Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Gravitational Dark Matter Direct Detection

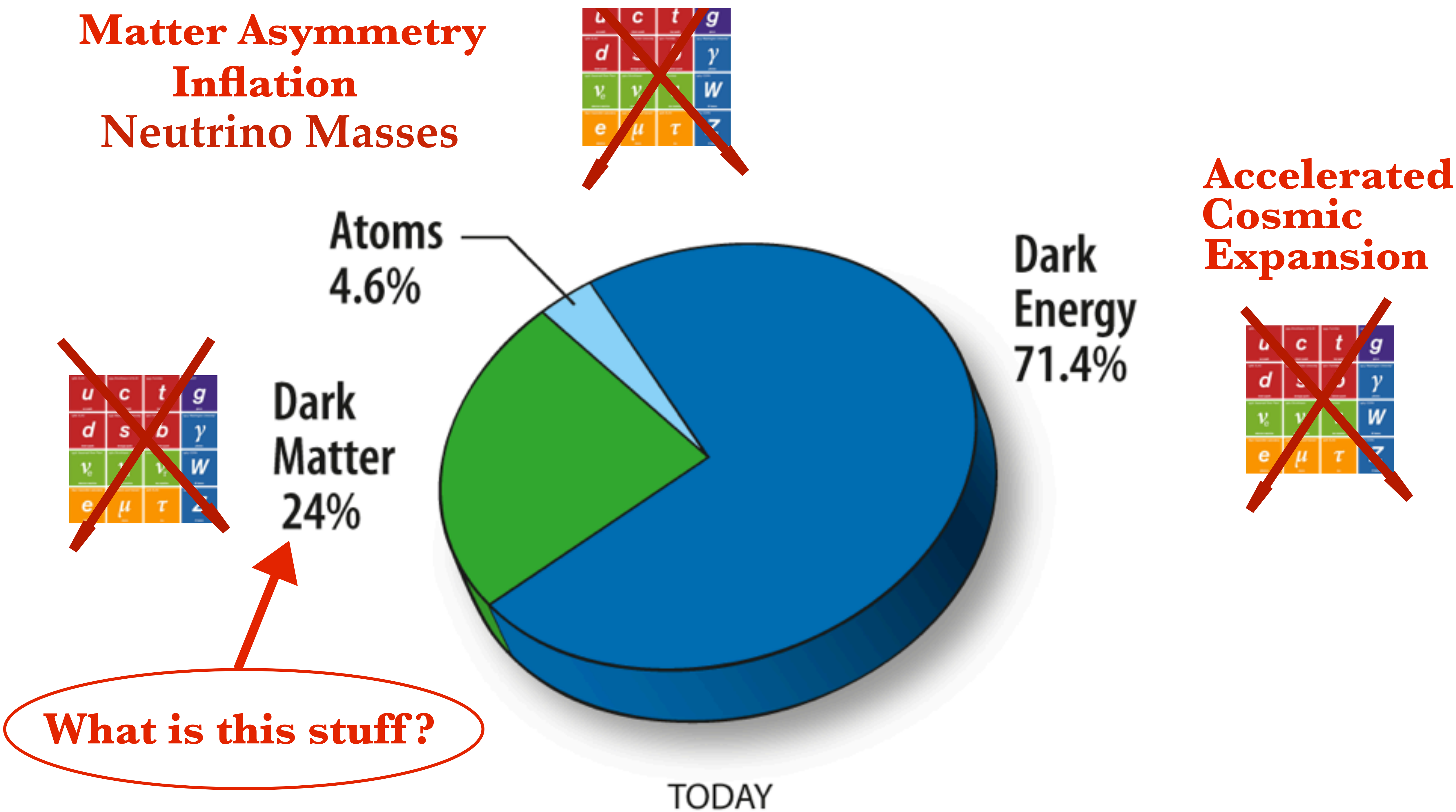
Gordan Krnjaic

+ Daniel Carney, Sohitri Ghosh, Jacob Taylor

1903.00492

APEC Seminar, Kavli IPMU, April 15, 2019

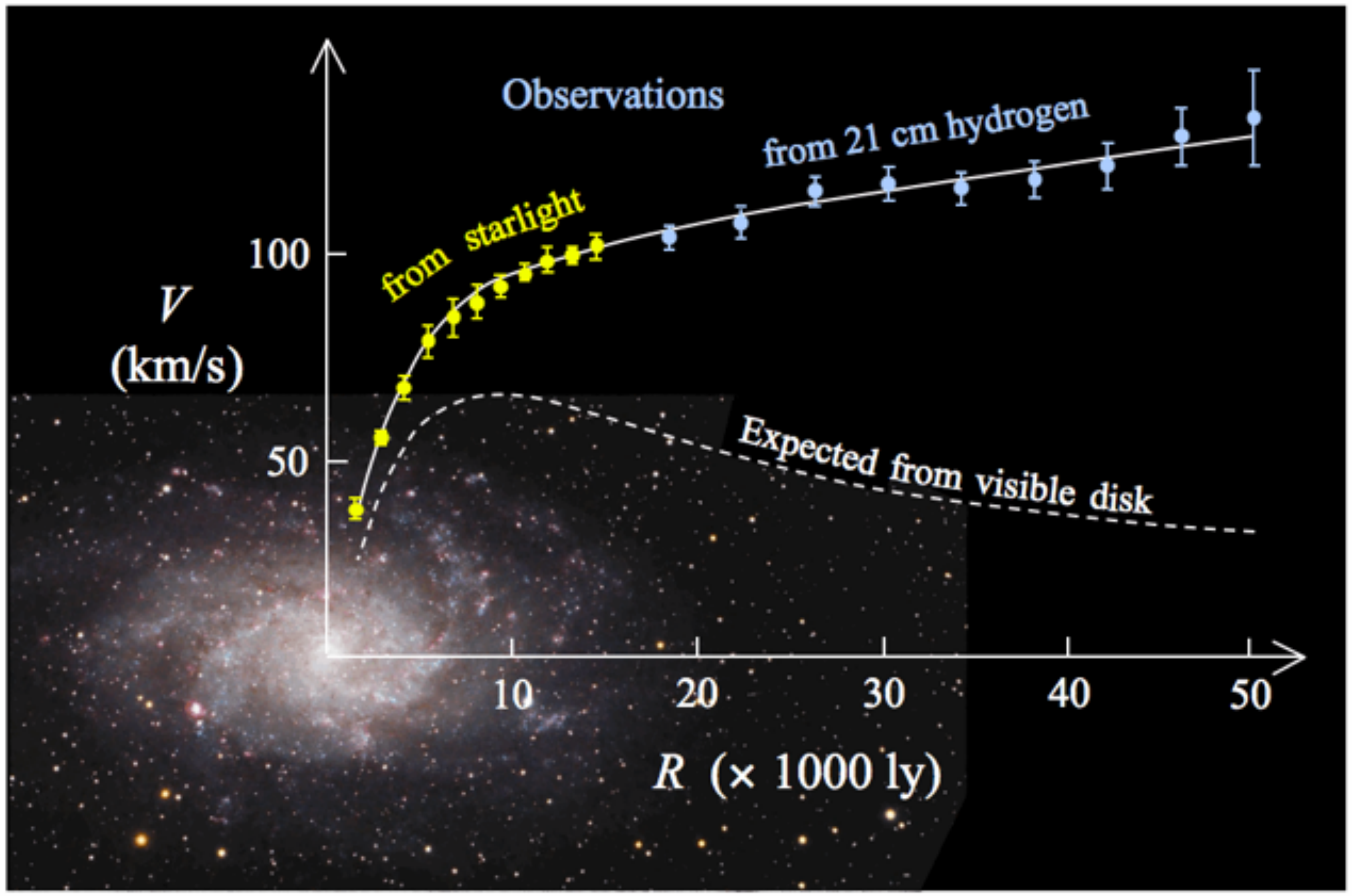
Open Questions in Fundamental Physics



Also Quantum Gravity

Evidence for Dark Matter

Galactic Rotation Curves

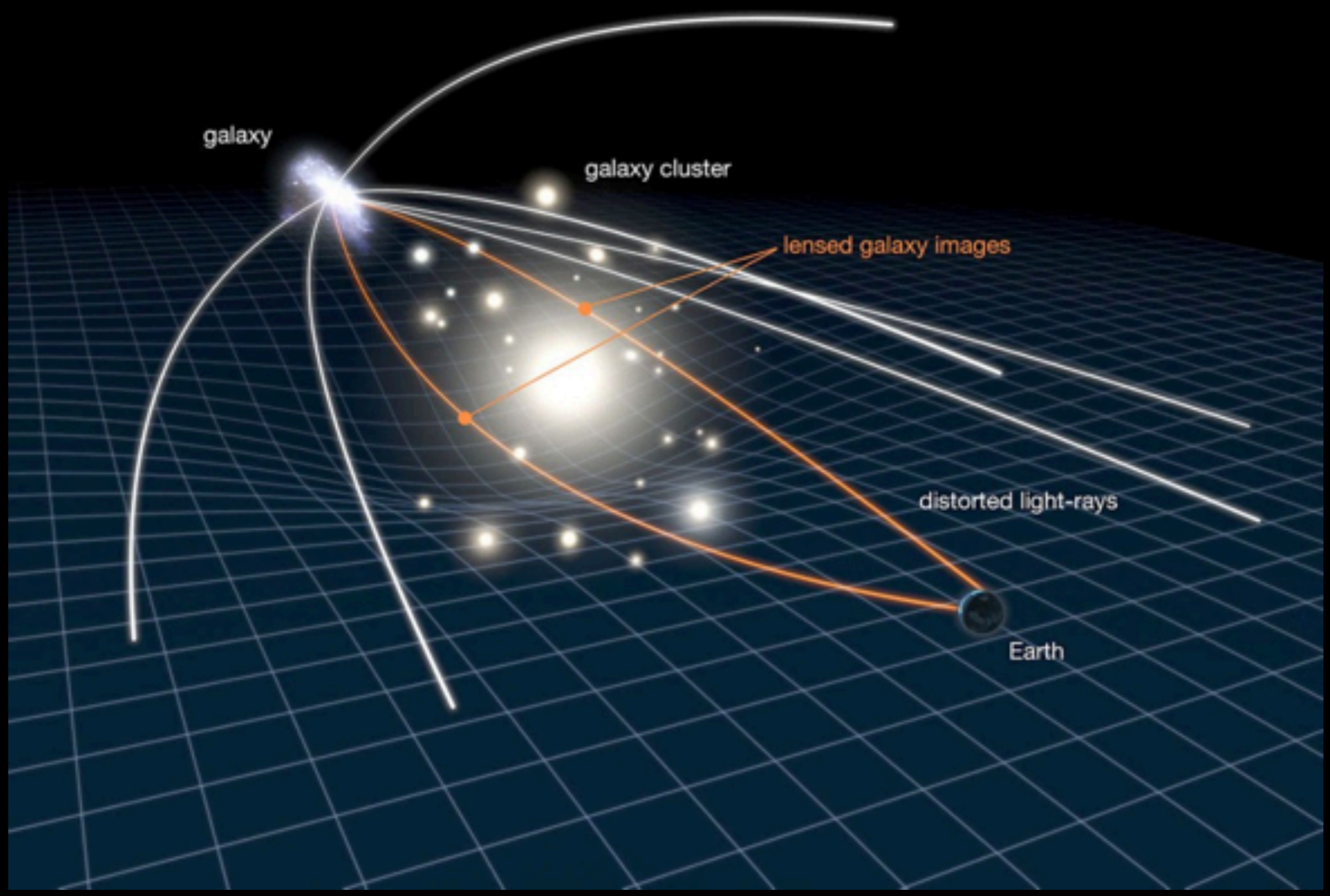


Dramatic effect: requires ~85% of matter to be "dark"

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

Evidence for Dark Matter

Gravitational Lensing



Images NASA/ESA

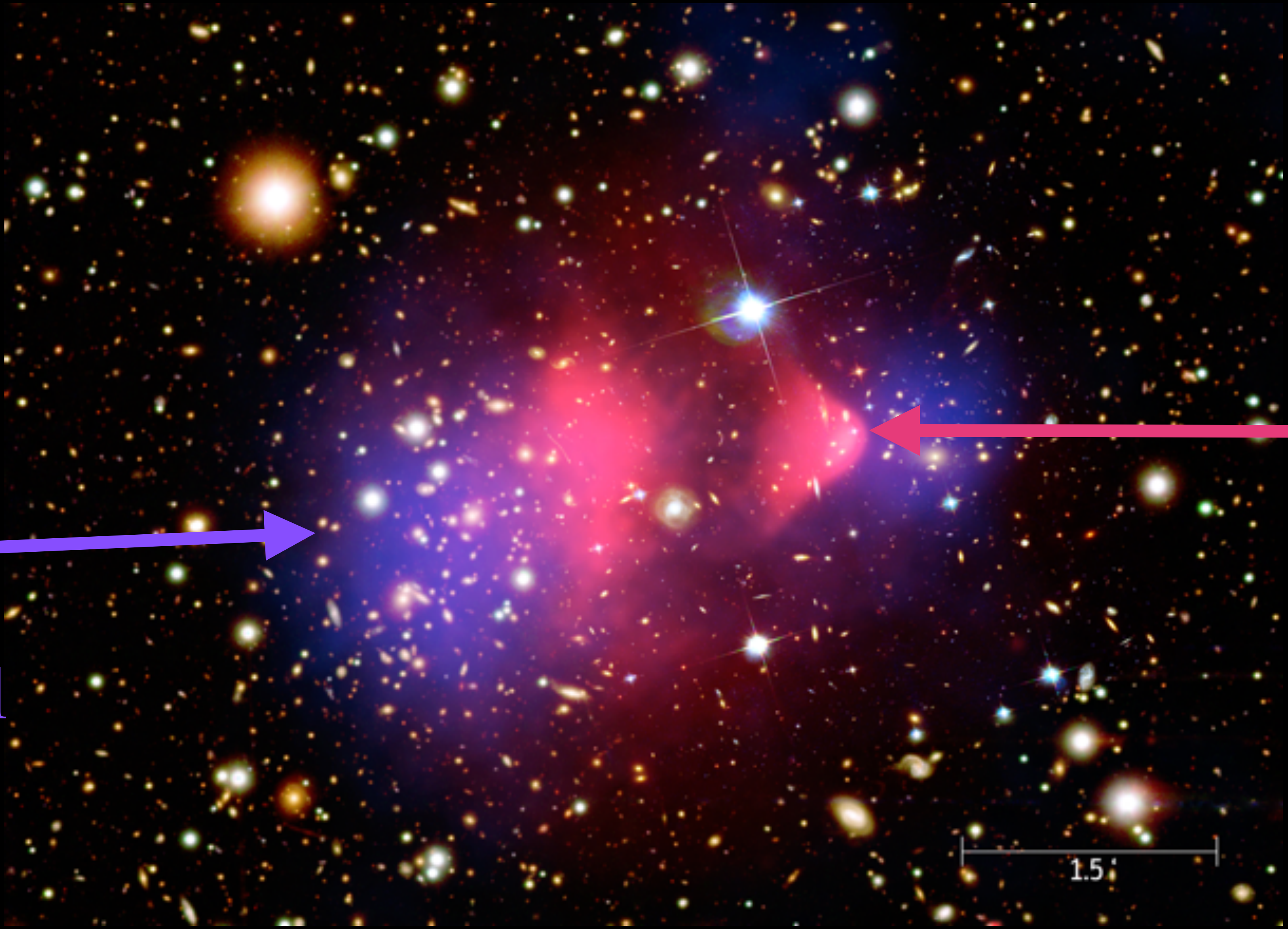
“Weighs” total matter: requires ~85% of matter to be “dark”

Evidence for Dark Matter

Galaxy Cluster Collisions

Total Matter

gravitational lensing



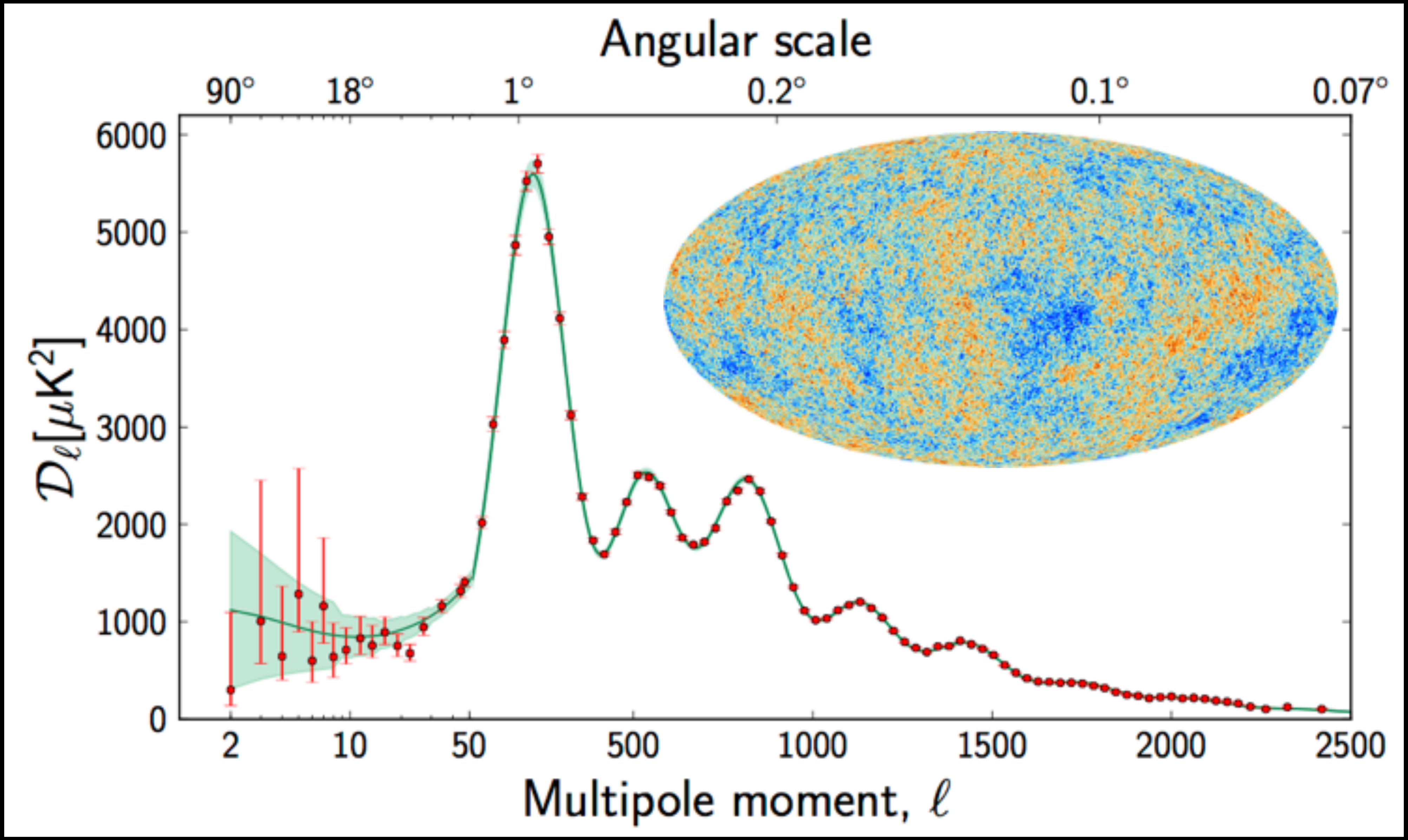
Visible Matter

Image overlay
Hubble & Chandra

~ 85% of total mass passed through without scattering

Evidence for Dark Matter

CMB Power Spectrum

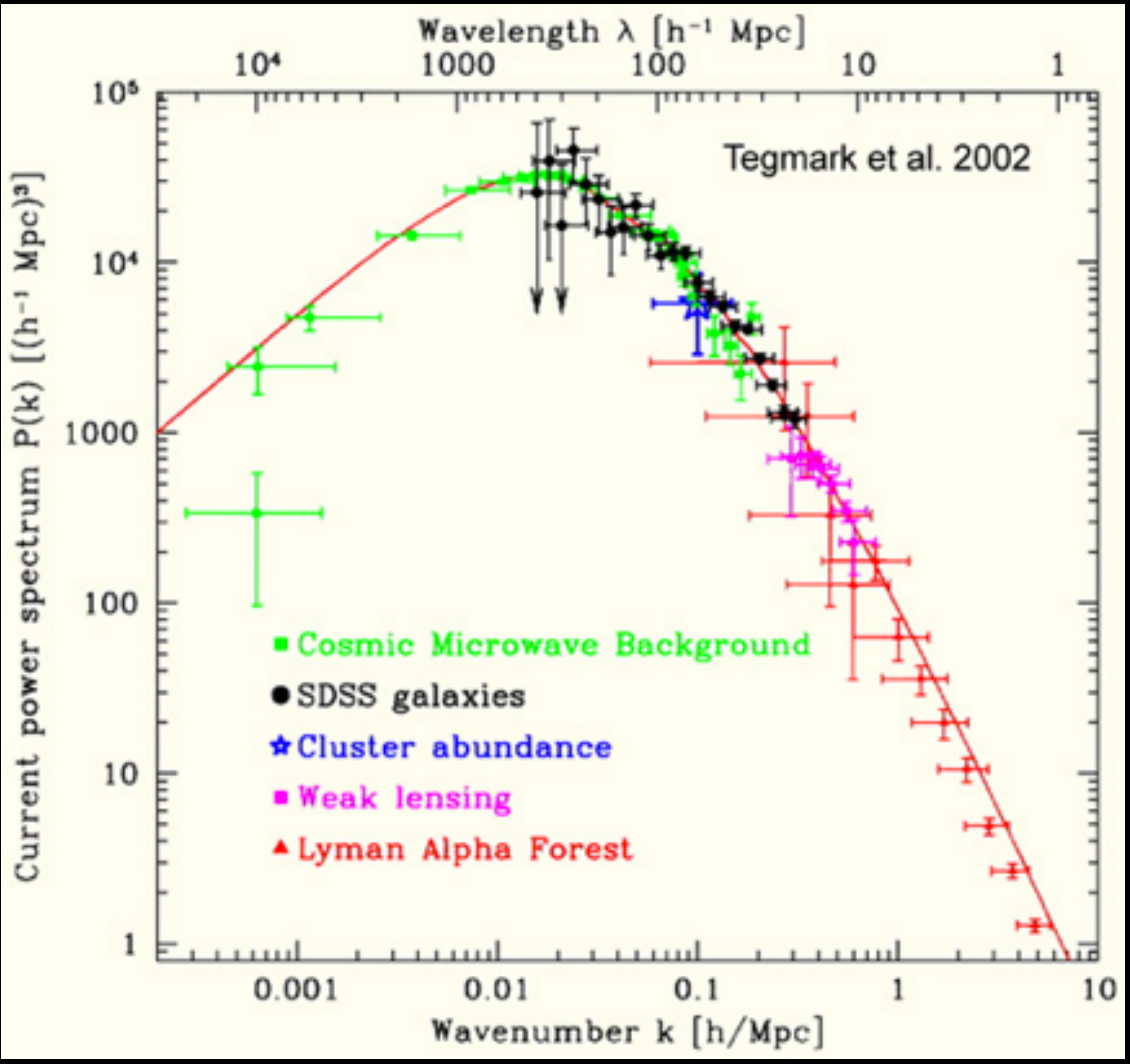


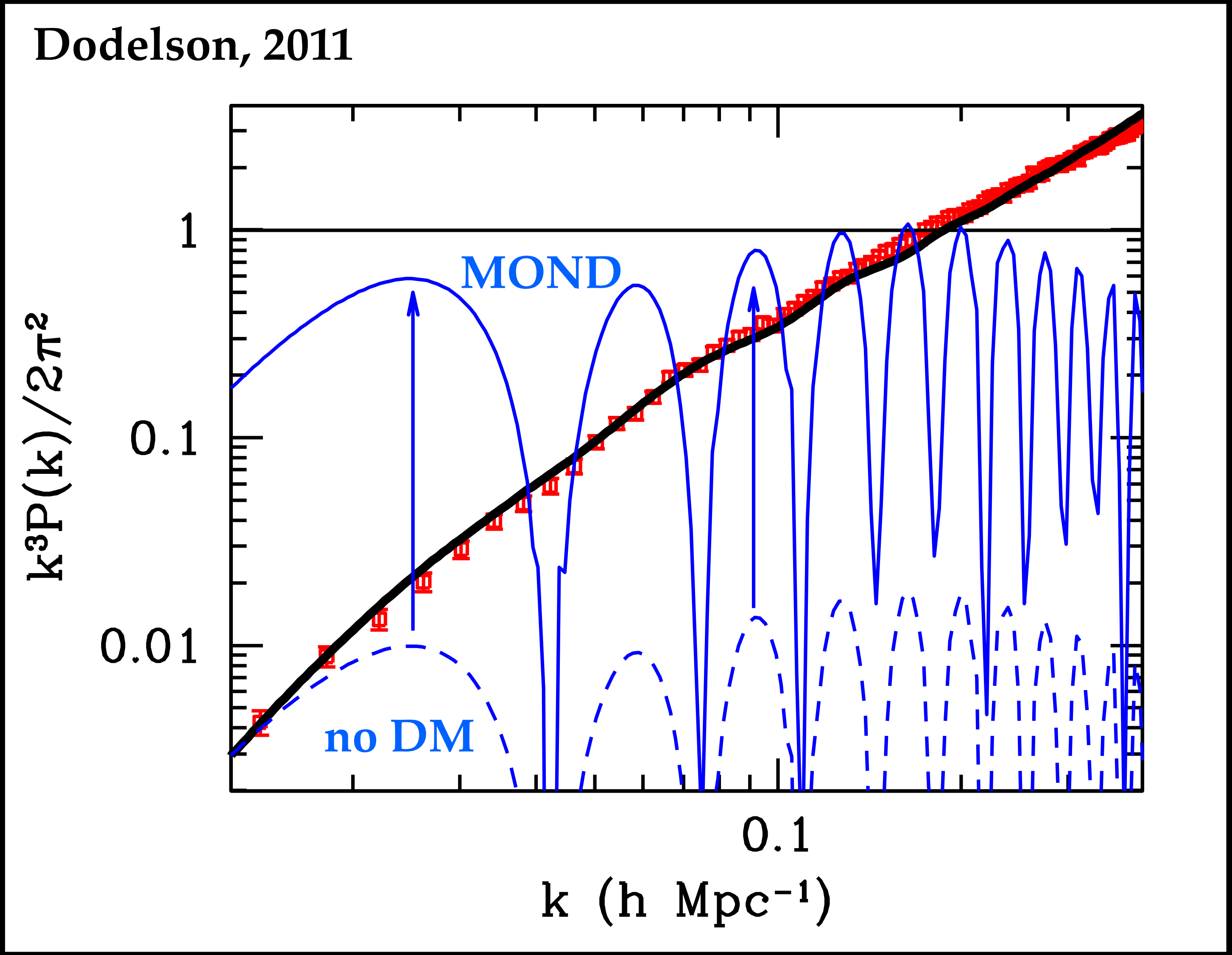
~85% of matter is gravitating, but not exerting pressure

Image:
Planck 2013

Evidence for Dark Matter

Matter Power Spectrum

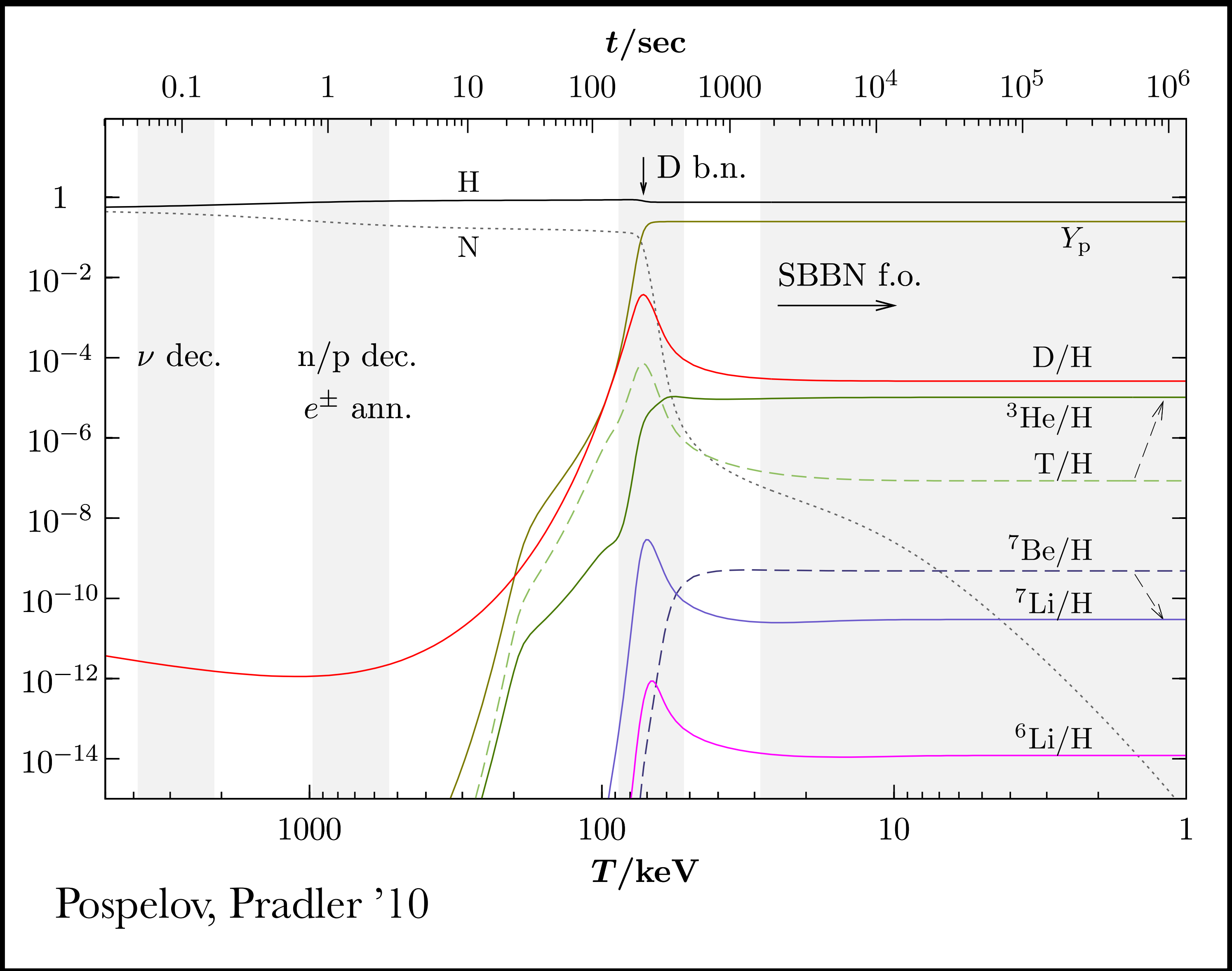


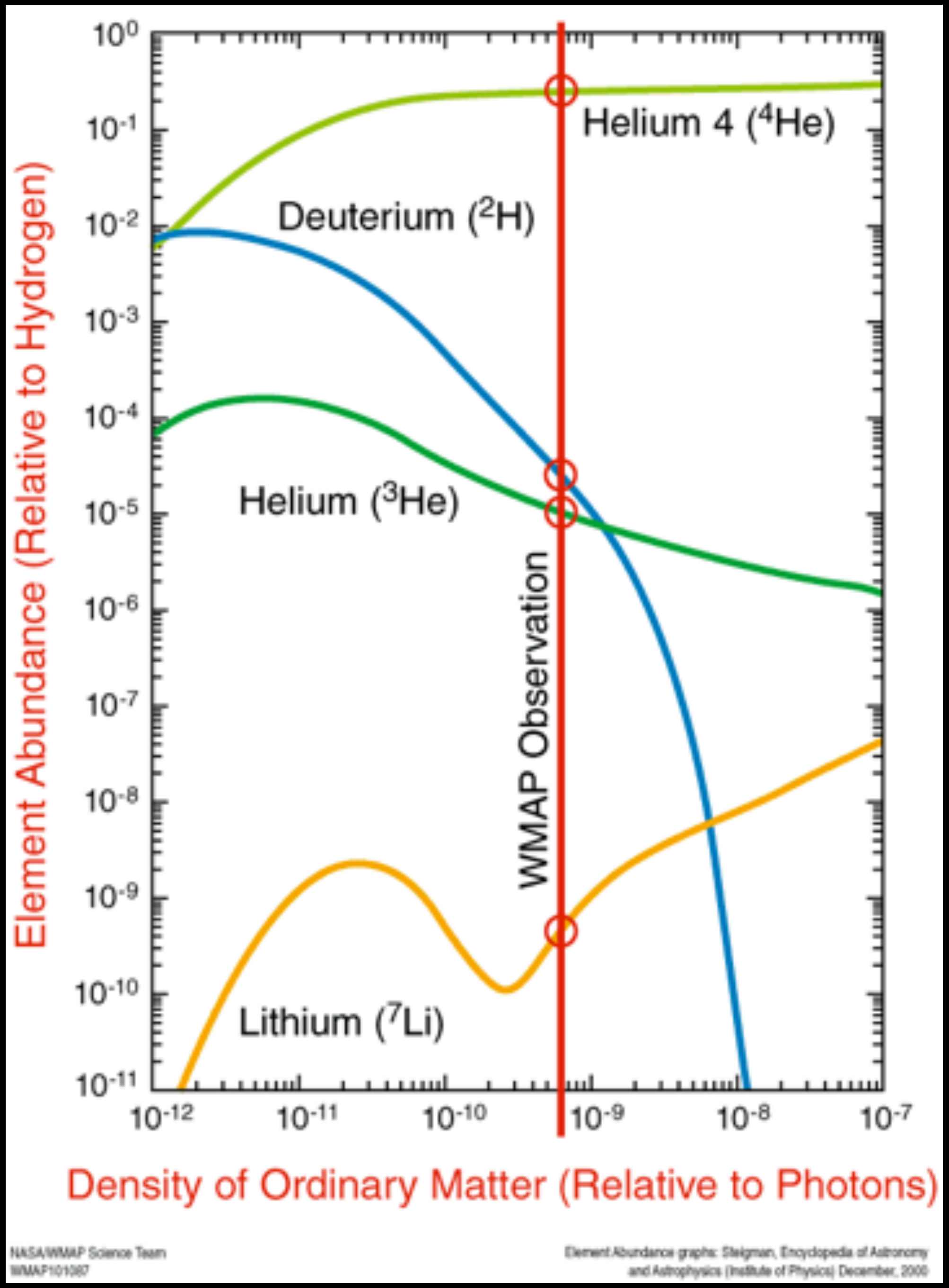


Observation & theory agree with
~85% pressure-less matter, 15% conventional "baryonic"

Evidence for Dark Matter

Light Element Yields @ BBN





Requires baryon density to be ~ 15% of total

Single parameter theory

$$\Omega_b \equiv \rho_b/\rho_{\text{tot.}}$$

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

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*

How do we usually approach DM?

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

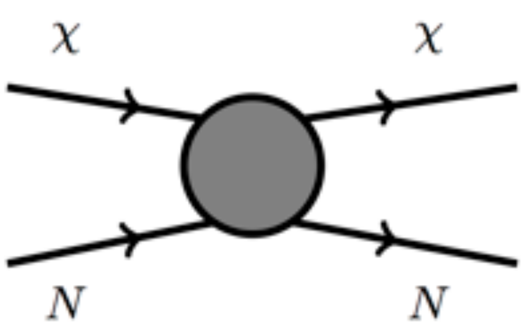
Choice usually dictated by technology

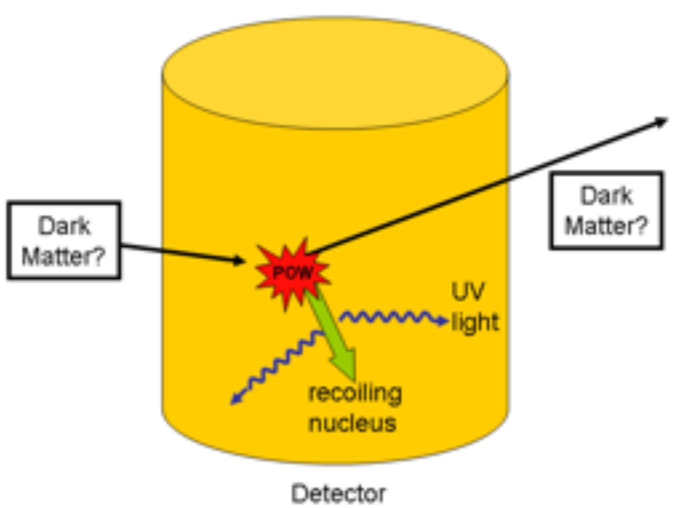
Concern: DM becomes moving target living under a lamp post

Hard to make firm statements about DM

How do we usually look for DM?

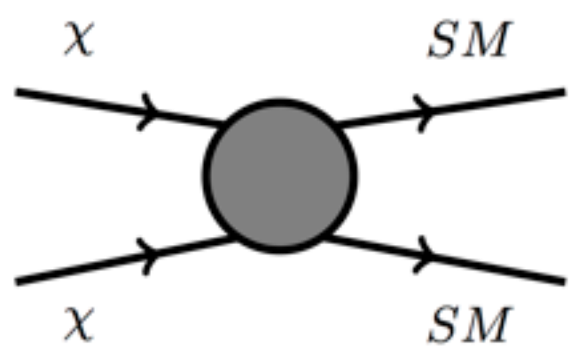
Direct Detection

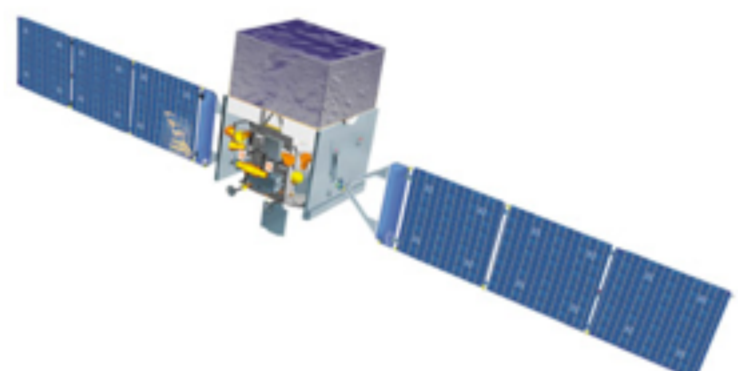




(scattering)

Indirect Detection

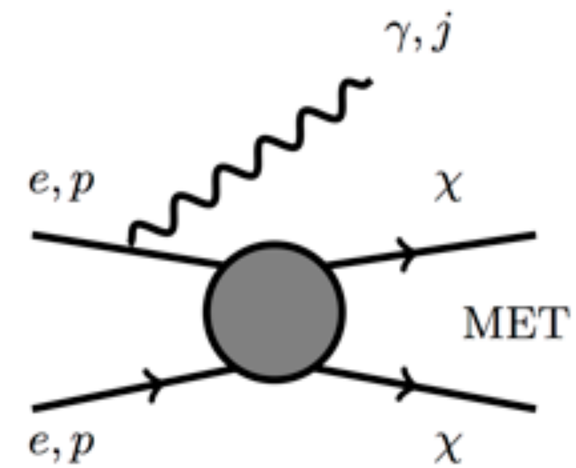


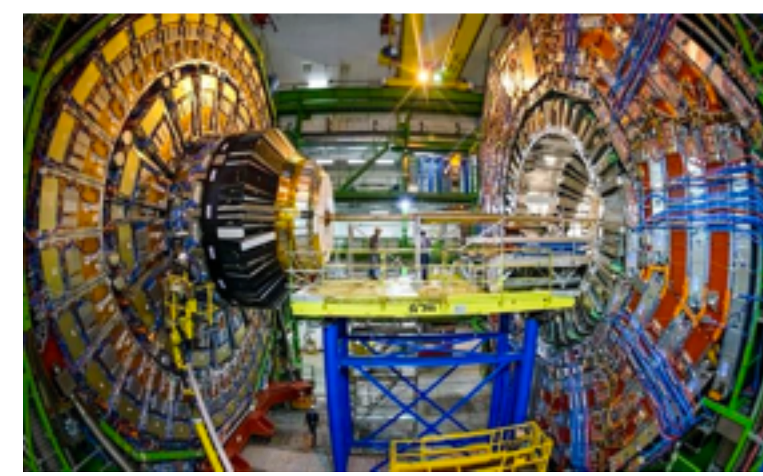


Fermi Telescope

(annihilation)

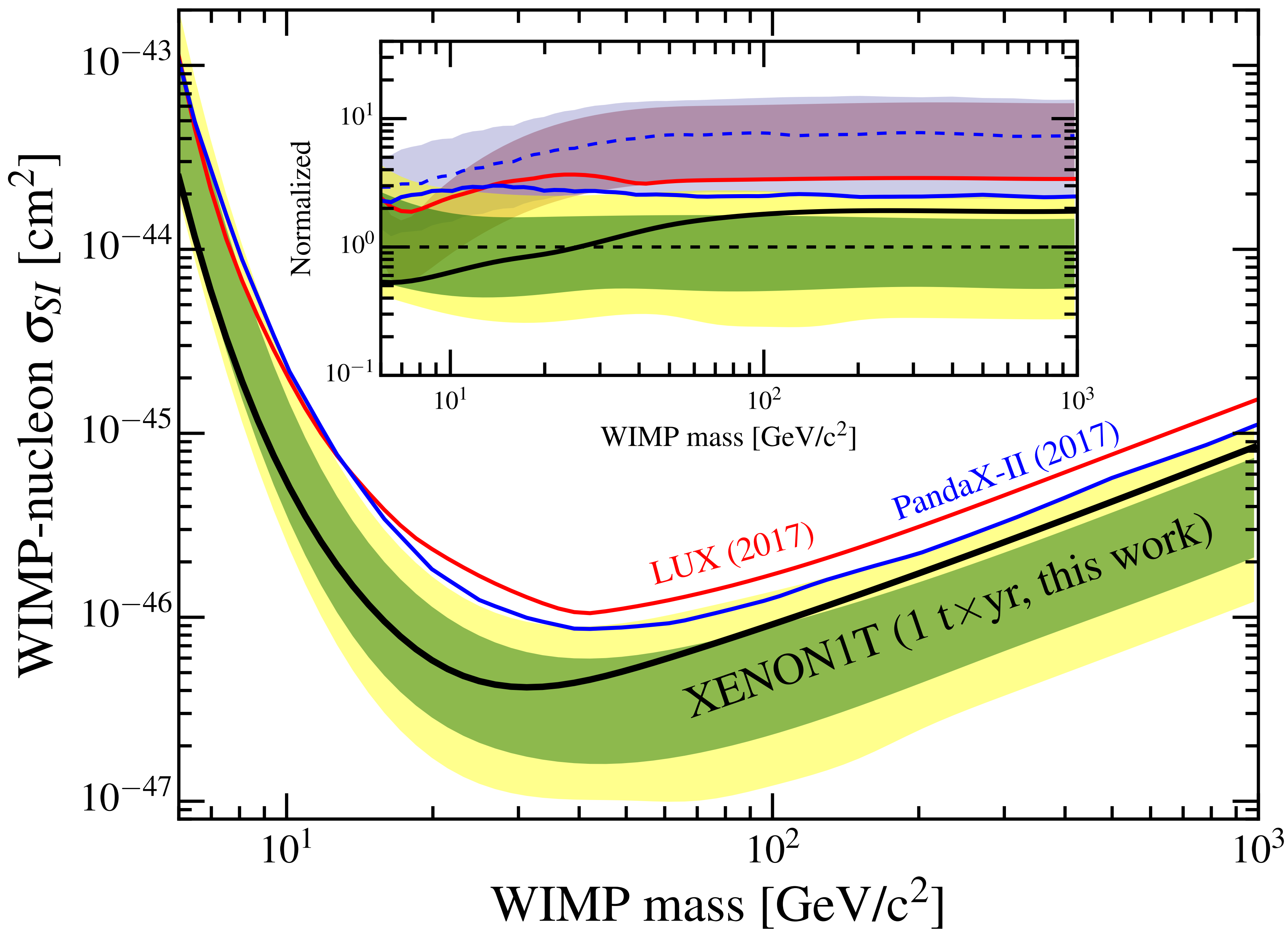
Colliders





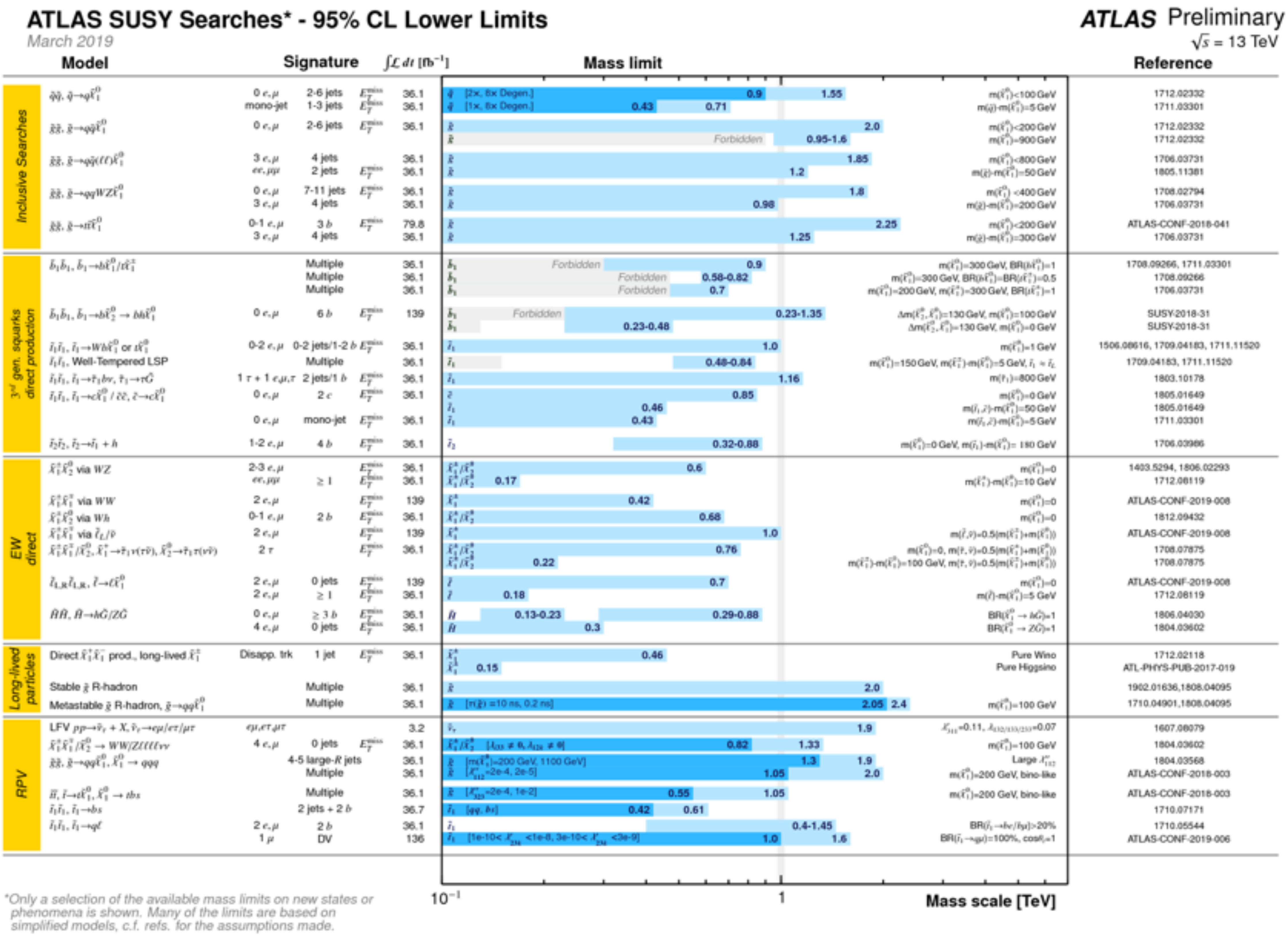
(production)

Updating Priors on WIMPs

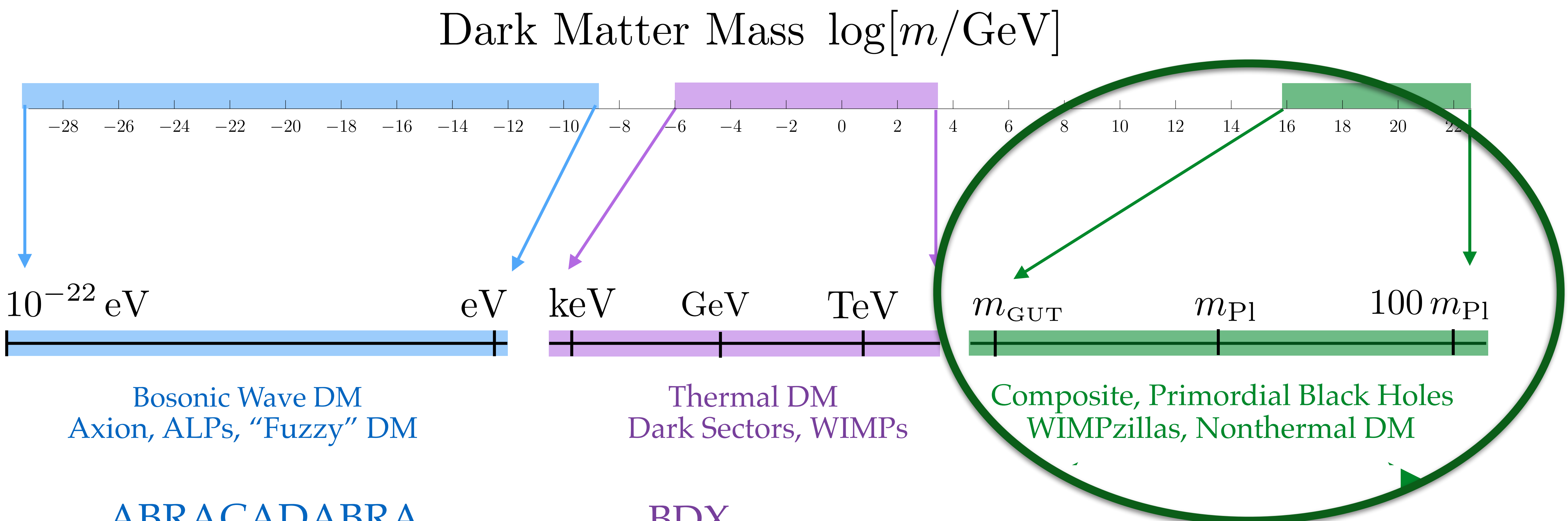


XENON 1T Collaboration arXiv:1805.12562

Updating Priors on WIMPs



Lots of new ideas for light DM detection < GeV



ABRACADABRA
ADMX
CASPER
DM Radio

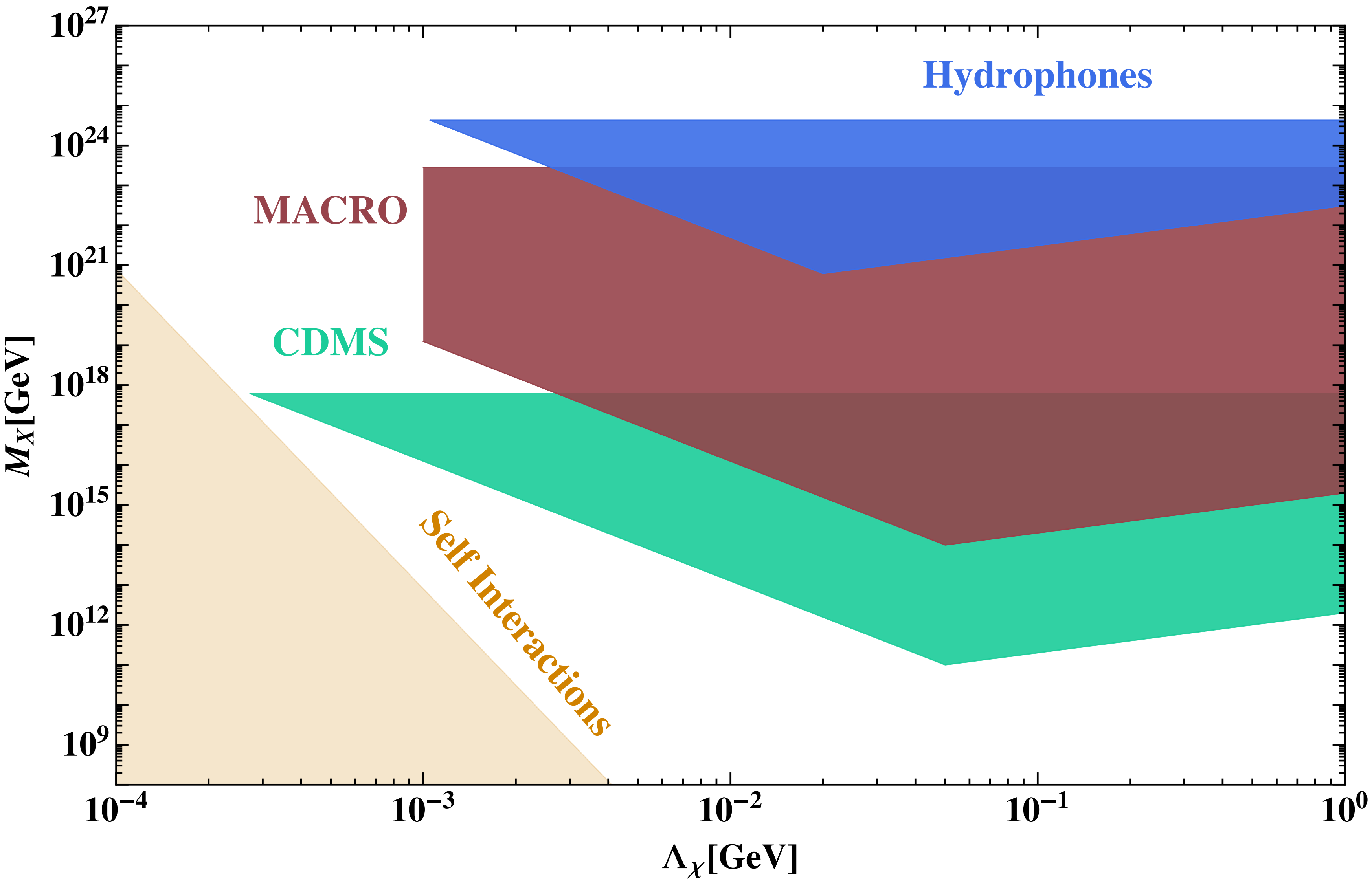
BDX
LDMX
MiniBooNE
SENSEI

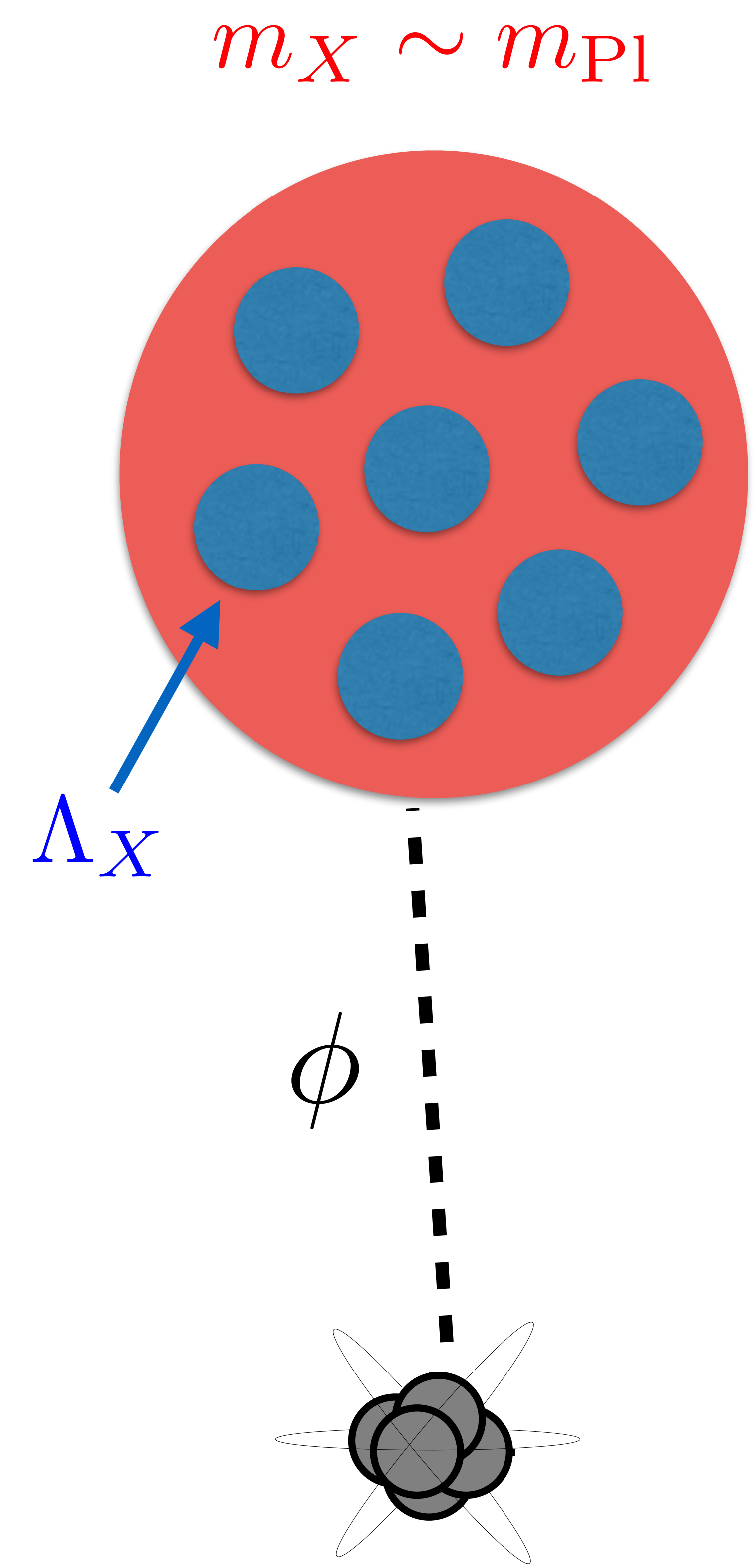
What about here?

For a review https://arxiv.org/abs/1707.04591

New Ideas in Heavy DM

Ultra heavy dark "blobs" (or nuclei)





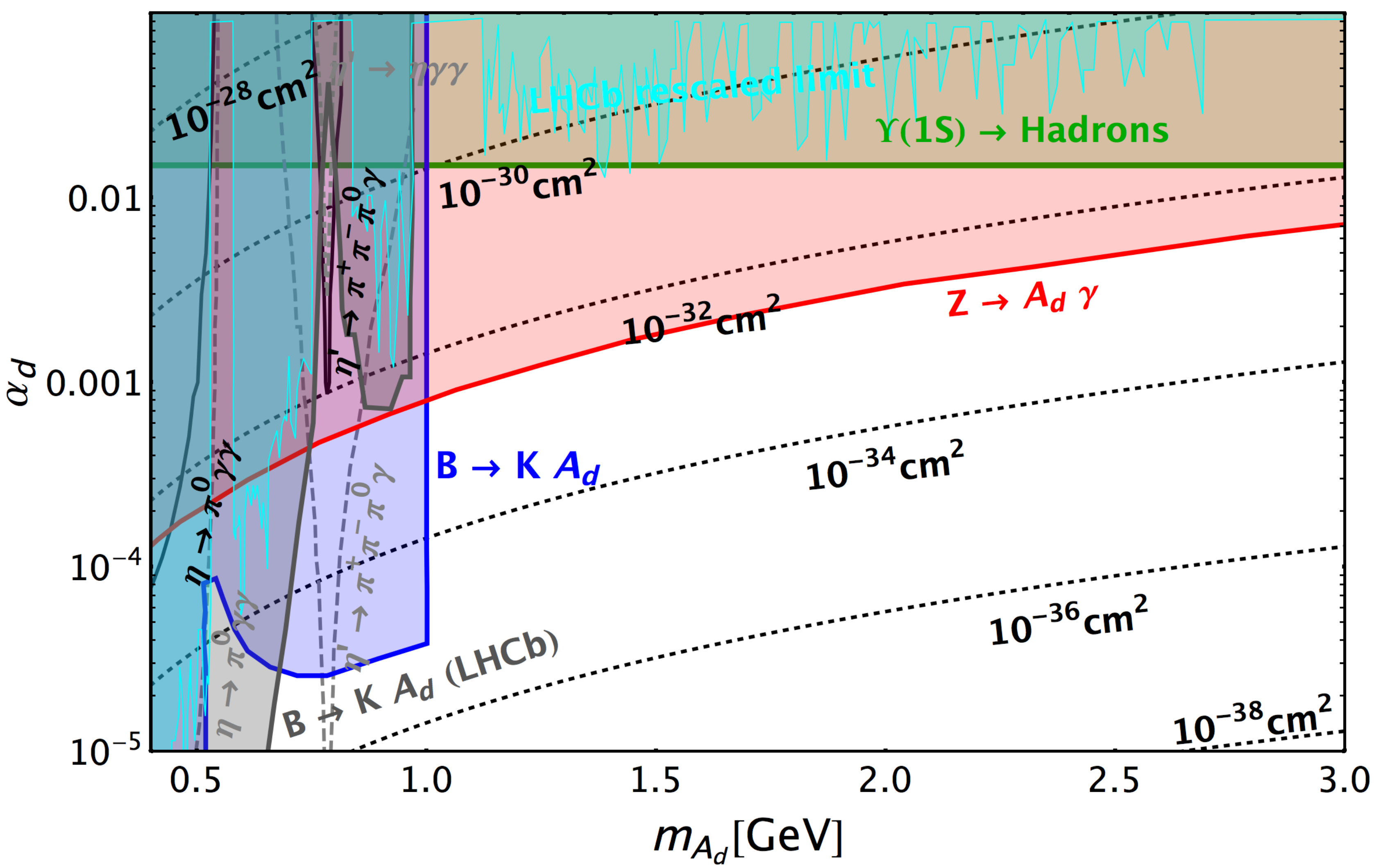
Can have large form factor enhancements

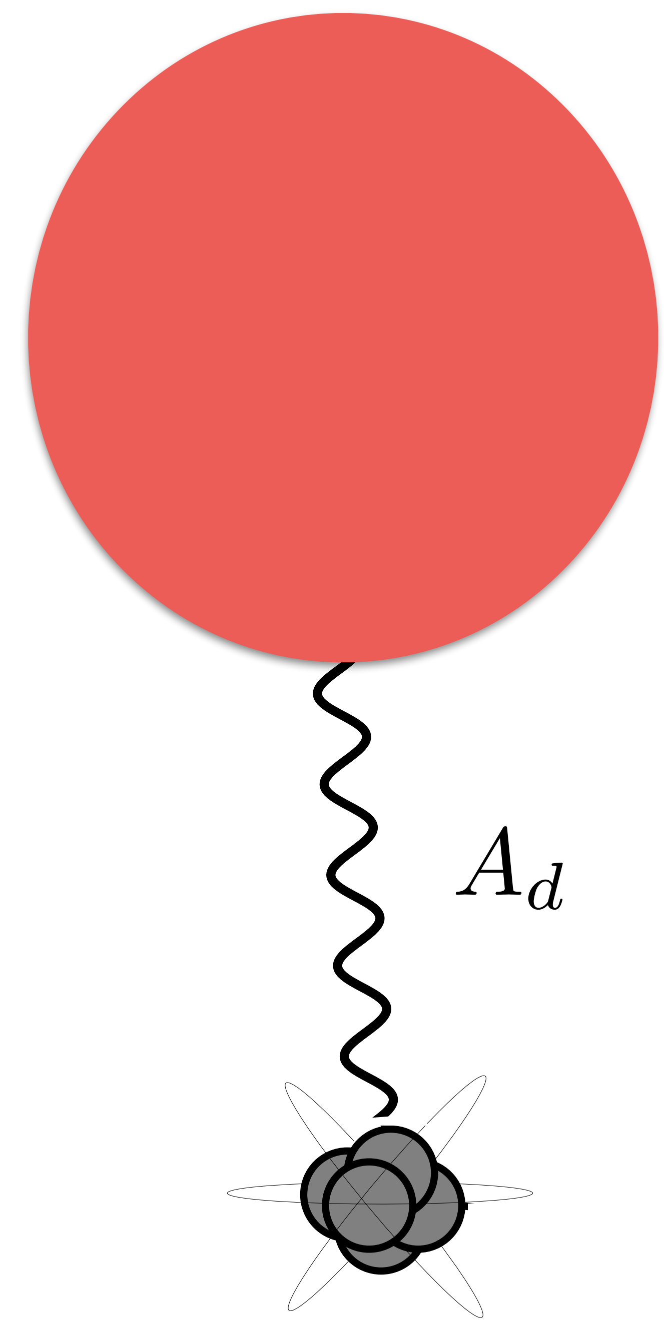
DD target

Grabowska, Melia, Rajendran 1807.03788

New Ideas in Heavy DM

Planck scale DM, GeV scale "mediator"





Can have large interaction rate

Multiple scattering at DD experiments

DD target

Davoudiasl, Mohlabeng 1809.07768

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:

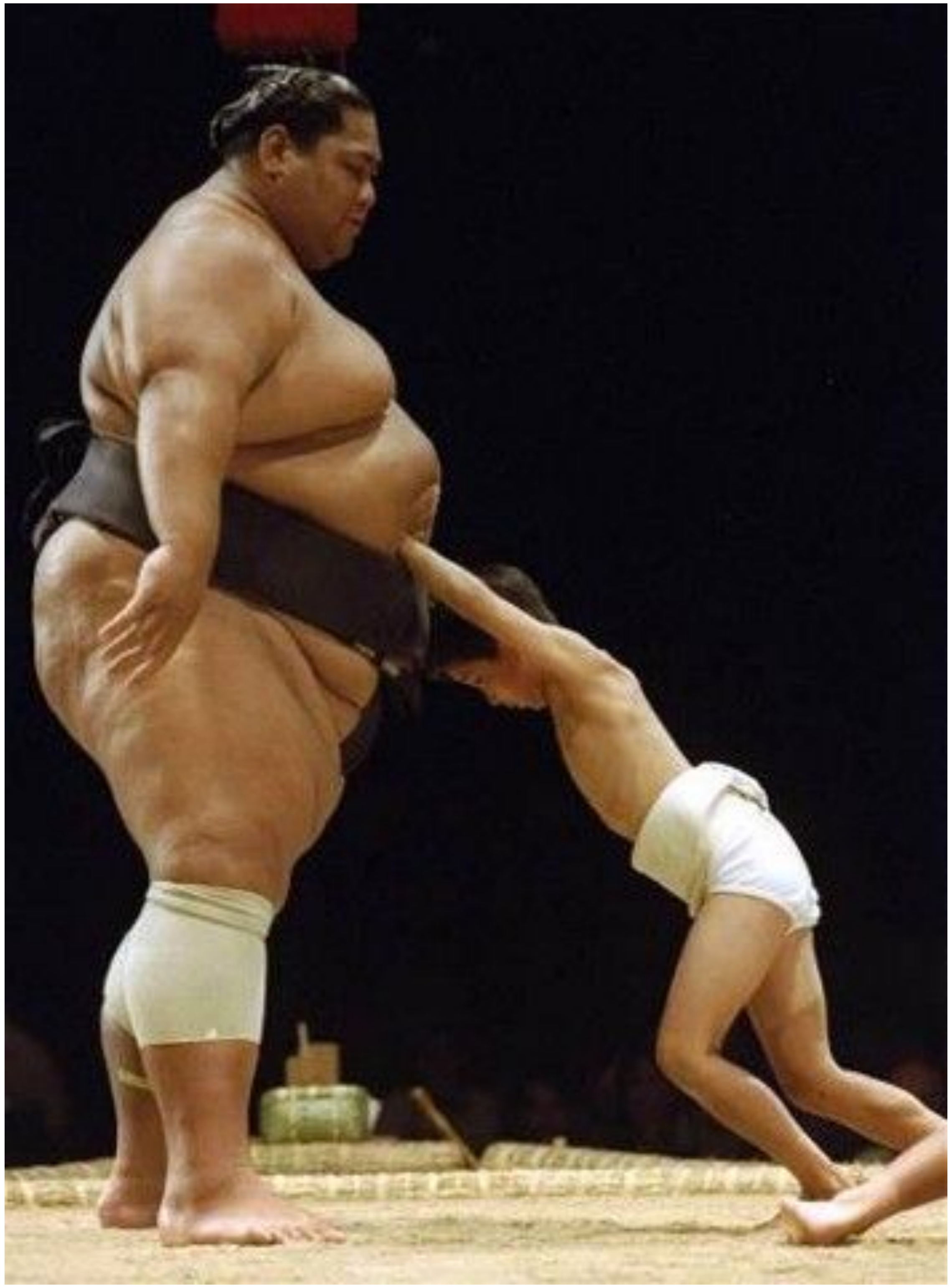
1) An *outline* of a new direct detection strategy

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 $m_{\rm Pl} \approx 0.2\,{\rm mg}$

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

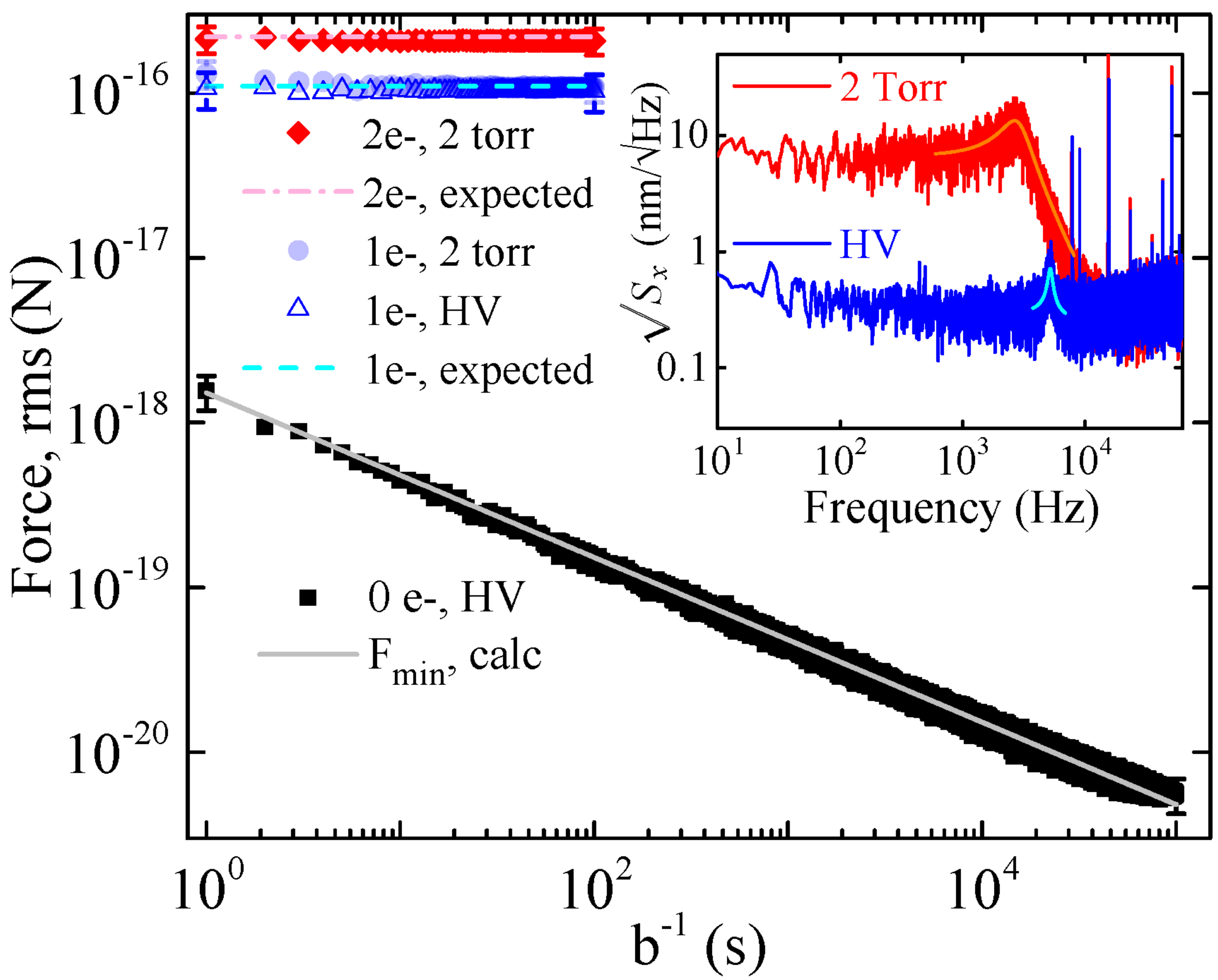
This is tiny…but smaller forces have already been measured!

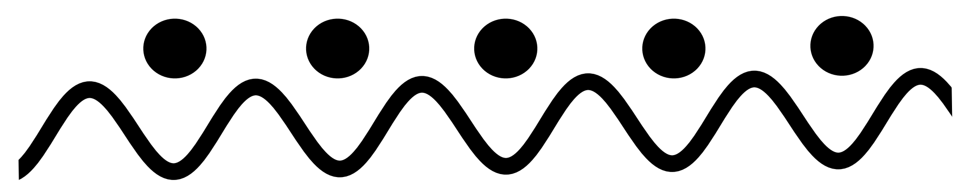
Zeptonewton Force Detection 10^{-21} N

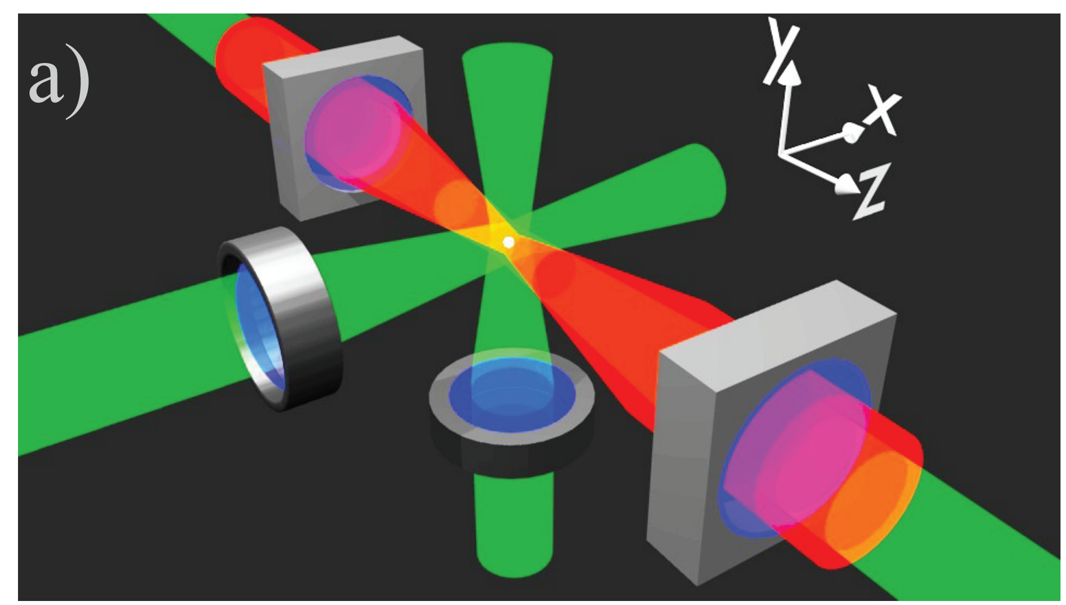
Zeptonewton force sensing with nanospheres in an optical lattice

Gambhir Ranjit, Mark Cunningham, Kirsten Casey, Andrew A. Geraci*
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

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

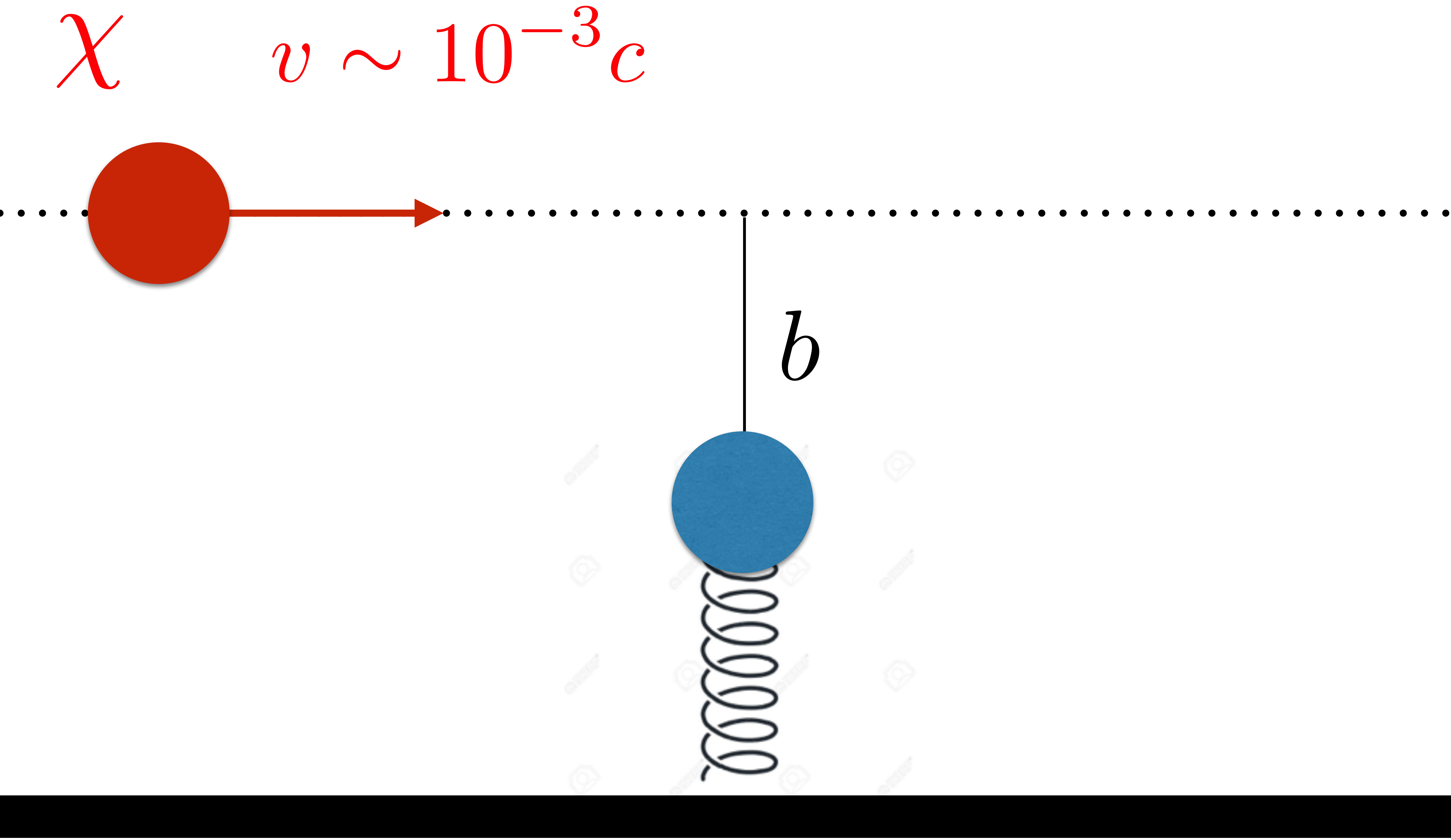
Total Force on Test Mass

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

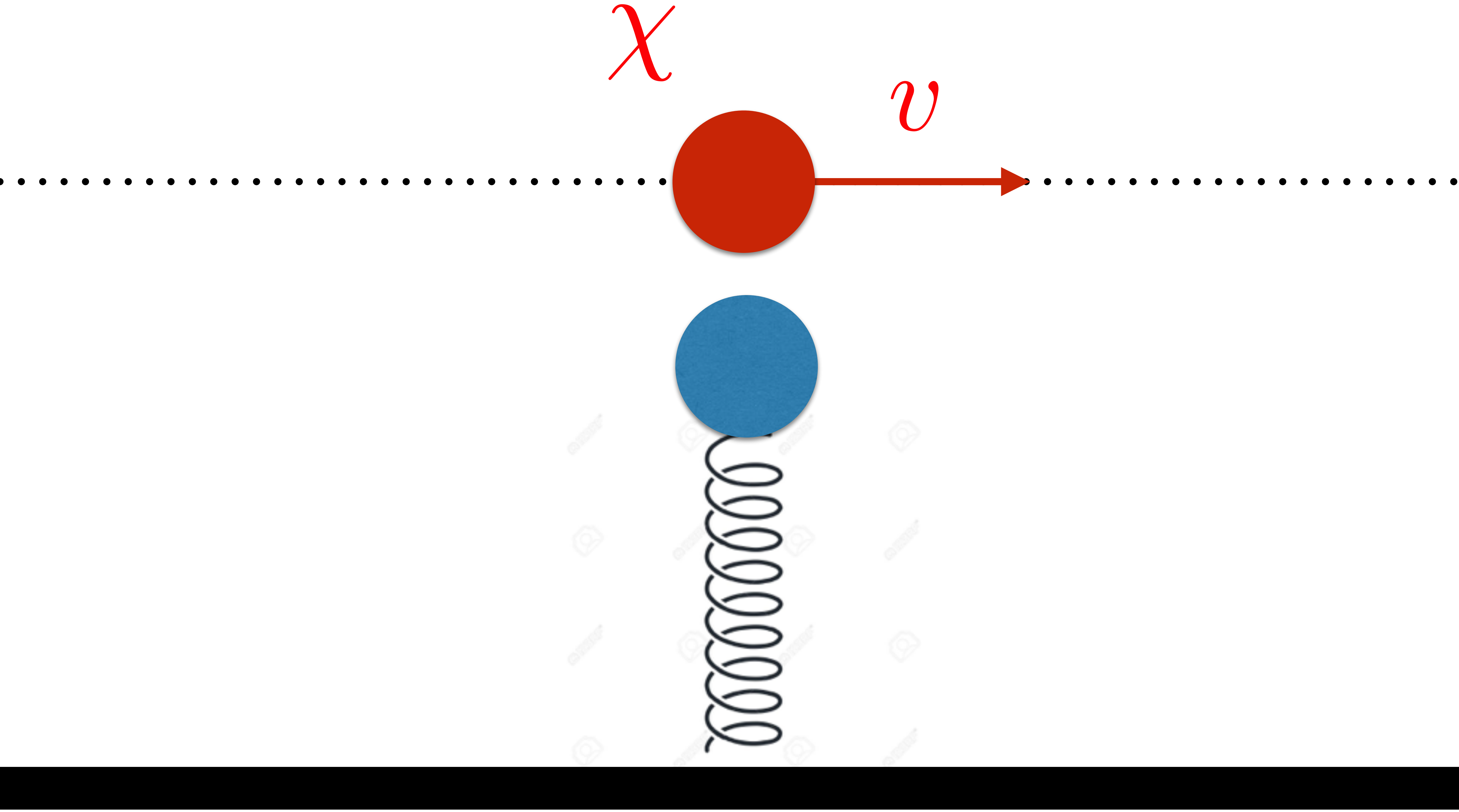
↓

Dark matter signal

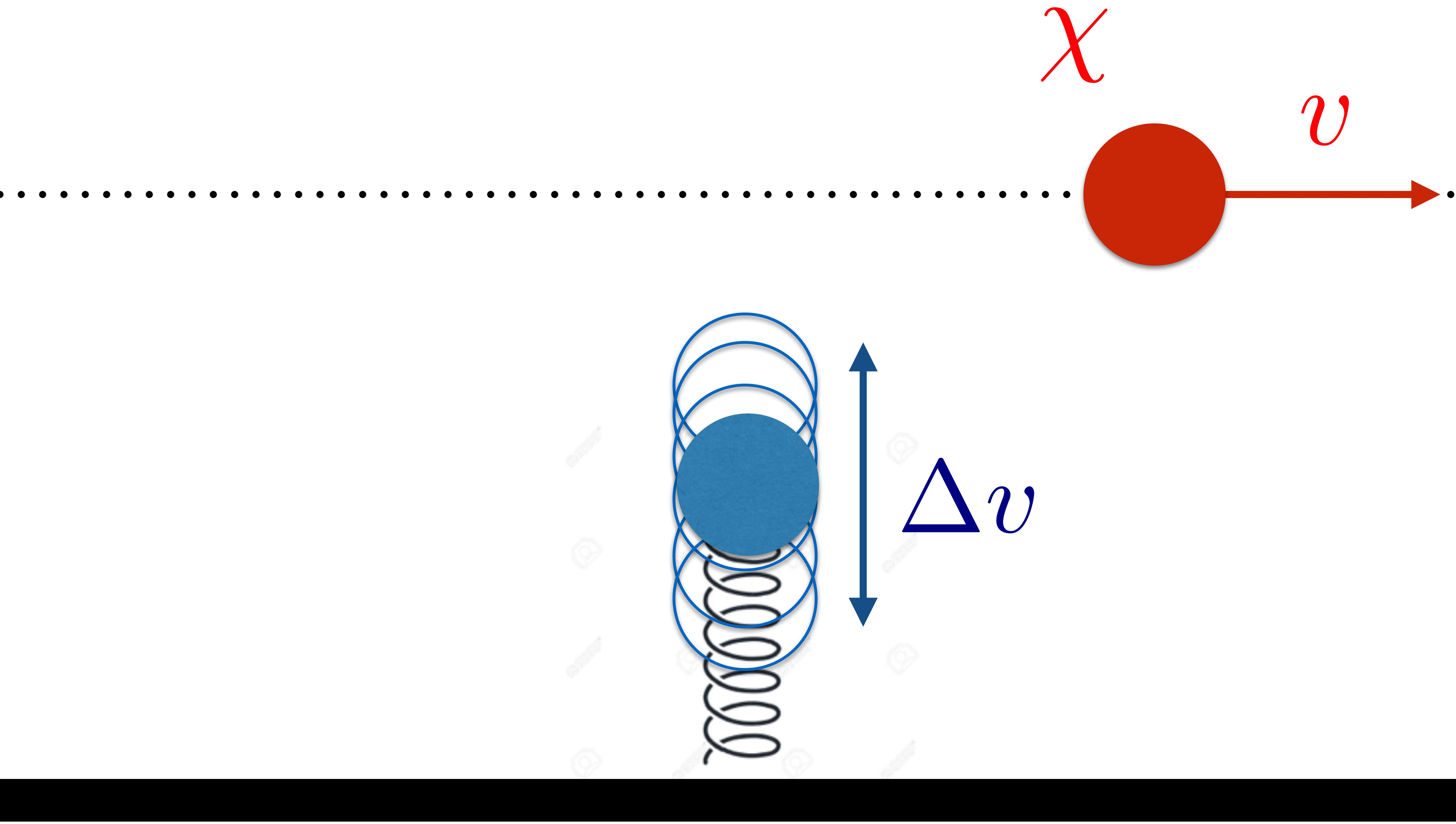
DM Signal: One Test Mass



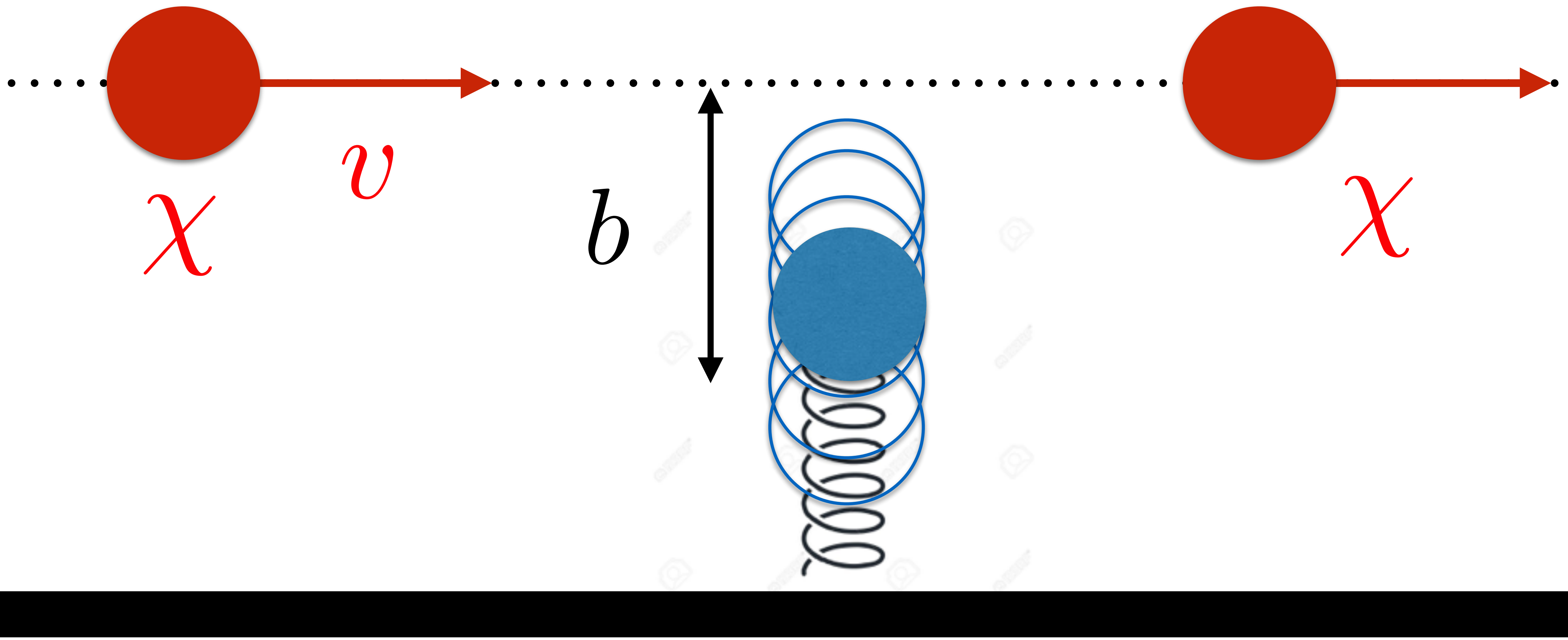
DM Signal: One Test Mass



DM Signal: One Test Mass



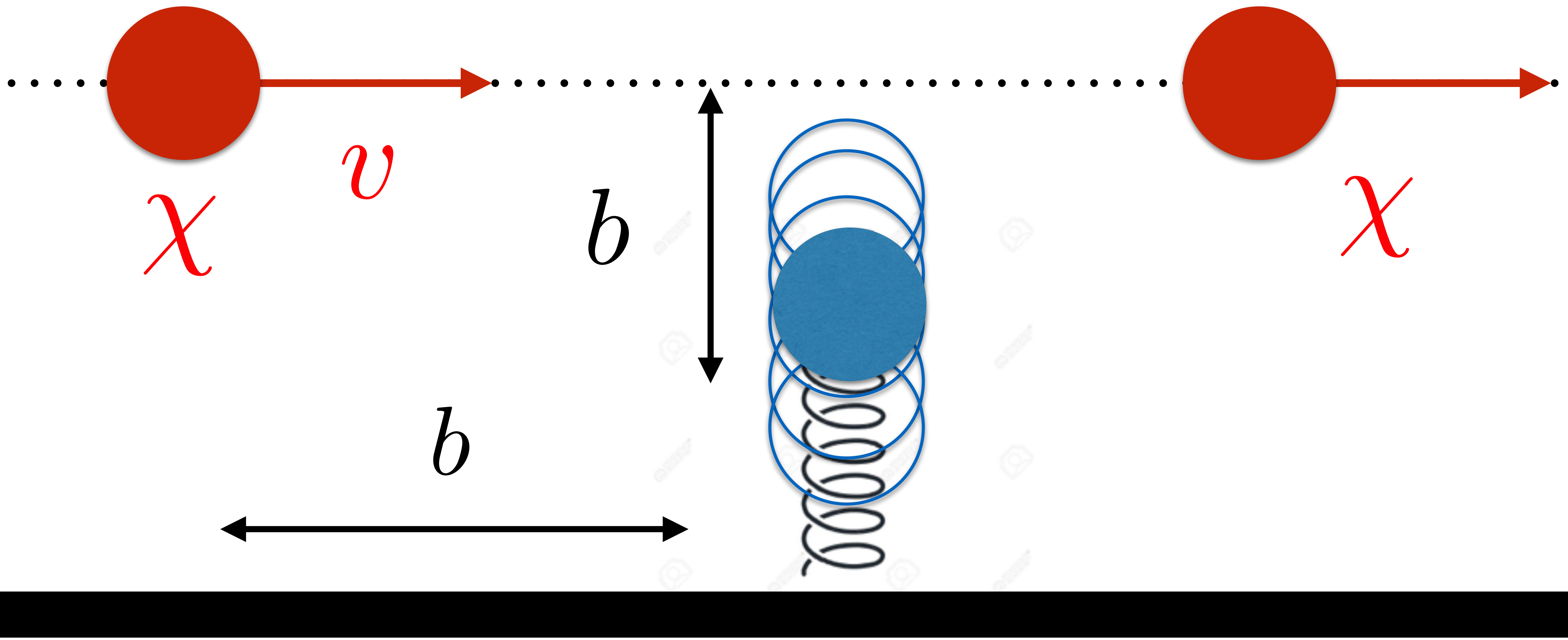
DM Signal: One Test Mass



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

Time dependent transverse force on test mass

DM Signal: One 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 $\tau = b/v \sim t_{\rm int}$

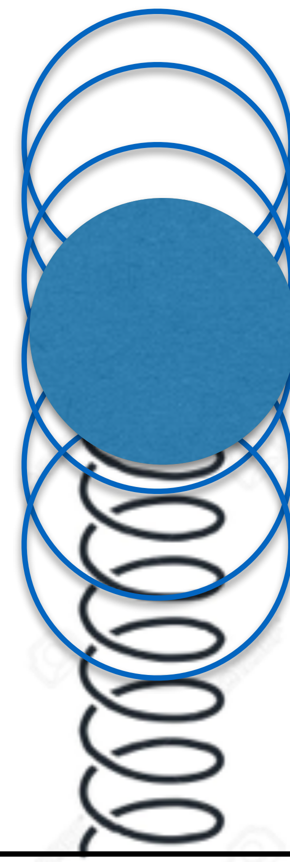
Total Force on Test Mass

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

↓

Thermal noise

Thermal Noise on Test Mass



$T \sim 10\,\mathrm{mK}$

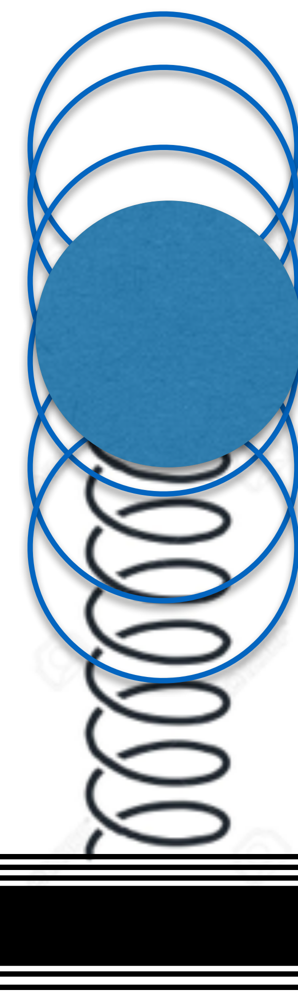
Oscillator at finite temp

Mechanical oscillator coupled to support structure

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

Impulse from random Brownian motion uncorrelated

Thermal Noise on Test Mass



$T \sim 10\,\mathrm{mK}$

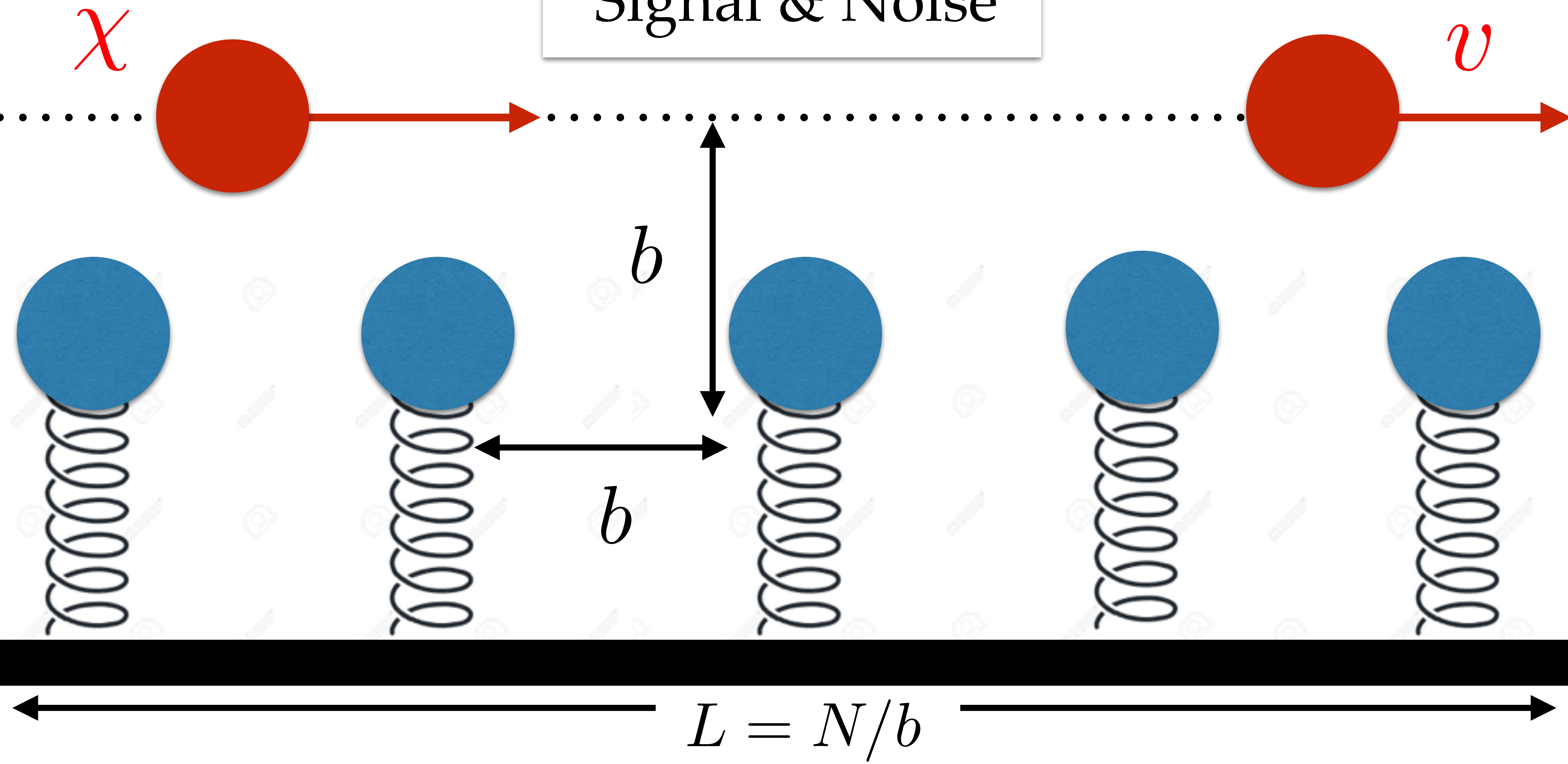
Oscillator at finite temp

Mechanical oscillator coupled to support structure

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

Thermal noise (squared) grows linearly with integration time

Signal & Noise

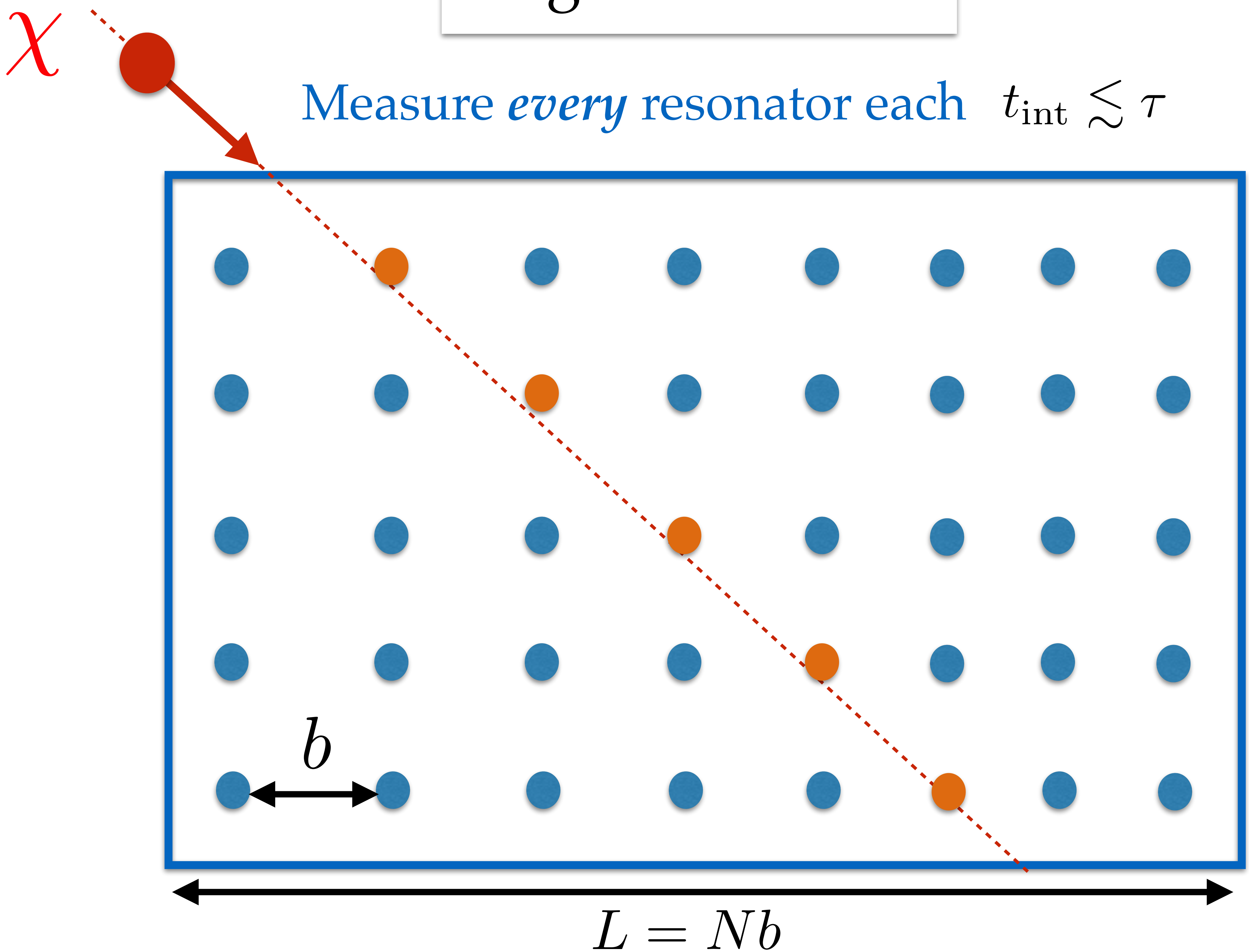


For N ***uncorrelated*** sensors, noise decreases as $\sqrt{N}$

$$I_{\text{sig}}^2 \propto N^2 \quad , \quad \Delta I_{\text{thermal}}^2 \propto N \quad \Longrightarrow \quad \text{SNR}^2 = \frac{I^2}{\Delta I^2} = \frac{4\bar{F}^2 N \tau}{\alpha}$$

Signal & Noise

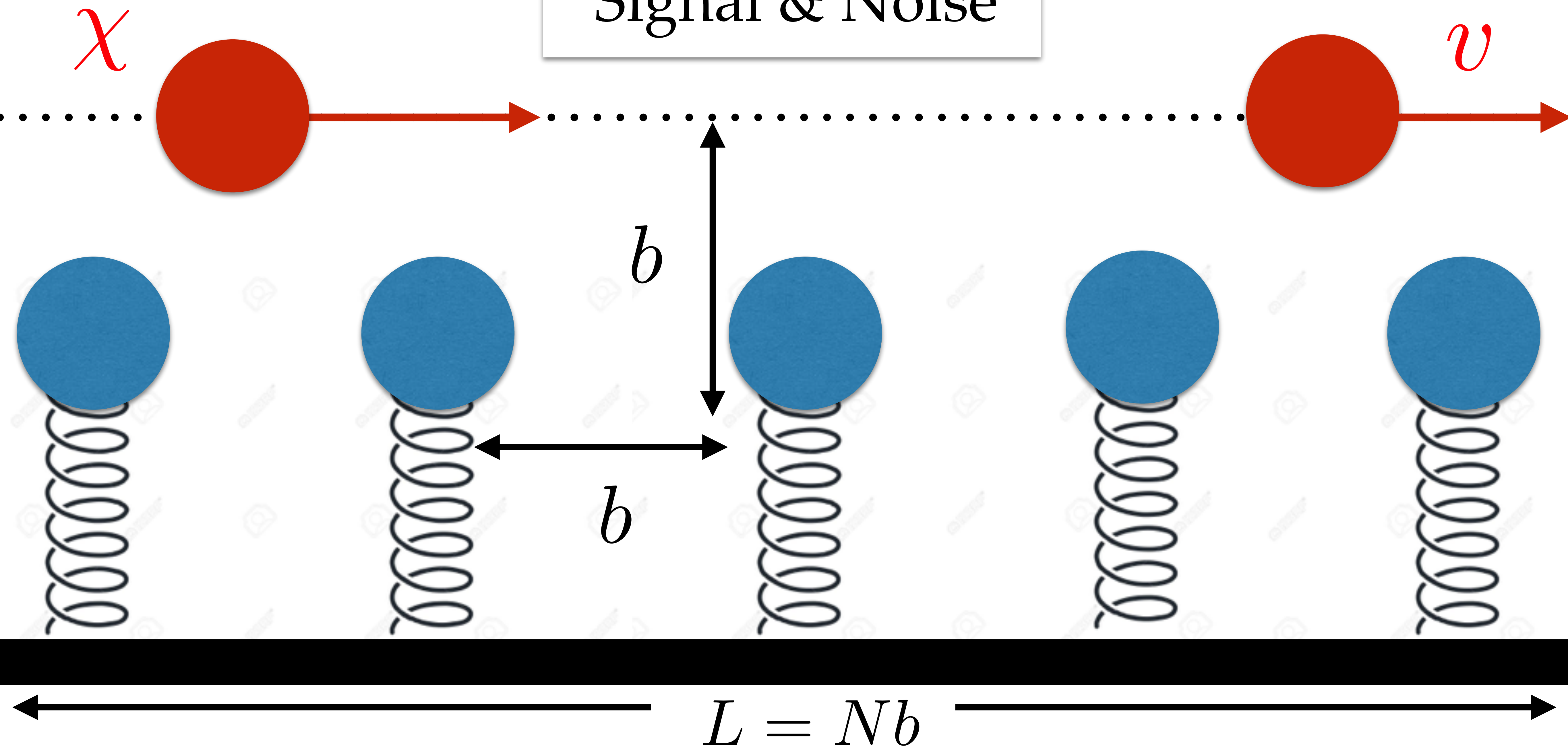
Measure ***every*** resonator each $t_{\rm int} \lesssim \tau$



Correlated signal along ***only one*** linear track

Uncorrelated along ***all other*** possible linear tracks

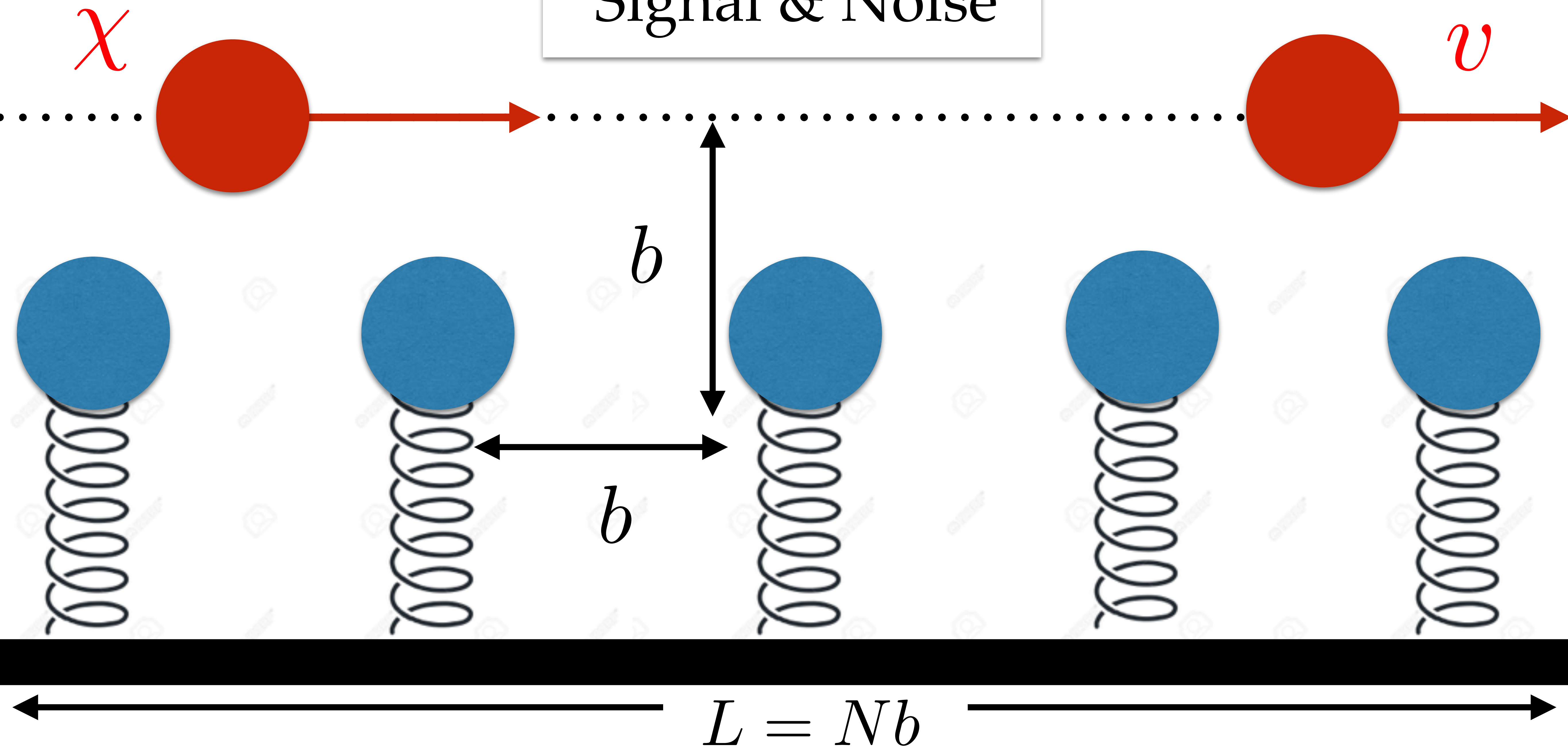
Signal & Noise



For mechanical oscillator $\quad \alpha_{\text{mech}} = 4 m_{\text{det}} k_B T \gamma$

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

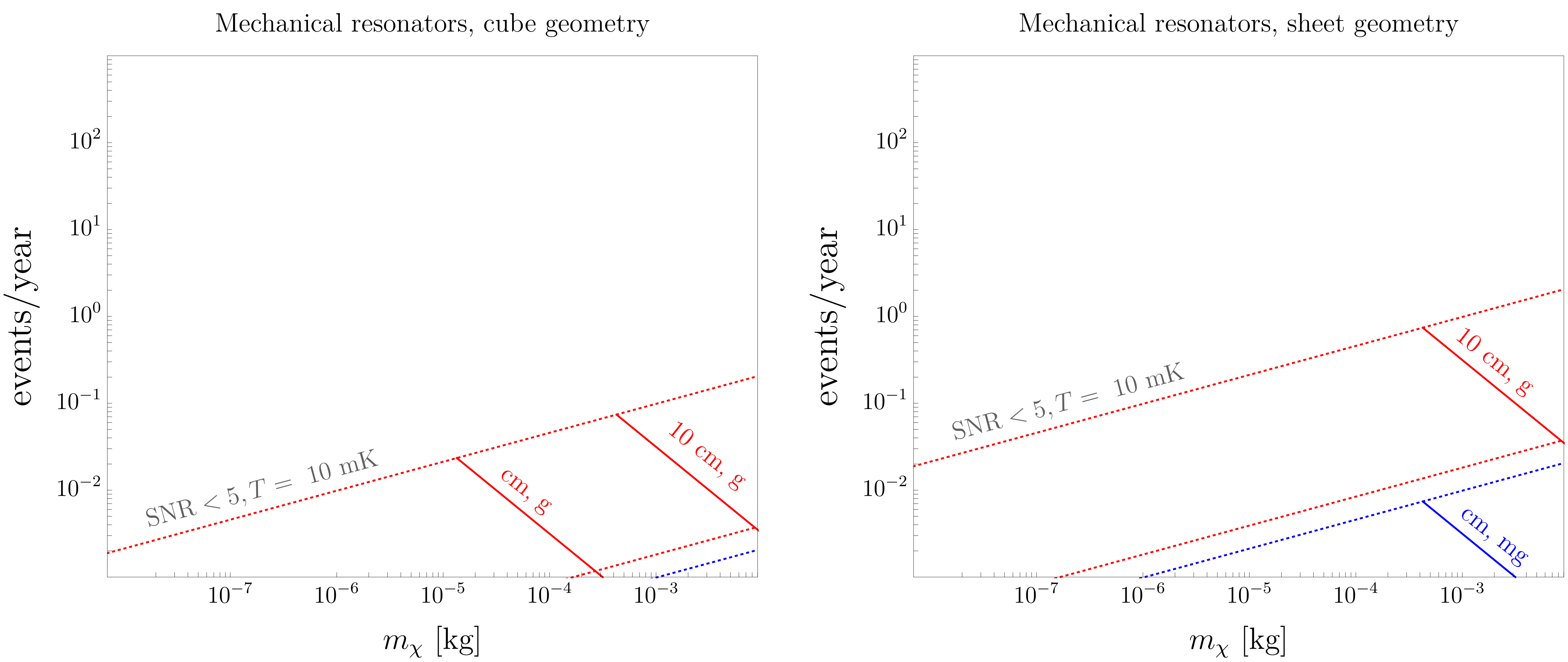
Signal & Noise



$$\mathrm{SNR}^2 \sim 10^{-1} \left(\frac{m_\chi}{\mathrm{mg}}\right)^2 \left(\frac{m_{\mathrm{det}}}{\mathrm{mg}}\right) \left(\frac{L}{\mathrm{m}}\right) \left(\frac{\mathrm{mm}}{b}\right)^4 \left(\frac{10\,\mathrm{mK}}{T}\right) \left(\frac{10^{-6}\mathrm{Hz}}{\gamma}\right)$$

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

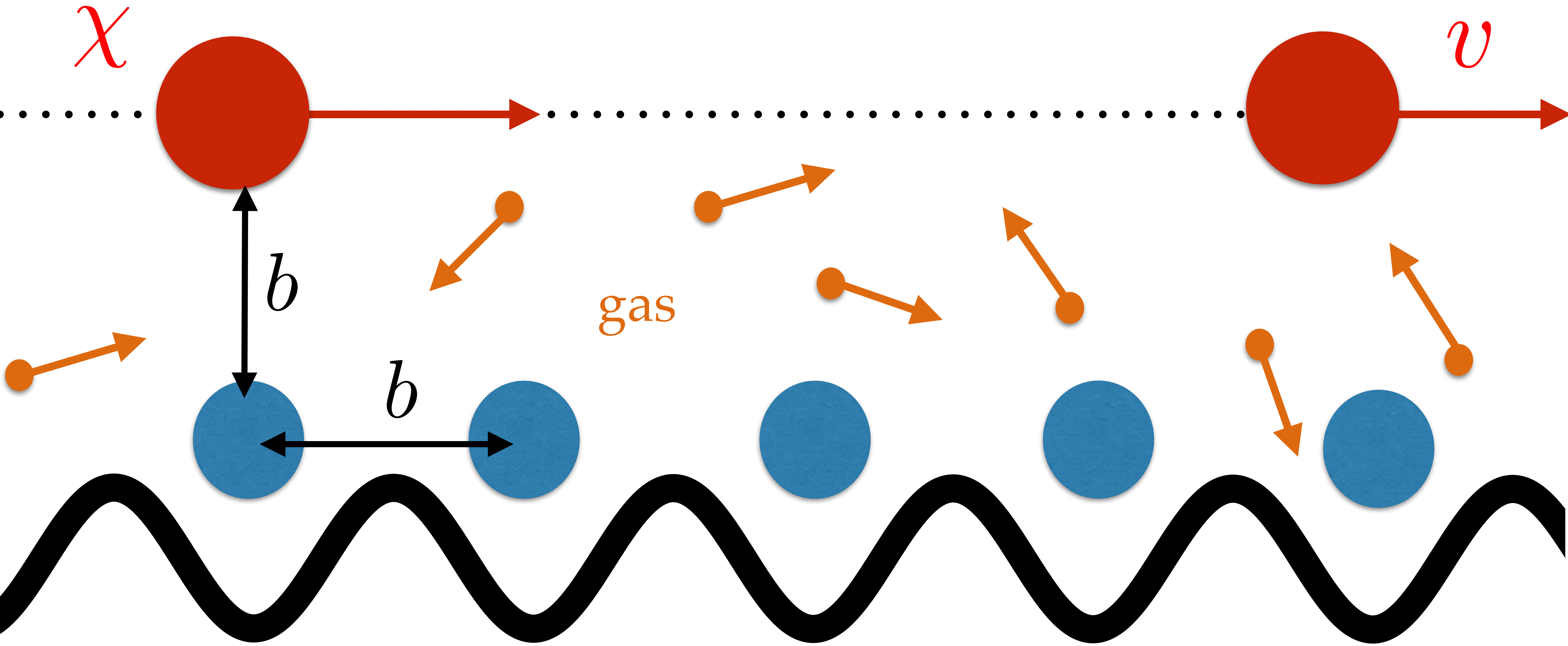
Event Rates: Mechanical Resonators



$$R = \frac{\rho v A}{m_\chi} \sim \frac{50}{\text{year}} \left(\frac{m_{\text{Pl}}}{m_\chi}\right) \left(\frac{A}{10^2\ \text{m}^2}\right).$$

Event rate (slope) set only by local DM flux

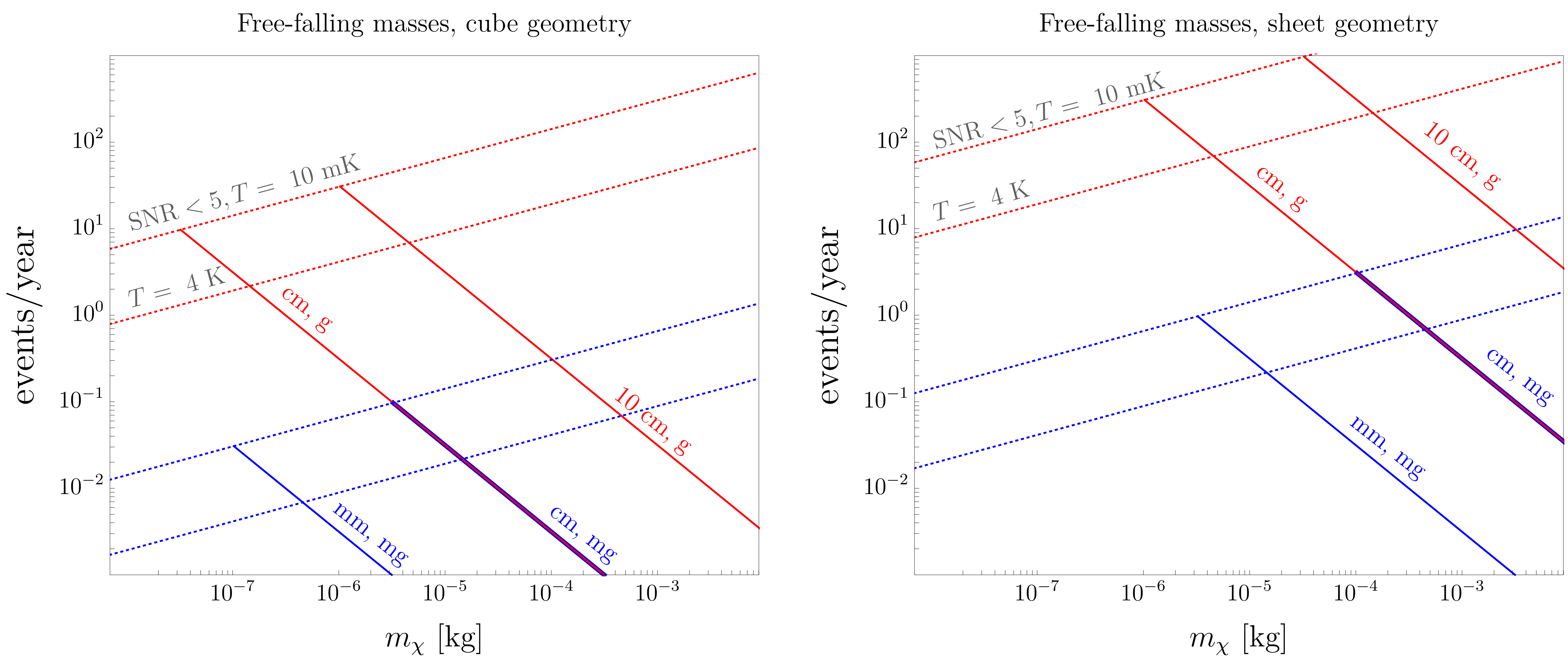
Signal & Noise: Free Falling Masses



For nanospheres $\alpha_{\rm gas} = P A_{\rm sph} \sqrt{m_{\rm gas} k_B T}$

$$\mathrm{SNR}^2 \sim 10^4 \left(\frac{m_\chi}{\mathrm{mg}}\right)^2 \left(\frac{m_{\rm det}}{\mathrm{mg}}\right)^2 \left(\frac{L}{\mathrm{m}}\right) \left(\frac{\mathrm{mm}}{b}\right)^4 \left(\frac{10\,\mathrm{mK}}{T}\right) \left(\frac{10^{-10}\,\mathrm{Pa}}{P}\right) \left(\frac{4\mathrm{u}}{m_{\rm gas}}\right)^{1/2}$$

Event Rates: Free Falling Masses



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Event rate (slope) set by local DM flux

Traditional DD Backgrounds?

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

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

↓

Measurement noise

Measurement Noise

Previous discussion valid only if thermal noise dominates

Prepare detector wave packet of size $\sim \Delta x \to \Delta p \gtrsim \hbar / \Delta x$

Measure again at later time $\tau \to \Delta x + \hbar \tau / \Delta x \, m_{\text{det}}$

Measurement Noise

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 $\tau \rightarrow \Delta x + \hbar\tau/\Delta x\, m_{\rm det}$

Optimize for position resolution: Standard Quantum Limit

$$\Delta x^2_{\rm SQL} \sim \hbar\tau/m_{\rm det} \rightarrow \Delta I^2_{\rm SQL} = \hbar m_{\rm det}/\tau^2$$

At SQL:

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

Need 50, 100 dB reduction in measurement noise to win if

$$T \sim 10\text{mK}\ ,\ \ \gamma \sim 10^{-6}\text{Hz}\ ,\ \ P = 10^{-10}\,\text{Pa}$$

Beating the SQL

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

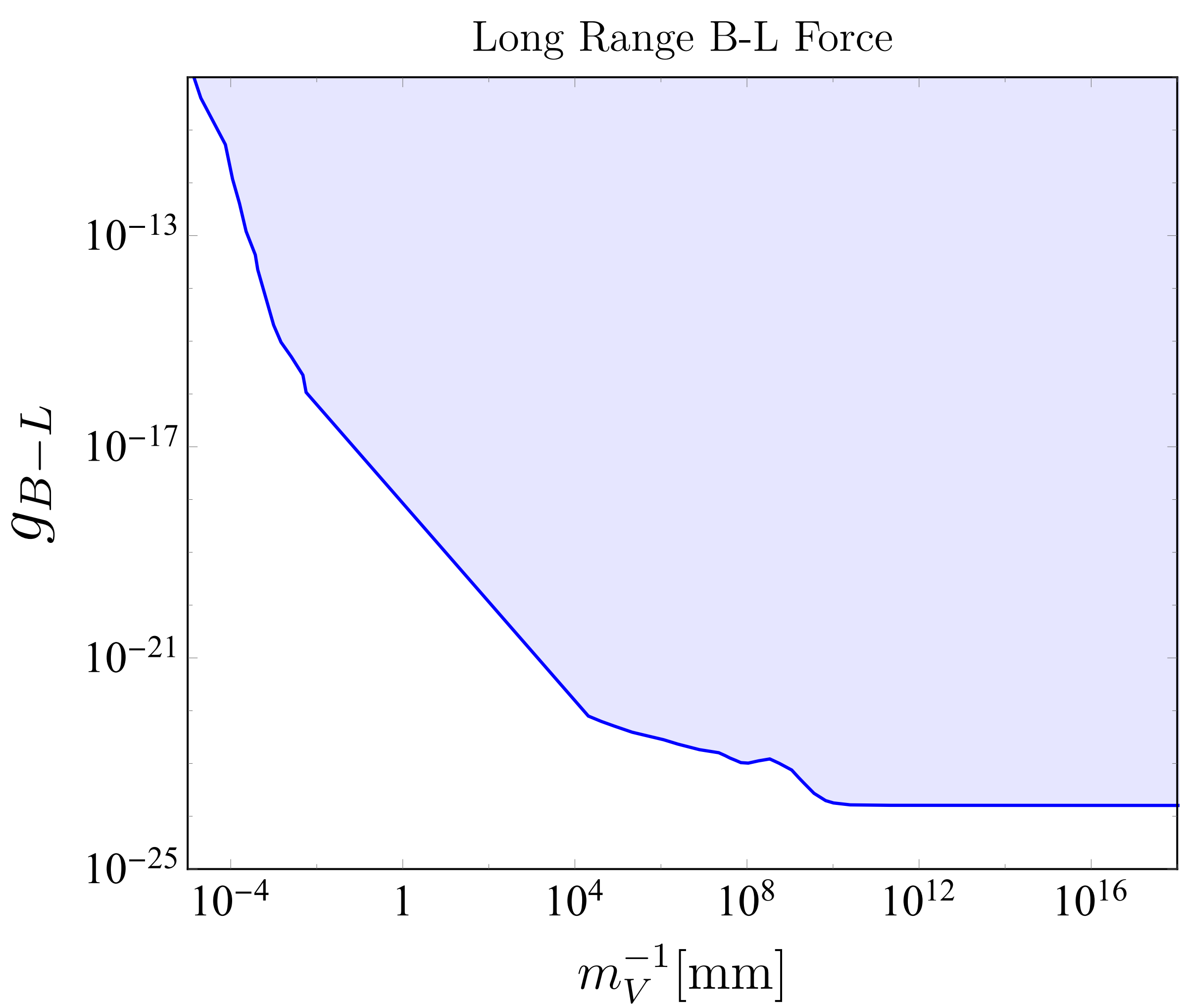
Knyazev, Danilishin, Hild, Khalili. 1701.01694
Braginsky and F. Khalili, Phys. Lett. A 147, 251 (1990).

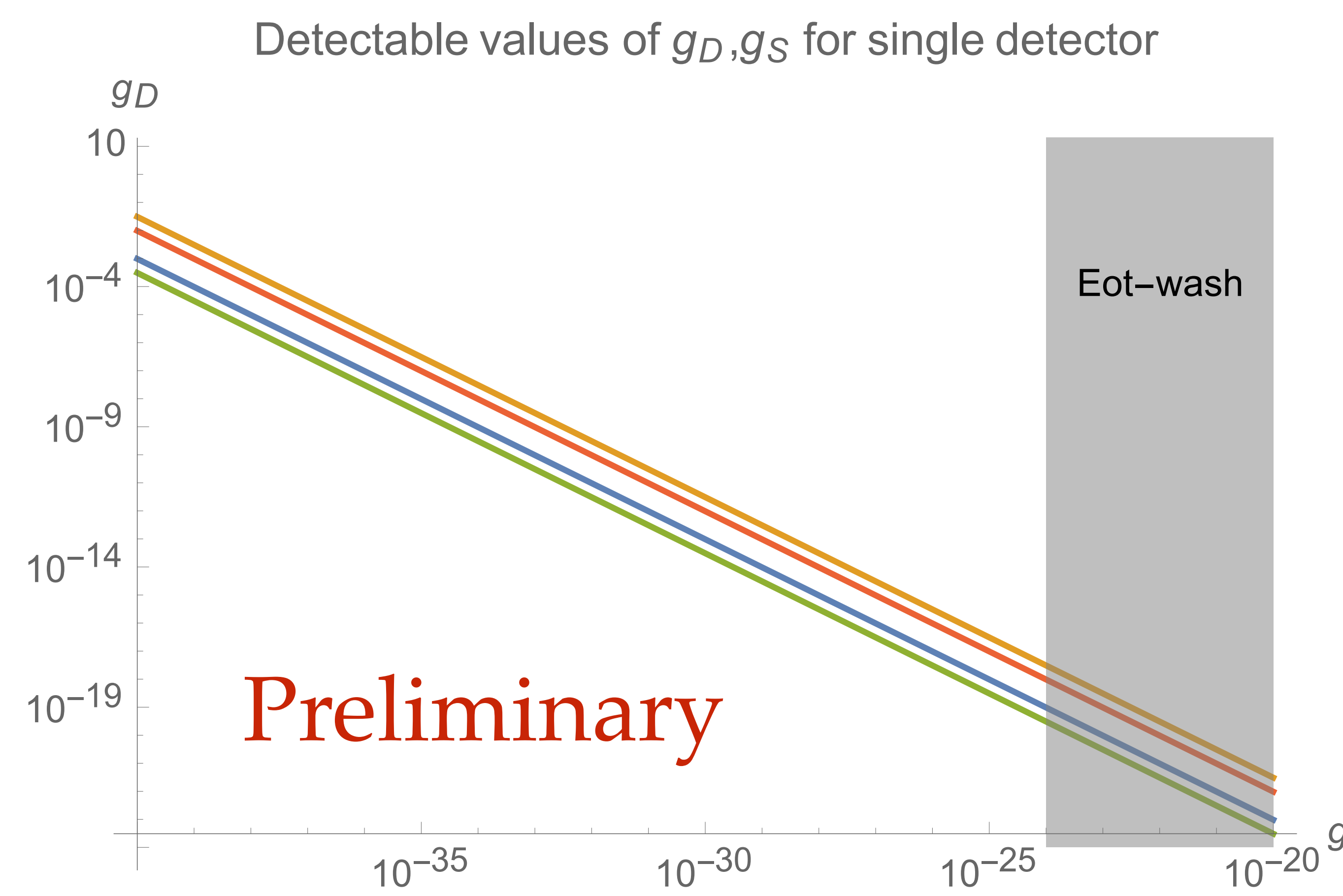
Other Long Range Forces

Same logic applies to other DM force with > mm range

$$U(1)_{B-L} \quad , \quad U(1)_{B-3L_i} \quad , \quad U(1)_{L_i-L_j}$$

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