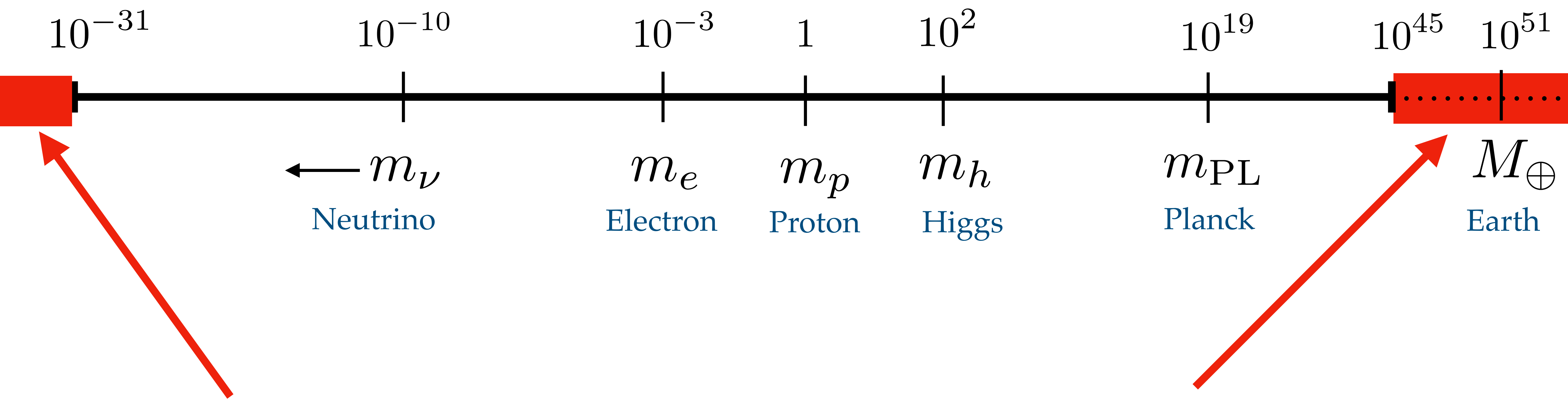
Novel Detection Strategies for Dark Matter
From ALPs to ′ZILLAS

Gordan Krnjaic
Fermilab & University of Chicago

IDM 2022, Vienna Austria,   July 18, 2022

Image: Volker Springel

Huge Range of Possible DM Masses



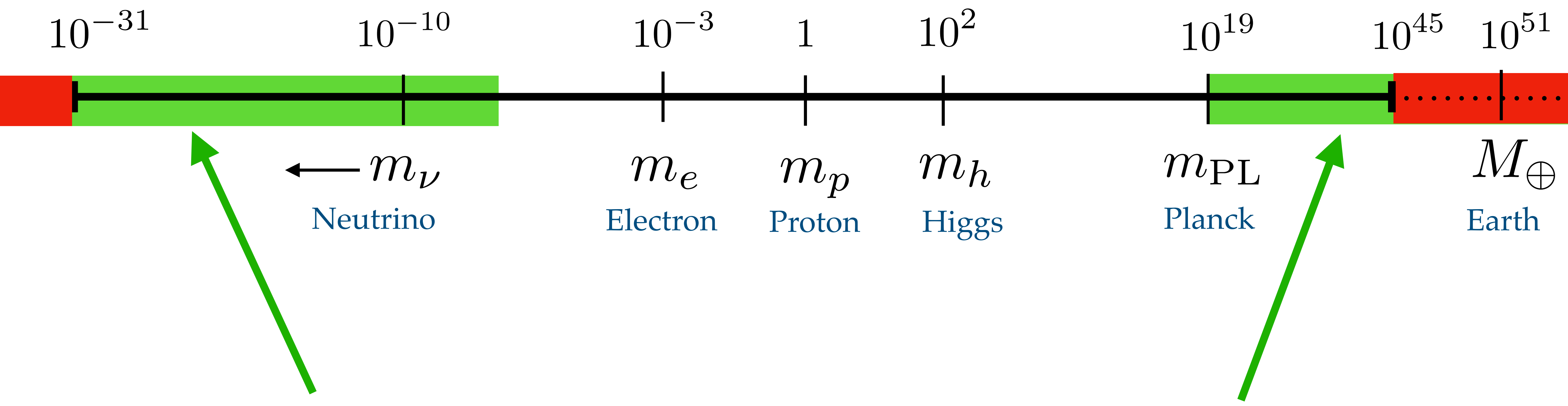
de Broglie wavelength can't exceed dwarf galaxy scales

Would have been observed indirectly via microlensing

Greene, Kavanagh 2007.10722

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

Huge Range of Possible DM Masses



Must be bosonic (integer spin)

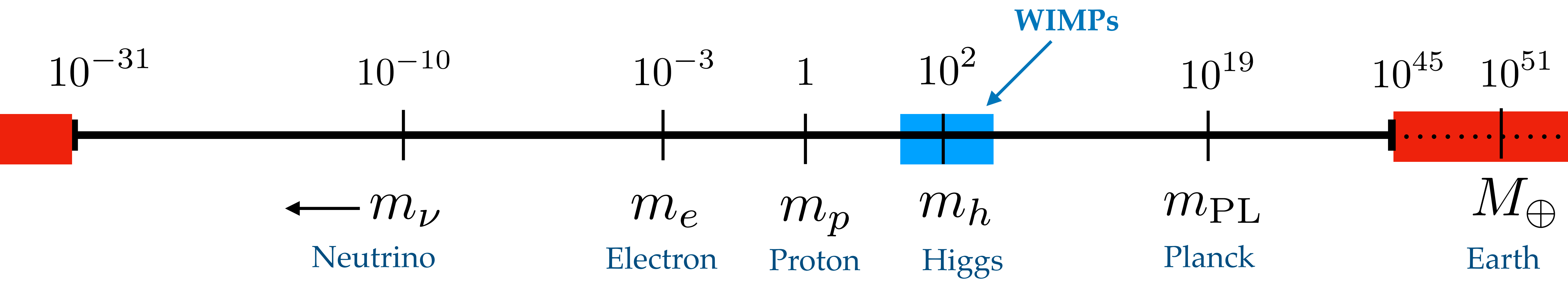
Pauli blocking limits fermion phase space density

Must be primordial black hole or extended object

example: dark nuclei

GK, Sigurdson 1406.1171 Phys. Lett. B.

Huge Range of Possible DM Masses



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

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

Organizing Principle:

Broad (& biased) survey of new ideas to detect DM
in non-traditional "laboratories"

Overview

Wavelike DM

Dark Sectors

WIMPZILLAs

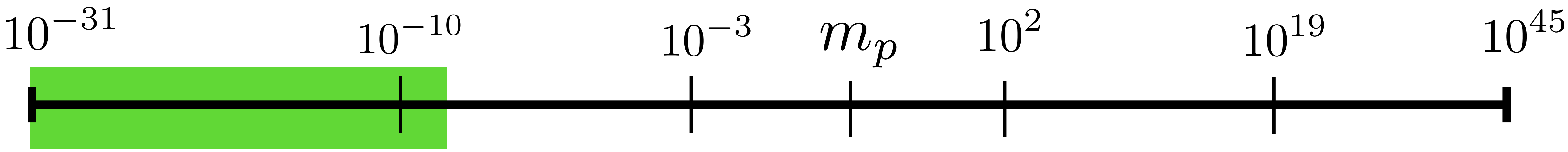
Overview

Wavelike DM

Dark Sectors

WIMPZILLAs

Wave-like Dark Matter

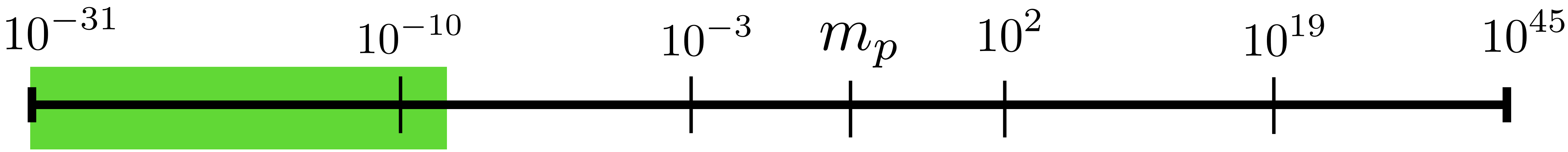


“Axions” proposed to explain absence of neutron electric dipole moment

More general category: Axion Like Particles — “ALPs“

Peccei, Quinn 1977, Phys. Rev. Lett.

Wave-like Dark Matter



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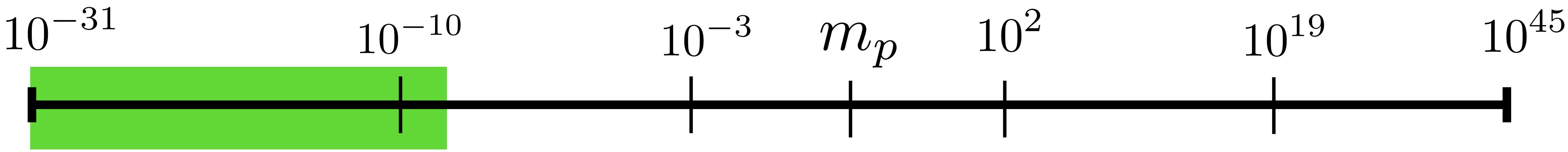

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Saturating lower bound yields “fuzzy” dark matter $m \sim 10^{-22}\,{\rm eV/c^2}$

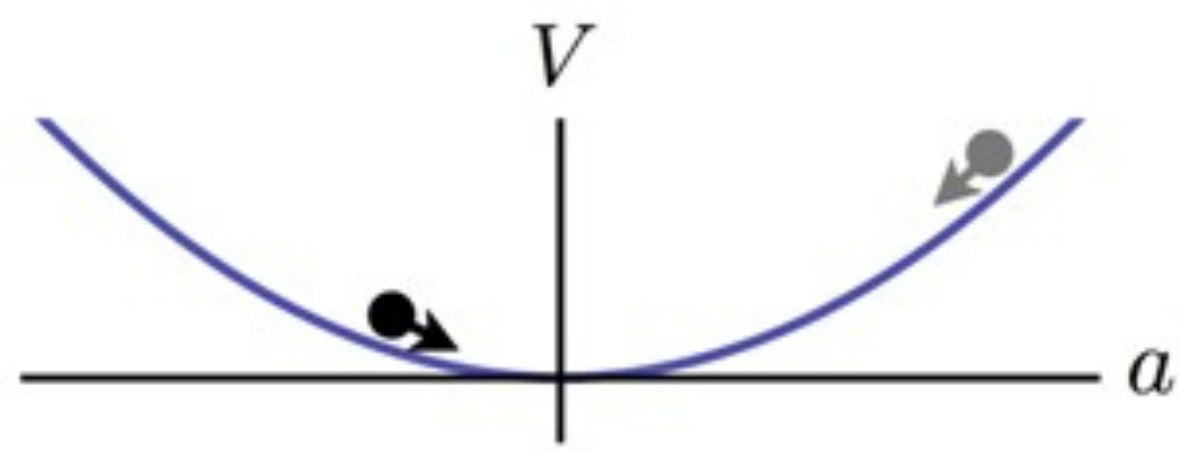
Doesn’t clump below ~ kpc scales, cuts off matter power spectrum

Hu, Barkana, Gruzinov astro-ph/0003365 Phys. Rev. Lett.

How can these be DM candidates?

Wave-like Dark Matter

Field initially displaced from minimum in the early universe



$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$a(t) = \frac{\sqrt{2\rho_a}}{m_a}\frac{\cos m_a t}{R^{3/2}}$$

scale factor

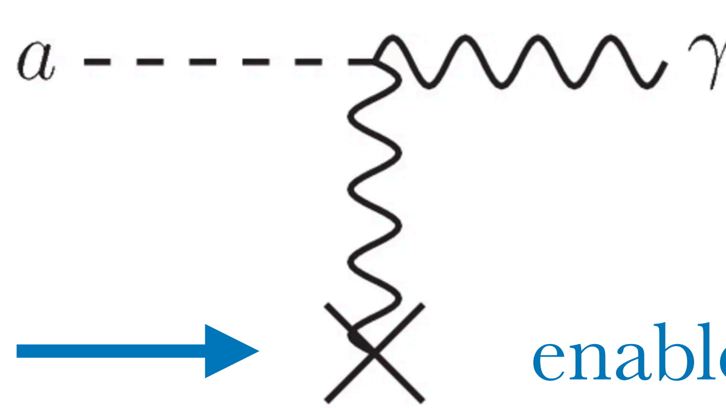
Begins oscillation when mass ~ Hubble $m_a \sim H$

Redshifts like non relativistic matter $\langle\rho_a\rangle \sim m_a^2 a^2 \propto R^{-3}$

deBroglie wavelength > inter particle spacing (like a classical field)

Wave-like DM + neutron stars

ALP coupling to photons $g_{a\gamma\gamma}\, a\vec{E} \cdot \vec{B}$ modifies Maxwell eqs.



$$E_\gamma \sim m_a(1 + v^2)$$

External B-field enables conversion $a \to \gamma$

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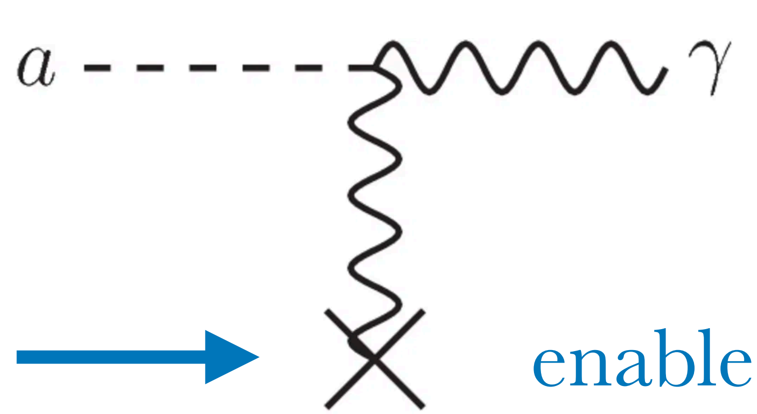

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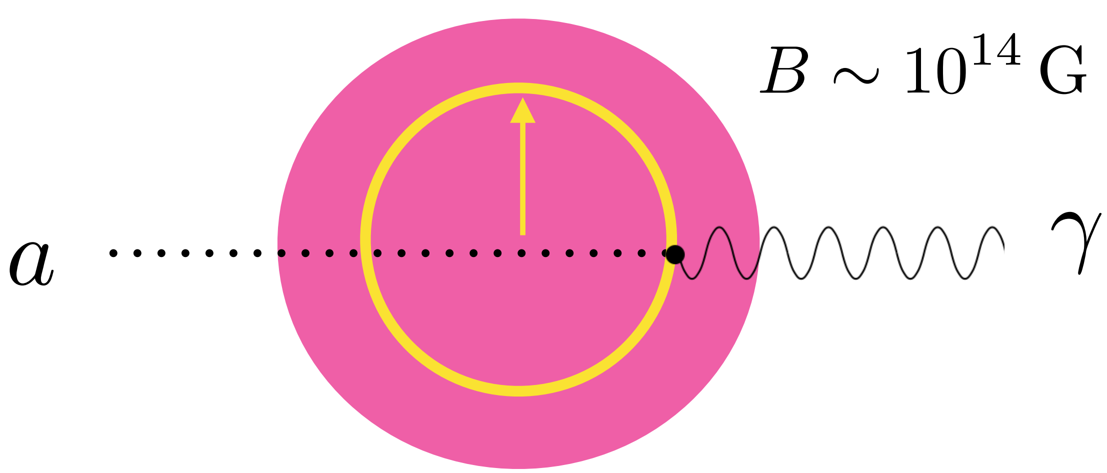
External B-field → enables conversion $a \to \gamma$

ALP passing through a neutron star can convert into radio line

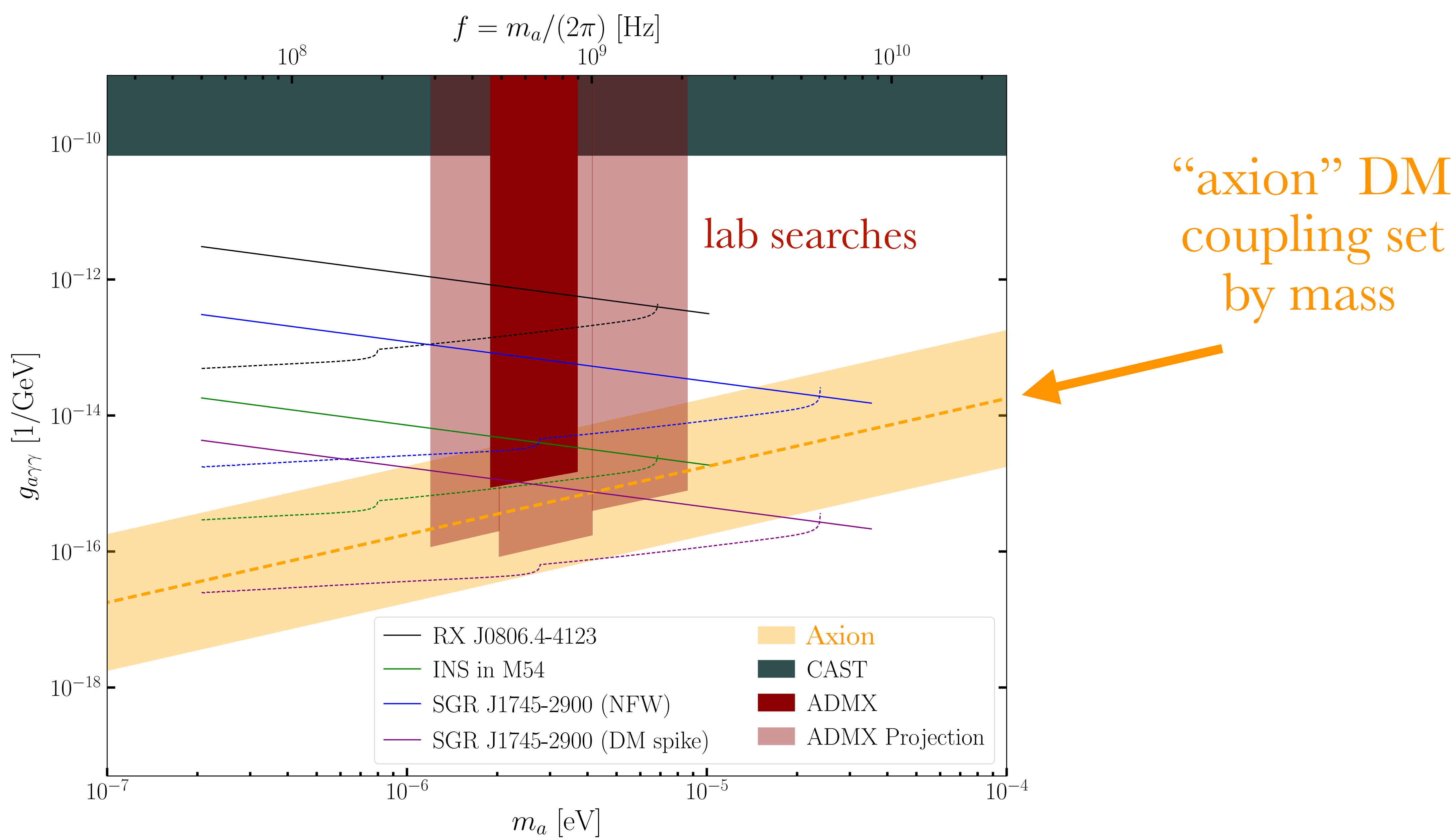


$$m_\gamma \approx \omega_p = \sqrt{\frac{4\pi\alpha n_e}{m_e}}$$

In plasma, photon gets longitudinal polarization "mixes" with ALP
conversion resonantly enhanced when $m_a \sim \omega_p$

Huang, Kadota, Sekiguchi, Tashiro 1803.08230 Hook, Kahn, Safdi, Sun 1804.03145

Wave-like DM + neutron stars



Projections for radio searches aimed at isolated neutron stars $M_{\rm NS} \sim M_\odot$

Assuming 100 hrs on Arecibo Telescope with effective flux $\Phi \sim 2\,\mathrm{Jy}$

No other radio emission except thermal

Huang, Kadota, Sekiguchi, Tashiro 1803.08230

Hook, Kahn, Safdi, Sun 1804.03145

Wave-like DM + **active** neutrinos

Neutrinos change flavor "oscillate" as they propagate

mass splitting

$\Delta m^2 \equiv m_i^2 - m_j^2$

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

mixing angle

GK, Machado, Necib, 1705.06740

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Now couple neutrinos to wavelike DM $\phi(t) = \left(2\rho_\phi^\odot / m_\phi^2\right)^{1/2} \cos m_\phi t$

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Time-dependent neutrino mass shift…

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

… modifies probability through

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

GK, Machado, Necib, 1705.06740

Wave-like DM + **active** 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: $t_{\rm obs} > \tau_\phi > t_{\nu\,\rm travel} = L/c$

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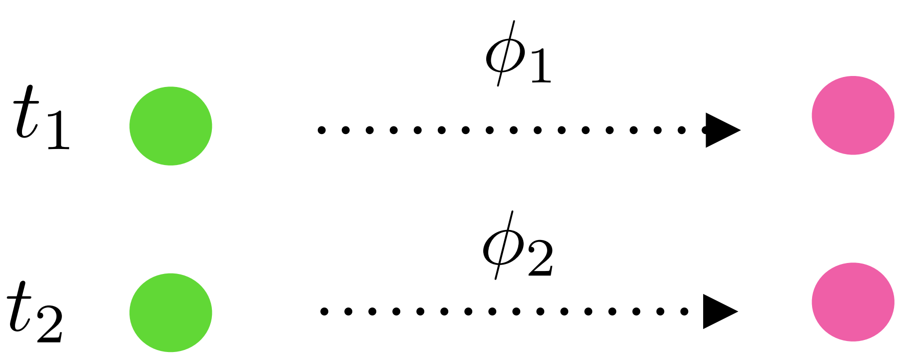
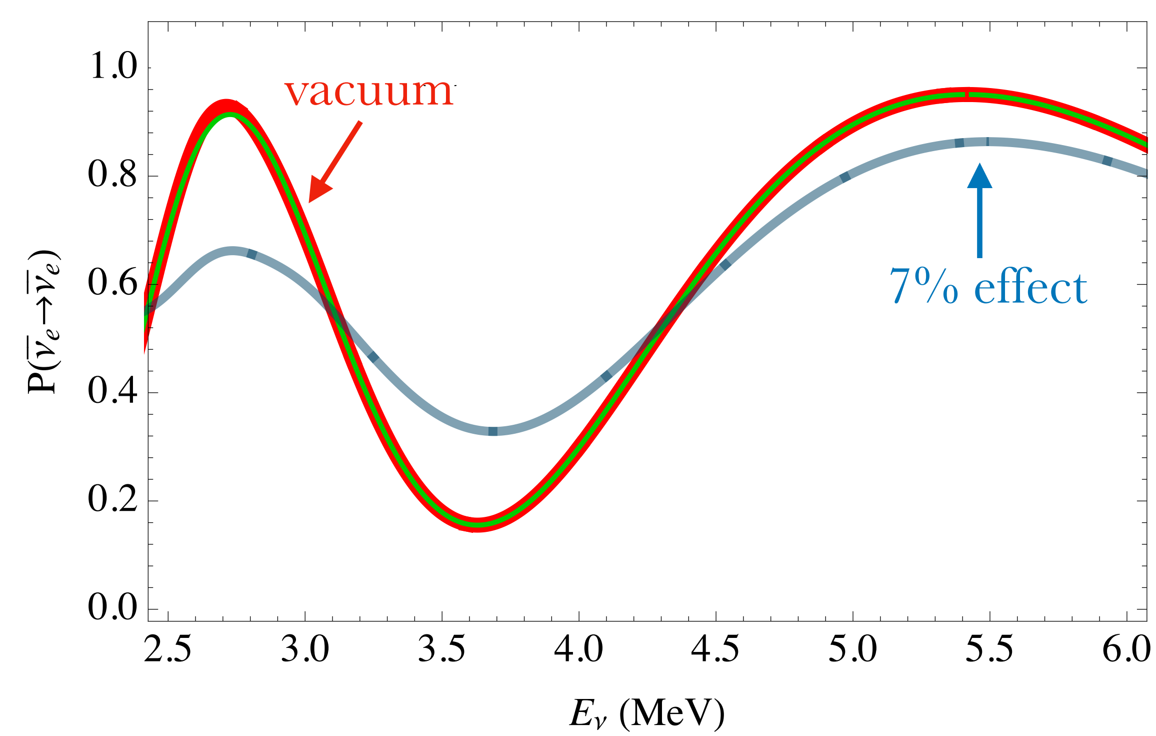
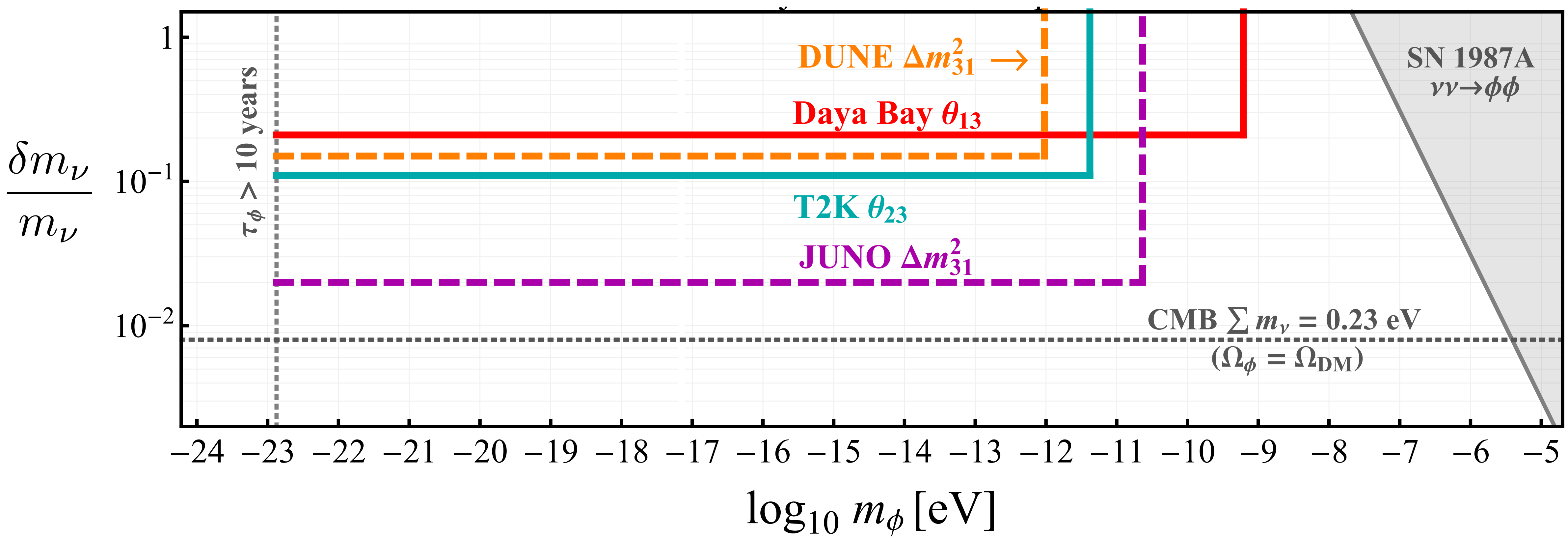


$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \int_0^{\tau_\phi} \frac{dt}{\tau_\phi} P(\nu_\alpha \to \nu_\beta)$$



GK, Machado, Necib, 1705.06740

Wave-like DM + **active** 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

Wave-like DM + **sterile/RH** neutrinos

Scalar DM induces Majorana mass for right handed neutrinos

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

Dev, GK, Machado, Ramani, 2205.06821

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DM field sets dynamical Majorana mass and ***tiny*** mass splitting

$$m_D = \frac{y_\nu v}{\sqrt{2}} \quad , \quad m_M = \frac{y_\phi}{2} \phi(t) \qquad\qquad m_M \ll m_D$$

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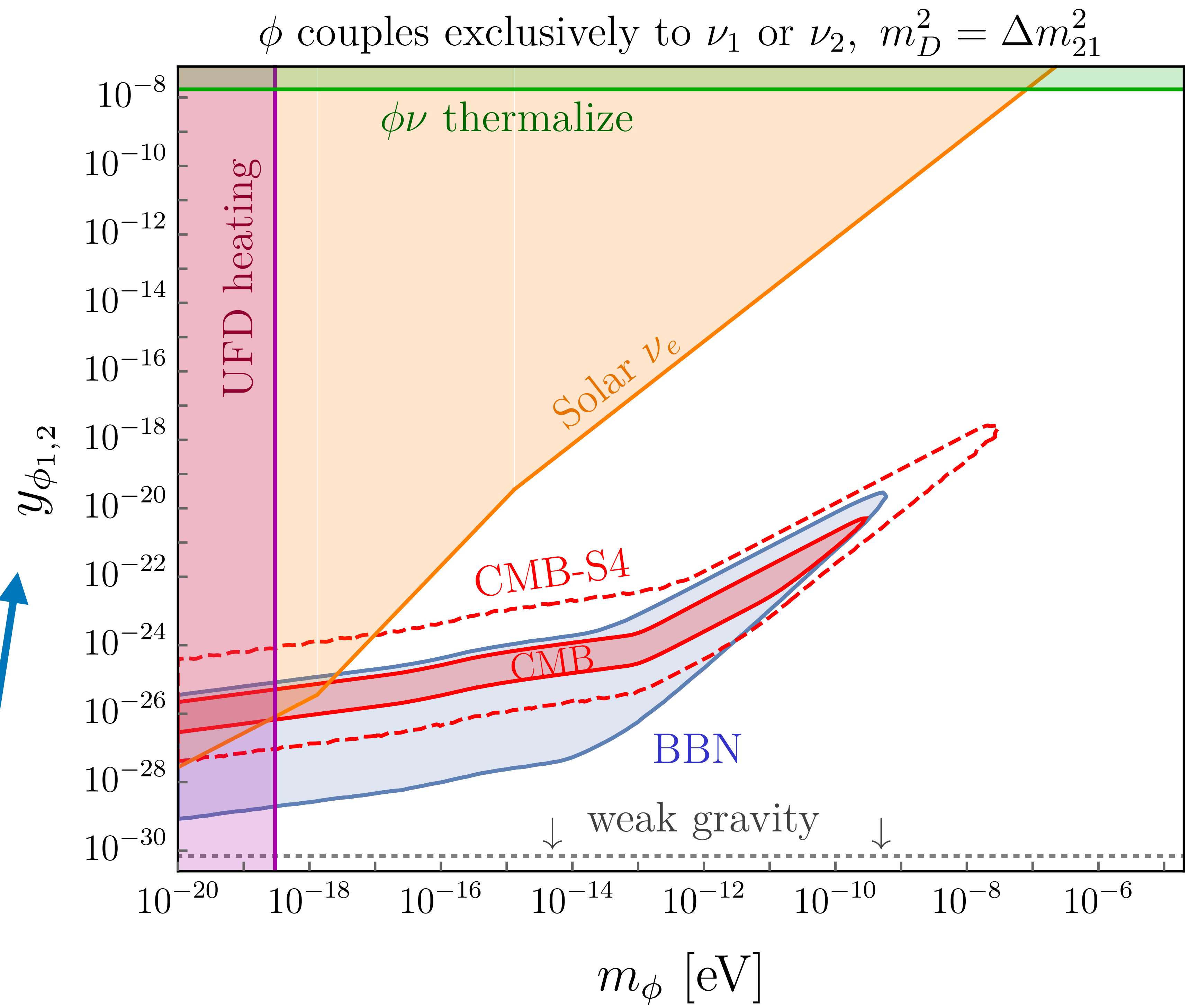
Mass basis has nearby active and sterile states that oscillate

$$P_{ee}(t) = |\langle \nu(t) | \nu_e \rangle|^2 = \cos^2 \left(\frac{1}{4E_\nu} \int_0^t dt' \delta m^2(t') \right)$$

Dev, GK, Machado, Ramani, 2205.06821

Wave-like DM + **sterile/RH** neutrinos



DM coupling to RHN

Dev, GK, Machado, Ramani, 2205.06821

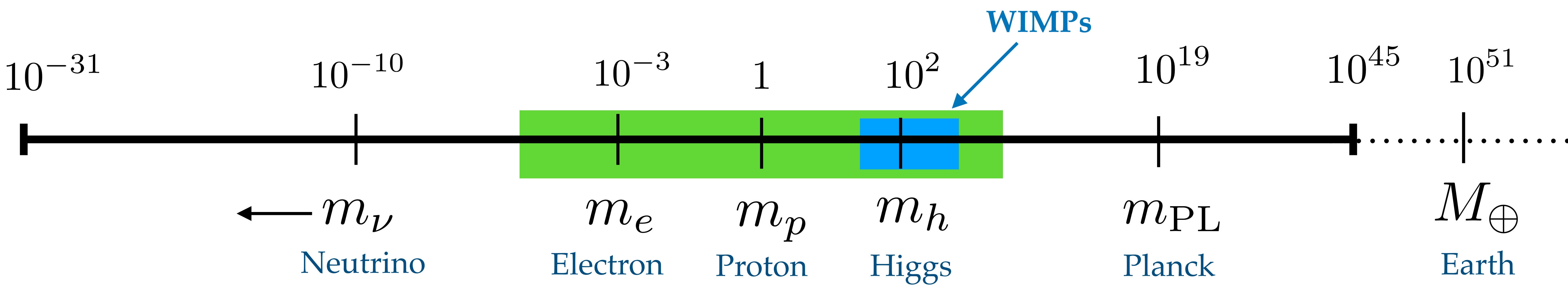
Overview

Wavelike DM

Dark Sectors

WIMPZILLAs

Dark Sectors “Generalized WIMPs”



Dark Sector models have WIMP-like features, but span a broader mass range

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

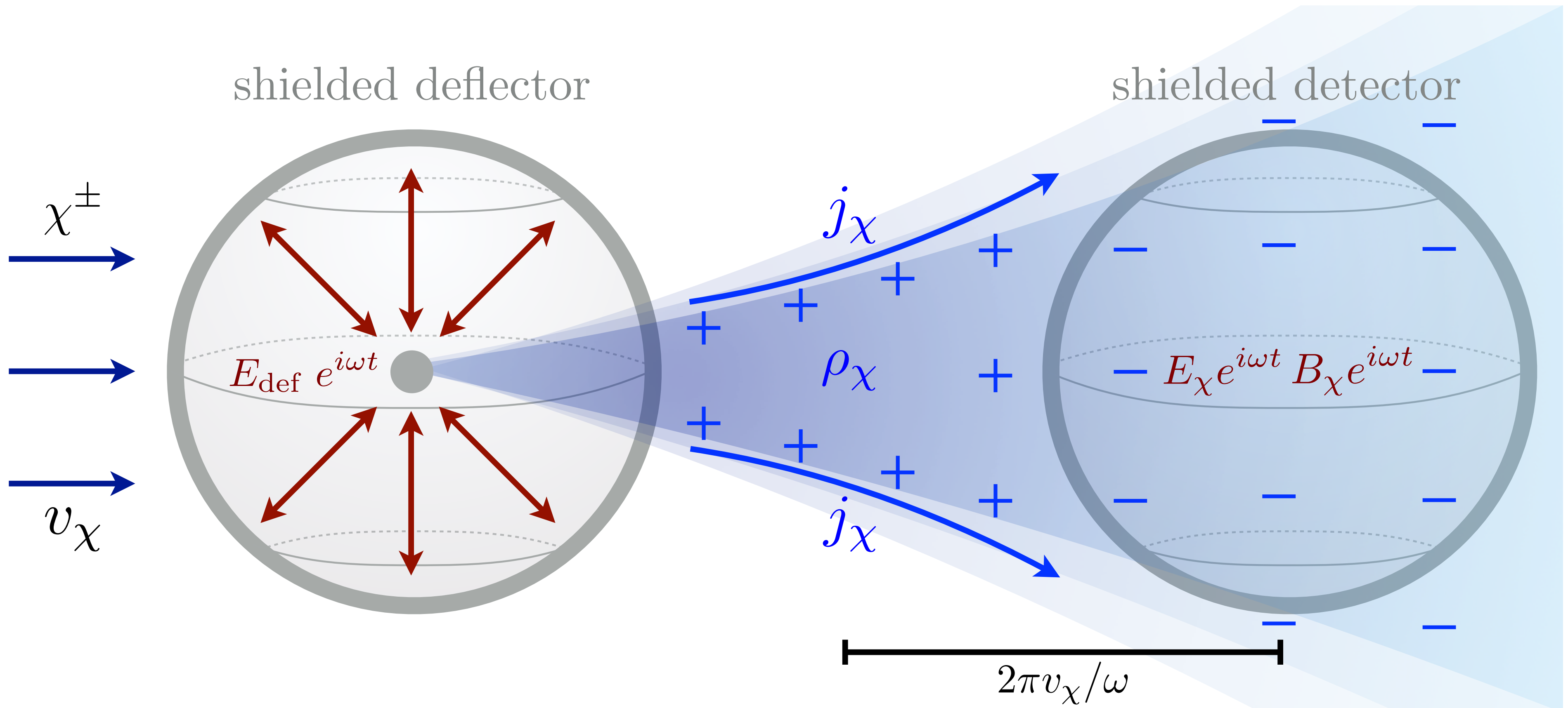
Like with WIMPs we care about $m_{\rm DM}, \sigma = \text{rate}/\text{flux}$

Unlike WIMPs, weak force doesn’t set interaction strength

Many mechanisms to produce DM abundance in early universe

Freeze out (like WIMPs)… but also “freeze-in” and “asymmetric DM”… etc.

Dark Sectors + “Direct Deflection"

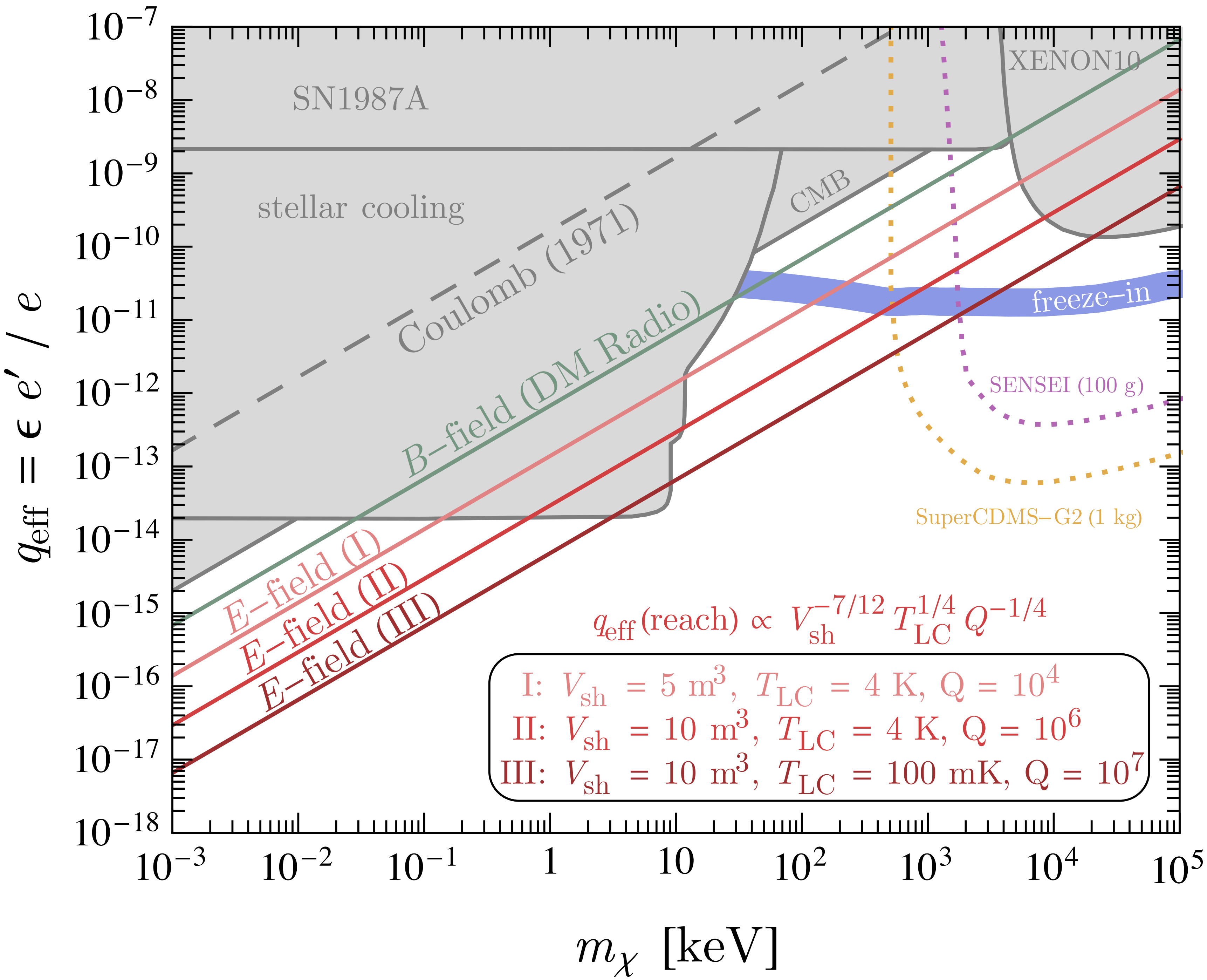


1) Millicharged DM charge separated using oscillating EM deflector cavity

2) Deflected current readout in shielded LC circuit w/ magnetometer

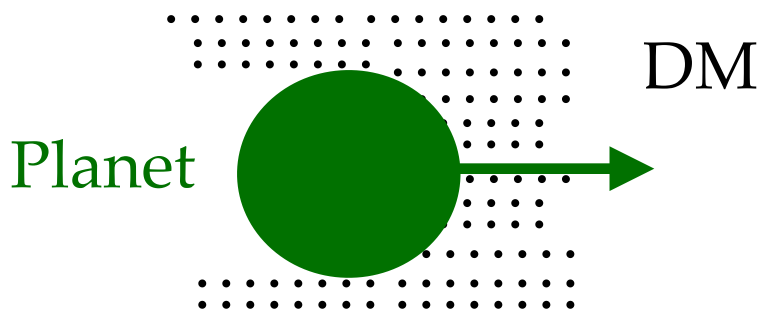
Berlin, D’Agnolo, Ellis, Schuster, Toro 1908.06982

Dark Sectors + “Direct Deflection"

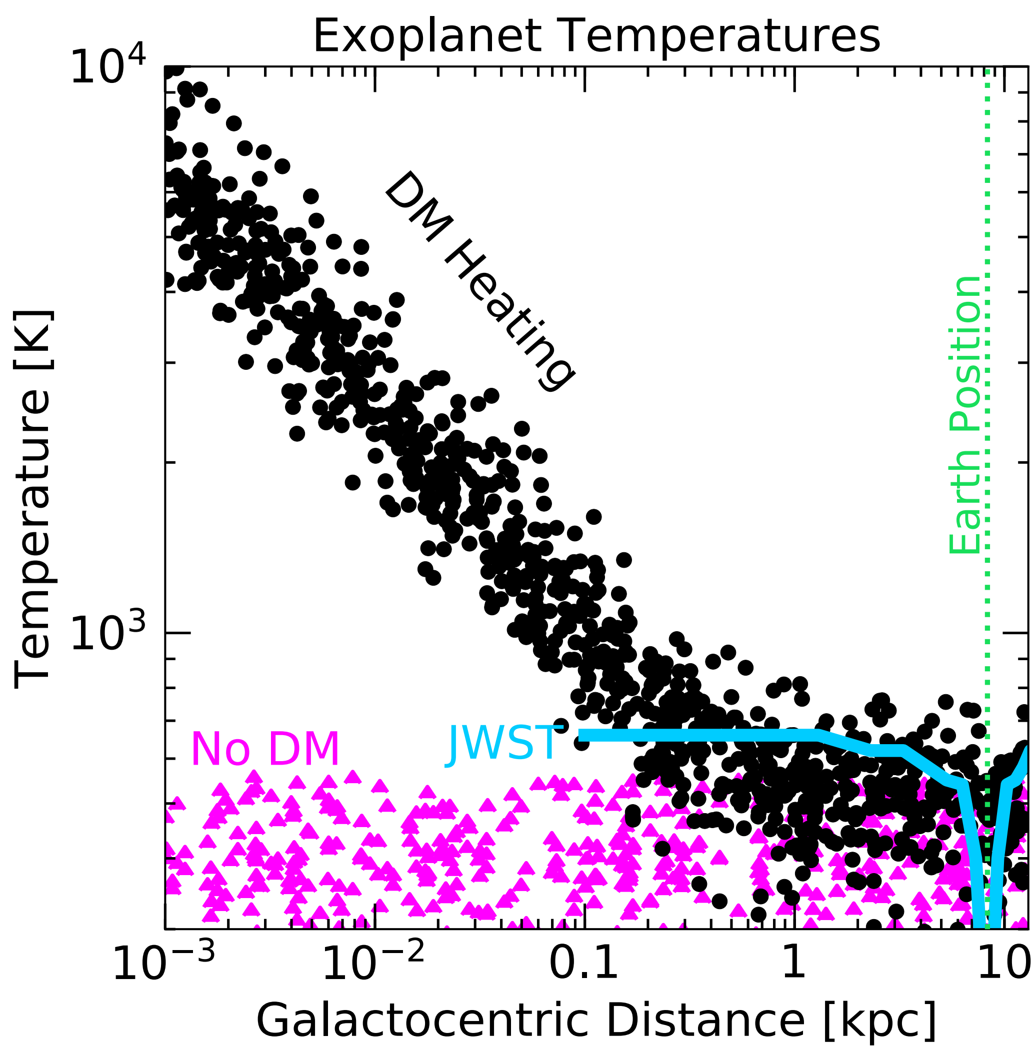


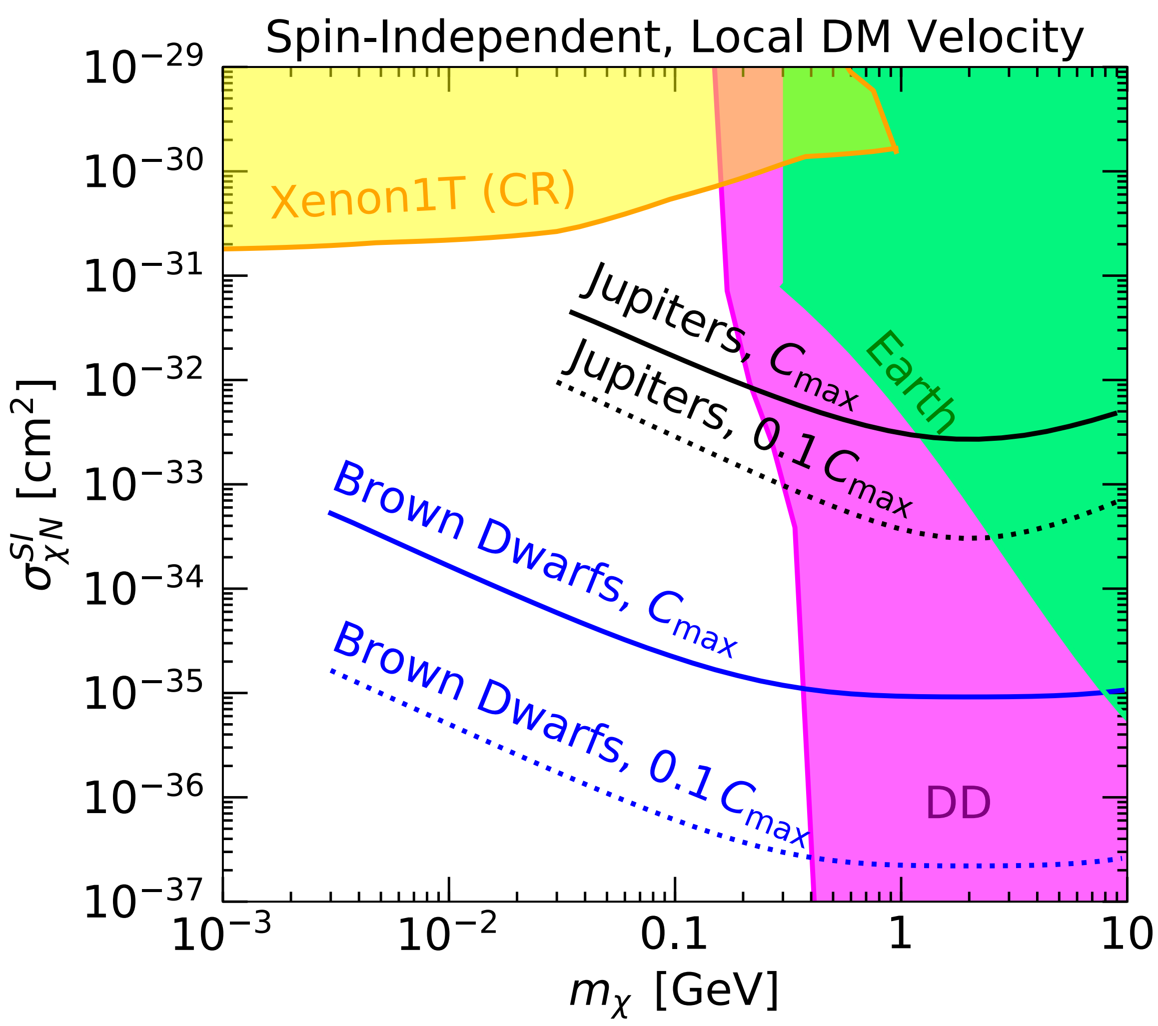
Berlin, D’Agnolo, Ellis, Schuster, Toro 1908.06982

Dark Sectors + Exoplanet "Detectors"



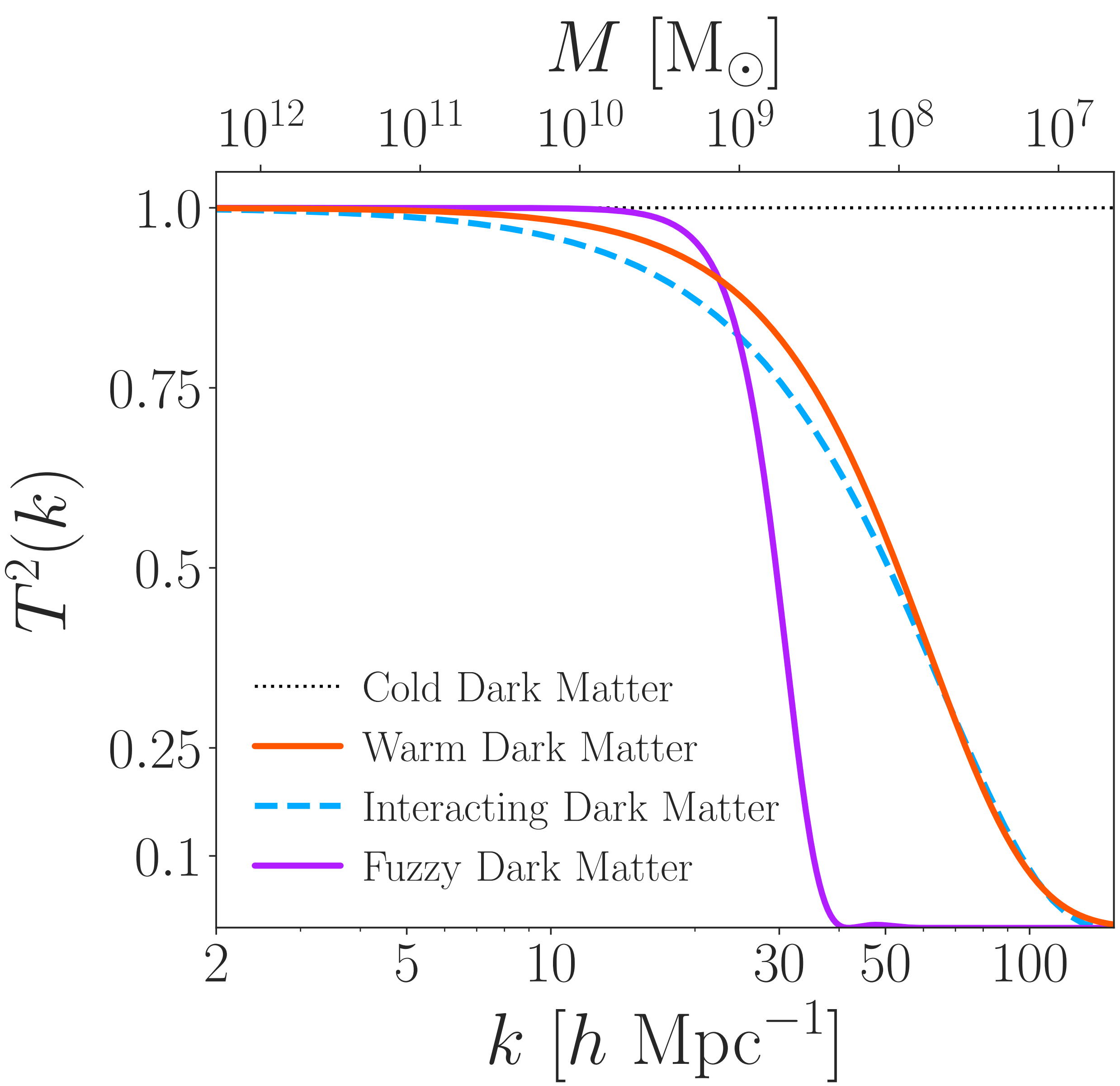
Exoplanet moving through DM "wind" may be heated through baryon-DM scattering and DM annihilation

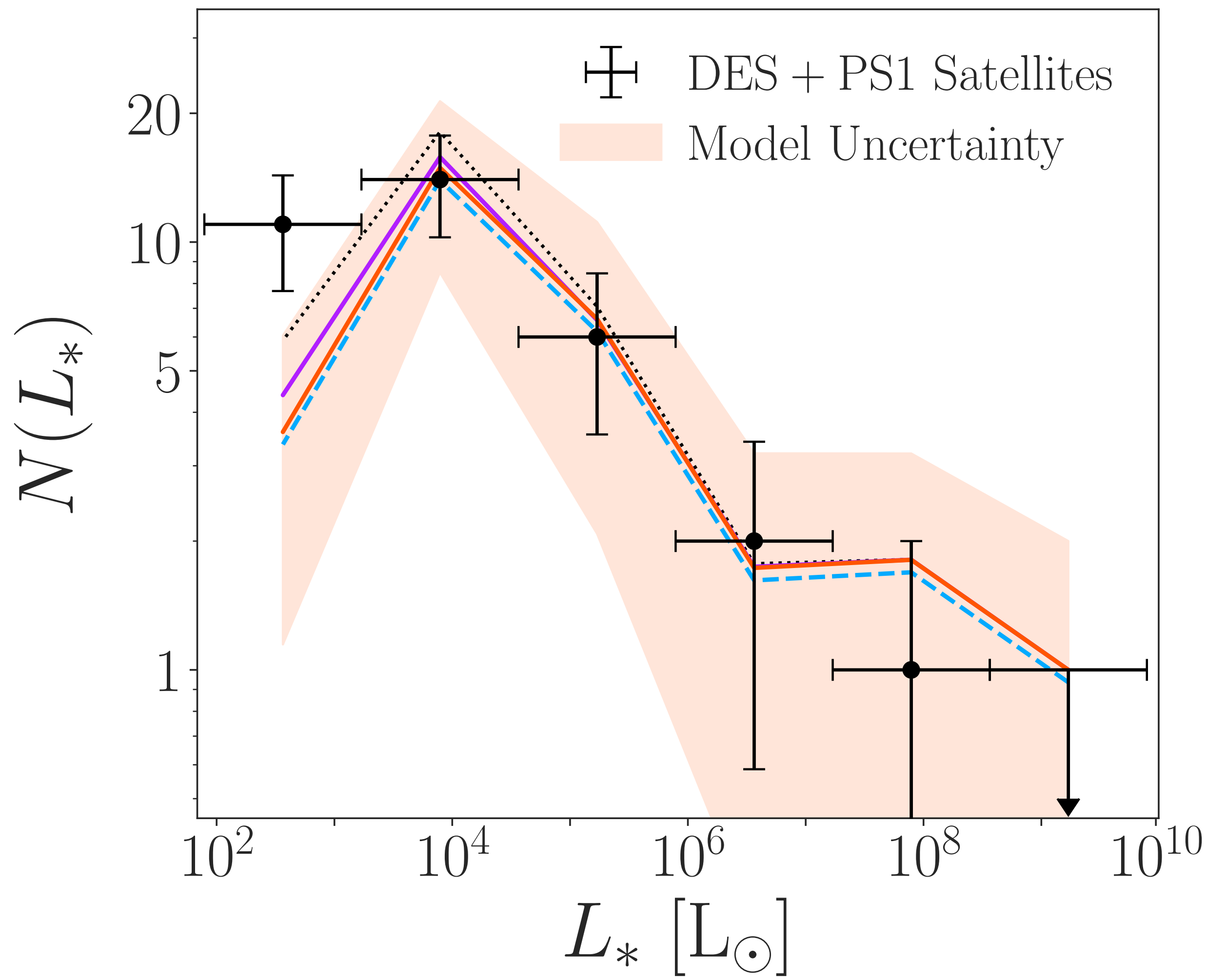




Leane and Smirnov 2010.00015

Dark Sectors + Milky Way Satellites

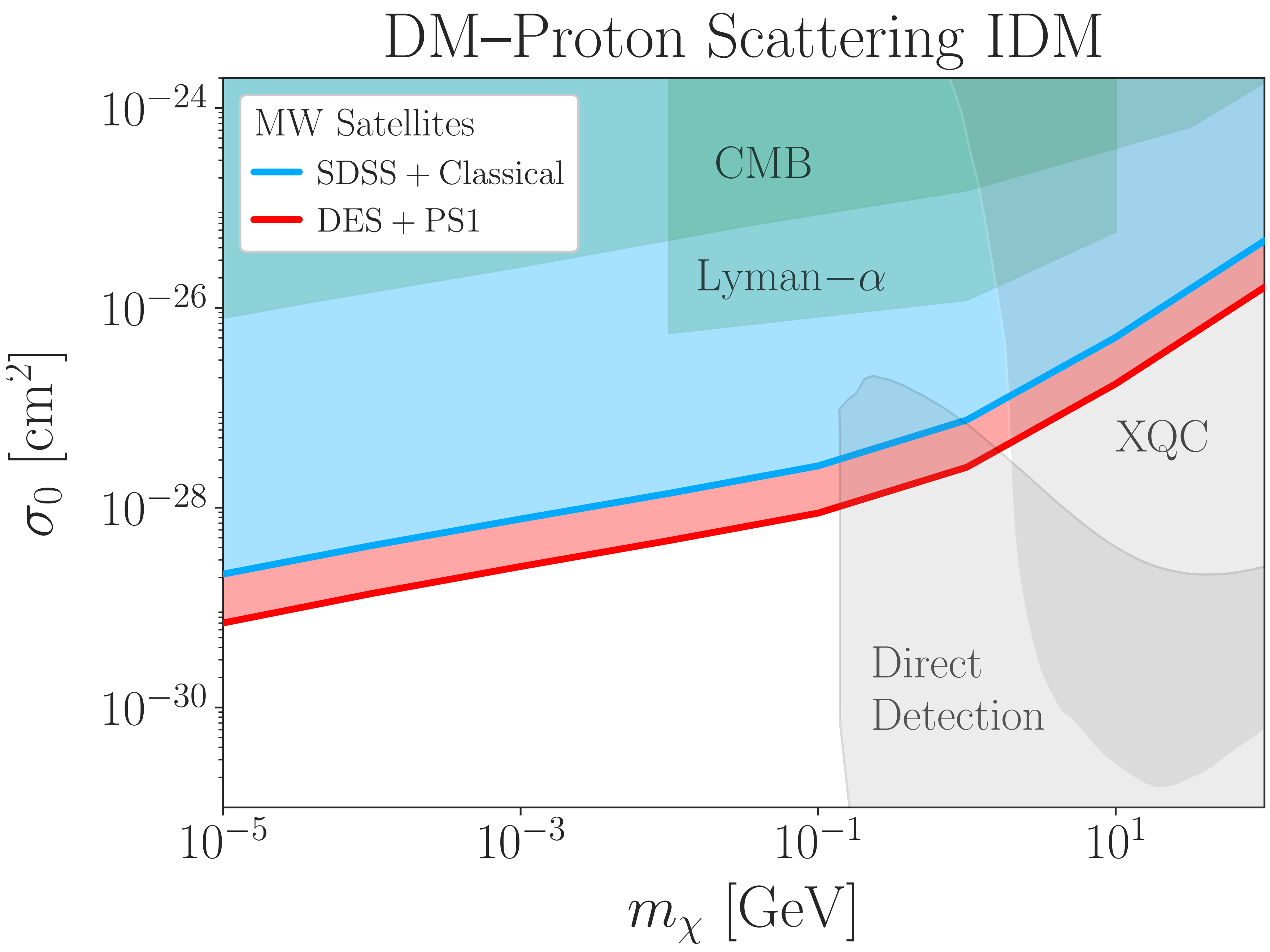




DM-baryon scattering pre-recombination washes out small scale structure

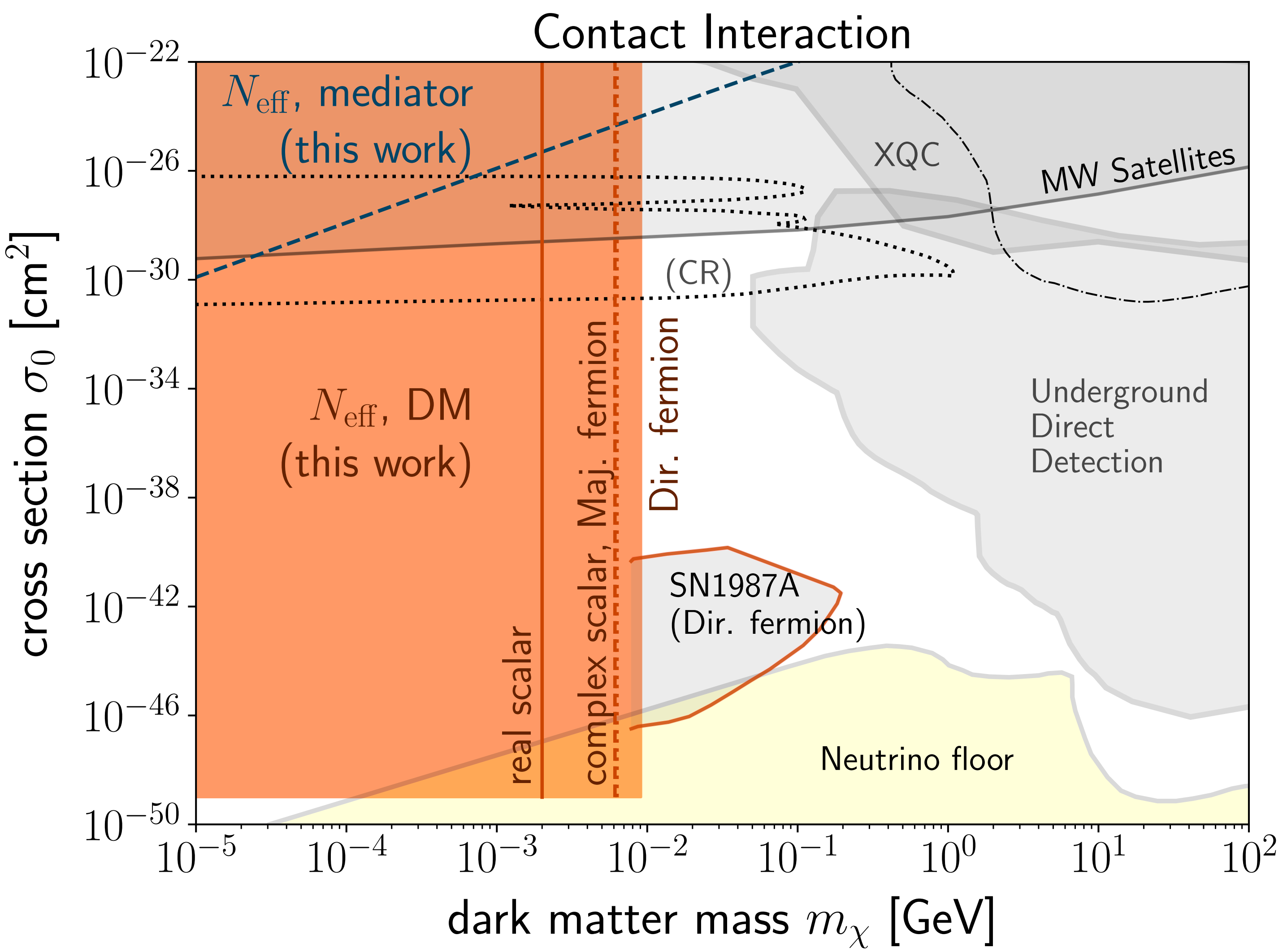
DES Collaboration 2008.00022

Dark Sectors + Milky Way Satellites



DES Collaboration 2008.00022

Dark Sectors + Milky Way Satellites + BBN



For a contact interaction, DM is chemical equilibrium during BBN $\quad \rho_{\rm DM} \sim T_\gamma^4$

Increases the Hubble rate and affects light elements $\quad \Delta N_{\rm eff} \propto \rho_{\rm rad}/\rho_\gamma \gtrsim 0.5$

GK, McDermott 1908.00007

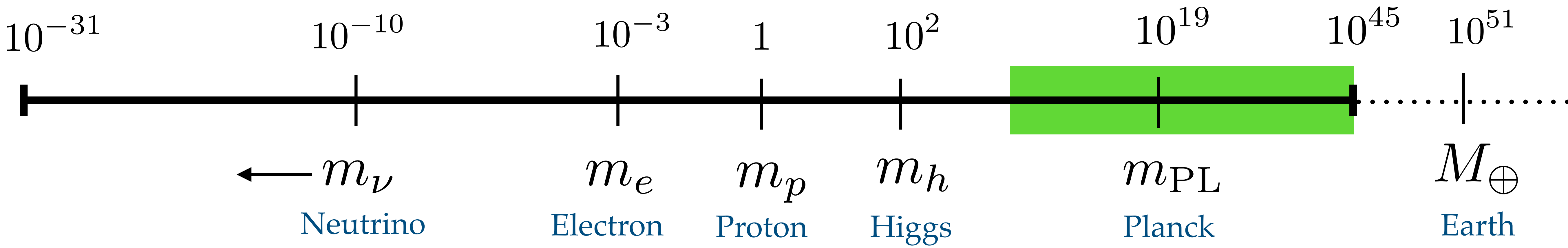
Overview

Wavelike DM

Dark Sectors

WIMPZILLAs

WIMPZILLAS and ultra heavy DM



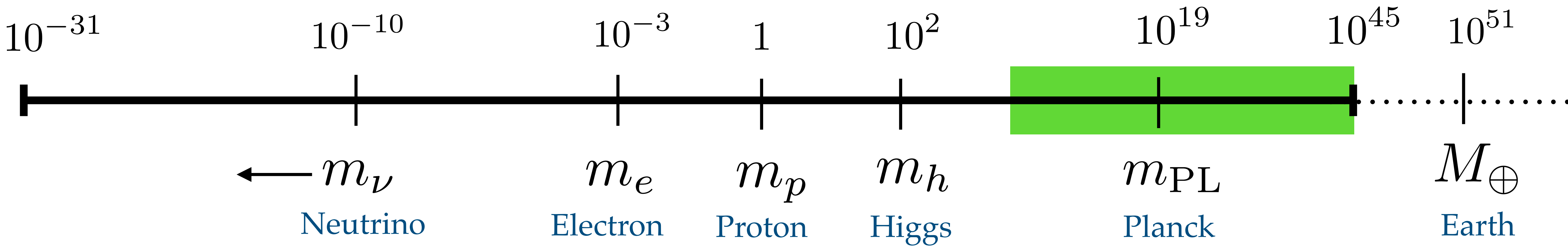
Broad category with many viable production mechanisms

Too heavy for thermal equilibrium in early universe

Kolb, Chung, Riotto arXiv/9810361

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

WIMPZILLAS and ultra heavy DM



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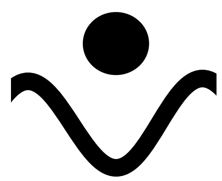
Could we ever detect it using gravity alone?

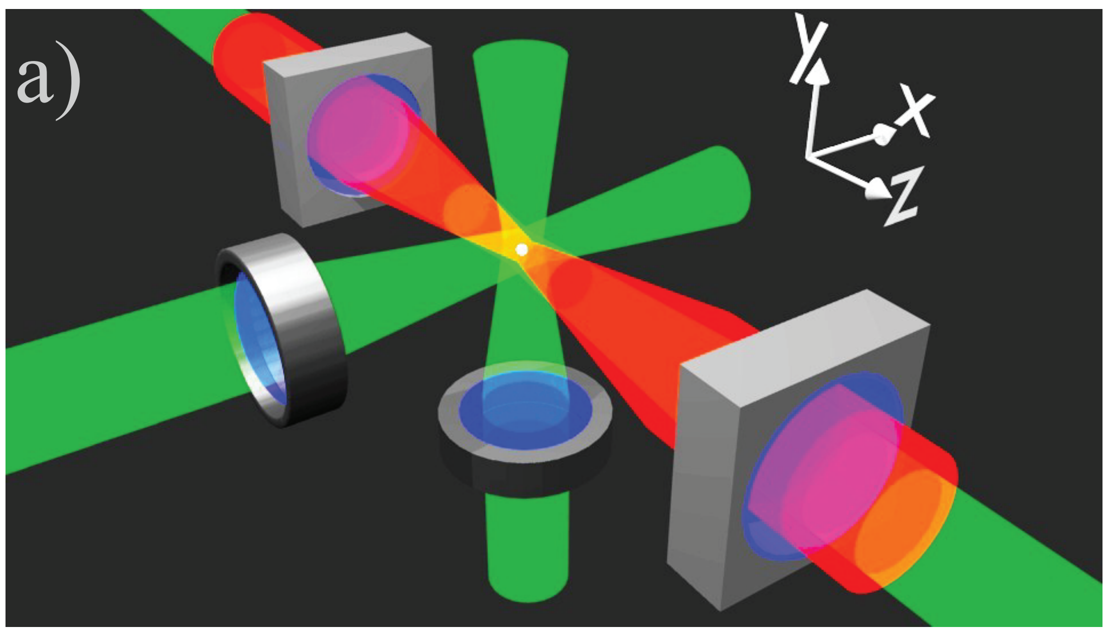
$$F_G = G_N \frac{m_{\rm DM} m_{\rm test}}{d^2} \approx \underbrace{10^{-21}{\rm N}}_{\text{“zeptonewton”}} \left(\frac{m_{\rm DM}}{m_{\rm PL}}\right) \left(\frac{m_{\rm test}}{m_{\rm PL}}\right) \left(\frac{5\,{\rm mm}}{d}\right)^2$$

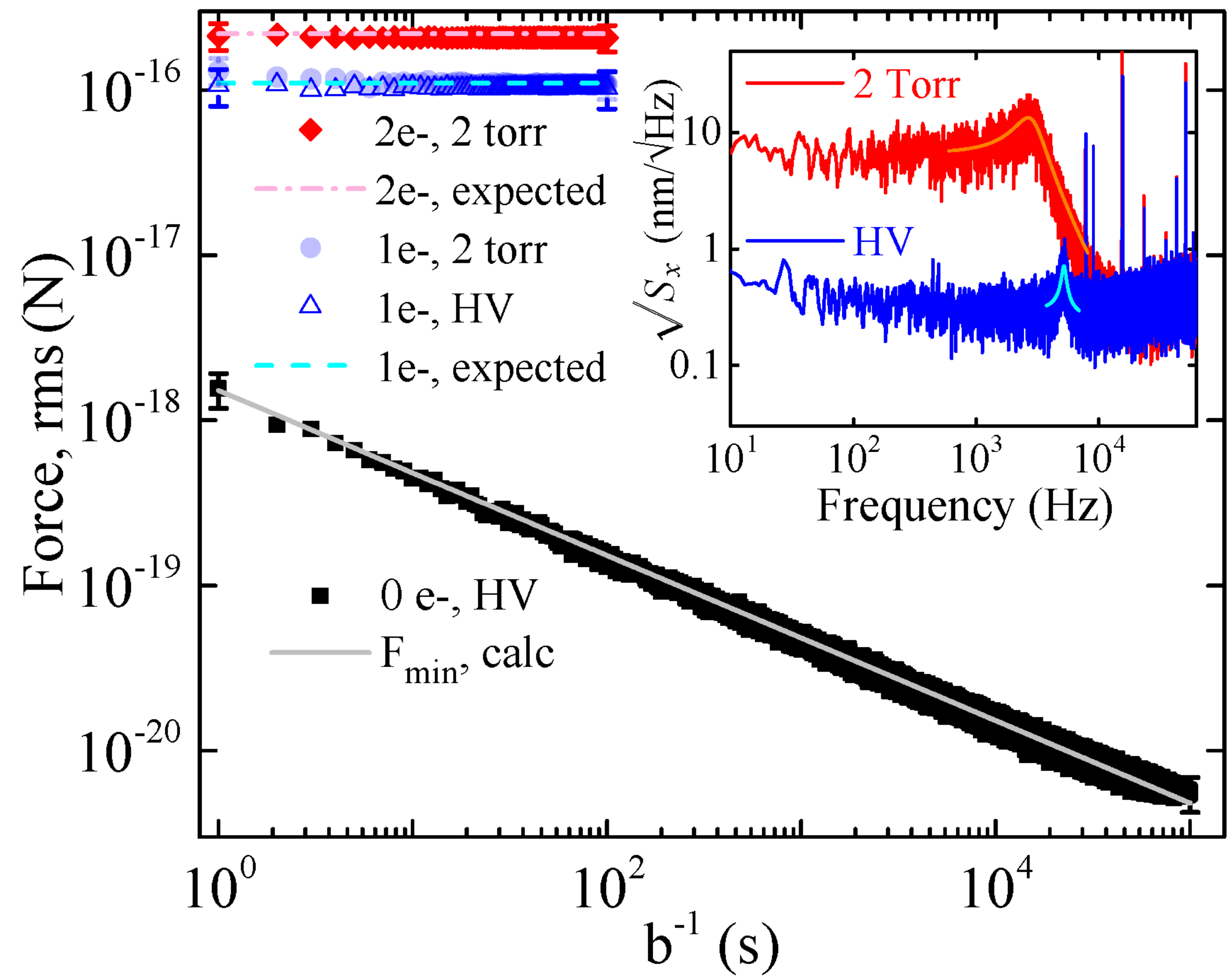
This sounds totally nuts, right?

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)



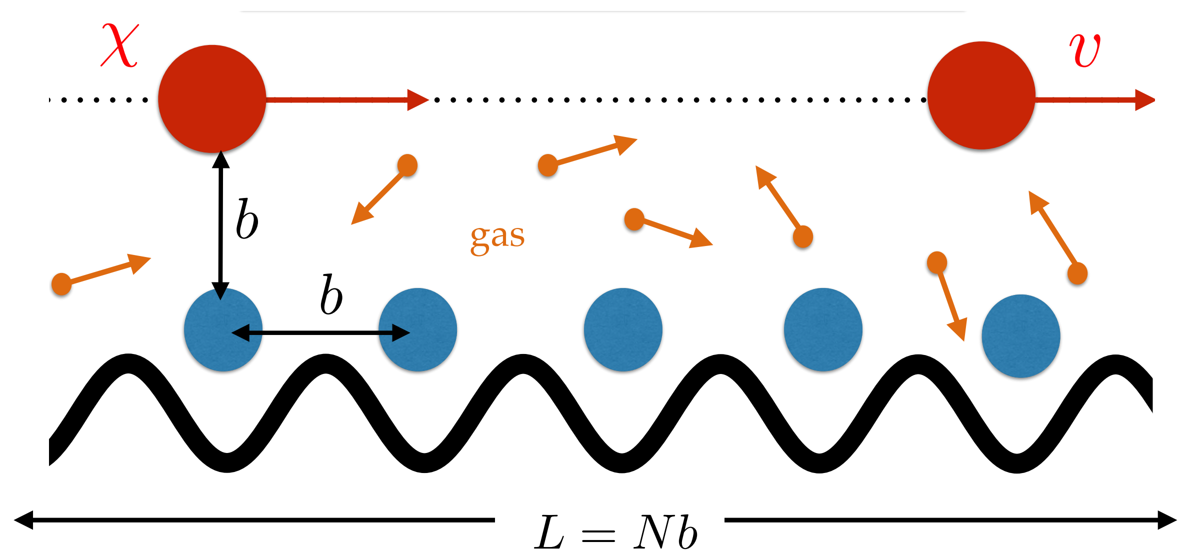




Can we use this to gravitationally detect WIMPZILLAS?

arXiv:1603.02122

Levitating Sensor Arrays "Windchime"



$$\tau = L/v$$

Signal to noise ratio gravitational impulse

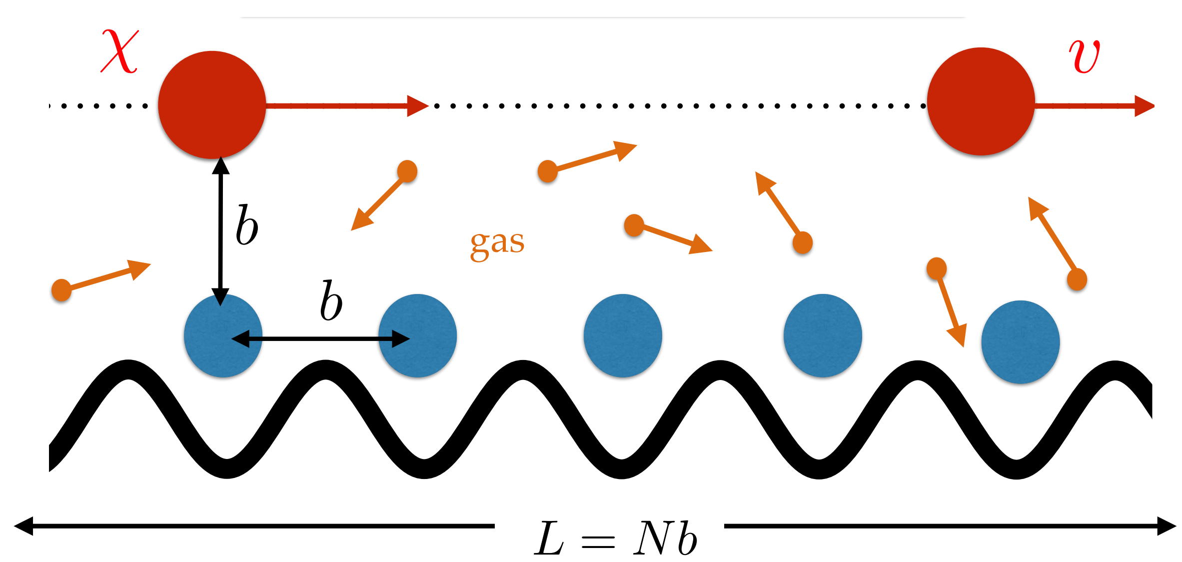
$$\mathrm{SNR}^2 = \frac{I^2}{\Delta I^2} = \frac{4\bar{F}^2 N\tau}{\alpha}$$

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"



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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

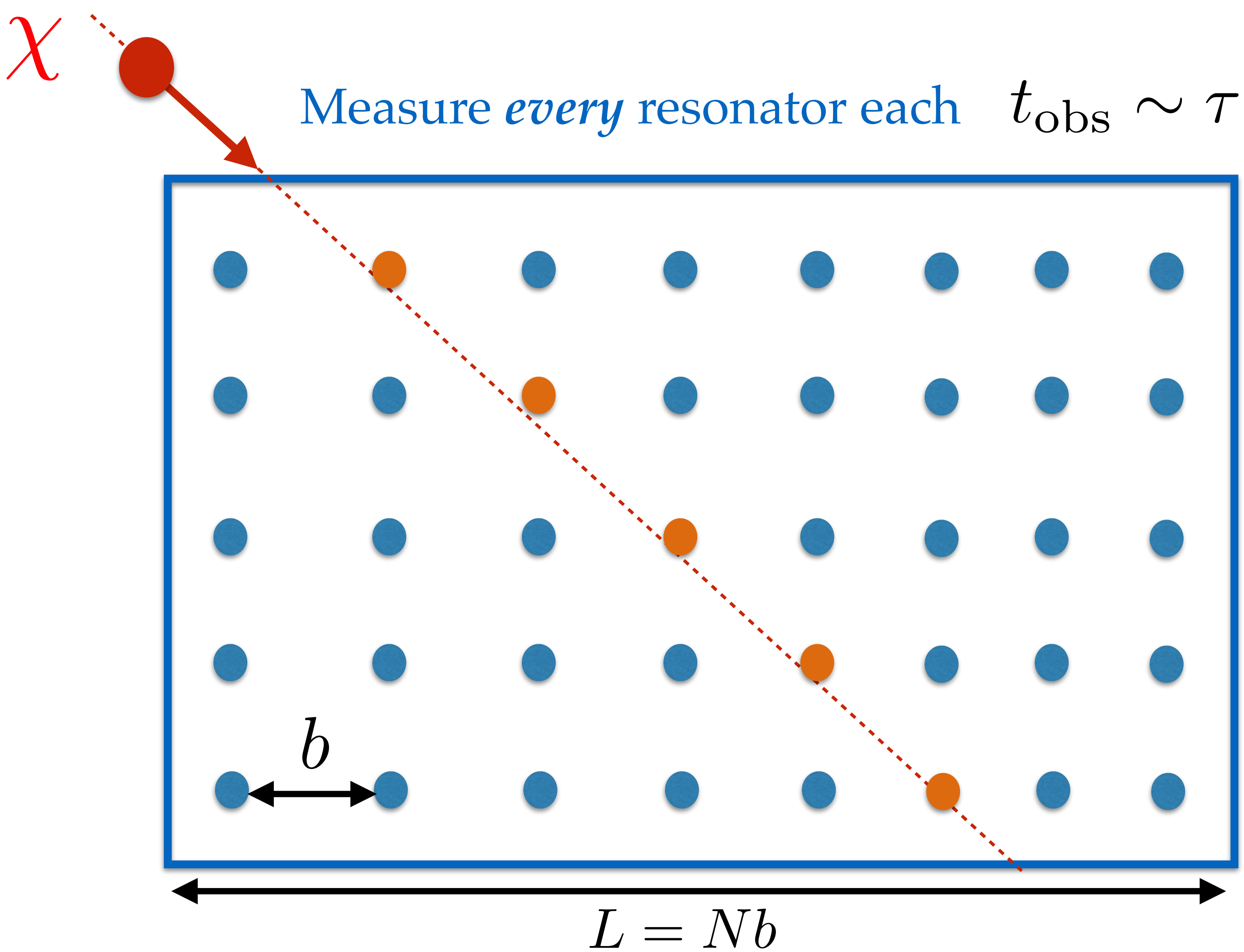
$$\mathrm{SNR}^2 \sim 10^4 \left(\frac{m_\chi}{\rm mg}\right)^2 \left(\frac{m_{\rm det}}{\rm mg}\right)^2 \left(\frac{L}{\rm m}\right) \left(\frac{\rm mm}{b}\right)^4 \left(\frac{10\,{\rm mK}}{T}\right) \left(\frac{10^{-10}\,{\rm Pa}}{P}\right) \left(\frac{4{\rm u}}{m_{\rm gas}}\right)^{1/2}$$

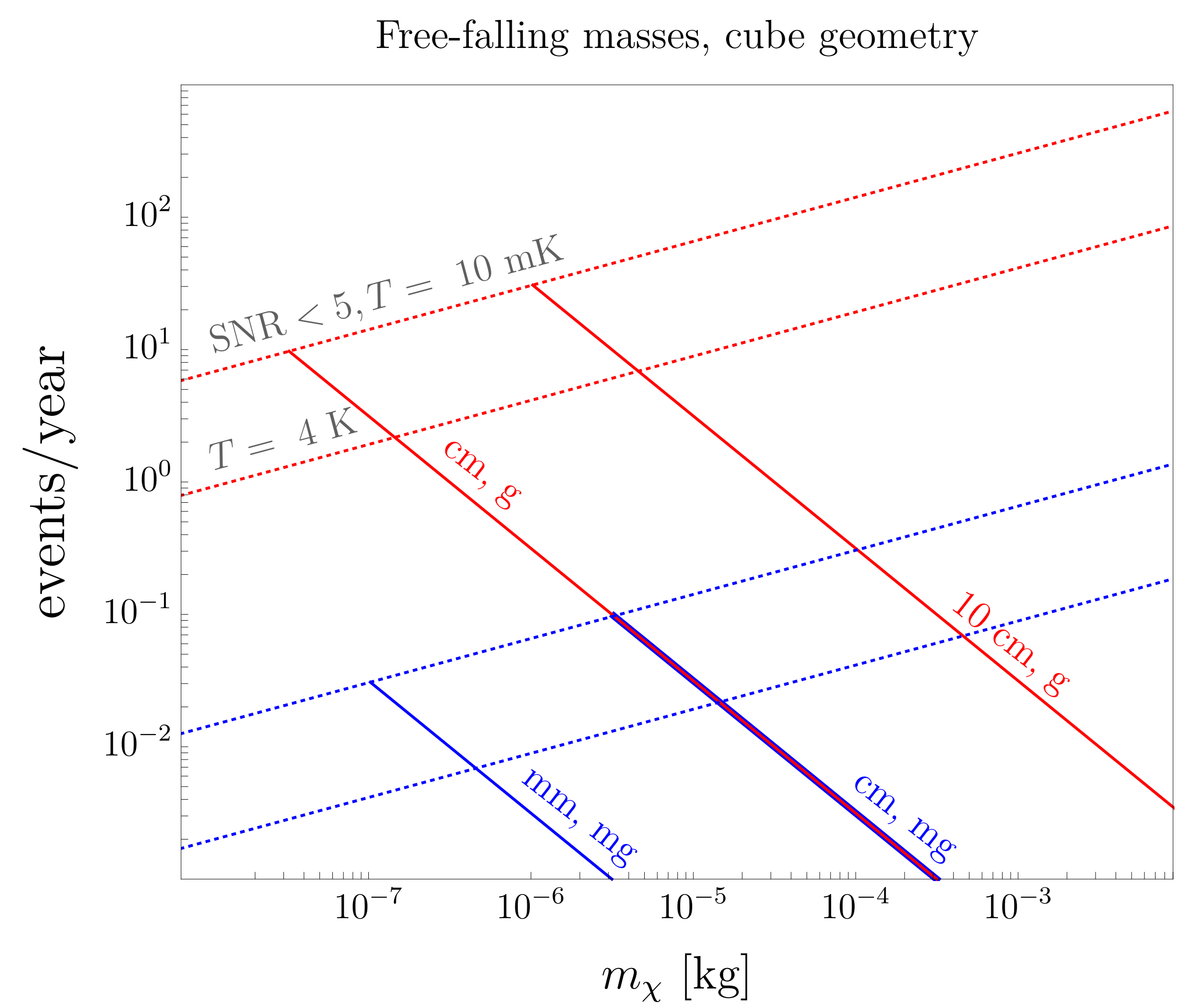
Very low rate — tradeoff with SNR:

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

Carney, Ghosh, GK, Taylor 1903.00492

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
$L = Nb \sim \text{m}$	$b \sim \text{mm}$	$\implies (L/d)^3 \sim 10^9$

Carney, Ghosh, GK, Taylor 1903.00492

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Nathaniel Scharping
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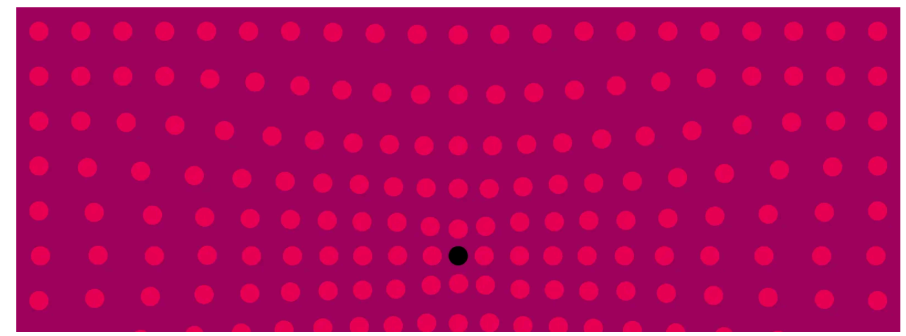

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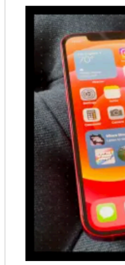

The iPhone 12 P

Caitlin McGarry

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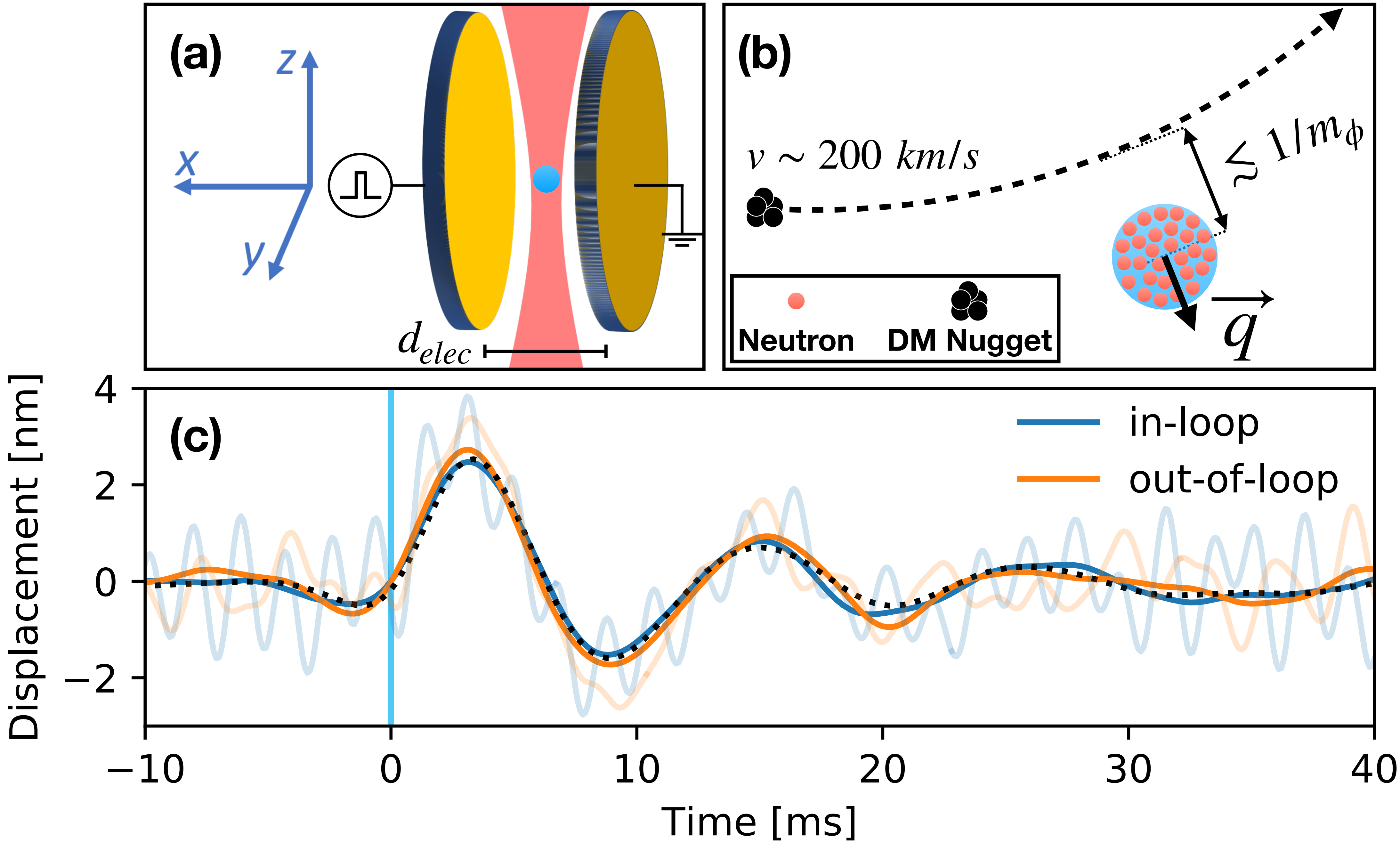
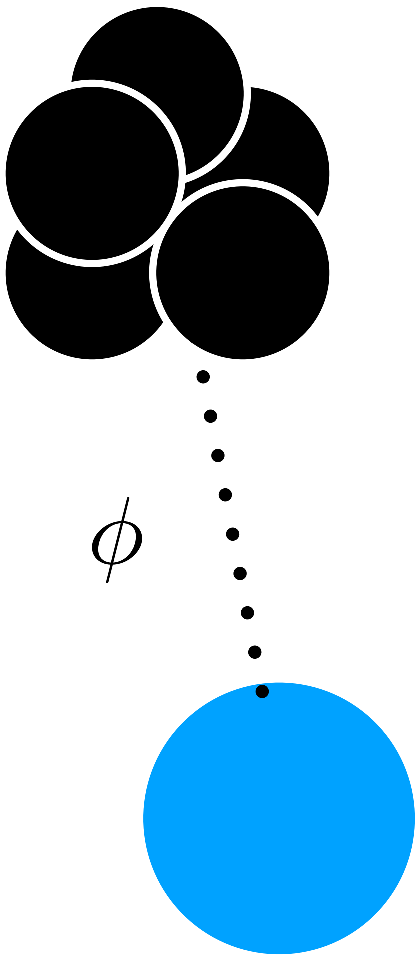
What can we do with only one sensor?

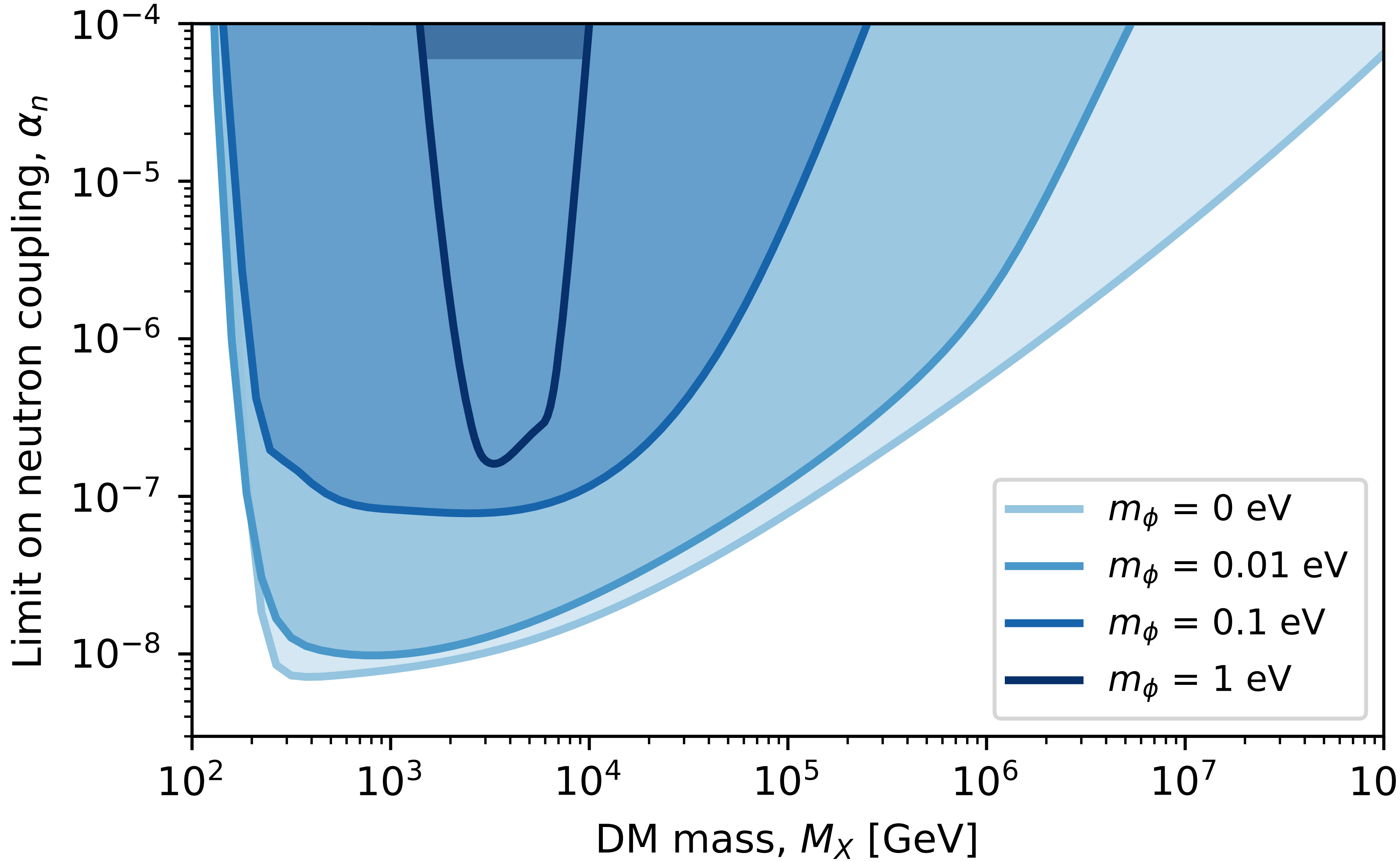
Nongravitational long range couplings of DM "nuggets" $V = \frac{\alpha_n}{r}\exp(-m_\phi r)$



Monteiro, Afek, Carney, GK, Wang, Moore 2007.12067, PRL

Single sensor prototype already setting new limits

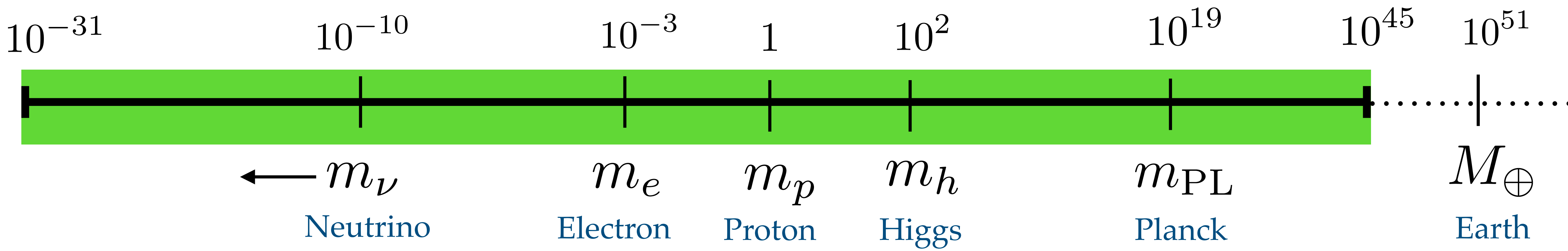




$$\alpha_n = \frac{(N_d g_d)(N_n g_n)}{4\pi}$$

Monteiro, Afek, Carney, GK, Wang, Moore 2007.12067, PRL

Concluding Remarks



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

Neutron Stars
Neutrino Oscill.

Dark Sectors

Exoplanets
MW Satelites
Direct Deflection

WIMPZILLAs

Nanospheres
Windchime Project

Thanks!