Cosmology for sub-GeV Dark Matter

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Based on the work with:
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Junji Hisano (Nagoya), Kiyotomo Ichiki (Nagoya)

Cosmology for sub-GeV Dark Matter

Outline

- Motivation:

Motivation for sub-GeV DM
Motivation for DM-baryon interactions

- ✓ Halo abundance
- ✓ 21 cm
- ✓ Minimum Protohalo Mass

- Concrete example for DM-baryon interactions
  Interaction via photon: How "dark" is dark matter?

- ✓ Dipole DM
- ✓ Millicharged DM

We know little about DM

Let's not get biased, and explore beyond the conventional paradigm

- Particle physics search for DM:

Dominated by the search for weakly interacting massive particles (WIMPs), 5~ 1000 GeV

Today's talk: interested in less than GeV

- Cosmological search (e.g. large scale structure of the Universe) :

Lambda-CDM model : Gravitational interactions, Cold, Non-baryonic

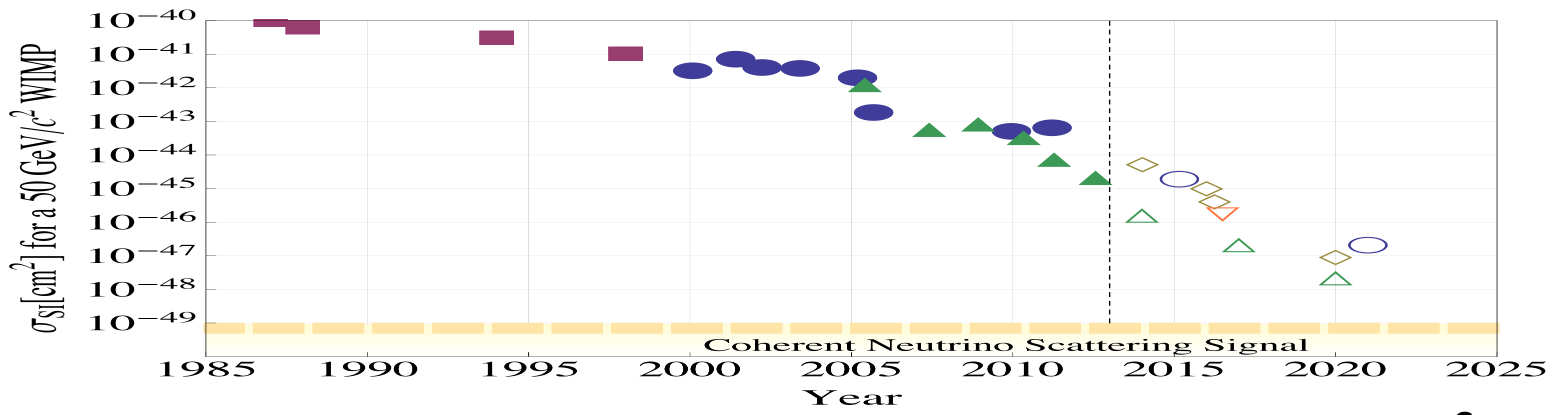
Today's talk: interested in DM-baryon interactions by the light mediator

(e.g. photon: dark matter is not completely "dark")

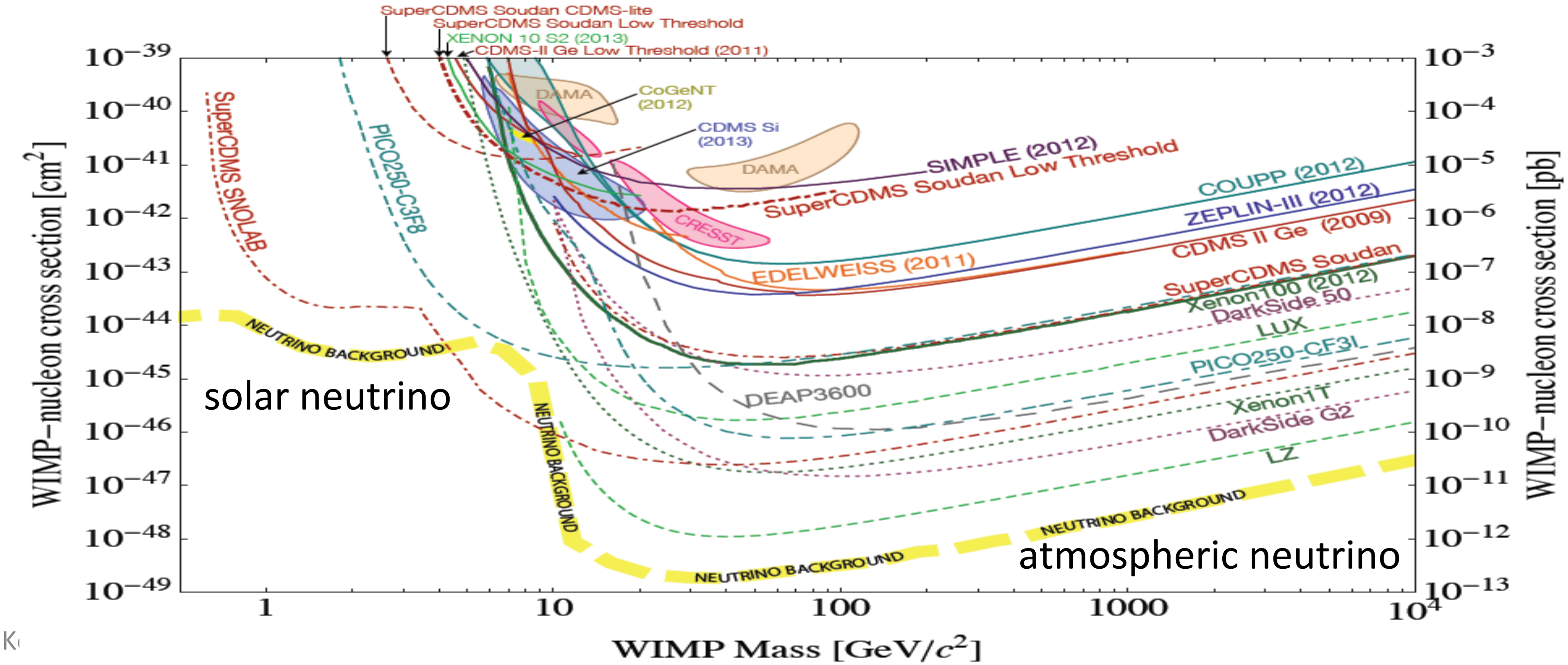
Motivation for sub-GeV

Direct detection experiments

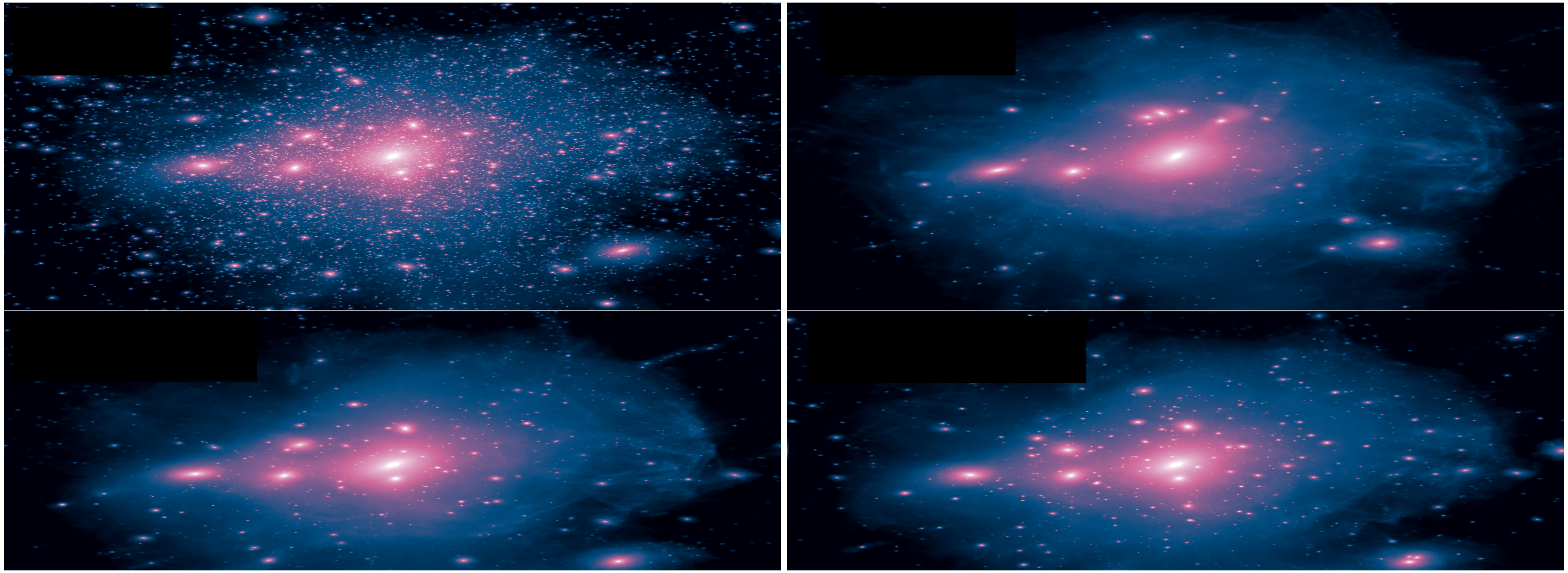
Moore's law for dark matter

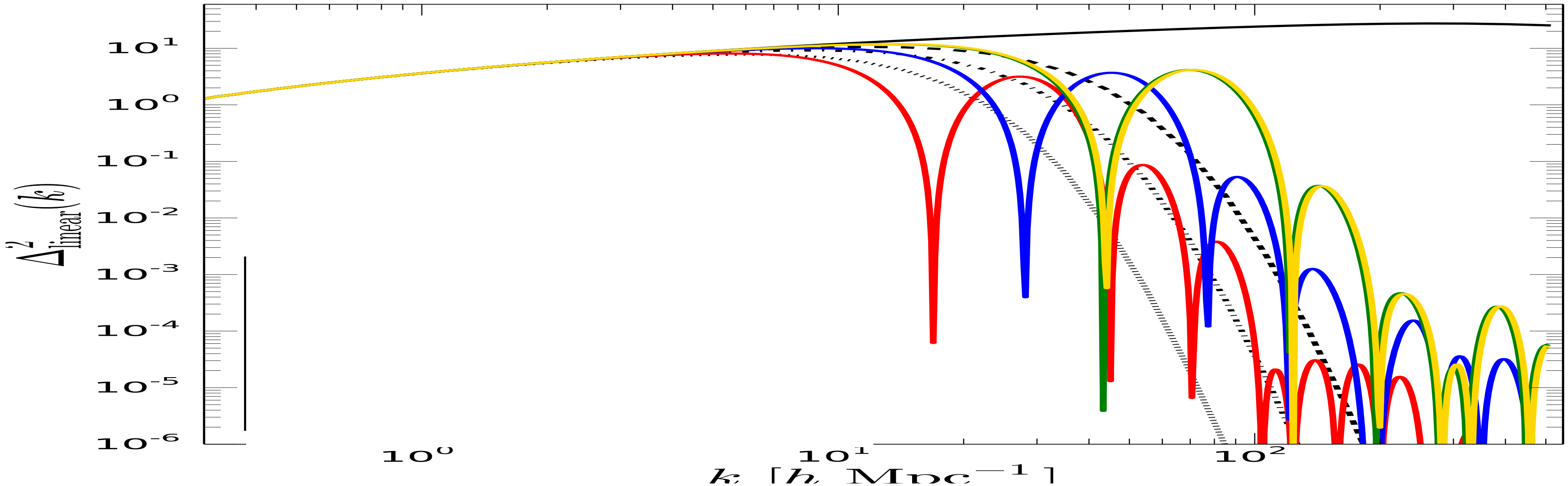


Snowmass 2013



Motivation for DM-baryon interactions, beyond ΛCDM





(Vogelsberger et al (2016))

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

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

Momentum transfer rate

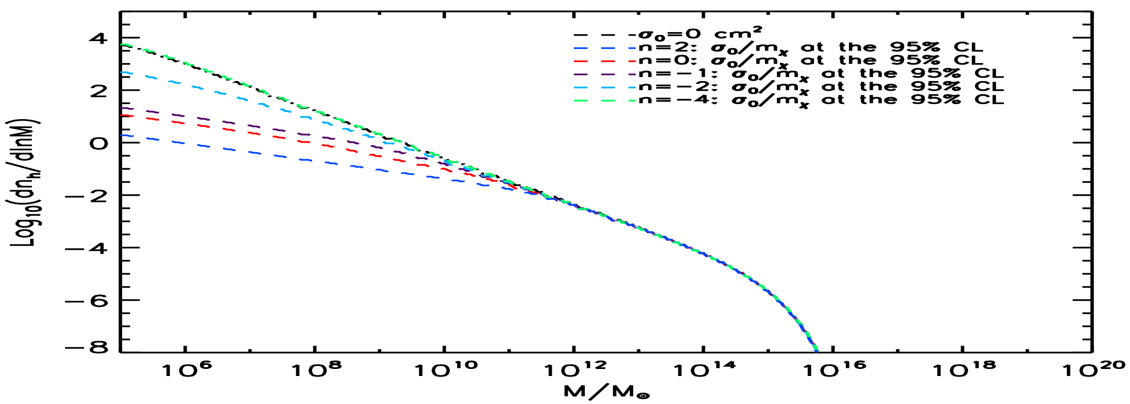
$$K_\gamma = \frac{4\rho_\gamma}{3\rho_b} n_e \sigma_T$$ (Compton collision rate)

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

$$\sigma(v) = \sigma_0 v^n$$

✧ 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}



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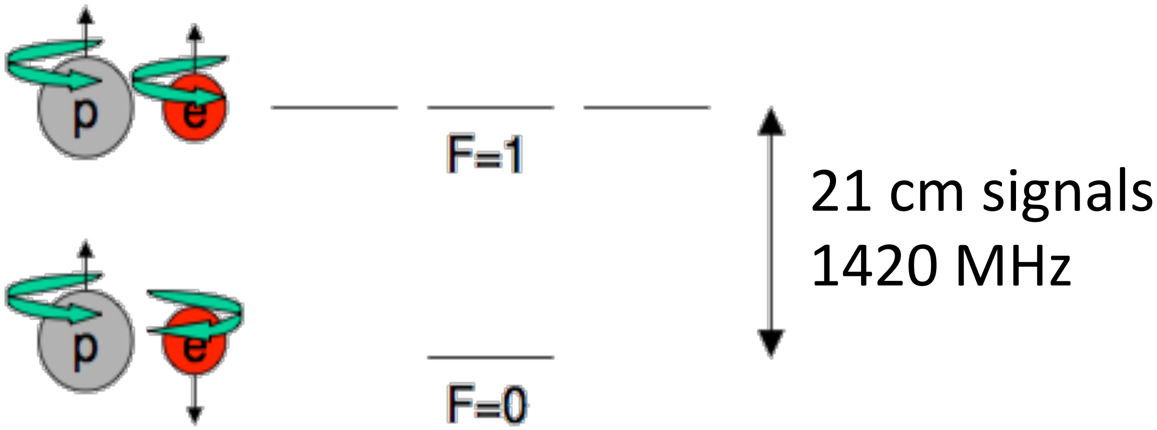
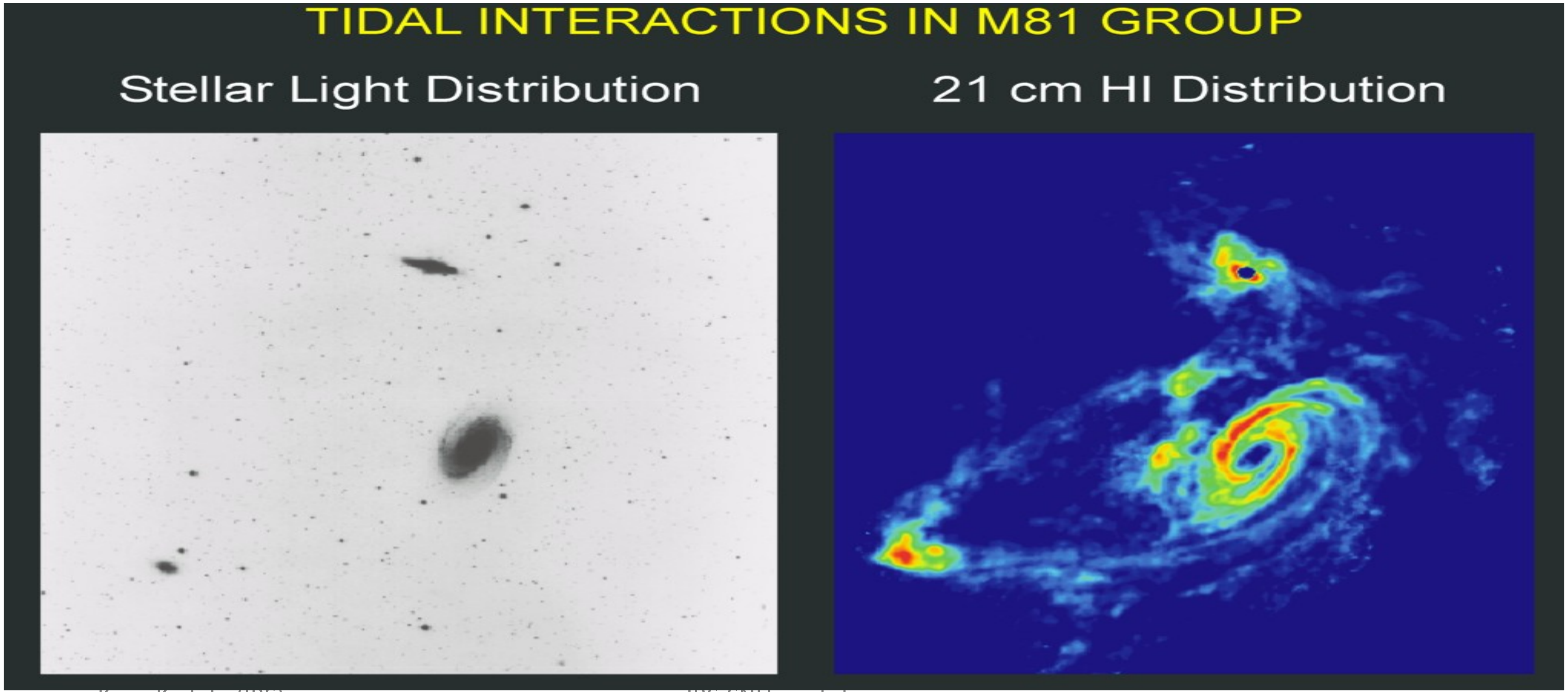
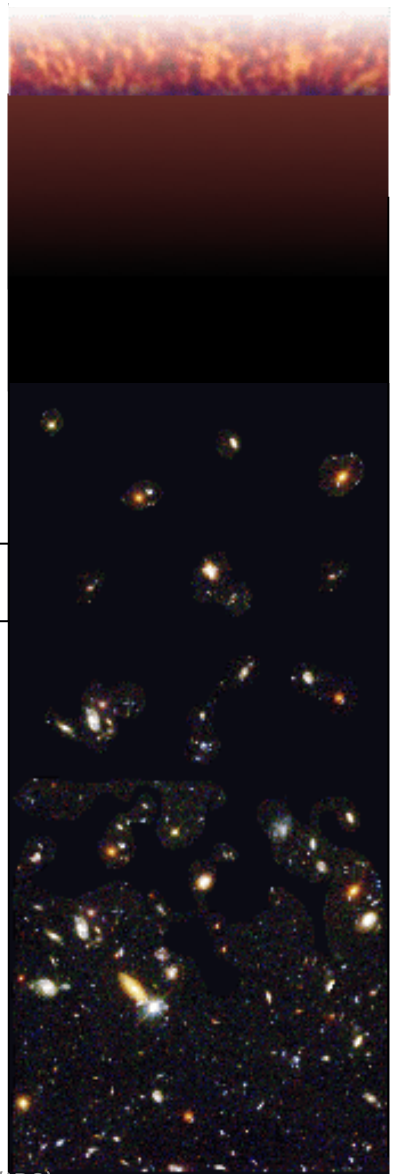

p
e
F=1
p
e
F=0
21 cm signals
1420 MHz


TIDAL INTERACTIONS IN M81 GROUP
Stellar Light Distribution
21 cm HI Distribution

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

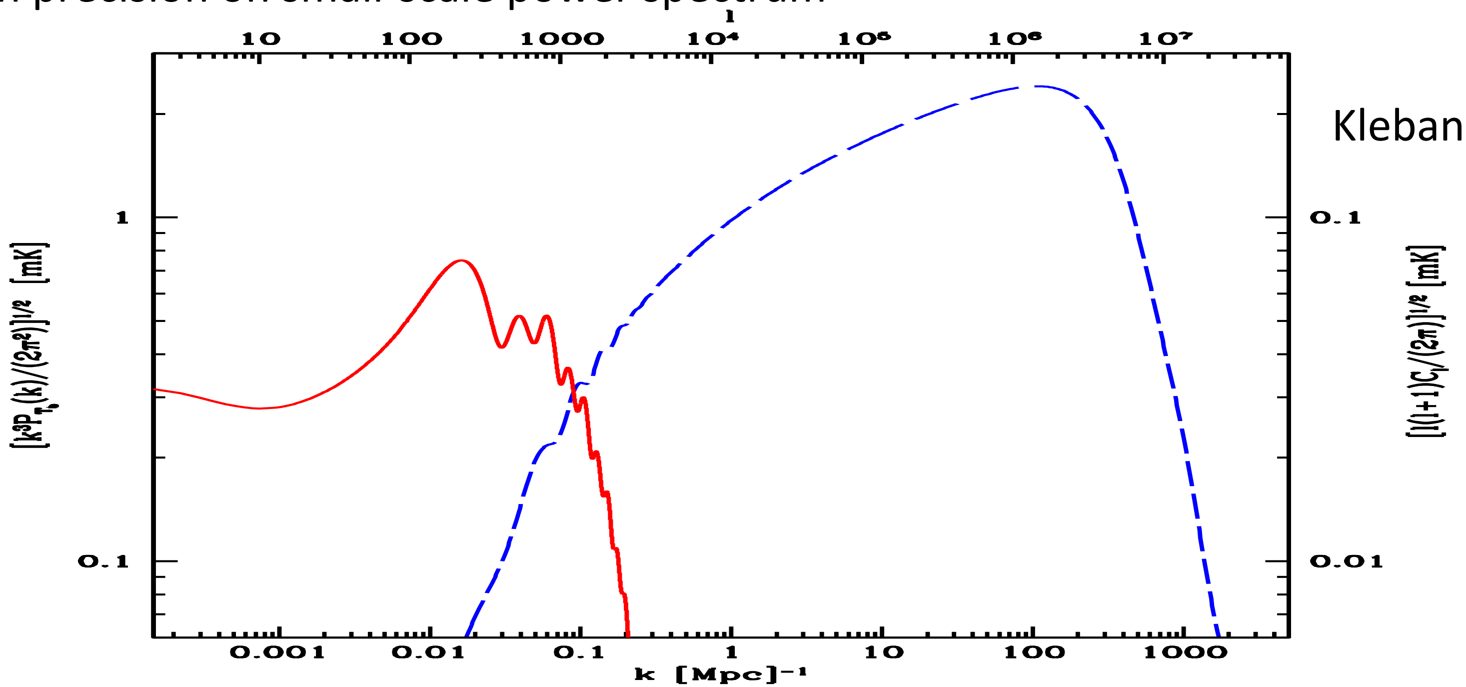
~13 billion (z=0)

← Today's structures

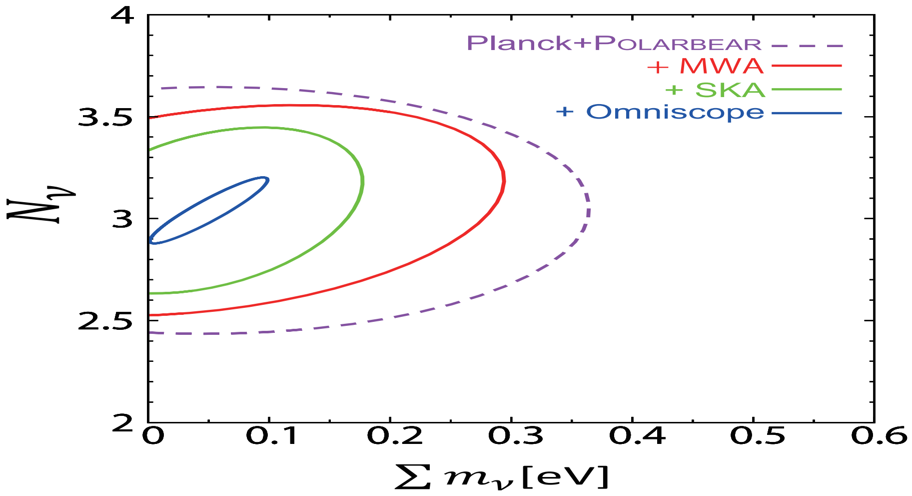
What can we do with 21cm?

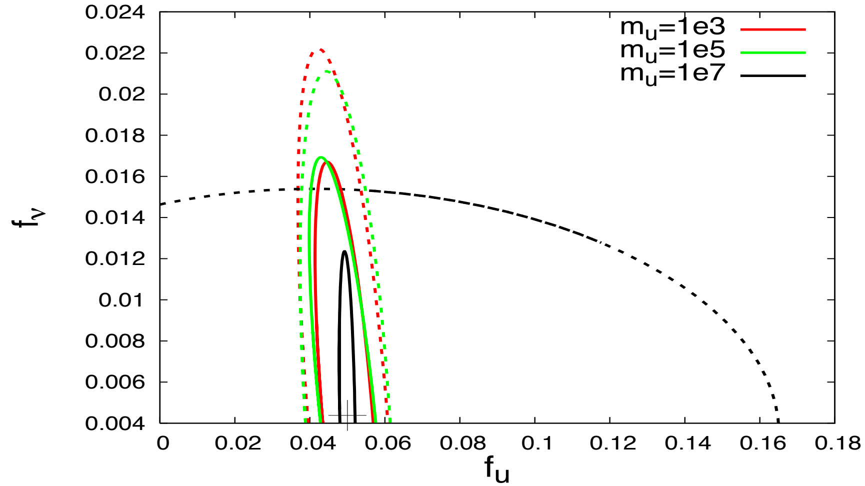
High precision on small-scale power spectrum

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



Kleban+(2007)



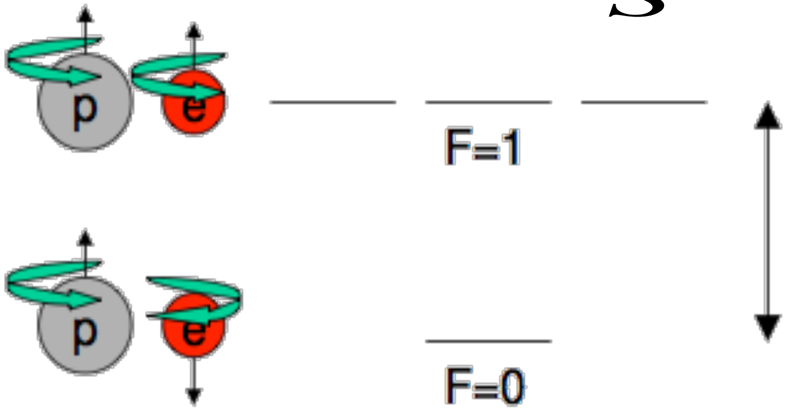


Oyama+(2013)

KK, Mao, Ichiki, Silk (2014)

What can we measure through 21cm signals?

Spin temperature T_S



Hyperfine spin flip transition

21 cm signals

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

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

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

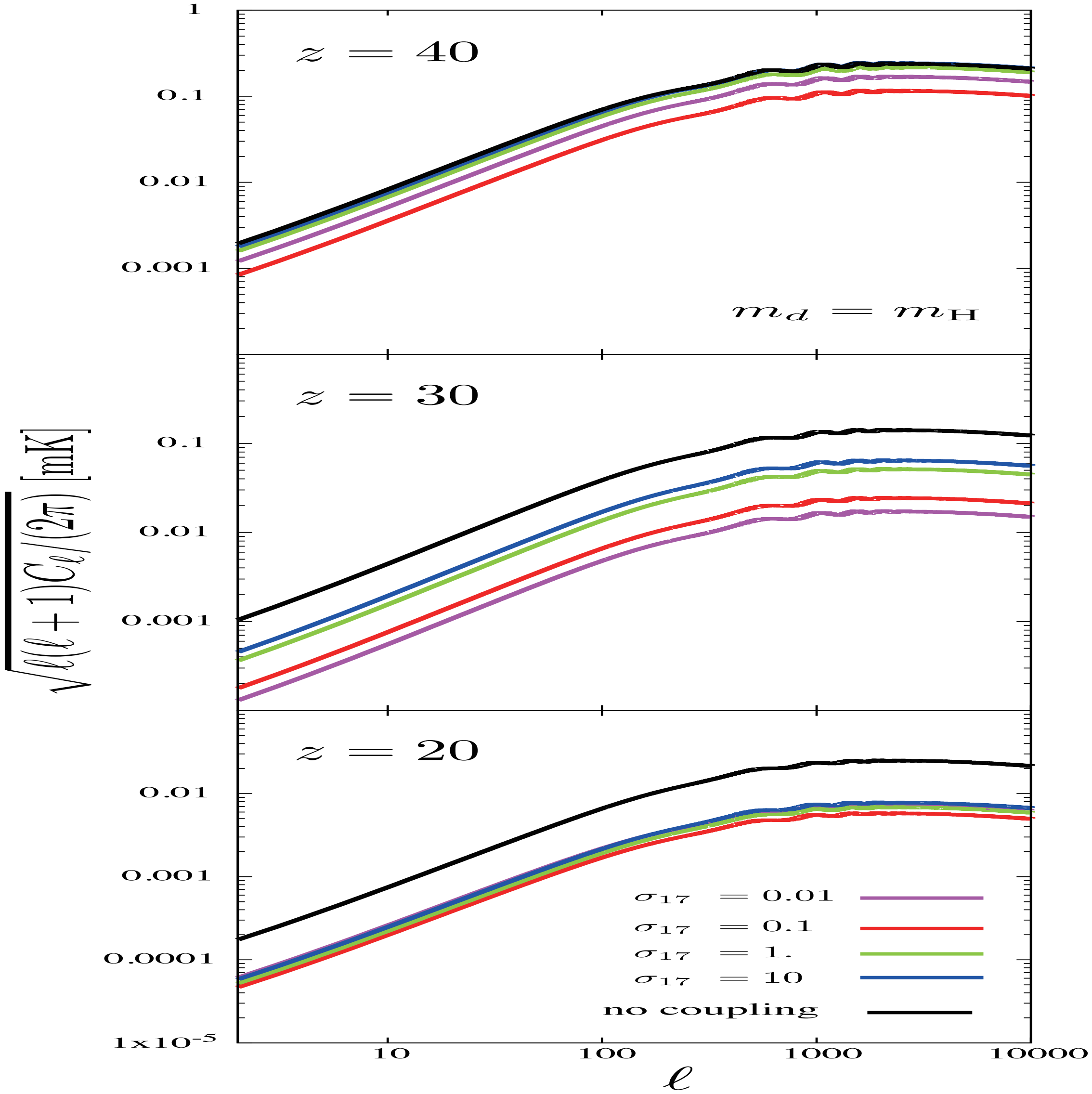
a) the absorption/stimulated emission from/to CMB photons
b) collision with other gas particles (other hydrogen atoms, protons and electrons).

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.

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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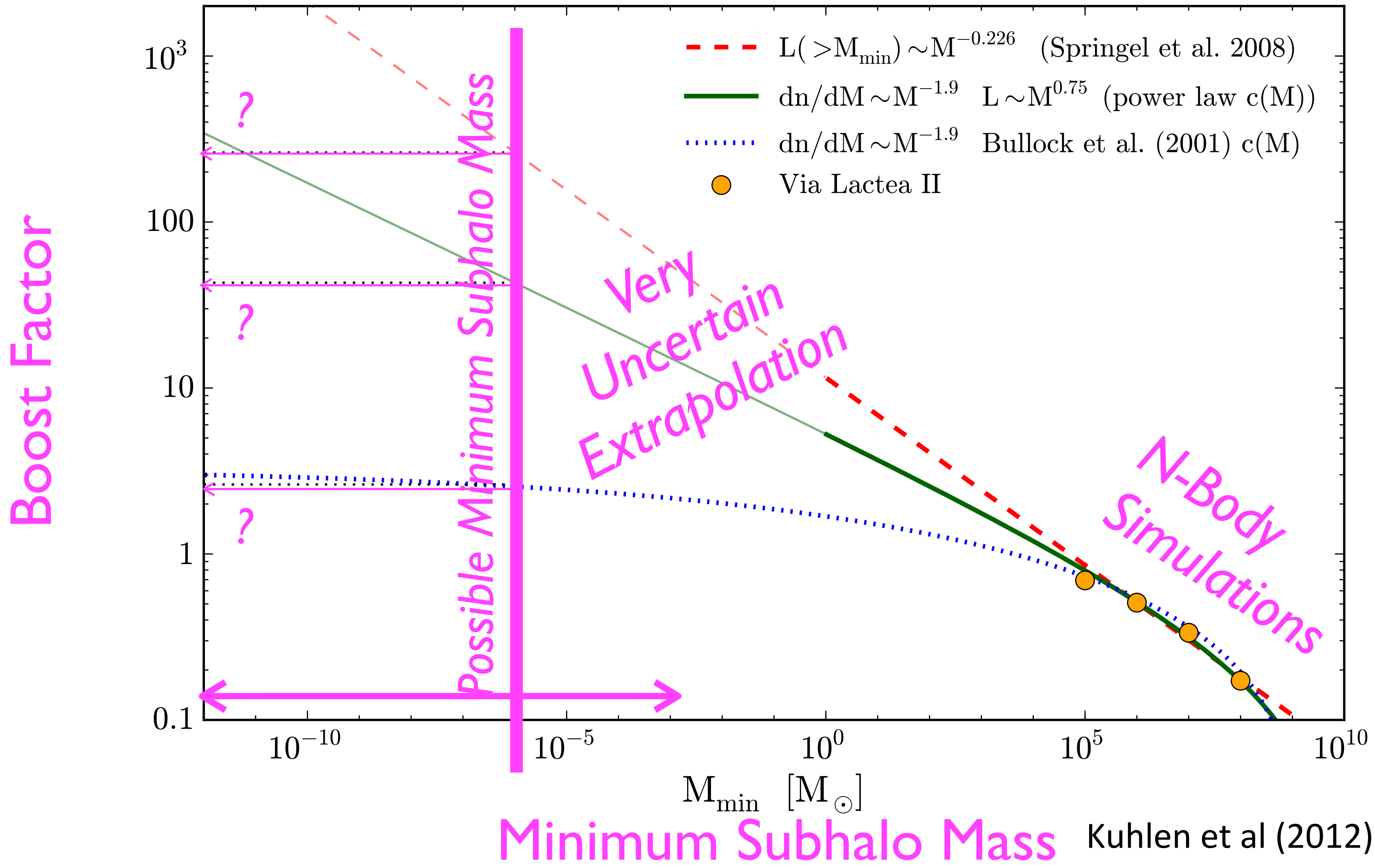
What is the size of the smallest gravitationally bound objects (protohalo)?

- Dark matter kinetic decoupling

- Analogous to:

Physics of baryon decoupling

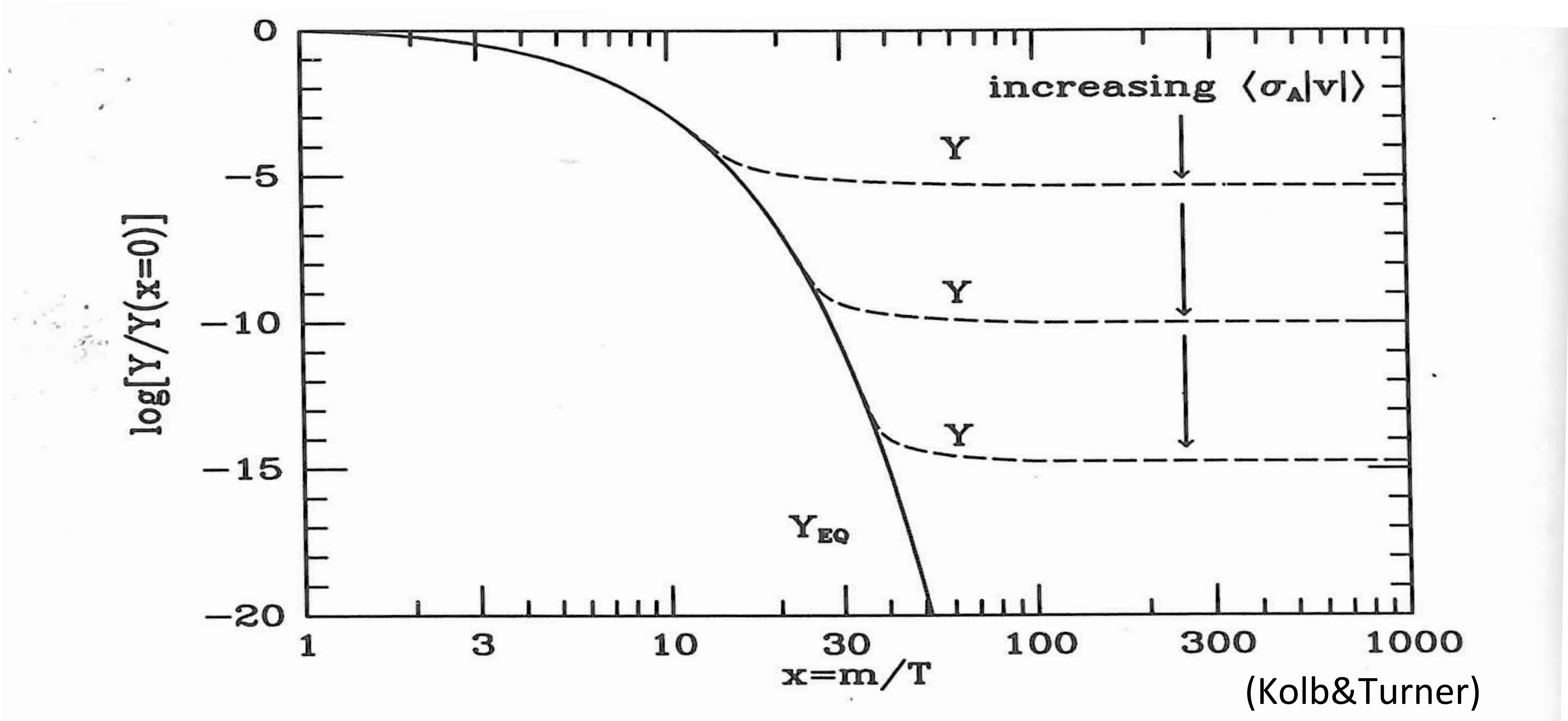
probing the nature of Universe via BAO and CMB



Kuhlen et al (2012)

Taken from P. Gondolo's talk

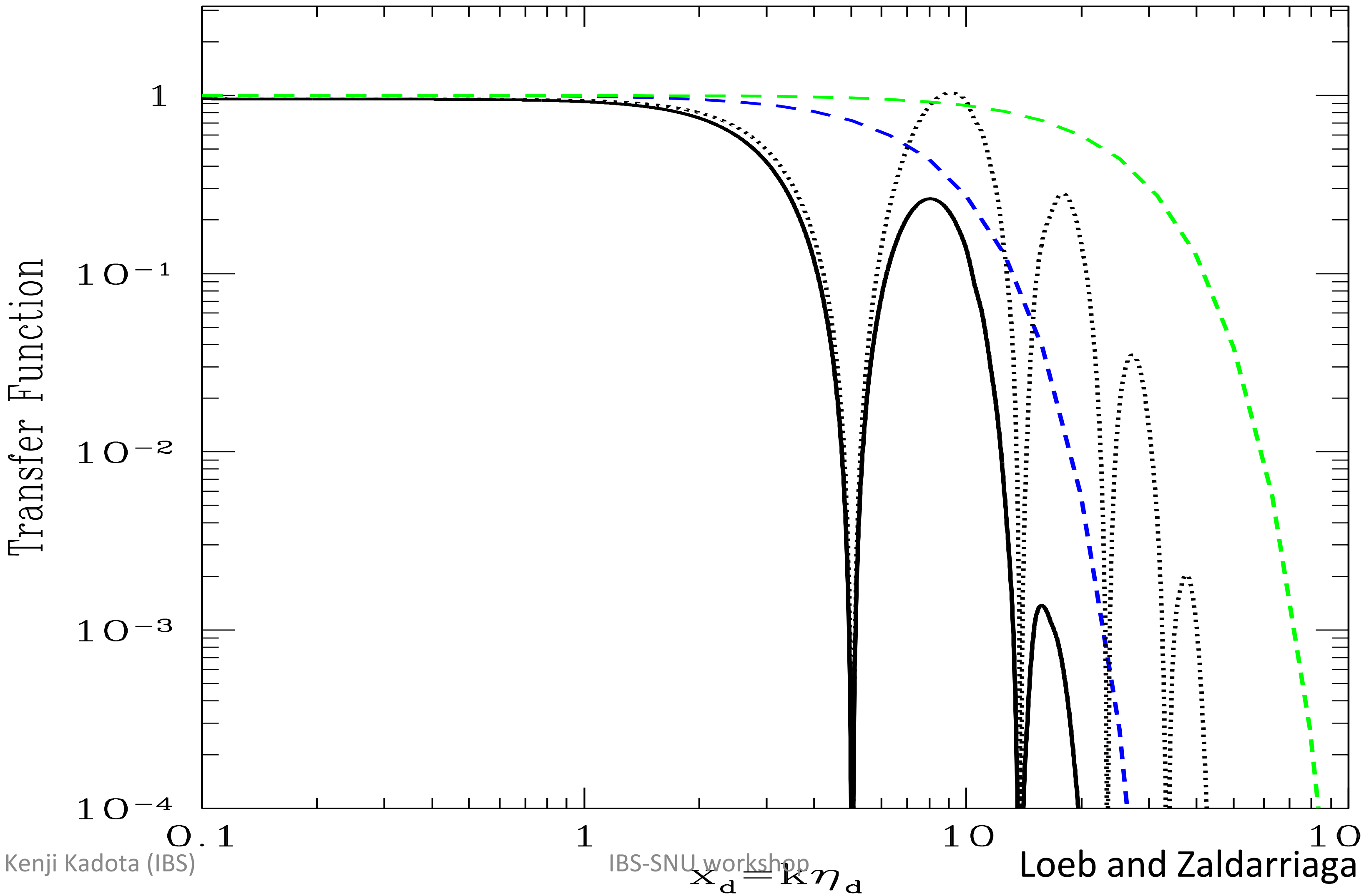
Chemical decoupling and kinetic decoupling



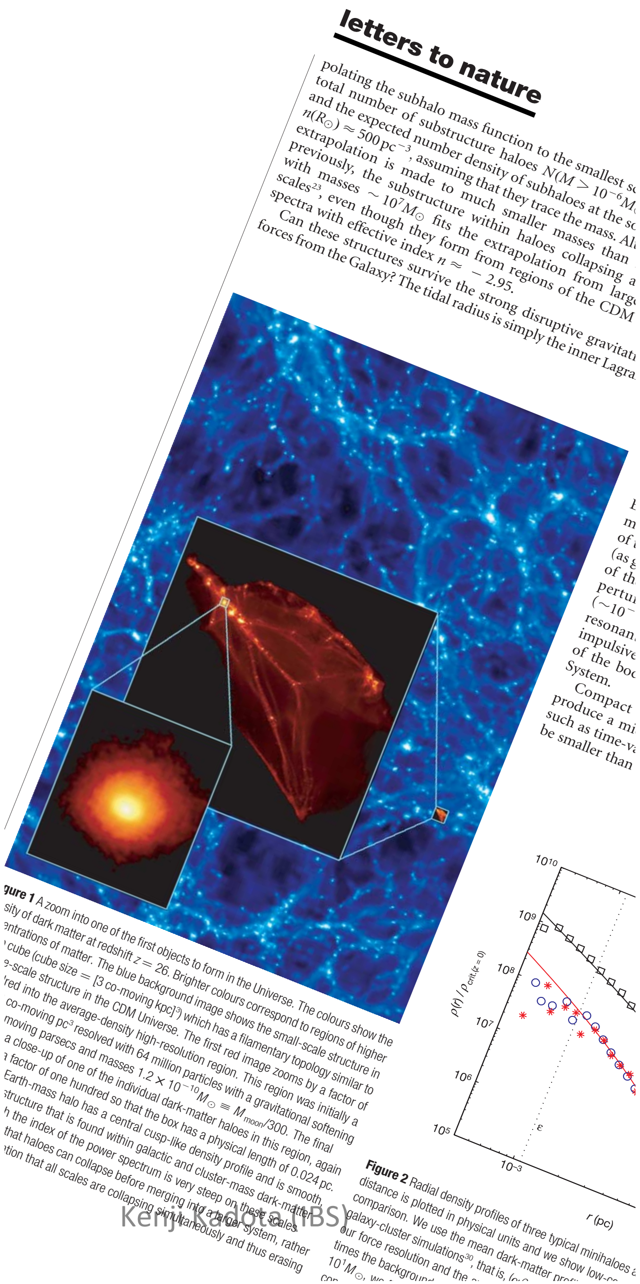
(Kolb&Turner)

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

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



Loeb and Zaldarriaga (2005)


letters to nature

polating the subhalo mass function to the smallest sc
total number of substructure haloes $N(M > 10^{-6}M$
and the expected number density of subhaloes at the so
$n(R_\odot) \approx 500\,\mathrm{pc}^{-3}$, assuming that they trace the mass. Al
extrapolation is made to much smaller masses than
Previously, the substructure within haloes collapsing a
with masses $\sim 10^7 M_\odot$ fits the extrapolation from large
scales[23], even though they form from regions of the CDM
spectra with effective index $n \approx -2.95$.
Can these structures survive the strong disruptive gravitat
forces from the Galaxy? The tidal radius is simply the inner Lagra

Earth-mass dark-matter haloes as the first structures in the early Universe

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The Universe was nearly smooth and homogeneous before a redshift of $z = 100$, about 20 million years after the Big Bang[1]. After this epoch, the tiny fluctuations imprinted upon the matter distribution during the initial expansion began to collapse because of gravity. The properties of these fluctuations depend on the unknown nature of dark matter[2–4], the determination of which is one of the biggest challenges in present-day science[5–7]. Here we report supercomputer simulations of the concordance cosmological model, which assumes neutralino dark matter (at present the preferred candidate), and find that the first objects to form are numerous Earth-mass dark-matter haloes about as large as the Solar System. They are stable against gravitational disruption, even within the central regions of the Milky Way. We expect over 10^{15} to survive within the Galactic halo, with one passing through the Solar System every few thousand years. The nearest structures should be among the brightest sources of γ-rays (from particle–particle annihilation).

The cosmological parameters of our Universe and initial conditions for structure formation have recently been measured via a combination of observations, including the cosmic microwave background (CMB)[8], distant supernovae[9,10] and the large-scale distribution of galaxies[11]. Cosmologists now face the outstanding problem of understanding the origin of structure in the Universe from its strange mix of particles and vacuum energy[12,13].

Most of the mass of the Universe must be made up of a kind of non-baryonic particle[1,14] that remains undetected in laboratory experiments. The leading candidate for this 'dark matter' is the neutralino, the lightest supersymmetric particle, which is predicted to solve several key problems in the standard model for particle physics[5]. This cold dark matter (CDM) candidate is not completely collisionless. It can collide with baryons, thus revealing its presence in laboratory detectors, although the cross-section for this interaction is extremely small. In a cubic-metre detector containing $\sim 10^{30}$ baryon particles, only a few collisions per day are expected from the $\sim 10^{13}$ dark-matter particles that flow through the experiment as the Earth moves through the Galaxy. The neutralino is its own anti-particle, and can self-annihilate, creating a shower of new particles including γ-rays[5]. The annihilation rate increases as the density squared; the central regions of the Galaxy and its satellites will therefore give the strongest signal[15–18]. However, the expected rate is very low—the flux of photons on Earth is the same as we would receive from a single candle placed on Pluto. Numerous experiments using these effects are under way that may detect the neutralino within the next decade[7]. Furthermore, in the next few years the Large Hadron Collider (LHC) at CERN will confirm or

density patch of the Universe that is nested within a hierarchy of larger and lower resolution grids of particles.

The fluctuations are imposed on the particles using accurate calculations of the linear theory power spectrum for a SUSY model with a particle mass $m_\chi = 100$ GeV. This includes collisional damping, free streaming and the transfer of fluctuations through the matter-radiation era of the Universe[2–4]. The resulting power spectrum is close to a power law of $P(k) \propto k^n$ with $n = -3$, with an exponential cut-off at 0.6 co-moving parsecs, which corresponds to a mass scale of $10^{-6}M_\odot$, where $M_\odot$ is the mass of the Sun. The cut-off scale depends on the neutralino mass and decoupling energy. From accelerator searches we know that $m_\chi > 37$ GeV and that the cosmic matter density sets an upper limit at 500 GeV. The damping scale for the allowed neutralino models differ from the model we used by less than a factor of three in mass[2–4] and structure formation is therefore very similar in all SUSY-CDM scenarios. A less popular CDM candidate is the axion, which has a much smaller damping scale of $10^{-13}M_\odot$. For comparison we simulated the high-resolution region with an axion CDM fluctuation spectrum on the resolved scales. Both models produce equal halo abundances above $5\times10^{-6}M_\odot$, but the axion model also forms bound structures down to the smallest resolved scales; see Fig. 3. Here we concentrate on the properties of the first structures to form in the SUSY-CDM model.

We evolve the initial particle distribution using a parallel multi-stepping tree code, starting at a redshift of $z = 350$ when the fluctuations are still linear. The high-resolution region forms the first nonlinear structures at $z = 60$ and the entire region quickly becomes distorted by the complex tidal field from the surrounding overdensities. By a redshift of $z = 26$, the high-resolution region begins to merge into the lower-resolution surroundings and we do not analyse the region further—however, this is sufficiently late that about 5% of the mass in the region has collapsed into bound dense structures (haloes); see Fig. 1.

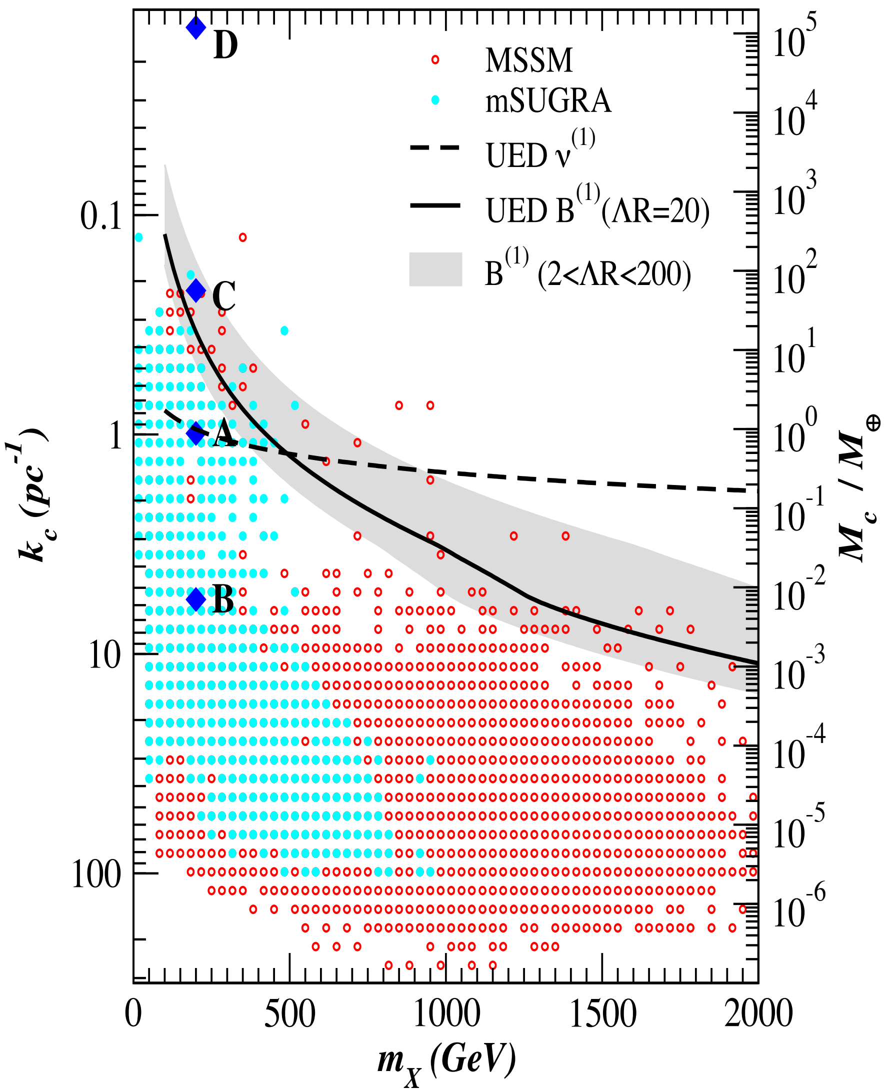
The first dark-matter haloes to collapse and virialize are smooth triaxial objects of mass $10^{-6}M_\odot$ and half-mass radii of 10^{-2} pc. Figure 2 shows the density profiles of three representative haloes at $z = 26$ that are well fitted by single power-law density profiles $\rho(r) \propto r^{-\gamma}$ with slopes γ in the range from 1.5 to 2, similar to galactic haloes shortly after their formation[20]. We note that the densities at the virial radius are about an order of magnitude higher than the density at $0.01r_{\mathrm{virial}}$ in a galactic halo today, which makes the survival of many of these haloes as galactic substructure possible. The central resolved densities reach 10^9 times the mean background density at 1% of their virial radii. Unlike galactic and cluster-mass CDM haloes, they do not contain substructure because no smaller-mass haloes have collapsed in the hierarchy.

Figure 3 shows the mass function of haloes. We use a 'friends of friends' algorithm with a linking length set to identify the dense central regions of collapsed haloes, then for each halo centre we recursively search for the radius r_{200} that is at an overdensity of 200 times the cosmic mean density. The resulting halo mass function is steep: $\mathrm{d}n(M)/\mathrm{d}\log M \propto M^{-1}$. For comparison we plot an extrapolation of the halo mass function found on much larger scales $> 10^7M_\odot$ (ref. 21), which fits surprisingly well up to the cut-off scale of $10^{-6}M_\odot$, below which we find no more structures.

At these epochs the baryons are kept sufficiently warm by the CMB that they are unable to cool and form visible objects such as

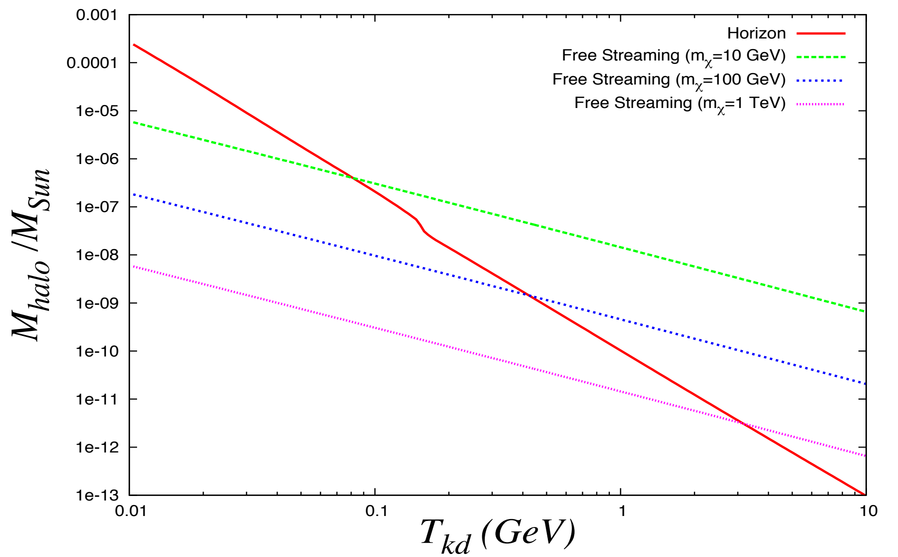
Profumo et al (2006)

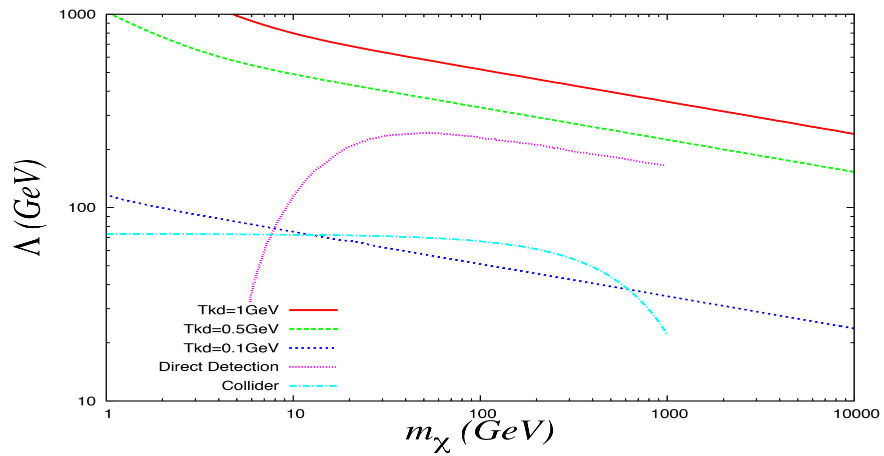
$M_{halo} : 10^{-6} M_{sun} \sim 100 M_{sun}$



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

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





(a) Scalar effective operator

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Dipole DM

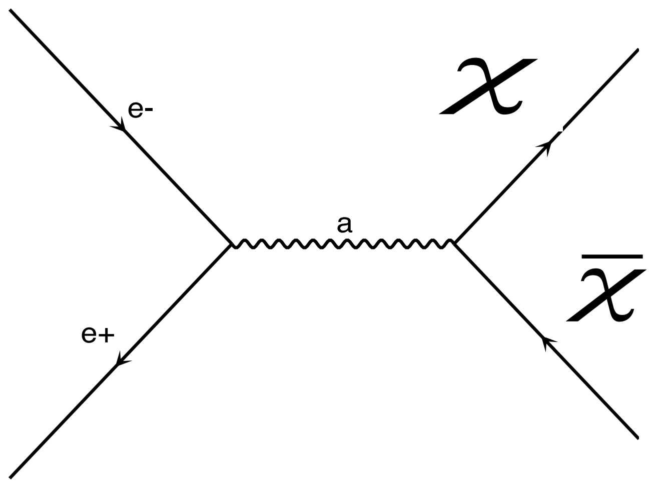
Pospelov et al (2000), Sigurson et al(2004), Barger et al (2012), Heo and Kim (2012),Graham (2012) Nobile et al (2013),..

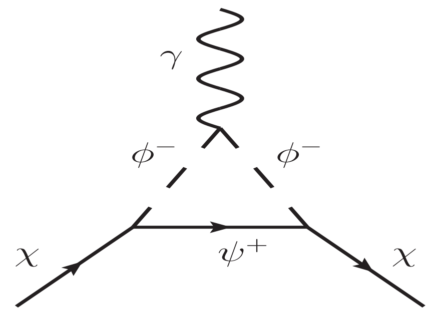
- DM with a dipole moment:

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

$$L_{MDM} = -\frac{i}{2}\mu\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$$

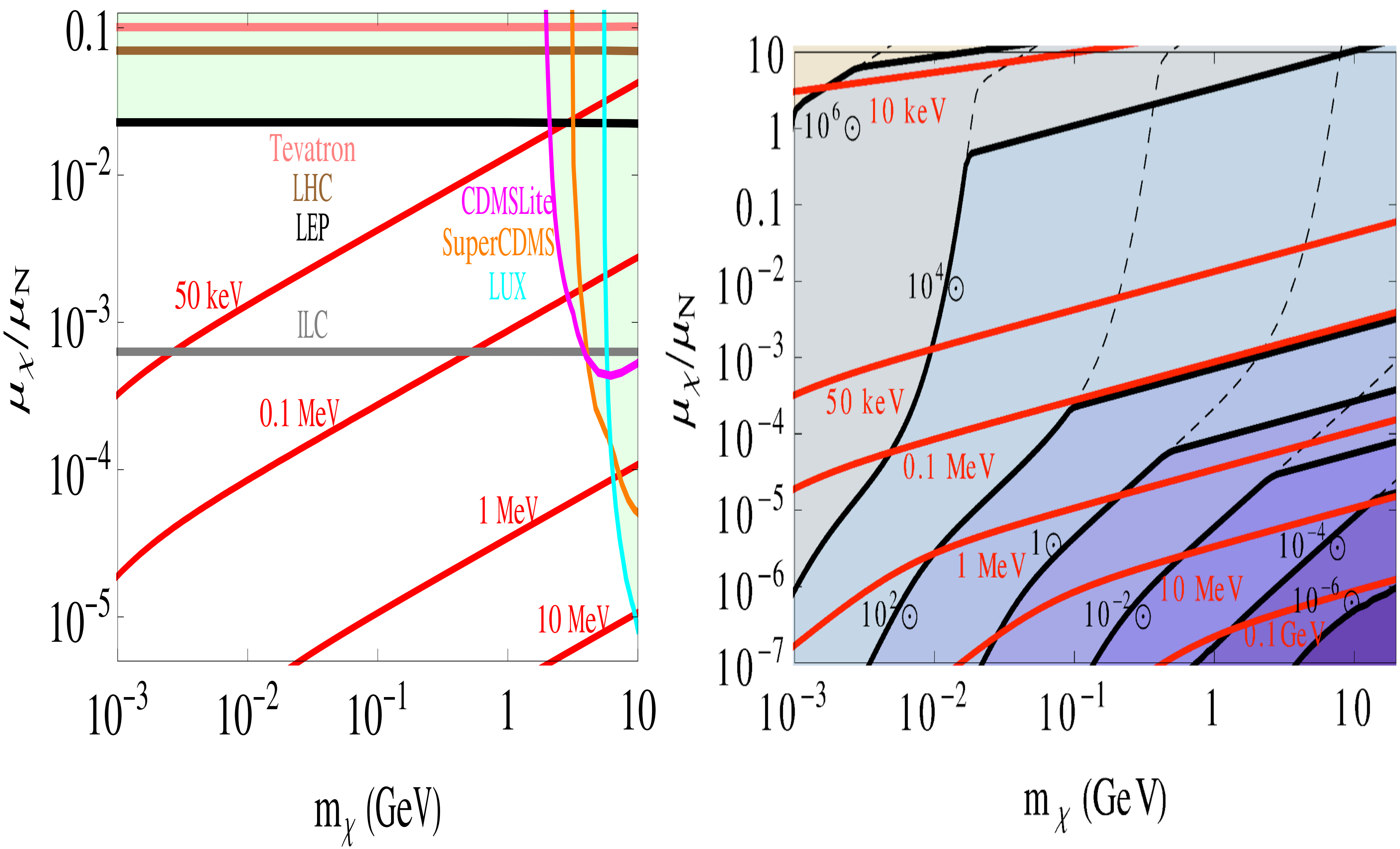
$$\mu \equiv \frac{1}{\Lambda}$$





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

P. Gondolo and KK(2016)



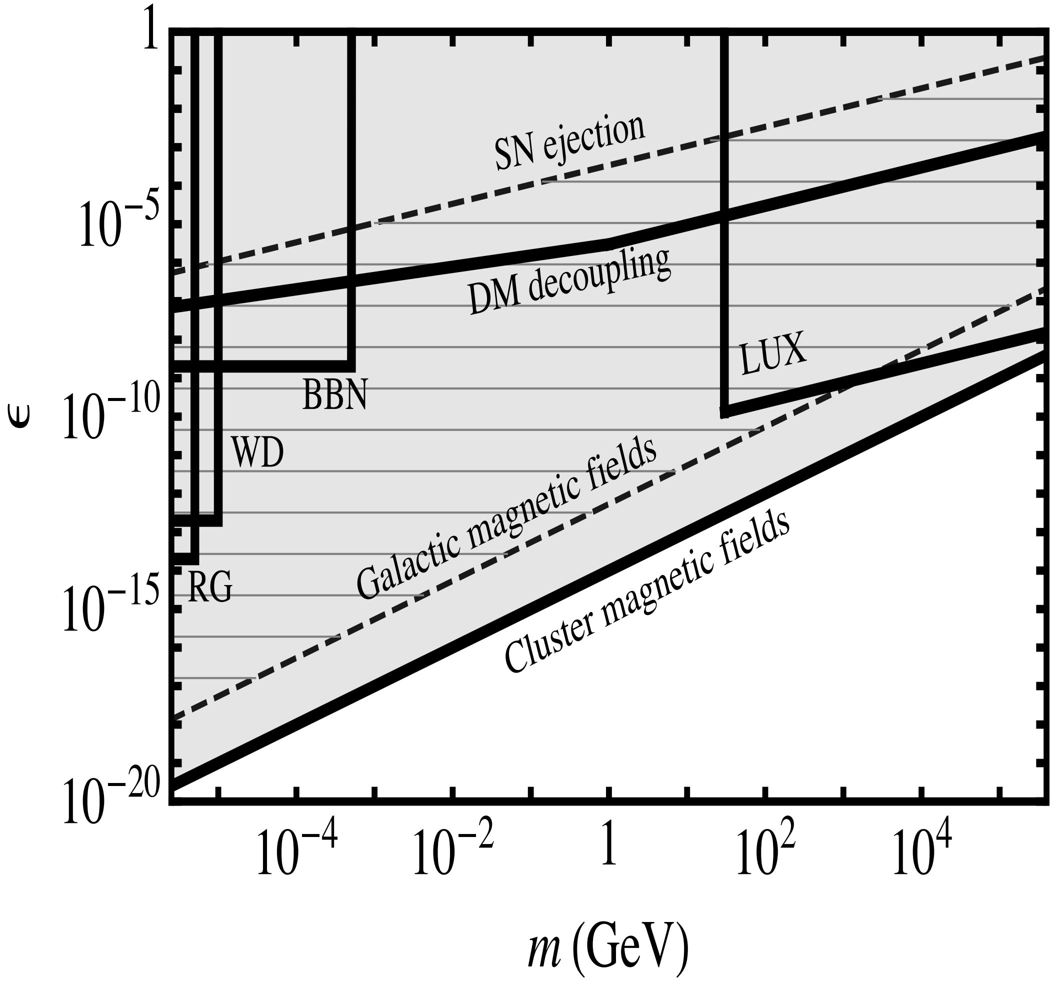
Millicharged DM: DM charge εe

Davidson et al (2000), Dubovsky et al (2004), Chuzhoy et al (2008), McDermott et ak(2011), Izaguirre et al (2015), ...

(KK, Sekiguchi & Tashiro (2016))

" The SU(2) x U(1) unification theory
is not particularly beautiful. ...
The problem is the U(1) charge..."
- Howard Georgi

" One would be surprised if nature had
made no use of it (magnetic monopole)"
- Paul Dirac



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Summary: Be open-minded. Multiple DM probes can be complementary

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