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

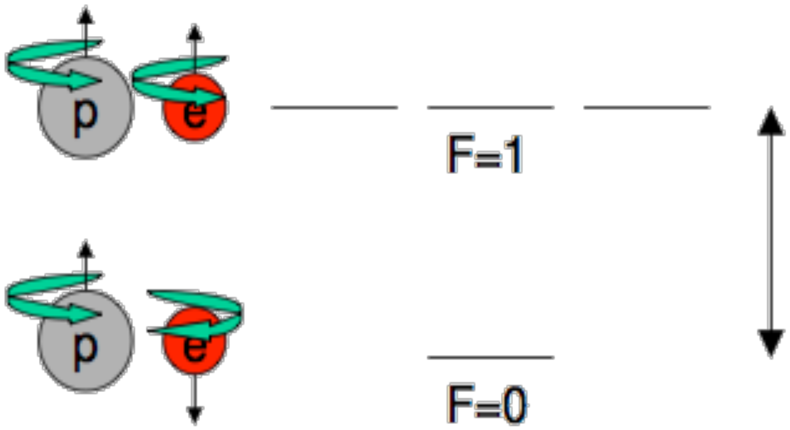
Example 2: 21 cm probes on the DM-baryon elastic scattering

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

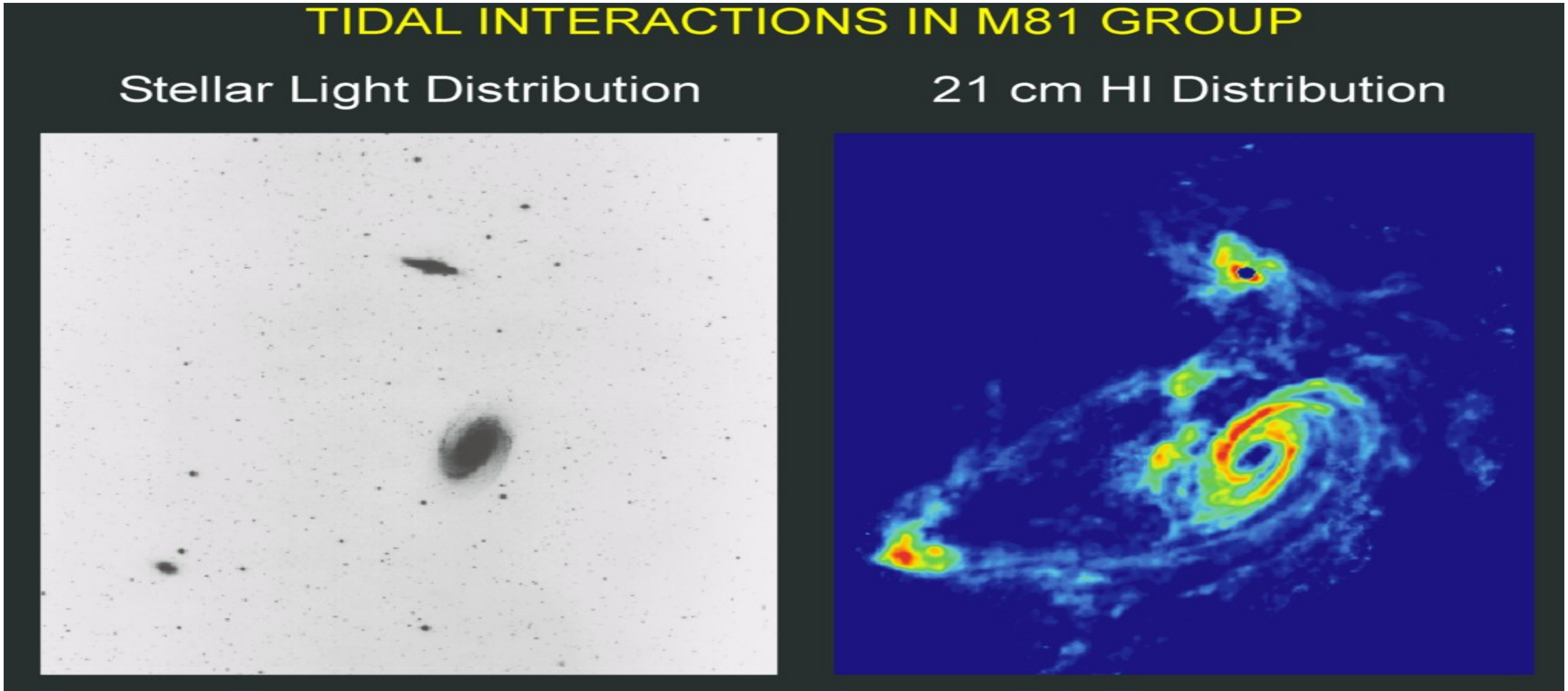
Complementarity: Cosmology and Particle physics connection

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

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

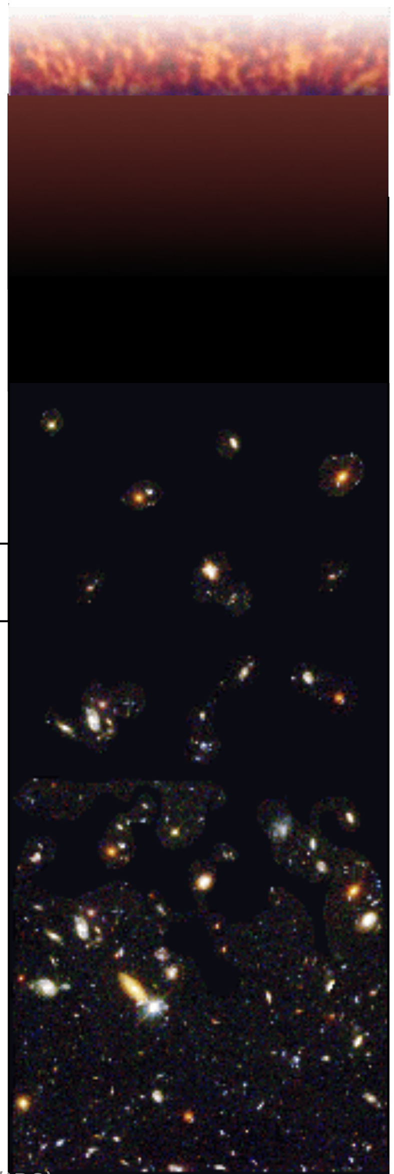


21 cm signals
1420 MHz



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)

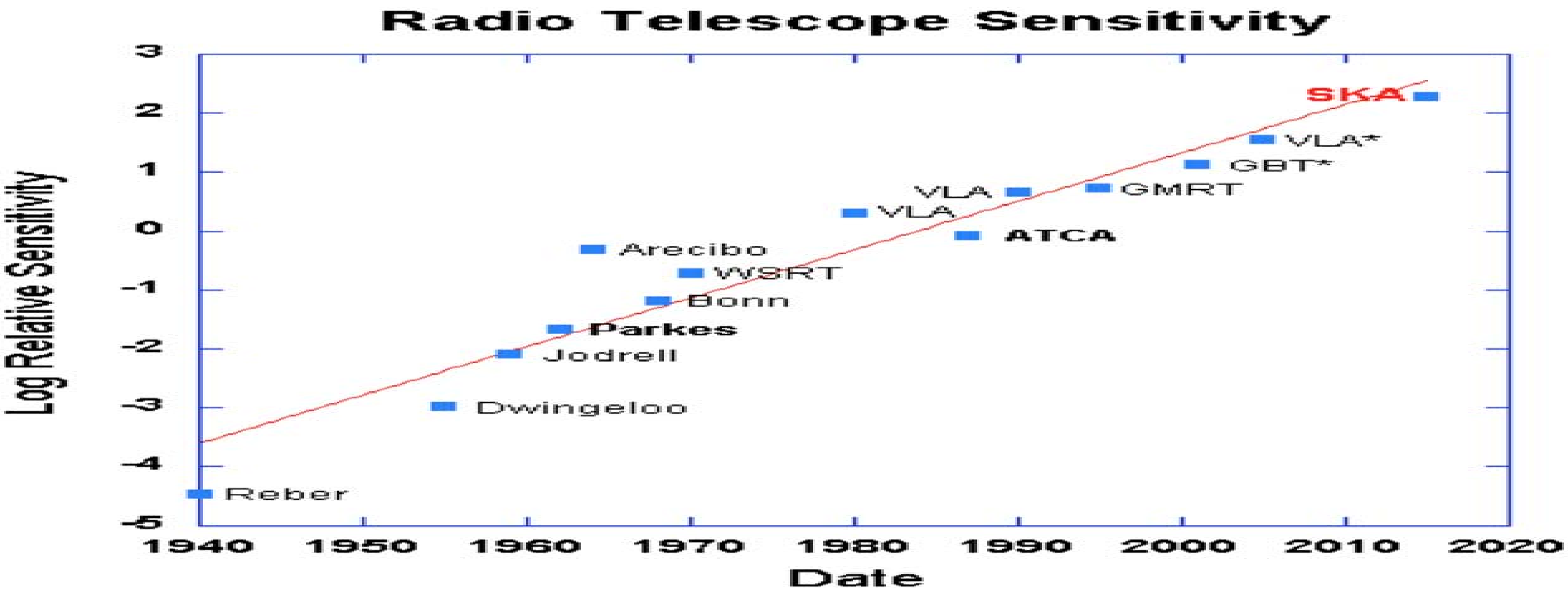
← Today's structures

Square Kilometer Array

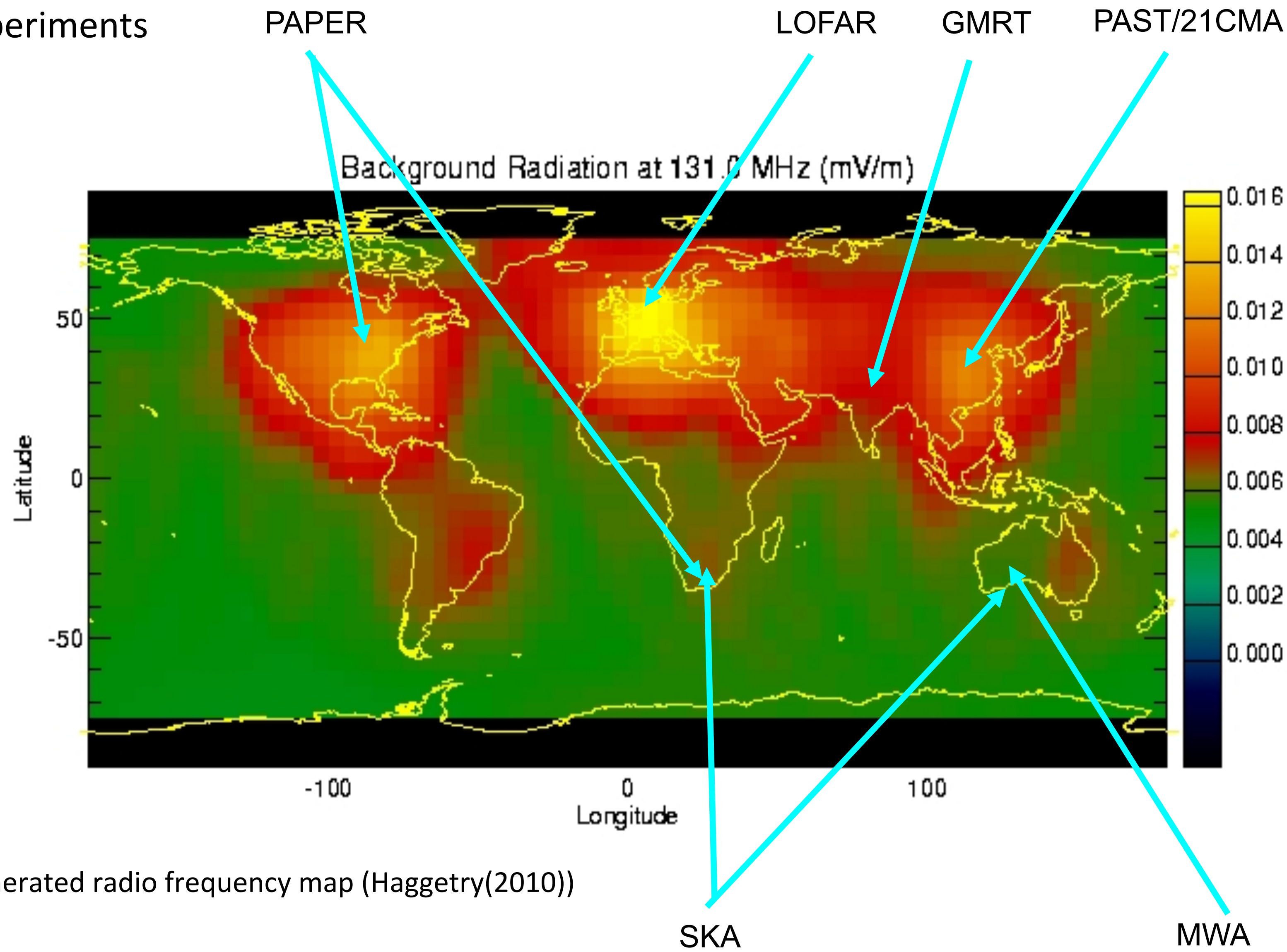
South Africa- Karoo
Australia- Western Outback

Detailed designing underway to fit cost cap of 650M Euros
Decision expected ~ March 2015

Initial construction ~2015, First data taking ~ 2020, Full operation ~ 2024



21cm experiments



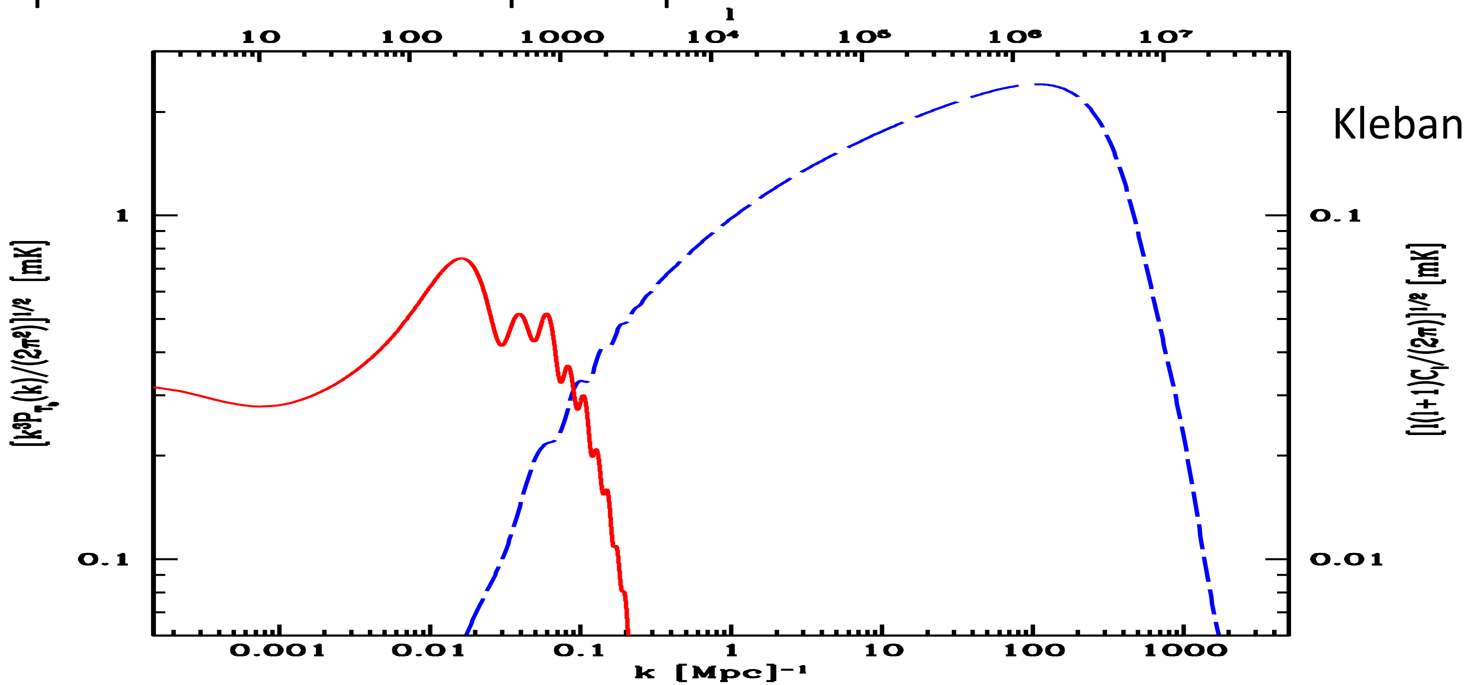
(Human generated radio frequency map (Haggetry(2010))

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

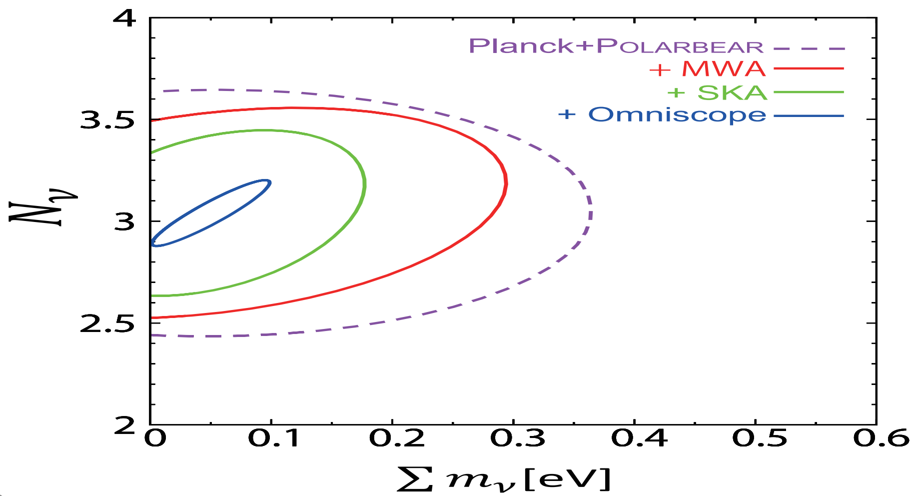
What can we do with 21cm?

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),…)

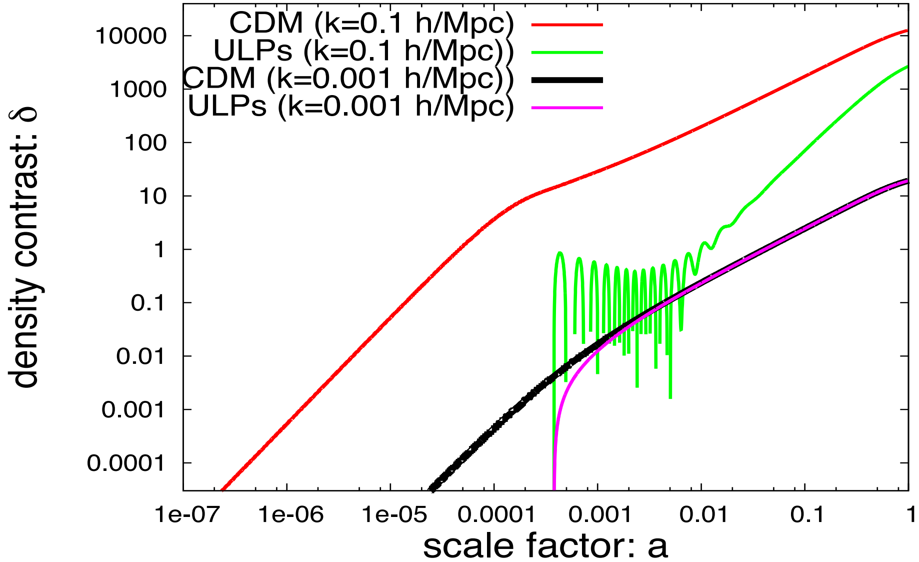
$m_u \sim 10^{-22} eV$ DM (Hu (2000),…)

$m_u \sim 10^{-22} eV - 10^{-10} eV$ 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)

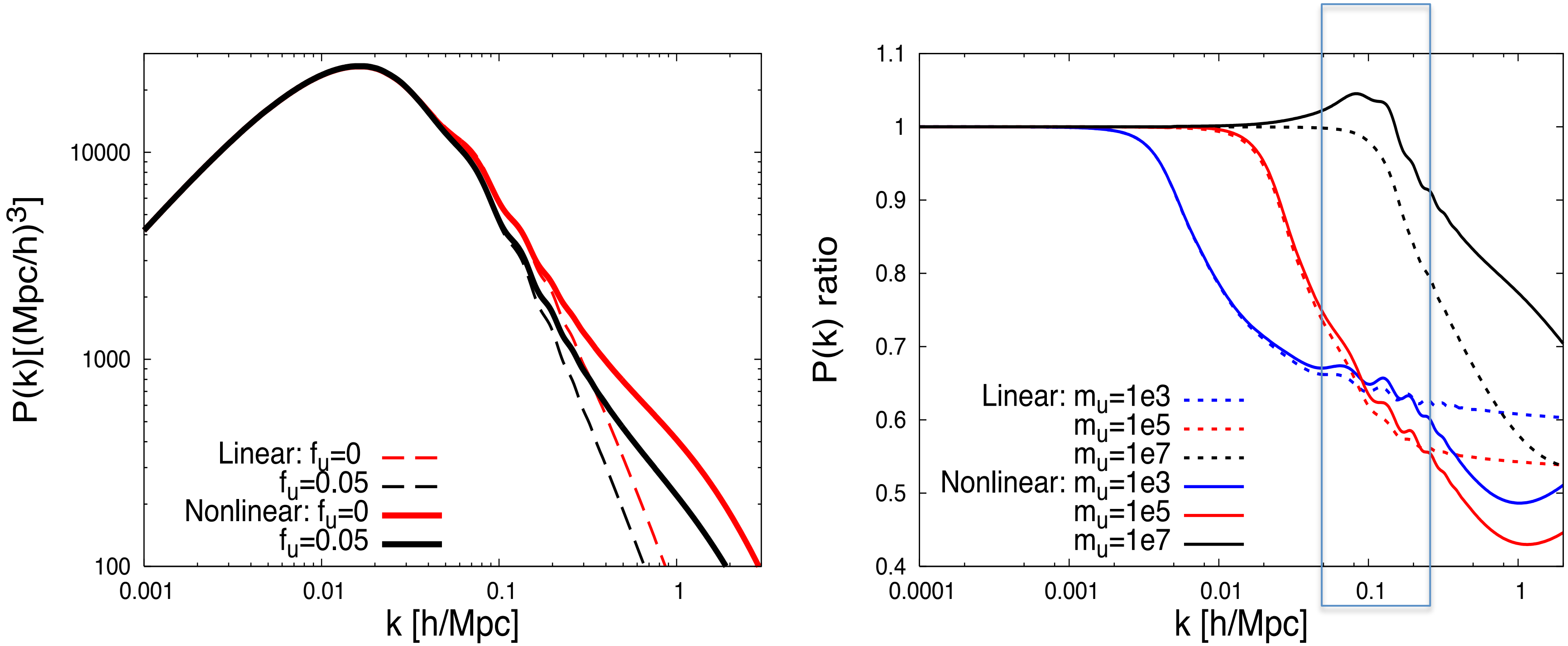
The perturbation evolutions for ULPs ($m_u = 10^5 H_0$, $f_u = 0.05$) and CDM.

Cannot grow inside the free streaming scale

Power spectrum P(k)

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

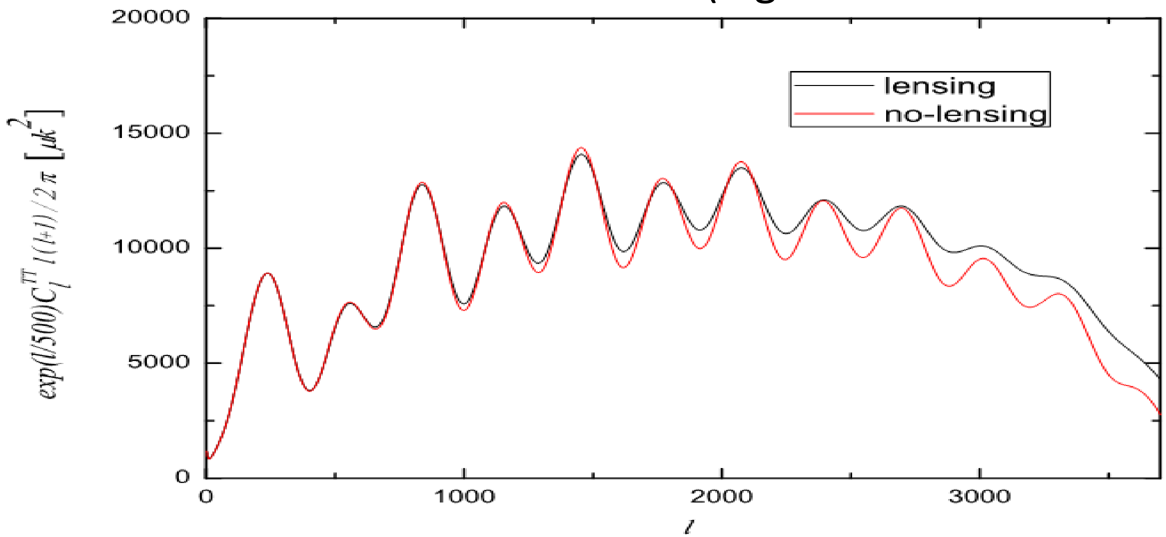
If oscillation starts during radiation domination : $z_{osc} \sim m^{1/2}, k_* \sim m^{1/2}$



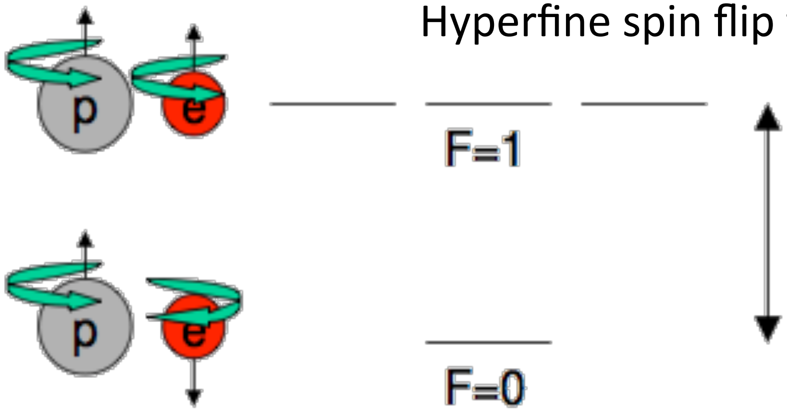
KK, Mao, Ichiki, Silk (2014)

Cosmological observables: CMB (including lensing) + 21cm

(e.g. Lewis & Challinor 2006)



Hyperfine spin flip transition



21 cm signals

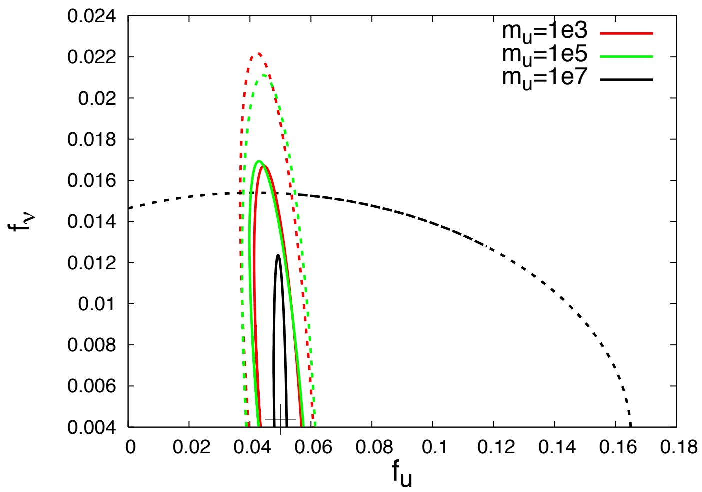
$\lambda = 21\,\mathrm{cm}$

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

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

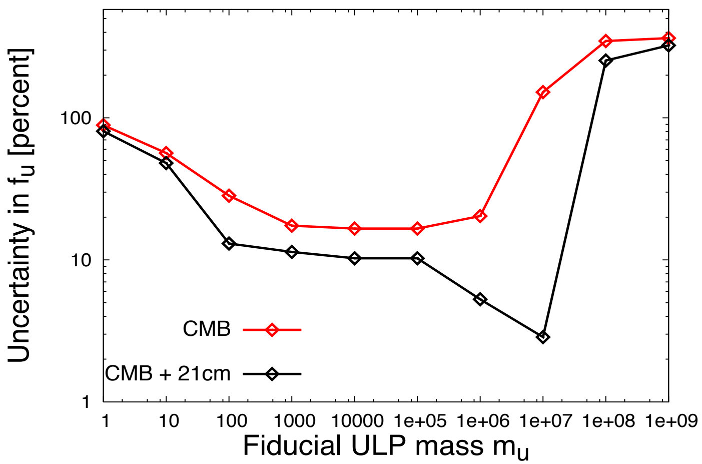
Uncertainties in f_u, m_u: 10~20 %

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)



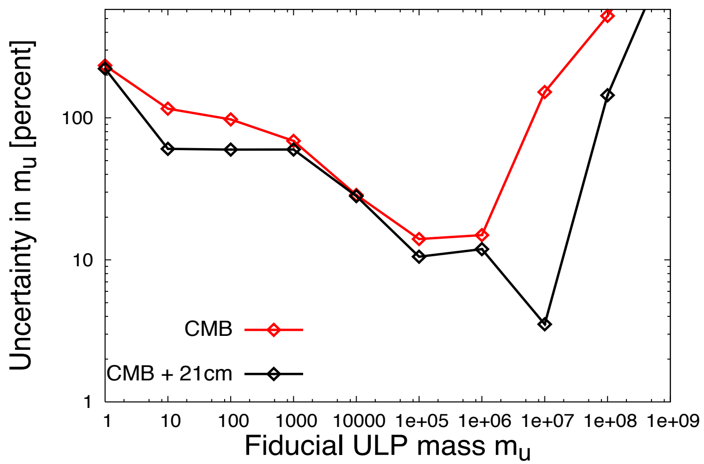


Figure 4: 1σ errors in f_u and m_u (the fiducial value $f_u = 0.05$) for several fiducial values of m_u in terms of $H_0 (\approx 2 \times 10^{-33}$ eV).

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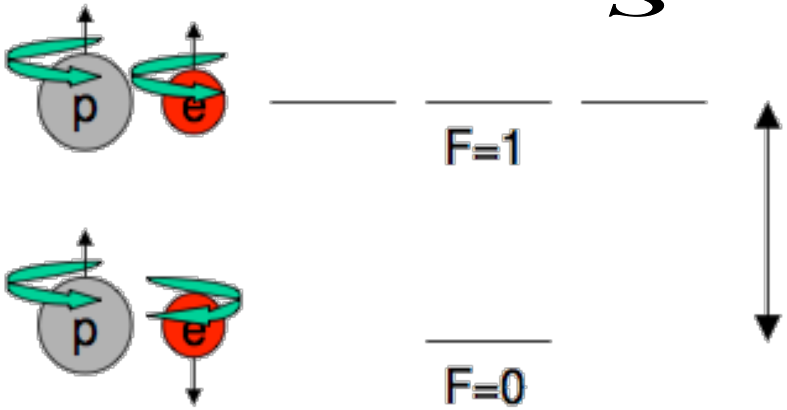
What can we measure through 21cm signals? $T_S - T_{CMB}$

Spin temperature T_S



Hyperfine spin flip transition

21 cm signals

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

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp(-T_* / T_S),$$

$\left(\frac{g_1}{g_0} = 3(\text{weights of singlet and triplet hyperfine levels}), T_* = h\nu_{10} / k\right)$

$(T_* = 0.0681K \text{ for 21cm line})$

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).

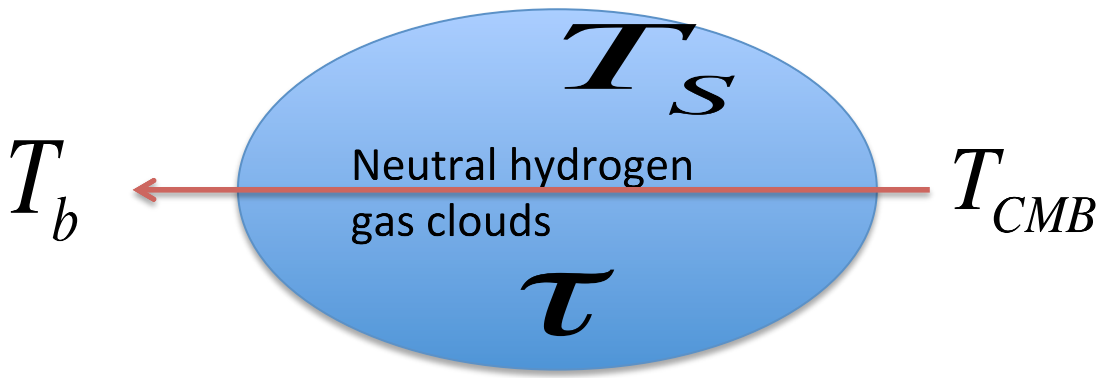
Ts is the weighted average of CMB temperature and gas temperature (Field (1958)):

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

If collision is efficient, coupling coefficient yc gets big and Ts->Tk
If yc or Tk gets small, Ts->Tcmb.

Brightness temperature T_b

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

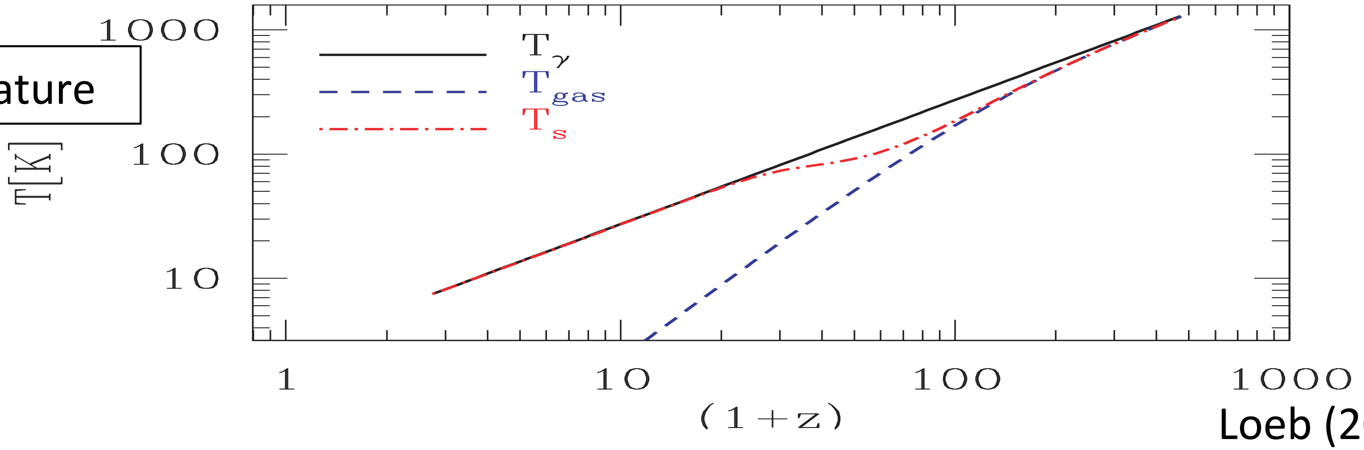


Differential brightness temperature:

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

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

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

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

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

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

$z \sim 40$ $T_S \to T_{CMB}$

Due to decreasing gas density and temperature, radiative coupling to the CMB photon absorption/emission dominates atomic collisions.

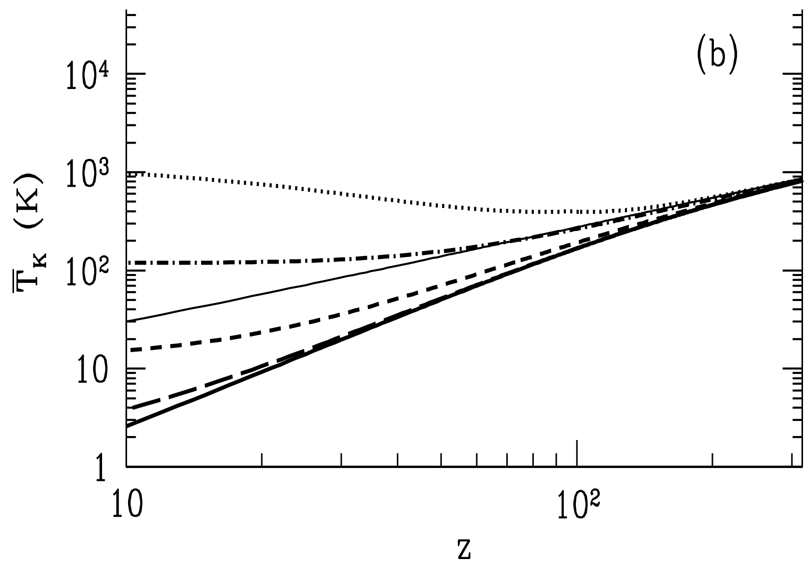
In the conventional scenarios, DM is irrelevant in estimating gas temperature
Non-standard cosmological scenarios can change the temperature evolution history

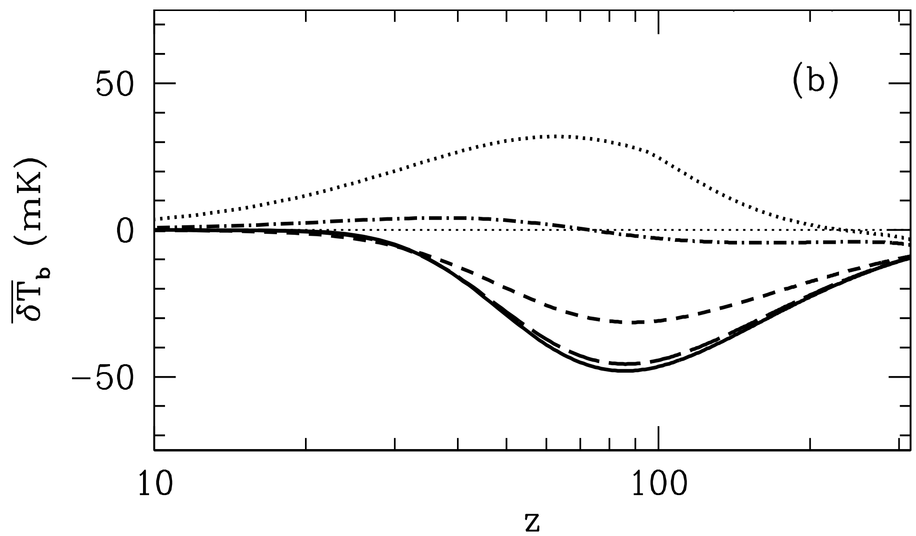
e.g. exotic heating sources:

- DM decay and annihilation during the cosmic dark ages (Chen&Kamionkowski(2004))

21cm observables can distinguish among the parameters

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

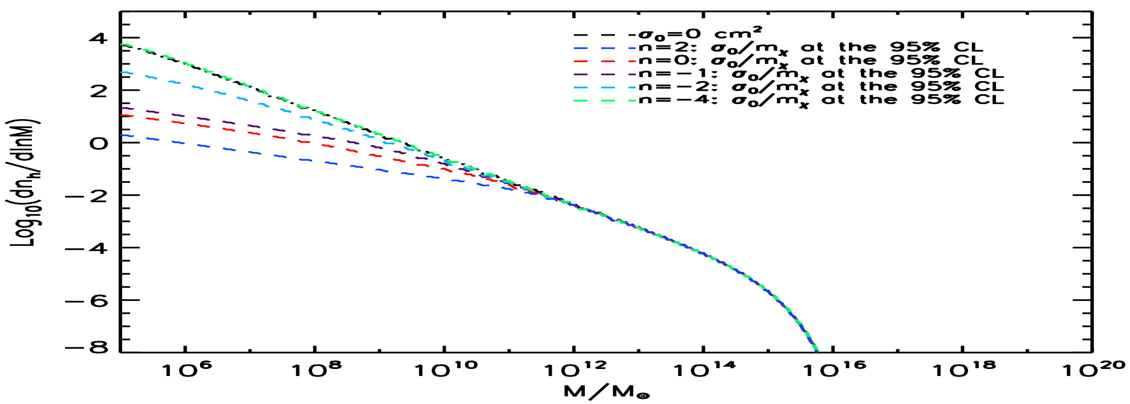
$$K_\gamma = \frac{4\rho_\gamma}{3\rho_b} n_e \sigma_T$$ (Compton collision rate)

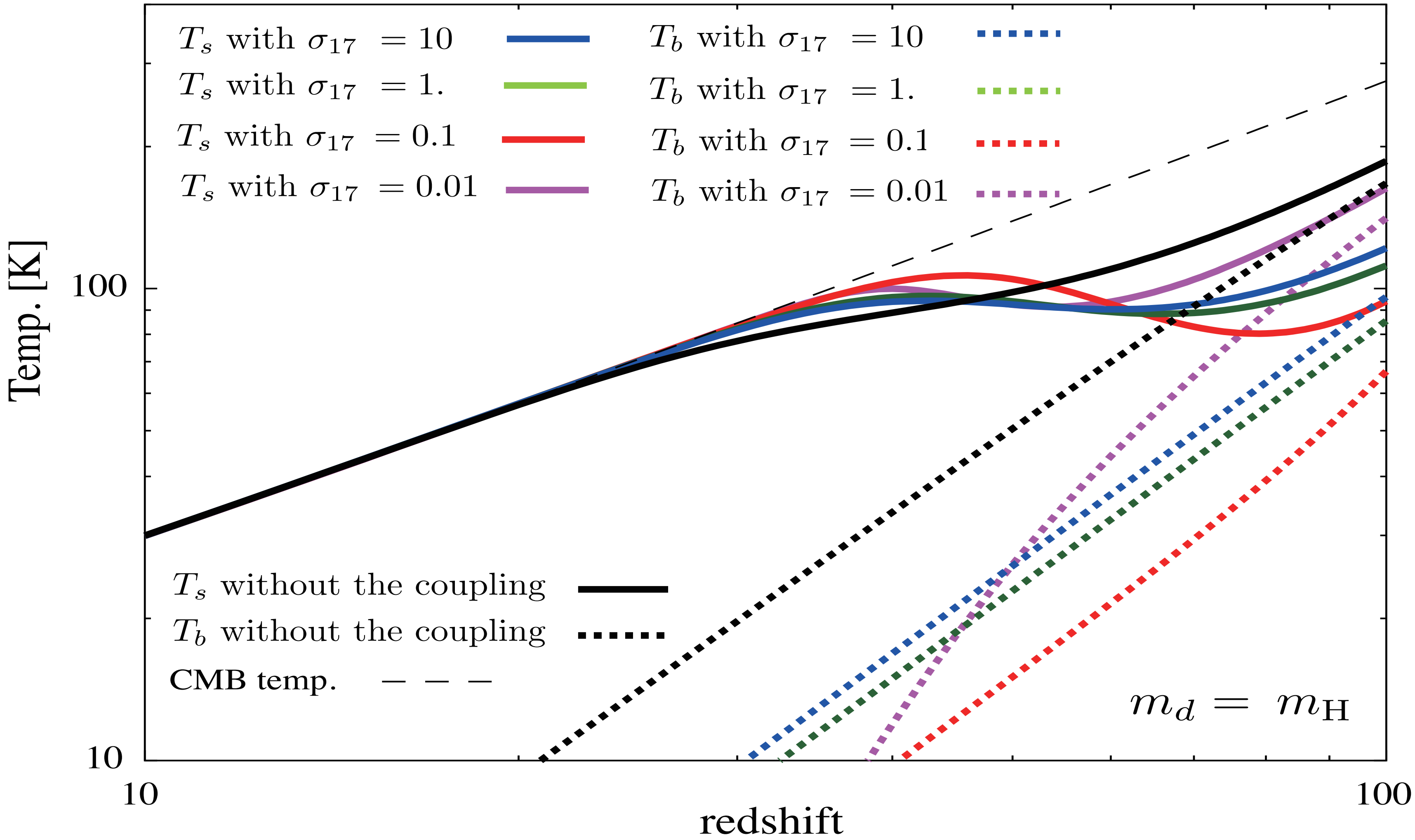
$$K_b = \frac{c_n \rho_b \sigma_0}{m_H + m_d}\left(\frac{T_b}{m_H} + \frac{T_d}{m_d}\right)^{\frac{n+1}{2}}, \qquad \sigma(v) = \sigma_0 v^n$$

✧ Planck+SDSS

Dvorkin, Blum and Kamionkowski (2013)

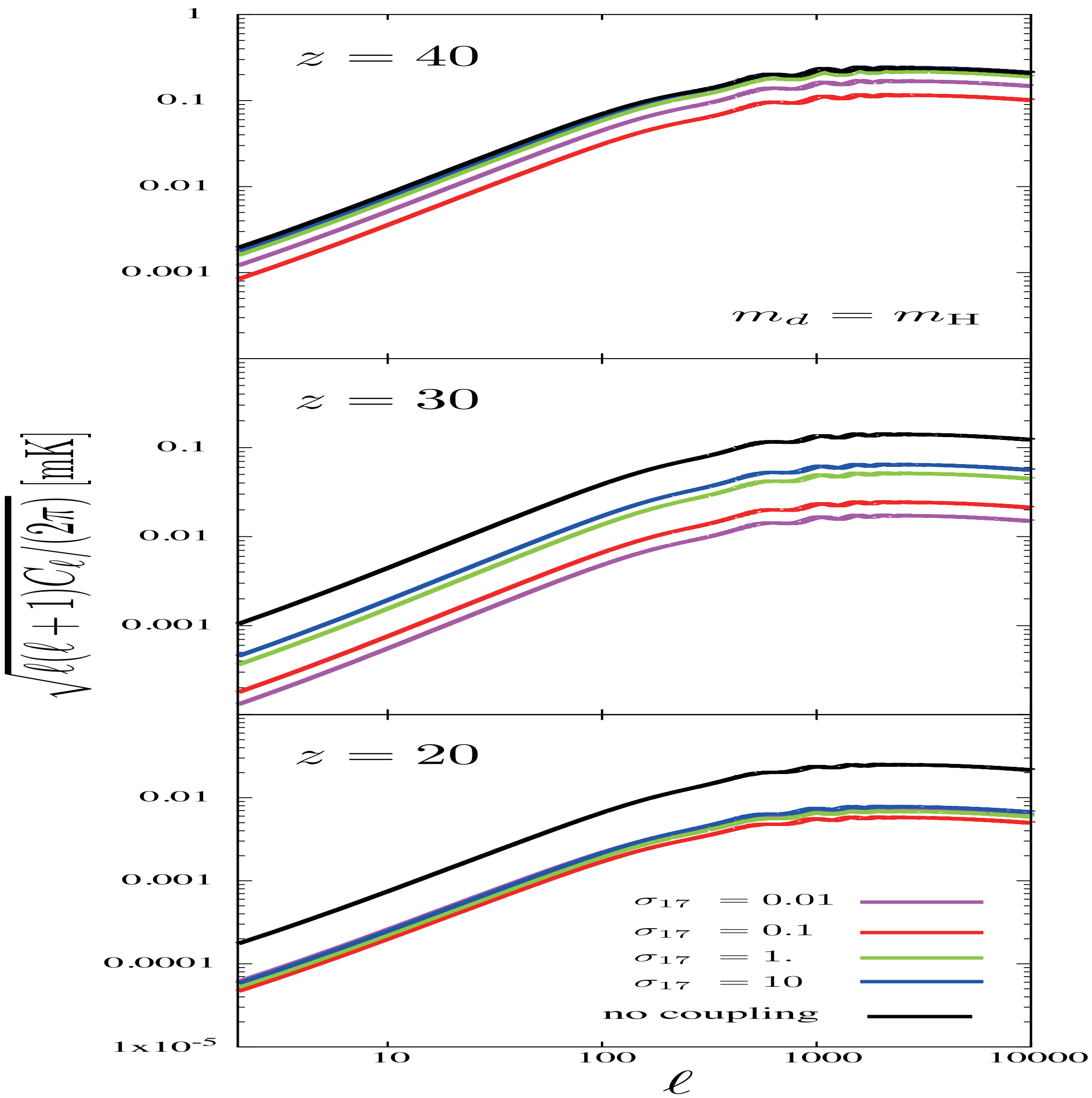
n	σ / m_{DM} (95%CL, cm^2/g)
-4	1.7×10^{-17}
-2	6.2×10^{-10}
-1	1.4×10^{-6}
0	3.3×10^{-3}
+2	9.5×10^{3}





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

Dark matter fluctuation growth constraints from the current data

✧ Planck+SDSS

Dvorkin, Blum and Kamionkowski (2013)

n	$(\sigma / m_{DM}$ (95%CL, cm^2/g)
-4	1.7×10^{-17}
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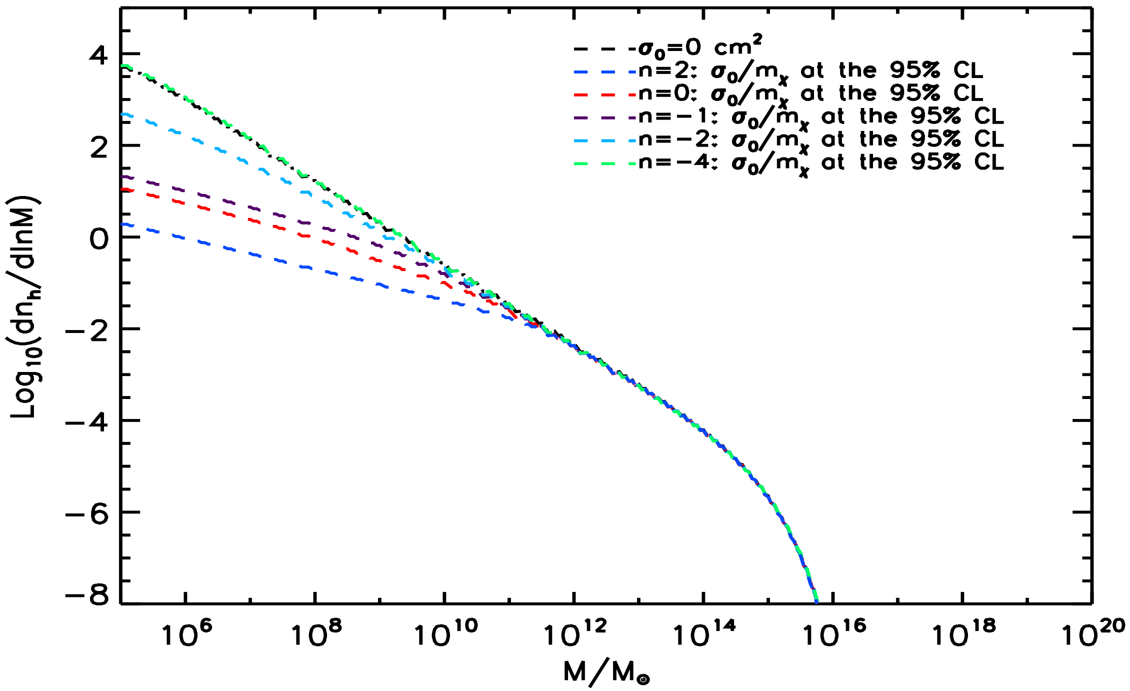
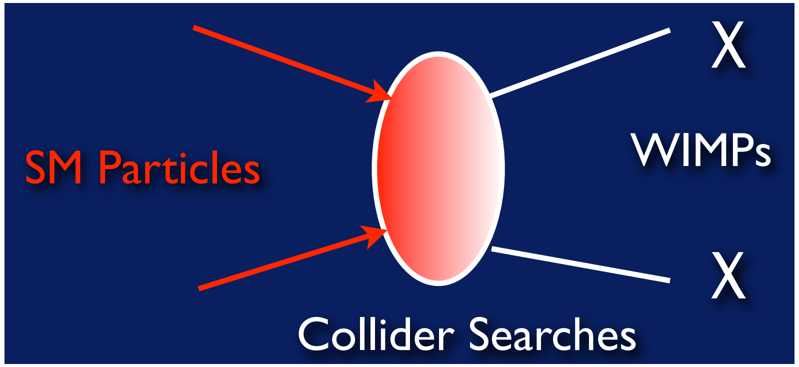
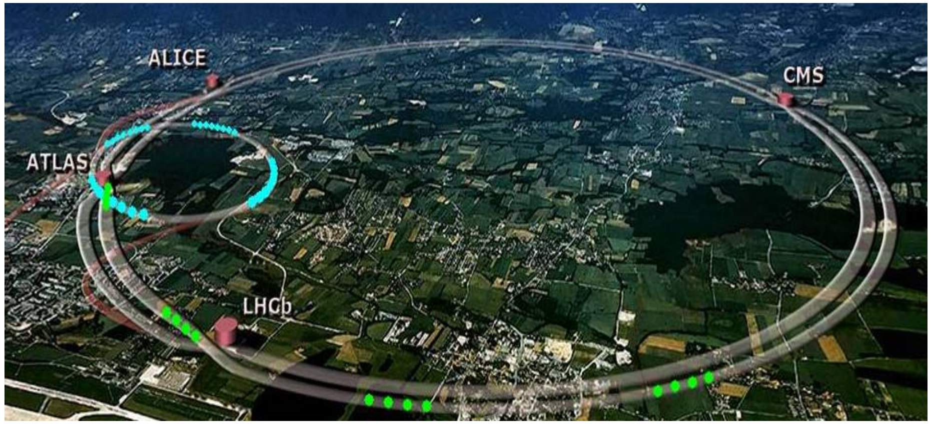
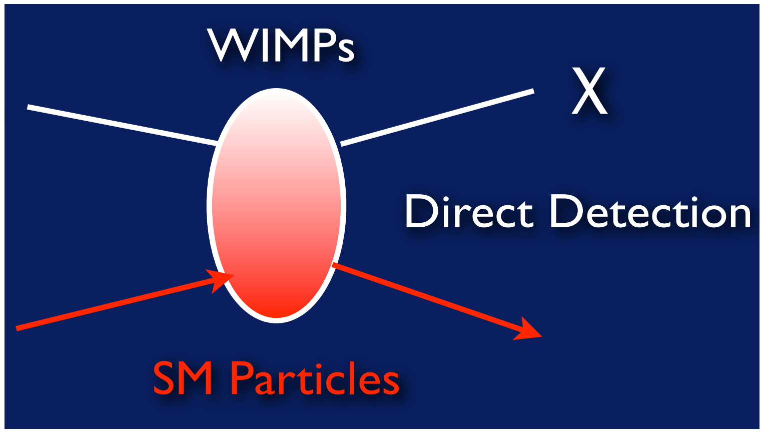
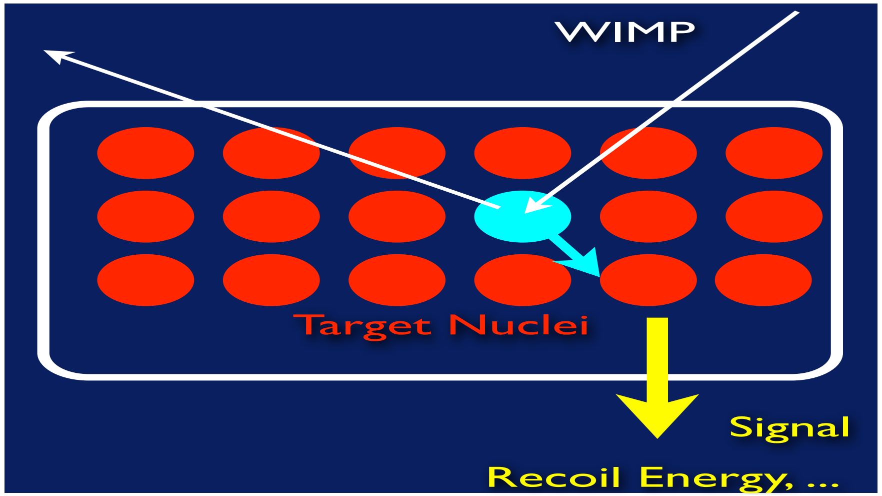


✧ LHC and Direct dark matter search experiments on DM-baryon elastic scattering
P. Gondolo, KK, J. Hisano, (2012)

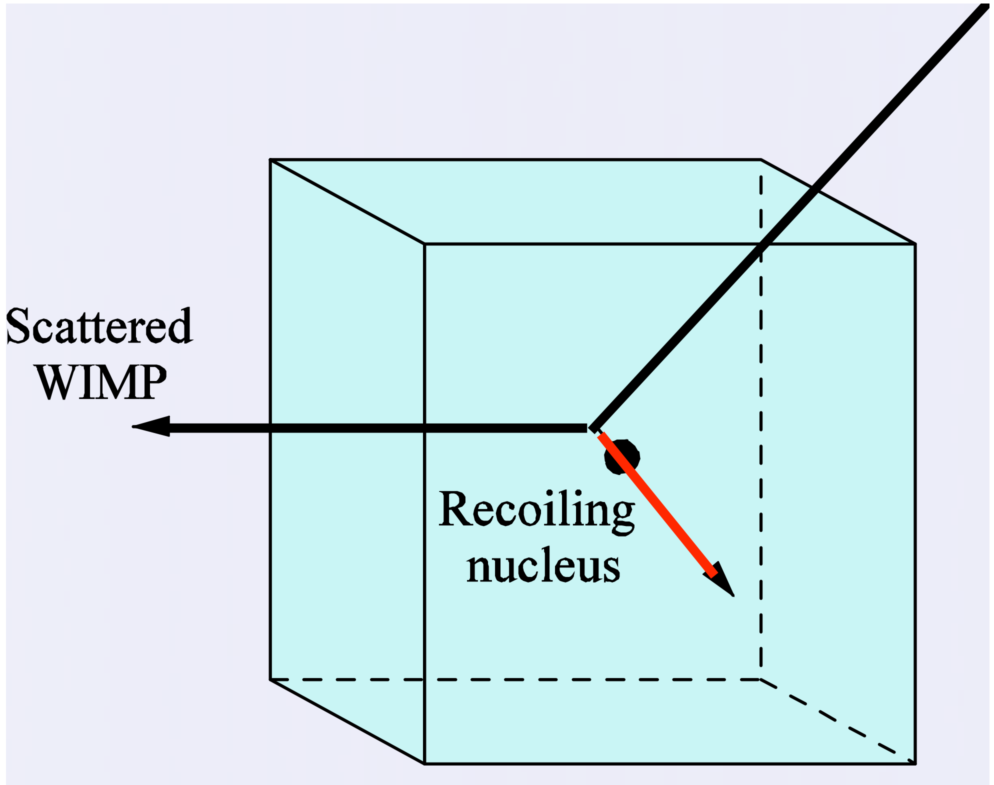








DM Direct Detection

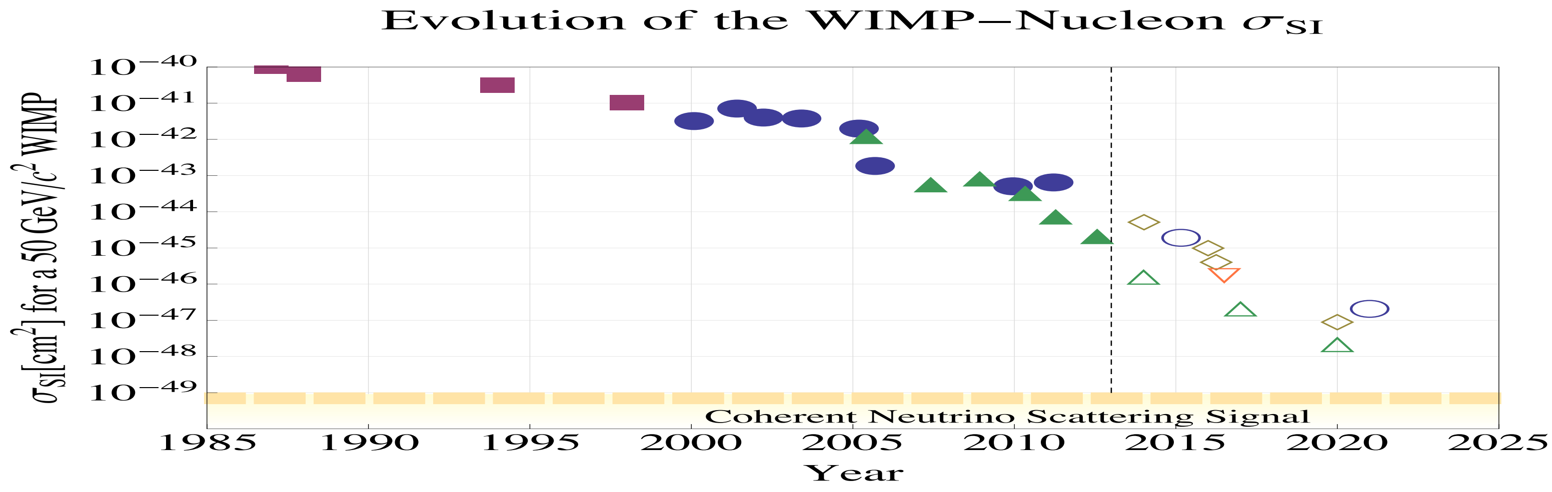


Measures nuclear recoil energy via

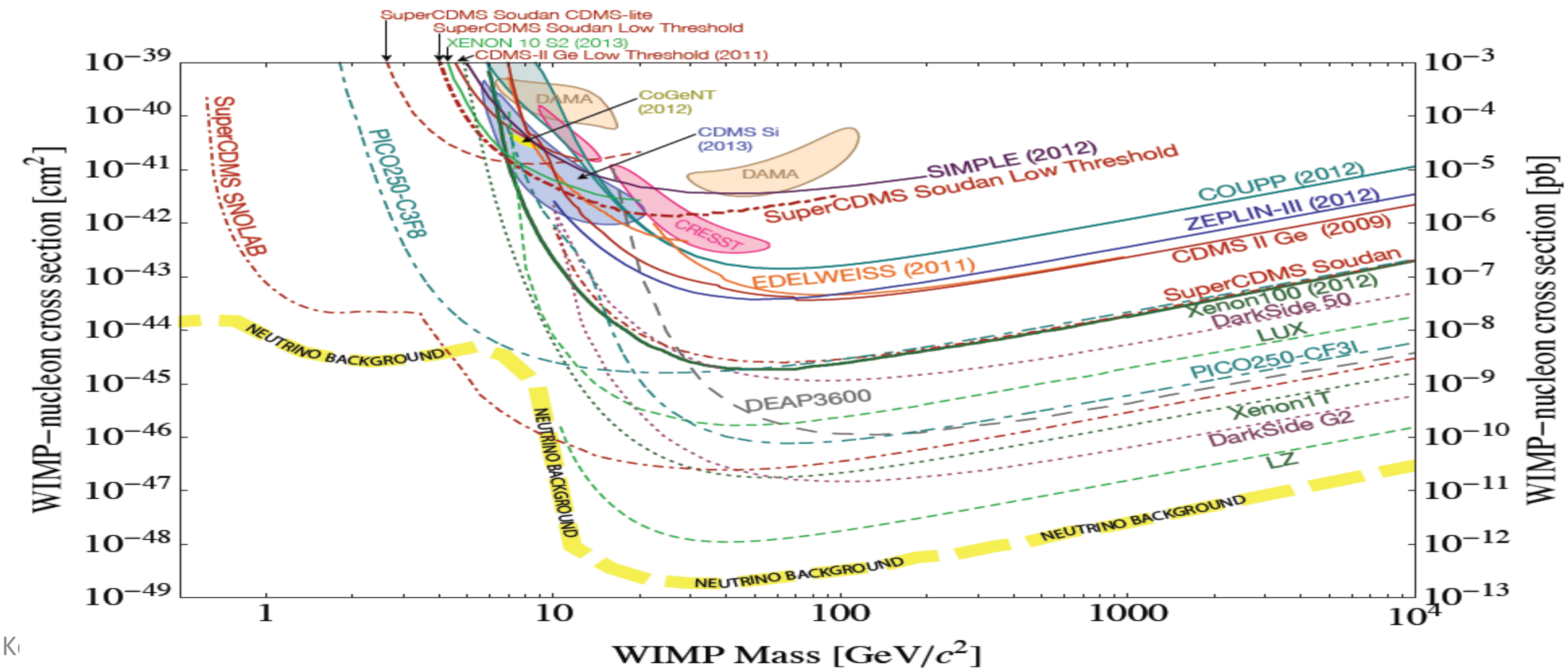
1) Ionization on solids (local release of charge)
2) Scintillators (emitted photons)
3) Temperature increase (released phonons)

Direct detection

Moore's law for dark matter



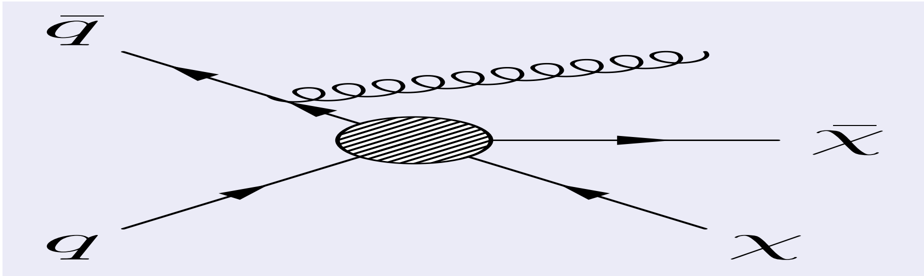
Snowmass 2013

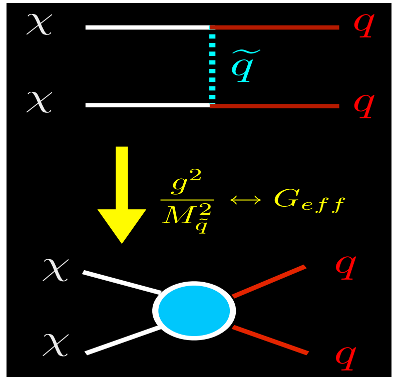


DM interactions: Effective operators

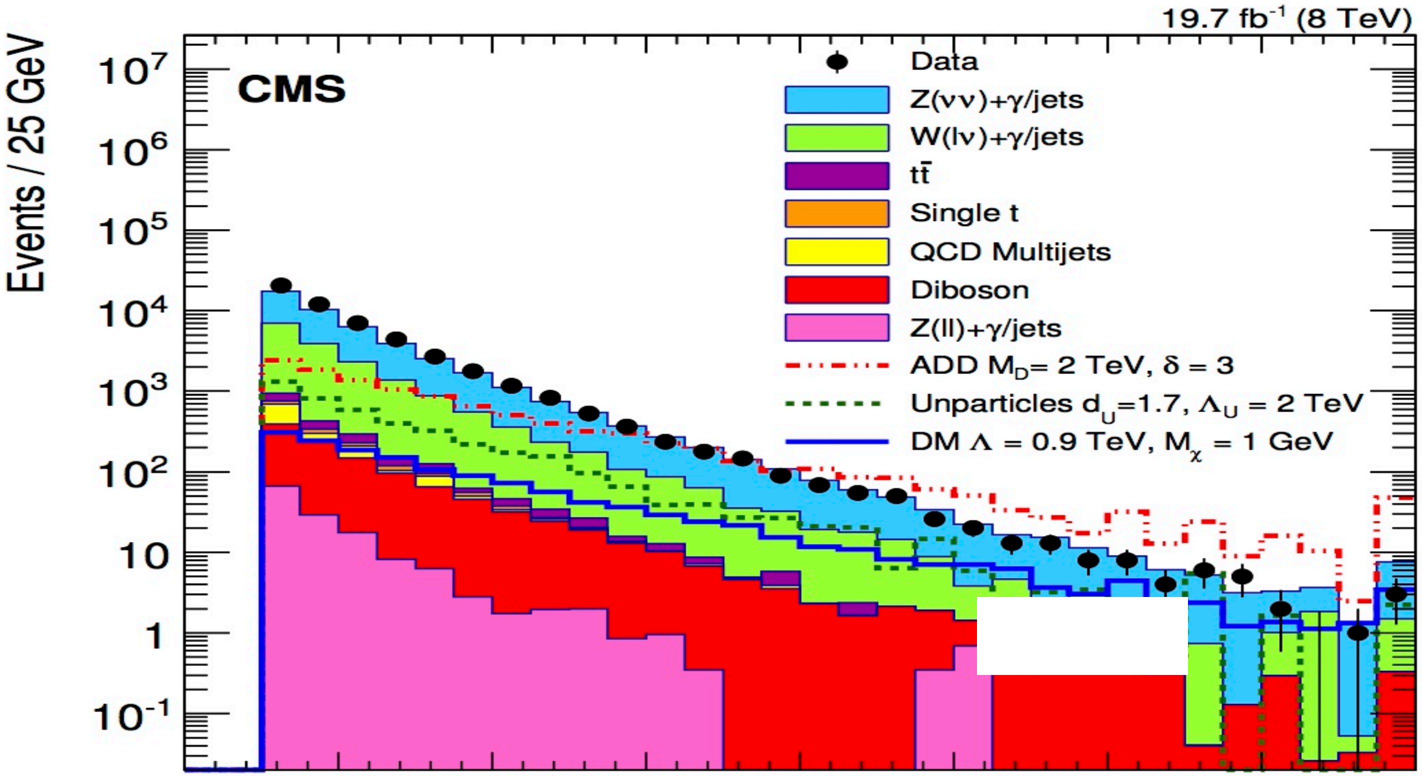
Beltran et al (2010), Agrawal et al (2010), Goodman et al (2010),Fox et al (2010), Rajaraman et al (2011),Cheung et al (2012), March-Rusell et al (2012),...)

e.g. Mono-jet

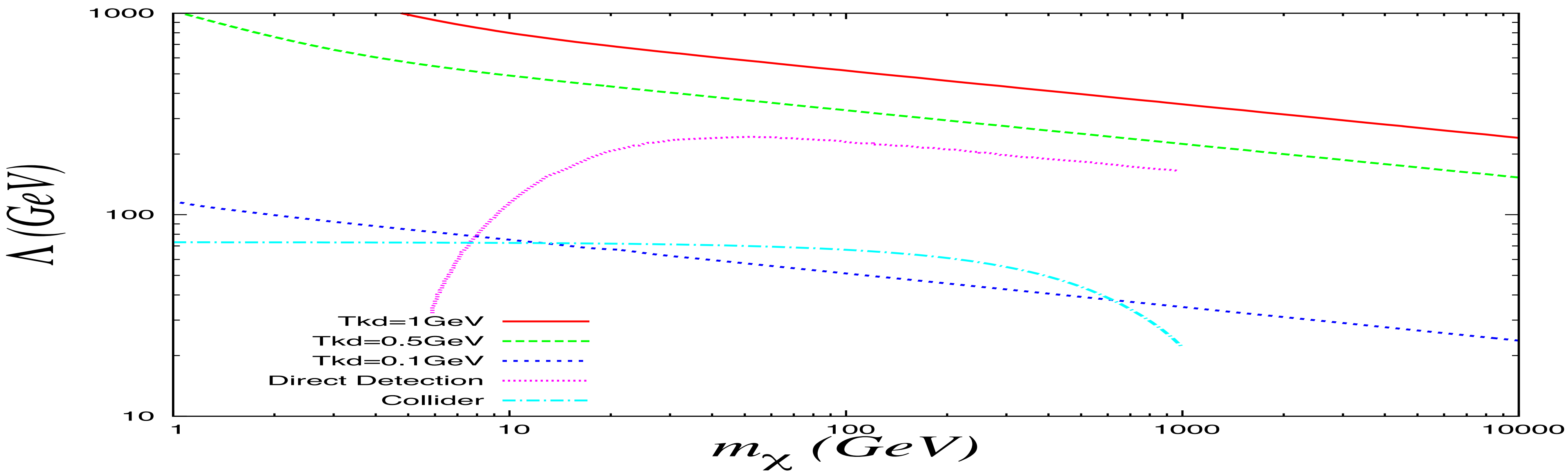


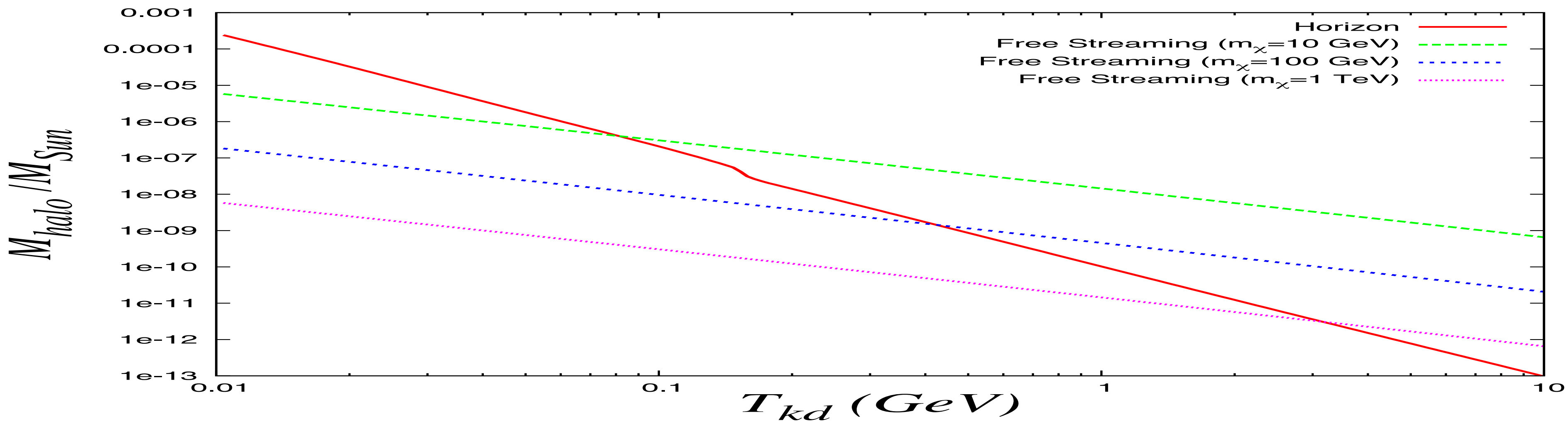


$$O_s = \sum_q \frac{1}{\Lambda^2} \bar{\chi}\chi\bar{q}q$$



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





- Results

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

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

→ 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)