Galaxy rotation cuves

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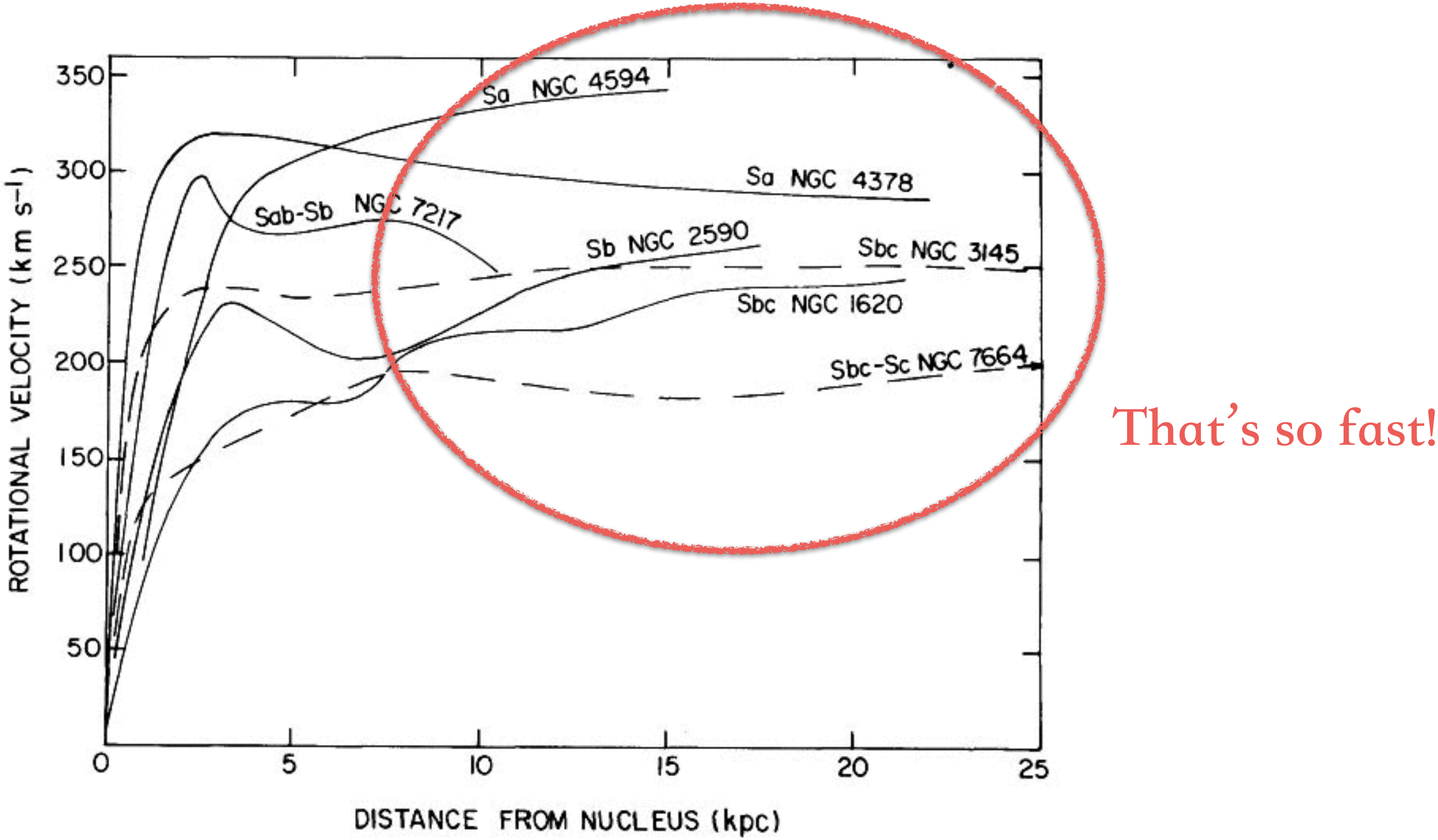

[Rubin, Ford, Thonnard 1980]

If dark matter is a particle,
what's its spin?

- - - - - - - We have no clue - - - - - - -

So what about spin-2?

However, see: Garcia-Cely, Heck 2016

Bigravity and Dark Matter

Marvin Lüben

PPSMC 21/2/19

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Outline of the talk

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1) Evidence for dark matter
2) Introduction to bigravity
3) Massive graviton as dark matter candidate
4) Other observational constraints
5) Conclusions

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Evidence for dark matter

Evidences for dark matter

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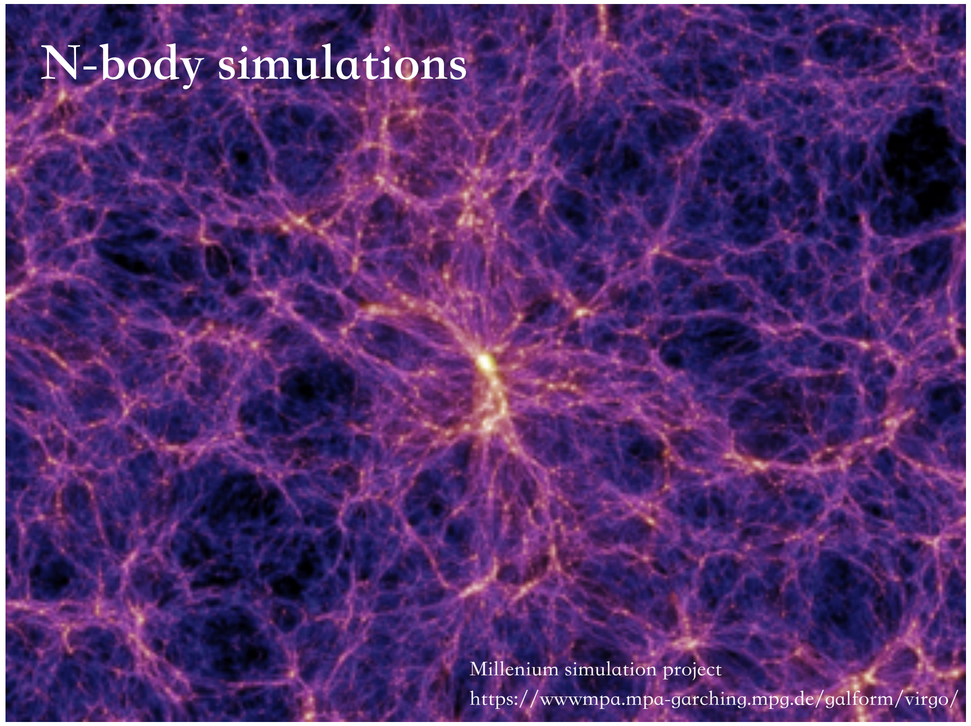
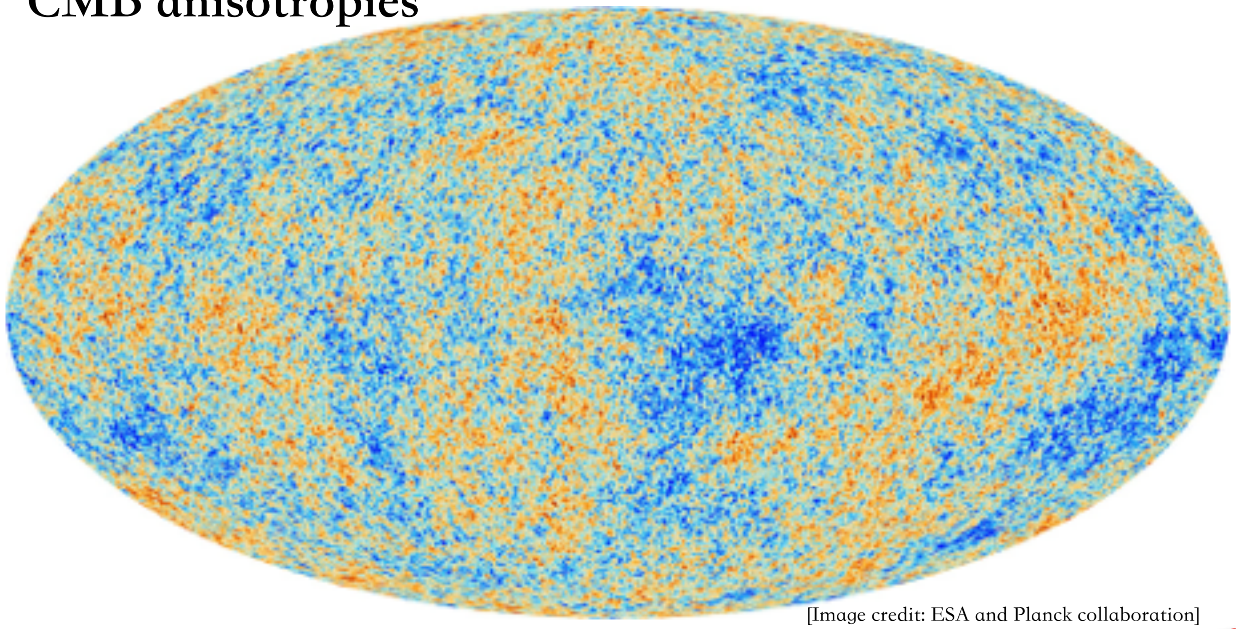
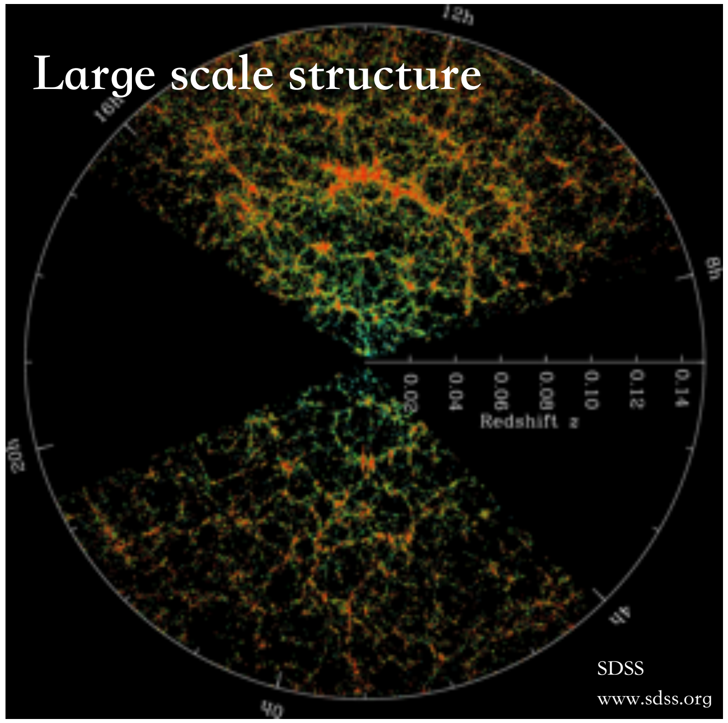


CMB anisotropies

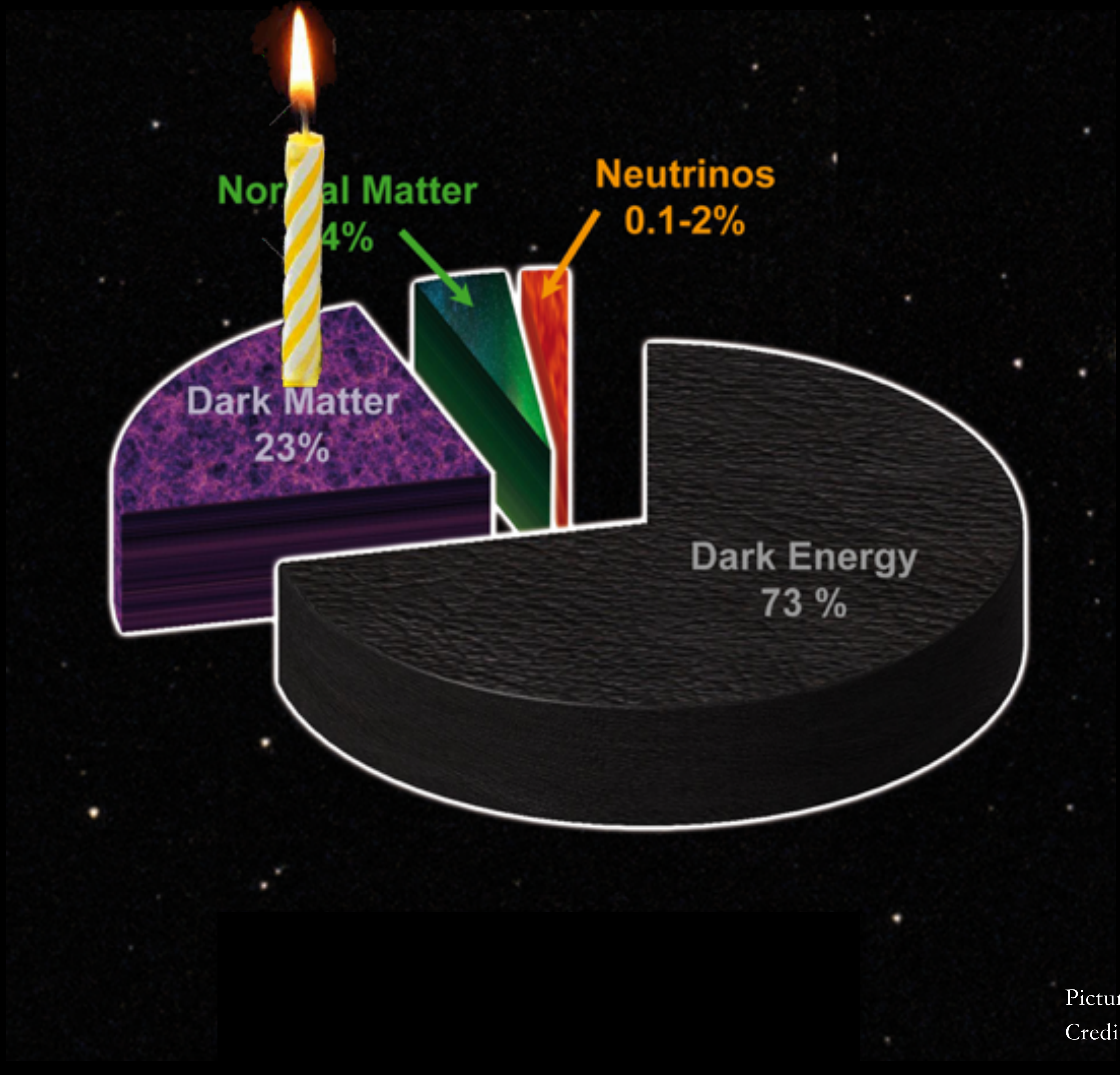


[Image credit: ESA and Planck collaboration]



etc etc etc

The cosmic pie today



Picture from http://www.ikp.kit.edu/edelweiss/english/darkmatter.php
Credit: HAP / A. Chantelauze

2 Introduction to bigravity

Field theories

	massless	massive
spin-0	Klein-Gordon	Klein-Gordon
spin-1	Maxwell	Proca
spin-2	(linearised) General relativity	(Fierz-Pauli) ???

Field theories

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	massless	**massive**
spin-0	Klein-Gordon	Klein-Gordon
spin-1	Maxwell	Proca
spin-2	(linearised) General relativity	(Fierz-Pauli) **Massive (bi)gravity**

Bigravity is the fully non-linear theory describing a massive and a massless spin-2 field

Action

[Hassen & Rosen 1109.3515, 1111.2070]

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$$S = m_g^2 \int d^4x \sqrt{-g}\, R(g) + m_f^2 \int d^4x \sqrt{-f}\, R(f) - 2m^2 \int d^4x\, V(g,f) + \int d^4x \sqrt{-g}\, L_m(g,\Phi)$$

Einstein-Hilbert | **Einstein-Hilbert** | **Potential** | **Matter**

Einstein-Hilbert:

1) Standard kinetic term for symmetric 2-tensor for . . .
2) 2 metric tensors g and f
3) Bare Planck masses mg and mf

Potential:

$$V(g,f) = \sqrt{-g} \sum_{n=0}^{4} \beta_n e_n(\sqrt{g^{-1} f})$$

1) Parameters β_0, β_4 are CC's for g, f
2) Parameters $\beta_1, \beta_2, \beta_3$ are interaction parameters
3) Unique!

Matter:

1) Matter minimally coupled to g. Choice!
2) More general matter couplings possible (see my last talk)

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1) Free of the notorious 6th d.o.f. (Boulwere-Deser ghost)
2) Invariant under simultaneous diff's, Lorentz-invariant, etc

deRham, Gabadadze 1007.0443
deRham, Gabadadze, Tolley 1011.1232
Hassan, Rosen 1103.6055, 1106.3344
Hassan, Rosen, Schmidt-May 1109.3230

Mass spectrum

[Hassan, Rosen 1109.3515; Hassen, Schmidt-May, von Strauss 1208.1515]

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1) Consider linear fluctuations around proportional background $\bar{f}_{\mu\nu} = c^2 \bar{g}_{\mu\nu}$:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}\,, \qquad f_{\mu\nu} = \bar{g}_{\mu\nu} + \ell_{\mu\nu}$$

2) A linear combination forms mass eigenstates: $(c=1)$

$$\delta G_{\mu\nu} = \frac{m_{\rm Pl}}{1+\alpha^2}\left(h_{\mu\nu} + \alpha^2 \ell_{\mu\nu}\right) \qquad \delta M_{\mu\nu} = \frac{\alpha\, m_{\rm Pl}}{1+\alpha^2}\left(\ell_{\mu\nu} - h_{\mu\nu}\right)$$

massless mode massive mode $m_{FP}^2 = \frac{m^2}{1+\alpha^2}(\beta_1 + 2\beta_2 + \beta_3)$

3) Background consistency relation

$$\beta_0 + 3\beta_1 + 3\beta_2 + \beta_3 = \frac{1}{\alpha^2}(\beta_1 + 3\beta_2 + 3\beta_3 + \beta_4) \equiv \frac{\Lambda}{m^2}$$

Limits

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$$\alpha = \frac{m_f}{m_g}$$

$\alpha \ll 1$ $\qquad$ $\alpha \gg 1$

GR limit

massless spin-2 field and dM decouples

$h_{\mu\nu} \sim \delta G_{\mu\nu}$

MG limit

massive spin-2 field

$h_{\mu\nu} \sim \delta M_{\mu\nu}$

$$h_{\mu\nu} = \frac{1}{m_{\mathrm{Pl}}}\left(\delta G_{\mu\nu} - \alpha \delta M_{\mu\nu}\right)$$

$$V \sim \frac{1}{m_{Pl}} h_{\mu\nu} \delta T^{\mu\nu}$$

Another GR limit: $m_{\mathrm{FP}} \gg \ell^{-1}$

Babichev, Crisostomi 1307.3640
Akrami et al. 1503.07521
Babichev et al. 1604.08564 1607.03497

3

Massive graviton as dark matter candidate

Interaction vertices

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Babichev et al. 1604.08564 1607.03497

Compute cubic (and higher order) action

δG^3	$\delta G^2 \delta M$	$\delta G \delta M^2$	δM^3
$1, \Lambda$	0	$1,\ \Lambda,\ m_{\mathrm{FP}}^2$	$\alpha,\ \alpha\,\Lambda,\ \alpha\, m_{\mathrm{FP}}^2,\ \frac{1}{\alpha},\ \frac{\Lambda}{\alpha},\ \frac{m_{\mathrm{FP}}^2}{\alpha}$

All vertices are Planck mass suppressed

Like in GR

No decay from massive to massless spin-2

Different α-dependency and possible enhancement

No α-dependence.
Massive spin-2 gravitates just like SM

Perturbative expansion valid for energies below $E < \alpha\, m_{\mathrm{Pl}}$.

Production mechanisms

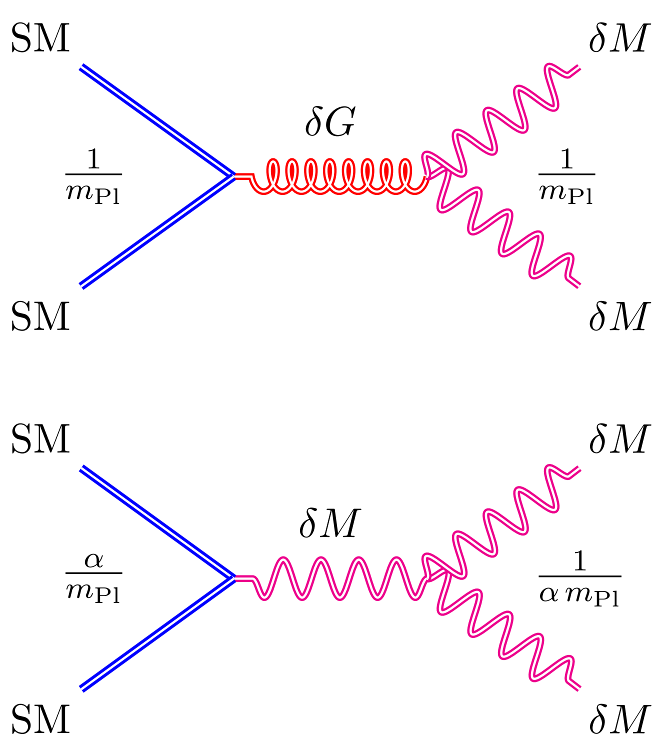
Babichev et al. 1604.08564 1607.03497

1) Usual scenario via **freeze-out** can be realized in a certain parameter region via self-thermalization. MeV to GeV scale DM

Chu, Garcia-Cely 1708.06764

3) **Freeze-in** in mechanism relies on a slow leakage of the thermal bath during reheating or radiation-domination

Thermal bath



DM

The inverse process will be subdominant at all times

The α-dependence cancels out

Decay & constraints

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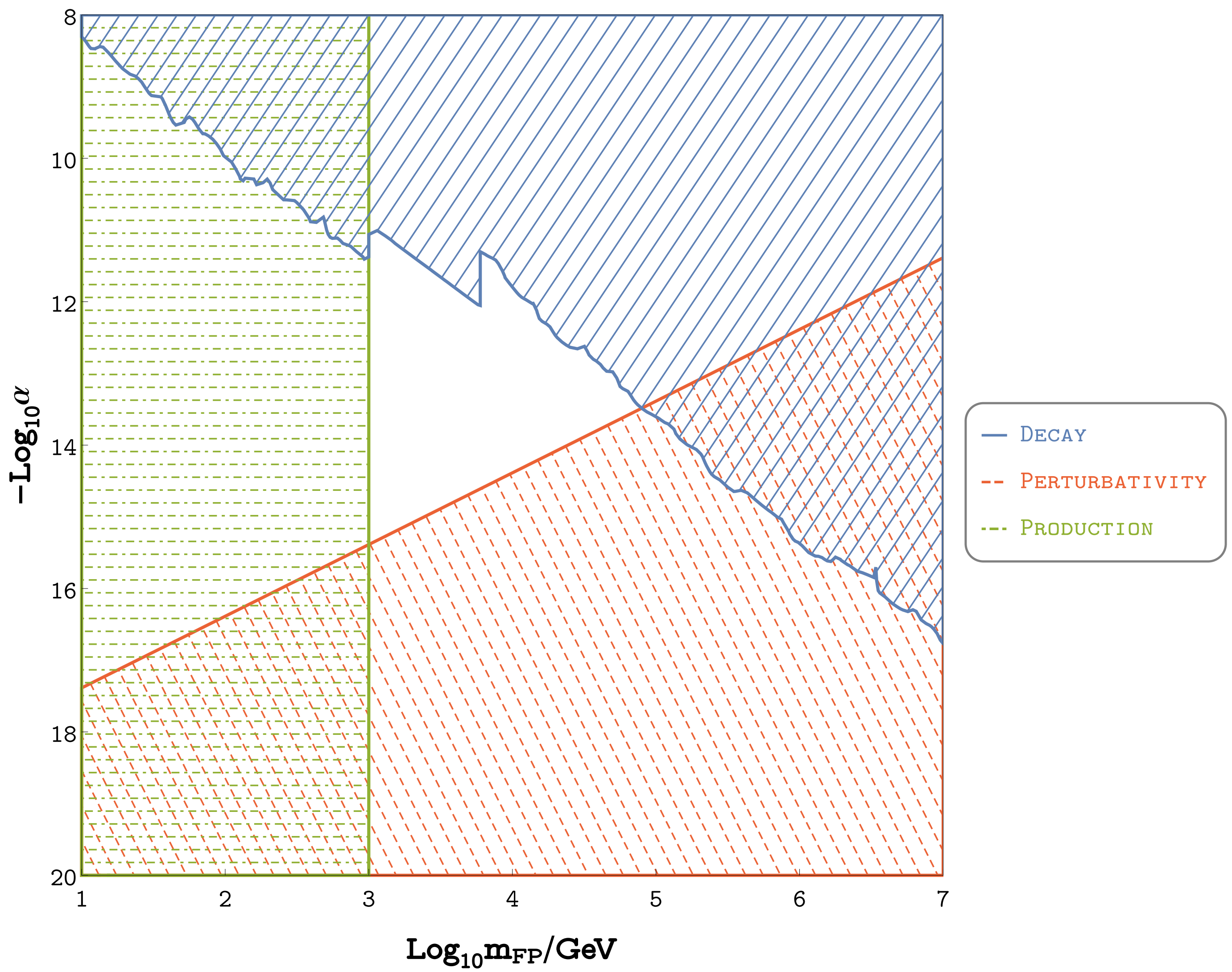
Babichev et al. 1604.08564 1607.03497



1) Heavy spin-2 can decay via all kinematically allowed channel (most important: decay into photons, neutrinos)

$$\Gamma(\delta M \to XX) = \frac{C_X}{80\pi}\frac{\alpha^2 m_{\mathrm{FP}}^3}{m_{\mathrm{Pl}}^2} f_X\left(\frac{m_X^2}{m_{\mathrm{FP}}^2}\right)$$

2) Validity of perturbative expansion

$$m_{\mathrm{FP}} \leq \alpha\, m_{\mathrm{Pl}}$$

3) Production via freeze-in requires is constrained by overproduction of tensor modes in CMB to

$$1 \text{ TeV} \lesssim m_{\mathrm{FP}} \lesssim 10^{11} \text{ GeV}$$

4) Stability on cosmological scales

$$\tau_U = 13.8 \text{ Gyr} \qquad \alpha^{2/3} m_{\mathrm{FP}} \lesssim 0.13 \text{ GeV}$$

$$1 \text{ TeV} \lesssim m_{\mathrm{FP}} \lesssim 66 \text{ TeV}$$

That's heavy! Cold DM!

Some comments

Babichev et al. 1604.08564 1607.03497

1) The phenomenon dubbed Dark Matter is a manifestation of gravity itself
2) Its coupling to the standard model is naturally Planck-suppressed, and additionally by alpha
3) Massive spin-2 field gravitates just like SM
4) The massive spin-2 field is cold (large mass) and behaves like dust (small self-interactions)

5) Can the massive gravitons clump and form halos?
   Yes! Make **Geon** („gravitational-electromagnetic entity" a la Wheeler) out of massive gravitons, but only first attempt so far.

Wheeler, Phys. Rev. 97 (1955) 511 – 536
Aoki et al. 1710.05606

4

Other observational constraints

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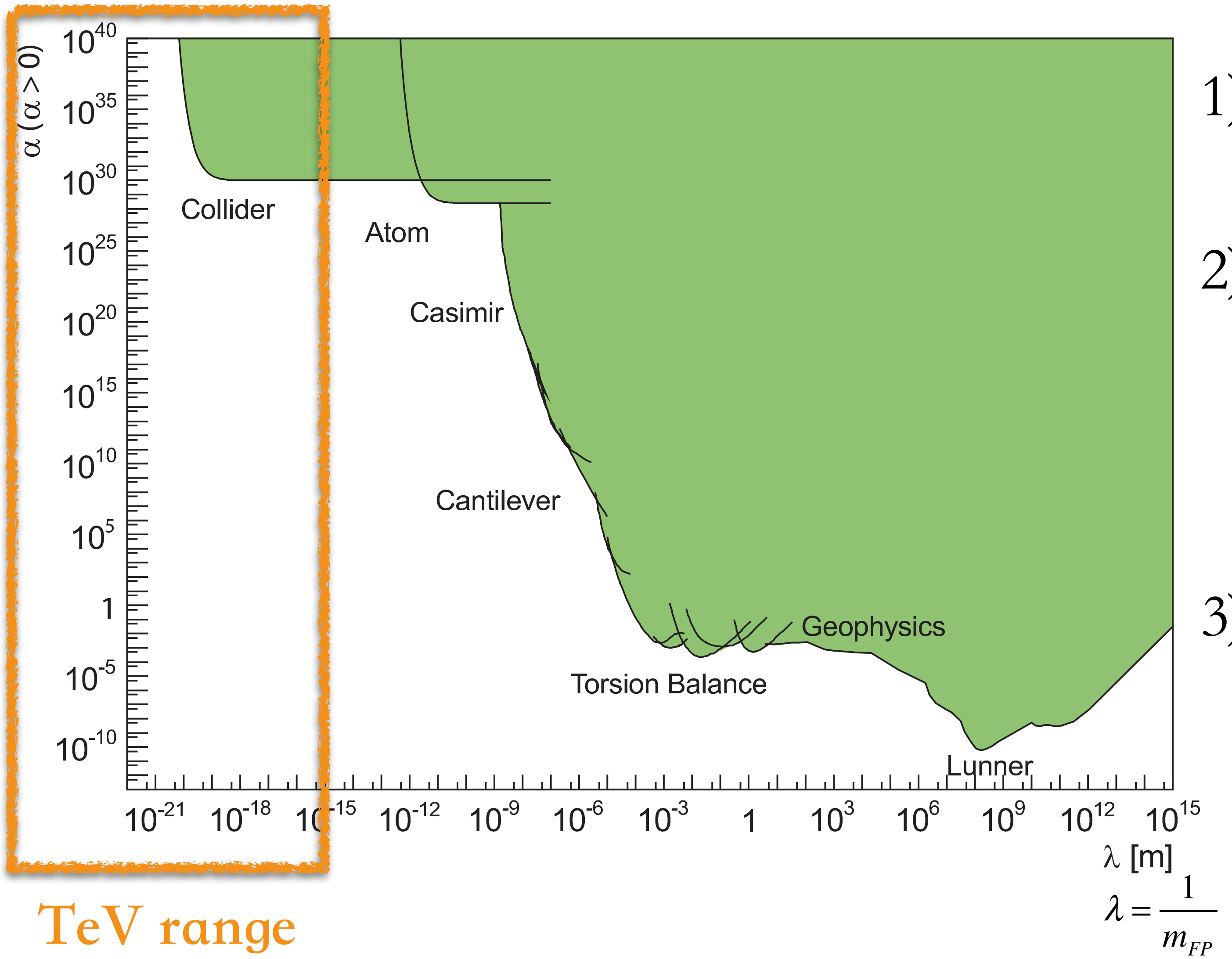
Local tests

Will 1403.7377



1) The usual tests of the Inverse-Square-law apply, but
2) Take into account **Vainshtein mechanism:**

Vainshtein, Phys.Lett. 39B (1972) 393-394

$$r_V = \left(\frac{r_S}{m_{\rm FP}^2}\right)^{1/3}$$

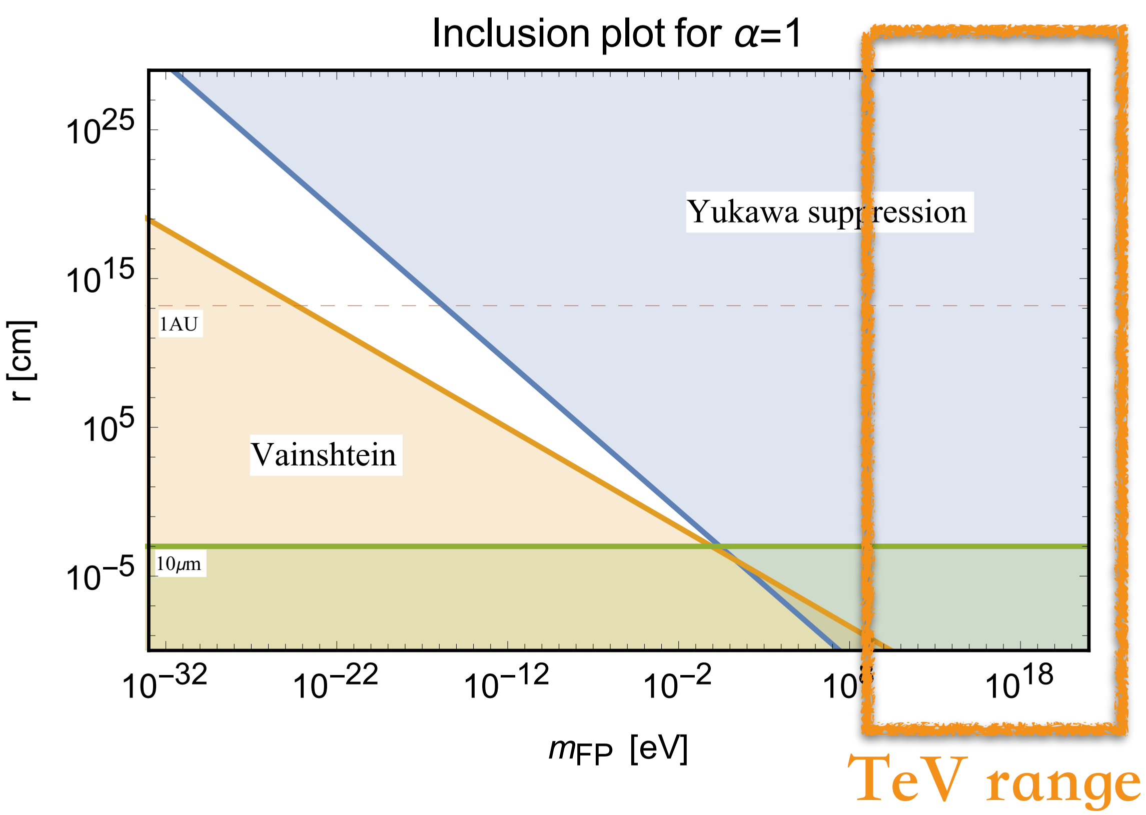
Babichev, Crisostomi 1307.3640

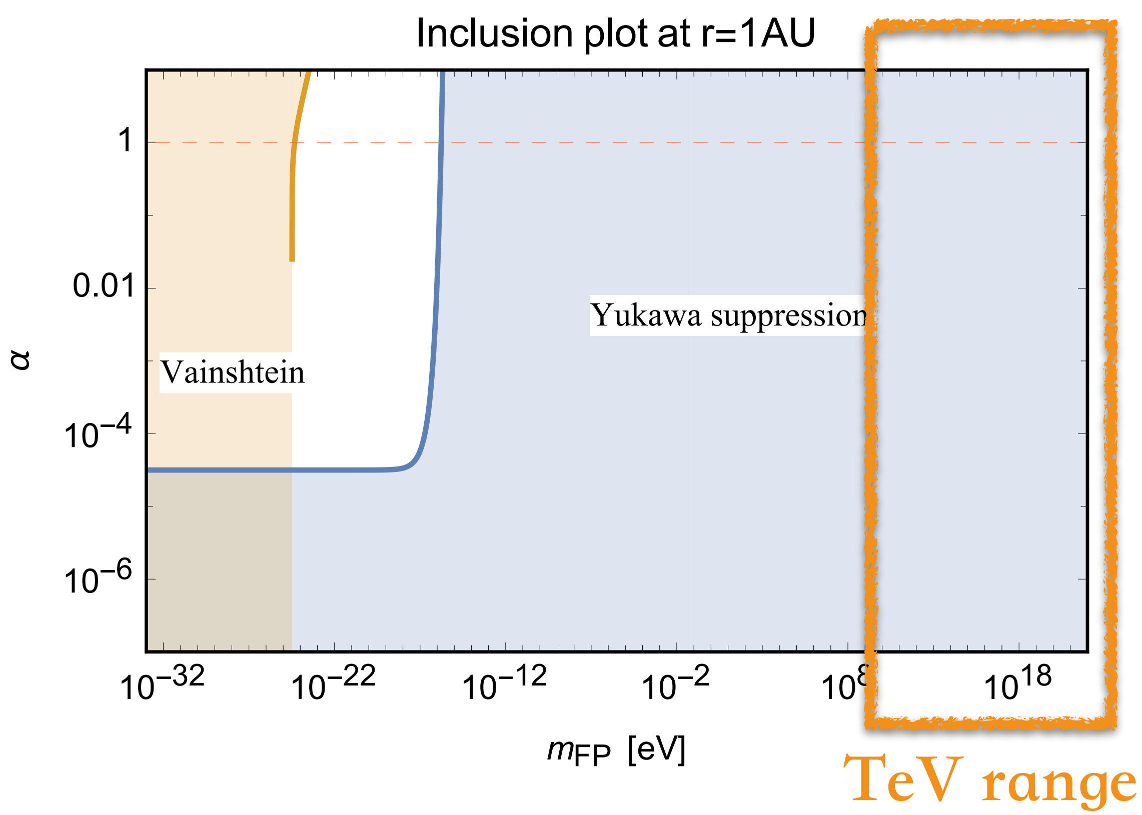
3) For a spin-2 mass of TeV scale, the Vainshtein radius is tiny

$$V(r) = -\frac{1}{M_{\rm Pl}^2}\left(\frac{1}{r} - \frac{\alpha^2 e^{-m_{\rm FP} r}}{r}\right)$$

Example: solar system

Lüben, Mörtsell, Schmidt-May 1812.08686





Conservative estimate:

Yukawa: $\alpha^2 e^{-m_{FP} r} \lesssim 10^{-9}$

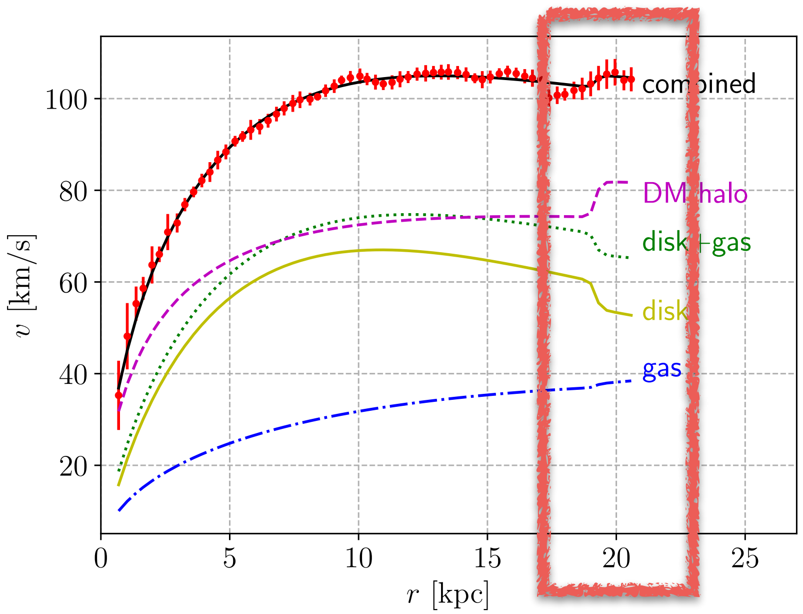
Vainshtein: $\left(\frac{r}{r_V}\right)^3 < 10^{-9}$

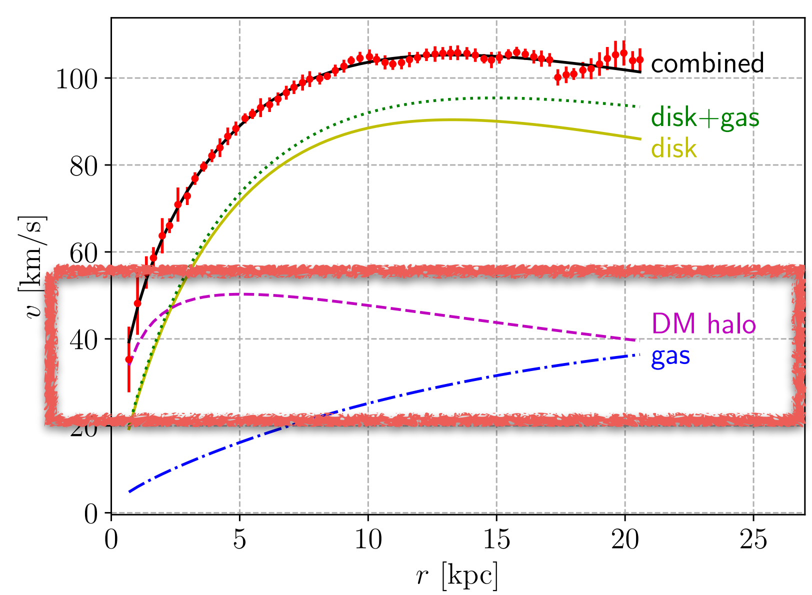
Enander, Mörtsell 1507.00912

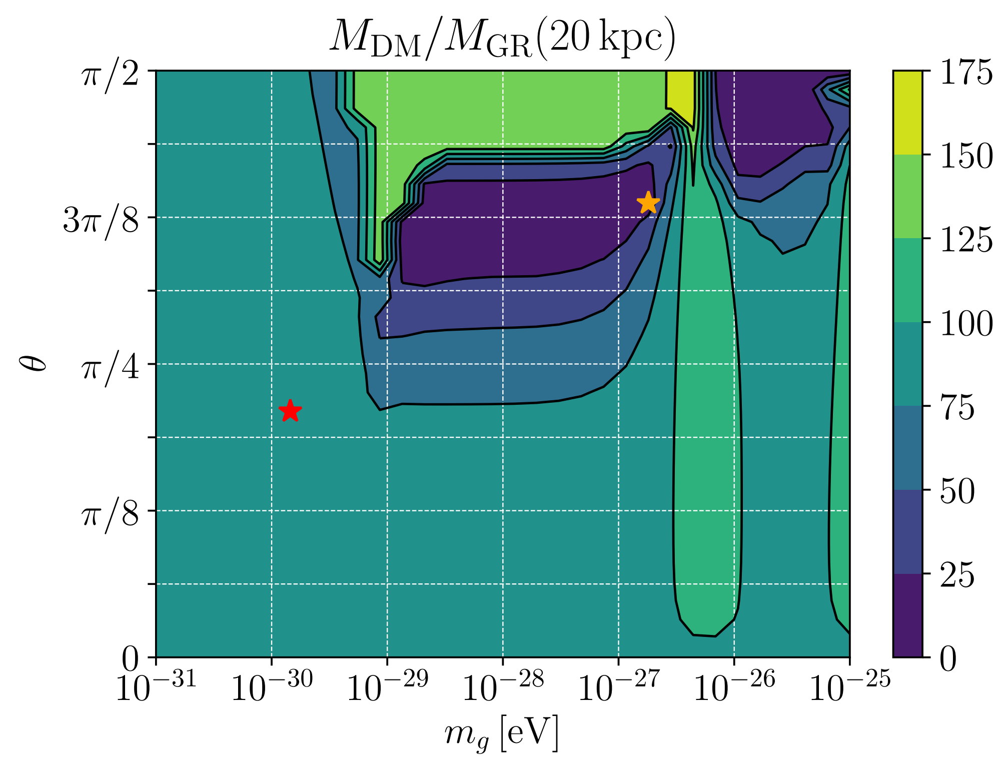
Galaxy rotation curves

Platscher et al. 1809.05318

NGC1052-DF2







Best fitting point

Vainshtein mechanism kicks in

Low DM fit

Necessary DM abundance for galaxy rotation curve: **Goes down to zero DM**

Gravitational lensing

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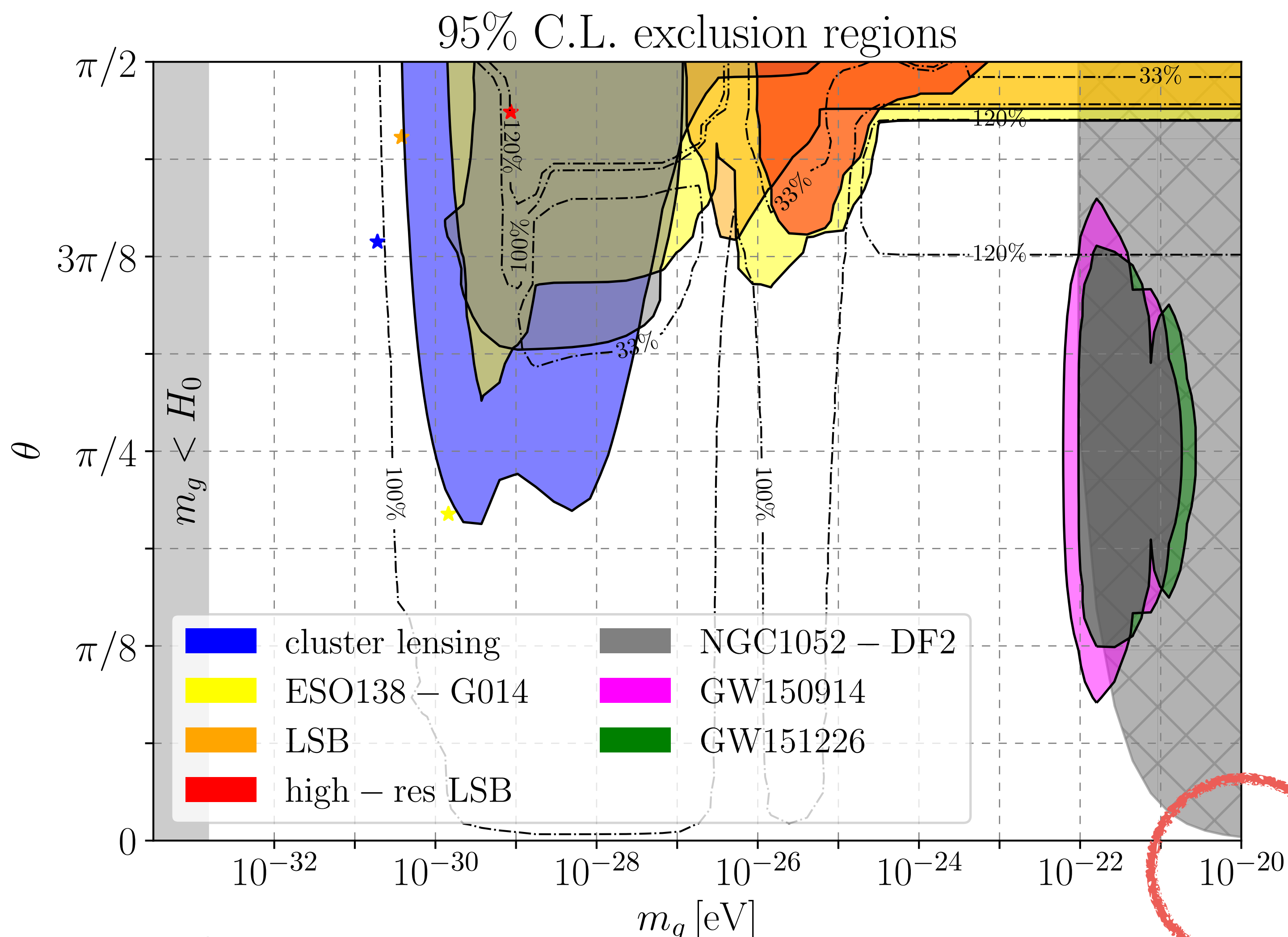
Platscher et al. 1809.05318



$\alpha = \tan\theta$

Exlusion plot from

1) Cluster lensing
2) LSB
3) Galaxy rotation curve
4) Gravitational waves

Extend to TEV scale!

What is missing?

Combine gravity constraints with each other including the Vainshtein mechanism and assuming DM is the massive graviton itself

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Conclusions & outlook

1) Bigravity has cosmological solutions with self-acceleration (no CC)

2) Due to the different laws of gravity compared to GR (Yukawa, Vainshtein), the by data required DM abundance is different

3) The massive spin-2 field itself is a dark matter perfect dark matter candidate (production via freeze-in, stable on cosmological scales, coupling to SM Planck-suppressed, cold)

4) The massive spin-2 field can form halos („geons")

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- - - But there is still a lot to do phenomenologically - - -

1) Cosmological perturbation theory: gradient instability
2) Combine different observational constraints while using the massive spin-2 as dark matter particle itself
3) Other production mechanisms?