From spin-1 to spin-2 SIMPs

Camilo Garcia Cely, ULB

Self-interacting Dark Matter Workshop
Copenhagen, Denmark
The Neils Bohr International Academy

August 3rd, 2017

In collaboration with N. Bernal, X. Chu, T. Hambye and B. Zaldivar
Based on JCAP 1603 (2016) no.03, 018 and arXiv:1708.xxxxx

How to produce self-interacting DM

Solution to small-scale problems: $\frac{\sigma_{\mathsf{SI}}}{m_{\mathsf{DM}}} \sim 0.1 - 10\,\mathrm{cm}^2/\mathrm{g}$

$$\sigma_{\mathsf{SI}} \sim 10^{11}\text{-}10^{13}\ \text{pb for } m_{\mathsf{DM}} \sim 1\,\text{GeV}$$

How to produce self-interacting DM

Solution to small-scale problems: $\frac{\sigma_{\mathrm{SI}}}{m_{\mathrm{DM}}} \sim 0.1 - 10\,\mathrm{cm}^2/\mathrm{g}$

$$\sigma_{\mathrm{SI}} \sim 10^{11}\text{-}10^{13}\ \text{pb for } m_{\mathrm{DM}} \sim 1\,\mathrm{GeV}$$

If $\sigma v_{\mathrm{annihilation}} \sim 1$ pb : $\Omega_{\mathrm{DM}} h^2 \sim 0.1$ (WIMP miracle)

How to produce self-interacting DM

Solution to small-scale problems: $\frac{\sigma_{SI}}{m_{DM}} \sim 0.1 - 10\,\mathrm{cm}^2/\mathrm{g}$

$$\sigma_{SI} \sim 10^{11}\text{-}10^{13} \text{ pb for } m_{DM} \sim 1\,\mathrm{GeV}$$

If $\sigma v_{\text{annihilation}} \sim 1$ pb : $\Omega_{DM} h^2 \sim 0.1$ (WIMP miracle)
If $\sigma v_{\text{annihilation}} \sim \sigma_{SI}$: $\Omega_{DM} h^2 \ll 1$

How to produce self-interacting DM

Solution to small-scale problems: $\frac{\sigma_{\mathrm{SI}}}{m_{\mathrm{DM}}} \sim 0.1 - 10\,\mathrm{cm}^2/\mathrm{g}$

$$\sigma_{\mathrm{SI}} \sim 10^{11}\text{-}10^{13}\ \mathrm{pb}\ \text{for}\ m_{\mathrm{DM}} \sim 1\,\mathrm{GeV}$$

If $\sigma v_{\mathrm{annihilation}} \sim 1$ pb : $\Omega_{\mathrm{DM}} h^2 \sim 0.1$ (WIMP miracle)
If $\sigma v_{\mathrm{annihilation}} \sim \sigma_{\mathrm{SI}}$: $\Omega_{\mathrm{DM}} h^2 \ll 1$

One option

Keep pb cross sections in the Early Universe but enhance the interactions in DM halos today

- Invoke a light mediator and consider non-perturbative effects

How to produce self-interacting DM

Solution to small-scale problems: $\frac{\sigma_{\text{SI}}}{m_{\text{DM}}} \sim 0.1 - 10\,\text{cm}^2/\text{g}$

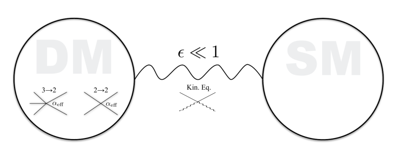
$$\sigma_{\text{SI}} \sim 10^{11}\text{-}10^{13}\ \text{pb for } m_{\text{DM}} \sim 1\,\text{GeV}$$

If $\sigma v_{\text{annihilation}}$ is of the same order of magnitude: $\Omega_{\text{DM}} \ll 1$

Another option: Suppress the interactions in the Early Universe.

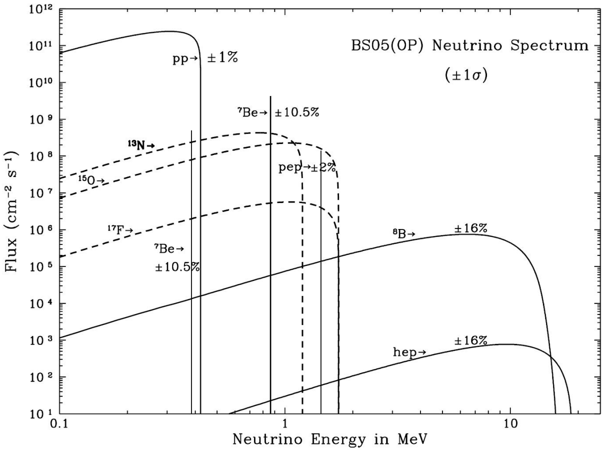
Consider annihilations of three DM particles into two of them.

SIMPs (Strongly Interacting Massive Particles)



Hochberg, Kuflik, Volansky, Wacker (PRL 2014)

Similar processes occur in the Sun



Bahcall et al. , (ApJ, 2005)

Concrete Implementations

Basic requirements

- An underlying principle for having 3-to-2 processes
- Dark Matter Stability

Concrete Implementations

Basic requirements

- An underlying principle for having 3-to-2 processes
- Dark Matter Stability

Examples:

- Z_3 dark matter Bernal et al. (2015), Soo-Min Choi (2015)
- QCD-like theories of dynamical chiral symmetry breaking Hochberg et al, 2014
- Dark Matter in a hidden gauge theory Yamanaka et al (2015)

$\vdots$

Concrete Implementations

Basic requirements

- An underlying principle for having 3-to-2 processes
- Dark Matter Stability

Examples:

- Z_3 dark matter Bernal et al. (2015), Soo-Min Choi (2015)
- QCD-like theories of dynamical chiral symmetry breaking Hochberg et al, 2014
- Dark Matter in a hidden gauge theory Yamanaka et al (2015)

$\vdots$

This talk

- Warm-up: spin-1 case (vector SIMPs) Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)
- Spin-2 case Preliminary

Spin-1 case: Hidden Vector DM model

Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$SU(2)_X$
H	1	2	$\frac{1}{2}$	0
ϕ	1	1	0	2
A'_μ	1	1	0	3

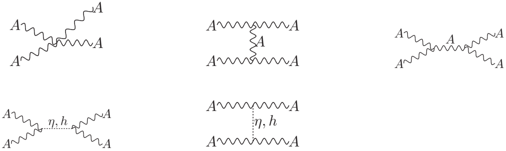
Local $SU(2)_X$	$\rightarrow$	Global $SO(3)$	
Gauge Fields A'_μ	$\rightarrow$	Massive Fields A_μ	Stable (DM Candidate)
Doublet ϕ	$\rightarrow$	Higgs-like η	It mixes with the Higgs

Hambye (JHEP 2009)

Vector SIMPs

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

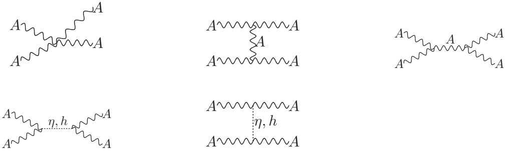
Dark Matter
Self-Interactions



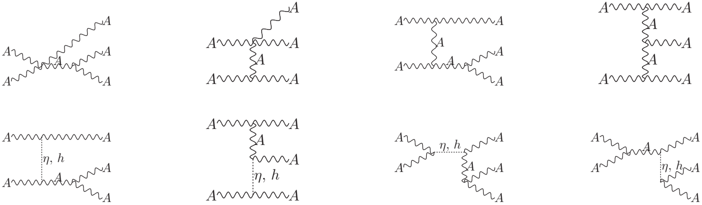
Vector SIMPs

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

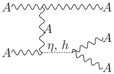
Dark Matter Self-Interactions



3-to-2 process



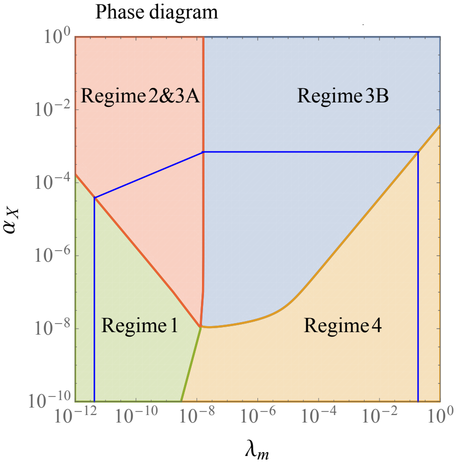
Annihilations into SM particles are naturally suppressed



Production Regimes

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

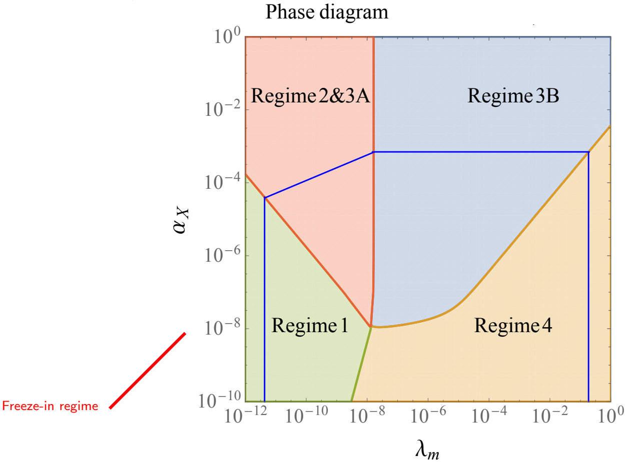
For fixed m_η and m_A



Production Regimes

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

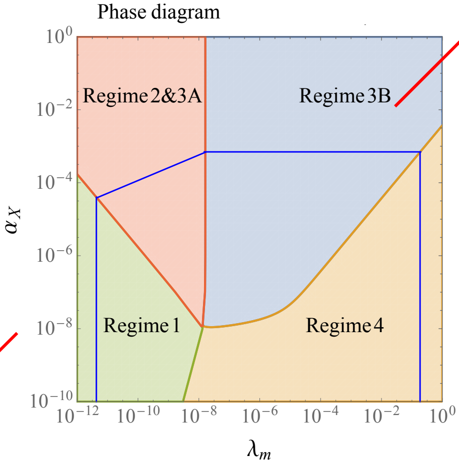
For fixed m_η and m_A



Production Regimes

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

For fixed m_η and m_A



SIMPs in kinetic equilibrium

Freeze-in regime

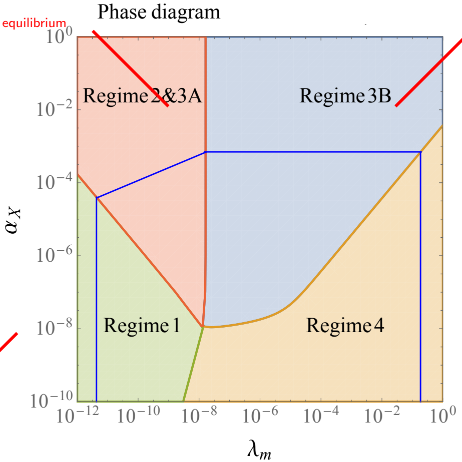
Production Regimes

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

For fixed m_η and m_A

SIMPs not in kinetic equilibrium

SIMPs in kinetic equilibrium

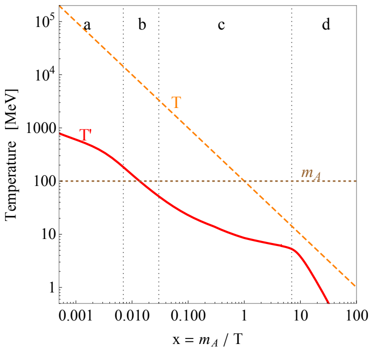


Freeze-in regime

Regime 3A for 3-to-2 processes

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

$m_A = 100$ MeV, $m_\eta = 300$ MeV, $\alpha_X = 0.08$ and $\lambda_m = 4.3 \times 10^{-12}$



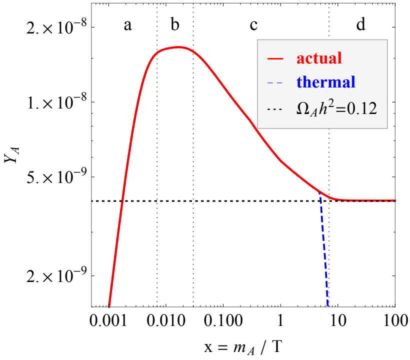
In (c), $T'/T \sim a/log(a)$

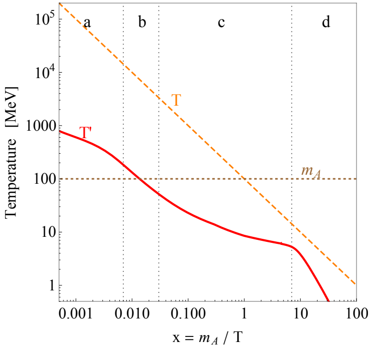
Carlson, Machacek, Hall (Astrophysics J 1992)

Regime 3A for 3-to-2 processes

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

$m_A = 100$ MeV, $m_\eta = 300$ MeV, $\alpha_X = 0.08$ and $\lambda_m = 4.3 \times 10^{-12}$





In (c), $T'/T \sim a/log(a)$

Carlson, Machacek, Hall (Astrophysics J 1992)

Regime 3A

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

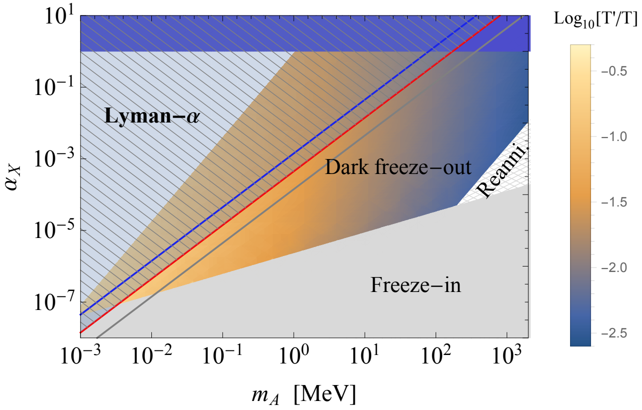


Figure: Parameter space for self-Interactions

How about spin-2 dark matter?

- Classical theory of free massive spin-2 fields. Fierz and Pauli (1939)

How about spin-2 dark matter?

- Classical theory of free massive spin-2 fields. Fierz and Pauli (1939)
- Interactions $\rightarrow$ Very hard!.

  Until very recently, it seemed that any interacting theory had ghosts.

  Boulware, Deser (PRD 1972)

How about spin-2 dark matter?

- Classical theory of free massive spin-2 fields. Fierz and Pauli (1939)
- Interactions $\rightarrow$ Very hard!.

  Until very recently, it seemed that any interacting theory had ghosts.

  Boulware, Deser (PRD 1972)
- Ghosts are absent for very restrictive interaction terms in bimetric theories. Hassan, Rosen (PRL 2012), Hassan, Rosen, Schmidt-May (JHEP 2012)

What is a bimetric theory?

- A massive spin-2 particle will generally mix with the gravitron.

What is a bimetric theory?

- A massive spin-2 particle will generally mix with the gravitron.
- Gravitron: fluctuation of the metric
  $\rightarrow$ Write down a theory with 2 metrics and have them interact.

$$\mathcal{S} \quad = \quad m_g^2 \int d^4x \left(\sqrt{-g} R(g) + \alpha^2 \sqrt{-f} R(f) \right) + \mathcal{S}_{\text{int}} + \mathcal{S}_{\text{matter}} \, .$$

No ghosts are present if

$$\mathcal{S}_{\rm int} = -2\alpha^2 m_g^4 \int d^4x \sqrt{-g}\, V(\sqrt{g^{-1}f})$$

$$V(S) = \beta_0 + \beta_1\, S^{\mu_1}{}_{\mu_1} + \beta_2\, S^{\mu_1}{}_{[\mu_1} S^{\mu_2}{}_{\mu_2]} + \beta_3\, S^{\mu_1}{}_{[\mu_1} S^{\mu_2}{}_{\mu_2} S^{\mu_3}{}_{\mu_3]} + \beta_4\, \mathrm{det} S$$

Consistent theory with few parameters

No ghosts are present if

$$\mathcal{S}_{\text{int}} = -2\alpha^2 m_g^4 \int d^4x \sqrt{-g}\, V(\sqrt{g^{-1}f})$$

$$V(S) = \beta_0 + \beta_1\, S^{\mu_1}{}_{\mu_1} + \beta_2\, S^{\mu_1}{}_{[\mu_1} S^{\mu_2}{}_{\mu_2]} + \beta_3\, S^{\mu_1}{}_{[\mu_1} S^{\mu_2}{}_{\mu_2} S^{\mu_3}{}_{\mu_3]} + \beta_4\, \det S$$

Consistent theory with few parameters

$$\sqrt{-g}\, V(g^{-1}f)\Big|_{\beta_n} = \sqrt{-f}\, V(f^{-1}g)\Big|_{\beta_{4-n}}$$

The metrics are treated symmetrically in S_{int}.

No ghosts are present if

$$\mathcal{S}_{\text{int}} = -2\alpha^2 m_g^4 \int d^4x \sqrt{-g}\, V(\sqrt{g^{-1}f})$$

$$V(S) = \beta_0 + \beta_1\, S^{\mu_1}{}_{\mu_1} + \beta_2\, S^{\mu_1}{}_{[\mu_1} S^{\mu_2}{}_{\mu_2]} + \beta_3\, S^{\mu_1}{}_{[\mu_1} S^{\mu_2}{}_{\mu_2} S^{\mu_3}{}_{\mu_3]} + \beta_4\, \det S$$

Consistent theory with few parameters

$$\sqrt{-g}\, V(g^{-1}f)\Big|_{\beta_n} = \sqrt{-f}\, V(f^{-1}g)\Big|_{\beta_{4-n}}$$

The metrics are treated symmetrically in S_{int}.

$$\mathcal{S}_{\text{matter}} = \int d^4x \sqrt{-g}\, \mathcal{L}_{\text{matter}}(g, \Phi_{\text{matter}})$$

Quadratic Lagrangian:

Spin-2 particles are fluctuations of the metrics around the same background

$$g_{\mu\nu} = \overline{g}_{\mu\nu} + \frac{1}{\mathsf{m_{Pl}}}\left(\delta G_{\mu\nu} - \alpha\delta M_{\mu\nu}\right), f_{\mu\nu} = \overline{g}_{\mu\nu} + \frac{1}{\mathsf{m_{Pl}}}\left(\delta G_{\mu\nu} + \alpha^{-1}\delta M_{\mu\nu}\right)$$

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

Quadratic Lagrangian:

Spin-2 particles are fluctuations of the metrics around the same background

$$g_{\mu\nu} = \overline{g}_{\mu\nu} + \frac{1}{\mathrm{m_{Pl}}}\left(\delta G_{\mu\nu} - \alpha\delta M_{\mu\nu}\right), f_{\mu\nu} = \overline{g}_{\mu\nu} + \frac{1}{\mathrm{m_{Pl}}}\left(\delta G_{\mu\nu} + \alpha^{-1}\delta M_{\mu\nu}\right)$$

$$\begin{aligned}\mathcal{S} \quad \supset \quad & \int d^4x\sqrt{-\overline{g}}\Bigg(\mathcal{L}_2^{\mathrm{kin}}(\delta G) + \mathcal{L}_2^{\mathrm{kin}}(\delta M) - \frac{m_{\mathrm{FP}}^2}{4}\left(\mathrm{tr}(\delta M^2) - \mathrm{tr}(\delta M)^2\right) \\ & -\frac{1}{\mathrm{m_{Pl}}}\left(\delta G_{\mu\nu} - \alpha\delta M_{\mu\nu}\right)T^{\mu\nu} + \mathcal{L}_\Lambda\Bigg)\end{aligned}$$

Two spin-2 particles:
one massless, one massive.

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

Quadratic Lagrangian:

Spin-2 particles are fluctuations of the metrics around the same background

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \frac{1}{\mathrm{m_{Pl}}}\left(\delta G_{\mu\nu} - \alpha\delta M_{\mu\nu}\right), f_{\mu\nu} = \bar{g}_{\mu\nu} + \frac{1}{\mathrm{m_{Pl}}}\left(\delta G_{\mu\nu} + \alpha^{-1}\delta M_{\mu\nu}\right)$$

$$\mathcal{S} \supset \int d^4x\sqrt{-\bar{g}}\Bigg(\mathcal{L}_2^{\mathrm{kin}}(\delta G) + \mathcal{L}_2^{\mathrm{kin}}(\delta M) - \frac{m_{\mathrm{FP}}^2}{4}\left(\mathrm{tr}(\delta M^2) - \mathrm{tr}(\delta M)^2\right)$$
$$-\frac{1}{\mathrm{m_{Pl}}}\left(\delta G_{\mu\nu} - \alpha\delta M_{\mu\nu}\right)T^{\mu\nu} + \mathcal{L}_\Lambda\Bigg)$$

Two spin-2 particles:
one massless, one massive.

- Fierz-Pauli mass: $m_{\mathrm{FP}} = \mathrm{m_{Pl}}\sqrt{\beta_1 + 2\beta_2 + \beta_3}$
- Reduced Planck mass: $\mathrm{m_{Pl}} = m_g\sqrt{1+\alpha^2}$
- $\Lambda = \alpha^2 m_g^2(\beta_0 + 3\beta_1 + 3\beta_2 + \beta_3) = m_g^2(\beta_4 + 3\beta_3 + 3\beta_2 + \beta_1)$

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

Dark Matter

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

This theory modifies GR $\rightarrow$ The laws of gravity change

- Make sure that the predictions are in agreement with those of GR where this has been tested.

Dark Matter

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

This theory modifies GR $\rightarrow$ The laws of gravity change

- Make sure that the predictions are in agreement with those of GR where this has been tested.
- Simplest possibility : take $\alpha \ll 1$

Dark Matter

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

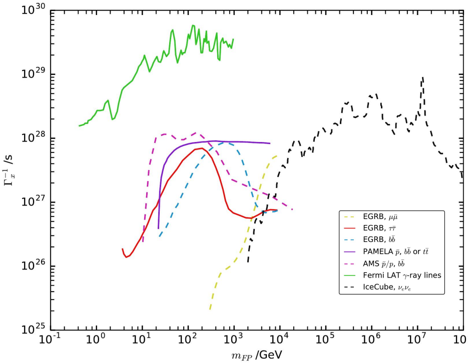
This theory modifies GR $\rightarrow$ The laws of gravity change

- Make sure that the predictions are in agreement with those of GR where this has been tested.
- Simplest possibility : take $\alpha \ll 1$

In this limit, δM is a dark matter candidate

- Vertex $\delta M \delta G \delta G = 0 \rightarrow \Gamma(\delta M \rightarrow \delta G \delta G) = 0$
- δM responds to δG (gravity) in the same way as the SM fields.

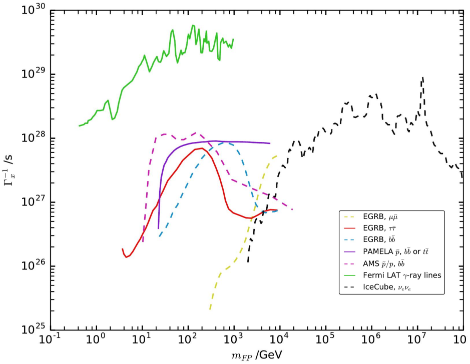
Heavy spin-2 DM



Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

$$\Gamma\left(\delta M \to \mathrm{SMSM}\right) \sim \frac{\alpha^2 m_{\mathrm{FP}}^3}{\mathrm{m}_{\mathrm{Pl}}^2}$$

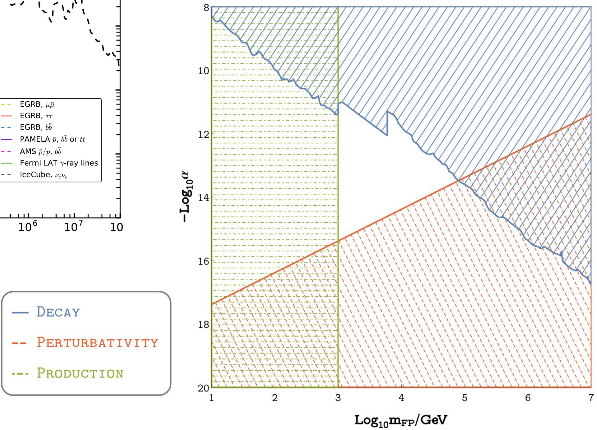
Heavy spin-2 DM



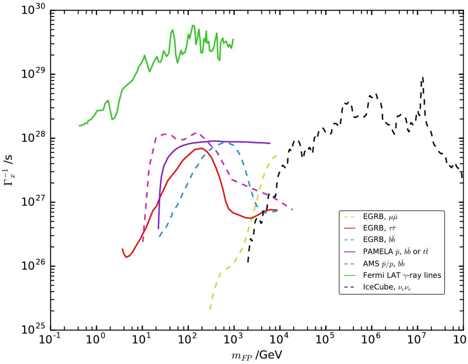
$$\Gamma\left(\delta M \rightarrow \mathrm{SMSM}\right) \sim \frac{\alpha^2 m_{\mathrm{FP}}^3}{\mathrm{m}_{\mathrm{Pl}}^2}$$

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

Production via Freeze-in

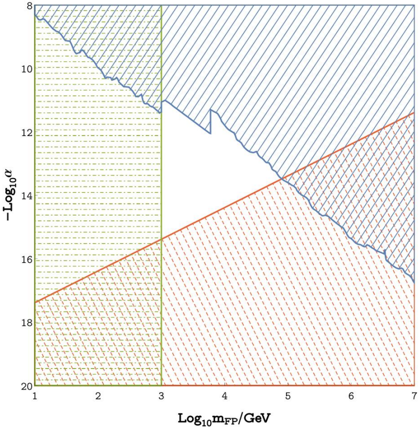


Heavy spin-2 DM



Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

Production via Freeze-in



$$\Gamma\left(\delta M \to \mathrm{SMSM}\right) \sim \frac{\alpha^2 m_{\mathrm{FP}}^3}{\mathrm{m}_{\mathrm{Pl}}^2}$$

Perturbativity condition:
typical energy $< \alpha\, \mathrm{m_{Pl}}$

— Decay
-- Perturbativity
-·- Production

Second surprise

PRELIMINARY

$$g_{\mu\nu} = \overline{g}_{\mu\nu} + \frac{\delta G_{\mu\nu}}{\mathrm{m_{Pl}}} + \mathcal{O}(\alpha^1)\,, \quad f_{\mu\nu} = \overline{g}_{\mu\nu} + \frac{1}{\alpha}\frac{\delta M_{\mu\nu}}{\mathrm{m_{Pl}}} + \mathcal{O}(\alpha^1)$$

Loosely speaking, the self-interactions of δM are the same as those of δG but enhanced by powers of $1/\alpha$.

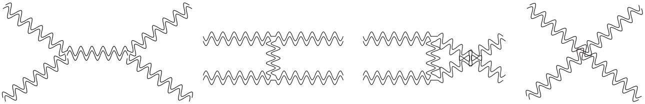


Figure: Bimetric theories naturally give rise to self-interacting spin-2 DM

Very predictive! Lengthy calculations

Self-interaction cross section

PRELIMINARY

$$\sigma_{\text{SI}} = \frac{(\beta_1 + 2\beta_2 + \beta_3)^2}{m_{\text{FP}}^2 \alpha^4} F(r)\,, \quad \text{with } r = \frac{\beta_1 - \beta_3}{\beta_1 + 2\beta_2 + \beta_3}$$

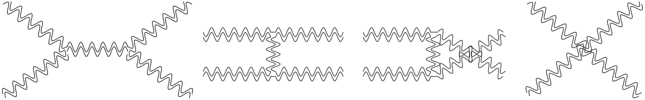
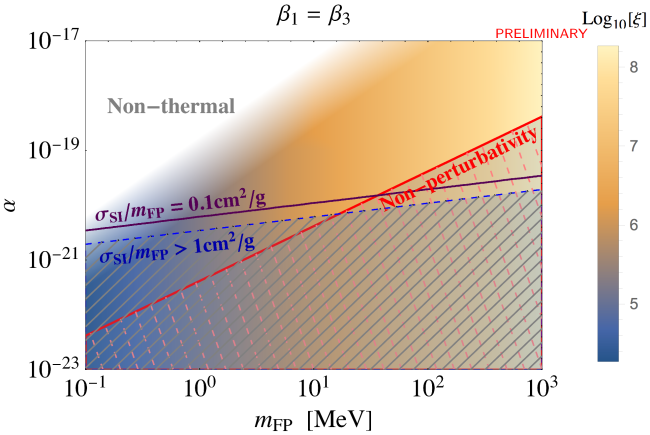
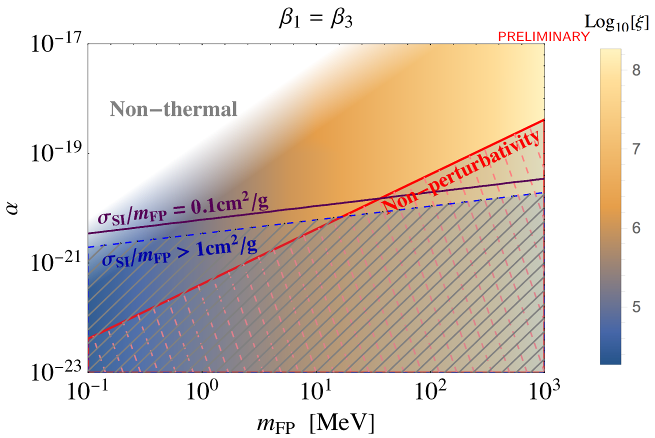
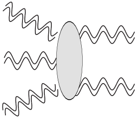


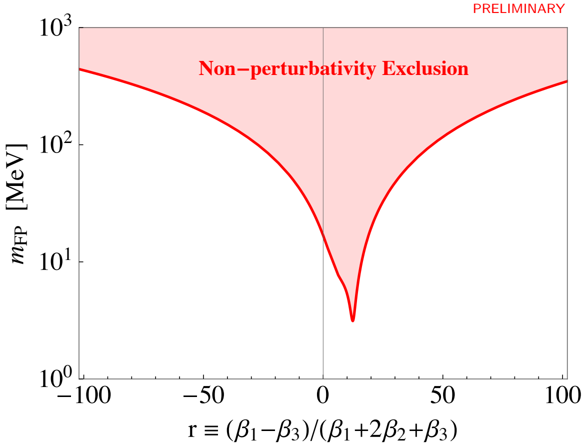
Figure: Bimetric theories naturally give rise to self-interacting spin-2 DM


$\beta_1 = \beta_3$
PRELIMINARY
$\mathrm{Log}_{10}[\xi]$
8
7
6
5
10^{-17}
10^{-19}
10^{-21}
10^{-23}
α
Non−thermal
$\sigma_{SI}/m_{FP} = 0.1\mathrm{cm}^2/\mathrm{g}$
$\sigma_{SI}/m_{FP} > 1\mathrm{cm}^2/\mathrm{g}$
Non−perturbativity
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
m_{FP} [MeV]



How can we produced them?  + no thermal equilibrium

(Regime 3A)


PRELIMINARY
Non−perturbativity Exclusion
10^3
10^2
10^1
10^0
m_{FP} [MeV]
−100
−50
0
50
100
$\mathrm{r} \equiv (\beta_1 - \beta_3)/(\beta_1 + 2\beta_2 + \beta_3)$

Conclusions

- In bimetric theories, requiring negligible interactions between the second metric and ordinary particles naturally leads to spin-2 SIDM capable of addressing the small-scale problems.
- SIDM without light mediators can be produced via 3-to-2 annihilations. The corresponding increase of temperature is not problematic if the two sectors have a large temperature ratio before freeze-out.