Aaron Vincent

New physics with GAMBIT

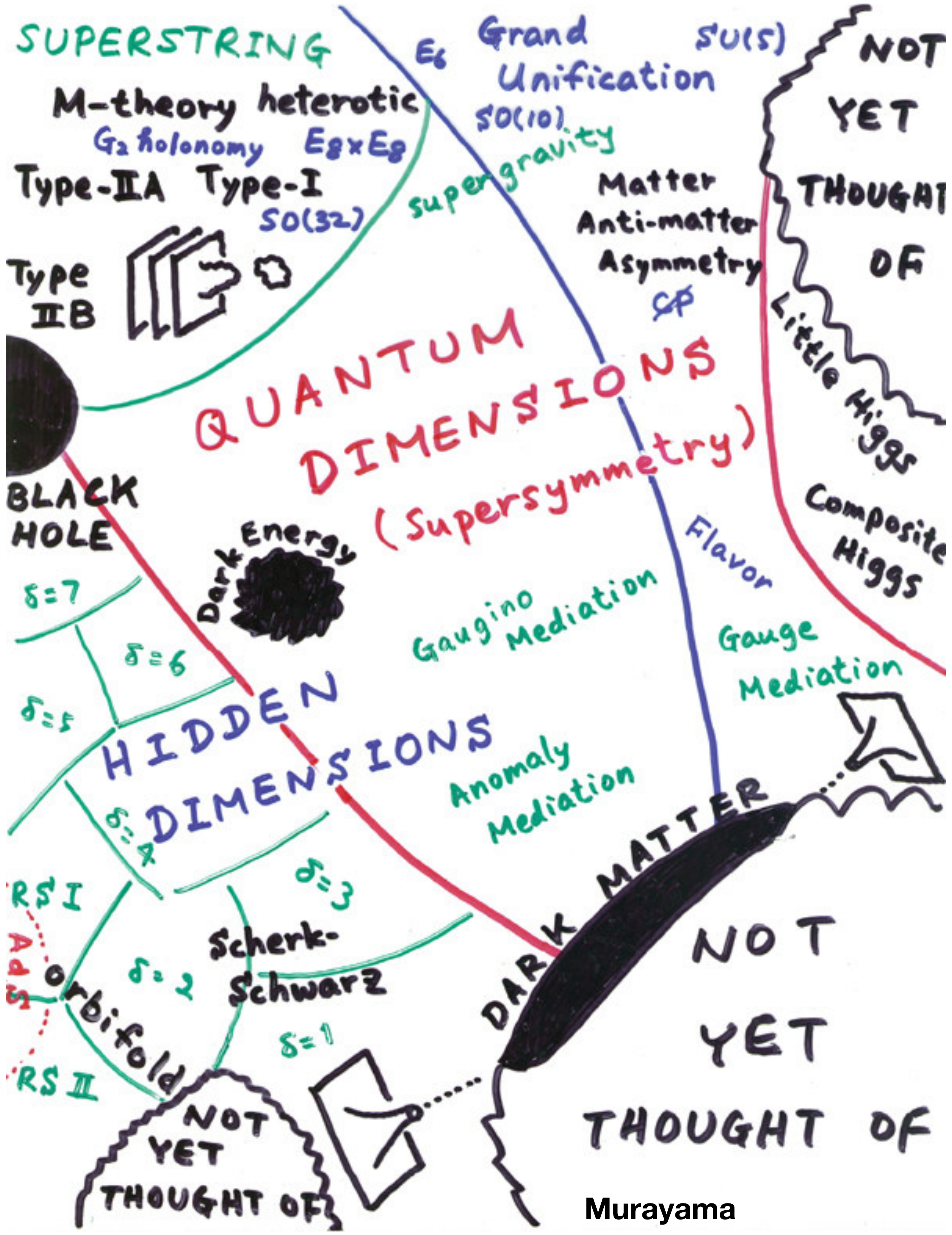
4th Uppsala workshop on Particle Physics at Neutrino Telescopes
Uppsala, Oct 7 2019

Queen's University

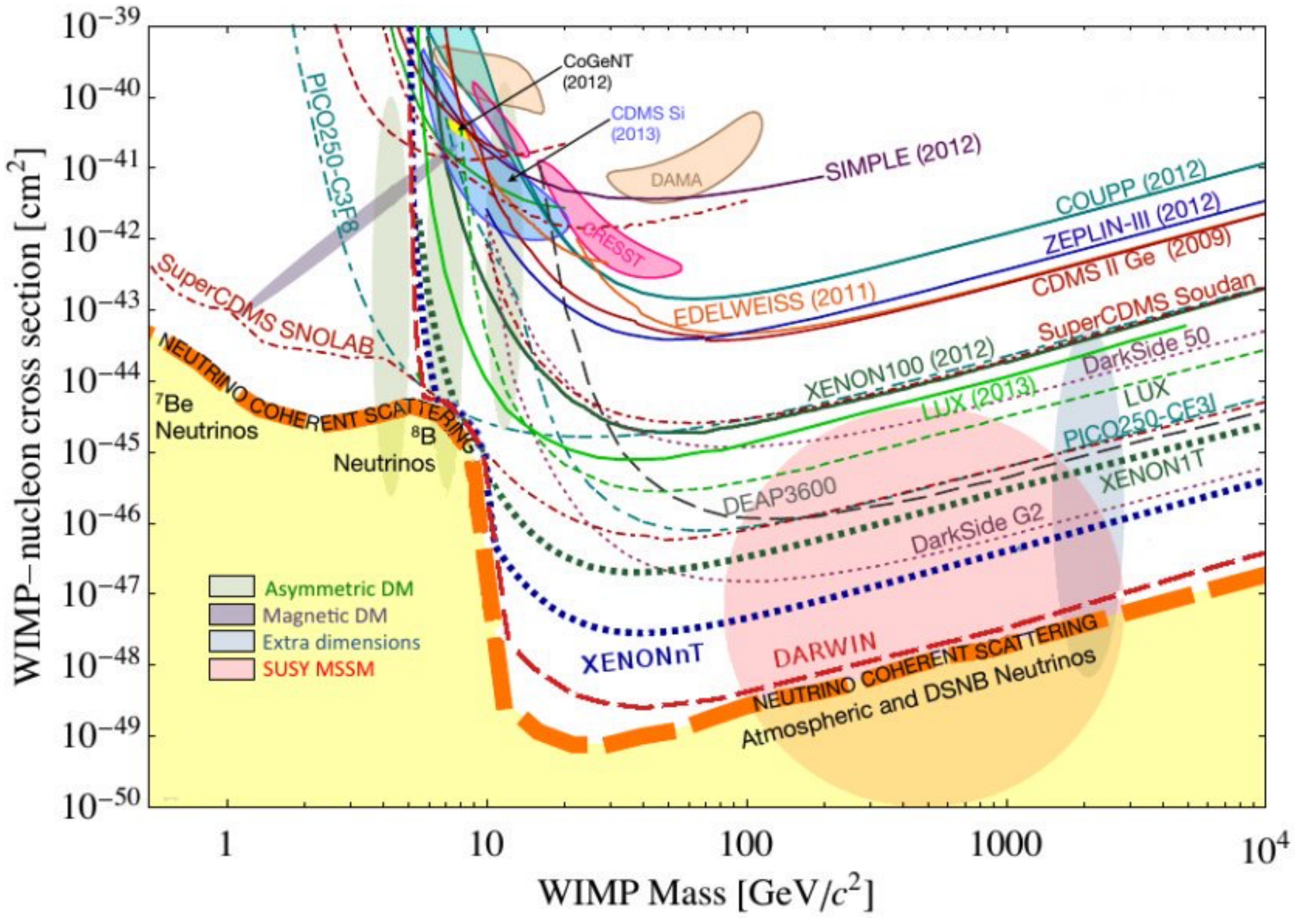
Centre de Recherche Canadien en Physique des Astroparticules
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute


GAMBIT
600 × 600

There are many models



Murayama

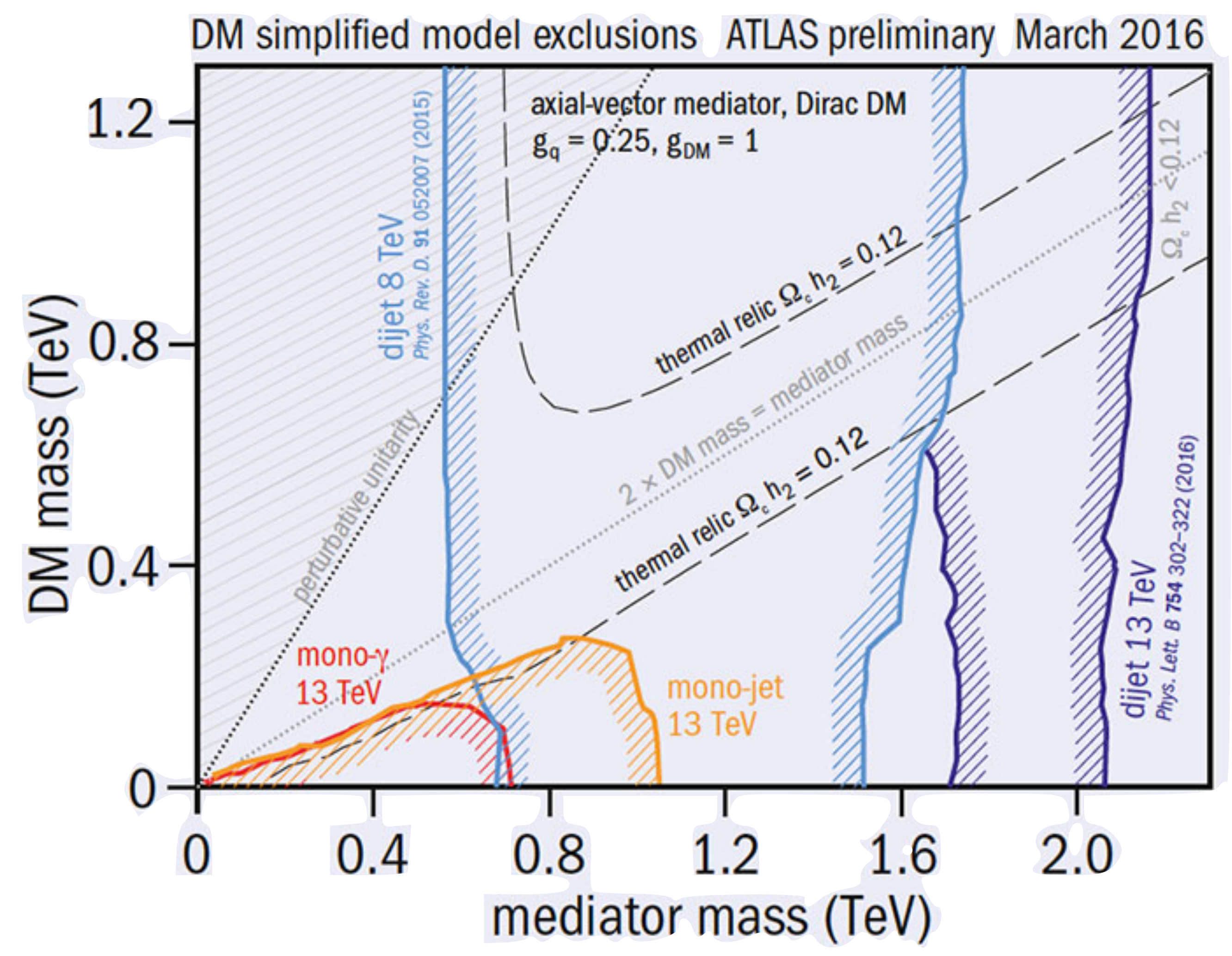


And many experiments

How do we combine them in a meaningful way?

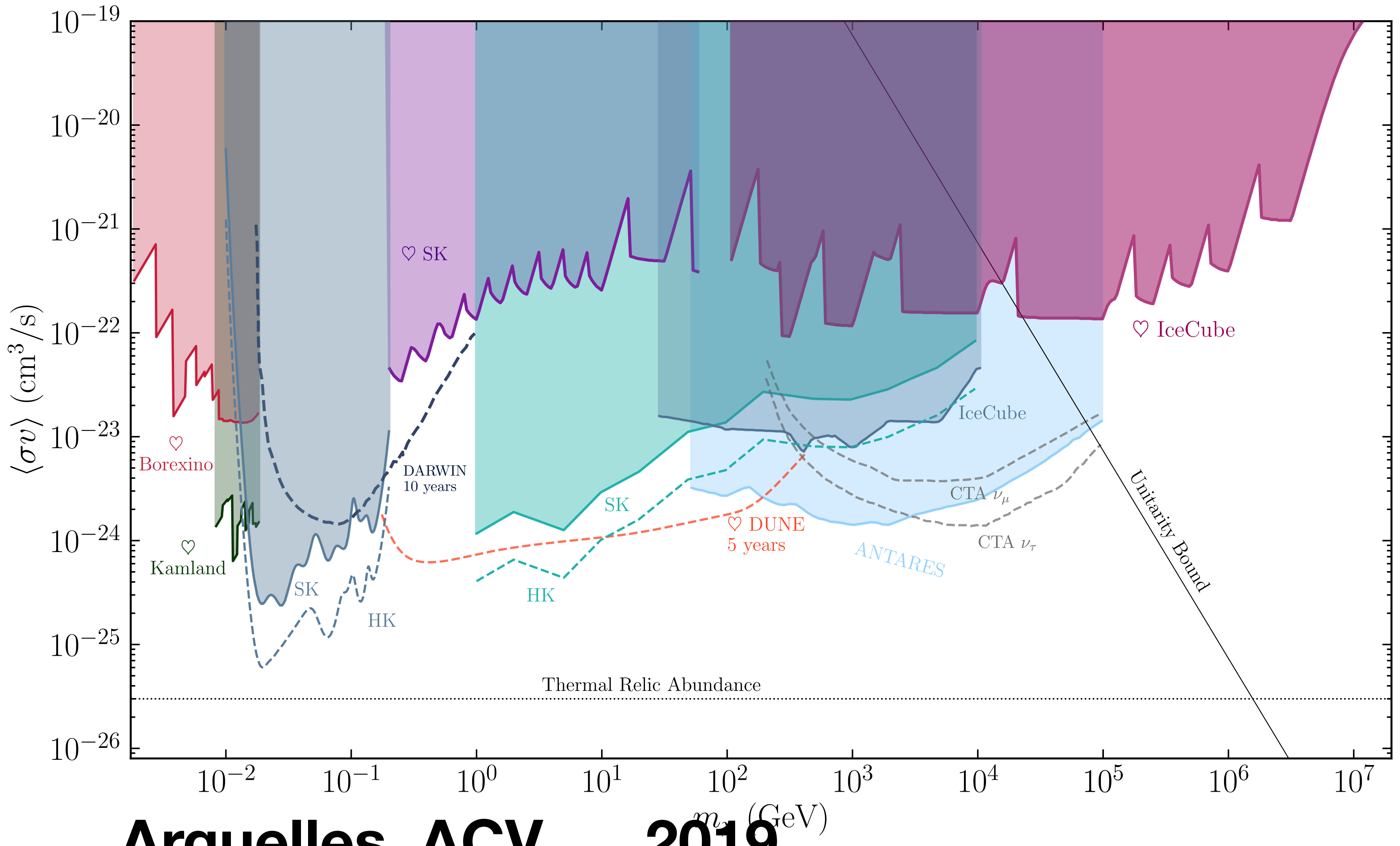
Example: Dark Matter

Collider



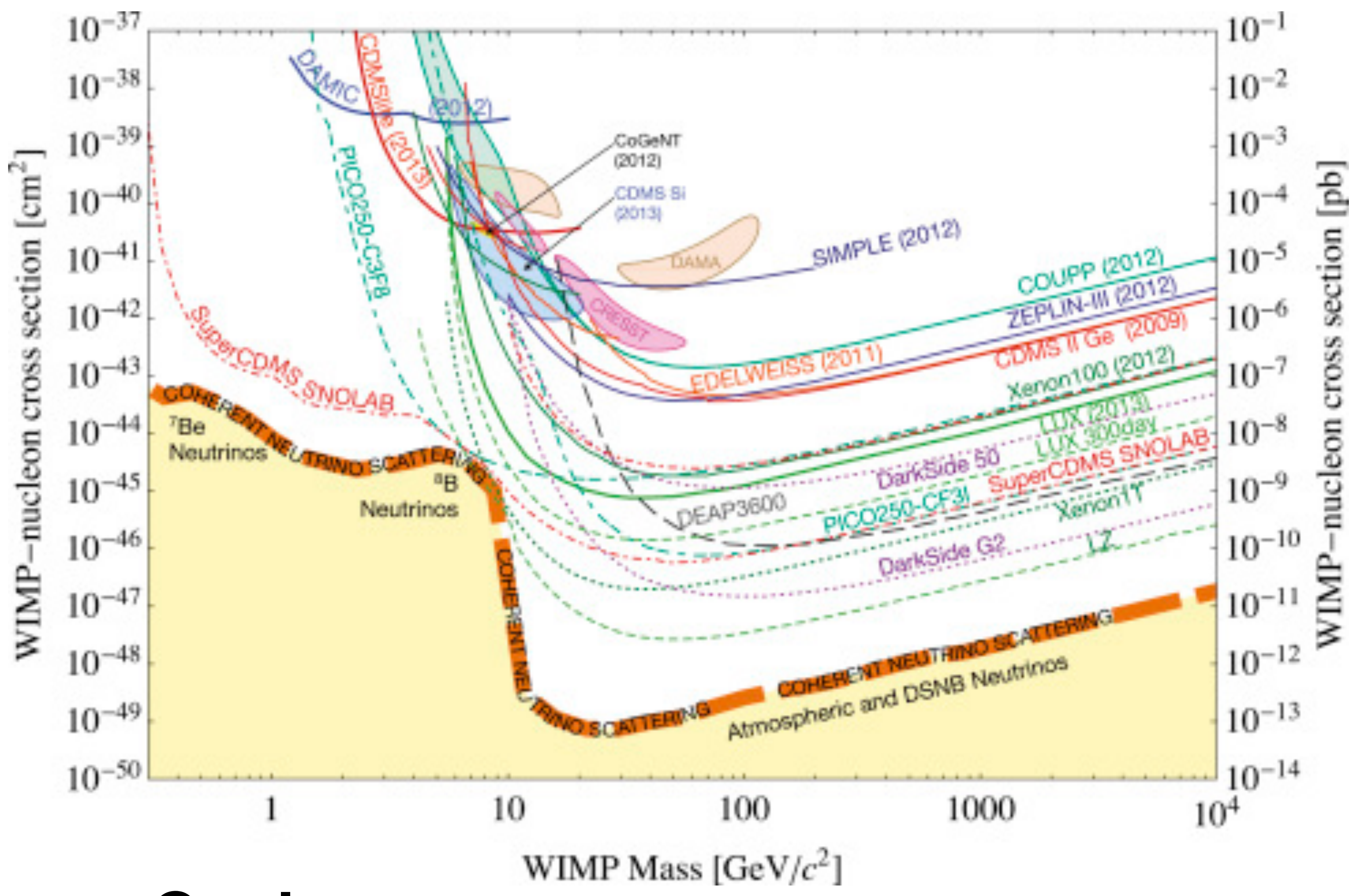
ATLAS

Indirect Detection



Arguelles, ACV, … 2019

Direct Detection

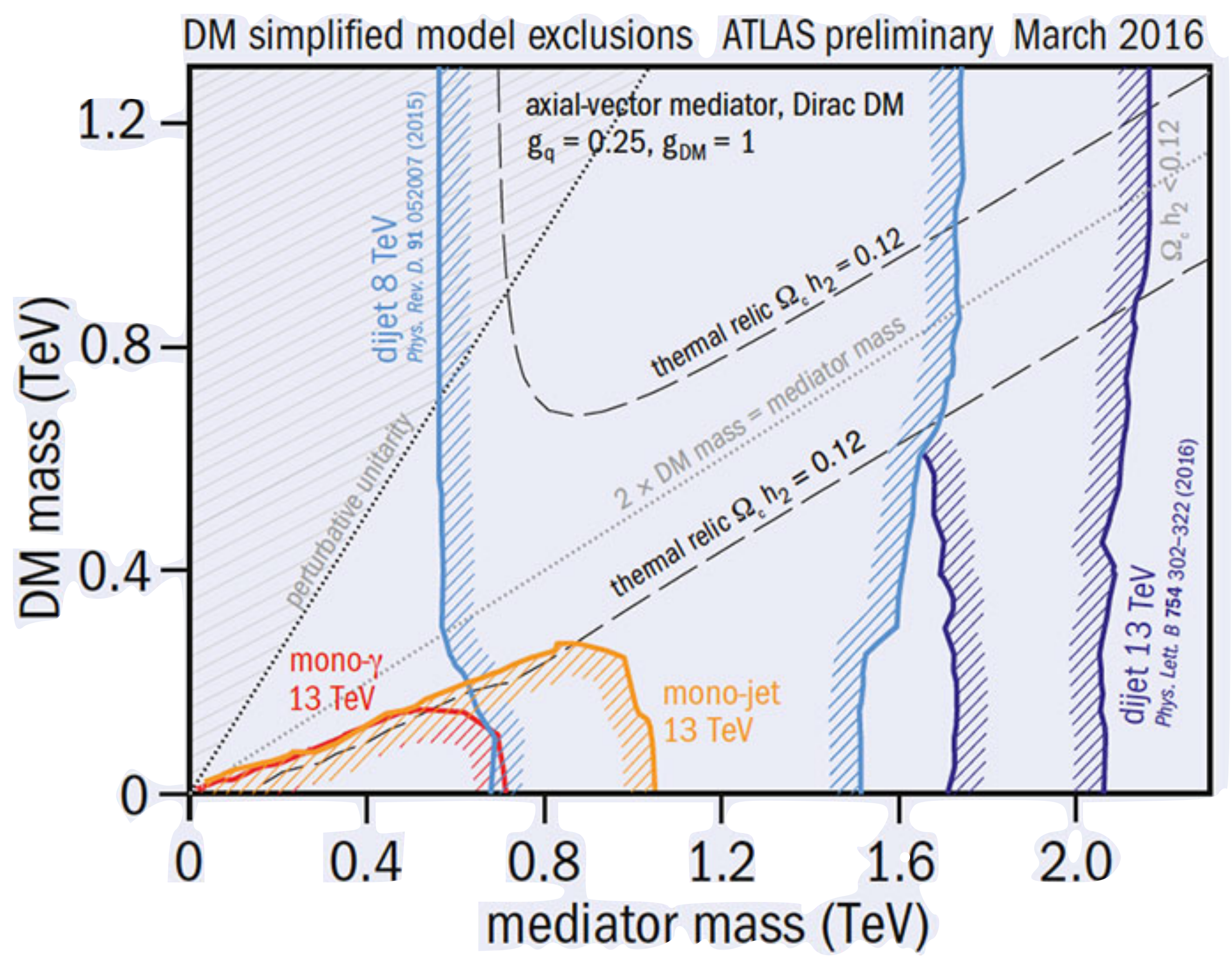


Cooley

Example: Dark Matter

Each type of constraint depends on a set of model **assumptions/ parameters,** experimental nuisance parameters

Collider



ATLAS

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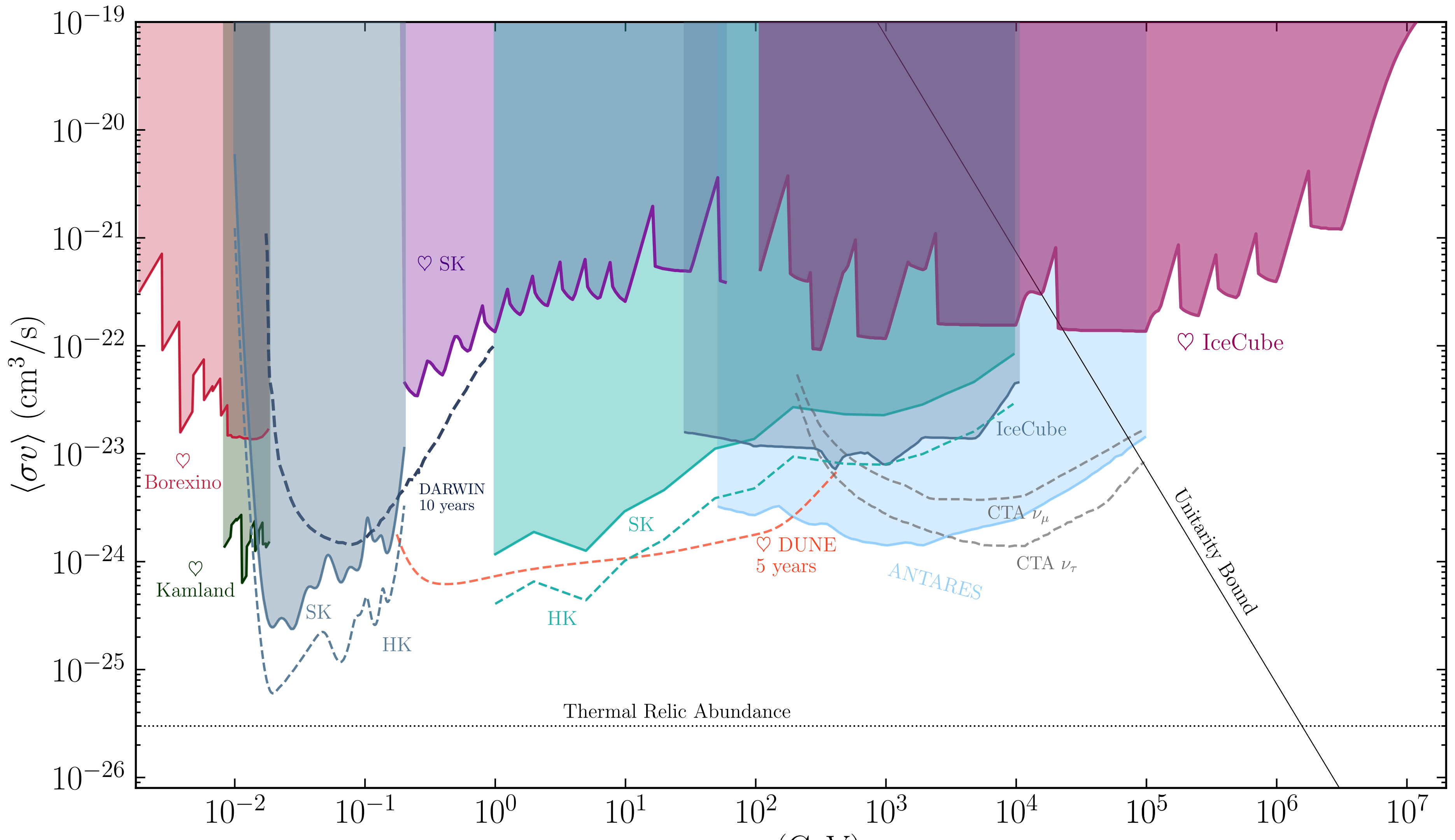

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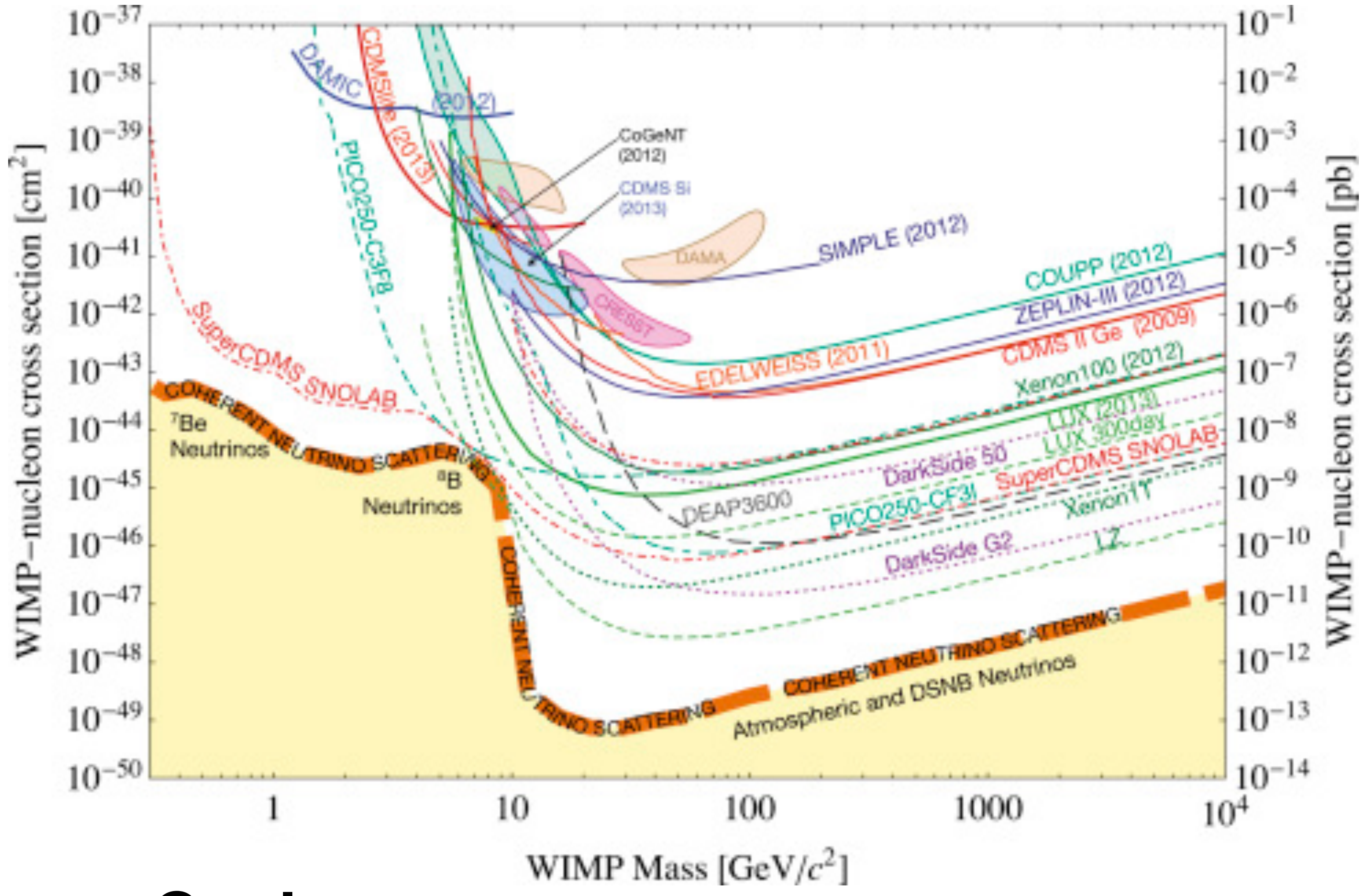


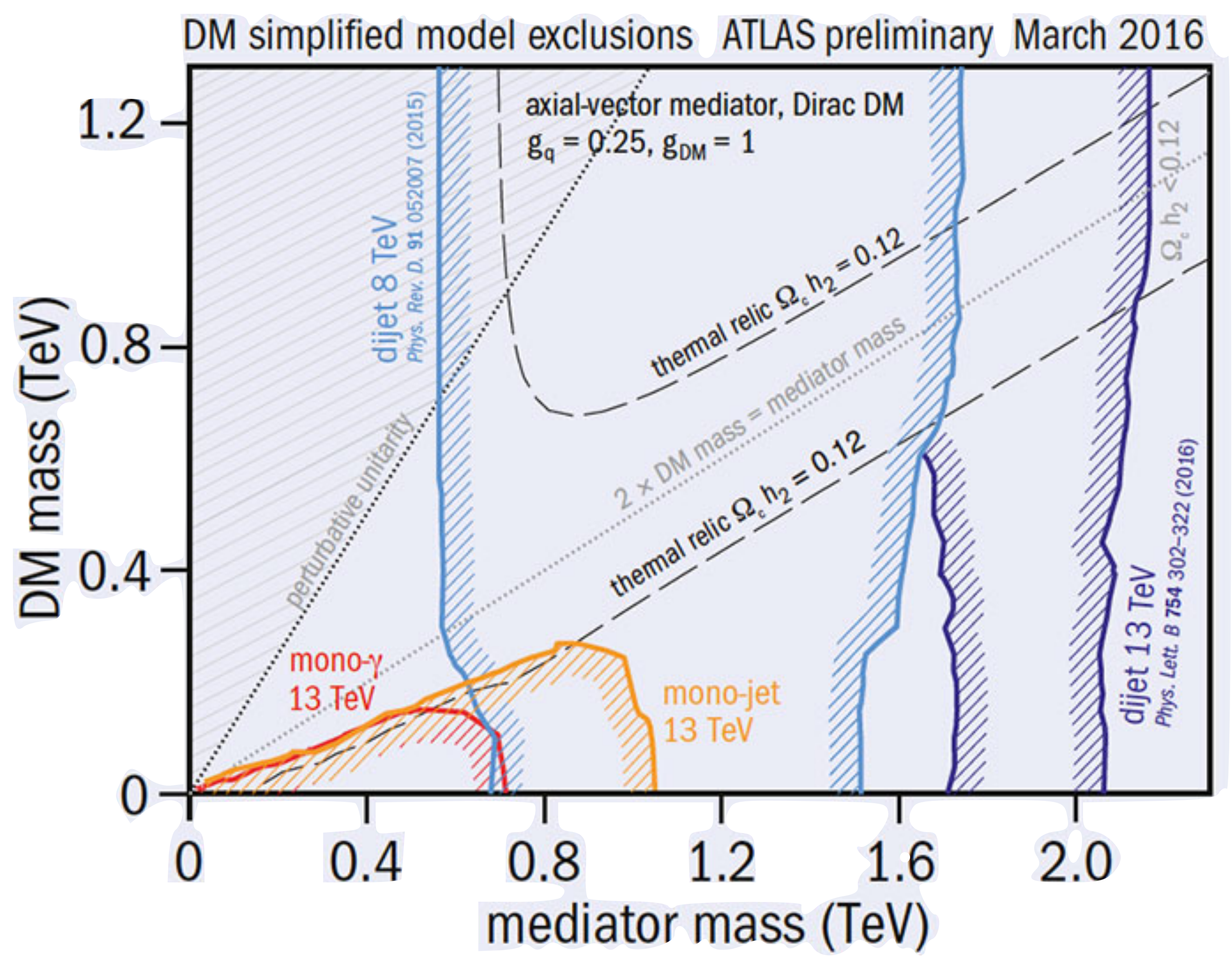
Cooley

Example: Dark Matter

Each type of constraint depends on a set of model **assumptions/ parameters,** experimental nuisance parameters

How do I interpret everything together?

Collider



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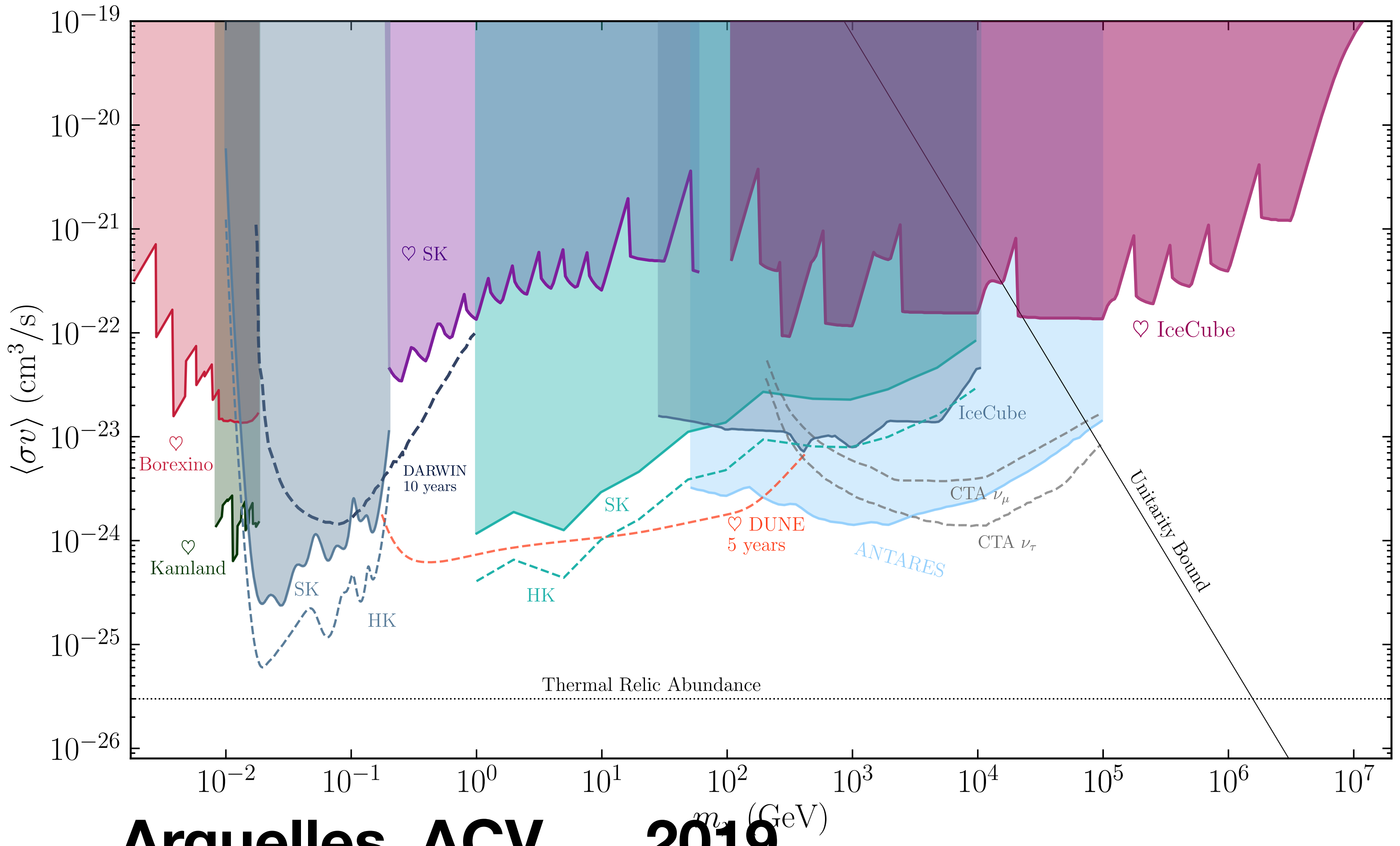

Arguelles, ACV, … 2019

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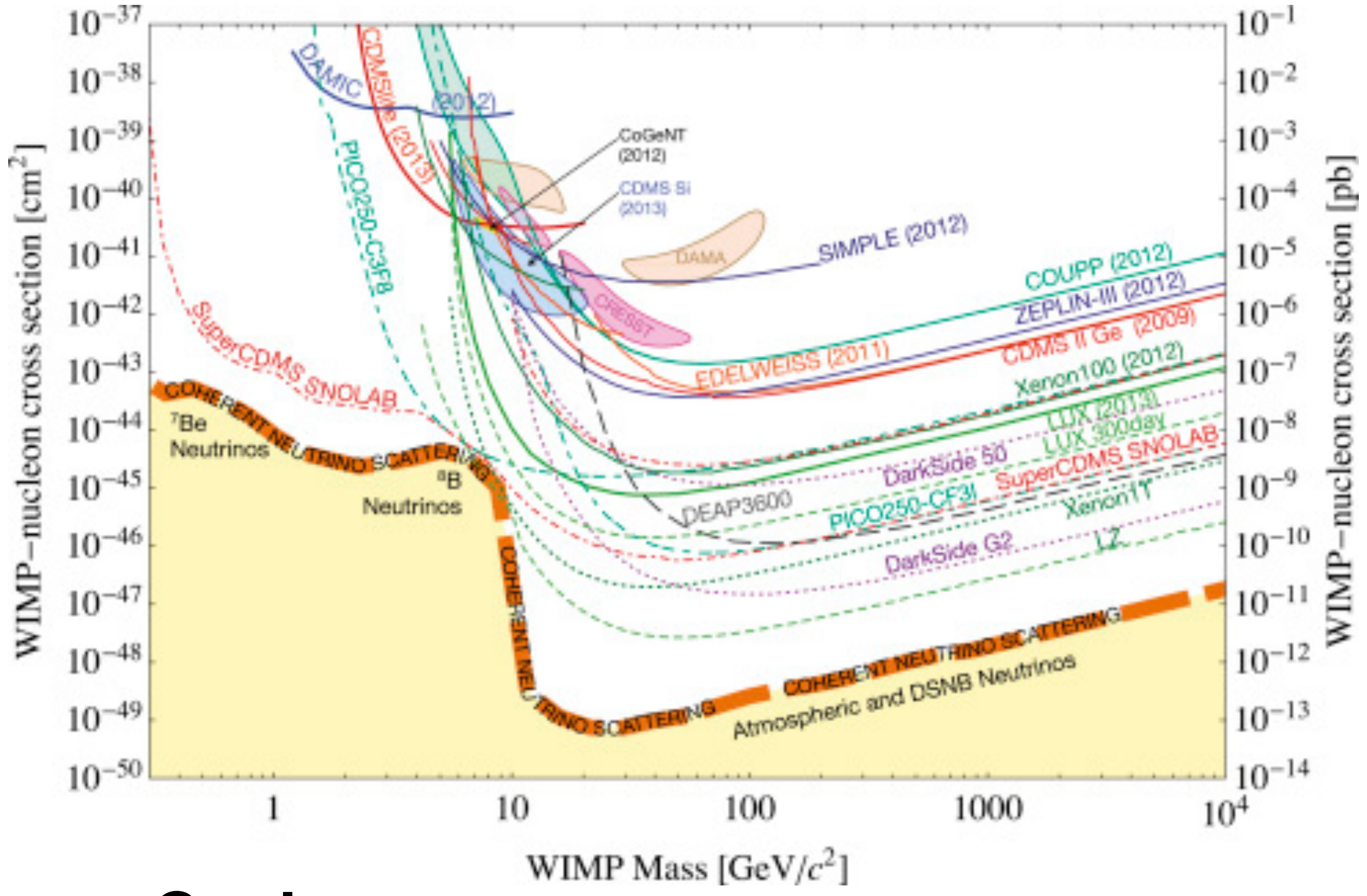
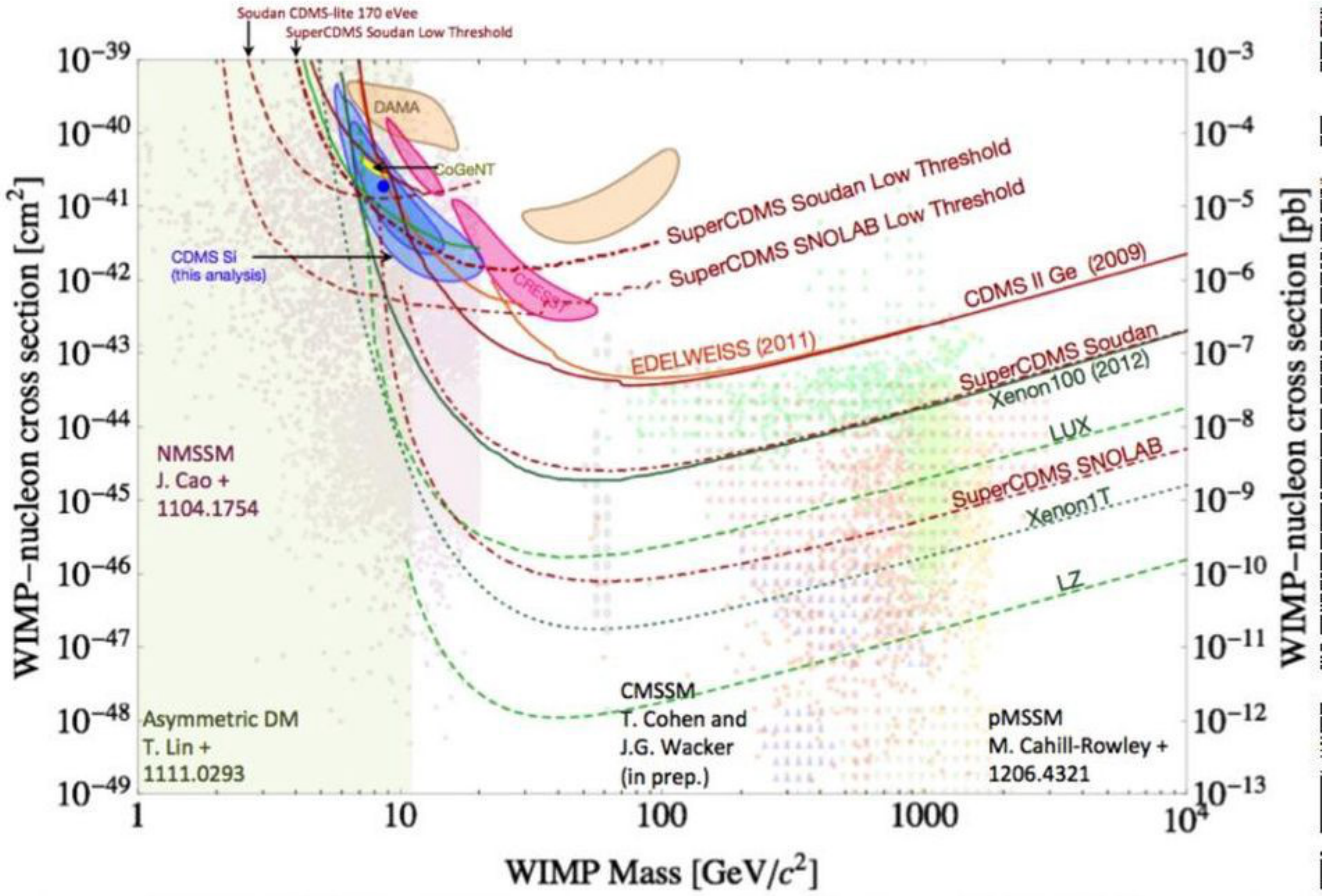


Cooley

The danger of bad sampling



The 'WIMP Miracle' Hope For Dark Matter Is Dead

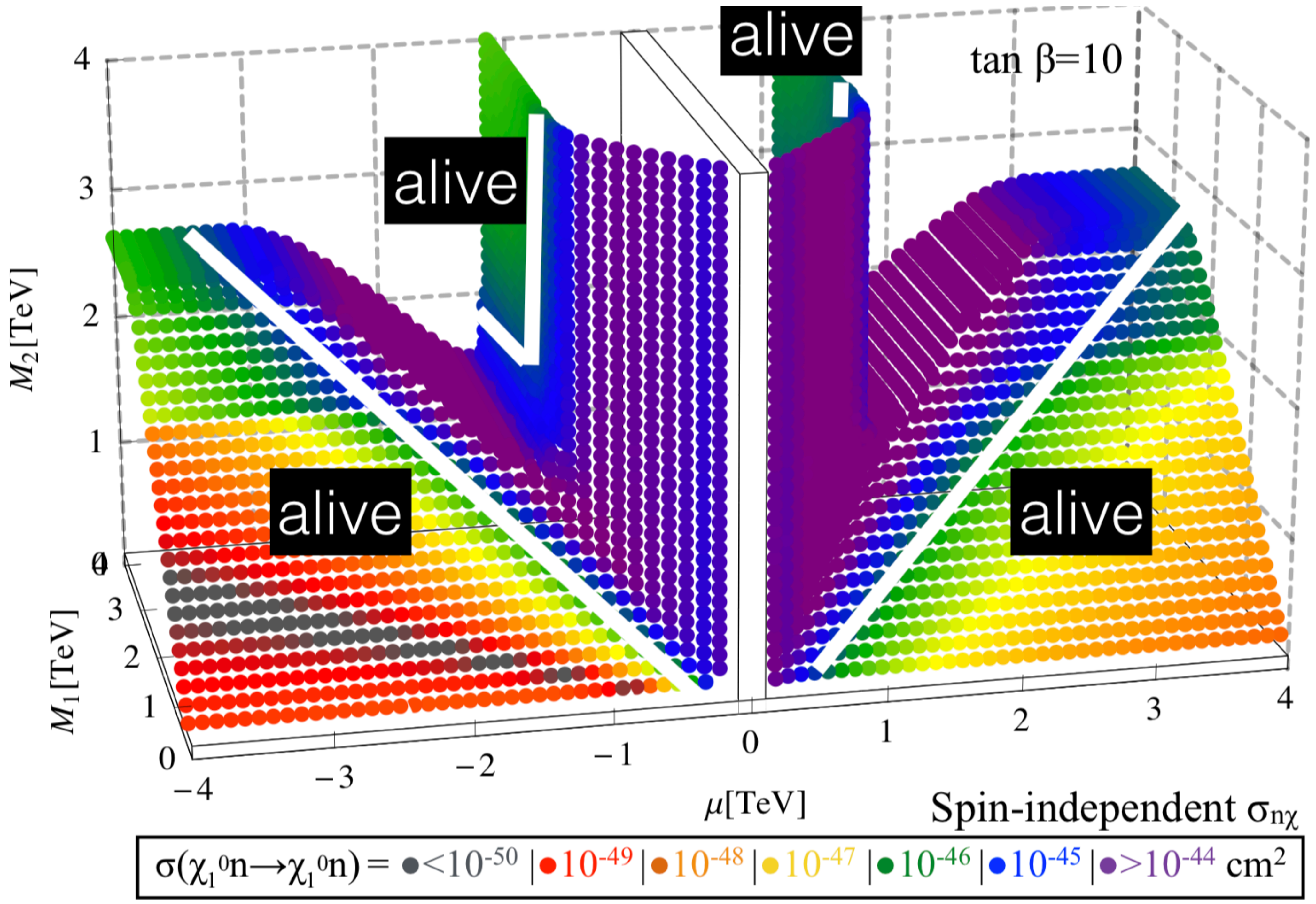
Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

WIMPs on Death Row

Posted on July 21, 2016 by woit

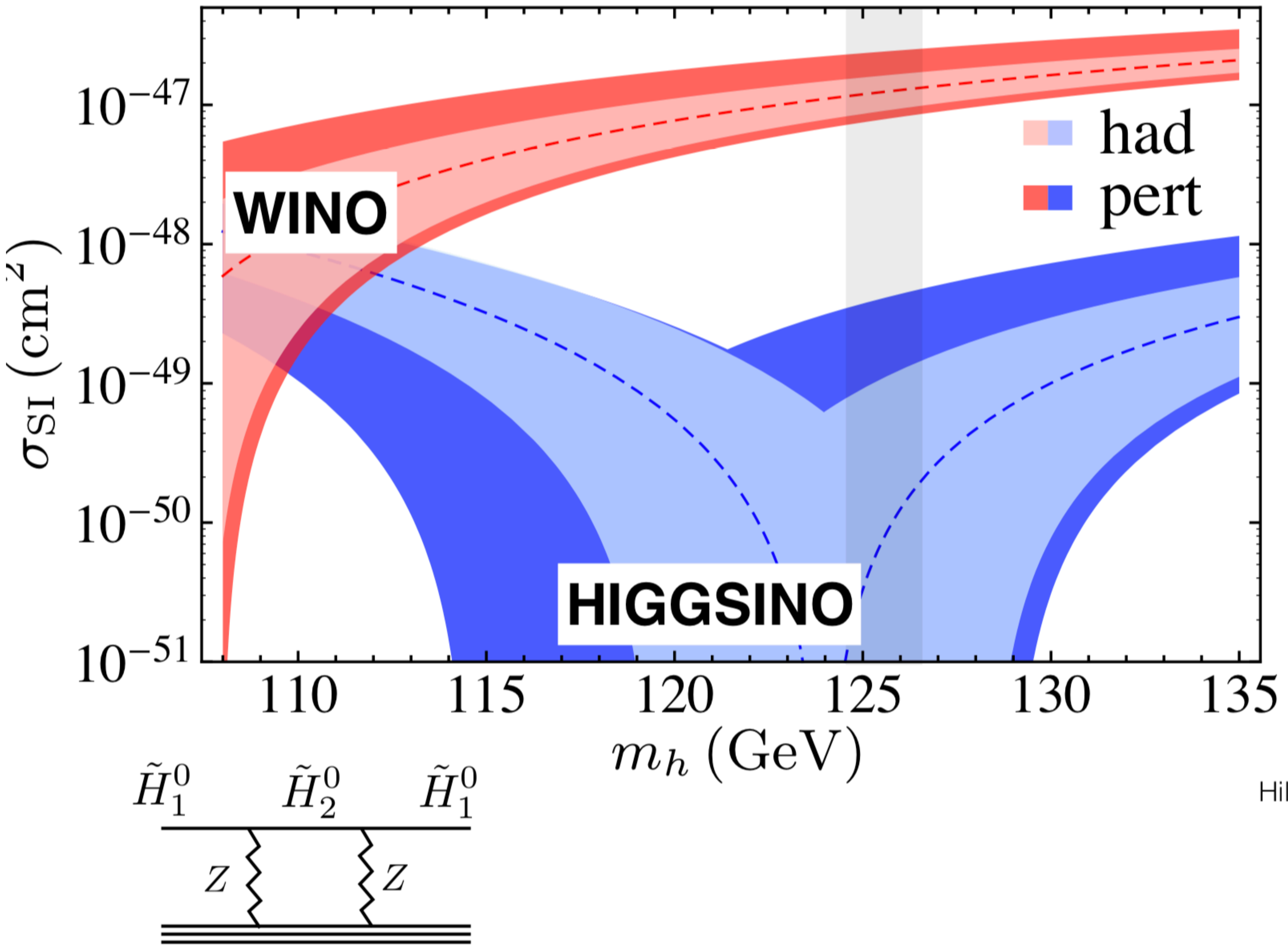
One of the main arguments given for the idea of supersymmetric extensions of th
standard model has been what SUSY enthusiasts call the "WIMP Miracle" (WIM
Interacting Massive Particle). This is the claim that such SUSY models include a
very massive weakly interacting particle that could provide an explanation for da

Neutralino (arguably the OG WIMP)
Not close to dead



Joe Bramante

WINO & Higgsino DM
should not have been found yet



Hill, Solon 1309.4092

The global fit

Rather than overlaying constraints, write a **combined likelihood:**

$$\log \mathcal{L} = \sum_{\text{everything}} \log \mathcal{L}_i(\{d\}_i, \{\theta\}_i)$$

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Deal with nuisance parameters* self-consistently

Profile likelihood

Posterior distribution

*things that vary even though you wish they didn't

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Deal with nuisance parameters* self-consistently

Profile likelihood

Posterior distribution

Provide **likelihoods/credible intervals** rather than single lines

*things that vary even though you wish they didn't

Need a way to do all of this at once:

- Write model of new physics
- Compute model observables
- Compute likelihoods for each experiment, based on the model you are looking for
- Combine likelihoods and scan parameter space in a sensible way
- Output something interpretable

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org EPJC **77** (2017) 784 arXiv:1705.07908

- Extensive model database – not just SUSY
- Extensive observable/data libraries
- Many statistical and scanning options (Bayesian & frequentist)
- *Fast* LHC likelihood calculator
- Massively parallel
- Fully open-source

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON
Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

40+ participants in 11 experiments and 14 major theory codes

How GAMBIT works

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1. User chooses a **model** to scan, **observables** to include, and the **scanning** method

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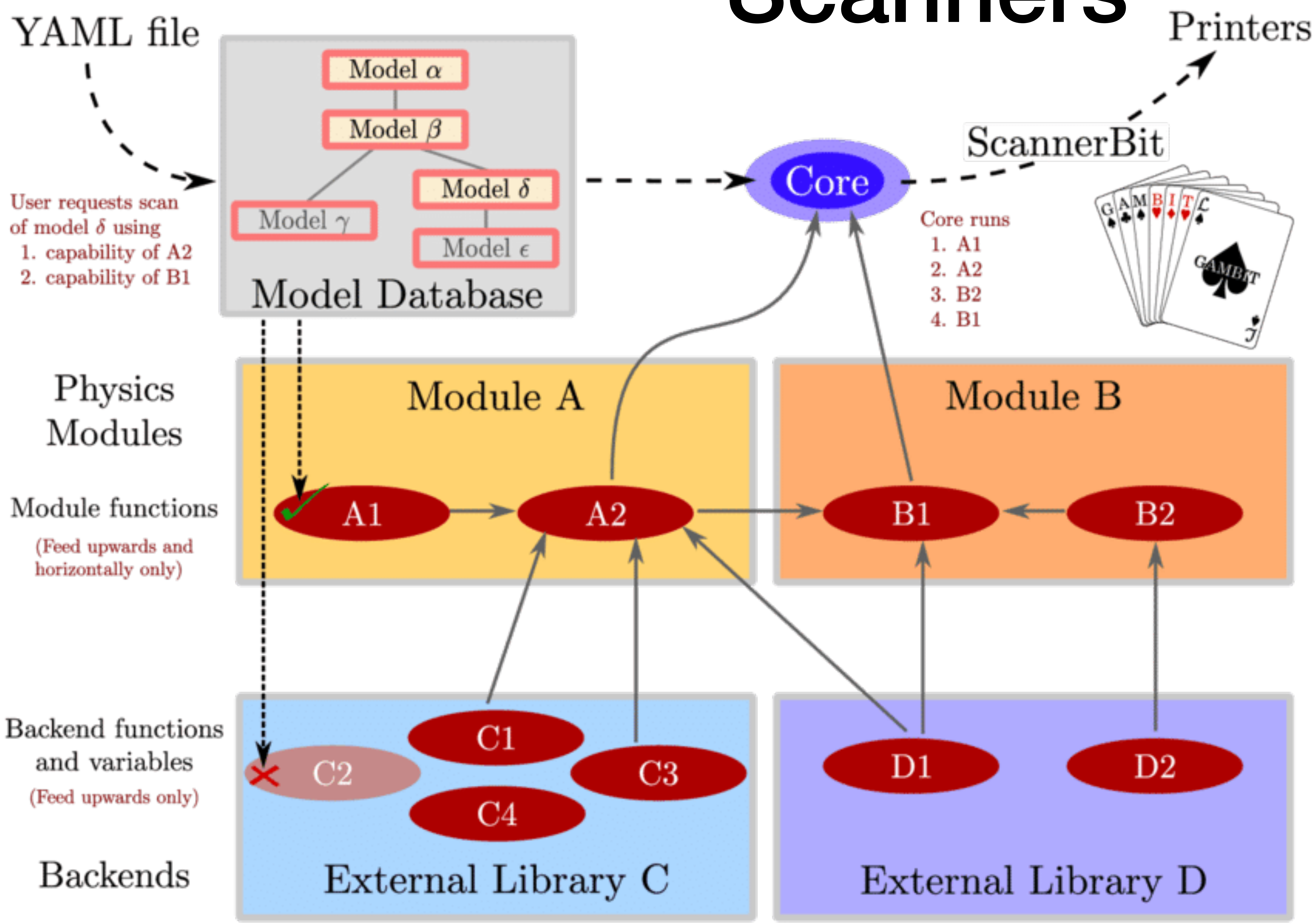
    3. Uses graph-theoretic methods to “solve” the graph to determine order in which to call each function
3. GAMBIT **scans the parameter space** by calling the necessary module and backend functions in the optimal order, for each parameter point

Model

Observables/ likelihoods

Scanners



Scanners

MCMC:
GREAT
T-WALK

Nested Sampling
MultiNest
PolyChord

Differential evolution
Diver

Scanners

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Modules

DarkBit
Dark matter stuff

ColliderBit
Collider stuff

FlavBit
Flavor physics

DecayBit
SM decays …

… you get the idea

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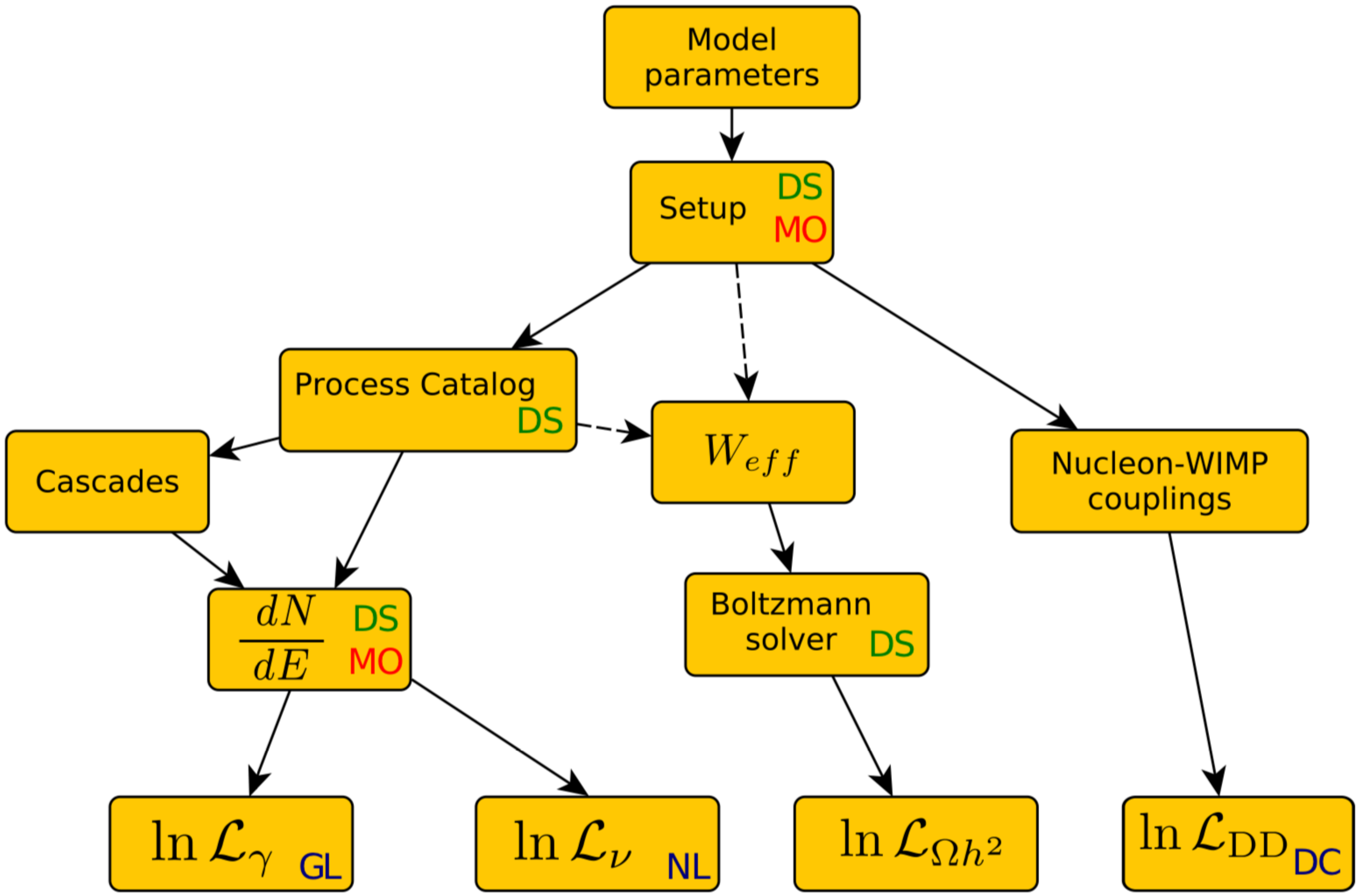
Backends

★ **CaptnGeneral** ★
DDCalc
DarkSUSY
FeynHiggs
HiggsBounds
HiggsSignals
MicrOmegas
Pythia
SPheno
gamLike
★ **nuLike** ★

…

DarkBit



Model parameters
Setup DS MO
Process Catalog DS
Cascades
W_{eff}
Nucleon-WIMP couplings
$\frac{dN}{dE}$ DS MO
Boltzmann solver DS
$\ln \mathcal{L}_\gamma$ GL
$\ln \mathcal{L}_\nu$ NL
$\ln \mathcal{L}_{\Omega h^2}$
$\ln \mathcal{L}_{\rm DD}$ DC

Data in DarkBit

- Direct detection: XENON1T, LZ, LUX, PandaX, PICO, DarkSide, SuperCDMS, CDMSLite,CRESST-II, SIMPLE

- Indirect detection: Fermi-LAT dwarfs, HESS/Fermi/CTA, CMB (Planck), **IceCube-79**

- Cosmology: Planck (more cosmology coming soon with **CosmoBit**)

- Axions: CAST, ALPS, ADMX, RBF, UF, HB stars, SN1987a, …

GAMBIT papers

Supersymmetric dark matter:

- CMSSM/NUHM1/NUHM2 (EPJC, arXiv:1705.07935)
- MSSM7 (EPJC, arXiv:1705.07917)
- 3.3σ local excess in combination of 12 different SUSY searches at the LHC, consistent in the (*non-simplified*) MSSM (EPJC, arXiv:1809.02097)

Other dark matter theories:

- Higgs portal: scalar singlet (EPJC, arXiv:1806.11281)
- Higgs portal: fermionic and vector singlet (EPJC, arXiv:1808.10465)
- Axions and axion-like particles (JHEP arXiv:1810.07192)
- EFT dark matter (coming soon)

Not focused on dark matter:

- Right-handed neutrinos (arXiv:1908.02302)
- Non-standard T_ν, N_{eff}
- Heavy(ish) unstable ALPs

(coming soon)

Slide stolen from Pat Scott

Neutrino telescope data in GAMBIT

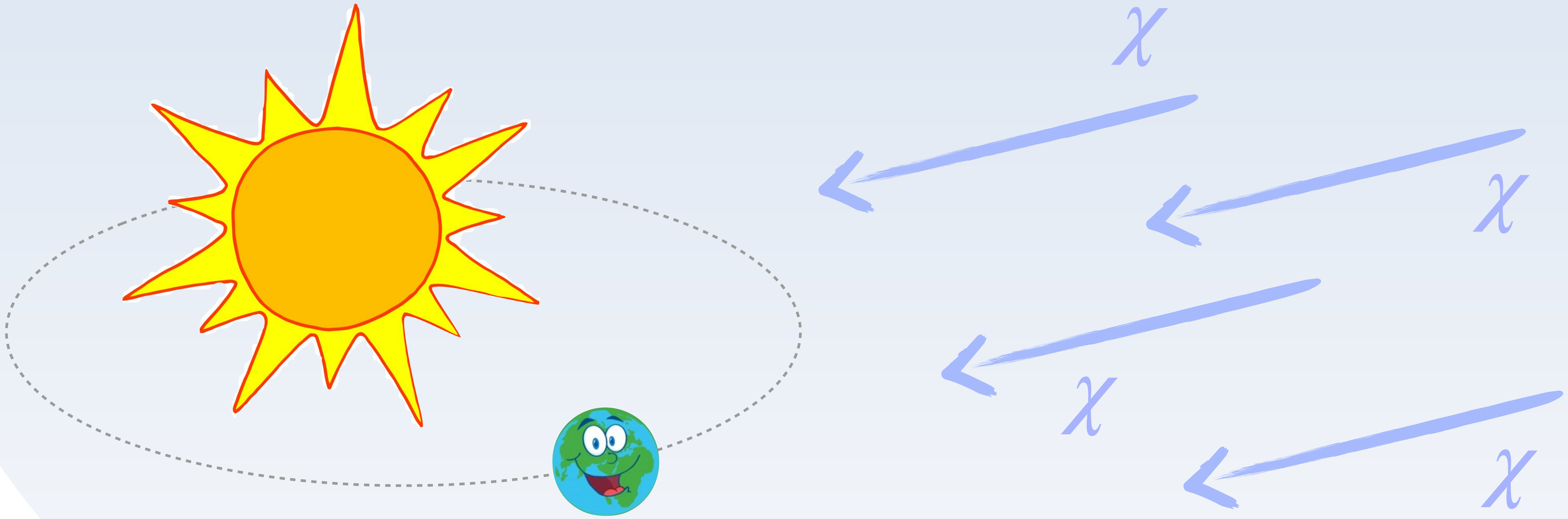
Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector

M. G. Aartsen *et al.* (IceCube Collaboration)
Phys. Rev. Lett. **110**, 131302 – Published 28 March 2013

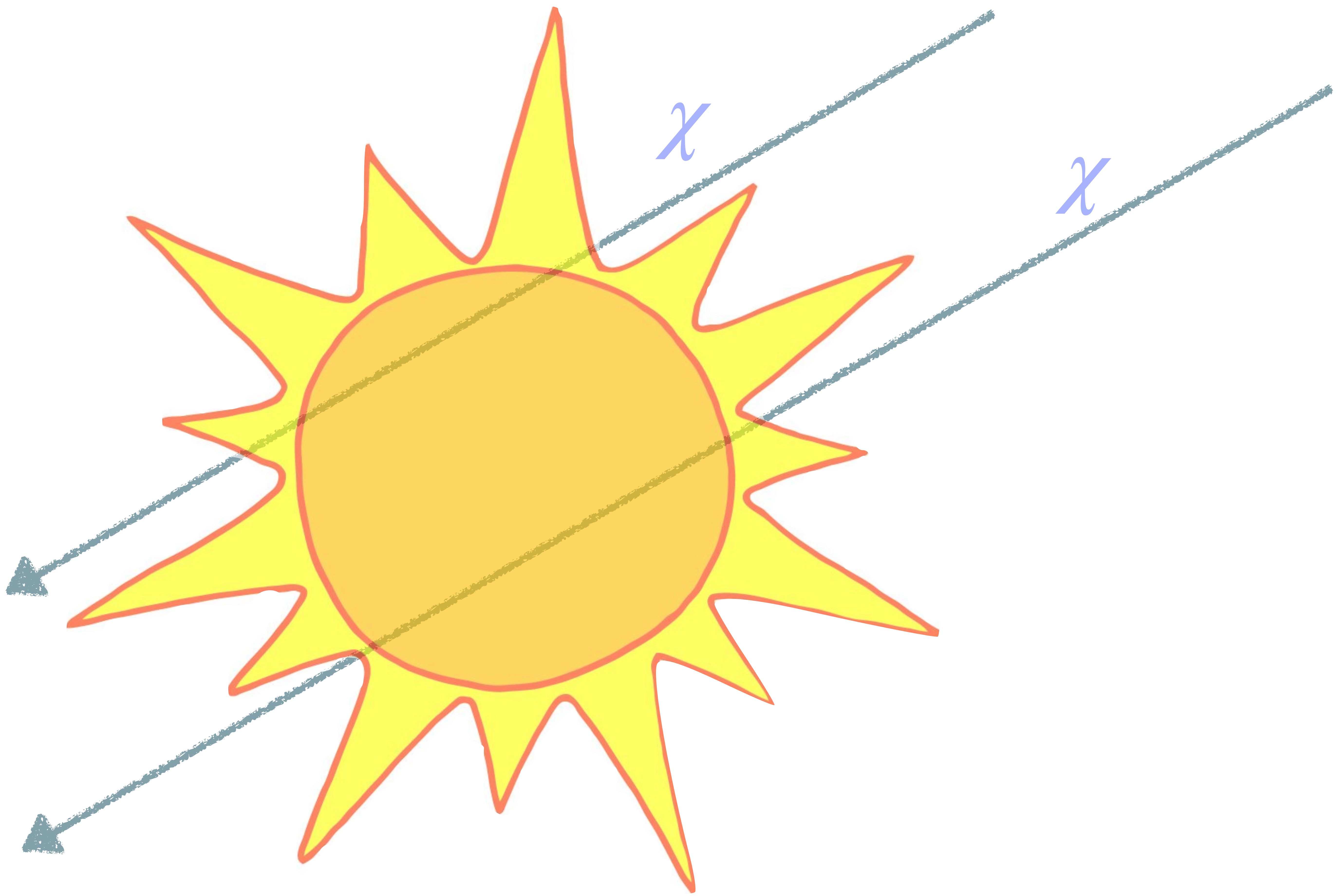
Physics See Synopsis: A Year-Long Search for Dark Matter

Dark matter in the Sun

See also nearly every other talk today



Capture



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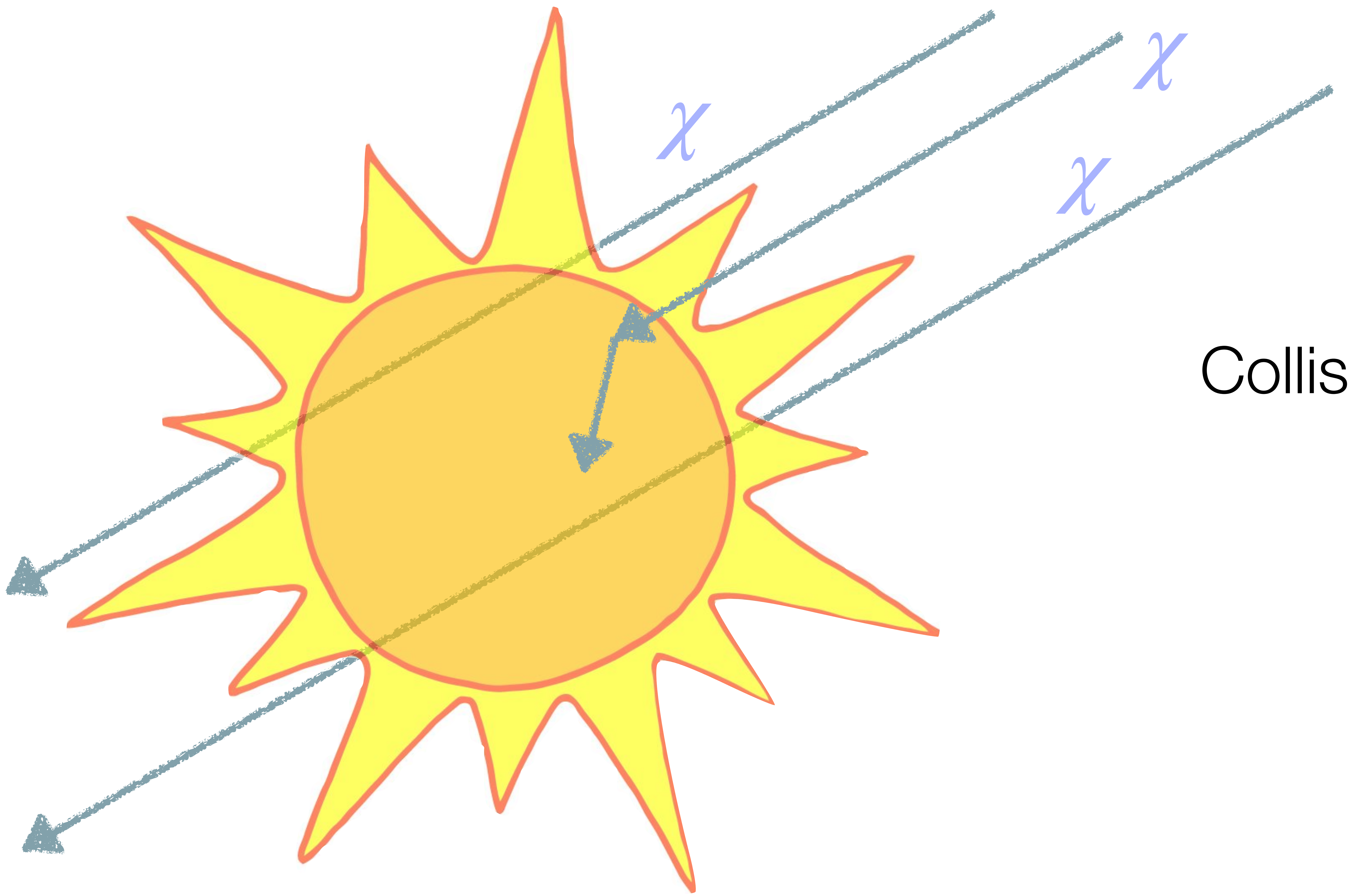
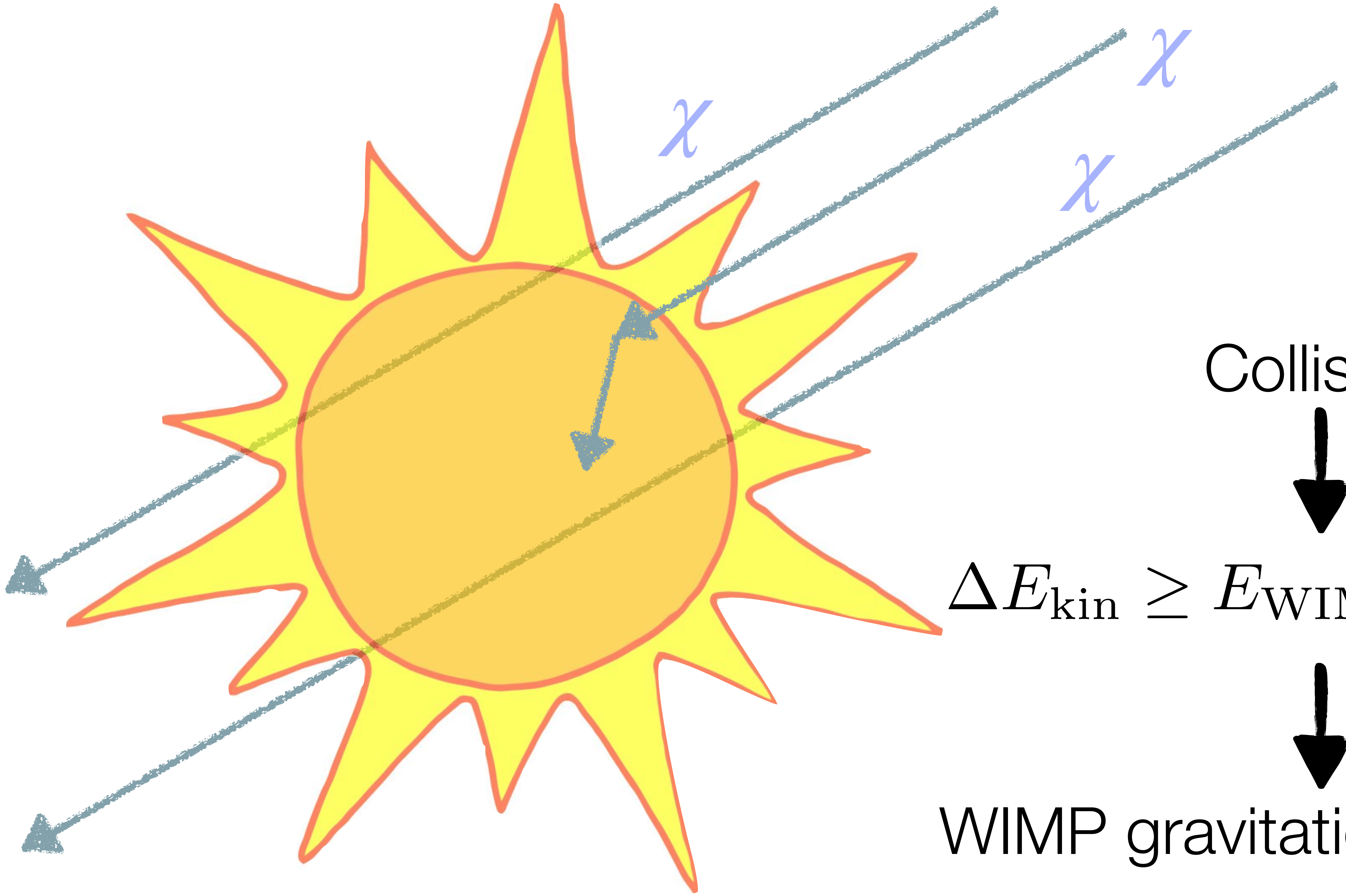


Collision

Capture



Collision

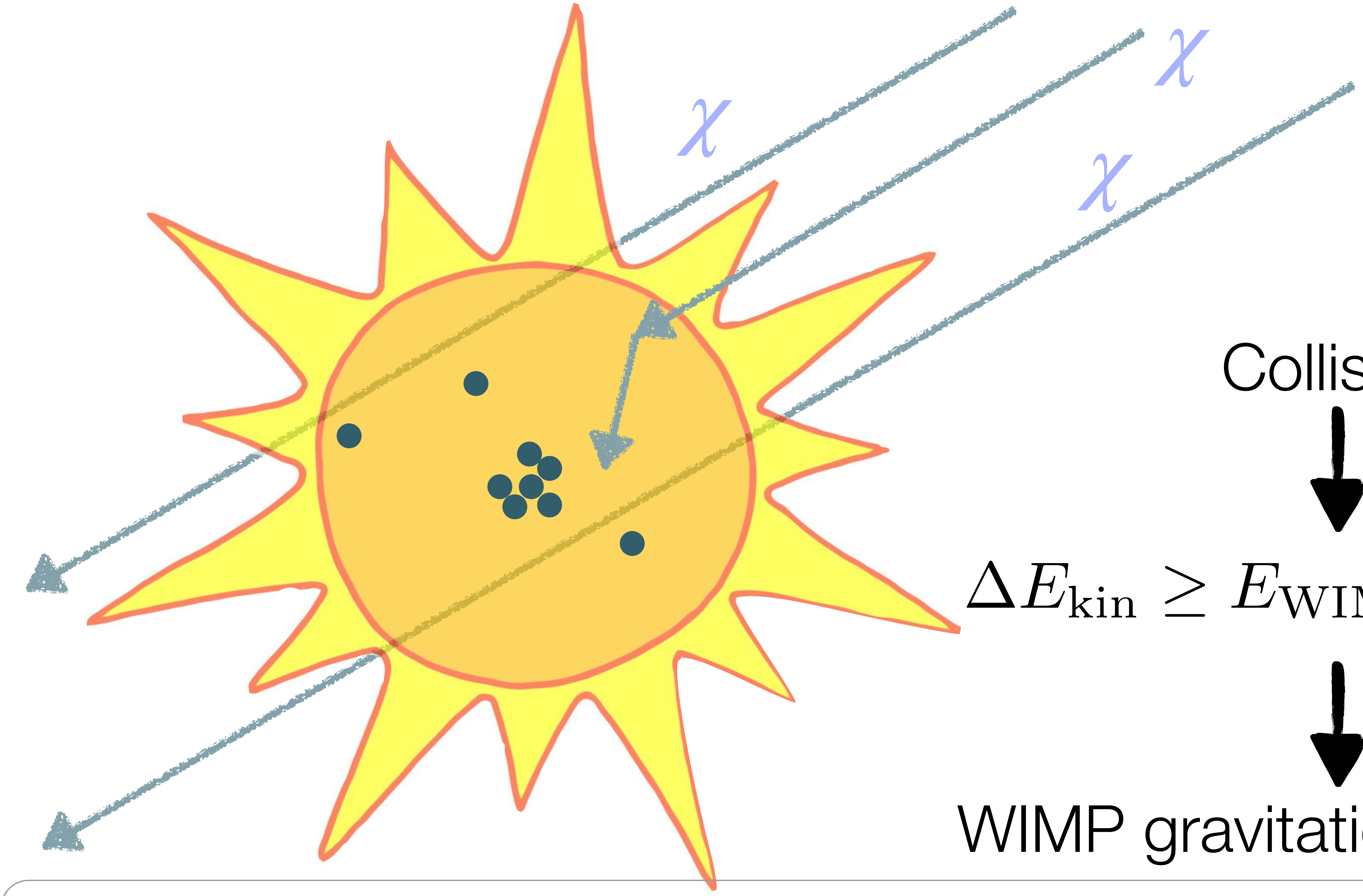
↓

$$\Delta E_{\mathrm{kin}} \geq E_{\mathrm{WIMP}} - E_{\mathrm{escape}}$$

↓

WIMP gravitationally bound

Capture



Collision

$$\Delta E_{\rm kin} \geq E_{\rm WIMP} - E_{\rm escape}$$

WIMP gravitationally bound

Population: $$\frac{dN_\chi}{dt} = C(t) - 2A(t) - E(t)$$

Capture rate

Velocity distribution in the Sun's frame

Chance to scatter below v_{esc}

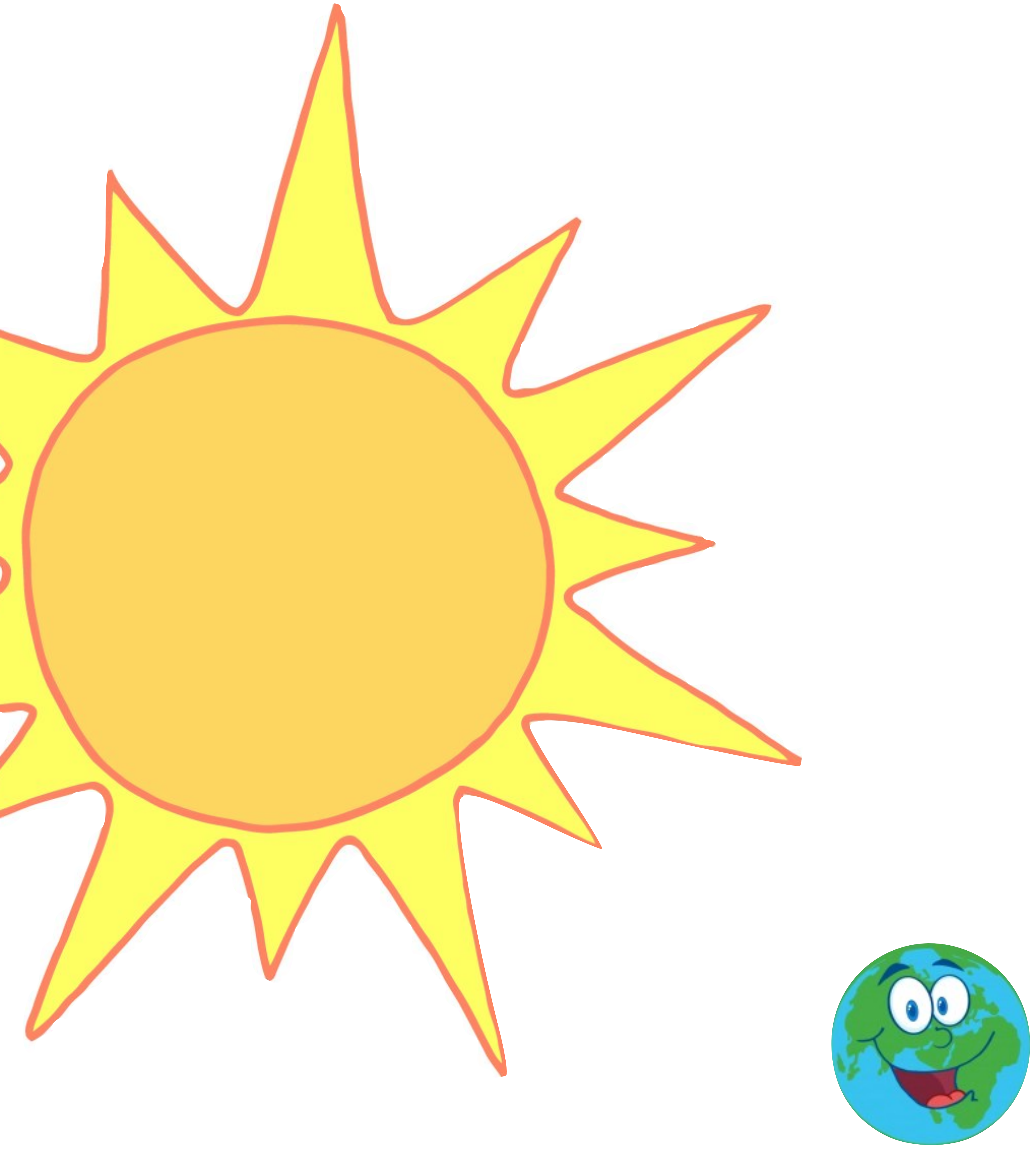
$$C_\odot(t) = 4\pi \int_0^{R_\odot} r^2 \int_0^\infty \frac{f_\odot(u)}{u} w\Omega(w)\, \mathrm{d}u\, \mathrm{d}r.$$

Saturation

$$\sigma_{\max} = \pi R_\odot^2(t),$$

$$\begin{aligned} C_{\max}(t) &= \pi R_\odot^2(t) \int_0^\infty \frac{f_\odot(u)}{u} w^2(u, R_\odot)\, \mathrm{d}u \\ &= \frac{1}{3}\pi \frac{\rho_\chi}{m_\chi} R_\odot^2(t) \left(e^{-\frac{3}{2}\frac{u_\odot^2}{u_0^2}} \sqrt{\frac{6}{\pi}} u_0 + \frac{6 G_\mathrm{N} M_\odot + R_\odot(u_0^2 + 3u_\odot^2)}{R_\odot u_\odot} \mathrm{Erf}\left[\sqrt{\frac{3}{2}} \frac{u_\odot}{u_0} \right] \right) \end{aligned}$$

Annihilation to (things that decay to) neutrinos



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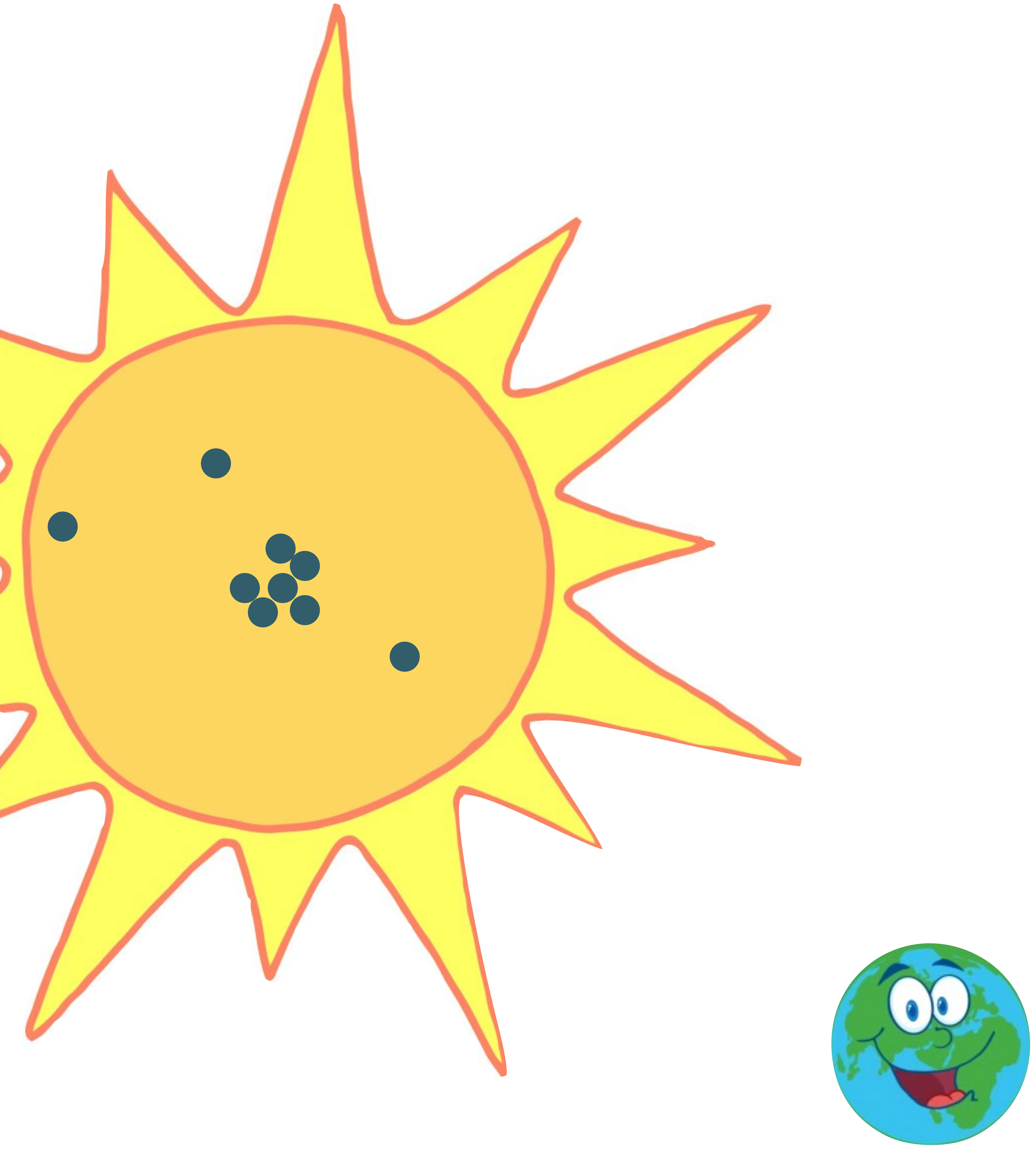

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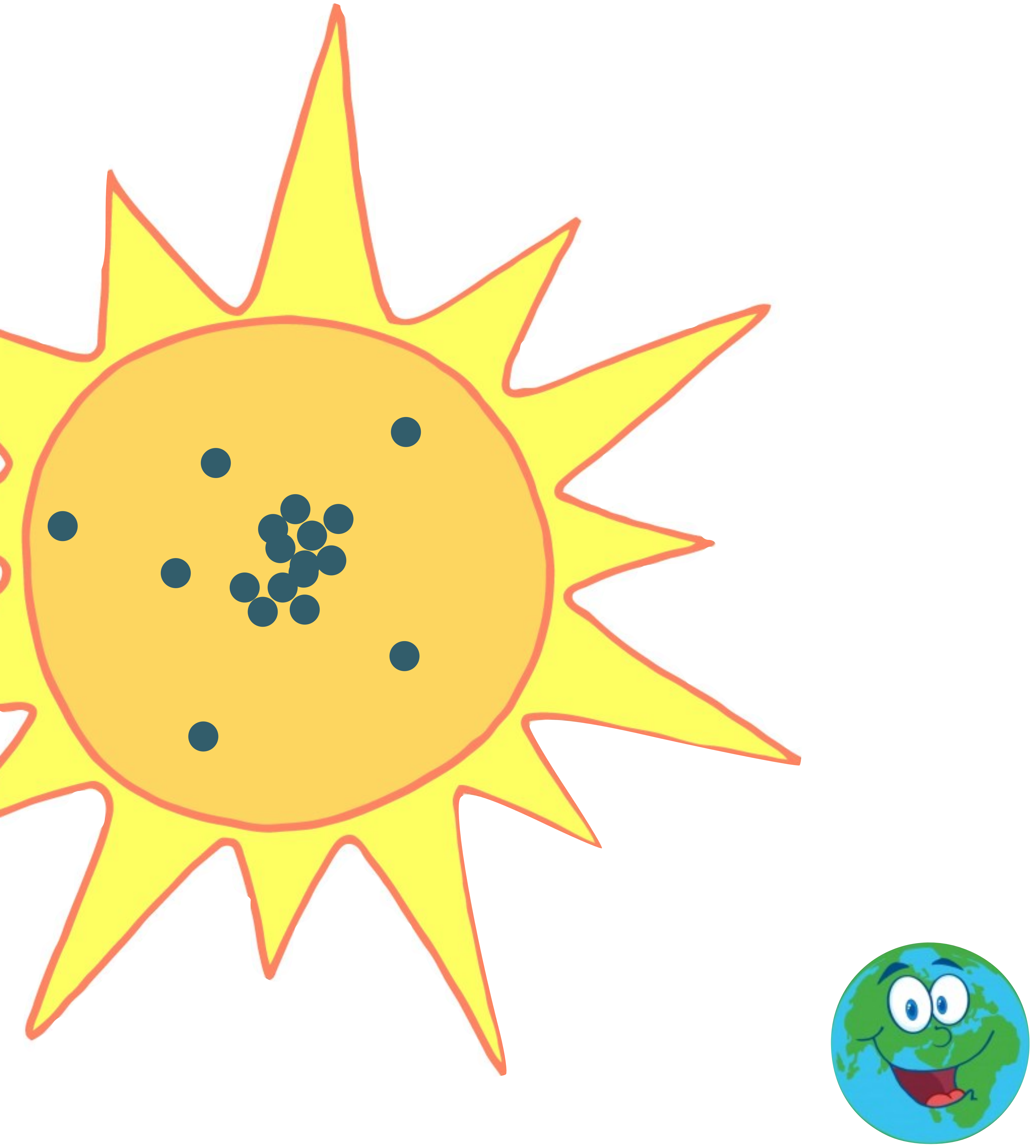

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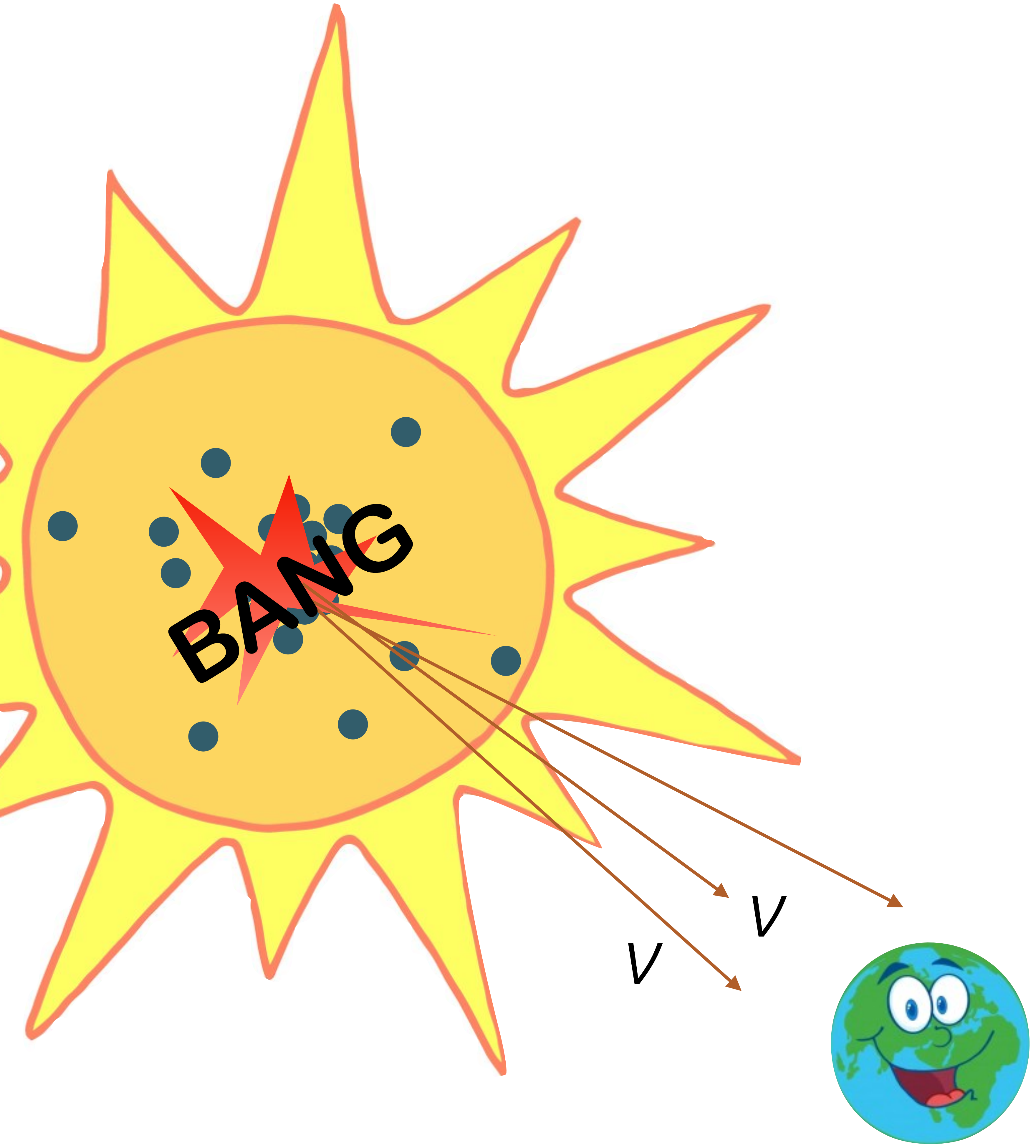

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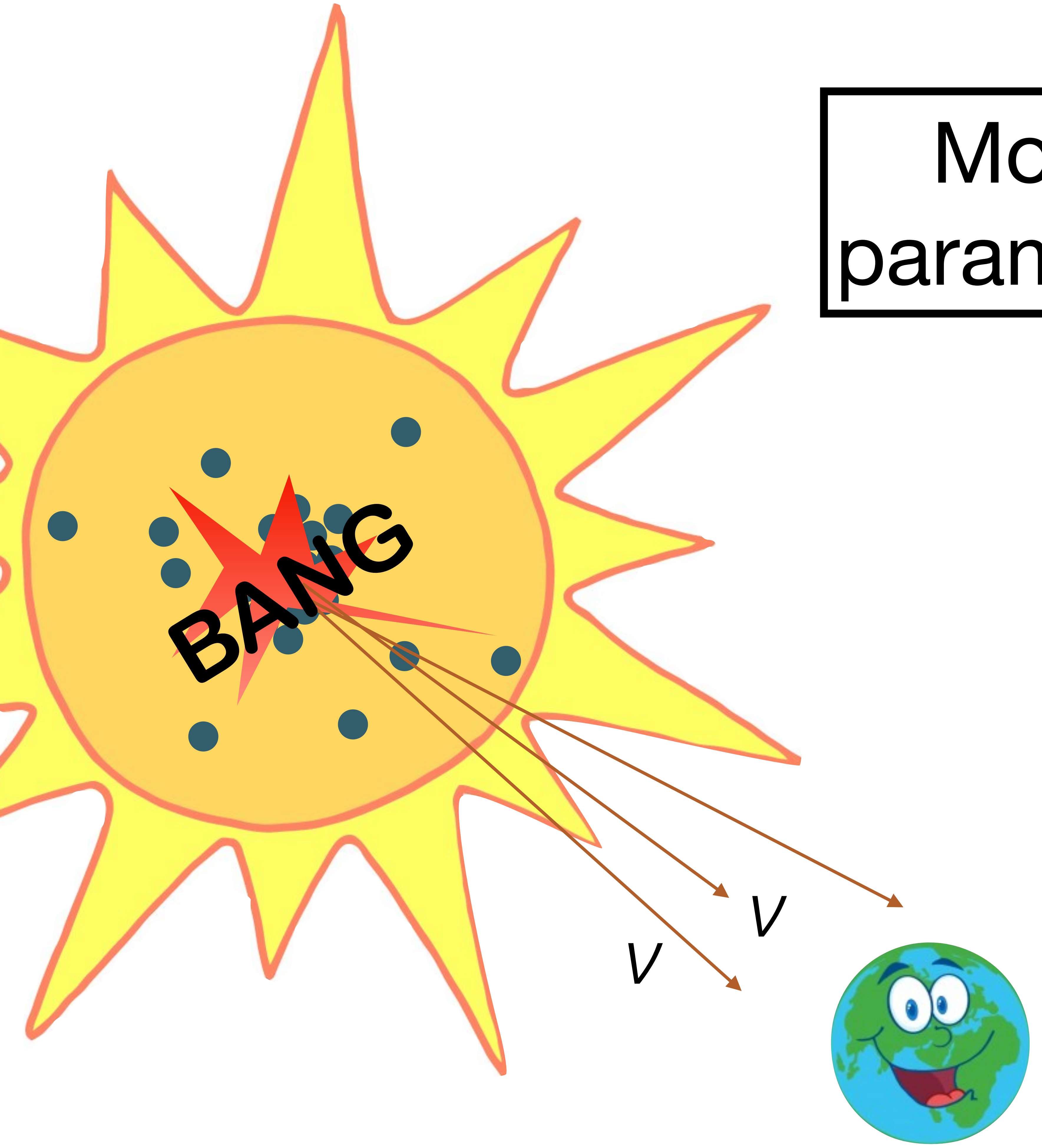

Model parameters

DarkBit:
computes
cross sections
annihilation rate

DarkSUSY
or
Capt'n General
Capture rates

DarkSUSY
computes fluxes

NuLike
computes
likelihoods
from data

Captn' general

Standalone code that calculates and returns the capture rate of dark matter given

e.g. Higgs-portal DM: axial coupling gives q^2 supppression to capture cross section

-mass
-cross section at reference v/q
-interaction type

$$\sigma = \sigma_0 \left(\frac{v_{\rm rel}}{v_0}\right)^n \quad \sigma = \sigma_0 \left(\frac{q}{q_0}\right)^n$$

Lives here: https://github.com/aaronvincent/captngen

Fortran 90 :-)

Can be compiled as a standalone program or as a shared library (e.g. for the GAMBIT backend, but also compatible with stellar evolution software)

CapGen v2: Non-relativistic effective operators (NREO)

$\mathcal{O}_1$	$1_\chi 1_N$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
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$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
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$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
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$v^\perp$ Component of relative velocity perpendicular to momentum transfer

q Exchanged momentum (scattering angle)

S_χ Dark matter spin

S_N Nucleon spin

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$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

$v^\perp$ Component of relative velocity perpendicular to momentum transfer

q Exchanged momentum (scattering angle)

S_χ Dark matter spin

S_N Nucleon spin

Note that if the spin of the target nucleus is zero, the average of e.g.

$$S_N \cdot \vec{q}$$

is not necessarily zero

Higgs portal Dark Matter

One of the simplest DM models

$$\mathcal{L} \sim \frac{\mu^2}{2} X^2 - \frac{\lambda}{2} X^2 H^\dagger H + \ldots$$

X = scalar (spin 0), fermion (spin 1/2, Majorana or Dirac), or vector (spin 1) gauge singlet with Z2 symmetry for stability

Scalar: EPJC, 1806.11281

Vector & Fermion: EPJC, 1808.10465

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gauge singlet with Z2 symmetry for stability

Interaction with Higgs gives usual DM phenomenology:

- Direct detection (including neutrinos from the Sun!)
- Indirect detection
- Thermal production
- Monojets at LHC
- But wait there’s more: Invisible Higgs decay at LHC

Scalar: EPJC, 1806.11281
Vector & Fermion: EPJC, 1808.10465

Higgs portal

Free parameters

Pre-EWSB Mass: μ

Effective coupling to $H^\dagger H$: λ/Λ

CP-violating phase: $\sin\theta$

Higgs portal

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Pre-EWSB Mass: μ

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Nuisance parameters

Parameter		Value (±Range)
Local DM density	ρ_0	0.2–$0.8\,\mathrm{GeV\,cm^{-3}}$
Most probable speed	v_{peak}	$240\,(24)\,\mathrm{km\ s^{-1}}$
Galactic escape speed	v_{esc}	$533\,(96)\,\mathrm{km\ s^{-1}}$
Nuclear matrix element	σ_s	$43\,(24)\,\mathrm{MeV}$
Nuclear matrix element	σ_l	$50\,(45)\,\mathrm{MeV}$
Higgs pole mass	m_h	124.1–$127.3\,\mathrm{GeV}$
Strong coupling	$\alpha_s^{\overline{MS}}(m_Z)$	$0.1181\,(33)$

Higgs portal

Free parameters

Pre-EWSB Mass: μ

Effective coupling to $H^\dagger H$: λ/Λ

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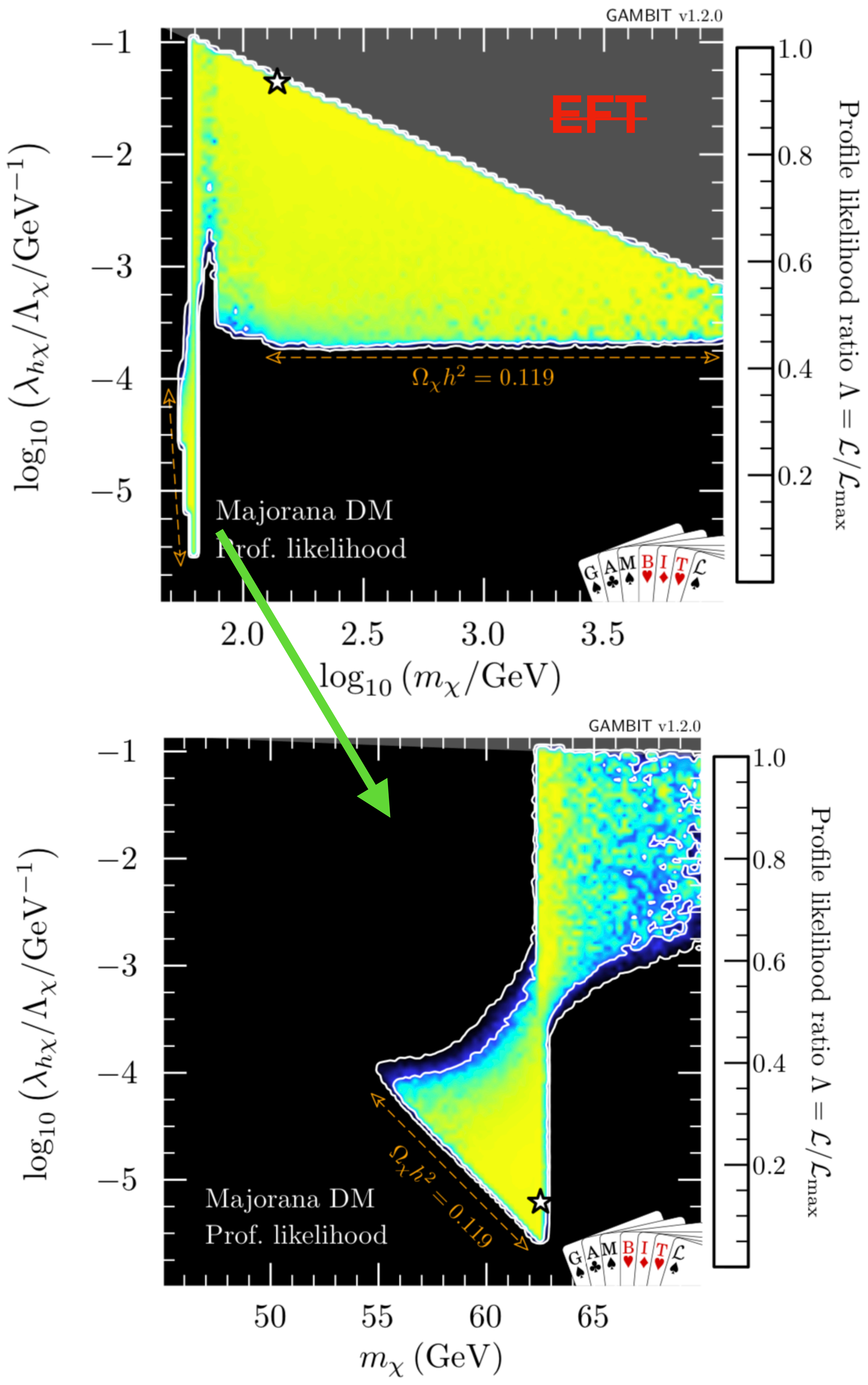
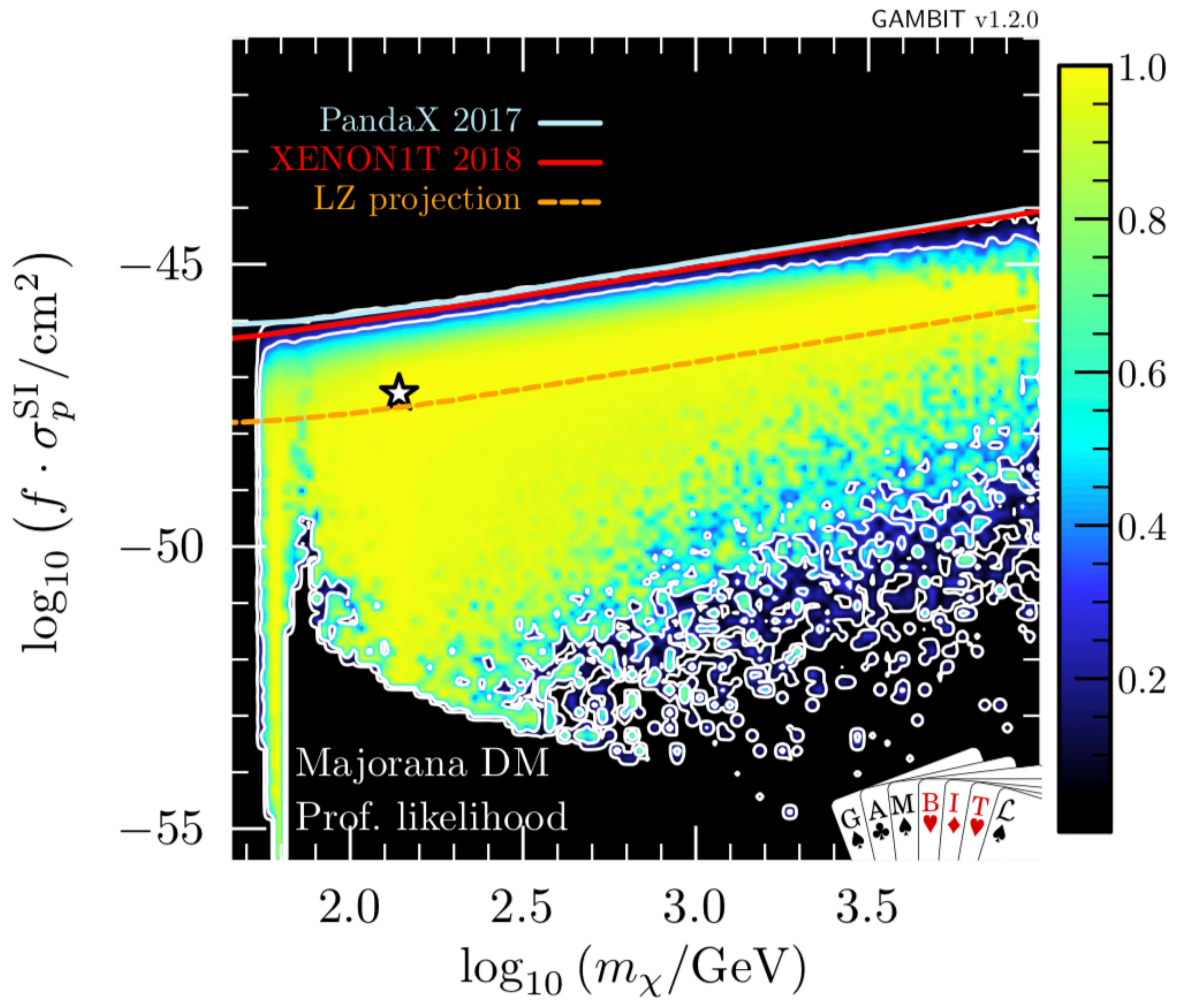
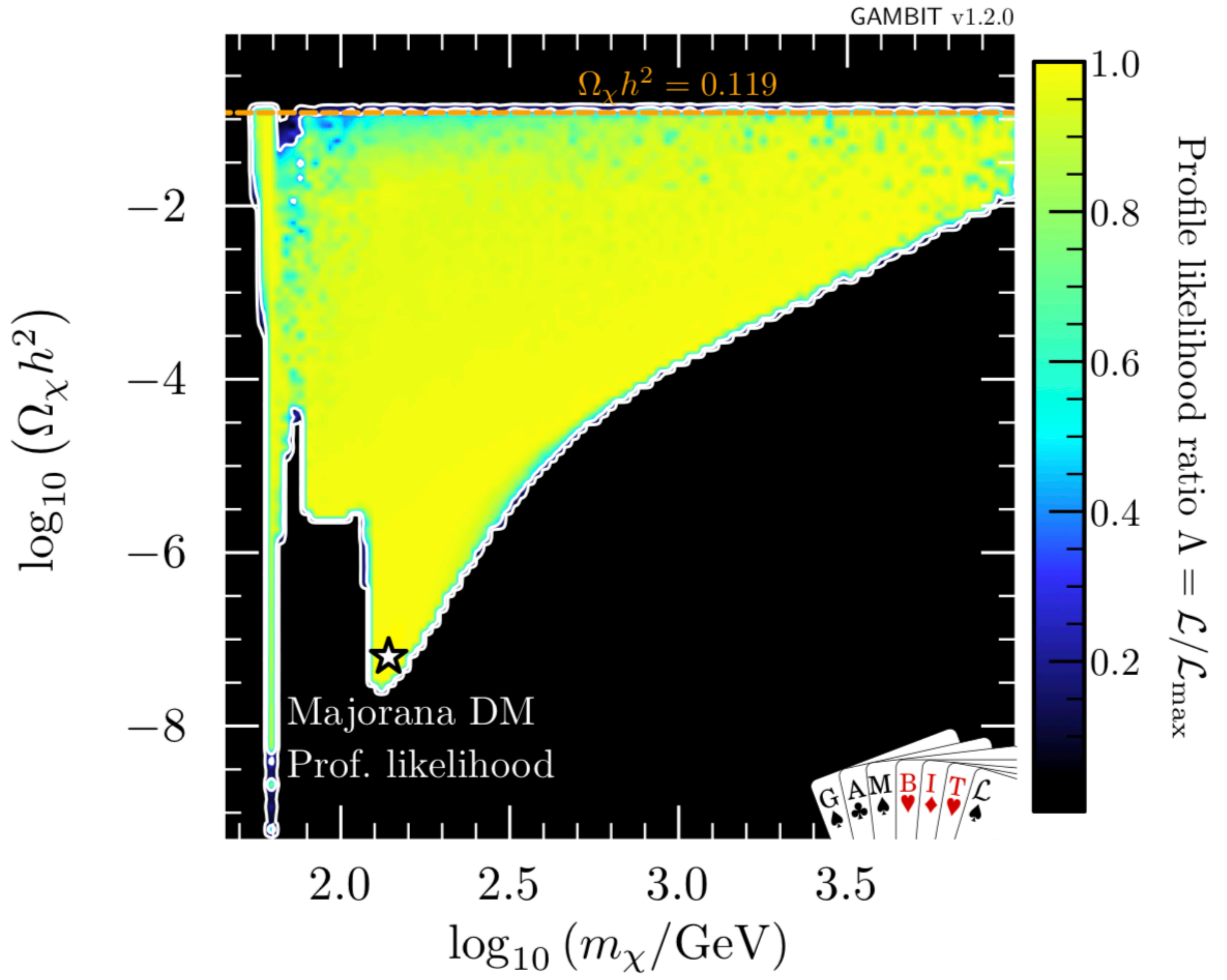
Data

Likelihoods	GAMBIT modules/backends
Relic density (*Planck*)	DarkBit
Higgs invisible width	DecayBit
Fermi-LAT dSphs	gamLike 1.0.0
LUX 2016 (Run II)	DDCalc 2.0.0
PandaX 2016	DDCalc 2.0.0
PandaX 2017	DDCalc 2.0.0
XENON1T 2018	DDCalc 2.0.0
CDMSlite	DDCalc 2.0.0
CRESST-II	DDCalc 2.0.0
PICO-60 2017	DDCalc 2.0.0
DarkSide-50 2018	DDCalc 2.0.0
IceCube 79-string	nulike 1.0.6

Higgs Portal: Majorana DM





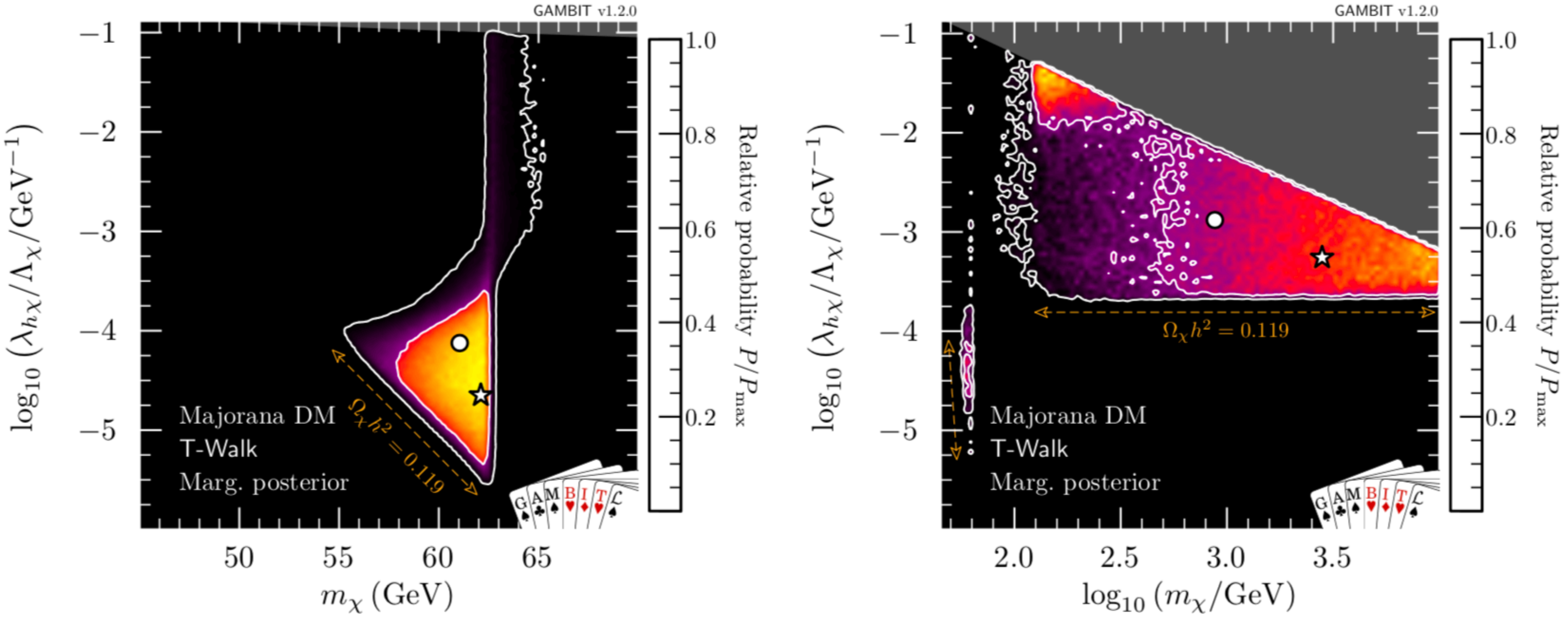


Direct detection and RD most constraining, but
Allowed candidates in nearly entire mass range!

CP violation $\theta = \pi/2$ preferred (suppresses direct detection signal ~ q^2)

See https://arxiv.org/pdf/1808.10465.pdf for Dirac, Vector DM, Posterior distributions

(For the Bayesians)



	$\Delta \ln \mathcal{L}$						
Log-likelihood contribution	Ideal	V_μ	V_μ + RD	χ	χ + RD	ψ	ψ + RD
Relic density	5.989	0.000	0.106	0.000	0.107	0.000	0.242
Higgs invisible width	0.000	0.000	0.000	0.000	0.001	0.000	0.000
γ rays (*Fermi*-LAT dwarfs)	−33.244	0.105	0.105	0.102	0.120	0.129	0.134
LUX 2016 (Run II)	−1.467	0.003	0.003	0.020	0.000	0.028	0.028
PandaX 2016	−1.886	0.002	0.002	0.013	0.000	0.018	0.017
PandaX 2017	−1.550	0.004	0.004	0.028	0.000	0.039	0.039
XENON1T 2018	−3.440	0.208	0.208	0.143	0.211	0.087	0.087
CDMSlite	−16.678	0.000	0.000	0.000	0.000	0.000	0.000
CRESST-II	−27.224	0.000	0.000	0.000	0.000	0.000	0.000
PICO-60 2017	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DarkSide-50 2018	−0.090	0.000	0.000	0.002	0.000	0.005	0.005
IceCube 79-string	0.000	0.000	0.000	0.000	0.000	0.001	0.001
Hadronic elements σ_s, σ_l	−6.625	0.000	0.000	0.000	0.000	0.000	0.000
Local DM density ρ_0	1.142	0.000	0.000	0.000	0.000	0.000	0.000
Most probable DM speed $v_{\rm peak}$	−2.998	0.000	0.000	0.000	0.000	0.000	0.000
Galactic escape speed $v_{\rm esc}$	−4.382	0.000	0.000	0.000	0.000	0.000	0.000
$\alpha_{\rm s}$	5.894	0.000	0.000	0.000	0.000	0.000	0.000
Higgs mass	0.508	0.000	0.000	0.000	0.000	0.000	0.000
Total	86.051	0.322	0.428	0.308	0.439	0.307	0.553

These models don’t give a spin-dependent elastic scattering cross section at tree level, so no surprise

But wait, aren't there 86 strings at IceCube? And other neutrino telescopes?

- Need data/likelihoods that can be recast as widely as possible!
- Specifically:
  - event-by-event energies
  - angle from Sun,
  - Angular resolution
  - effective area, (area **and** volume preferable)
  - Energy response
  - exposure

Want to contribute?

gambit.hepforge.org

- GAMBIT code is public, and so are results, samples, best fits, …
  https://www.zenodo.org/communities/gambit-official

- The WIMP (and SUSY) are far from dead

- Neutrino telescopes are underrepresented. We need more data!

- Get in touch — there are many ways to contribute to GAMBIT

- 2 PhD studentships available at U. Of Queensland, Brisbane (at least one to work on neutrinos) with Pat Scott starting next year! Keep an eye on INSPIRE

- Much more GAMBIT goodness to come…

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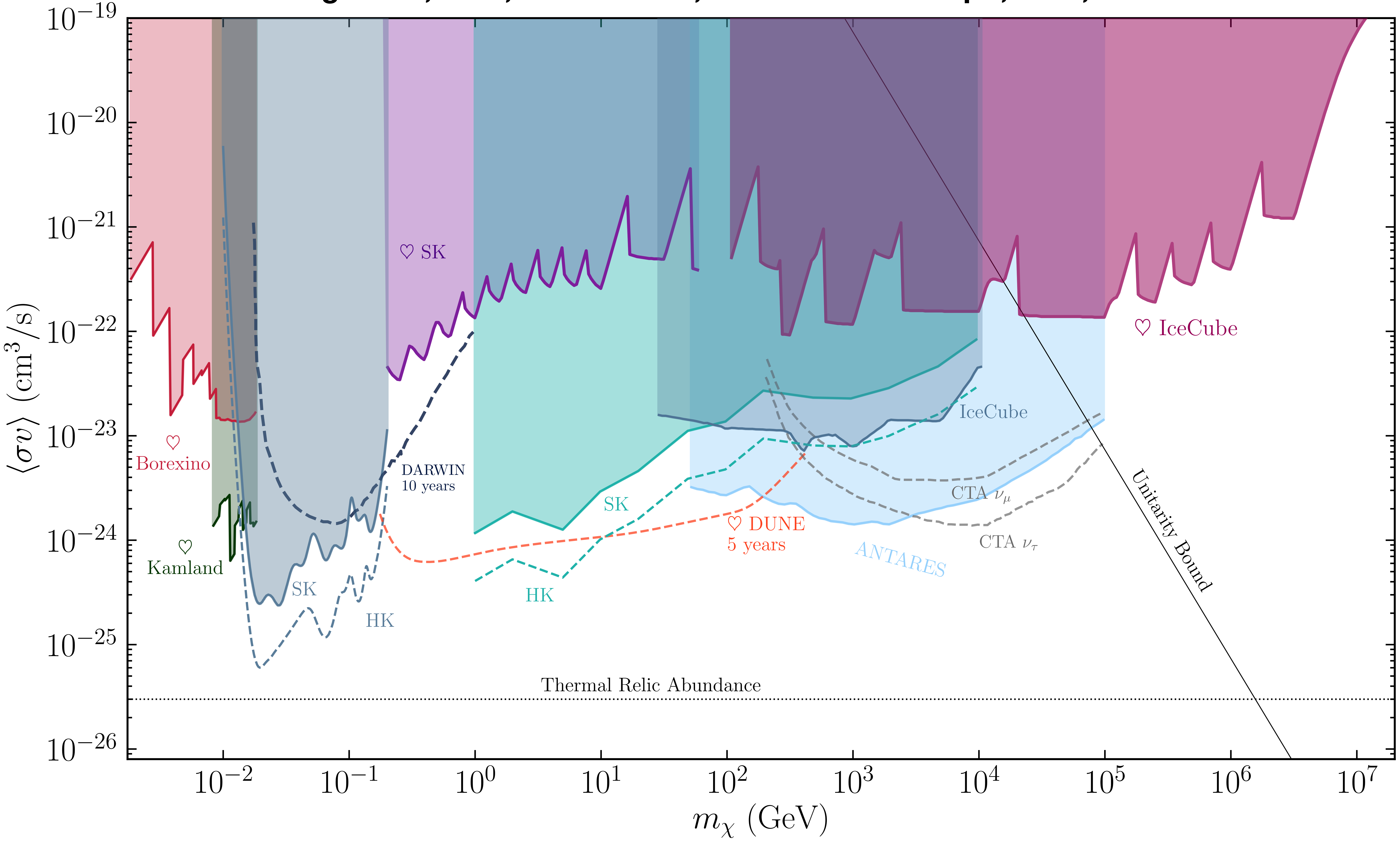
DM annihilation into Neutrinos

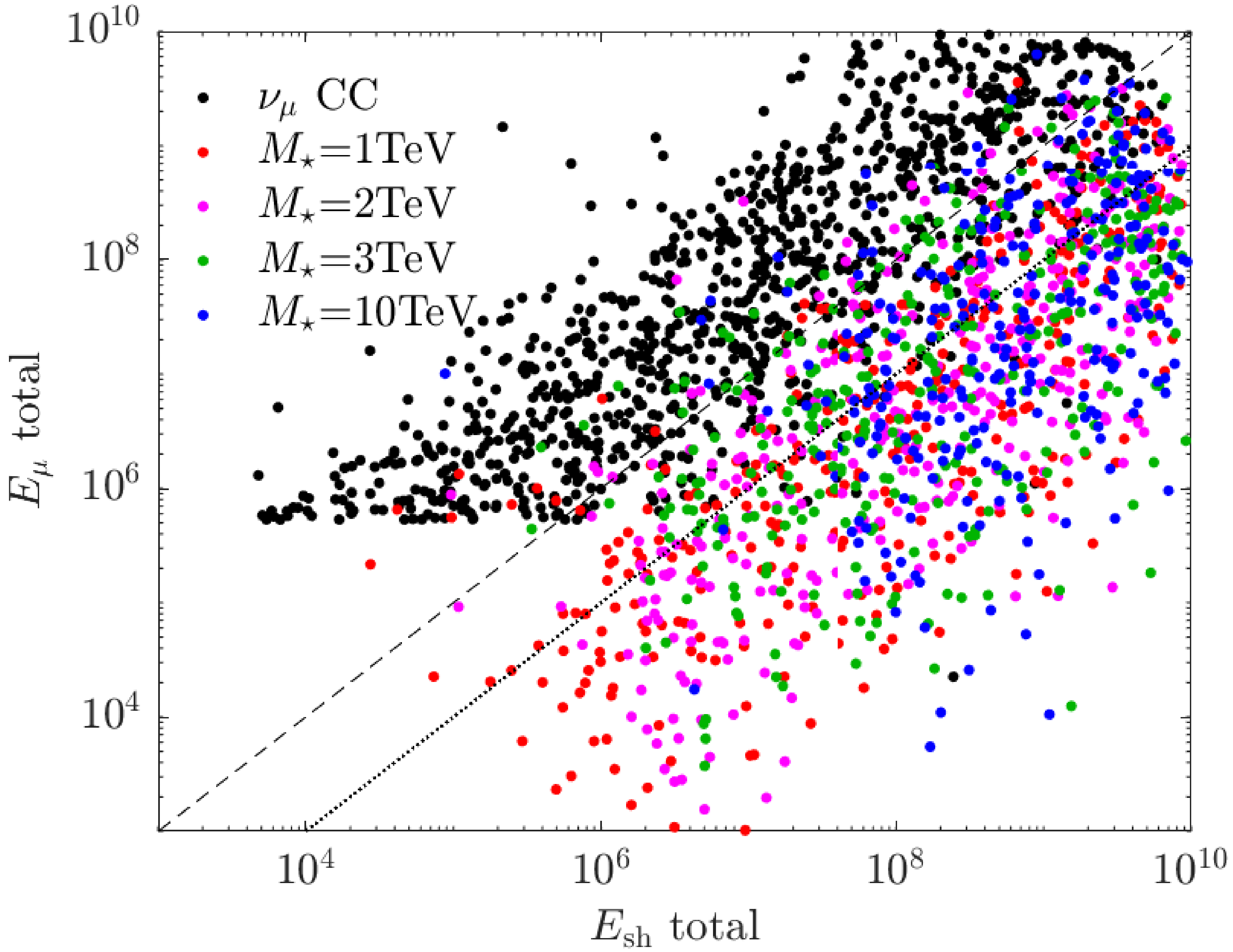
Arguelles, Diaz, Kheirandish, Olivares-del-Campo, Safa, ACV

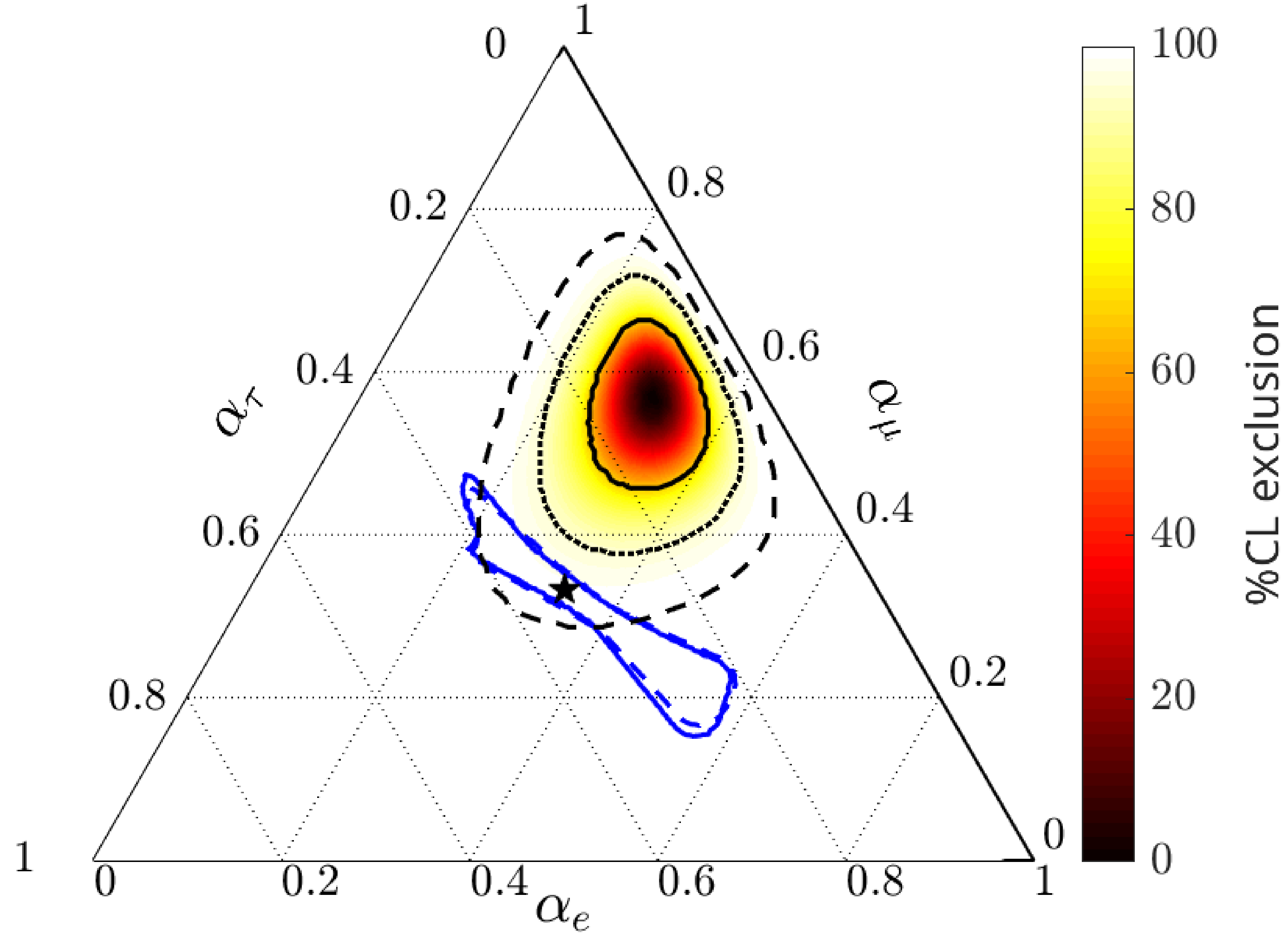


Coming soon!

Black Holes at IceCube?

K. Mack, N. Song, ACV

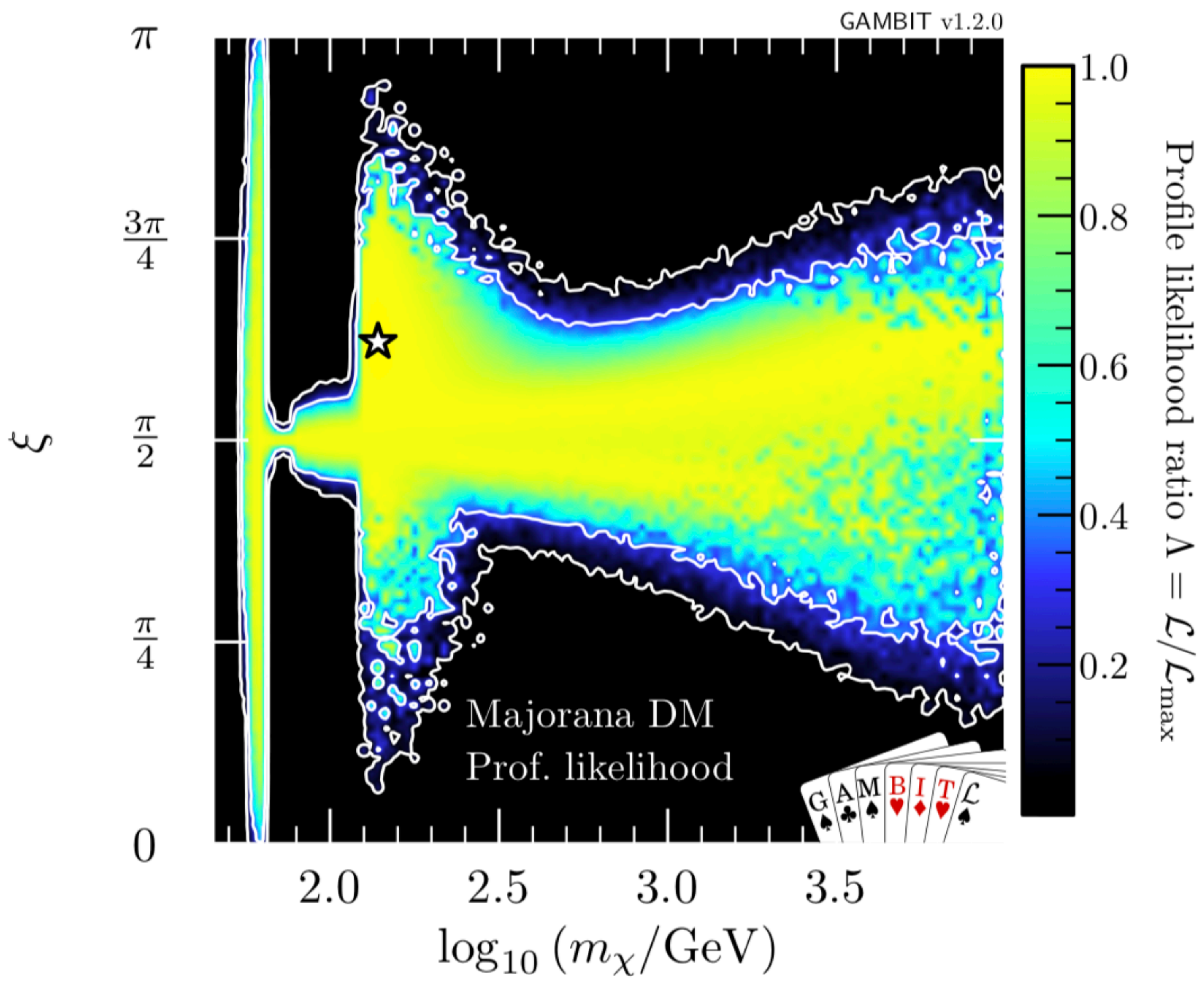


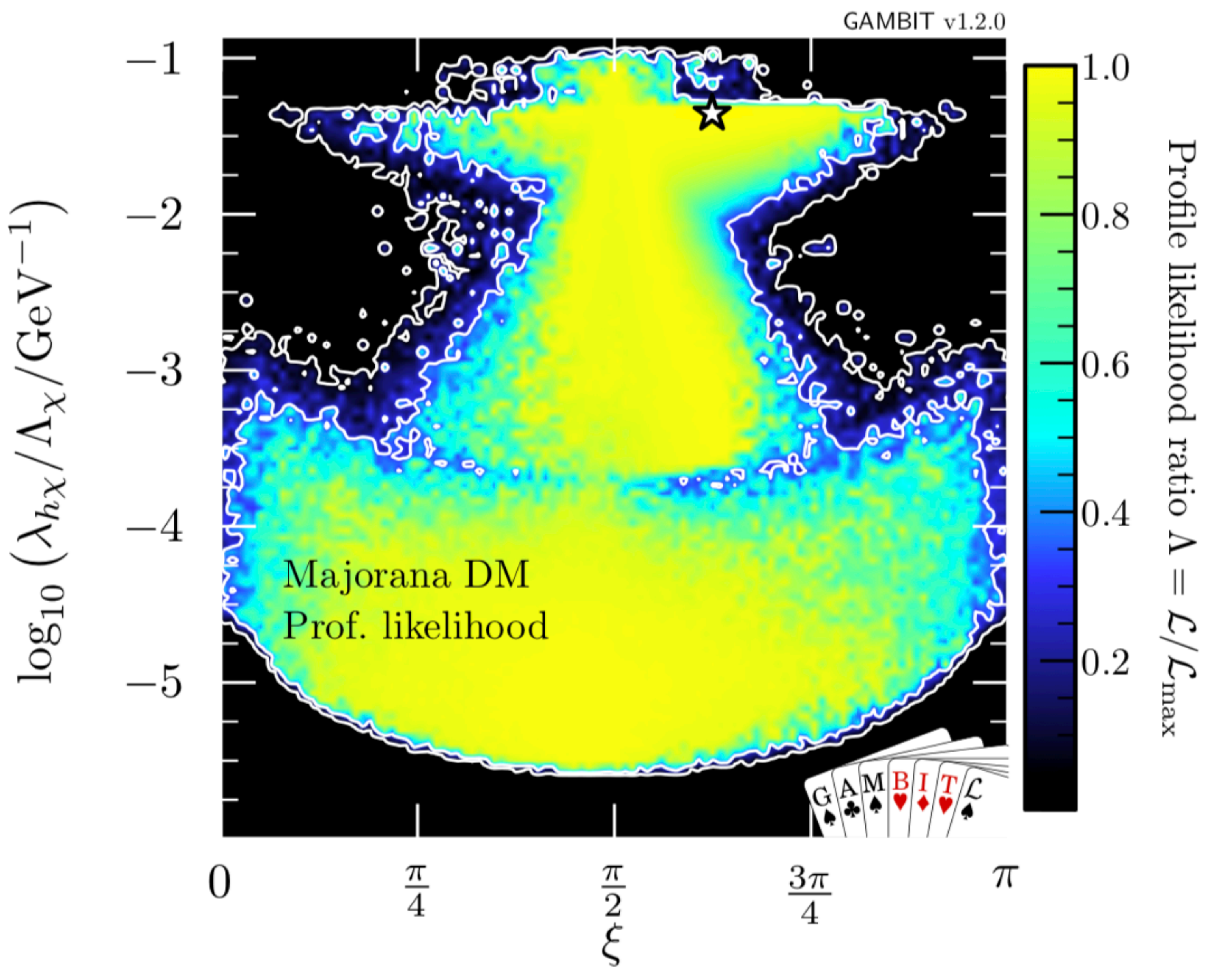


Coming soon!

Thanks

Majorana DM





$$\frac{d\sigma_{\rm SI}^X}{dq^2} = \frac{1}{v^2}\left(\frac{\lambda_{hX}}{\Lambda_X}\right)^2 \frac{A^2F^2(E)f_N^2 m_N^2}{4\pi m_h^4} \times \left(\cos^2\xi + \frac{q^2}{4m_X^2}\sin^2\xi\right),$$

Model	Relic density condition	λ_{hX}	m_X (GeV)	ξ (rad)	$\Omega_X h^2$	$\Delta \ln \mathcal{L}$
Vector	$\Omega_V h^2 \lesssim \Omega_{DM} h^2$	4.9×10^{-4}	62.46	—	9.343×10^{-2}	0.322
	$\Omega_V h^2 \sim \Omega_{DM} h^2$	4.5×10^{-4}	62.46	—	1.128×10^{-1}	0.428
Majorana	$\Omega_\chi h^2 \lesssim \Omega_{DM} h^2$	4.5×10^{-2} GeV^{-1}	138.4	1.96	6.588×10^{-8}	0.308
	$\Omega_\chi h^2 \sim \Omega_{DM} h^2$	6.3×10^{-6} GeV^{-1}	61.03	1.41	1.128×10^{-1}	0.439
Dirac	$\Omega_\psi h^2 \lesssim \Omega_{DM} h^2$	6.3×10^{-4} GeV^{-1}	9.950×10^3	2.06	3.813×10^{-2}	0.307
	$\Omega_\psi h^2 \sim \Omega_{DM} h^2$	3.6×10^{-4} GeV^{-1}	9.895×10^3	2.07	1.155×10^{-1}	0.553

Bayes factors

Model	Comparison model and priors			Odds
$\xi = 0$	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	70:1
$g_\mathrm{p}/\Lambda_\mathrm{p} = 0$	m_χ: log	$g_\mathrm{s}/\Lambda_\mathrm{s}$: log	$g_\mathrm{p}/\Lambda_\mathrm{p}$: log	140:1

Table 8: Odds ratios for CP violation for the singlet Majorana fermion Higgs portal model. Here the odds ratios are those against a pure CP-even Higgs portal coupling, as compared to two different parametrisations (and thus priors) of the model in which the CP nature of the Higgs portal can vary freely.

Model	Parameters and priors			Odds
S		m_S: log	λ_{hS}: log	1:1
V_μ		m_V: log	λ_{hV}: log	6:1
χ	m_χ: log	$\lambda_{h\chi}/\Lambda_\chi$: log	ξ: flat	1:1
ψ	m_ψ: log	$\lambda_{h\psi}/\Lambda_\psi$: log	ξ: flat	1:1

Table 9: Odds ratios against each singlet Higgs portal DM model with $\mathbb{Z}_2$ symmetry, relative to the scalar model.