21 cm probes on particle dark matter

Kenji Kadota
IBS Center for Theoretical Physics of the Universe, Institute for Basic Science

Outline:

Example 1: 21 cm probes on the ultra-light particle dark matter (DM)

KK, Yi Mao (IAP), Kiyotomo Ichiki (Nagoya), Joseph Silk (IAP, Johns Hopkins,Oxford), JCAP 1406 (2014) 011

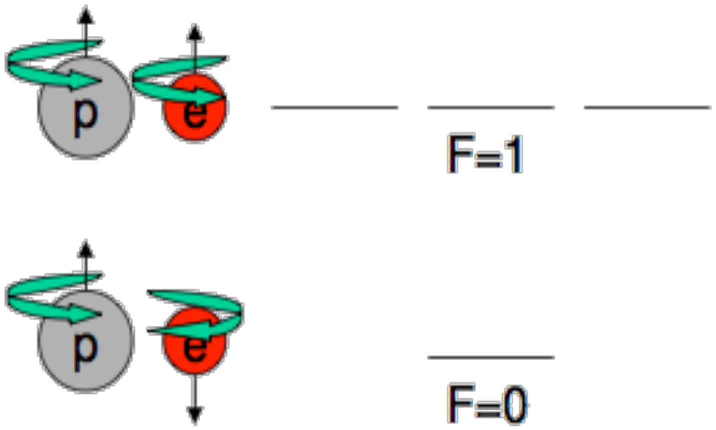
Example 2: 21 cm probes on the DM-baryon elastic scattering

Hiroyuki Tashiro (Nagoya), KK, Joseph Silk (IAP, JHU,Oxford), Phys.Rev. D90 (2014) 8, 083522

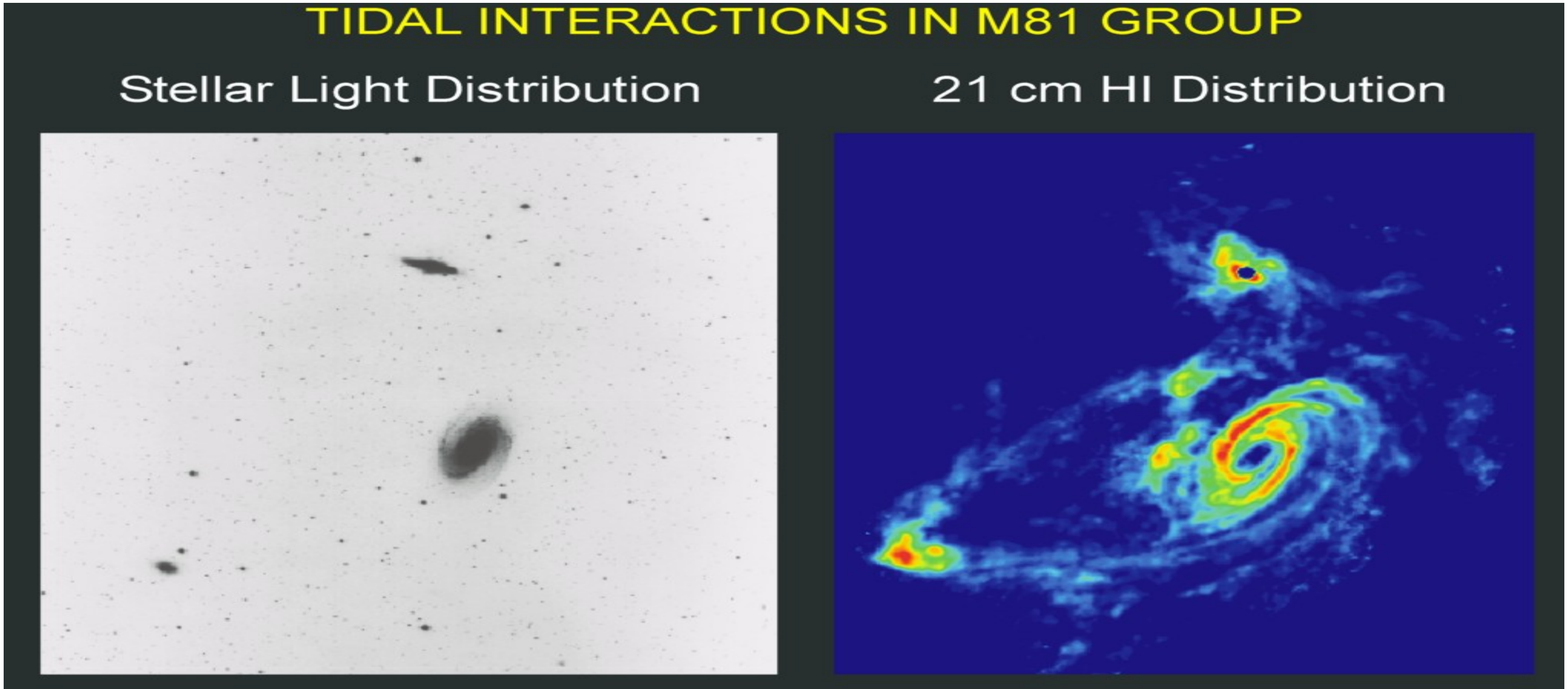
Complementarity: Cosmology and Particle physics connection

LHC and dark matter search experiments on the DM-baryon elastic scattering

Paolo Gondolo (Utah) Junji Hisano (Nagoya), KK, PRD 86(2012)83523

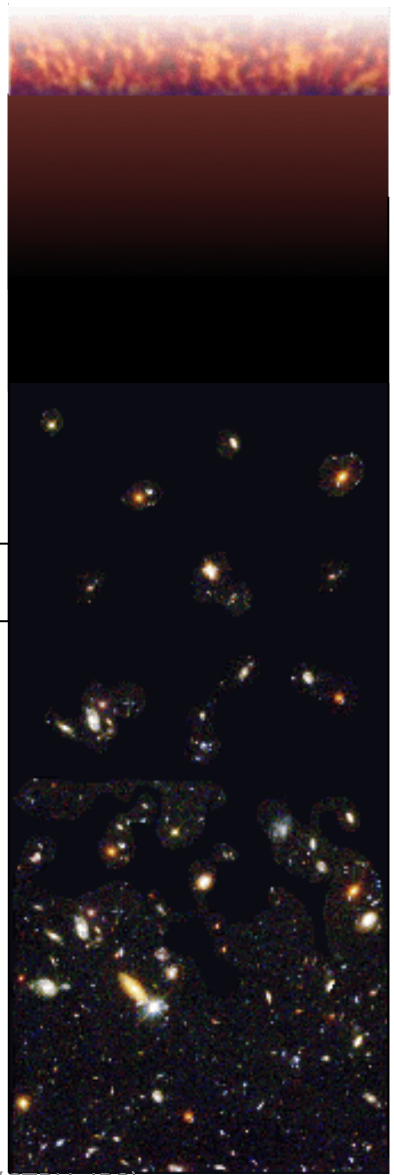


21 cm signals
1420 MHz



Brief History of Universe

Years since the Big Bang



← Big Bang:
the Universe is filled with ionized gas

~300000 (z~1000)

← 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

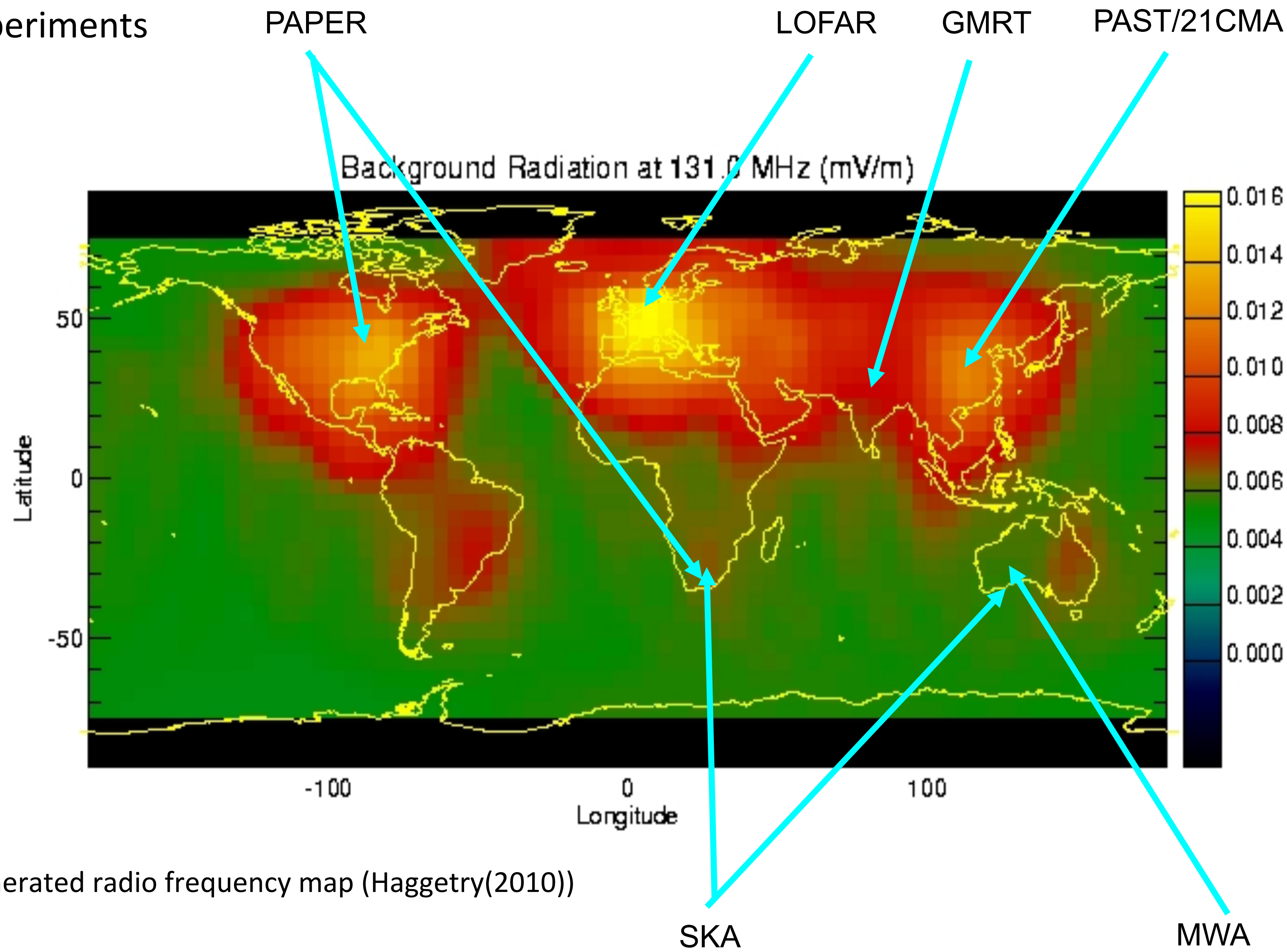
~1 billion (z~6)

← Reionization is complete

~13 billion (z=0)

← Today's structures

21cm experiments



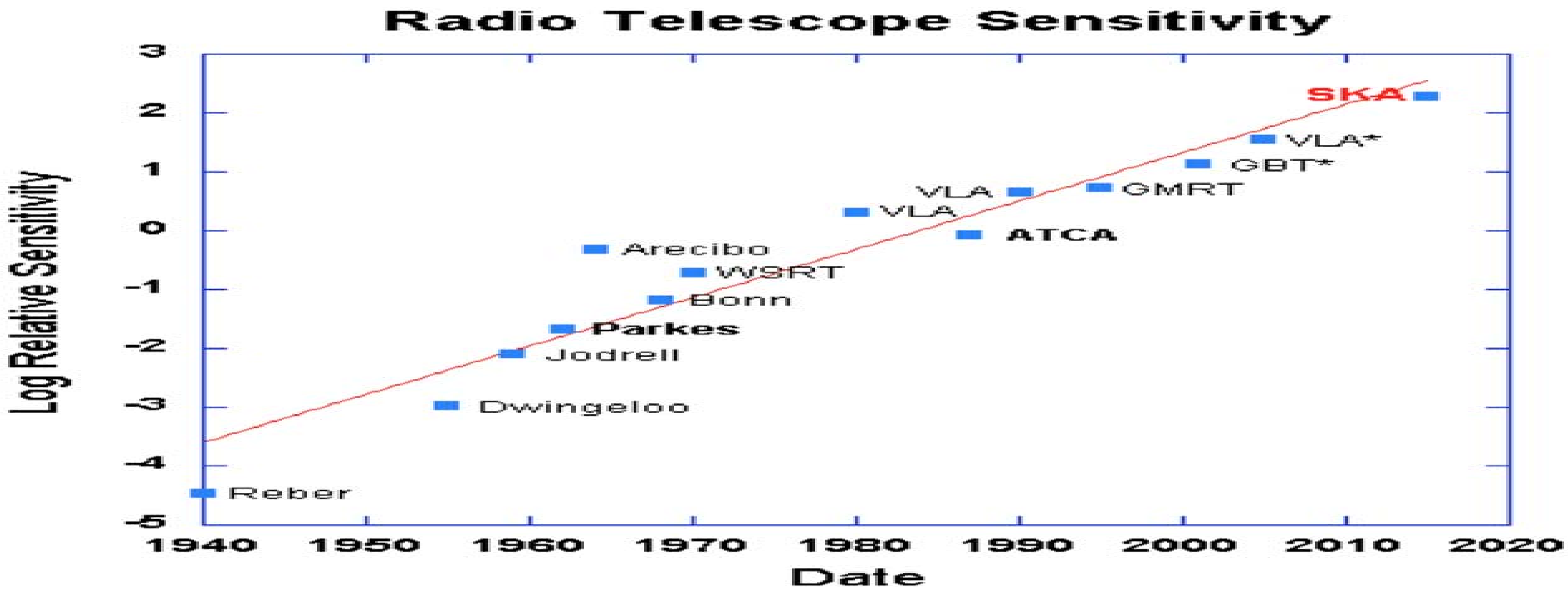
(Human generated radio frequency map (Haggetry(2010))

Pathfinders for SKA:
GMRT(2010), LOFAR(2010),PAPER(2011),MWA(2011),SKA(2020)

Square Kilometer Array

South Africa- Karoo
Australia- Western Outback

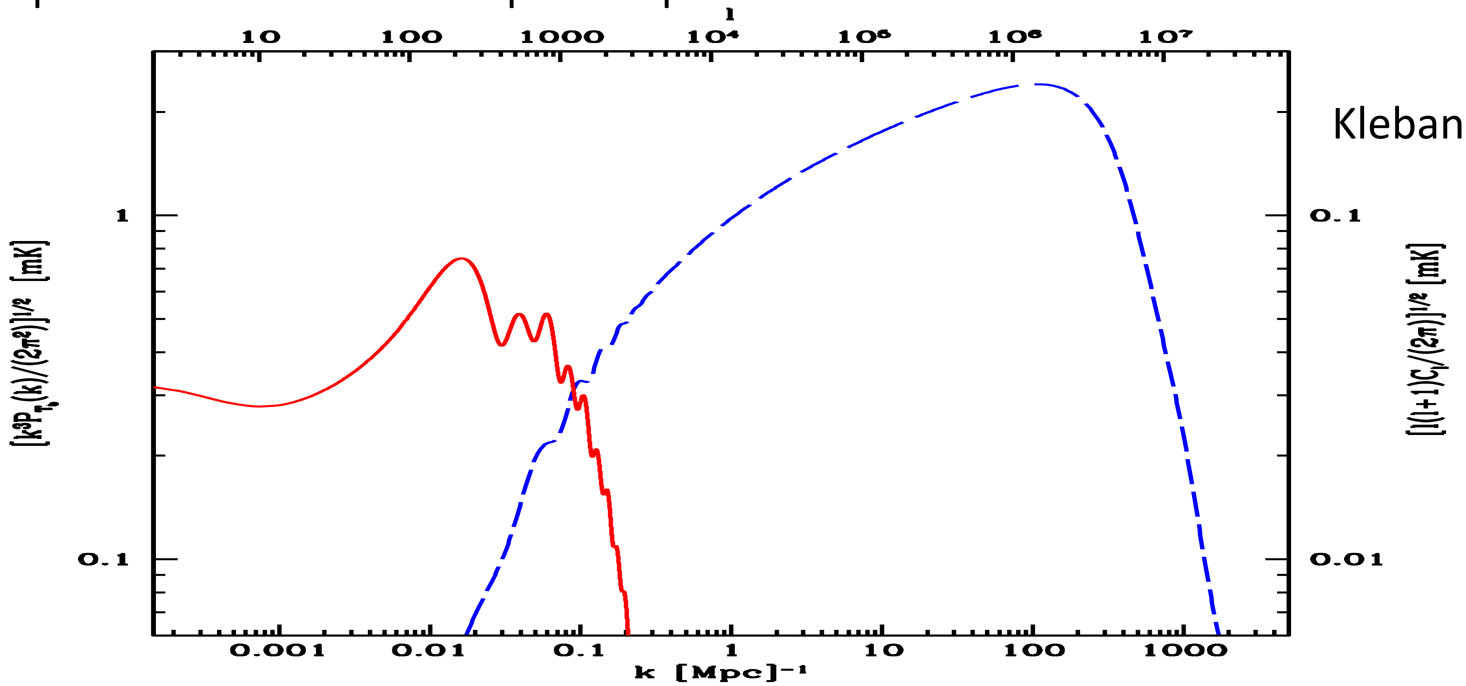
Construction 2017-2023, Early Science 2020-, Full Science 2023-2028
Cost: ~650 M Euros, Operation ~ 50 M Euros per year.



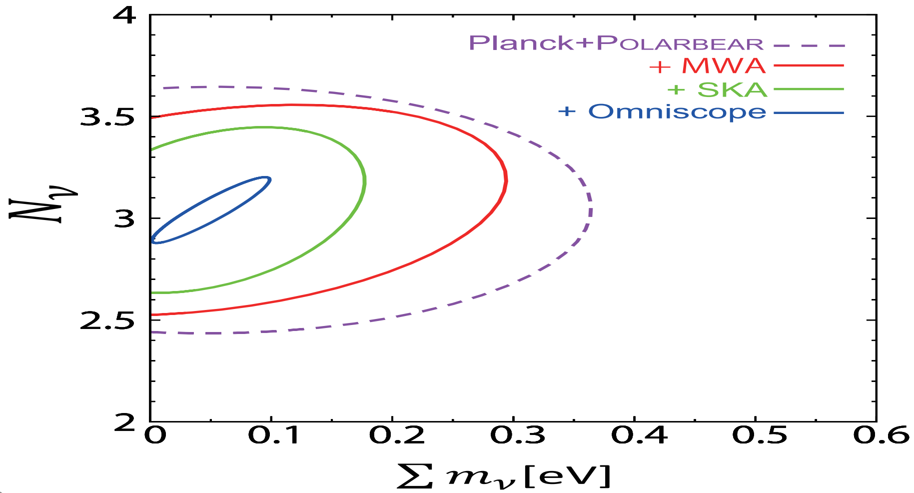
What can we do with 21cm?

High precision on small-scale power spectrum

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



Kleban+(2007)



Oyama+(2013)

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Model: Ultra-light scalars

- Ultra-light mass :

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

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

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

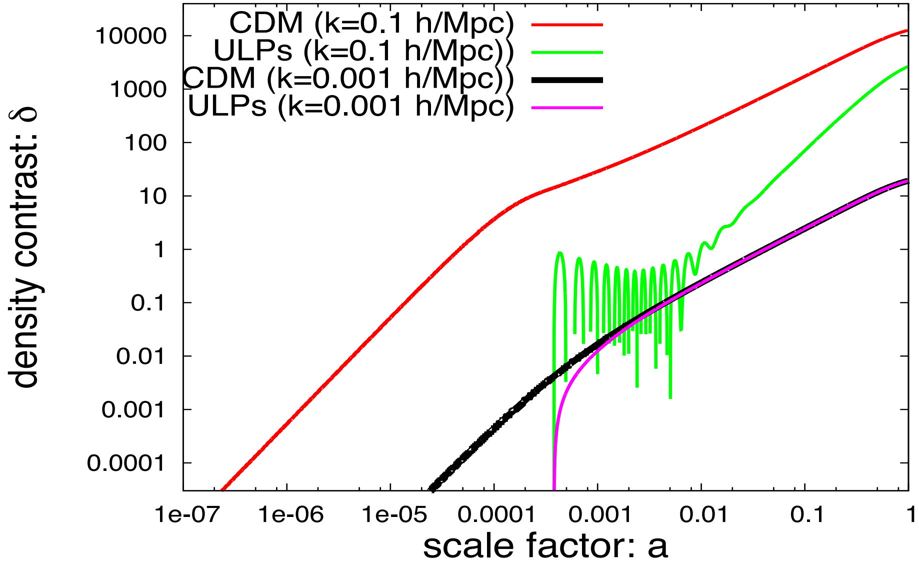
(Likelihood analysis: Amendola et al (2005), Marsh et al (2013)…)

$$m_u, f_u = \Omega_u / \Omega_m \sim O(0.01)$$

$$m_u \leq H(t) : \rho_u = const$$

$$m_u > H(t) : \rho_u \propto 1/a^3$$

Fluctuations of ultra-light particles

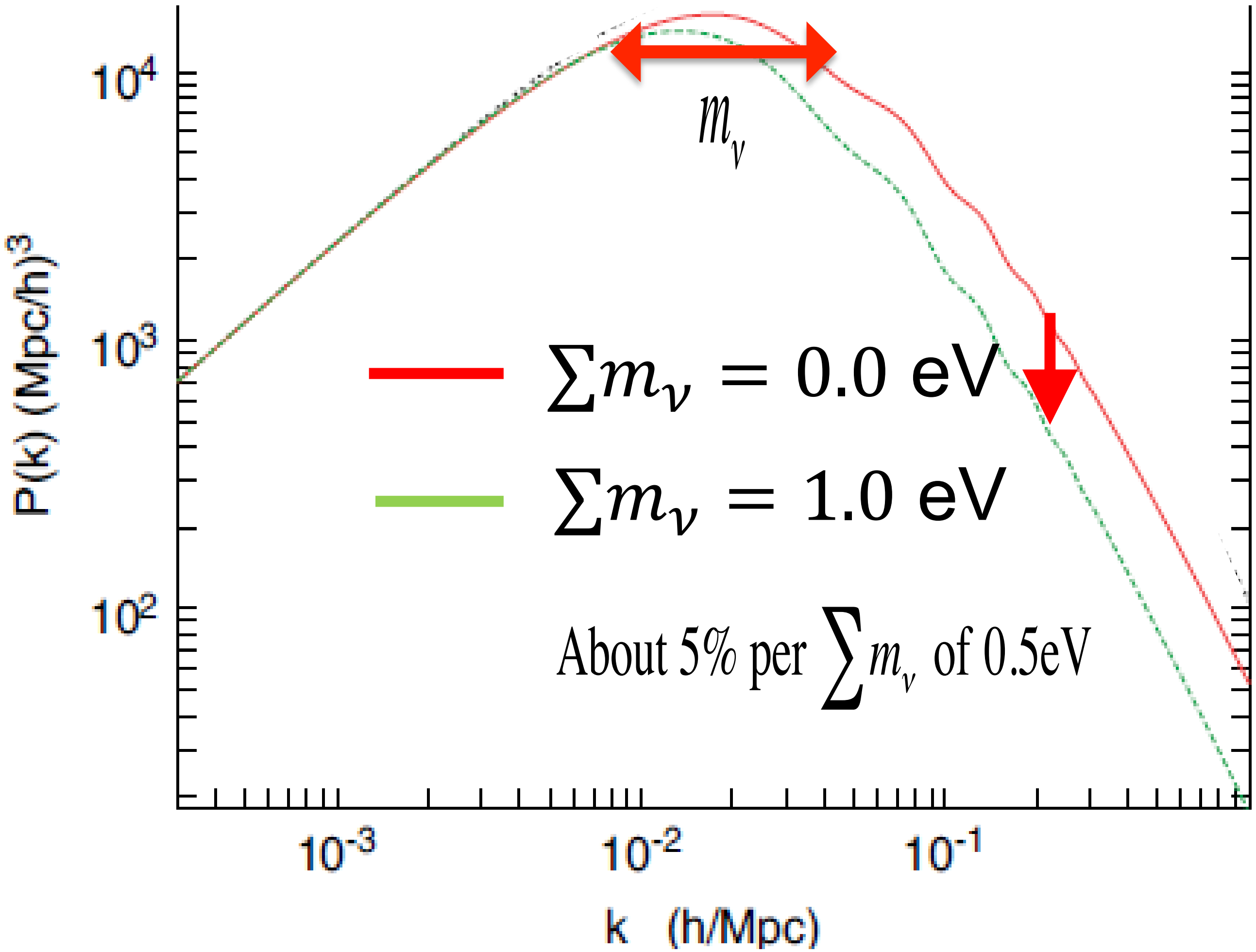


KK, Mao, Ichiki, Silk (2014)

The perturbation evolutions for ULPs ($m_u = 10^5 H_0$, $f_u = 0.05$) and CDM.

Cannot grow inside the free streaming scale

Review: Massive Neutrino effects on Large Scale Structure (c.f. Lesgourgues&Pastor 06)



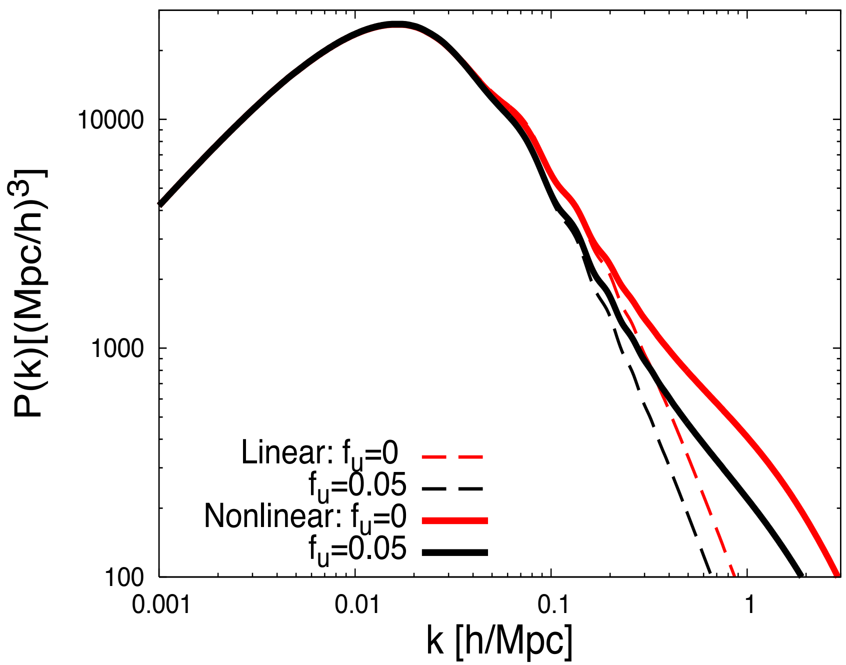
$$\delta \propto a^{1-3f_\nu/5} (f_\nu \equiv \Omega_\nu / \Omega_m)$$

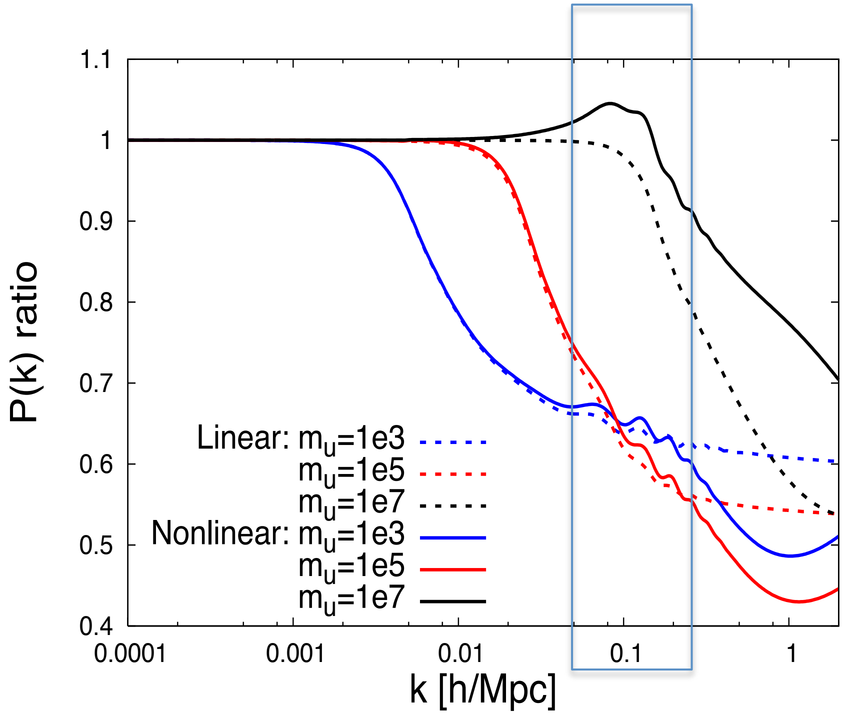
$$\frac{\Delta P}{P} \sim -8 \frac{\Omega_\nu}{\Omega_m} \quad \text{(Hu et al 1998)}$$

Power spectrum P(k)

If oscillation starts during matter domination : $z_{osc} \sim m^{2/3}, k_* \sim m^{1/3}$

If oscillation starts during radiation domination : $z_{osc} \sim m^{1/2}, k_* \sim m^{1/2}$

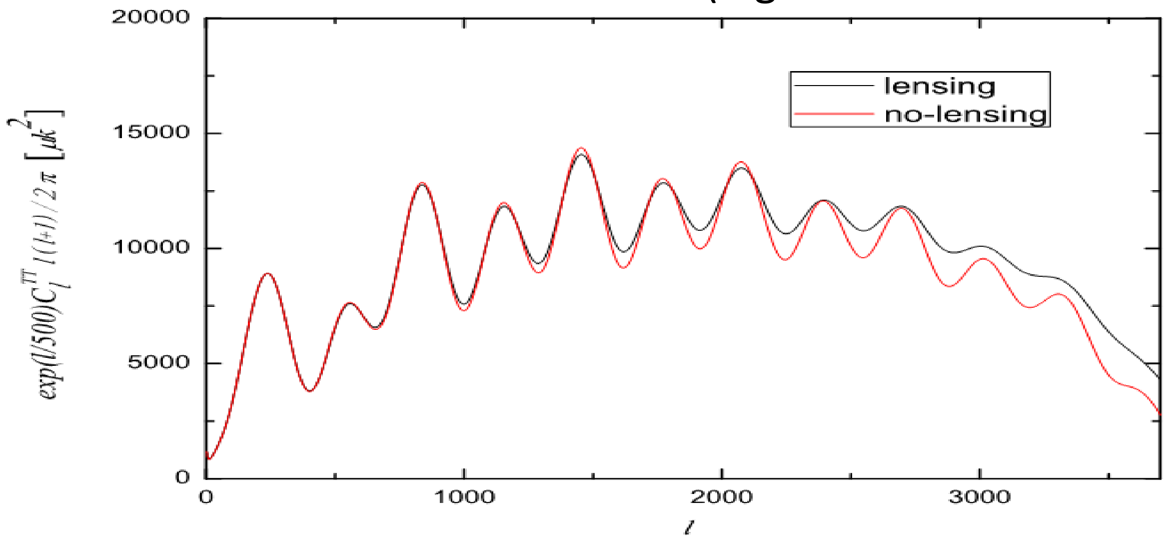




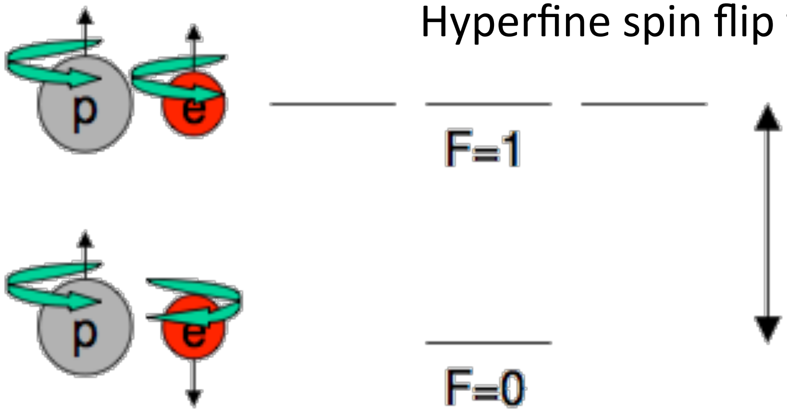
KK, Mao, Ichiki, Silk (2014)

Cosmological observables: CMB (including lensing) + 21cm

(e.g. Lewis & Challinor 2006)



Hyperfine spin flip transition



21 cm signals

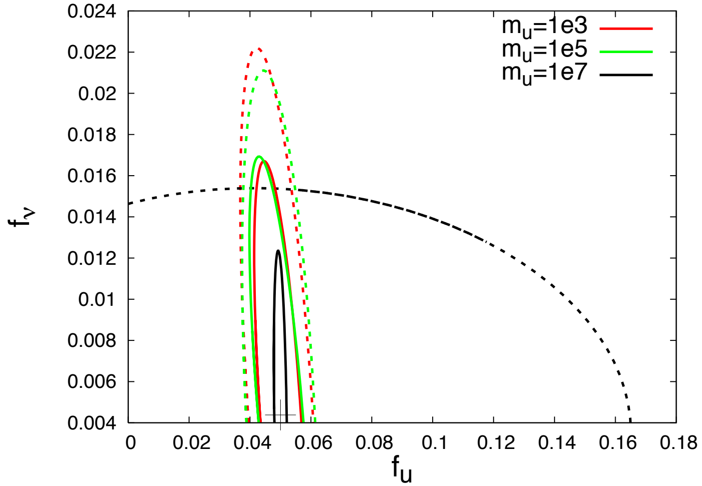
$\lambda = 21\,\mathrm{cm}$

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

Likelihood analysis

- Fisher forecasts: CMB + 21cm.

$$\Omega_\Lambda, \Omega_m h^2, \Omega_b h^2, n_s, A_s, \tau, N_{eff}, m_a, f_u, f_\nu, x_{HI}, b_{HII}(z)$$



➢ Forecast Results

Uncertainties in f_u, m_u: 10~20 %

Most sensitive m_u:

$$CMB: m_u \sim 10^{4-6} H_0 (10^{-29\sim-27} eV)$$

$$21cm: m_u \sim 10^{7} H_0 (10^{-26} eV)$$

KK, Mao, Ichiki, Silk (2014)

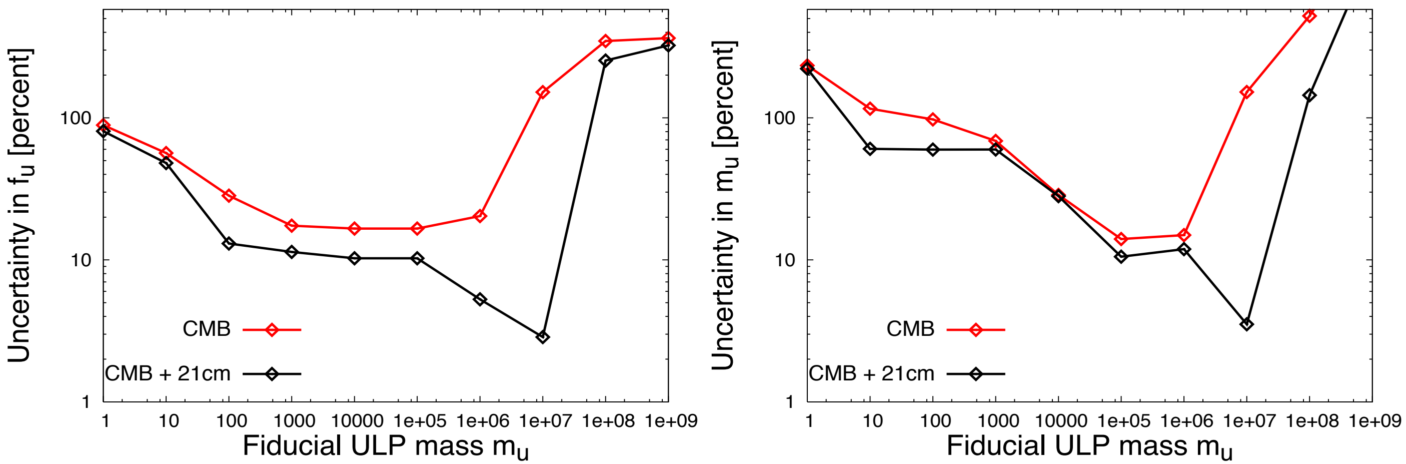


Figure 4: 1σ errors in f_u and m_u (the fiducial value $f_u = 0.05$) for several fiducial values of m_u in terms of $H_0 (\approx 2 \times 10^{-33}$ eV).

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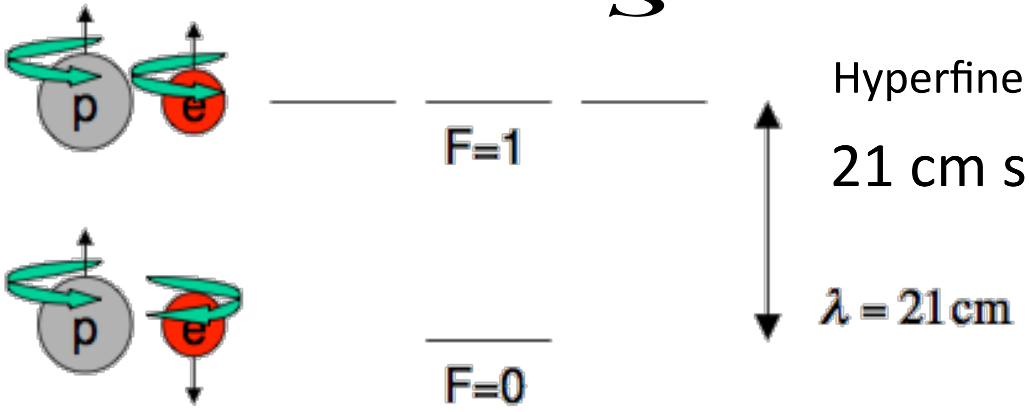
What can we measure through 21cm signals?

Spin temperature T_S



Hyperfine spin flip transition

21 cm signals

$$\frac{n_1}{n_0} \sim \exp(-T_* / T_S) \quad (T_* = 0.0681K \text{ for 21cm line})$$

The occupation number of each level (equivalently spin temperature) can be altered by

a) the absorption/stimulated emission from/to CMB photons

b) collision with other gas particles (other hydrogen atoms, protons and electrons).

Ts is the weighted average of CMB temperature and gas temperature (Field (1958)):

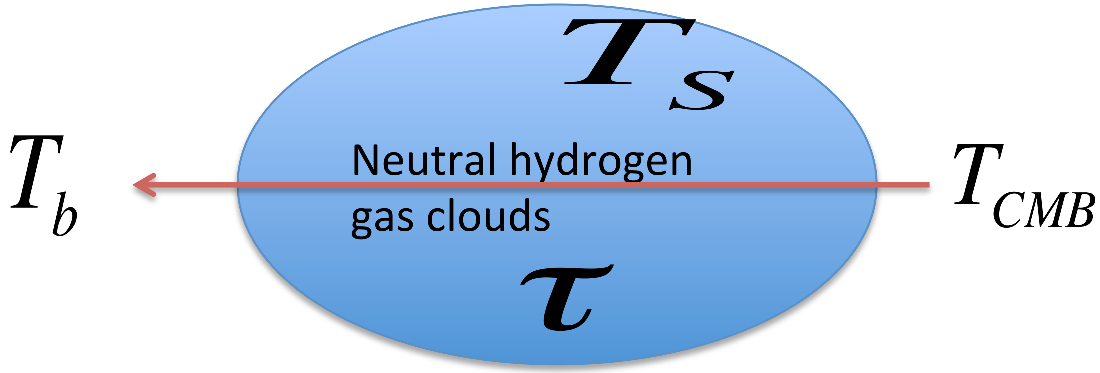
$$T_S = \frac{T_{CMB} + y_c T_k}{1 + y_c}$$

If collision is efficient, coupling coefficient yc gets big and Ts->Tk

If yc or Tk gets small, Ts->Tcmb.

Brightness temperature T_b

$$T_b(\nu) \equiv T_S(1-e^{-\tau}) + T_{CMB}(\nu)e^{-\tau}$$

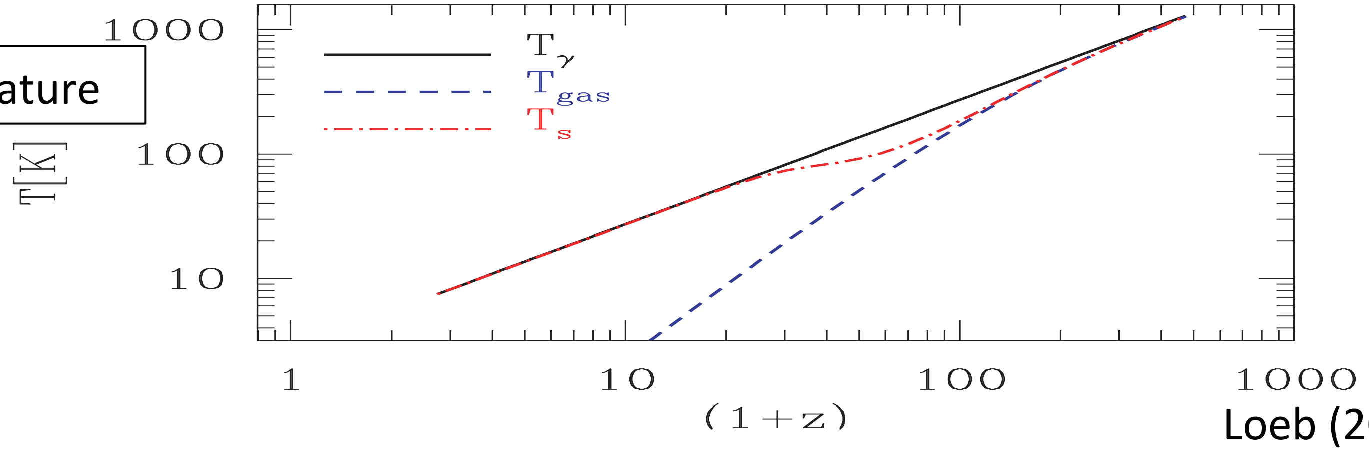


Differential brightness temperature:

$$\delta T_b = \frac{T_b - T_{CMB}}{1+z} \approx \frac{T_S - T_{CMB}}{1+z}\tau$$

21cm signal as emission (Ts>Tcmb) or absorption (Ts<Tcmb)

Evolution of temperature



Loeb (2006)

$z \geq 200;$ $T_K \sim T_{CMB} \sim (1+z)$ Compton scattering between CMB photons and free electrons in the gas leftover from recombination

$T_K \sim T_S$ Big gas density lets collisional coupling dominate

$z \leq 200$ $T_K < T_{CMB}$

$Radiation: T_{CMB} \sim 1/a \sim (1+z)$

$Adiabatically\ cooling\ \mathrm{gas}: T_K \sim 1/a^2 \sim (1+z)^2$

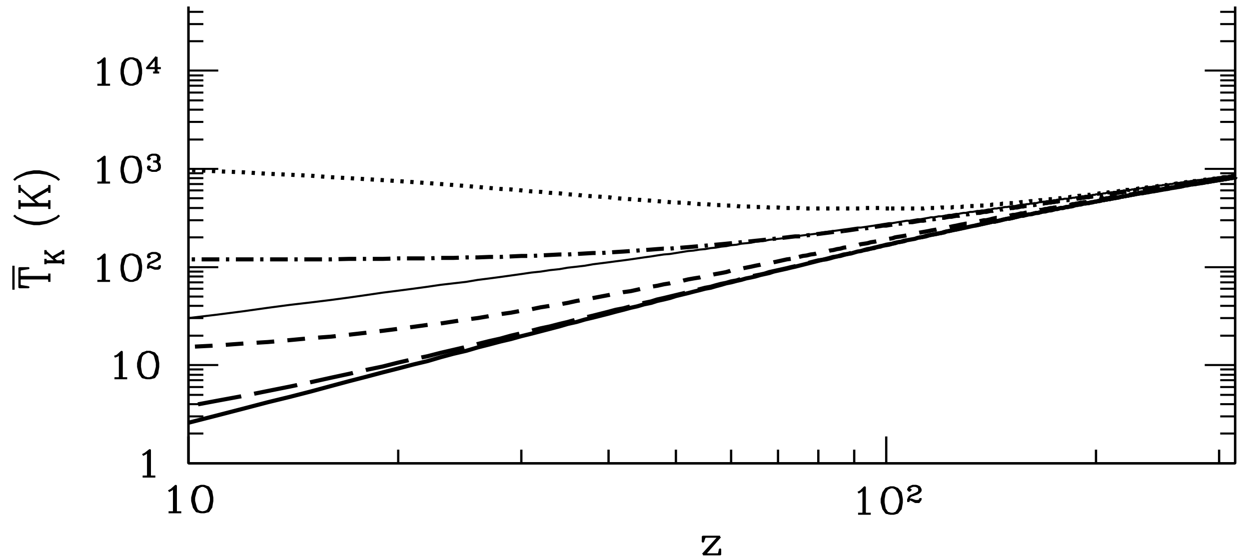
$T_S \rightarrow T_K < T_{CMB}$ Atomic collisions dominate CMB photon absorption

$z \sim 40$ $T_S \rightarrow T_{CMB}$ Due to decreasing gas density and temperature, radiative coupling to the CMB photon absorption/emission dominates atomic collisions.

e.g. exotic heating sources:

- DM decay and annihilation during the cosmic dark ages

(Chen&Kamionkowski(2004), Furlanetto+(2006): DM decay)



Our work: DM elastic scattering

$$(1+z)\frac{dT_d}{dz} = 2T_d + \frac{2m_d}{m_d+m_H}\frac{K_b}{H}(T_d - T_b),$$

$$(1+z)\frac{dT_b}{dz} = 2T_b + \frac{2\mu_b}{m_e}\frac{K_\gamma}{H}(T_b - T_\gamma) + \frac{2\mu_b}{m_d+m_H}\frac{\rho_d}{\rho_b}\frac{K_b}{H}(T_b - T_d)$$

Momentum transfer rate

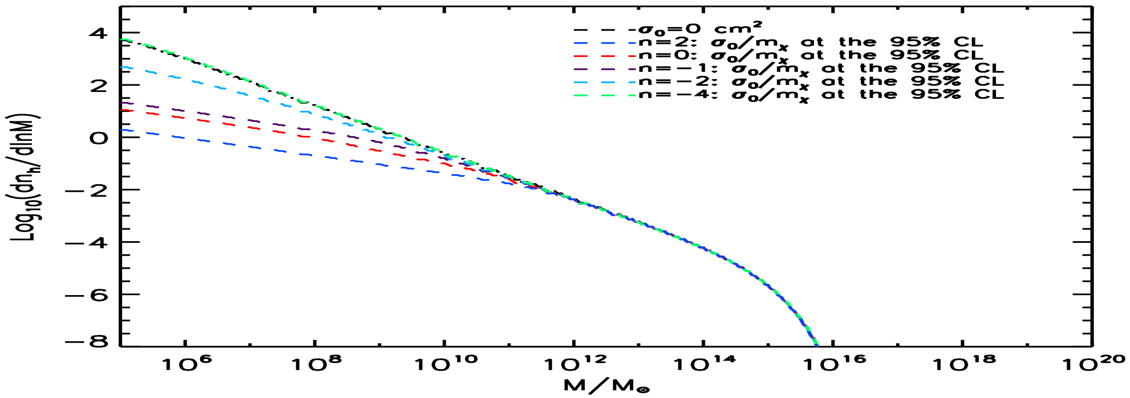
$$K_\gamma = \frac{4\rho_\gamma}{3\rho_b} n_e \sigma_T$$ (Compton collision rate)

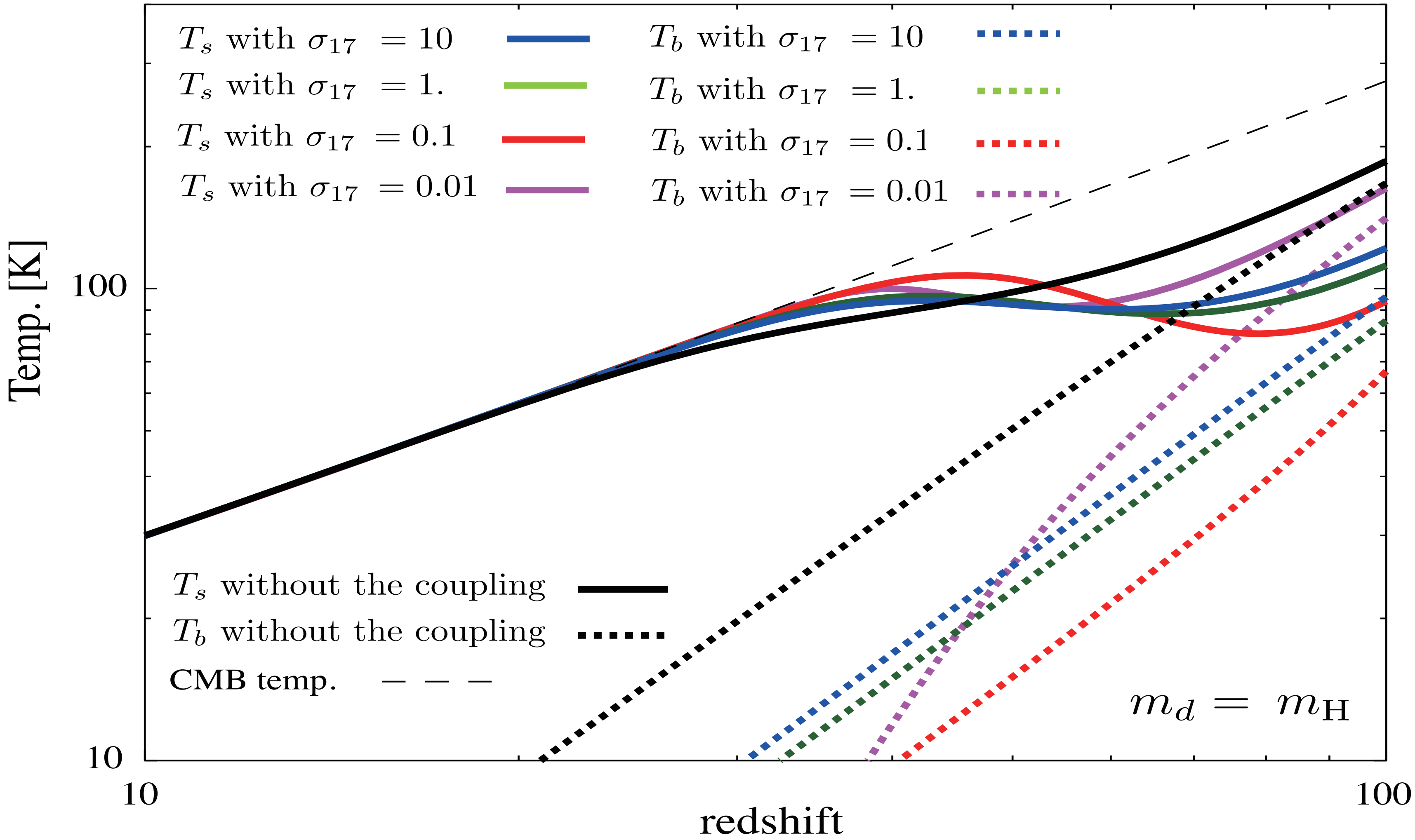
$$K_b = \frac{c_n \rho_b \sigma_0}{m_H + m_d}\left(\frac{T_b}{m_H} + \frac{T_d}{m_d}\right)^{\frac{n+1}{2}}, \qquad \sigma(v) = \sigma_0 v^n$$

✧ Planck+SDSS

n	σ / m_{DM} (95%CL, cm^2/g)
-4	1.7×10^{-17}
-2	6.2×10^{-10}
-1	1.4×10^{-6}
0	3.3×10^{-3}
+2	9.5×10^{3}

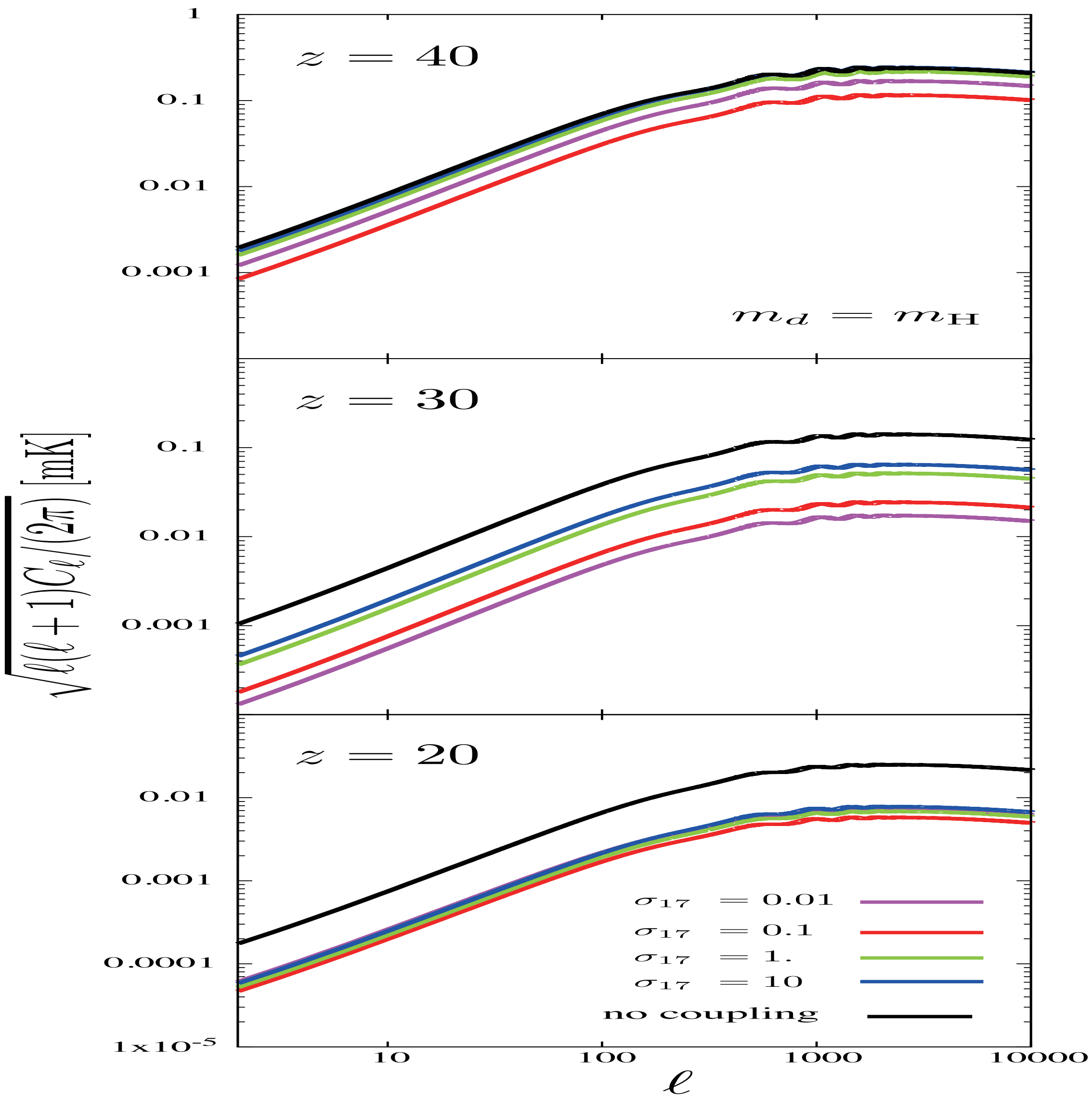
Dvorkin, Blum and Kamionkowski (2013)





Tashiro, KK, Silk (2014)

21 cm signals



Tashiro, KK, Silk (2014)

$$C_l \sim (\delta T_b)^2, \delta T_b \sim 26mK\left(1-\frac{T_\gamma}{T_s}\right)\left(\frac{1+z}{10}\right)$$

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Kinetic decoupling of DM

- Chemical decoupling (Temperature ~ 10 GeV)

DM annihilation rate < expansion rate of the Universe

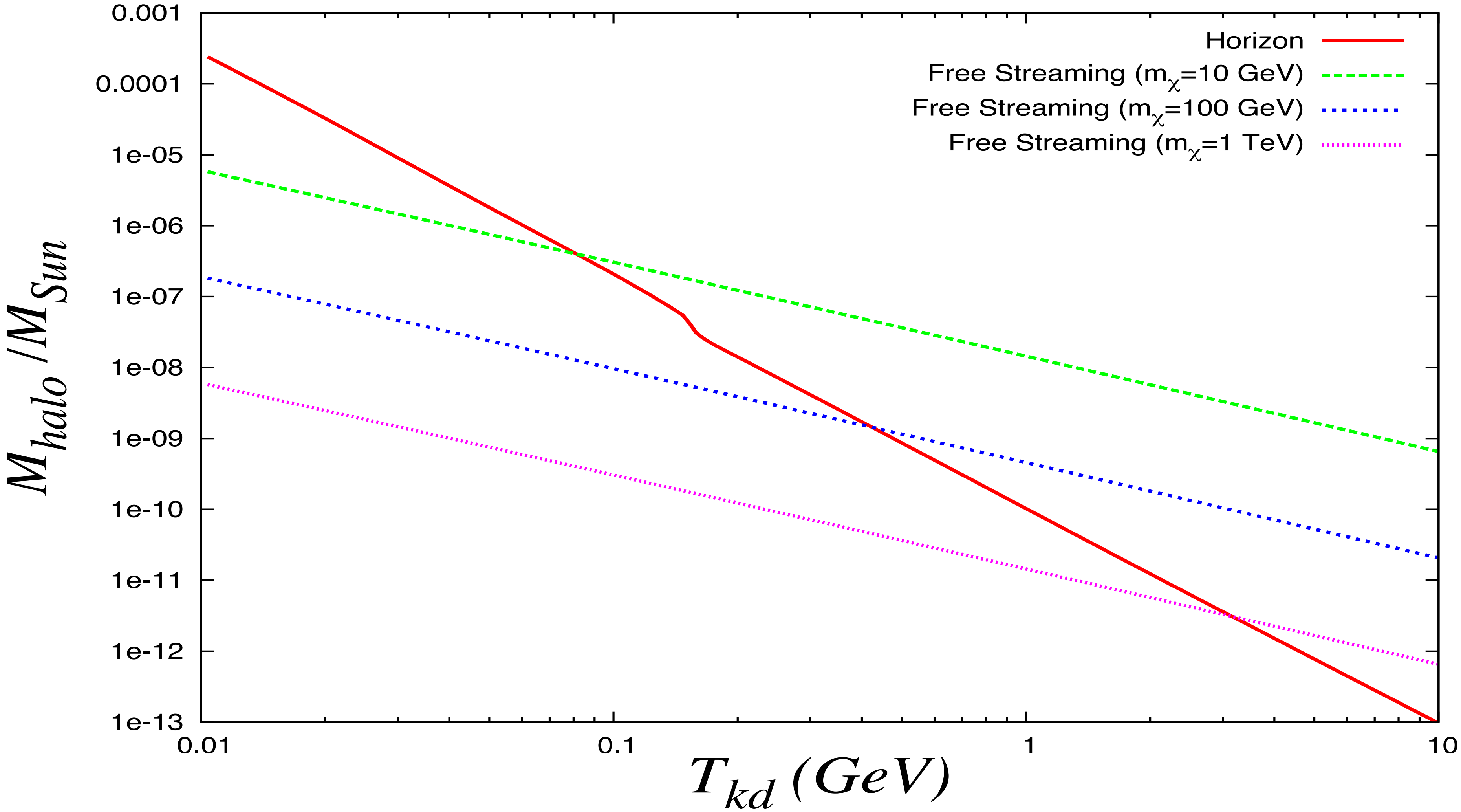
- Kinetic decoupling (Temperature ~ 10 MeV)

DM scattering rate < expansion rate of the Universe

Why bother with DM kinetic decoupling?

Probe on the nature of dark matter (DM)
An application:
The size of smallest dark matter halo

•Analogous to:
Physics of baryon decoupling
probing the nature of Universe via BAO and CMB



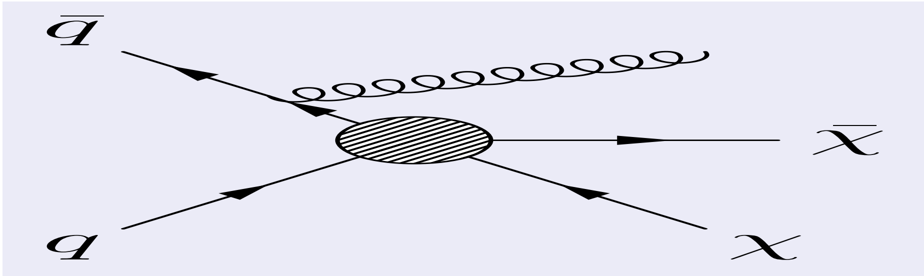
P. Gondolo, J. Hisano, KK (2012)

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

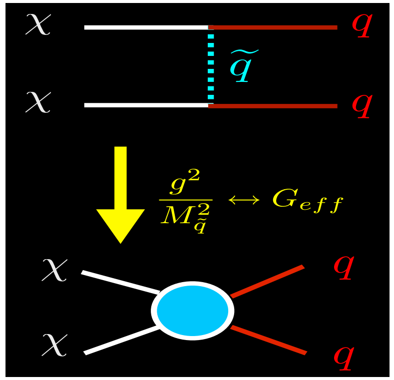
DM interactions: Effective operators

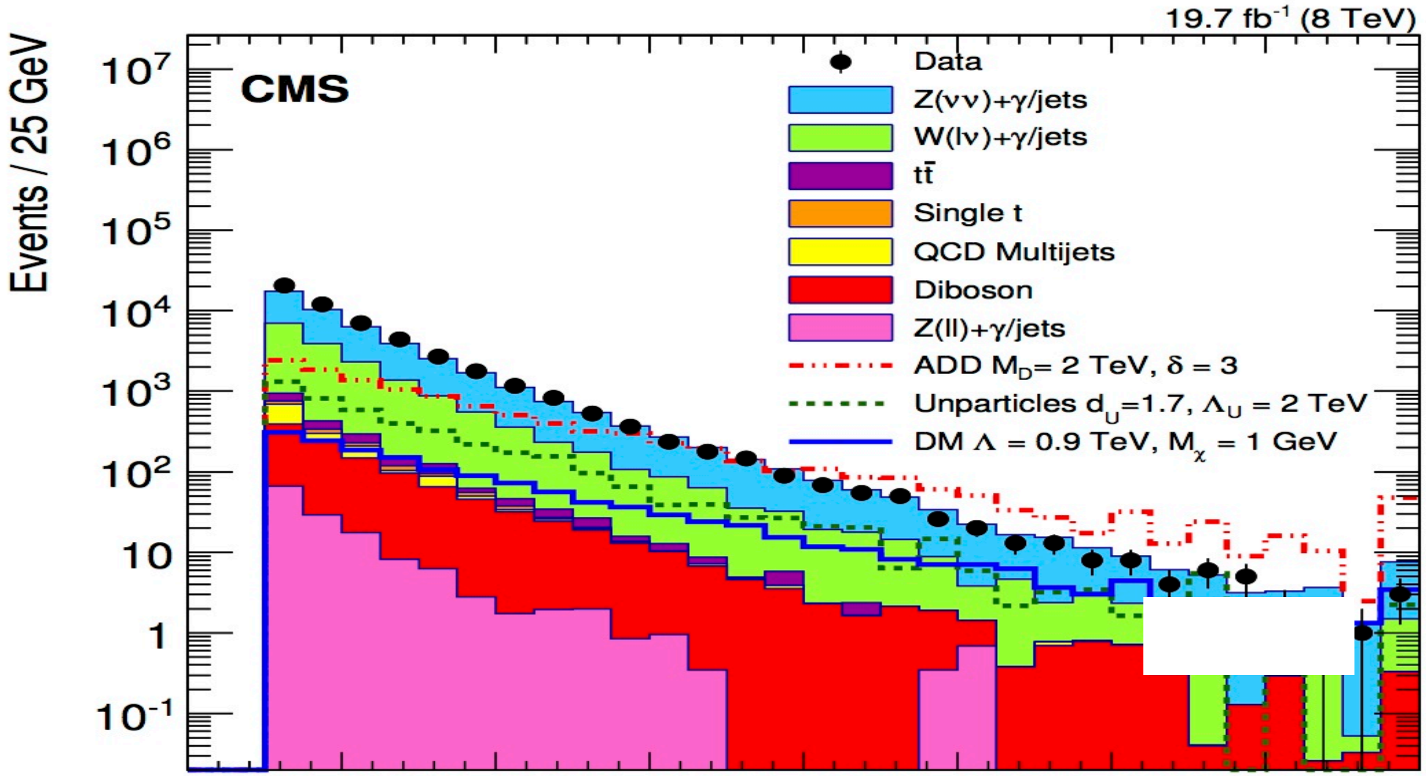
Beltran et al (2010), Agrawal et al (2010), Goodman et al (2010),Fox et al (2010), Rajaraman et al (2011),Cheung et al (2012), March-Rusell et al (2012),...)

e.g. Mono-jet



$$O_s = \sum_q \frac{1}{\Lambda^2} \bar{\chi}\chi\bar{q}q$$

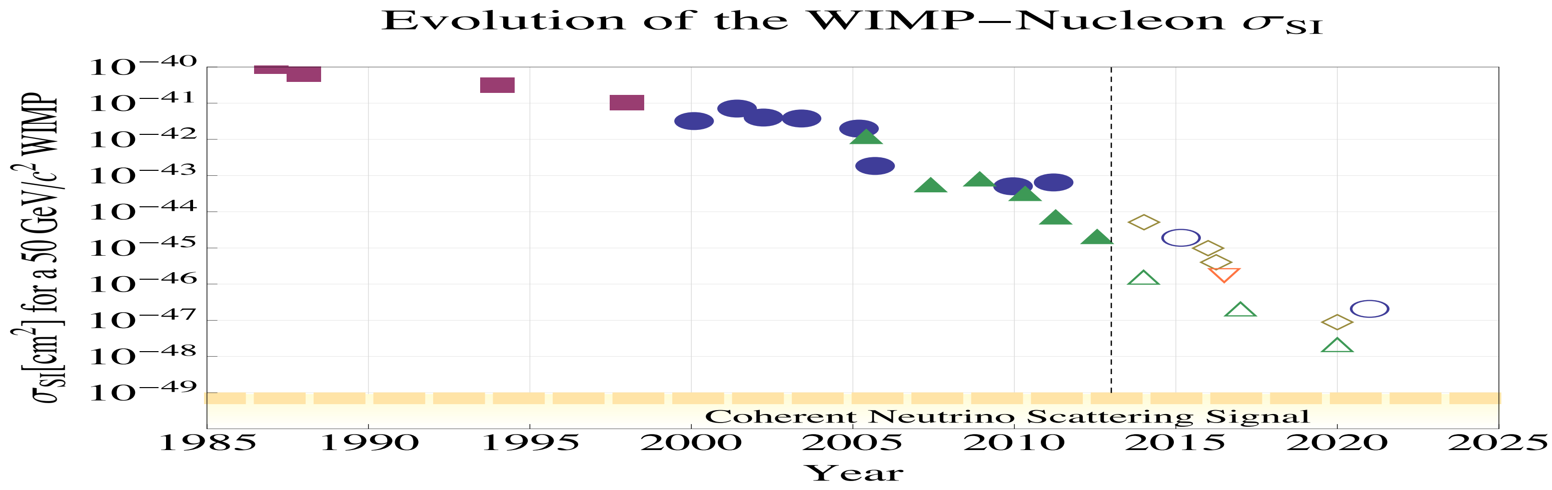




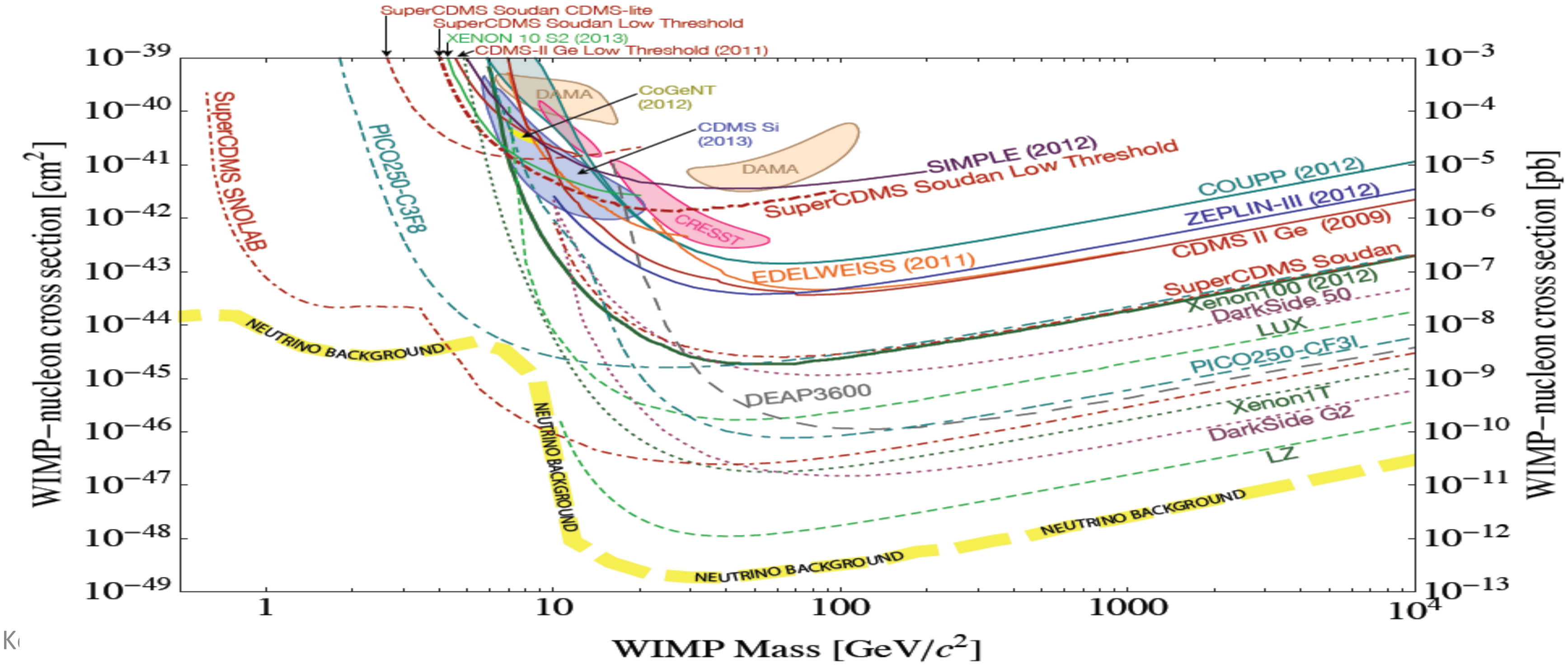
Pt>110GeV,|η|<2.4
MET >350GeV

Direct detection

Moore's law for dark matter



Snowmass 2013



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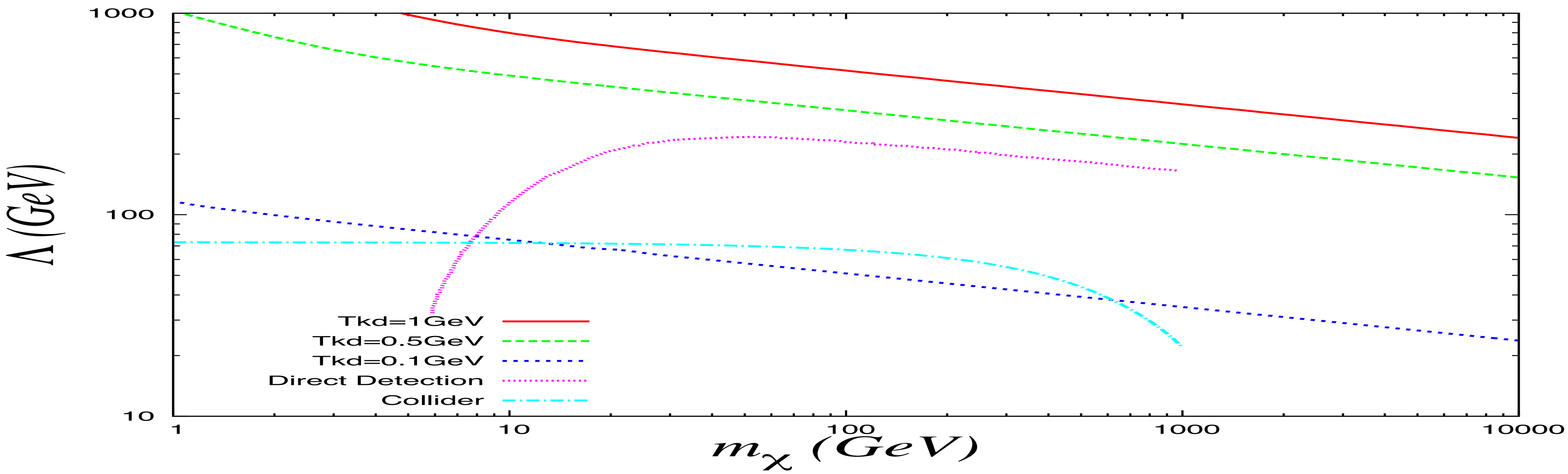

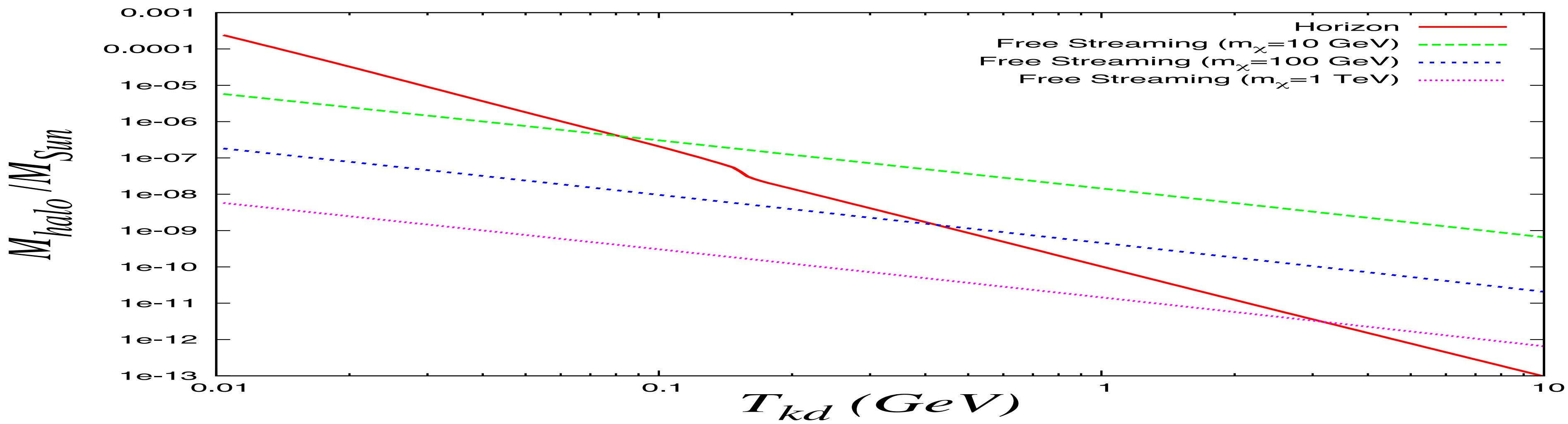

- Results

The smallest dark matter halo mass: Earth size(10^{-6} M_{sun})

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→ Illustration of the potential power on the cosmological parameters

Example 2: 21 cm probes on the DM-baryon elastic scattering

→ Can change the 21cm signals by 100% or more compared with no coupling scenarios

Complementarity: Cosmology and Particle physics connection

→ Multiple probes would be essential to study the DM properties
(DM direct/indirect detection experiments, collider, large scale structure, CMB)