Dark Matter in 2022:
A (parameter) Space Odyssey

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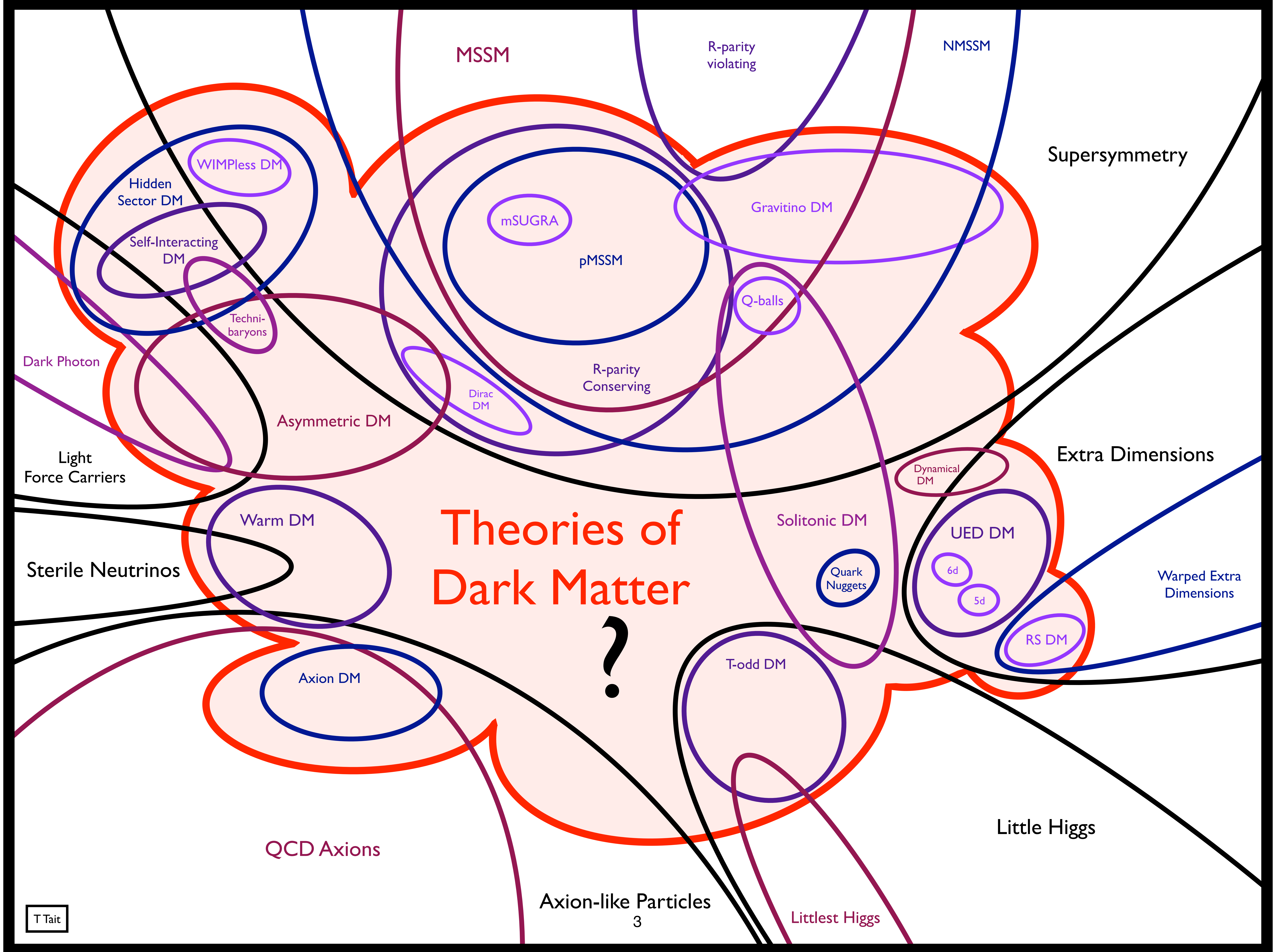
33e Rencontres de Blois | May 23 2022

TeV Particle Astrophysics

TeVPA 2022

AUGUST 8-12
QUEEN'S UNIVERSITY
KINGSTON, ON

https://indico.cern.ch/e/TeVPA2022


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Quark Nuggets
6d
5d
Warped Extra Dimensions
Sterile Neutrinos
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

(Dark matter exists)

A Map of The Charted and Uncharted Territories of Dark Matter and its Theories

A. C. Vincent

Cold dark matter

The WIMP

Exploring other Shores

Problems with CDM? ($\lesssim$ 2015)

Missing dwarfs: MW galaxy has only a fraction of total satellite galaxies compared with DM-only simulations

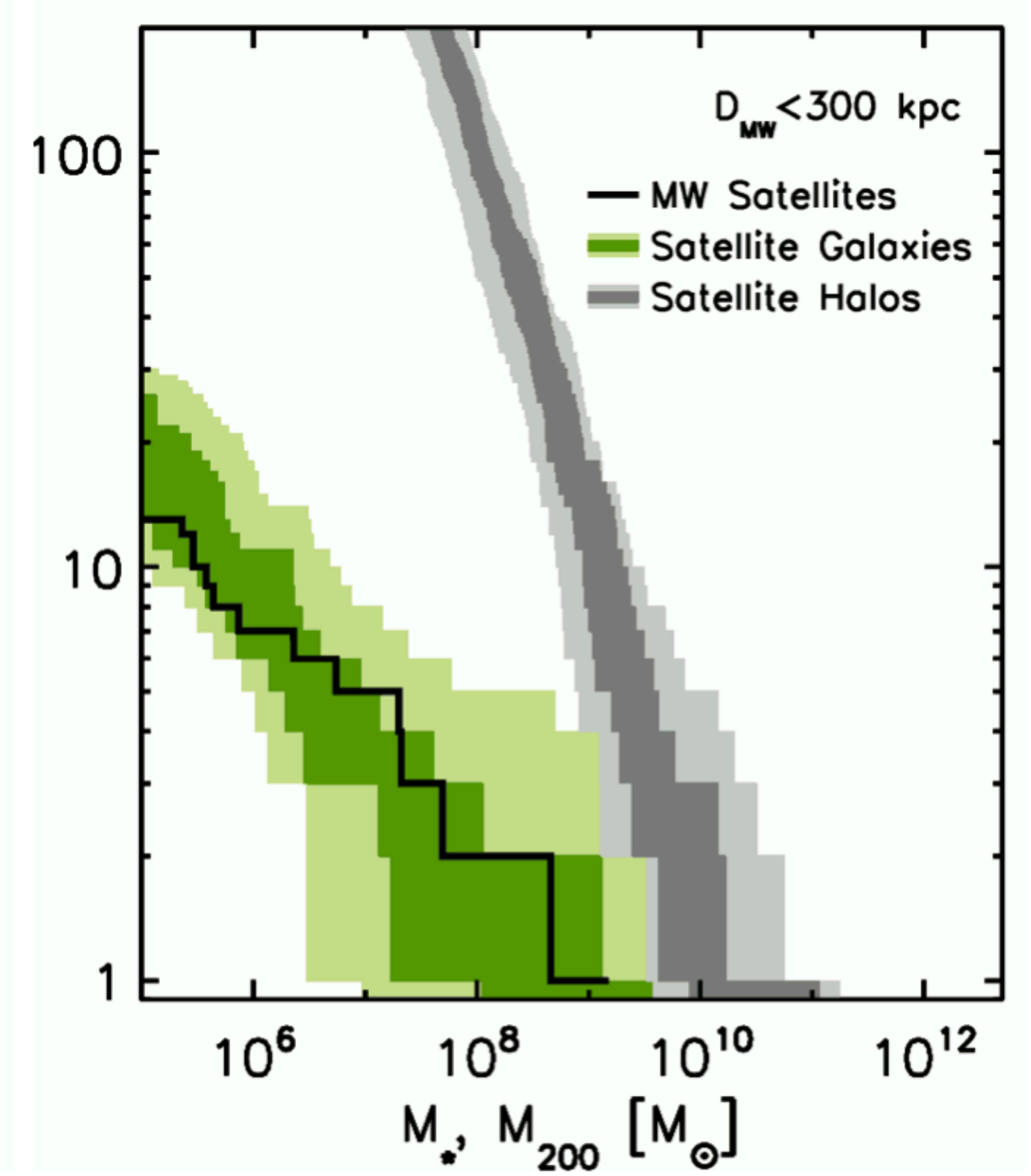
Too big to fail: MW galaxy contains only ~ 1/3 of the largest satellite halos vs DM-only simulations

Core/Cusp Controversy: DM-only simulations predict a universally cuspy profile; dwarf galaxies appear to be cored

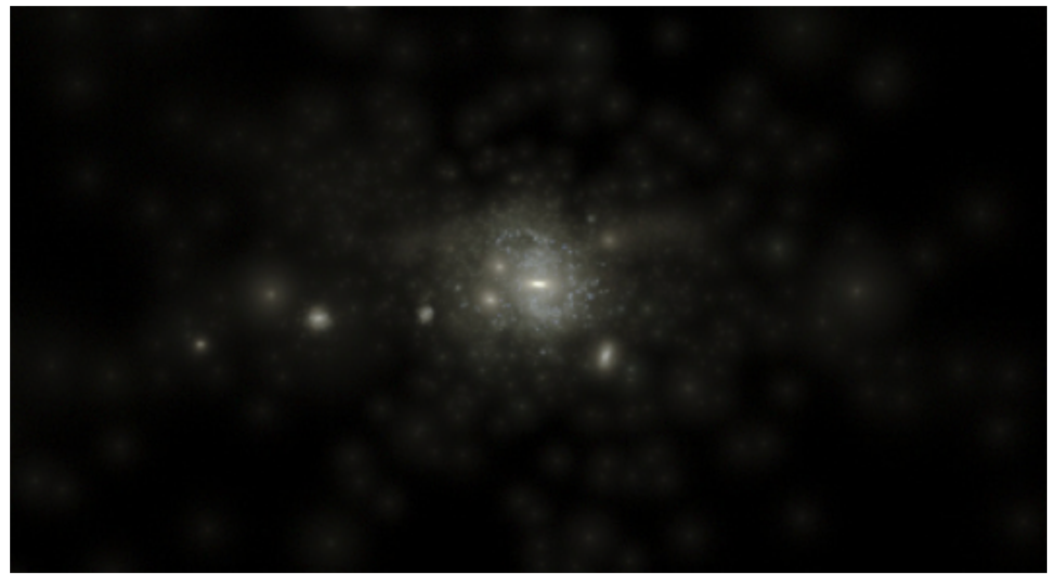
Diversity problem, alignment problem, ….

Still used as a very strong motivation for alternatives to CDM

APOSTLE Simulations: DM + Baryons — Sawala et al. 1511.01098

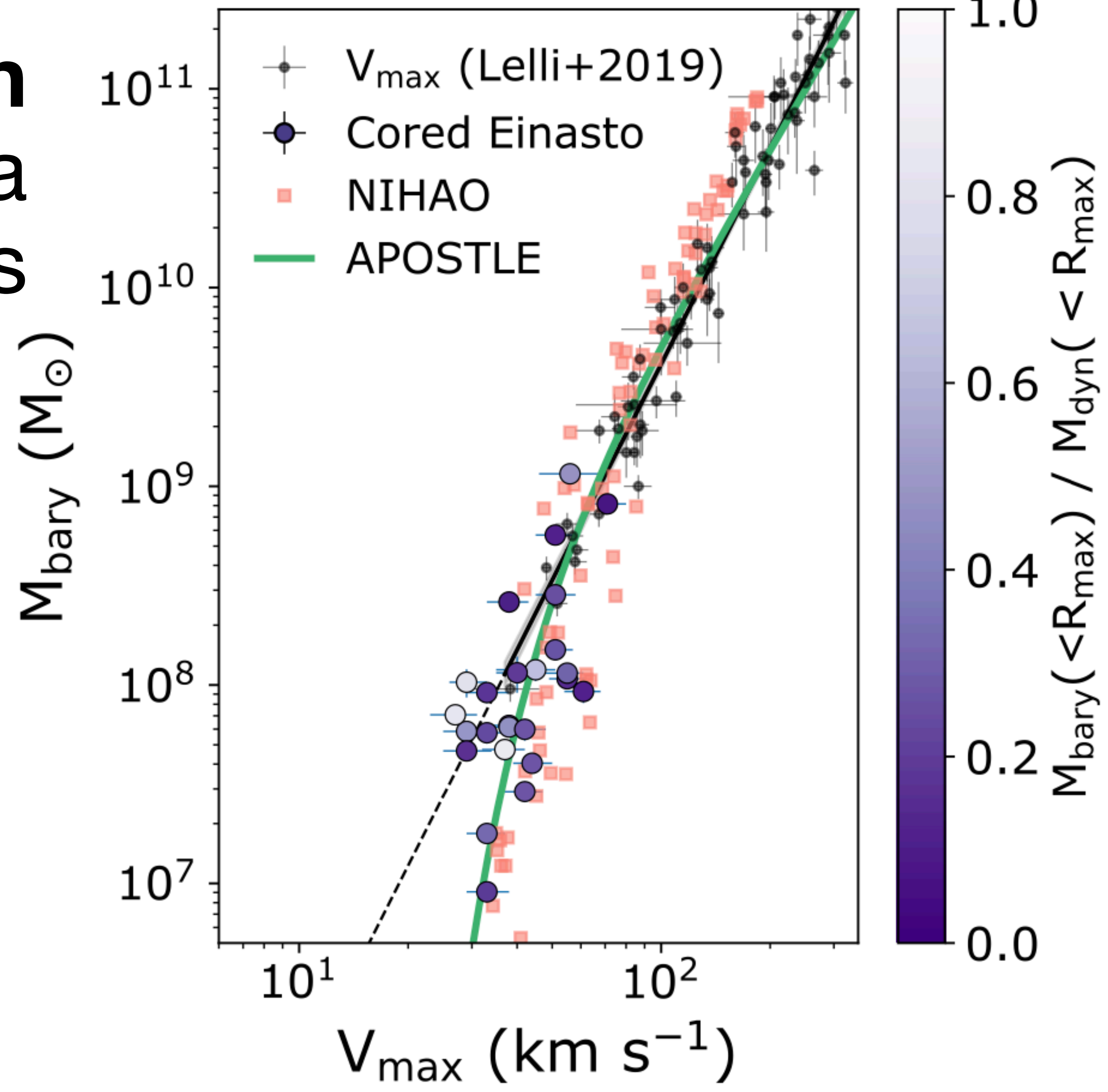


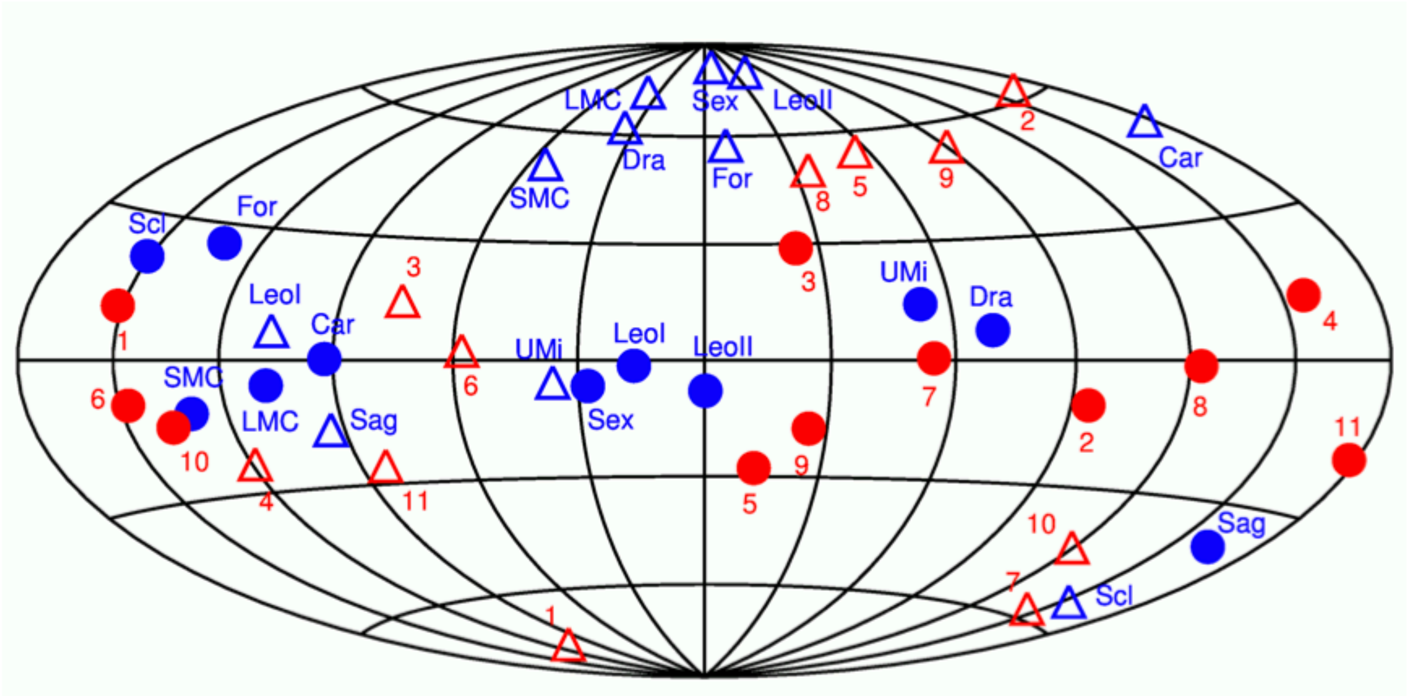
Baryonic feedback leads to a reduction in mass of smaller galaxies and, combined with **reionization**, of baryonic content in larger ones (“baryon bailout”)



Baryonic Tully-Fisher relation in simulations and data consistent with **cored** dwarfs

McQuinn et al. 2203.10105



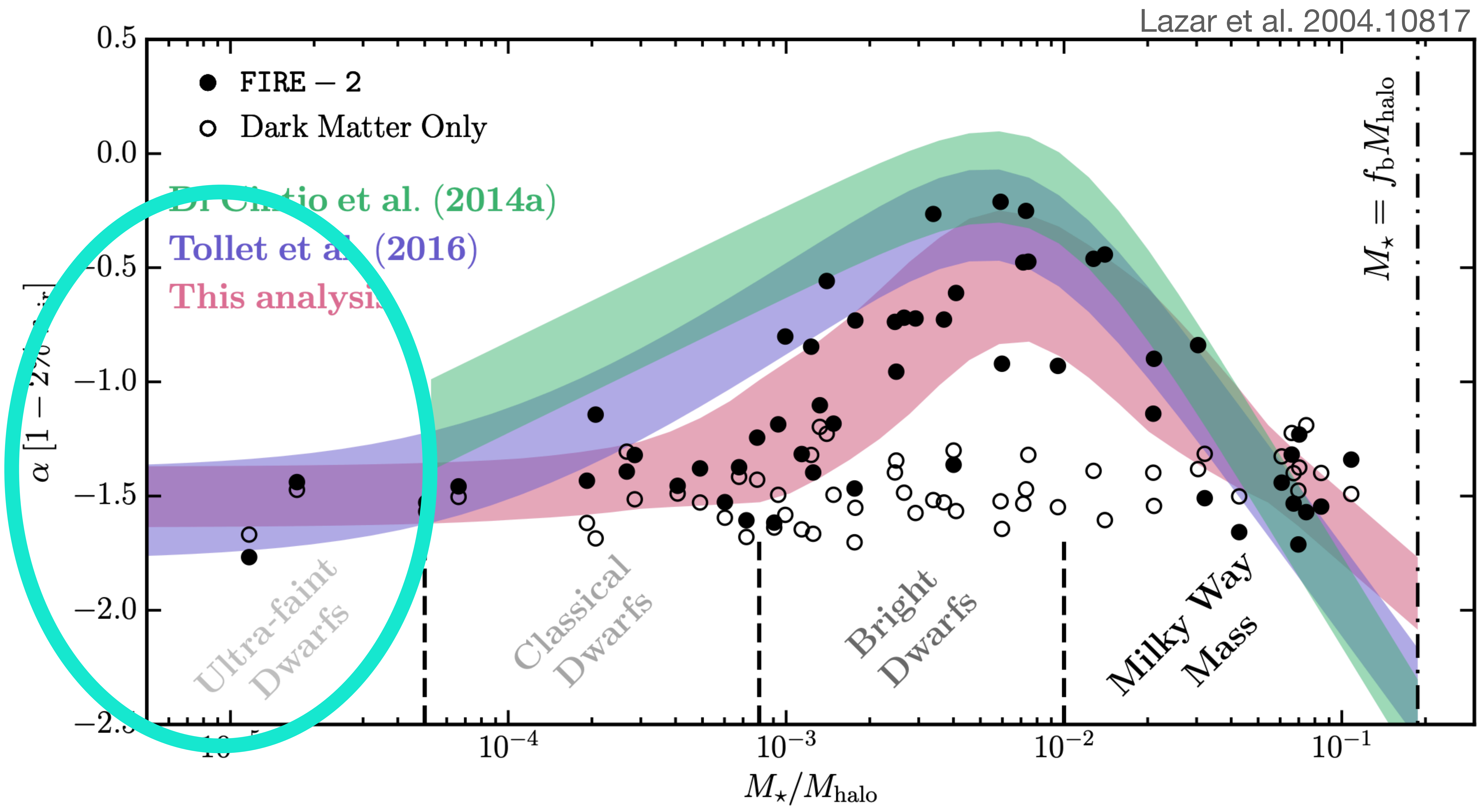


Systems as anisotropic as the MW are predicted (but not typical)

	CDM+Baryons	WDM+Baryons	SIDM+Baryons
Bulge-less disk galaxies	✓	✓	✓
The Cusp/ Core Problem	✓	✓	✓
Missing Dwarfs	✓	✓	✓
Too Big To Fail	✓	✓	✓

Alyson Brooks

We *should* be looking at simulated vs observed structure to understand DM and its properties.



Seeing cored ultra-faint dwarfs (not detected yet) could be the hint we are looking for: and a way to test **SIDM**, **WDM**, **ultralight DM**, …

Cold dark matter

The WIMP

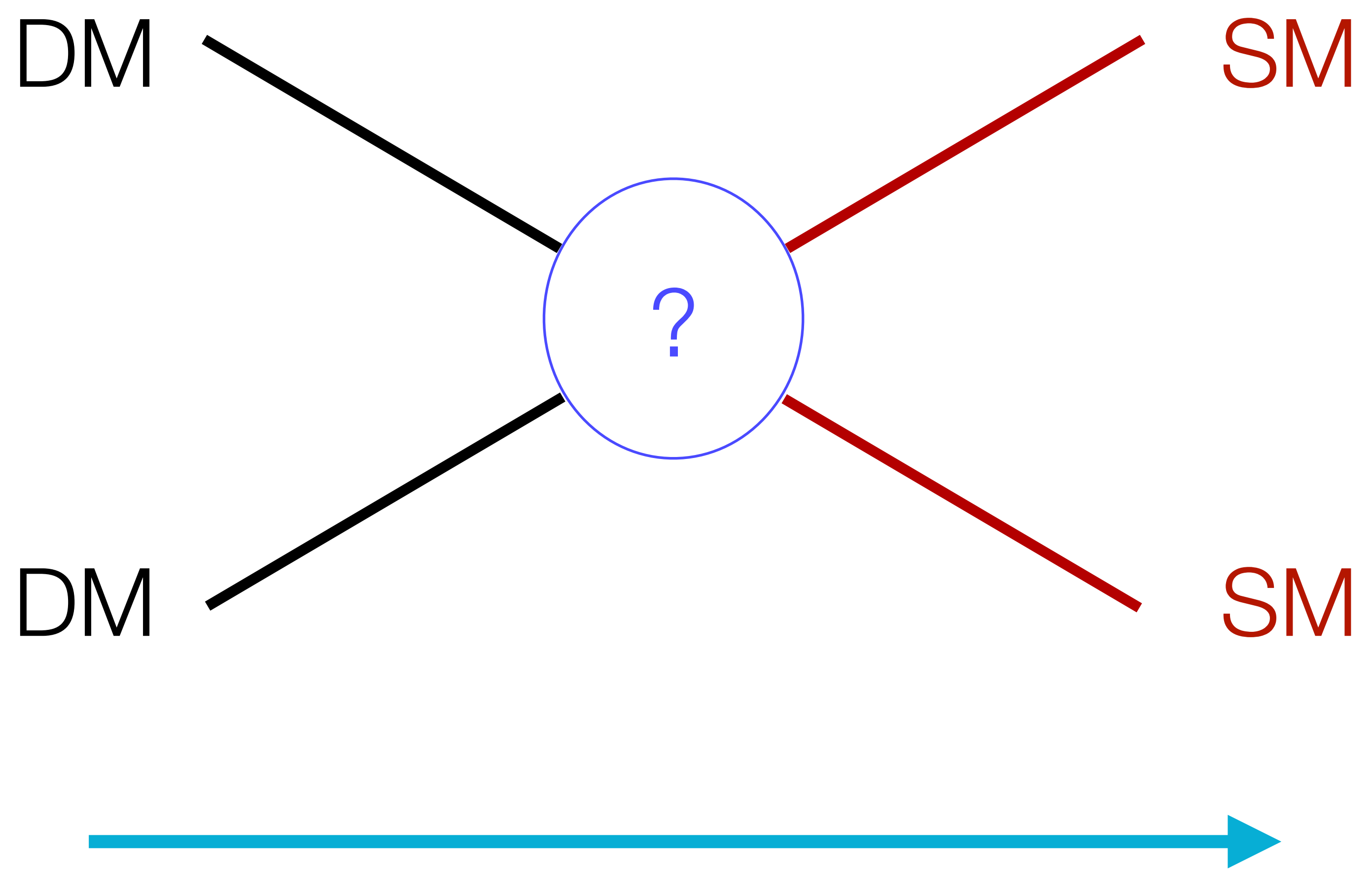
Exploring other Shores

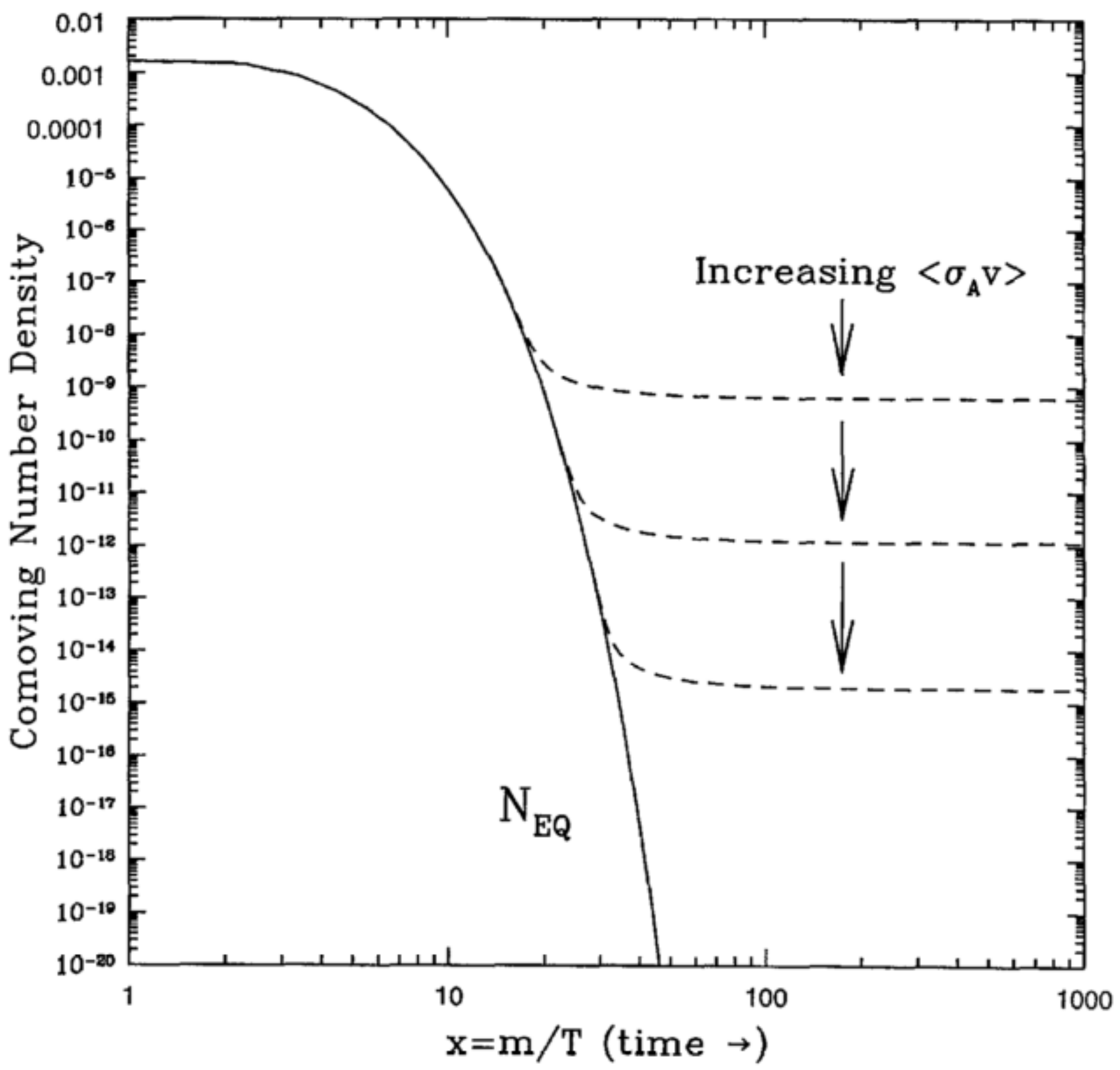
(What is a WIMP?)

- Weakly Interacting Massive Particle, whose abundance is set by **thermal freeze-out** in the Early Universe

$$M_\chi \sim 1 - 1000\ \mathrm{GeV}$$

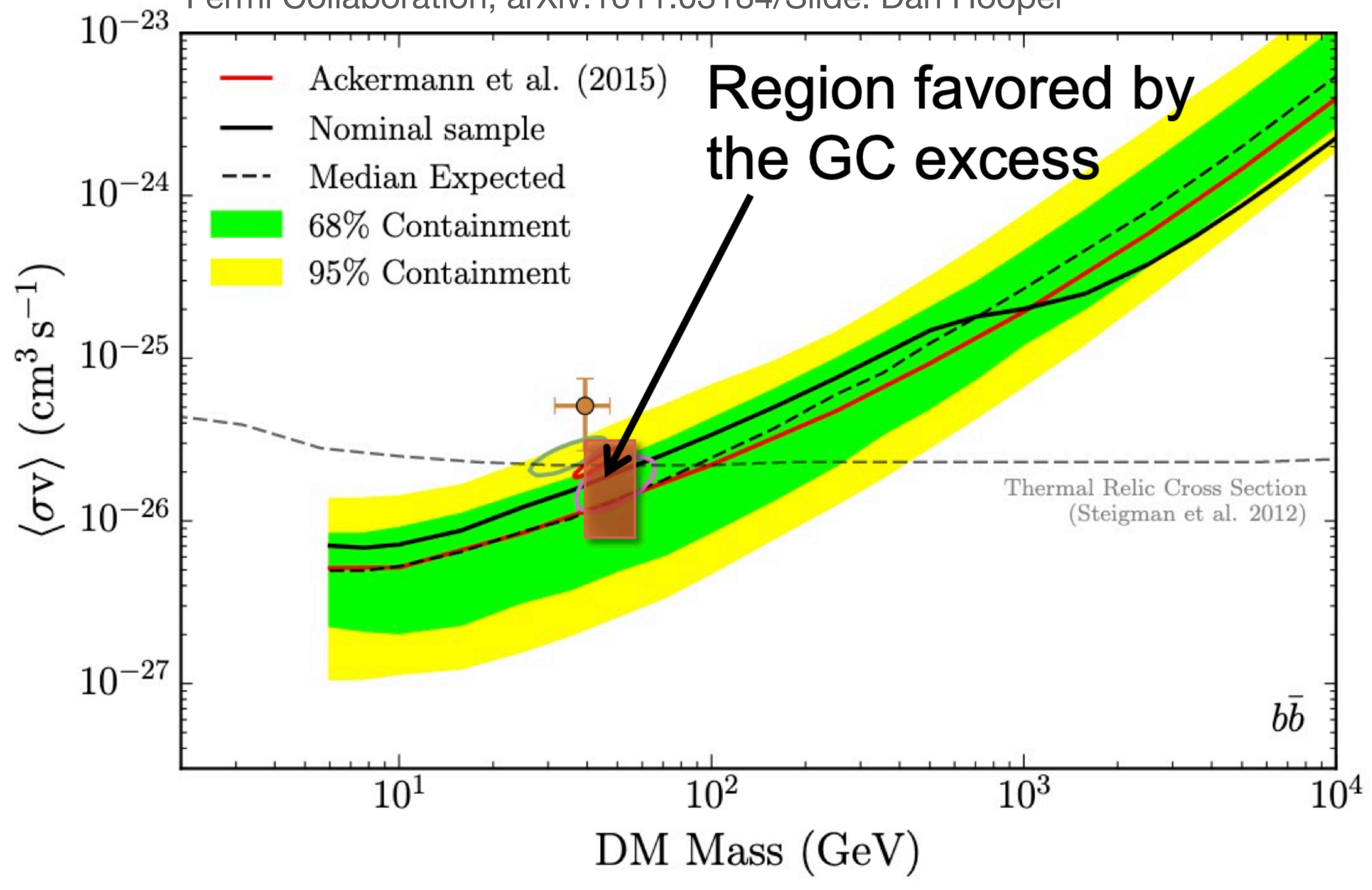
$$\langle \sigma v \rangle \simeq 10^{-26}\ \mathrm{cm^3 s^{-1}}$$





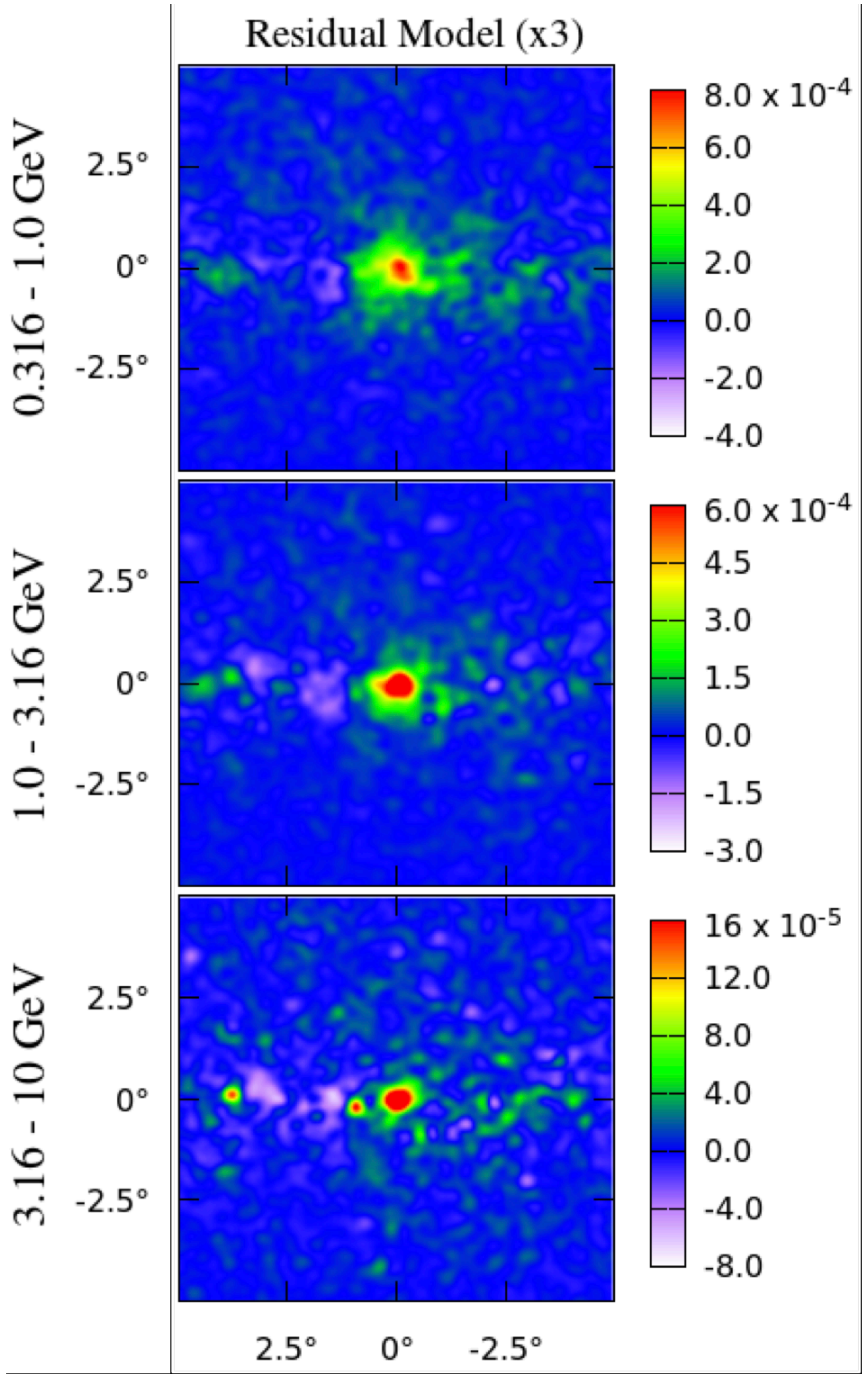
Hints from the galactic centre?

Fermi Collaboration, arXiv:1611.03184/Slide: Dan Hooper



$$\langle \sigma v \rangle \simeq 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

Consistent in energy & morphology with an annihilating WIMP.

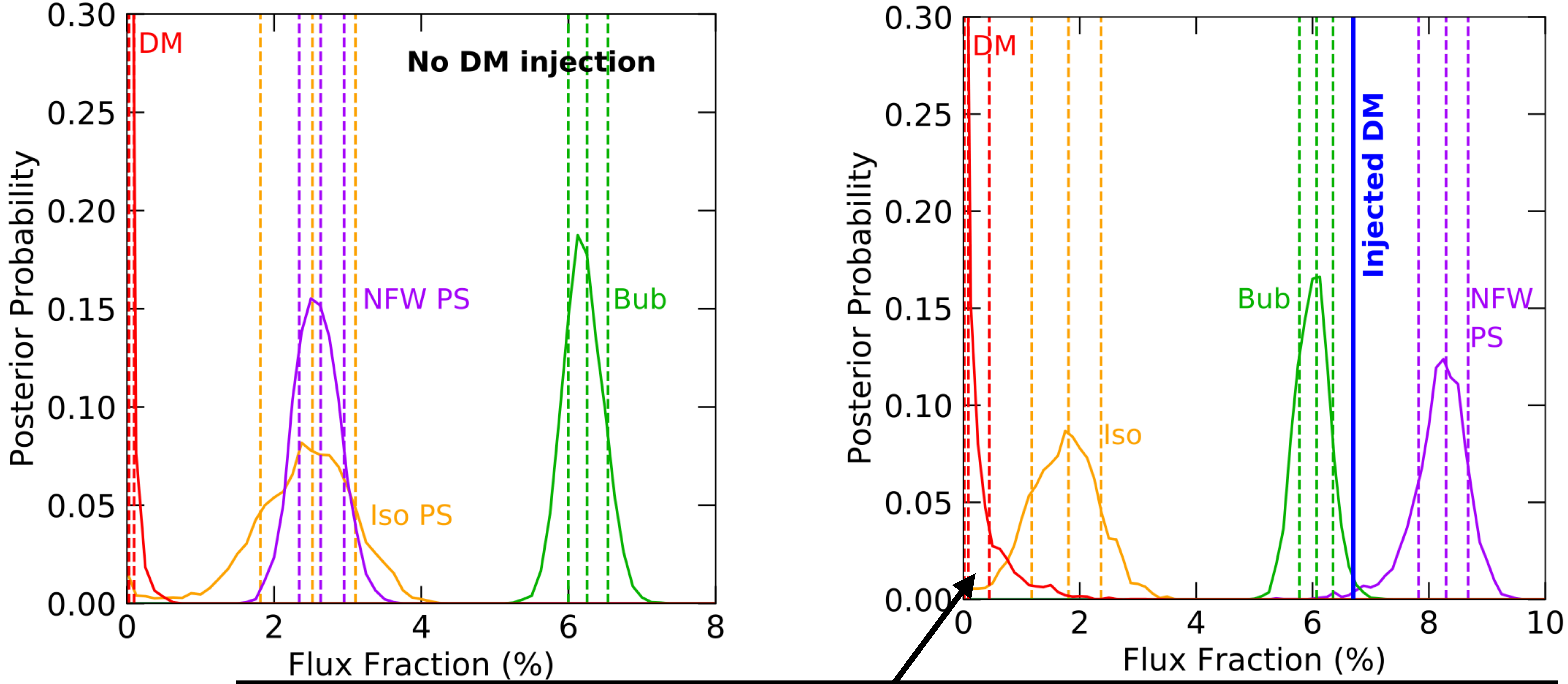


Fermi-LAT/ Hooper & Goodenough + many others

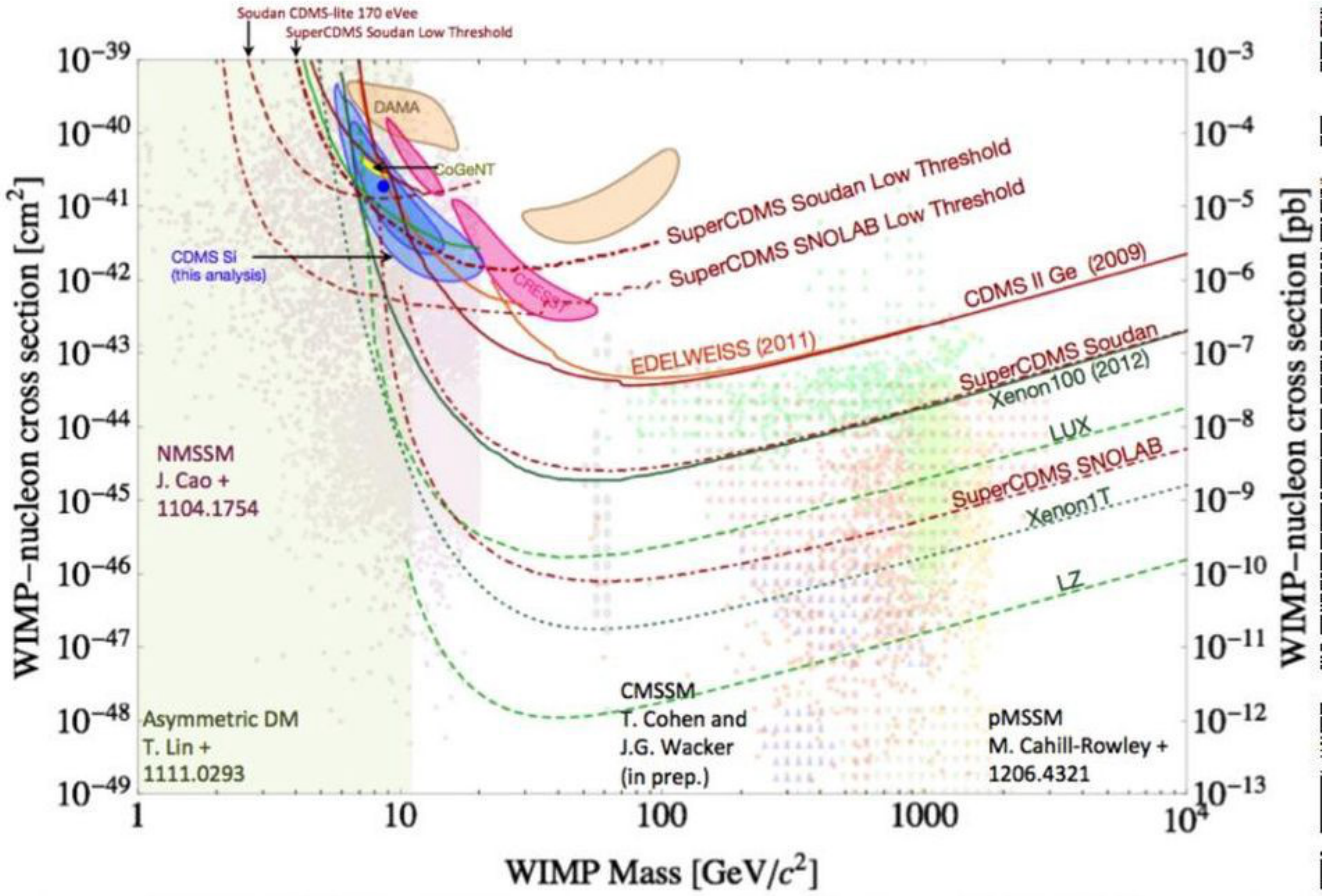
(the usual caveats apply)

(Lee et al. 1506.05124)

Galactic centre excess: Leane & Slatyer 2019



Injected dark matter signal not seen with this analysis method



The 'WIMP Miracle' Hope For Dark Matter Is Dead

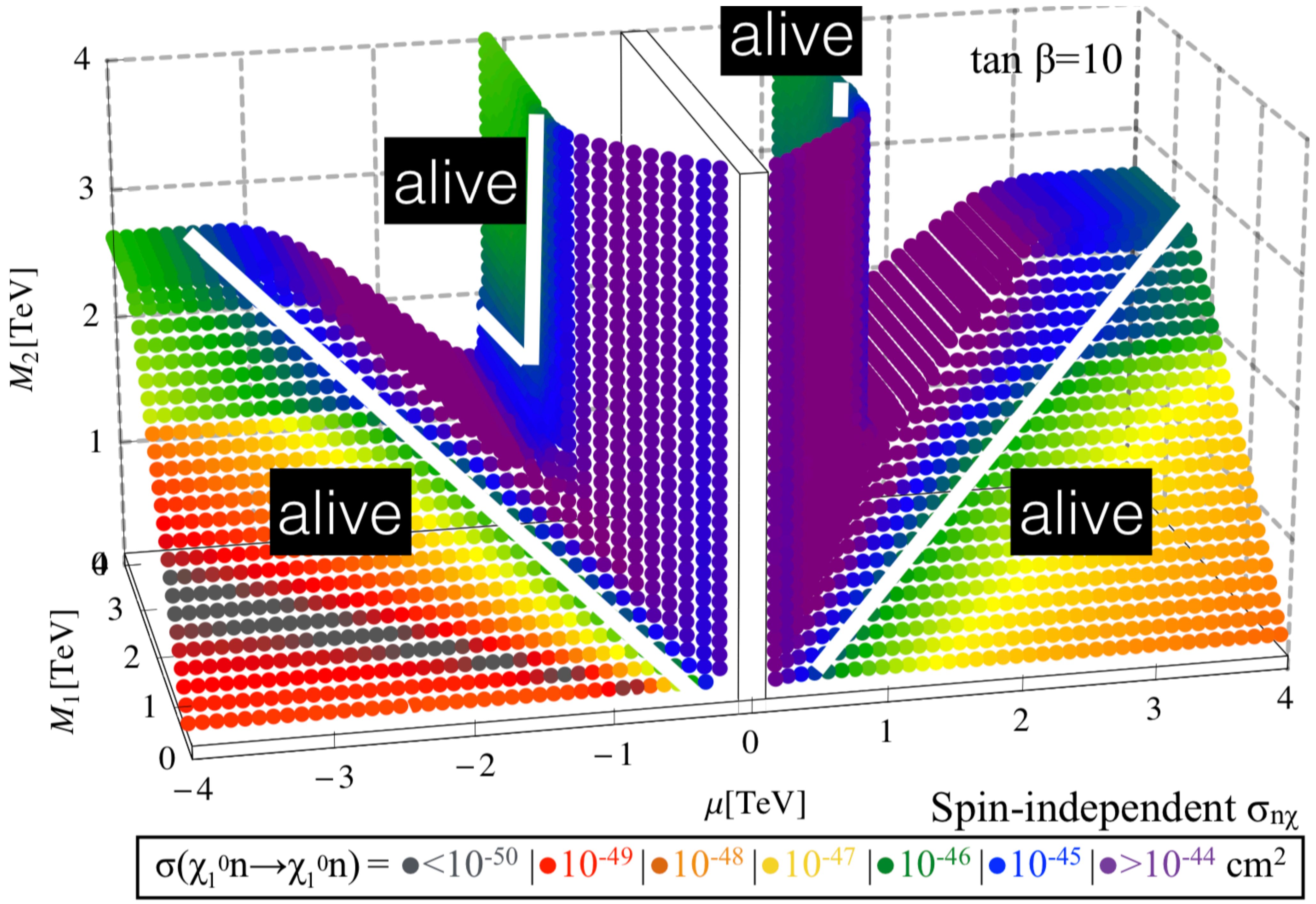
Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

WIMPs on Death Row

Posted on July 21, 2016 by woit

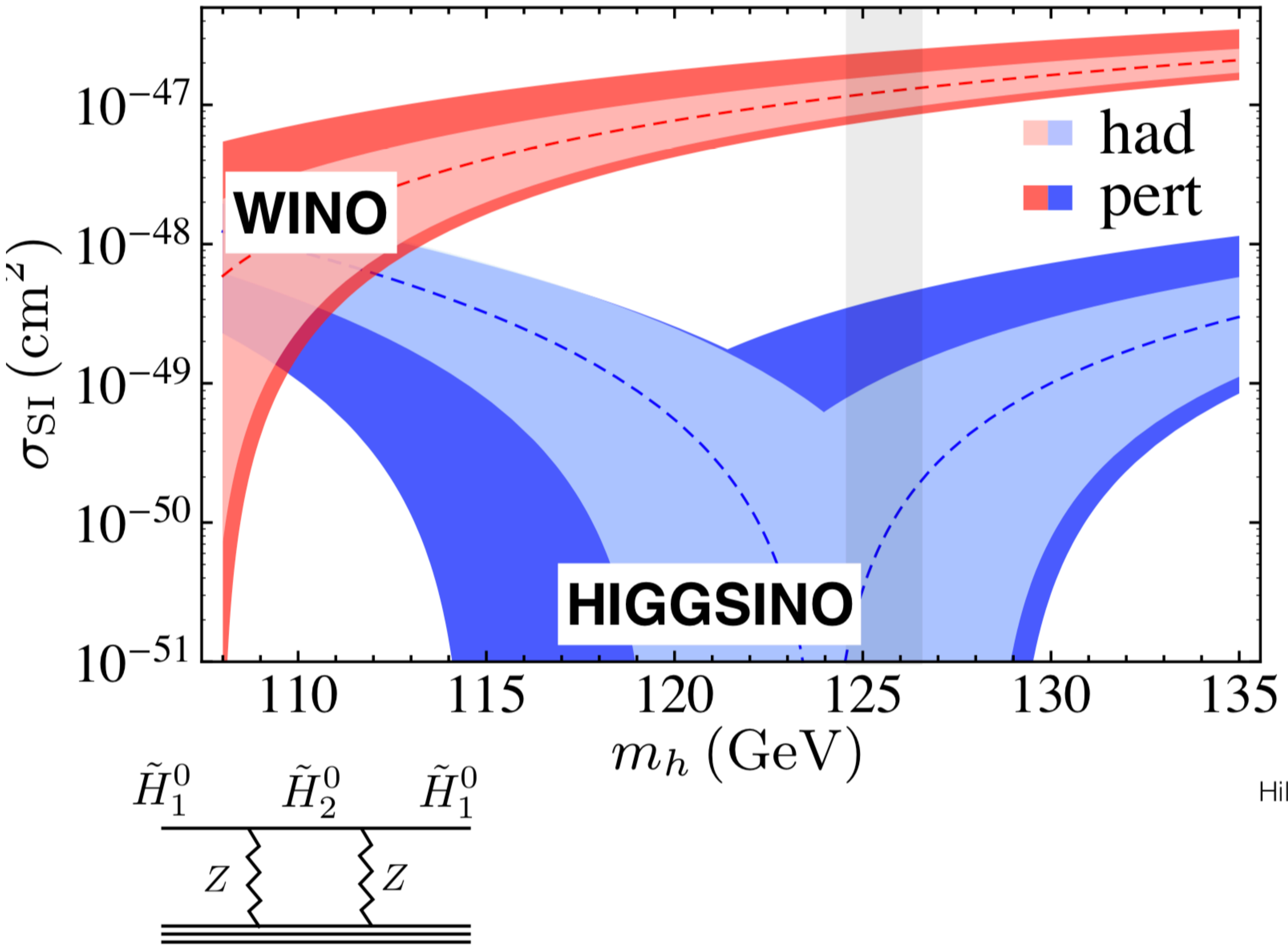
One of the main arguments given for the idea of supersymmetric extensions of th standard model has been what SUSY enthusiasts call the "WIMP Miracle" (WIM Interacting Massive Particle). This is the claim that such SUSY models include a very massive weakly interacting particle that could provide an explanation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

EFT Dark matter search

ADP-21-9/T1156, CERN-TH-2021-084, CP3-21-15, P3H-21-038, TTK-21-19, gambit-physics-21

Thermal WIMPs and the Scale of New Physics: Global Fits of Dirac Dark Matter Effective Field Theories

The GAMBIT Collaboration: Peter Athron[1,2], Neal Avis Kozar[3,4], Csaba Balázs[1], Ankit Beniwal[5,a], Sanjay Bloor[6,7,b], Torsten Bringmann[8], Joachim Brod[9], Christopher Chang[7], Jonathan M. Cornell[10], Ben Farmer[11], Andrew Fowlie[2], Tomás E. Gonzalo[1,12,c], Will Handley[13,14], Felix Kahlhoefer[12,d], Anders Kvellestad[8], Farvah Mahmoudi[15,16], Markus T. Prim[17], Are Raklev[8], Janina J. Renk[6,18], Andre Scaffidi[19,20], Pat Scott[6,7], Patrick Stöcker[12], Aaron C. Vincent[3,4,21], Martin White[19], Sebastian Wild[22], Jure Zupan[9]

Eur. Phys. J. C 81, 992 https://arxiv.org/abs/2106.02056

Let's take on a Dirac dark matter candidate coupled to the SM,
and not make too many assumptions

Possible interactions with quark sector up to dimension 7

$$\mathcal{L}_\chi = \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \sum_{a,d}\frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}\mathcal{Q}_a^{(d)}$$

$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)$$

$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)$$

$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$

$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$

Direct detection signals:

- Spin-independent – not suppressed
- Spin-independent – suppressed
- Spin-dependent – not suppressed
- Spin-dependent – suppressed

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G_{\mu\nu}^a$$

$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G_{\mu\nu}^a$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}_{\mu\nu}^a$$

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}_{\mu\nu}^a$$

$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)$$

$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)$$

$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)$$

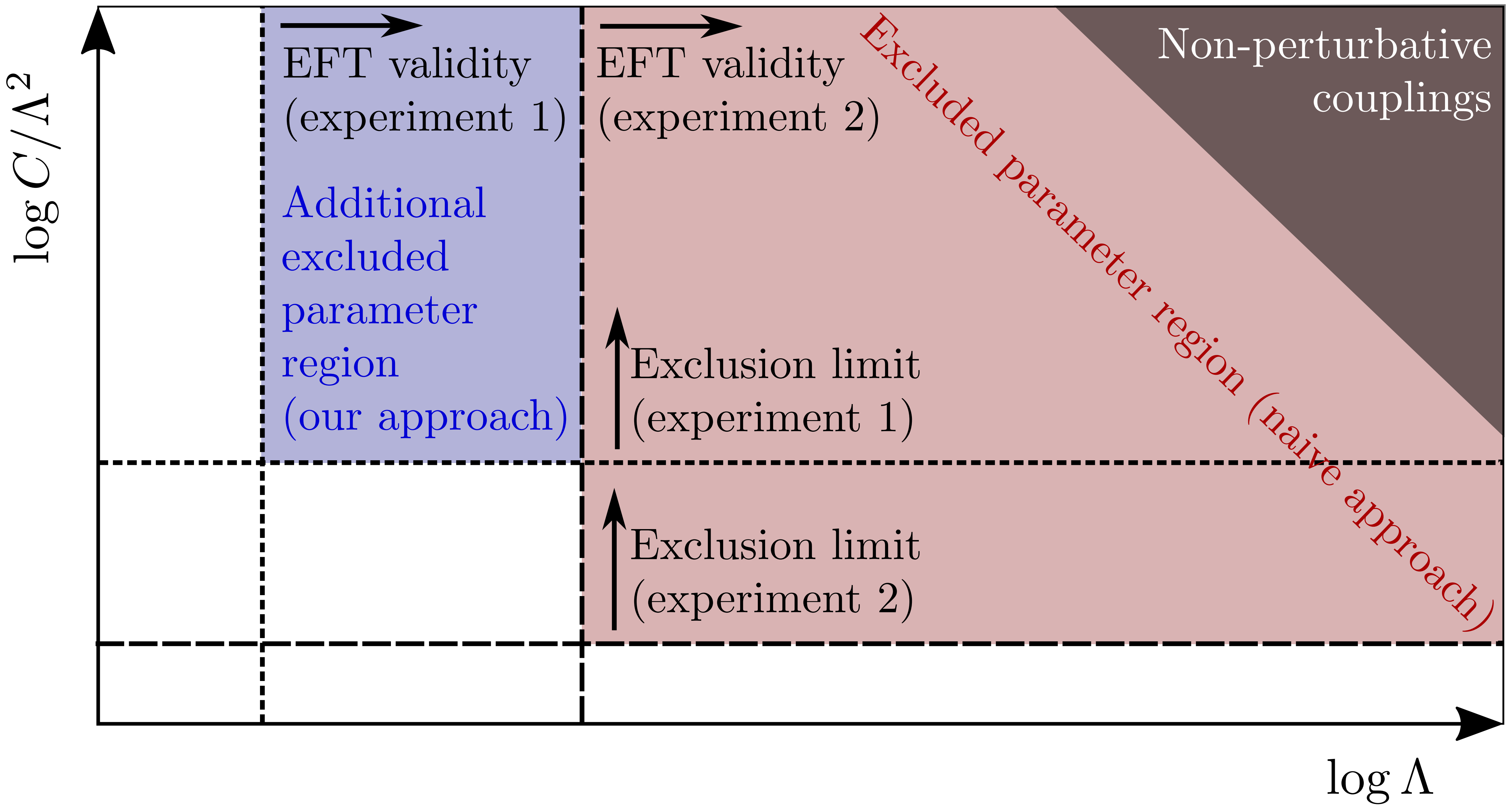
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)$$

$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)$$

Eur. Phys. J. C 81, 992 https://arxiv.org/abs/2106.02056

Dark Matter EFT search

- We vary the scale of new physics Λ as an independent parameter
- Relic density calculation requires $\Lambda > 2m_\chi$
- If ($\Lambda >$ scale probed by other experiments), we compute $\ln \mathscr{L}_{experiment}$ otherwise, we set $\ln \mathscr{L}_{experiment} = 0$
- For LHC, we smoothly cut off the spectrum to suppress events with MET $> \Lambda$



Eur. Phys. J. C 81, 992 https://arxiv.org/abs/2106.02056

Observables

- **Direct detection**
  - **DirectDM**: Fully automated RG evolution from Λ to low energies and matching to non-relativistic effective operators at hadronic scale
  - **DDCalc** :Large database of direct detection constraints including astrophysical and nuclear uncertainties
- **LHC** constraints (**ColliderBit**)
  - Monoject analyses: ATLAS 139 fb^{-1} based on full Run 2 datasets + CMS 36 fb^{-1}
  - Fast profiling of LHC nuisance parameters
- **Indirect detection**
  - **DarkSUSY**: Relic density calculation
  - **GUM**: Fully automated calculation of cross sections and gamma-ray spectra
  - **CosmoBit**: CMB constraints on energy injection from annihilation
  - **Capt'n General** Solar Capture + neutrinos with arbitrary DM-nucleon interaction
- Interface with **DIVER** differential sampler fully automated in GAMBIT

Slide: P. Scott

Eur. Phys. J. C 81, 992 https://arxiv.org/abs/2106.02056

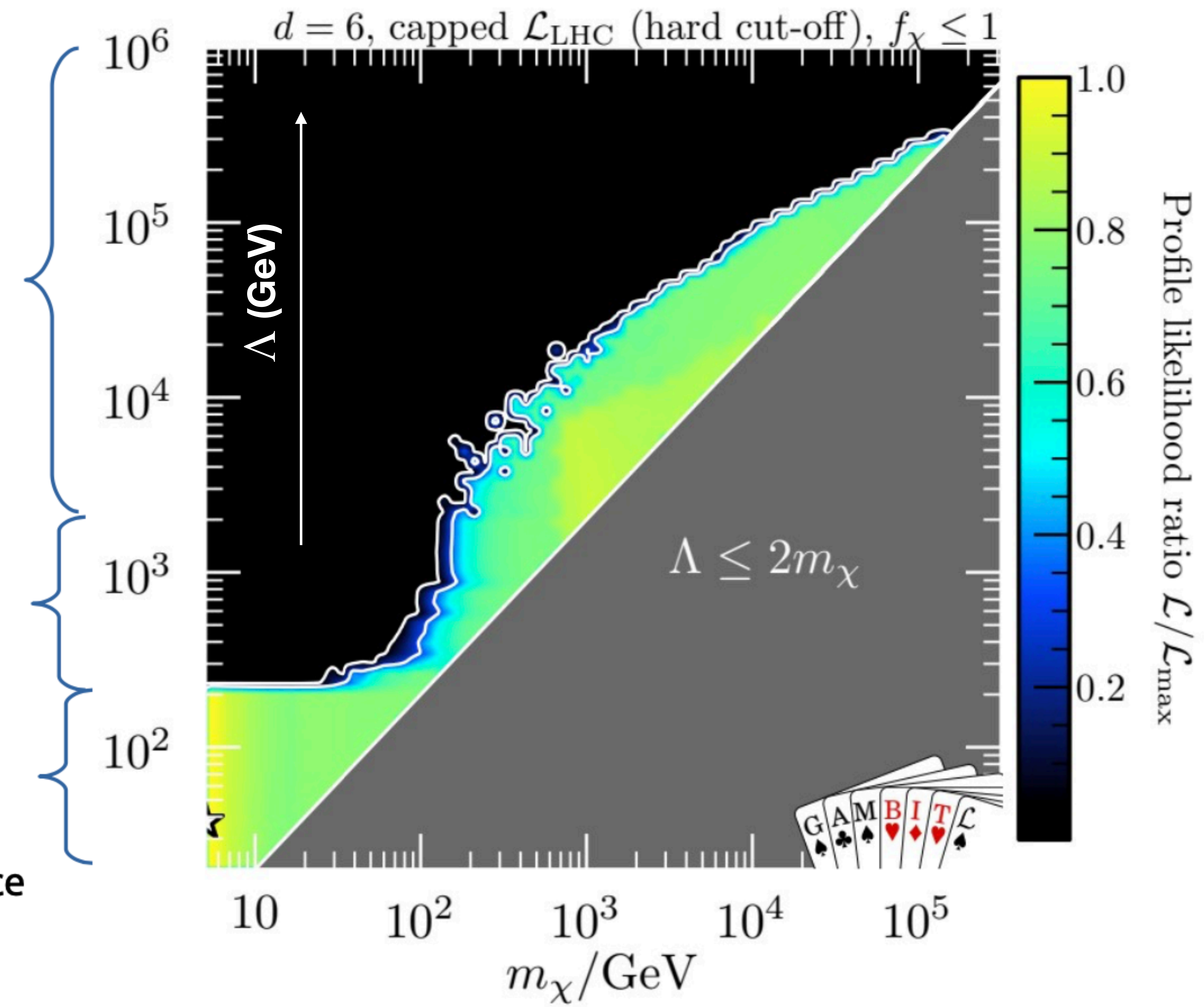
DMEFT Results - General picture

New physics scale Λ:

- EFT valid for all constraints
- Most experiments are insensitive
- Constraints driven by relic density requirement

- Λ comparable to LHC energies
- Strong LHC constraints

- Λ below LHC energies
- Large viable parameter space



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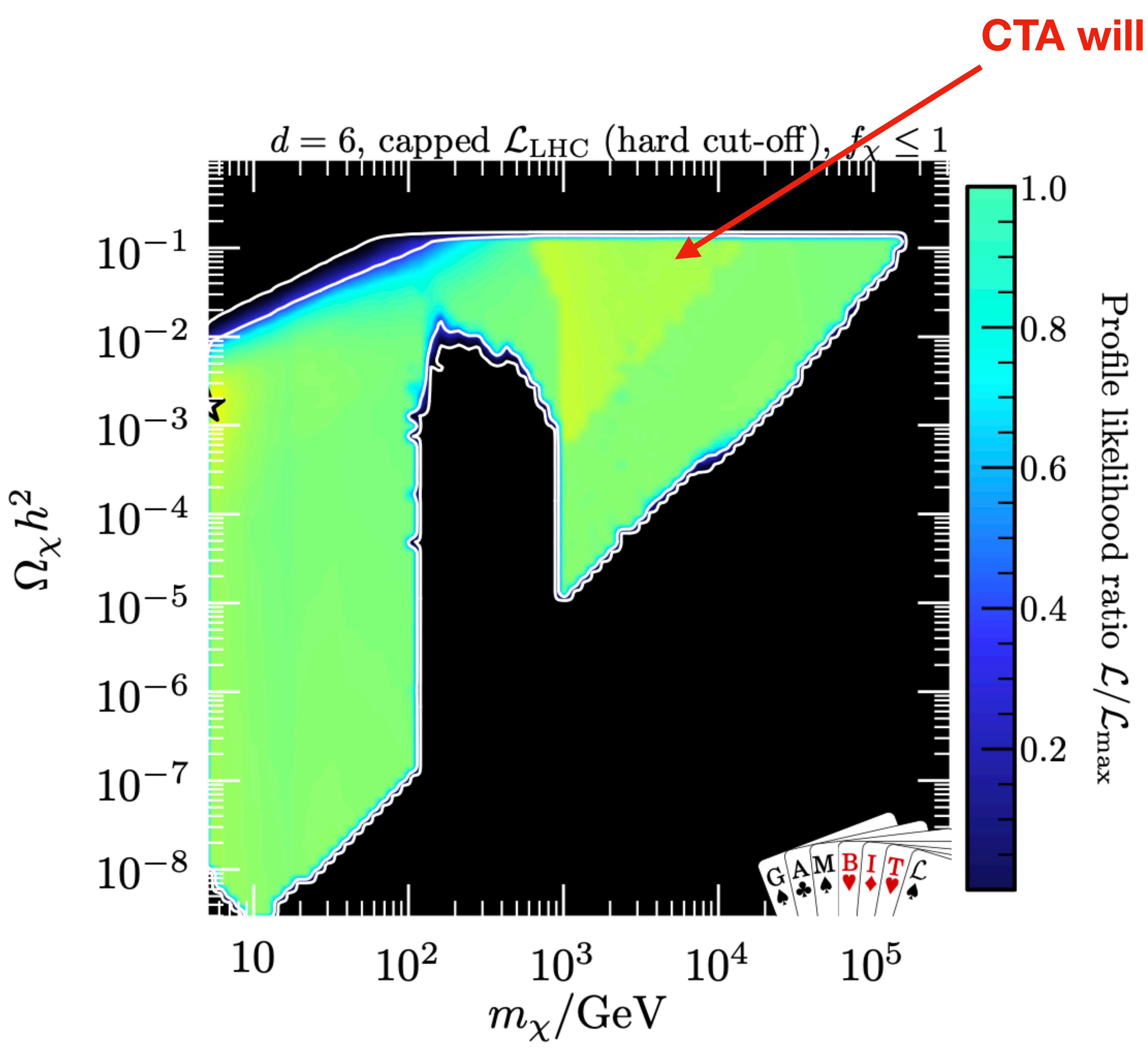
DMEFT: Allowed DM parameters



Low-mass ($m_\chi \lesssim 100$ TeV) DM allowed if:

•Underabundant *or* CP-violating

e.g. $\mathcal{Q}_{3,q}^{(6)} = (\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu\gamma^5 q)$ spin-dependent and velocity suppressed

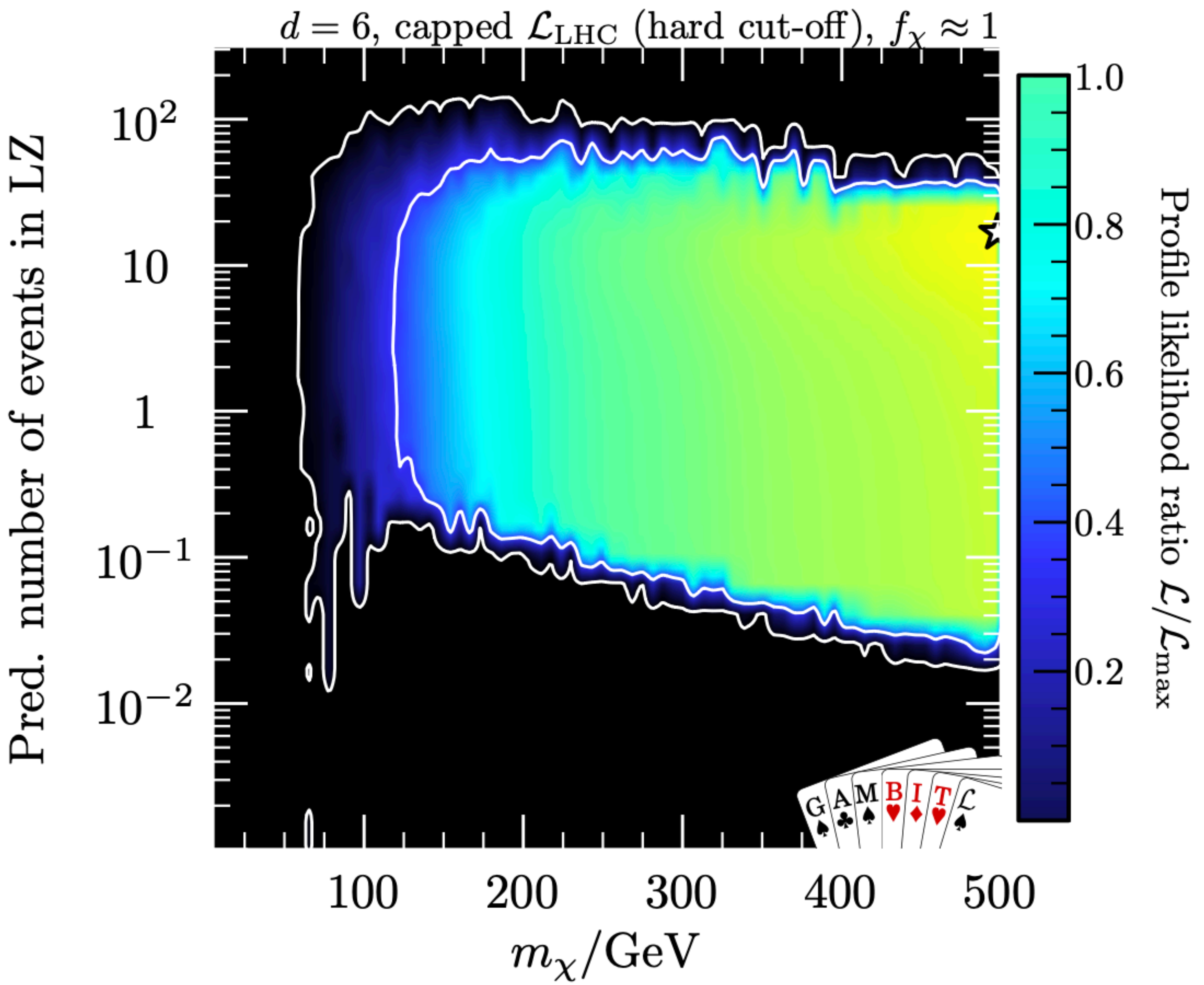
•Low Λ s.t. LHC constraints invalid (but mediator would probably show up…)

Eur. Phys. J. C 81, 992 https://arxiv.org/abs/2106.02056

Slide: P. Scott, F. Kahlhoefer

Enforcing 100% of the dark matter

- DM must be heavy
- High chance of being seen at e.g. LZ (mainly due to loop-induced operator mixing, which could be suppressed by other interactions)



Slide: P. Scott, F. Kahlhoefer

Eur. Phys. J. C 81, 992 https://arxiv.org/abs/2106.02056

Many remaining WIMP identities
(Dan Hooper, PHENO 2022)

1) **Co-annihilations** between the dark matter and another state

2) Annihilations to **W, Z and/or Higgs** bosons; scattering with nuclei only through highly suppressed **loop diagrams**

3) Interaction which suppress elastic scattering with nuclei by **powers of velocity or momentum**

4) Dark matter that is **lighter** than a few GeV (relaxing direct constraints)

5) Departures from radiation domination in the **early universe** (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

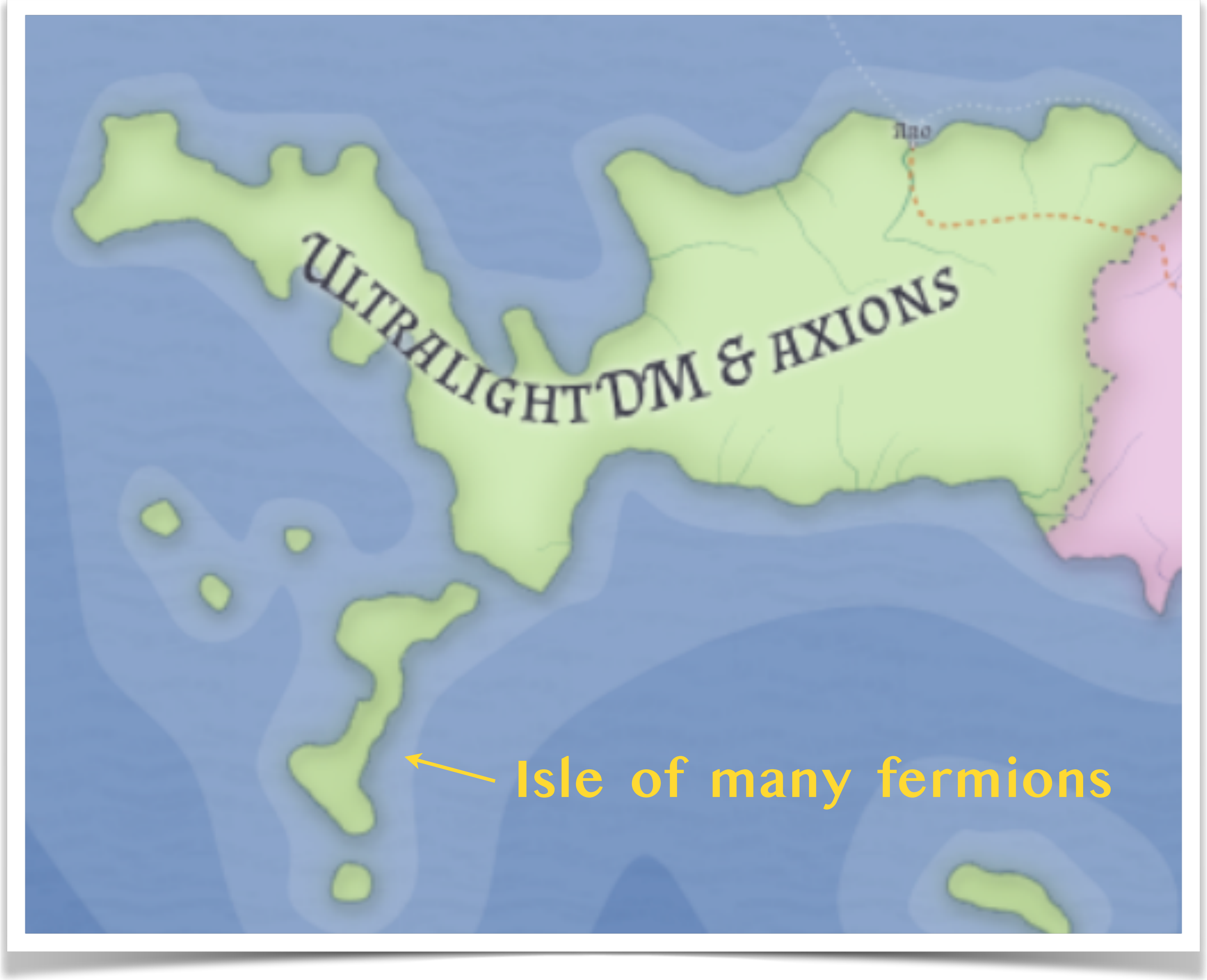
6) The dark matter annihilates to unstable non-Standard Model states (ie. **hidden sector** models)

Cold dark matter

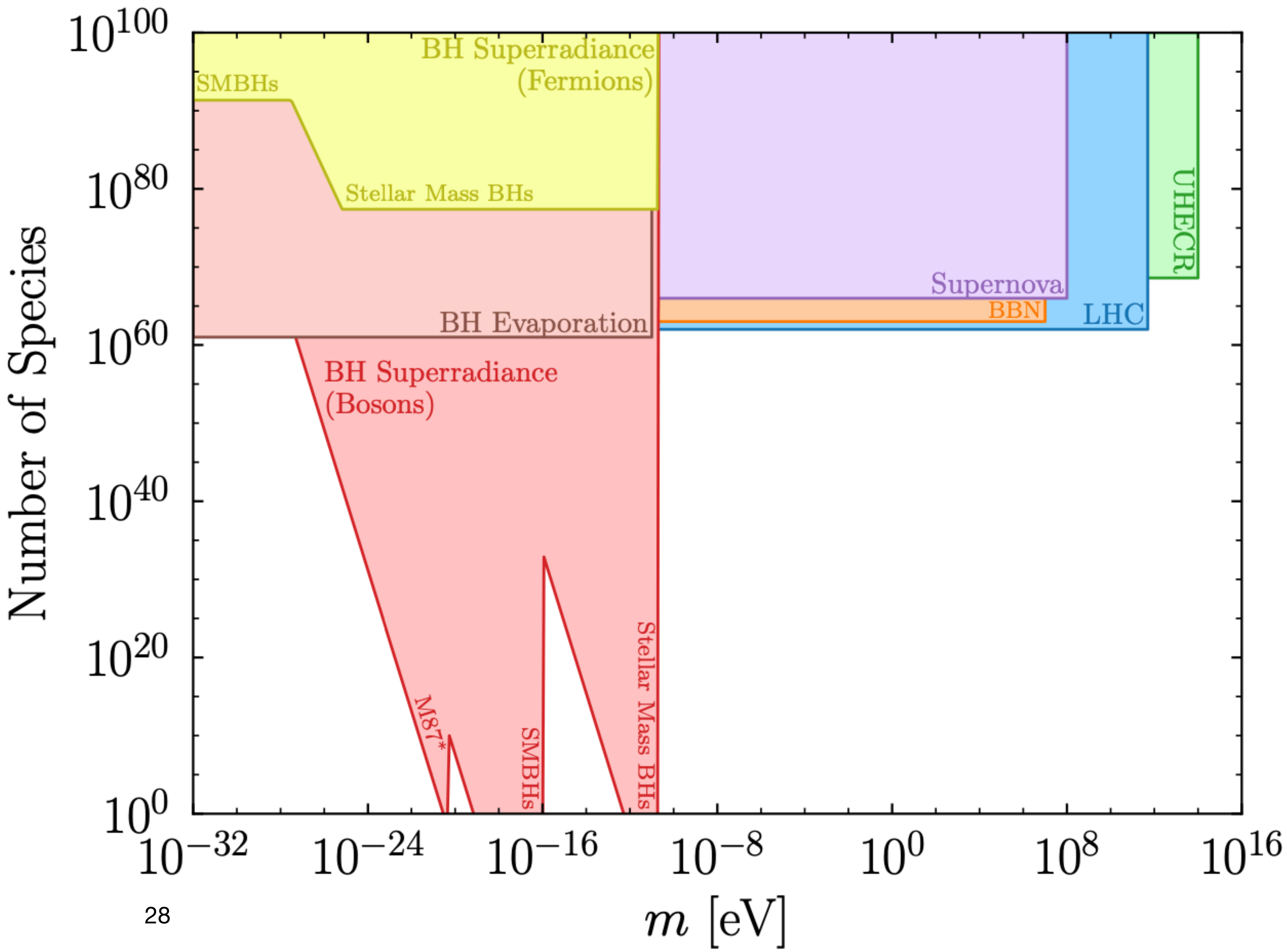
The WIMP

Exploring other Shores

A Map of The Charted and Uncharted Territories of Dark Matter ands its Theories



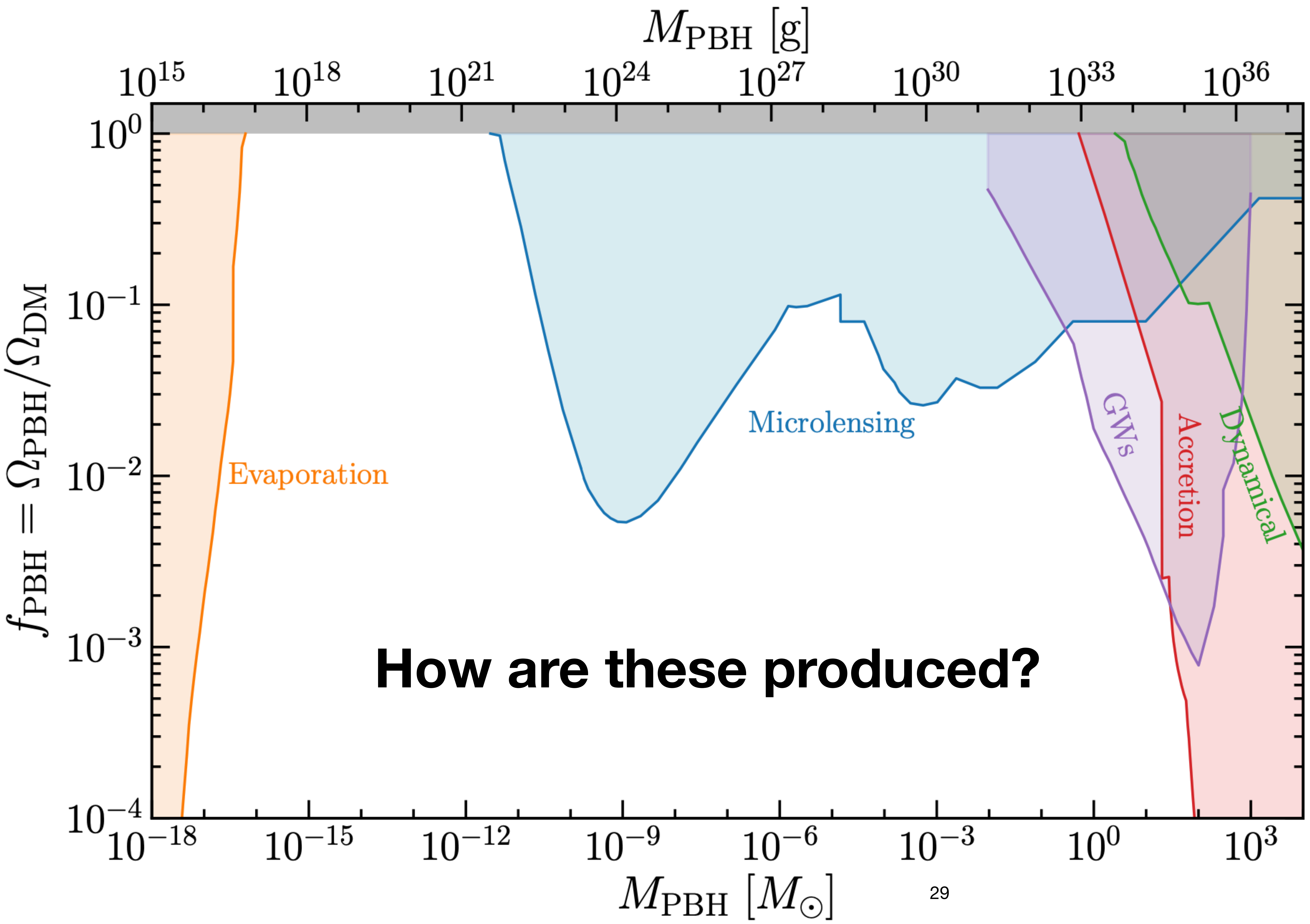
Many guiding principles, e.g. Tremaine Gunn (limit on number of Fermions in the galactic centre due to Pauli exclusion -> limit on DM mass $\gtrsim$ few eV) can be circumvented by being clever enough



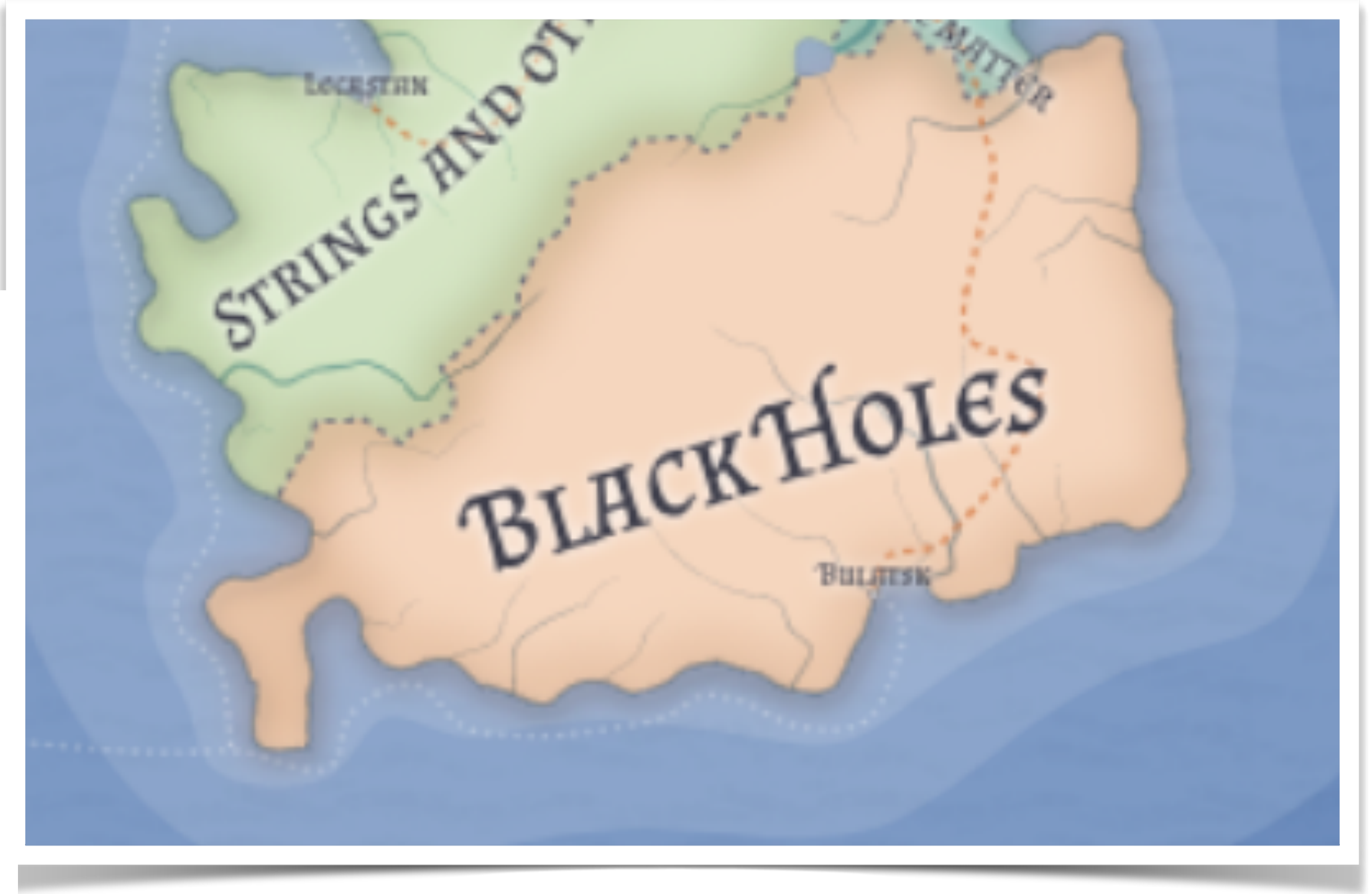
Ultralight Fermionic Dark Matter

Hooman Davoudiasl* and Peter B. Denton†
High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

David A. McGady‡
Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, SE-106 91 Stockholm, Sweden
(Dated: August 14, 2020)



How are these produced?

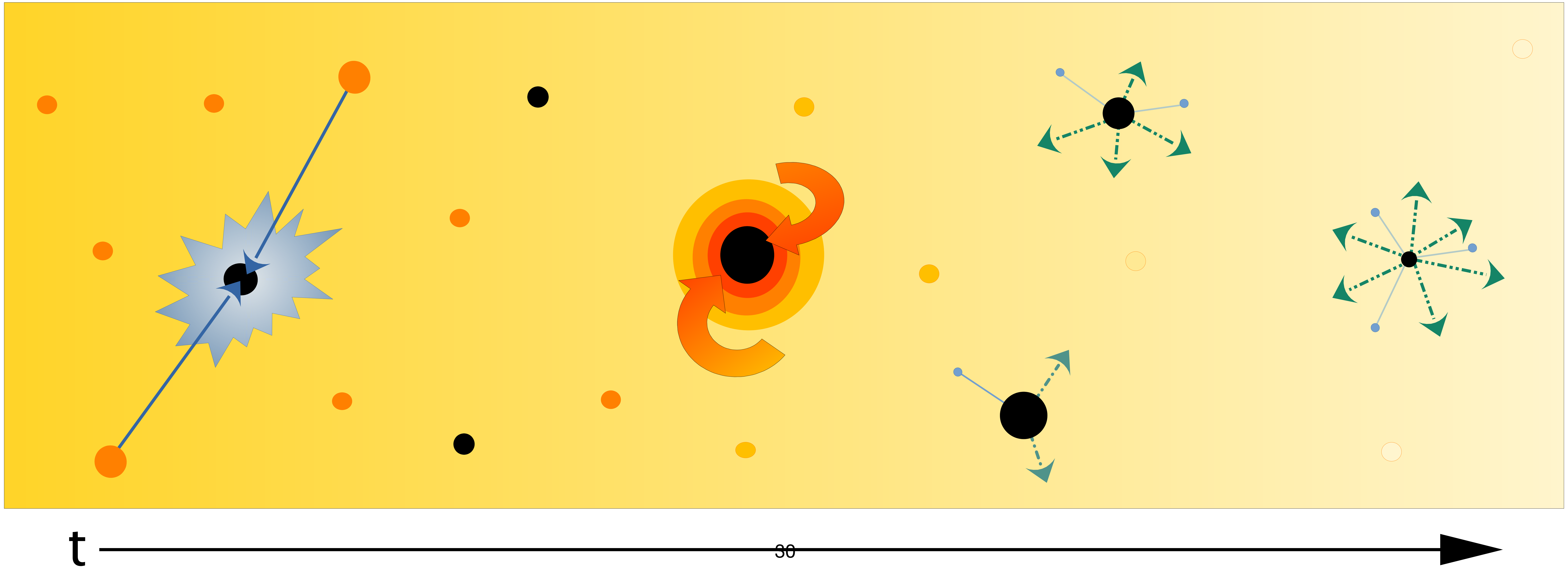


Green & Kavanagh 2007.10722

New & rediscovered mechanisms and predictions for primordial black hole dark matter

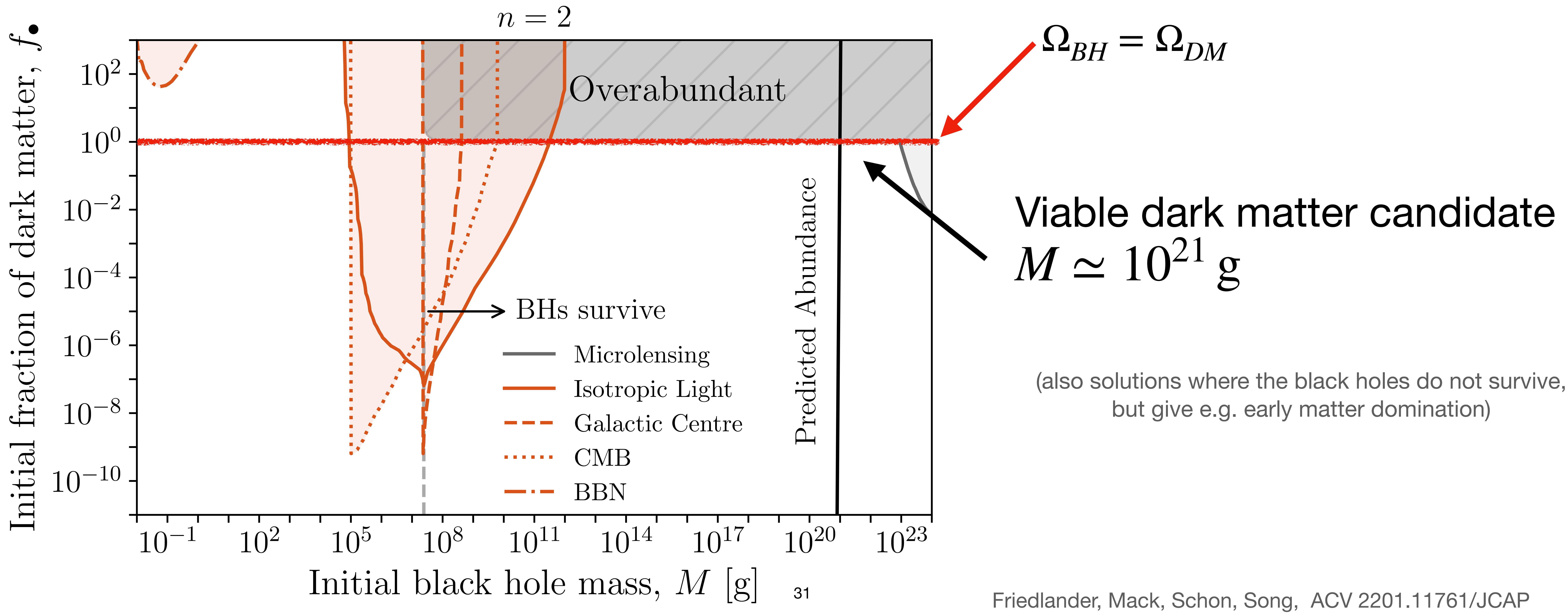
In theories of large extra dimensions (e.g. Arkani-Hamed et al), collisions in the hot dense plasma of the Early Universe can make **black holes** which grow to macroscopic size by accreting plasma (see Conley & Wizansky 2006).

Friedlander, Mack, Schon, Song, ACV 2201.11761/JCAP



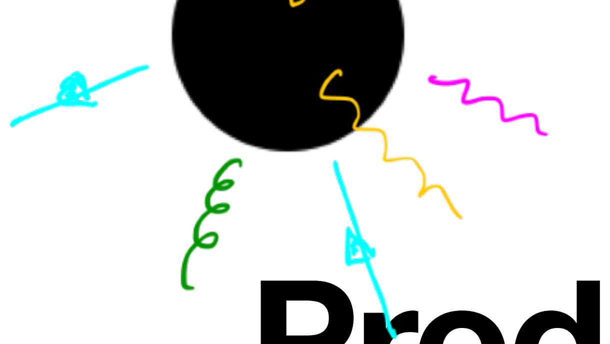
Extra-dimensional primordial black holes

- These exhibit **a different lifetime, Hawking temperature and spectrum** from their 4d counterparts



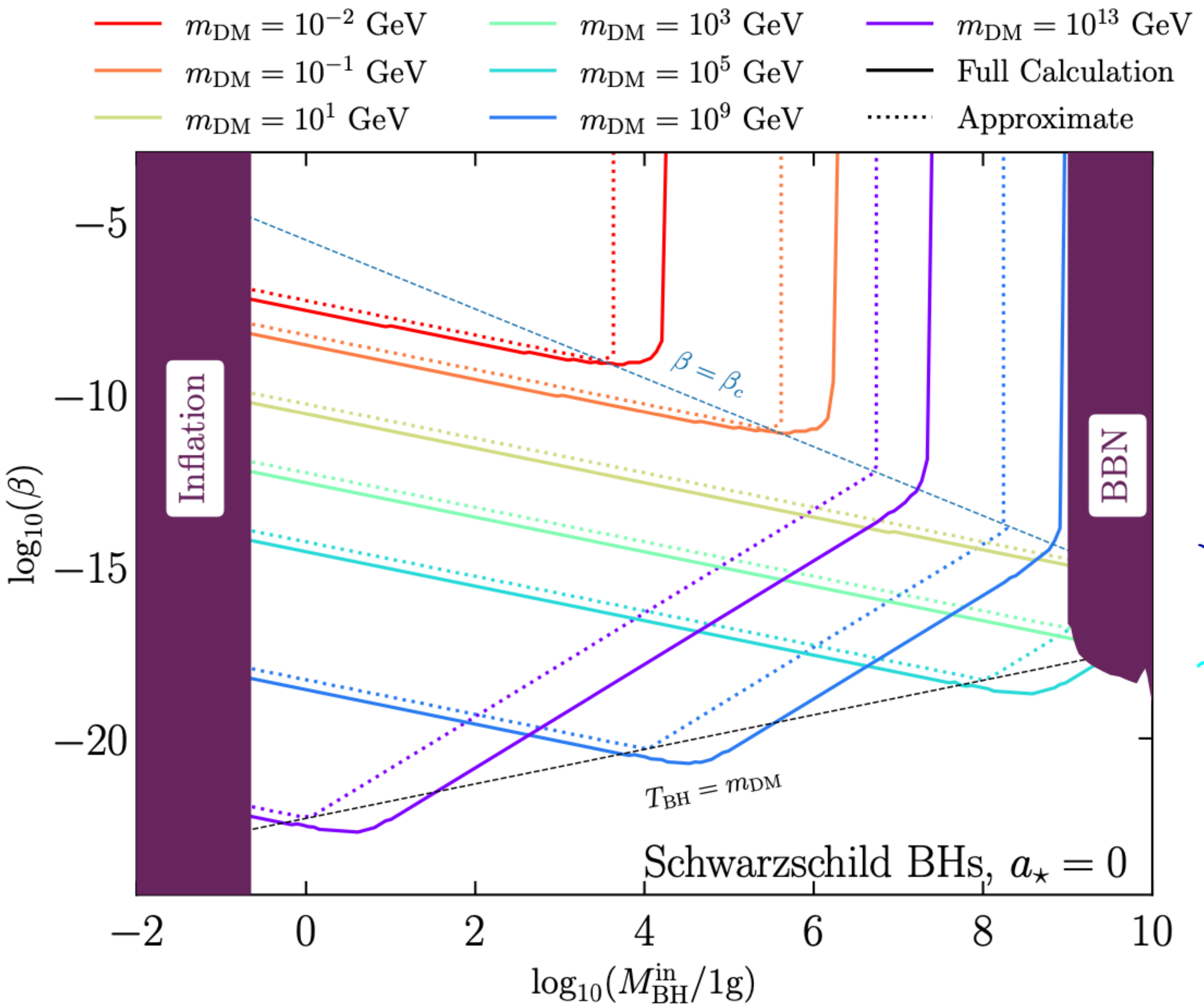
(also solutions where the black holes do not survive, but give e.g. early matter domination)

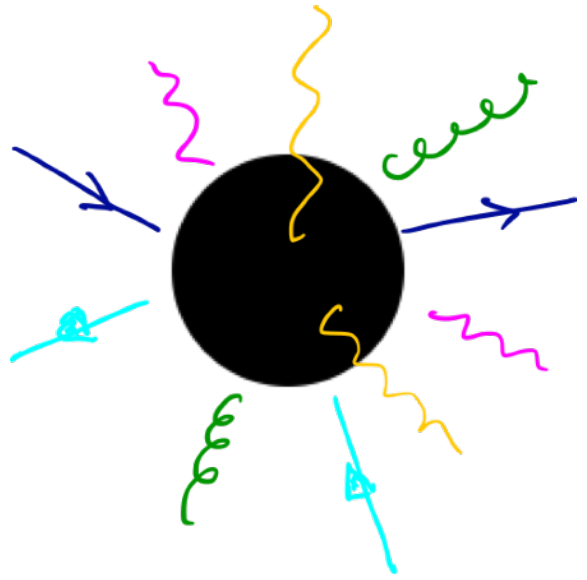
Friedlander, Mack, Schon, Song, ACV 2201.11761/JCAP

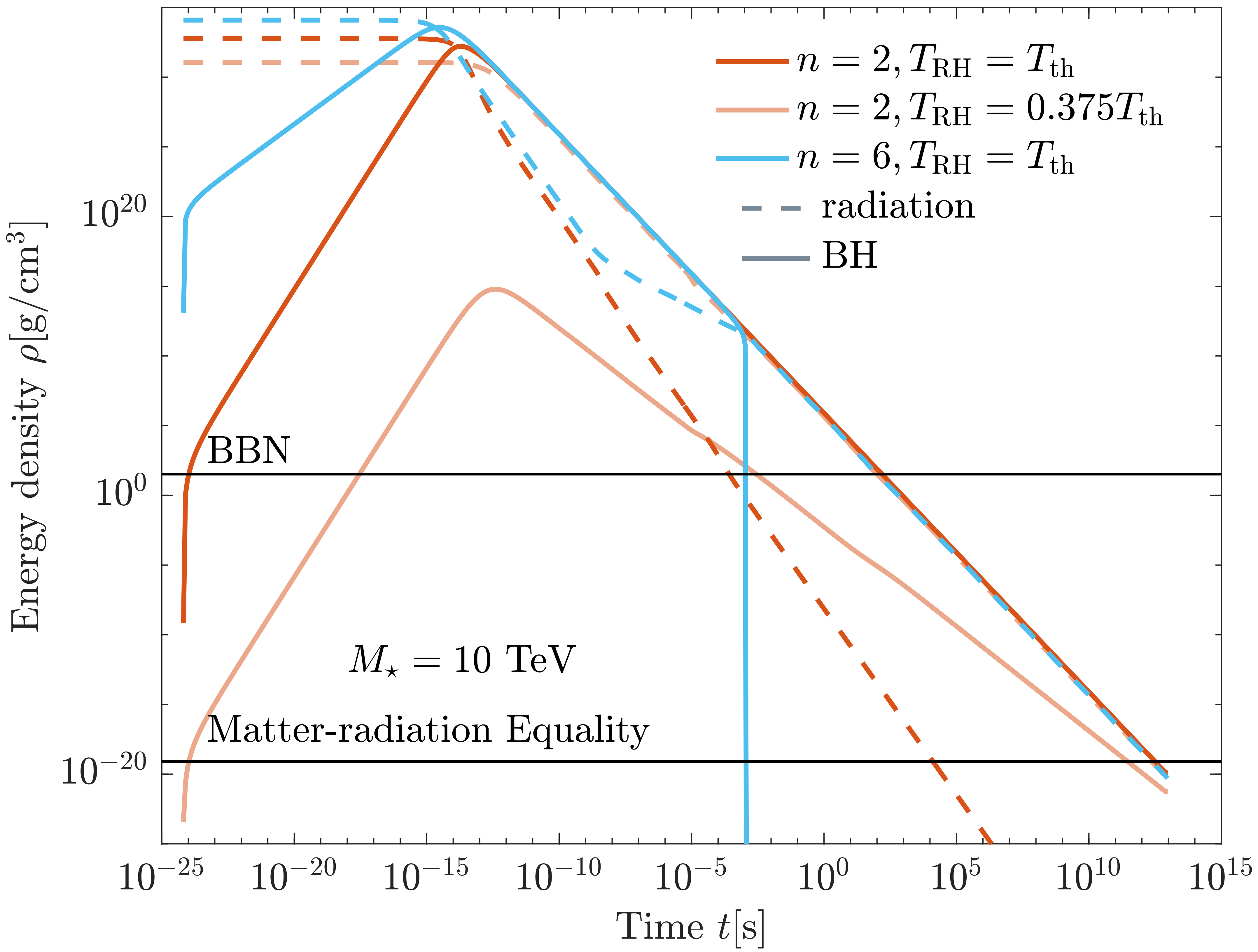


Producing sequestered sectors from black hole evaporation?

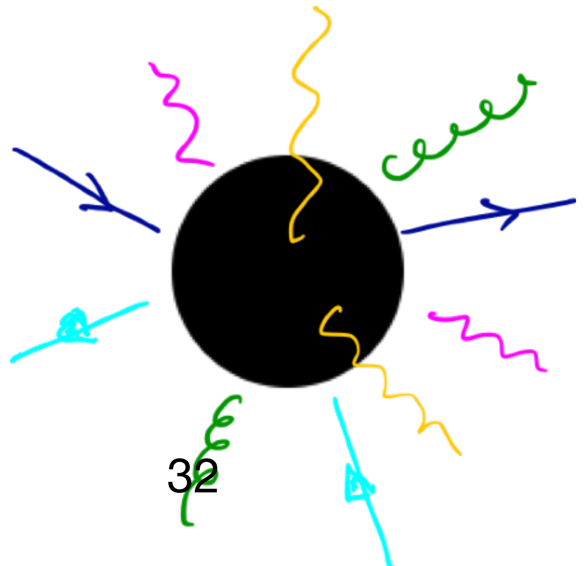
e.g. Cheek et al. 2107.00016, 2104.03297

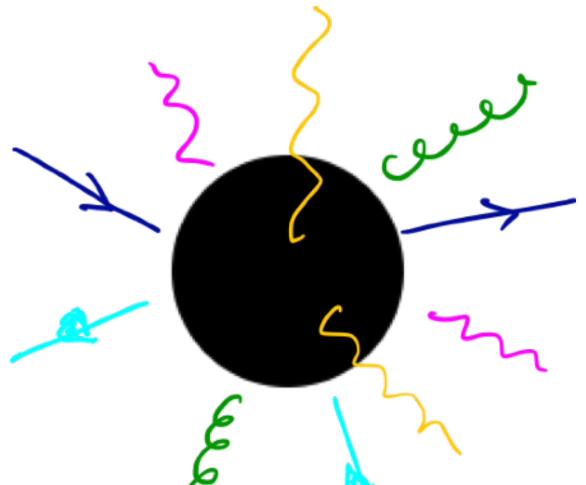






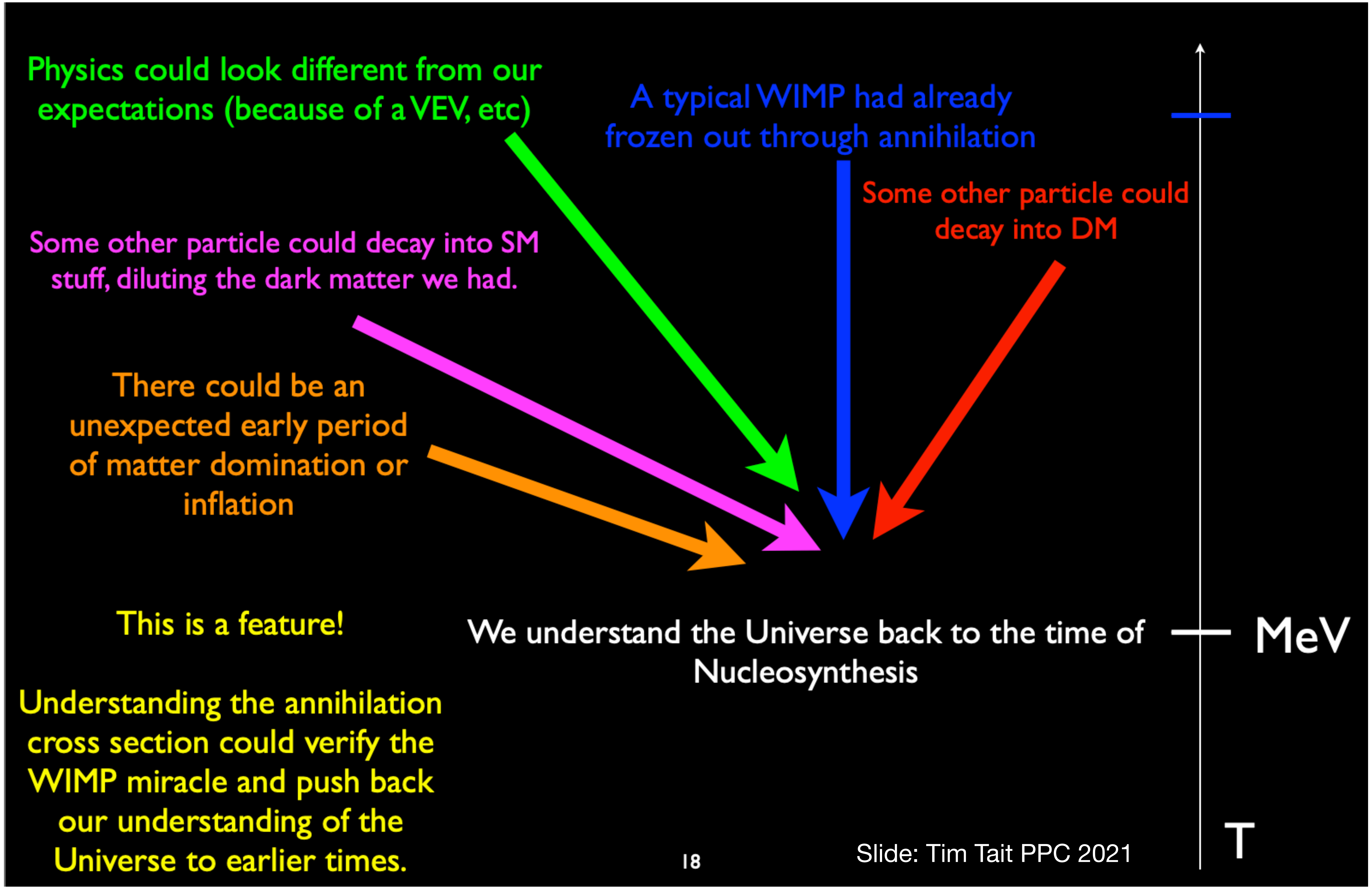
Early Matter domination -> decay (Friedlander…ACV 2022)





At colliders: Song & ACV https://arxiv.org/abs/1907.08628

Whatever happens, detecting dark matter and measuring its properties tells us far more than we now know about the early Universe



Conclusions

- CDM still works quite well, but alternatives are worth pursuing
- The WIMP have survived challenges, even if the WIMP parameter space is shrinking
- Each new challenge brings new ideas, as the parameter space for other models keeps growing
- Simulation and theory guide us, but ultimately experiment will tell us what DM is — and by extension will unlock much more particle physics, and knowledge of the Early Universe

MERCI

TeV Particle Astrophysics

TeVPA 2022

AUGUST 8-12
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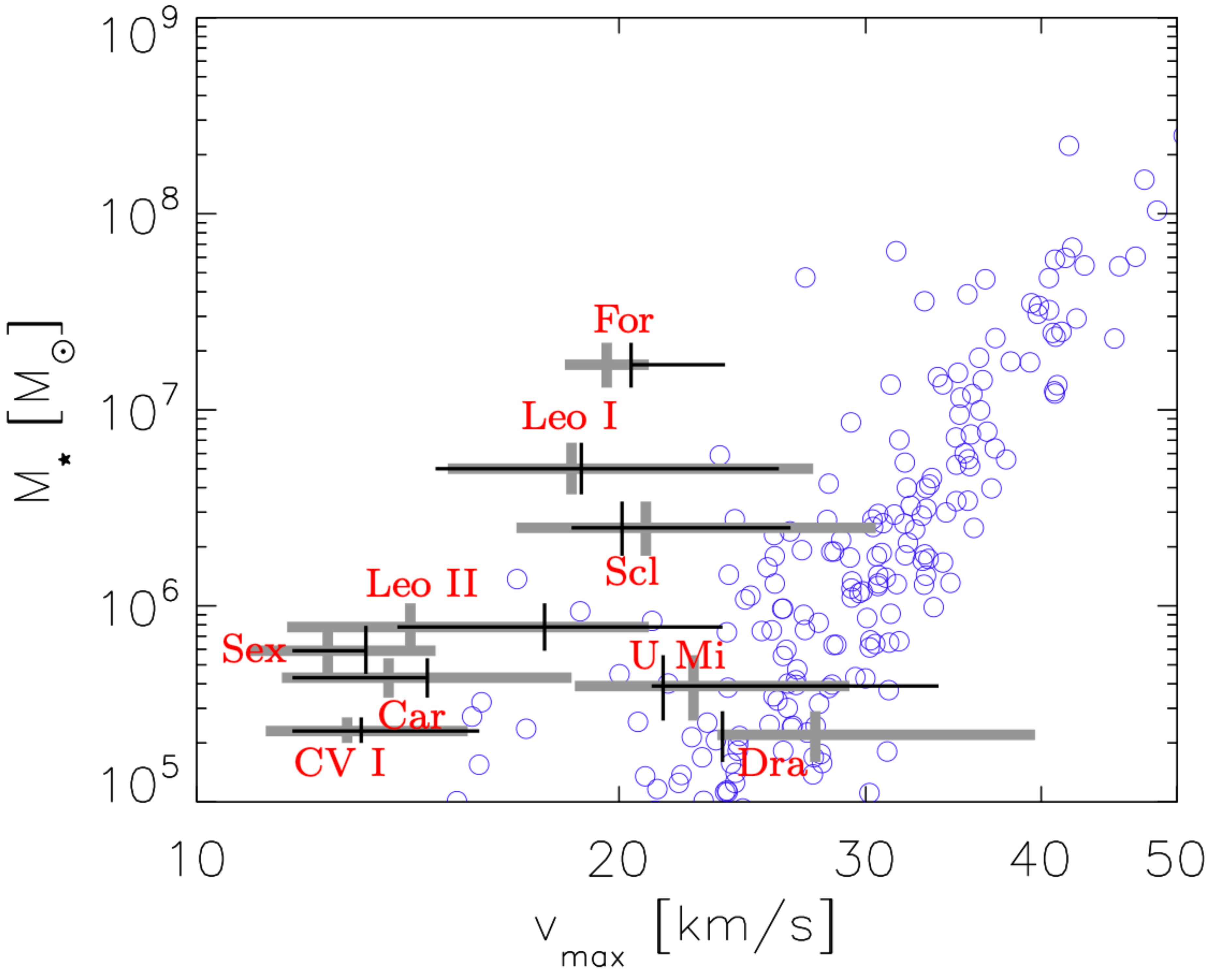
KINGSTON, ON

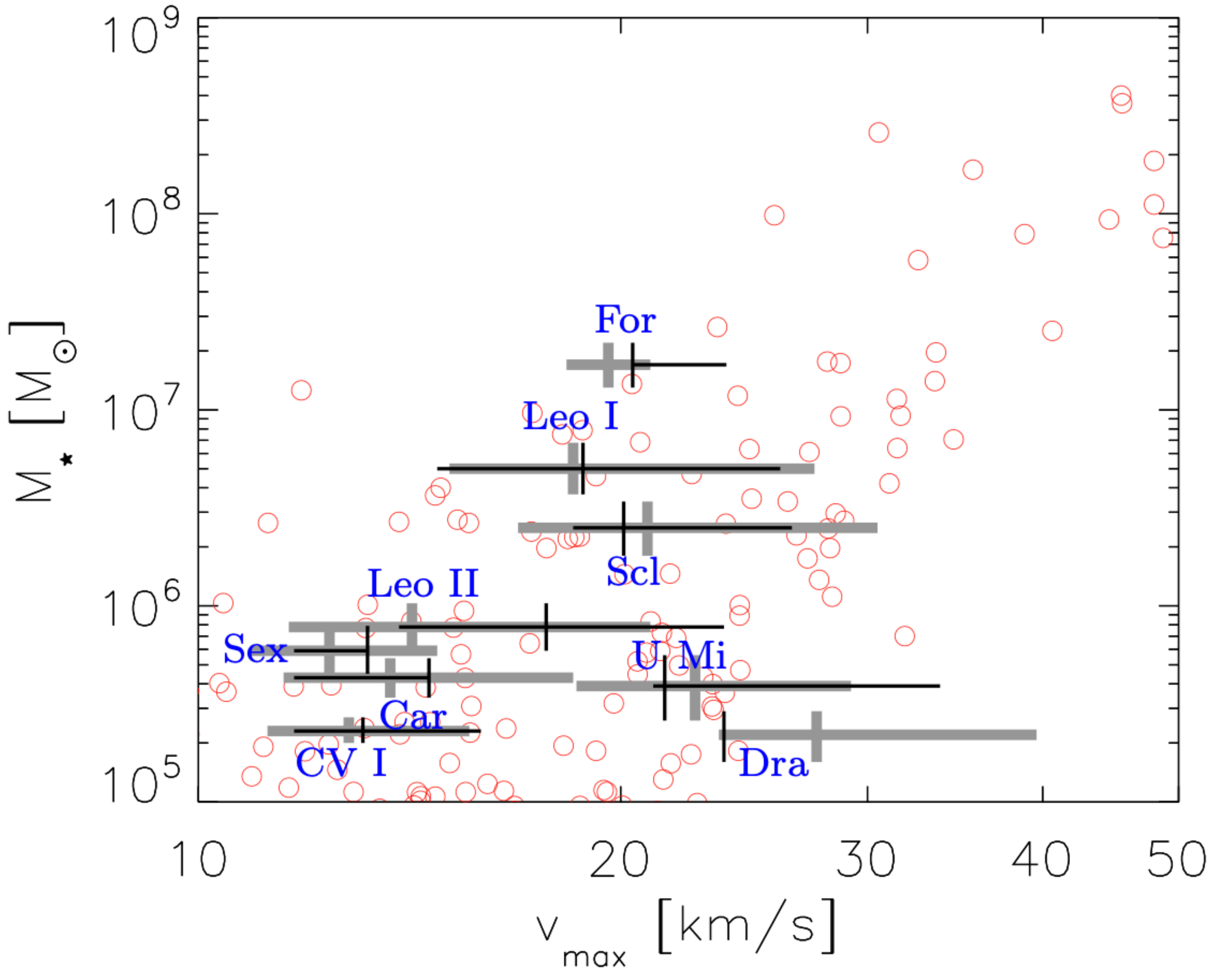
We are looking forward to seeing everyone at Queen’s in August!

Contact: tevpa2022@gmail.com — https://indico.cern.ch/e/TeVPA2022

Extras

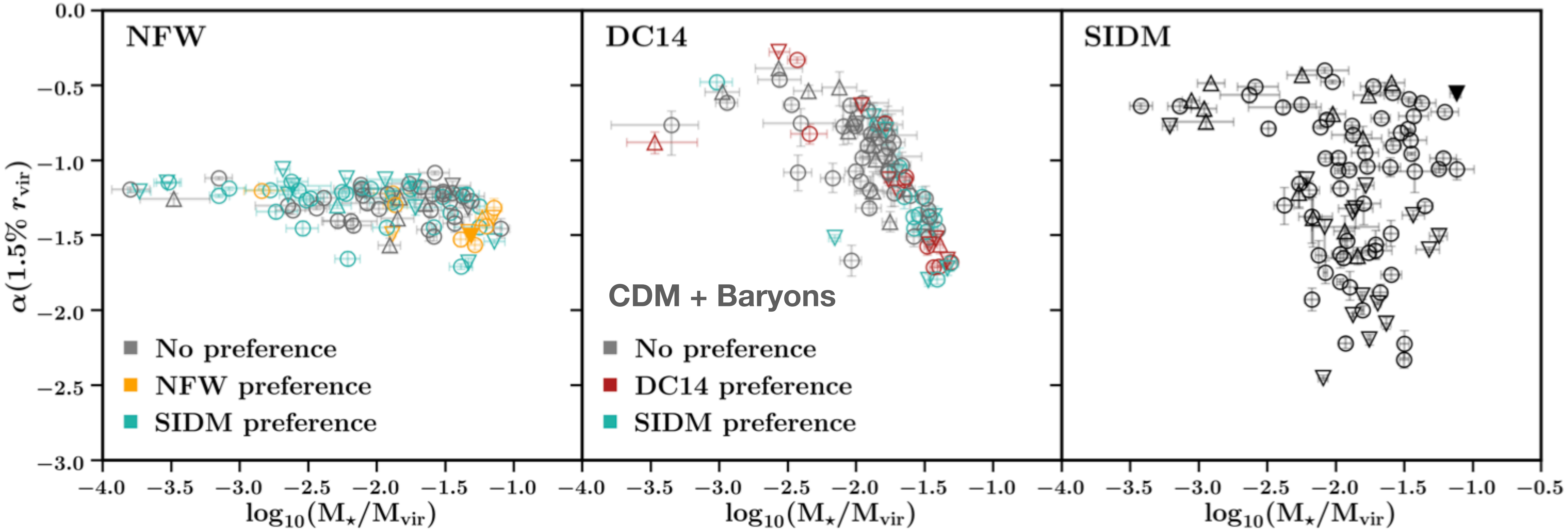


Isolated galaxies

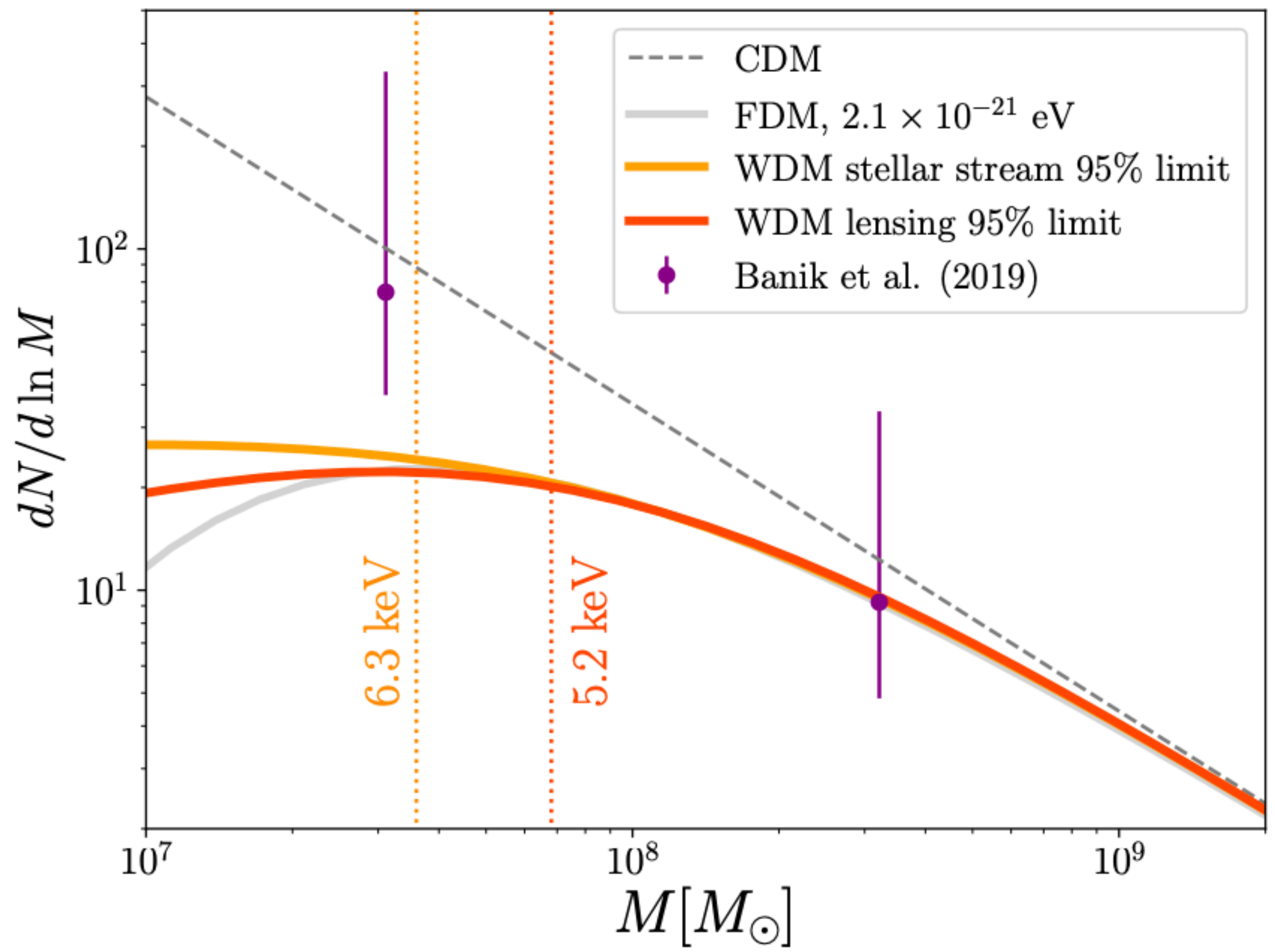


Satellite galaxies

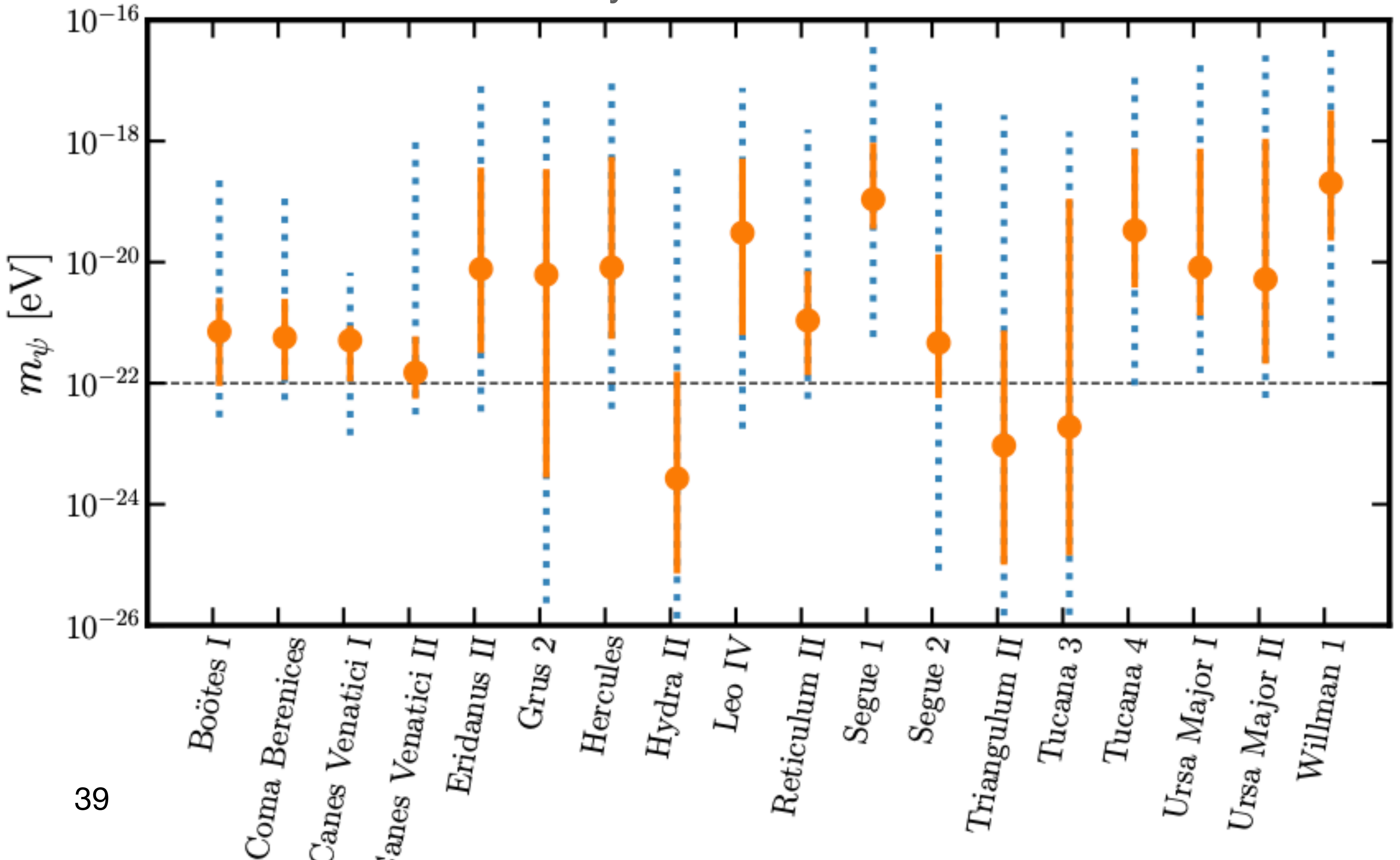
Diversity of inner slopes Zentner et al. 2202.00012



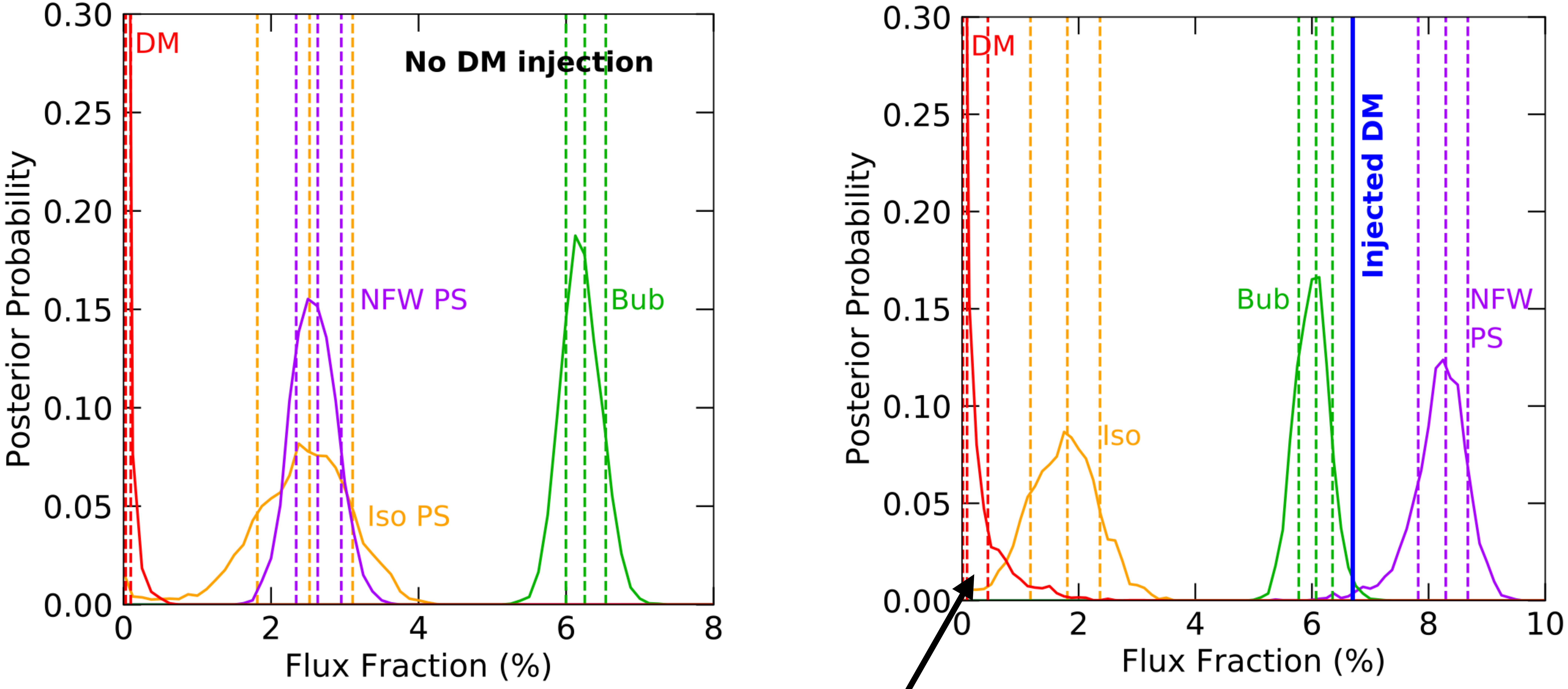
Halo Mass function of ULDM, Schutz 2001.05503



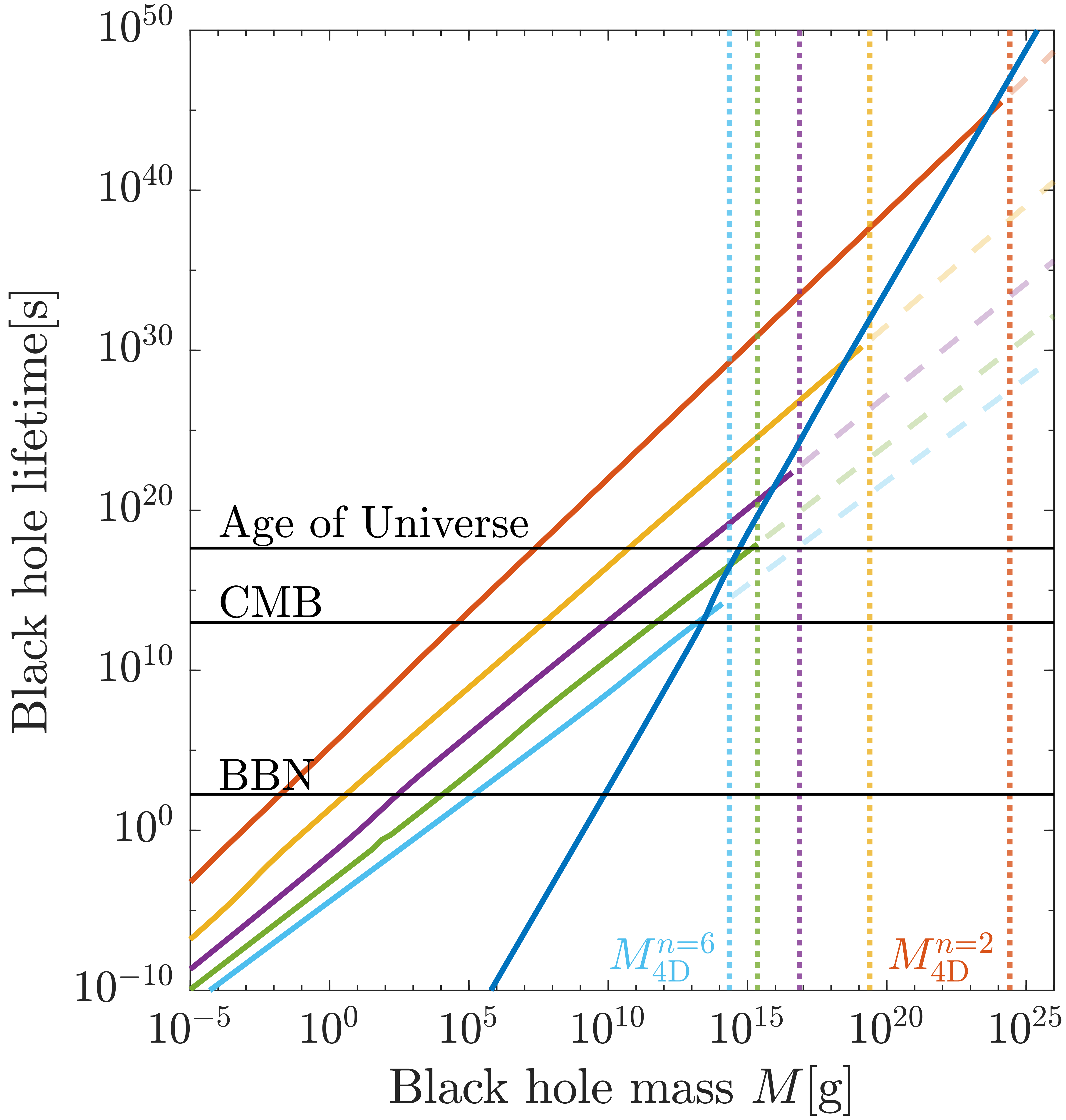
Hayashi et al. 2102.05300



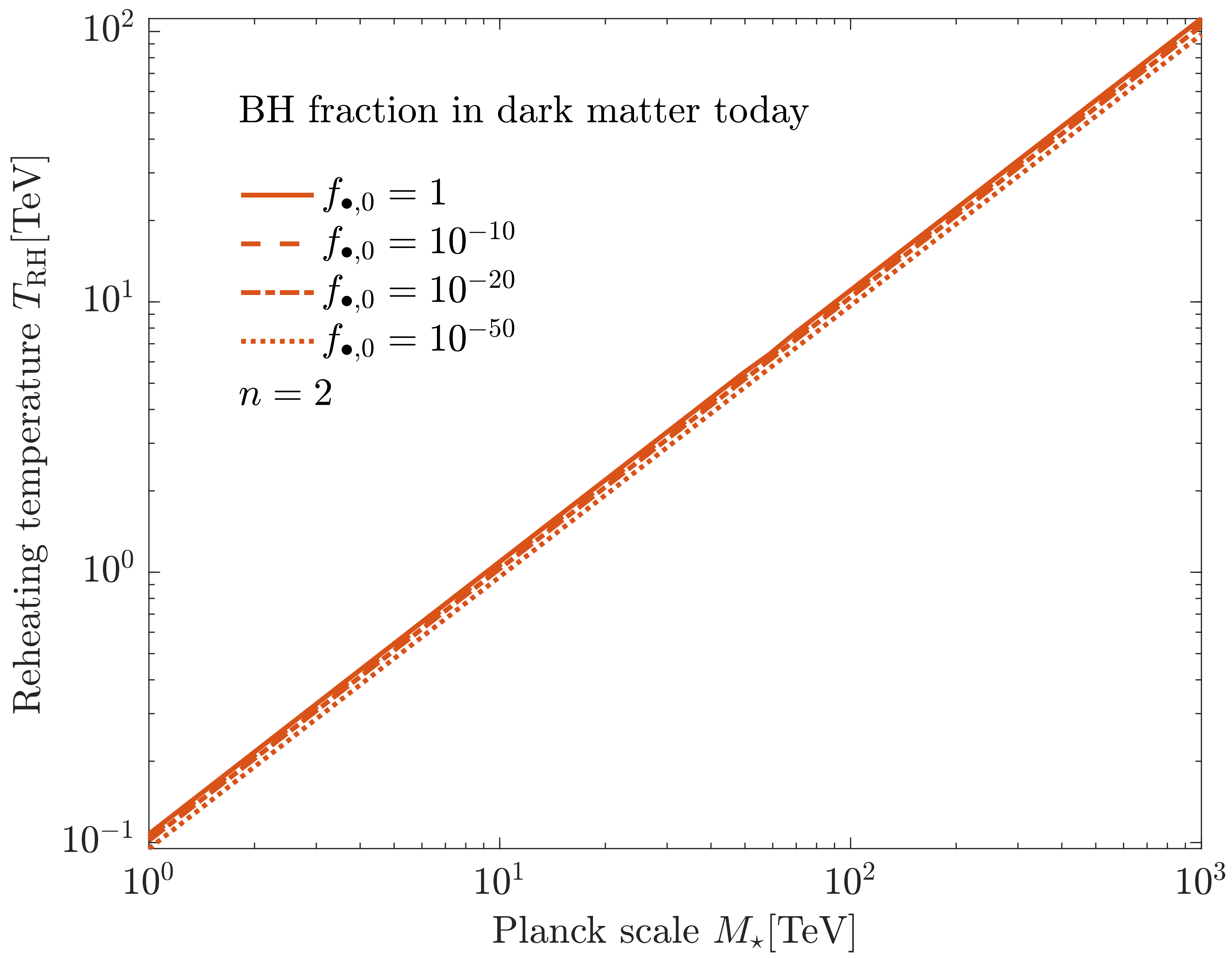
Galactic centre excess: Leane & Slatyer 2019



Dark matter not seen with this analysis method



10^{50}
10^{40}
10^{30}
10^{20}
10^{10}
10^{0}
10^{-10}
Black hole lifetime[s]
Age of Universe
CMB
BBN
$M_{4D}^{n=6}$
$M_{4D}^{n=2}$
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
10^{25}
Black hole mass M[g]



10^{2}
10^{1}
10^{0}
10^{-1}
Reheating temperature $T_{\rm RH}$[TeV]
BH fraction in dark matter today
$f_{\bullet,0} = 1$
$f_{\bullet,0} = 10^{-10}$
$f_{\bullet,0} = 10^{-20}$
$f_{\bullet,0} = 10^{-50}$
$n = 2$
10^{0}
10^{1}
10^{2}
10^{3}
Planck scale $M_\star$[TeV]


$n = 0$
Overabundant
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, M [g]
$n = 4$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, M [g]
$n = 5$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, M [g]
$n = 3$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, M [g]
$n = 2$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, M [g]
$n = 6$
Overabundant
Predicted Abundance
BHs survive
Microlensing
Isotropic Light
Galactic Centre
CMB
BBN
Initial fraction of dark matter, $f_\bullet$
Initial black hole mass, M [g]