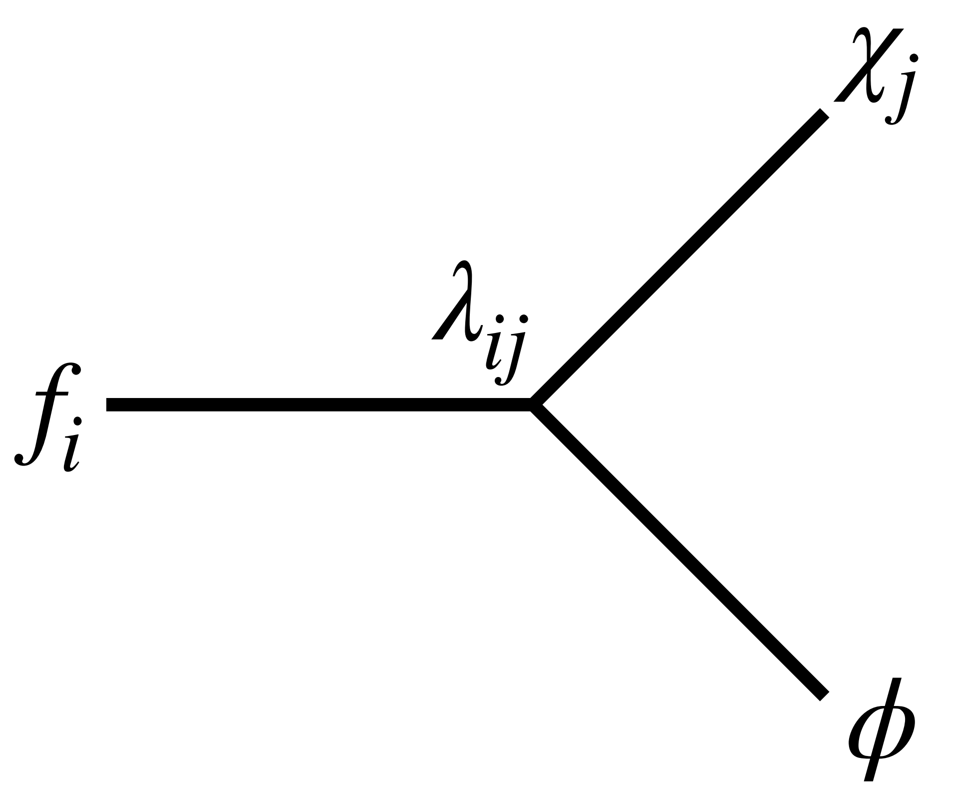

X_j	Y	f_i

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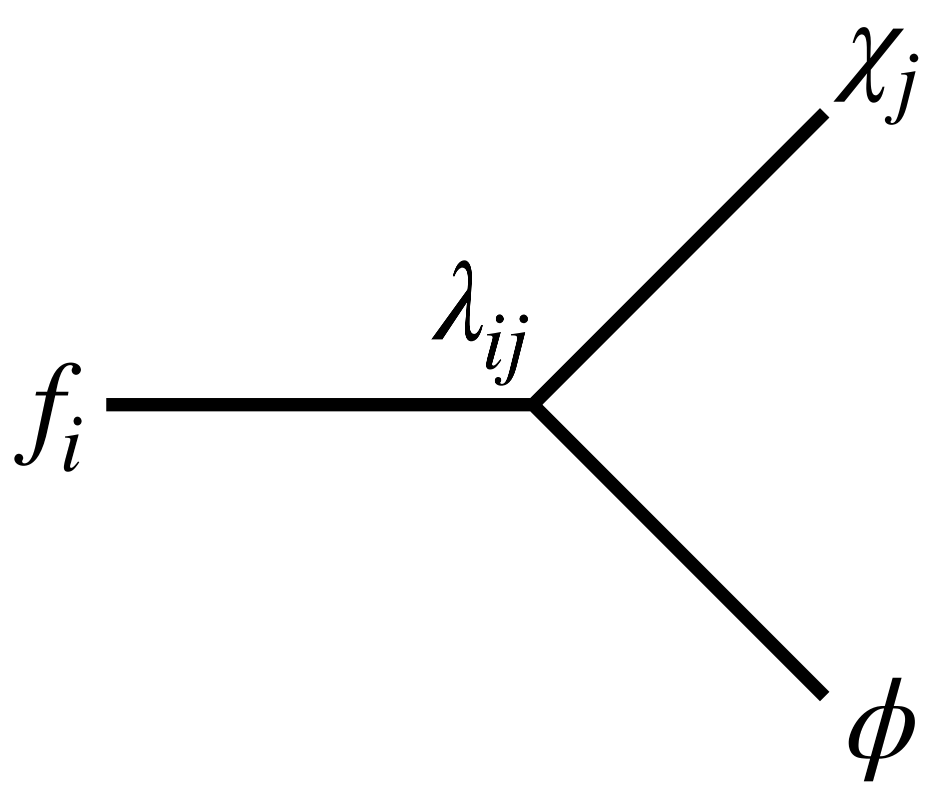

X_j		Y	f_i
Spin 0	• Real scalar • Complex scalar	• Vector-like fermion	

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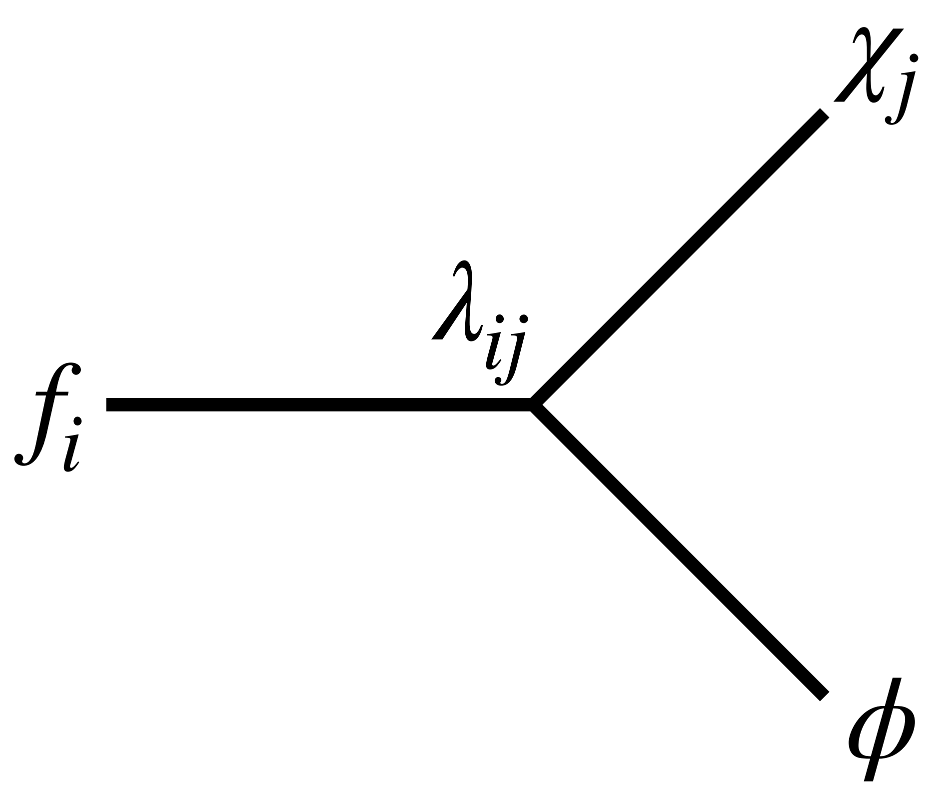

	X_j	Y	f_i
Spin 0	• Real scalar • Complex scalar	• Vector-like fermion	
Spin 1/2	• Majorana fermion • Dirac fermion	• Complex scalar	

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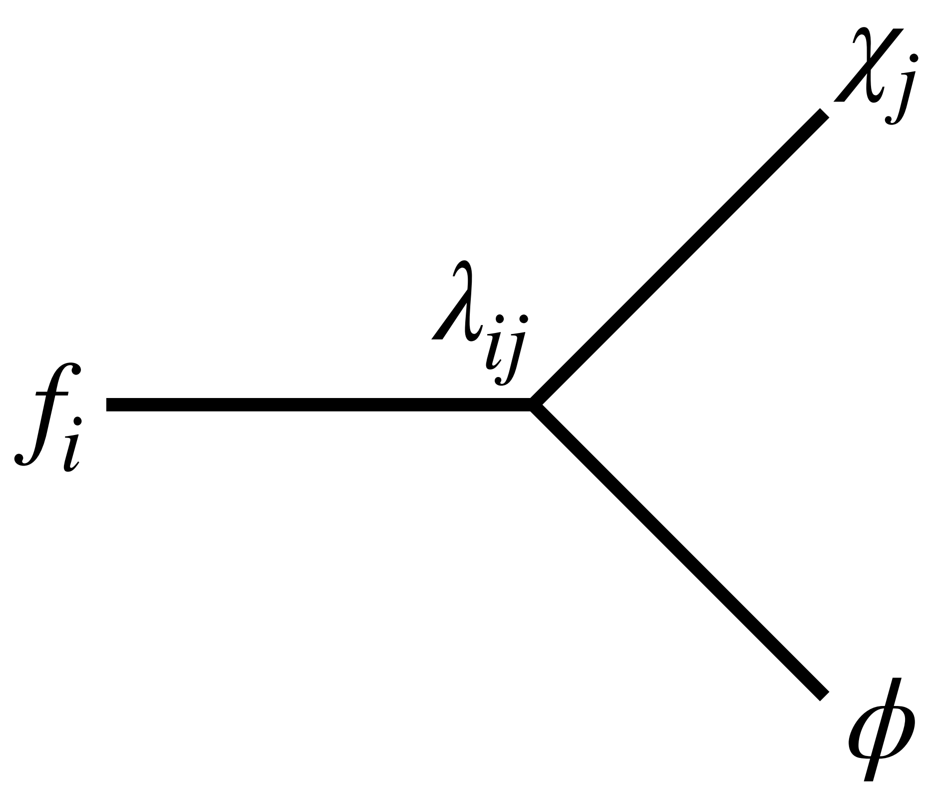

	X_j	Y	f_i
Spin 0	• Real scalar • Complex scalar	• Vector-like fermion	• Up-type quarks u_R • Down-type quarks d_R • Charged leptons e_R
Spin 1/2	• Majorana fermion • Dirac fermion	• Complex scalar	• Quark doublet q_L • Lepton doublet ℓ_L

Previously Studied Models

	u_R	d_R	q_L	e_R	ℓ_L
Real scalar DM	✗	✗	✗	✗	✗
Complex scalar DM	✗	✗	✗	[Acaroglu, Agrawal, Blanke 2022] [Acaroglu, Blanke, Tabet 2022] [Acaroglu, Agrawal, Blanke 2023]	[Acaroglu, Agrawal, Blanke 2022]
Dirac fermion DM	[Blanke, Kast 2017] [Jubb, Kirk, Lenz 2017] [Blanke et al. 2021]	[Agrawal, Blanke, Gemmler 2022] [Bensalem, Stolarski 2022]	[Blanke, Das, Kast 2018] [Blanke et al. 2021]	[Chen, Huang, Takhistov 2016]	✗
Majorana fermion DM	[Acaroglu, Blanke 2022] [Acaroglu, **LR** et al. 2024]	✗	✗	✗	✗

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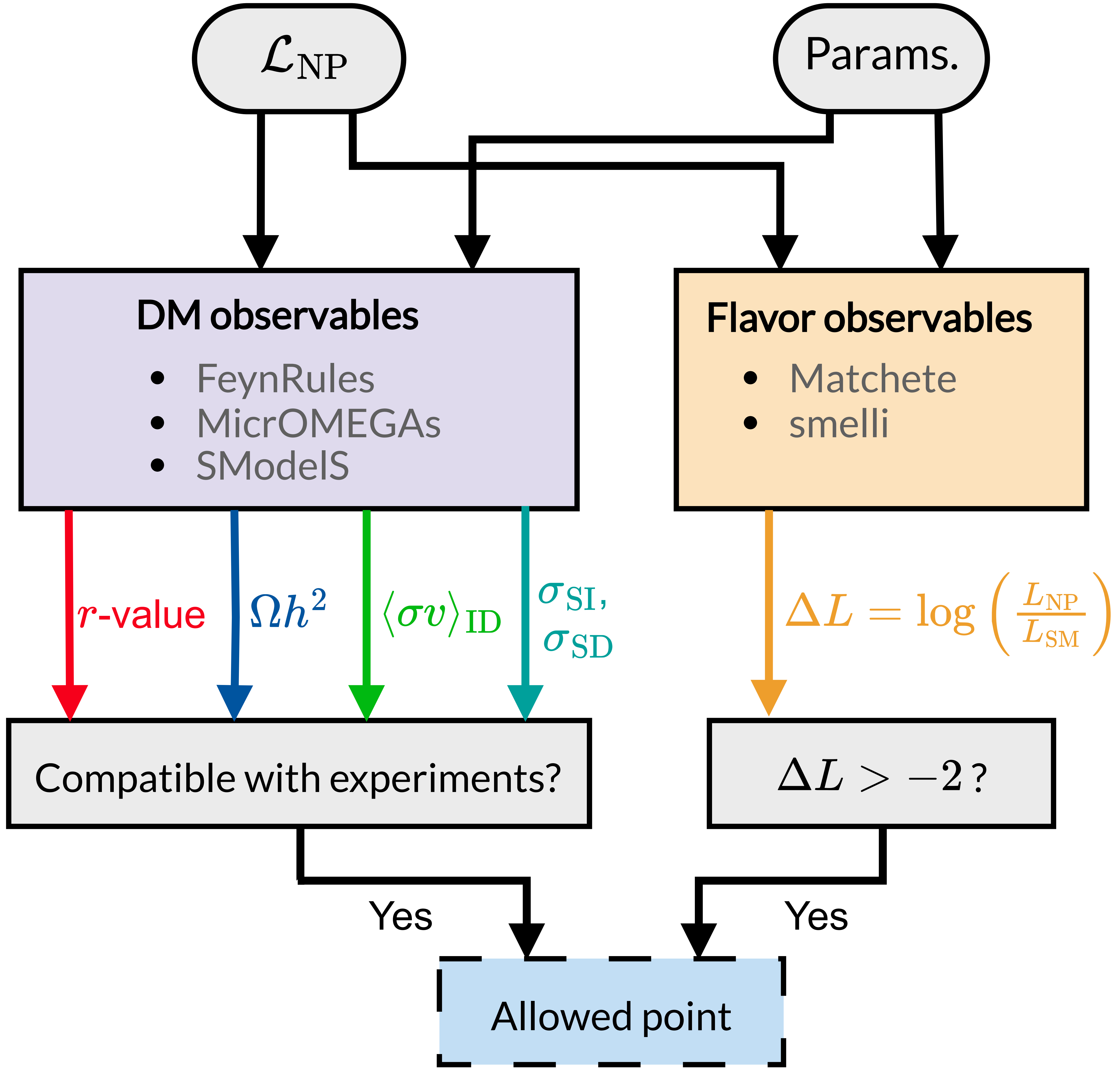
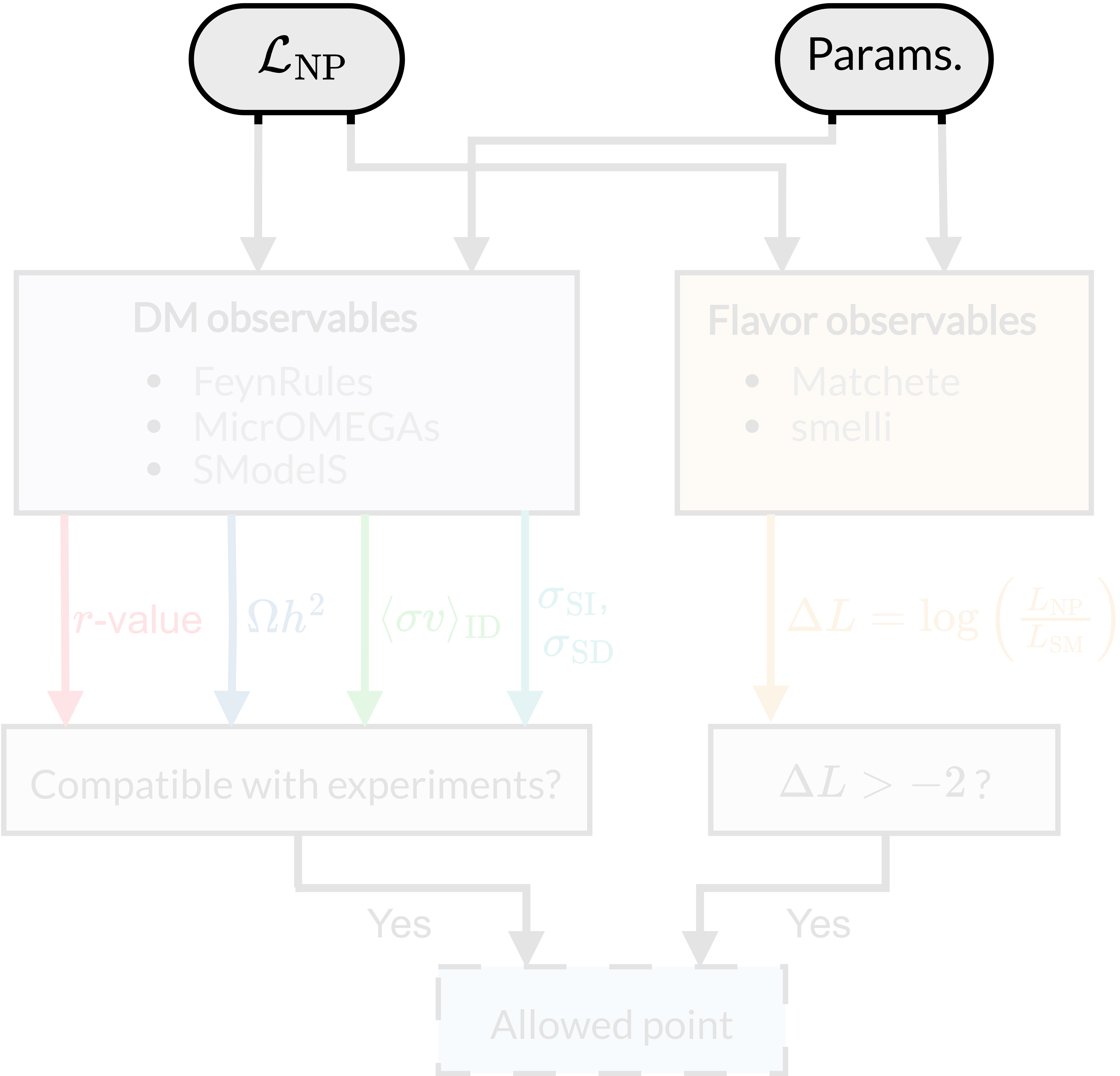
→ Develop framework to study phenomenology of all possible models

Tool-Chain


$\mathcal{L}_{\rm NP}$
Params.
DM observables
• FeynRules
• MicrOMEGAs
• SModelS
Flavor observables
• Matchete
• smelli
r-value
Ωh^2
$\langle \sigma v \rangle_{\rm ID}$
$\sigma_{\rm SI}$, $\sigma_{\rm SD}$
$\Delta L = \log\left(\frac{L_{\rm NP}}{L_{\rm SM}}\right)$
Compatible with experiments?
$\Delta L > -2$?
Yes
Yes
Allowed point

Tool-Chain - Input

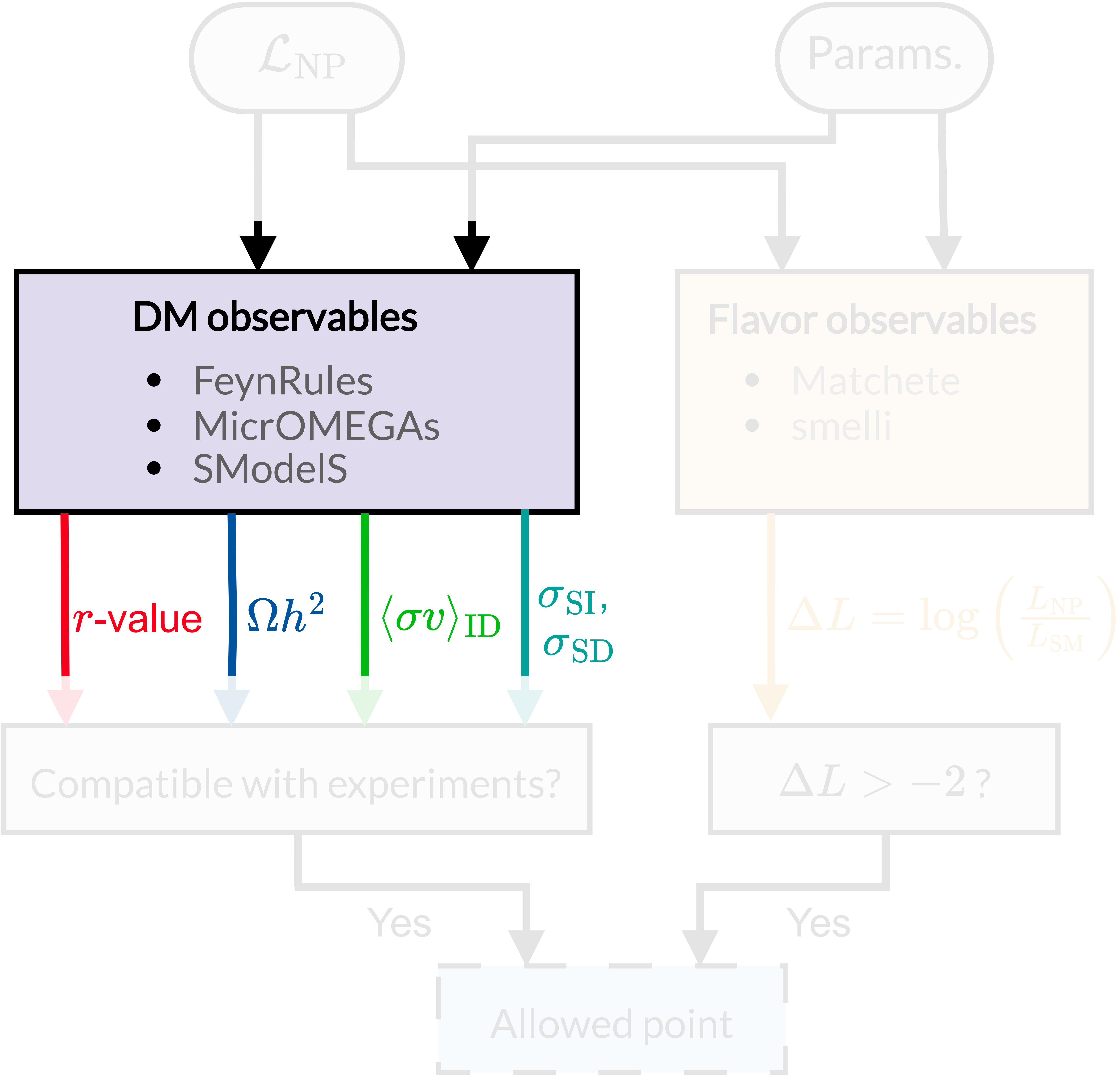
- Lagrangian $\mathscr{L}_{\mathrm{NP}}$ describing all new physics (NP) interactions of DM model
- Values for masses M_{X_i} and M_Y
- Values for couplings to SM particles



Tool-Chain - DM Observables

[Alloul et al. 2014]

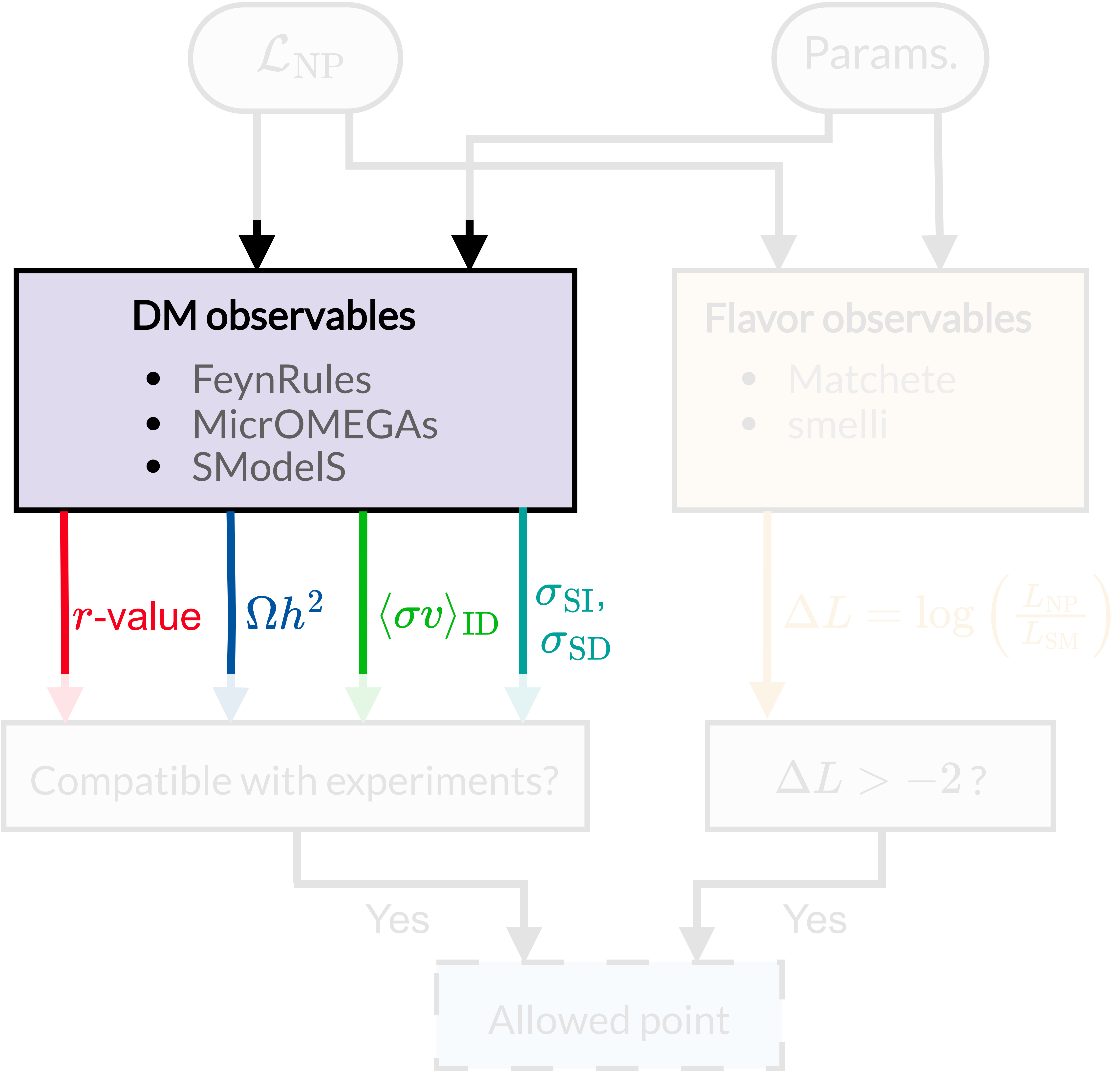
- Implemented all models in FEYNRULES
- All FeynRules, CalcHEP and UFO model files available on GitHub in lena-ra/Flavored-Dark-Matter
- CalcHEP files used for implementation in MICROMEGAS



Tool-Chain - DM Observables

[Bélanger et al. 2018]
[Altakach et al. 2024]

- MicrOMEGAs computes DM properties:
  - Relic abundance Ωh^2
  - Annihilation cross section $\langle \sigma v \rangle$ for every annihilation channel for indirect detection
  - Spin (in)dependent DM-nucleon cross section $\sigma_{\mathrm{SI/SD}}$



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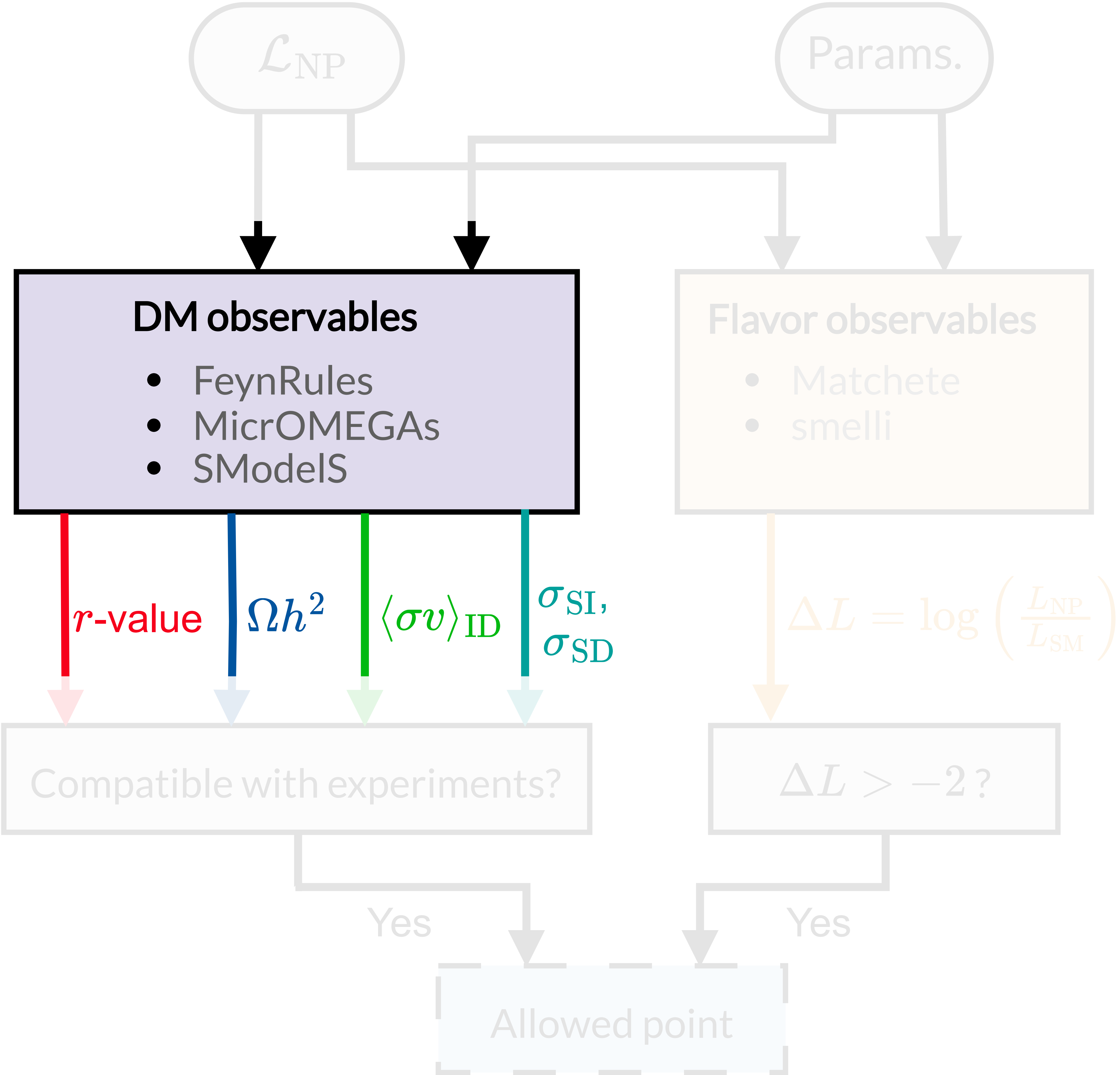
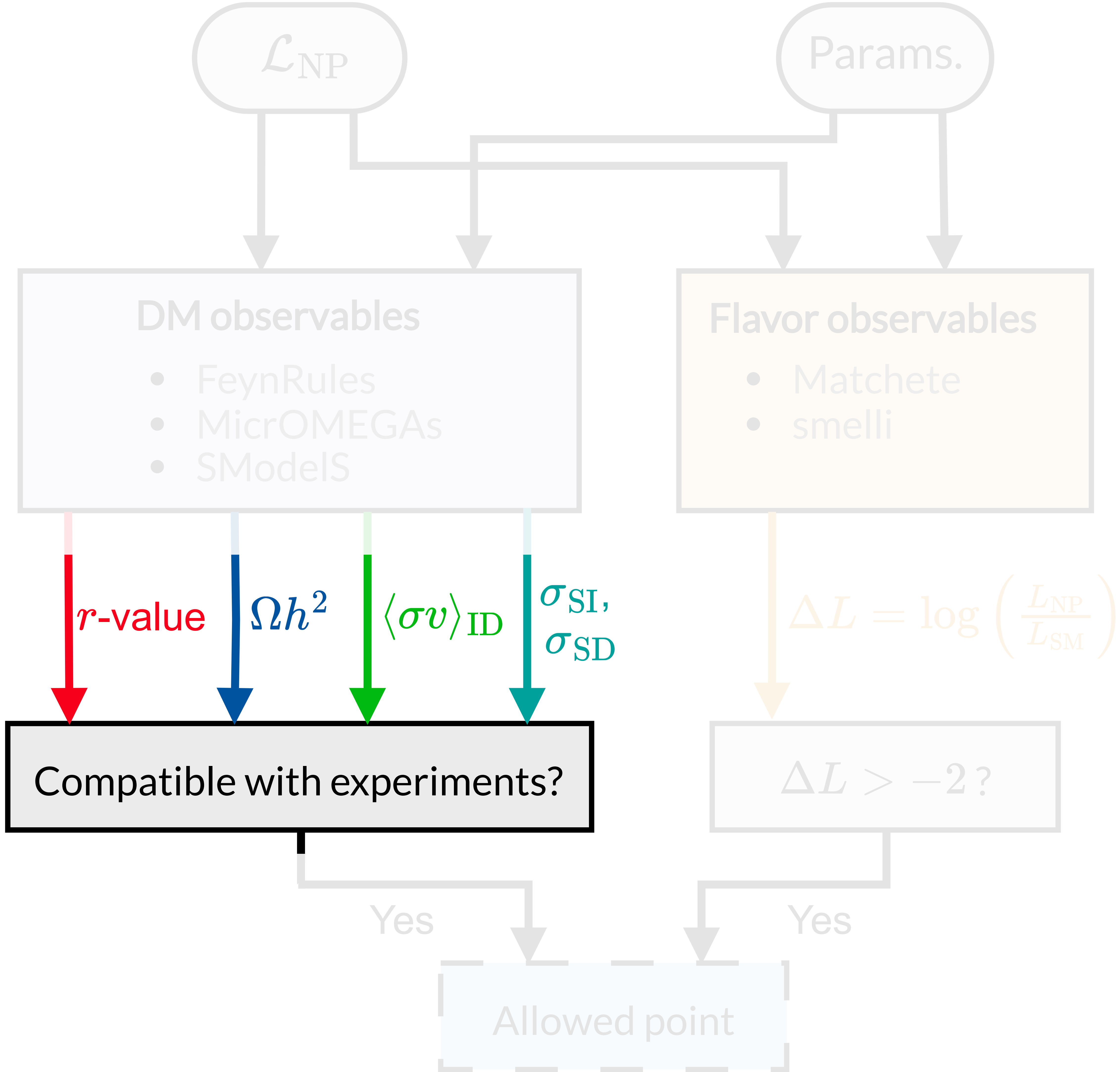
  - Spin (in)dependent DM-nucleon cross section $\sigma_{\mathrm{SI/SD}}$
- SModelS computes constraints from colliders, returns

$$r\text{-value} = \frac{\text{signal cross section}}{\text{experimental upper limit}}$$



Tool-Chain - Check Constraints

- Exclude parameter point if one of the following is true:
  - r-value ≥ 1
  - Ωh^2 not within [0.11, 0.13]
  - $\langle \sigma v \rangle_{\rm ID}$ > experimental limit from γ-ray, $\bar{p}$, e^+ and ν data
  - $\sigma_{\rm SI}$ or $\sigma_{\rm SD}$ > experimental limits from CRESST-III, LZ, XENON1T, DarkSide-50, PICO-60



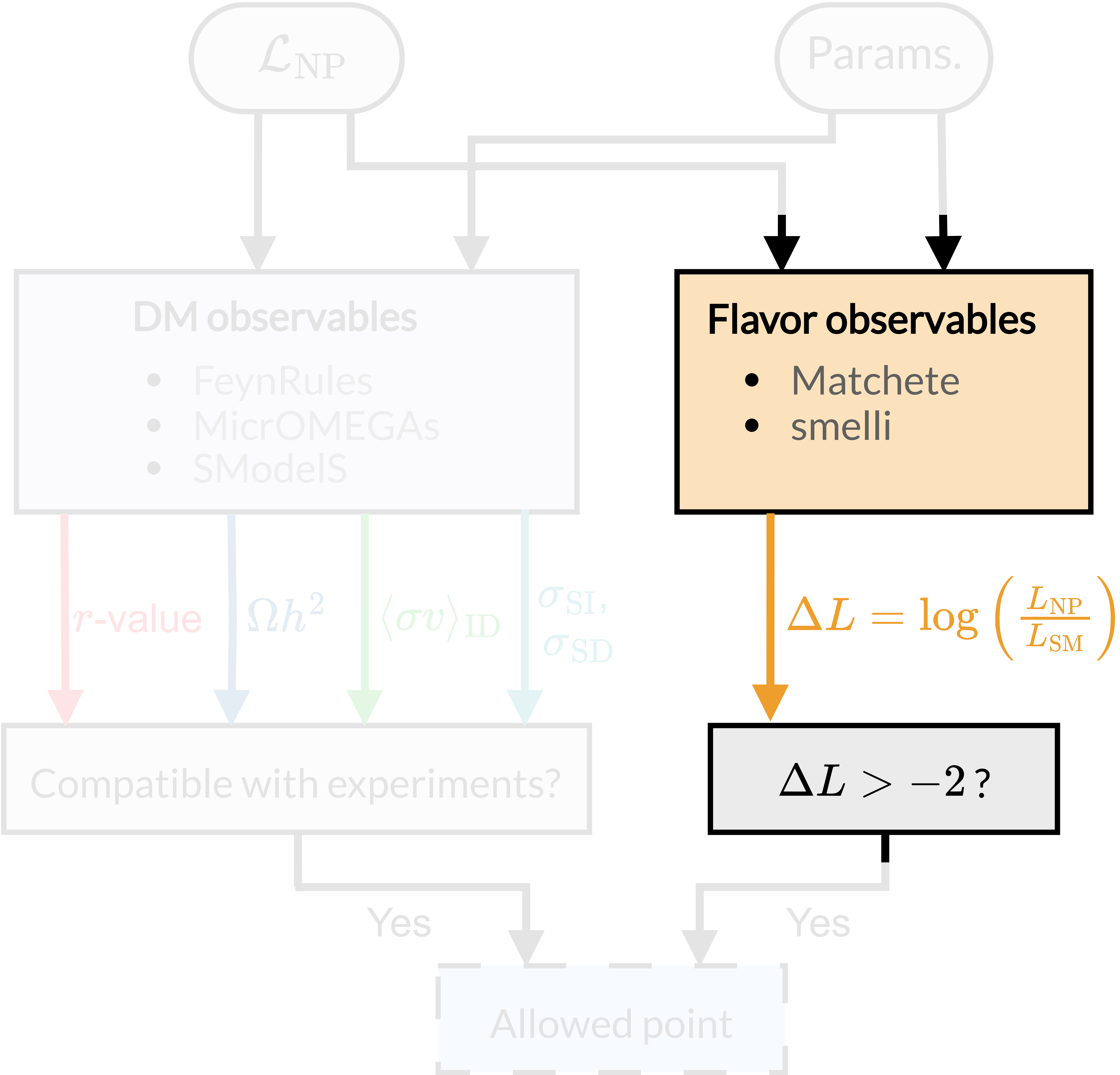
Tool-Chain - Flavor Observables

[Fuentes-Martín et al. 2023]
[Aebischer et al. 2019]

- MATCHETE computes matching of DM model to SM Effective Field Theory
- SMELLI evolves SMEFT Wilson coefficients from high energy scale to low energy scale where flavor observables are measured
- Computes flavor observables
- Provides log-likelihood ratio

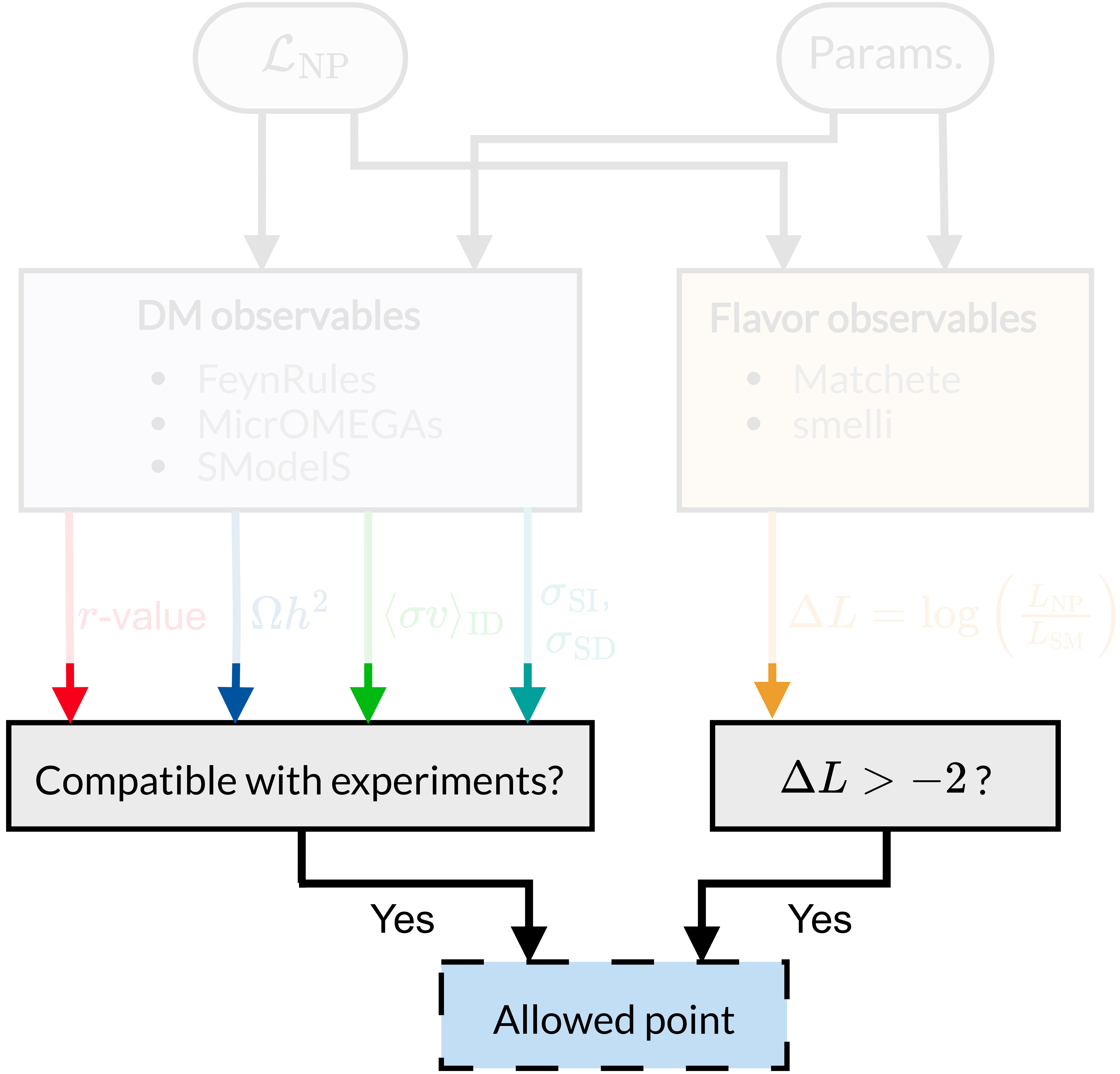
$$\Delta L = \log\left(\frac{L_{\mathrm{NP}}}{L_{\mathrm{SM}}}\right)$$

- Keep point if $\Delta L > -2$



Tool-Chain - Allowed Parameters

- Perform random parameter scan
- Keep point if not excluded by any observable
- Obtain viable parameter space for any of the flavored DM models



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- Dark matter flavor triplet $\tilde{\chi}$, mediator φ

Majorana DM coupling to e_R

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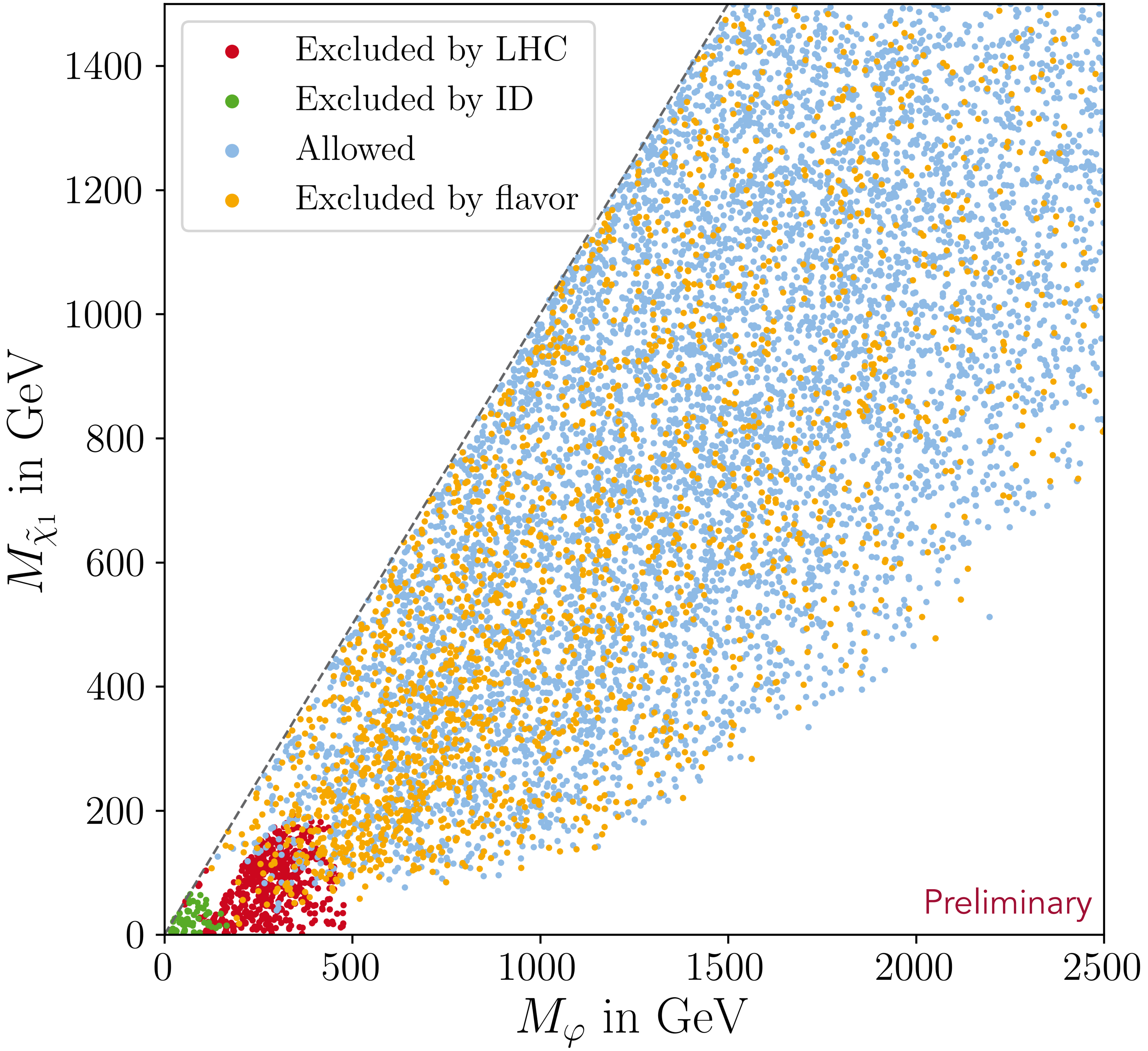
- New physics contribution with flavour and CP violating interaction:

$$\mathscr{L}_{\rm NP} \supset \frac{1}{2}\bar{\tilde{\chi}}(i\partial\!\!\!/ - M_{\tilde{\chi}})\tilde{\chi} + (D_\mu\varphi)^\dagger(D^\mu\varphi) - m_\varphi^2\varphi^\dagger\varphi + (\lambda_{ij}\,\bar{e}_{R,i}\,\tilde{\chi}_j\,\varphi + \mathrm{h.c.}) + \lambda_{\varphi\varphi}(\varphi^\dagger\varphi)^2 + \lambda_{\varphi H}(\varphi^\dagger\varphi)(H^\dagger H)$$

- Mass matrix cannot be generic → expand mass matrix in powers of λ:

$$M_{\tilde{\chi}} = m_{\tilde{\chi}}\left[\mathbf{1} + \frac{\eta}{2}(\lambda^\dagger\lambda + \lambda^T\lambda^*) + \mathcal{O}(\lambda^4)\right] \xrightarrow{\text{Diagonalize}} M_{\tilde{\chi}}^D = \mathrm{diag}(M_{\tilde{\chi}_1}, M_{\tilde{\chi}_2}, M_{\tilde{\chi}_3})$$

Majorana DM coupling to e_R



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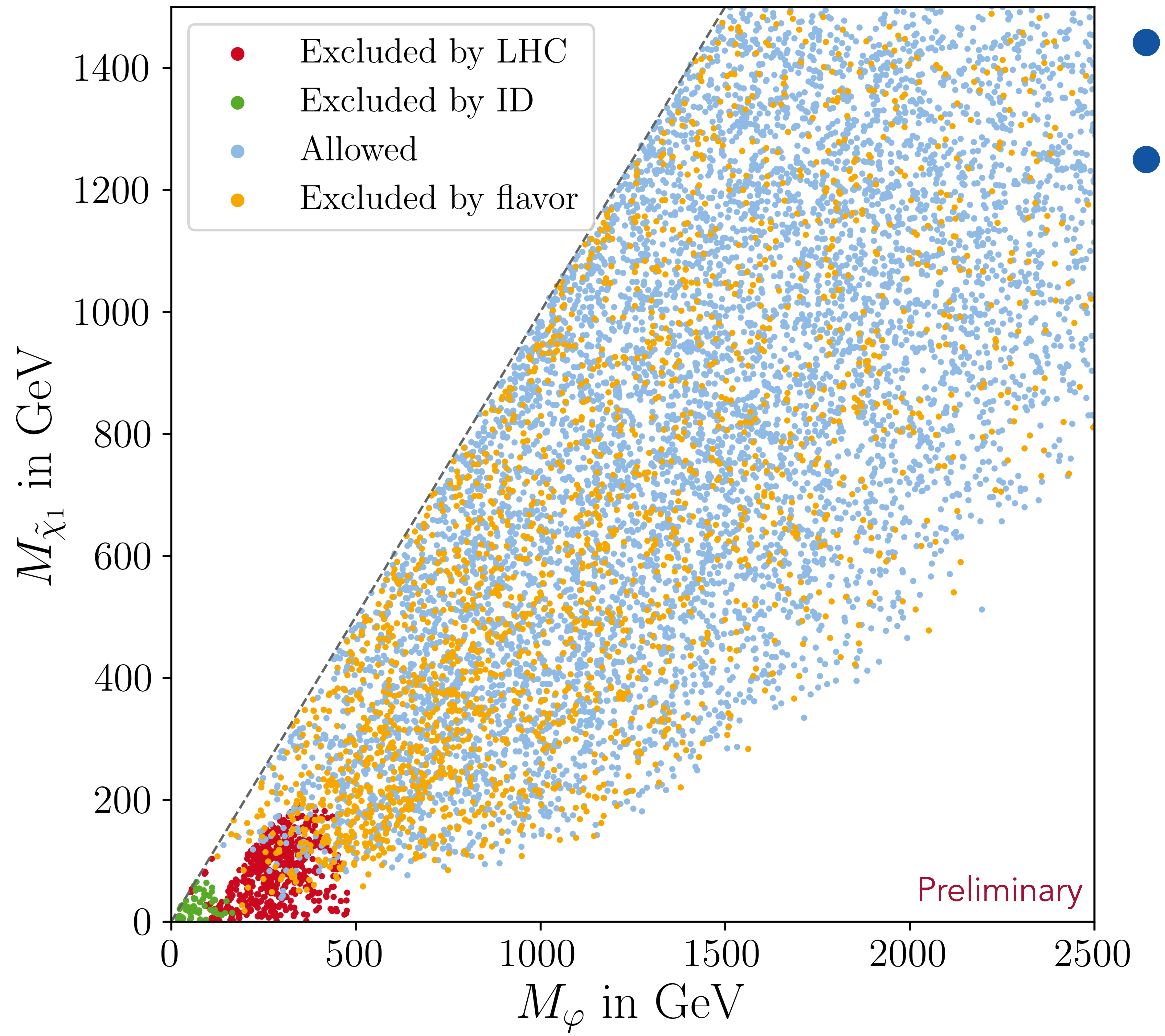
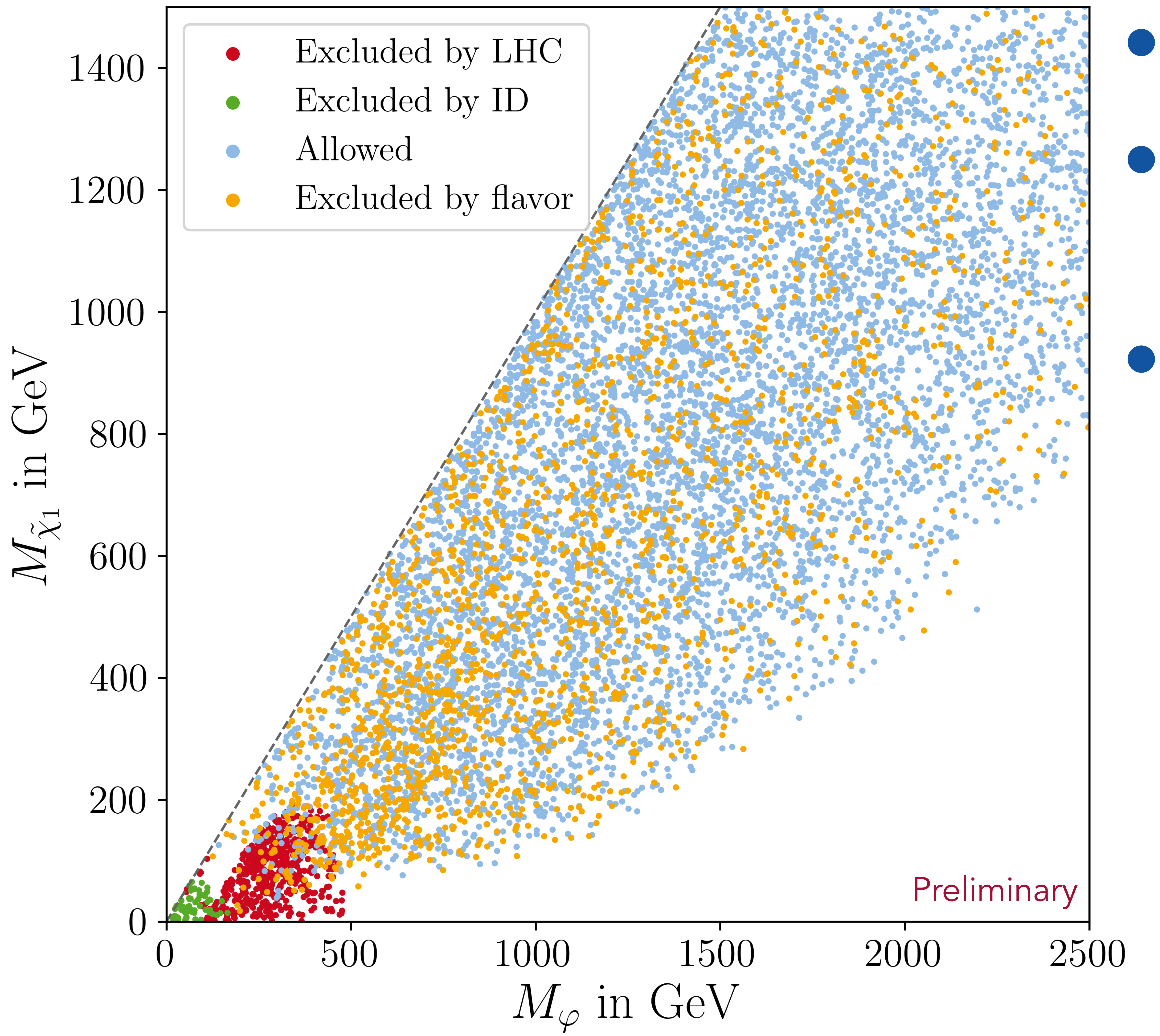


- Relic abundance most constraining
- Lower bound on DM mass because of upper limit on coupling

Majorana DM coupling to e_R



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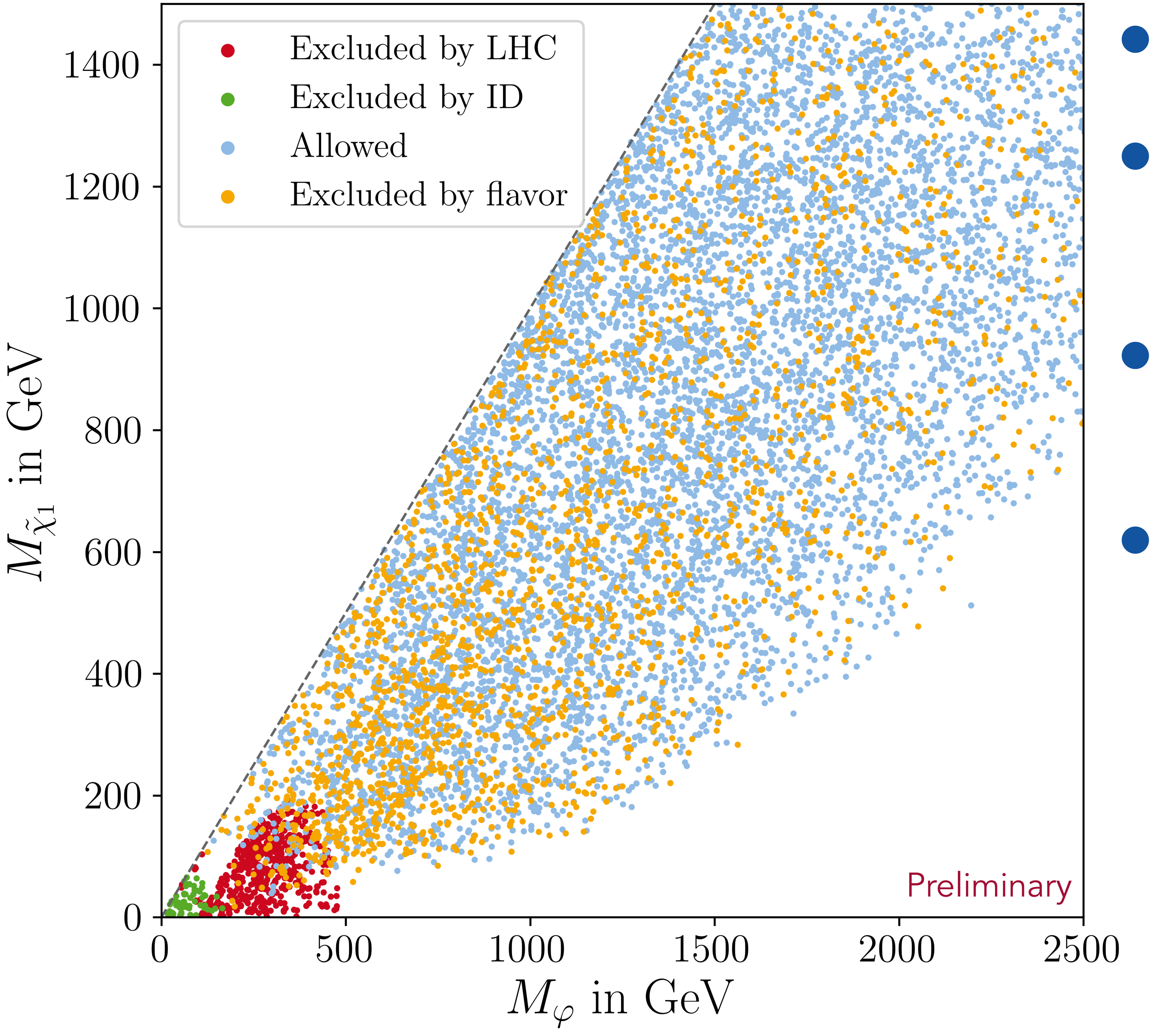

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- Lower bound on DM mass because of upper limit on coupling
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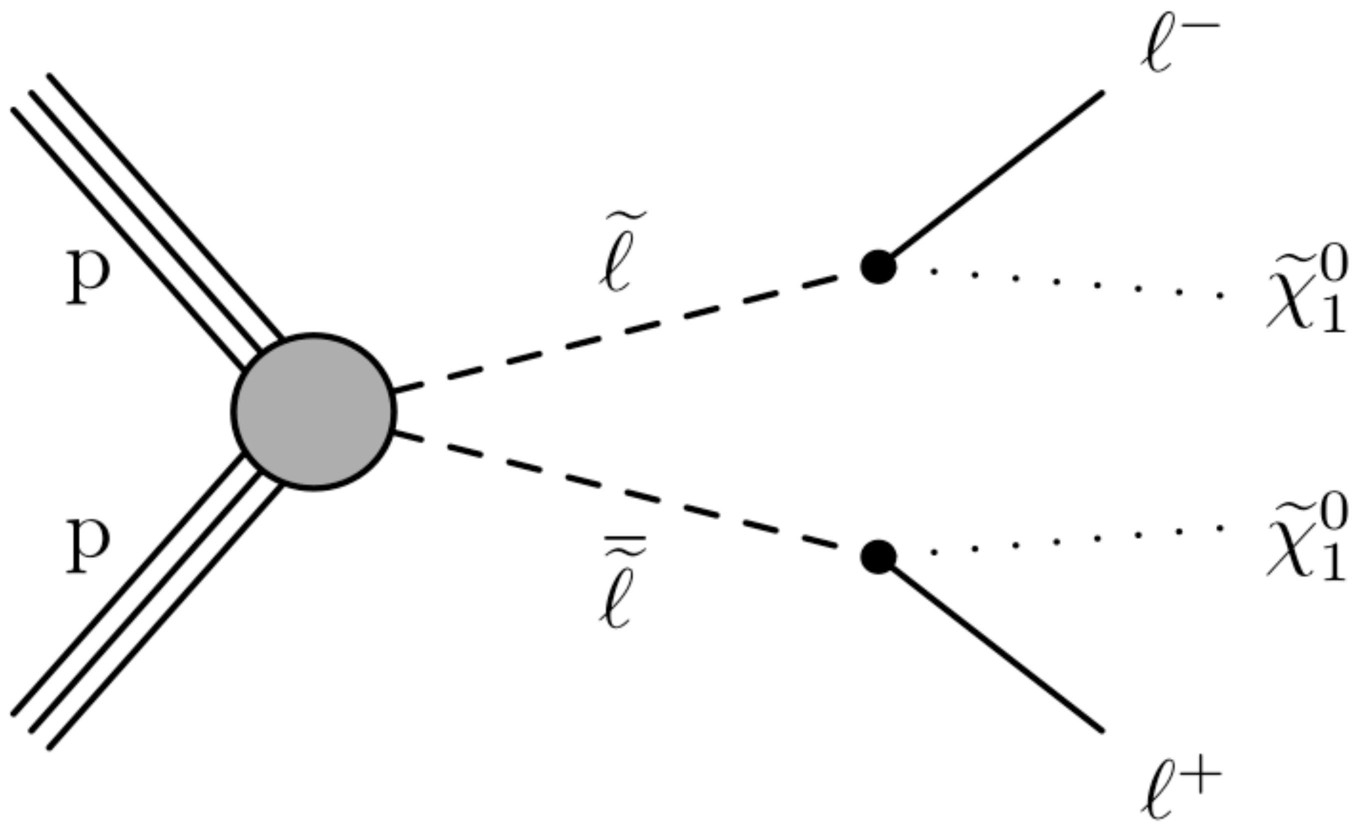
- Drell-Yan production of mediator pair decaying into leptons + $\not{E}_T$ is dominant LHC signal



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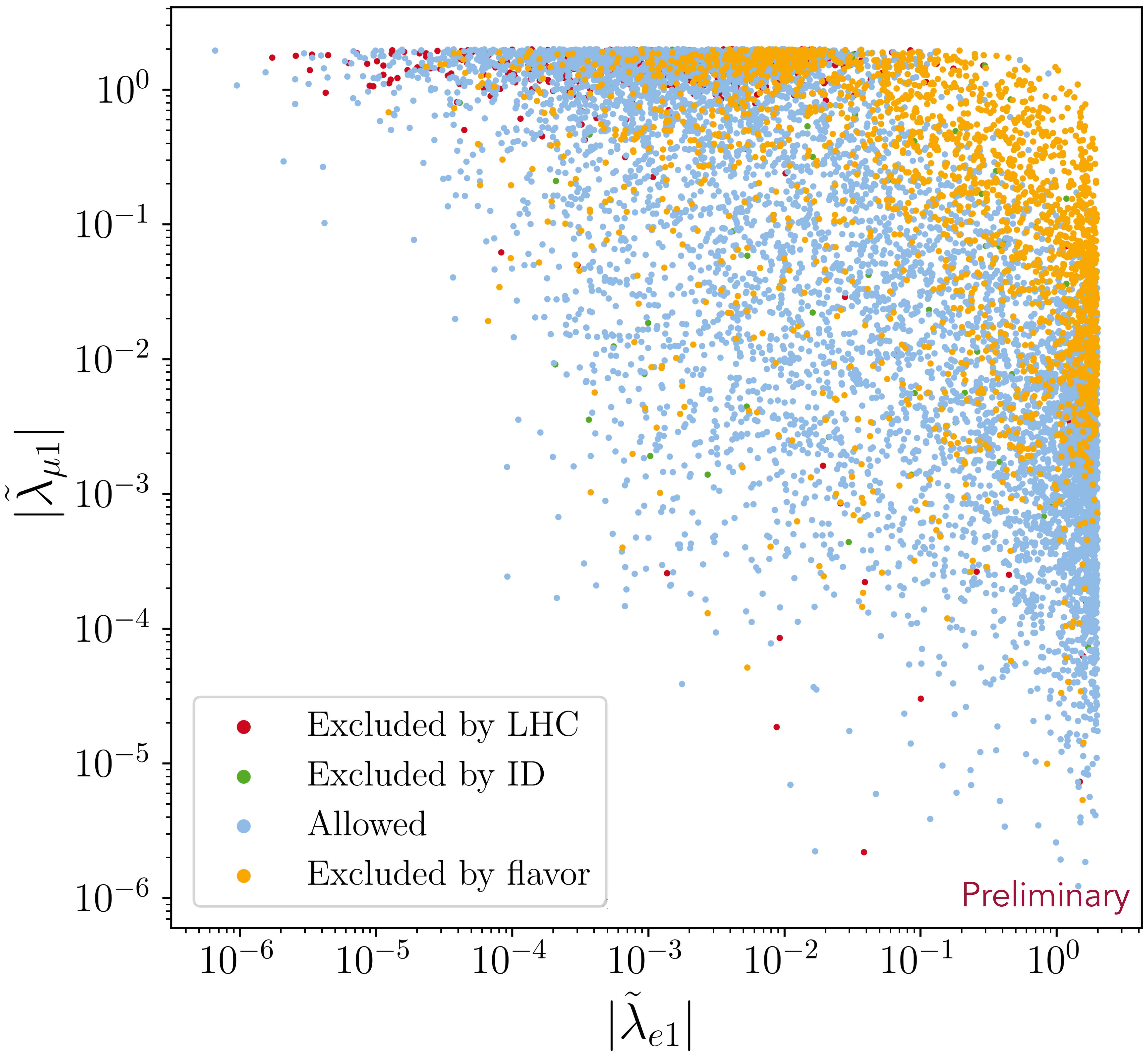

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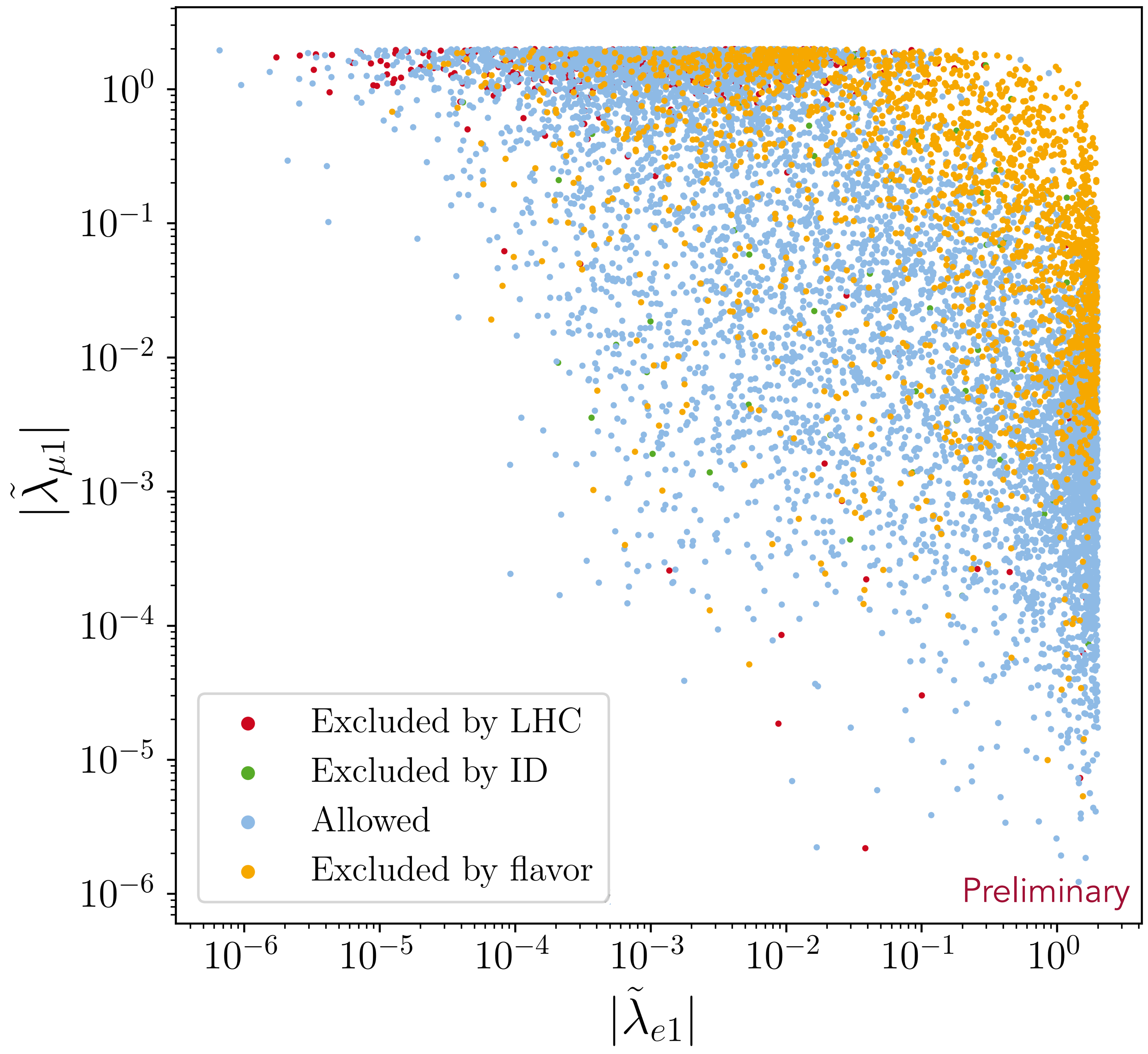
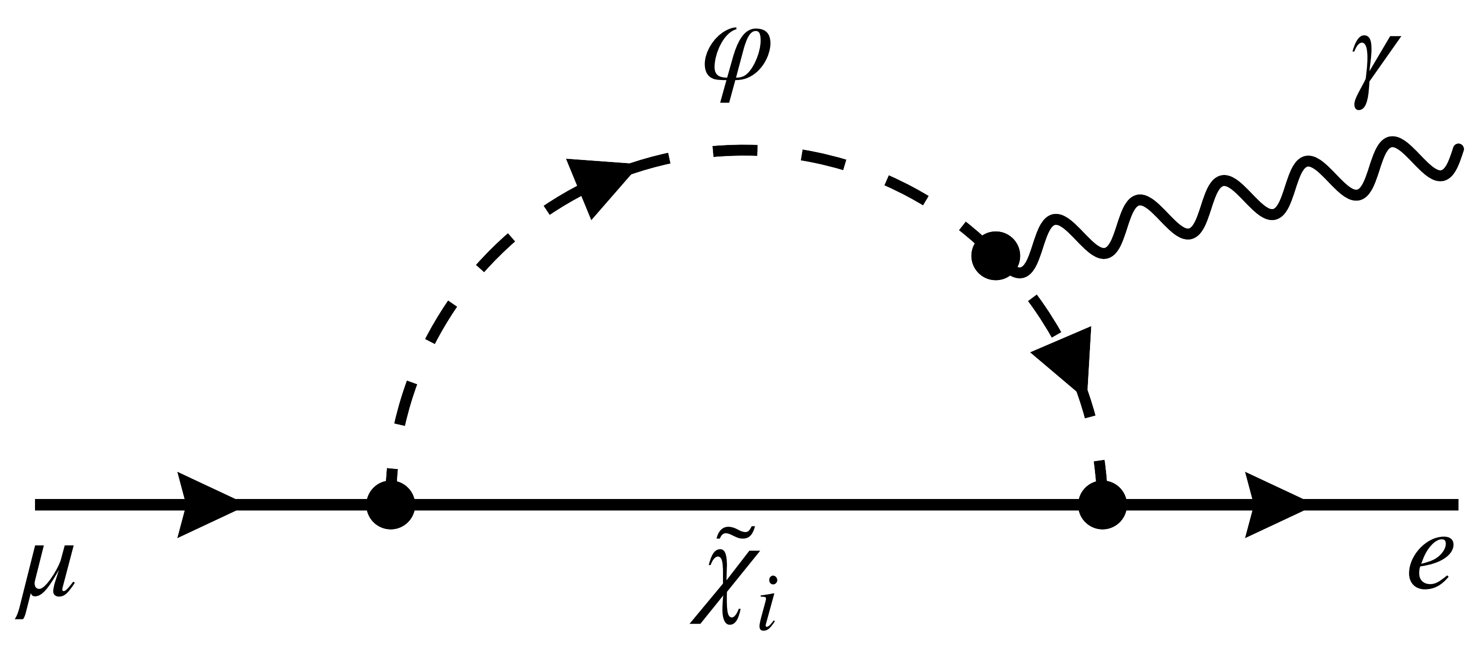


- Strong flavor constraints from lepton-flavor violating decays



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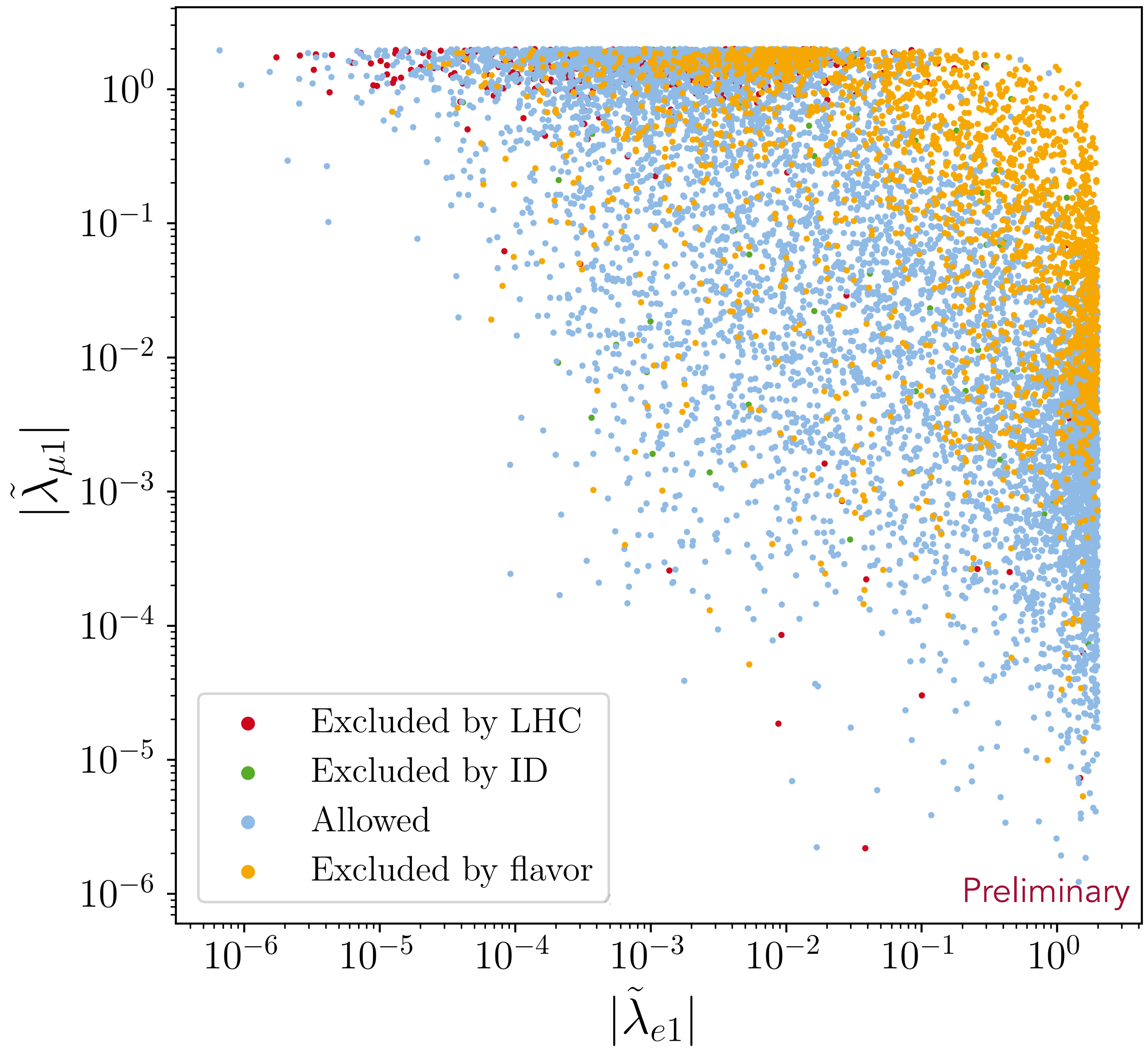

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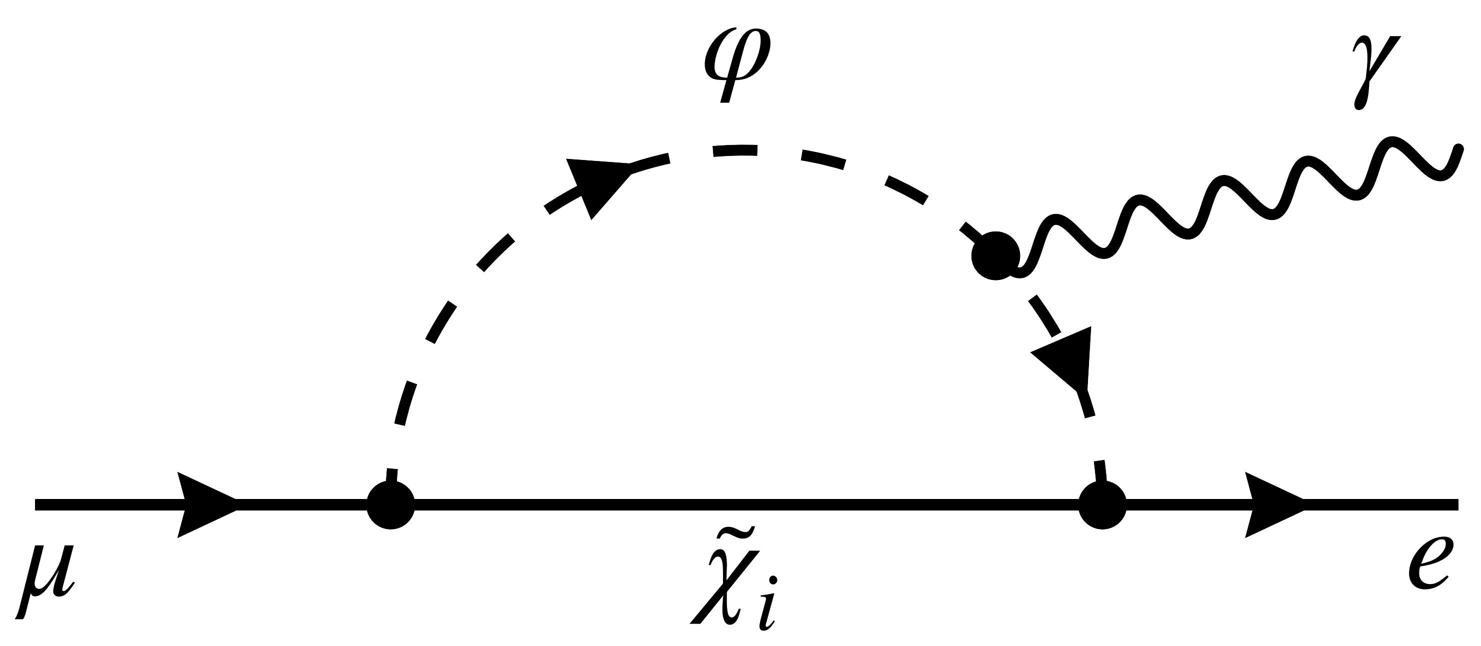
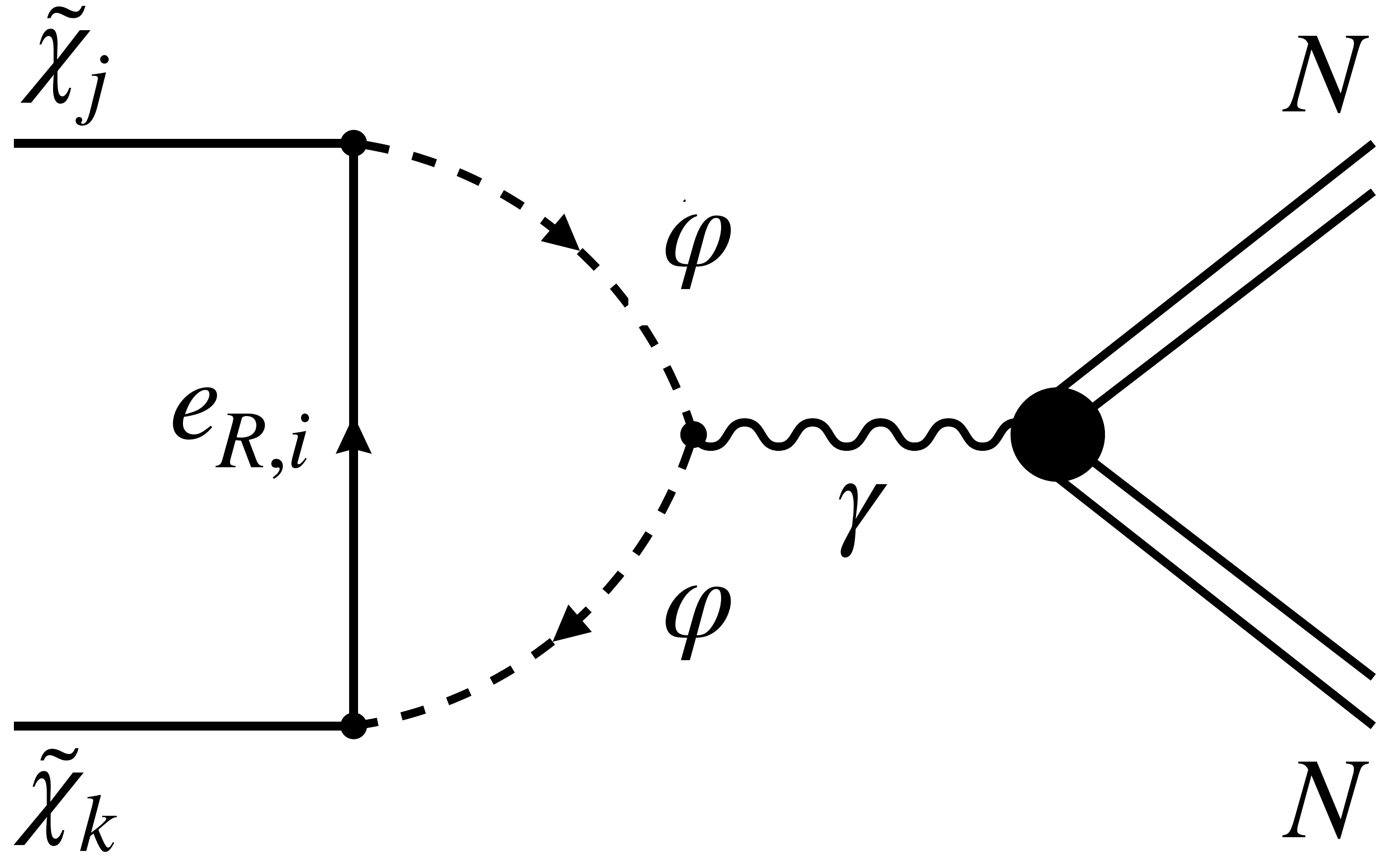


- DD constraints absent as only possible contribution is very suppressed



Conclusions

- Flavored DM models have rich phenomenology but many models have not been studied
- Developed framework to study different flavored DM models including constraints from relic density, direct & indirect detection, collider and flavor observable
- Showed constraints on Majorana DM coupling to e_R
- Strongest constraints from correct relic abundance and lepton-flavor violating decays, collider and ID constraints only relevant for small DM masses
- Outlook: Study other missing models

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Thank you!

Backup Slides

Parameterization of λ

$$\lambda = U\,\mathrm{diag}(D_1, D_2, D_3)\,O\,d$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^\theta_{23} & s^\theta_{23} e^{-i\delta_{23}} \\ 0 & -s^\theta_{23} e^{i\delta_{23}} & c^\theta_{23} \end{pmatrix} \begin{pmatrix} c^\theta_{13} & 0 & s^\theta_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s^\theta_{13} e^{i\delta_{13}} & 0 & c^\theta_{13} \end{pmatrix} \begin{pmatrix} c^\theta_{12} & s^\theta_{12} e^{-i\delta_{12}} & 0 \\ -s^\theta_{12} e^{i\delta_{12}} & c^\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^\phi_{23} & s^\phi_{23} \\ 0 & -s^\phi_{23} & c^\phi_{23} \end{pmatrix} \begin{pmatrix} c^\phi_{13} & 0 & s^\phi_{13} \\ 0 & 1 & 0 \\ -s^\phi_{13} & 0 & c^\phi_{13} \end{pmatrix} \begin{pmatrix} c^\phi_{12} & s^\phi_{12} & 0 \\ -s^\phi_{12} & c^\phi_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$d = \mathrm{diag}(e^{i\gamma_1}, e^{i\gamma_2}, e^{i\gamma_3})$$

Sampling of Parameters

- D_i in $[0,2]$, linearly
- θ_{12} and ϕ_{12} in $[10^{-6},10^{-2}]$, logarithmically
- Remaining angles in $[10^{-4}, \pi/4]$, logarithmically.
- δ_{ij} and γ_i in $[0,2\pi)$, linearly
- $M_{\tilde{\chi}}$ in $[100,1500]$ GeV, linearly
- M_φ in $[M_{\tilde{\chi}_1}, M_{\tilde{\chi}_1} + 2000]$ GeV, linearly
- $\lambda_{\phi H}$ and η in $\pm[10^{-3},1]$, logarithmically

Indirect detection

Final state	Gamma rays	Antiprotons	Positrons	Neutrinos
e^+e^-	[50, 51]	–	[52]	–
$\mu^+\mu^-$	[53]	–	[52]	[53]
$\tau^+\tau^-$	[54, 55]	–	[52]	–
$q\bar{q}$ (light)	–	[56]	–	–
$c\bar{c}$	[50]	–	–	–
$b\bar{b}$	[57]	[56]	–	–
$t\bar{t}$	[50, 58]	–	–	–
W^+W^-	[53, 59]	[56]	–	–
ZZ	[50, 60]	–	–	–
hh	–	[56]	–	–
$\nu\bar{\nu}$ (any flavor)	–	–	–	[61, 62]

Treatment of limit for mixes final states AB:

$$\langle\sigma v\rangle_{AB} = \frac{1}{2}\left(\langle\sigma v\rangle_{AA} + \langle\sigma v\rangle_{BB}\right)$$

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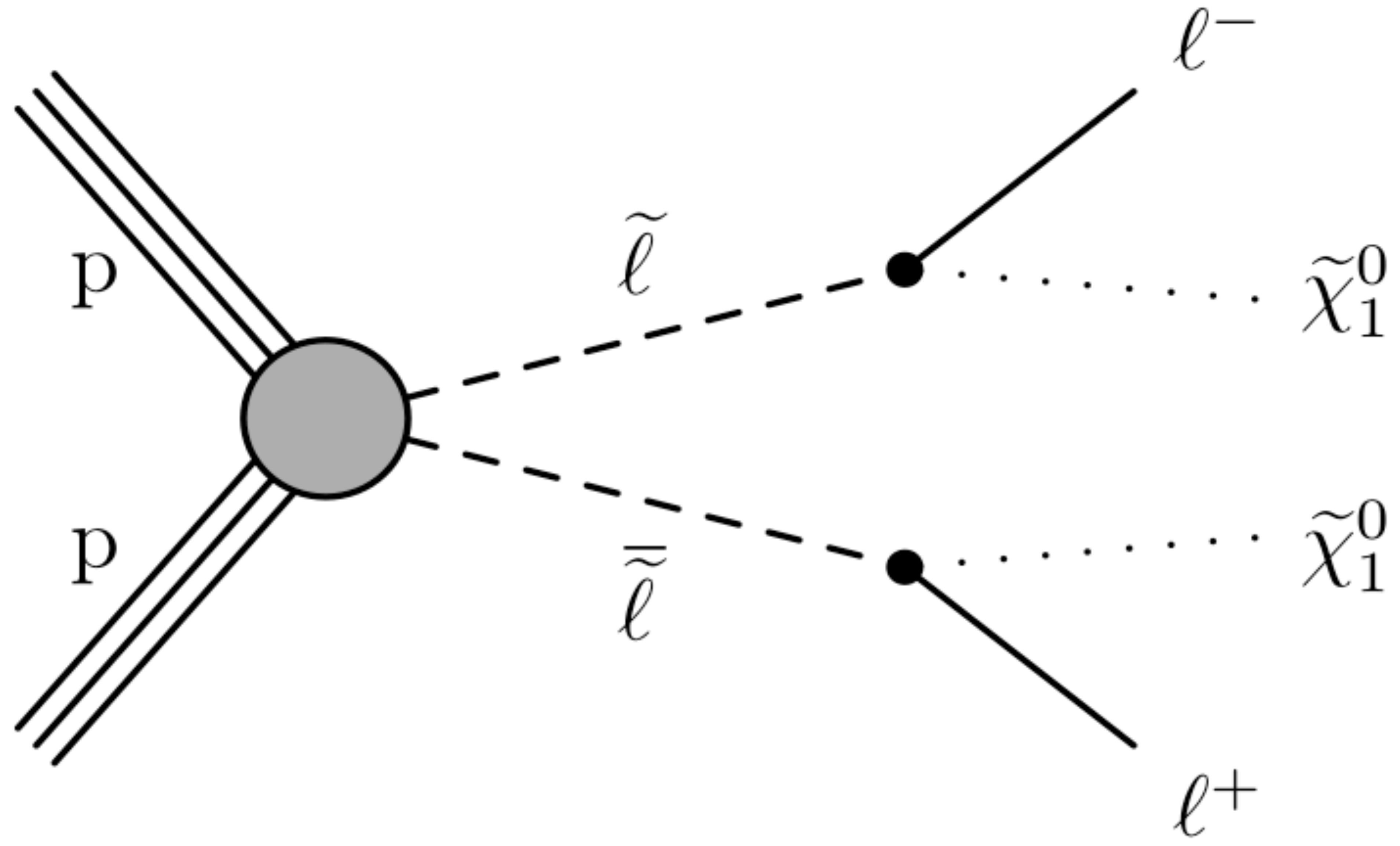
[61] T. I. Collaboration, R. Abbasi, M. Ackermann, J. Adams, S. K. Agarwalla, et al., *Search for neutrino lines from dark matter annihilation and decay with icecube,* 2023.

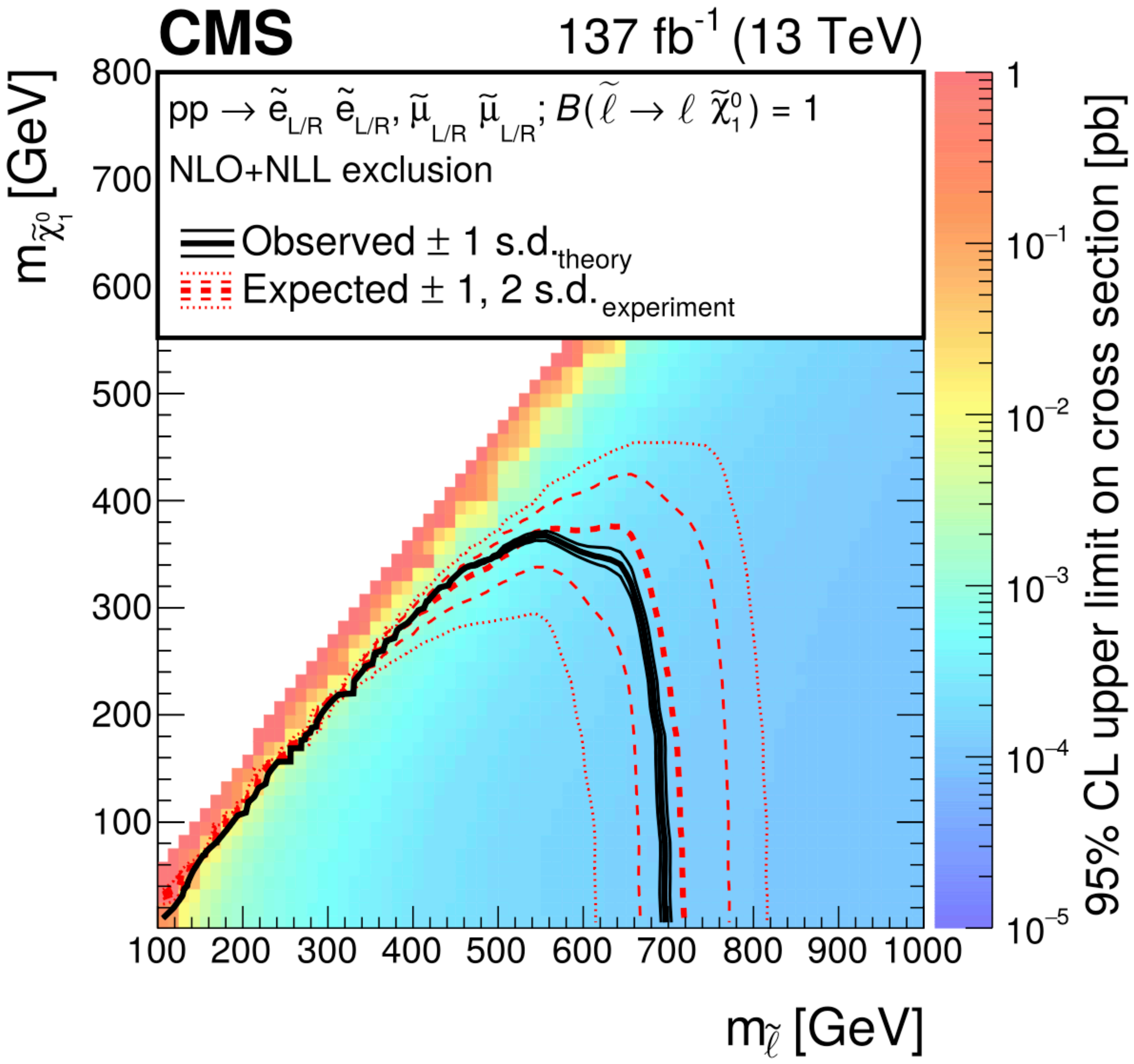
[62] A. Albert, M. André, M. Anghinolfi, G. Anton, M. Ardid, et al., *Search for dark matter towards the galactic centre with 11 years of antares data,* *Physics Letters B* **805** (June, 2020) 135439.

Collider constraints

[Sirunyan et al. 2021]

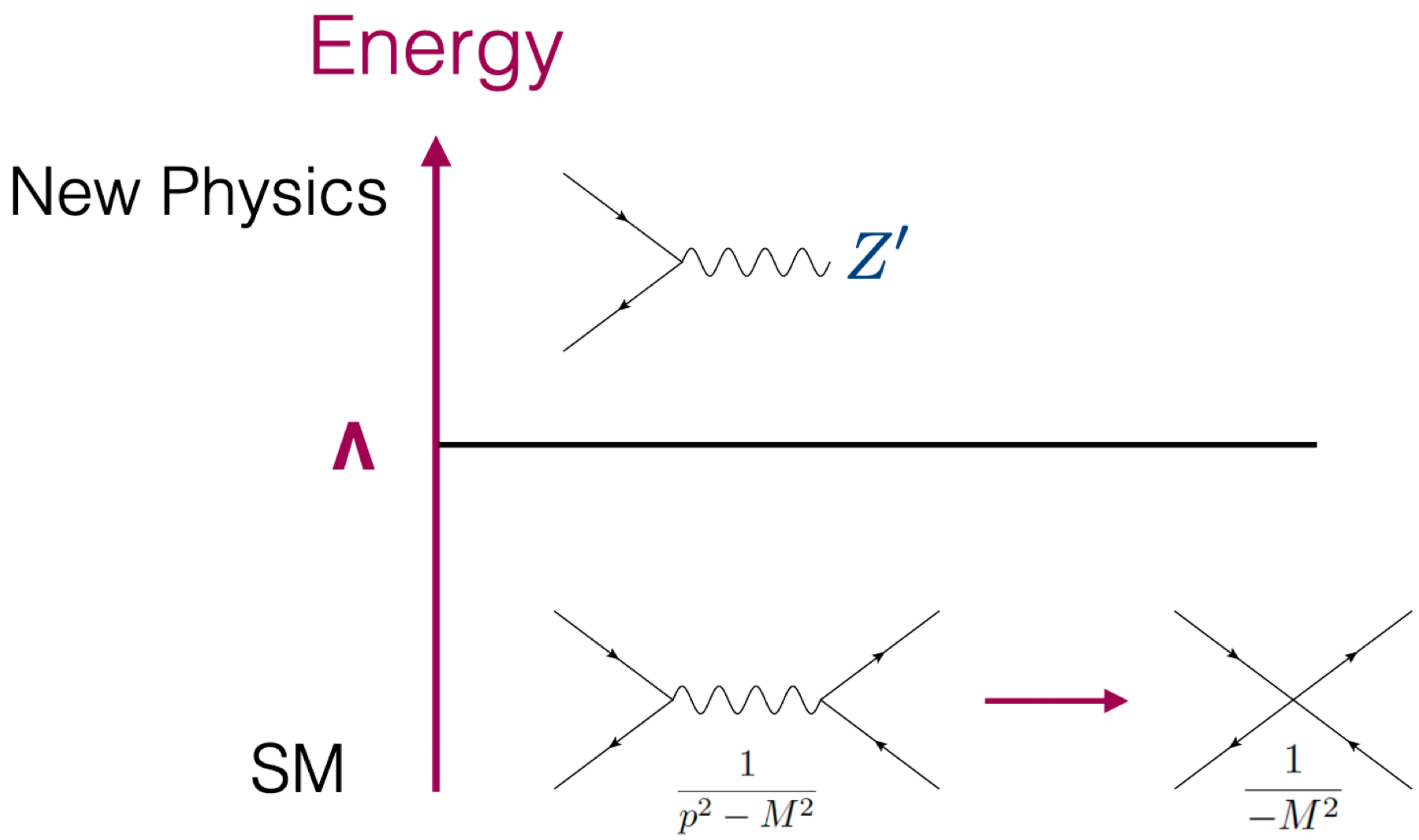
- Most sensitive CMS search





SMEFT

- SM Effective Field Theory $\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda} \mathcal{O}_i^{d=5} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{d=6}$
- Need to compute Wilson coefficients C_i



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Example: Majorana DM coupling to e_R