Dark Matter at

Martin Bauer

March 26, 2019

Dark Matter at AION

This is a review of the workshop on Dark Matter with Quantum Sensors from March 6th at Kings College…

.. with the focus on AION.

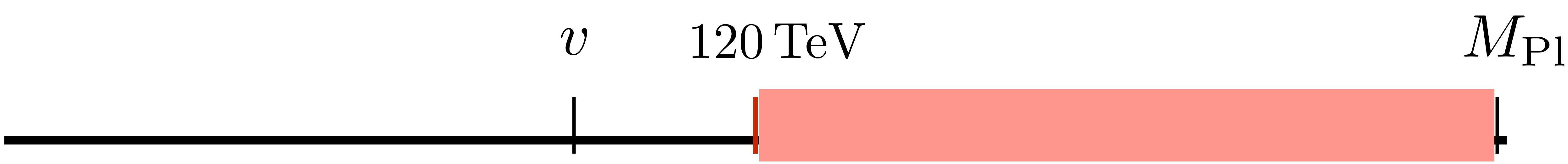
What is the DM scale?

$$\left(\frac{\Omega_X}{0.2}\right) \approx \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\sigma}$$

$$\sigma \sim \frac{g^4}{m_\chi^2}$$

$$g^2 \lesssim 4\,\pi$$

$$\Rightarrow \quad m_\chi \lesssim 120\,\mathrm{TeV}$$



What is the DM scale?

$$\left(\frac{\Omega_X}{0.2}\right) \approx \frac{10^{-8}\,\mathrm{GeV}^{-2}}{\sigma}$$

$$\Gamma = n \cdot \sigma = H$$

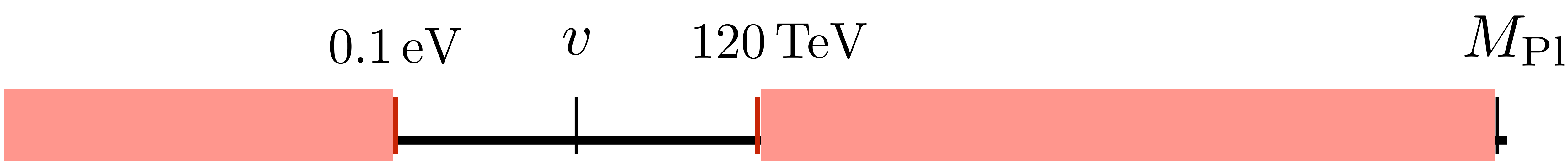
$$(m_\chi T)^{\frac{3}{2}} e^{-\frac{m_\chi}{T}} \cdot \sigma = \frac{T^2}{M_{\mathrm{Pl}}}$$

$$m_\chi > \frac{1}{\sigma M_{\mathrm{Pl}}} \qquad \Rightarrow m_\chi > 0.1\,\mathrm{eV}$$

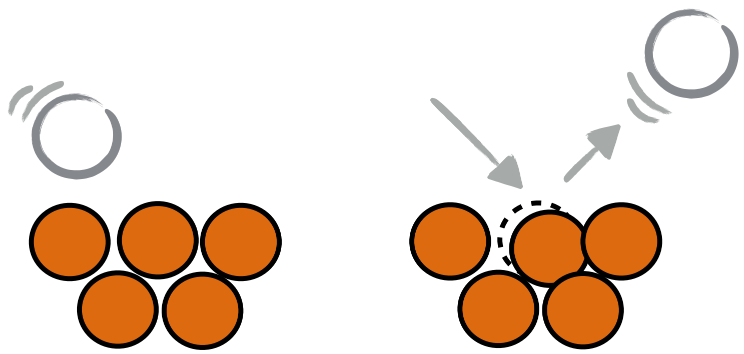
$$\sigma \sim \frac{g^4}{m_\chi^2}$$

$$g^2 \lesssim 4\,\pi$$

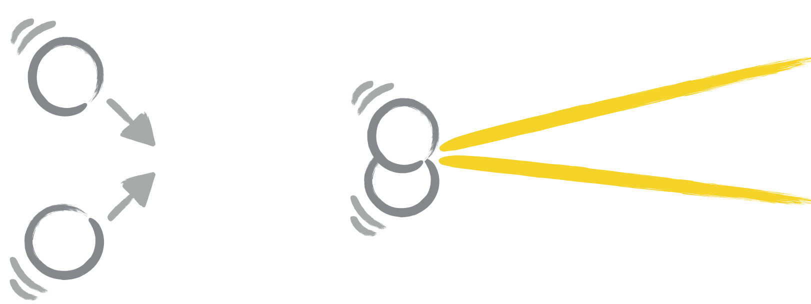
$$\Rightarrow \qquad m_\chi \lesssim 120\,\mathrm{TeV}$$



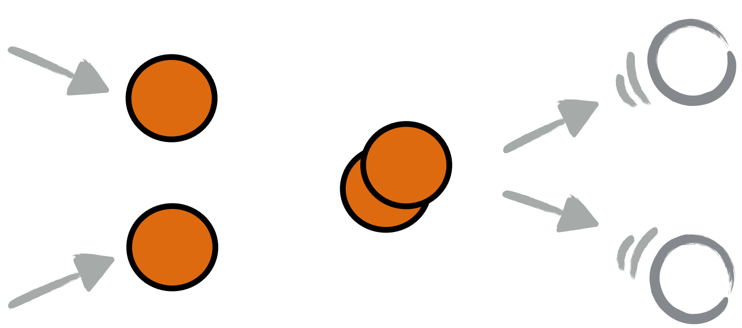
Extensive Programme



Direct detection



Indirect detection



Collider searches

What is the DM scale?

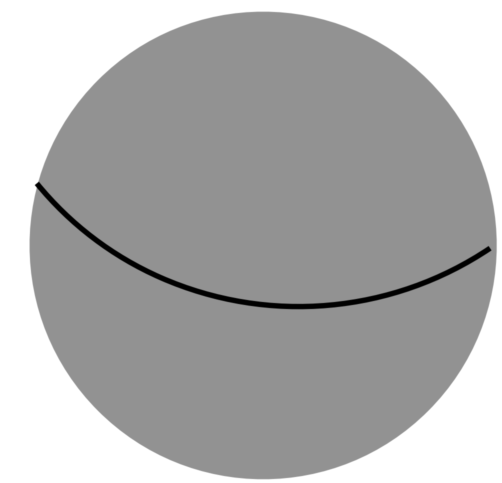
What do we know about the scale of DM?

What is the DM scale?

What do we know about the scale of DM?

For Fermions, the Pauli exclusion principle provides a lower limit

dwarf galaxies

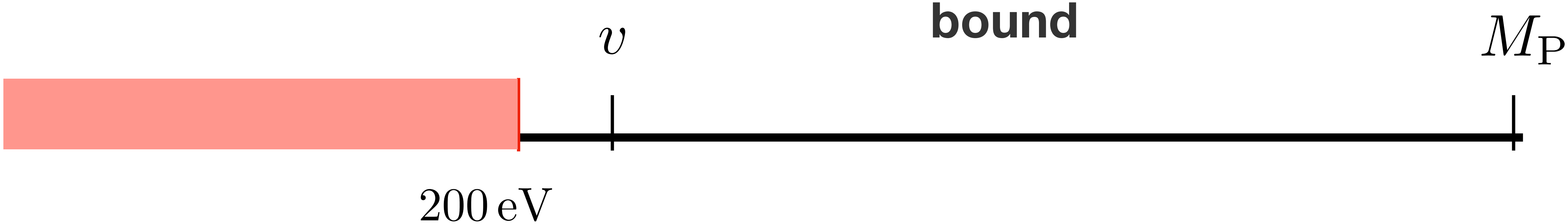


$$\left(\frac{9\pi M}{4m_\chi^4 R^3}\right)^{1/3} \leq \sqrt{\frac{2G_N M}{R}}$$

$$M \approx 10^7 M_\odot$$
$$R \approx 500\,\mathrm{pc}$$

$$\Rightarrow \quad m_\chi \gtrsim 200\,\mathrm{eV}$$

Tremaine-Gunn bound



What is the DM scale?

For bosons there is no such lower limit.

Dark bosons can be arbitrary light, but for a mass of

$$m_\phi \lesssim 10^{-25}\,\mathrm{eV}$$

the de Broglie wavelength is larger than a few hundred kpc and galaxy-size structures don't form.

What is the DM scale?

For bosons there is no such lower limit.

There is however a scale that is particularly motivated:

$$m_\phi \approx 10^{-22}\,\text{eV} \qquad \Rightarrow \qquad \lambda_{dB} = \frac{hc}{10^{-3} m_\phi} \approx 1\,\text{kpc}$$

Ultralight Dark Matter

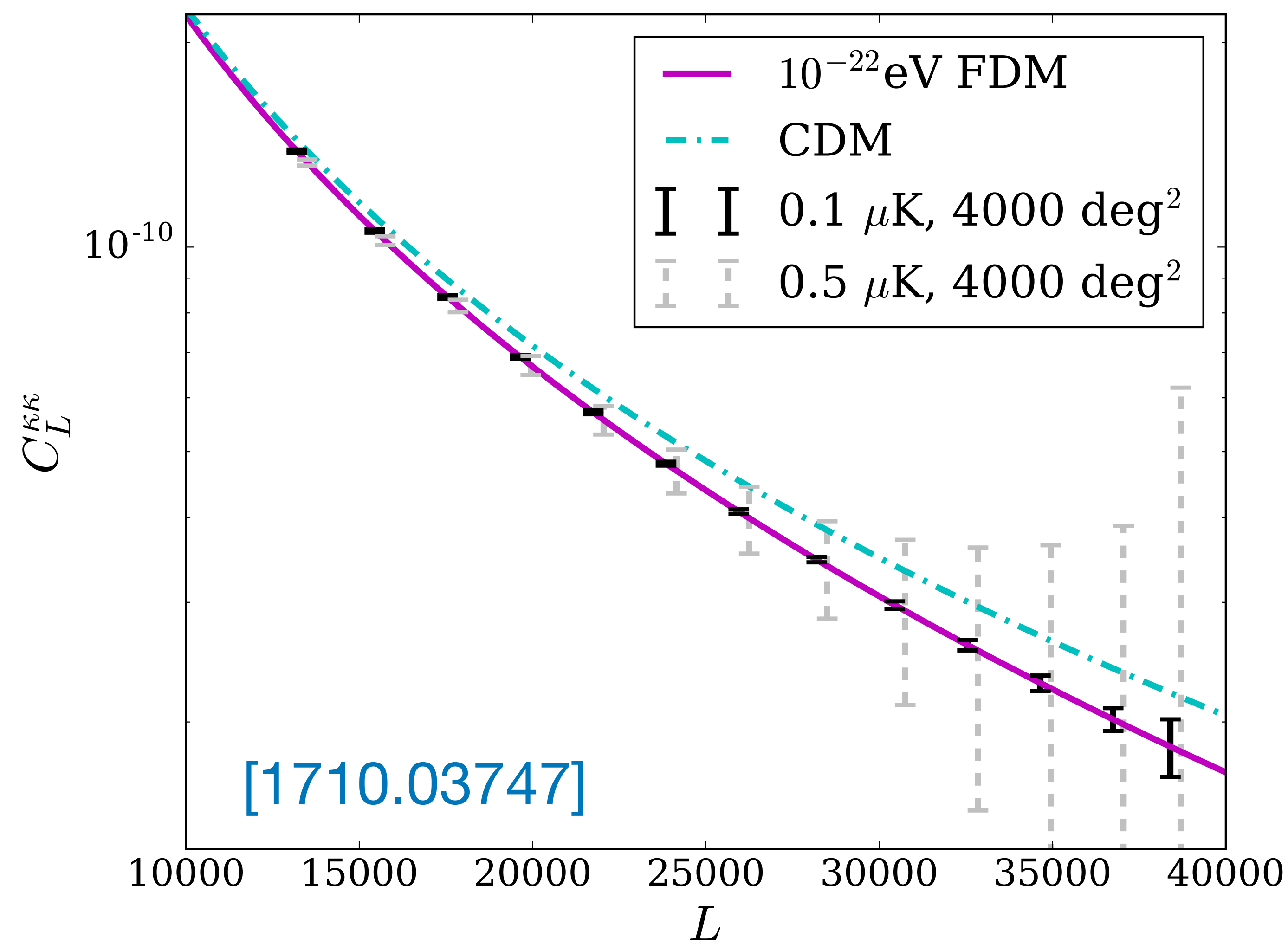
For bosons there is no such lower limit.

There is however a scale that is particularly motivated:

Fit the small scale power spectrum:

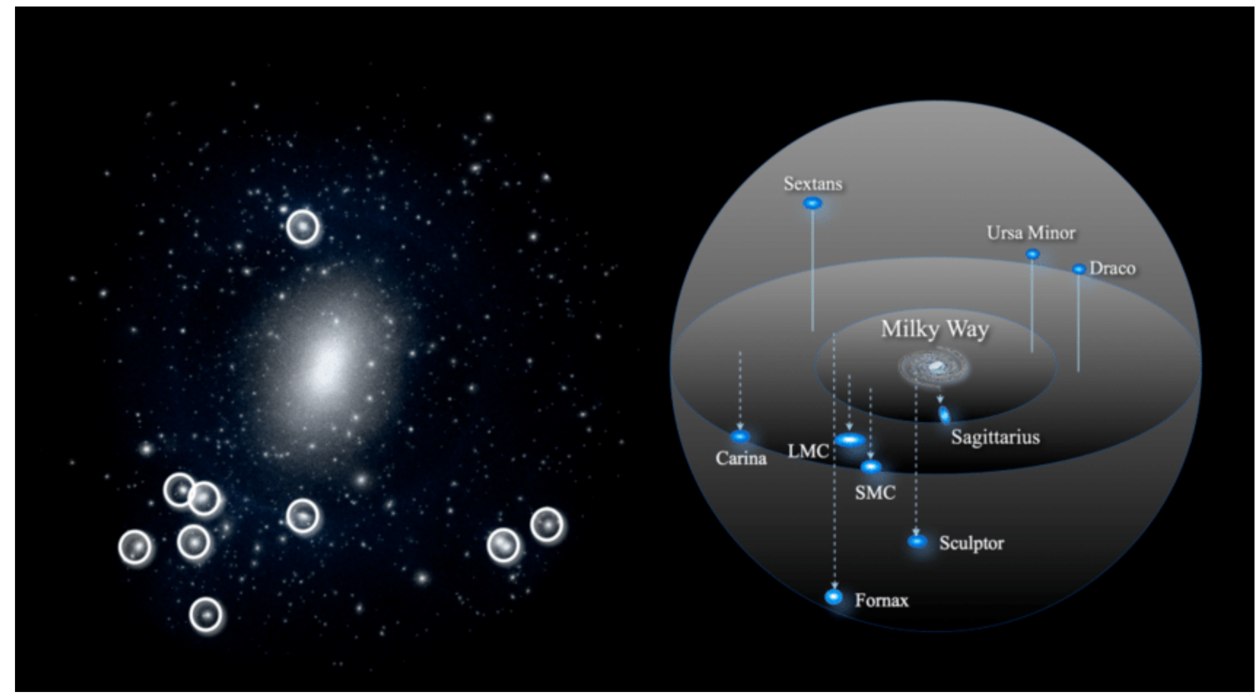
$$m_\phi \approx 10^{-22}\,\mathrm{eV} \qquad \Rightarrow$$

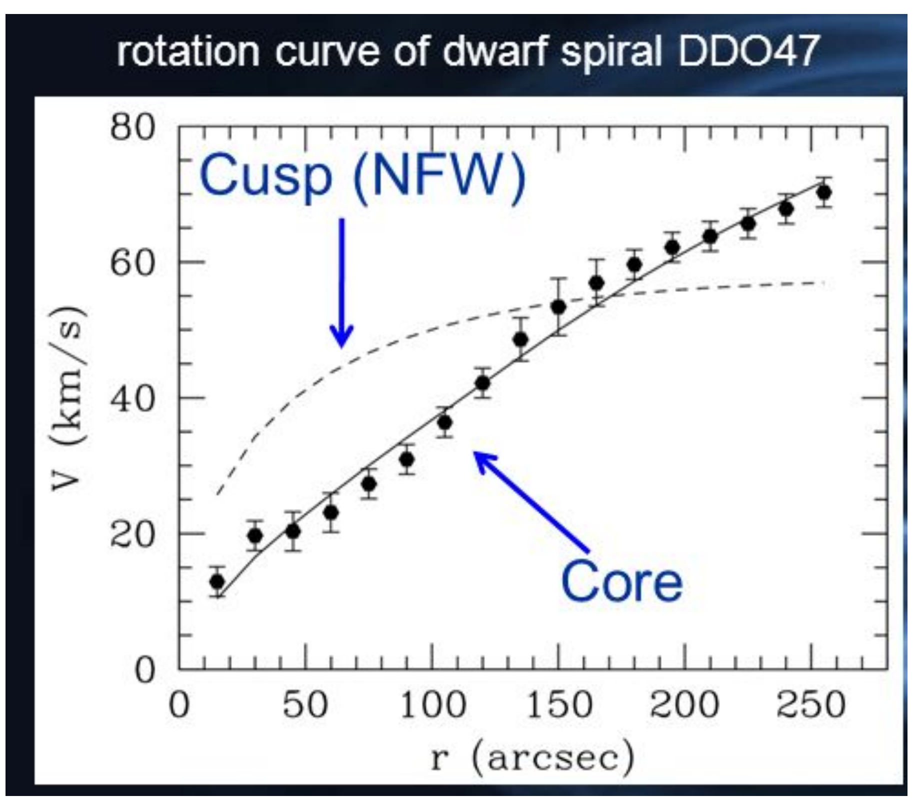
$$\lambda_{dB} = \frac{hc}{10^{-3} m_\phi} \approx 1\,\mathrm{kpc}$$



Ultralight Dark Matter

Missing satellite problem





Core cusp problem

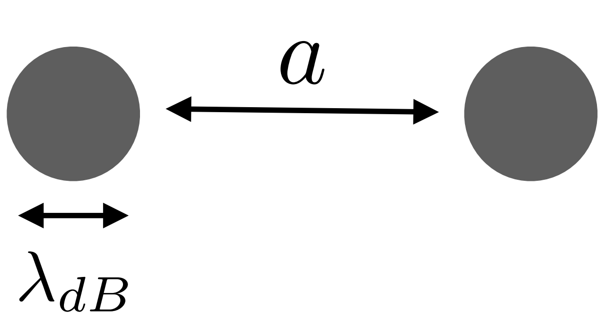
[Salucci, Martin, 2009]

What is the DM scale?

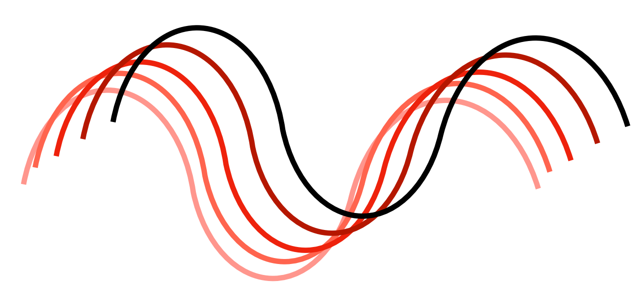
For very light scalar fields, the occupation number is very high and the field can be treated classically.

QFT

Large spacing.
Particle mechanics



Large (continuous) occupation number.
Classical field theory



Ultralight Dark Matter

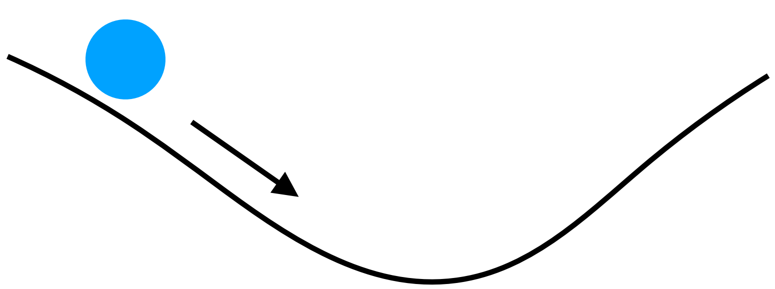
For very light scalar fields, the occupation number is very high and the field can be treated classically.

Dark Matter relic density from misalignment:

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

$$H(t) > m_a$$

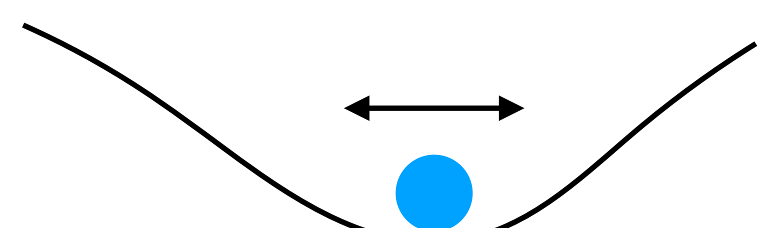
Solution $a(t) = \text{const.}$



early universe: Hubble friction

$$H(t) < m_a$$

harm. oscillator: $a(t) = a_0 \cos(m_a t)$



late universe: oscillations

Cosmological implications

Mass is fixed by halo size $m_a \lesssim 10^{-22}\,\mathrm{GeV}$

Cosmological implications

Mass is fixed by halo size $$m_a \lesssim 10^{-22}\,\mathrm{GeV}$$

Amplitude is fixed by the dark matter energy density $$\rho_a = \frac{1}{2} m_a^2 a_0^2 \stackrel{!}{=} \rho_{\mathrm{DM}} = 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Cosmological implications

Mass is fixed by halo size $m_a \lesssim 10^{-22}\,\mathrm{GeV}$

Amplitude is fixed by the dark matter energy density

$$\rho_a = \frac{1}{2} m_a^2 a_0^2 \overset{!}{=} \rho_{\mathrm{DM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

The angular frequency is determined by the rest mass.

$$\omega \sim m_a$$

Small corrections from the kinetic energy

$$\frac{\Delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$$

$v \approx 10^{-3}$

Cosmological implications

Mass is fixed by halo size $$m_a \lesssim 10^{-22}\,\mathrm{GeV}$$

Amplitude is fixed by the dark matter energy density $$\rho_a = \frac{1}{2} m_a^2 a_0^2 \stackrel{!}{=} \rho_{\mathrm{DM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

The angular frequency is determined by the rest mass. $$\omega \sim m_a$$

$v \approx 10^{-3}$

Small corrections from the kinetic energy $$\frac{\Delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$$

Coherence time is set by the frequency spread $$\tau_c = \frac{2\pi}{\Delta\omega} = \frac{2\pi}{m_a v^2} \approx 1\mathrm{s}\left(\frac{\mathrm{MHz}}{m_a}\right)$$

Cosmological implications

Experimental consequences:

$$\frac{\Delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$$

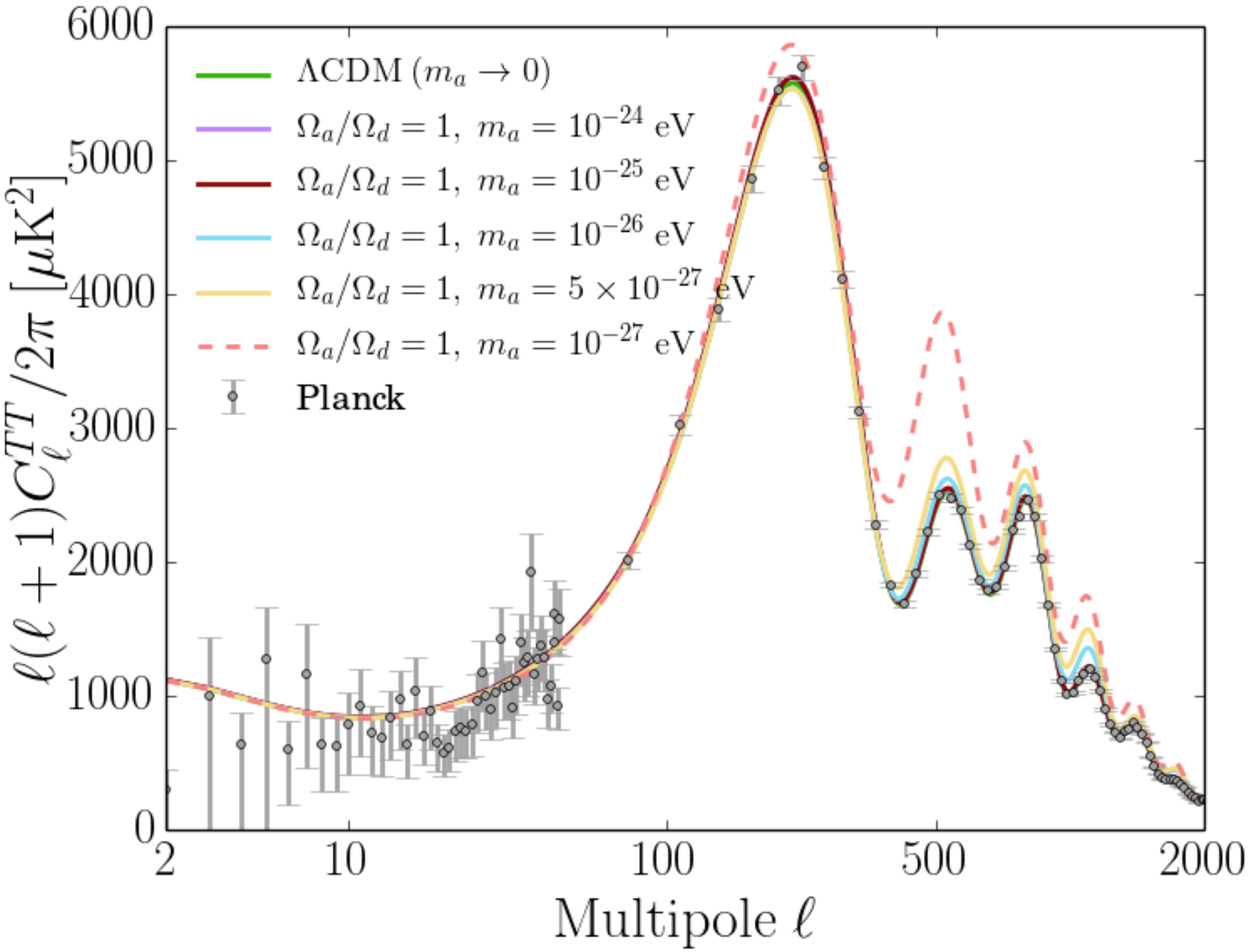
Resonant detection possible with $Q \approx 10^6$ periods.

The linewidth is characteristic for ultralight dark matter.

Annual modulations provide a smoking gun signal.

Cosmological constraints

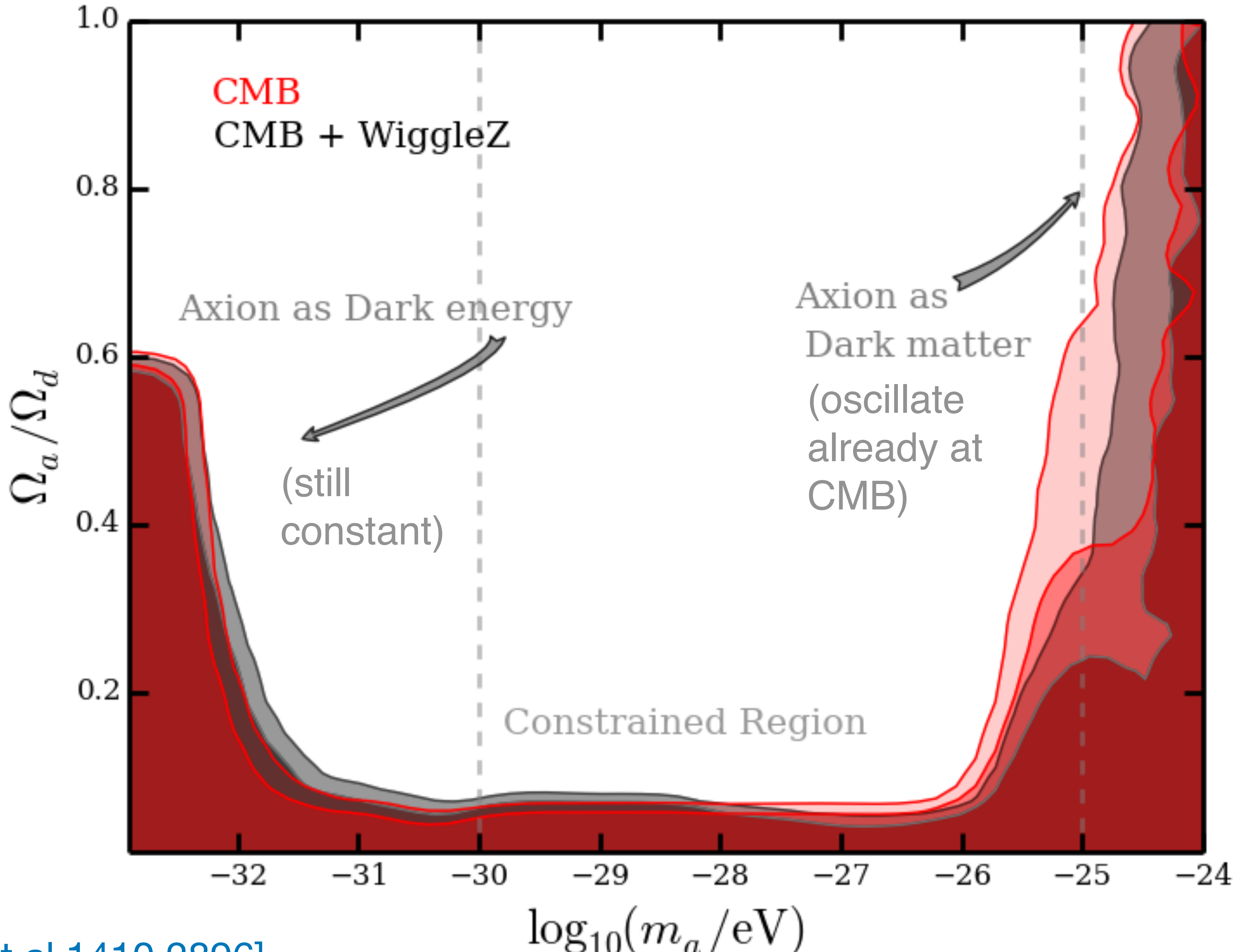
Axions behave as Dark Energy before they begin to oscillate



[Marsh et al 1410.2896]

Cosmological constraints

Fraction of DM



[Marsh et al 1410.2896]

Ultralight Dark Matter

Scalar Dark Matter

$$\mathcal{L} = \frac{\phi}{\Lambda} m_\psi \bar{\psi}\psi - \frac{1}{4g^2}\frac{\phi}{\Lambda} F^{\mu\nu}F_{\mu\nu} + \ldots$$

$$\phi = \phi_0 \cos(m_\phi t)$$

Time-dependent fundamental constants

$$m_\psi \to \left(1 + \frac{\phi_0}{\Lambda}\cos(m_\phi t)\right)$$

$$\alpha \to \left(1 - \frac{\phi_0}{\Lambda}\cos(m_\phi t)\right)$$

Pseudoscalar Dark Matter (Axion)

$$\mathcal{L} = \frac{\partial^\mu a}{f}\bar{\psi}\gamma_\mu\gamma_5\psi - \frac{a}{f}F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

$$a = a_0 \cos(m_a t)$$

Time varying spin-dependent effects

Vector Dark Matter (Hidden Photon)

$$\mathcal{L} = -\frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu} + \ldots$$

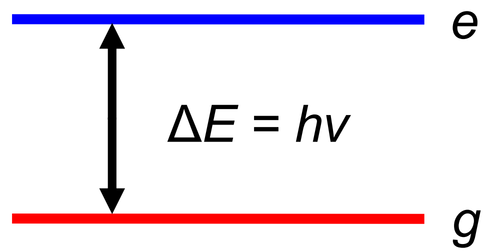
$$\vec{A} = A_0 \hat{n} \cos(m_A t)$$

Directional dependence

Ultralight Dark Matter

Scalar Dark Matter	Pseudoscalar Dark Matter (Axion)	Vector Dark Matter (Hidden Photon)
$\mathcal{L} = \frac{\phi}{\Lambda} m_\psi \bar{\psi}\psi - \frac{1}{4g^2}\frac{\phi}{\Lambda} F^{\mu\nu}F_{\mu\nu} + \ldots$	$\mathcal{L} = \frac{\partial^\mu a}{f}\bar{\psi}\gamma_\mu\gamma_5\psi - \frac{a}{f}F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$	$\mathcal{L} = -\frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu} + \ldots$
Atomic clocks	Magnetometers	DM radio
Optical Cavities	Nuclear magnetic Resonance	EM resonators
Fifth-force searches	Torsion Pendula	

Scalar Dark Matter

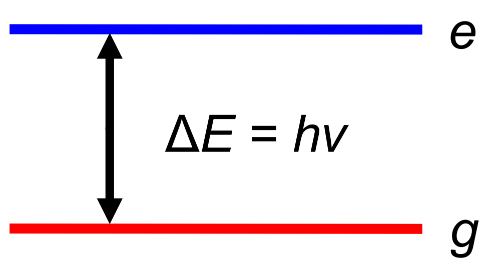


Atomic spectroscopy (clocks)

$\delta(\nu_1/\nu_2) \propto \cos(m_\varphi t)$ 10^{-23} eV $< m_\varphi <$ 10^{-16} eV

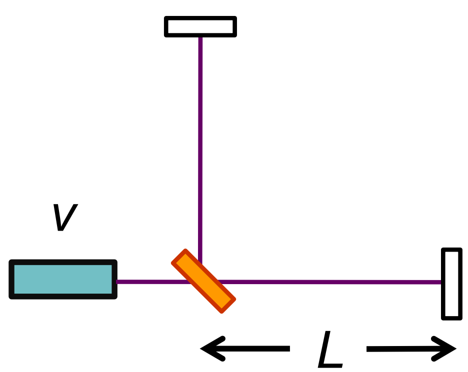
slide from Y. Stadnik

Scalar Dark Matter



Atomic spectroscopy (clocks)

$\delta(\nu_1/\nu_2) \propto \cos(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV

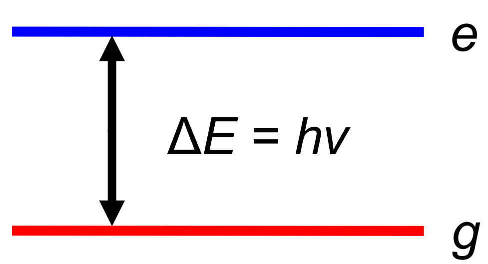


Laser interferometry (cavities)

$\delta\Phi \propto \delta(\nu L) \propto \cos(m_\varphi t)$ 10^{-20} eV < m_φ < 10^{-15} eV

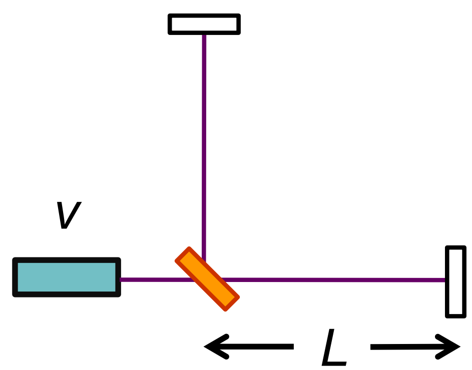
slide from Y. Stadnik

Scalar Dark Matter



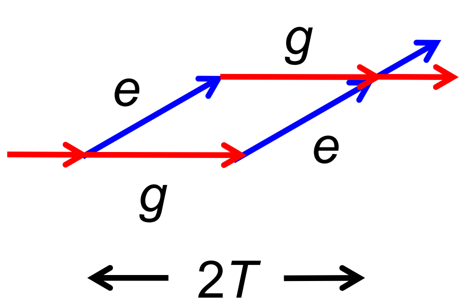
Atomic spectroscopy (clocks)

$\delta(v_1/v_2) \propto \cos(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV



Laser interferometry (cavities)

$\delta\Phi \propto \delta(vL) \propto \cos(m_\varphi t)$ 10^{-20} eV < m_φ < 10^{-15} eV

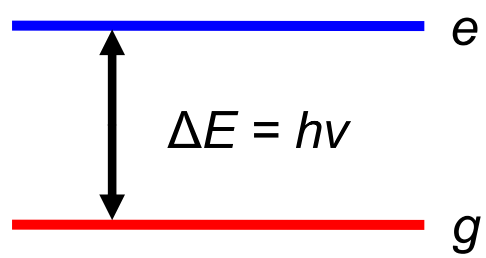


Atom interferometry

$\boldsymbol{F}(t) \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV

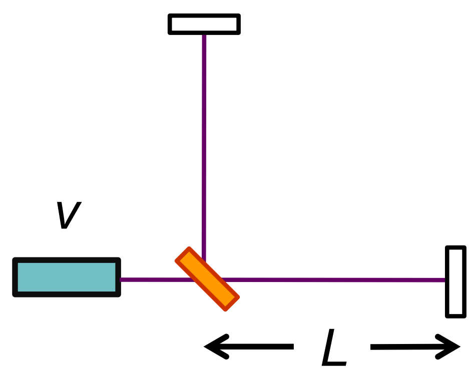
slide from Y. Stadnik

Scalar Dark Matter



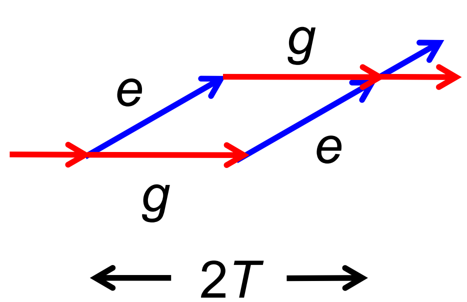
Atomic spectroscopy (clocks)

$\delta(\nu_1/\nu_2) \propto \cos(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV



Laser interferometry (cavities)

$\delta\Phi \propto \delta(\nu L) \propto \cos(m_\varphi t)$ 10^{-20} eV < m_φ < 10^{-15} eV



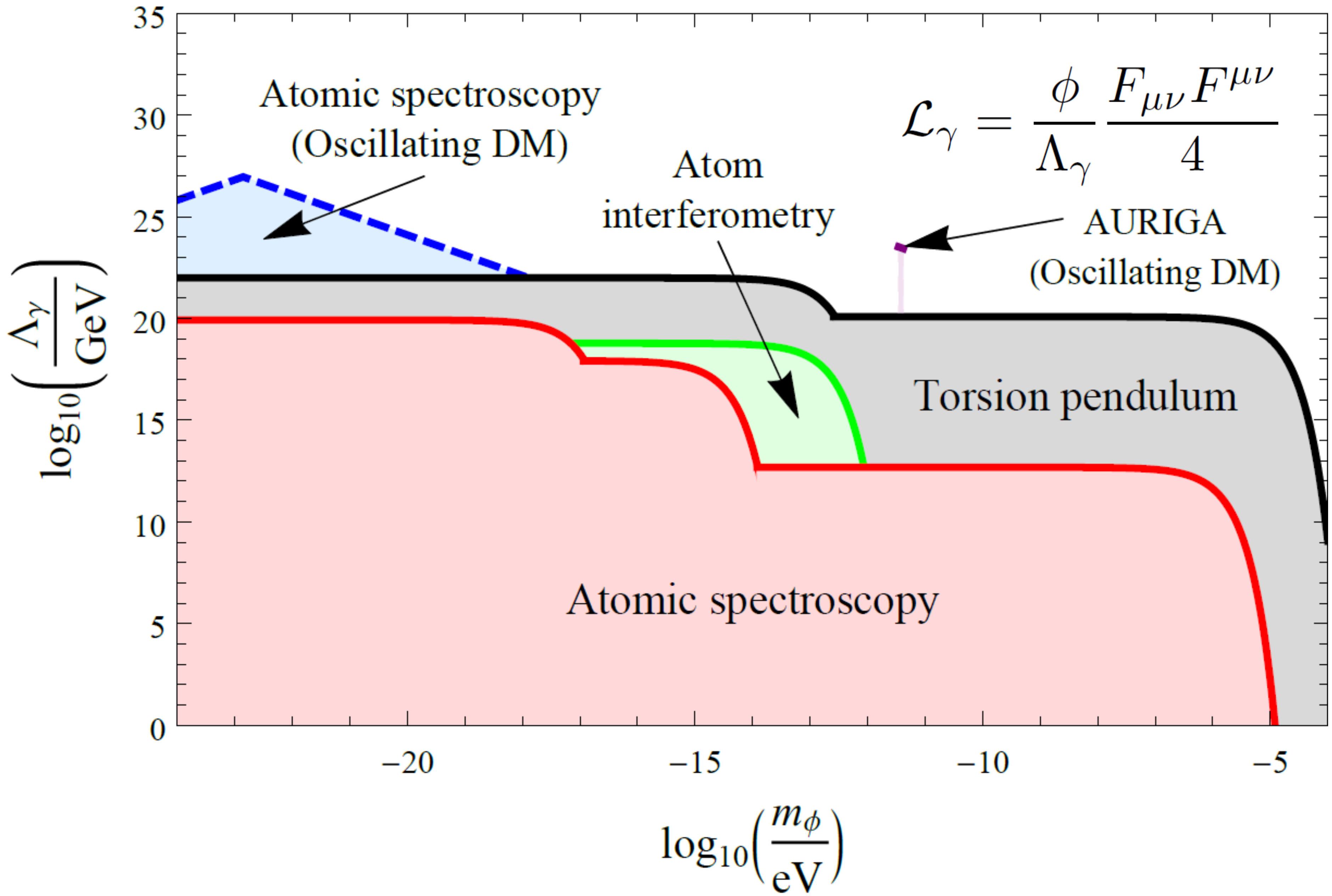
Atom interferometry

$\boldsymbol{F}(t) \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV

suppressed by small momenta

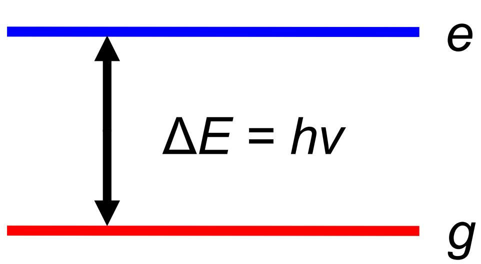
slide from Y. Stadnik

Scalar Dark Matter



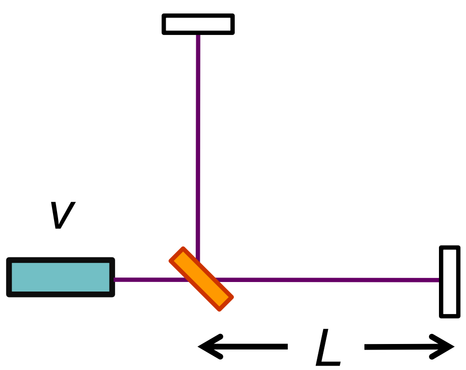
slide from Y. Stadnik

Scalar Dark Matter



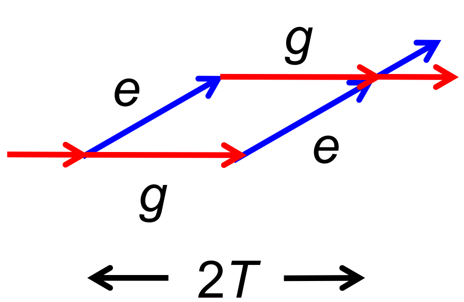
Atomic spectroscopy (clocks)

$\delta(v_1/v_2) \propto \cos(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV



Laser interferometry (cavities)

$\delta\Phi \propto \delta(vL) \propto \cos(m_\varphi t)$ 10^{-20} eV < m_φ < 10^{-15} eV

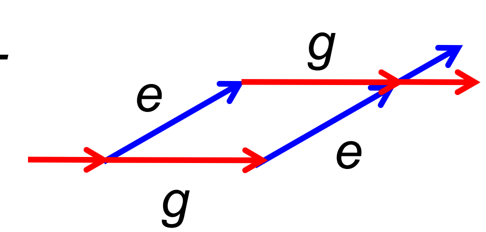


Atom interferometry

$\boldsymbol{F}(t) \propto \boldsymbol{p}_\varphi \sin(m_\varphi t)$ 10^{-23} eV < m_φ < 10^{-16} eV

$\delta\Phi(T,L)$ = max. for $2\pi/m_\varphi \sim 2T$

10^{-17} eV < m_φ < 10^{-15} eV

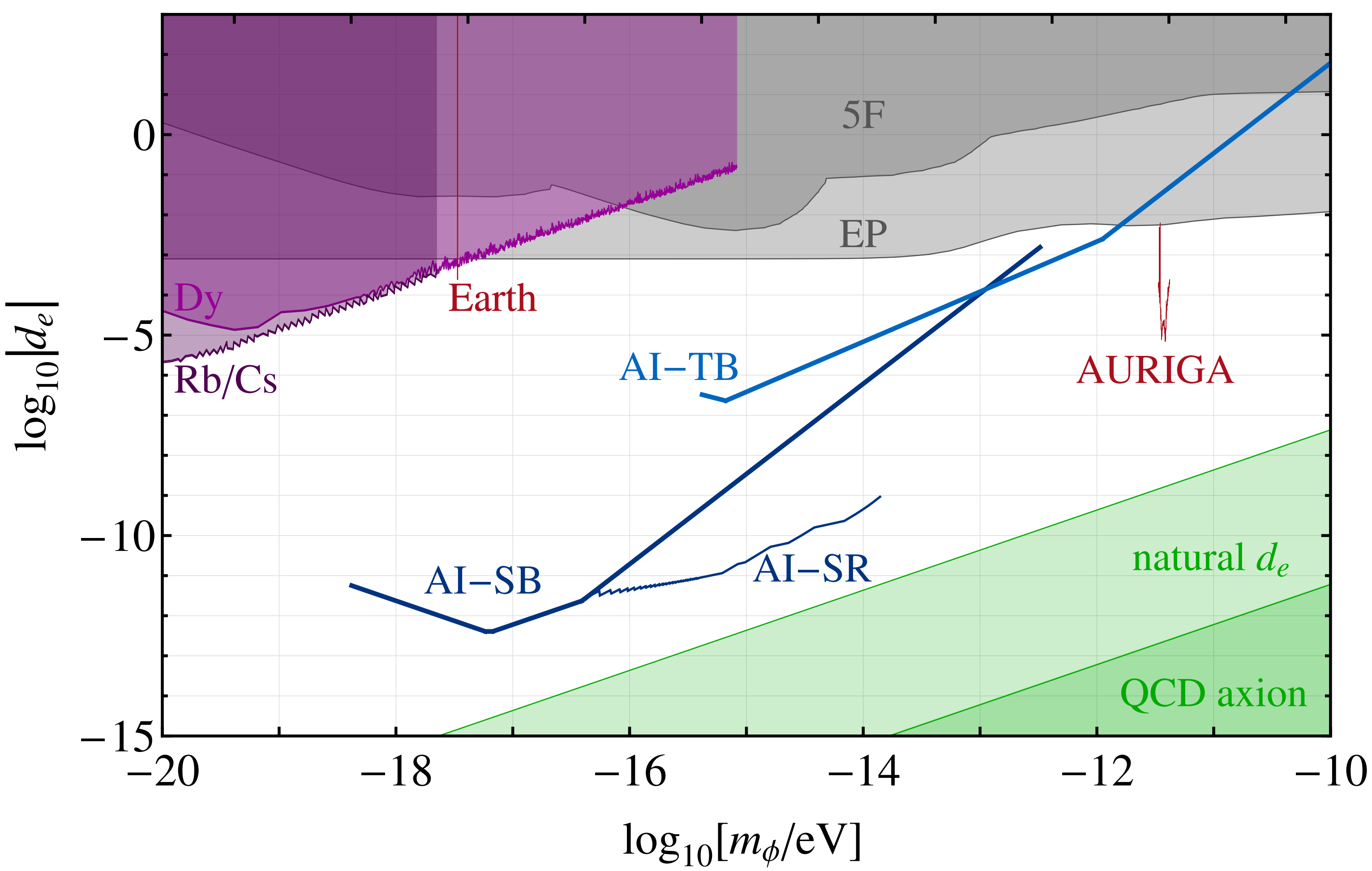


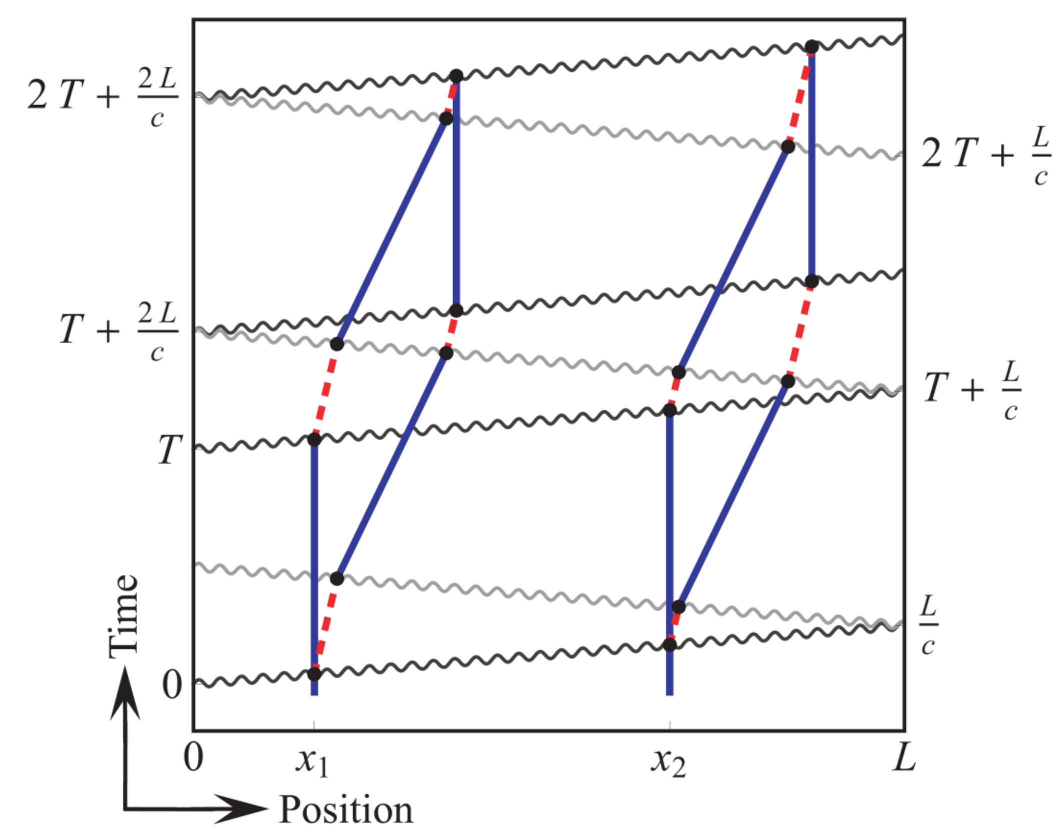
Interferometric sequence = period of the DM wave

slide from Y. Stadnik

Scalar Dark Matter

By comparing 2 spatially separated atom interferometers phase differences can be measured.



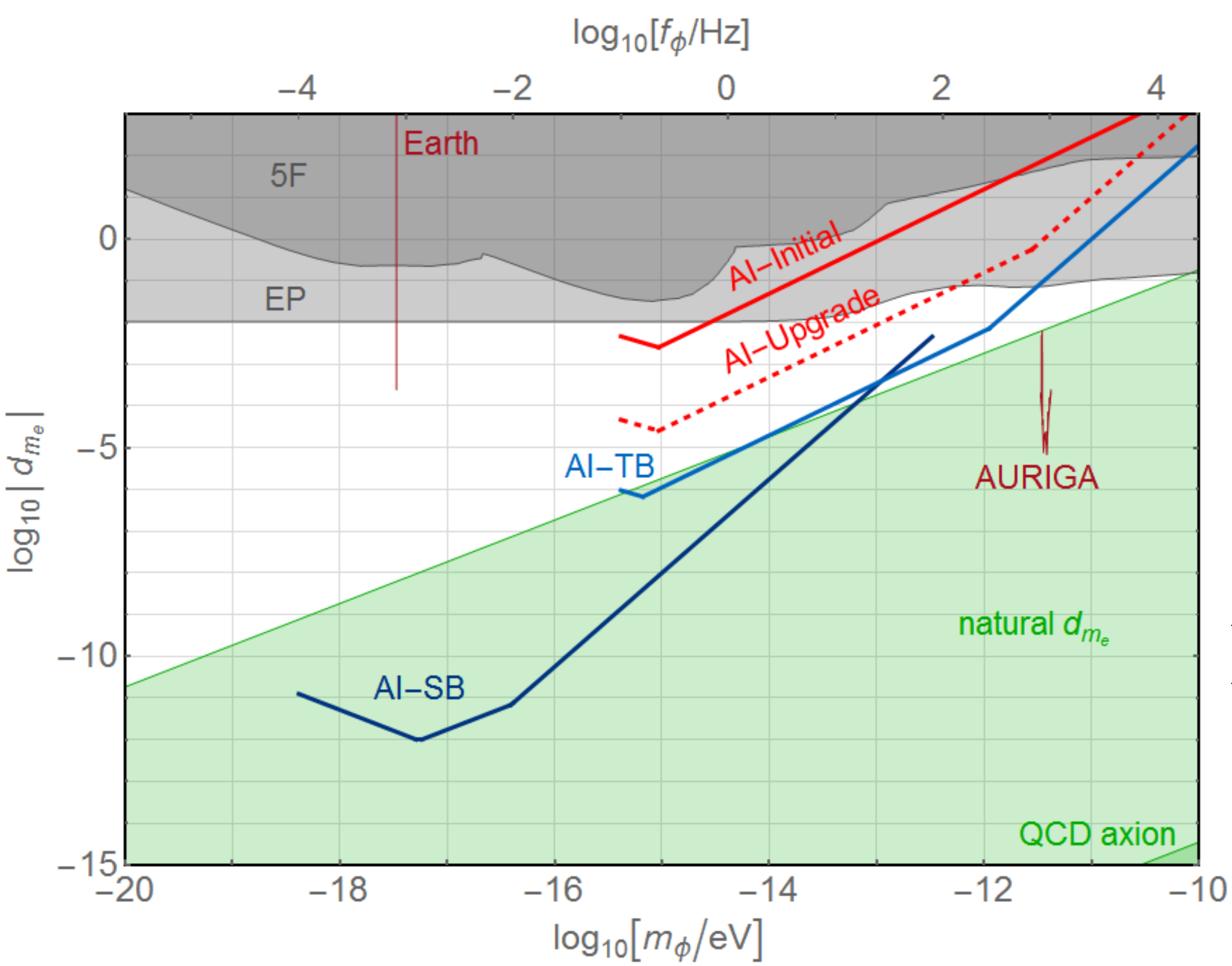


Graham et. al. 1606.04541

Scalar Dark Matter

By comparing 2 spatially separated atom interferometers phase differences can be measured.

$$\Delta\phi \propto \omega_a (2L/c)$$



100-meter detector:

Initial: 100 ħk, 1e6/s flux

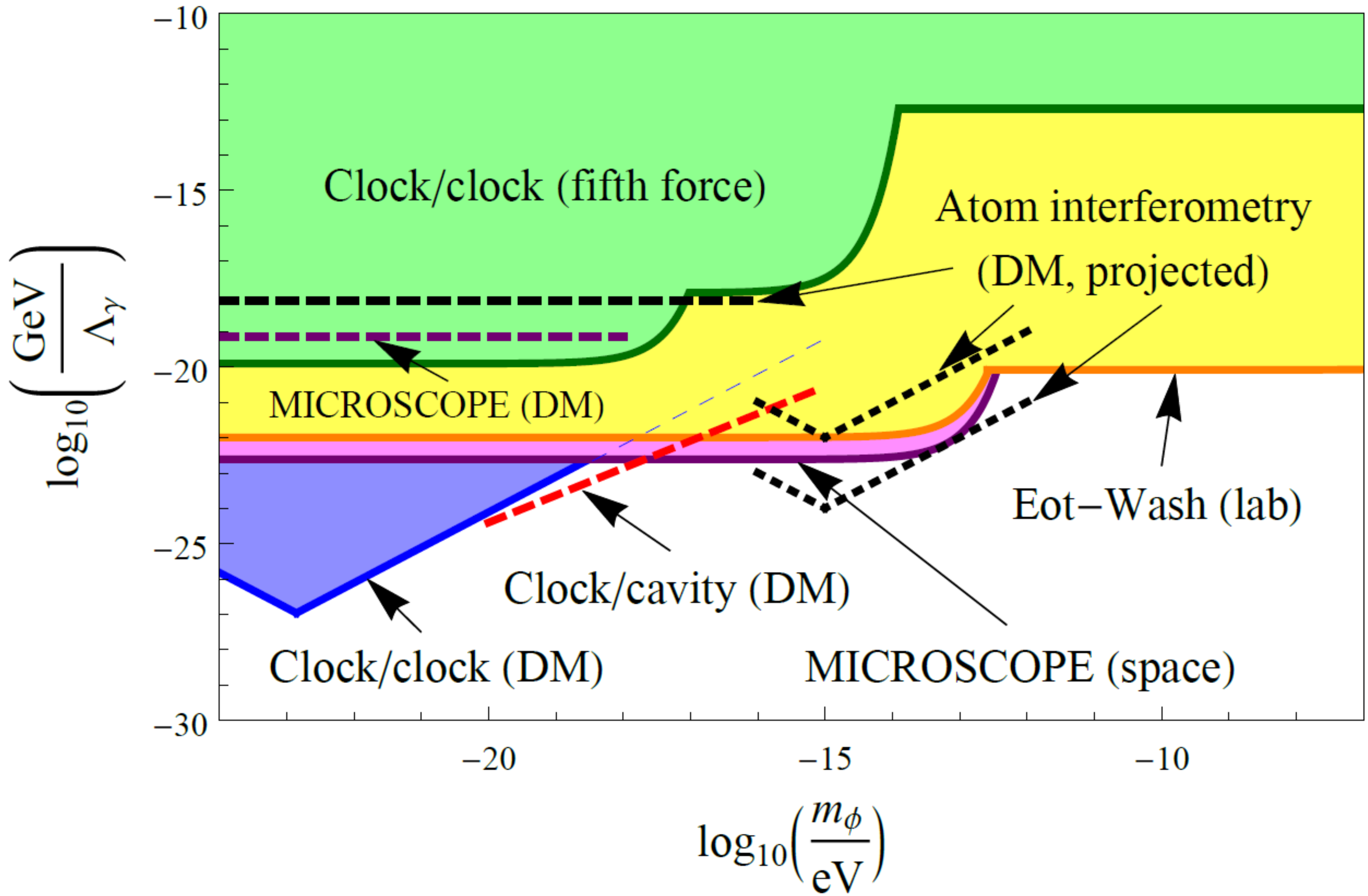
Upgrade: 1000 ħk, 1e8/s flux

AI-TB: km baseline

AI-SB: Space GW detector

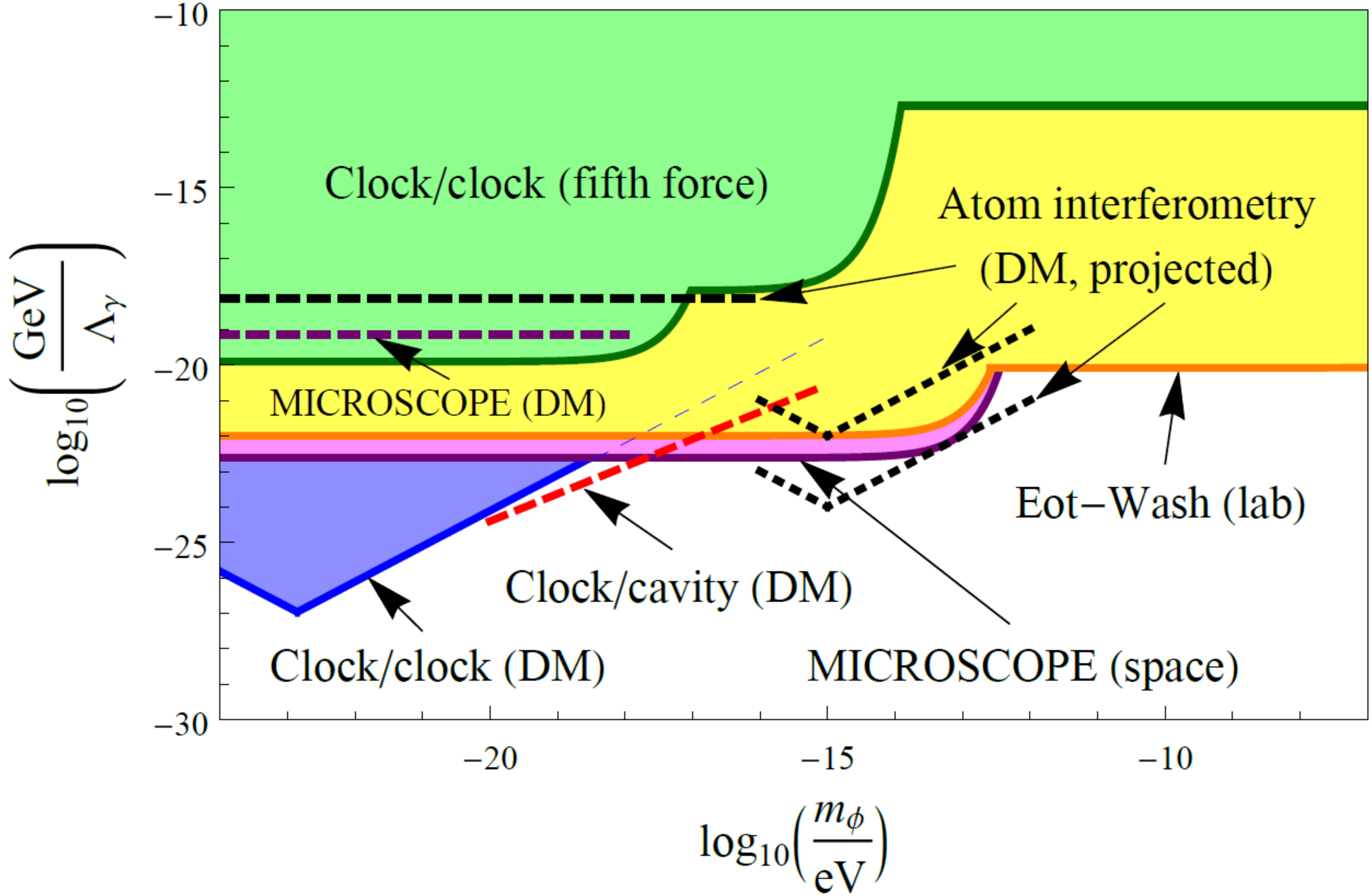
slide from Graham

Scalar Dark Matter



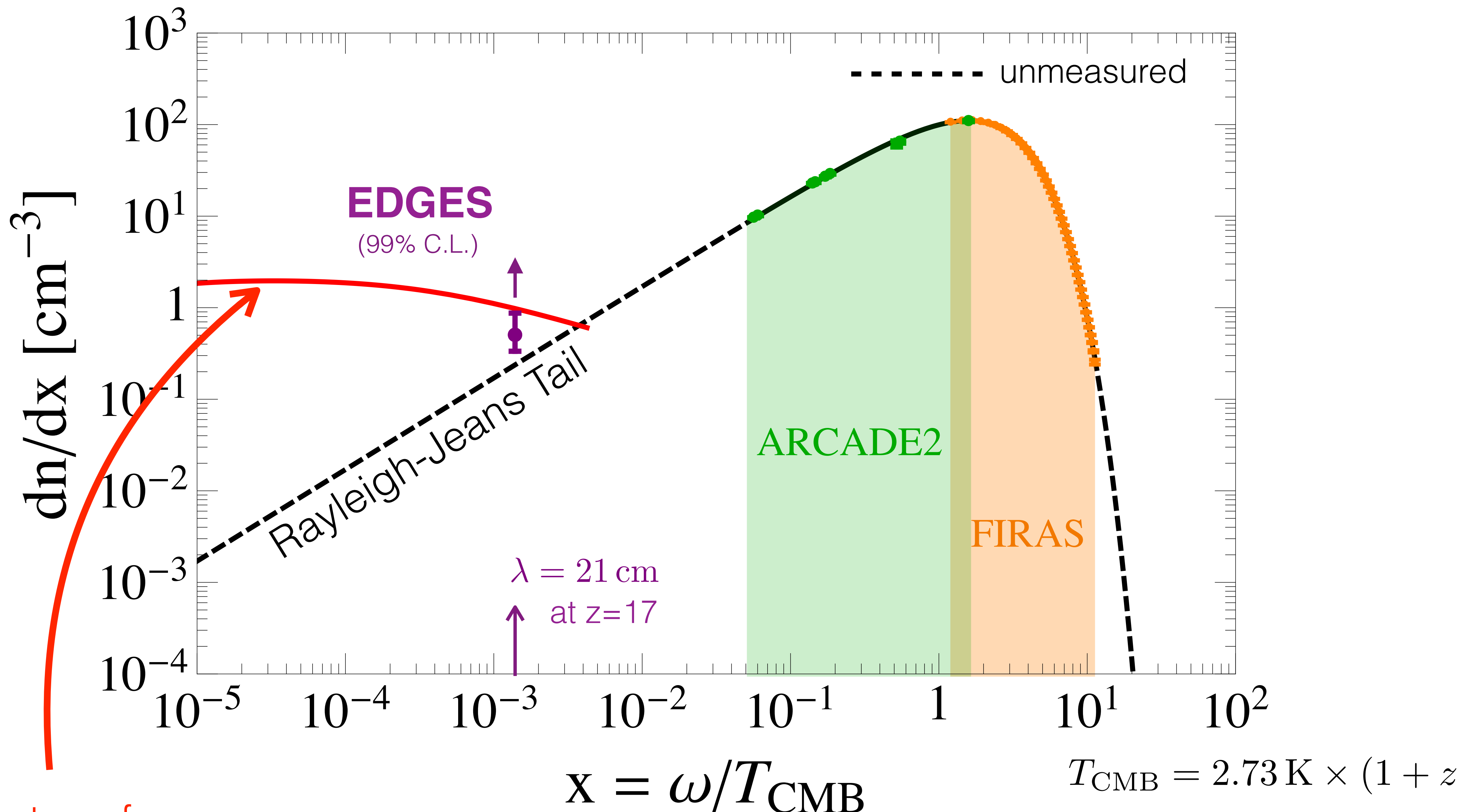
slide from Y. Stadnik

Vector Boson Dark Matter



slide from Y. Stadnik

Cosmic Microwave Background Spectrum



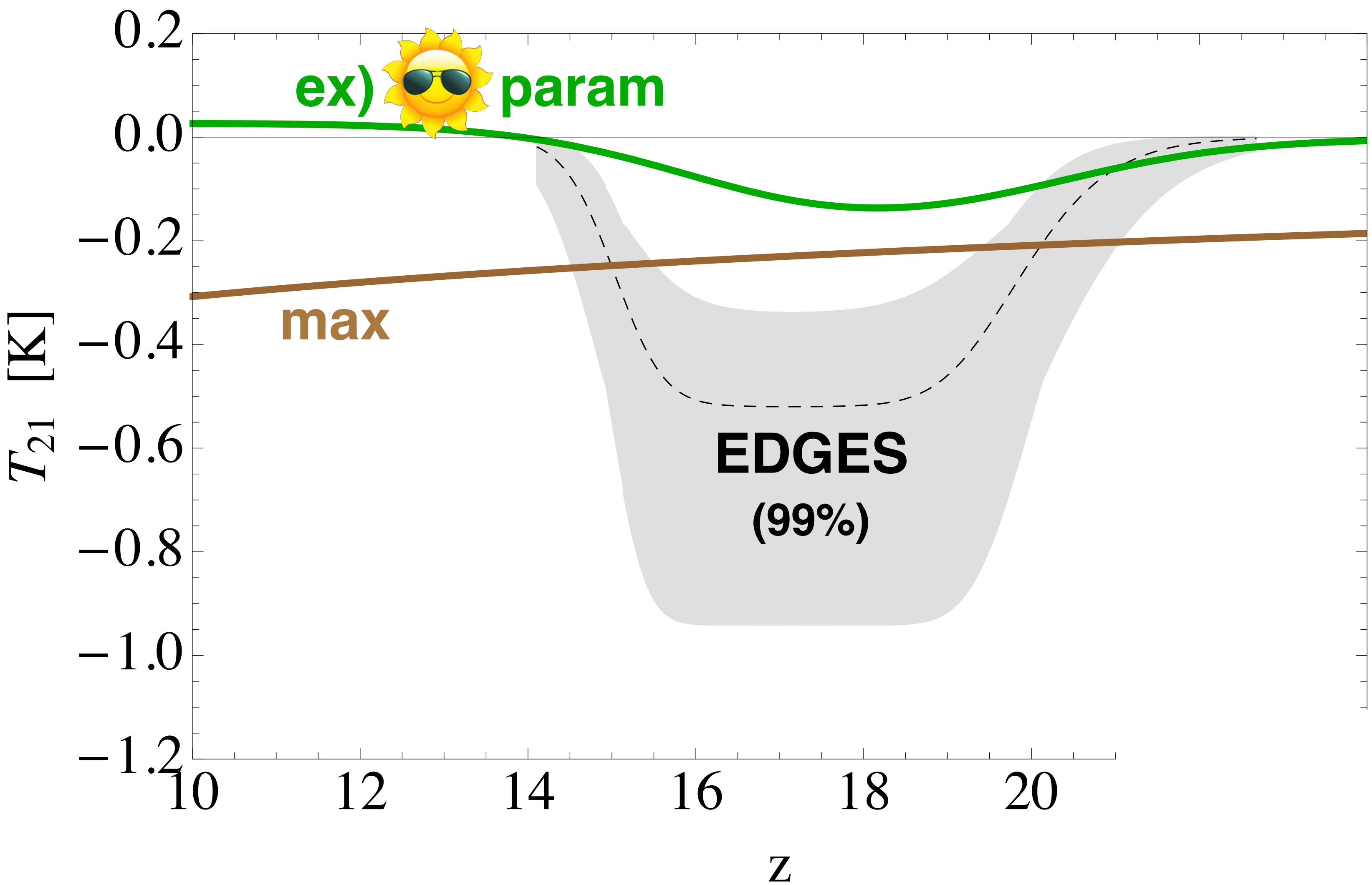
new photons from
dark photon oscillations

$\gamma_d \to \gamma$

Bowman *et. al.* Nature **555**, 67 (2018)

slides by Josh Ruderman

EDGES vs. Theory



astro uncertainties:

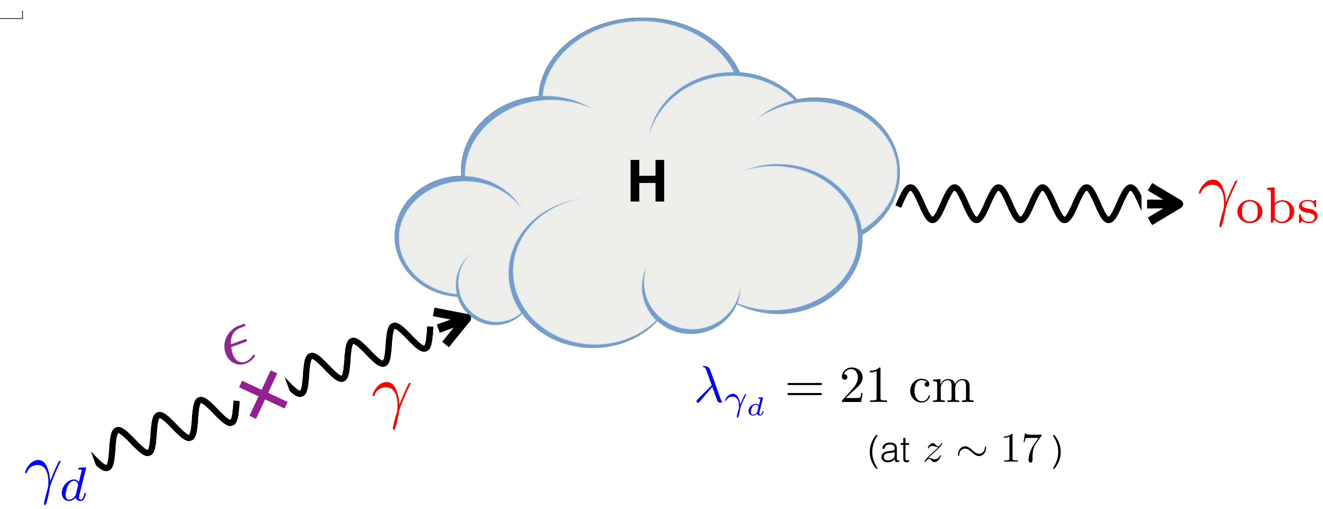
Lyman-α and X-ray fluxes

max absorption:

(marginalized over astro uncertainties)

1) $T_s \approx T_k$

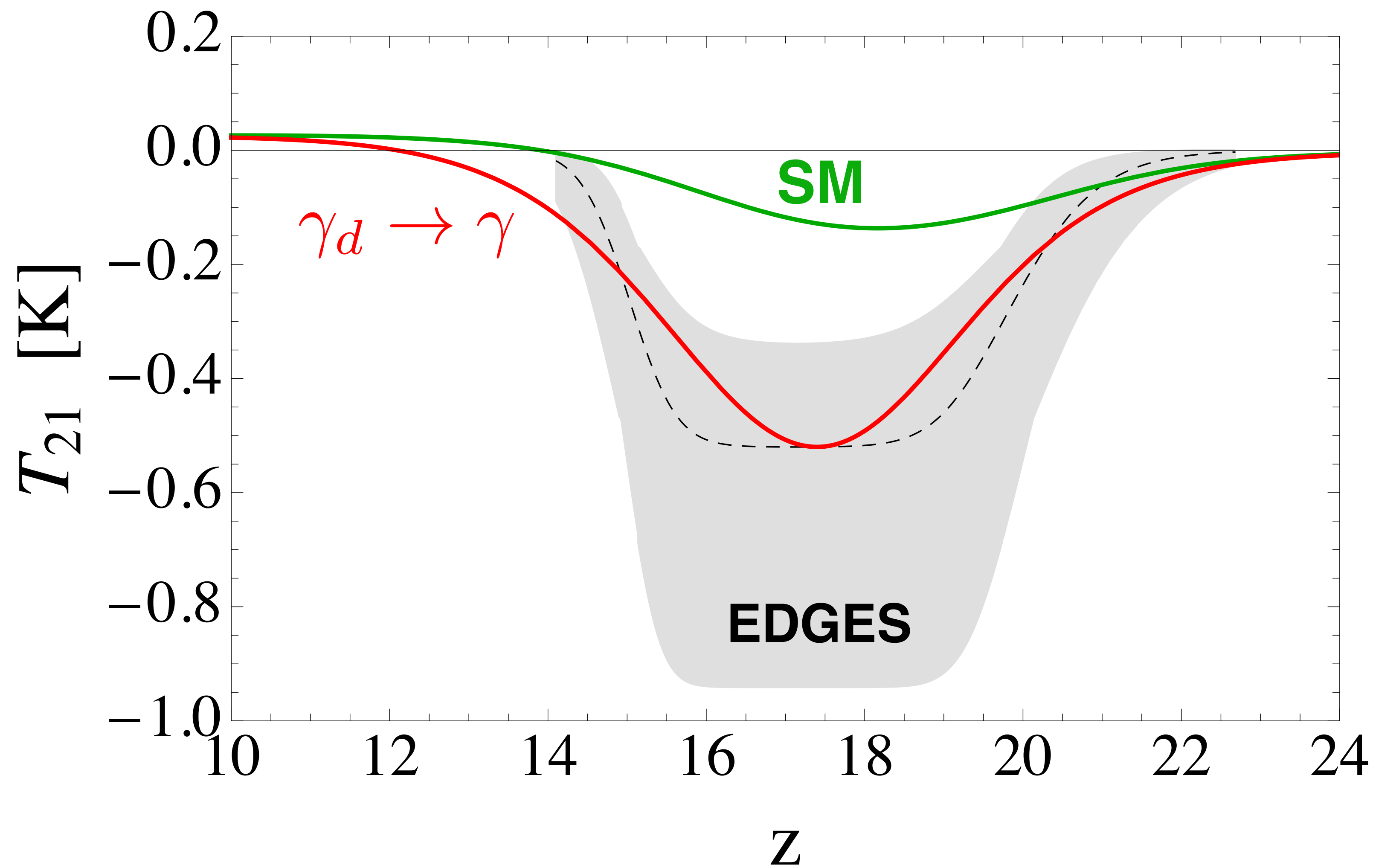
- absorption: **~7σ**
- **extra** absorption: **~4σ**



slides by Josh Ruderman

EDGES vs. Theory

EDGES band



astro uncertainties:

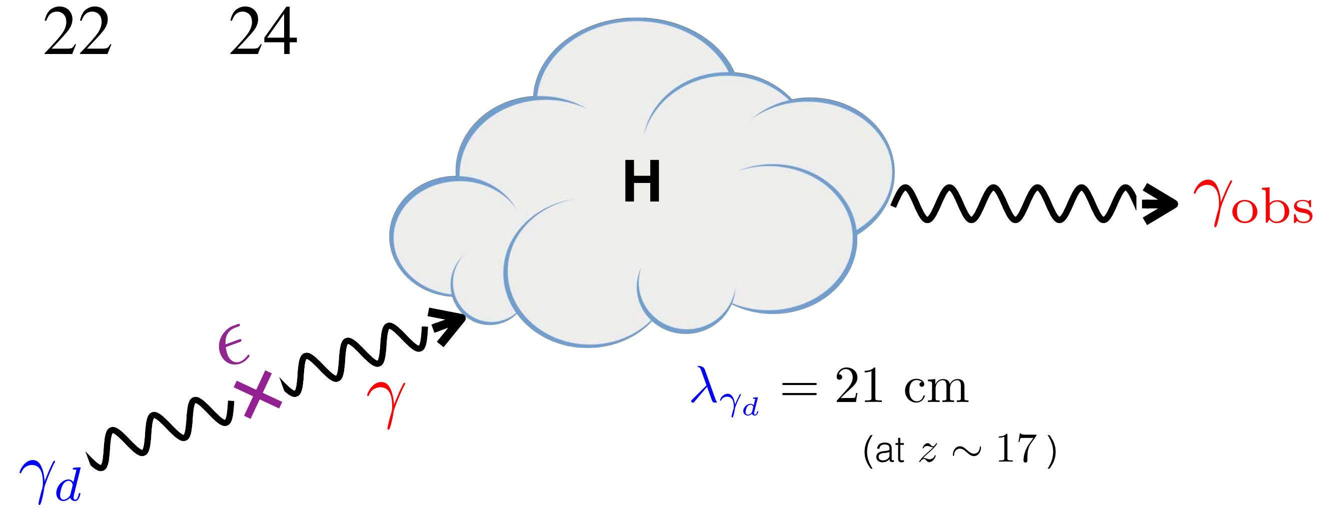
Lyman-α and X-ray fluxes

max absorption:

(marginalized over astro uncertainties)

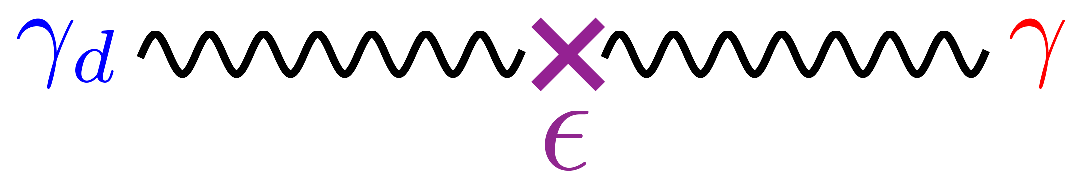
1) $T_s \approx T_k$

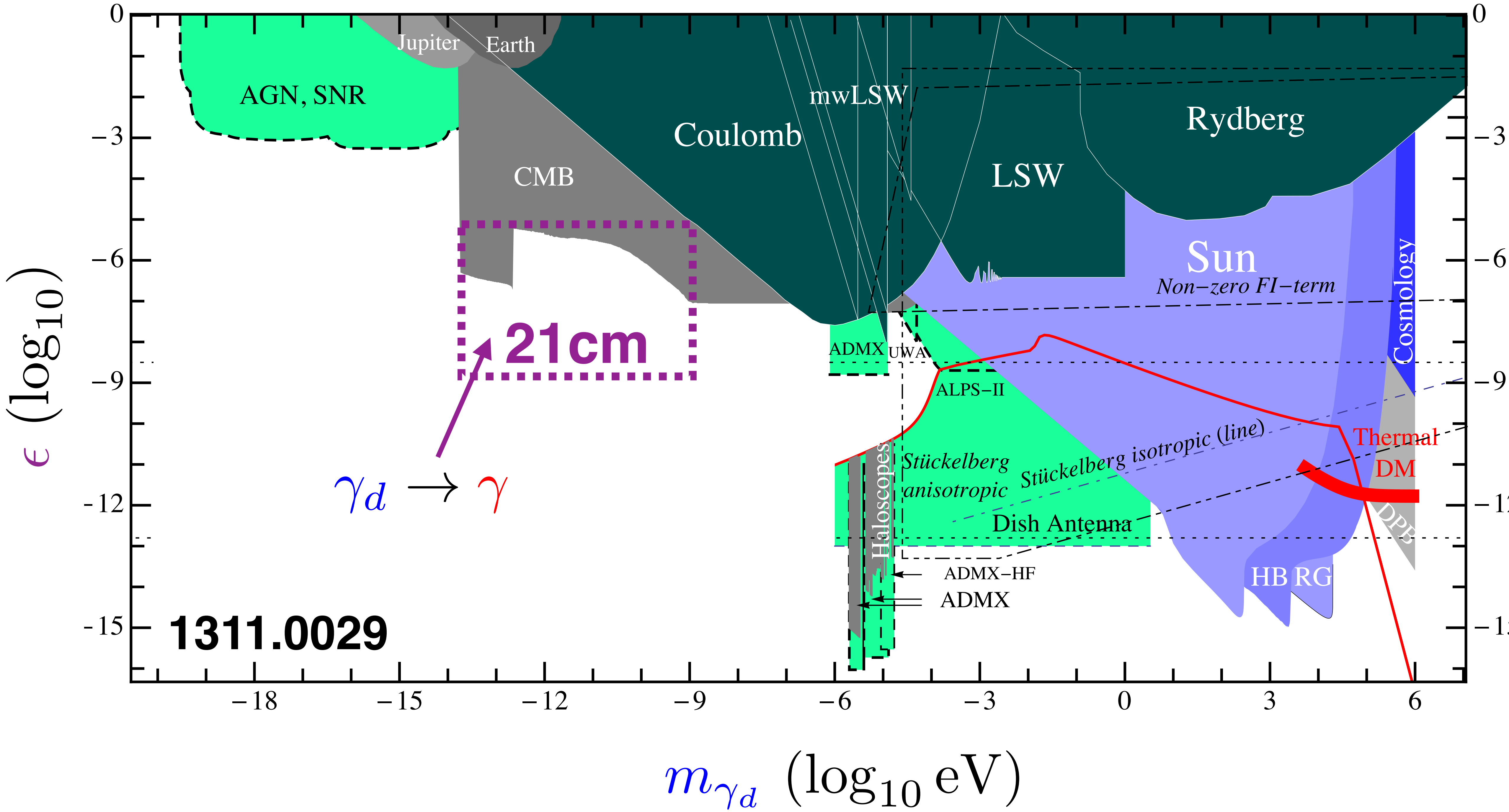
- absorption: **~7σ**
- **extra** absorption: **~4σ**



slides by Josh Ruderman

Dark Photon


γ_d
ϵ
γ


AGN, SNR
Jupiter
Earth
CMB
Coulomb
mwLSW
LSW
Rydberg
Sun
Non−zero FI−term
Cosmology
21cm
ADMX
UWA
ALPS−II
Stückelberg anisotropic
Stückelberg isotropic (line)
Dish Antenna
Haloscopes
ADMX−HF
ADMX
HB
RG
Thermal DM
DPB
1311.0029
$\gamma_d \to \gamma$
ϵ ($\log_{10}$)
m_{γ_d} ($\log_{10}$ eV)

Conclusions

Ultralight bosons represent a well-motivated Dark Matter candidate.

Atom interferometer provide new tools to search for ultralight dark matter.

Different Atom interferometer running in parallel can provide world-leading limits in a mass region hard to probe by clocks.

Backup

Misalignment Mechanism

Action:

$$\frac{1}{\sqrt{|g|}}\mathscr{L} = (\partial^\mu \phi^*)(\partial_\mu \phi) - V(\phi) = (\partial^\mu \phi^*)(\partial_\mu \phi) - m_\phi^2\, \phi^* \phi$$

EL-equations:

$$\begin{aligned}
0 &= \partial_t \left(\frac{\partial \mathscr{L}}{\partial(\partial_t \phi^*)} \right) - \frac{\partial \mathscr{L}}{\partial \phi^*} \\
&= \partial_t \left(\sqrt{|g|}\, \partial_t \phi \right) + \sqrt{|g|}\, m_\phi^2 \phi \\
&= (\partial_t \sqrt{|g|})\,(\partial_t \phi) + \sqrt{|g|}\, \partial_t^2 \phi + \sqrt{|g|}\, m_\phi^2 \phi \\
&= \sqrt{|g|} \left[\frac{(\partial_t \sqrt{|g|})}{\sqrt{|g|}} (\partial_t \phi) + \partial_t^2 \phi + m_\phi^2 \phi \right] . \\
&= \frac{(\partial_t a^3)}{a^3} (\partial_t \phi) + \partial_t^2 \phi + m_\phi^2 \phi = \frac{3\dot{a}}{a}\, \dot{\phi} + \ddot{\phi} + m_\phi^2 \phi
\end{aligned}$$

appr. flat $|g| = a(t)^6$

yields:

$$\boxed{\ddot{\phi}(t) + 3H\dot{\phi}(t) + m_\phi^2 \phi(t) = 0}$$