Hidden sectors in cosmology: Models, tools, and constraints

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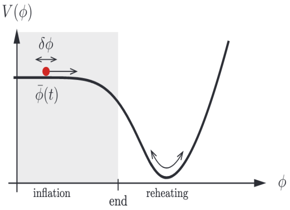
Strong and Electroweak Matter 2022

based on
arXiv:2105.06477 / arXiv:2203.02229
Published in Collaboration with Chiara Arina, Jan Hajer

Better Constraining Hidden Sectors in Cosmology

- Impact on early universe generically constrains hidden sectors:

Inflation



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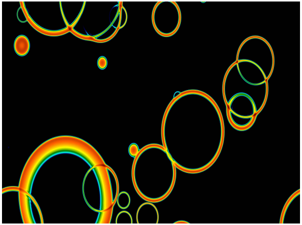
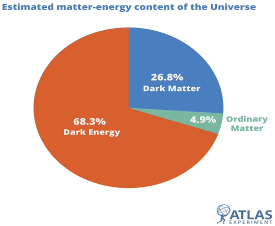
Phase Transitions



arXiv:1705.01783

Dark Matter/Radiation



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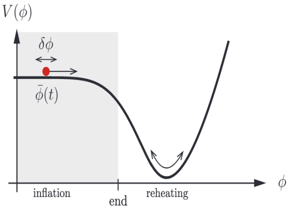

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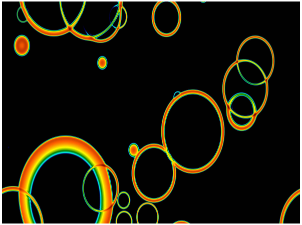

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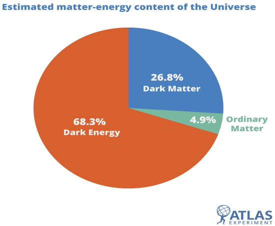

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- Translation into mass, coupling constraints often model-dependent
  $\Rightarrow$ Inflexible, work-intensive

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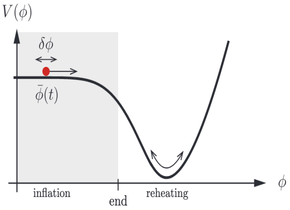

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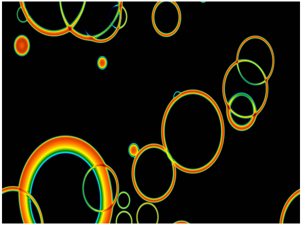

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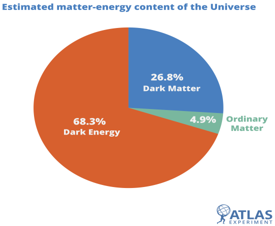

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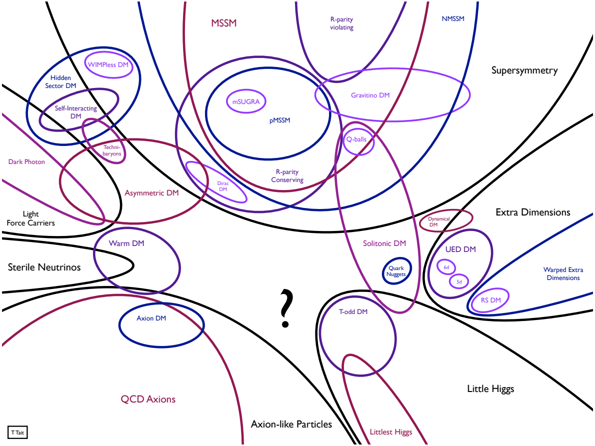
What can we do to be more model-independent?

Effective Field Theories: Good But Not Perferct

- EFTs fine for heavy new physics (NP)



Made by T. Tait, see arXiv:1401.6085

Effective Field Theories: Good But Not Perferct

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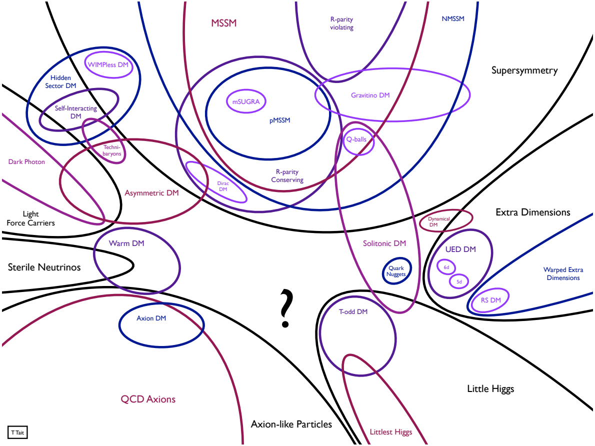
- EFTs, simplified models for light NP useful but simplistic



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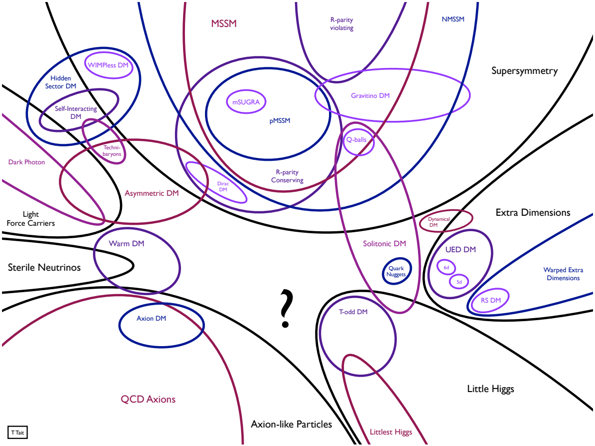
Effective Field Theories: Good But Not Perferct

- EFTs fine for heavy new physics (NP)
- EFTs, simplified models for light NP useful but simplistic
- Need more model-indep. tools for finite T, finite H, etc.



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Model-dependence enters in many ways

1. SM $\leftrightarrow$ hidden Interaction Rates
   - Exchanging energy, conserved charges with hidden sectors (e.g. Leptogenesis, Dark Matter production)
   - Equilibration between SM + hidden sectors
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Small Portal Couplings Ensure Factorization

See arXiv:2203.02229

- Most general SM extension:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{hidden}} + \epsilon \boldsymbol{A}_d \boldsymbol{B}^d$$

$\boldsymbol{A}_d$ = SM operator / $\boldsymbol{B}^d$ = hidden operator / ϵ = coupling / $d \geq 4$ allowed

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$$\Gamma\left(\text{SM} \to \text{SM'} + \text{hidden}\right) \propto \epsilon^2 \boldsymbol{M}_d \boldsymbol{M}_e^\dagger \boldsymbol{J}^{de} + \mathcal{O}\left(\epsilon^3\right) \quad \boldsymbol{J}^{de} = \underset{\substack{\uparrow \\ \text{Indistinguishable final states}}}{\sum} \boldsymbol{J}^d \boldsymbol{J}^{e\dagger}$$

$\boldsymbol{M}$ = reduced matrix elements (SM only, model-independent)

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2. With portal EFTs: Model-independent constraints

Portal Effective Theory Framework

See arXiv:2105.06477

SM and heavy NP

EFT fields and symmetries

SMEFT, HEFT, LEFT,
NRQCD, HQET, χPT, ...

Hidden sector with light NP

Messenger fields

$0 \;,\; 1/2 \;,\; 1 \;,\; 3/2 \;,\; 2$
$s_i \;,\; \xi_j \;,\; v_k^\mu \;,\; \xi_l^\mu \;,\; t_m^{\mu\nu}$

Secluded fields

Additional fields not directly
interacting with the SM

SM operators

O_n^{SM}

Portal operators

$O_{nm}^{\text{portal}} = O_n^{\text{SM}} O_m^{\text{hidden}}$

Hidden operators

O_m^{hidden}

Portal currents

$J_n^{\text{portal}} = \sum_m O_{nm}^{\text{portal}}$

PET framework

- We constructed Portal SMEFTs, LEFTs, and ChPTs with all leading flavour conserving, violating operators

Example computation: $K^+ \to \ell^+ +$ hidden Decays

- Relevant portal interactions (see arXiv:2105.06477):

$$\mathcal{L}_{\text{portal}} \supset \underbrace{v\ \nu\, \boldsymbol{B}_\nu + \frac{V_{\text{us}}}{v^2}(s^\dagger \overline{\sigma}_\mu u)(\boldsymbol{B}_\ell^\dagger \overline{\sigma}^\mu \ell)}_{n=2 \text{ portal operators}} \quad \Rightarrow$$

Two portal vertices (Missing mass q^2)

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- Compute M_ℓ / M_ν $\Rightarrow$ Master decay rate:

$$\frac{\mathrm{d}}{\mathrm{d}x_q} \frac{\Gamma\left(K^+ \to \ell^+ + \text{NP}\right)}{\Gamma\left(K^+ \to \ell^+ + \nu\right)} = \frac{\rho(x_q)}{\rho(0)} \underbrace{\frac{1}{2\pi x_q} \text{tr}_D \left\{ \not{q} \boldsymbol{J}^{\ell\ell} - 2\,\text{Re}\, v\, \boldsymbol{J}^{\ell\nu} + \frac{\not{q}}{q^2} v^2 \boldsymbol{J}^{\nu\nu} \right\}}_{= \frac{F(x_q)}{2\pi}}$$

$\rho(x_q)$ is phase-space factor

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Use constraints on $F(x_q)$ to compare and contrast different models!

Application to cosmology: Freeze-in processes

Hidden Particle Production via decay of SM particle:

$$\dot{e}_h + 3H(e_h + p_h) = \left\langle \frac{1}{\gamma} \right\rangle n_{\mathrm{SM}} \times \int_0^m \mathrm{d}q_0 \, \frac{\mathrm{d}\Gamma\left(\mathrm{SM} \to \mathrm{SM'} + \mathrm{NP}\right)}{\mathrm{d}q_0}$$

$\gamma = k_0/m_{\mathrm{SM}}$ gamma factor / n_{SM} SM particle number density / Γ factorizes

Two caveats:

- Have to fix hidden sector equation of state (coupling to gravity) $\Rightarrow$ Further model dependence
- Hidden particle decay, inverse decay, scattering processes often important as well

More work needed!

Summary and Outlook

- Many hidden sectors can impact cosmology, but deriving model-independent constraints is challenging

- Hidden Particle Production Rates Factorize:

$$\Gamma\left(\mathrm{SM} \to \mathrm{SM'} + \mathrm{hidden}\right) \propto \epsilon^2 \boldsymbol{M}_d \boldsymbol{M}_e^\dagger \boldsymbol{J}^{de} + \mathcal{O}\left(\epsilon^3\right)$$

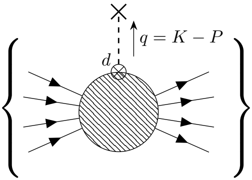
  - Simplifies adapting rates to new models, observables
  - Simplifies joining cosmology to experiment
  - With portal EFTs: Model independent constraints

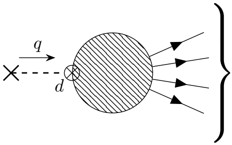
Future work

- Factorizing inverse decay / scattering / finite temperature rates
- Compute cosmology observables in terms of factorized rates, equations of state, etc.

Thank you for your attention!

M_d, J^d are standard Feynman diagram sums

$\mathrm{i}\,M_d = \mathcal{K}$  $\mathcal{P}$

$\mathrm{i}\,J_d =$  $\mathcal{Q}$

Re-interpreting a prior HNL search (see arXiv:2005.09575)

General form factor structure:

$$\frac{F(x)}{2\pi} = \sum_i A_i \delta(x - x_i) + B \qquad\qquad x_i = \frac{m_i^2}{m_K^2}$$

Resulting bounds:

$$\rho(x_e, x_i) A_i \lesssim 7 \cdot 10^{-11} \qquad\qquad \rho(x_e, x_q) B(x_q) \lesssim 2 \cdot 10^{-4}$$

HNL Hidden Currents

$$\boldsymbol{B}_d = \sum_i c_{di}\xi_i \qquad\qquad d = \nu, \ell$$

$$J^{\nu\nu}_{\dot\beta\alpha} = \sum_i \frac{c^\dagger_{\nu i} c_{\nu i}}{2\omega_i} (q_i^\mu \overline{\sigma}_\mu)_{\dot\beta\alpha} 2\pi\delta(q_0 - \omega_i)$$

$$J^{\ell\nu}_{\beta\alpha} = \sum_i \frac{c^\dagger_{\ell i} c_{\nu i}}{2\omega_i} m_i \epsilon_{\beta\alpha} 2\pi\delta(q_0 - \omega_i)$$

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$$\frac{F_\ell(x_q)}{2\pi} = \sum_i U_i^2 \Theta(q_0)\delta(x_q^2 - x_i^2) \qquad x_i = \frac{m_i^2}{m_K^2} \qquad U_i^2 = \left| c_{\ell i} - \frac{v c_{\nu i}}{m_i} \right|^2$$

Strong Scale PETs: $d = 6, 7$ and $|\Delta F| = 1$ Portal Operators

	d	Two quarks	Quark dipole	Four fermions
s_i	6	$s_i s_j s_k\, \overline{d} d$ $\partial^2 s_i\, \overline{d} d$ $s_i \partial_\mu s_j\, d^\dagger \overline{\sigma}^\mu d$	$s_i\, F^{\mu\nu} \overline{d} \sigma_{\mu\nu} d$ $s_i\, G^{\mu\nu} \overline{d} \sigma_{\mu\nu} d$	
	7	$s_i s_j s_k s_l\, \overline{d} d$		$s_i\, d^\dagger \overline{q}^\dagger \overline{q} d$ $s_i\, q^\dagger \overline{\sigma}^\mu q q^\dagger \overline{\sigma}_\mu q$ $s_i\, d^\dagger \overline{\sigma}^\mu d \overline{q} \sigma_\mu \overline{q}^\dagger$ $s_i\, e^\dagger \overline{\sigma}_\mu \nu u^\dagger \overline{\sigma}^\mu d$ $s_i\, \nu^\dagger \overline{\sigma}_\mu \nu d^\dagger \overline{\sigma}^\mu d$
ξ_a h.c.	6	$\xi_a^\dagger \overline{\sigma}_\mu\, e d^\dagger \overline{\sigma}^\mu u$ $\xi_a^\dagger \overline{\sigma}_\mu\, \nu d^\dagger \overline{\sigma}^\mu d$		