Sub-GeV Dark Matter

Kenji Kadota
IBS Center for Theoretical Physics of the Universe (CTPU)
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Mass: Light mass

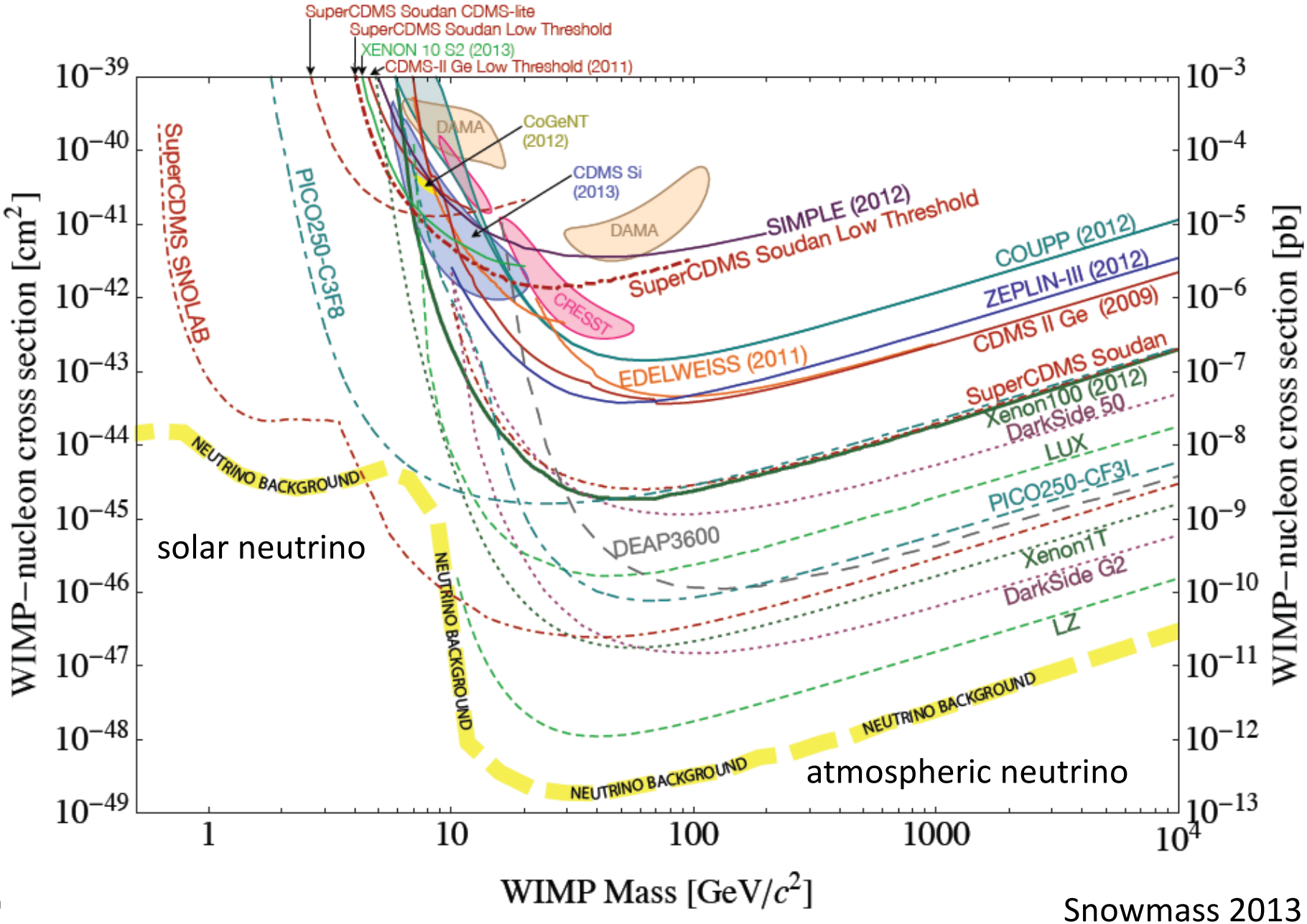
- Concrete example for light DM:
  - ✓ Sterile neutrino DM
  - ✓ Axion-like Particle
  - ✓ Axion

Interactions: beyond ΛCDM
DM-baryon interactions with a light mediator

- Concrete example for light mediator:
  - ✓ Dark photon

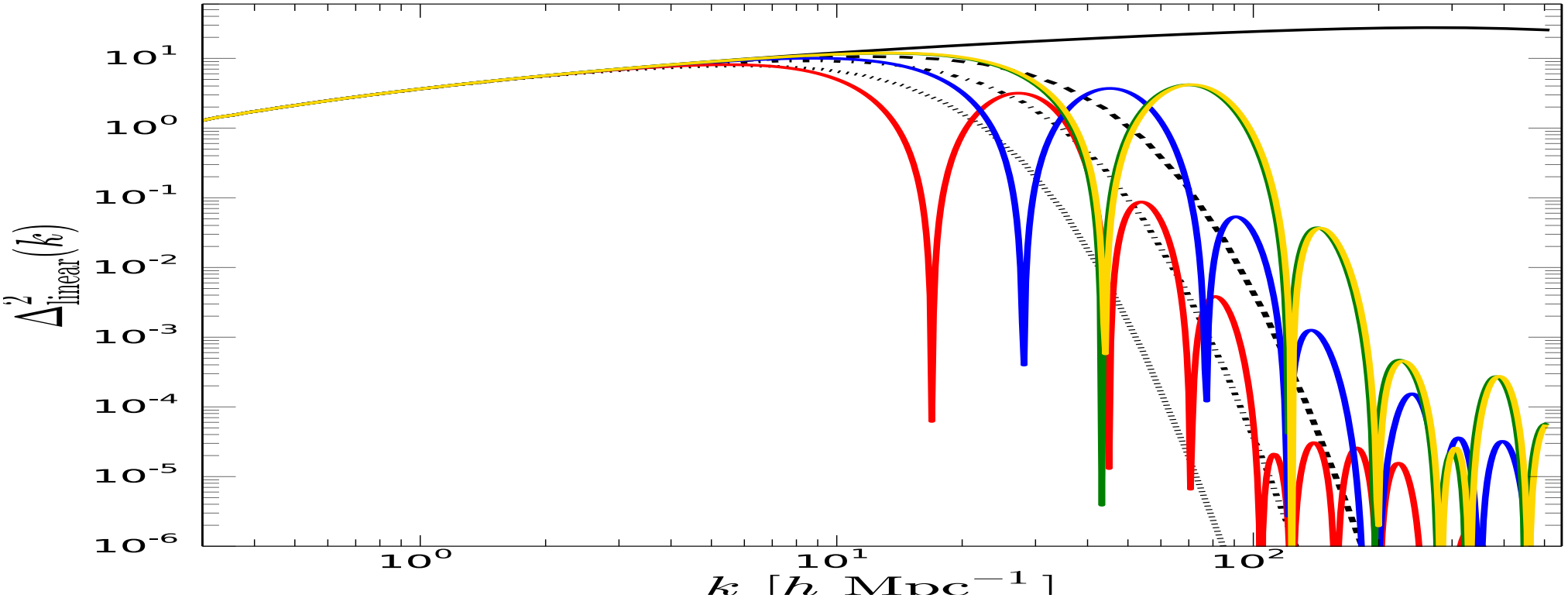
Motivation for sub-GeV

Direct detection experiments



Snowmass 2013

Cosmological motivation for sub-GeV: Small scale suppressions



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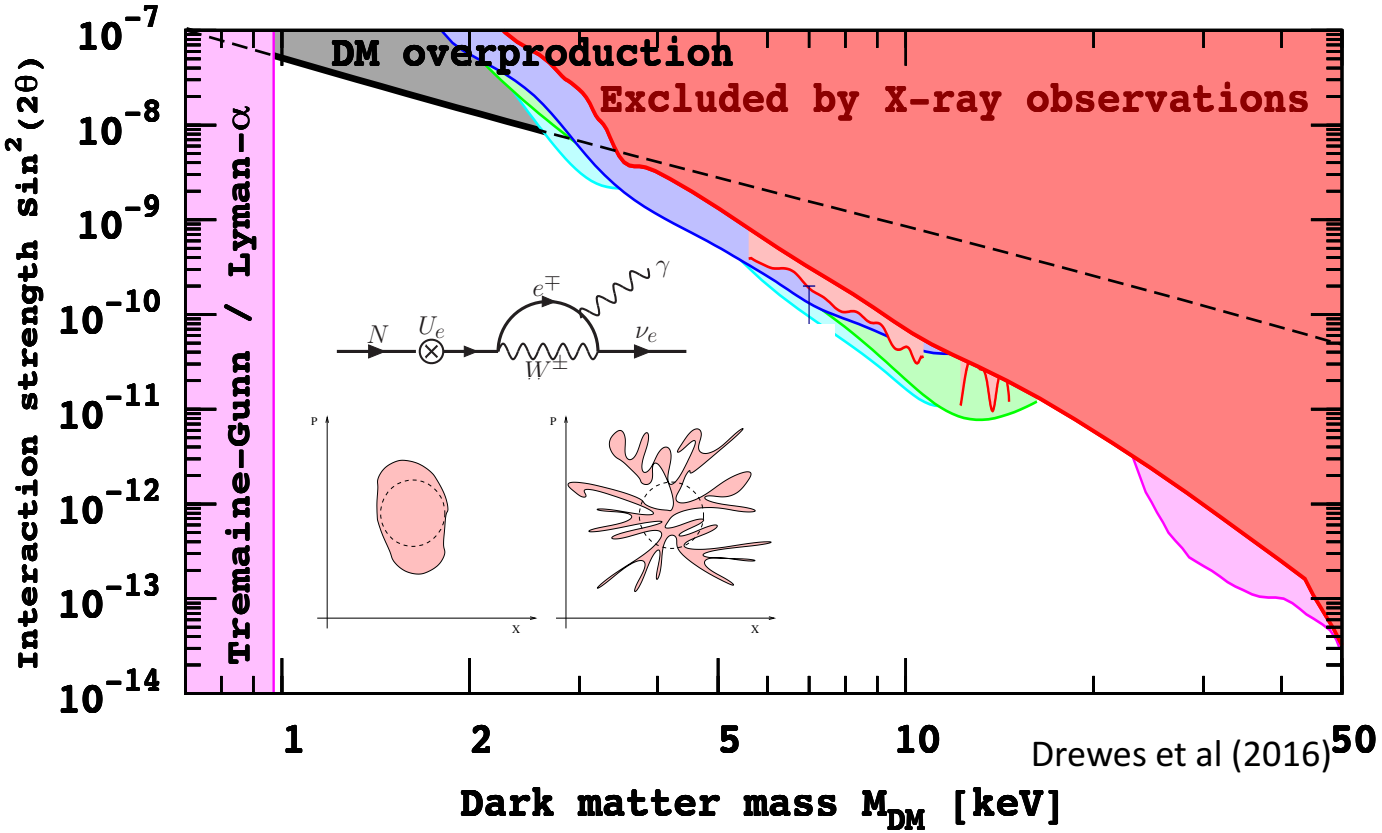
A concrete example for the warm dark matter: Sterile Neutrinos

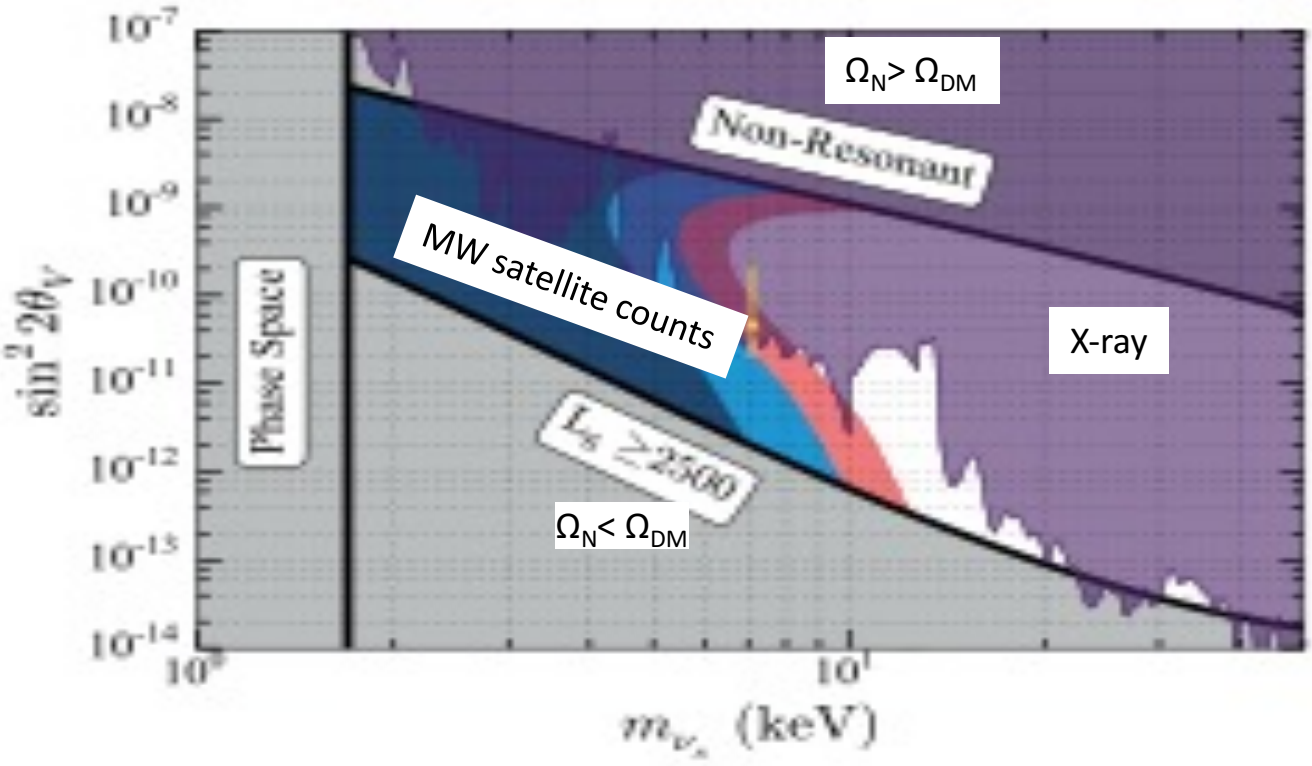
Dodelson-Widrow mechanism: Thermal active neutrinos conversion to sterile neutrinos

$$L = -yNLH - \frac{1}{2}MNN \qquad \theta = \frac{y\langle H \rangle}{M}$$



Drewes et al (2016)

Production from (active-sterile) neutrino oscillation



Cherry,Horiuch(2017)

DM constraints heavily depend on the production mechanism!

1) Active-Sterile neutrino oscillation (e.g. Dodelson-Widrow)

2) Active-Sterile neutrino oscillation with the resonance (e.g. Shi-Fuller)

3) Decay of a heavier particle, Thermal freeze-out, variable mixing angle, ...
(e.g. Kusenko, Petraki, Asaka, Shaposhnikov, Merle, Schneider ,Berlin, Hooper,..)

4) Sterile-sterile oscillation! (KK and Kaneta (2017))

Also the left-handed neutrino masses via the seesaw mechanism!

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_N,$$

$$\mathcal{L}_N = \overline{\nu}_R i\partial\!\!\!/ \nu_R - \left[\nu_R^{c\,T} y_\nu L H - \frac{1}{2} \nu_R^{c\,T} \mathcal{M}_N \nu_R^c + h.c. \right]$$

$$\Omega_{N1} h^2 \propto \sin^2 2\theta_N M_1 (y_\nu y_\nu^+)_{22}$$

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Model: ALP (Axion-like particles) i.e. Ultra-light scalars

- Ultra-light mass :

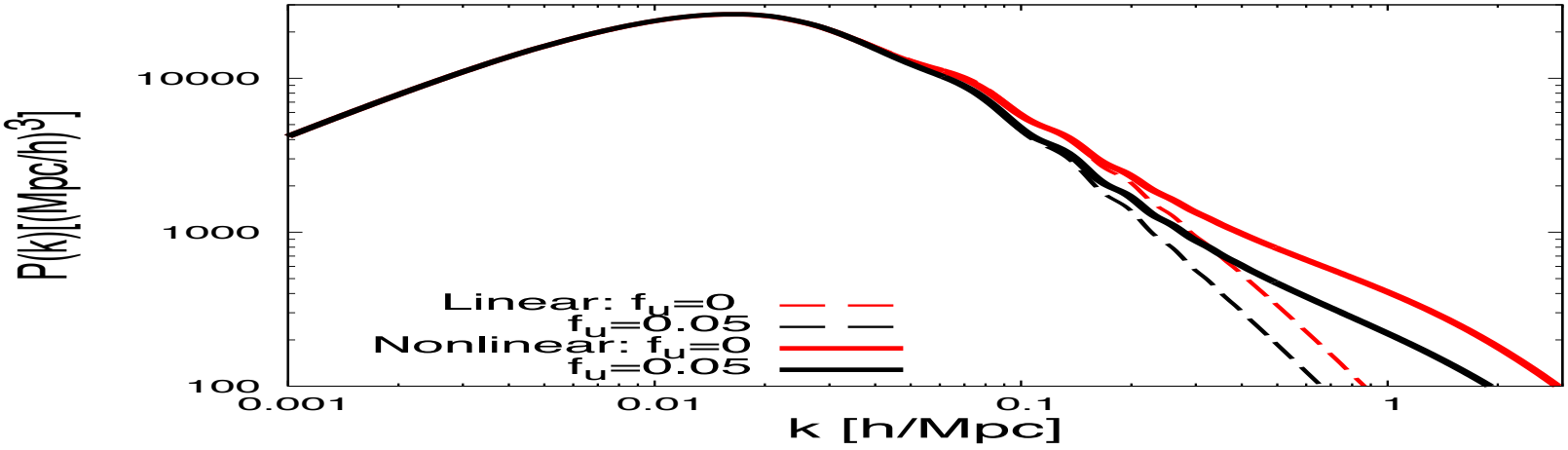
$m_u \sim H_0 \sim 10^{-33} eV$ DE (Barbieri et al (2005),…)

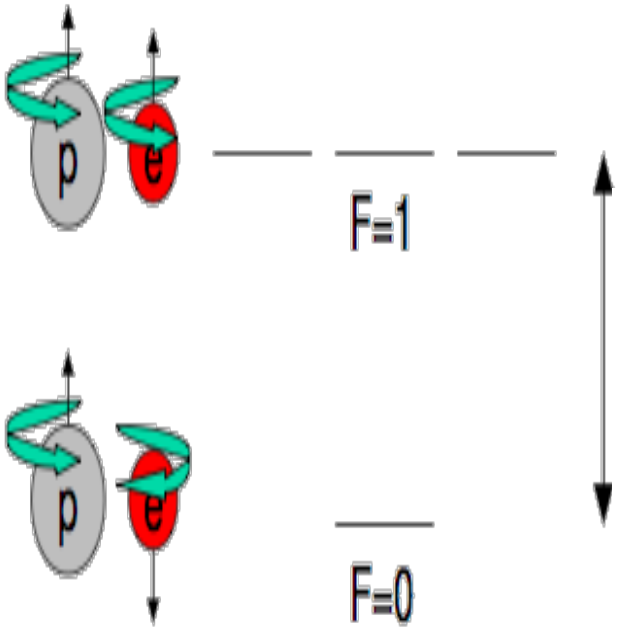
$m_u \sim 10^{-22} eV$ Fuzzy DM (Hu (2000),…)

$m_u \sim 10^{-22} eV - 10^{-10} eV$ String axiverse (Arvanitaki et al (2009),…)

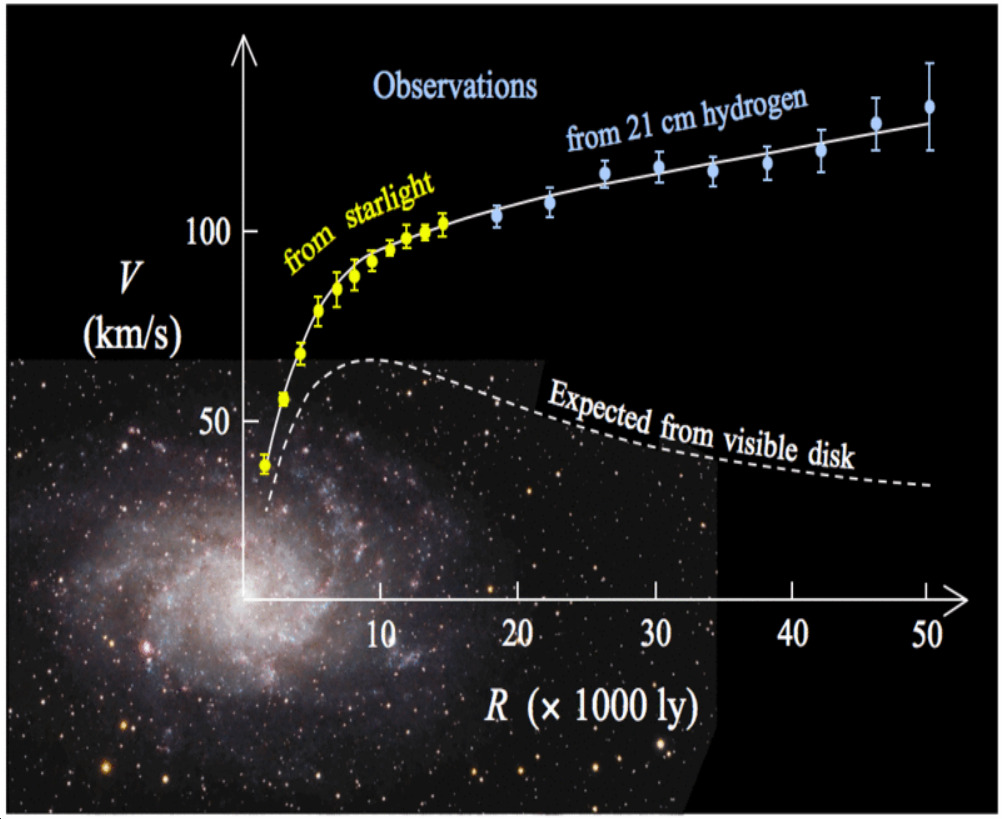
$$m_u \, , f_u = \Omega_u / \Omega_m \sim O(0.01)$$
$$m_u \leq H(t) : \rho_u = const$$
$$m_u > H(t) : \rho_u \propto 1/a^3$$

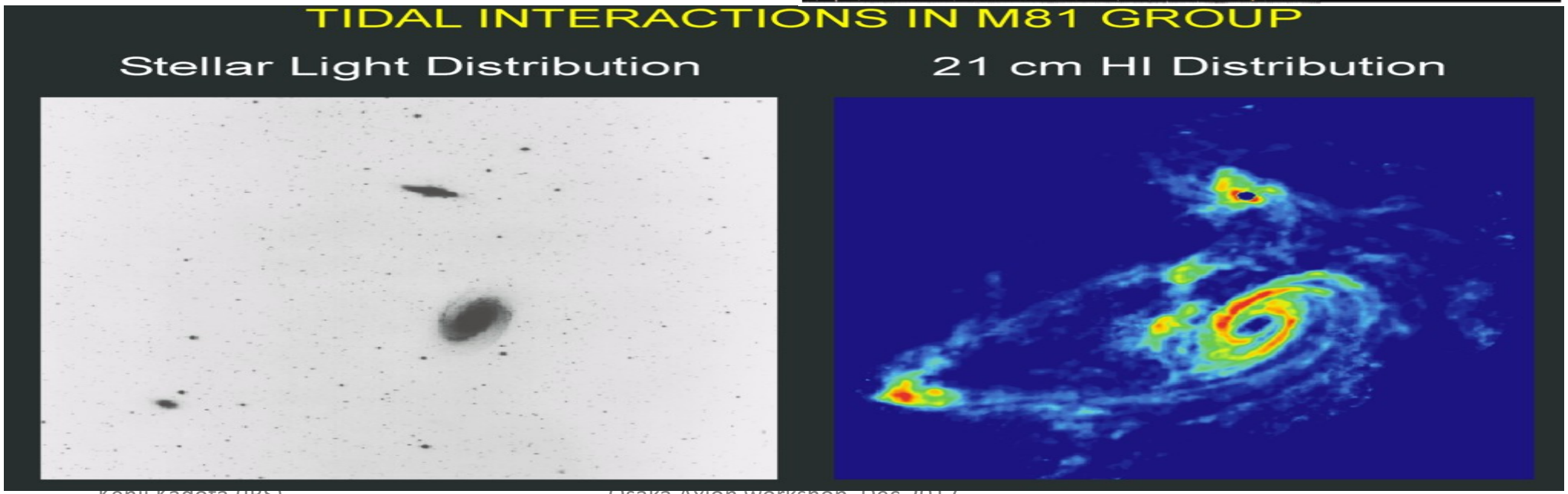
KK, Mao, Ichiki, Silk (2014)





21 cm signals
1420 MHz





Brief History of Universe

Years since the Big Bang

~300000 (z~1000)

← Big Bang: the Universe is filled with ionized gas

← Recombination: The gas cools and becomes neutral

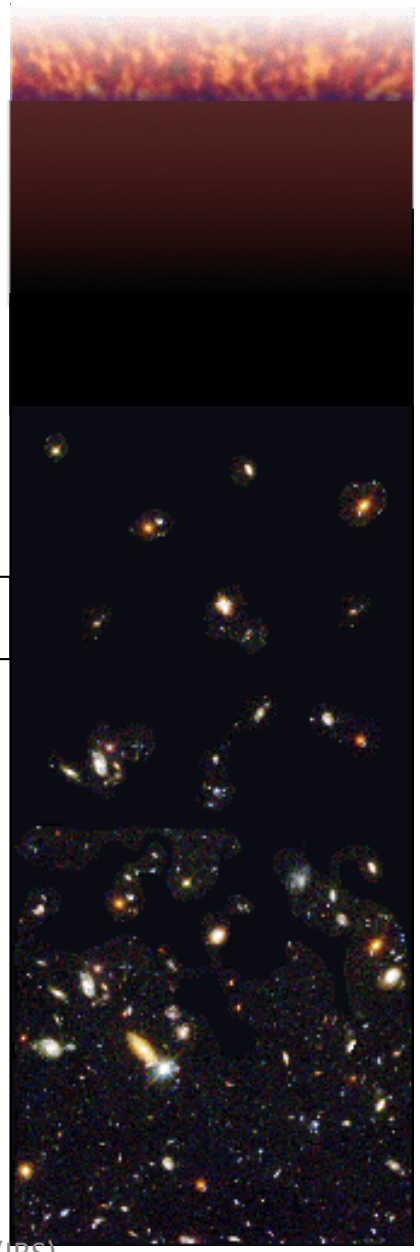
Dark Ages

~100 million (z~20-40)

← The first structures begin to form.

Reionization starts (z ~12)

Reionization



~1 billion (z~6)

← Reionization is complete

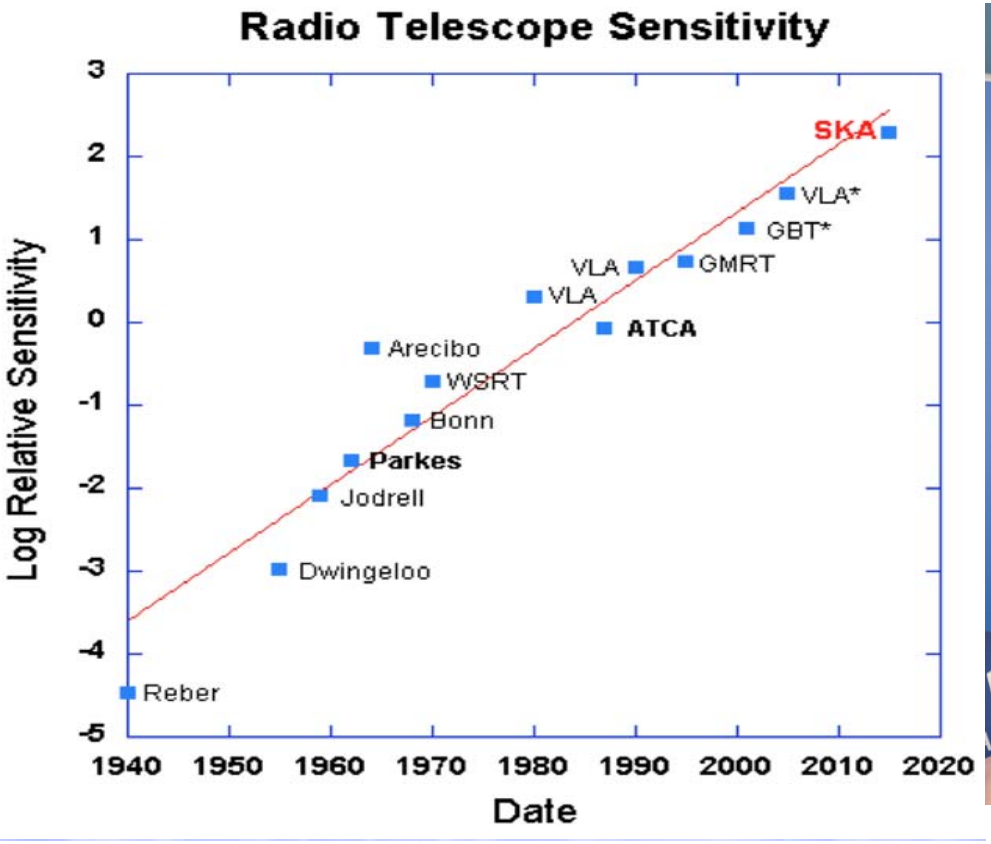
~13 billion (z=0)

← Today's structures

Square Kilometer Array

South Africa- Karoo
Australia- Western Outback

Construction 2019-2025, Early Science 2022-, Full Science 2025-2030
Cost: ~650 M Euros, Operation ~ 50 M Euros per year.

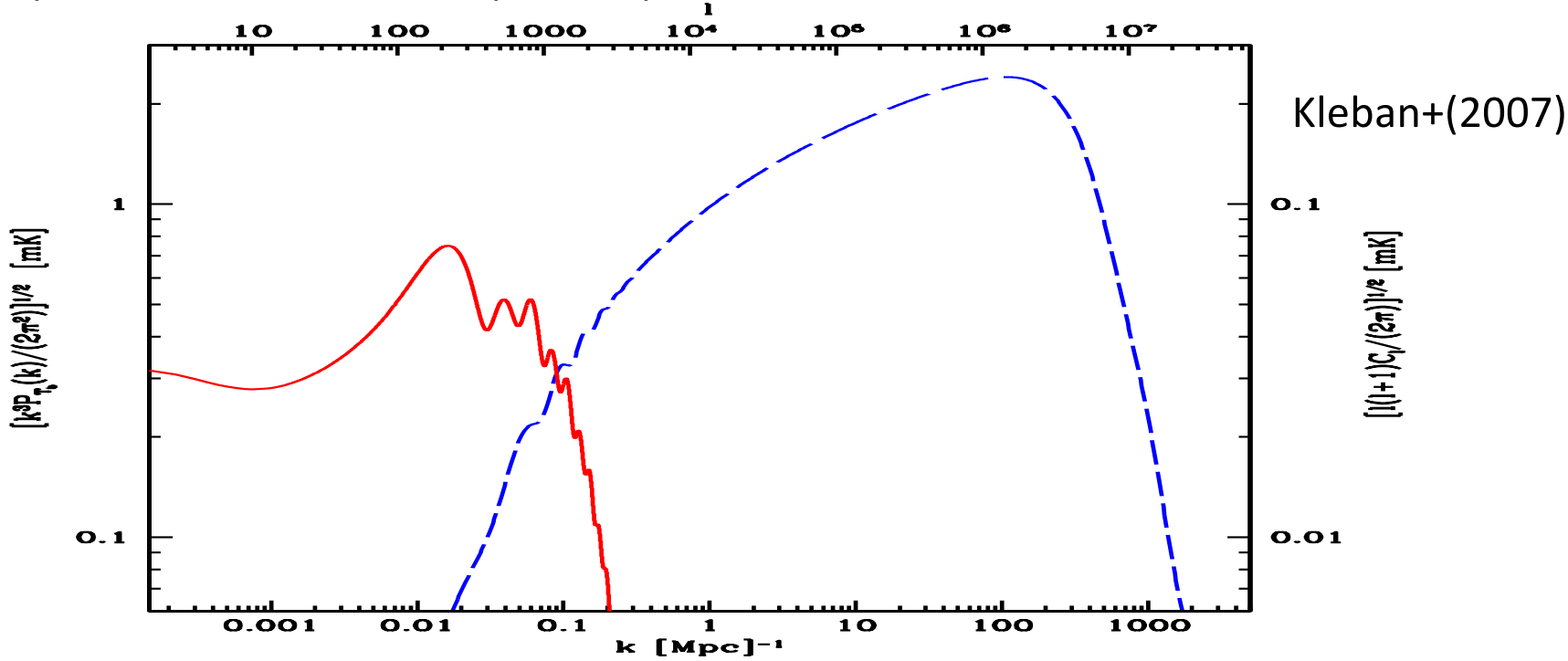


CERN-SKA Big data co-operation agreement

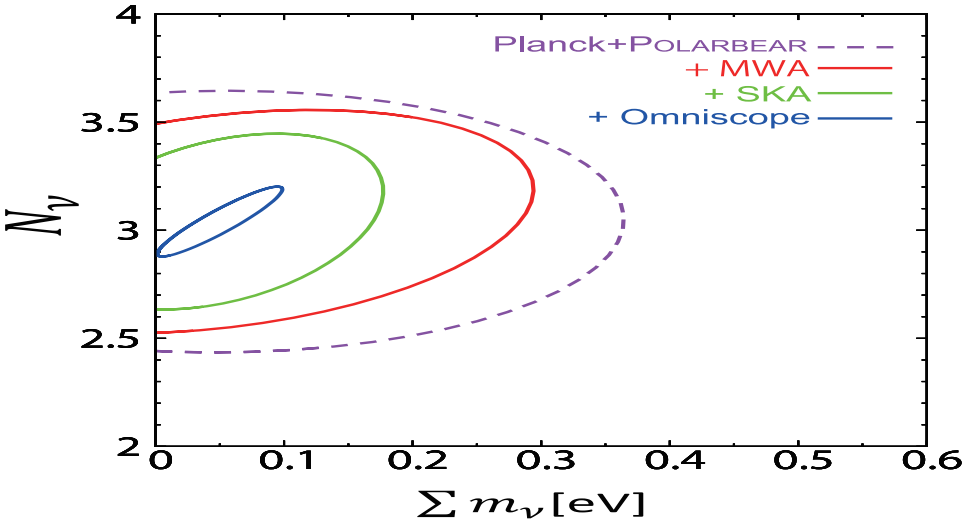
What can we do with 21cm?

High precision on small-scale power spectrum

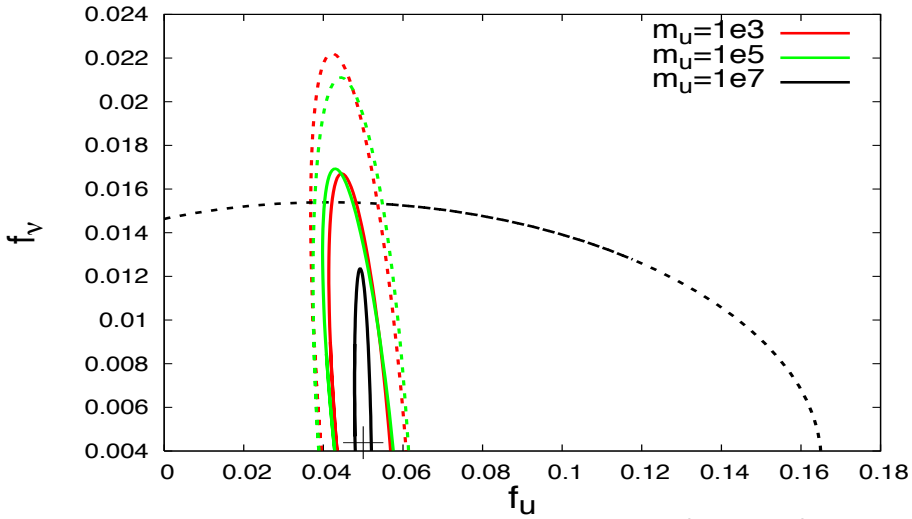
$$\Delta P / P \sim 1 / \sqrt{N}$$



Kleban+(2007)

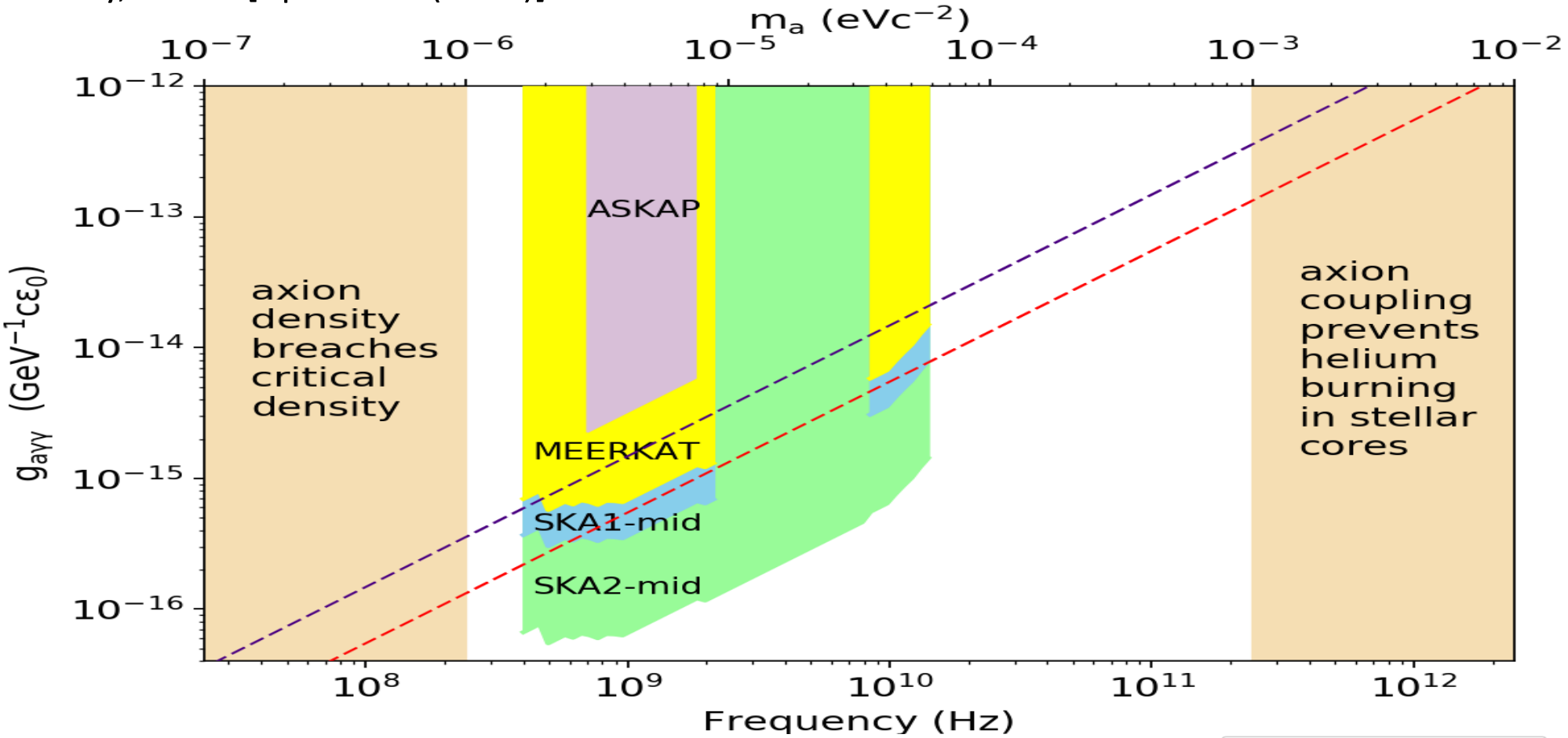


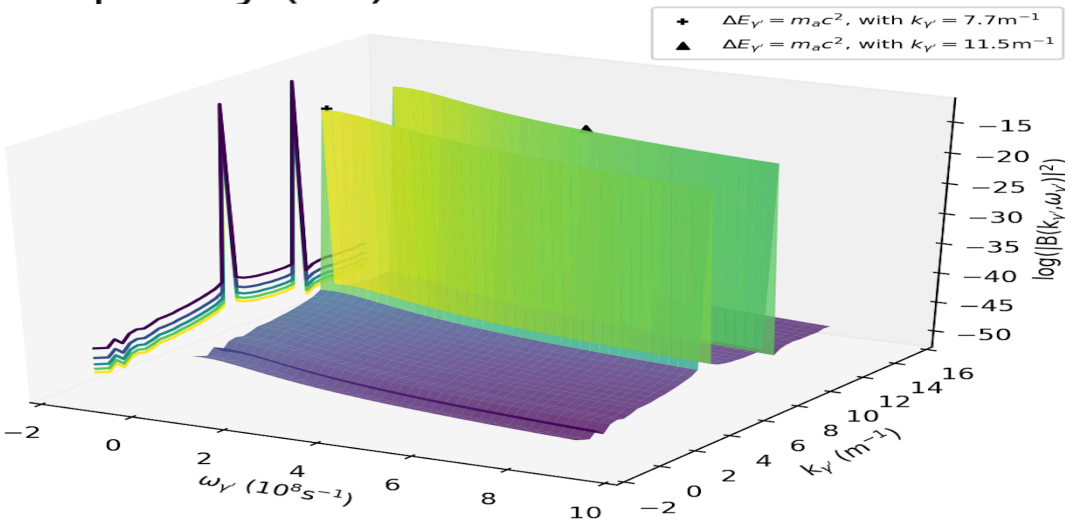
Oyama+(2013)



KK, Mao, Ichiki, Silk (2014)

Kelley, Quinn [ApJ Letter (2017)]





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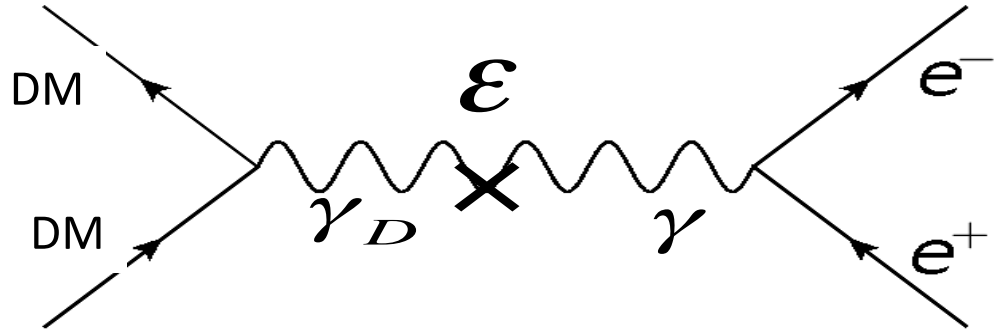
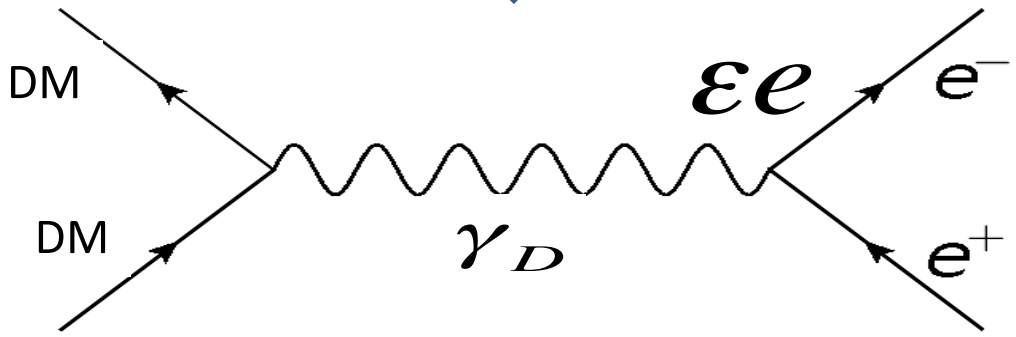
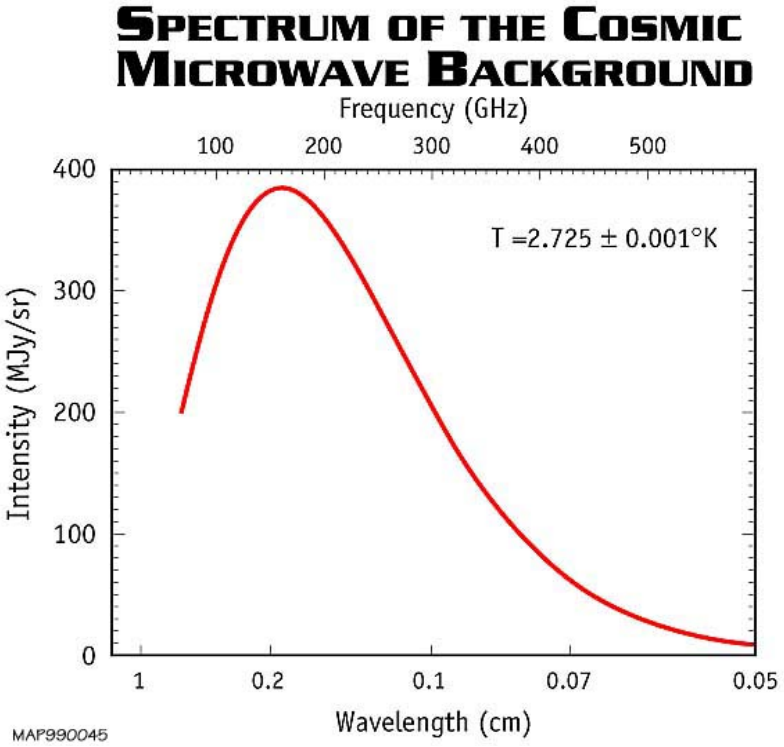
$$-\frac{\varepsilon}{2} Z_{\mu\nu} F^{\mu\nu}$$

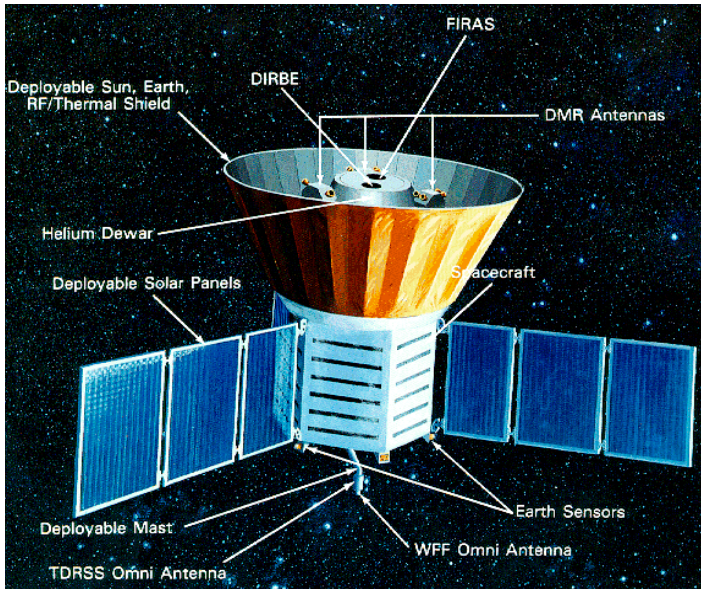


Field re-definition to the mass eigenstates (ie physical states)



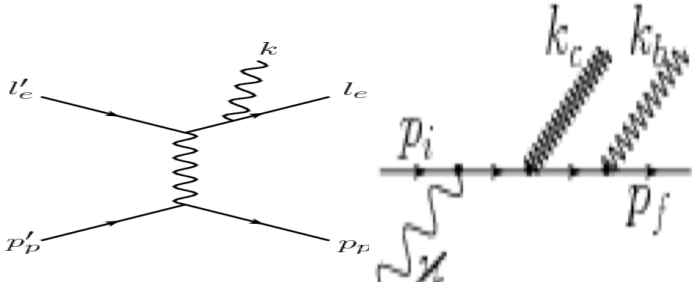
(B. Holdom (1986))





CMB spectral distortion: FIRAS: $|\mu| < 9 \times 10^{-5}$

Thermal equilibrium:



Chemical equilibrium: Creation and destruction of photons

Radiative (double) Compton scattering: $e+\gamma \leftrightarrow e+\gamma+\gamma$

Bremsstrahlung: $e+N \leftrightarrow e+N+\gamma$

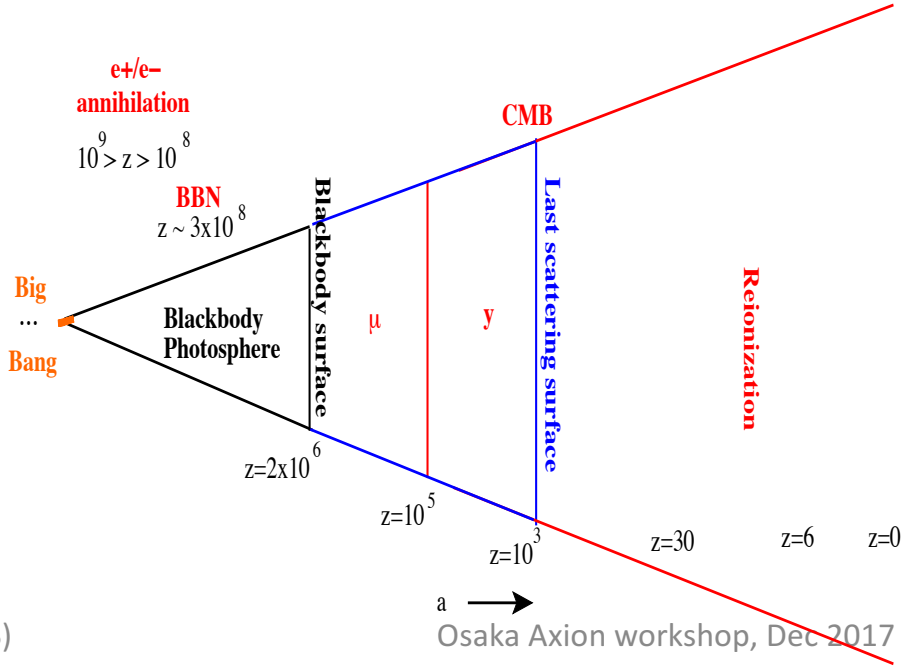
Kinetic equilibrium: Energy distribution changes by scattering

Compton scattering: $e+\gamma \leftrightarrow e+\gamma$

μ-type distortion: The number stays same but modifies the phase space distribution

Thomson scattering: $e+\gamma \leftrightarrow e+\gamma$

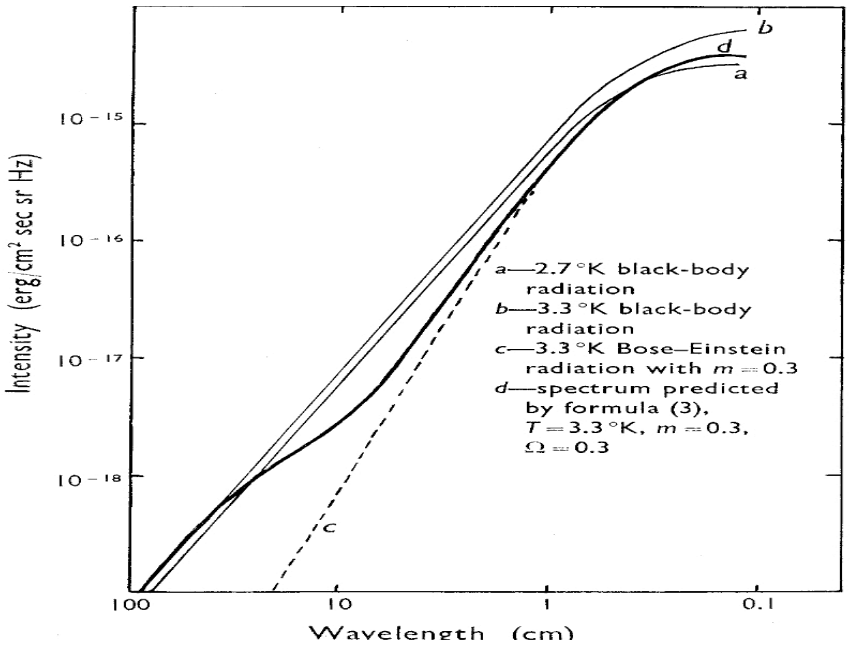
y-type distortions: Kinematically decouple too, so it just adds energy shift



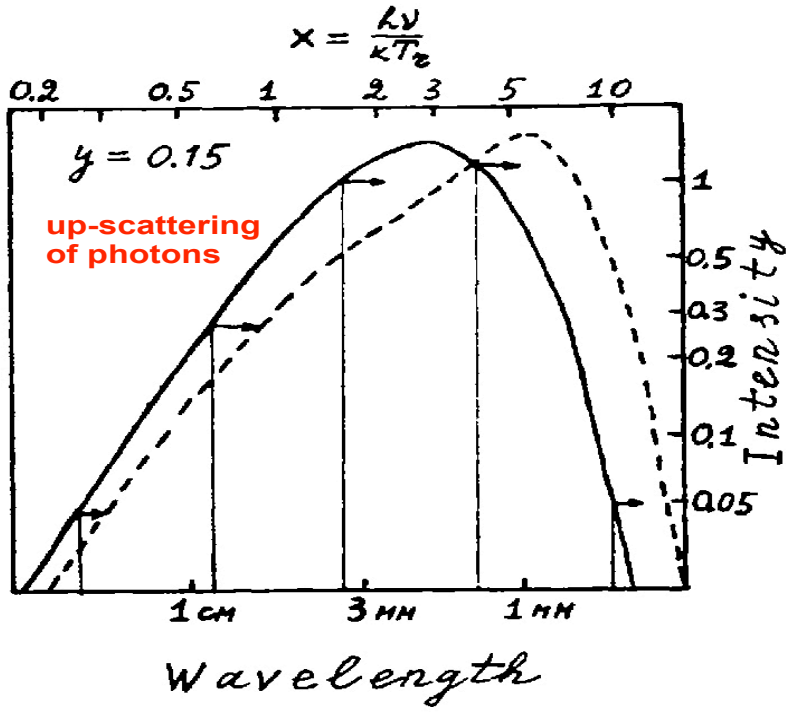
$$f = [e^{(E-\mu)/T} - 1]^{-1}$$

$$y \sim \sigma_T n_e k T_e$$

Khatri&Sunyaev'12



Zeldovich, Sunyaev (1969)



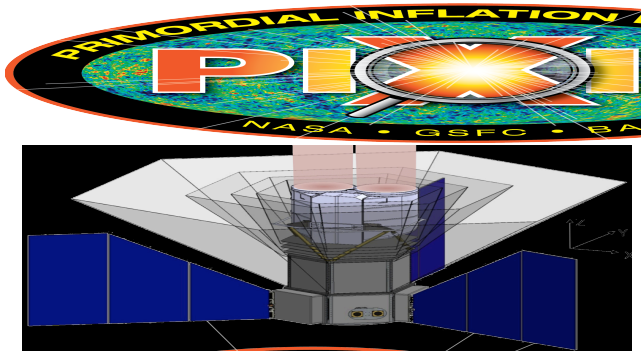
Zeldovich, Sunyaev (1970)

Current Limits: $|\mu| < 9 \times 10^{-5}(95\%CL), y < 1.2 \times 10^{-5}(95\%CL)$

PIXIE: $|\mu| \sim 10^{-8}$

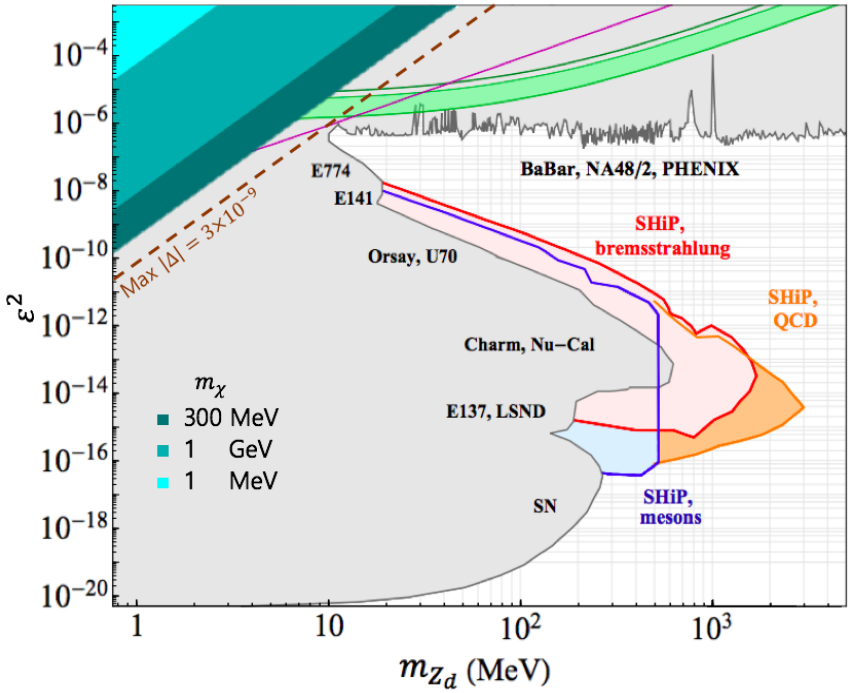
Process	μ
electron-positron annihilation	10^{-178}
BBN tritium decay	2×10^{-15}
BBN ^{7}Be decay	10^{-16}
WIMP dark matter annihilation	$3 \times 10^{-9} f_\gamma \frac{10\text{GeV}}{m_{\text{WIMP}}}$
Silk damping	$10^{-8} - 10^{-9}$
Adiabatic cooling of matter and Bose-Einstein condensation	-2.7×10^{-9}

Process	y
WIMP dark matter annihilation	$6 \times 10^{-10} f_\gamma \frac{10\text{GeV}}{m_{\text{WIMP}}}$
Silk damping	$10^{-8} - 10^{-9}$
Adiabatic cooling of matter and Bose-Einstein condensation	-6×10^{-10}
Reionization	10^{-7}
Mixing of blackbodies: CMB $\ell \geq 2$ multipoles	8×10^{-10}



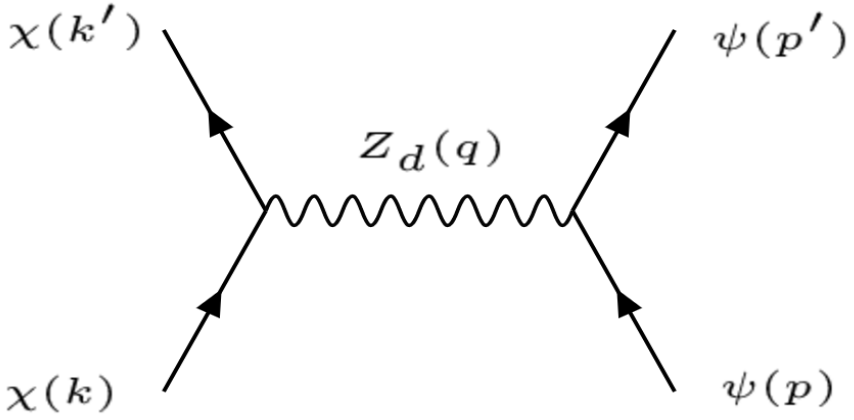
PIXIE: $|\mu| \sim 10^{-8}$

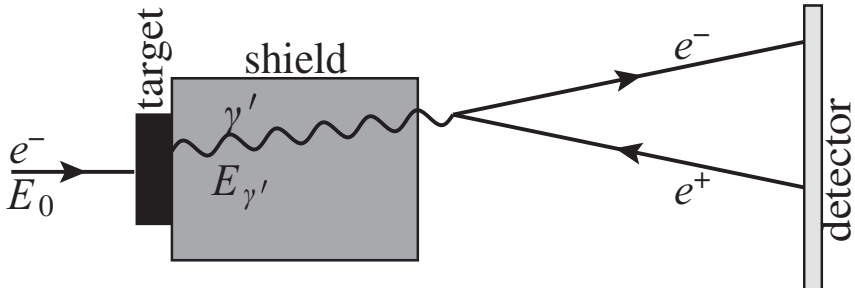
Choi, KK and Park (2017)



Dark Photon Model

$$-\frac{\varepsilon}{2} Z_{\mu\nu} F^{\mu\nu}$$





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Conclusion:
Let us be open minded.
Complimentarity between particle physics and cosmology.

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