matter and radiation seminar, Stavanger,
12 Oct 2020

The quest for the cosmological dark matter

image credit: NASA (Hubble deep field)

Torsten Bringmann

UiO : University of Oslo

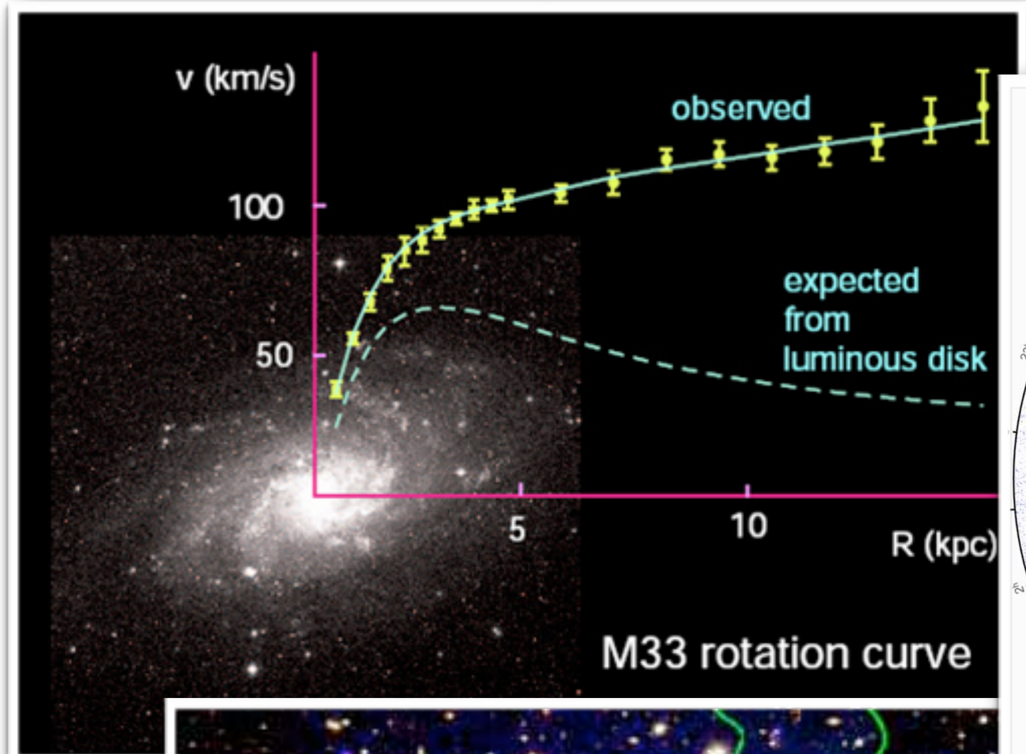
Outline

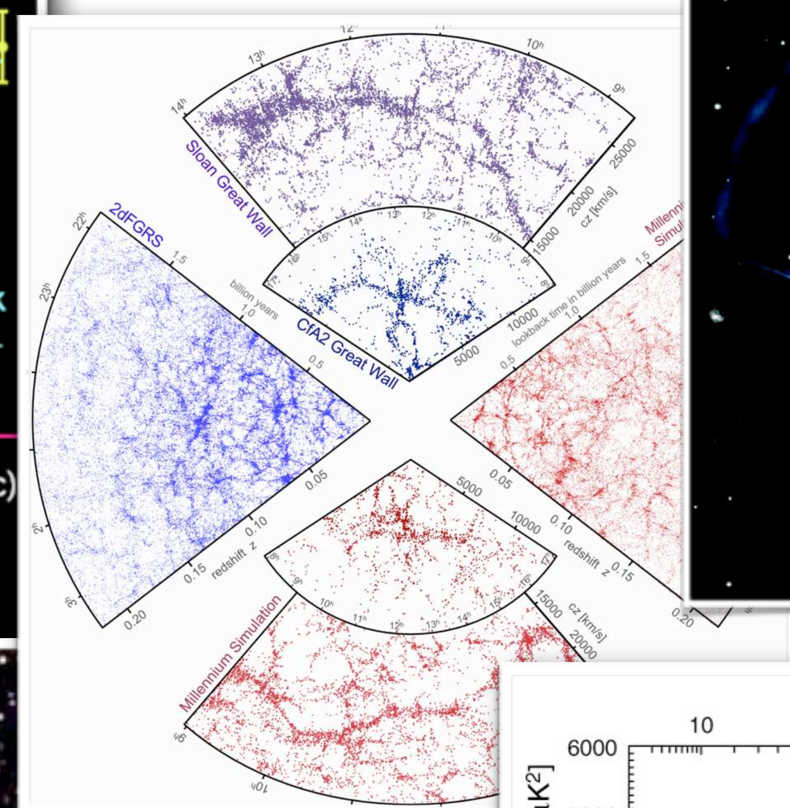
- Introduction
  - Evidence
  - Candidates & Tools
- Direct searches
  - ‘reverse’ direct detection
- Indirect searches
  - Gamma rays
- Other astrophysical probes
  - The matter power spectrum
  - Self-interacting dark matter
  - ETHOS

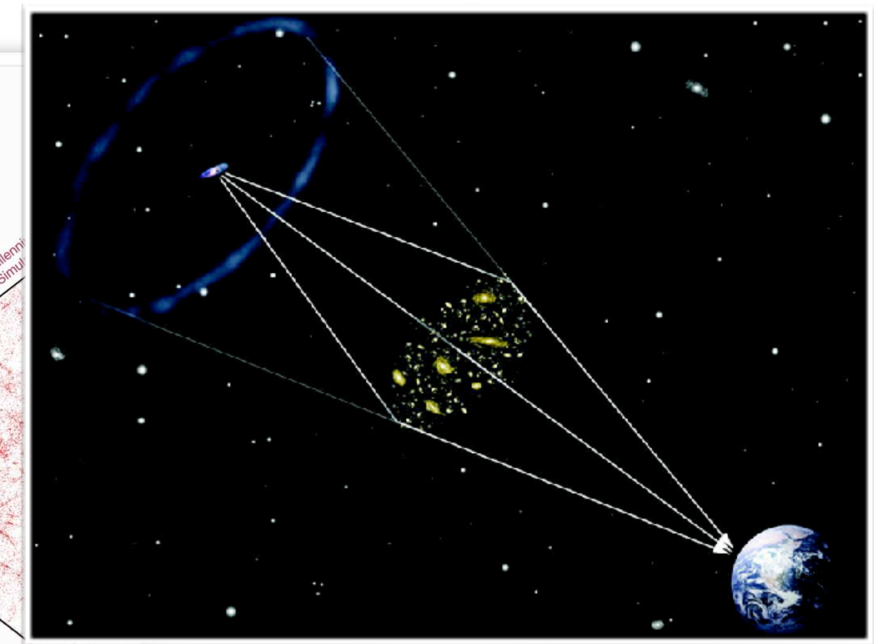
Health warning:

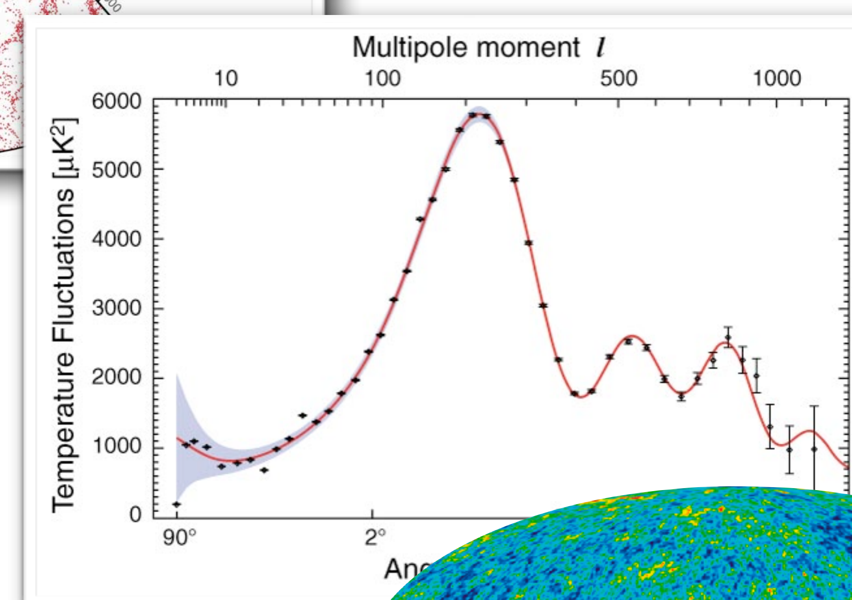
Expect strong personal bias in selection of examples

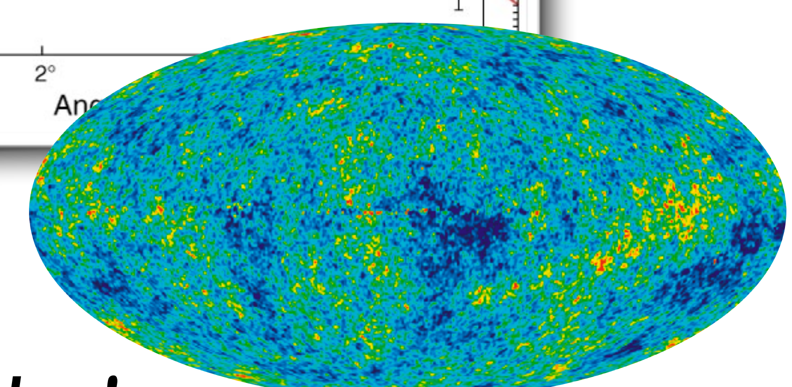
Dark matter all around









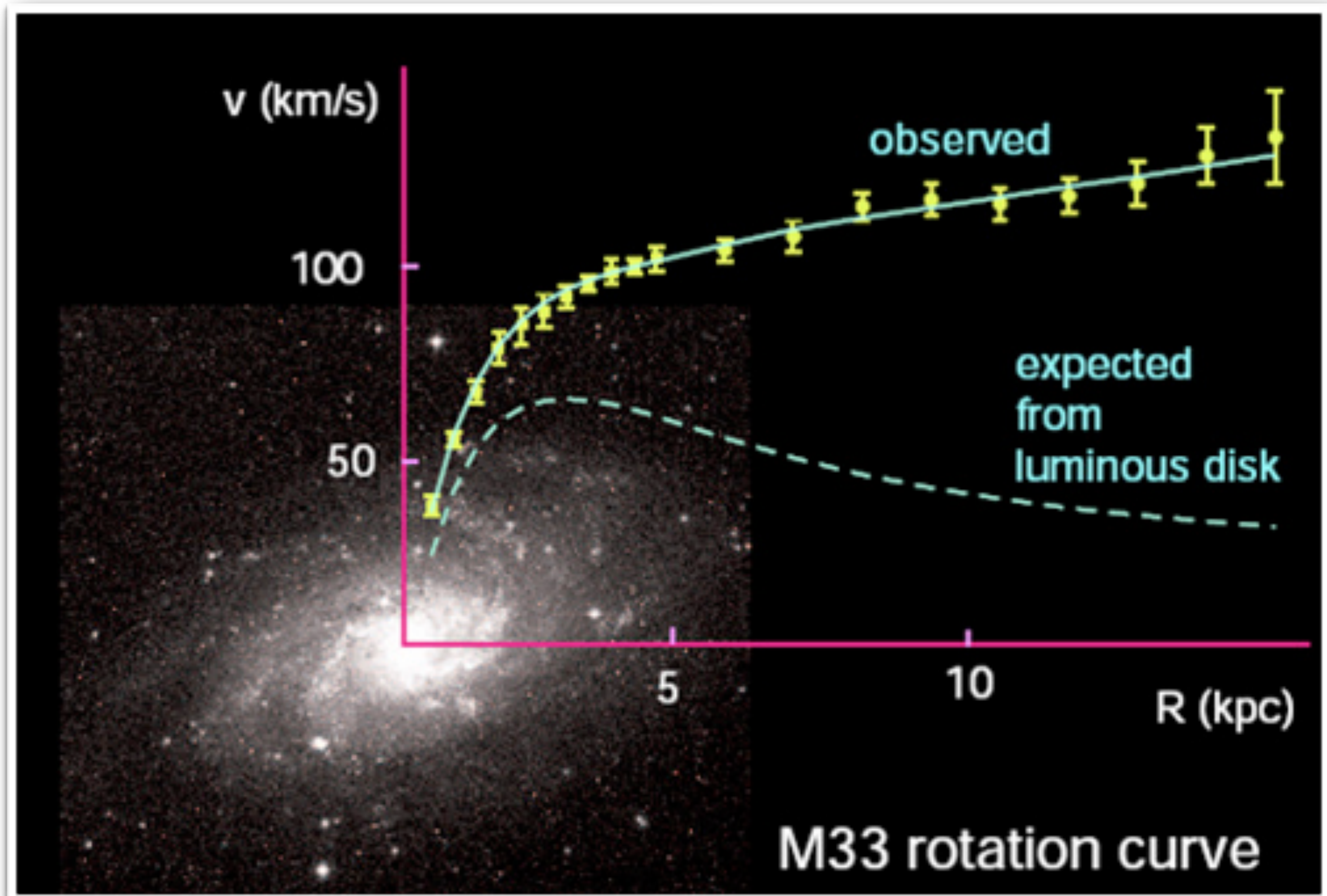


➡ *overwhelming evidence on* ***__all__*** *scales!*

Galactic scales

Newton:

$$G_N m_\odot \frac{M(r<R)}{R^2} = m_\odot \frac{v^2}{R}$$

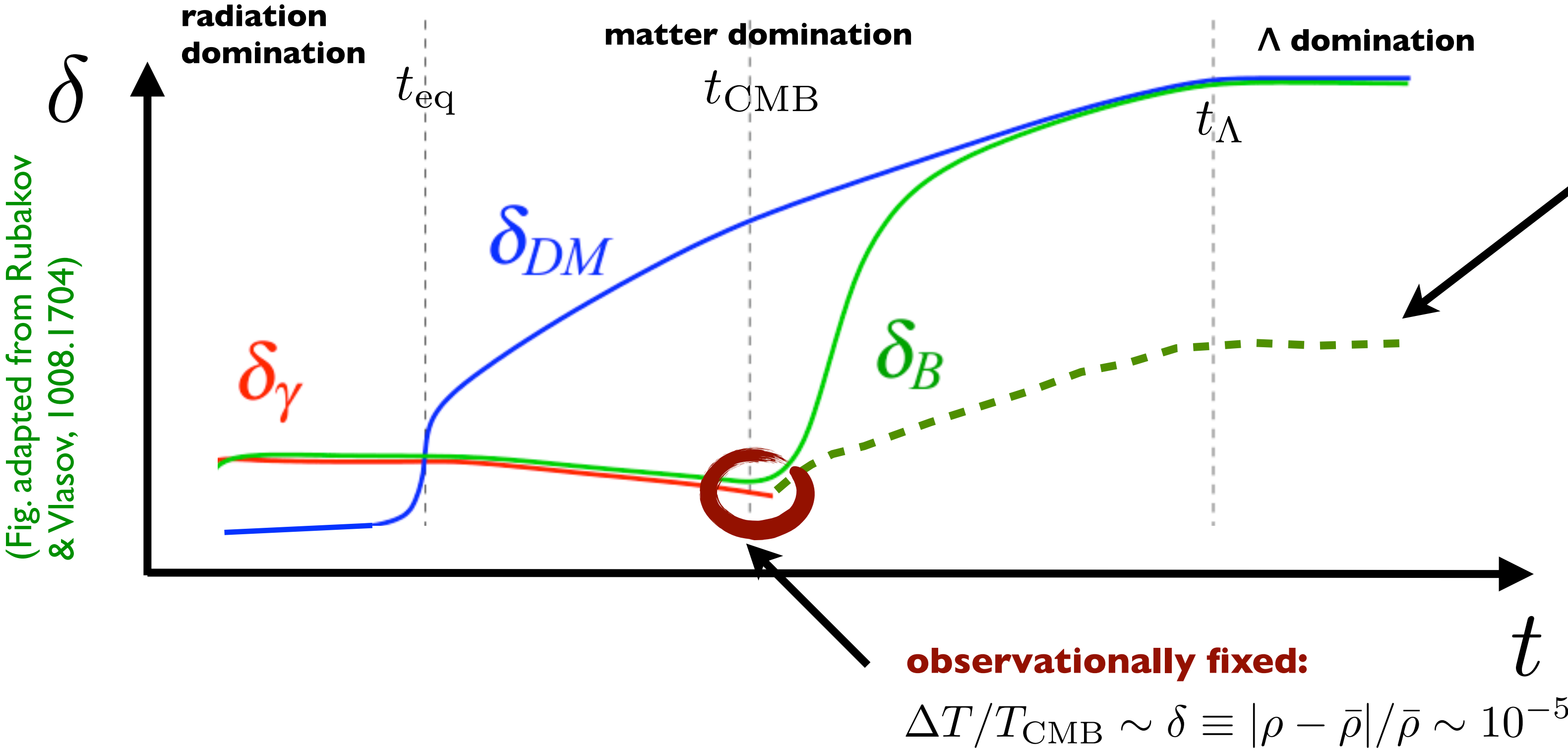


What is this
missing mass
made of ?

- Rotation curves no longer main argument for *existence* of dark matter !!!
  - observed rotation curves rather diverse
  - other potential explanations (for this particular discrepancy)

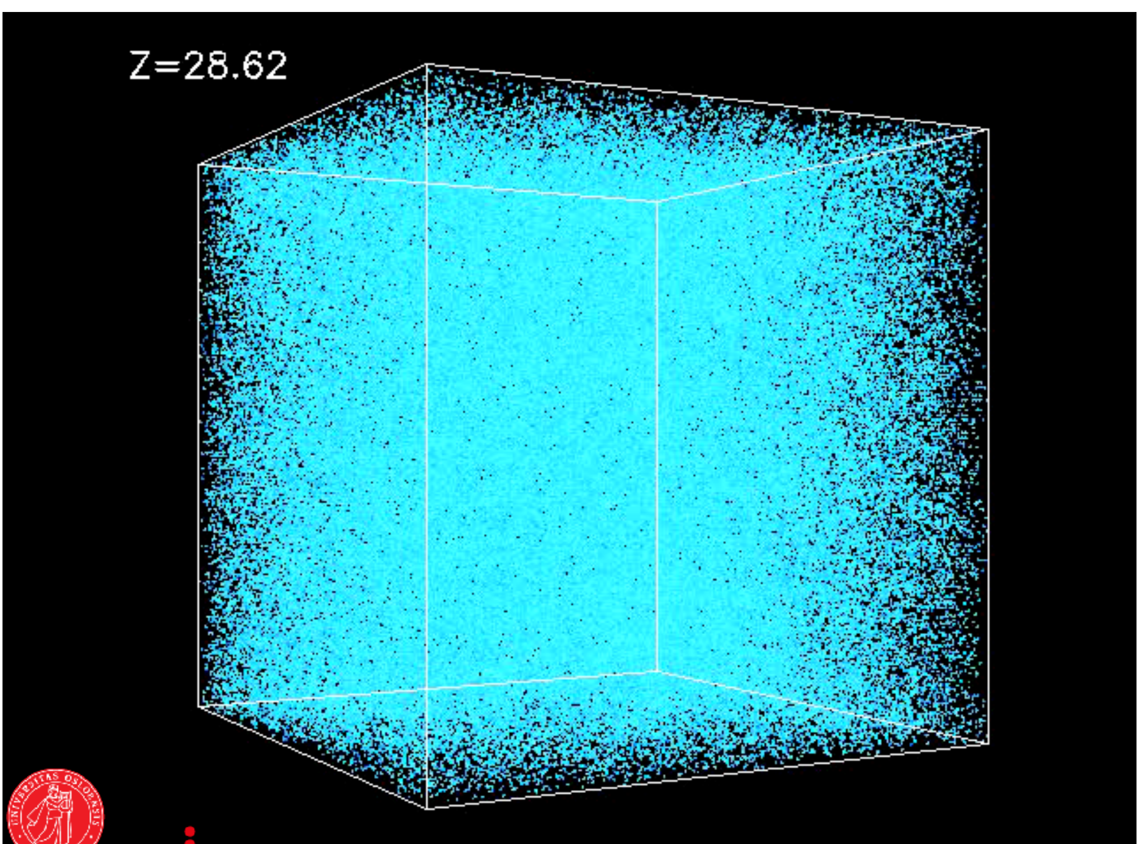
Cosmological scales

- Linear gravity $\rho(t,\mathbf{x}) = \bar{\rho}(t)[1+\delta(t,\mathbf{x})]$



assuming no DM: $\delta_b^{\rm today} \simeq \delta_\gamma^{\rm rec}(1+z^{\rm rec}) \sim 10^{-2}$

⇒ Without DM, still in the linear regime: no *galaxies*, *stars*, *planets*… life!



- Non-linear evolution
  - Need simulations
  - Dark matter required to reach ~perfect agreement with observations (at large scales)

From evidence to precision

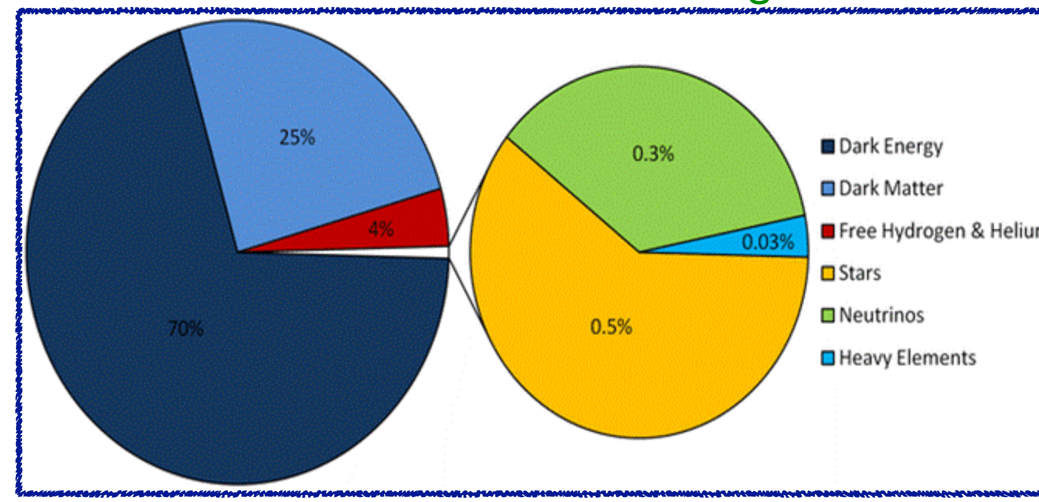
- DM is a crucial ingredient of cosmological SM!
  - constant co-moving energy density
  - only gravitational interactions
  - cold + dissipation-less

➡ $\Omega_{\rm CDM} h^2 = 0.1188 \pm 0.0010$

Ade+ [Planck Coll.], A&A '16

Percent-level measurements of a single parameter!

Image credit: KIAS



- DM conversion into (in)visible energy?
  - E.g. decays, late-time annihilation, coalescing PBHs, …

➡ $\Omega_{\rm CDM}$ decrease of up to 10% possible during matter domination!

(*model-independent*; but much more allowed during RD)

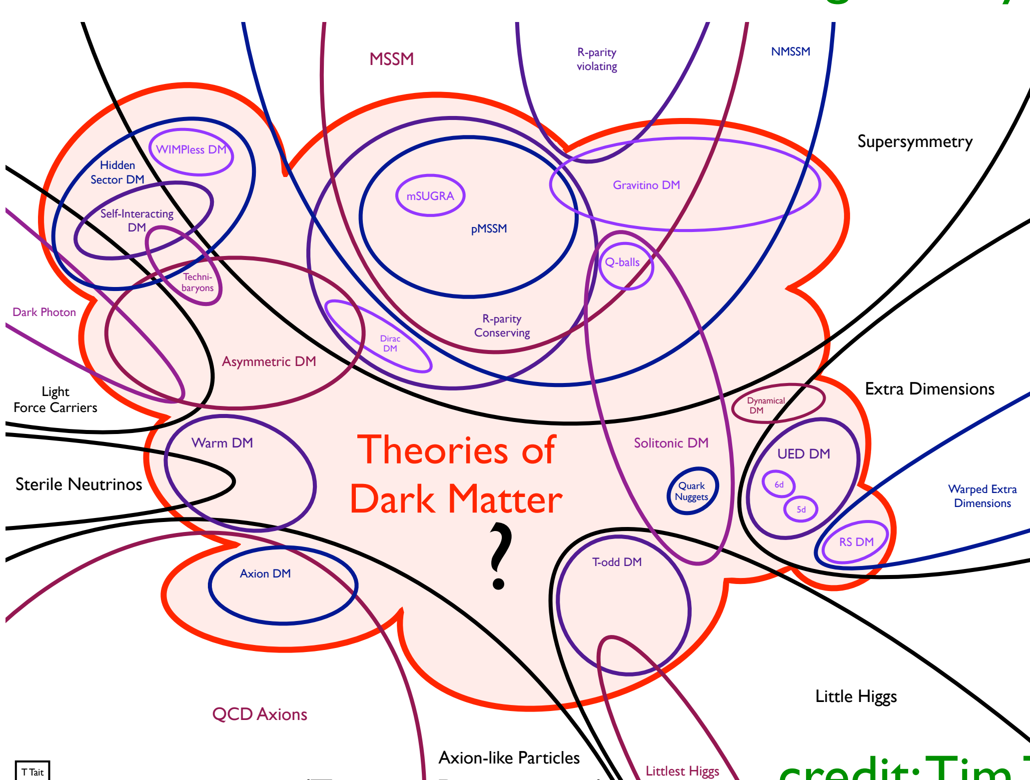
TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRD '18

- Q: Can't we explain *all* this also by modified gravity?
  - A: **No!** [though definitely yes for *selected* observations]

Candidates

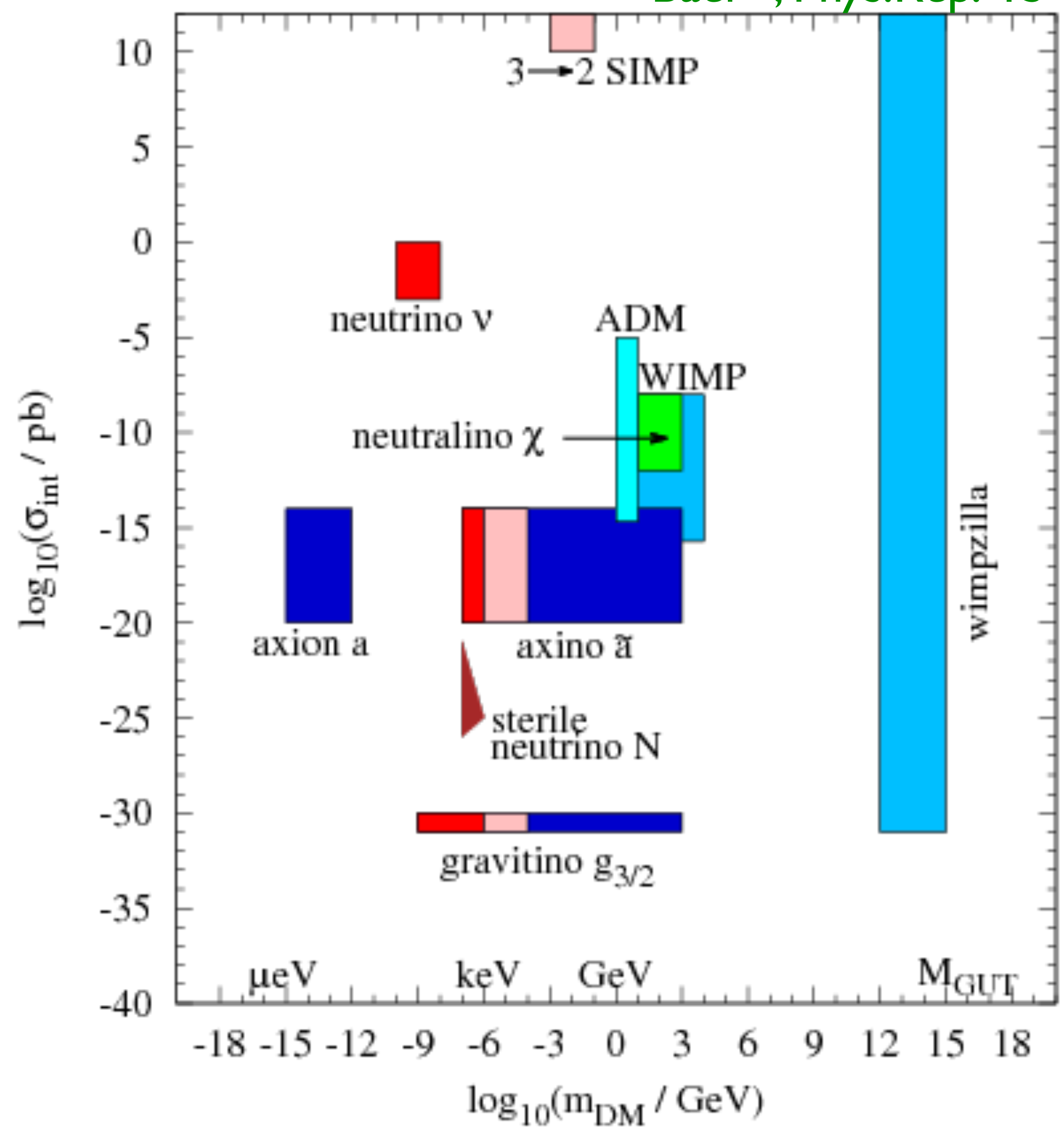
- Existence of (particle) DM = evidence for BSM physics!
  - \+ rather good handle on what it is ***not***
- Unfortunately, this still leaves too many options…

credit: Oleg Ruchaysky



credit: Tim Tait

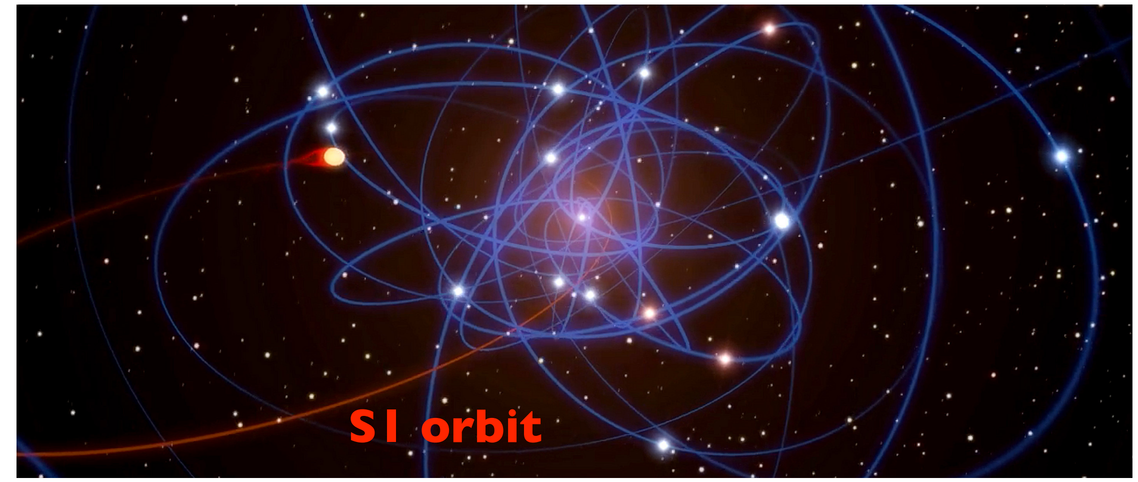
Baer+, Phys.Rep.'15



Black holes (I)

- Wouldn't (super-)solar mass black holes be an "obvious" / "conventional" candidate?

  [#  2017, 2020]



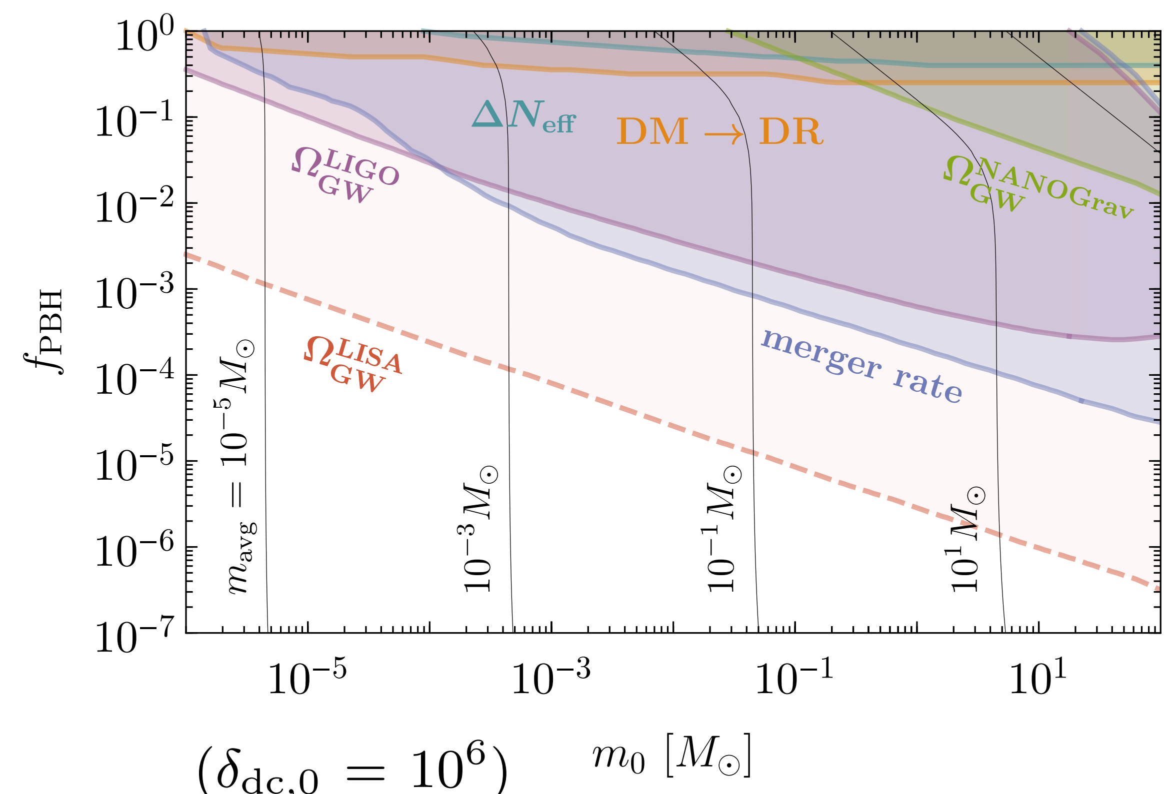
- Strongly constrained by micro-lensing and CMB!

  ➡ Black holes can only be a sub-dominant DM component

overview: Carr, Kohri, Sendouda & Yokoyama, 2002.12778

- Conclusion does not change for large black hole clustering…

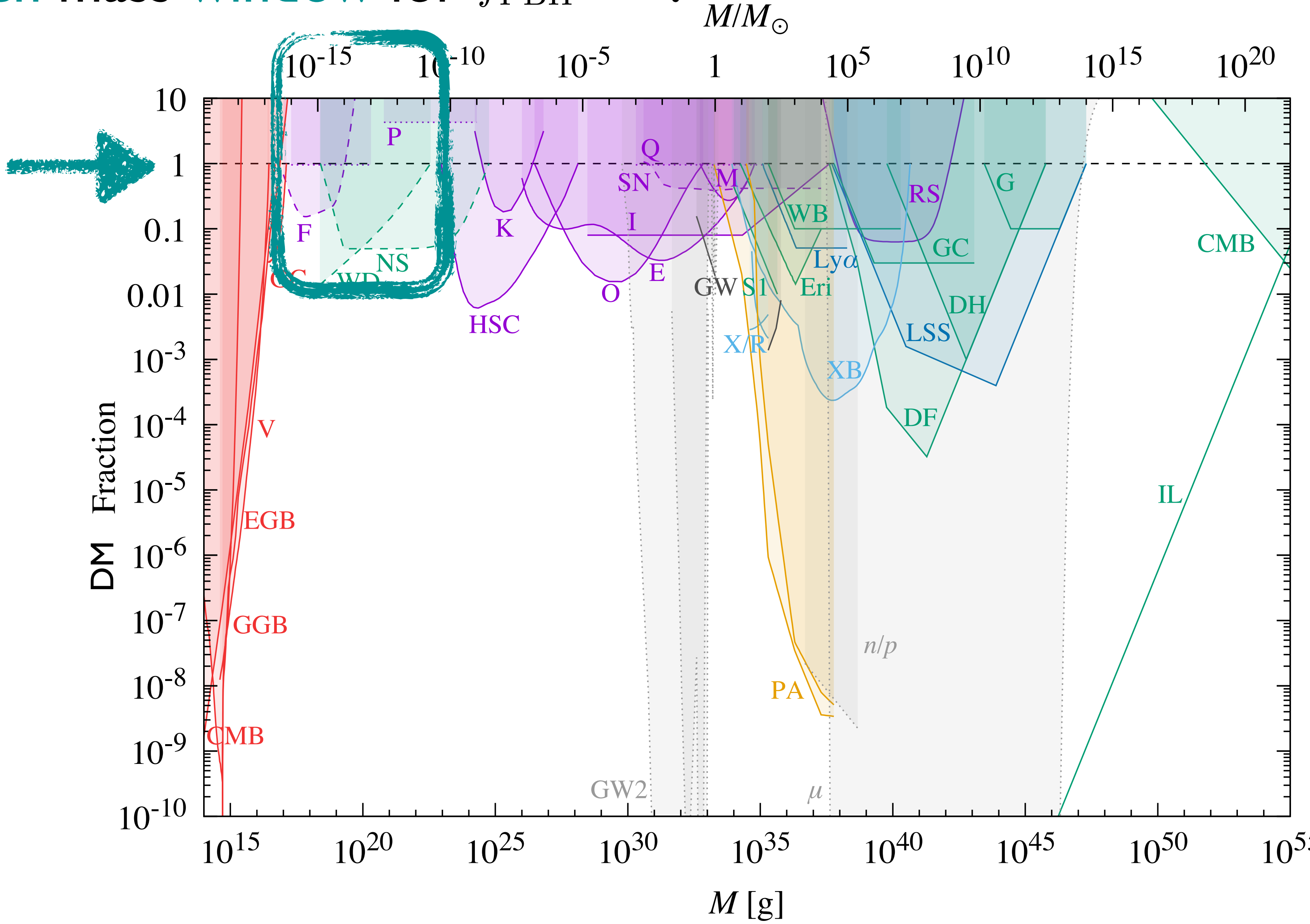
c.f. García-Bellido & Clesse, PDU '18
…



TB, Depta, Hufnagel & Schmidt-Hoberg, PRD '19

Black holes (II)

- Primordial black holes can be much smaller
  - ⇨ open mass window for $f_{\rm PBH} \sim 1$! Katz, Kopp & Sibiryakov, JCAP '18



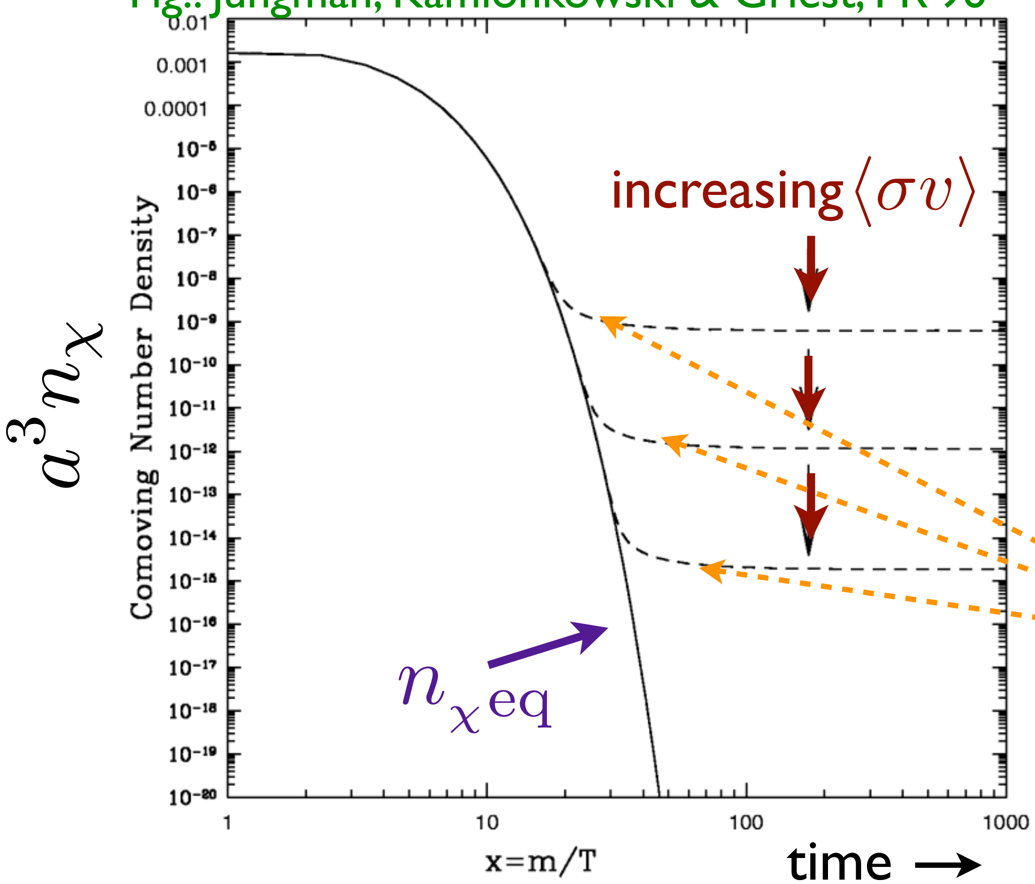
Carr, Kohri, Sendouda & Yokoyama, 2002.12778

- But this would also not be "SM physics" … !
  - *formation* (+ requirement of $f_{\rm PBH} \sim 1$) requires BSM physics

Weakly Interacting Massive Particles

- well-motivated from particle physics [SUSY, EDs, …]
- thermal production in early universe:

Fig.: Jungman, Kamionkowski & Griest, PR'96



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$

(thermal average)

"Freeze-out" when annihilation rate falls behind expansion rate

➡ Relic density (today): $\Omega_\chi h^2 \sim \frac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

for weak-scale interactions!

= a 'miracle' ?

- WIMP DM is seriously pressured, but not (yet) 'dead' !

Arcadi+, EPJC '18
Athron+, EPJC '19
(+ many more)

Dead or alive ?

Forbes Billionaires Innovation Leadership Money Business Small Business Lifestyle Lists Advisor Featured Breaking More

52,696 views | Feb 22, 2019, 02:00am

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.

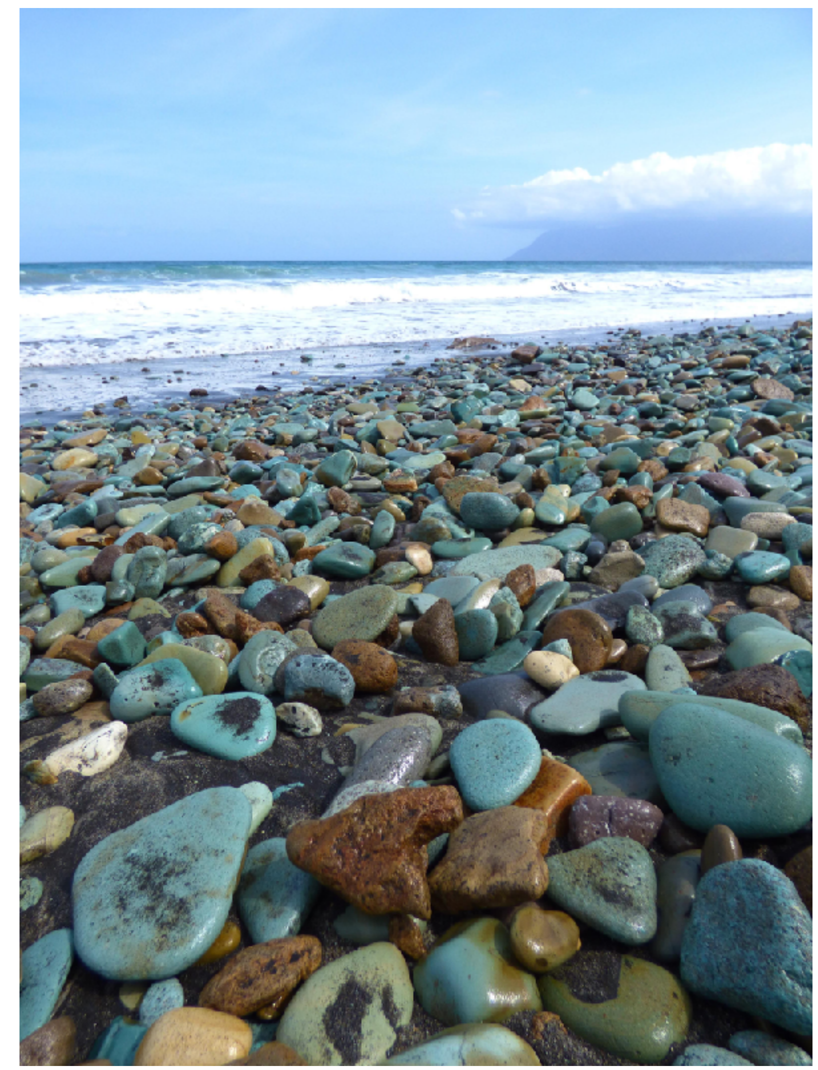
Dan Hooper @DanHooperAstro Follow

While I agree that direct detection experiments and the LHC have put some strain on the WIMP hypothesis, there are still plenty of WIMP models that have not been ruled out. WIMPs may have looked better in the past, but they are still very much alive. #DarkMatter

• • •

Where next?

- If fine-tuning isn't a good guiding principle, what about the alternatives?
  - quite hard to 'automatically' get the DM relic density right, even for 'nice' models!



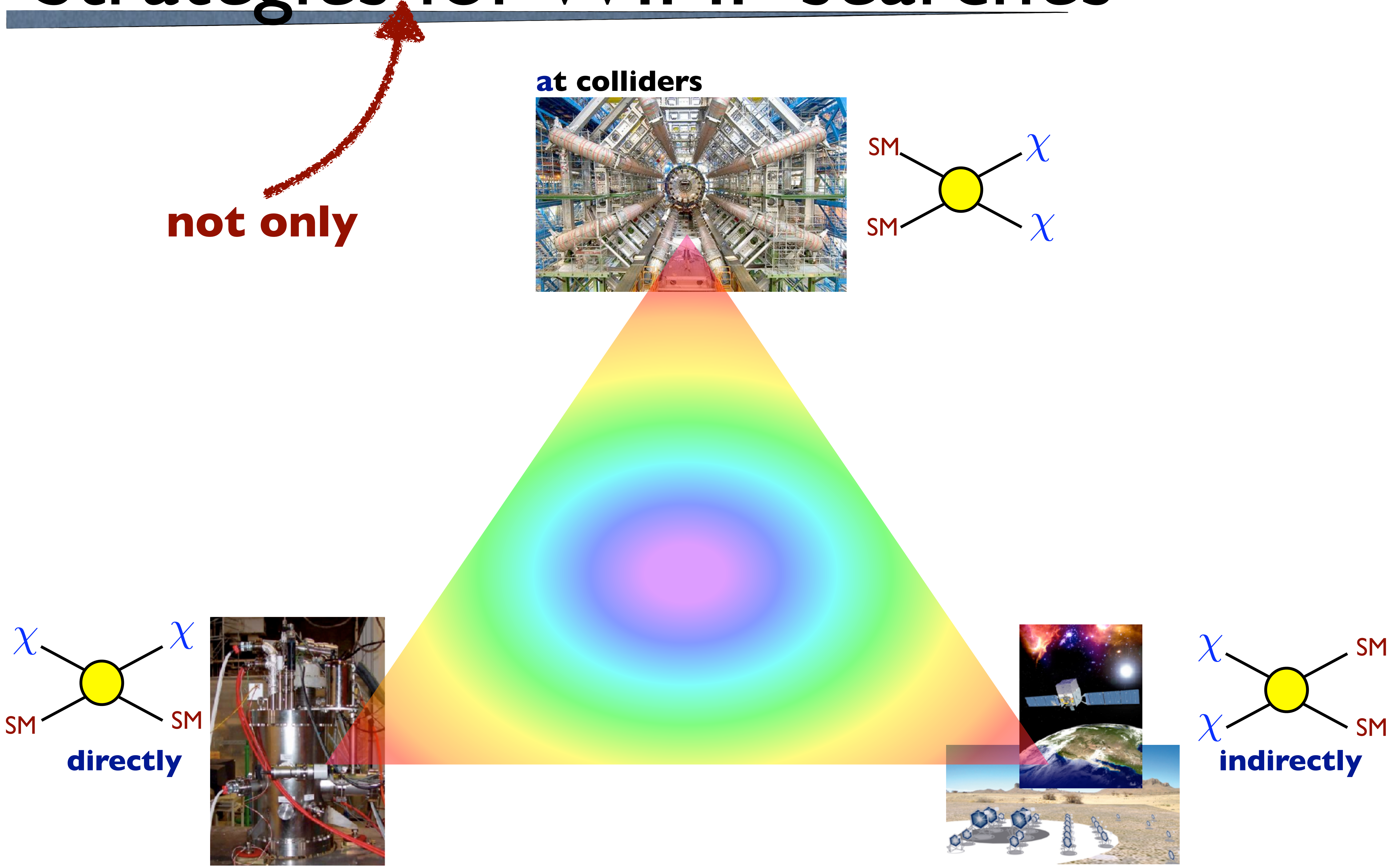
- Or should we give up on theoretical guiding principles, leaving 'no stone unturned'?

Bertone & Tait, Nature '18

  - Problem: there might be quite a few of them (not even counting those that cannot be unturned)…

➡ *Challenge for the field: Stay open-minded yet focussed !*

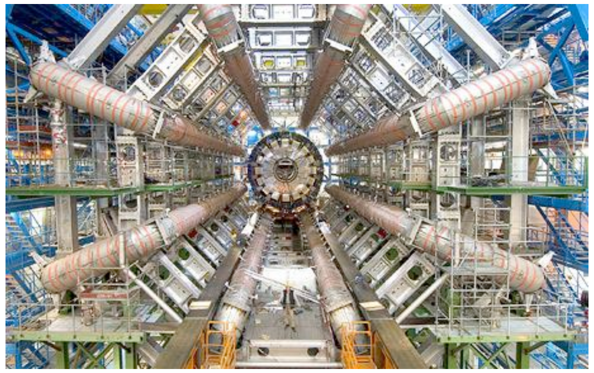
Strategies for WIMP searches



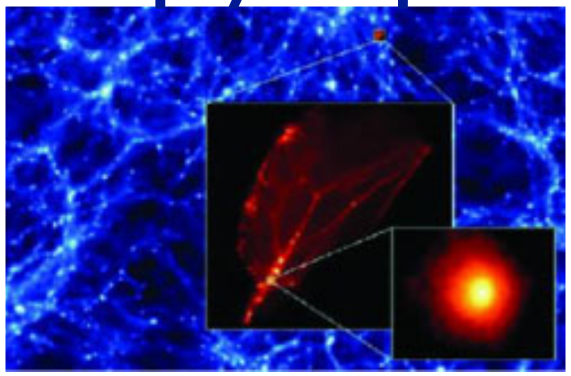
➡ *all complementary !*

Strategies for dark matter searches

at colliders

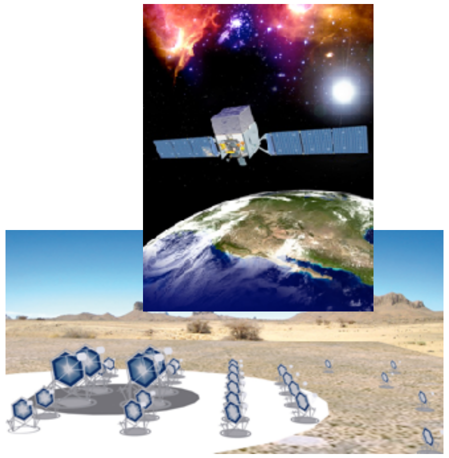


astrophysical probes



of matter distribution

directly



indirectly

DarkSUSY

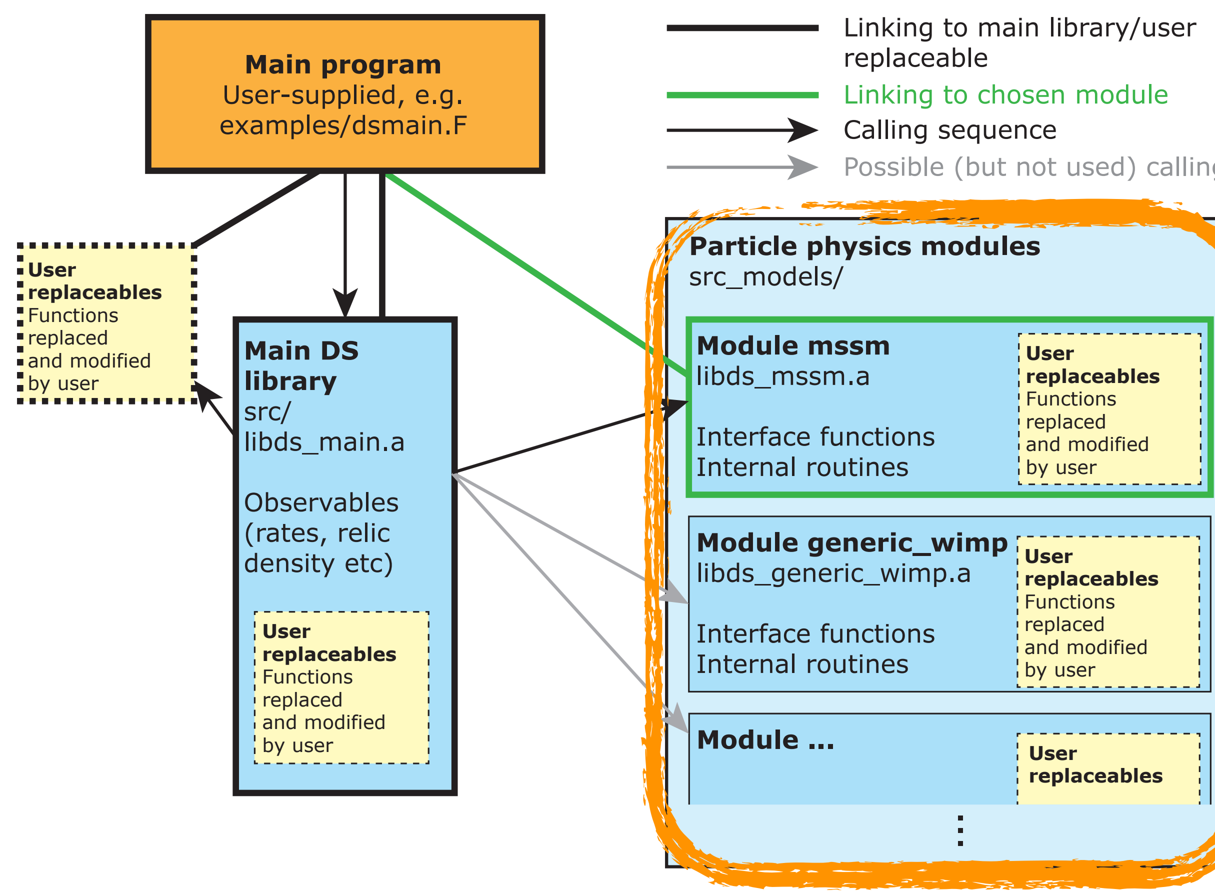
FREE DOWNLOAD ;)

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://darksusy.hepforge.org

Since version 6: no longer restricted to supersymmetric DM !

- Numerical package to calculate 'all' DM related quantities:
  - *relic density + kinetic decoupling* **(also for** $T_{\rm dark} \neq T_{\rm photon}$ **)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - particle yields for generic DM annihilation or decay
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - …



since 6.1: DM self-interactions

since 6.2: 'reverse' direct detection
(also Q^2 -dependent scattering!)

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

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

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

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

(slide stolen form Pat Scott)

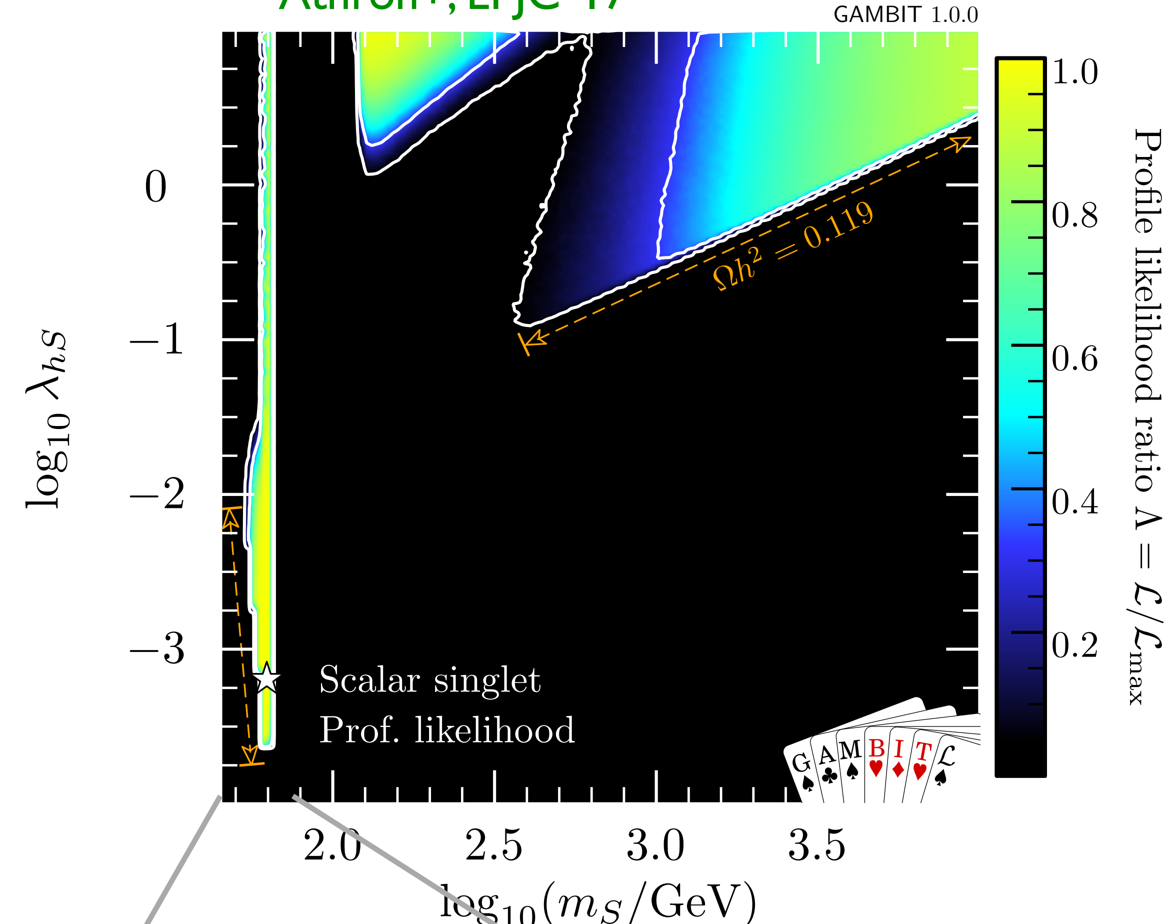
Dark matter with GAMBIT

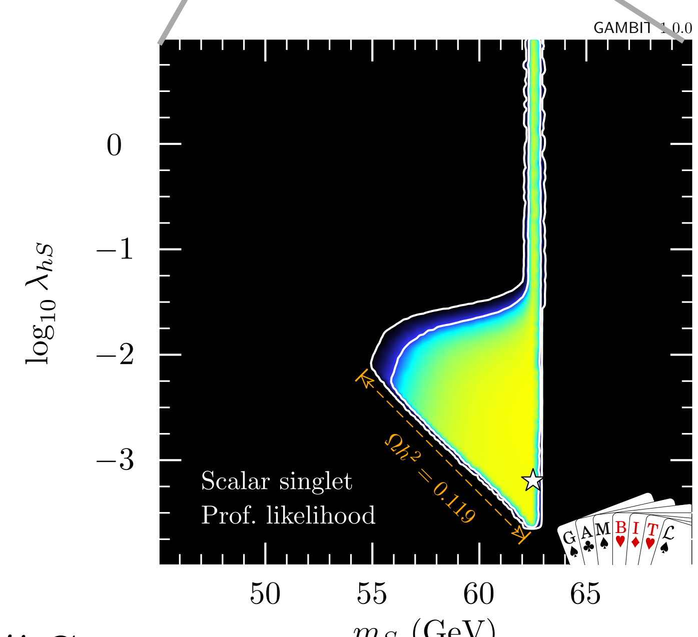
- **DarkBit** TB+, EPJC '17
  - takes input (DM observables) from 'backended' codes like DarkSUSY, micrOMEGAs, DDCalc, nuLike, gamLike…
  - adds fully 'native' observables (e.g. astrophysical axion limits)
  - returns likelihoods for a plethora of experimental data
- **GAMBIT**
  - adds likelihoods from other 'Bits' (Collider, Flavour, …)
  - performs global scan over model parameters
- **Example: The Scalar Singlet**

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S$$

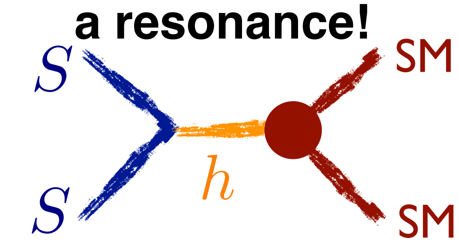
Silveira & Zee, PLB '85

Athron+, EPJC '17





But do not (blindly) trust relic density calculations very close to a resonance!



Binder, TB, Gustafsson & Hryczuk, PRD '17

- Introduction
  - Evidence
  - Candidates & Tools
- Direct searches
  - ‘reverse’ direct detection
- Indirect searches
  - Gamma rays
- Other astrophysical probes
  - The matter power spectrum
  - Self-interacting dark matter
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Direct searches

- Look for dark matter collisions with atomic nuclei

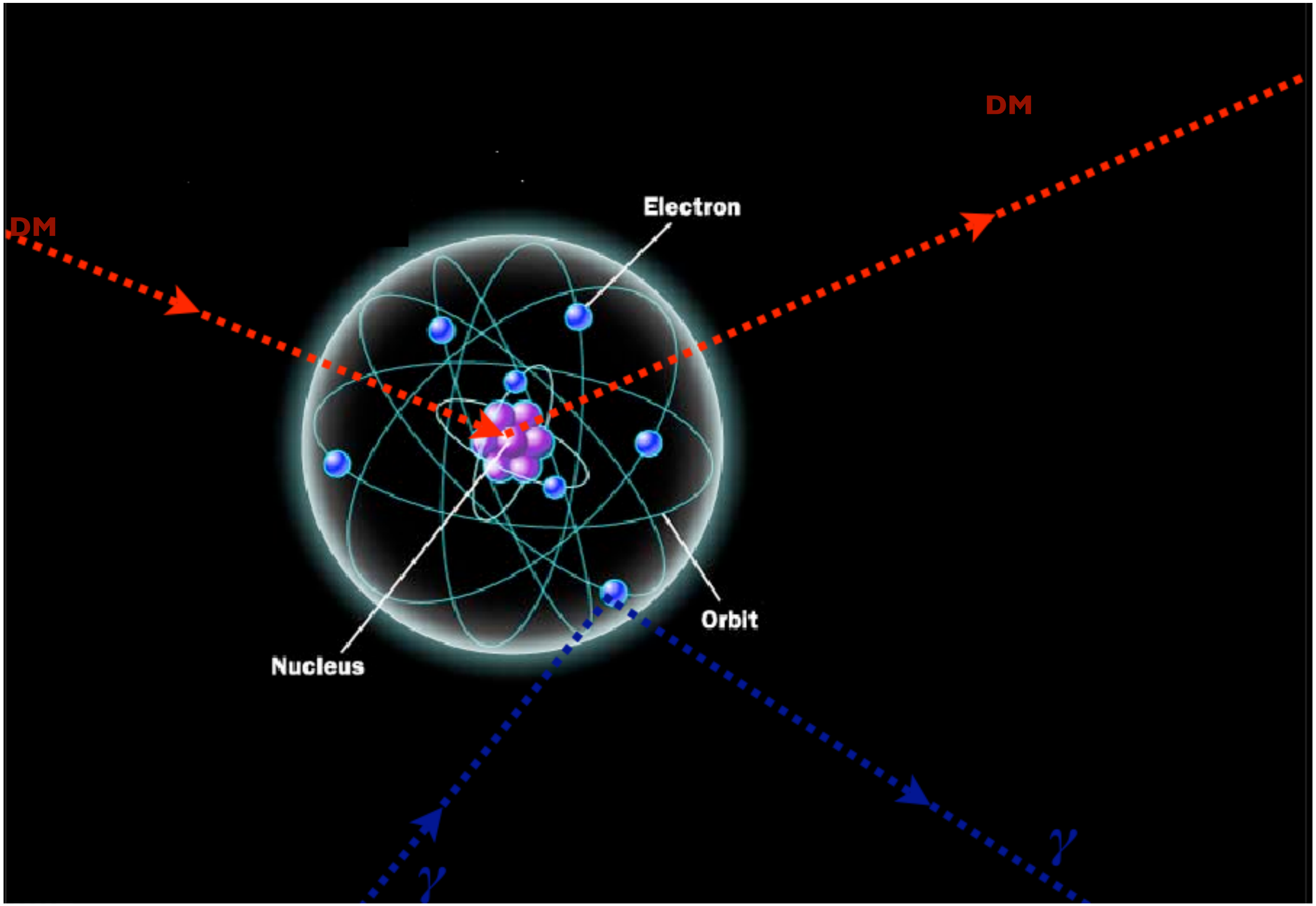


Fig.: Queiroz, 1605.08788

Experiments typically aim at 'background-free' setting !

Recoil rate [per unit detector mass]

$$\frac{dR}{dE_R} = \frac{\rho_\odot^\chi}{m_\chi m_N} \int_{v_{\min}}^{v_{\max}} \frac{d\sigma_{\chi N}}{dE_R} v f(v) dv$$

- Astrophysical input
  - $\rho_\odot^\chi \sim 0.4\,\mathrm{GeV\,cm^{-3}}$ — *average DM density at Sun's distance to Galactic center relatively well measured*
  - $f(v) \sim (\pi v_0^2)^{-\frac{3}{2}} e^{-\frac{\mathbf{v}^2}{v_0^2}}$ — *standard halo model (SHM) in galactic* frame *rests on isothermal density profile*

    $v_0 \sim 220\,\mathrm{km/s}$

    [from $\rho_\odot^\chi$]

    $\rightsquigarrow$ *NB: exact form only roughly corresponds to what is seen in simulations*
  - $v_{\max} \sim 544\,\mathrm{km/s}$ — *galactic escape velocity, well measured*

- Recoil energy

$$E_R = \frac{Q^2}{2m_N} = \frac{4m_\chi m_N T_\chi}{(m_\chi + m_N)^2} \frac{1-\cos\theta_{\mathrm{cm}}}{2} \Rightarrow v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

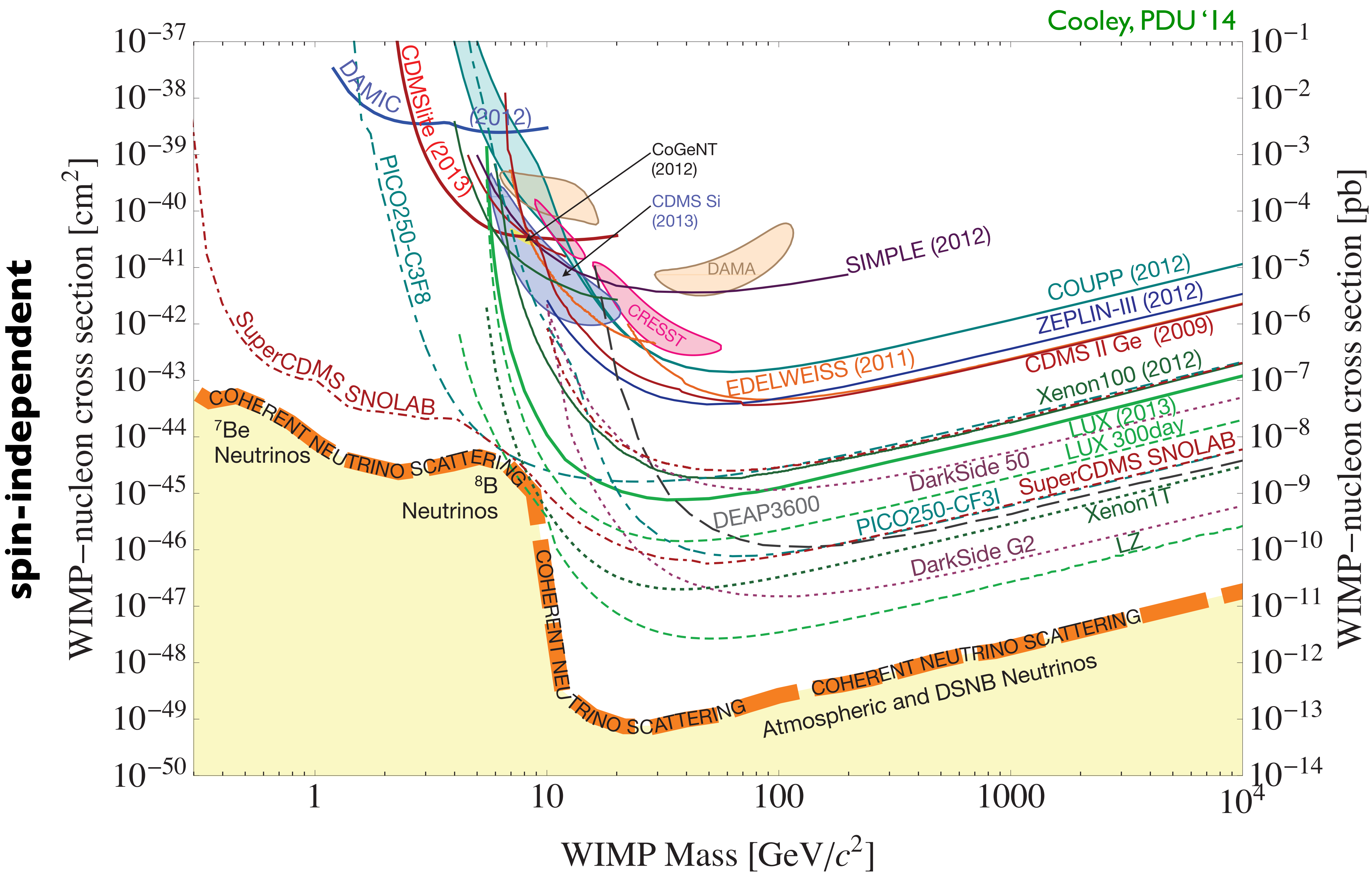
$m_\chi \gg m_N$: $21.2\,\frac{\mathrm{km}}{\mathrm{s}} \times \left(\frac{E_R}{\mathrm{keV}}\right)^{\frac{1}{2}} \left(\frac{m_N}{100\,\mathrm{GeV}}\right)^{-\frac{1}{2}}$

$\ll v_0 \rightsquigarrow$ *sample full $f(v)$*

$m_\chi \ll m_N$: $2120\,\frac{\mathrm{km}}{\mathrm{s}} \times \left(\frac{m_\chi}{\mathrm{GeV}}\right)^{-1} \left(\frac{E_R}{\mathrm{keV}}\right)^{\frac{1}{2}} \left(\frac{m_N}{100\,\mathrm{GeV}}\right)^{\frac{1}{2}}$

$\gg v_0 \rightsquigarrow f(v)$ *exp. suppressed*

A vast experimental effort



Need lower threshold

$v_{\rm min} \gg v_0$

(rate exponentially suppressed)

$v_{\rm min} \ll v_0$

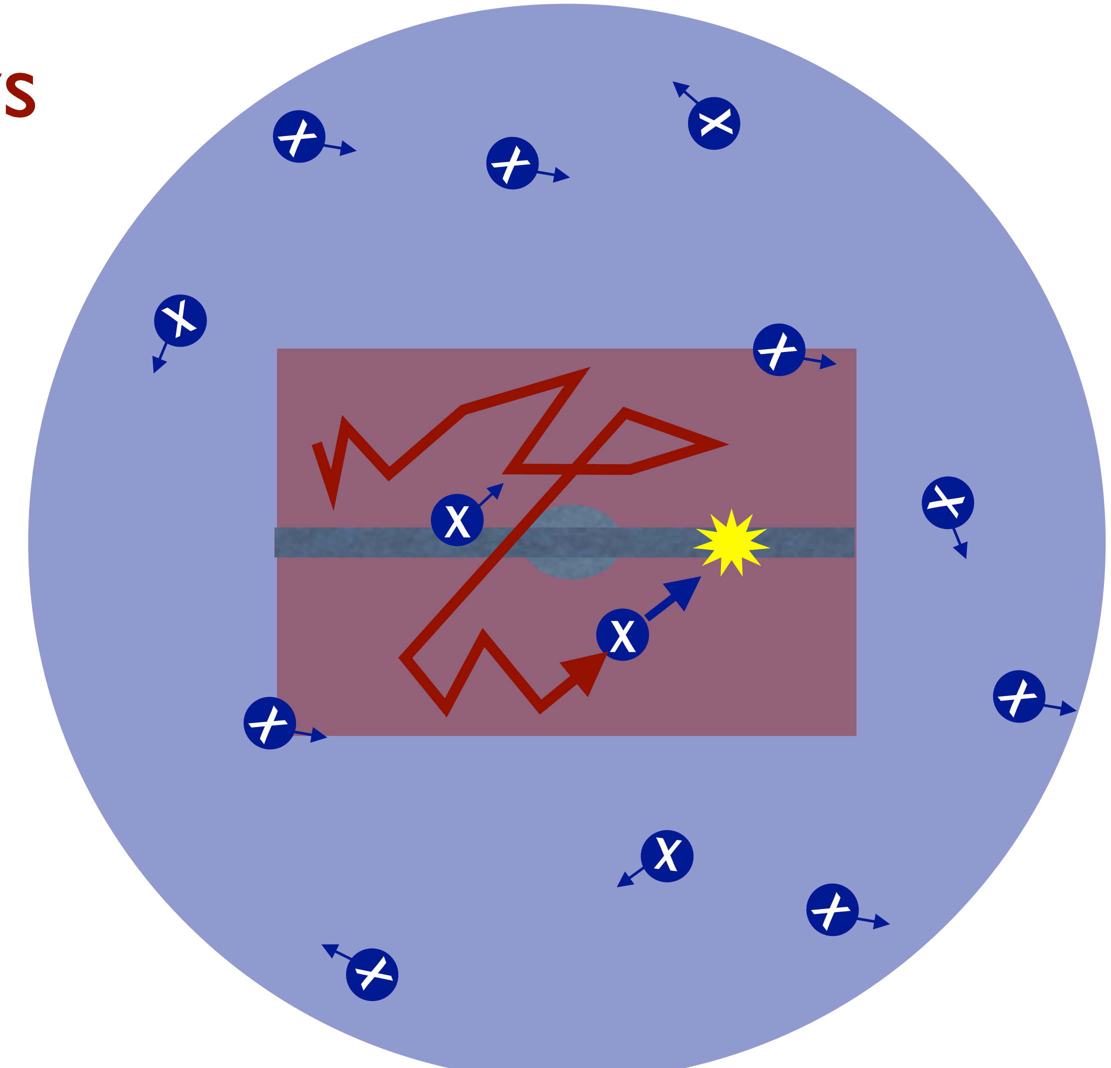
(rate $\propto n_\chi \propto m_\chi^{-1}$)

Need higher exposure (mass)

Reverse direct detection

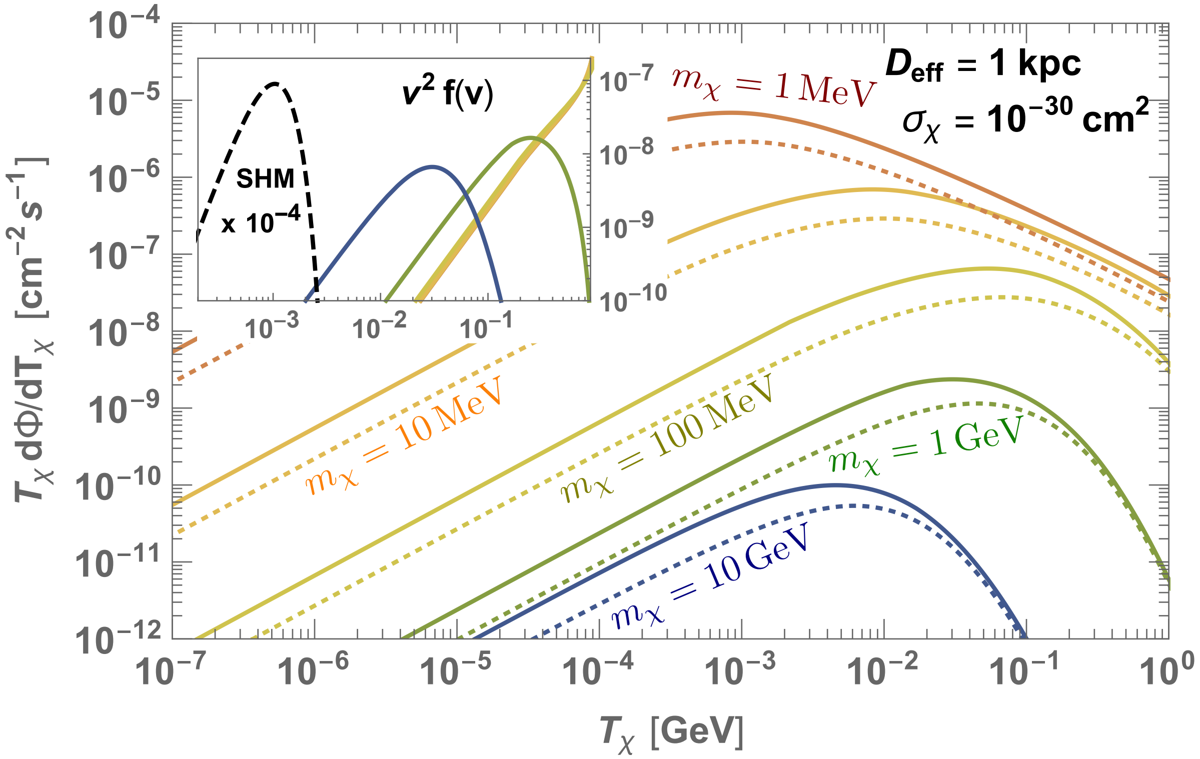
- Light DM really only accessible with lower thresholds?
- Not if part of the DM distribution moves fast!
  - 'Boosted DM' from decays — Agashe, Cui, Necib & Thaler, JCAP '14
  - DM accelerated in the sun — Kouvaris, PRD '15; An, Pospelov, Pradler & Ritz, PRL '18; Emken, Kouvaris & Nielsen, PRD '18
- *New idea:* high-energy cosmic rays should up-scatter DM initially (almost) at rest! — TB & Pospelov, PRL '19

Cappiello, Ng & Beacom, PRD '19
Ema, Salo & Sato, PRL '19
Dent, Dutta, Newstead & Shoemaker, 1907.03782
Bondarenko+, 1909.08632
…

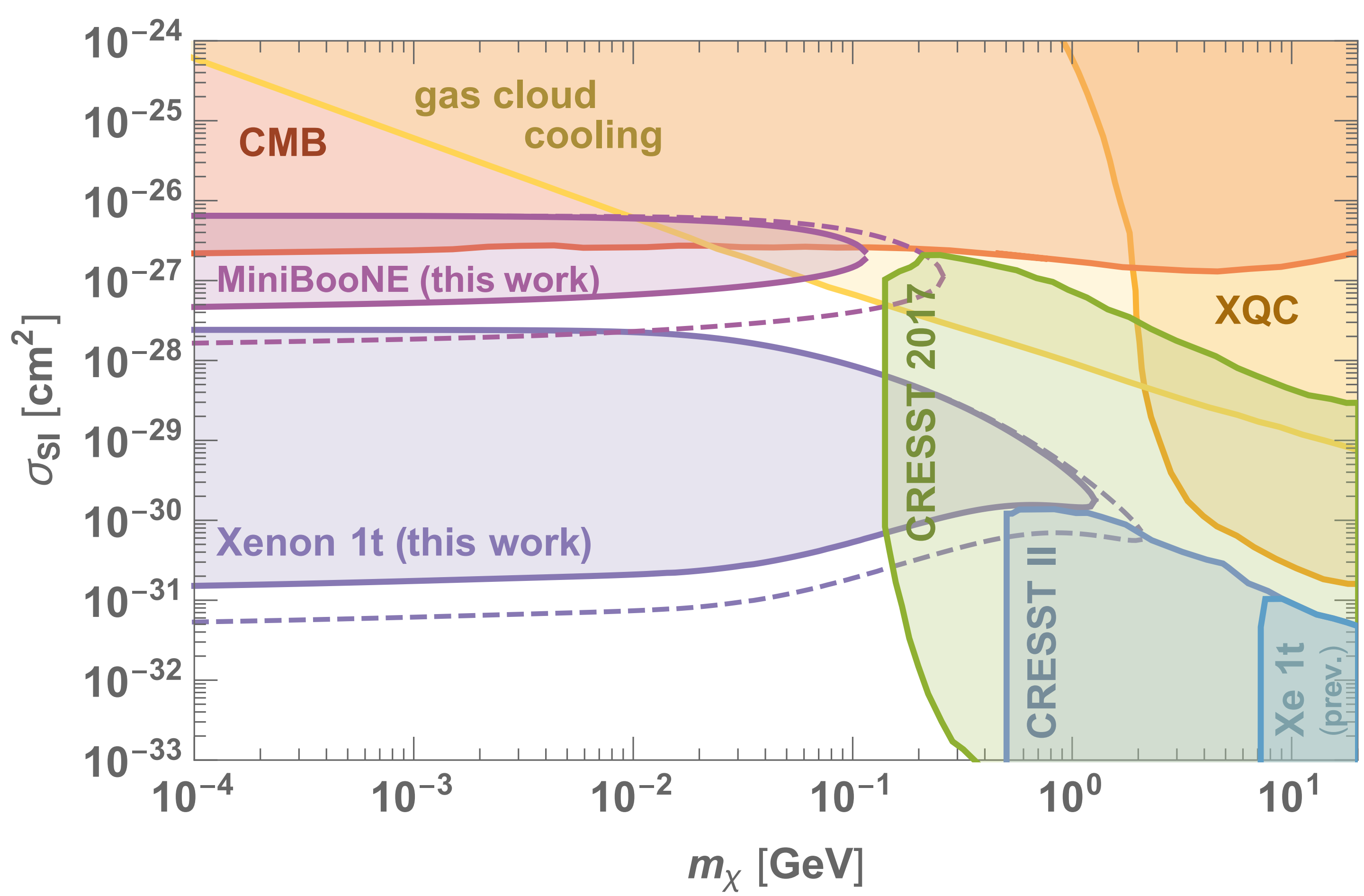


Cosmic-ray up-scattered DM

TB & Pospelov, PRL '19



- Isotropic CRDM flux
  - ⊕ highly energetic
  - ⊖ highly subdominant



- Re-interpreting Xenon 1t results leads to **significantly improved limits** at low DM masses!
  - even neutrino detectors (MiniBooNE, Borexino, …) can now be used for DM searches!

see also Cappiello & Beacom, PRD '19

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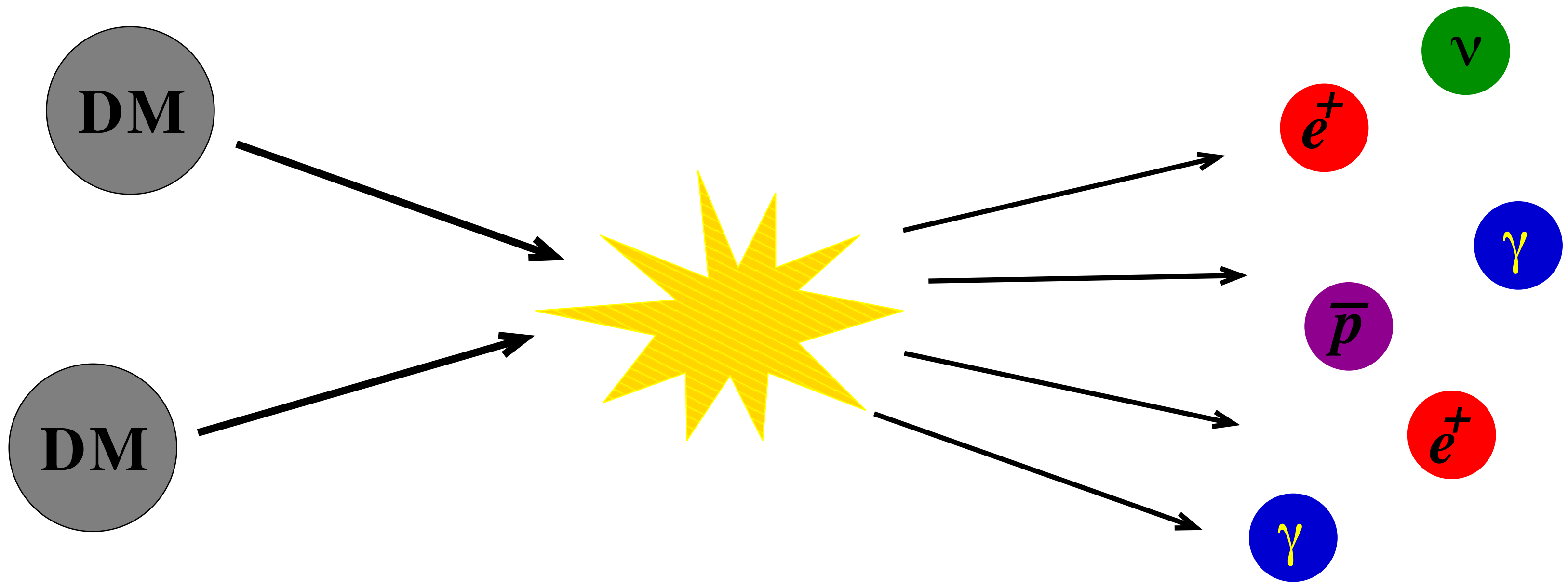
Indirect dark matter searches



- DM has to be (quasi-)stable against decay...
- … but can usually pair-annihilate into SM particles
- Try to spot those in cosmic rays of various kinds

- The challenge: i) absolute rates
  - ⇝ regions of high DM density
  - ii) discrimination against other sources
  - low background; clear signatures

'Indirect' searches are the only in situ probe, directly(!) testing thermal production of DM in the early universe

The 'golden' channel

Review: TB & Weniger, PDU '12

The expected gamma-ray flux [GeV^{-1}cm^{-2}s^{-1}sr^{-1}] from a source with DM density ρ is given by

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \Delta\psi) = \int_{\Delta\psi} \frac{d\Omega}{\Delta\psi} \int_{\text{l.o.s}} d\ell(\psi)\rho^2(\mathbf{r}) \; \frac{\langle\sigma v\rangle_{\text{ann}}}{8\pi m_\chi^2 S_\chi} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}$$

astrophysics | particle physics

for point-like sources: $\simeq (D^2\Delta\psi)^{-1} \int d^3r\, \rho^2(\mathbf{r})$

$\Delta\psi$: angular res. of detector

D : distance to source

$\langle\sigma v\rangle_{\text{ann}}$: total annihilation cross section

m_χ : DM mass

B_f : branching ratio into channel f

N_γ^f : number of photons per ann.

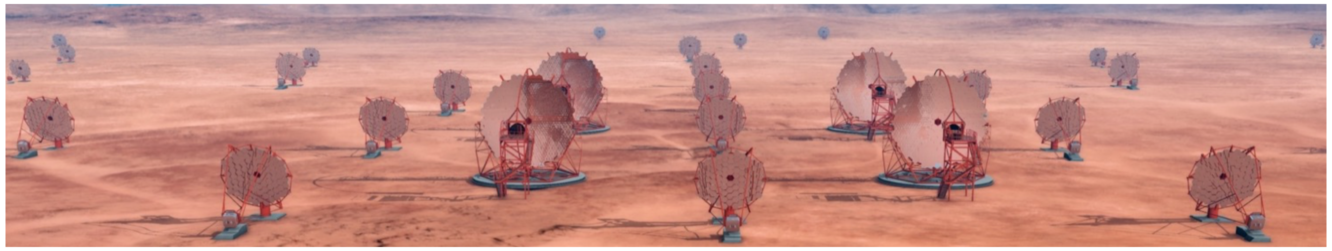
S_χ : 1 for $\chi = \bar{\chi}$ (2 otherwise)

angular information
+ rather uncertain normalization

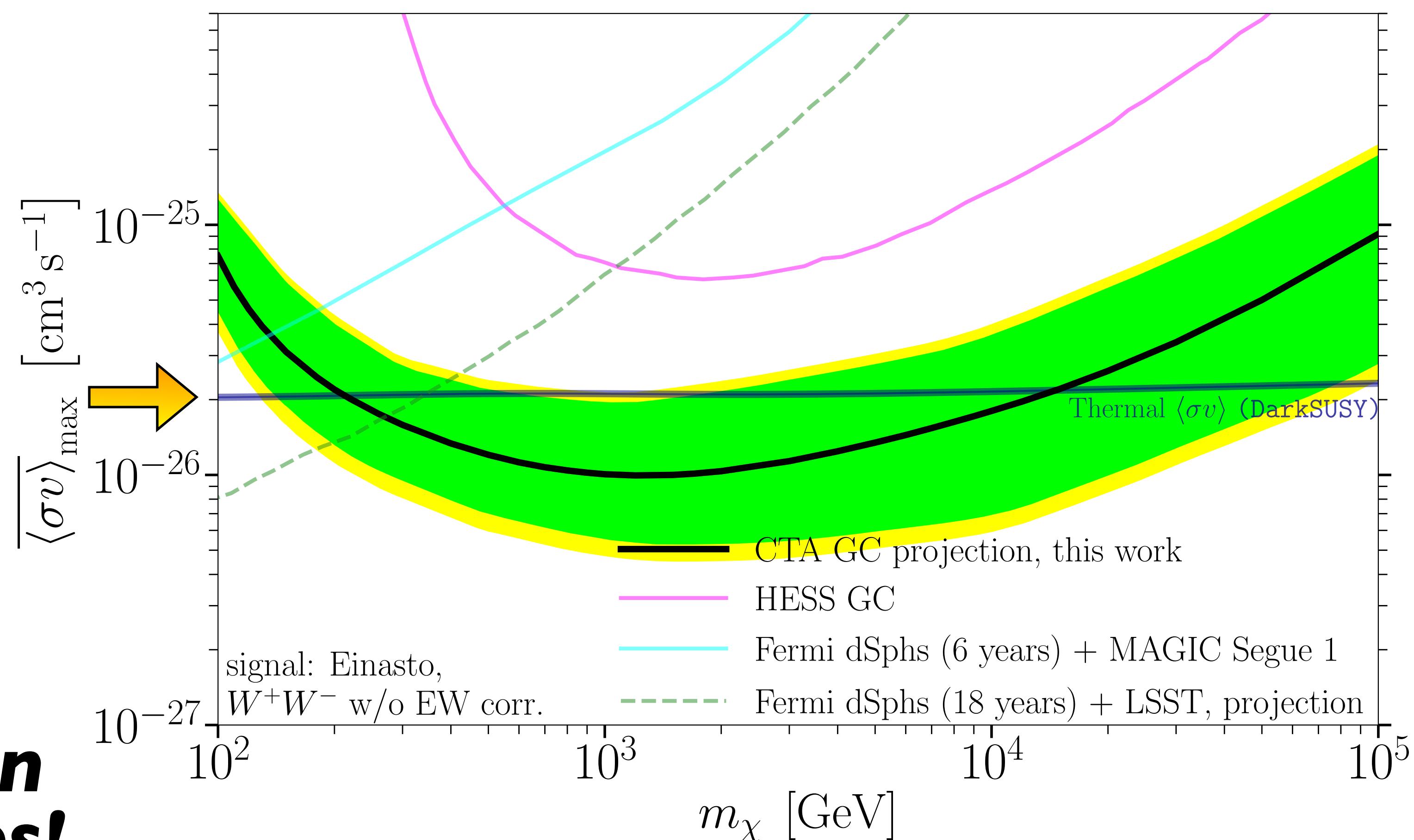
high accuracy
spectral information

CTA prospects

- The next-generation ground-based gamma-ray observatory
  - Two sites (Chile & Canary Islands)
  - Large arrays of differently sized telescopes ⇝ energy range ~10 GeV — ~300 TeV
  - unprecedented sensitivity + survey mode: ideal for DM observations



- Detailed sensitivity study for Galactic centre observations
  - template analysis (DM, CRs + all relevant astro BGs)
  - fully include systematic uncertainty



➡ ***'Thermal' cross section in reach for TeV DM masses!***

Acharyya+, 2007.16129
[TB, Eckner, Sokolenko, Yang & Zaharijas, for the CTA collaboration]

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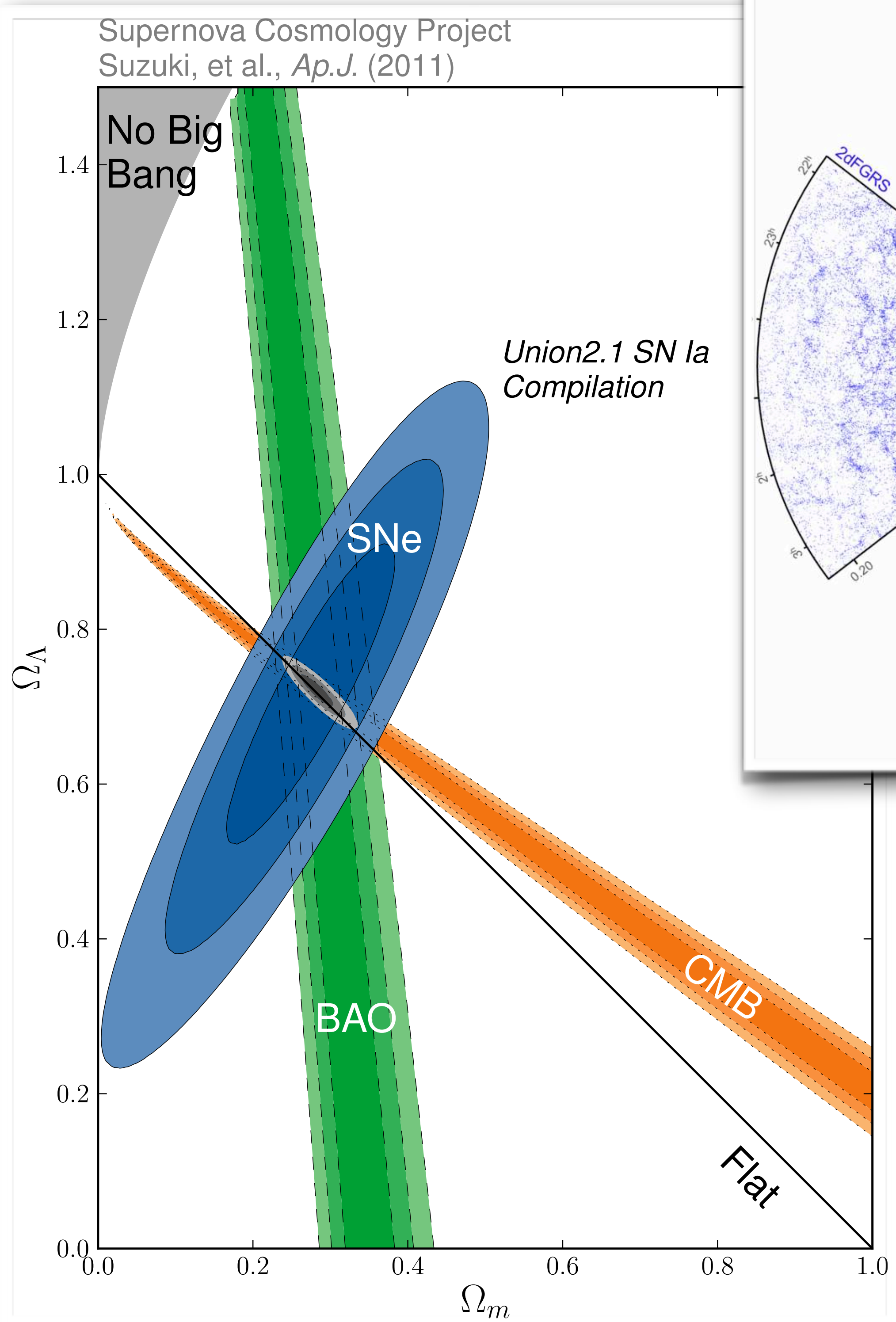
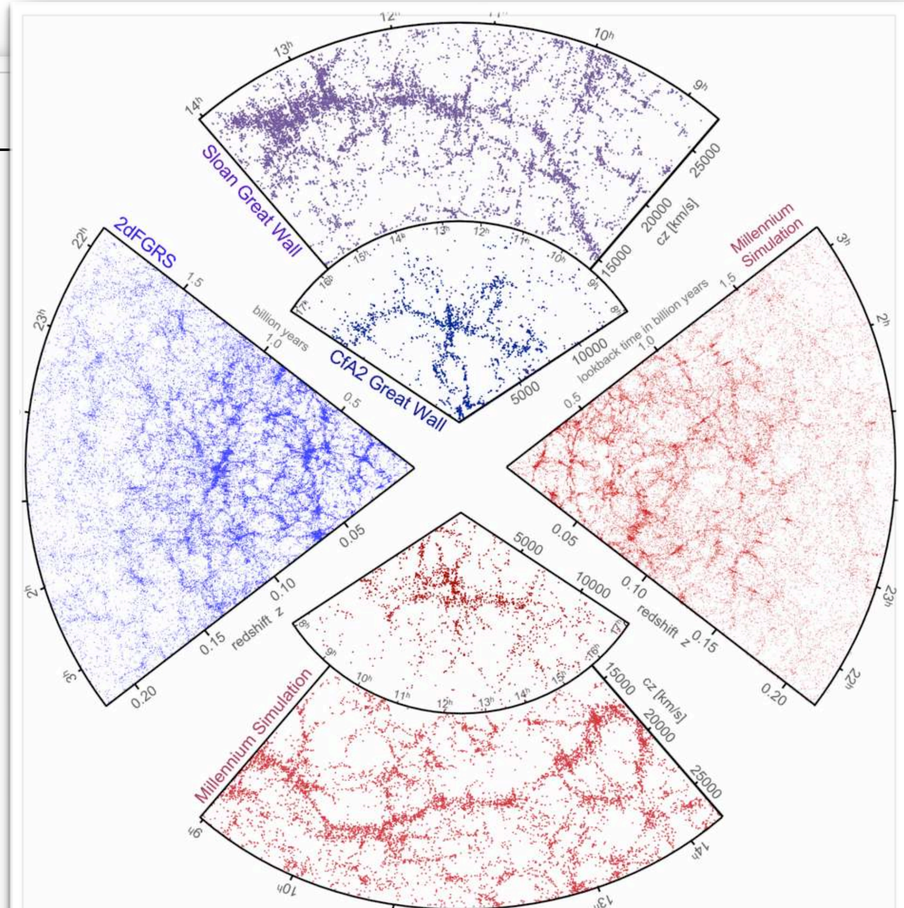
ΛCDM cosmology

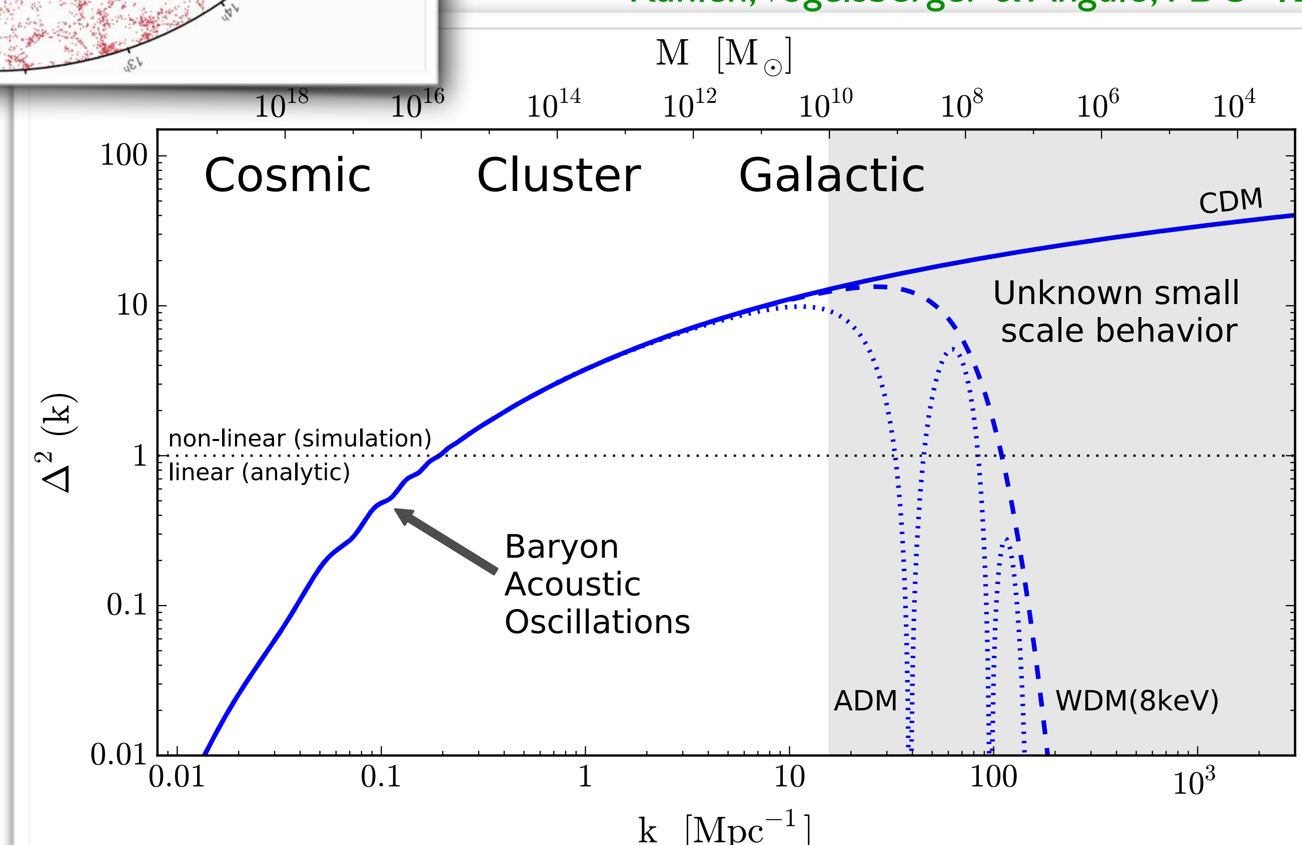




Springel, Frenk & White, Nature '06

A great success on large scales…

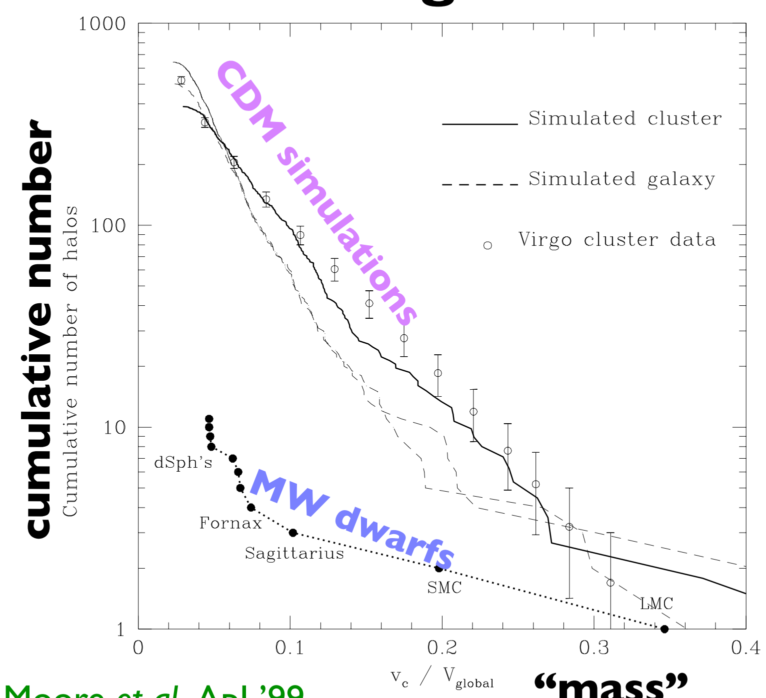
Kuhlen, Vogelsberger & Angulo, PDU '12



Small-scale problems?

Potential observables!

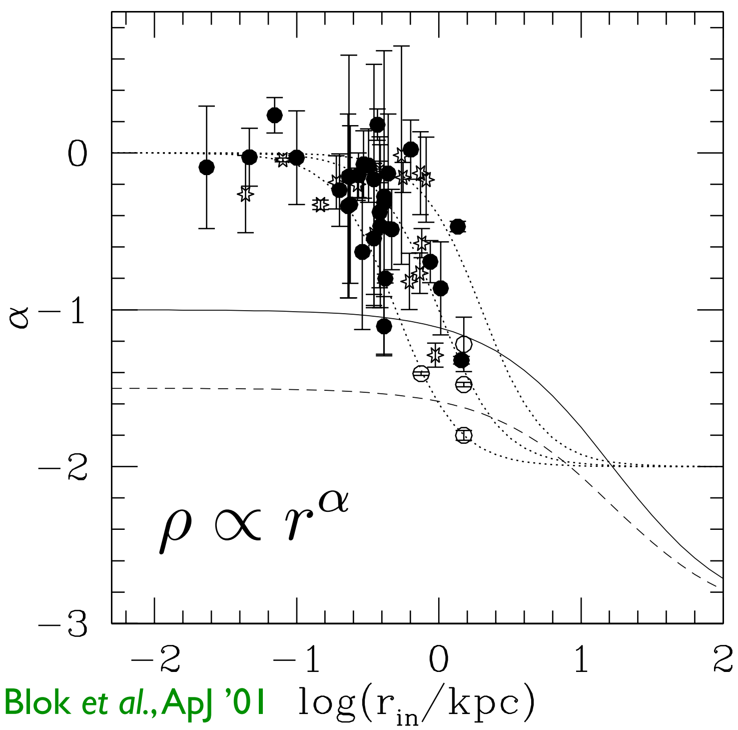
1. Missing satellites?



Moore *et al.*, ApJ '99

More satellites in simulations of MW-like galaxies than observed

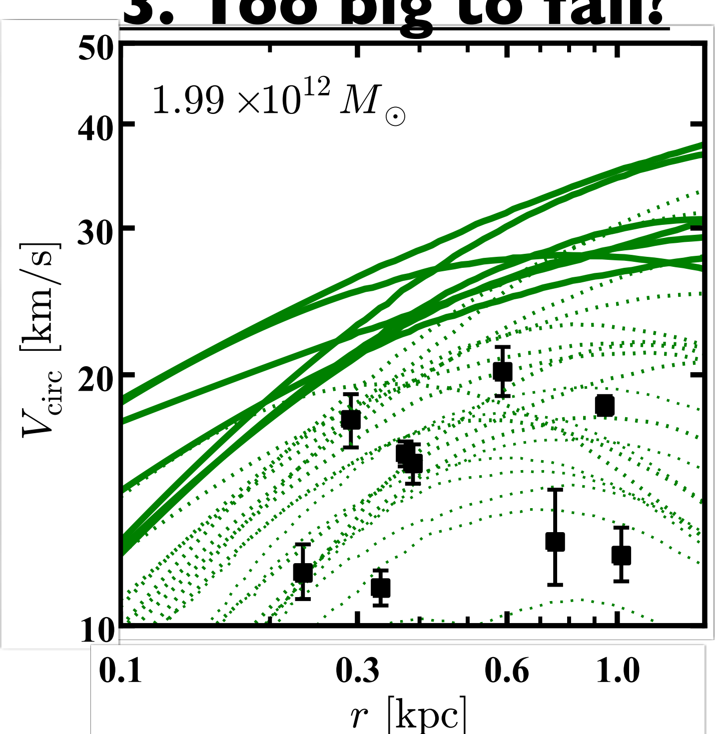
2. Cusps or cores?



Blok *et al.*, ApJ '01

Cuspy inner density profiles predicted by simulations not found in (all) observations

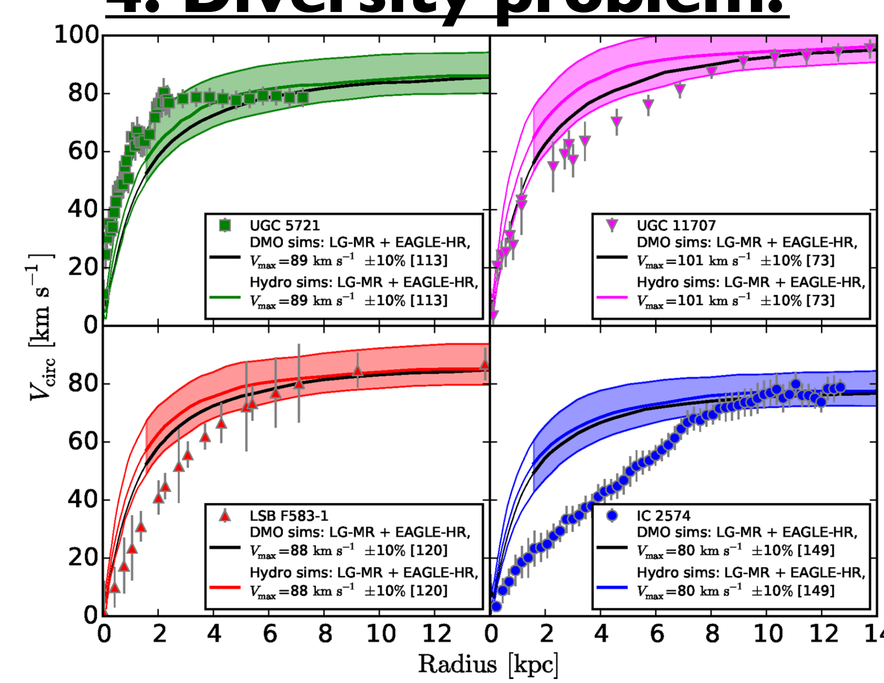
3. Too big to fail?



Boylan-Kolchin, Bullock & Kaplinghat, '11

Most massive simulated sub-halos too dense to form observed brightest dwarf galaxies

4. Diversity problem?



Oman+, MNRAS '15

Real rotation curves vary more than in simulations with(!) baryons

Generic dark sector models

$SU(3)_c \times SU(2)_L \times U(1)_Y$

Standard Model

- SM particles

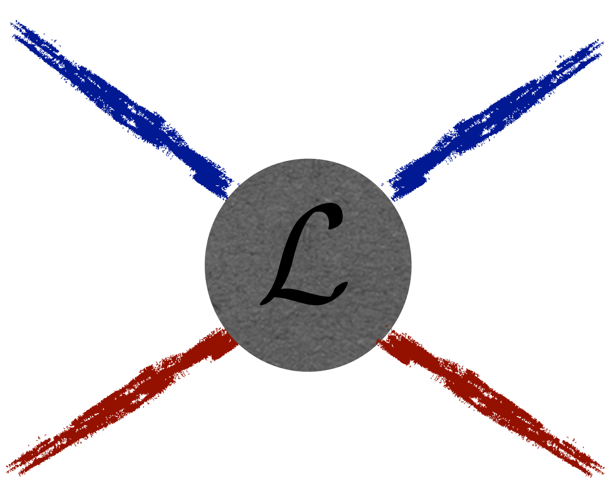
e.g. $U(1)_X \times \ldots$

Dark Sector

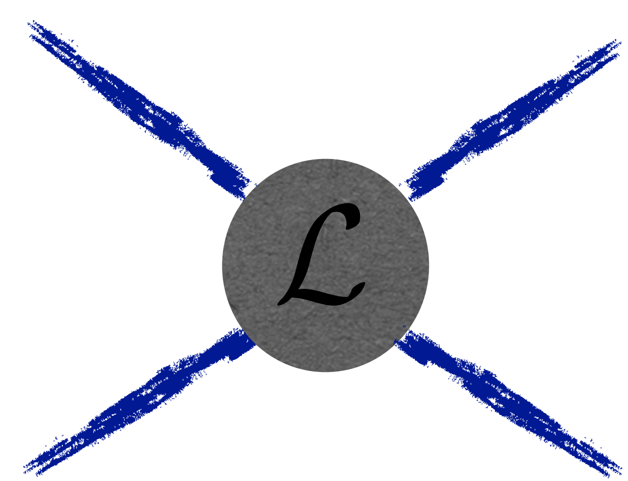
- Dark matter
- Dark radiation
  ('sterile neutrinos', 'dark photons', ...)

e.g. $\mathcal{L}_{\rm Higgs} \supset \kappa |\phi|^2 |\Theta|^2$

- A 'portal' typically still ensures thermalisation at high temperatures
  - Separate entropy conservation after decoupling $\rightsquigarrow T_{\rm photon} \neq T_{\rm dark}$



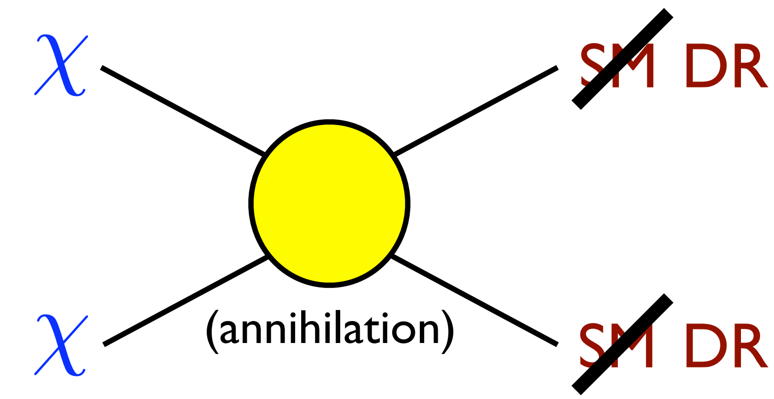
need to treat consistently!

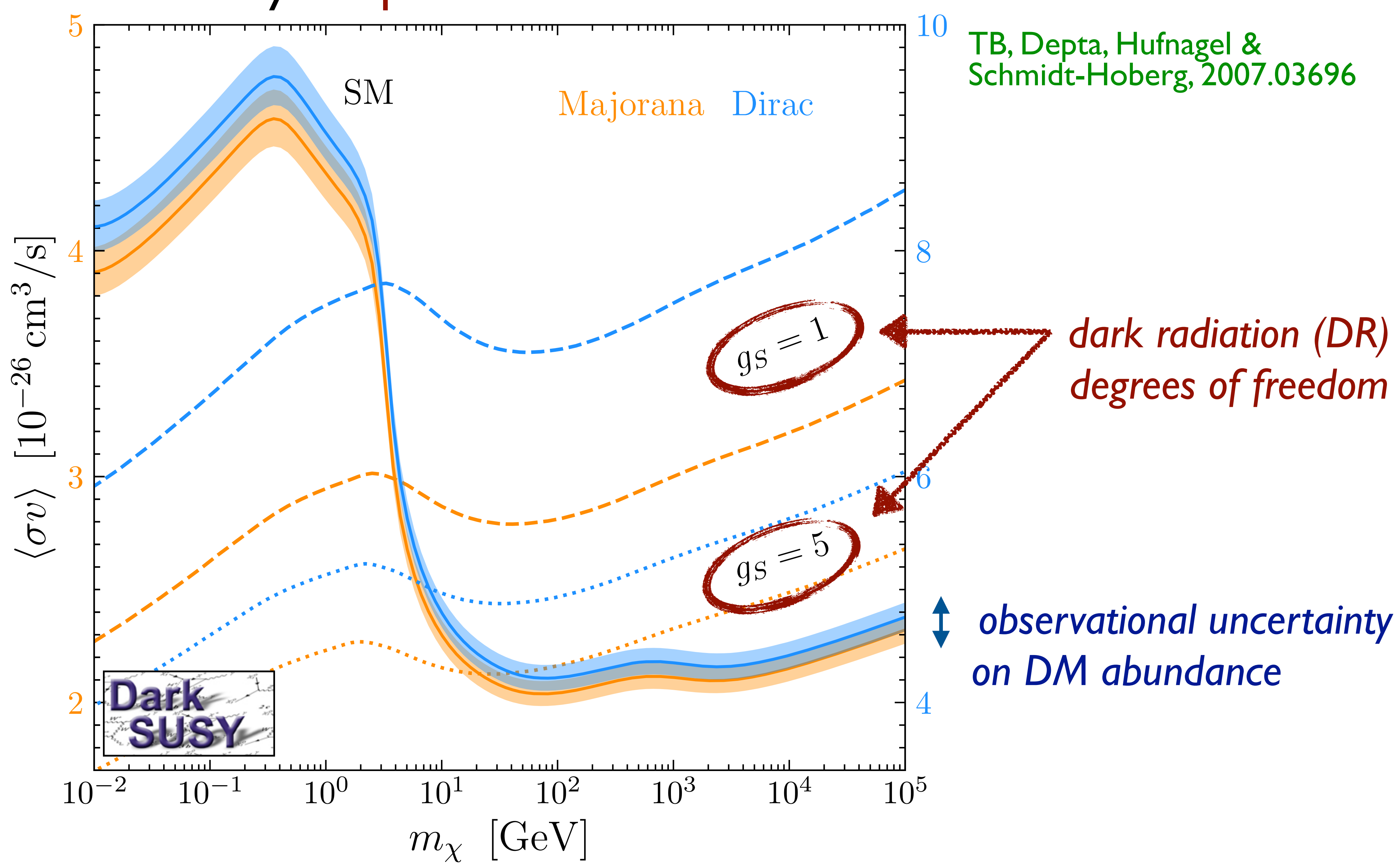


- imprints on linear $\mathcal{P}(k)$
- imprints on inner (sub-)halo structure

Freeze-out of 'hidden' dark matter

- Thermal production works equally well in fully decoupled dark sector
  - but details need to be implemented correctly for precision treatment



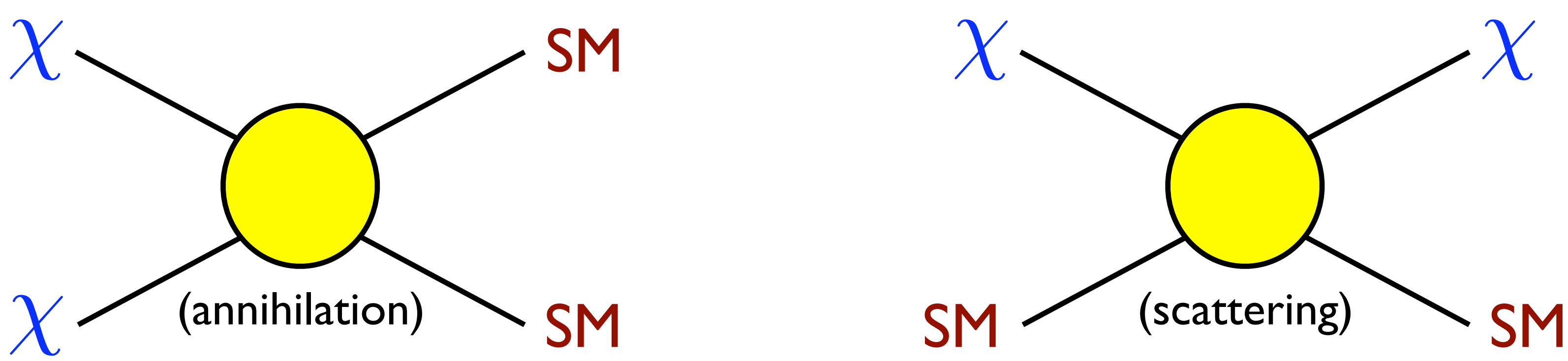


TB, Depta, Hufnagel & Schmidt-Hoberg, 2007.03696

Freeze-out ≠ decoupling !

- Expect WIMPs (and similar DM particles) to stay much longer in kinetic than in chemical equilibrium:

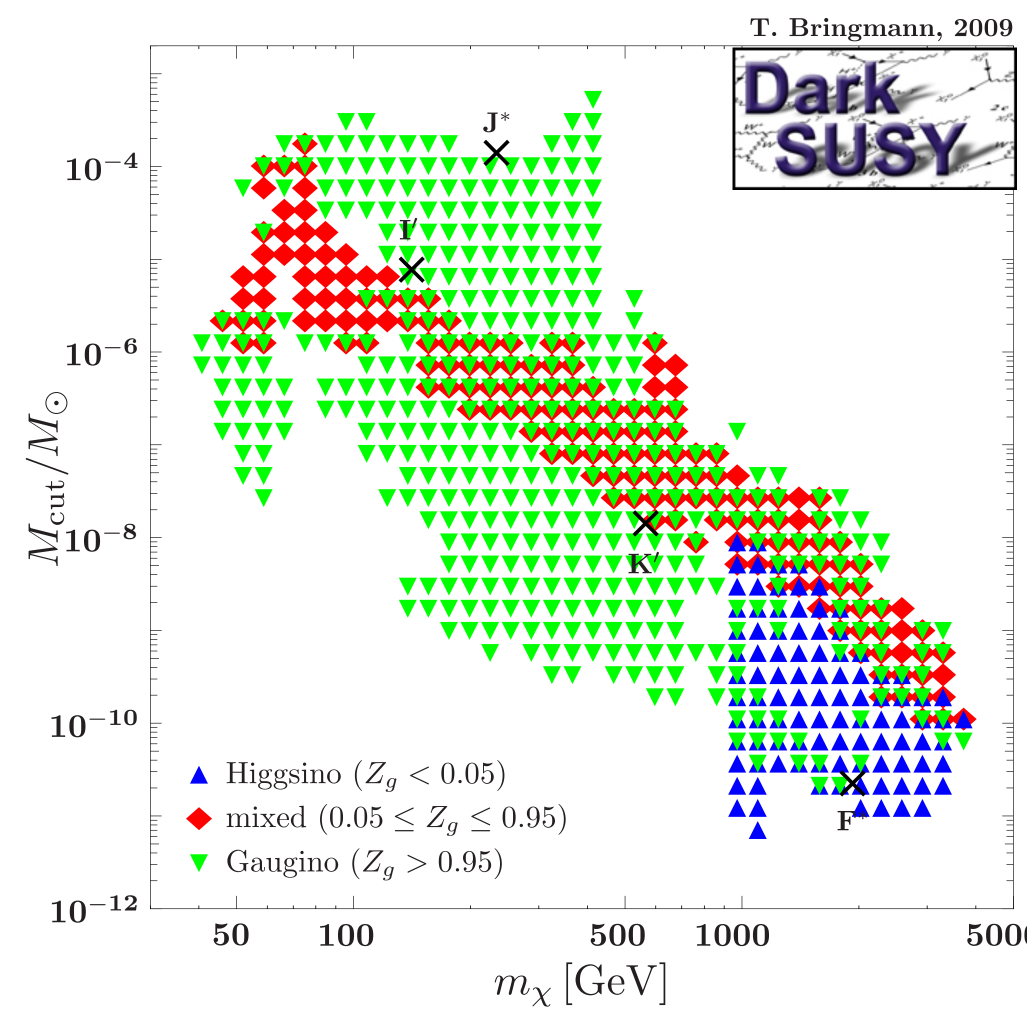
Review: TB, NJP '09



- Density contrasts can only grow after kinetic decoupling
  - ⇨ Model-dependent small-scale cutoff in power-spectrum (*not* 'about earth-mass' !)

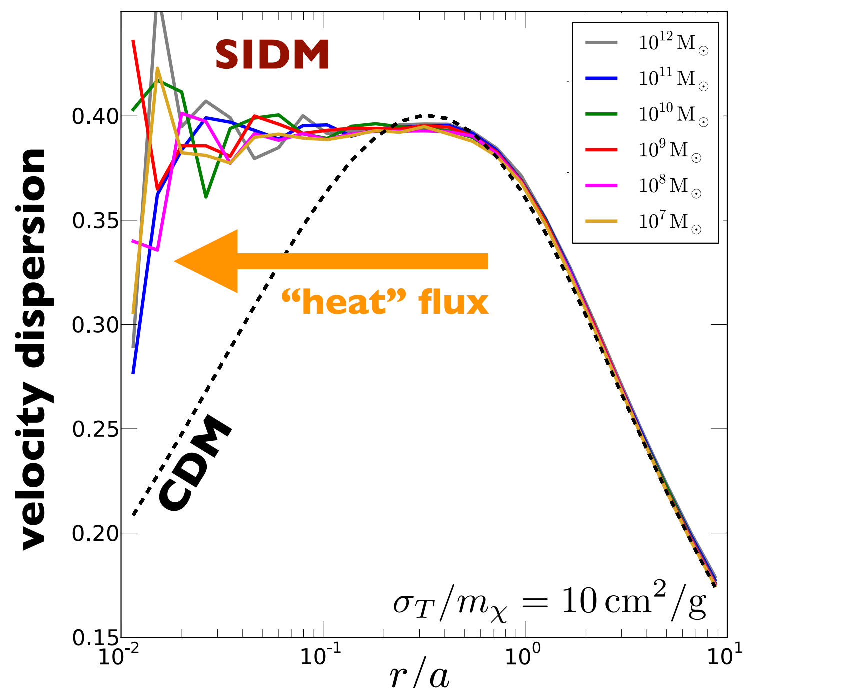
- Much later kinetic decoupling possible for scattering with dark radiation
  - way to address the missing satellite 'problem'

TB, Ihle, Kersten & Walia, PRD '16
[full simplified model classification]

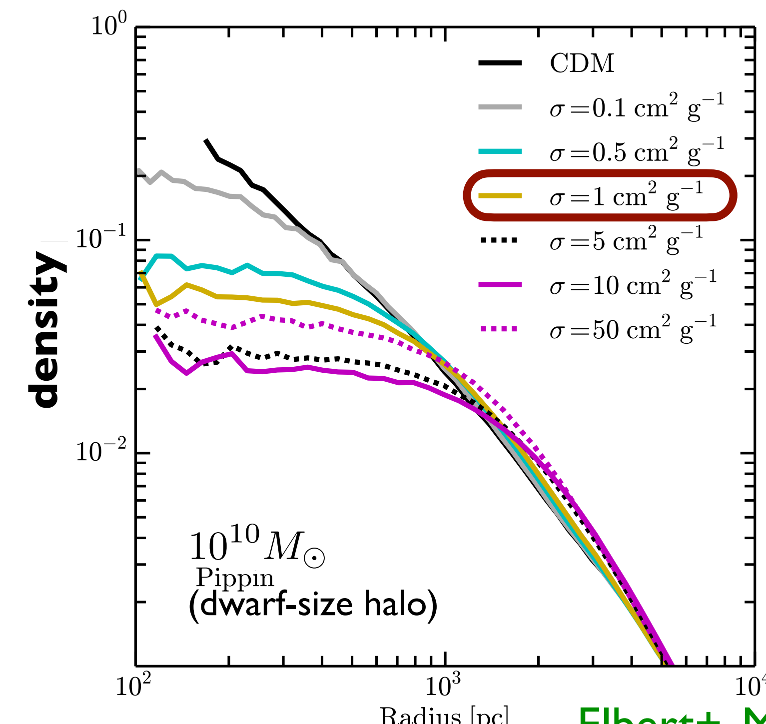


Self-interacting DM (SIDM)

- DM-DM scatterings Spergel & Steinhardt, PRL '99
  - do not affect linear perturbations (number densities too small)
  - but isotropise DM distribution in inner parts of halo:
    - ⇨ core formation once $\mathcal{O}(1)$ scatters per dynamical time



Vogelsberger, Zavala & Loeb, MNRAS '12

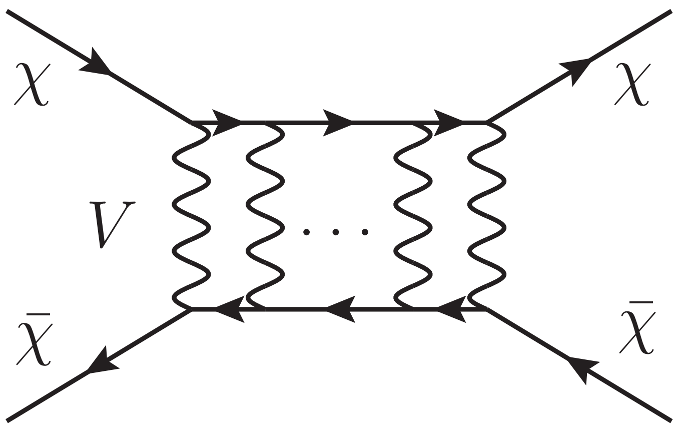


roughly needed for **cusp/core**

Elbert+, MNRAS '15

- Simple analytic models to predict core radius from $\sigma_{\rm SIDM}$
  - reproduce CDM simulation results for $\rho_\chi(r)$ remarkably well Kaplinghat, Tulin & Yu, PRL '15
  - but underlying (microphysics) assumptions not really satisfied Sokolenko+, JCAP '18
    - ⇨ *Use caution when applied to systems including baryons!*

Effective Theory of Structure Formation

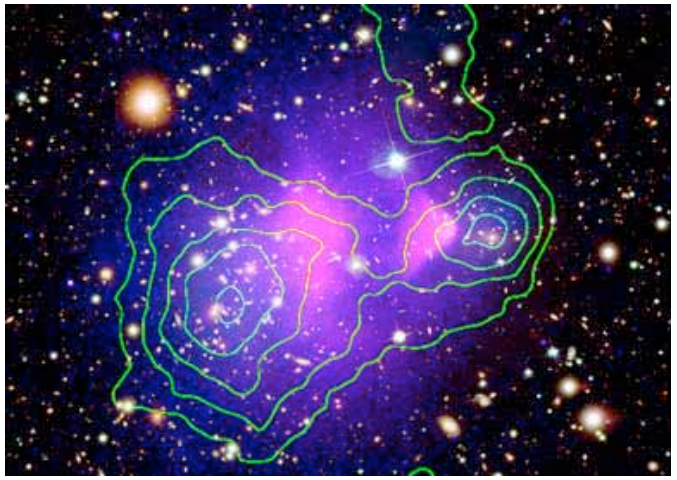


particle model

task 1

cosmological simulations

task 2



astrophysical observables

input:
masses, spins, coupling constants

input:
consistent initial conditions, non-gravitational forces between "particles"

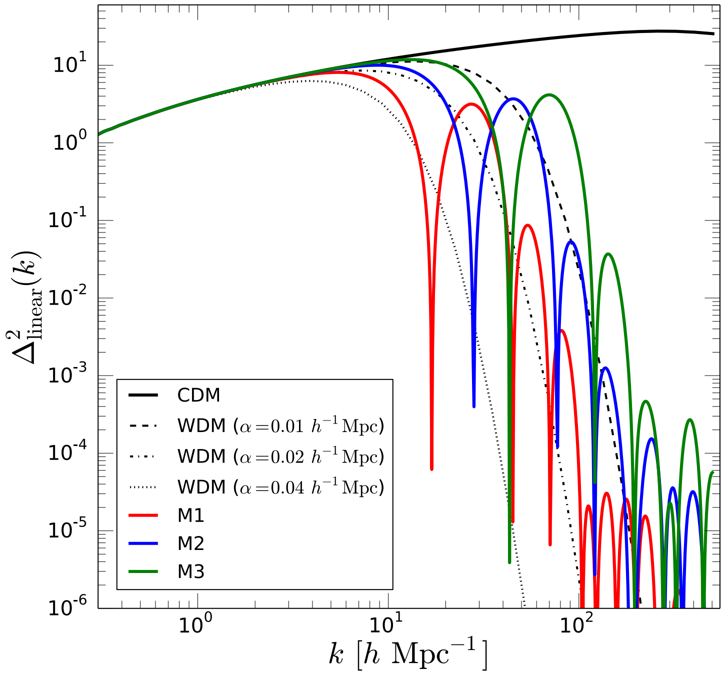
input
(for interpretation of data):
output from simulations

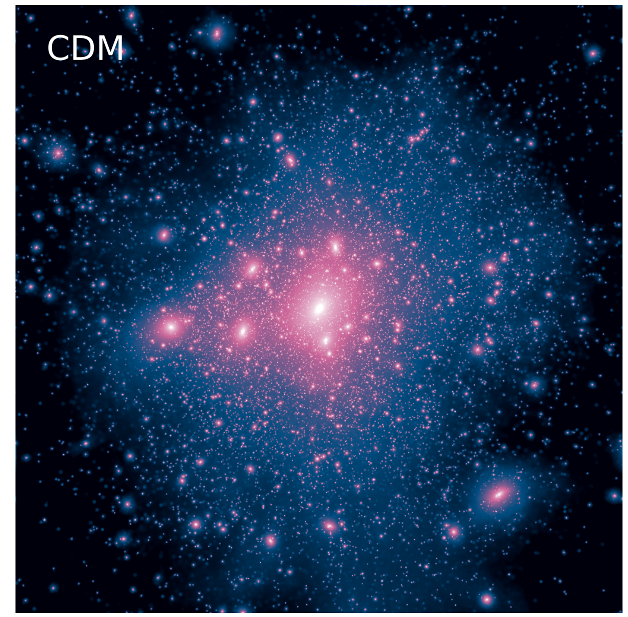
- The first task can be demanding, the second in addition computationally very expensive
- But expect large degeneracies, so very inefficient…
- **Idea of ETHOS**: identify effective parameters and provide maps for each of those steps ($\rightsquigarrow$ no need to re-compute each model!)

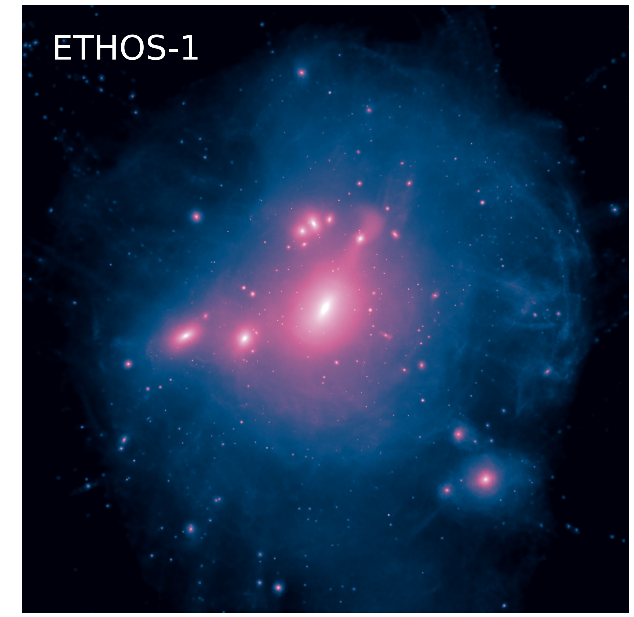
Cyr-Racine+, PRD'16; Vogelsberger+, MNRAS '16

Late kinetic decoupling

- Select four benchmarks: Vogelsberger+, MNRAS'16







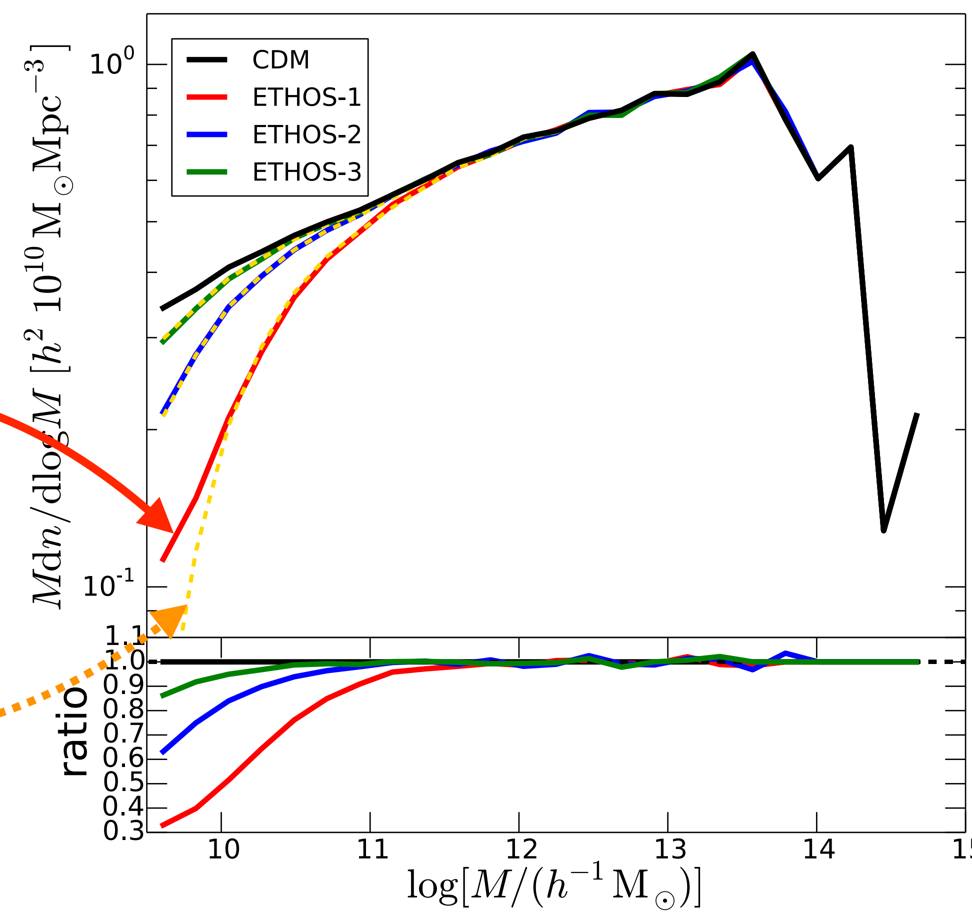
- Almost identical suppression of halo mass function as for WDM cosmology:

$$M_{\rm cut,kd} = 5 \cdot 10^{10} \left(\frac{T_{\rm kd}}{100\,\mathrm{eV}}\right)^{-3} h^{-1}\, M_\odot$$

[solid lines; NB: up to factor ~2 same as analytic estimate!**]**

$$M_{\rm cut,WDM} = 10^{11} \left(\frac{m_{\rm WDM}}{\mathrm{keV}}\right)^{-4} h^{-1}\, M_\odot$$

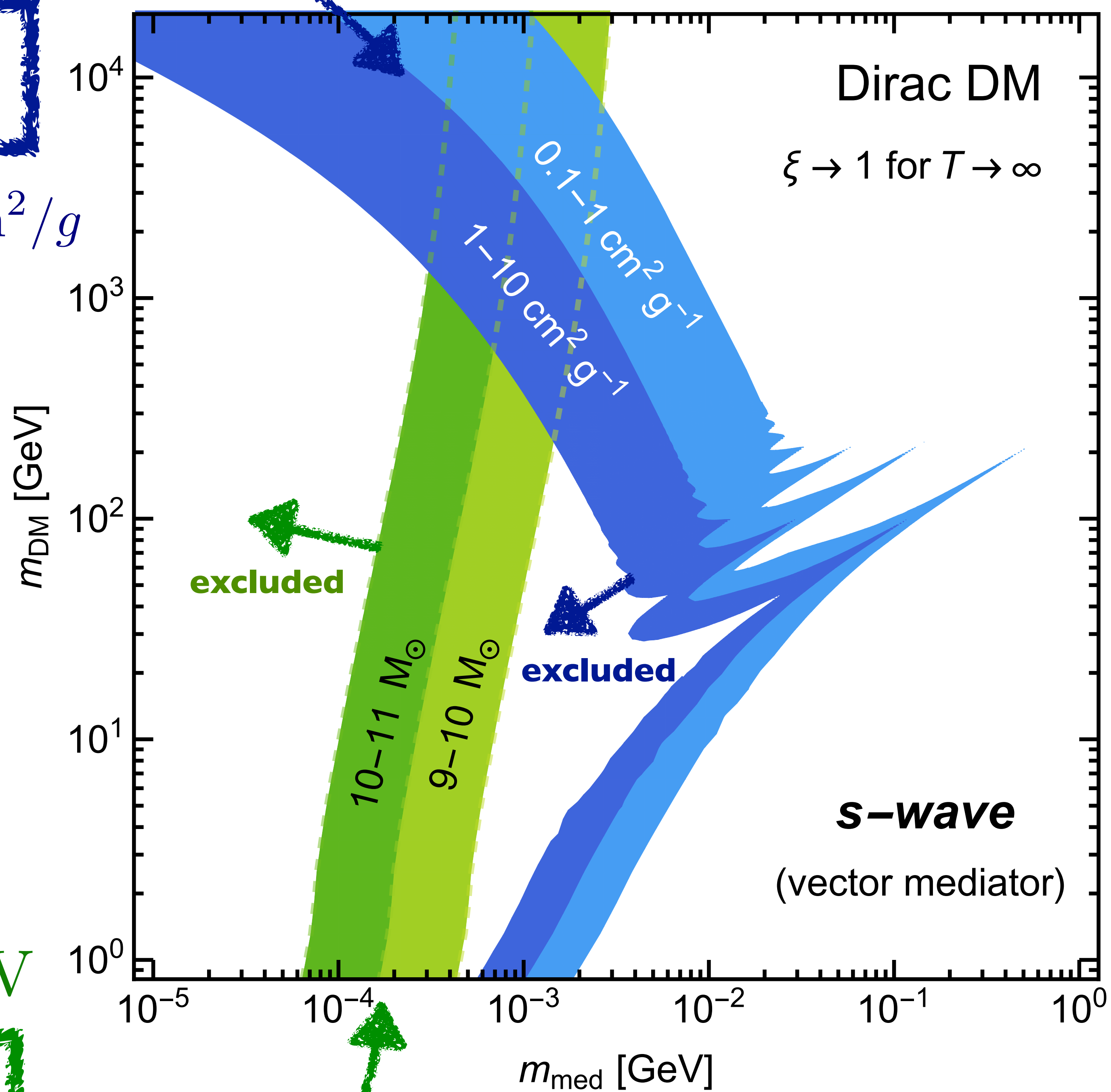
[dashed lines; would-be result from WDM free-streaming**]**



Full parameter scan

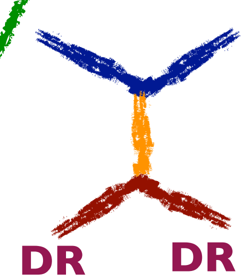
affect core/ cusp + TBTF

$\langle \sigma_T \rangle / m_\chi \sim 1\,\mathrm{cm}^2/g$



$T_{\mathrm{kd}} \sim 0.1\,\mathrm{keV}$

address missing satellites ?

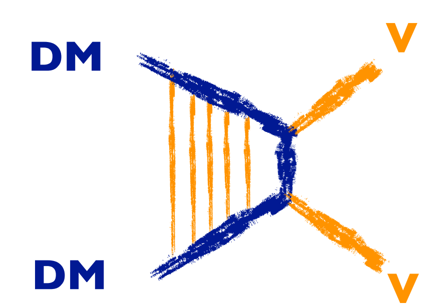


DarkSUSY

TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

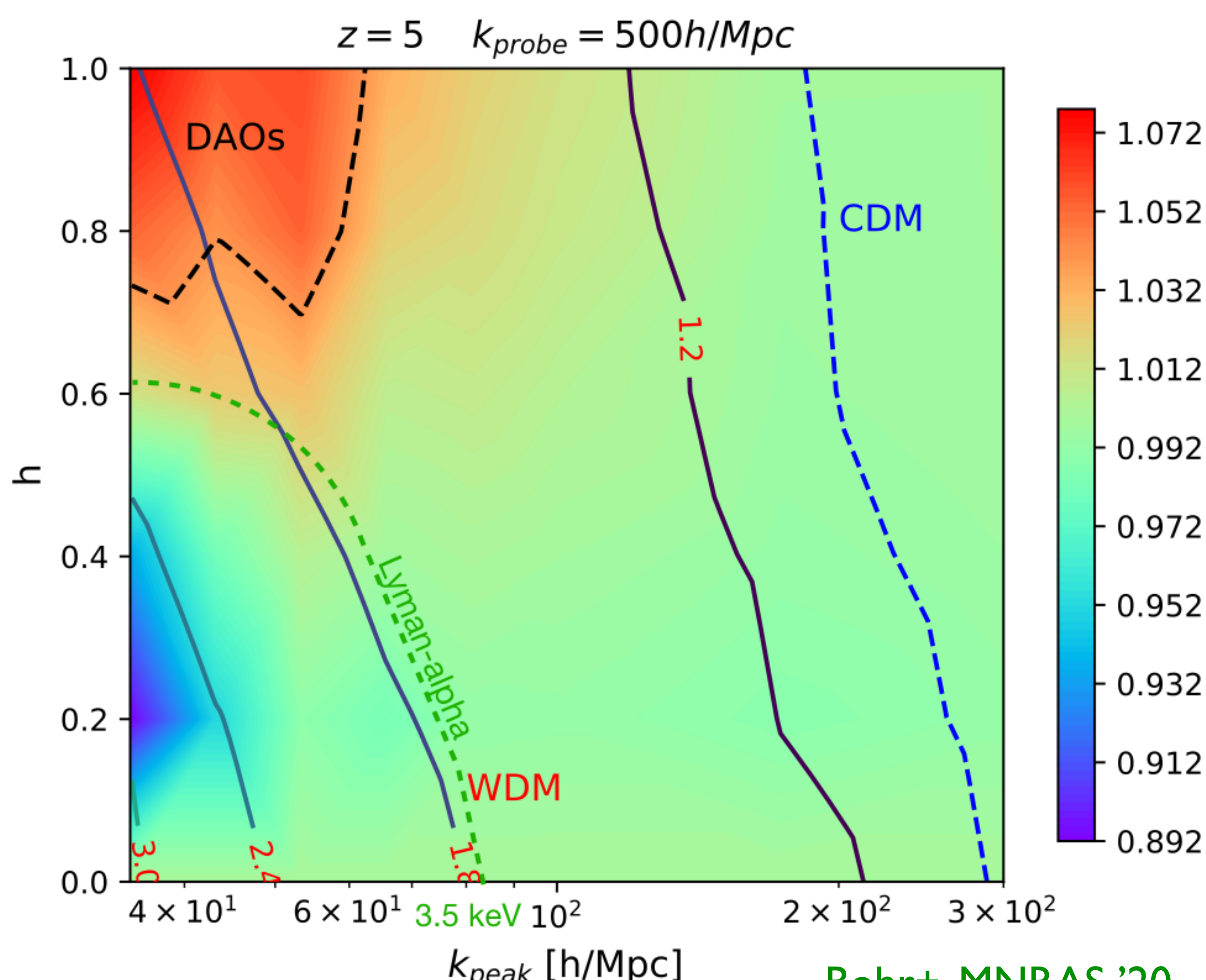
- NEW since v6.1:
  - SIDM
  - Sommerfeld
  - handle varying $\xi \equiv T_{\mathrm{dark}} / T_{\mathrm{photon}}$

coupling fixed by thermal relic density

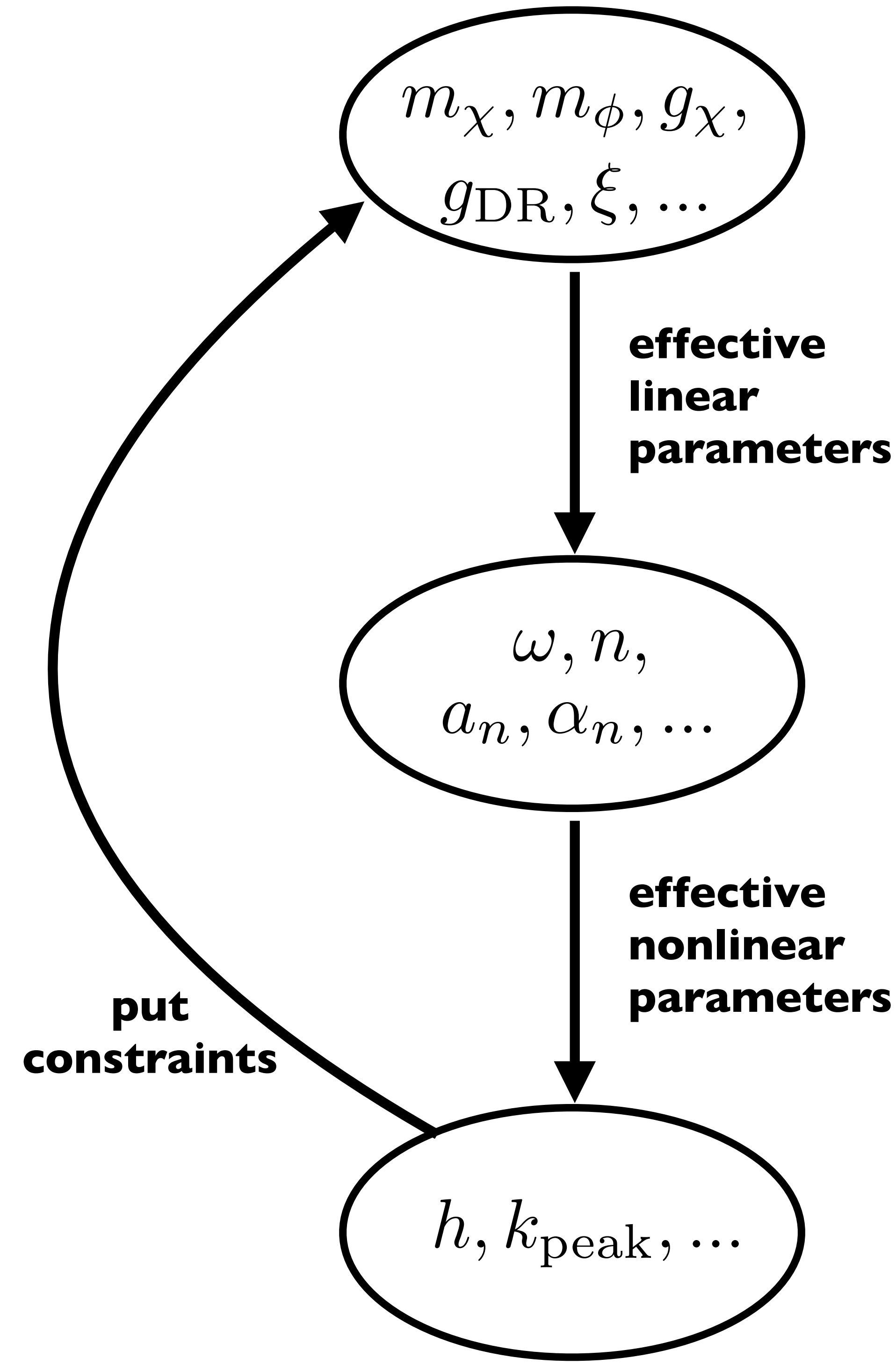


Outlook ?

- Goal: a fast and automated map instead of running expensive simulations!



Bohr+, MNRAS '20



Conclusions

- Impossible to find DM without first installing DarkSUSY ;)

- The cosmos *might* be the only laboratory to test the *particle* DM hypothesis
  (though of course it would be *nicer* to detect DM in multiple experiments)
- We have not yet detected DM, other than gravitationally
- The field is at the crossroad — which implies interesting times ahead!

Thanks for your attention!