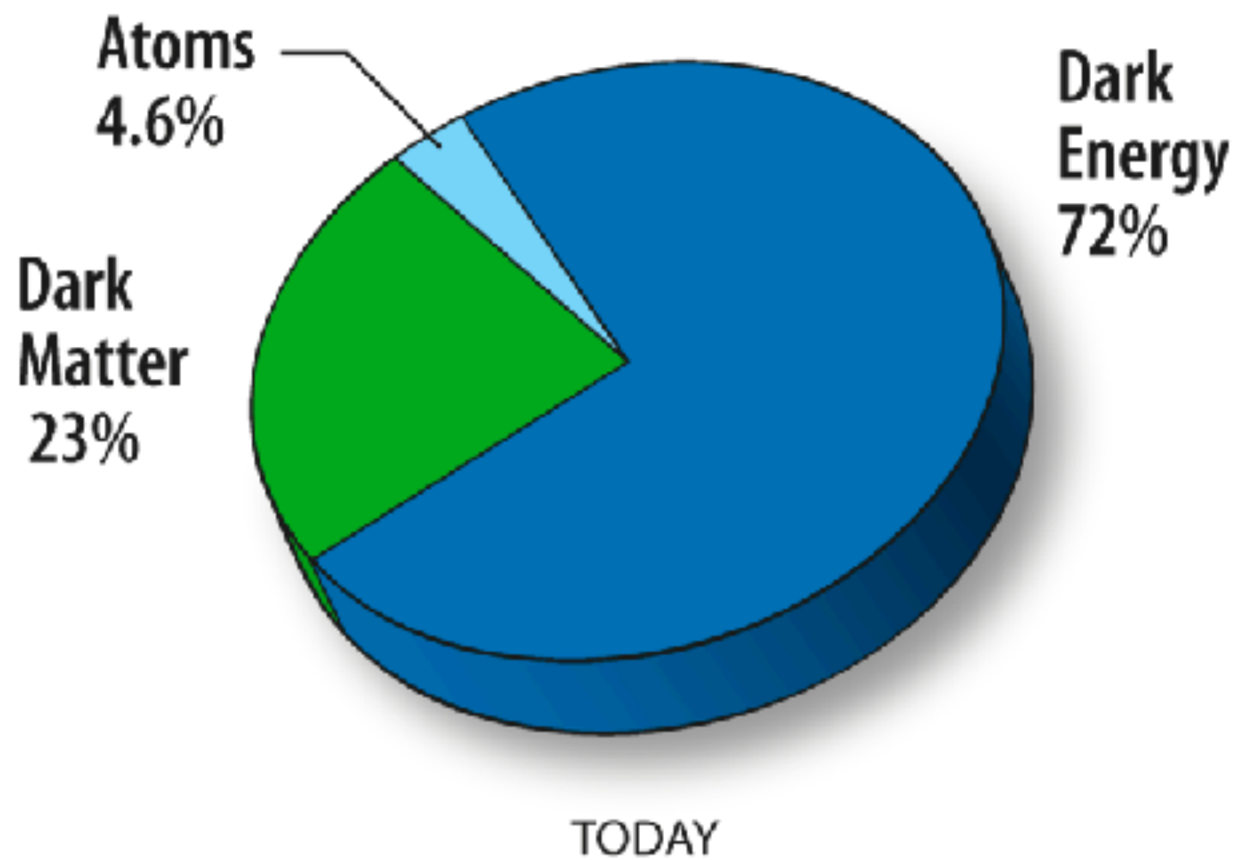
From ALPs to 'Zillas

Discovering Dark Matter in Novel Laboratories

Gordan Krnjaic

Fermilab Colloquium May 17, 2023

The Cosmic Inventory



What is dark matter and how do we learn more about it?

Overview

What's the evidence for dark matter?

What can we deduce from first principles?

What can we learn in new places?

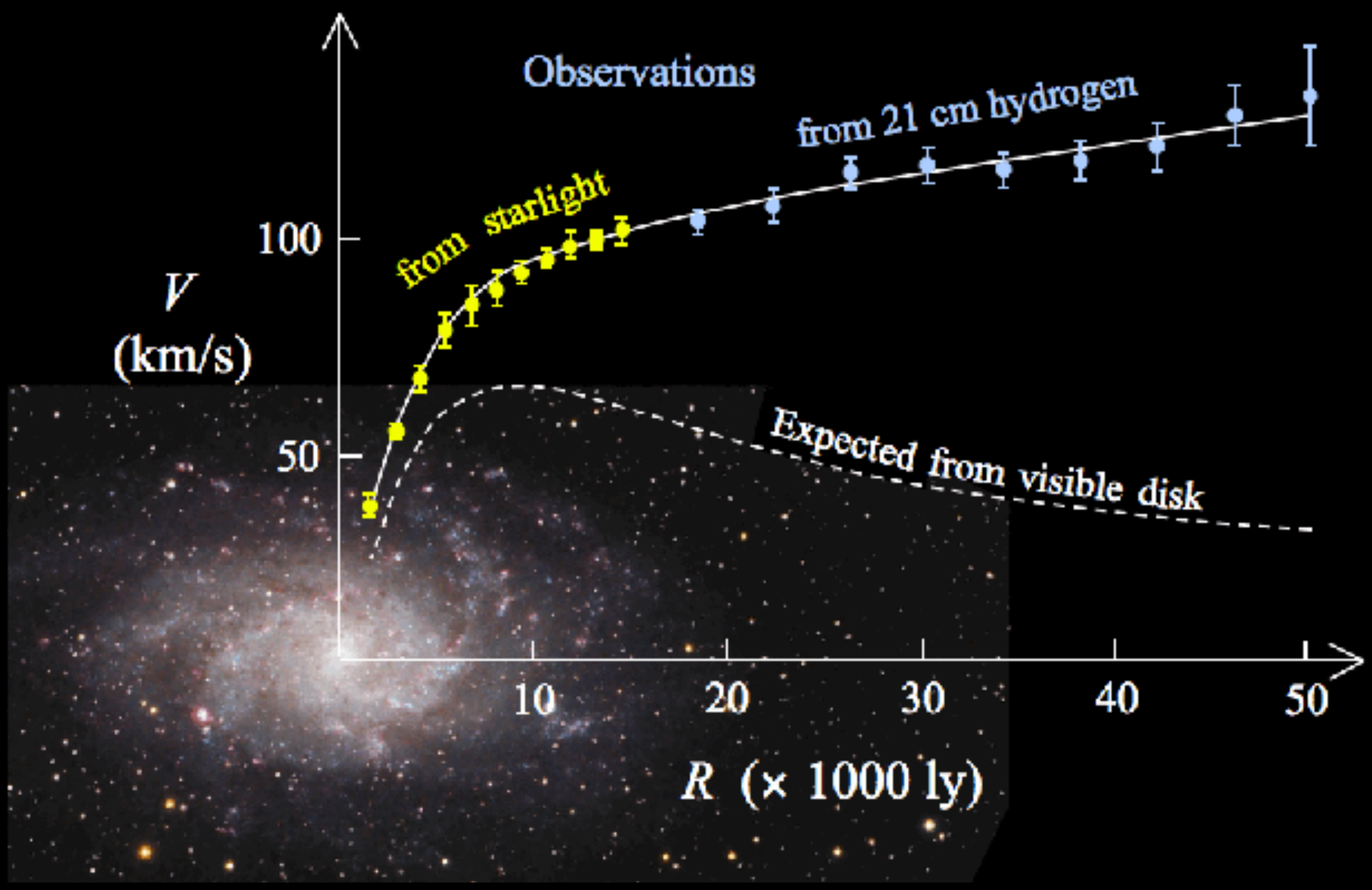
Overview

What's the evidence for dark matter?

What can we deduce from first principles?

What can we learn in new places?

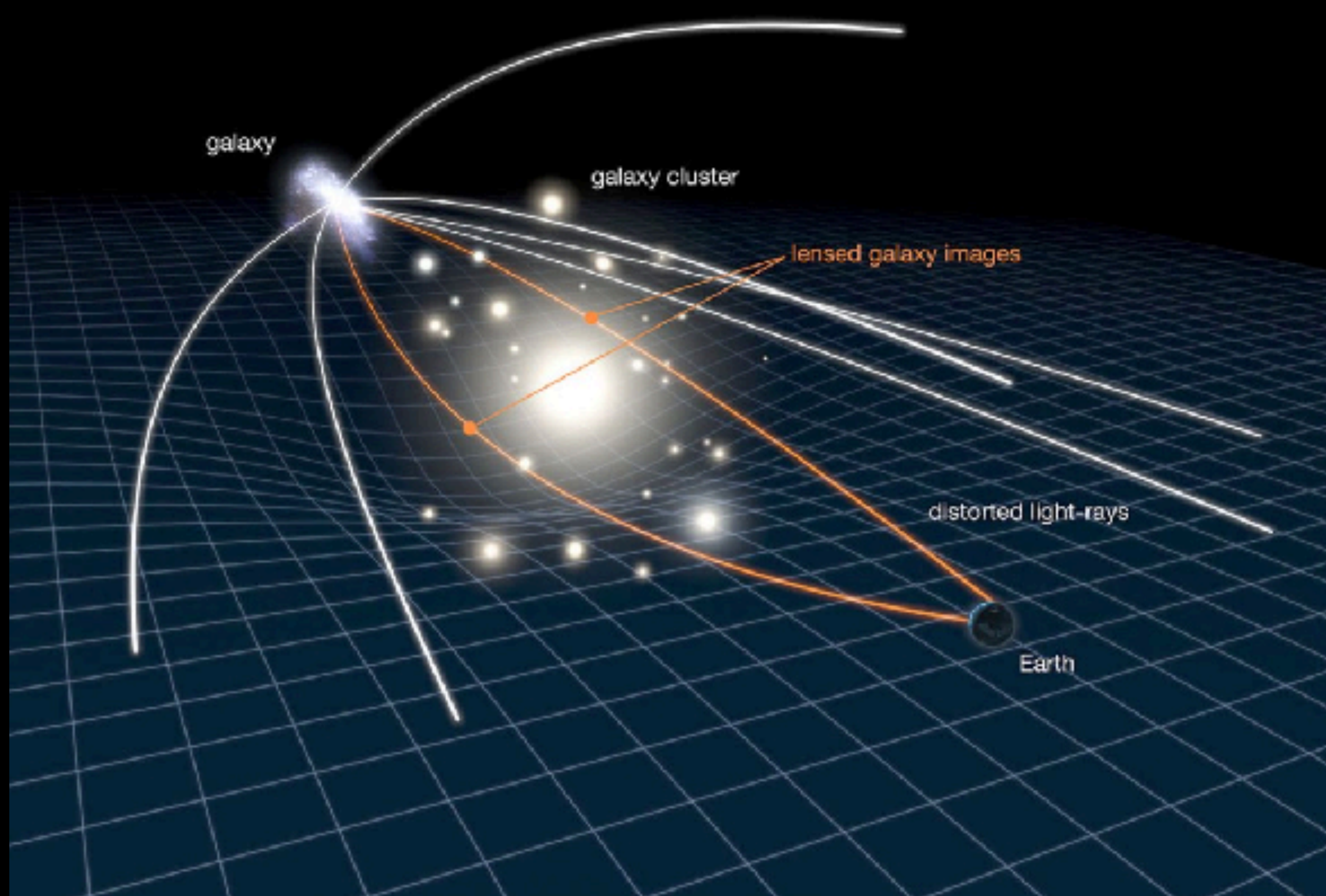
Galaxy Rotation Curves

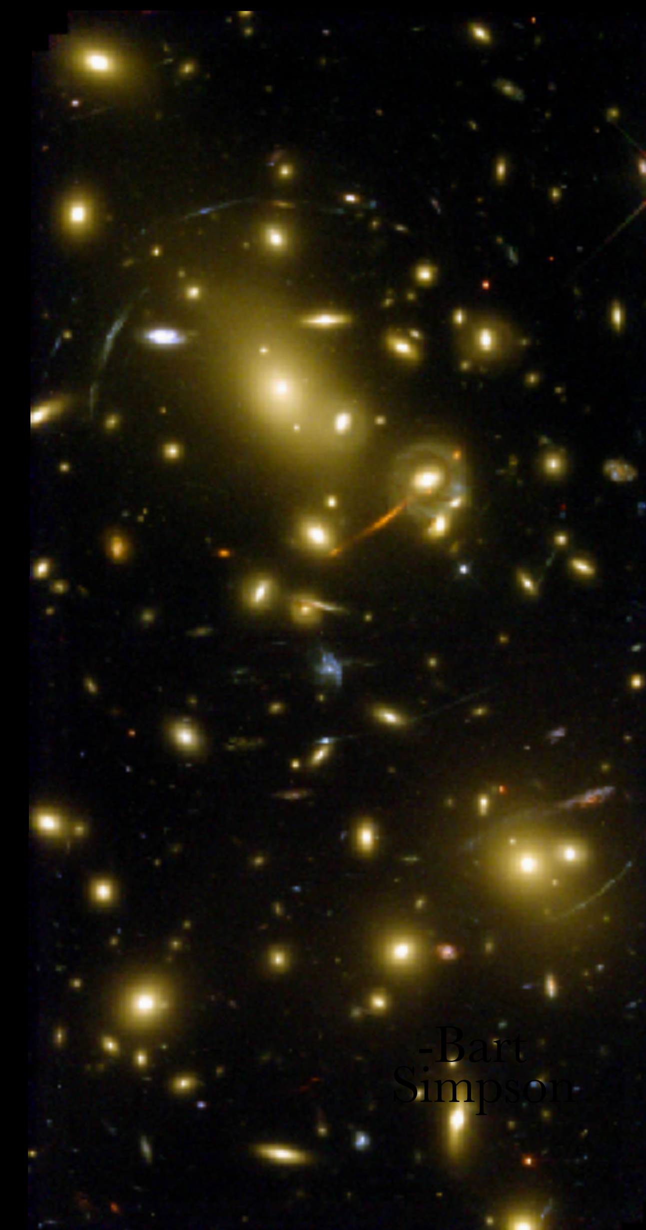


Dramatic effect: requires ~85% of matter to be "dark"
… and must surround galaxies in halo-like clouds

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

Gravitational Lensing





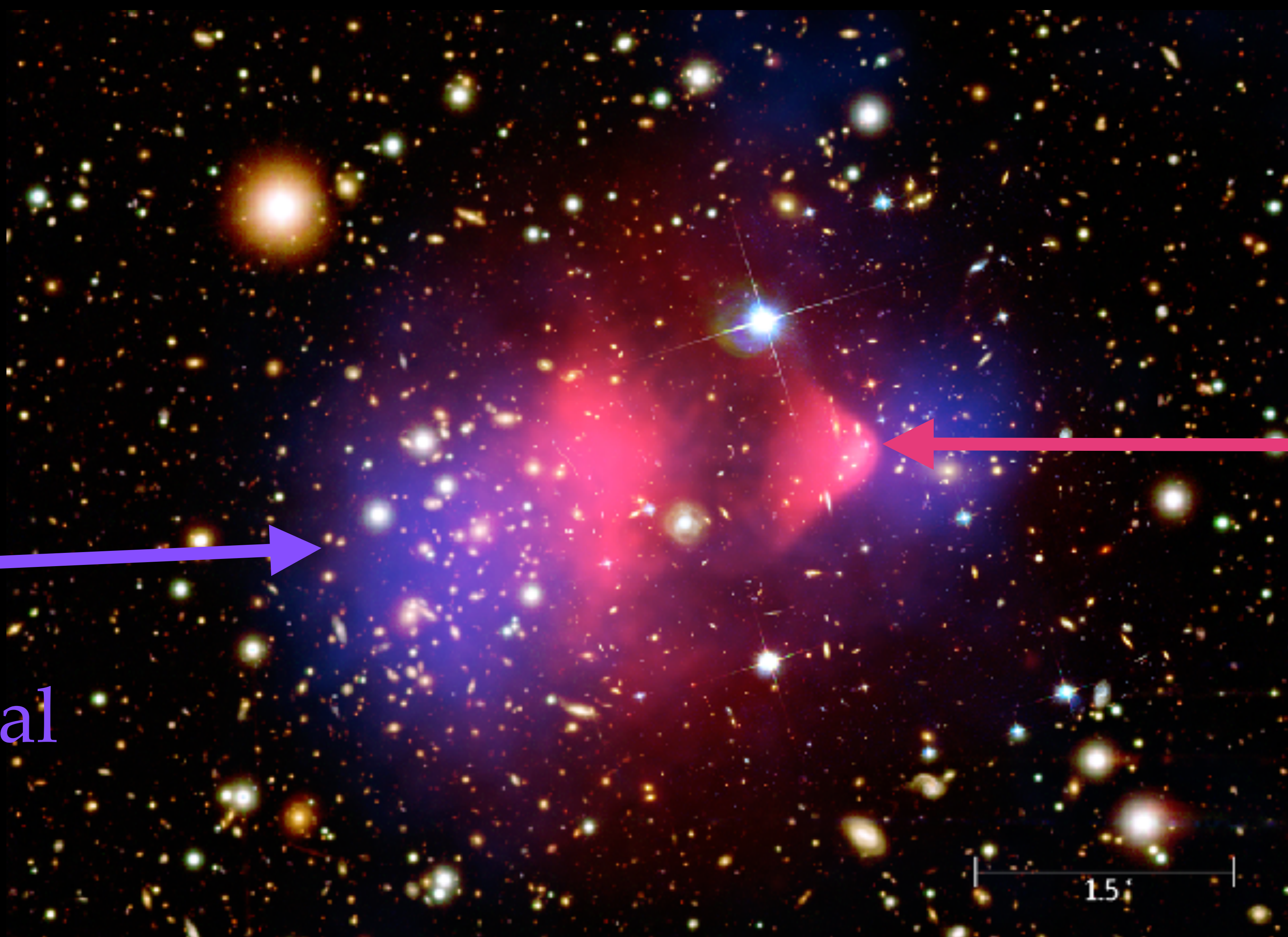
Measures total matter: requires ~85% to be "dark"

Images NASA/ESA

Galaxy Cluster Collisions

Total Matter

gravitational lensing



Visible Matter

Image overlay
Hubble & Chandra

~ 85% of total mass passed through without scattering

CMB Power Spectrum

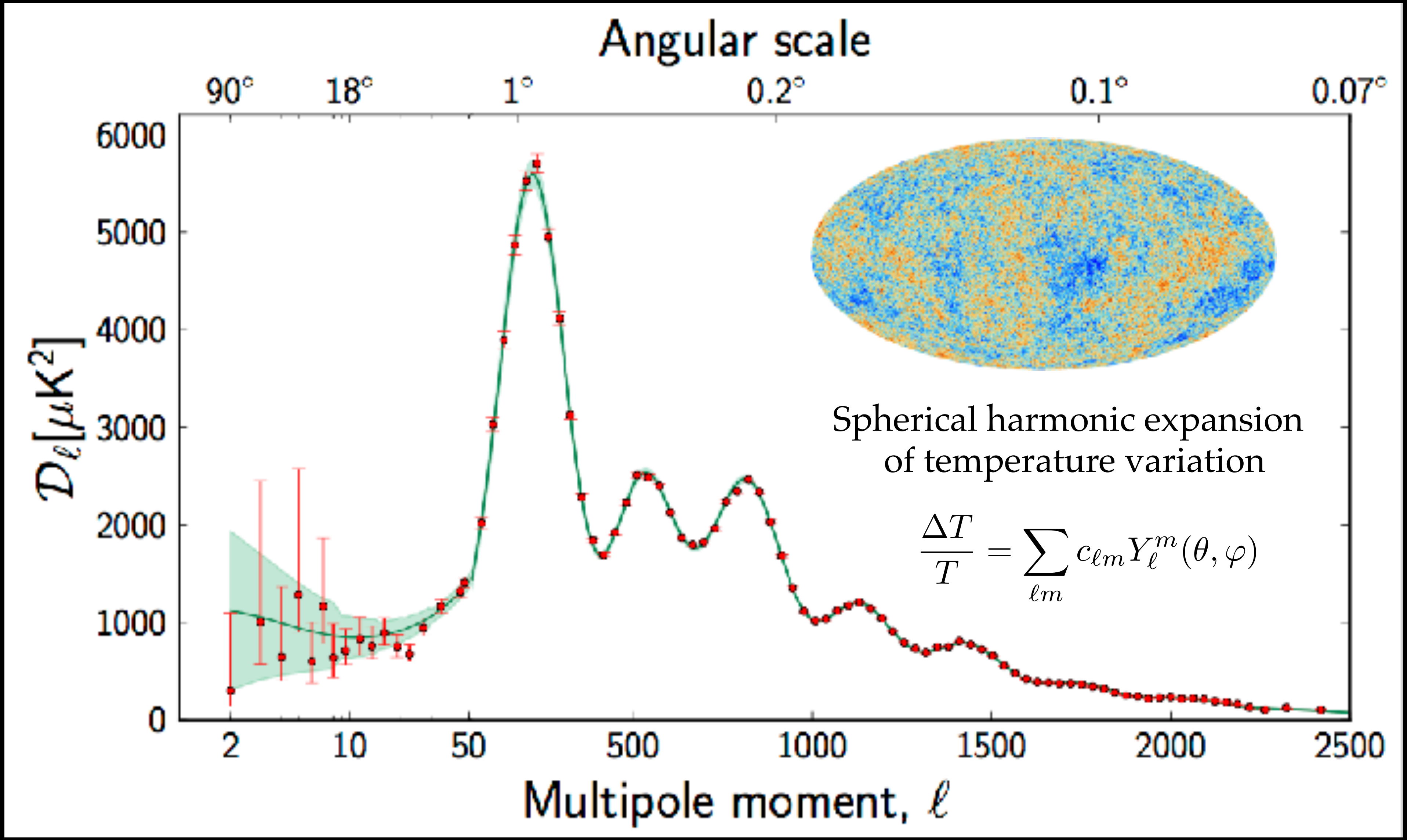
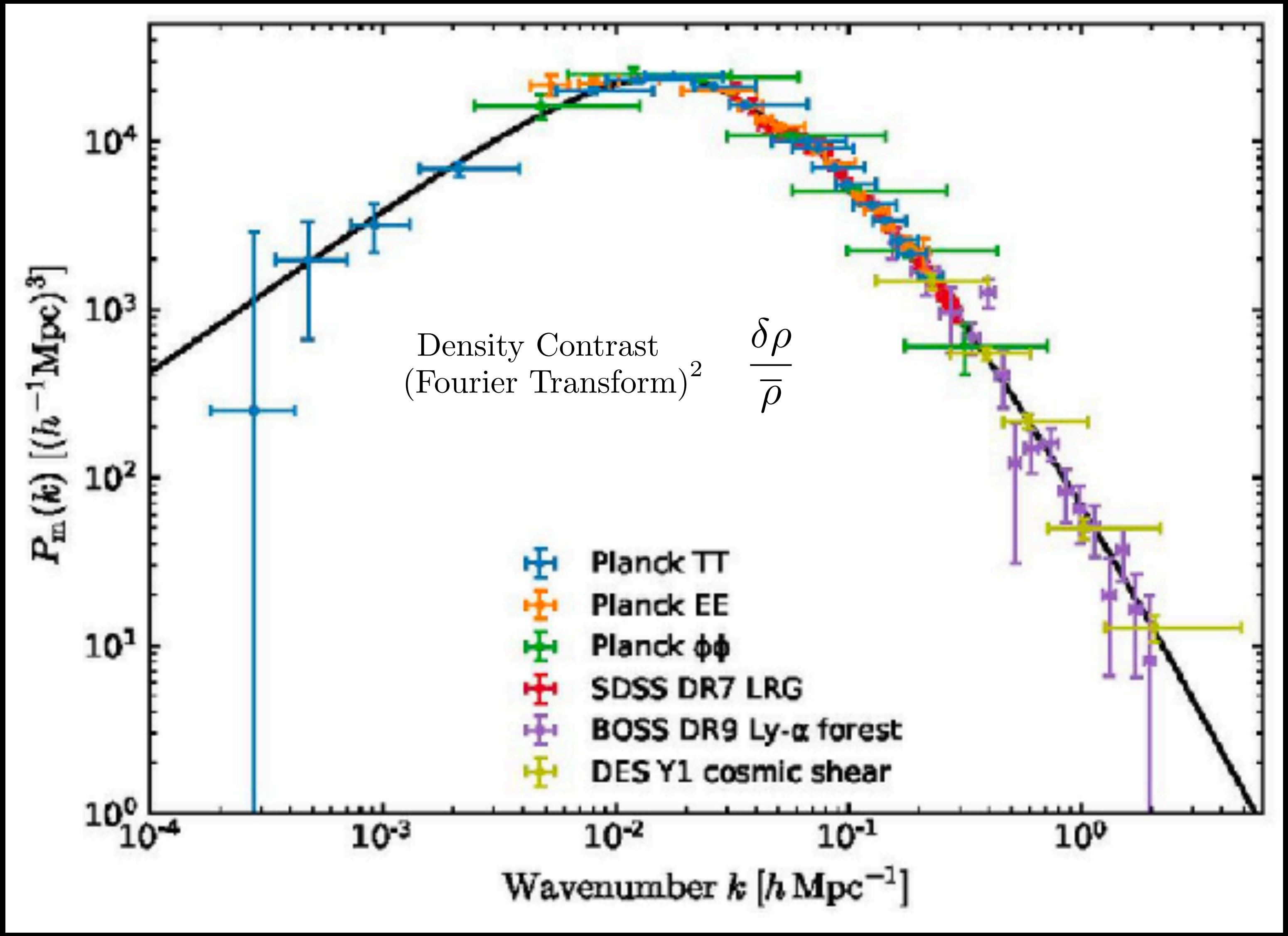


Image: Planck

Observation & theory agree with

~85% pressure-less matter, 15% conventional baryonic…

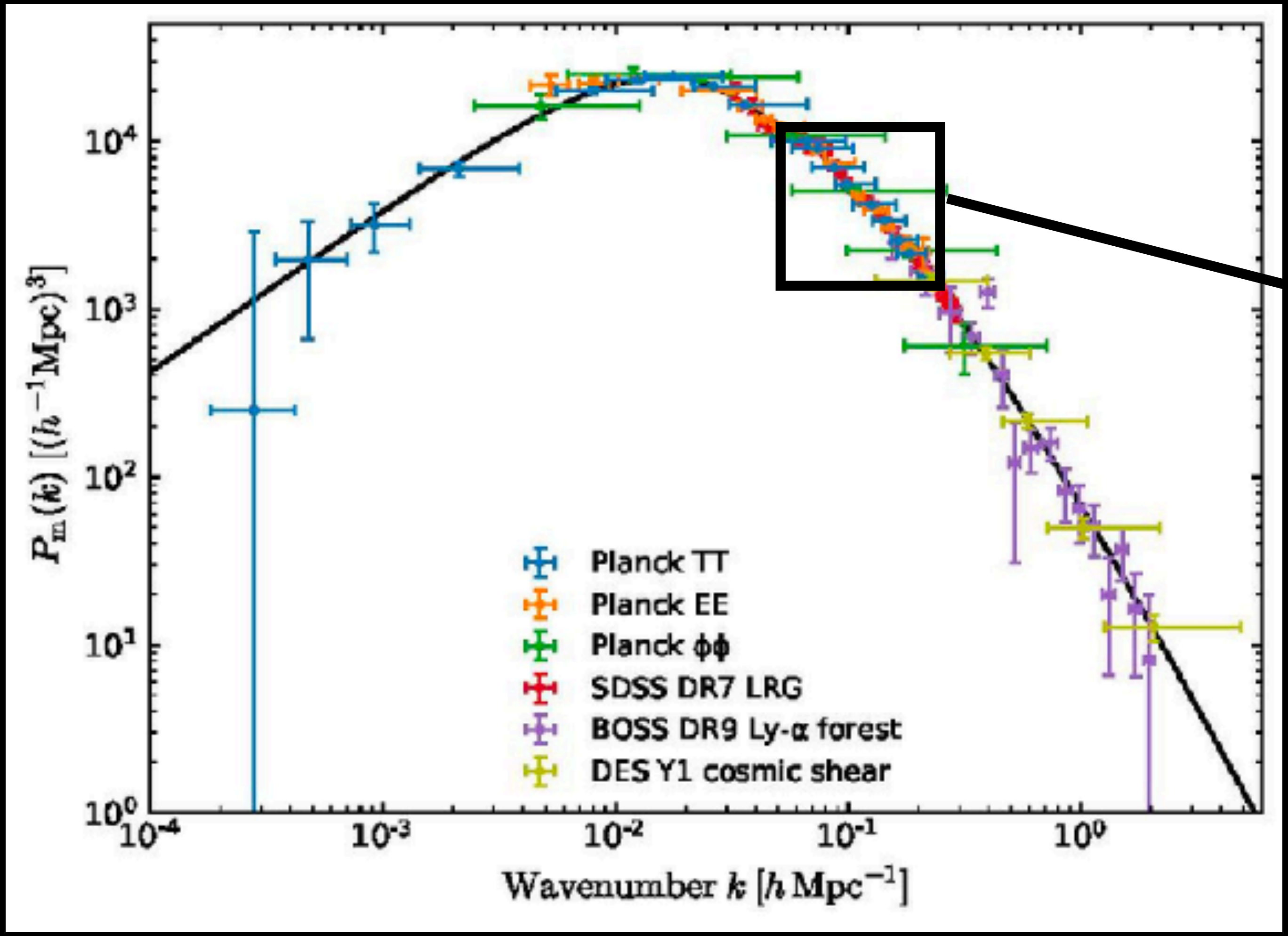
Matter Power Spectrum

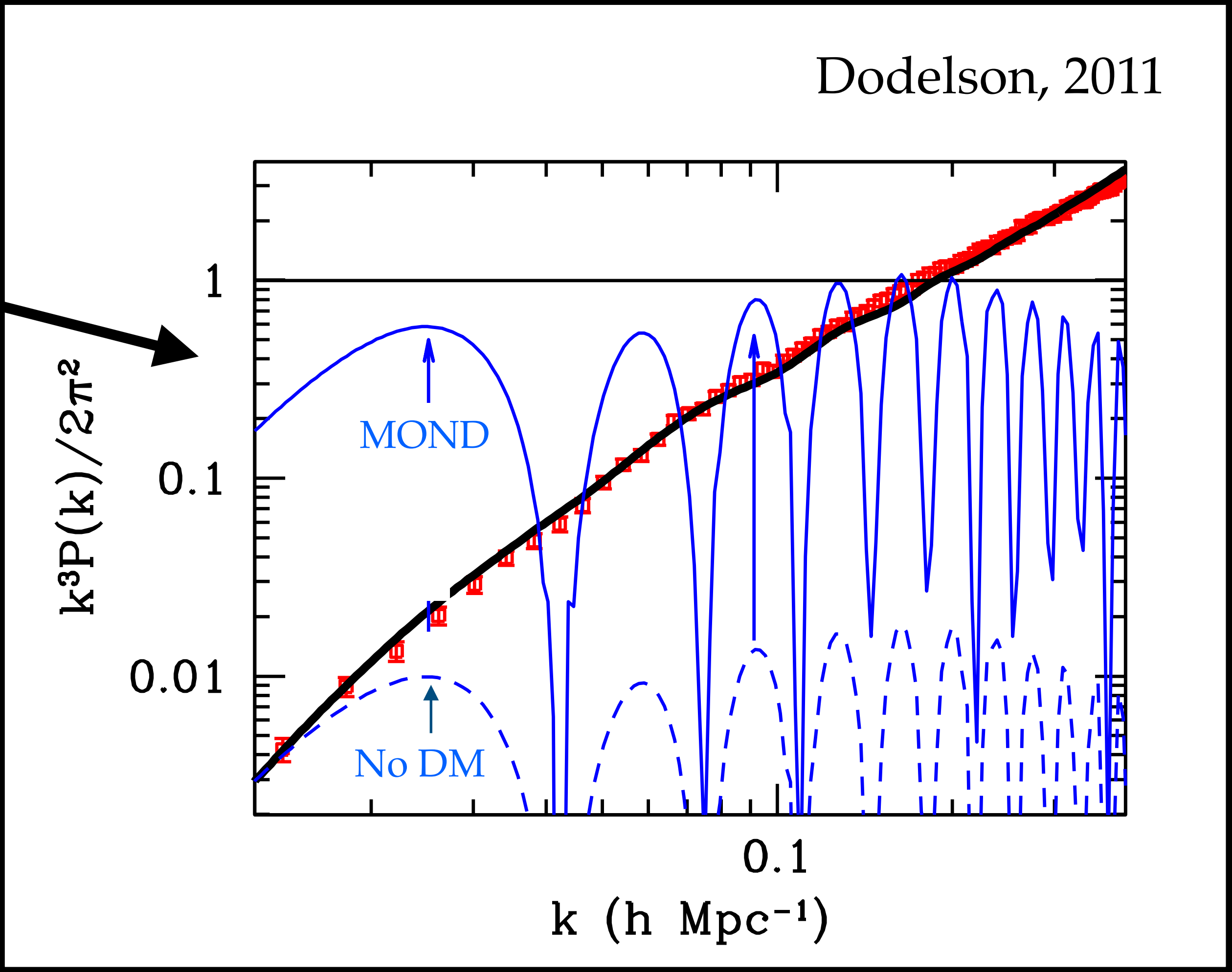


Observation & theory agree with

~85% pressure-less matter, 15% conventional baryonic…

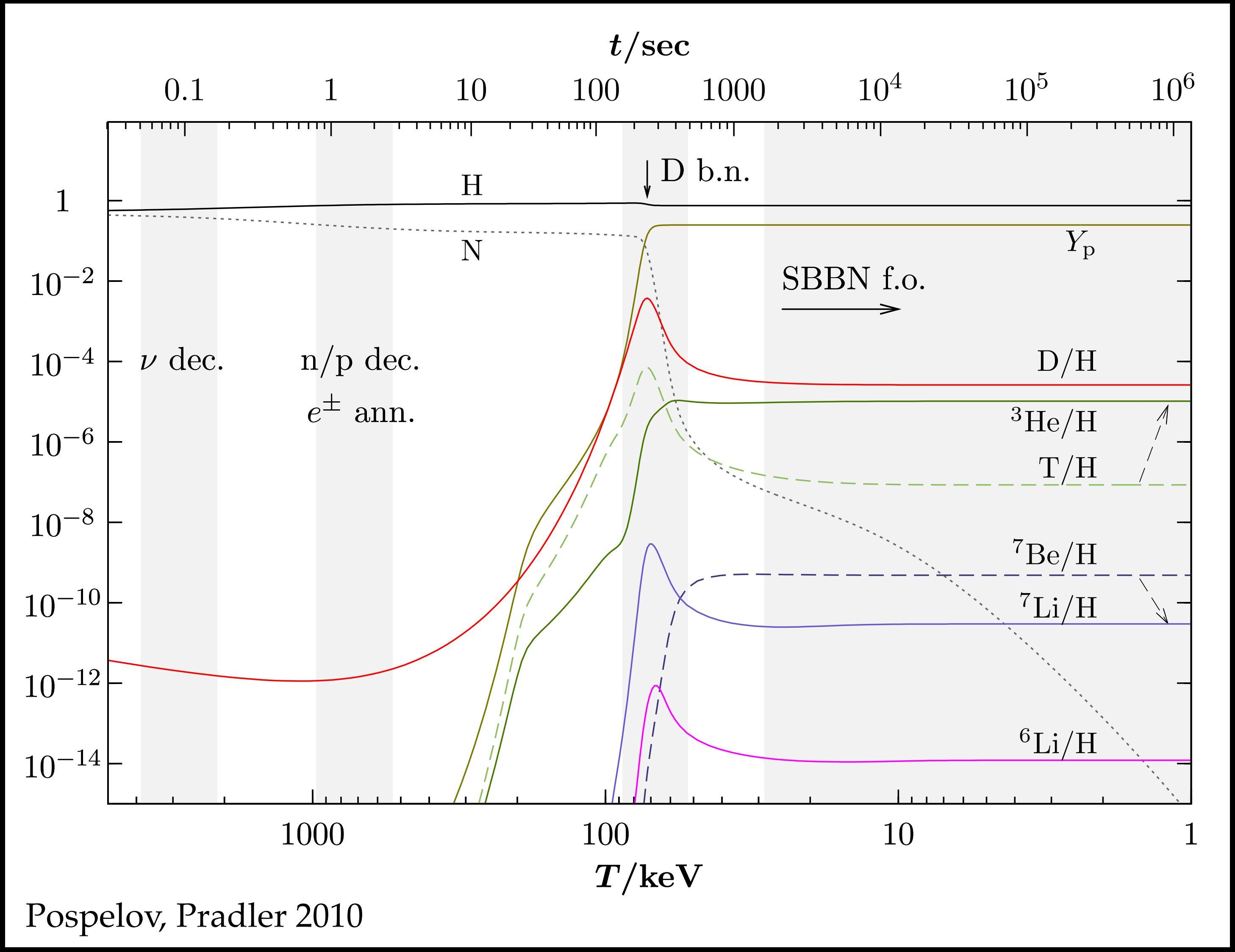
Matter Power Spectrum

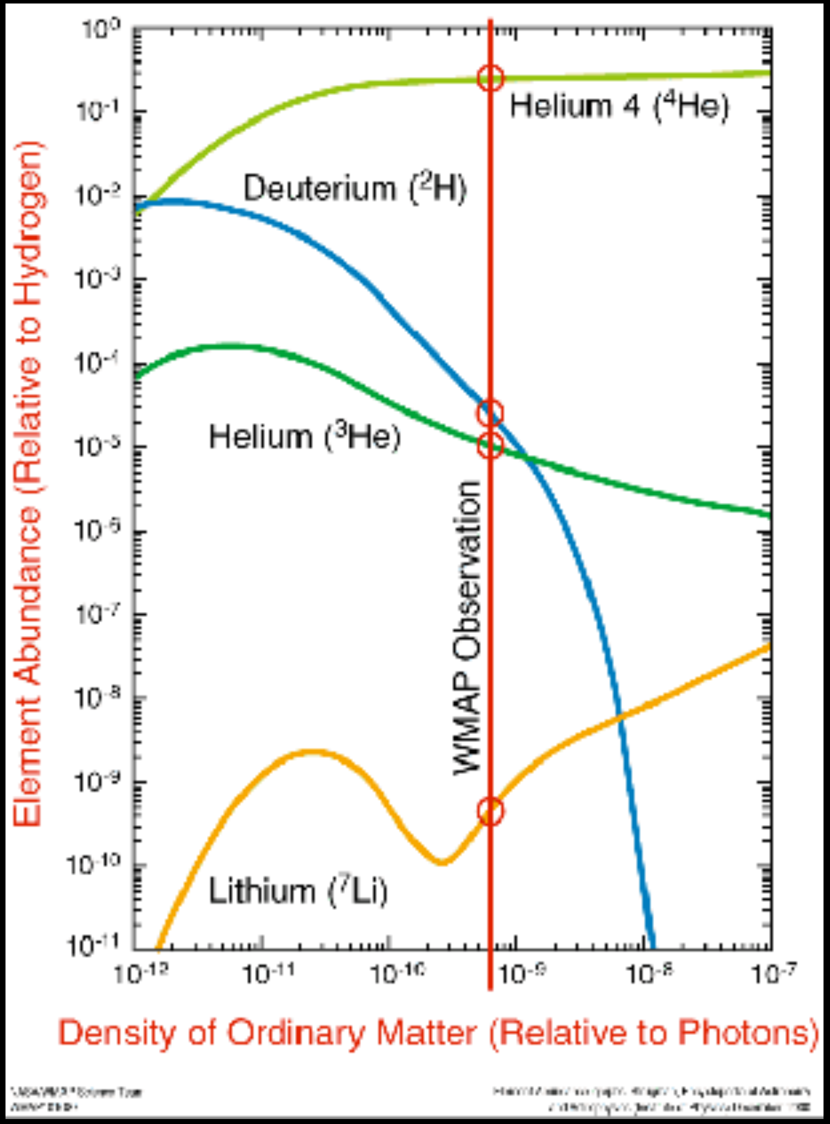




… and wildly disagree without DM, even in modified gravity theories

Big Bang Nucleosynthesis
Light Element Abundances





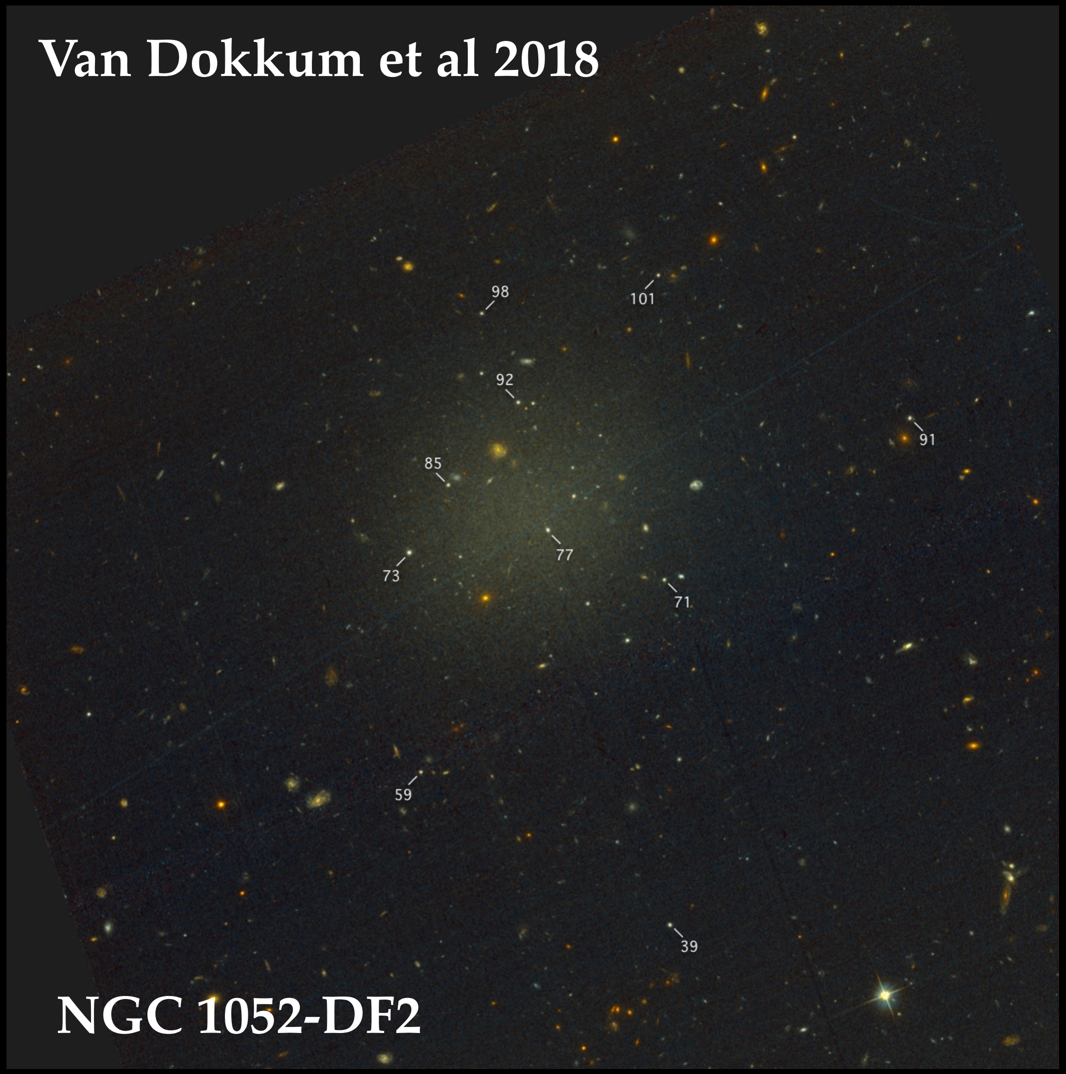
Requires present baryon density to be ~ 15% of total

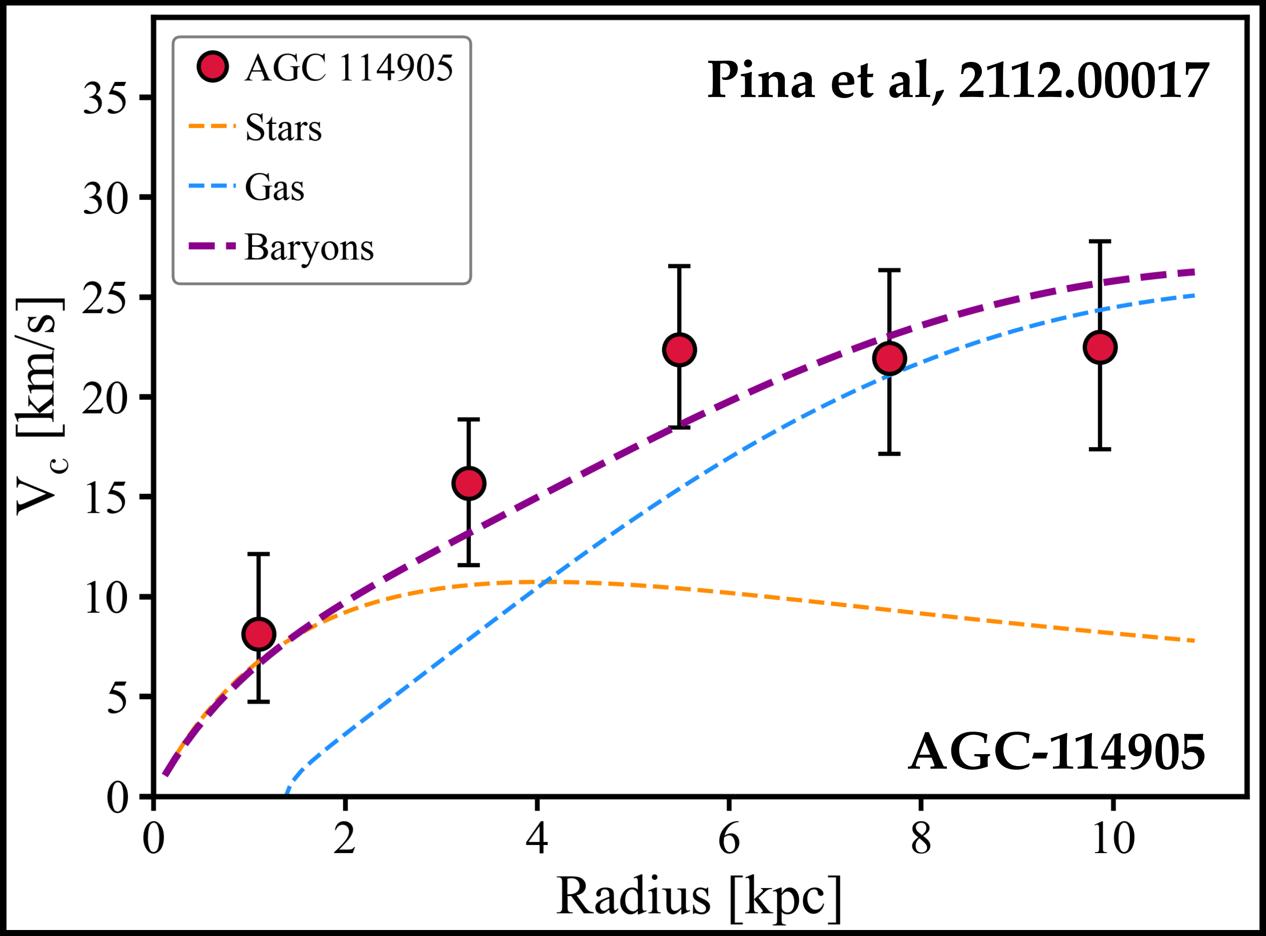
Observations extract: $\Omega_b \equiv \rho_b/\rho_{\rm tot.}$

DM can't be disguised baryons

Outlier Galaxies *Without* Dark Matter

Rotation curves consistent with visible matter only



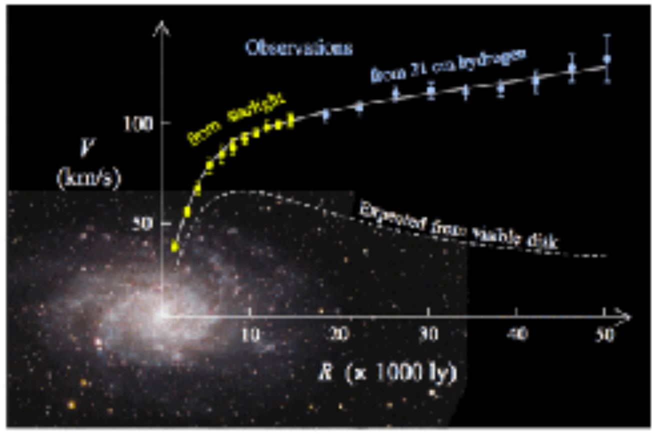


Perversely this strengthens the case for dark matter!

Modified gravity predicts deviations from Newton in **all** galaxies

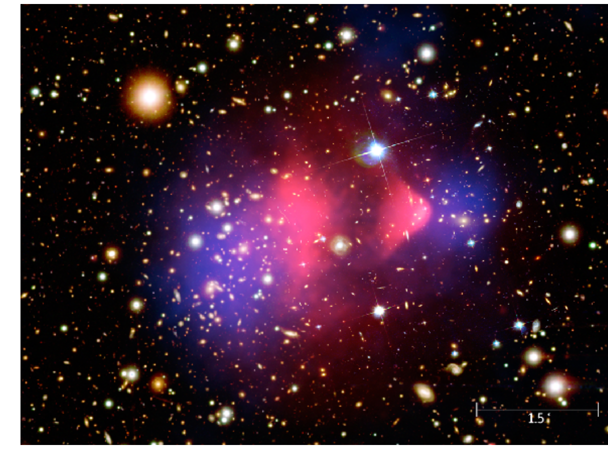
Caution: still fairly new observations with some controversy

Remarkable Evidence of Dark Matter

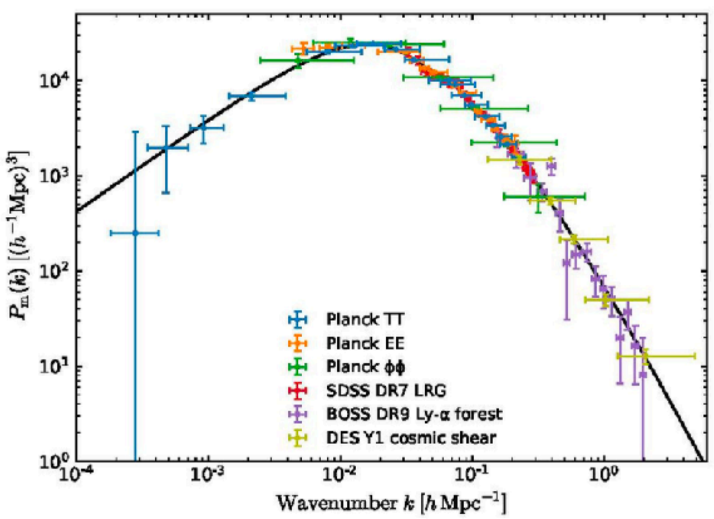


Rotation Curves

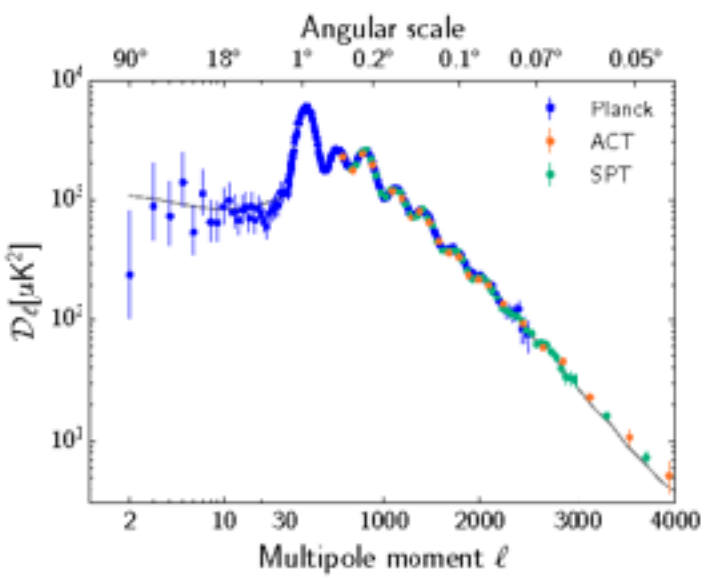
Gravitational Lensing



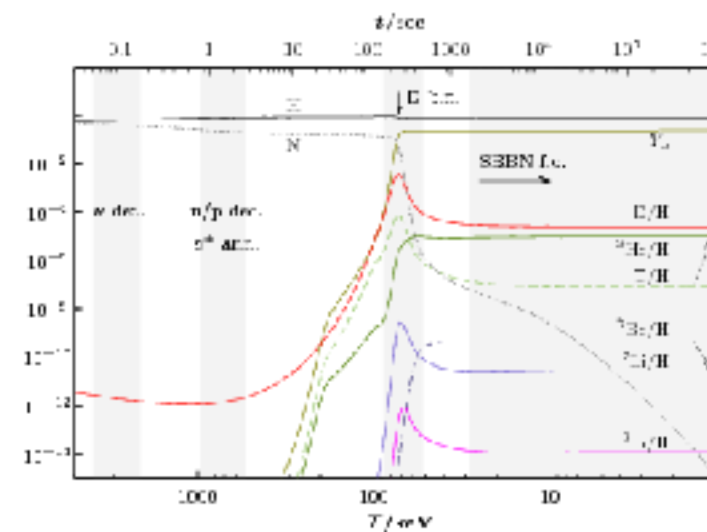
Cluster Collisions



Matter Power Spectrum



CMB Power Spectrum



BBN Light Element Yields

Independent, consistent observations spanning nearly all of spacetime

kpc-Gpc scales and redshifts $z \sim 3400 \rightarrow 0$

Holy Grail: extend knowledge to smaller scales

Overview

What's the evidence for dark matter?

What can we deduce from first principles?

What can we learn in new places?

What do we know about DM?

1) Current evidence is based on gravity

Fortunately, many DM candidates exert other forces too

What do we know about DM?

1) Current evidence is based on gravity

Fortunately, many DM candidates exert other forces too

2) Must be stable or *extremely* long lived

It was present since at least redshift $z = 3400$ and is still here 13.7 Gyr later

What do we know about DM?

1) Current evidence is based on gravity

Fortunately, many DM candidates exert other forces too

2) Must be stable or *extremely* long lived

It was present since at least redshift $z = 3400$ and is still here 13.7 Gyr later

3) Must be largely non relativistic

Relativistic particles don't clump to match matter power spectrum

What do we know about DM?

1) Current evidence is based on gravity

Fortunately, many DM candidates exert other forces too

2) Must be stable or *extremely* long lived

It was present since at least redshift $z = 3400$ and is still here 13.7 Gyr later

3) Must be largely non relativistic

Relativistic particles don't clump to match matter power spectrum

4) Can't interact (much) via strong or electromagnetic forces

Otherwise would have been observed through these

What do we know about DM?

1) Current evidence is based on gravity

Fortunately, many DM candidates exert other forces too

2) Must be stable or *extremely* long lived

It was present since at least redshift $z = 3400$ and is still here 13.7 Gyr later

3) Must be largely non relativistic

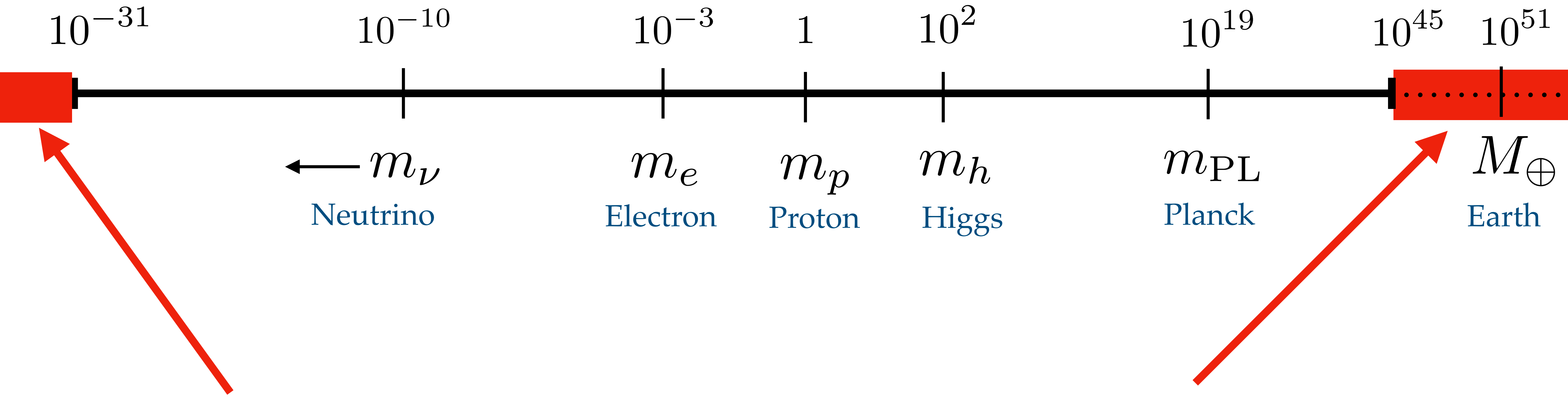
Relativistic particles don't clump to match matter power spectrum

4) Can't interact (much) via strong or electromagnetic forces

Otherwise would have been observed through these

5) *Might* interact via the weak force or a new fifth force

Huge Range of Possible DM Masses

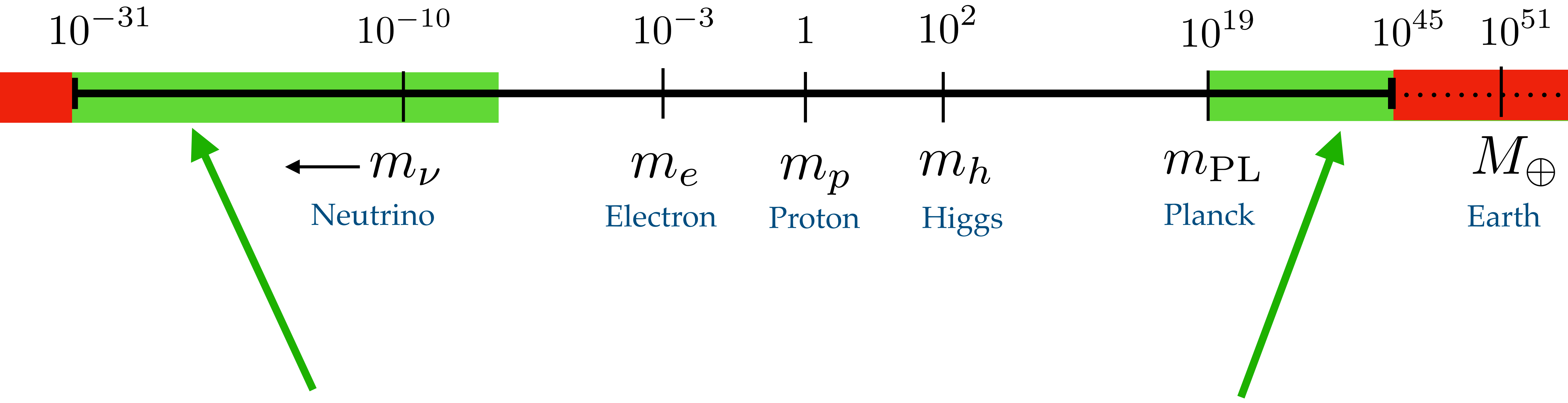


de Broglie wavelength can't exceed dwarf galaxy scales

Would have been observed indirectly (lensing/LIGO…)

$$\lambda_{\rm dB} = \frac{2\pi}{mv} = 0.4\,{\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m_{\rm DM}}\right)\left(\frac{10^{-3}c}{v}\right)$$

Huge Range of Possible DM Masses

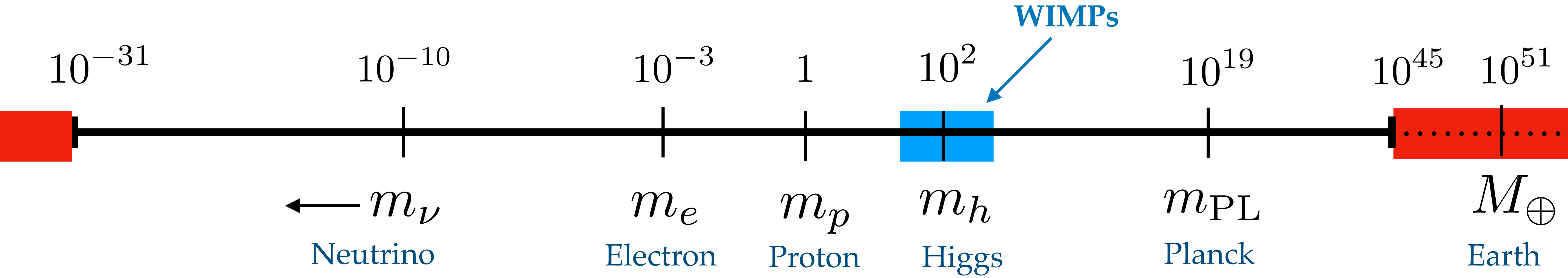


Must be bosonic

Can't fit enough fermions inside galaxies (Pauli exclusion)

Must be primordial black hole or extended object

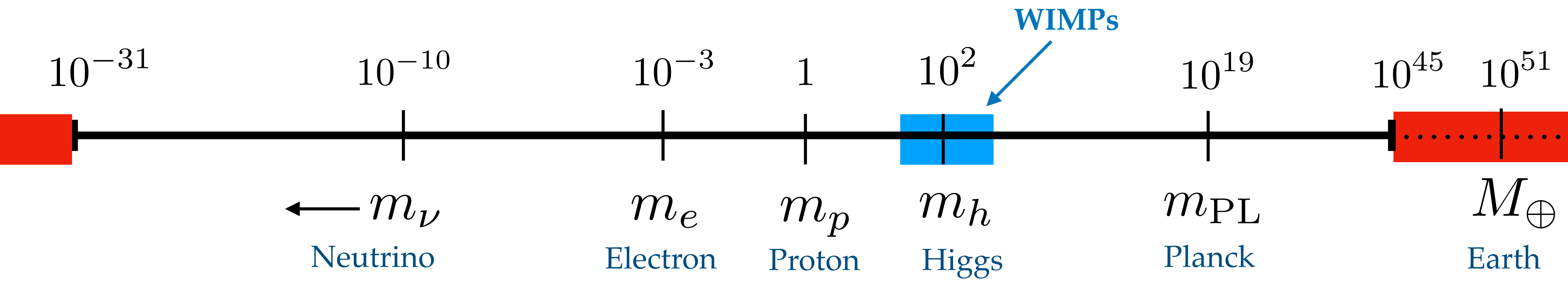
Huge Range of Possible DM Masses



$m_p \approx \mathrm{GeV}/c^2 \approx 10^{-24}\,\mathrm{gram}$

$m_{\mathrm{PL}} = G_N^{-1/2}$

Huge Range of Possible DM Masses



Traditional DM searches for WIMPs near the weak scale

Updating priors: null results from LHC & WIMP direct-detection

What can we learn in new places?

Overview

What's the evidence for dark matter?

What can we deduce from first principles?

What can we learn in new places?

Wavelike Particle-like Macroscopic

Overview

What's the evidence for dark matter?

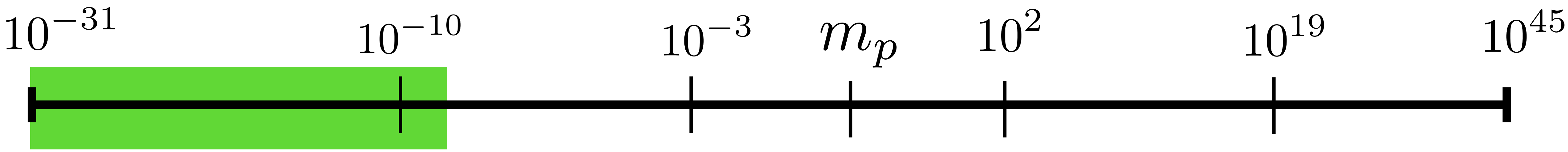
What can we deduce from first principles?

What can we learn in new places?

Wavelike Particle-like Macroscopic

Ultra light DM —- e.g. axion-like particle "ALP"

Wave-like Dark Matter

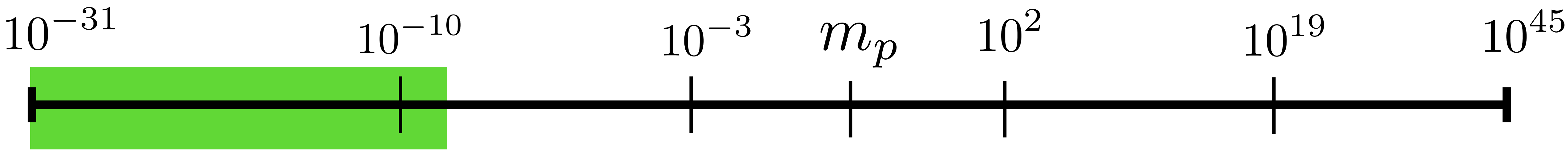


"Axions" proposed to explain absence of neutron electric dipole moment

More general category: Axion Like Particles — "ALPs"

Peccei, Quinn 1977, Phys. Rev. Lett.

Wave-like Dark Matter



"Axions" proposed to explain absence of neutron electric dipole moment

More general category: Axion Like Particles — "ALPs"

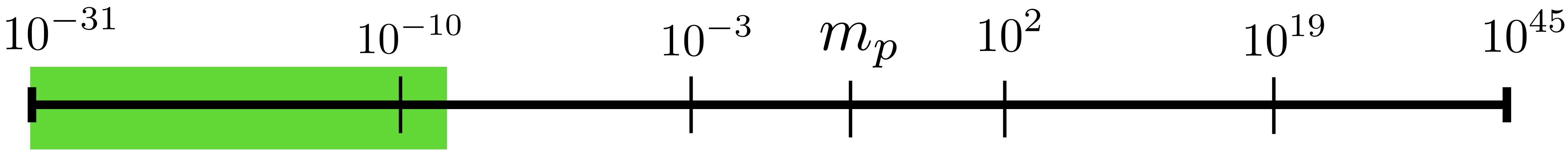
Peccei, Quinn 1977, Phys. Rev. Lett.

Must be produced very "cold" in the early universe

Otherwise would be highly relativistic

Only works with **ultra-feeble** SM interactions

Wave-like Dark Matter



"Axions" proposed to explain absence of neutron electric dipole moment

More general category: Axion Like Particles — "ALPs"

Peccei, Quinn 1977, Phys. Rev. Lett.

Must be produced very "cold" in the early universe

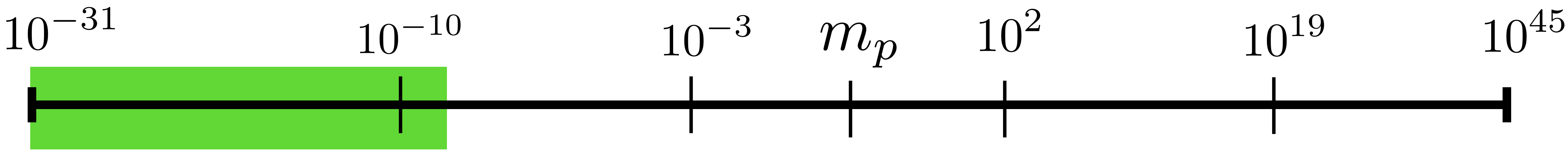
Otherwise would be highly relativistic

Only works with **ultra-feeble** SM interactions

Quantum wavelength exceeds inter-particle separation

Behaves like non-relativistic classical field, hence "wavelike"

Wave-like Dark Matter



"Axions" proposed to explain absence of neutron electric dipole moment

More general category: Axion Like Particles — "ALPs"

Peccei, Quinn 1977, Phys. Rev. Lett.

Must be produced very "cold" in the early universe

Otherwise would be highly relativistic

Only works with **ultra-feeble** SM interactions

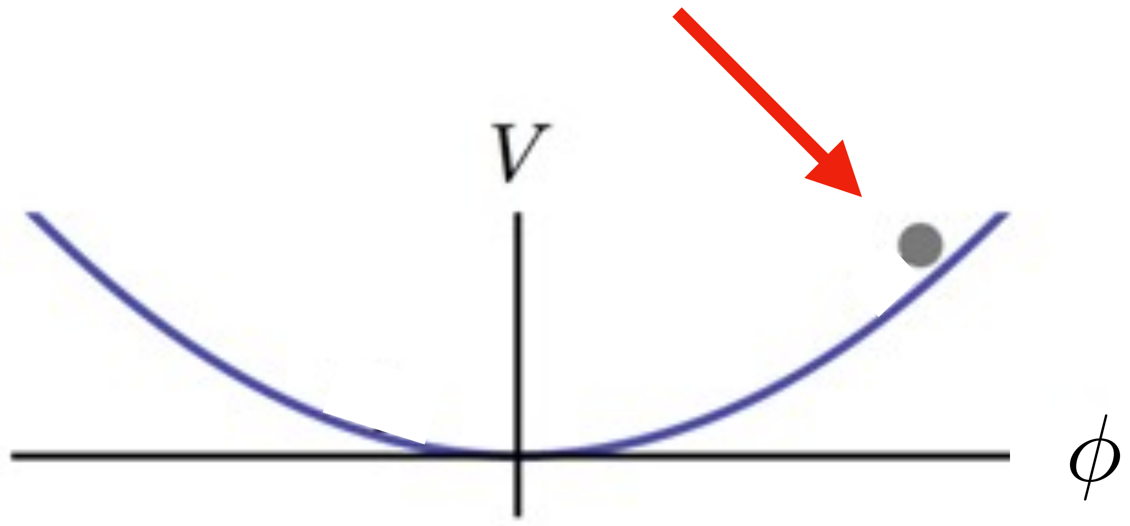
Quantum wavelength exceeds inter-particle separation

Behaves like non-relativistic classical field, hence "wavelike"

How can these be DM candidates?

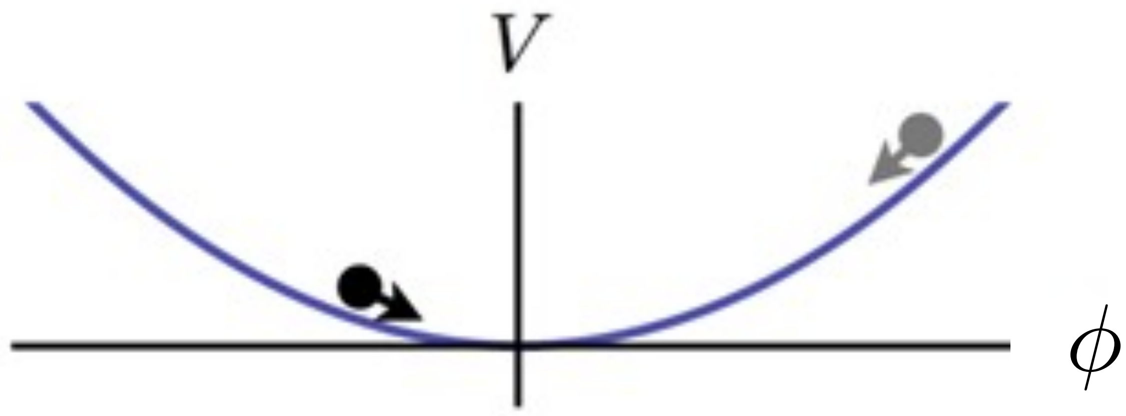
Wavelike DM: Cosmological Evolution

Early universe misalignment — original field value set by initial conditions



Wavelike DM: Cosmological Evolution

Early universe misalignment — original field value set by initial conditions

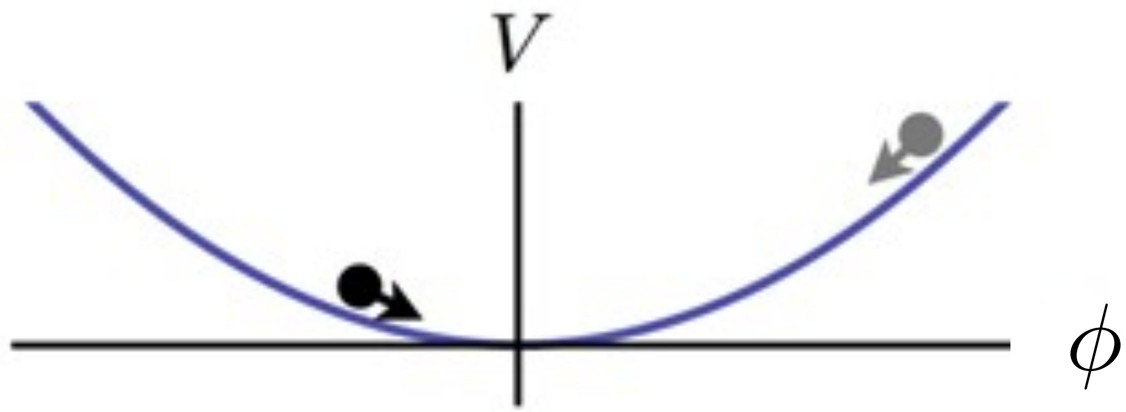


$$\phi(\vec{r}, t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi} \cos(m_\phi t)$$

Begins oscillation when mass = Hubble expansion $m_\phi \sim H$

Wavelike DM: Cosmological Evolution

Early universe misalignment — original field value set by initial conditions



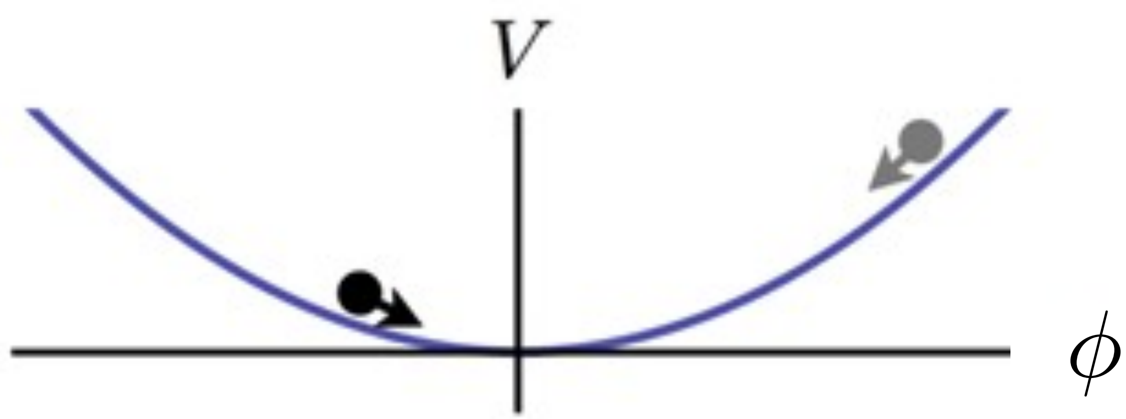
$$\phi(\vec{r}, t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_\phi} \cos(m_\phi t)$$

Begins oscillation when mass = Hubble expansion $m_\phi \sim H$

Redshifts like non relativistic matter $\rho_\phi \sim m_\phi^2 \phi^2 \propto a^{-3}$

Wavelike DM: Cosmological Evolution

Early universe misalignment — original field value set by initial conditions



$$\phi(\vec{r}, t) = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi} \cos(m_\phi t)$$

Begins oscillation when mass = Hubble expansion $m_\phi \sim H$

Redshifts like non relativistic matter $\rho_\phi \sim m_\phi^2 \phi^2 \propto a^{-3}$

Scalar field value set by DM density (locally & cosmologically)

Couple Wavelike DM to ***Neutrinos***

DM interaction gives neutrino time-dependent mass splitting

$$\mathcal{L}_{\rm int} = \left[m_\nu + \underbrace{g\phi(t)}_{\equiv\, \delta m_\nu(t)}\right] \bar{\nu}\nu$$

$$\Delta m^2 \rightarrow \Delta m^2 \left(1 + \frac{2\delta m_\nu(t)}{m_\nu}\right)$$

GK, Machado, Necib, 1705.06740 Phys. Rev. D

Couple Wavelike DM to *Neutrinos*

DM interaction gives neutrino time-dependent mass splitting

$$\mathcal{L}_{\rm int} = [m_\nu + \underbrace{g\phi(t)}_{\equiv\, \delta m_\nu(t)}]\, \bar{\nu}\nu$$

$$\Delta m^2 \to \Delta m^2 \left(1 + \frac{2\delta m_\nu(t)}{m_\nu}\right)$$

↓

Oscillation modified by DM

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Couple Wavelike DM to ***Neutrinos***

DM interaction gives neutrino time-dependent mass splitting

$$\mathcal{L}_{\rm int} = [m_\nu + \underbrace{g\phi(t)}_{\equiv\, \delta m_\nu(t)}]\,\bar{\nu}\nu$$

$$\Delta m^2 \to \Delta m^2 \left(1 + \frac{2\delta m_\nu(t)}{m_\nu}\right)$$

Oscillation modified by DM

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

"Distorted Neutrino Oscillations" (DINOs)

GK, Machado, Necib, 1705.06740 Phys. Rev. D

Couple Wavelike DM to *Neutrinos*

What's the relevant timescale? $\tau_\phi = \frac{2\pi}{m_\phi} \sim 10\,\mathrm{min}\left(\frac{10^{17}\,\mathrm{eV}}{m_\phi}\right)$

If period **short** wrt neutrino travel time: effect averages to zero

If period **long** wrt observation time: unobservable

Need: $t_{\rm obs} > \tau_\phi > t_{\nu\,\rm travel} = L/c$

GK, Machado, Necib, 1705.06740 Phys. Rev. D

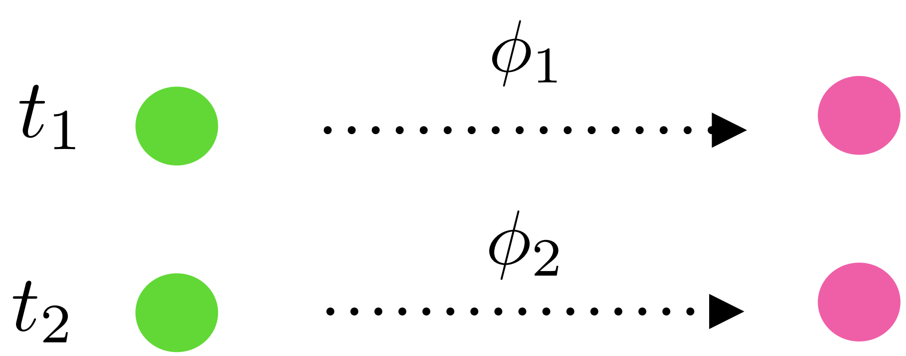
Couple Wavelike DM to ***Neutrinos***

What's the relevant timescale? $$\tau_\phi = \frac{2\pi}{m_\phi} \sim 10\,\mathrm{min}\left(\frac{10^{17}\,\mathrm{eV}}{m_\phi}\right)$$

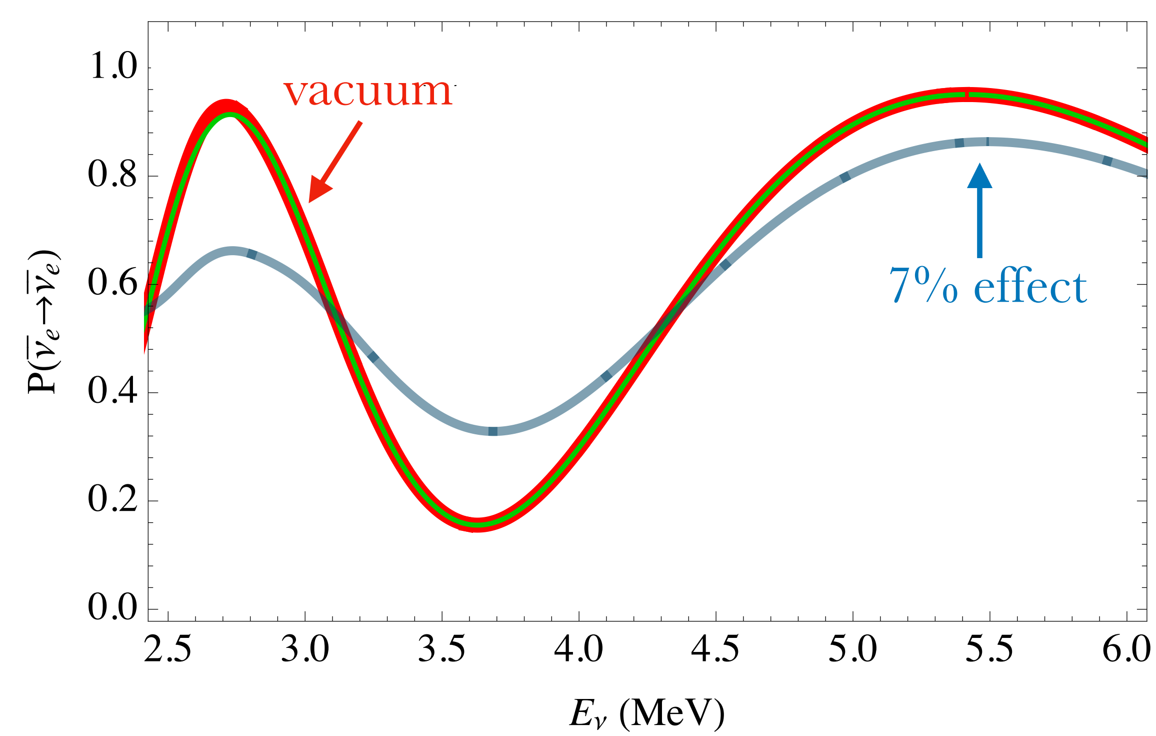
If period **short** wrt neutrino travel time: effect averages to zero

If period **long** wrt observation time: unobservable

Need: $$t_{\mathrm{obs}} > \tau_\phi > t_{\nu\,\mathrm{travel}} = L/c$$

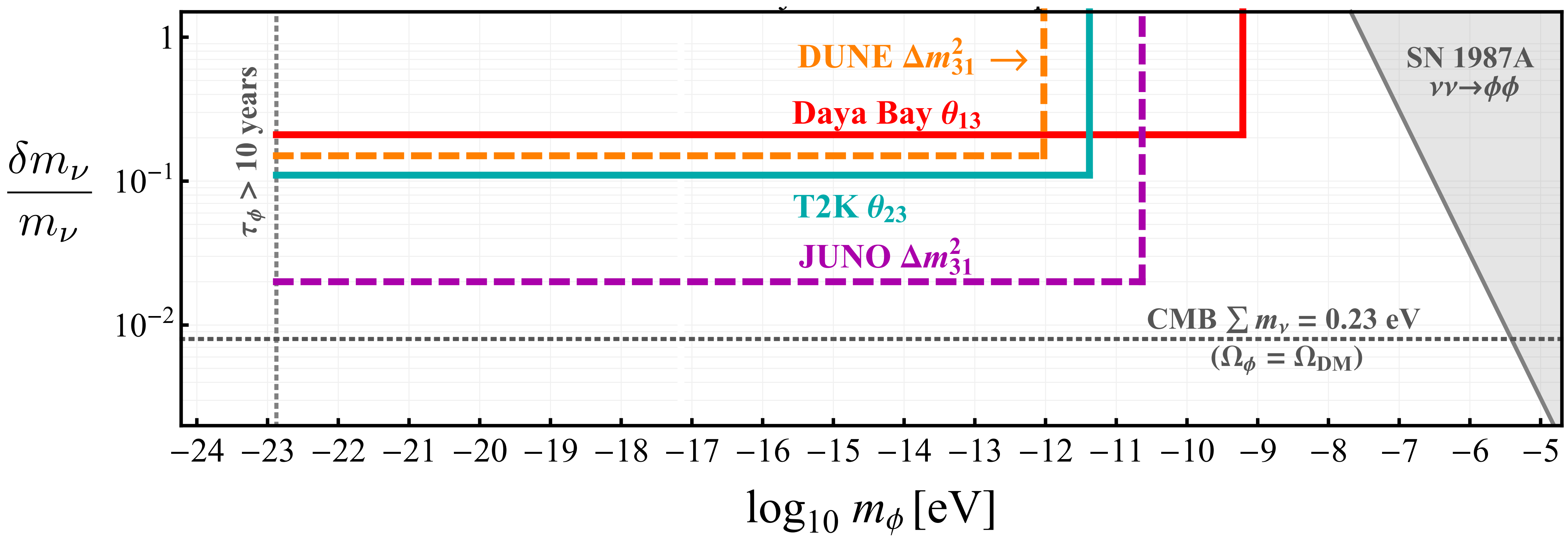


$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \int_0^{\tau_\phi} \frac{dt}{\tau_\phi} P(\nu_\alpha \to \nu_\beta)$$



GK, Machado, Necib, 1705.06740 Phys. Rev. D

Couple Wavelike DM to *Neutrinos*



Effect likely also important for ultra high energy and supernova neutrinos
Longer travel times and different energy profiles than terrestrial sources

(accelerators + nuclear reactors)

dashed = projection
solid = excluded

GK, Machado, Necib, 1705.06740 Phys. Rev. D

Couple Wavelike DM to ***Right Handed Neutrinos***

If cosmic DM density gives tiny Majorana mass to RH Neutrinos N

$$\mathcal{L} \supset y_\nu H \ell N + \frac{y_\phi}{2} \phi N N + h.c.$$

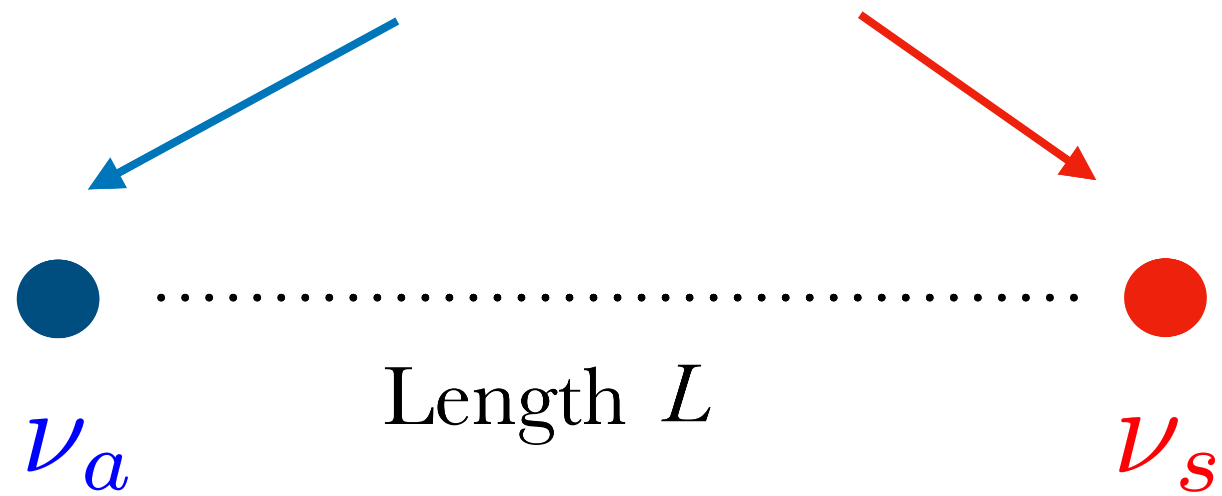
Dev, GK Machado, Ramani 2205.06821, PRD

Couple Wavelike DM to ***Right Handed Neutrinos***

If cosmic DM density gives tiny Majorana mass to RH Neutrinos N

$$\mathcal{L} \supset y_\nu H \ell N + \frac{y_\phi}{2} \phi N N + h.c.$$

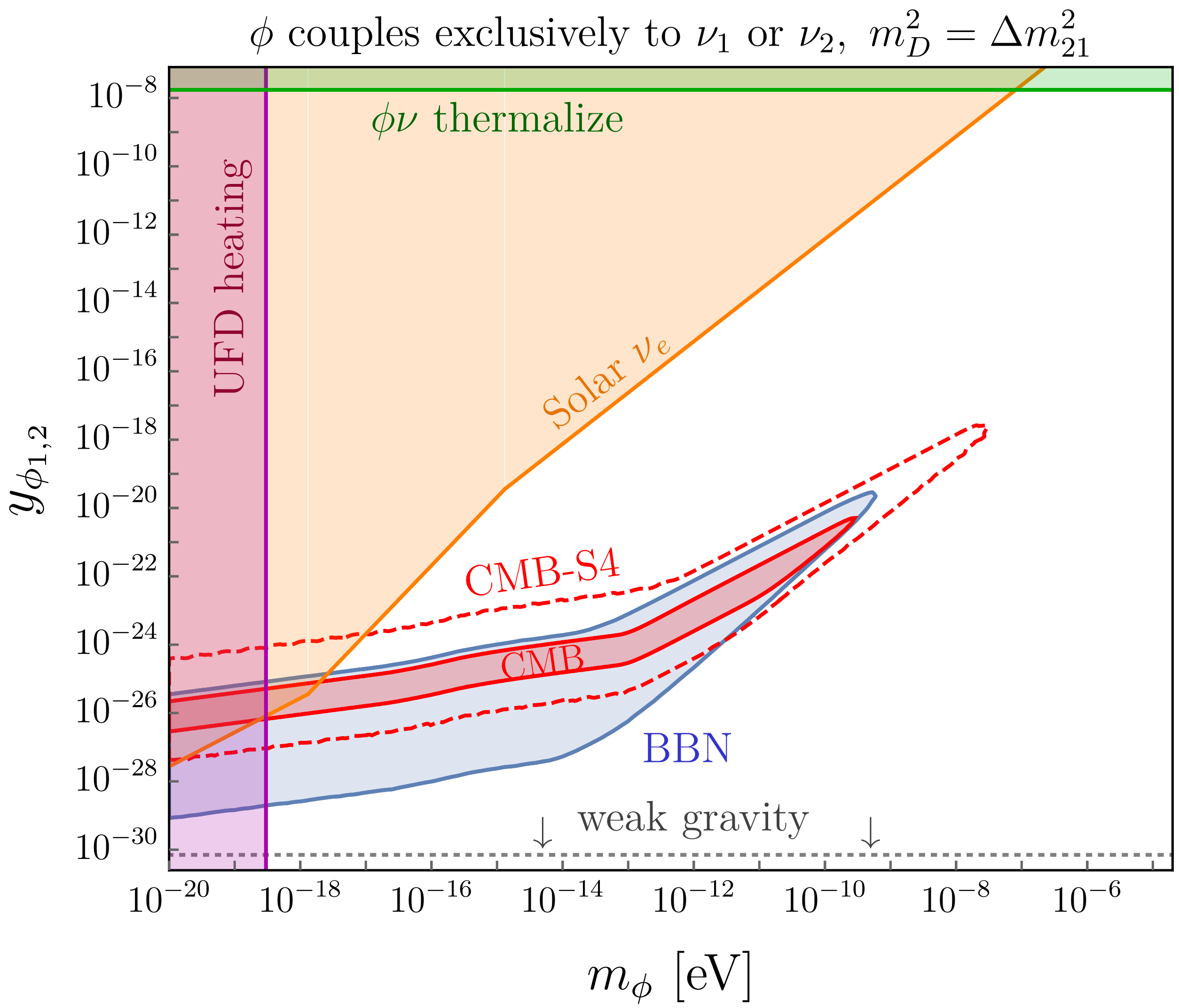
Eigenstates are **active** and **sterile** neutrinos

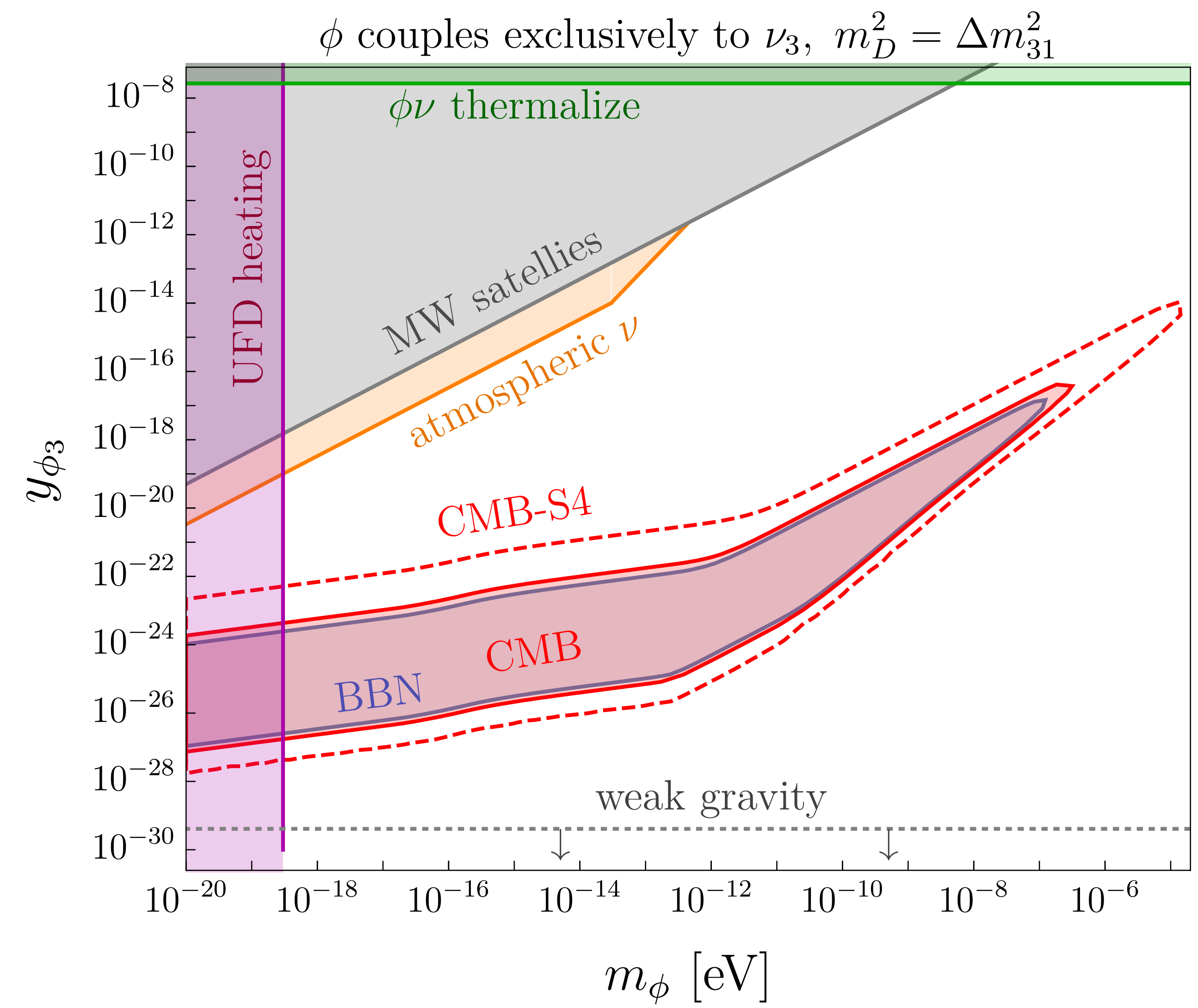


Observables are deficits of active neutrinos correlated with DM background

Dev, GK Machado, Ramani 2205.06821, PRD

Couple Wavelike DM to ***Right Handed Neutrinos***





Limits interactions comparable to gravity between neutrinos

Dev, GK Machado, Ramani 2205.06821, PRD

Overview

What's the evidence for dark matter?

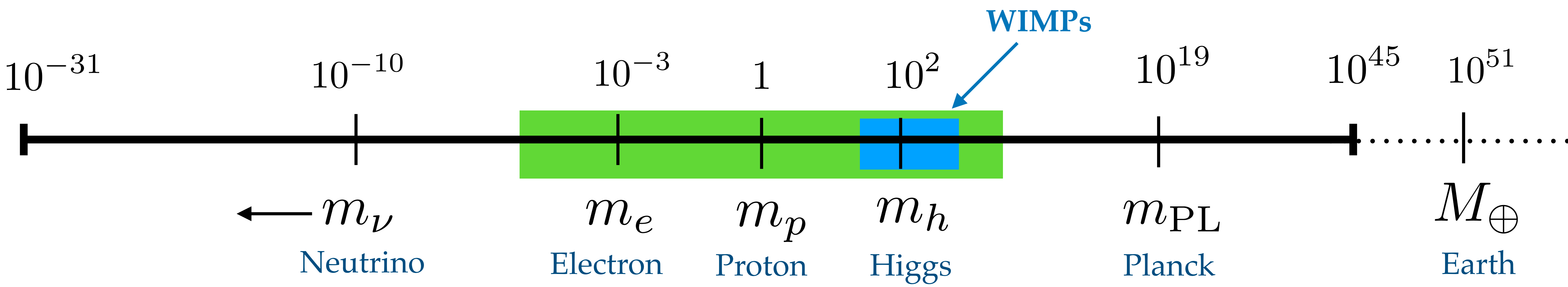
What can we deduce from first principles?

What can we learn in new places?

Wavelike **Particle-like** Macroscopic

Middleweight DM — e,g, WIMPs and their cousins

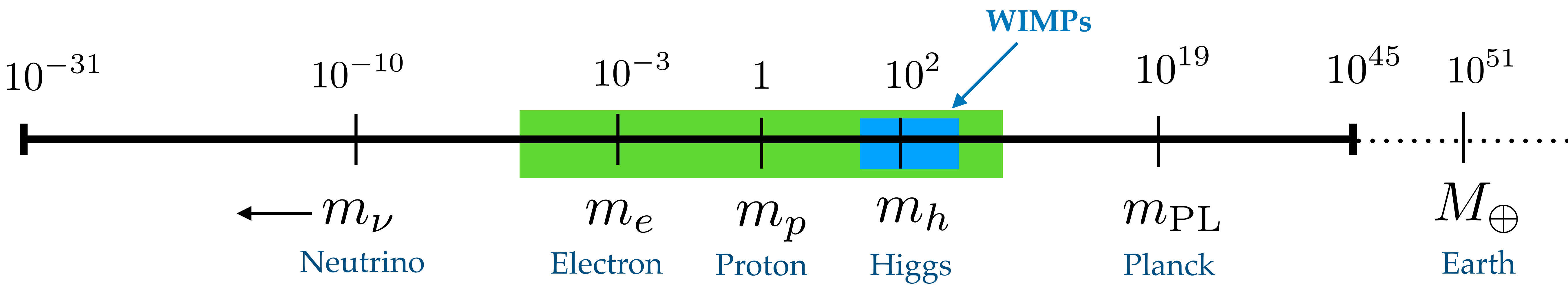
Dark Sectors "Generalized WIMPs"



Particle-like dark sectors: WIMP-like features, broader mass range

DM is microscopic particle and new 5th force couples it to visible matter

Dark Sectors "Generalized WIMPs"



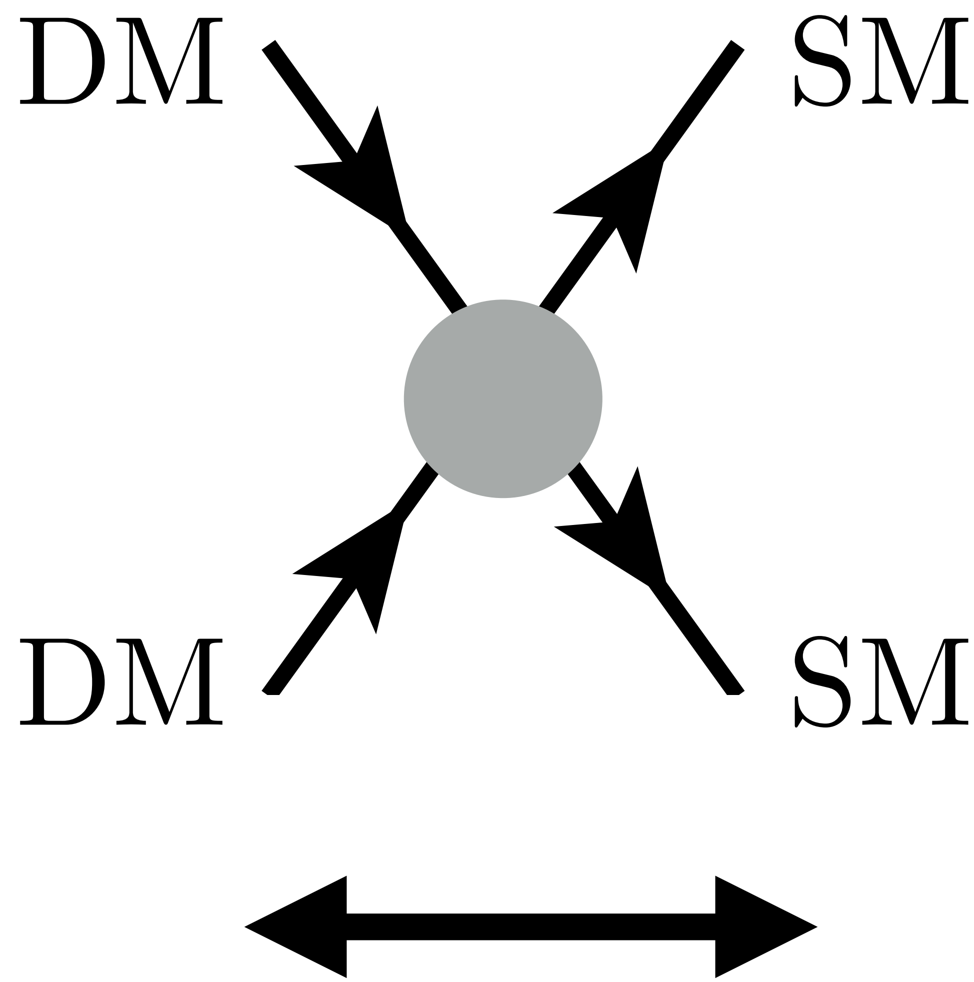
Particle-like dark sectors: WIMP-like features, broader mass range

DM is microscopic particle and new 5th force couples it to visible matter

This mass range allows a *thermal* origin

Why is this an amazing feature?

Was DM ever in equilibrium with SM?



Chemical equilibrium: DM production $=$ annihilation
just after the big bang when $T \gg m_{\rm DM}$

Was DM ever in equilibrium with SM?

NO

How was it populated?

Was DM ever in equilibrium with SM?

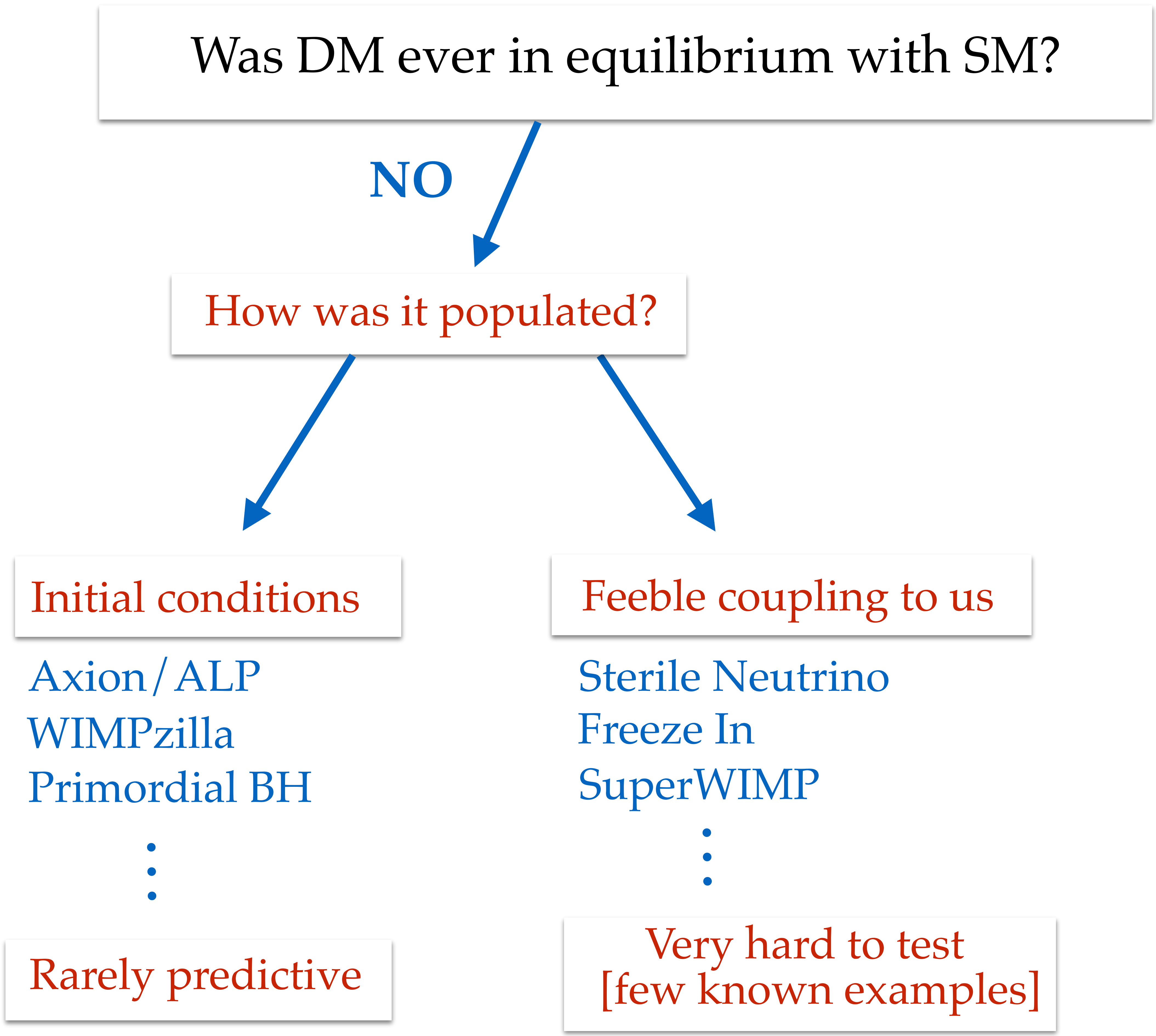
NO

How was it populated?

Initial conditions

Axion / ALP
WIMPzilla
Primordial BH
⋮

Rarely predictive


Was DM ever in equilibrium with SM?
NO
How was it populated?
Initial conditions
Axion / ALP
WIMPzilla
Primordial BH
Rarely predictive
Feeble coupling to us
Sterile Neutrino
Freeze In
SuperWIMP
Very hard to test
[few known examples]

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

$$n_i^{\rm eq} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto T^3 \qquad (T \gg m)$$

In equilibrium, number density set by temperature

All relativistic species have comparable numbers

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

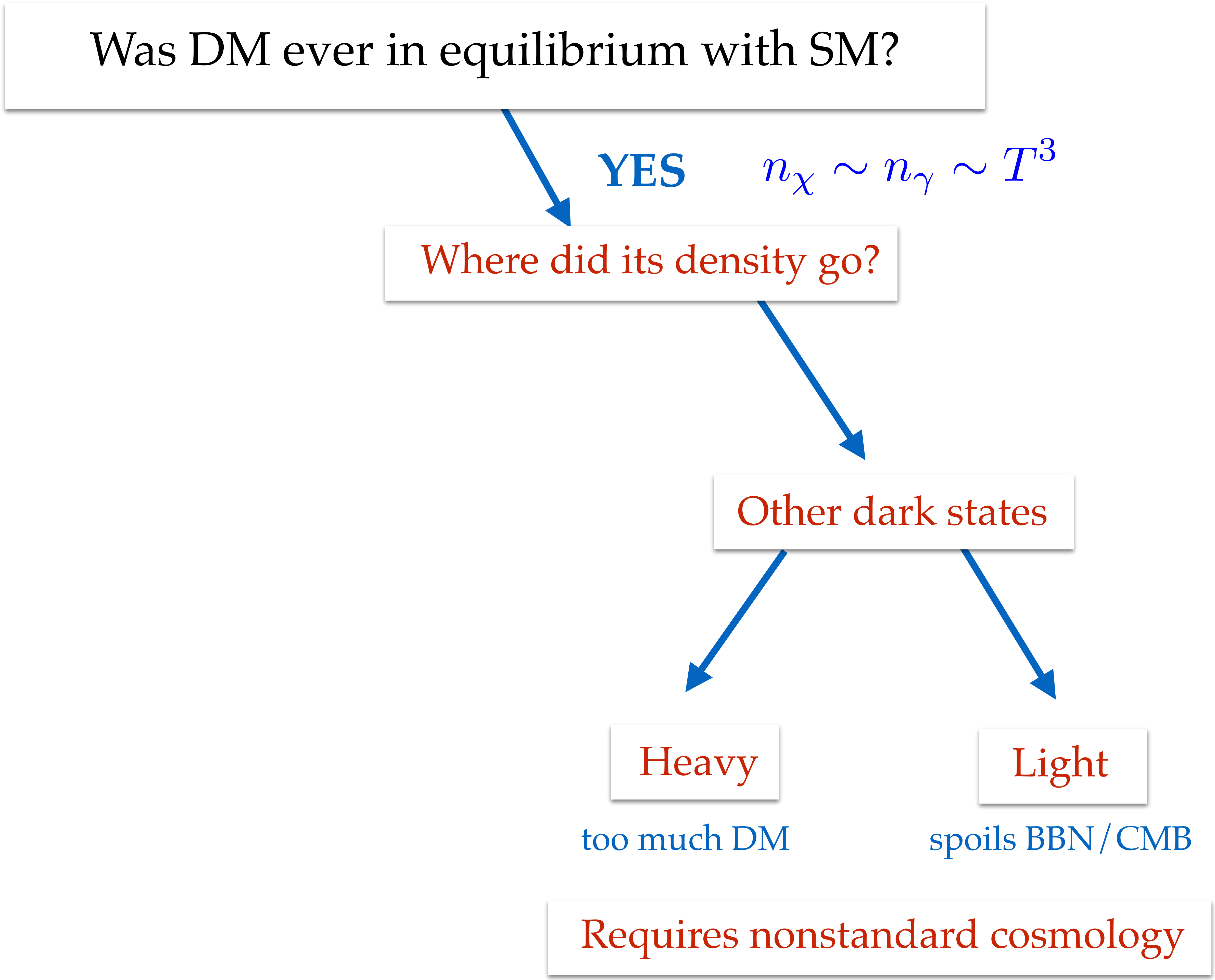
Where did its density go?

Stayed the same

We've measured the DM mass density so equilibrium predicts particle mass

$$m_\chi \approx \rho_\chi / n_\chi \sim 10\,\mathrm{eV}$$

Too hot, ruled out!


Was DM ever in equilibrium with SM?
YES
$n_\chi \sim n_\gamma \sim T^3$
Where did its density go?
Other dark states
Heavy
too much DM
Light
spoils BBN / CMB
Requires nonstandard cosmology

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

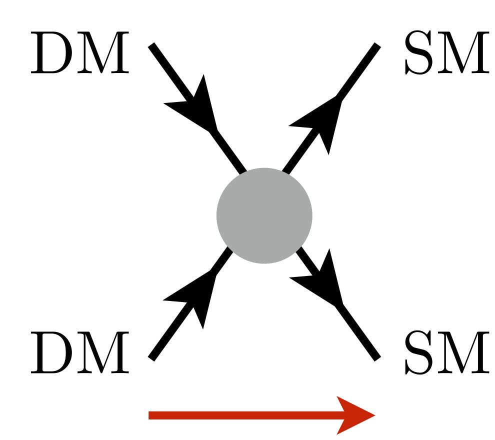
Where did its density go?

Visible matter

Direct Annihilation

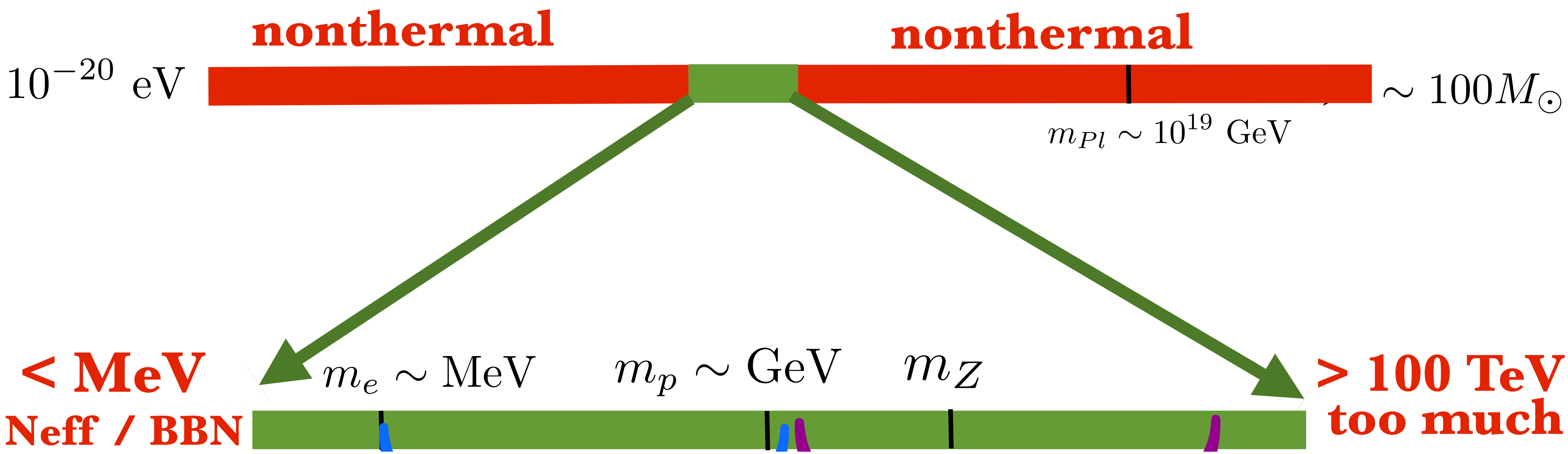
1) Predicts ***minimum*** SM coupling

2) The **only** production scenario that is insensitive to unknown* cosmic epochs



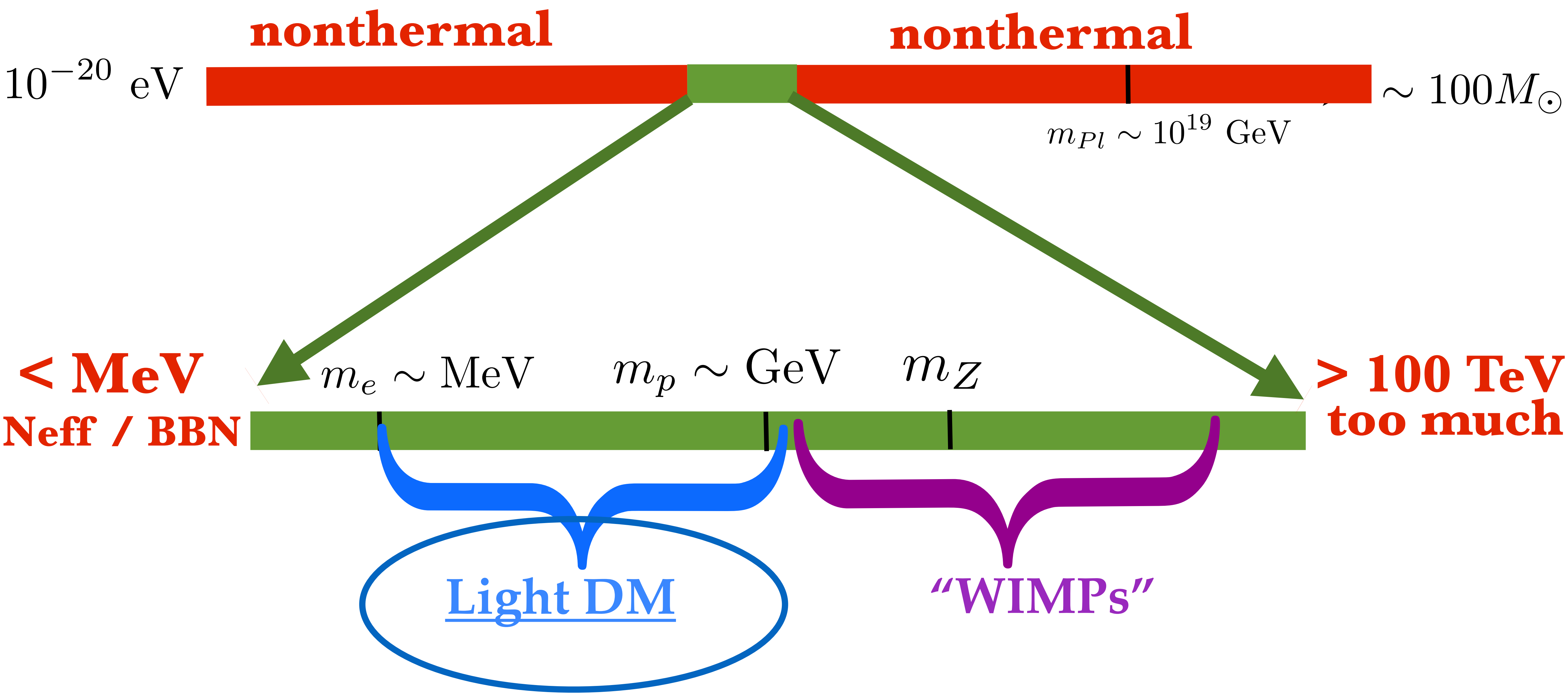
*(example: inflation)

Equilibrium Narrows Mass Range!



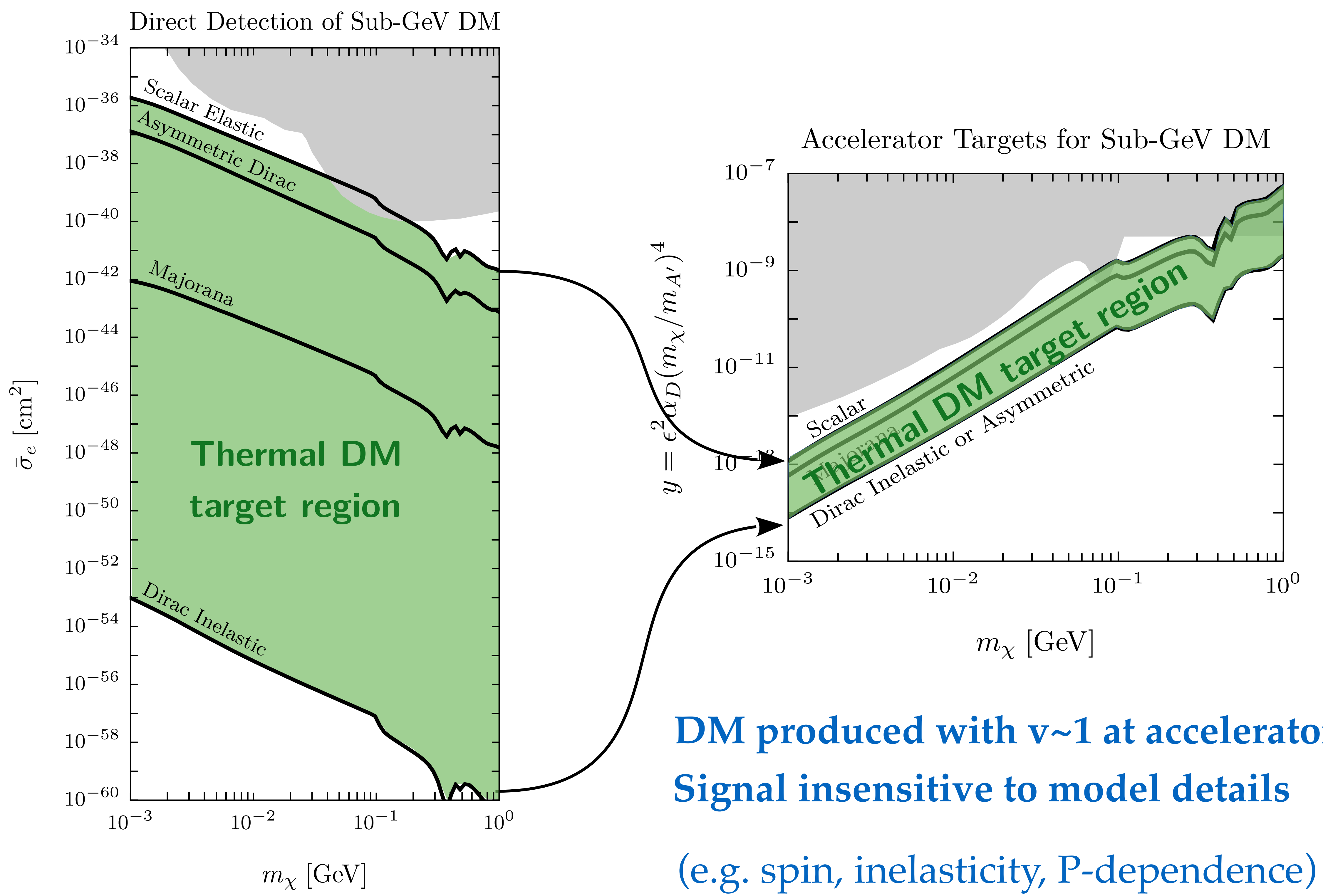
Any DM candidate outside this range is ruled out if theory allows thermalization with the SM

Equilibrium Narrows Mass Range!



Fixed Target Accelerators

Advantages of Accelerator Searches



DM produced with v~1 at accelerators

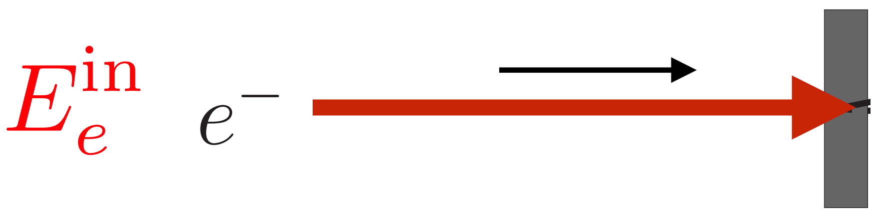
Signal insensitive to model details

(e.g. spin, inelasticity, P-dependence)

Izaguirre, GK Schuster, Toro 1505.00011 PRL

Slide: Nikita Blinov

Missing Momentum Strategy

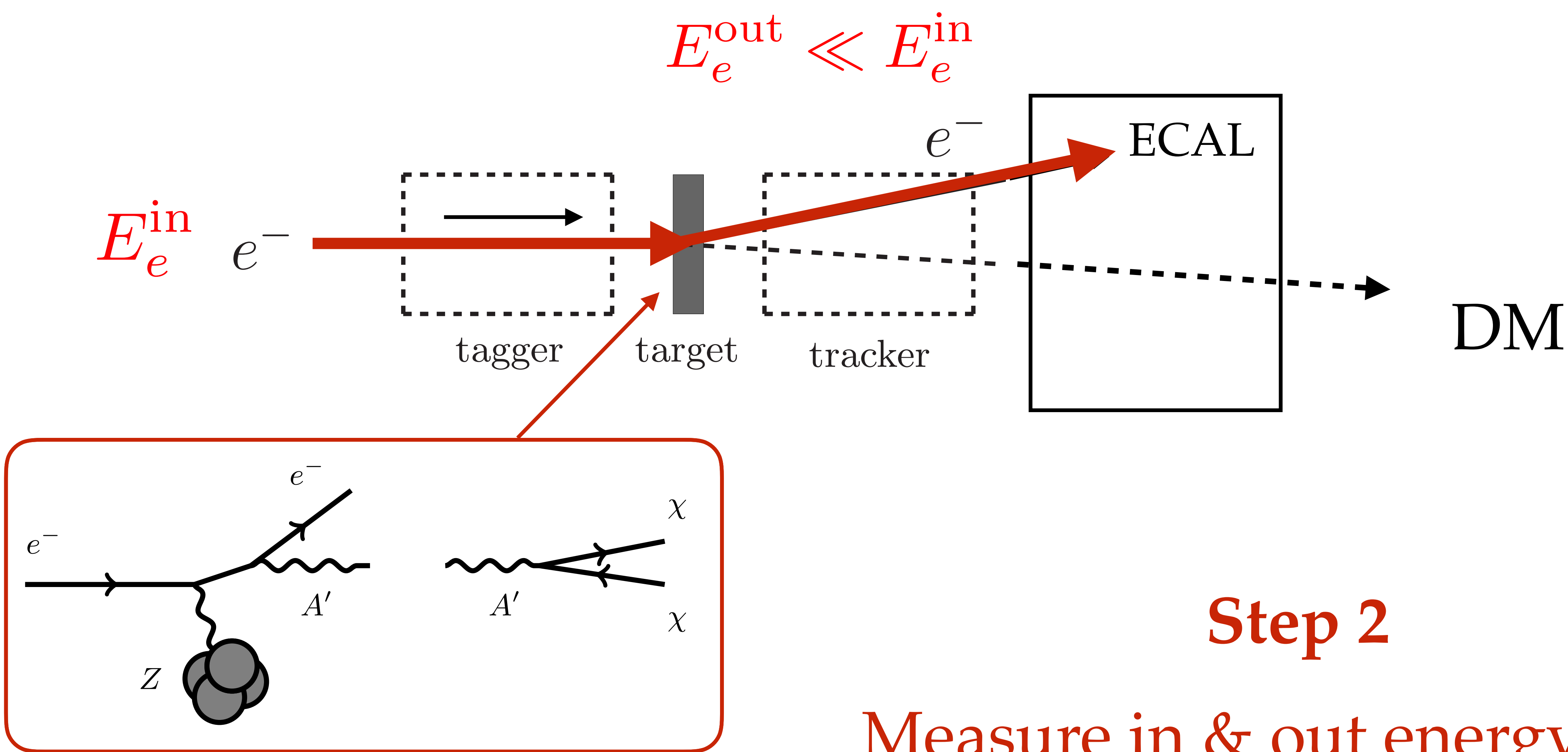


Step 1

Deliver **single** ~ 10 GeV electron to thin target

Izaguirre, GK, Schuster, Toro arXiv:1411.1404 [Phys.Rev. D]

Missing Momentum Strategy



Step 2

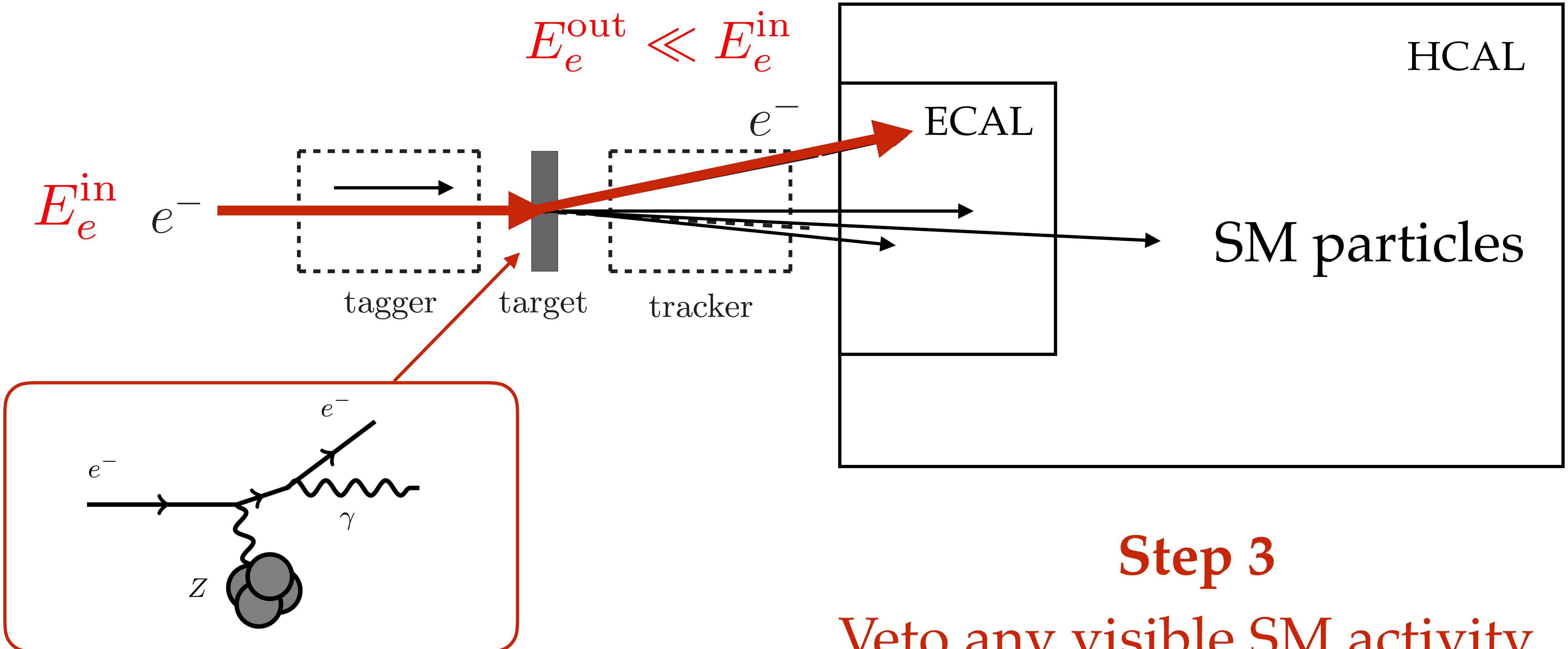
Measure in & out energy @ ECAL

Trigger on large missing E/P

If DM is produced, beam electron loses large E/P fraction

Izaguirre, GK, Schuster, Toro arXiv:1411.1404 [Phys.Rev. D]

Missing Momentum Strategy



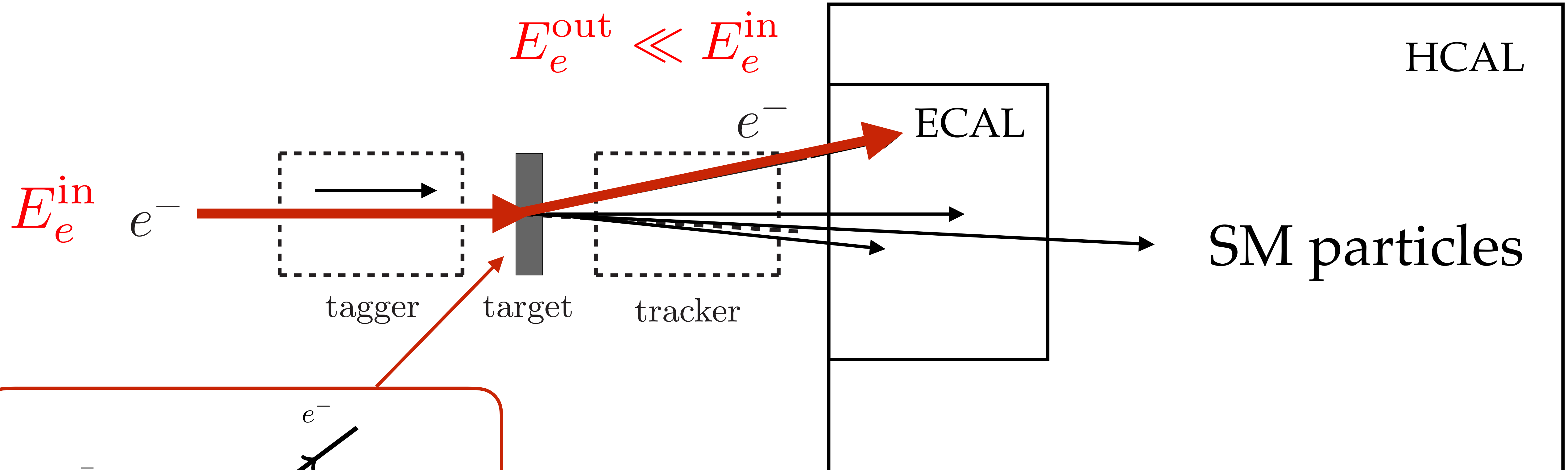
Step 3

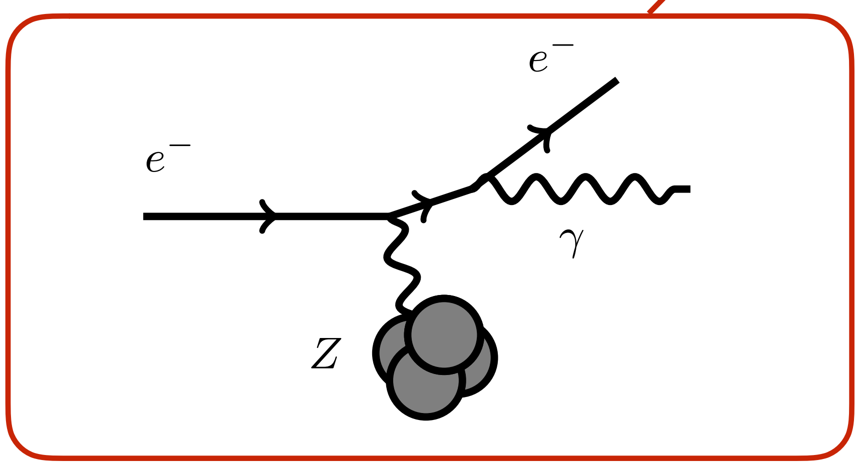
Veto any visible SM activity

If SM particles produced, reject all events with ECAL/HCAL

Izaguirre, GK, Schuster, Toro arXiv:1411.1404 [Phys.Rev. D]

Missing Momentum Strategy





1) Measure **each** e- energy in/out
2) Trigger on missing momentum
3) ECAL/HCAL veto SM activity

Step 4

Repeat steps 1-3 $N_e \simeq 10^{16}$ times

Izaguirre, GK, Schuster, Toro arXiv:1411.1404 [Phys.Rev. D]

FERMILAB-PUB-19-620-SCD, SLAC-PUB-17495

A High Efficiency Photon Veto for the Light Dark Matter eXperiment

Torsten Åkesson,[1] Nikita Blinov,[2] Lene Bryngemark,[3] Owen Colegrove,[4] Giulia Collura,[4] Craig Dukes,[5] Valentina Dutta,[4] Bertrand Echenard,[6] Thomas Eichlersmith,[7] Craig Group,[5] Joshua Hiltbrand,[7] David G. Hitlin,[6] Joseph Incandela,[4] Gordan Krnjaic,[2] Juan Lazaro,[4] Amina Li,[4] Jeremiah Mans,[7] Phillip Masterson,[4] Jeremy McCormick,[8] Omar Moreno,[8] Geoffrey Mullier,[1] Akshay Nagar,[4] Timothy Nelson,[8] Gavin Niendorf,[4] James Oyang,[6] Reese Petersen,[7] Ruth Pöttgen,[1] Philip Schuster,[8] Harrison Siegel,[4] Natalia Toro,[8] Nhan Tran,[2] and Andrew Whitbeck[9]

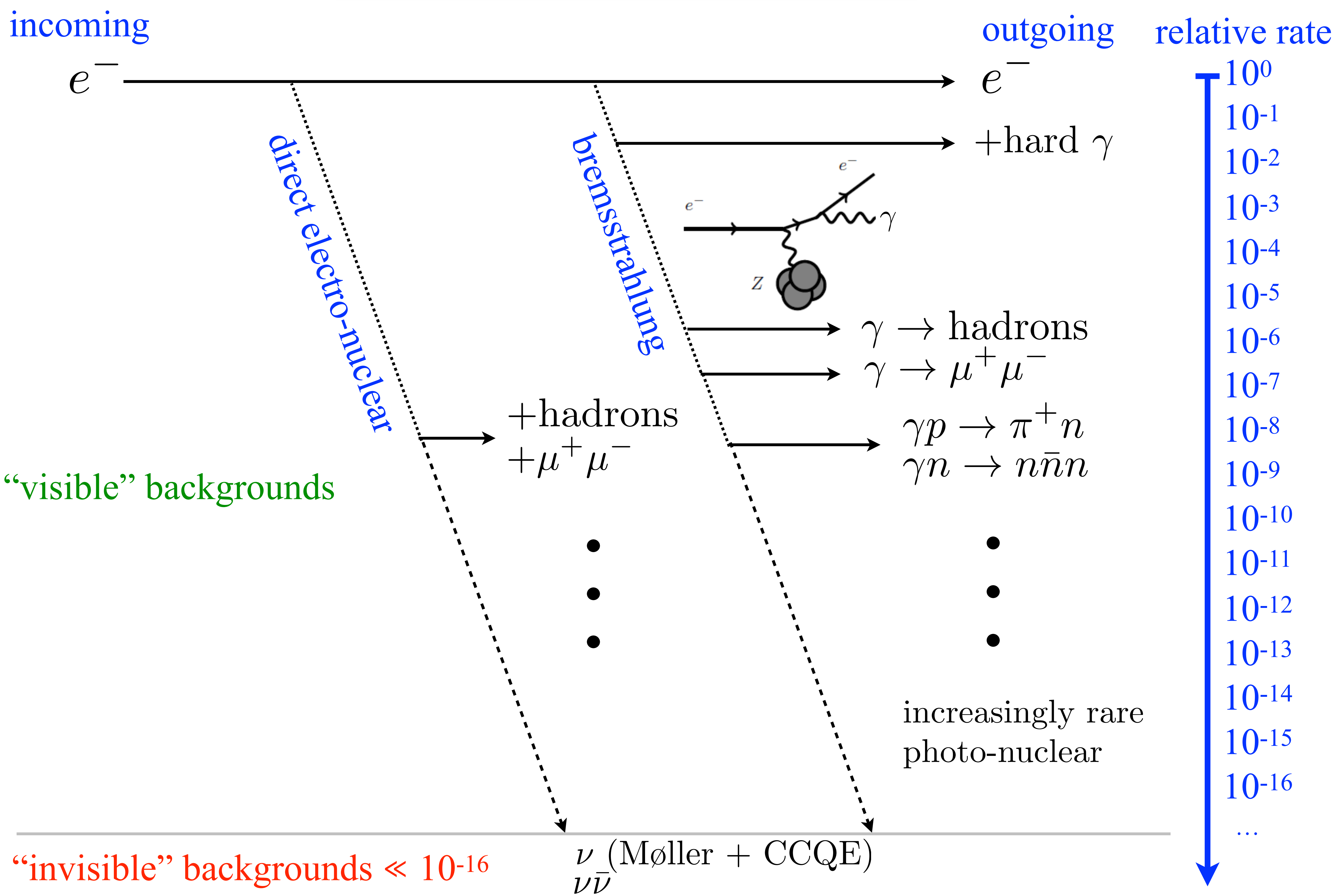
[1]*Lund University, Department of Physics, Box 118, 221 00 Lund, Sweden*
[2]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[3]*Stanford University, Stanford, CA 94305, USA*
[4]*University of California at Santa Barbara, Santa Barbara, CA 93106, USA*
[5]*University of Virginia, Charlottesville, VA 22904, USA*
[6]*California Institute of Technology, Pasadena, CA 91125, USA*
[7]*University of Minnesota, Minneapolis, MN 55455, USA*
[8]*SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA*
[9]*Texas Tech University, Lubbock, TX 79409, USA*

(Dated: December 12, 2019)

LDMX Collaboration awarded DOE DM New Initiatives funding

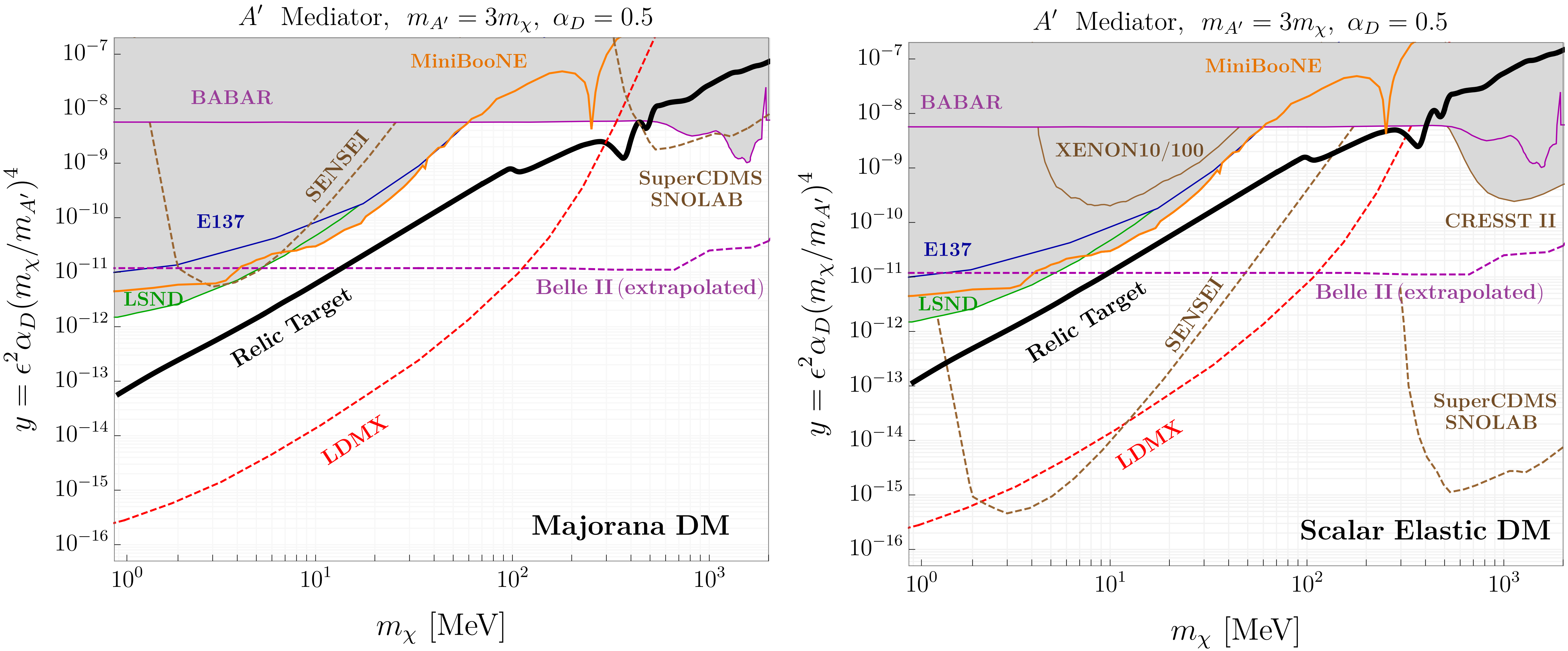
LDMX Collaboration 1912.05535

Background Rates



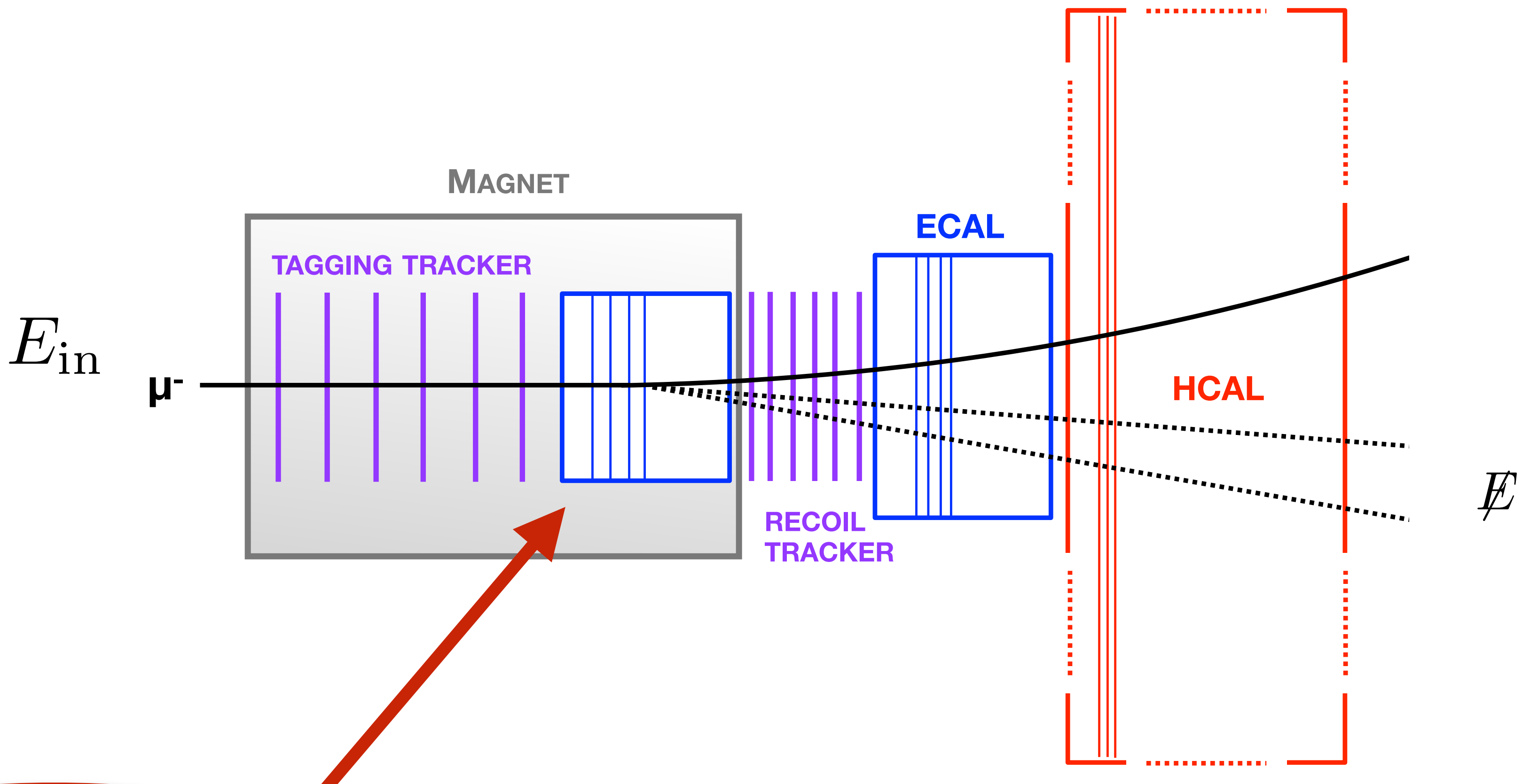
LDMX Collaboration 1912.05535

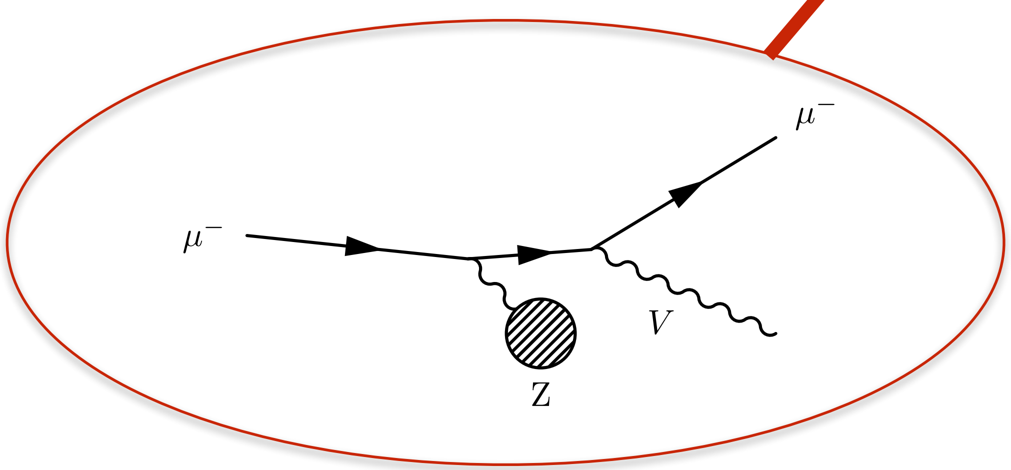
LDMX Projected Reach



Blinov, Berlin, GK, Schuster, Toro arXiv:1807.01730

M³: Muon Missing Momentum @ FNAL





1) Measure E in/out with B field

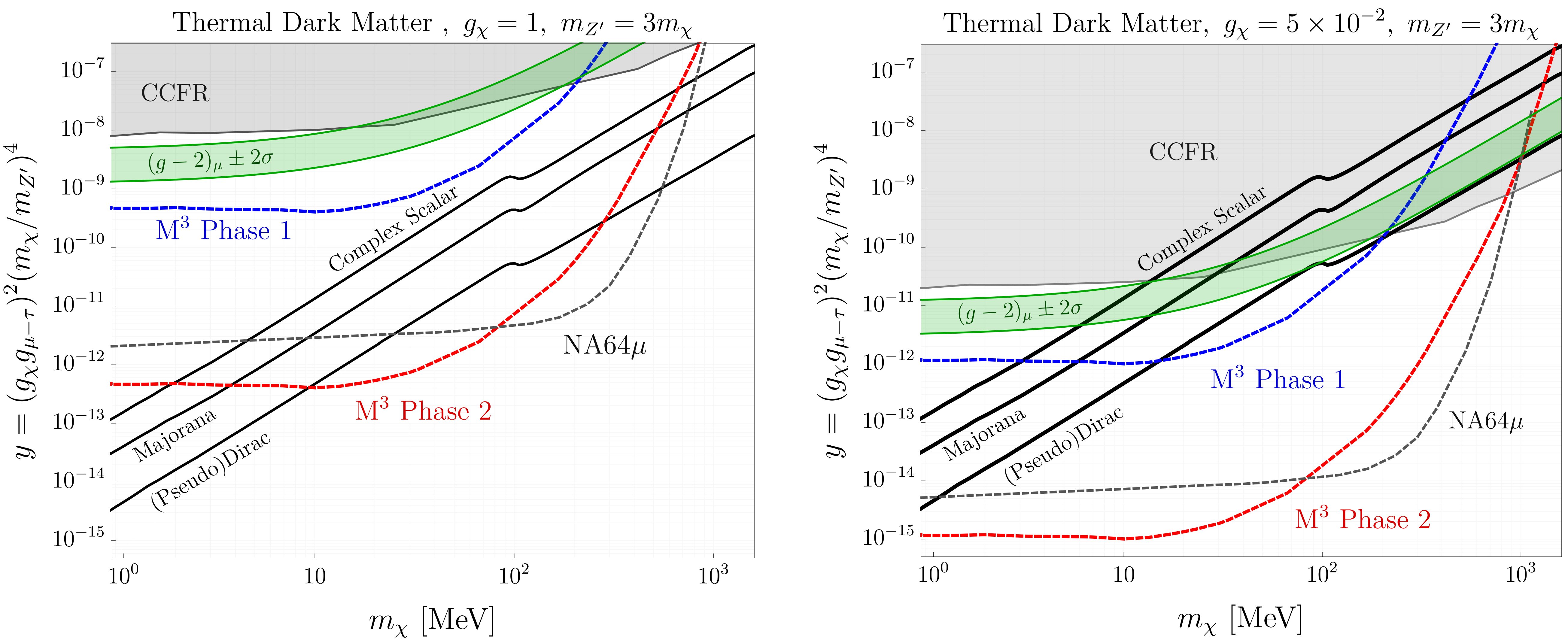
2) Trigger on missing P

3) Veto additional SM activity

Fermilab

Kahn, GK, Tran, Whitbeck 1804.03144, LDRD supported

M³: Muon Missing Momentum @ FNAL



Covers predictive thermal production targets for muon-philic DM. Including models that also explain g-2 anomaly

Holst, Hooper, GK, 2107.09067 PRL

Kahn, GK, Tran, Whitbeck 1804.03144, LDRD supported

Overview

What's the evidence for dark matter?

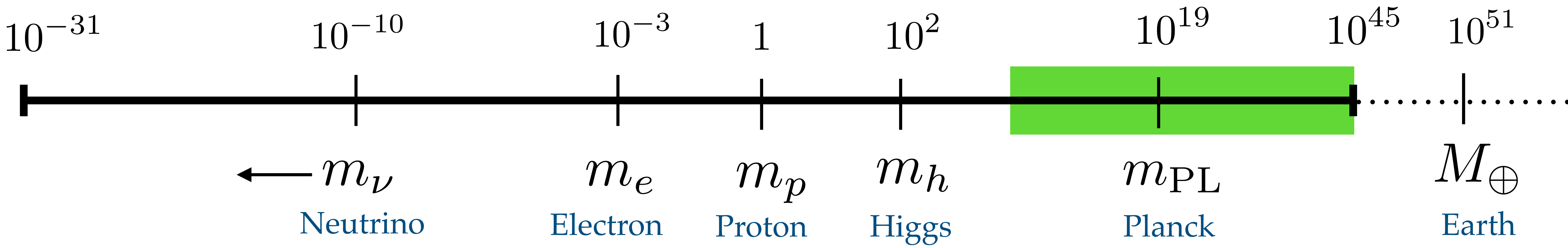
What can we deduce from first principles?

What can we learn in new places?

Wavelike Particle-like **Macroscopic**

Ultra Heavy DM (e.g. "WIMPZILLA!")

WIMPZILLAS and ultra heavy DM

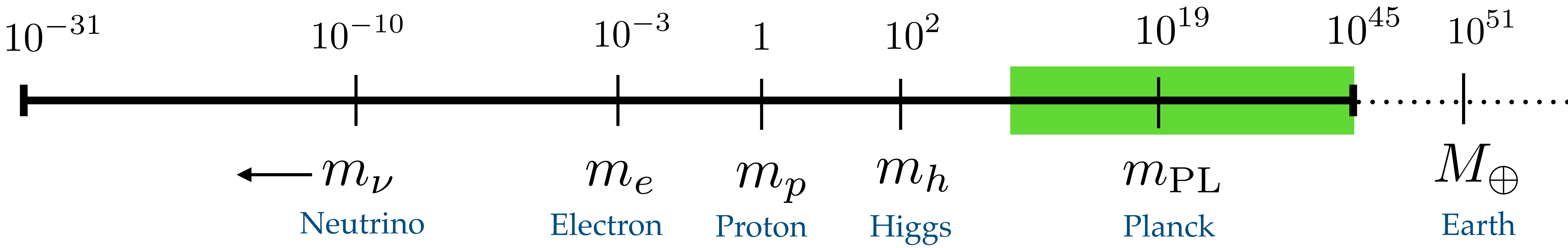


Broad category with many viable production mechanisms

Too heavy for thermal equilibrium in early universe

Kolb, Chung, Riotto arXiv/9810361

WIMPZILLAS and ultra heavy DM



Broad category with many viable production mechanisms

Too heavy for thermal equilibrium in early universe

Kolb, Chung, Riotto arXiv/9810361

Could we ever detect it using gravity alone?

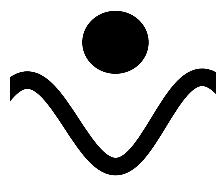
$$F_G = G_N \frac{m_{\rm DM} m_{\rm test}}{d^2} \approx \underbrace{10^{-21}\mathrm{N}}_{\text{“zeptonewton”}} \left(\frac{m_{\rm DM}}{m_{\rm PL}}\right)\left(\frac{m_{\rm test}}{m_{\rm PL}}\right)\left(\frac{5\,\mathrm{mm}}{d}\right)^2$$

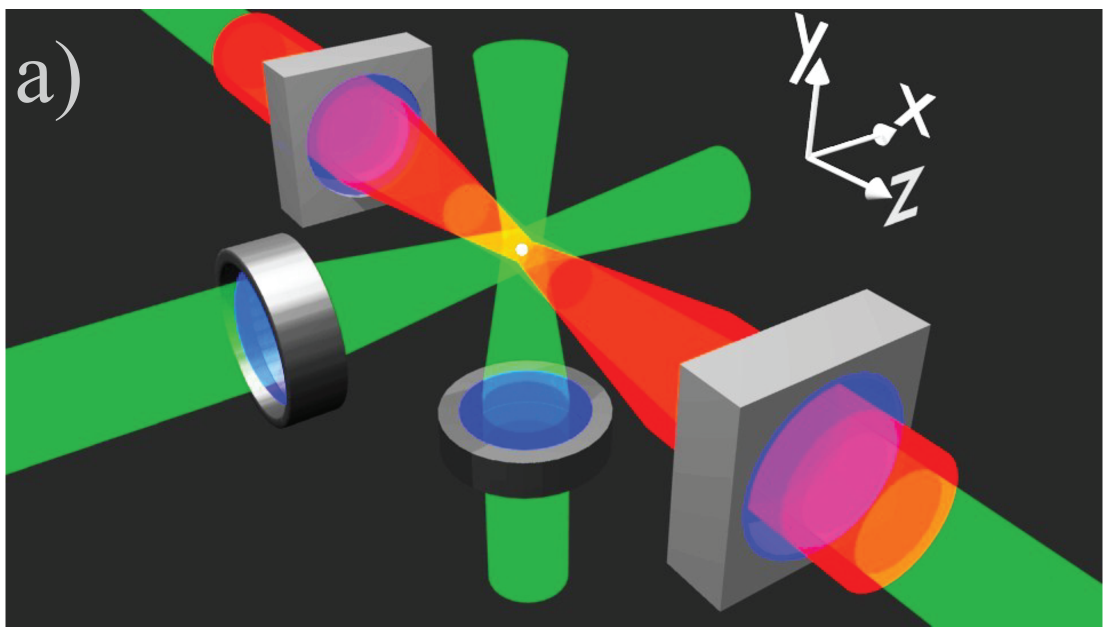
$m_{\rm PL} = 2.2 \times 10^{-5}$ gram

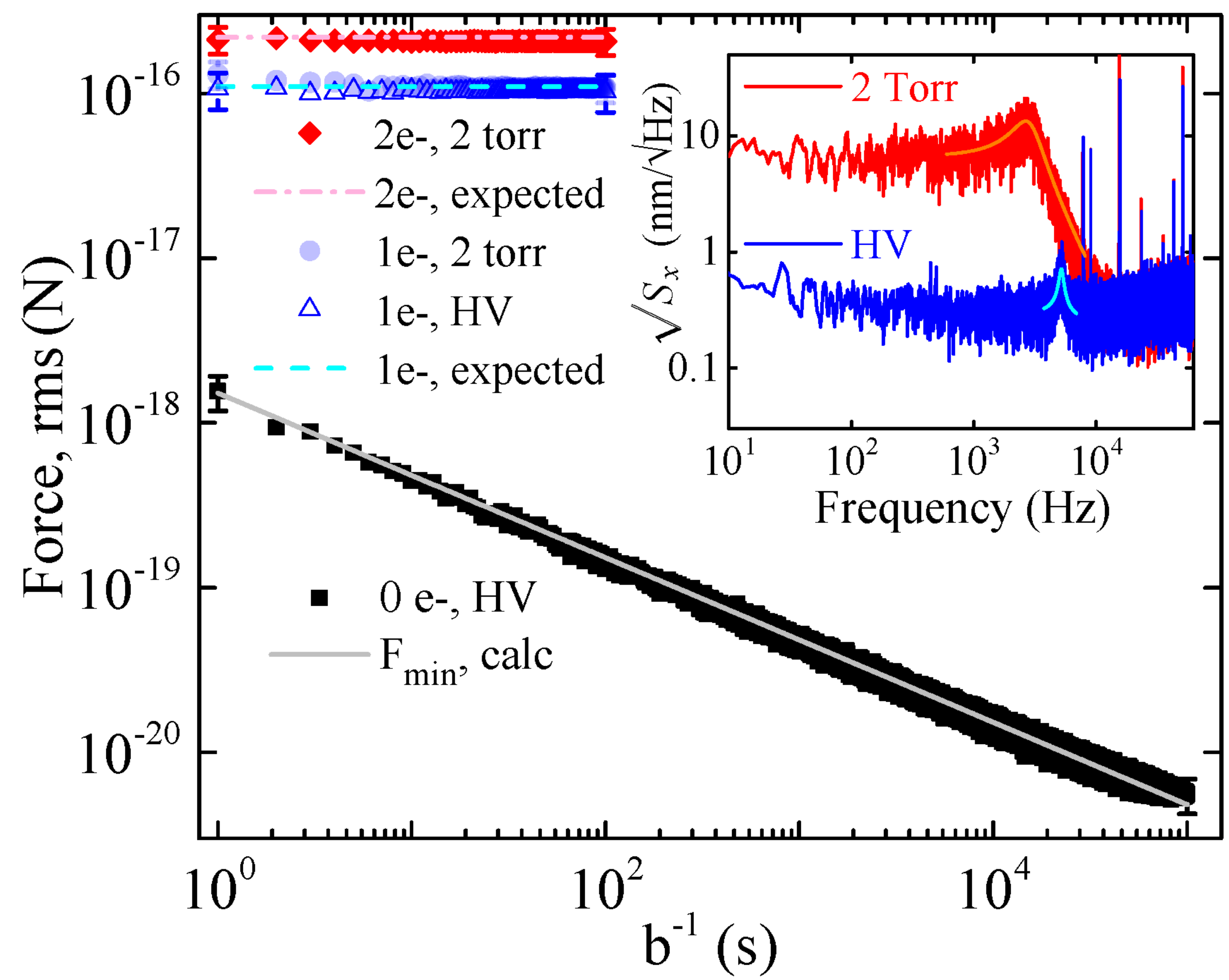
This sounds totally nuts, right?

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
(Dated: March 10, 2016)



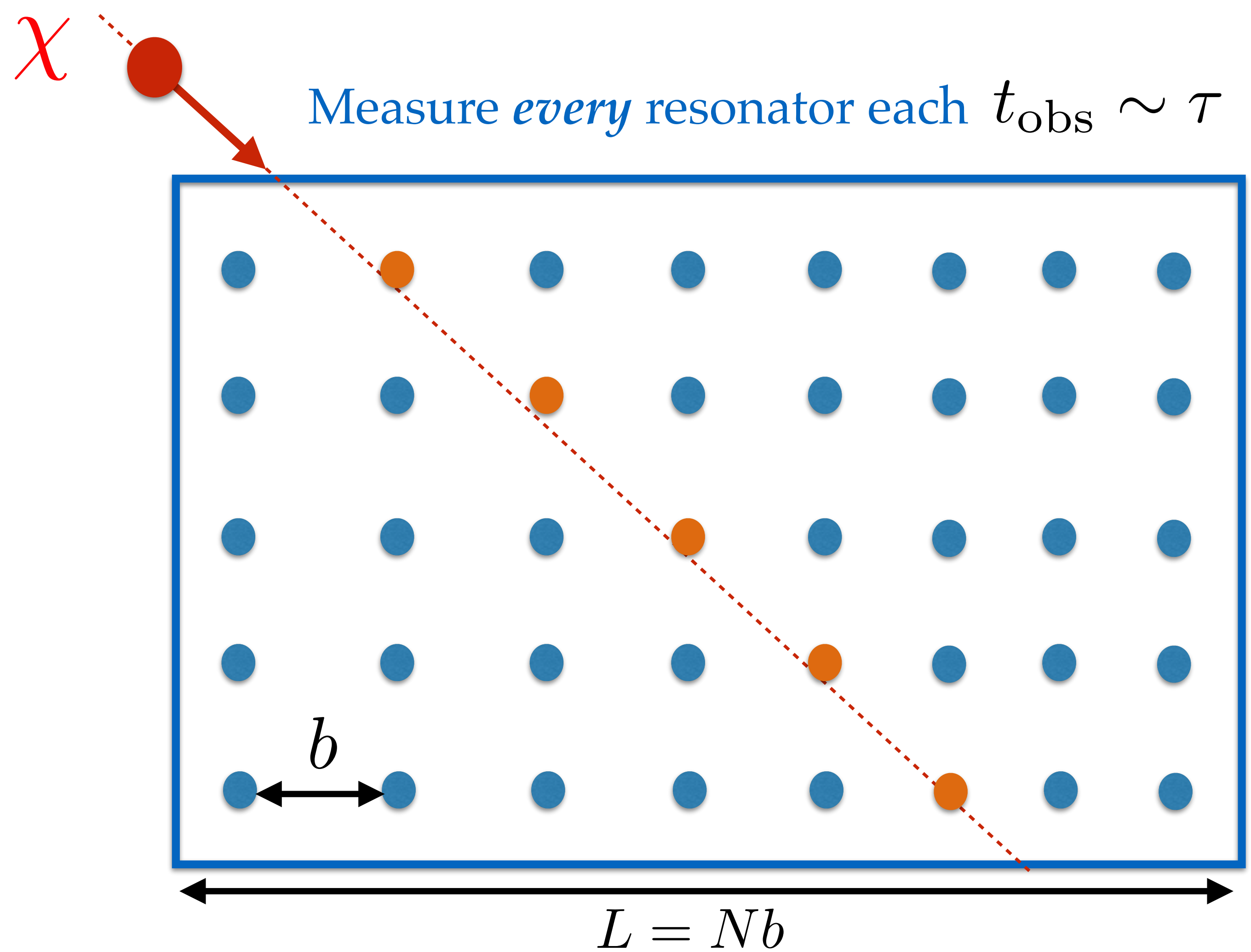




Can we use this to gravitationally detect WIMPZILLAS?

arXiv:1603.02122

Levitating Sensor Arrays "Windchime"

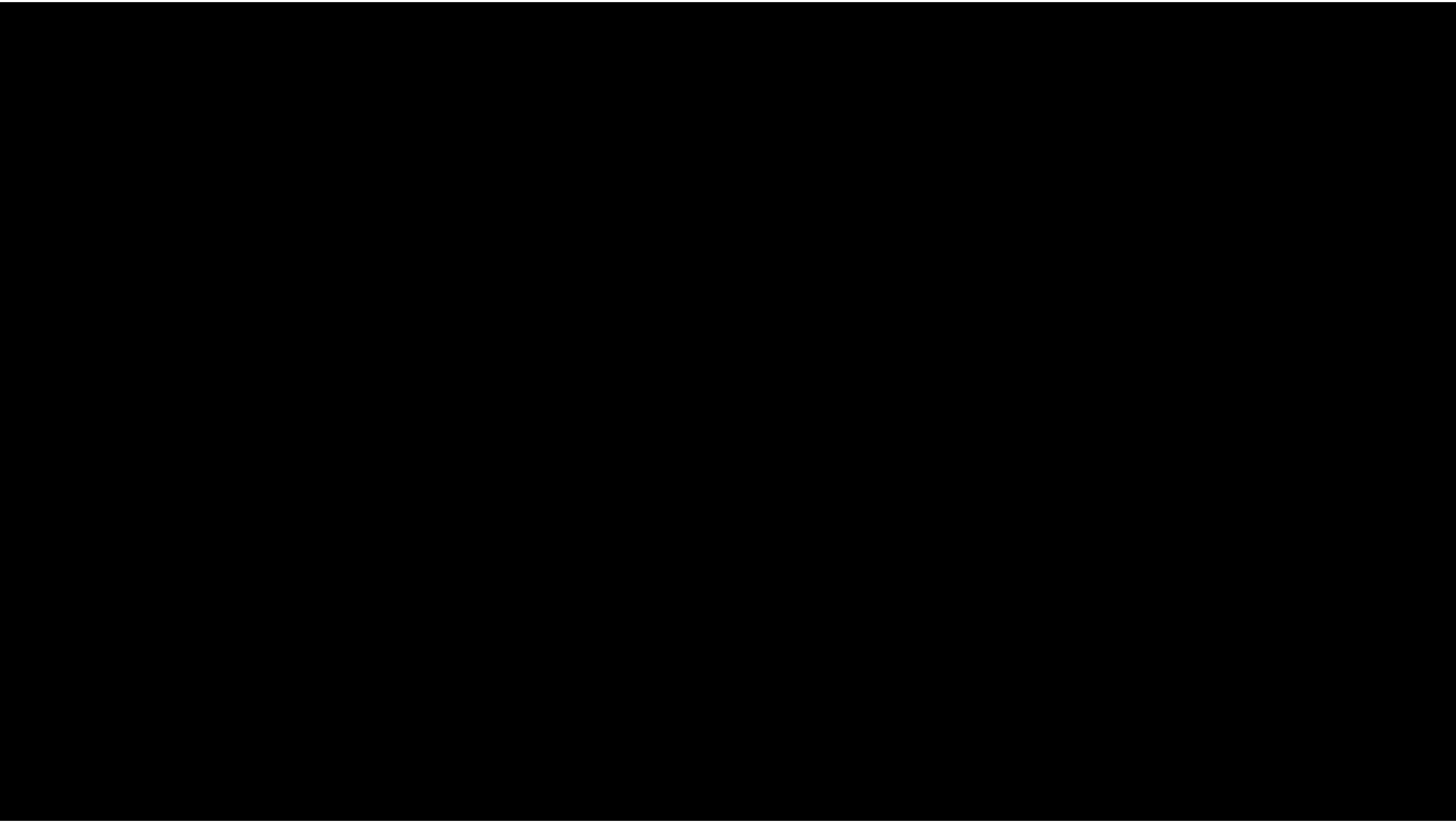


Correlated signal along ***only one*** linear track
Uncorrelated along ***all other*** possible linear tracks

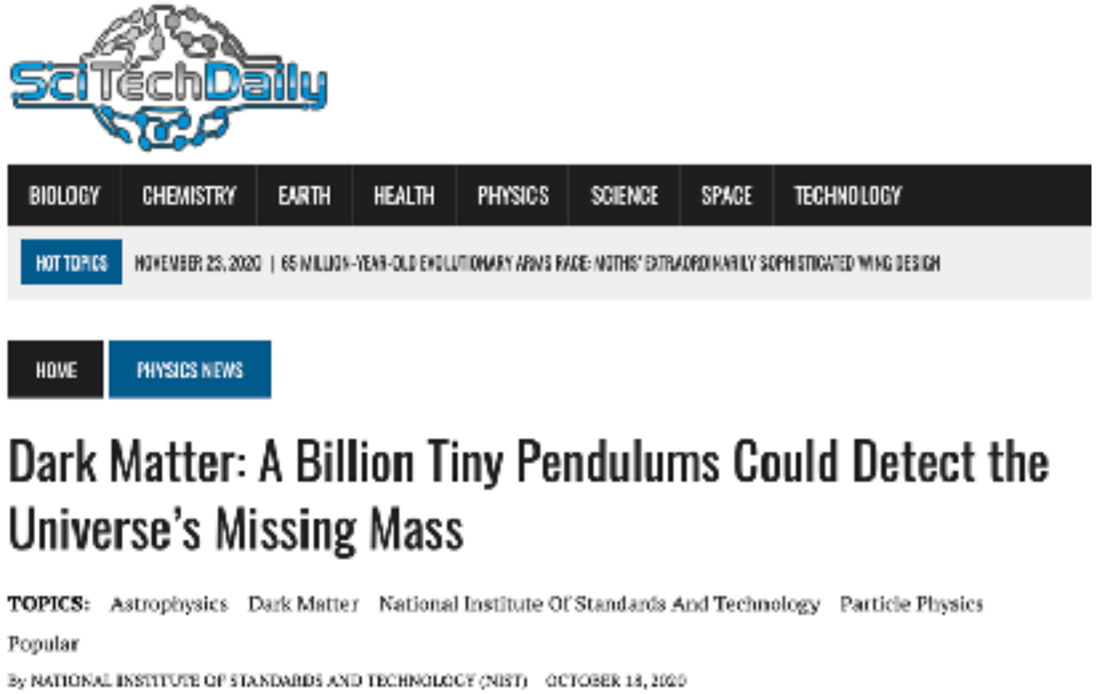
Need big detector volume	Need small spacing	Total detector count
$L = Nb \sim \mathrm{m}$	$b \sim \mathrm{mm}$	$\Longrightarrow \ (L/d)^3 \sim 10^9$

Carney, Ghosh, GK, Taylor 1903.00492 PRD

Cue video…



Video by Sean Kelley (NIST)



SciTechDaily

BIOLOGY CHEMISTRY EARTH HEALTH PHYSICS SCIENCE SPACE TECHNOLOGY

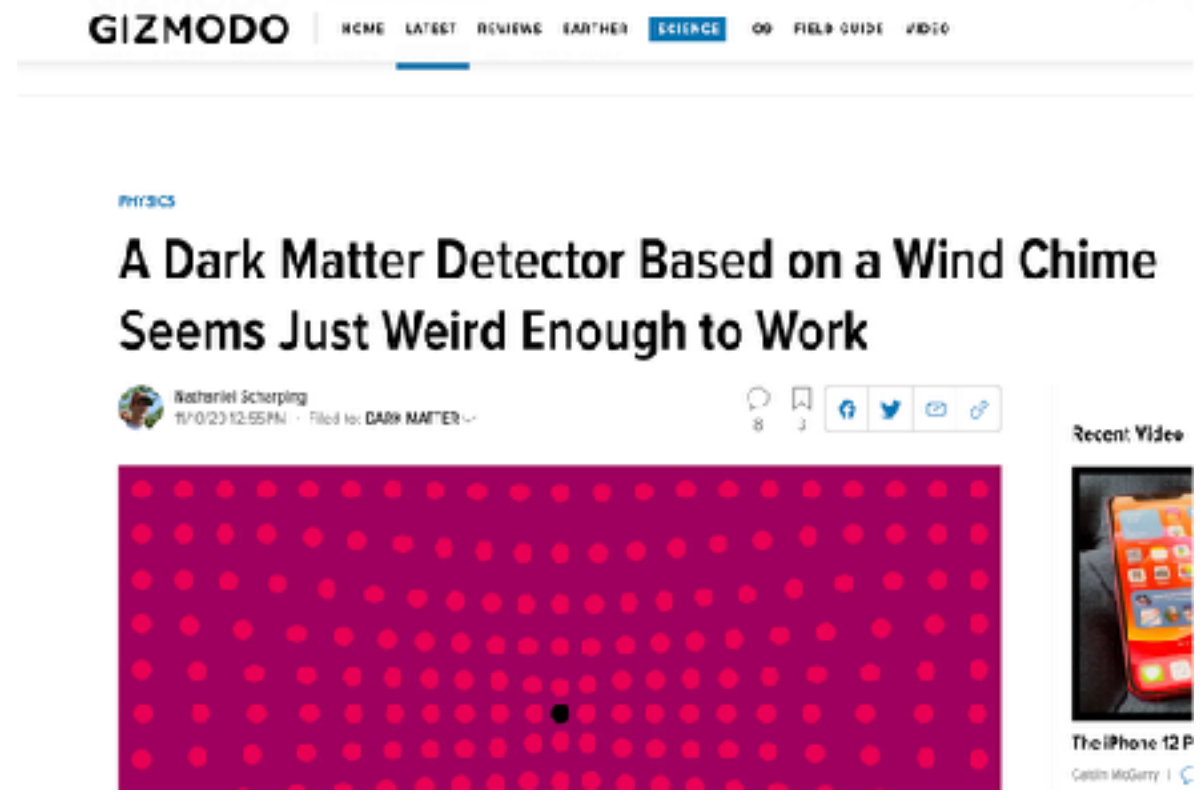
HOT TOPICS NOVEMBER 23, 2020 | 65 MILLION-YEAR-OLD EVOLUTIONARY ARMS RACE: MOTHS' EXTRAORDINARILY SOPHISTICATED WING DESIGN

HOME PHYSICS NEWS

Dark Matter: A Billion Tiny Pendulums Could Detect the Universe's Missing Mass

TOPICS: Astrophysics Dark Matter National Institute Of Standards And Technology Particle Physics Popular

By NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST) OCTOBER 18, 2020



GIZMODO HOME LATEST REVIEWS EARTHER SCIENCE IO9 FIELD GUIDE VIDEO

PHYSICS

A Dark Matter Detector Based on a Wind Chime Seems Just Weird Enough to Work

Nathaniel Scharping

Filed to: DARK MATTER

Recent Video

NewScientist

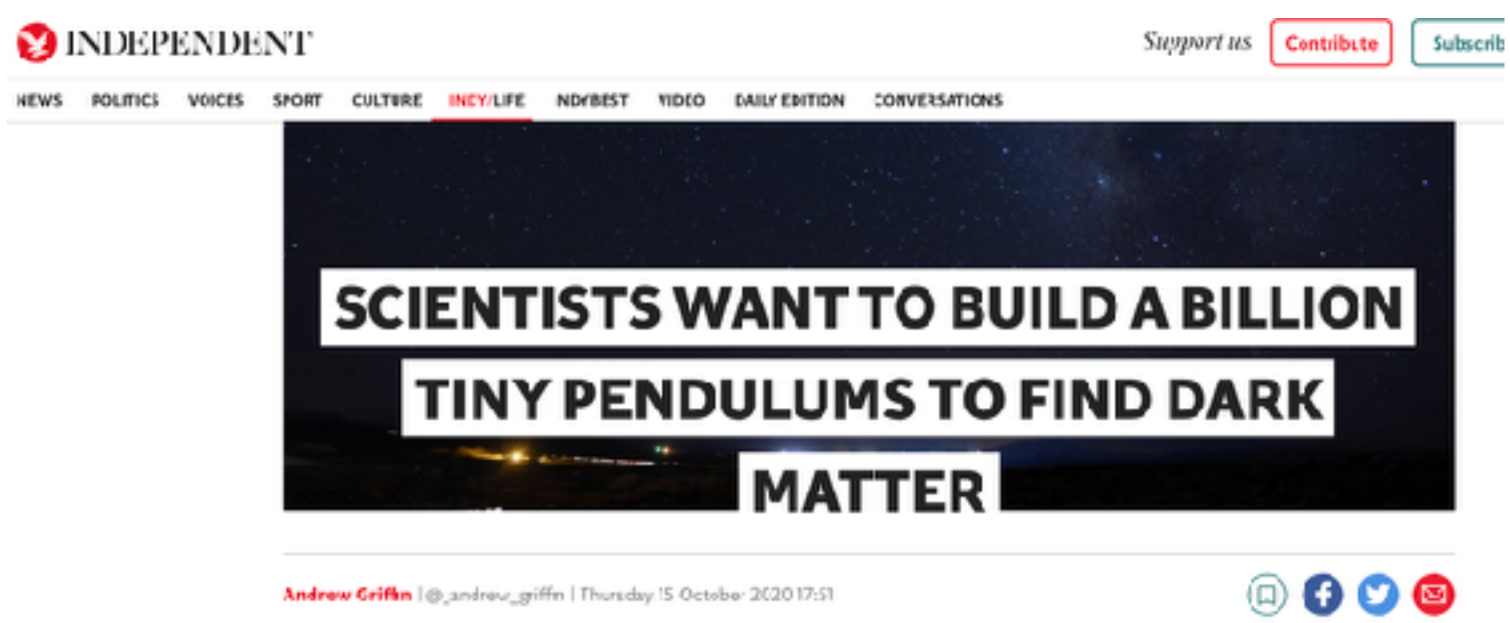
News Podcasts Video Technology Space Physics Health More Shop Courses Events

The detector with a billion sensors that may finally snare dark matter

Dark matter must exist, but has evaded all attempts to find it. Now comes our boldest plan yet – sensing its minuscule gravitational force as it brushes past us

SPACE 1 July 2020

By Adam Mann



INDEPENDENT Support us Contribute

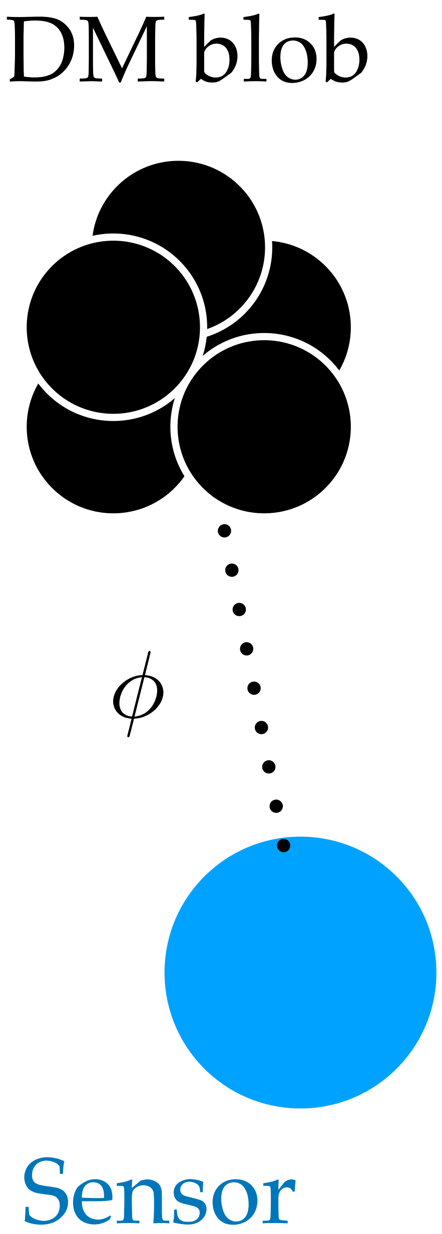
NEWS POLITICS VOICES SPORT CULTURE INDY/LIFE INDYBEST VIDEO DAILY EDITION CONVERSATIONS

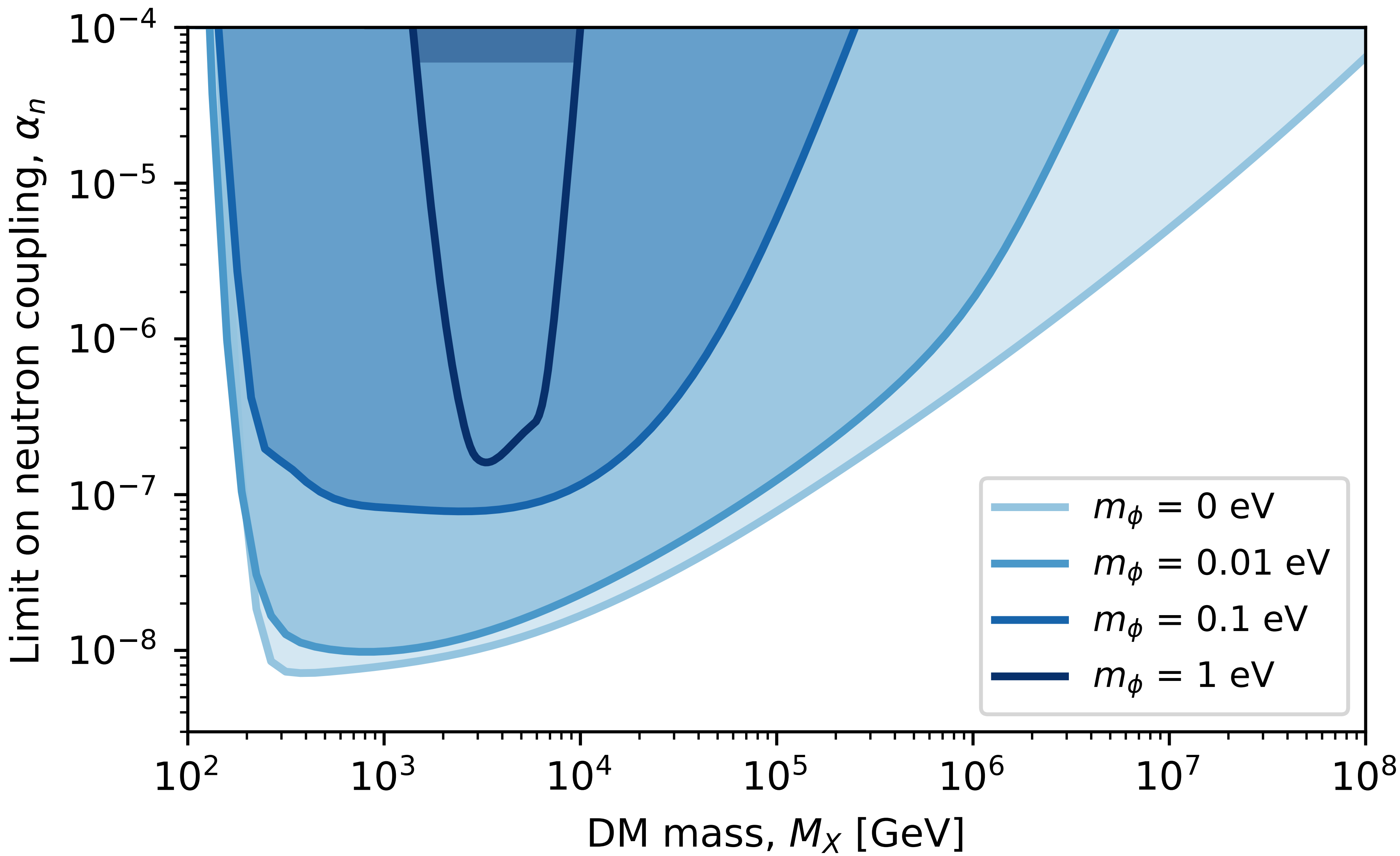
SCIENTISTS WANT TO BUILD A BILLION TINY PENDULUMS TO FIND DARK MATTER

Andrew Griffin | @_andrew_griffin | Thursday 15 October 2020 17:51

Nature, Gizmodo, New Scientist, NIST Tech Beat The Independent New Atlas Medium Newsbreak

Single sensor prototype already setting new limits

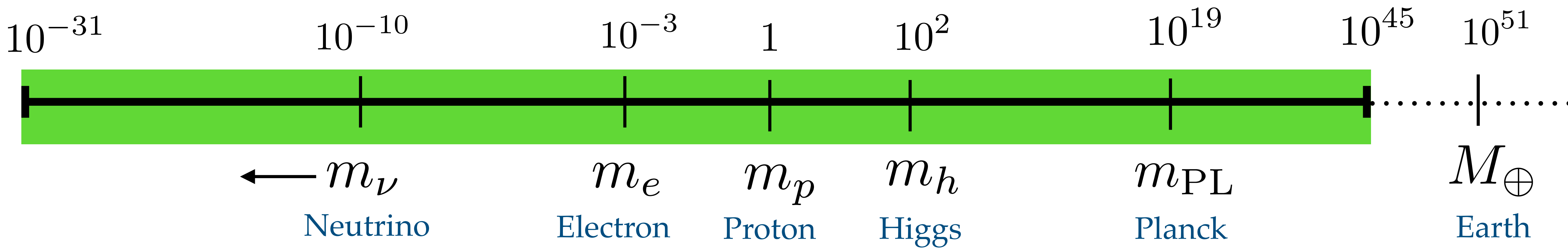




First ever DM limit using CM motion of macroscopic object

Monteiro, Afek, Carney, GK, Wang, Moore 2007.12067, Phys. Rev. Lett.

Concluding Remarks



Remarkable evidence for dark matter

CMB, LSS, BBN, rotation curves, lensing, cluster collisions

DM search effort has vastly expanded in scope

Broader priors on WIMP DM since 2010s motivate wider mass range

Many models, many novel "laboratories"

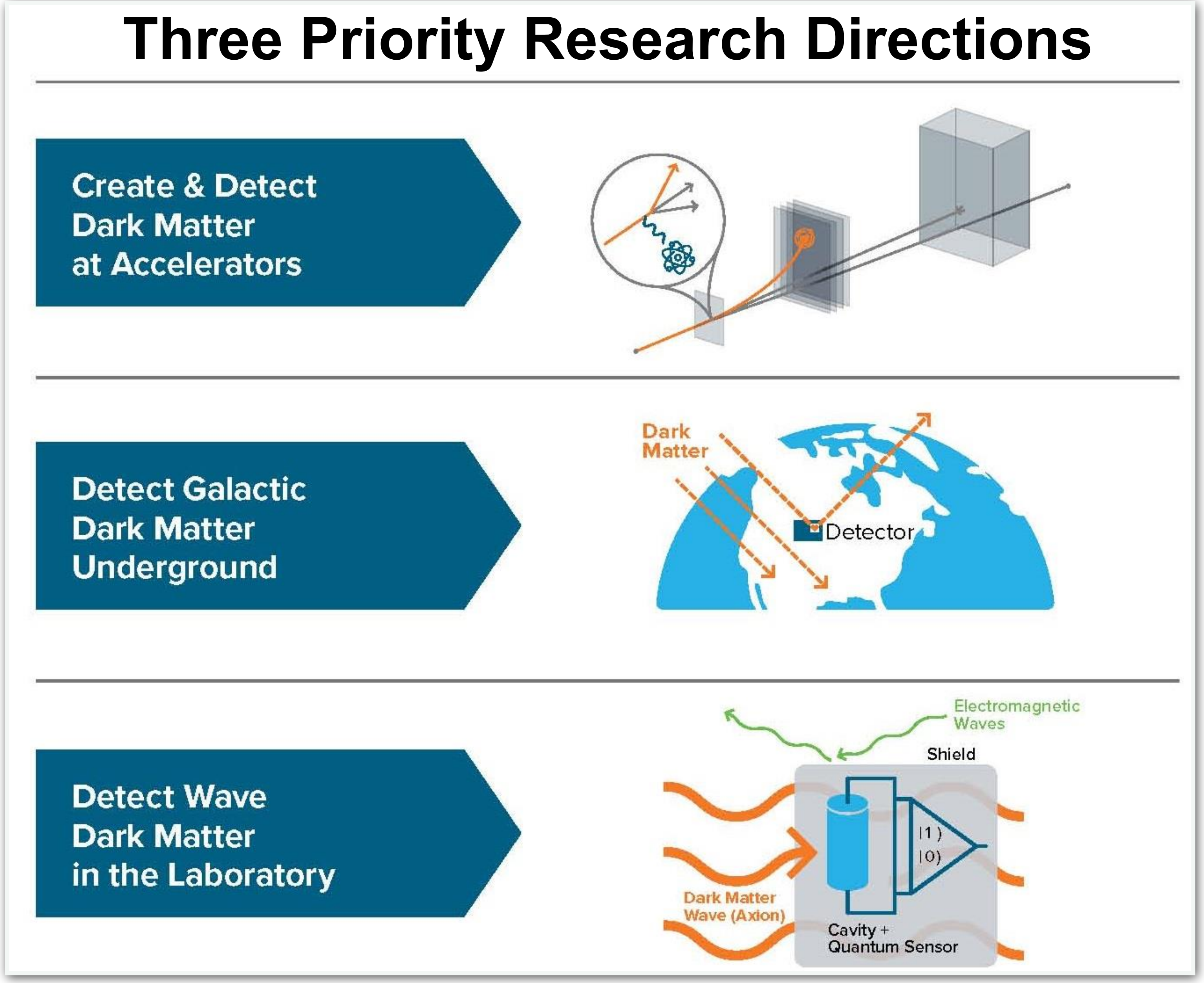
Wavelike DM	Particle-like DM	Macroscopic DM
Neutrino oscillations	Electron + Muon	Nanospheres
Accelerator + cosmic	Fixed-target exp	Gravity coupling
	LDMX + M3	Windchime

DOE Basic Research Needs Report

LDMX
M3

Windchime

DINOs



FNAL BRN report authors: Aaron Chou, Juan Estrada, Roni Harnik, GK, Nhan Tran

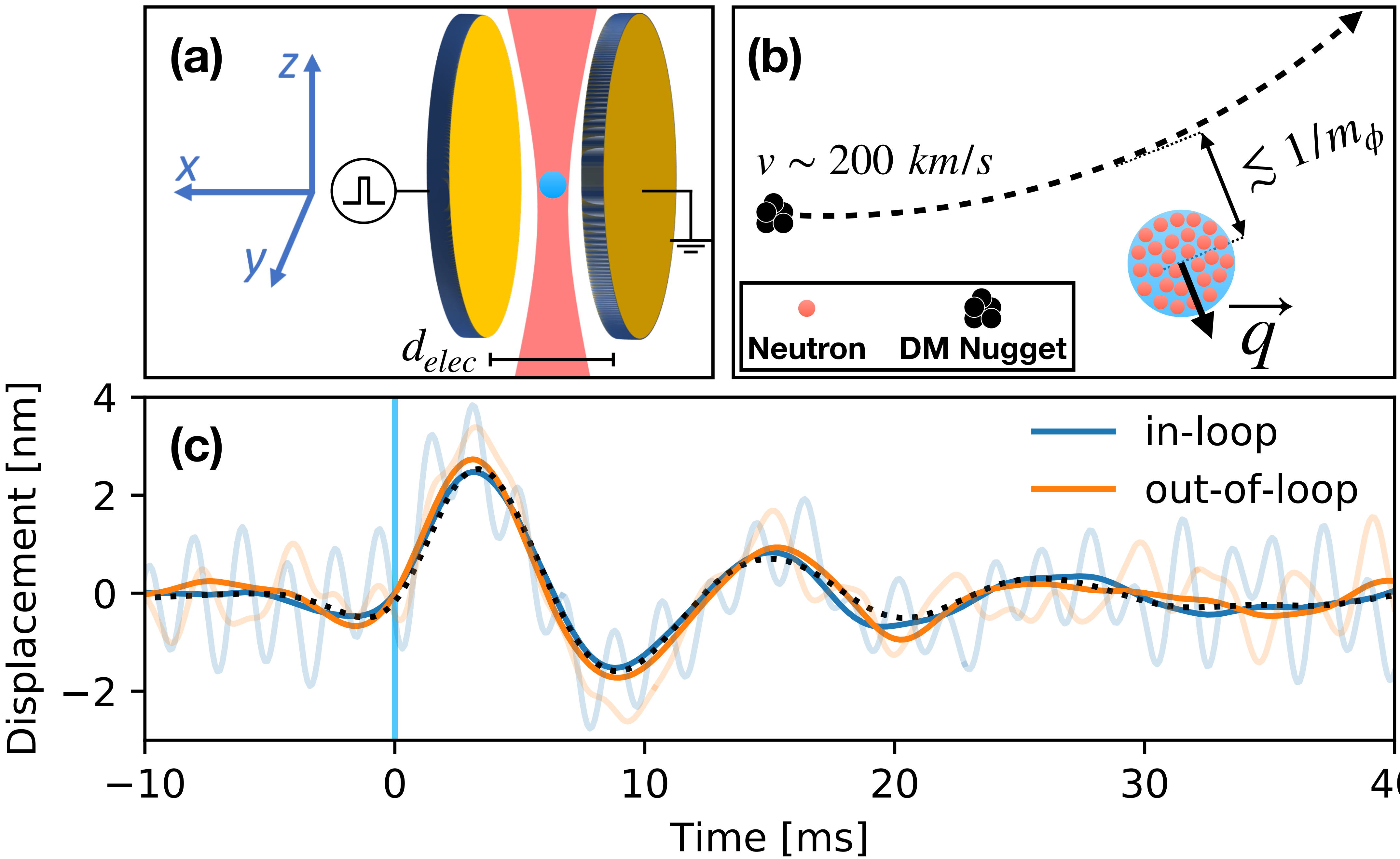
https://science.energy.gov/~/media/hep/hepap/pdf/201811/RKolb-HEPAP_201811.pdf

https://science.energy.gov/~/media/hep/hepap/pdf/201811/BRN_Dark-Matter-Brochure_HEPAP_201811.pdf

Thanks!

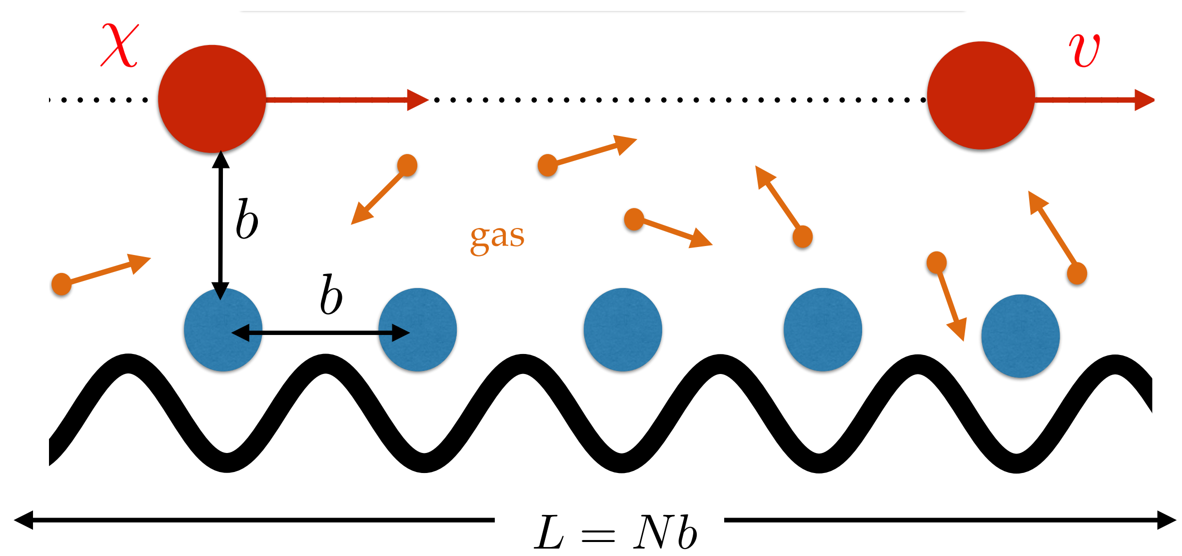
What can we do with only one sensor?

Nongravitational long range couplings of DM "nuggets" $V = \frac{\alpha_n}{r} \exp(-m_\phi r)$



Monteiro, Afek, Carney, GK, Wang, Moore 2007.12067, Phys. Rev. Lett.

Levitating Sensor Arrays "Windchime"



$$\tau = L/v$$

Signal to noise ratio gravitational impulse

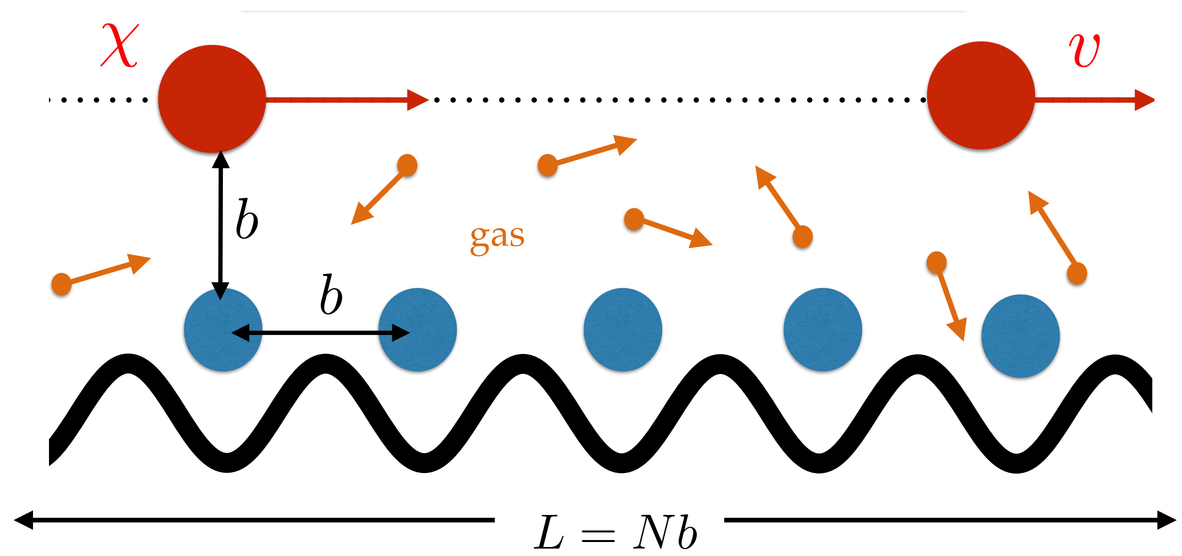
$$\mathrm{SNR}^2 = \frac{I^2}{\Delta I^2} = \frac{4\bar{F}^2 N\tau}{\alpha}$$

RMS noise impulse from gas

$$\alpha = PA\sqrt{m_{\mathrm{gas}} k_B T}$$

Carney, Ghosh, GK, Taylor 1903.00492 PRD

Levitating Sensor Arrays "Windchime"



$$\tau = L/v$$

Signal to noise ratio gravitational impulse

$$\mathrm{SNR}^2 = \frac{I^2}{\Delta I^2} = \frac{4\bar{F}^2 N\tau}{\alpha}$$

RMS noise impulse from gas

$$\alpha = PA\sqrt{m_{\rm gas} k_B T}$$

If all noise is uncorrelated and thermal, for a single track

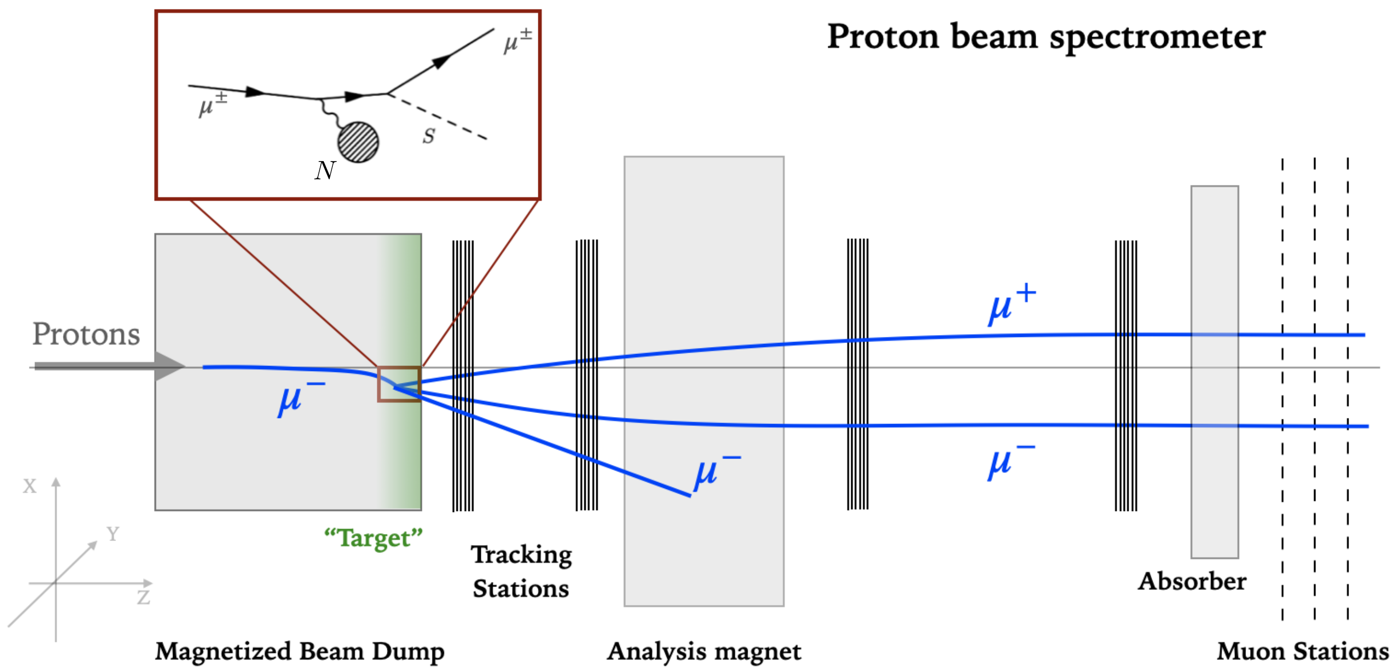
$$\mathrm{SNR}^2 \sim 10^4 \left(\frac{m_\chi}{\rm mg}\right)^2 \left(\frac{m_{\rm det}}{\rm mg}\right)^2 \left(\frac{L}{\rm m}\right) \left(\frac{\rm mm}{b}\right)^4 \left(\frac{10\,{\rm mK}}{T}\right) \left(\frac{10^{-10}\,{\rm Pa}}{P}\right) \left(\frac{4{\rm u}}{m_{\rm gas}}\right)^{1/2}$$

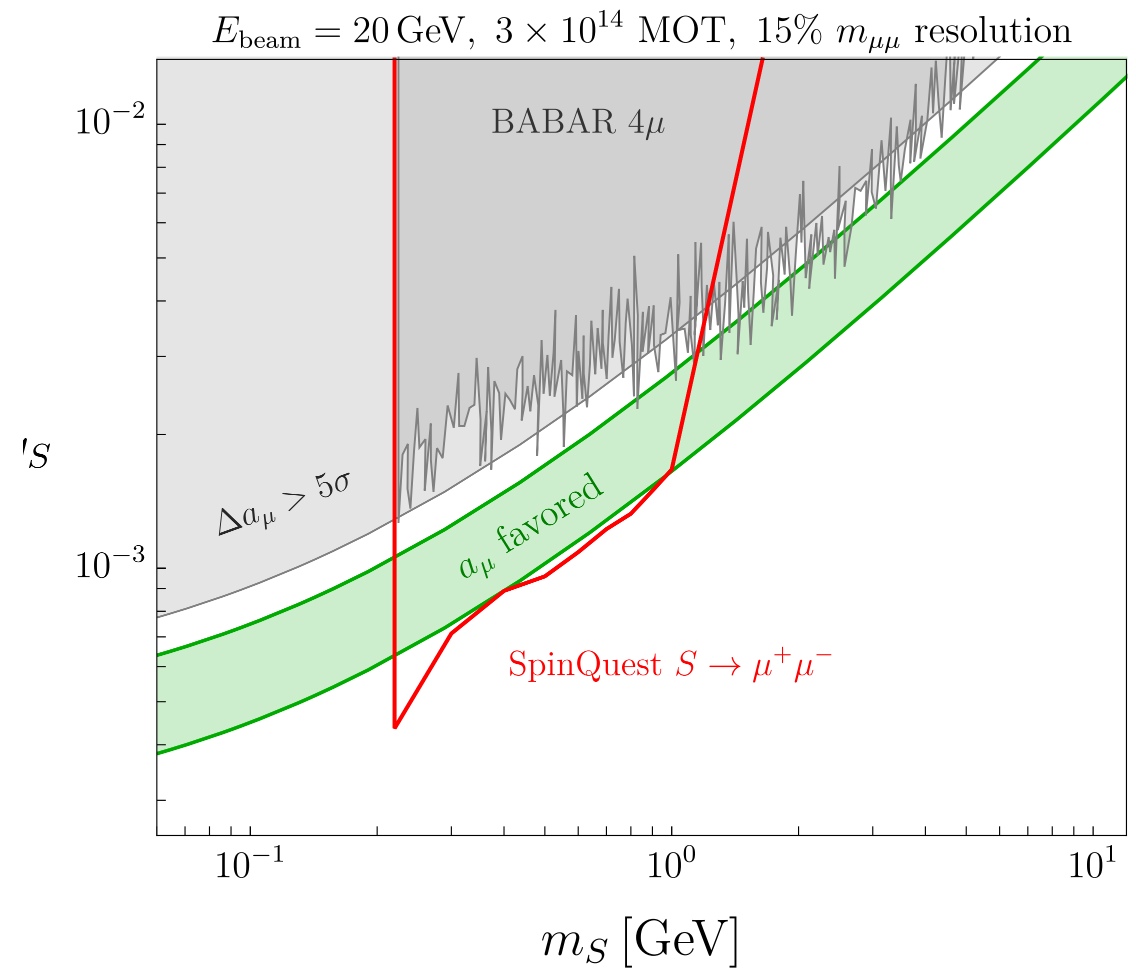
Very low rate — tradeoff with SNR:

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

Carney, Ghosh, GK, Taylor 1903.00492 PRD

Muonic Forces & g-2 at SpinQuest





Proposed bump search for BSM dimuon decays at proton spectrometer

Parasitic on existing SpinQuest @ FNAL experiment

Coverage of low-mass BSM solutions to muon g-2

Forbes, Herwig, Kahn, **Krnjaic**, Suarez, Tran, Whitbeck 2212.00033

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

Optimize for position resolution: Standard Quantum Limit

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

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).