Dark Matter Theory

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Evidence for Dark Matter

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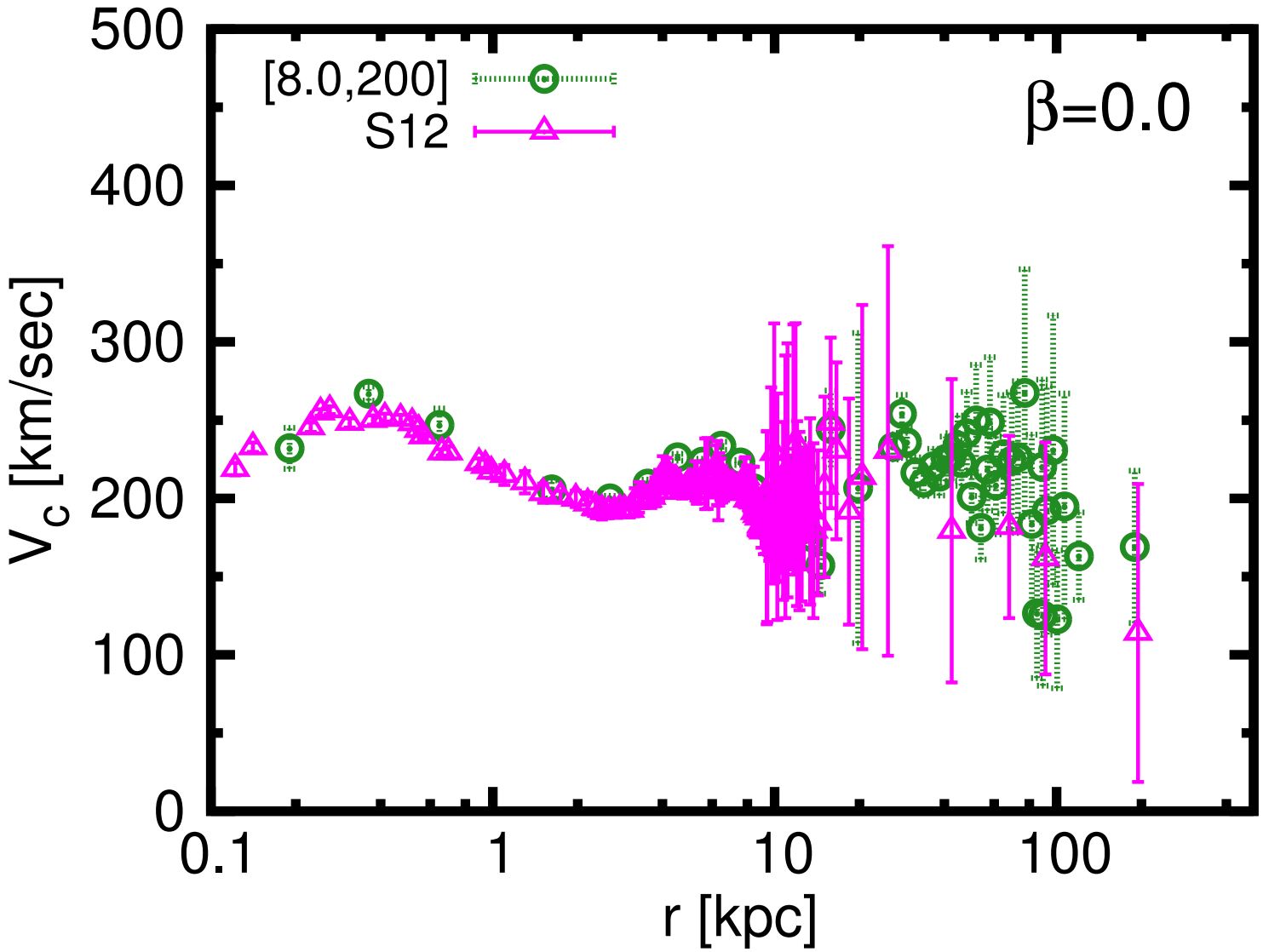
(a) Galactic Scales: Rotation curves! (Vera Rubin . . .)

Measure rotation velocity as fct of distance from center. If mass tracks light: expect $v(r) \propto 1/\sqrt{r}$ (true in solar system!) observe $v(r) \simeq$ const!

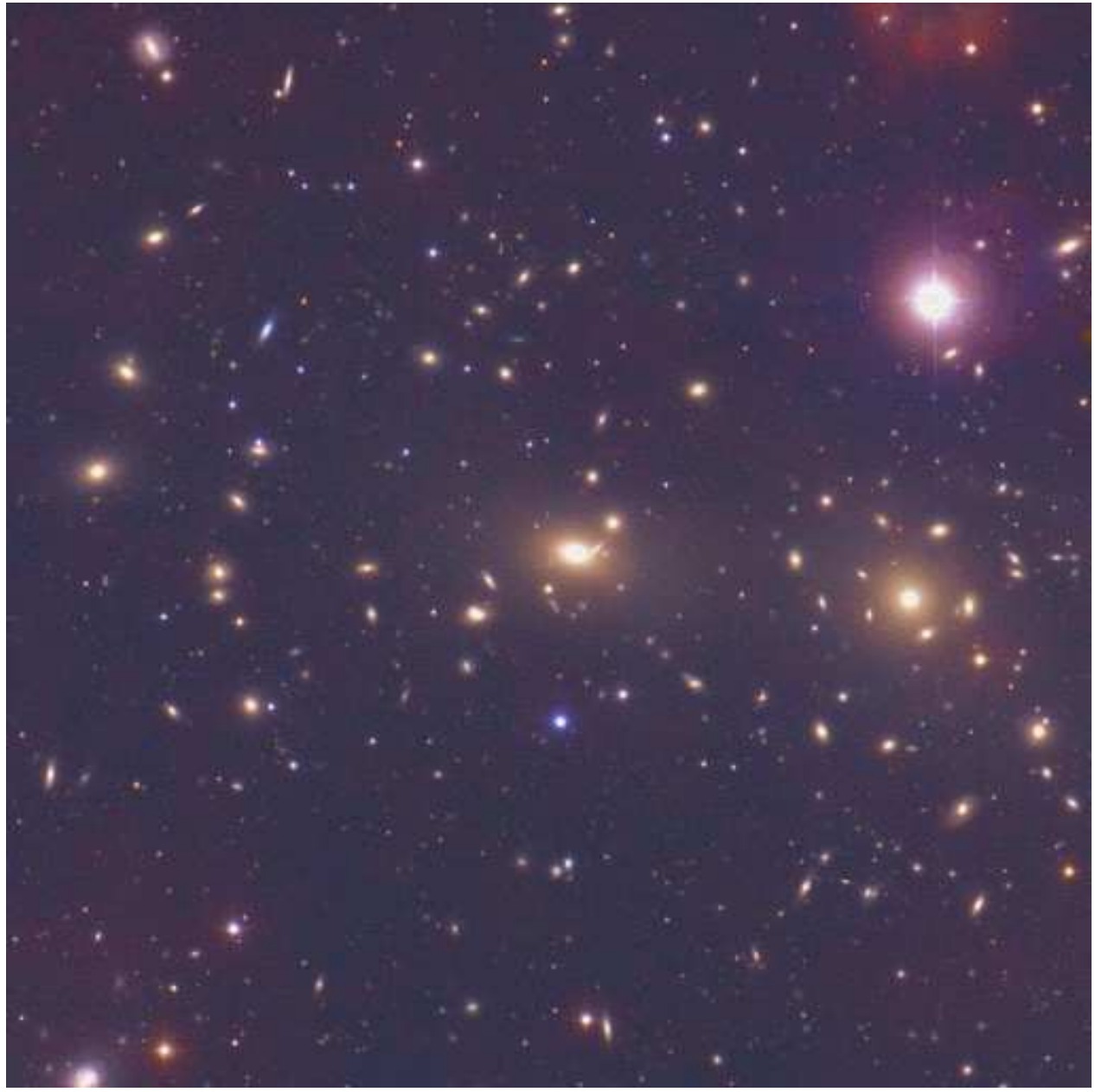
$\Longrightarrow$ Most galactic mass not in baryons!

Rotation Curve of the Milky Way

Bhattacharjee et al., Astrophys.J. 785 (2014) 63



A typical galaxy cluster



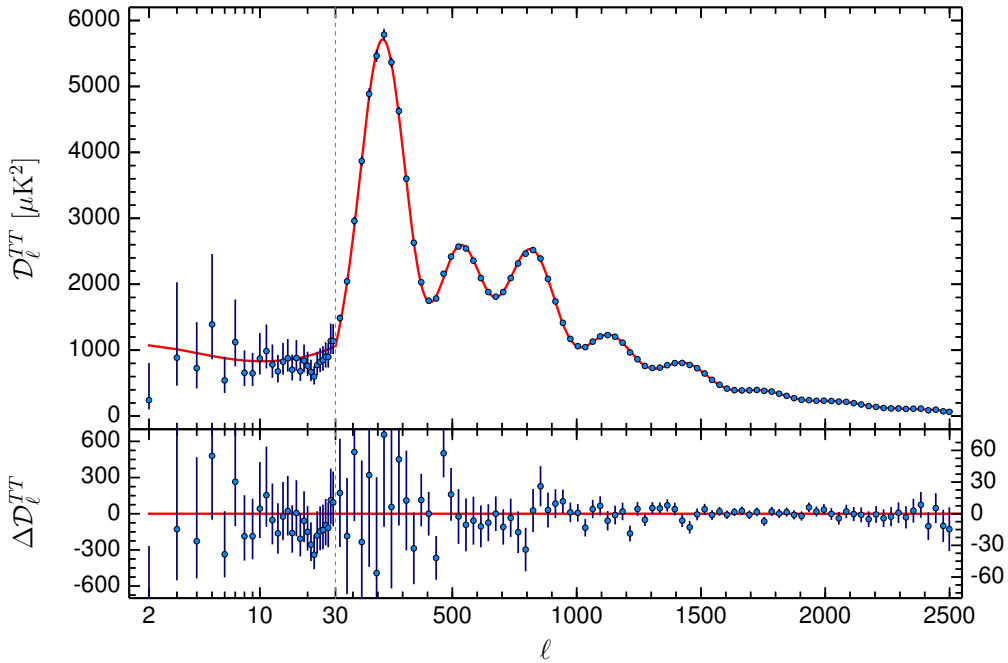
(b) Clusters of Galaxies

- Virial theorem: $\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm pot}\rangle \propto M_{\rm cluster}$ Zwicky 1933
- Similar argument holds for single atoms:
  Temperature of gas in cluster $\propto M_{\rm cluster}$!
  Gives consistent result.
- Gravitational lensing: Mass deflects light, by angle $\propto$ mass: Most direct way to measure $M_{\rm cluster}$!

$\sim 80\%$ of mass of cluster is *not* baryonic!

(c) Cosmology: CMB

Pattern of CMB anisotropies requires most mass to be non–baryonic (does not feel radiation pressure)



PLANCK collab. 2015

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- Big Bang Nucleosynthesis (BBN): confirms CMB determination of total baryon density; not sensitive to DM density

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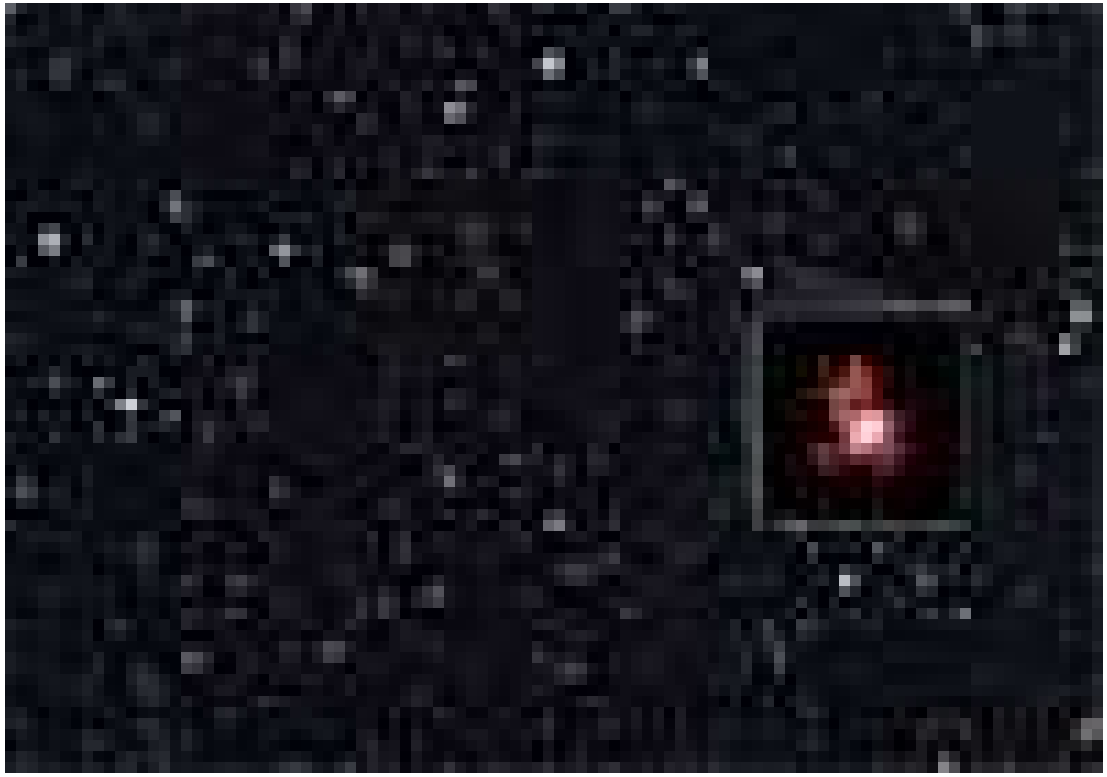
- Big Bang Nucleosynthesis (BBN): confirms CMB determination of total baryon density; not sensitive to DM density
- Cannot form galaxies sufficiently early w/o DM: one seen at $z \simeq 11$! (GN-z11) Oesch et al., arXiv:1603.00461, ApJ



Evidence for DM: Summary

Many independent observations at distance scales between (few) kpc to Gpc (Hubble radius) can be explained consistently iff cold Dark Matter exists!

Alternatives to Particle DM: Modified Gravity?

- All evidence for DM assumes standard GR (in fact, mostly Newtonian gravity sufficient); what if gravity is stronger at weak accelerations? (MOND: Milgrom)

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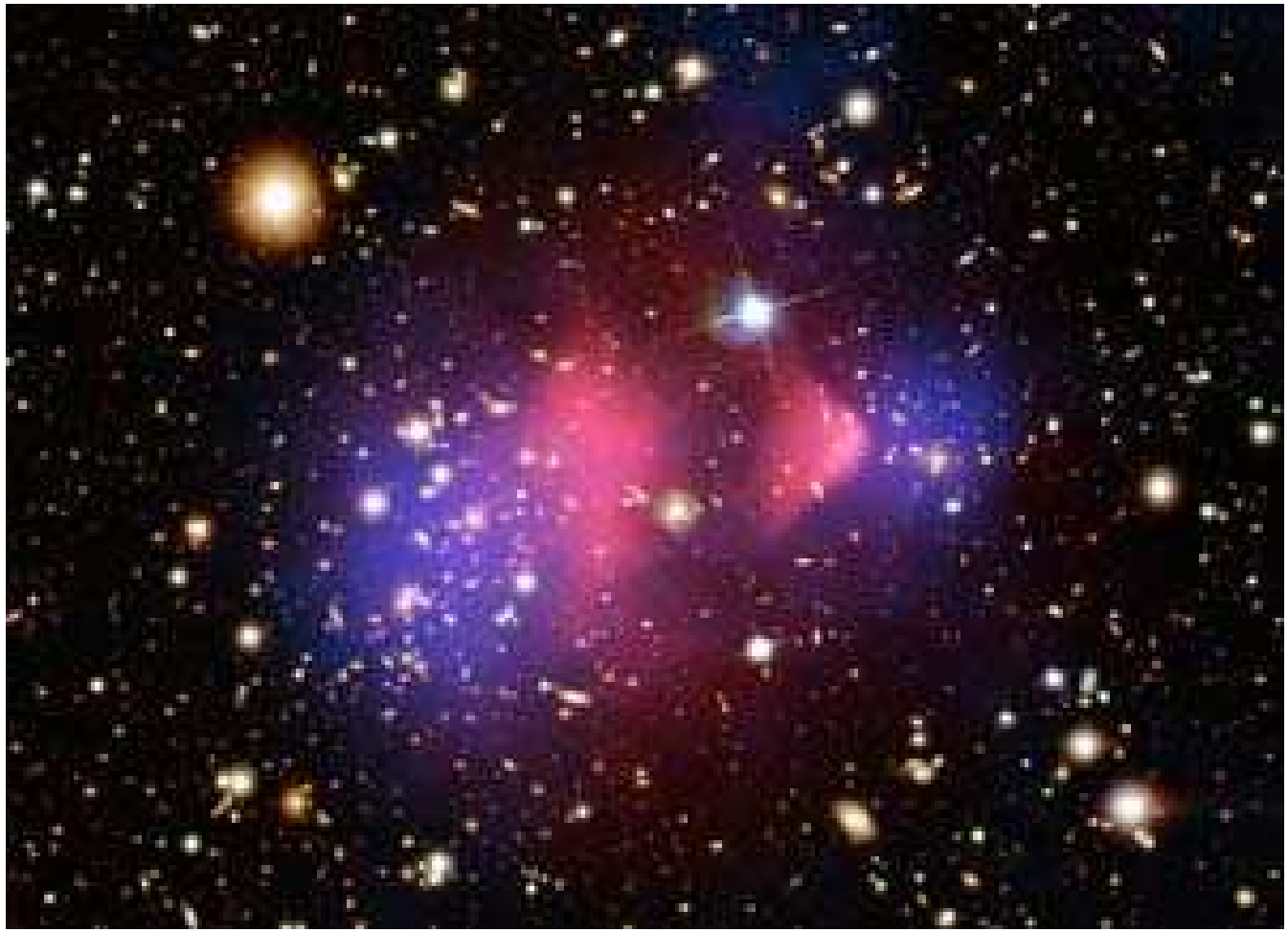
Looks very implausible to me!

Bullet cluster



Alternatives to Particle DM: Primordial Black Holes?

Must have formed before on–set of BBN, i.e. in first second after Big Bang.

Arguments in favor:

- First black holes mergers detected by LIGO indicate surprisingly large BH masses
- Might seed supermassive BHs found in center of galaxies, incl. AGNs

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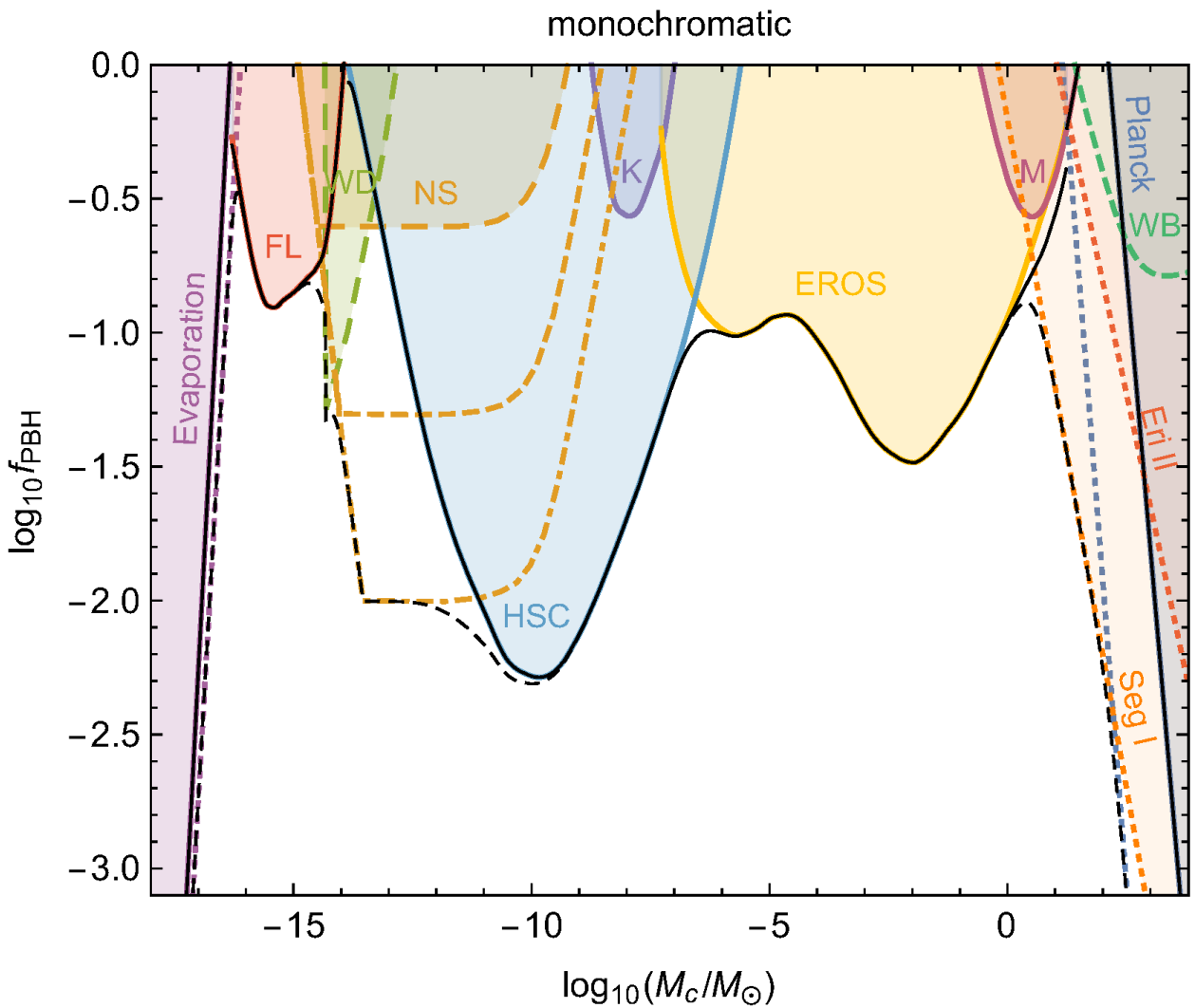
Looks almost as implausible as MOND to me.

Constraints on Primordial Black Holes

Carr et al., arXiv:1705.05567



Particle Physics Candidates: Properties

Mass range:

Bosons:
$1/r_{\rm galaxy} \sim 10^{-22}\ {\rm eV} \lesssim m_{\rm DM} \lesssim M_{\rm Pl}$: 50 orders of magnitude

Fermions (or thermally produced bosons):
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Lifetime:

$$\begin{aligned} \tau_{\rm DM} &\gtrsim \tau_U \simeq 5 \cdot 10^{17}\ {\rm s}\ \ ({\rm all\ masses}) \\ &\gtrsim 10^{25}\ {\rm s}\ \ (m_{\rm DM} \gtrsim 1\ {\rm GeV}:\ {\rm search\ for\ decay\ products}) \end{aligned}$$

DM Properties (cont'd)

Self interactions:

$\sigma \lesssim 1\ \mathrm{b} \cdot \frac{1\ \mathrm{GeV}}{m_{\mathrm{DM}}}$ for short–range interaction (bullet cluster): protons are factor ~ 30 below this bound

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DM should be significantly less dissipative than baryonic matter. Note: ordinary matter dissipates energy and angular momentum through emission of photons, mostly off electrons.

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This is basically all we know about properties of DM particles!

No particle with these properties exists in the SM!

Particle DM Candidates

Many hypothetical particles satisfy these conditions:

- Extremely light bosons ("fuzzy DM") Hu et al., astro-ph/0003365
- Axions or ALPs (10^{-12} eV $\lesssim m_a \lesssim 10^{-3}$ eV)
- keV–ish sterile neutrinos
- Dark photons ($m =$?)
- Gravitinos ($m \gtrsim 1$ keV)
- Weakly Interacting Massive Particles (WIMPs)
- WIMPZILLAs ($m \sim 10^{10}$ GeV)
- ...

My preference

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- And it would be nice if it could be detected somehow: QCD axion, some WIMPs
- I've never worked on axions . . .

Some News on WIMPs

In standard cosmology: relic density of particle χ that once was in thermal equilibrium:

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma_{\rm ann} v \rangle|_{T \simeq T_F}}$$

$\Omega_\chi = \rho_\chi / \rho_{\rm crit}$: scaled mass density
$\sigma_{\rm ann}$: (effective) total annihilation cross section
v: relative velocity in cms frame;
$\langle \ldots \rangle$: thermal averaging
$T_F \simeq m_\chi / 20$: freeze–out temperature

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Get correct relic density if $\langle \sigma_{\rm ann} v \rangle \simeq 1 \text{ pb} \cdot c$: points towards weak scale, connection to hierarchy/naturalness problem?

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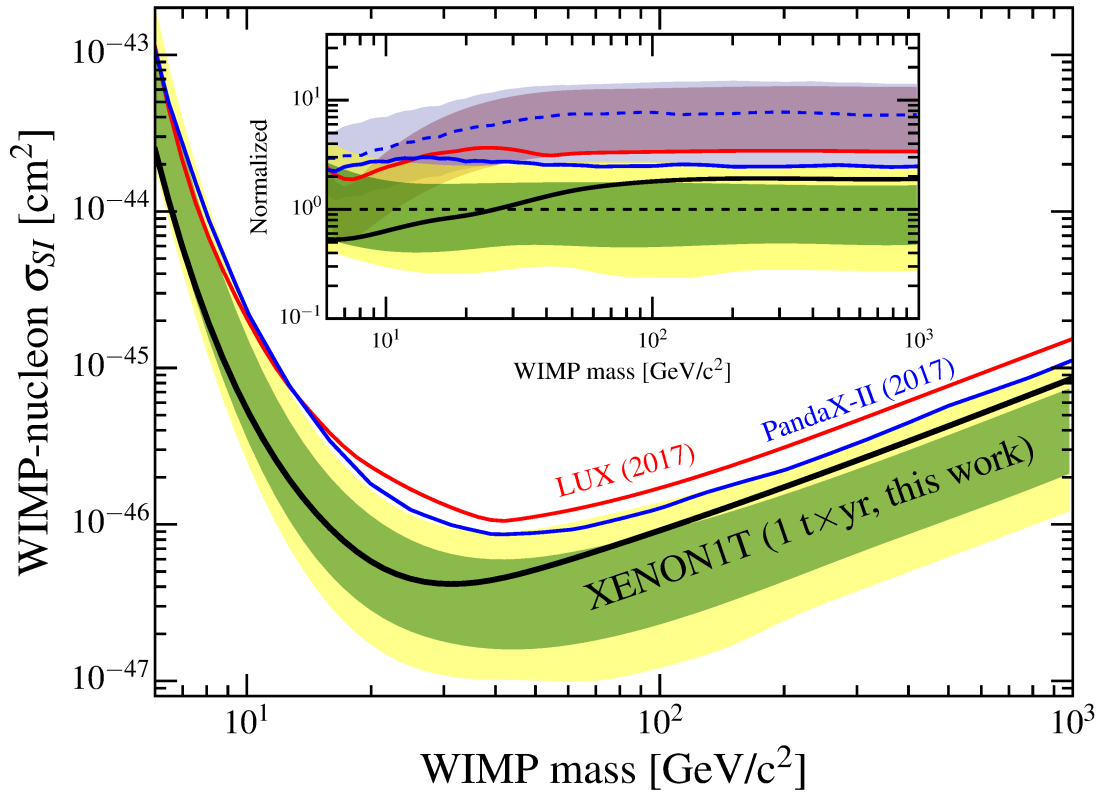
- At colliders: Searches for direct WIMP production not promising, but searches for “mediators” or “partners” (e.g., squarks) can be.
- Direct searches: Look for elastic WIMP–nucleus scattering; signal: recoil energy of the nucleus. (Probably) no signal found (DAMA??)

Most recent direct search bound

XENON1T collab., arXiv:1805.12562



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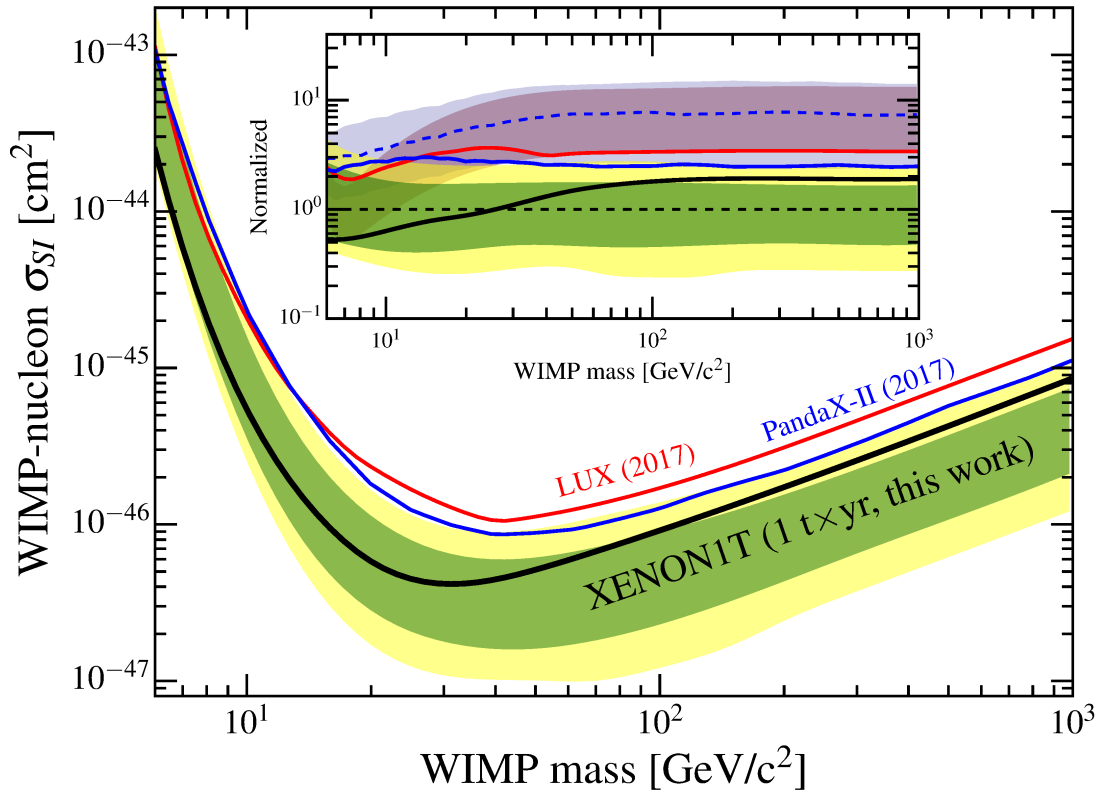

The bound is somewhat weaker than the expected sensitivity, i.e. there is a slight excess of events

Direct WIMP Searches

Kinematics:

$$E_{\rm recoil} \leq 2v_\chi^2 m_N \left(\frac{m_\chi}{m_N+m_\chi}\right)^2 \rightarrow \begin{cases} 2v_\chi^2 m_N, & m_\chi \gg m_N \\ 2v_\chi^2 m_\chi^2/m_N, & m_\chi \ll m_N \end{cases}$$

Allows to understand shape of excluded parameter space:

- Small m_χ: recoil energy below threshold $\Rightarrow$ complete loss of sensitivity
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This drives a fair amount of recent model building!

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In standard cosmology, need light mediator(s) (dark gauge boson, dark Higgs, ...) to get sufficiently large $\sigma_{\rm ann}$:

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- New opportunities for low$-\sqrt{s}$ collider, fixed target experiments
- Need new techniques for direct detection
- Not clear what the smallest mass of a “WIMP” is (GeV? MeV? keV??)

Very Heavy WIMPs: Upper Bounds on Mass

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  - $m_{\tilde{B}} \lesssim 6$ TeV, if $\delta m/m < 0.5\%$: stoponium mass $< 2m_{\tilde{B}}$! Biondini & Laine, 1801.05821

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- How about resonant annihilation?

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(Reasonably) well motivated model:

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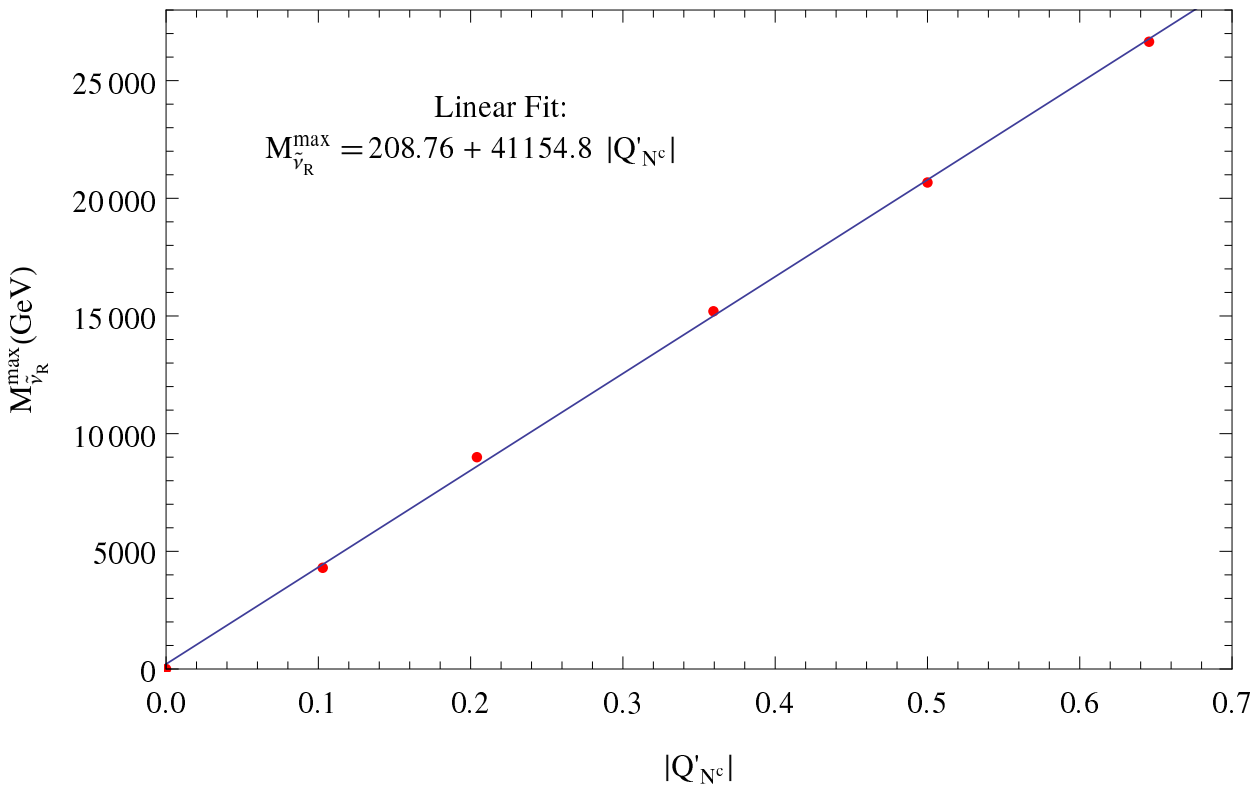
Relic density minimized, if N coupling to final state $\simeq g_{N\tilde{\nu}_R\tilde{\nu}_R^*}$: achieved by tuning doublet Higgs masses

Result MD, F.A. Gomes Ferreira, to appear



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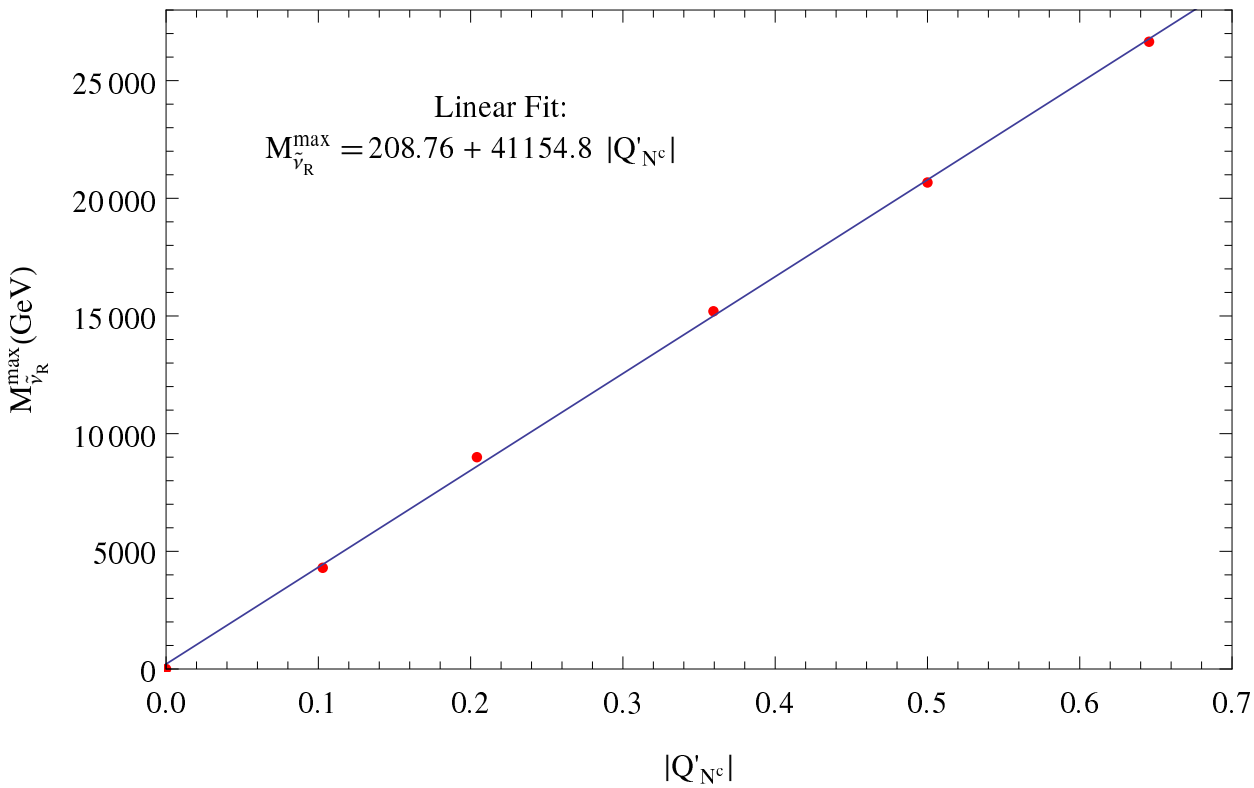

Allows $m_{\tilde{\nu}_R}$ up to 26 TeV!

WIMPs from "Moduli"

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Need $m_\Phi > 10\ {\rm TeV}$!

(Problem with hierarchy, if $m_\Phi \simeq m_{\rm sparticle}$.)

Impact on WIMP Density

e.g. Acharya et al. 2009, Kane et al. 2015

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Hence WIMP density can be smaller or larger than in standard cosmology! Gelmini et al., hep-ph/0605016

Three evolution equations:

$$\frac{d\,n_\Phi}{dt} = -3Hn_\Phi - \Gamma_\Phi n_\Phi\,;$$

$$\frac{d\,n_\chi}{dt} = -3Hn_\chi - \langle\sigma_{\rm ann}v\rangle\left[n_\chi^2 - \left(n_\chi^{\rm eq}\right)^2\right] + n_\Phi\Gamma_\Phi B(\Phi\to\chi)\,;$$

$$\frac{d\,T}{dt} = \frac{1}{1+\frac{T}{3h_*}\frac{dh_*}{dT}}\left\{-HT + \frac{1}{3s}\left[n_\Phi m_\Phi\Gamma_\Phi + 2m_\chi\langle\sigma_{\rm ann}v\rangle\left[n_\chi^2 - \left(n_\chi^{\rm eq}\right)^2\right.\right.\right.$$

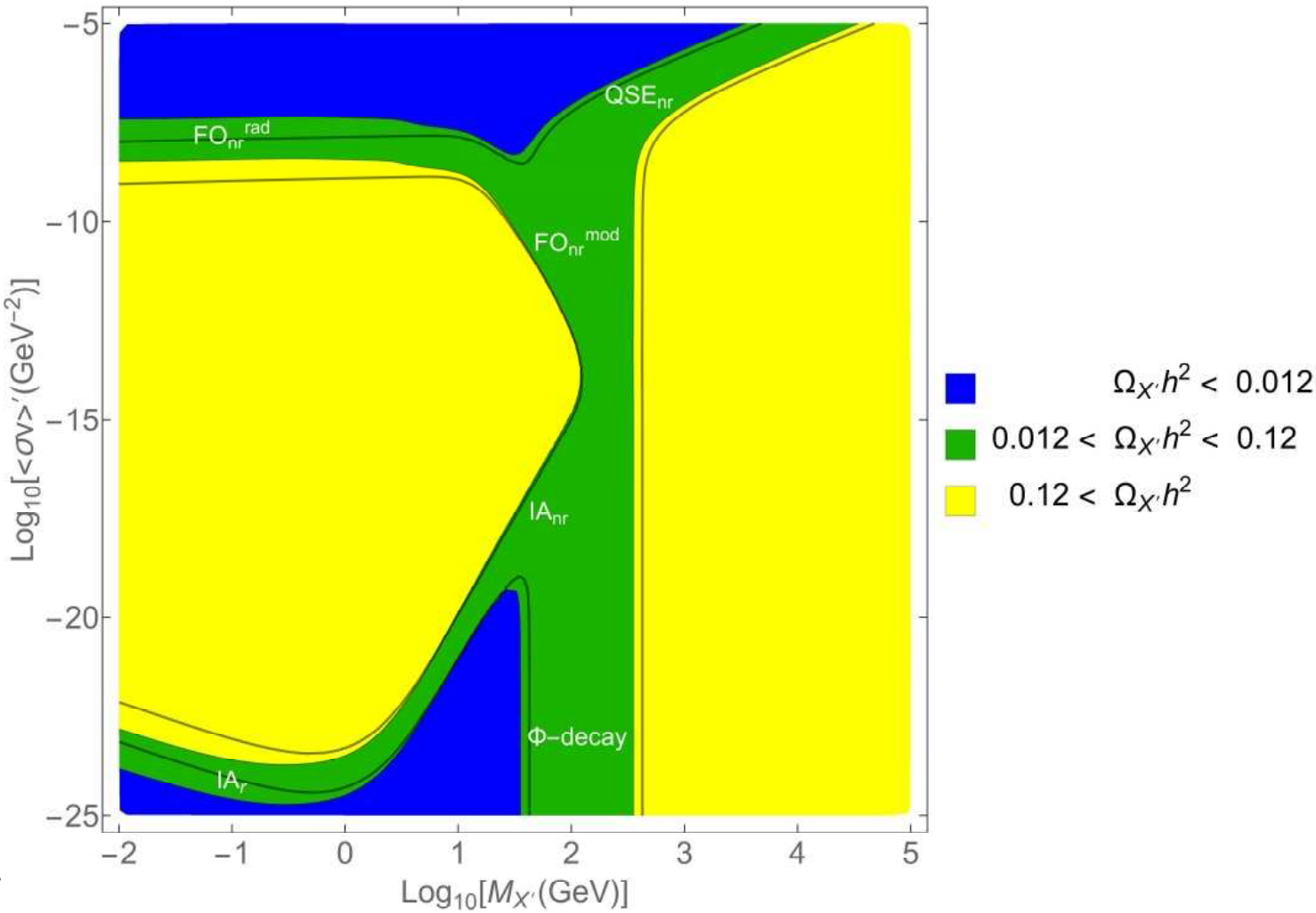
Here, entropy density $s = \frac{2\pi^2}{45}h_*T^3$.

Note:

- Entropy is *not* conserved during Φ decay!
- Still normalize DM density to $s \Longrightarrow$ need to keep track of s accurately, including T dependence of h_*.

$m_\Phi = 5 \cdot 10^3$ TeV, $T_{\rm RH} = 850$ MeV, $B(\Phi \to \chi) = 10^{-5}$

MD, F. Hajkarim, JCAP 1802, 057



WIMPs from Moduli: Results

- If WIMP has overdensity in standard cosmology: Need:
  - $Br(\Phi \to \chi) \lesssim 10^{-4} \cdot \frac{100\ \mathrm{GeV}}{m_\chi}$ and
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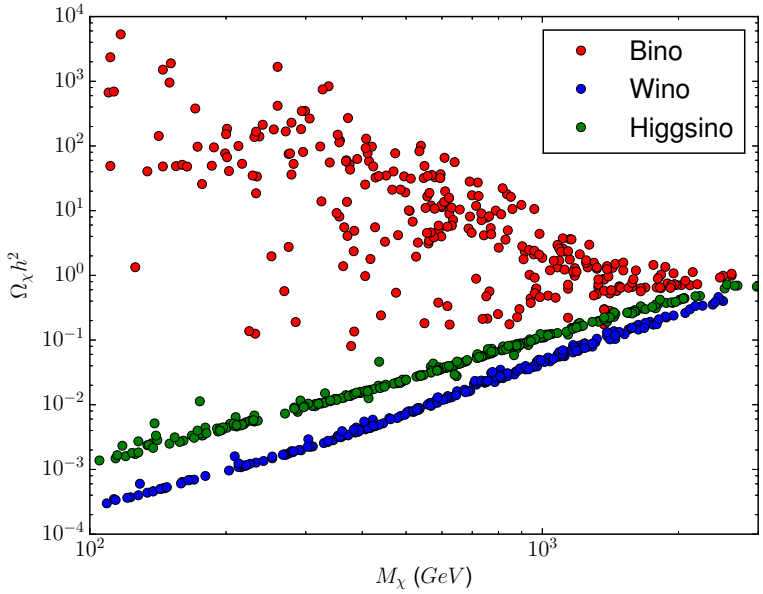
- Can (e.g.) find extended region with good bino–like WIMP

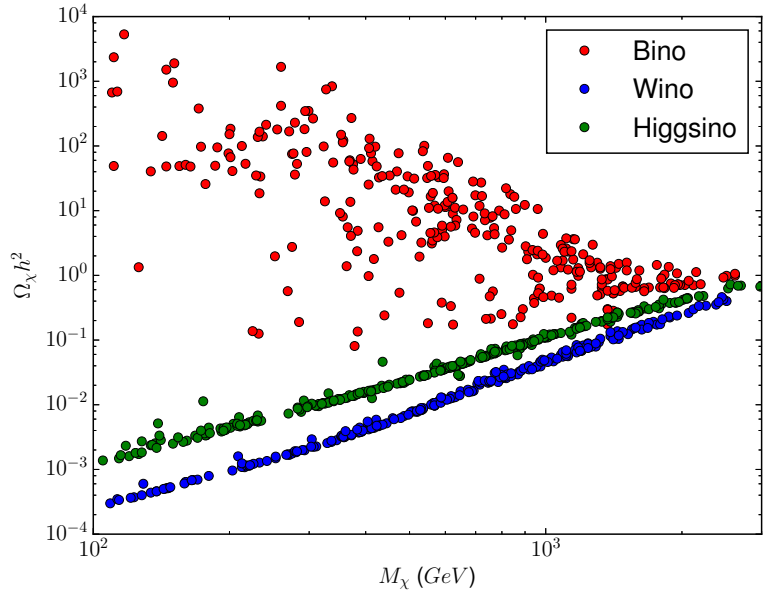
E.g. pMSSM scan with $m_\Phi = 5 \cdot 10^4$ TeV

MD, F. Hajkarim, to appear

$$Br(\Phi \to \chi) = 10^{-5}$$



$$Br(\Phi \to \chi) = 10^{-7}$$



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- Most likely, no DM particle has been found yet

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- WIMPs are getting squeezed $\Longrightarrow$ theorists are extending WIMP parameter space