#### Fermilab Office of Science



# **Gravitational Dark Matter Direct Detection Gordan Krnjaic**

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APEC Seminar, Kavli IPMU, April 15, 2019

### **Open Questions in Fundamental Physics**



**Also Quantum Gravity** 

#### **Galactic Rotation Curves**



Dramatic effect: requires ~85% of matter to be "dark"

M33 Galaxy, E. Corbelli, P. Salucci (2000)



"Weighs" total matter: requires ~85% of matter to be "dark"



~ 85% of total mass passed through without scattering

#### **CMB** Power Spectrum



~85% of matter is gravitating, but not exerting pressure

Image: Planck 2013

#### **Matter Power Spectrum**



Observation & theory agree with ~85% pressure-less matter, 15% conventional "baryonic"

#### 10<sup>0</sup> Light Element Yields @ BBN 10-1 Element Abundance (Relative to Hydrogen) Deuterium (2H) t/sec10-2 $10^{6}$ $10^{4}$ $10^{5}$ 0.11000 1 1010010-3 D b.n. Η 1 10-4 $Y_{\rm p}$ Ν $10^{-2}$ SBBN f.o. Helium (<sup>3</sup>He) 10-5 $\nu$ dec. n/p dec. D/H $10^{-4}$ 10-6 $e^{\pm}$ ann. $^{3}\mathrm{He/H}$ $10^{-6}$ T/H10-7 $10^{-8}$ $^{7}\mathrm{Be/H}$ 10-8 $10^{-10}$ $^{7}$ Li/H 10-9 $10^{-12}$ 10-10 $^{6}$ Li/H Lithium (<sup>7</sup>Li) $10^{-14}$ 10-11 10-12 10-10 10-11 1000 100 10T/keVDensity of Ordinary Matter (Relative to Photons)

Pospelov, Pradler '10

10-8

10.7

Helium 4 (<sup>4</sup>He)

WMAP Observation

10-9

#### **Requires baryon density to be ~ 15% of total**

Single parameter theory

$$\Omega_b \equiv \rho_b / \rho_{\rm tot}$$

**Key point:** DM can't be SM particles This counts everything

NASA/WMAP Science Tea

# Impressive Evidence for Dark Matter

**Galactic Rotation Curves** 

**Gravitational Lensing** 

**CMB** Power Spectrum

**Matter Power Spectrum** 

**BBN Element Yields** 

But all ultimately based how DM gravitates Holy Grail: understand its *particle nature*  Step 1: \*guess\* plausible non-gravitational interaction
Optional — available evidence all relies on gravity
Broad — endless variety of viable choices

**Step 2: choose mass optimized for an experimental technique** Every technique has a finite sensitivity range Choice usually dictated by technology

**Concern: DM becomes moving target living under a lamp post** Hard to make firm statements about DM

### How do we usually look for DM?



(scattering)

(annihilation)

(production)

#### Updating Priors on WIMPs



XENON 1T Collaboration arXiv:1805.12562

### Updating Priors on WIMPs

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

March 2019										$\sqrt{s} = 13$ lev
Model		Signa	ture ∫	`£ dt [ſЪ`	'] Ma:	ss limit				Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{t}_{1}^{0}$	0 e, μ 2-6 mono-jet 1-3	ets $E_T^{miss}$ ets $E_T^{miss}$	36.1 36.1	↓ [2x, 8x Degen.] ↓ [1x, 8x Degen.]	0.43	0.9 0.71	1.55	m(ຊັ <sup>0</sup> <sub>1</sub> )<100 GeV m(ຢູ່)-m(ຊັ <sup>0</sup> <sub>1</sub> )=5 GeV	1712.02332 1711.03301
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{g}\tilde{t}_{1}^{0}$	0 e,µ 2-6	jets $E_T^{miss}$	36.1	R R		Forbidden	2.0 0.95-1.6	m(ξ <sup>0</sup> <sub>1</sub> )<200 GeV m(ξ <sup>0</sup> <sub>1</sub> )=900 GeV	1712.02332 1712.02332
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell \ell)\tilde{k}_{1}^{0}$	3 e,μ 4 je ee,μμ 2 je	Hs $E_T^{miss}$	36.1 36.1	R R			1.85	m( $\hat{t}_{1}^{0}$ )<800 GeV m( $\hat{t}_{1}^{0}$ )=50 GeV	1706.03731 1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{t}_{1}^{0}$	0 e.μ 7-11 3 e.μ 4 je	jets E <sup>miss</sup> NS	36.1 36.1	Ř Ř		0.98	1.8	$m(\tilde{t}_{1}^{0}) <400 \text{ GeV}$ $m(\tilde{\chi})-m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{t}_1^0$	0-1 <i>e</i> ,μ 3 3 <i>e</i> ,μ 4 je	b E <sub>T</sub> miss Ms	79.8 36.1	Ř Ř			1.25	5 m(ξ <sup>0</sup> <sub>1</sub> )<200 GeV m(ξ)-m(ξ <sup>0</sup> <sub>1</sub> )=300 GeV	ATLAS-CONF-2018-041 1706.03731
3 <sup>rd</sup> gen, squarks direct production	$b_1 b_1, b_1 {\rightarrow} b \hat{t}_1^0 / t \hat{t}_1^x$	Mult Mult	iple iple iple	36.1 36.1 36.1	$egin{array}{ccc} eta_1 & Forbidden \ eta_1 & eta_1 \ eta_1 & eta_1 \end{array}$	Forbidden Forbidden	0.9 0.58-0.82 0.7	$m(\tilde{t}_1^0)$	$m(\hat{t}_{1}^{0})=300 \text{ GeV}, BR(i\hat{t}_{1}^{0})=1$ $m(\hat{t}_{1}^{0})=300 \text{ GeV}, BR(i\hat{t}_{1}^{0})=BR(i\hat{t}_{1}^{0})=0.5$ $=200 \text{ GeV}, m(\hat{t}_{1}^{+})=300 \text{ GeV}, BR(i\hat{t}_{1}^{+})=1$	1708.09266, 1711.03301 1708.09266 1706.03731
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{t}_2^0 \rightarrow b h \tilde{t}_1^0$	0 <i>e</i> ,µ 6	$b = E_T^{miss}$	139	δ <sub>1</sub> Forbidden δ <sub>1</sub>	0.23-0.48	0	.23-1.35	$\begin{array}{l} \Delta m(\tilde{k}_{2}^{0},\tilde{k}_{1}^{0}){=}130{\rm GeV},m(\tilde{k}_{1}^{0}){=}100{\rm GeV}\\ \Delta m(\tilde{k}_{2}^{0},\tilde{k}_{1}^{0}){=}130{\rm GeV},m(\tilde{k}_{1}^{0}){=}0{\rm GeV} \end{array}$	SUSY/2018-31 SUSY/2018-31
	$\tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow Wb\tilde{t}_{1}^{0} \text{ or } t\tilde{t}_{1}^{0}$ $\tilde{t}_{1}\tilde{t}_{1}, \text{ Well-Tempered LSP}$ $\tilde{t}_{1}\tilde{t}_{1}, \tilde{t}_{1} \rightarrow \tilde{t}_{1}bv, \tilde{\tau}_{1} \rightarrow \tau \tilde{G}$	0-2 e,μ 0-2 jet: Mult 1 τ + 1 e,μ,τ 2 jet:	1-2 <i>b</i> E <sub>T</sub> miss liple 1/1 <i>b</i> E <sub>T</sub> miss	36.1 36.1 36.1	i i i i		1.0 0.48-0.84	m( $\tilde{t}_1^0$	$m(\tilde{t}_{1}^{0})=1 \text{ GeV}$ =150 GeV, $m(\tilde{t}_{1}^{2})-m(\tilde{t}_{1}^{0})=5 \text{ GeV}$ , $\tilde{t}_{1} \approx \tilde{t}_{L}$ $m(\tilde{t}_{1})=800 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1803.10178
	$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow c \tilde{\mathcal{K}}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\mathcal{K}}_1^0$	0 e,μ 2 0 e,μ mon	$c = E_T^{miss}$ p-jet $E_T^{miss}$	36.1 36.1	2 71 71	0.46 0.43	0.85		m( $\tilde{k}_{1}^{0}$ )=0 GeV m( $\tilde{t}_{1},\tilde{z}$ )-m( $\tilde{k}_{1}^{0}$ )=50 GeV m( $\tilde{t}_{1},\tilde{z}$ )-m( $\tilde{k}_{1}^{0}$ )=5 GeV	1805.01649 1805.01649 1711.00301
	$\tilde{t}_2\tilde{t}_2,\tilde{t}_2{\rightarrow}\tilde{t}_1+h$	1-2 e, µ 4	$b = E_T^{miss}$	36.1	i <sub>2</sub>		0.32-0.88		$m(\tilde{t}_1^0)$ =0 GeV, $m(\tilde{r}_1)$ - $m(\tilde{t}_1^0)$ = 180 GeV	1706.03966
EW direct	$\hat{\chi}_{1}^{\pm}\hat{\chi}_{2}^{0}$ via $WZ$	$2-3 e, \mu$ $ee, \mu\mu \ge$	$E_T^{miss}$ 1 $E_T^{miss}$	36.1 36.1	$\frac{\hat{x}_{1}^{*}/\hat{x}_{2}^{*}}{\hat{x}_{1}^{*}/\hat{x}_{2}^{*}} = 0.17$	0.6	8	$m(\tilde{t}_{1}^{n})=0$ $m(\tilde{t}_{1}^{n})-m(\tilde{t}_{1}^{n})=10 \text{ GeV}$		1403.5294, 1806.02293 1712.08119
	$\bar{\chi}_1^{\pm} \bar{\chi}_2^{\mp}$ via WW $\bar{\chi}_1^{\pm} \bar{\chi}_2^{0}$ via Wh	2 e,μ 0-1 e,μ 2	$E_T^{min}$ $E_T^{min}$	139 36.1	$\hat{x}_{1}^{h}$ $\hat{x}_{1}^{h}/\hat{x}_{2}^{h}$	0.42	0.68		$m(\tilde{t}_1^0)=0$ $m(\tilde{t}_1^0)=0$	ATLAS-CONF-2019-008 1812-09432
	$\begin{array}{c} \chi_1 \chi_1 \; \text{via} \; \ell_L / \tilde{\nu} \\ \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0, \tilde{\chi}_1^{\pm} {\rightarrow} \tilde{\tau}_1 \nu (\tau \tilde{\nu}), \tilde{\chi}_2^0 {\rightarrow} \tilde{\tau}_1 \tau (\nu \tilde{\nu}) \end{array}$	2 <i>1</i> ,µ 2 <i>1</i>	$E_T$ $E_T^{miss}$	36.1	$\frac{X_1}{\hat{X}_1^4/\hat{X}_2^4}$ $\frac{X_1^4/\hat{X}_2^4}{\hat{X}_1^4/\hat{X}_2^4}$ 0.22		0.76	$\begin{array}{c} m(t, \hat{v}) = 0.5(m(\tilde{\kappa}_1^-) + m(\tilde{\kappa}_1^-)) \\ m(\tilde{\kappa}_1^-) = 0, \ m(\tilde{\tau}, \hat{v}) = 0.5(m(\tilde{\kappa}_1^+) + m(\tilde{\kappa}_1^0)) \\ m(\tilde{\kappa}_1^-) - m(\tilde{\kappa}_1^0) = 100 \ \text{GeV}, \ m(\tilde{\tau}, \hat{v}) = 0.5(m(\tilde{\kappa}_1^-) + m(\tilde{\kappa}_1^0)) \end{array}$		1708.07875 1708.07875
	$\tilde{\ell}_{\mathbf{L},\mathbf{R}}\tilde{\ell}_{\mathbf{L},\mathbf{R}}, \tilde{\ell} \rightarrow \ell \tilde{\ell}_{1}^{0}$	2 <i>e</i> ,µ 0)e 2 <i>e</i> ,µ ≥	1 $E_T^{miss}$ 1 $E_T^{miss}$	139 36.1	2 2 0.18		0.7	$m(\tilde{t}_{1}^{0})=0$ $m(\tilde{t})-m(\tilde{t}_{1}^{0})=5 \text{ GeV}$		ATLAS-CONF-2019-008 1712.08119
	ĤĤ, Ĥ→ħĜ/ZĜ	0 e,μ ≥ 3 4 e,μ 0 je	$b = E_{T_{mixs}}^{mixs}$ Ms $E_{T}^{mixs}$	36.1 36.1	ÎI 0.13-0.23 ÎI 0.3		0.29-0.88		$BR(\tilde{t}_1^0 \rightarrow h\tilde{G})=1$ $BR(\tilde{t}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602
Long-lived particles	$\operatorname{Direct} \hat{x}_1^* \hat{x}_1^- \operatorname{prod.}, \operatorname{long-lived} \hat{x}_1^\pm$	Disapp. trk 1 j	et $E_T^{miss}$	36.1	$ \frac{\tilde{x}_{1}^{+}}{\tilde{x}_{1}^{+}} = 0.15 $	0.46			Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\ell}_1^0$	Mult	iple iple	36.1 36.1	2 χ [τ(χ) =10 ns, 0.2 ns]		_	2.0	2.4 m(t <sup>a</sup> )=100 GeV	1902.01636,1808.04095 1710.04901,1808.04095
RPV	LFV $pp \rightarrow \bar{v}_r + X_r \bar{v}_r \rightarrow e\mu/e\tau/\mu\tau$ $\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$ $\tilde{g}_{\tilde{\chi}}^- \tilde{g} \rightarrow qq \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$	εμ,ετ.μτ 4 ε.μ 0 jr 4-5 larg Mult	nts E <sup>miss</sup> e-Rjets iple	3.2 36.1 36.1 36.1	$\hat{v}_{\tau}$ $\hat{X}_{1}^{*}/\hat{X}_{2}^{*} = [\lambda_{03} \neq 0, \lambda_{124} \neq 0]$ $\hat{k} = [m(\hat{X}_{1}^{*})=200 \text{ GeV}, 1100 \text{ GeV}]$ $\hat{k} = [X_{112}^{*}=20.4, 20.5]$		0.82	1.9 1.33 1.3 1.9 5 2.0	$\lambda'_{111}$ =0.11, $\lambda_{112(110/23)}$ =0.07 m( $\tilde{t}_{1}^{0}$ )=100 GeV Large $\lambda''_{112}$ m( $\tilde{t}_{1}^{0}$ )=200 GeV, bino-like	1607.06079 1804.03602 1804.03568 ATLAS-CONF-2018-003
	$u_1, t \rightarrow t \mathcal{K}_1, \mathcal{K}_1 \rightarrow t b s$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b s$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q \ell$	2 jets 2 e,μ 2 1 μ D	+2b b V	36.1 36.7 36.1 136	$ \begin{array}{l} \bar{x}_{11} = [qq, b_1] \\ \bar{x}_{11} = [qq, b_2] \\ \bar{x}_{11} = [1e{-}10{<} x'_{211} < 1e{-}0,  3e{-}10{<} x'_{212} \\ \end{array} $	0.55 0.42 0.6 <3e-9]	1.0	0.4-1.45 1.6	m( $r_i$ )=200 GeV, bino-like BR( $\tilde{r}_i \rightarrow b_V / \bar{r}_{34}$ )>20% BR( $\tilde{r}_i \rightarrow g_H$ )=100%, cosR,=1	ATLAS-CONF-2018-003 1710.07171 1710.05544 ATLAS-CONF-2019-006

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10-1

ATLAS Preliminary

5 12 ToV

Mass scale [TeV]

1

#### Lots of new ideas for light DM detection < GeV





Grabowska, Melia, Rajendran 1807.03788

DD target

New Ideas in Heavy DM

#### Planck scale DM, GeV scale "mediator"



 $A_d$ 

Can have large interaction rate Multiple scattering at DD experiments

Davoudiasl, Mohlabeng 1809.07768

DD target

# How do we usually approach DM?

**Step 1: choose mass optimized for an experimental technique** Every technique has a finite sensitivity range Choice usually dictated by technology

Step 2: \*guess\* plausible non-gravitational interaction Optional — available evidence all relies on gravity Broad — endless variety of viable choices

**Goal of this talk:** 

How far can we just using gravity in the laboratory?

Necessary Caveats

#### This talk is NOT:

- 1) An experimental proposal or
- 2) A realistic present-day strategy

Necessary Caveats

#### This talk is NOT:

- 1) An experimental proposal or
- 2) A realistic present-day strategy

#### This talk IS:

- 1) An *outline* of a new direct detection strategy
- 2) The beginning of a conversation to identify new opportunities
- 3) What is necessary to detect DM gravity w/ existing technology

# Think Big & Small



Heavy DM

Planckian masses

# Tiny gravitational forces

Think Big & Small

Naively this is crazy because

$$\frac{G_N}{G_F} \sim \left(\frac{v}{m_{\rm Pl}}\right)^2 \sim 10^{-34}$$

But gravity is long range and heavy DM has large "charge"

e.g. for Planckian DM  $m_{\rm Pl} \approx 0.2 \,\mathrm{mg}$ 

$$F_{\rm sig} = \frac{G_N m_{\chi} m_{\rm det}}{b^2} \simeq 7 \times 10^{-17} \,\mathrm{N} \,\left(\frac{m_{\chi}}{\mathrm{mg}}\right) \left(\frac{m_{\rm det}}{\mathrm{mg}}\right) \left(\frac{\mathrm{mm}}{b}\right)^2$$

This is tiny...but smaller forces have already been measured!

### Zeptonewton Force Detection $10^{-21}$ N

#### Zeptonewton force sensing with nanospheres in an optical lattice

Gambhir Ranjit, Mark Cunningham, Kirsten Casey, Andrew A. Geraci<sup>\*</sup> Department of Physics, University of Nevada, Reno, Reno NV, USA

Optically trapped nanospheres in high-vacuum experience little friction and hence are promising for ultra-sensitive force detection. Here we demonstrate measurement times exceeding  $10^5$  seconds and zeptonewton force sensitivity with laser-cooled silica nanospheres trapped in an optical lattice. The sensitivity achieved exceeds that of conventional room-temperature solid-state force sensors by







Ranjit, Cunningham, Casey, Geraci arXiv:1805.12562

#### Total Force on Test Mass

$$F_{\rm in}(t) = F_{\rm sig}(t) + F_{\rm th}(t) + F_{\rm meas}(t).$$

$$F_{\rm in}(t) = F_{\rm sig}(t) + F_{\rm th}(t) + F_{\rm meas}(t).$$
3
Dark matter signal

5

DM Signal: One Test Mass



# DM Signal: One Test Mass



DM Signal: One Test Mass





$$F_{\rm sig} = \frac{G_N m_d m_{\chi} b}{(b^2 + v^2 t^2)^{3/2}}.$$

5

#### Time dependent transverse force on test mass



$$I = \int_0^{t_{\rm int}} dt F_{\rm sig}(t) \to \frac{2G_N m_\chi m_{\rm det} \tau}{b^2} \equiv 2\bar{F}\tau$$

Impulse delivered in one DM crossing time  $\tau = b/v \sim t_{int}$ 

#### Total Force on Test Mass



5

#### Thermal Noise on Test Mass



Mechanical oscillator coupled to support structure

$$\langle \Delta I^2 \rangle \equiv \int dt \int dt' F_{\text{noise}}(t) F_{\text{noise}}(t') \propto \delta(t-t')$$

Impulse from random Brownian motion uncorrelated

#### Thermal Noise on Test Mass



Mechanical oscillator coupled to support structure

$$\langle \Delta I^2 \rangle \propto \delta(t - t') \qquad \Delta I^2 = \alpha t_{\rm int} \qquad \alpha \ {\rm damping \ parameter}$$

Thermal noise (squared) grows linearly with integration time



For *N* uncorrelated sensors, noise decreases as  $\sqrt{N}$  $I_{\text{sig}}^2 \propto N^2$ ,  $\Delta I_{\text{thermal}}^2 \propto N \implies \text{SNR}^2 = \frac{I^2}{\Delta I^2} = \frac{4\bar{F}^2 N\tau}{\alpha}$ 



Correlated signal along *only one* linear track Uncorrelated along *all other* possible linear tracks



For mechanical oscillator  $\alpha_{mech} = 4m_{det}k_BT\gamma$ 

$$\mathrm{SNR}^2 = \frac{4\bar{F}^2 N\tau}{\alpha} = \left(\frac{G_N^2 m_{\chi}^2}{v}\right) \left(\frac{L}{b^4}\right) \left(\frac{m_{\mathrm{det}}}{k_B T\gamma}\right)$$

$$\begin{array}{c} \chi \\ & & \\ &$$

Not very promising in this basic formulation (need~ 5)

#### **Event Rates: Mechanical Resonators**



Dark Matter Mass  $\log m / C_0 V$ 



#### Event Rates: Free Falling Masses



For ~ mg mass detectors, usual DD BGs *are* thermal noise e.g. neutrons, cosmic rays, radiological activity... induce **uncorrelated** forces on different sensors

Possible concern from charged particles passing through detector In principle can be vetoed/reduced with shielding Can also apply B field to curve track

**Unlike LIGO, seismic noise does not fake the signal** Seismic activity affects **all** sensors simultaneously DM signal only yields signal in **one** linear track

#### Total Force on Test Mass



#### Previous discussion valid only if thermal noise dominates

Prepare detector wave packet of size  $\sim \Delta x \rightarrow \Delta p \gtrsim \hbar/\Delta x$ Measure again at later time  $\tau \rightarrow \Delta x + \hbar \tau / \Delta x m_{det}$ 

#### Previous discussion valid only if thermal noise dominates

Prepare detector wave packet of size  $\sim \Delta x \rightarrow \Delta p \gtrsim \hbar/\Delta x$ Measure again at later time  $\tau \rightarrow \Delta x + \hbar \tau / \Delta x m_{det}$ 

**Optimize for position resolution: Standard Quantum Limit**  $\Delta x_{SQL}^2 \sim \hbar \tau / m_{det} \rightarrow \Delta I_{SQL}^2 = \hbar m_{det} / \tau^2$ 

At SQL: 
$$\frac{\Delta I_{meas}^2}{\Delta I_{th}^2} = \begin{cases} \hbar v^2 / 4k_{\rm B}T\gamma d^2, & \text{mechanical} \\ \hbar m_{\rm d}/PA_{\rm d}d^2\sqrt{m_{\rm a}k_{\rm B}T}, & \text{free-falling.} \end{cases}$$

Need 50, 100 dB reduction in measurement noise to win if  $T\sim 10 {\rm mK}~,~\gamma\sim 10^{-6} {\rm Hz}~,~P=10^{-10}\,{\rm Pa}$ 

#### **Measuring With Squeezed States of Light**

Mechanical position encoded only in phase quadrature Reduce noise in phase, increase noise in amplitude Beating SQL demonstrated, but only ~ 12 dB so far

Caves, PRD 23, 1693 (1981) Purdy et. al. PRX 3, 031012 (2013) Asai et. al. Nature Photonics 7, 613 (2013)

**Back-Action Evasion (Quantum Speedometer)** Back action noise = random fluctuations in radiation pressure Possible for shot noise to cancel back-action noise Measure velocity instead of position

Knyazev, Danilishin, Hild, Khalili. 1701.01694 Braginsky and F. Khalili, Phys. Lett. A 147, 251 (1990). Other Long Range Forces

Same logic applies to other DM force with > mm range  $U(1)_{B-L}$ ,  $U(1)_{B-3L_i}$ ,  $U(1)_{L_i-L_j}$ 

Strong bounds on SM coupling from 5th force searches



Viable DM models testable with smaller setup

### Conclusions

Great advances in quantum control over mechanical systems
Single sensor zepto-Newton sensitivity already achieved
Detect ~ mg DM gravity w/ large array of precision sensors
Probe models with non thermal histories (WIMPzillas, pBH...)
Trigger on signal across DM path; no correlation elsewhere

Mechanical Resonators: practically limited by thermal noise Free Falling Masses: difficult setup, but promising SNR scaling

#### **Key Challenges:**

Scaling up existing concepts (need ~1e9 in ~meter volume) Evading measurement noise (e.g. squeezed light)

Potential sensitivity to other possible DM-SM long range forces