Cosmological Exploration for Light Dark Matter

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Based on the work with

- Kunio Kaneta (IBS), in preparation
- Paolo Gondolo (Utah) (JCAP 1606 (2016) 012)

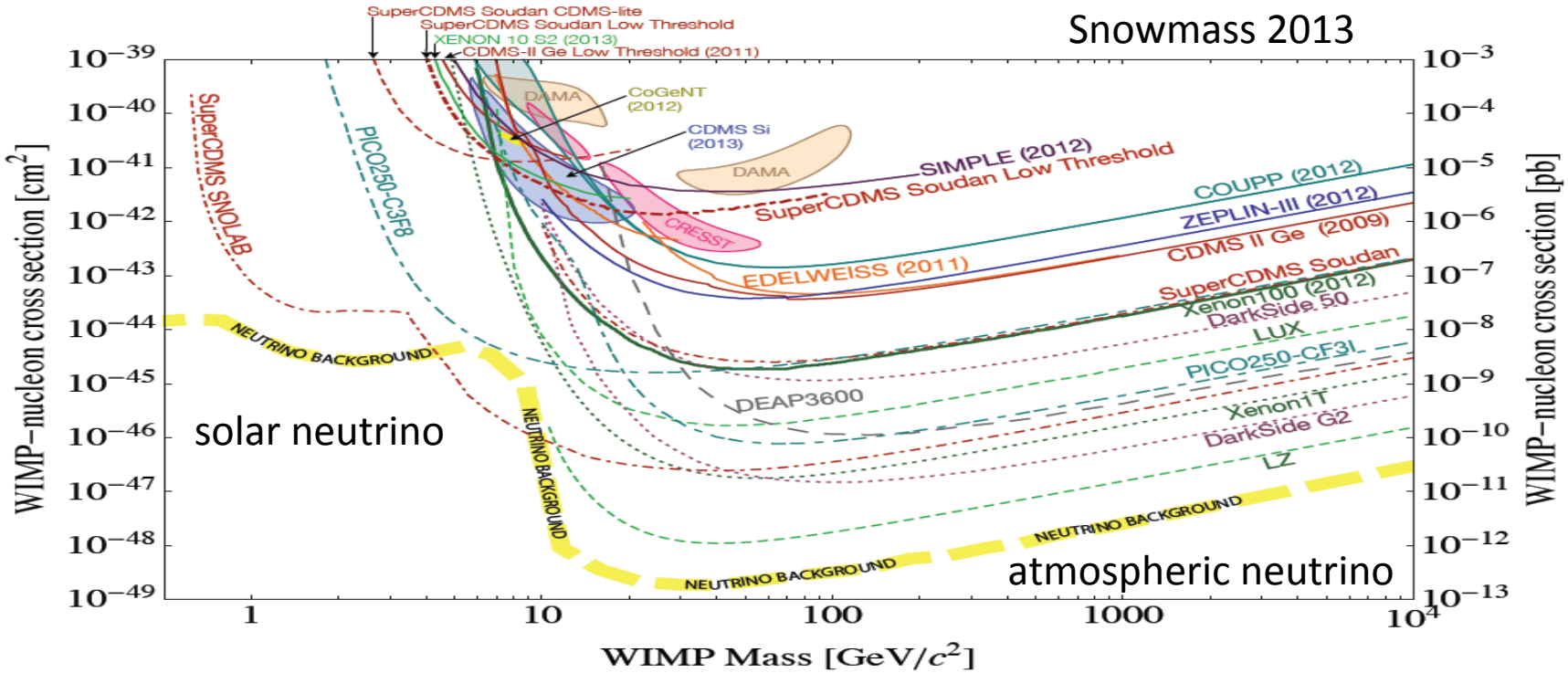
Cosmological Exploration for Light Dark Matter

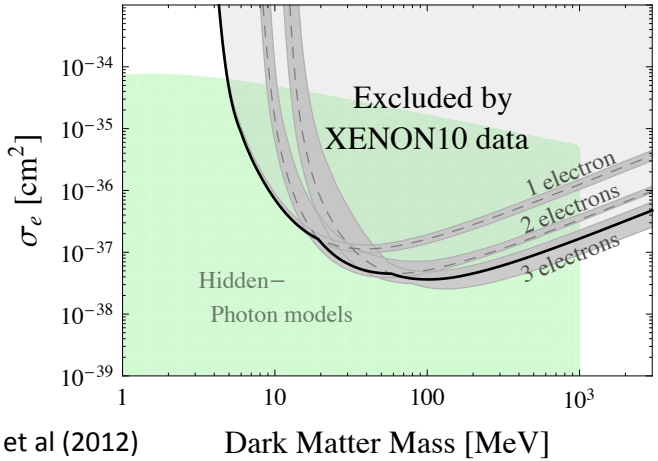
Outline

- Motivation:
  - ✓ Light mass
  - ✓ Free streaming
- Concrete examples for light dark matter
  - ❖ Sterile neutrino
  - ✓ Free streaming
  - ✓ Production mechanism
- More on Free Streaming
  - ✓ Minimum Protohalo Mass
  - ✓ Connection to particle physics: Collider and DM Direct Search
  - ❖ Dipole dark matter
- Conclusion

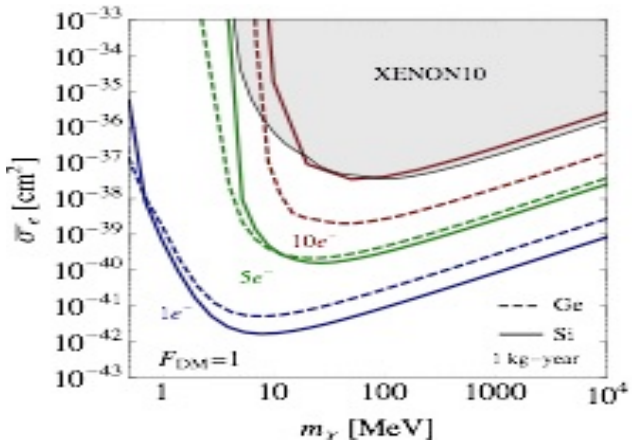
Motivation for sub-GeV

Direct detection experiments





Essig et al (2012)



Essig et al (2015)

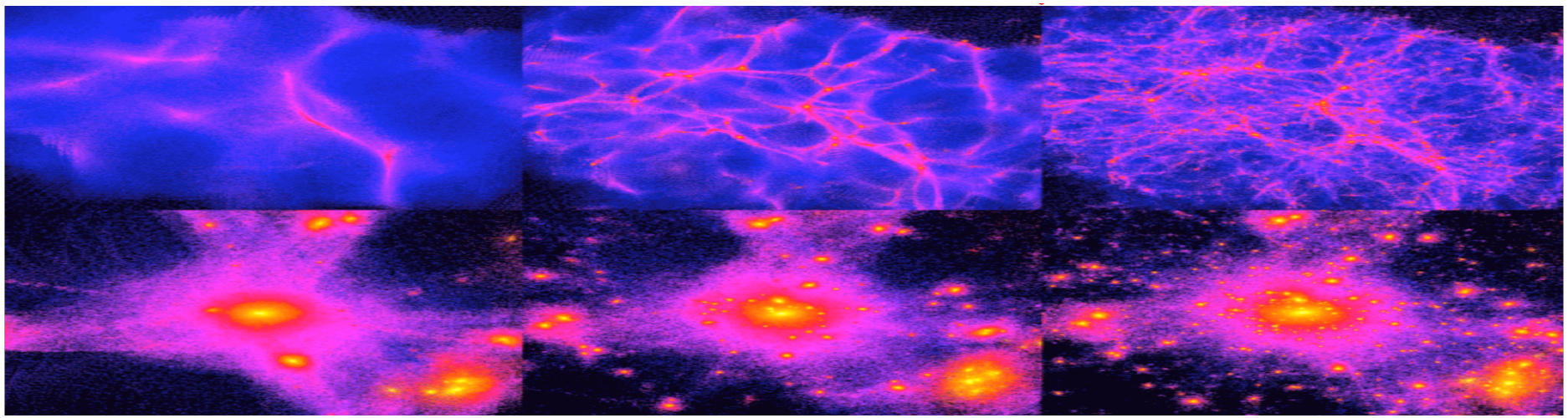
Light Dark Matter in Cosmology

"Cold", "Warm","Hot" coined in 1983
(J. Bond, J. Centrella, A. Szalay, J. Wilson, and J. Primack, G. Blumenthal)

"Cold" Typically mass above MeV (but depends on couplings too), ree streaming unimportant
e.g. SUSY weak scale neutralino

"Warm" fluctuations smaller than galaxy size ~ 10**11 solar mass get erased out
e.g. serile neutrino with the mass~ keV

'Hot" fluctuations smaller than supercluster size ~ 10**15 solar mass get erased out
e.g. SM neutrinos $\lambda_\nu \sim O(10^3)(0.1eV/m_\nu)Mpc$ $M_{FS} \sim \rho(\lambda/2)^3 \sim O(10^{19})(0.1eV/m_\nu)^2(10^{-1}/\Omega_\nu)M_{sun}$



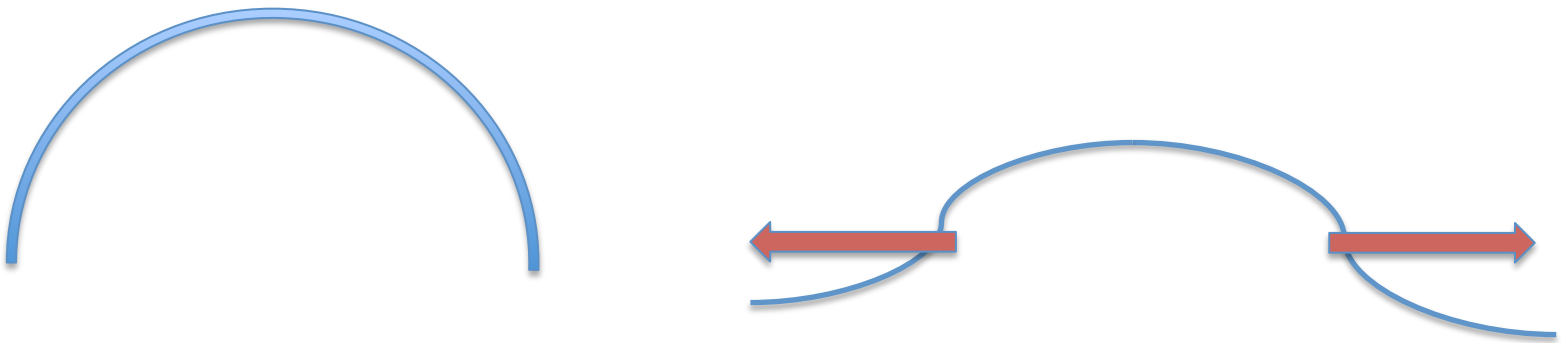
Free streaming scale

Free streaming length (c.f. Kolb and Turner)

$$\lambda \equiv a(t_0)\int_{t_{dec}}^{t_0} dt v(t)/a(t) = a(t_0)a(t_{dec})v(t_{dec})\int_{t_{dec}}^{t_0} dt 1/a^2(t)$$

$$a \sim t^{1/2}, a \sim t^{2/3}$$

$$v(t_{dec}) \sim \sqrt{T(t_{dec})/m}$$



$$\lambda_{FS} \sim 1Mpc\left(\frac{keV}{m_N}\right)\left(\frac{\langle p_N\rangle}{3.15T}\right) \quad \langle p(t)\rangle = \frac{\int d^3p p f(p,t)}{\int d^3p f(p,t)}$$

(e.g. Dodelson-Widrow: <p>~2.7 T)

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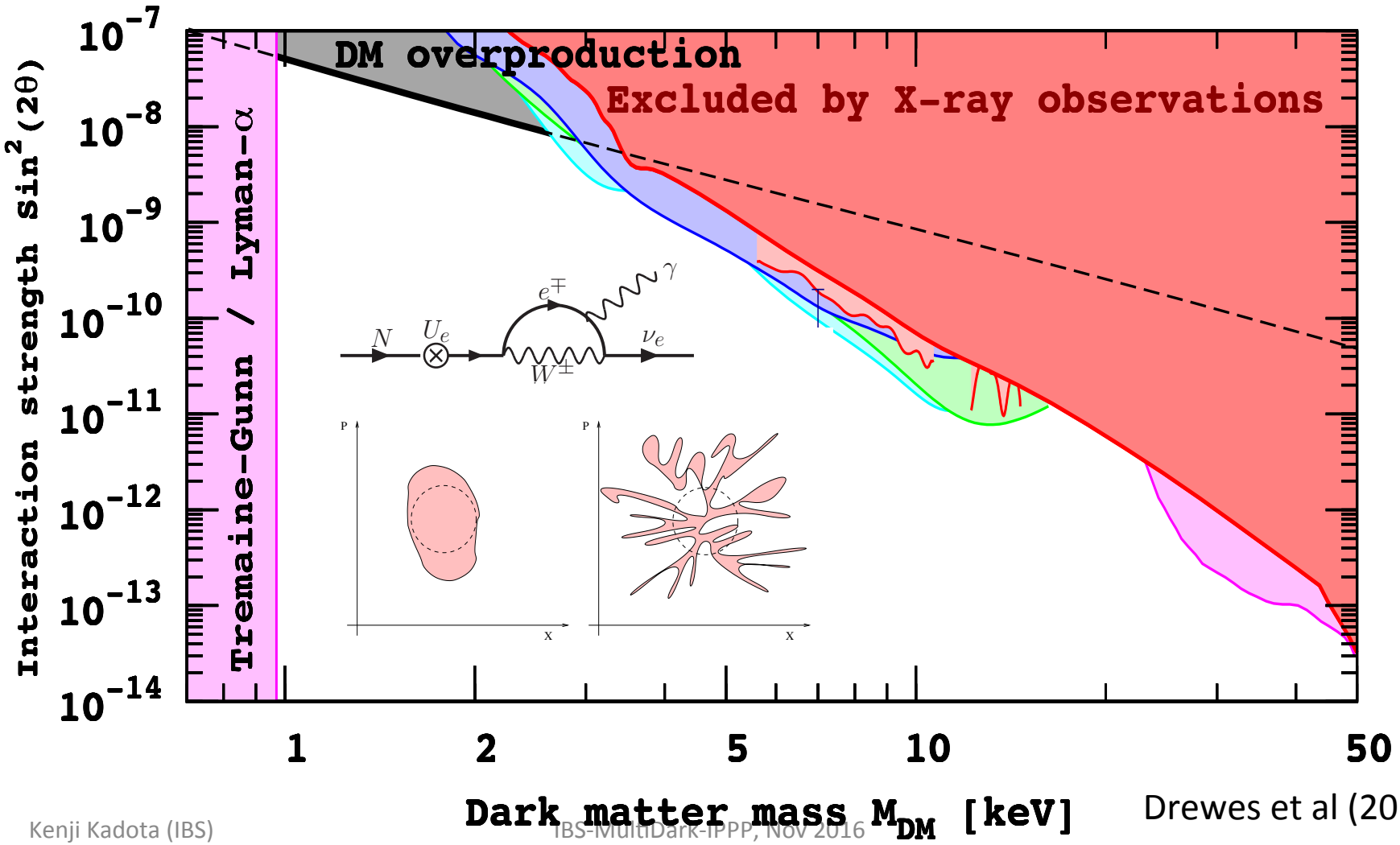
A concrete example for the warm dark matter: keV Sterile Neutrinos

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

$$L = -yNLH - \frac{1}{2}MNN$$

$$\theta = \frac{y\langle H \rangle}{M}$$



Drewes et al (2016

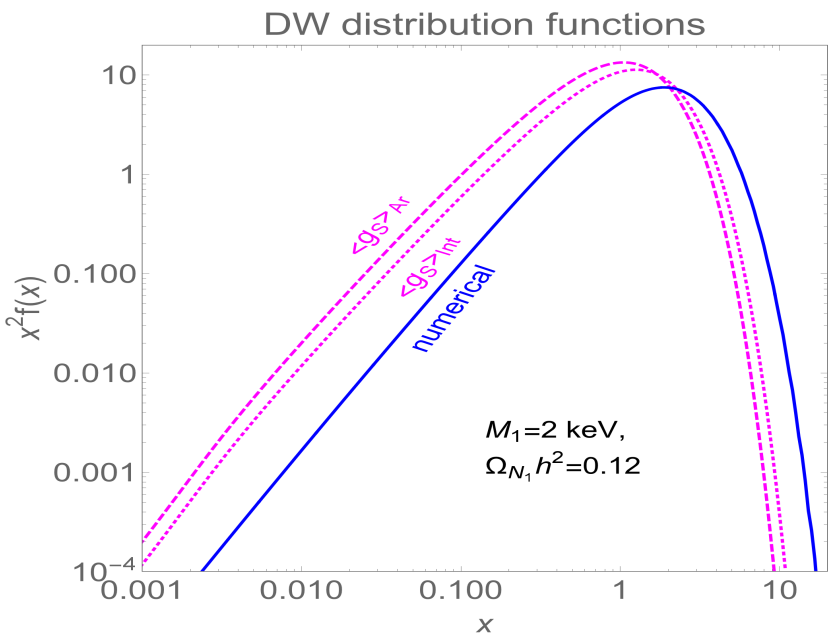
e.g. DW scenario

$$\frac{d}{dt} f(T,p) = \text{Collision term} = C(T,p)[f_{th} - f]$$

$$f(T,p) = \int^{T} dT' f_{th}(T',p) C(T',p)$$

$$f(T,p) \sim F(\langle g_s \rangle) \int^{T} dT' C(T',p)$$

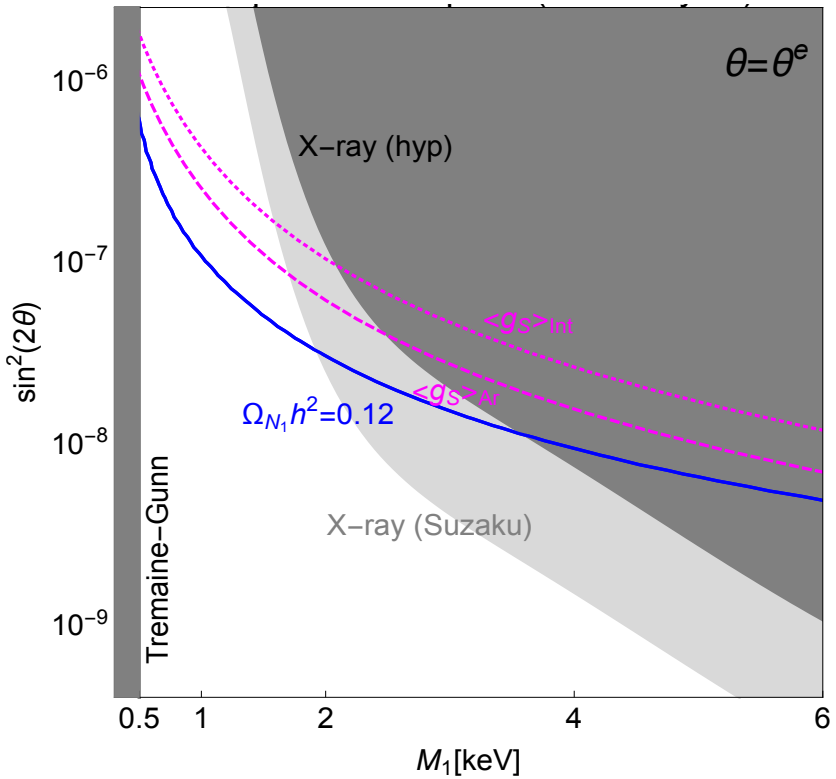
$$\langle g_S \rangle_A = \frac{g_S(T_{ini}) - g_S(T_{final})}{2} \quad \langle g_S \rangle_{\text{int}} = \frac{1}{T_{ini} - T_{final}} \int_{T_{ini}}^{T_{final}} dT g_S(T)$$

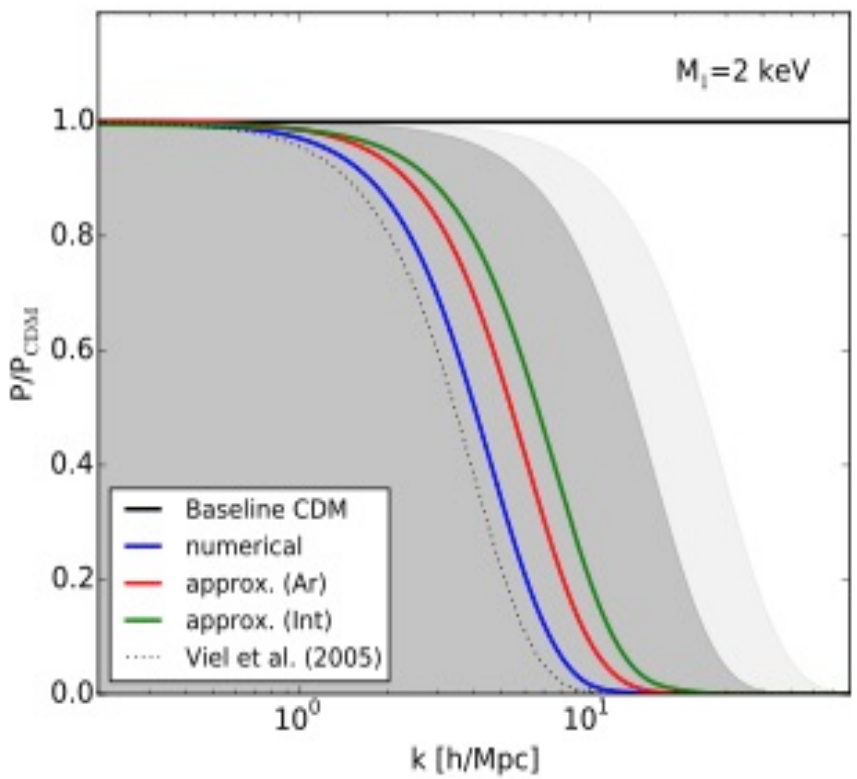


$$n = \int \frac{d^3 p}{(2\pi)^3} f(p)$$

$$\langle p(t) \rangle = \frac{\int d^3 p\, p f(p,t)}{\int d^3 p f(p,t)}$$

Merle et al (2016)





Merle et al (2016)

Constraints heavily depend on production mechanisms:

Dodelson-Widrow

$$f(p) = \frac{\chi(<<1)}{e^{p/T}+1}, T_{DW} = \left(\frac{4}{11}\right)^{1/3} T_\nu, \Omega_{DW} h^2 = \chi \frac{m_{DW}}{94eV}$$

Early-decoupled scenarios

$$f(p) = \frac{1}{e^{p/T}+1}, \Omega h^2 = \left(\frac{T}{T_\nu}\right)^3 \frac{m_{dm}}{94eV}$$

Two constraints: abundance and free streaming length scale match

$$m_{DW} \sim 4keV \left(\frac{m_{dm}}{1keV}\right)^{4/3} \left(\frac{\Omega_{DM} h^2}{0.12}\right)^{-1/3}$$

Eg. The Ly-alpha constrains DM mass if there is a simple one to one correspondence for FS and mass

More production mechanisms:

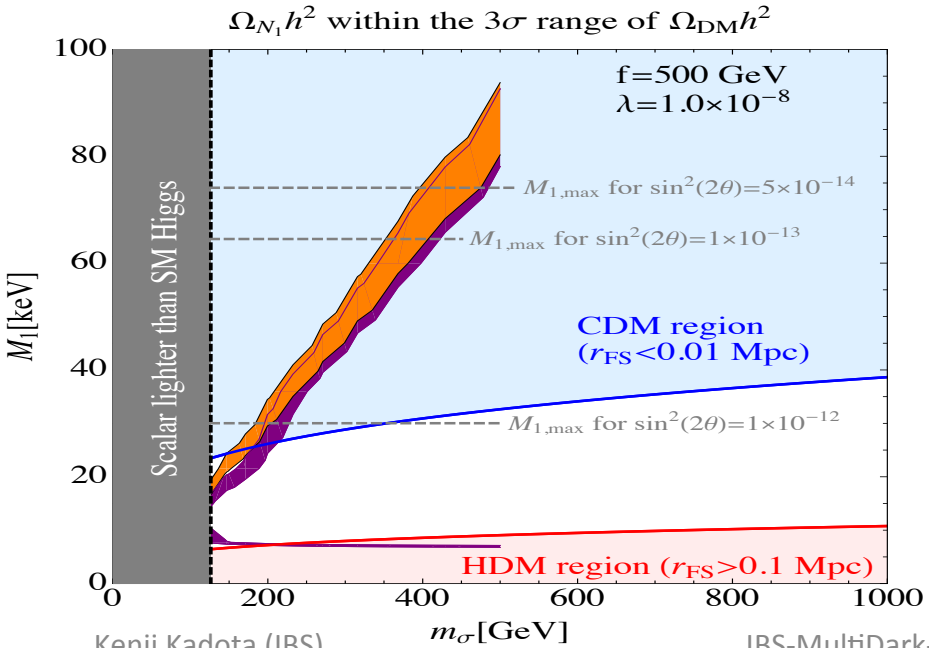
- Introducing an additional scalar :

e.g. $L = -\lambda \sigma N N$ Kusenko, Petraki, Asaka, Shaposhnikov, Merle, Schneider,..

- More than one right-handed flavor:

e.g. $L = -y_{ij} N_i L_j H$ KK, Kunio Kaneta (in preparation)

Merle et al (2014)



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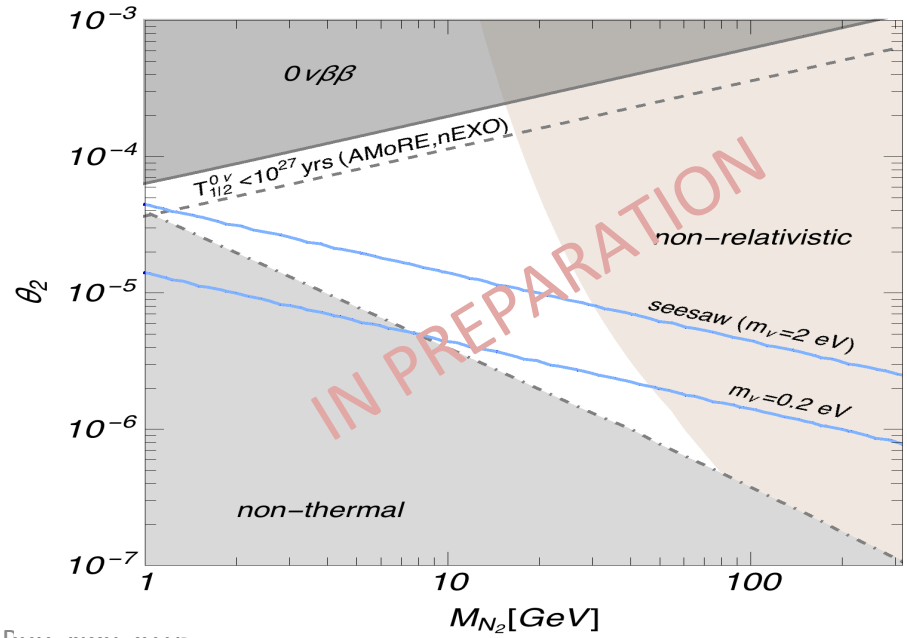

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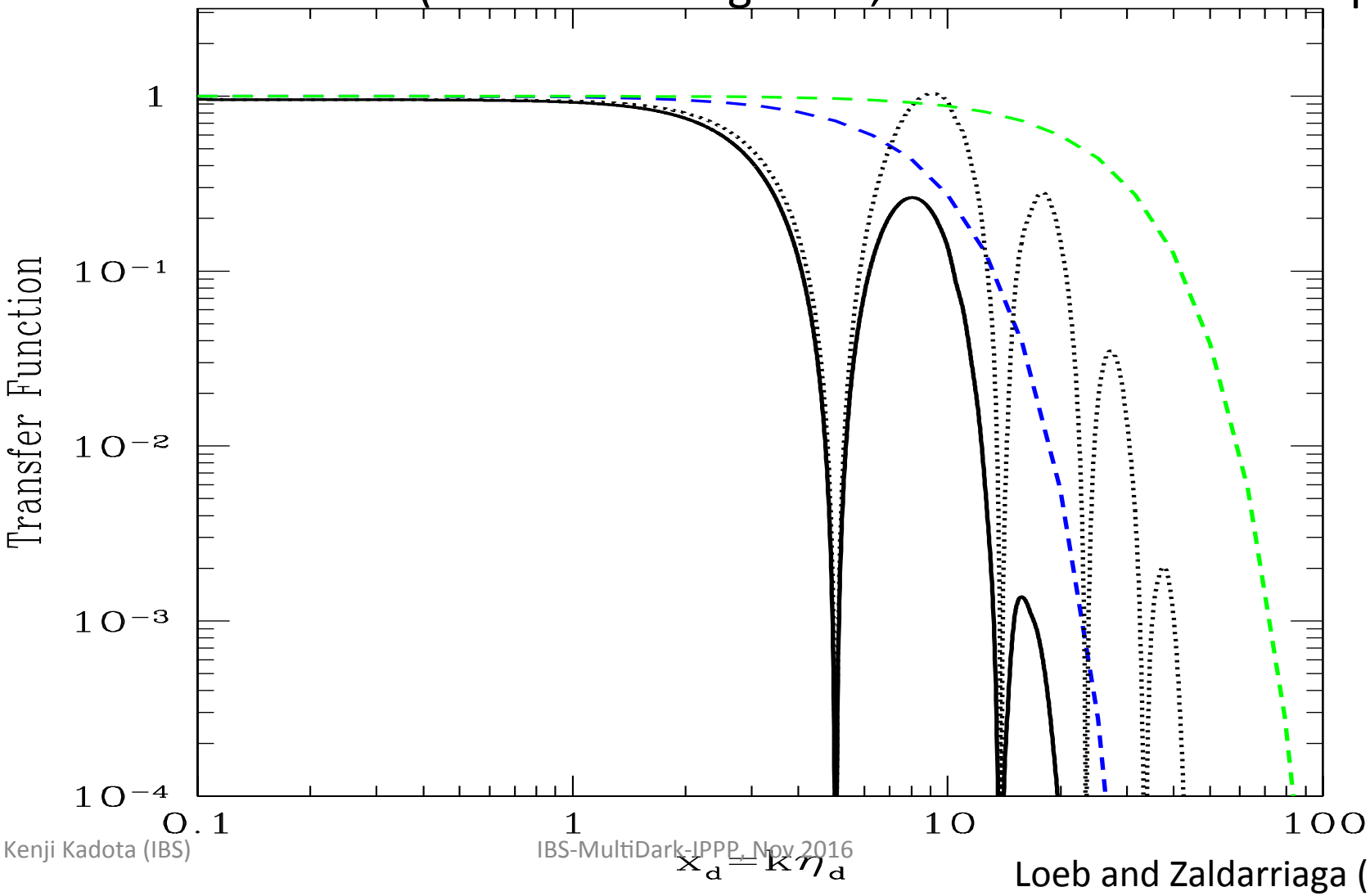
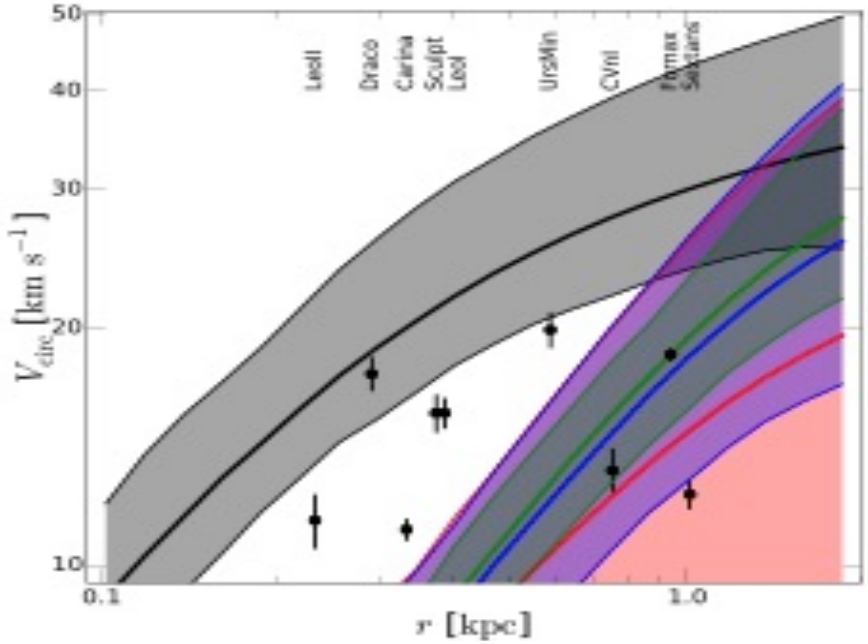
Structures cannot form below free streaming scale

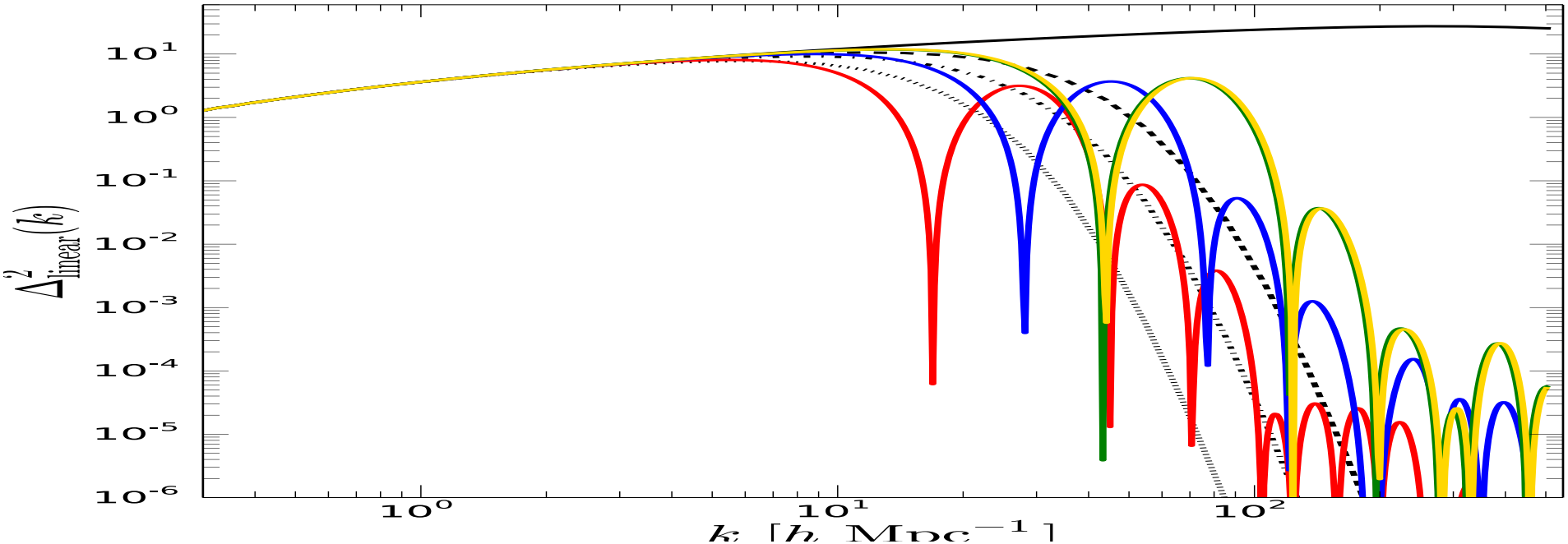
Smallest dark matter halo size:
Max (Free streaming scale, Horizon size at decoupling)



Loeb and Zaldarriaga (2005)

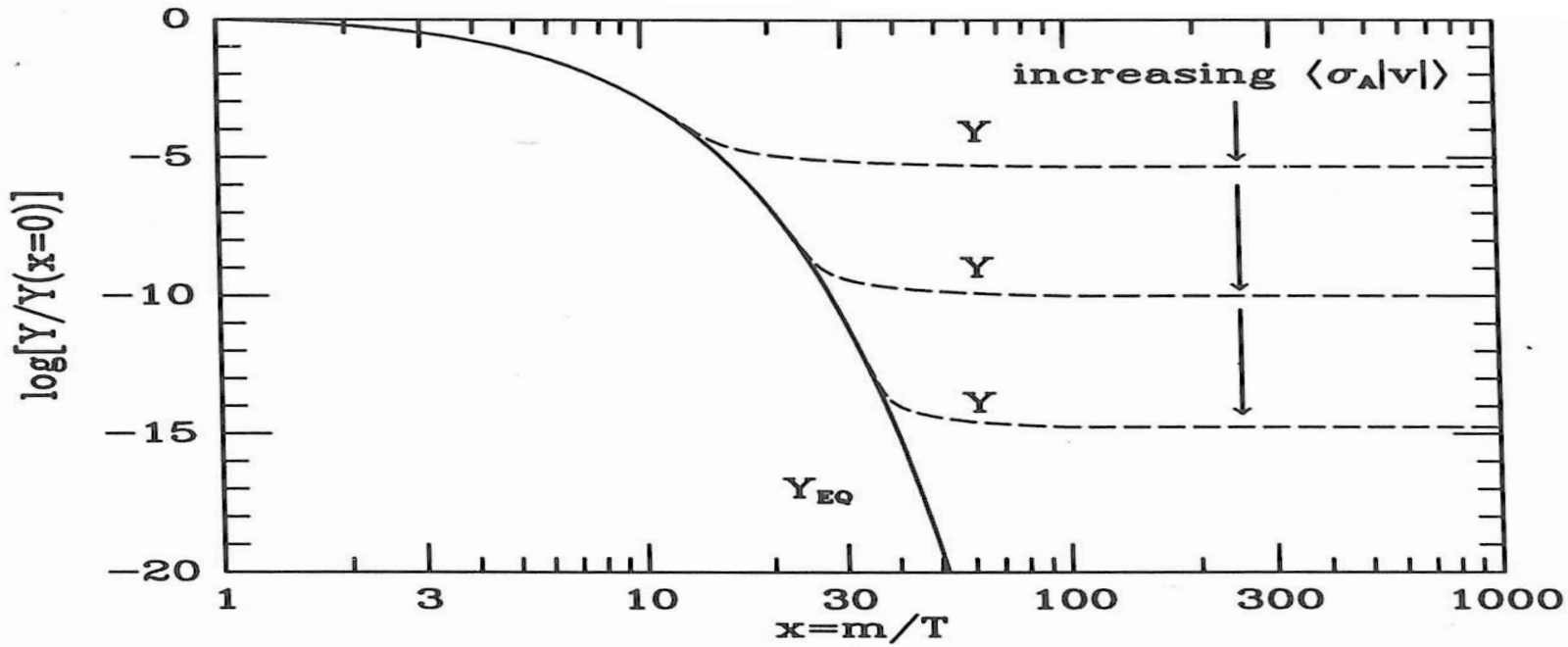
Motivation for DM-baryon interactions, beyond ΛCDM





DM-baryon interactions affect DM decouplings

(Kolb&Turner)

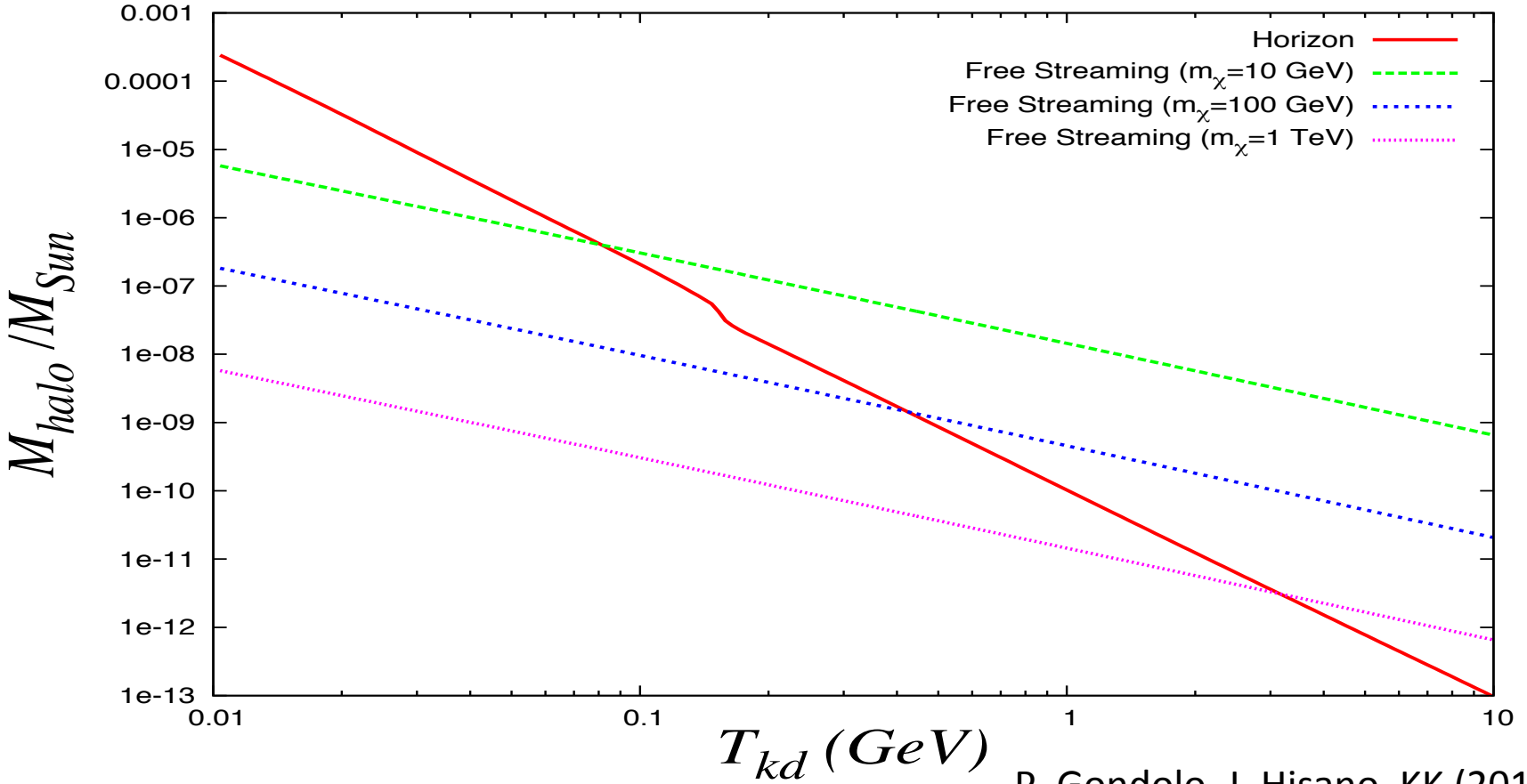


- Chemical decoupling:
  Annihilation < Hubble expansion, $T \sim m_\chi/20$
- Kinetic decoupling:
  Elastic scattering < Hubble expansion, $T \sim m_\chi/2000$

The dark matter kinetic decoupling

(Schmidt, Schwarz, Widerin, Fayet, Chen, Kamionkowski, Zhang, Kasahara, Hoffman, Green, Profumo, Ullio, Sigurdson, Berezinsky, Dokuchaev, Eroshenko, Boehm, Loeb, Zaldariaga, Bertchinger, Bringmann, Cornell,...)

$$M_{halo} : 10^{-6} M_{sun} \sim 100 M_{sun}$$

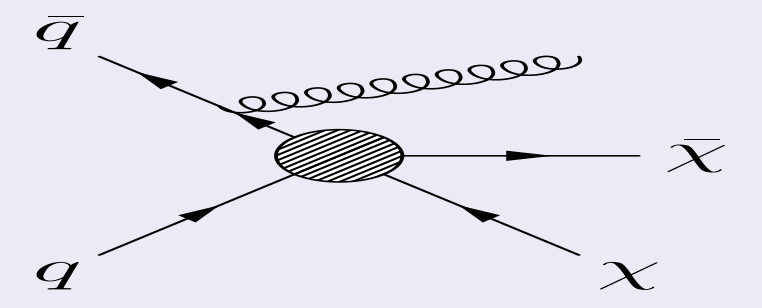


P. Gondolo, J. Hisano, KK (2012)

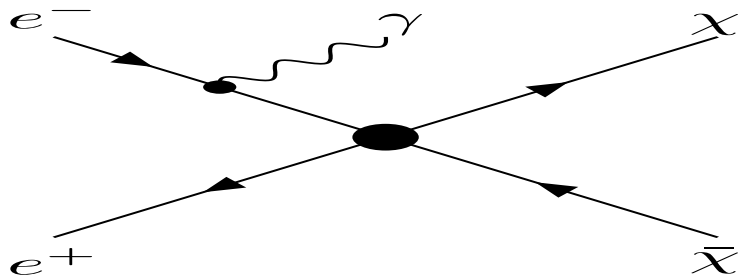
The constraints from collider and direct search experiments:

Collider:

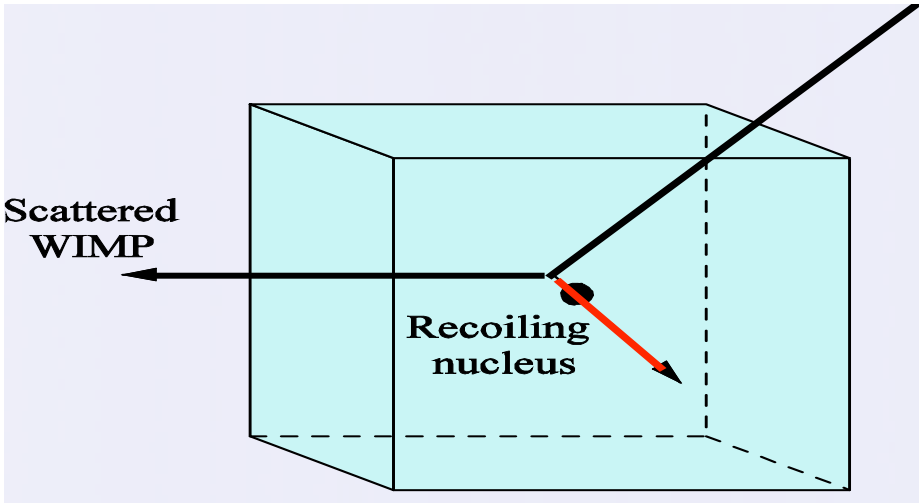
Hadron collider



Lepton collider



Direct detection:



Measures nuclear recoil energy via

1) Ionization on solids
   (local release of charge)
2) Scintillators (emitted photons)
3) Temperature increase (released phonons)

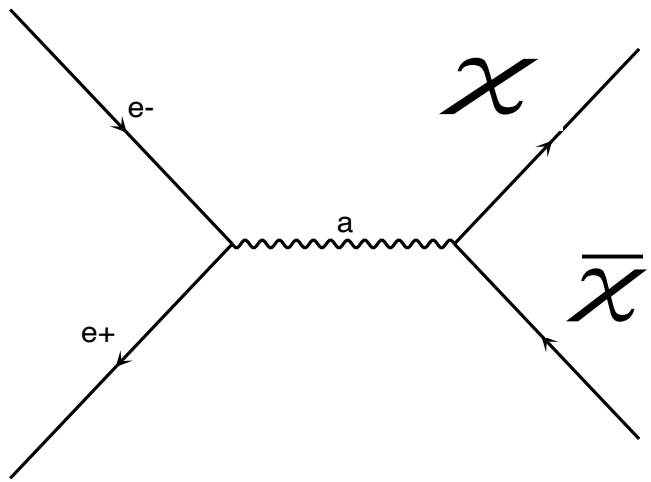
Dipole DM

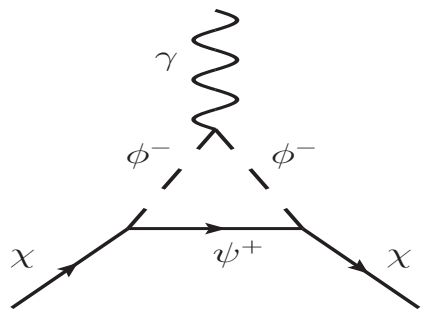
Pospelov et al (2000), Sigurson et al(2004), Barger et al (2012), Heo and Kim (2012),Graham (2012) Nobile et al (2013),..

- DM with a dipole moment:

The lowest dimensional coupling between DM fermions and the SM gauge bosons

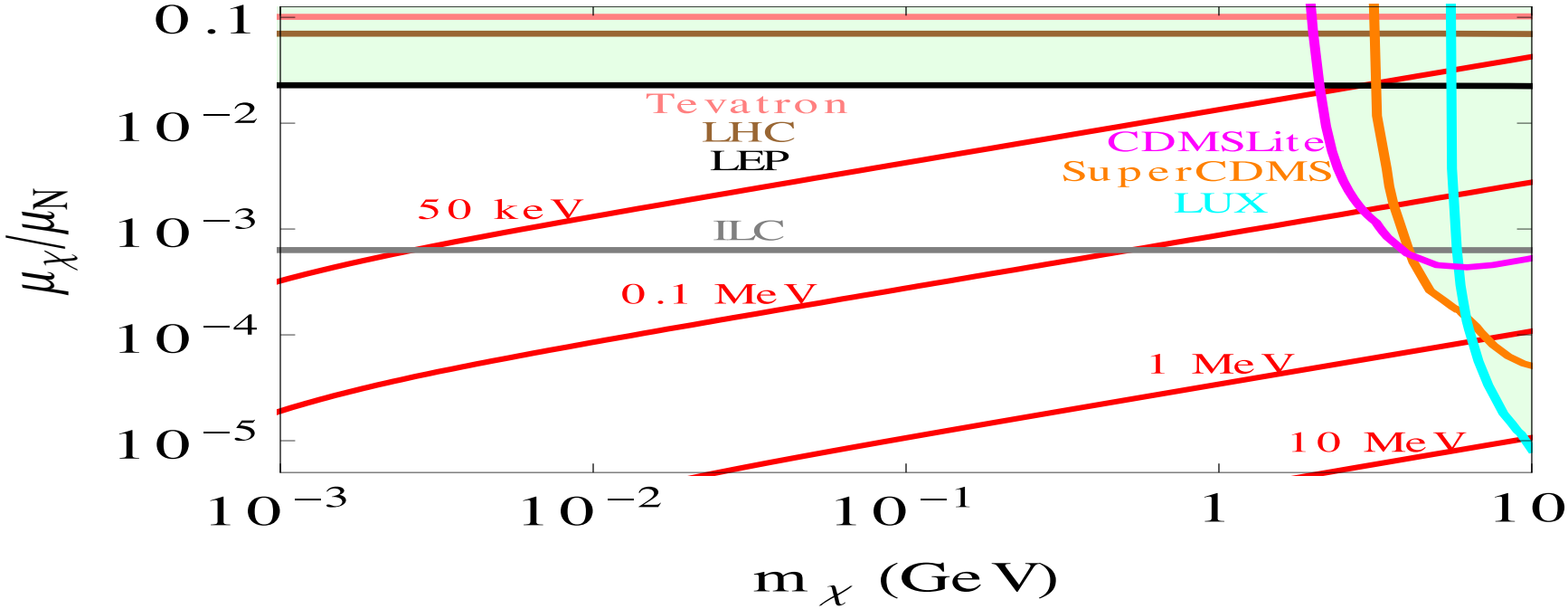
$$\boxed{L_{MDM} = -\frac{i}{2}\mu\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}} \qquad \mu \equiv \frac{1}{\Lambda}$$

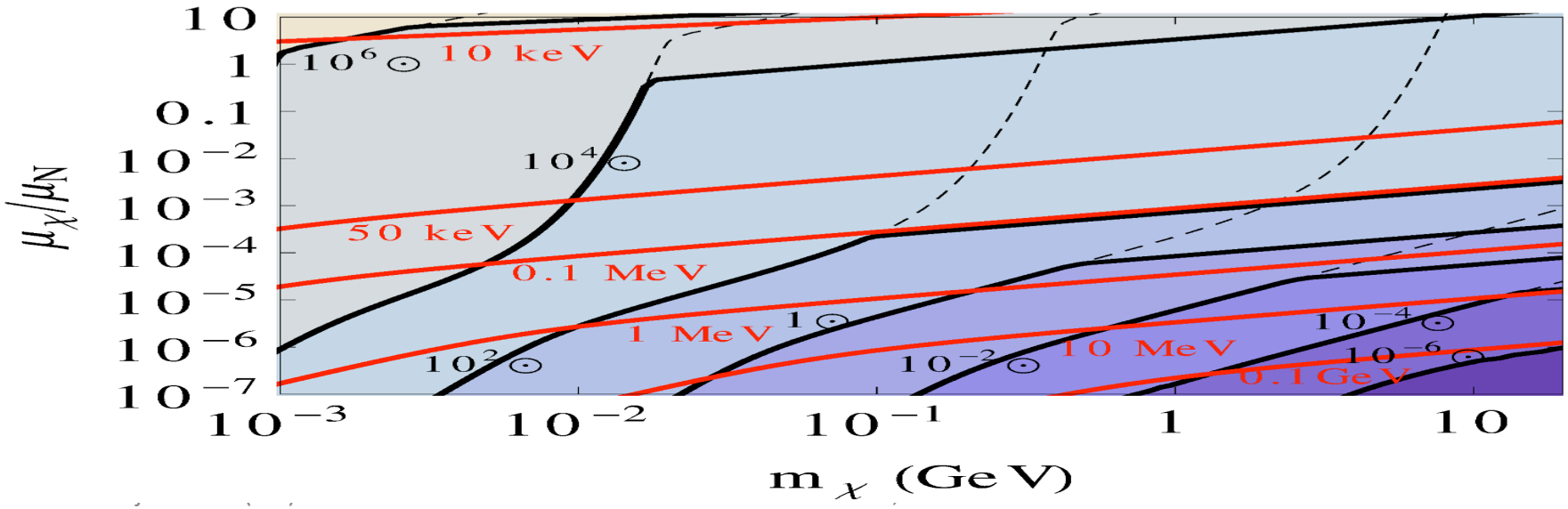




$$\mu \sim \frac{eg^2}{M}$$

P. Gondolo and KK(2016)





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Conclusions: Let's not get biased, and explore beyond conventional paradigms

- ✓ Beyond the weak scale dark matter
- ✓ Beyond Lambda-CDM

Complementary study from particle physics and cosmology would be essential!