Search for scalar Dark Energy with ATLAS

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on behalf of the ATLAS collaboration

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The University of Iowa

OVERVIEW & MOTIVATION

What is DE

Cosmology

observations
isotropic CMB
+
assumptions
(cosm. principle)

Metric
(geometry of space-time)

General Relativity

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$T_{\mu\nu} = \mathrm{diag}(\rho, p, p, p)$$

Friedmann equations

matter governs evolution of space-time

Types of matter

- Radiation: p=ρ/3 ⇒ decelerating expansion
- (Baryonic/Dark) Matter: p=0 ⇒ (more slowly) decelerating expansion
- **"Dark Energy"**: p < -ρ/3 ⇒ **accelerating expansion**
    - Cosmological constant Λ: p=-ρ ⇒ exponentially accelerating expansion

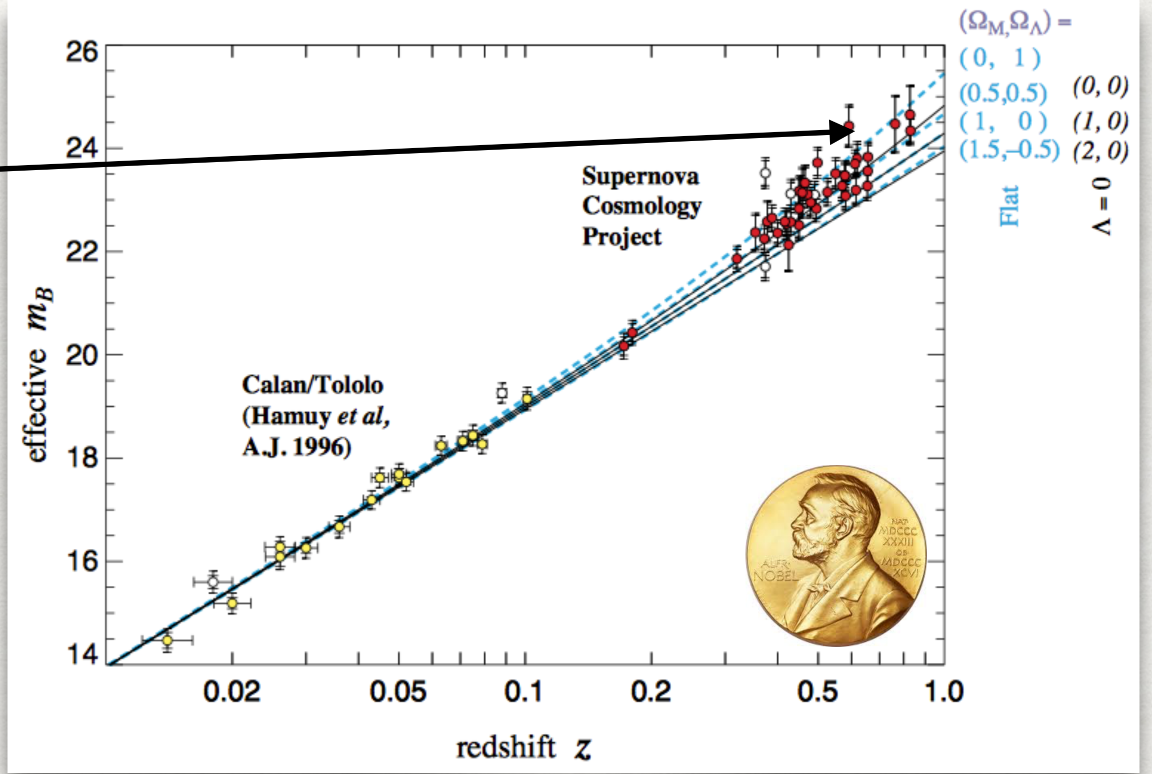
Particle Physics

- Cosmological constant = **vacuum energy density** (120 orders of magnitude off)
- Many **new BSM fields** can also reproduce eq. of state of Dark Energy

How we know it exists

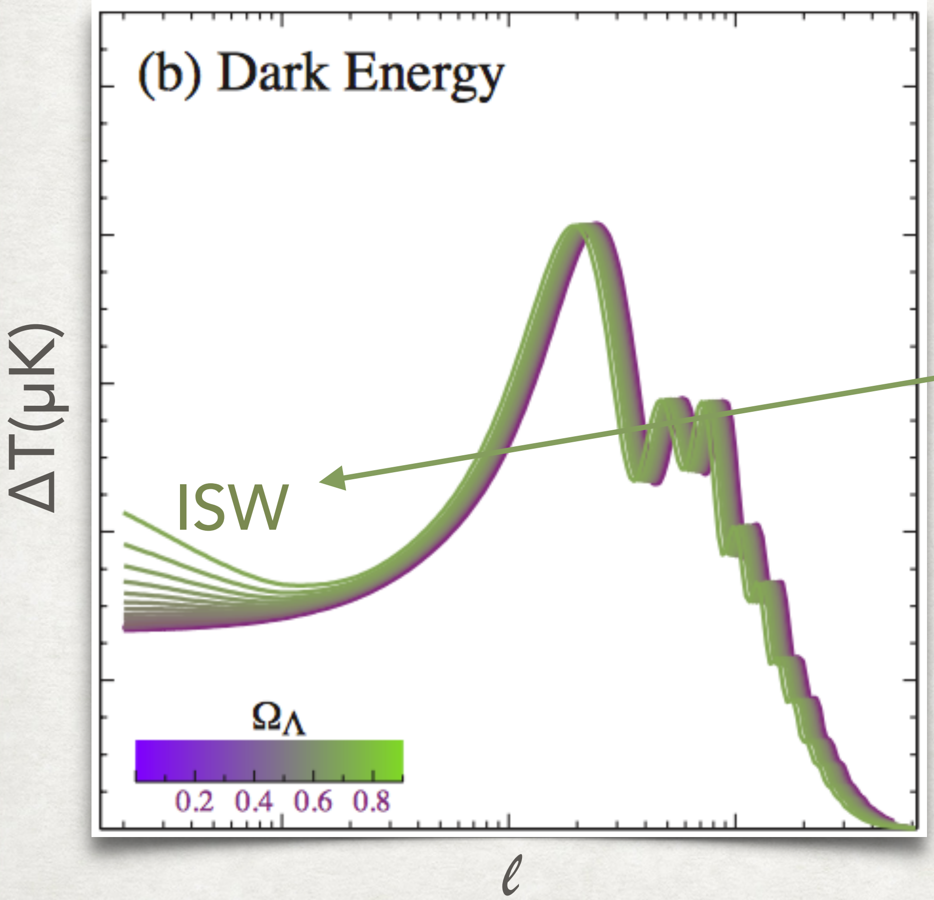
DE = higher distance at higher redshifts

- distance measurements
  - SN farther than expected
- age of globular clusters
  - without DE: $t_{universe} \sim 10$ Gyr while age oldest clusters >11 Gyr



Perlmutter et al, Astrophys.J.517:565-586,1999

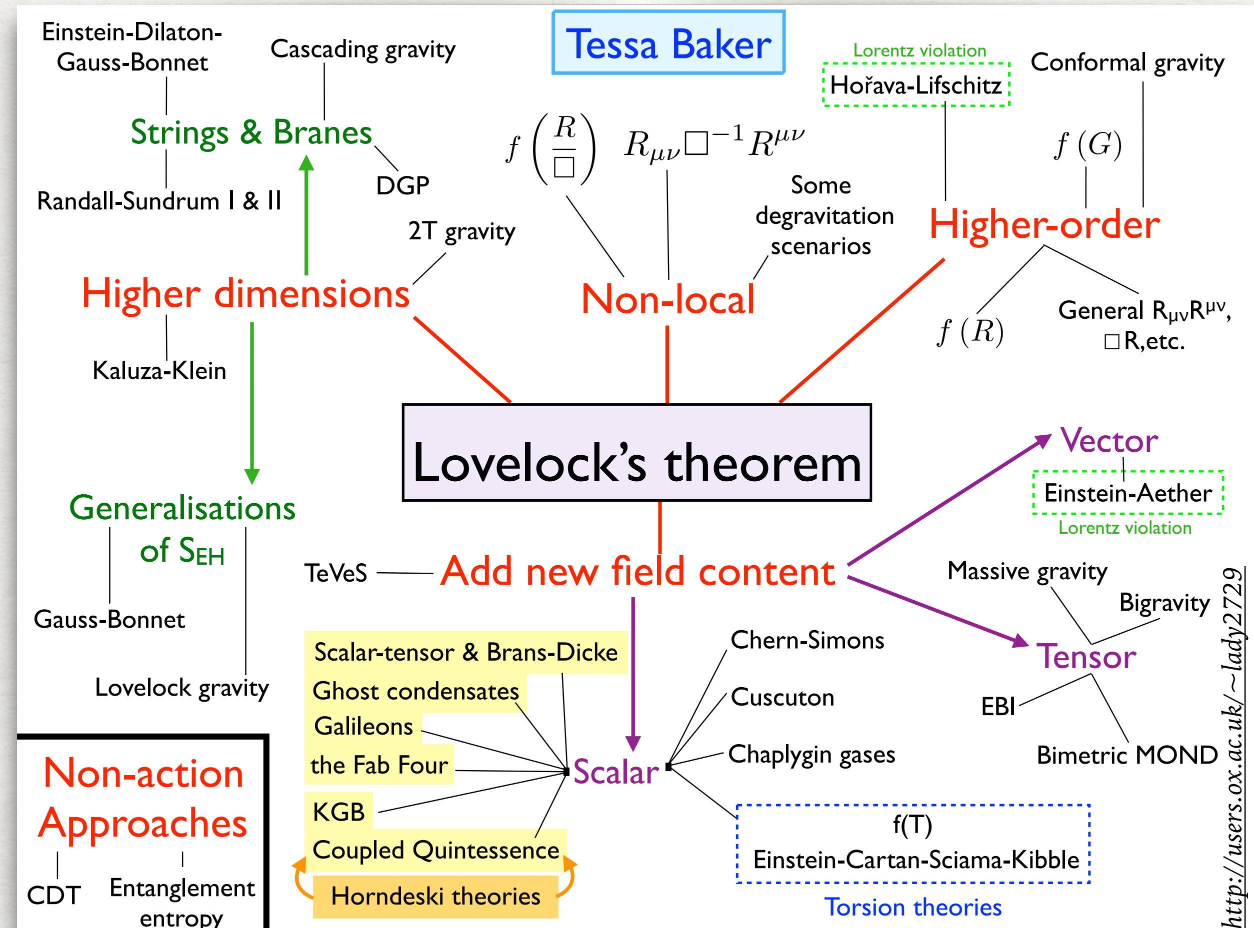
Effect of DE on CMB



- CMB radiation
  - position of acoustic peaks
  - late-time int. Sachs-Wolfe effect
- Baryon Acoustic Oscillations
  - angular distance vs redshift
- Large Scale Structure
  - structure formation slows down

Hu, Dodeldson, Ann.Rev.Astron.Astrophys.40:171-216,2002

Theory & experiment landscape



Slide by T. Baker

Laboratory:

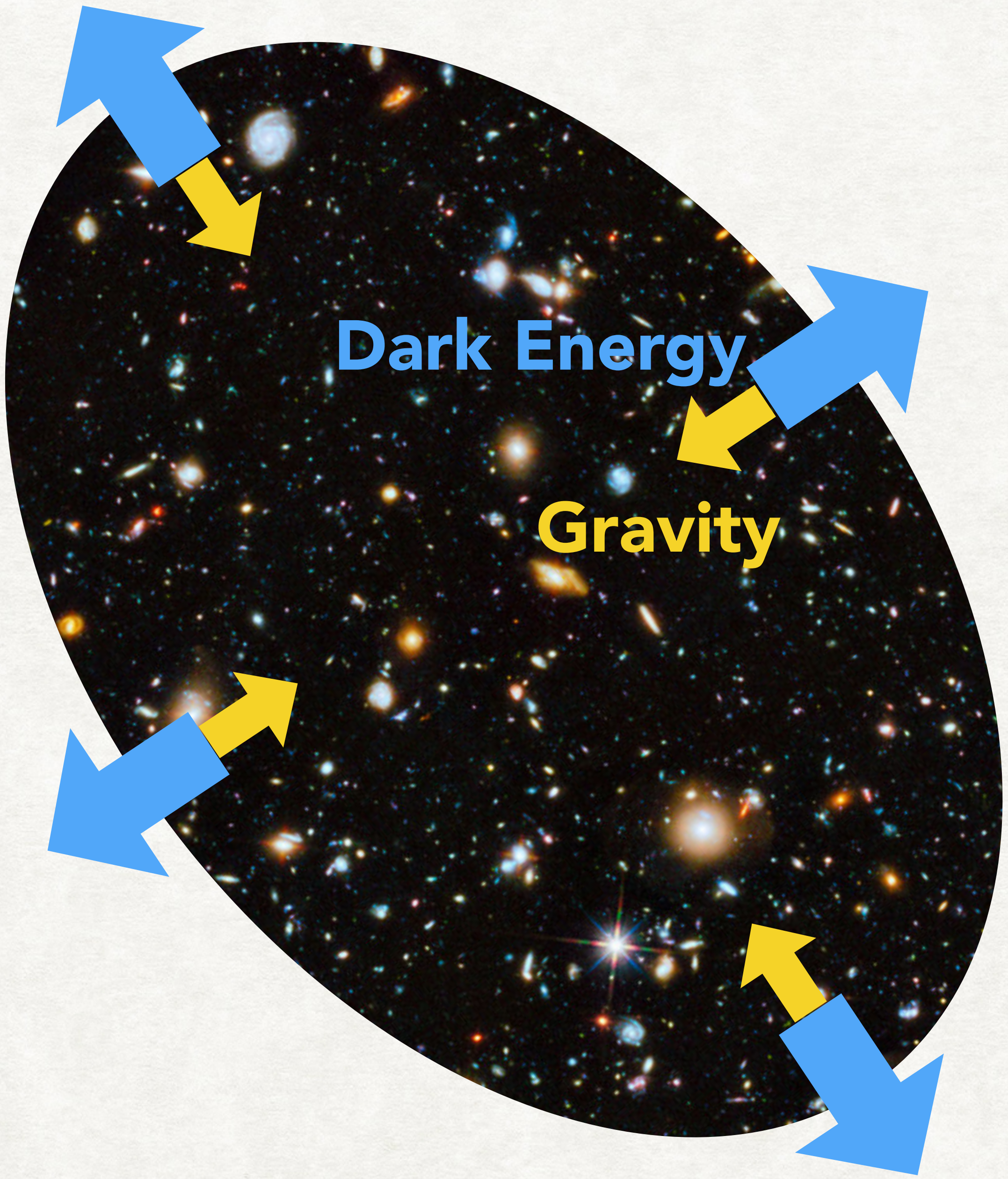
- torsion balance: Eöt-Wash [9,11]
- Casimir forces [9,11]
- Interferometry [9,11]
- Coupling to photons: CAST, CHASE [12,13]

Cosmology/Astro:

- SN/BAO (distance/redshift relations) [14]
- Structure growth [14]
- Lensing [14]
- Stellar burning [9]
- Multi-messenger signals with GW (new!) [10]

- **The landscape of viable models is enormous!**
- **Need multiple experiments to provide as much information as possible**
- **BUT many questions remain open …**

Open questions



- new particle or modified gravity?
- constant or dynamic?
- interacting or not?
- microscopic nature?

Why search for DE at colliders

- Interaction of DE with SM particles arises naturally in many models
  - Screening of 5th forces: escape detection at high density regions $\rightarrow$ DE must "feel" the density of SM matter $\rightarrow$ non-zero DE/SM interaction

  $\Rightarrow$ DE can be produced and constrained at colliders [1]

- Dark degeneracy
  - modified gravity models can lead to same phenomenology as DE

$$\tilde{G}_{\mu\nu} = 8\pi G\, \tilde{T}_{\mu\nu}$$

  $\Rightarrow$ need particle physics to distinguish modified gravity from dark energy [2]

- Complementarity with non-collider experiments

  $\Rightarrow$ collider experiments sensitive to multitude of signatures

  $\Rightarrow$ access different parts of parameter space

  $\Rightarrow$ investigate microscopic nature of DE

So far no direct search by collider experiments

AN EFT MODEL OF SCALAR DE

The model

- New model based on Effective Field Theory [Brax, Burrage, Englert, Spannowsky - PRD94 084054 (2016)]
- Using framework of **Horndeski theories**
  (most general theories with scalar field with 2nd order eq. of motion)
  ⇒ **assumption: DE couples to matter**

  ⇒ independent of microscopic models - offers **general framework to study DE**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \mathcal{L}_i = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{M^{d-4}} \mathcal{O}^{(d)}$$

- **Idea**: extend SM Lagrangian with extra operators suppressed by new physics scale M
  ⇒ **measure M - translate to the parameters of UV models**
- At LO M controls the DE cross-section

EFT operators

- **2 classes of operators:**
  ⇒ shift symmetry invariant

  ⇒ shift symmetry breaking (**φ** can decay to SM fields - not considered here)

- **9 shift-symmetric operators:**
  - kinetic conformal couplings
  - disformal couplings
  - kinetic term for DE field
  - Galileons

⇒ so far we have studied only these 2

- **These operators appear in cosmological/non-collider searches**
  - Gravitational waves/CMB [5] $\mathcal{L}_7, \mathcal{L}_8$
  - Atom interferometers/Chameleon search [6] $\frac{1}{2}\mathcal{L}_{6,1} + \mathcal{L}_{10,1} + \mathcal{L}_{11,1}$
  - Torsion pendulum search for symmetron DE [7] $-\frac{1}{2}\mathcal{L}_{6,1} - \frac{1}{2}\mathcal{L}_{10,2} + \frac{1}{2}\mathcal{L}_{11,2} - \frac{1}{4!}\mathcal{L}_{11,4}$

Conformal & disformal couplings - signatures

$$\mathcal{L}_1 = \frac{\partial_\mu\phi\partial^\mu\phi}{M^4}T^\nu_\nu$$

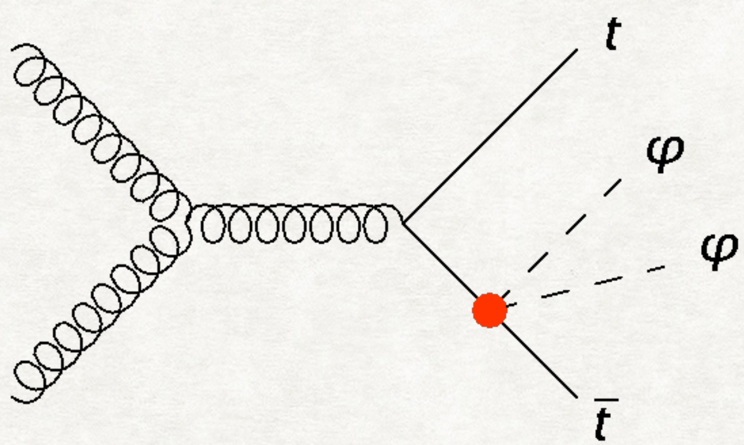
(kinetic) conformal coupling

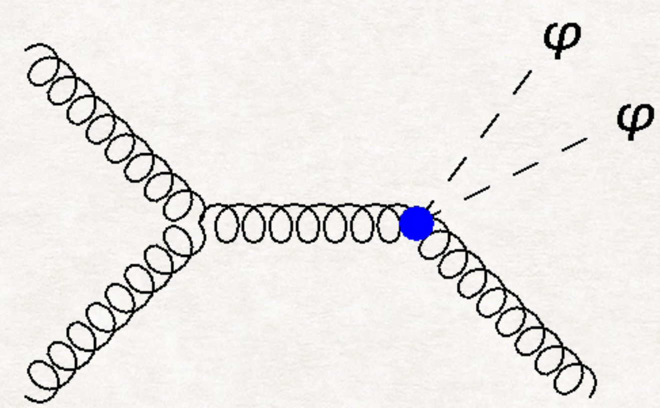
⇒ enhanced for **heavy final states**

$$\mathcal{L}_2 = \frac{\partial_\mu\phi\partial_\nu\phi}{M^4}T^{\mu\nu}$$

disformal coupling

⇒ enhanced for **high momentum**





- Top final states: enhanced sensitivity to L_1 due to high top mass
- Mono-jet final states: enhanced sensitivity to L_2 due to high momentum transfers
- **DE particle φ** stable and non-interacting ⇒ seen as **missing energy** in the detector

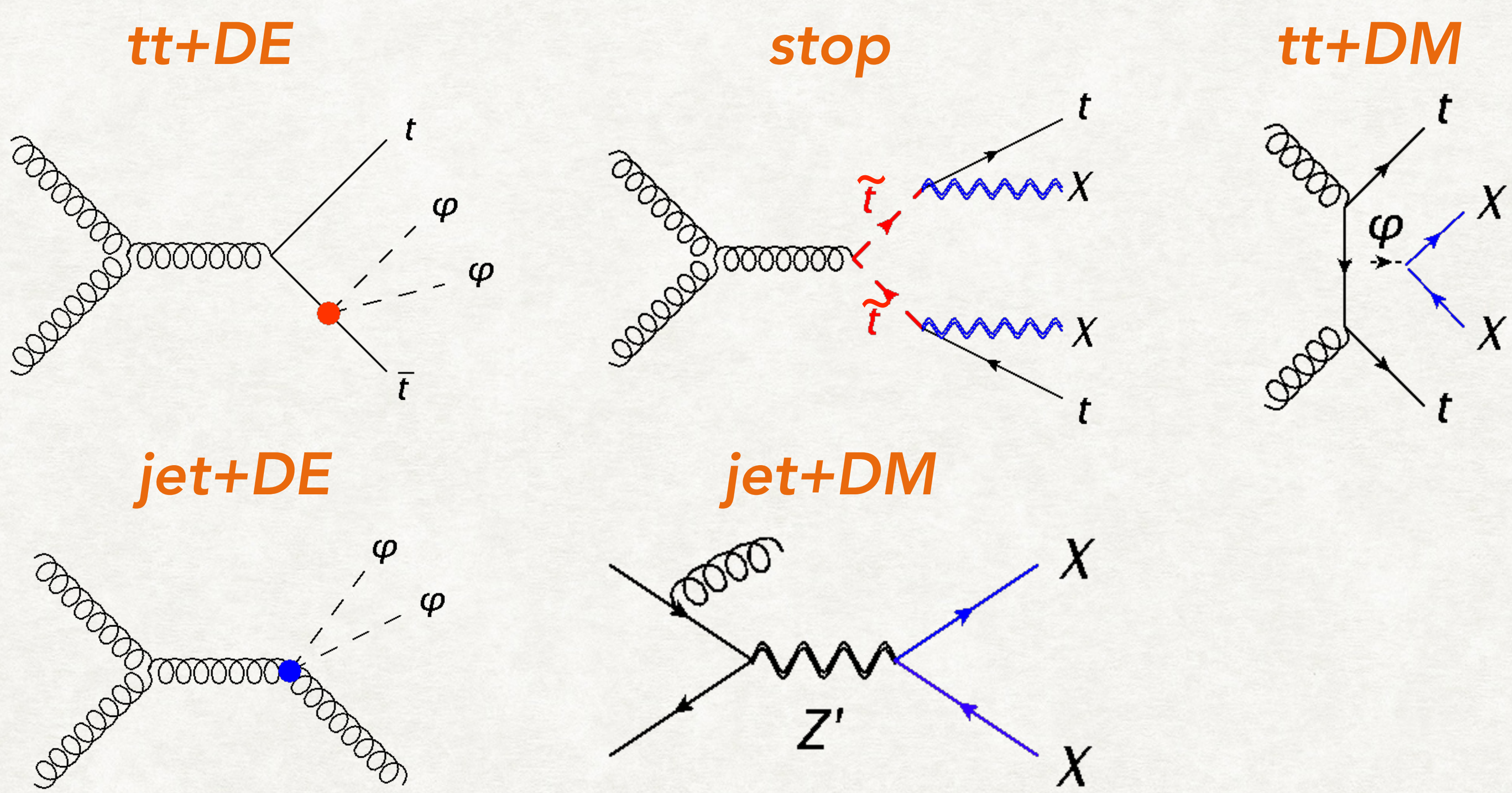
⇒ **Signatures: tt+ E_T^{miss} , jet+ E_T^{miss}**

THE SEARCH

JHEP 05 (2019) 142

How DE events look

- **Same signatures as DM searches** (both DM and DE give MET signature)
- tt+MET: also same signature as stop search - slightly more sensitive than tt+DM

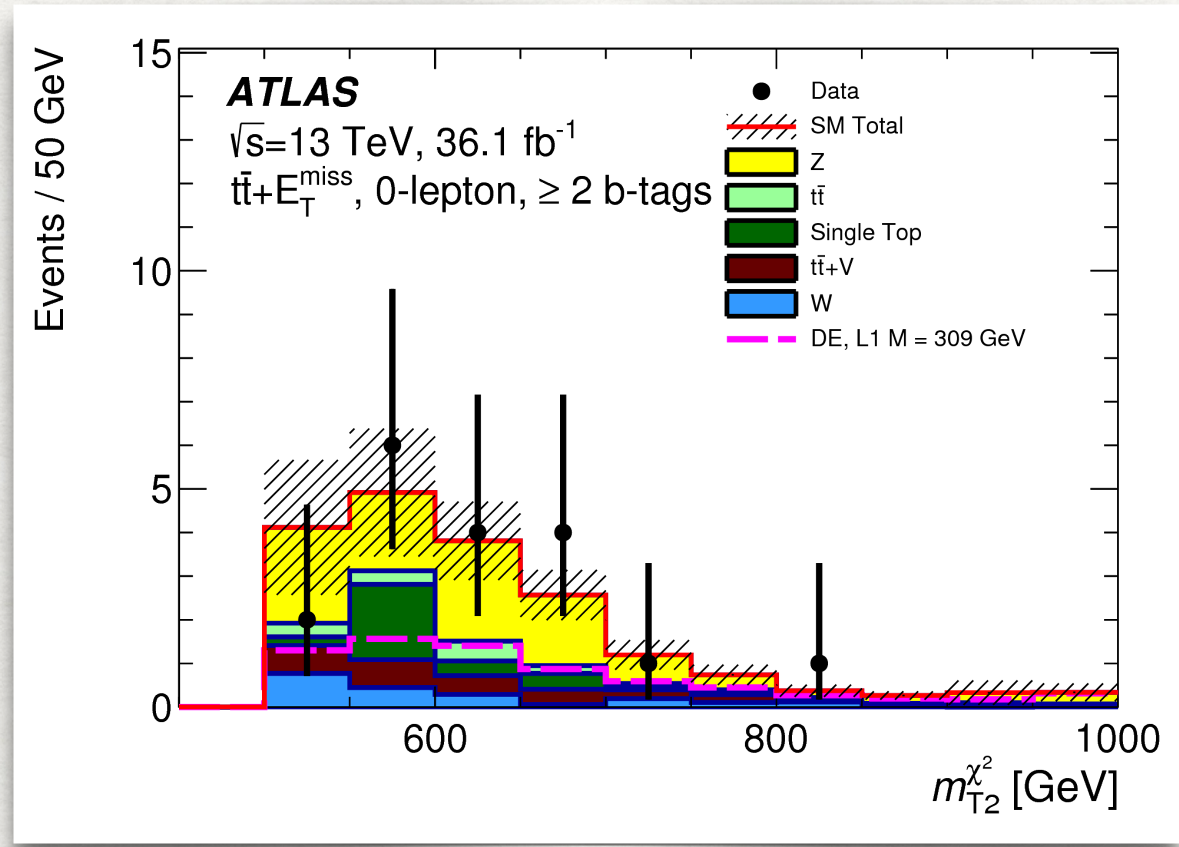


- Re-interpret results of:
  - L_1: stop search *[ATLAS, JHEP 12 (2017) 085]*
  - L_2: mono-jet DM search *[ATLAS, JHEP 01 (2018) 126]*

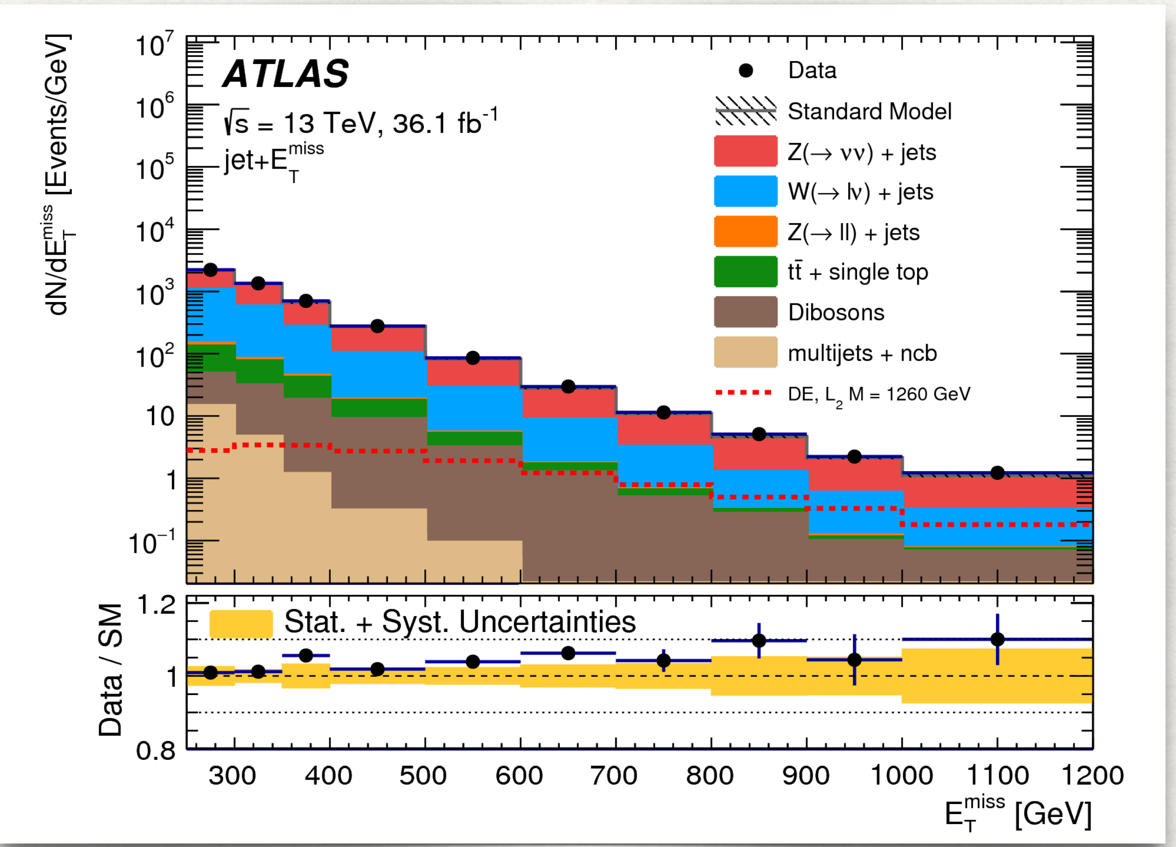
Analysis

- Find variable that can discriminate signal vs background
- Fit background templates (Monte Carlo) - is there an excess of data?

Stransverse mass in tt+E_T^{miss} analysis



E_T^{miss} in mono-jet analysis



- No excess ⇒ what is the maximum amount of signal that the data can accommodate?
- Upper limit on production cross-section for L_1, L_2
  - $\sigma(L_1) < 26$ fb ⇒ $M_1 > 309$ GeV
  - $\sigma(L_2) < 0.23$ fb ⇒ $M_2 > 1260$ GeV

INTERPRETATION

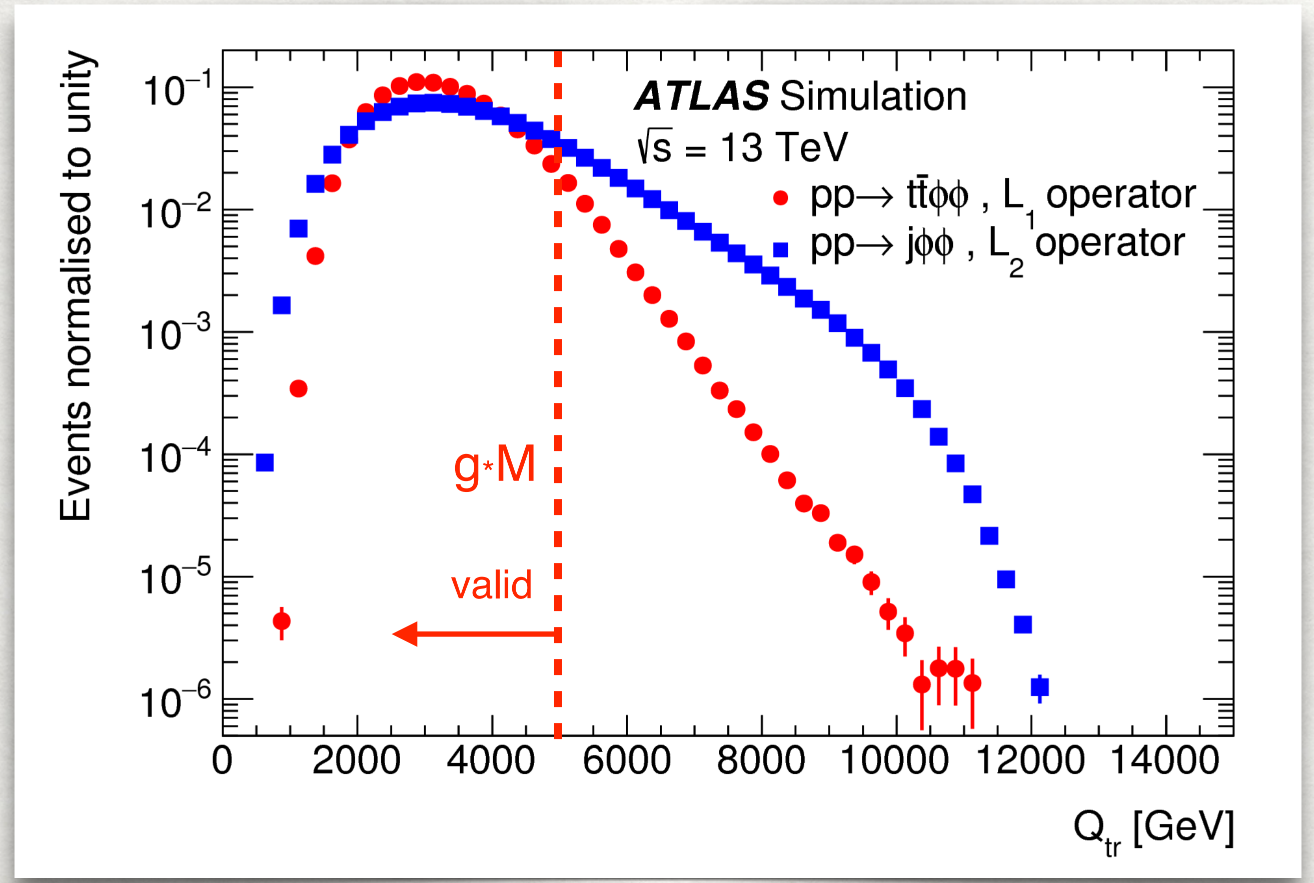
Validity of EFT model

- **EFT approximation valid when momentum transfer not enough to resolve the interaction: $Q_{tr} \ll M$**
- In practice use

$$Q_{\rm tr} < g_* M$$

$g_\star$: effective coupling related to UV completion of EFT ($g_\star < 4\pi$)
M : lower limit on EFT suppression scale

Momentum transfer

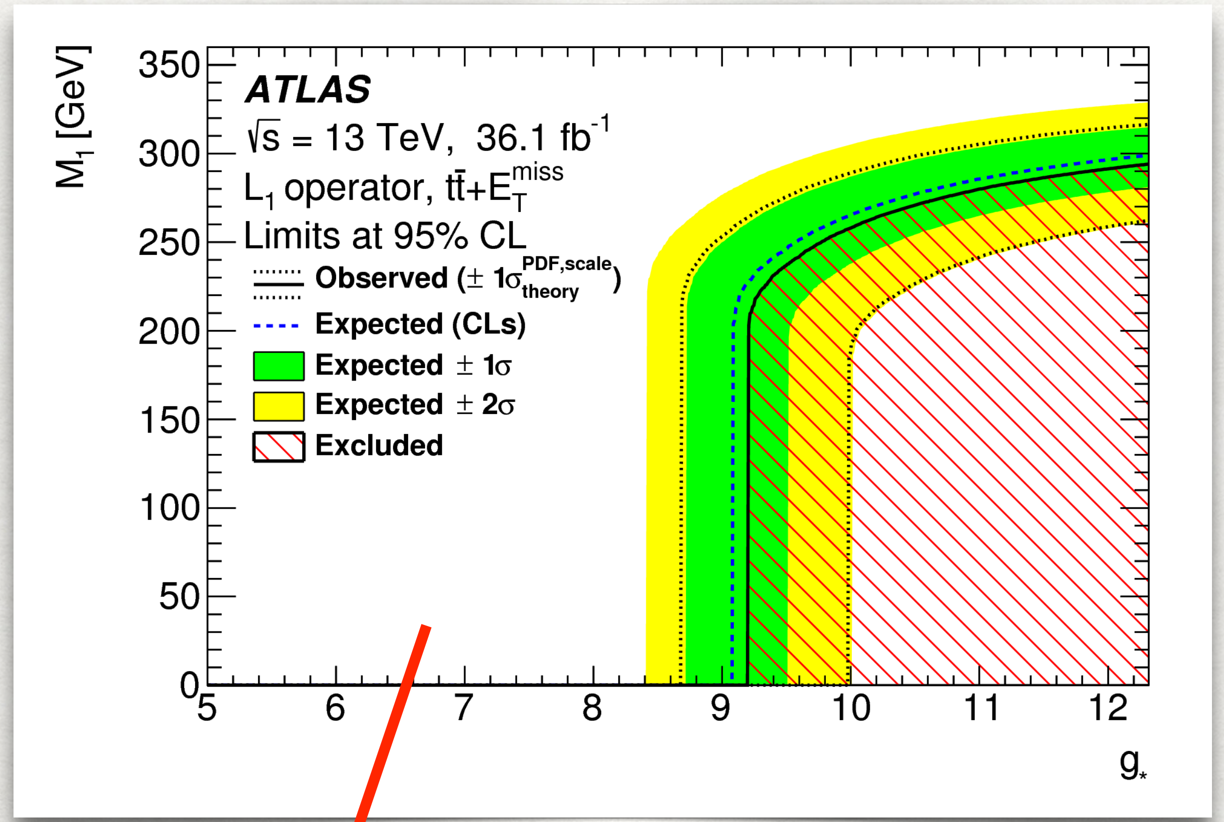


- **Rescale the limit** (conservative) to account for events violating the above assumption

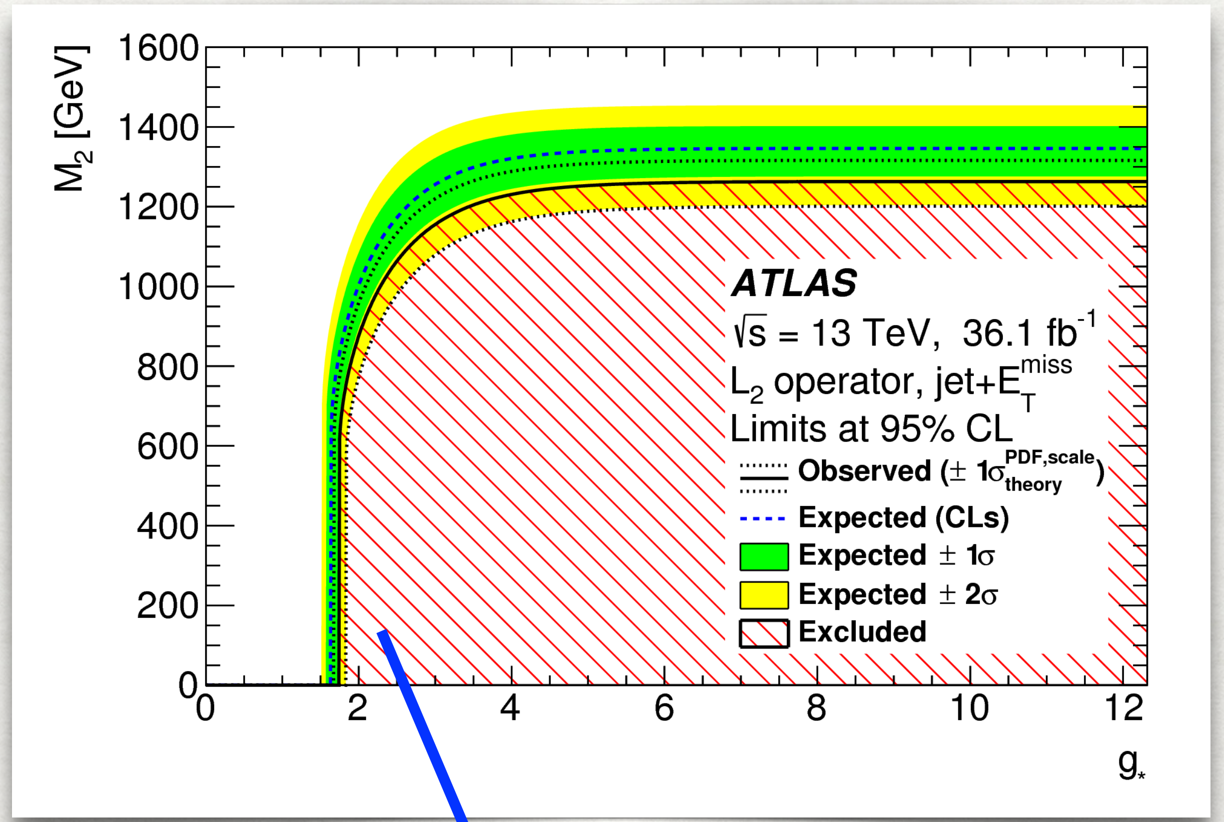
$$M_{\rm resc} = R^{1/8} M$$

Interpretation

Exclusion limit vs coupling for L_1



Exclusion limit vs coupling for L_2



No sensitivity yet to weakly coupled models for L_1:

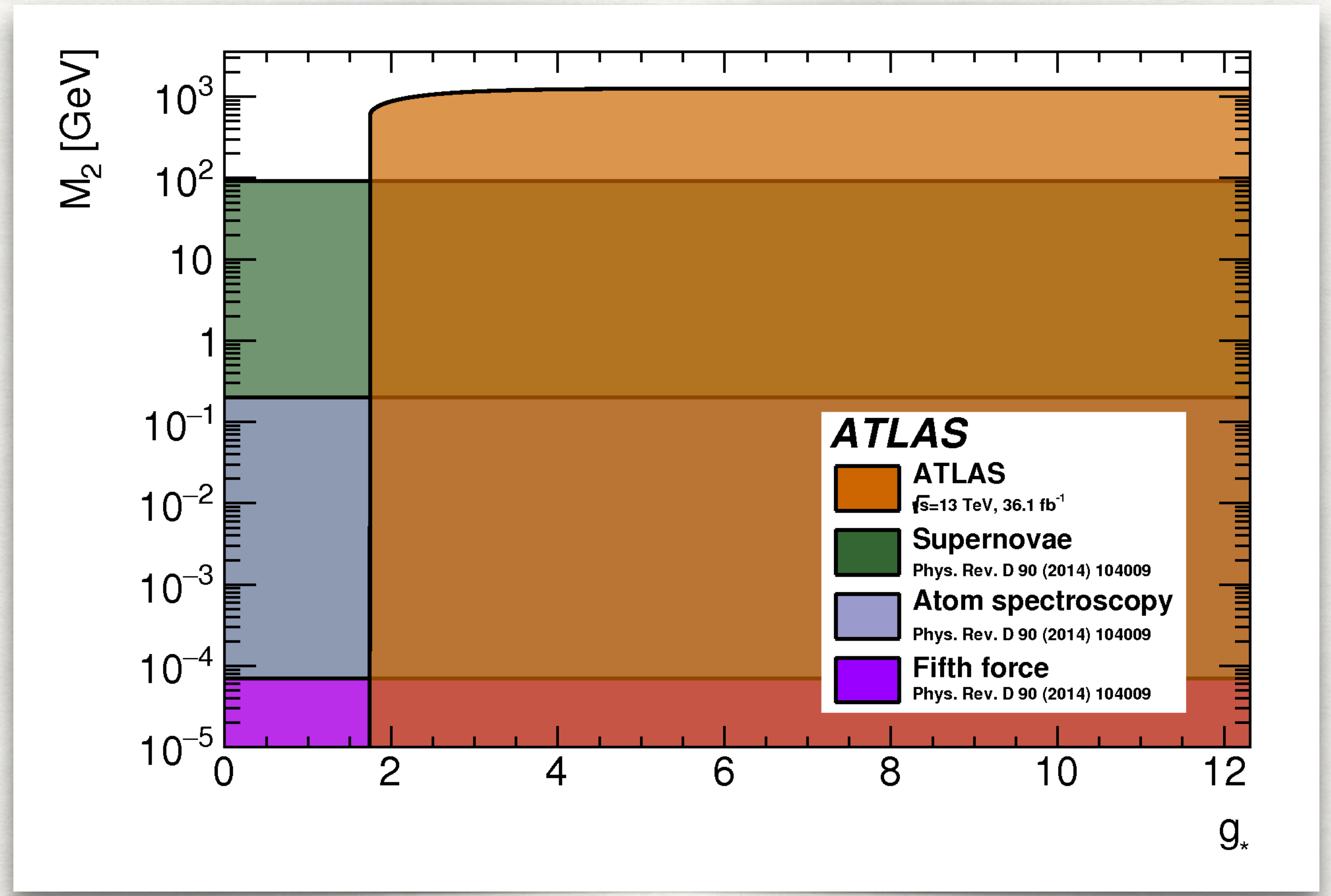
- very high momentum transfers due to high top mass
- should improve with higher data/more sensitive search

Sensitivity extends to lower couplings for L_2:

- higher limit
- lower momentum transfers wrt $tt+E_T^{miss}$

Comparison with other experiments

- Disformal coupling analysis already performed for non-collider probes
  - supernovae, atom spectroscopy, fifth force experiments [9 - Brax, Burrage, PRD 90, 104009 (2014)]
- Momentum transfers in these processes are small so we can assume that EFT limit is completely valid and compare the limits:



➡ ***Colliders several orders of magnitude more sensitive to disformal couplings!***

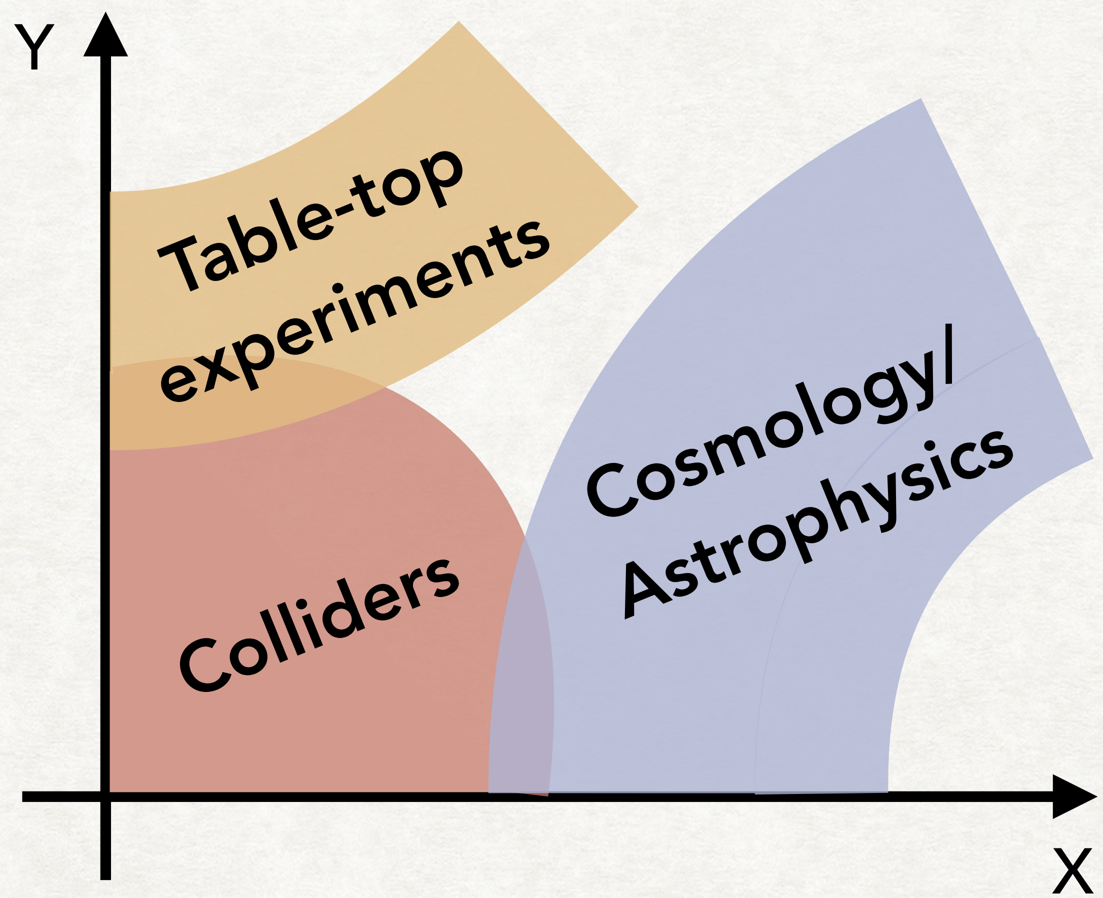
Summary and Outlook

- ✓ colliders can provide complementary constraints for some DE models
- ✓ first time experimental collaboration sets limits on DE using collider data
- ✓ most stringent constraints on kinetic conformal and disformal couplings
  - several orders of magnitude stronger than non-collider limits [9]

Things for the future:

- improvement in Run-3 with more data (better limit, pushing $g_\star$ to lower values)
- **optimise search strategy** (e.g. adding dedicated selections, combining channels)
- **probe more final states** ⇒ stronger constraints / enlarged EFT validity
- **more operators**:
  - additional operators can alter E_T^{miss} shape
  - complementary with non-collider searches?
- **theorists**:
  - any signatures that we are missing?
  - translate constraints into specific benchmark models (?)

Would something like this be feasible/useful?



With thanks to the conference organisers for the invitation and P. Brax, C. Burrage, C. Englert, M. Spannowsky for helpful discussions

BACKUP

References

[1] A. Joyce, et al, Phys. Rept. 568 (2015) 1, arXiv: 1407.0059 [astro-ph.CO]

P. Brax, Rep. Prog. Phys., 81 (2018) 016902

[2] Kunz PRD 80 (2009) 123001

Kunz, Sapone PRL 98 (2007) 121301

[3] P. Brax et al, Phys. Rev. D94 084054 (2016)

[4] P. Brax, P. Valageas, Phys. Rev. D 95, 043515 (2017)

[5] Sakstein, Jain, Phys. Rev. Lett. 119, 251303 (2017)

[6] Burrage, Copeland, Hinds, JCAP 03 (2015) 042

[7] Upadhye, PRL 110 (2013) 031301

[9] Brax, Burrage, Phys. Rev. D 90, 104009 (2014)

[10] LIGO/Virgo Phys. Rev. Lett. 119 (2017) 161101 ; LIGO/VIRGO Astrophys. J. 848 (2017) L12

[11] Burrage, Sakstein, JCAP11 (2016) 045

[12] CHASE, Science 349 (2015) 849

[13] CAST, Phys. Lett. B749 (2015) 172

[14] Weinberg et al, Phys. Rept. 430 (2013) 87

Shift symmetric models [4]

- Nearly massless field needed for cosmic acceleration
  - model with complex scalar field **Φ** with global U(1) symmetry
  - Goldstone mode **φ** below symmetry breaking scale f (**φ** plays role of DE)

$$S = \int d^4x \sqrt{-\tilde{g}}[-\tilde{g}^{\mu\nu}\partial_\mu \bar{\Phi} \partial_\nu \Phi - V(|\Phi|^2)]$$

$$\Phi = f e^{i\phi/(\sqrt{2}f)}$$

- Residual symmetry in the broken phase ⇒ shift symmetry
  - forbids Yukawa interactions of DE field with SM matter

Event selection

tt+E_T^{miss}

Variable	Region		
	SRA_TT	SRA_TW	SRA_T0
N^{jet}	≥ 4 within $\lvert\eta\rvert < 2.7$		
$N^{\text{b-jet}}$	≥ 2		
P_T^{jet}	> 80, 80, 40, 40 GeV		
$m^0_{\text{jet},R=1.2}$	> 120 GeV		
$m^1_{\text{jet},R=1.2}$	> 120 GeV	[60, 120] GeV	< 60 GeV
$m_T^{b,\text{min}}$	> 200 GeV		
$N_{b-\text{jet}}$	≥ 2		
τ-veto	yes		
$\lvert\Delta\phi(\text{jet}^{0,1,2}, \mathbf{p}_T^{\text{miss}})\rvert$	> 0.4		
$m^0_{\text{jet},R=0.8}$	> 60 GeV		
$\Delta R(b,b)$	> 1	-	
$m_{T2}^{\chi^2}$	> 400 GeV	> 400 GeV	> 500 GeV
E_T^{miss}	> 400 GeV	> 500 GeV	> 550 GeV

Mono-jet

$E_T^{\text{miss}} > 250$ GeV
leading jet $p_T > 250$ GeV and $\lvert\eta\rvert < 2.4$
≤ 4 selected jets with $P_T > 30$ GeV and $\lvert\eta\rvert < 2.8$
$\Delta\phi\left(jet, \vec{p}_T^{\,miss}\right) > 0.4$ for all selected jets
no identified electron with $p_T > 20$ GeV
no identified muon with $p_T > 10$ GeV

Iterative limit rescaling

- Taken from ATL-PHYS-PUB-2014-007
- Start with nominal expected limit assuming 100% validity
- Until $R_i = 1$ or 0
  - Calculate $Q_{tr}^{max}(i) = 4\pi M_{in}(i) = 4\pi\, M_{out}(i-1)$
  - Calculate $R_i = N(Q_{tr} < Q_{tr}^{max}(i))/N(Qtr < Q_{tr}^{max}(i-1))$
  - Evaluate $M_{out}(i) = R_{tot}^{1/8} \cdot M_{in}(i)$
- Determine $M_{resc} = (\prod R_i)^{1/8} \cdot M_{in}$

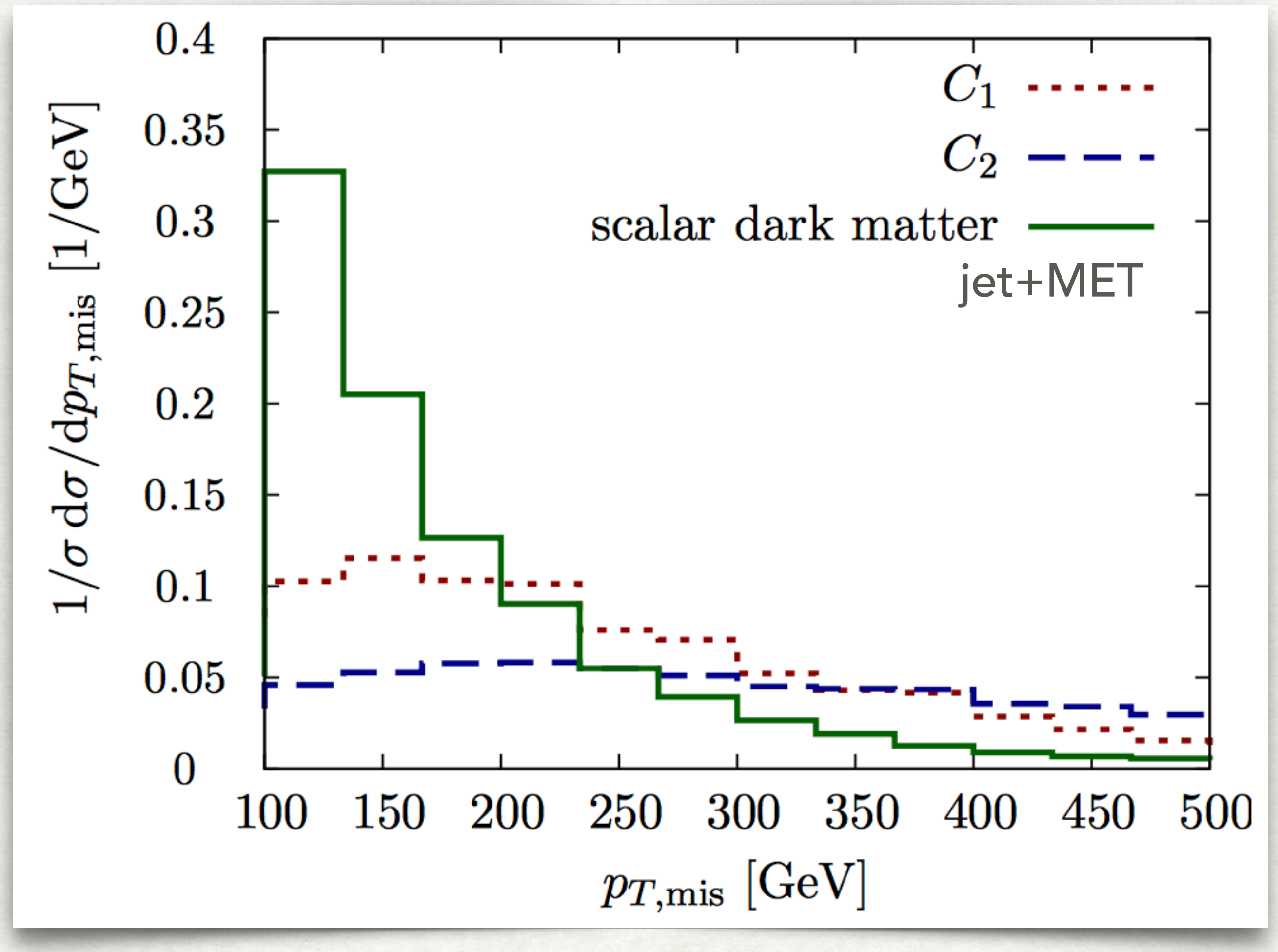
Example for L_2 with $g_\star$=4				
M_{in}	$Q_{tr}^{max}(i)$	$Q_{tr}^{max}(i-1)$	R_i	M_{out}
1263	5052	13000	0.83	1234
1234	4937	5052	0.98	1231
1231	4924	4937	1	1231

Operators

Kinetic conformal couplings	$\mathcal{L}_1 = \frac{\partial_\mu\phi\partial^\mu\phi}{M^4}T^\nu_\nu$
	$\mathcal{L}_{3,n} = \left(\frac{\partial_\mu\phi\partial^\mu\phi}{M^4}\right)^n T^\nu_\nu$
Disformal couplings	$\mathcal{L}_2 = \frac{\partial_\mu\phi\partial_\nu\phi}{M^4}T^{\mu\nu}$
	$\mathcal{L}_{4,n} = \left(\frac{\partial_\alpha\phi\partial^\alpha\phi}{M^4}\right)^n \frac{\partial_\mu\phi\partial_\nu\phi}{M^4}T^{\mu\nu}$
	$\mathcal{L}_{5,n-1} = \frac{1}{M^{4n}}\partial_{\alpha_1}\phi\partial_{\beta_1}\phi\cdots\partial_{\alpha_n}\phi\partial_{\beta_n}\phi\frac{2^{n-1}}{\sqrt{-g}}\frac{\partial^{n-1}(\sqrt{-g}T^{\alpha_1\beta_1})}{\partial g_{\alpha_2\beta_2}\cdots\partial g_{\alpha_n\beta_n}}$
DE kinetic term	$\mathcal{L}_{6,n} = \frac{(\partial_\mu\phi\partial^\mu\phi)^n}{M^{4(n-1)}}$
Galileon	$\mathcal{L}_7 = \frac{1}{M^3}\partial_\mu\phi\partial^\mu\phi\Box\phi$
	$\mathcal{L}_8 = \frac{1}{M^6}\partial_\mu\phi\partial^\mu\phi[2(\Box\phi)^2 - 2D_\alpha D_\beta\phi D^\beta D^\alpha\phi]$
	$\mathcal{L}_9 = \frac{1}{M^9}\partial_\mu\phi\partial^\mu\phi[(\Box\phi)^3 - 3(\Box\phi)D_\alpha D_\beta\phi D^\beta D^\alpha\phi + 2D_\alpha D^\beta\phi D_\beta D^\gamma\phi D_\gamma D^\alpha\phi]$

DE vs DM

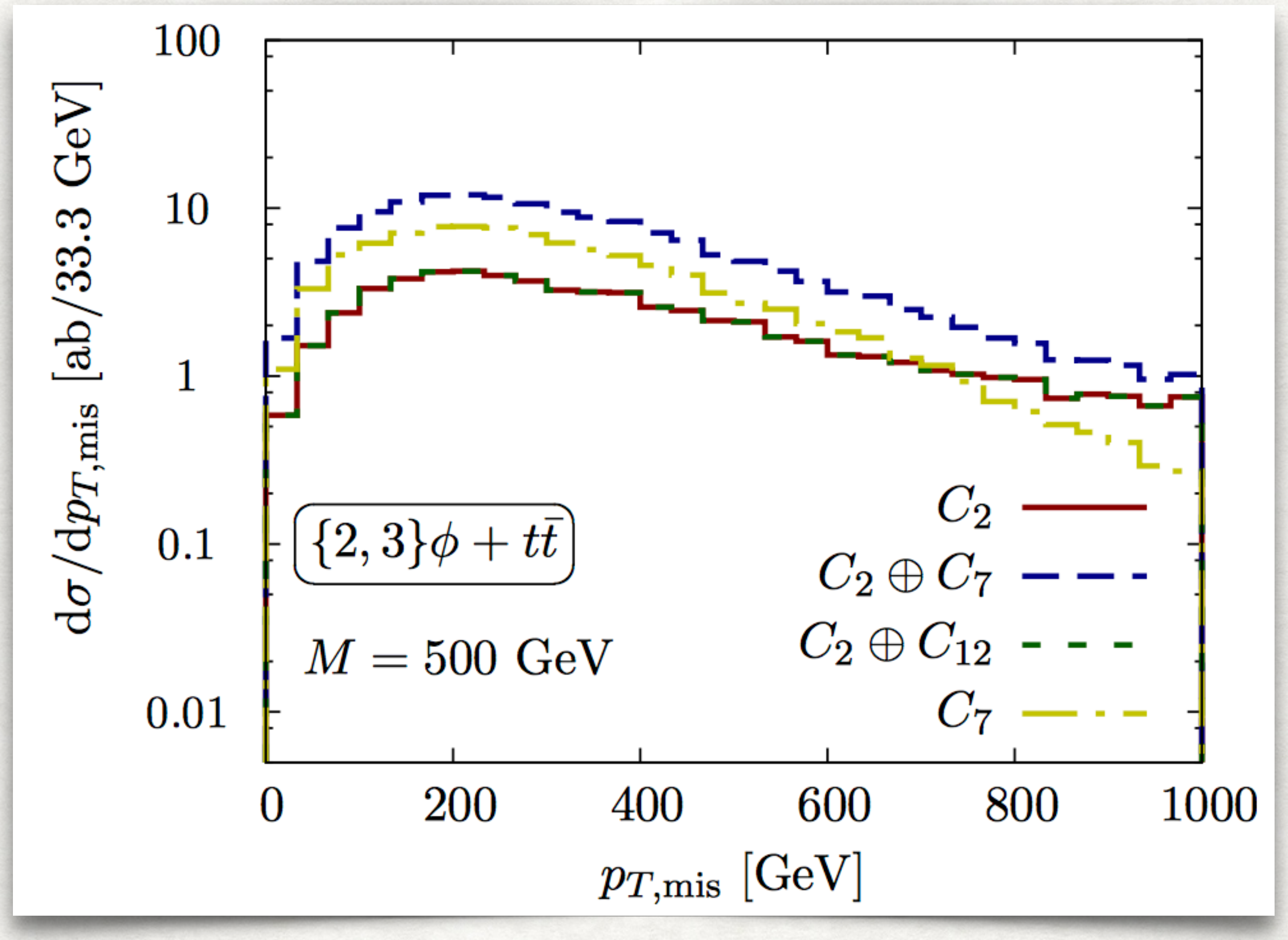
- Much higher MET in general than DM
    - although this obviously depends on the model parameters
    - DE would be indistinguishable from DM in such a search



Brax et al., Phys. Rev. D 94, 084054 (2016)

Effect of additional operators

- Additional operators would alter both the cross-section and the normalisation
- More sophisticated analysis necessary

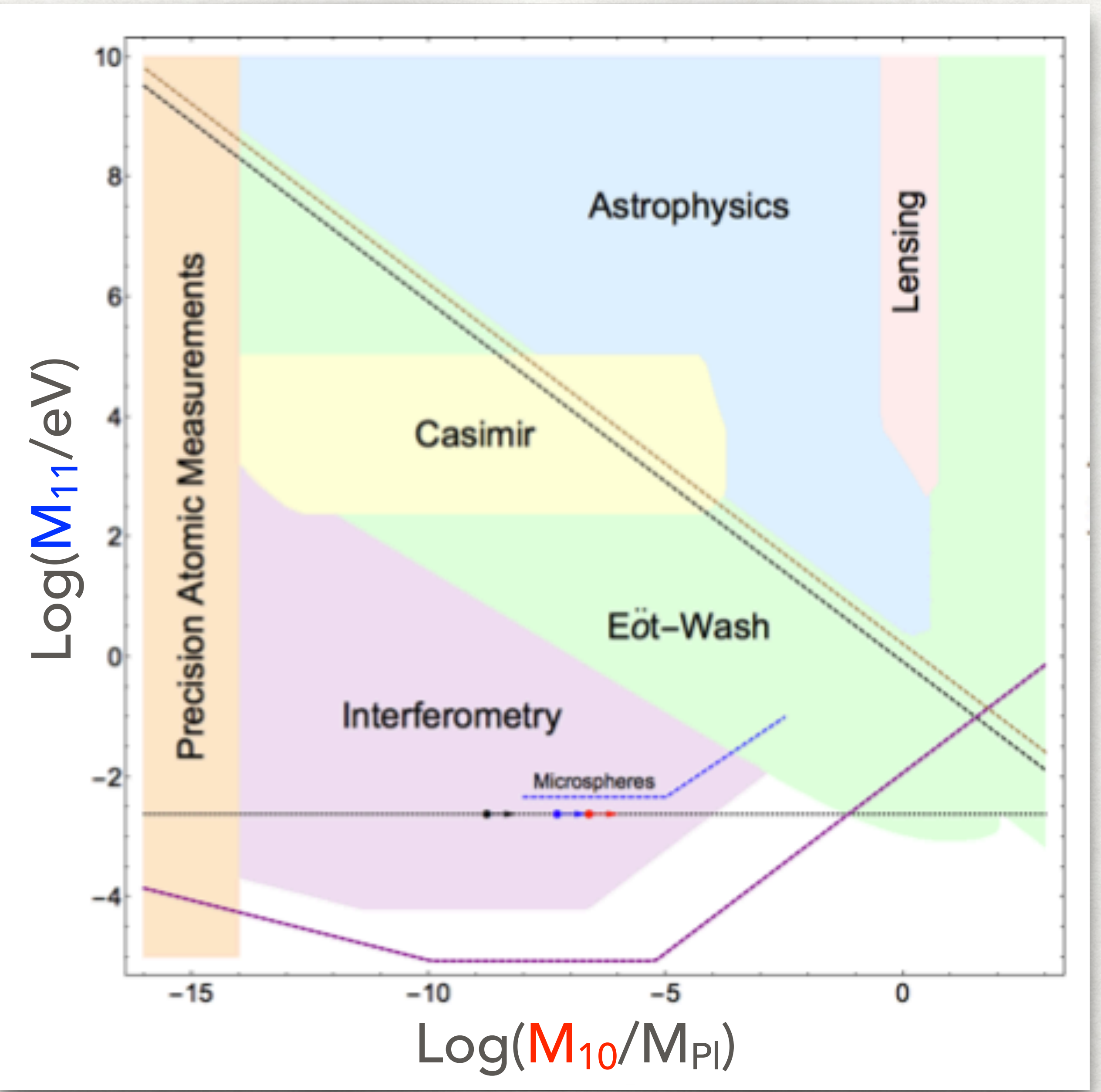


Brax et al., Phys. Rev. D 94, 084054 (2016)

Limits on disformal coupling from other sources

Source of bound	Lower bound on M in GeV	Environment	Discussed in Section
Unitarity at the LHC	30	Lab. vac.	3
CMS mono-lepton	120	Lab. vac.	3
CMS mono-photon	490	Lab. vac.	3
Torsion Balance	7×10^{-5}	Lab. vac.	4.1
Casimir effect	0.1	Lab. vac.	5.1
Hydrogen spectroscopy	0.2	Lab. vac.	6
Neutron scattering	0.03	Lab. vac.	7
Bremsstrahlung	4×10^{-2}	Sun	8.3
	0.18	Horizontal Branch	8.3
Compton Scattering	0.24	Sun	8.4
	0.81	Horizontal Branch	8.4
Primakov	4×10^{-2}	Sun	8.5
	0.35	Horizontal Branch	8.5
Pion exchange	~ 92	SN1987a	8.6

Comparing limits



Burrage, Sakstein JCAP 11 (2016) 045

- plot here shows constraints on chameleons:

$$\mathcal{L} = \frac{1}{2}\mathcal{L}_{6,1} + \mathcal{L}_{10,1} + \mathcal{L}_{11,-n}$$
$$= \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{{M_{11}}^{4+n}}{\phi^n} + \frac{\phi T^\mu_\mu}{M_{10}}$$

- does it make sense to have something similar for M_1, M_2 including collider and non-collider experiments?