Phenomenology of self-interacting WIMPs.

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Open Questions in Particle Physics and Cosmology

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based on **arXiv:1612.00845** in collaboration with Torsten Bringmann, Kai Schmidt-Hoberg and Parampreet Walia

and **work in preparation** in collaboration with Kai Schmidt-Hoberg and Sebastian Wild

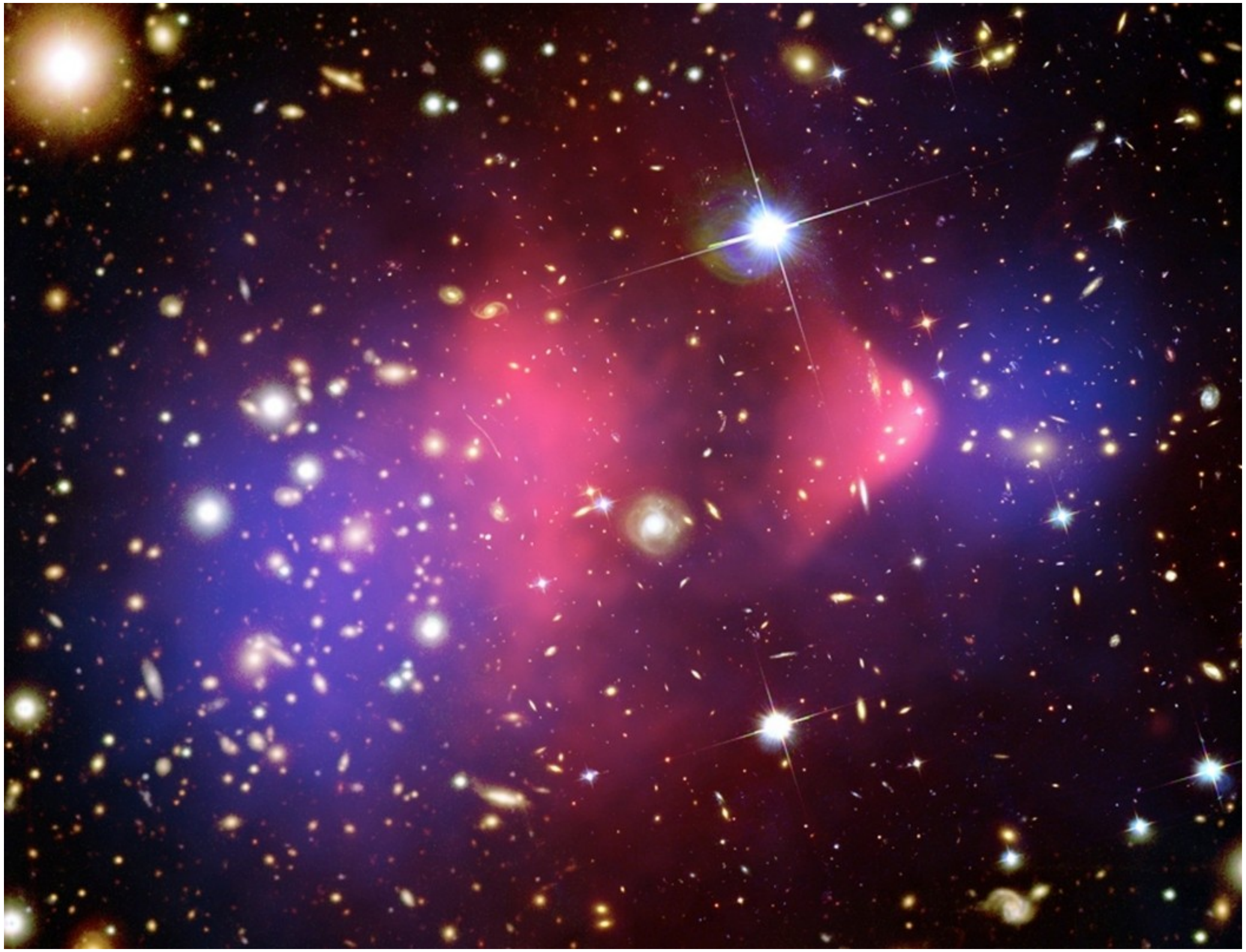
HELMHOLTZ ASSOCIATION

DESY

Outline

- Motivation for self-interacting dark matter
- Self-interactions from new light mediators
- Light mediator phenomenology
- CP-violating self-interactions
- Conclusions

The Bullet Cluster



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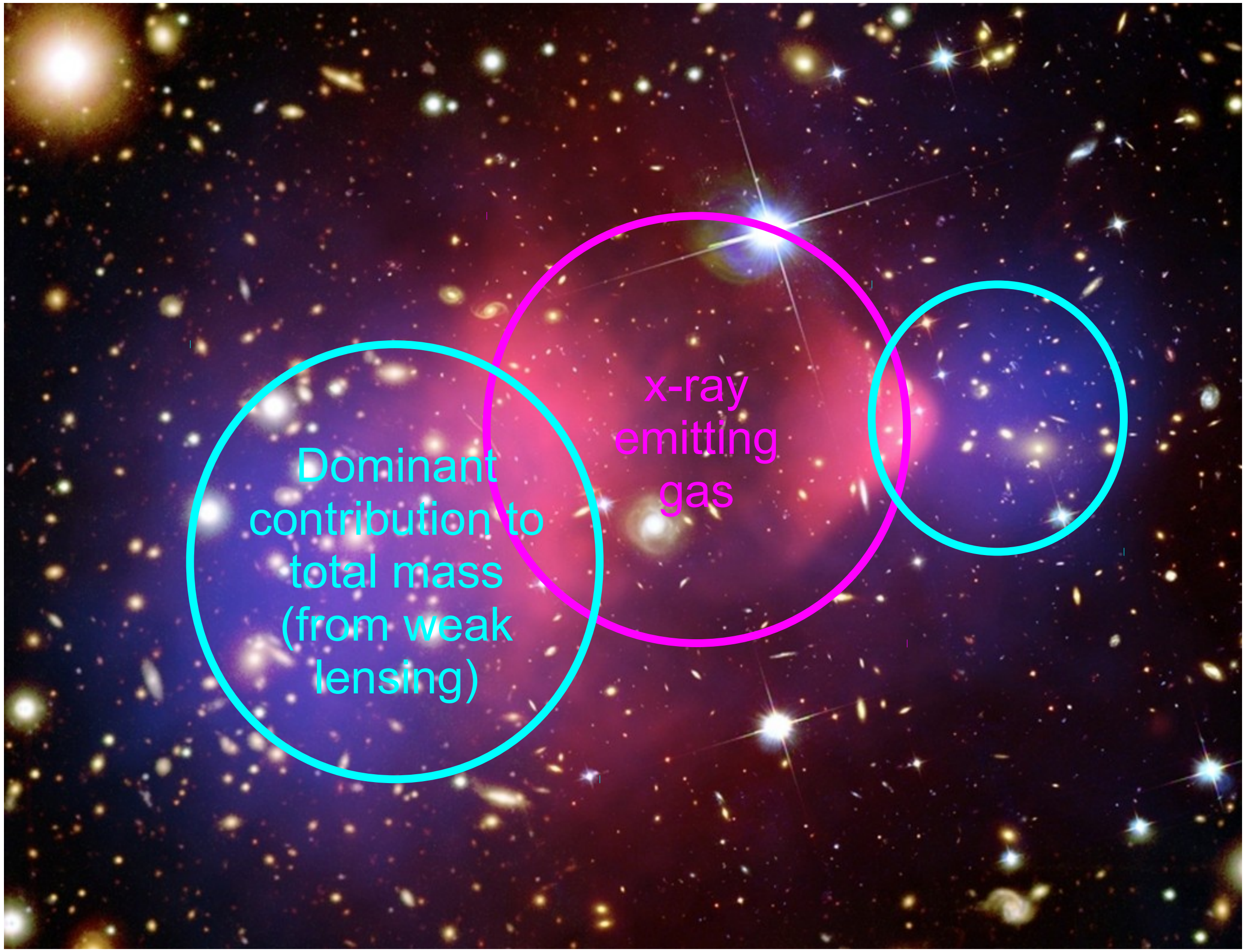
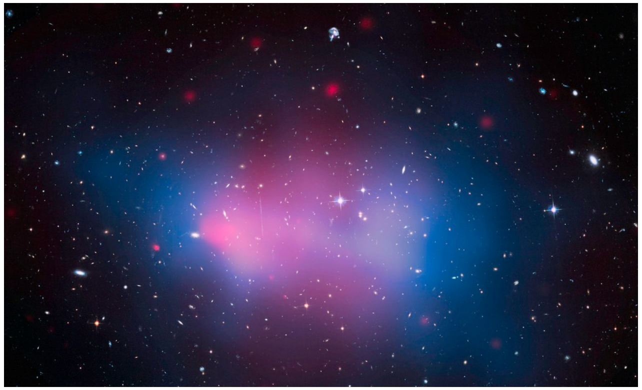


The Bullet Cluster

- Observations of the Bullet Cluster tell us that the dominant form of matter in galaxy clusters behaves very differently from baryonic gas:
  - No emission of x-ray radiation
  - No significant dissipation of energy
  - No loss of direction
- In fact, the dark matter behaves much more like the collisionless galaxies in the two galaxy clusters.
- Many similar observations in other major mergers

Abel 520



El Gordo

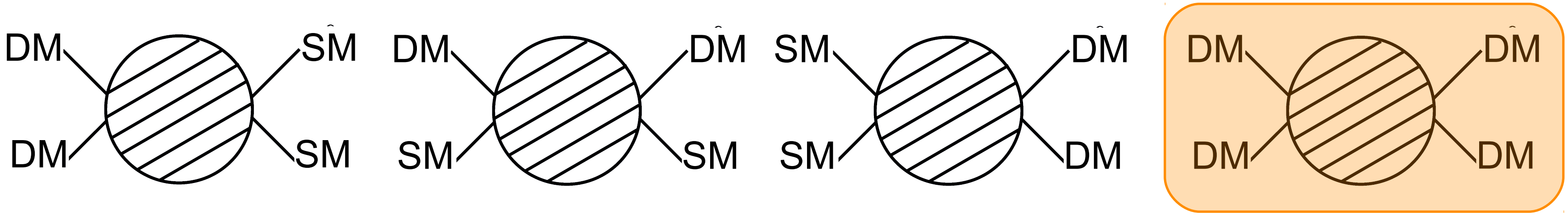
Baby Bullet

Collisionless dark matter?

- If DM consists of new elementary particles, collisions of galaxy clusters seem to imply that these particles would have small self-interactions.
- To obtain an approximate upper bound on the self-scattering cross section, we can calculate the projected (surface) DM density of a galaxy cluster.
- For the central region of the Bullet Cluster, we find $\Sigma \sim 0.3\ \mathrm{g/cm^2}$.
- In order for the majority of DM particles to travel from one end of the Bullet Cluster to the other without scattering, we require $\Sigma\sigma / m_\chi \lesssim 0.5$, and thus $\sigma / m_\chi \lesssim 1.5\ \mathrm{cm^2/g}$.
- Note that this is not at all a small cross section ($1.5\ \mathrm{cm^2/g} = 3\ \mathrm{barn/GeV}$). In fact, it is comparable to nucleon-nucleon scattering!

Self-interacting dark matter

- In order to be observable on astrophysical scales, DM self-interactions actually have to be very large.
- Nevertheless, even such large cross sections cannot be tested in the laboratory, so astrophysics gives us a completely different window to study DM properties.



- Any clear astrophysical evidence for DM self-scattering would rule out many popular DM models (neutralinos, axions, …).
- Instead: Point towards more complex dark sectors with additional structure.

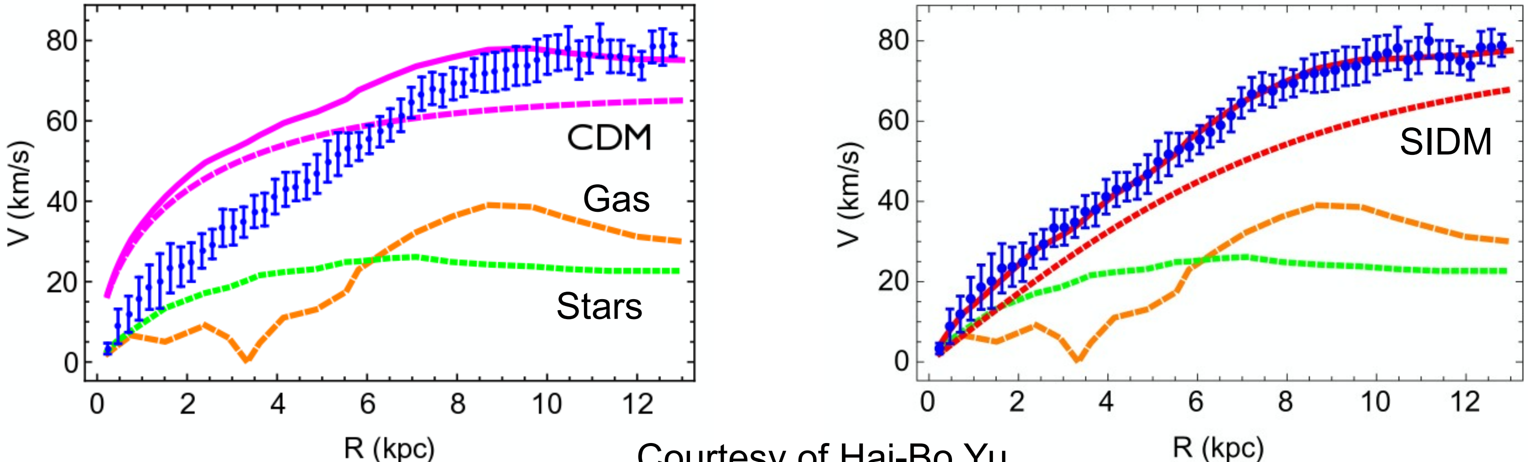
Hints for self-interacting dark matter?

- There are various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:
  - Too-big-to-fail problem

    Boylan-Kolchin, Bullock, Kaplinghat: 1103.0007, 1111.2048
  - Missing-satellites problem

    Klypin et al.: astro-ph/9901240; Moore et al.: astro-ph/9907411
  - Cusp-vs-core problem

    Moore (1994); Flores, Primack: astro-ph/9402004

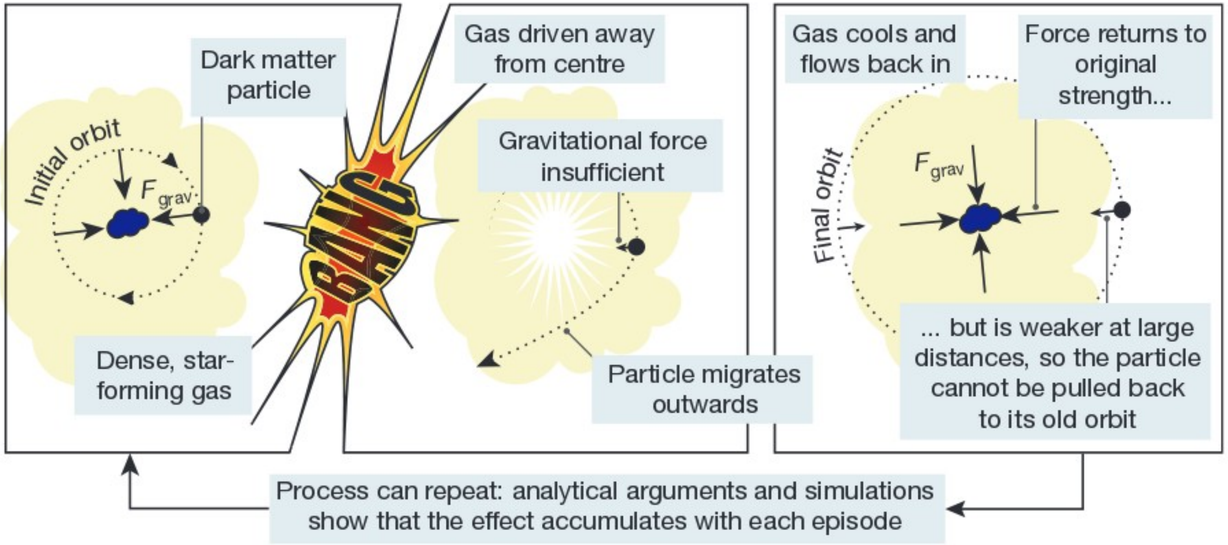


Courtesy of Hai-Bo Yu

Hints for self-interacting dark matter?

- The observational situation concerning the "small-scale crisis" is not yet clear. Maybe we just need to discover more Milky Way satellites (already many new discoveries in 2015 & 2016).
- Even if fully established, it remains unclear whether baryonic feedback can equally provide an explanation for missing satellites and cored dwarf galaxies.

Pontzen & Governato, Nature 506, 171–178 (2014)



Hints for self-interacting dark matter?

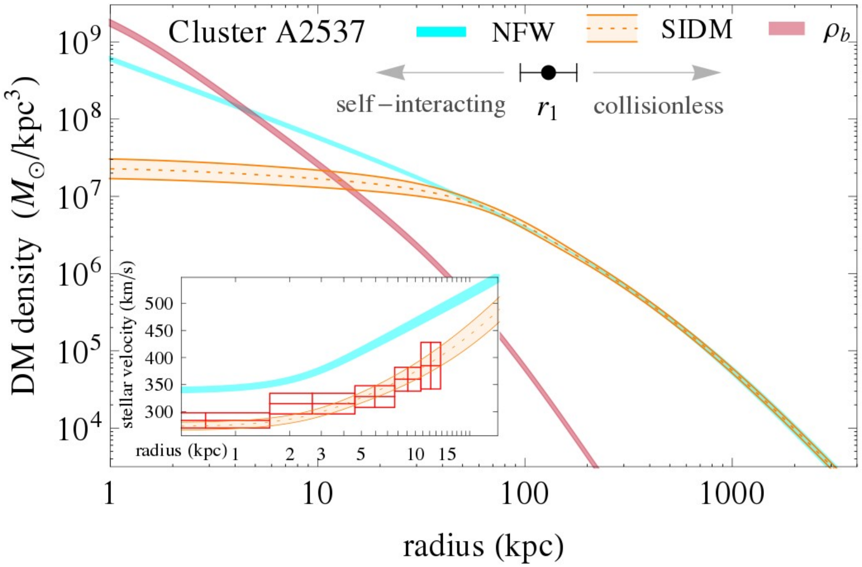
- It is nevertheless intriguing that DM self-interactions may solve these problems.

  Spergel & Steinhard: astro-ph/9909386

- Basic idea: In the central regions of DM halos, self-interactions can be sufficiently frequent to allow for energy transfer between DM particles.

- This energy transfer will heat up DM particles that sit deep in the gravitational potential and create an isothermal core.

Kaplinghat et al., arXiv:1508.03339



- Moreover, sub-halos moving through a bigger DM halo will also heat up and potentially evaporate.

Three main avenues of model-building

1) Very light dark matter
   - Large DM number densities lead to large self-interaction rates
   - Relic density set e.g. by direct annihilation into SM states

Heikinheimo et al., arXiv:1604.02401; Chu et al., arXiv:1609.00399

2) Confinement in the dark sector
   - New strong dynamics leads to large self-scattering
   - Relic density set e.g. via 3 → 2 processes

Hochberg et al., arXiv:1402.5143; arXiv:1512.07917; Kamada et al., arXiv:1606.01628

3) New light mediator in the dark sector
   - Self-interactions are enhanced by the small mediator mass
   - Relic density set by direct annihilation into pairs of mediators

Feng, Kaplinghat, Yu: arXiv:0905.3039; Buckley & Fox: arXiv:0911.3898;
Loeb & Weiner: arXiv:1011.6374

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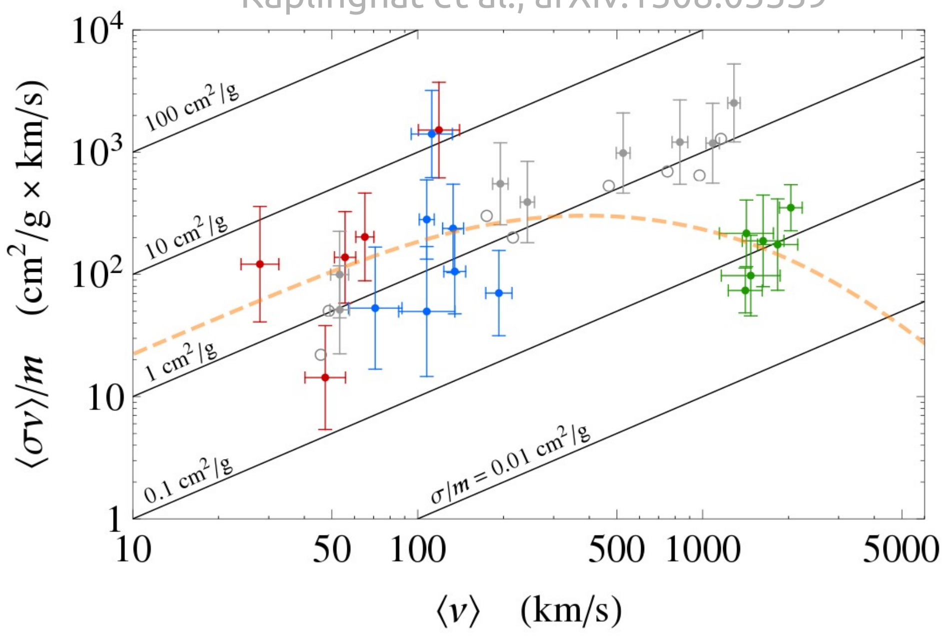
Velocity-dependent self-interactions

Feng, Kaplinghat, Yu: arXiv:0905.3039; Buckley & Fox: arXiv:0911.3898; Loeb & Weiner: arXiv:1011.6374

Velocity dependent self-interactions

- Aim: Large DM self- interaction rates on dwarf galaxy scales consistent with bounds from galaxy clusters.
- DM self-interactions need to depend on the typical relative velocity of DM particles.

Kaplinghat et al., arXiv:1508.03339

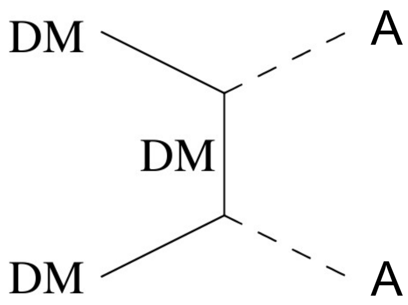


- Consider a mediator with mass $m_{\text{med}} \sim m_{\text{DM}}\, v_{\text{DM}}$:
  - Scattering for small momentum transfer ($q < m_{\text{med}}$) proportional to $1/m_{\text{med}}^4$
  - Scattering for large momentum transfer ($q > m_{\text{med}}$) proportional to $1/q^4$

A new light mediator

- Such new light mediators arise naturally, e.g. if the stability of DM arises from a charge under a new spontaneously broken U(1)' gauge group.

- Interesting feature: The relic abundance is typically set by annihilations into pairs of mediators (so-called dark sector freeze-out):



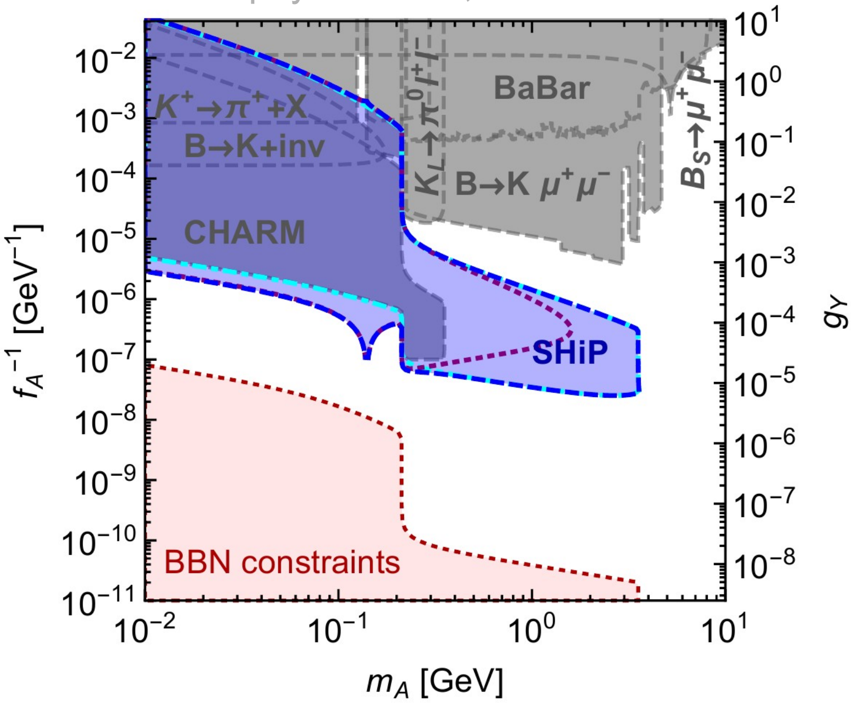
$$\Omega_\psi h^2 = 0.119 \times \frac{\langle \sigma v \rangle_{\text{thermal}}}{\langle \sigma v \rangle}$$

- It is always possible to fix the coupling in the dark sector in such a way that the observed DM relic abundance is reproduced.

Constraints on new light mediators

- To avoid overclosing the Universe, the mediator should ultimately decay into SM states, so its couplings to SM states cannot be arbitrarily small.
- In fact, to avoid potential constraints from primordial nucleosynthesis, the mediator lifetime should be smaller than a few seconds.
- At the same time, beam dump experiments and rare decay measurements place an upper bound on the coupling of the new state to SM particles.

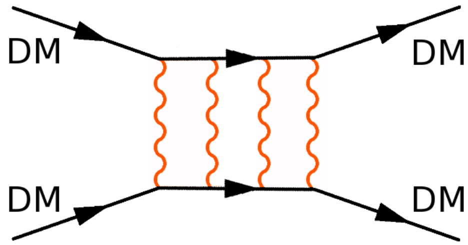
The SHiP physics case, arXiv:1504.04855



- Additional strong constraints from astrophysics (e.g. from horizontal branch stars and SN1987a) for small mediator masses.

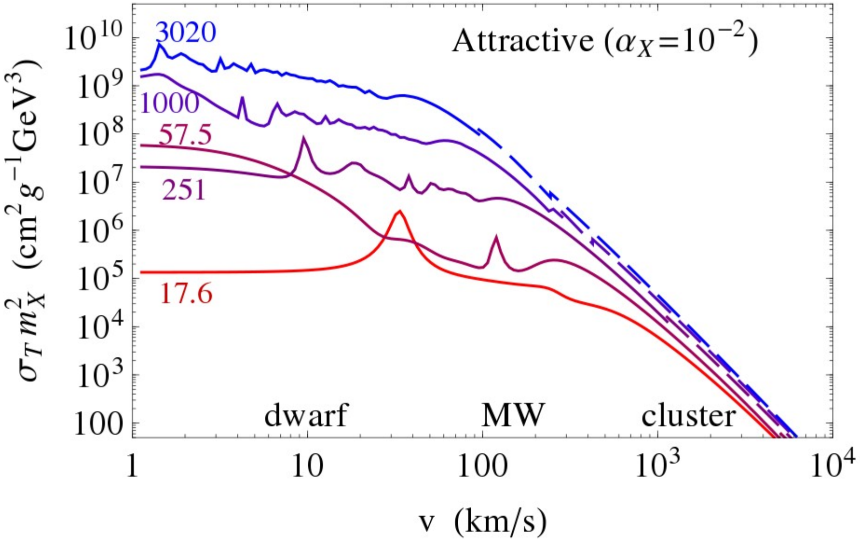
Enhancement of DM self-interactions

- DM self-interactions are not just enhanced by the small mediator mass, but also by non-perturbative effects due to multiple mediator exchange.



- These effects can be calculated by solving the non-relativistic Schroedinger equation for the potential induced by the mediator.

Tulin et al., arXiv:1302.3898



- In many relevant cases, mediator exchange gives rise to a Yukawa potential:

$$V_S(r) = \alpha_S \, e^{-m_\phi r}/r$$

- For $\alpha_S m_\psi \gtrsim m_\phi$ resonances appear and modify the results of the tree-level calculation.

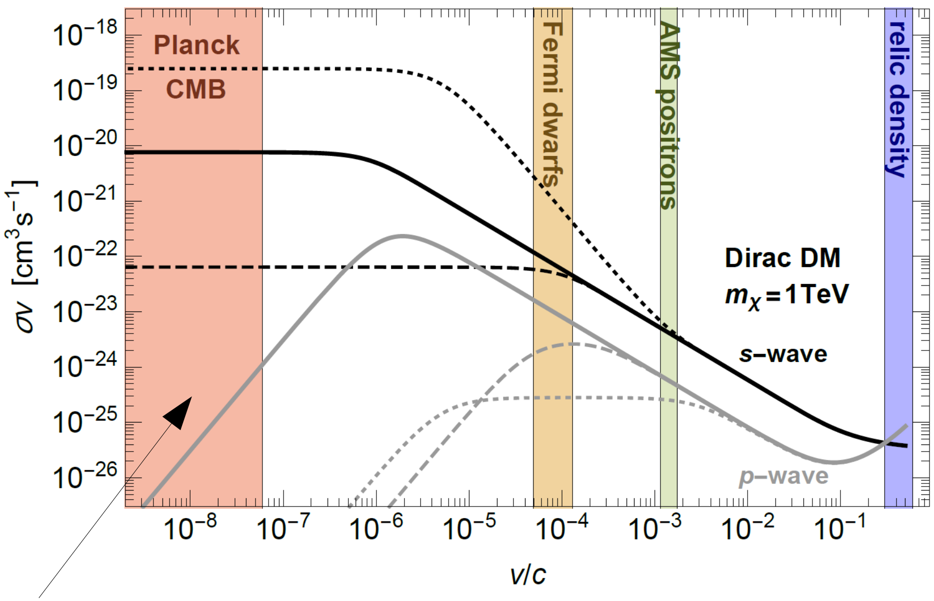
Enhancement of DM annihilations

- The Yukawa potential also modies the wave-function of the annihilating DM pair (so-called Sommerfeld enhancement).

- Signicant non-perturbative corrections to the tree-level annihilation rate.

- Effects small during freeze-out, but increase with decreasing DM velocity.

Bringmann, FK et al., arXiv:1612.00845



During recombination dark matter particles move at walking speed.

CMB constraints on self-interacting DM

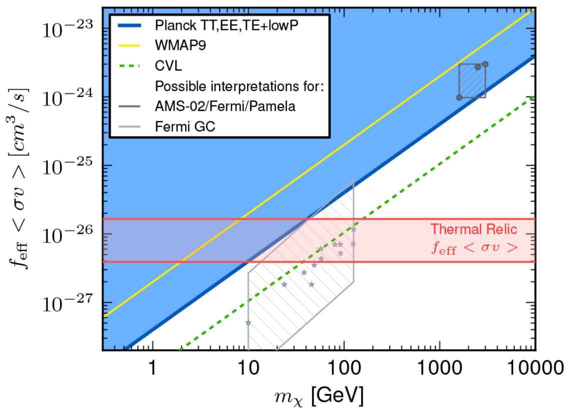
- DM annihilations during recombination, followed by mediator decays into SM particles, inject energetic electrons and photons into the plasma.

- These energetic particles can re-ionize neutral atoms and thereby spoil the excellent agreement between predictions and measurements of the CMB.

- Recent Planck measurements imply

$$\frac{\langle\sigma v\rangle_{\rm rec}}{N_\chi} \lesssim 4\times 10^{-25}\,{\rm cm}^3\,{\rm s}^{-1}\left(\frac{f_{\rm eff}}{0.1}\right)^{-1}\left(\frac{m_\chi}{100\,{\rm GeV}}\right)$$

Planck Collaboration, arXiv:1502.01589



- where the efficiency factor $f_{\rm eff}$ depends slightly on the mediator decay mode.

- Without Sommerfeld enhancement $\langle\sigma v\rangle_{\rm rec} \sim 3 \times 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$, so one can typically exclude $m_\chi < 10$ GeV.

- With Sommerfeld enhancement $\langle\sigma v\rangle_{\rm rec}$ can be much larger and hence one can potentially probe much larger DM masses.

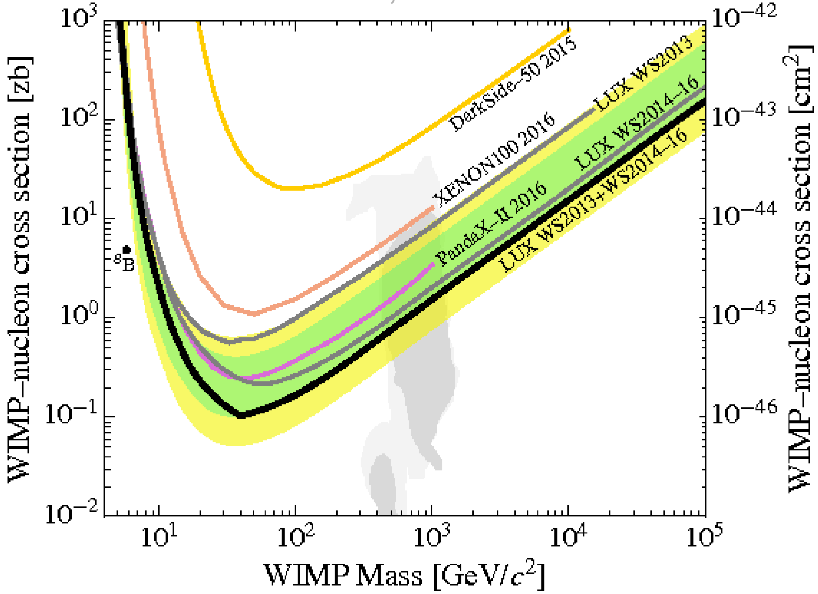
Direct detection constraints

- The DM-nucleon scattering cross section is strongly enhanced for light mediators

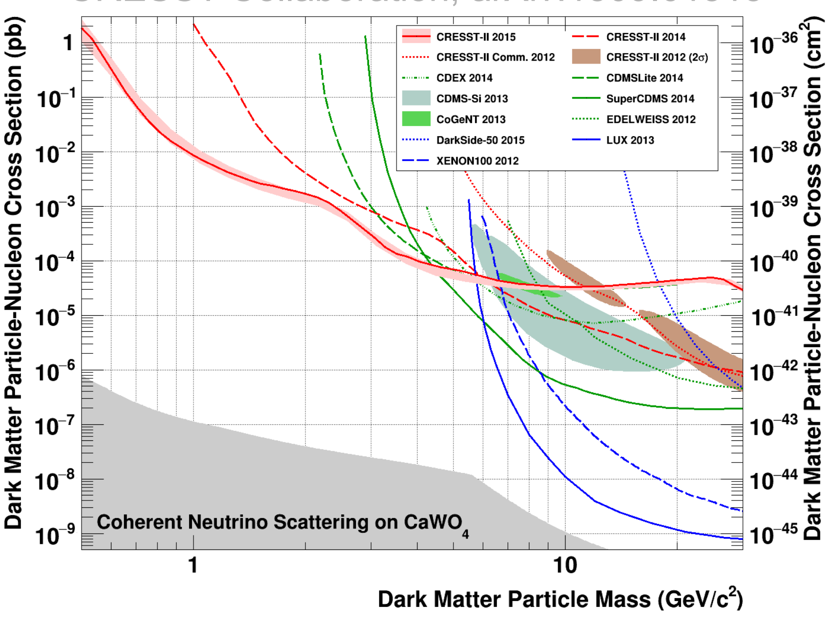
$$\sigma_N = \frac{f_N^2\, m_N^2\, \mu_{\chi N}^2}{\pi\, v^2} \frac{y_\psi^2\, y_{\rm SM}^2\, \cos^2\delta_\psi\, \cos^2\delta_{\rm SM}}{(m_\phi^2 + q^2)^2}$$

- We can expect a number of relevant constraints from direct detection experiments!

LUX Collaboration, arXiv:1608.07648



CRESST Collaboration, arXiv:1509.01515



Mediator typology

- Possible options for a very light mediator:

Mediator	Spin	Parity	CP
Vector	1	–	–
Axialvector	1	+	–
Scalar	0	+	+
Pseudoscalar	0	–	–

Mediator typology

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- A very light axial-vector behaves like a combination of a vector mediator (transverse modes) and a pseudoscalar mediator (longitudinal mode).
- There can also be mixed states (e.g. scalar-pseudoscalar) that do not conserve CP.

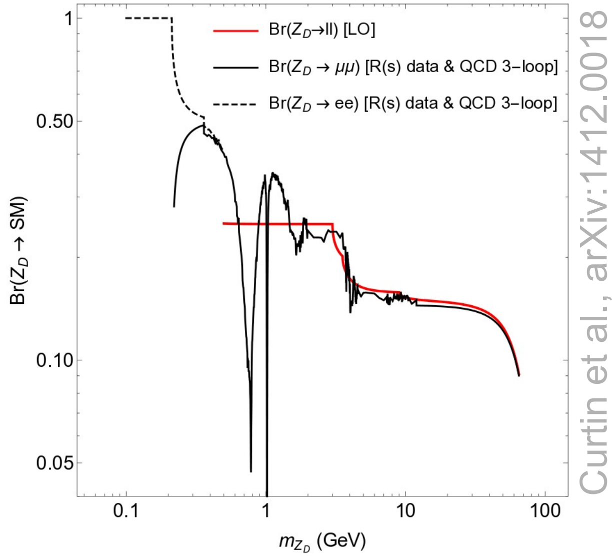
Vector mediators

- Example: A new gauge boson from a spontaneously broken U(1)' gauge group that mixes with the neutral gauge bosons of the Standard Model.

$$\mathcal{L} \supset -g_\chi^V \phi^\mu \bar{\chi}\gamma_\mu\chi - \frac{1}{2}\sin\epsilon\, B_{\mu\nu}\phi^{\mu\nu} - \delta m^2 \phi^\mu Z_\mu$$

Kinetic mixing:
Mediator obtains photon-like couplings

Mass mixing:
Mediator obtains Z-like couplings

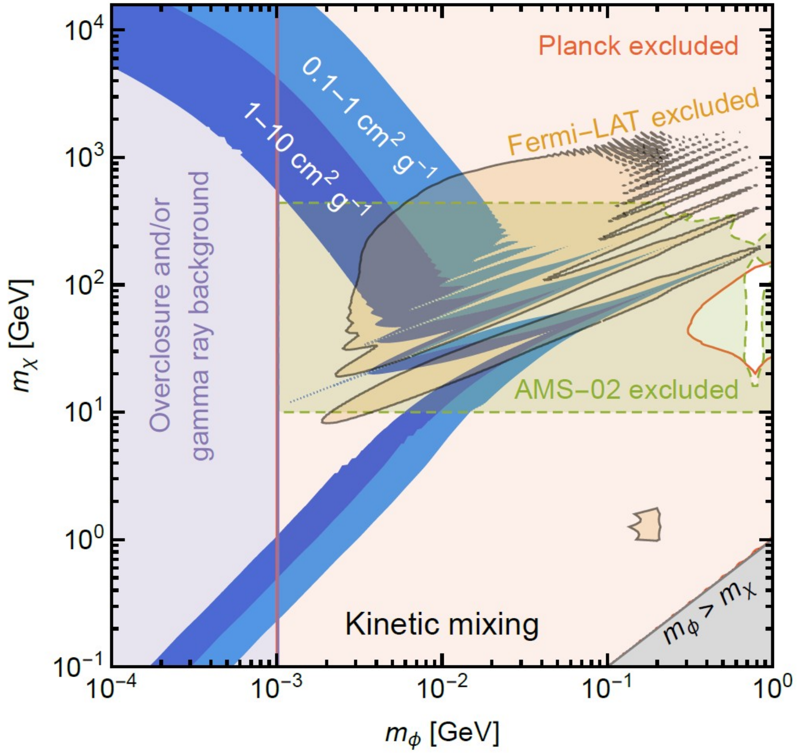


- Main difference:
  - A gauge boson with kinetic mixing is effectively stable below the electron threshold.
  - Mass mixing induces sizeable decay rates into neutrinos

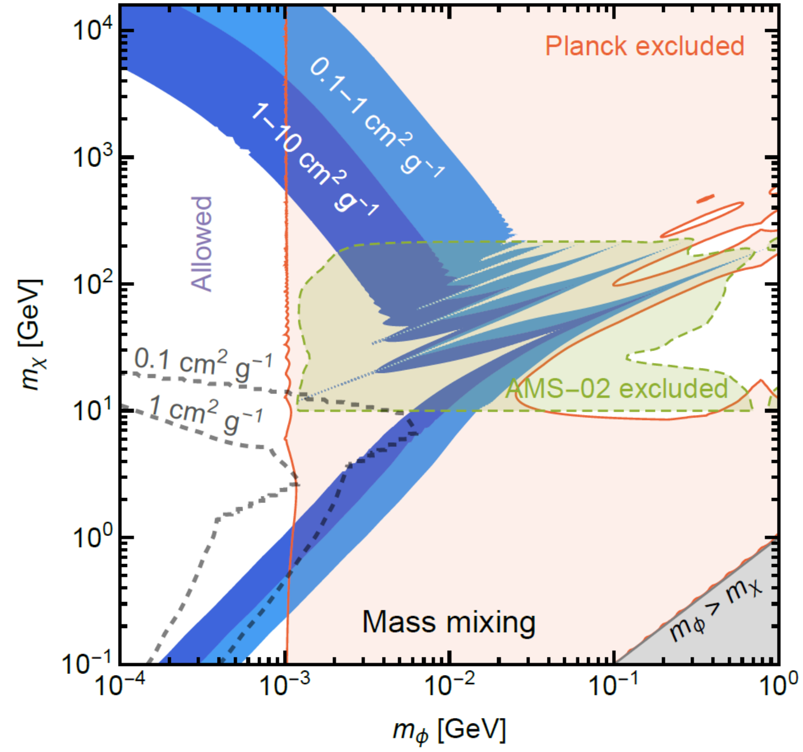
Constraints on vector mediators

- For vector mediators, DM annihilation proceeds via s-wave:
  - Large Sommerfeld enhancement for small velocities
  - Strong constraints from indirect detection and CMB measurements

Bringmann, FK et al., arXiv:1612.00845



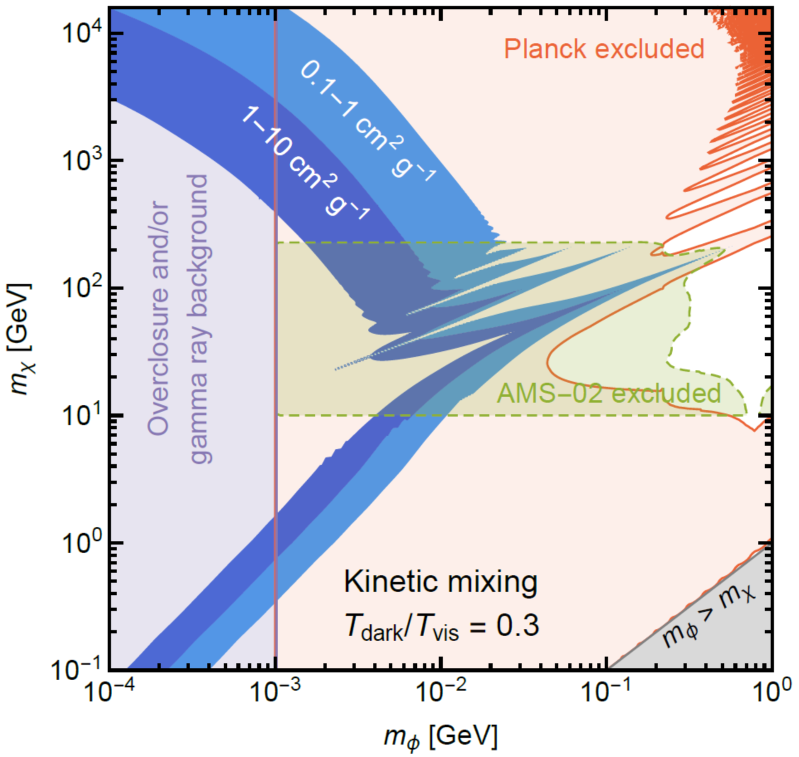
Bringmann, FK et al., arXiv:1612.00845



Constraints on vector mediators

- Indirect constraints on vector mediators are very strong!
- Allowed parameter space if the mediator decays only into neutrinos.
- Constraints are essentially independent of the mixing between the mediator and the SM.
- Only assumption: The two sectors are in thermal equilibrium in the early Universe.
- But even for different temperatures in the two sectors, we find strong constraints.

Bringmann, FK et al., arXiv:1612.00845



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Scalar mediators

- Example: A real scalar singlet that obtains a vacuum expectation value and mixes with the SM Higgs boson.

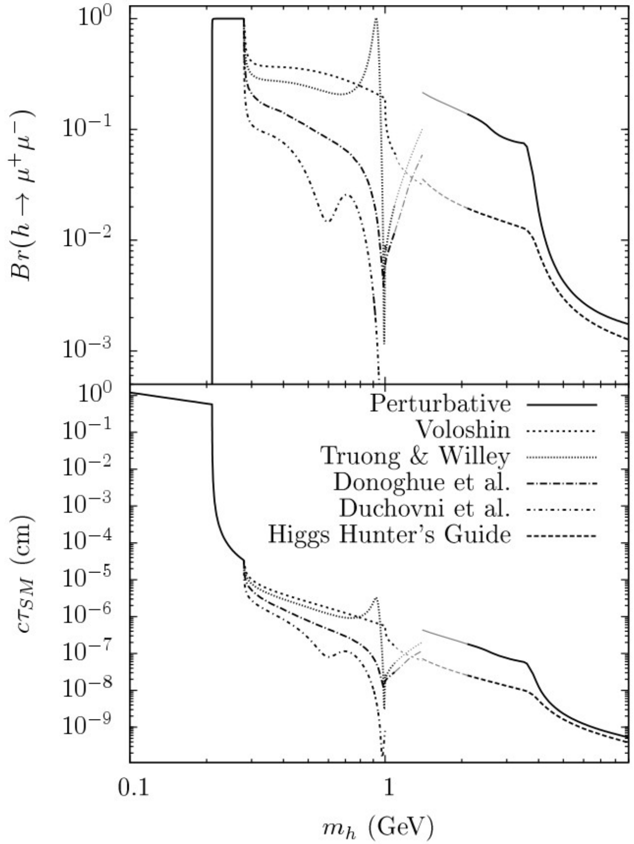
- This mixing induces couplings to SM fermions consistent with minimal flavour violation:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{g_y \, m_f}{v} \phi \bar{f} f \; - \frac{1}{2} \kappa \phi \bar{\chi} \chi$$

- Branching ratios in the GeV region are difficult to calculate due to hadronic resonances

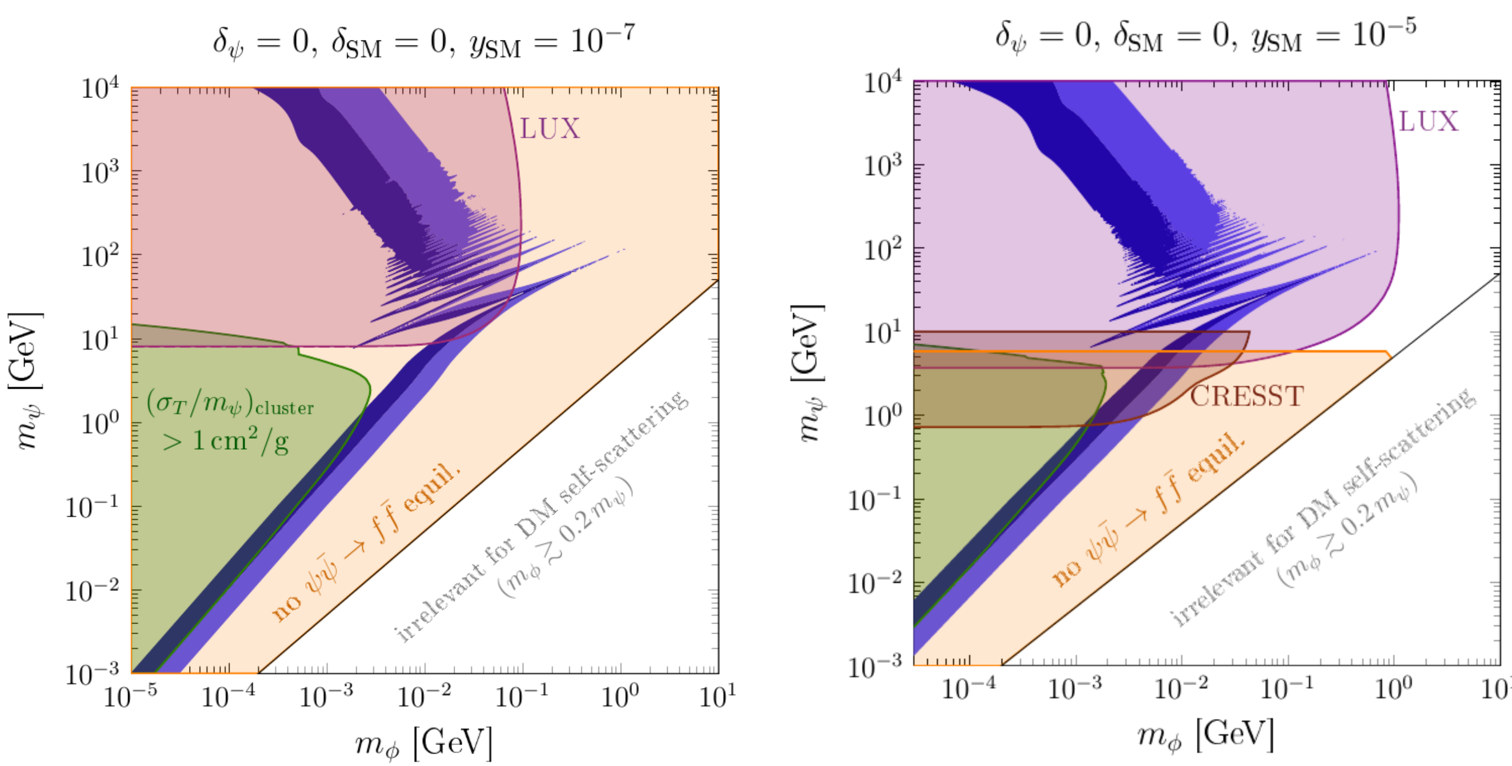
- Below the pion threshold the leptonic and photonic decay modes are well understood .

Clarke et al., arXiv:1310.8042



Constraints on scalar mediators

- For fermionic DM and scalar mediators annihilation proceeds via p-wave (due to CP conservation).
- No constraints from indirect detection or the CMB.
- Direct detection constraints are very strong for scalar mediators.

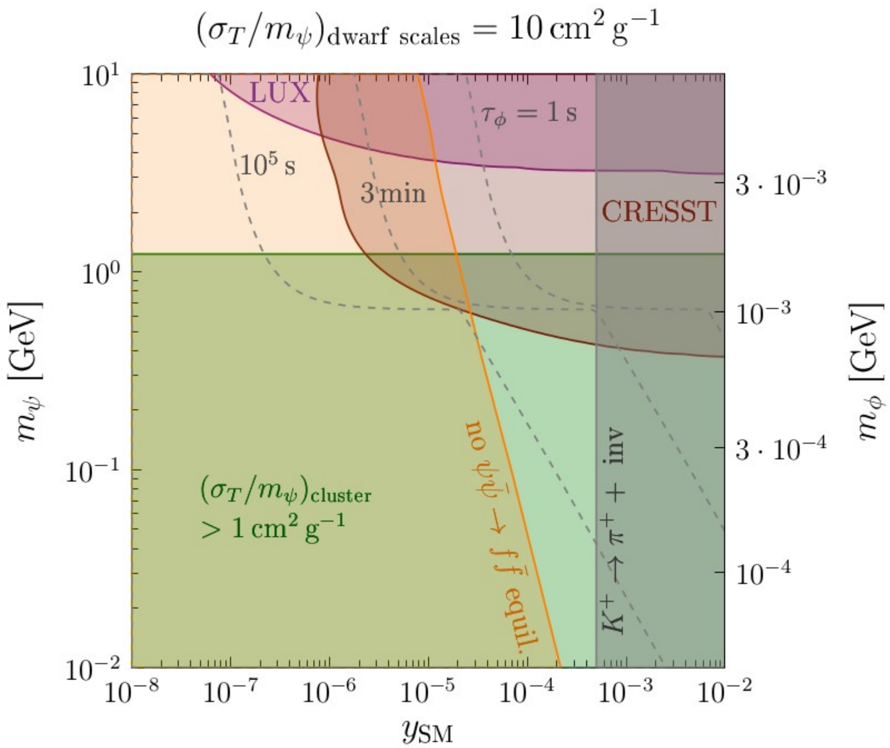


FK, Schmidt-Hoberg, Wild, in preparation

Constraints on scalar mediators

- Direct detection constraints can be suppressed if the mediator couples very weakly to the SM.
- If the couplings become very small, two new problems arise:
  - The mediator can no longer bring the dark sector in thermal contact with the visible sector.
  - The mediator obtains a lifetime τ > 1 s, so that it typically decays during or after BBN.
- Impossible to satisfy all requirements and have large self-interaction cross sections.

FK, Schmidt-Hoberg, Wild, in preparation

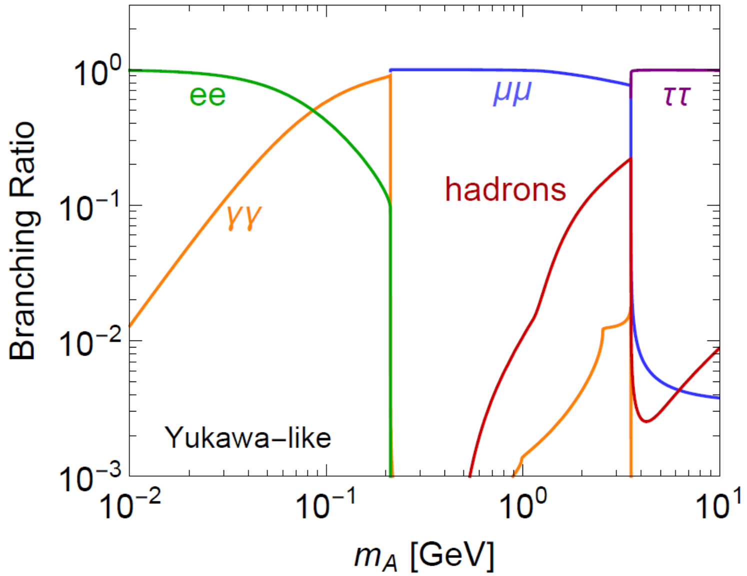


Pseudoscalar mediators

- Example: An axion-like particle that obtains its couplings to SM quarks for example via mixing with a second Higgs doublet.

$$\mathcal{L}_{\text{DM}} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi \qquad \mathcal{L}_{\text{SM}}^{(Y)} = i\, g_Y \sum_{f=q,\ell} \frac{\sqrt{2}\, m_f}{v} A\, \bar{f}\gamma^5 f$$

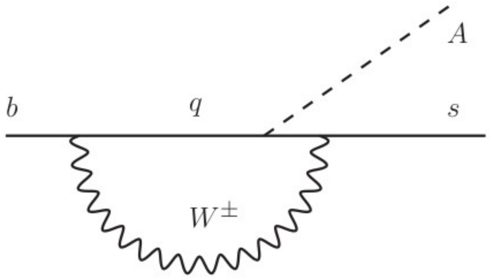
Dolan, FK et al., arXiv:1412.5174



Pseudoscalar mediators

- In the non-relativistic limit, scattering via the exchange of pseudoscalar mediators is strongly suppressed by powers of the momentum transfer.
- Direct detection constraints are therefore effectively absent.
- Strongest bounds come from direct searches for light pseudoscalars.

Dolan, FK et al., arXiv:1412.5174



- The same effect suppresses DM self-scattering.
- It is impossible to obtain large self-interaction cross sections from pseudoscalar exchange.
- This conclusion still holds when including loop-induced processes and Sommerfeld enhancement.

Summary (so far)

- Possible options for a very light mediator:

Mediator	Spin	Parity	CP	Phenomenology
Vector	1	–	–	Strong constraints from indirect detection and CMB
Scalar	0	+	+	Strong constraints from direct detection
Pseudoscalar	0	–	–	No sizeable self-interactions

A mediator with CP violation

- Let's assume that CP is not a good symmetry of the DM interactions

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Vector	1	–	–	Strong constraints from indirect detection and CMB
Scalar	0	+	+	Strong constraints from direct detection
Pseudoscalar	0	–	–	No sizeable self-interactions
Mixed state	0	?	?	?

$$\mathcal{L}_{\rm DM} \supset y_\psi \cos\delta_\psi \; \bar\psi\psi\phi + y_\psi \sin\delta_\psi \; i\bar\psi\gamma^5\psi\phi$$

$$\mathcal{L}_{\rm mixing} = y_{\rm SM} \sum_f \left[\frac{m_f}{v} \cos\delta_{\rm SM} \; \bar f f \phi + i\frac{m_f}{v} \sin\delta_{\rm SM} \; \bar f \gamma^5 f \phi\right]$$

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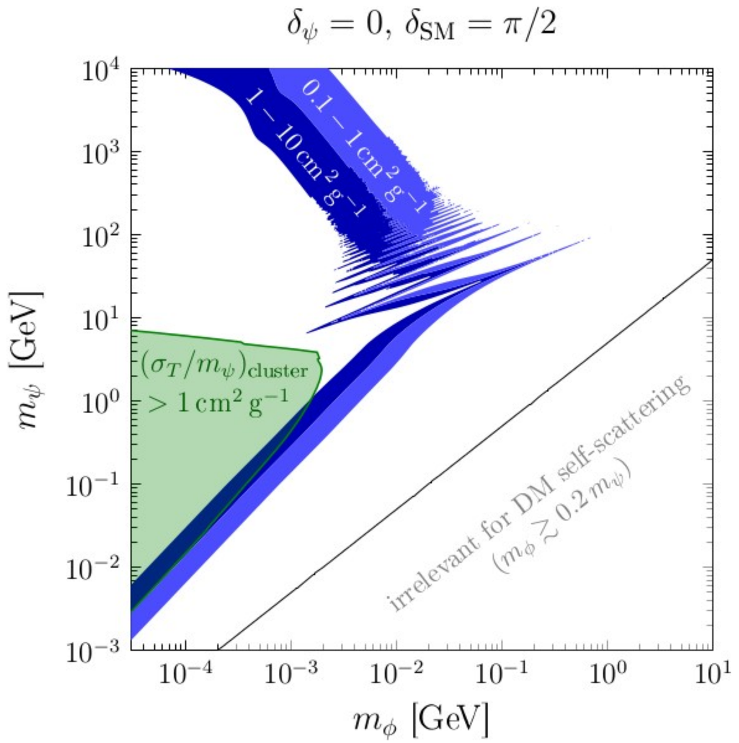
The key idea

- For $\delta_\psi \sim 0$ (like a scalar) DM self-interactions can be large.
- For $\delta_{SM} \sim \pi/2$ (like a pseudoscalar) direct detection constraints are strongly suppressed.
- Sizeable differences between δ_ψ and δ_{SM} can arise for example in models with spontaneous CP violation in the dark sector.
- Large allowed parameter space!

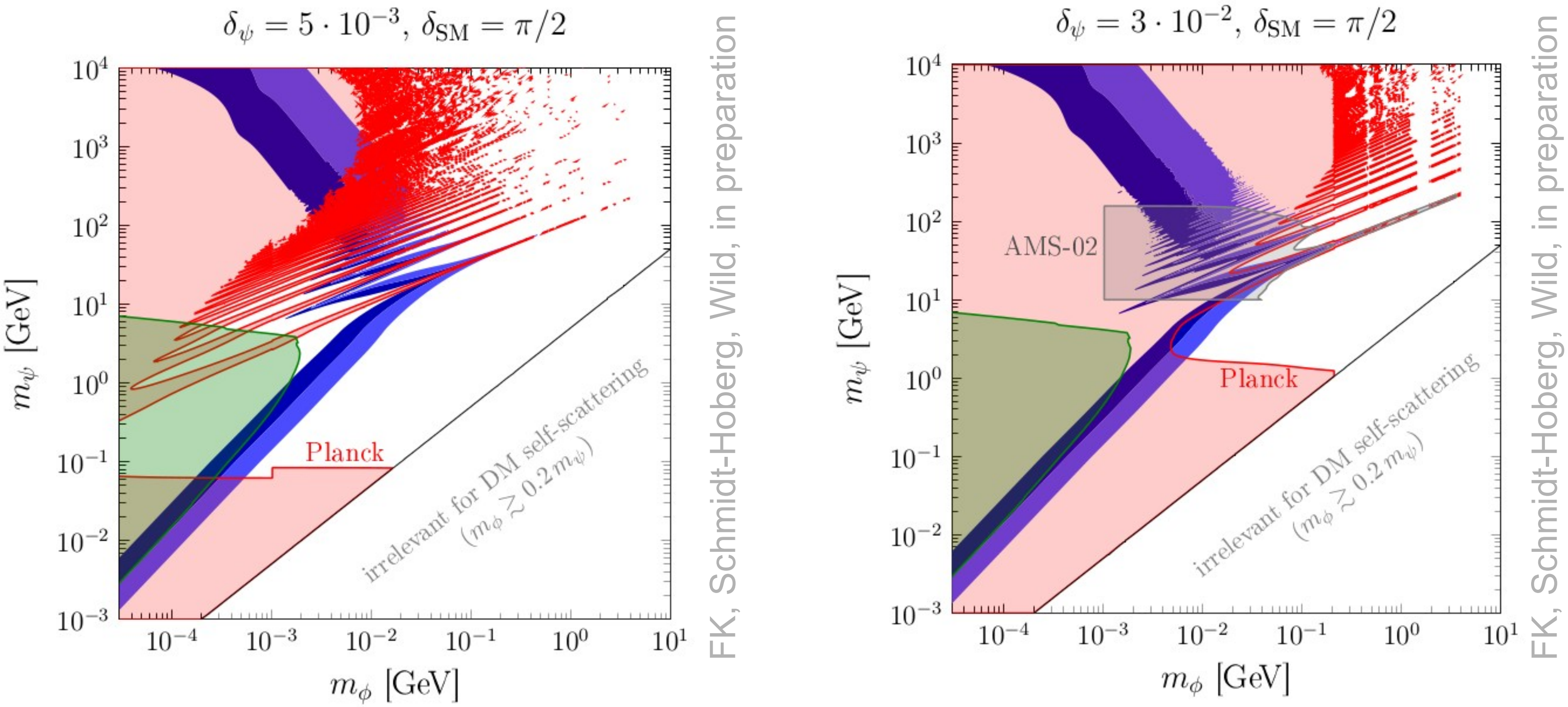


- Constraints on the CP-violating phase δ_{SM} (e.g. from electron EDMs) can be satisfied even for very light mediators as long as y_{SM} is sufficiently small ($y_{SM} \ll 10^{-2}$).

FK, Schmidt-Hoberg, Wild, in preparation

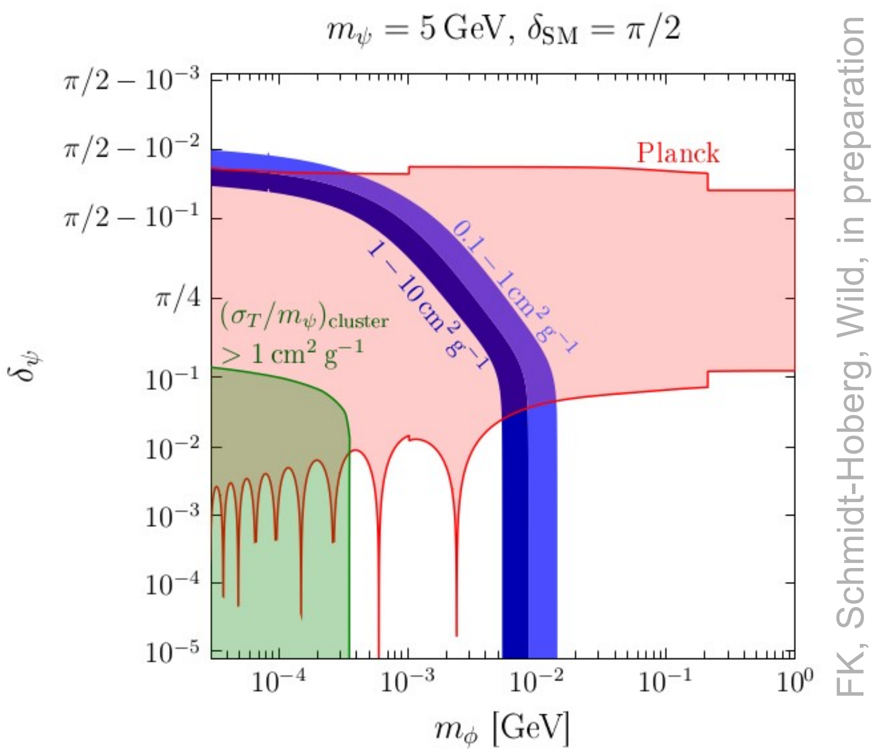
The return of CMB constraints

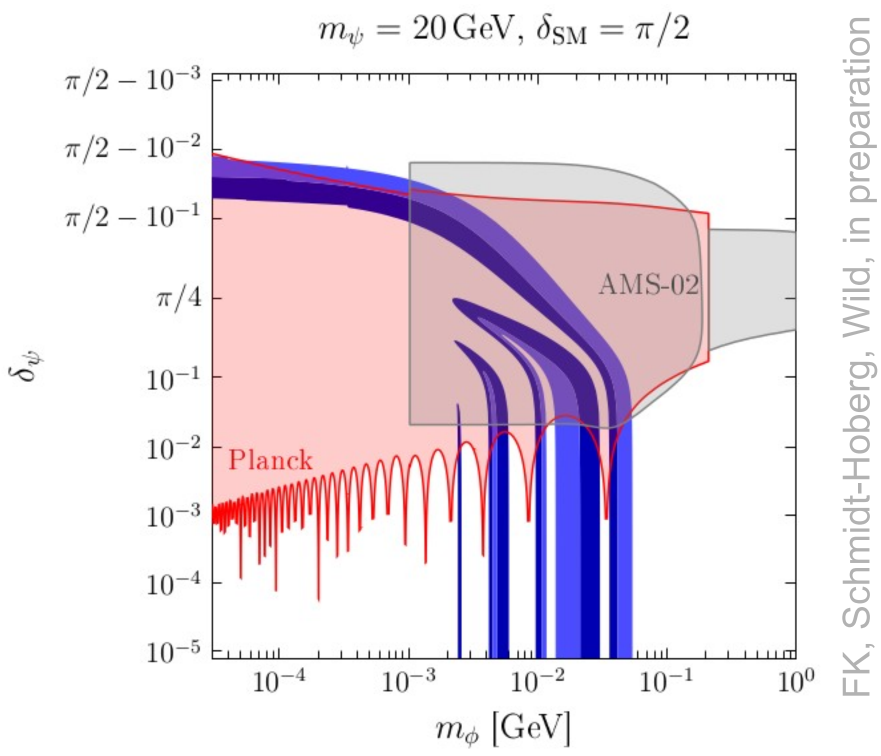
- Central problem: The fact that annihilation can only proceed via p-wave was a consequence of CP conservation.
- As soon as δ_ψ is not exactly zero, s-wave annihilation is again possible and will receive huge Sommerfeld enhancement.



How much tuning is required?

- To obtain large self-interaction cross sections and evade CMB constraints, we typically require $\delta_\psi < 10^{-1}$.





- A second solution with $\delta_\psi > \pi/2 - 10^{-2}$ is also marginally allowed.

Summary

Mediator	Spin	Parity	CP	Phenomenology
Vector	1	–	–	Strong constraints from indirect detection and CMB
Scalar	0	+	+	Strong constraints from direct detection
Pseudoscalar	0	–	–	No sizeable self-interactions
Mixed state	0	?	?	Large self-interactions possible for appropriately tuned CP phases

Future directions for light mediators

- There are a number of ways to evade the various constraints
  - Inert decays of the mediator, for example into (sterile) neutrinos
  - Thermalization via a different mechanism (possibly leading to different temperatures during freeze-out)
  - No thermalization (DM production via the freeze-in mechanism)

    Bernal et al., arXiv:1510.08063
  - Suppressed couplings to quarks (to evade direct detection constraints)
- Nevertheless, constraints from BBN and from the CMB are very generic and will generally be relevant to any model of DM interacting via a new light mediator.
- Exciting phenomenology and interesting model-building challenges!

Conclusions

- Astrophysical probes of dark matter self-interactions offer a promising new window for exploring the dark sector.
- To obtain large effects on small scales consistent with bounds from galaxy cluster scales, self-interactions must be velocity dependent.
- Dark matter interacting via the exchange of light mediators offers an attractive framework for obtaining dark matter with velocity-dependent self-interactions from thermal freeze-out.
- The simplest possibilities (scalar or vector mediator coupling to fermionic dark matter with no additional new states) are in strong tension with direct and indirect detection experiments.
- Out of the many interesting avenues for model-building, one particularly attractive idea is spontaneous CP violation in the dark sector, leading to different CP phases in the dark and visible sector.

Backup

Spontaneous CP violation

- Consider a fermionic DM particle coupled to a real pseudoscalar P:

$$\mathcal{L}_{\rm DM} = \bar{\psi}(i\partial\!\!\!/ - m_0)\psi - (i y_\psi P \bar{\psi}_L \psi_R + \text{h.c.}) - V(P)$$

- The pseudoscalar acquires a vev: $P = v_P + \phi$

$$\mathcal{L}_{\rm DM} = \bar{\psi}\left[i\partial\!\!\!/ - (m_0 + i y_\psi v_P \gamma^5)\right]\psi - (i y_\psi \phi \bar{\psi}_L \psi_R + \text{h.c.}) - V(\phi)$$

- Perform a chiral rotation: $\psi \to \exp(i\gamma^5 \alpha/2)\psi$

  with $\tan\alpha = y_\psi v_P / m_0$

$$\mathcal{L}_{\rm DM} = \bar{\psi}(\partial\!\!\!/ - m_\psi)\psi - y_\psi \phi \bar{\psi}(\cos\delta_\psi + i \sin\delta_\psi \gamma^5)\psi$$

Spontaneous CP violation

- SM fermions can obtain couplings to the pseudoscalar mediator for example via mixing with a second Higgs doublet:

$$\mathcal{L}_{\text{mixing}} \supset -\sin\theta \sum_f \frac{y_f}{\sqrt{2}} P \bar{f} \gamma^5 f$$

- The pseudoscalar vev then leads to complex fermion masses:

$$m_f = \frac{y_f}{\sqrt{2}} (v + i \sin\theta \, v_P)$$

- A chiral rotation with $\alpha_{\text{SM}} = \sin\theta \, v_P / v$ makes the masses real, but introduces CP-violating pnases:

$$\mathcal{L}_{\text{mixing}} = -y_{\text{SM}} \sum_f \frac{y_f}{\sqrt{2}} \phi \bar{f} (\sin\delta_{\text{SM}} + i \cos\delta_{\text{SM}} \gamma^5) f$$

- Crucially, since $\theta \ll 1$, one finds $\delta_{SM} = \pi/2 - \theta \, v_P / v \approx \pi/2$.