Going beyond WIMP Dark Matter with Large Scale Structure

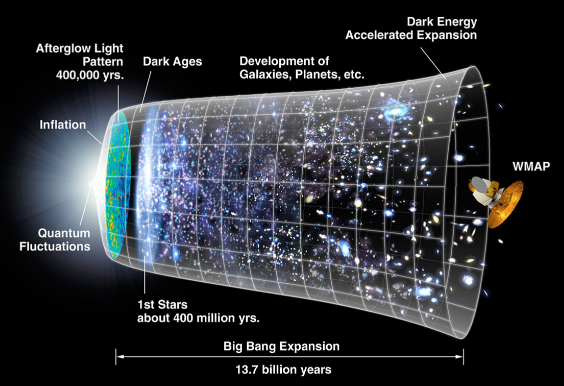
Roland de Putter

JPL/Caltech

DAMASC-II 9/24, Caltech

Most properties of simplest WIMP dark matter are out of reach of cosmological data

- cold/heavy (m_x≈*10-1000 GeV*)
- early decoupling from visible sector
- stable
- annihilation weak (but affects CMB)
- self-interaction weak
- “simple” dark sector

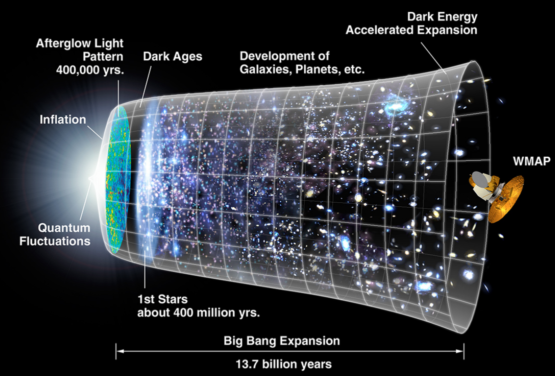


Most properties of simplest WIMP dark matter are out of reach of cosmological data

- ~~**Cold/heavy (*m_x≈10-1000 GeV*)**~~ — 1. *WDM*
- ~~**Early decoupling from visible sector**~~ — 2. *SIMP's*
- Stable
- Annihilation weak (but affects CMB)
- Self-interaction weak
- ~~**"simple" dark sector**~~ — **3.** *PIDM*

Less restrictive DM models can affect the matter power spectrum on linear and mildly non-linear scales. Probed by

- Lyman-α forest
- weak gravitational lensing
- Galaxy clustering



1: Warm Dark Matter ***(WDM)*** has cosmologically interesting free-streaming scale

$$m_x \approx 0.1 - 10 \text{ keV}$$

Examples:

- Heavy Sterile Neutrino (*Dodelson & Widrow 1994)*
- Warm thermal relic (*e.g. gravitino*)
- Resonantly Produced Heavy Sterile Neutrino (*Shi & Fuller 1999)*

Evolution of WDM perturbations is determined by $\mathbf{T_x/m_x}$ ratio

Cosmological Large Scale Structure cares about:

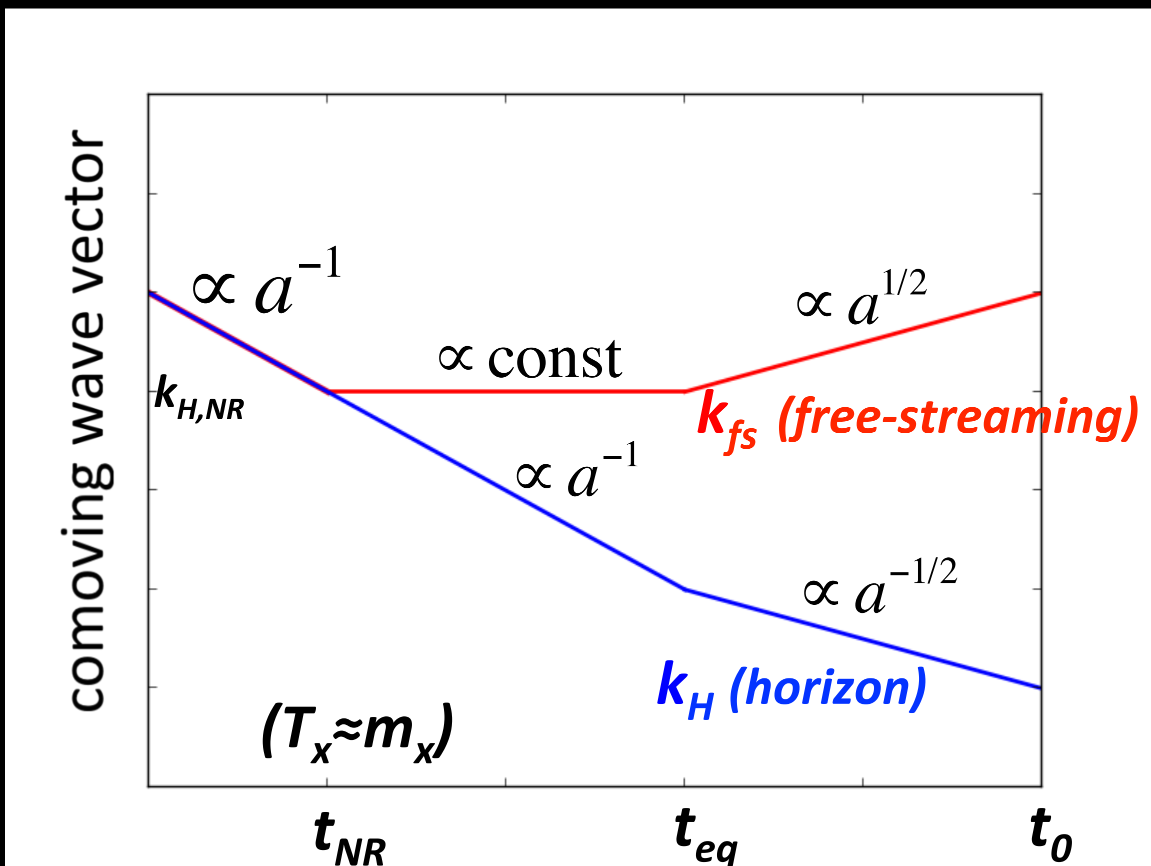
- Background matter density $\boldsymbol{\rho_x}$
- Velocity distribution, which is fully specified by $\mathbf{T_{x,0}/m_x}$

No clustering below free-streaming length:

$$\lambda_{fs}(a) \approx (aH)^{-1} \cdot v_{rms}(a)$$

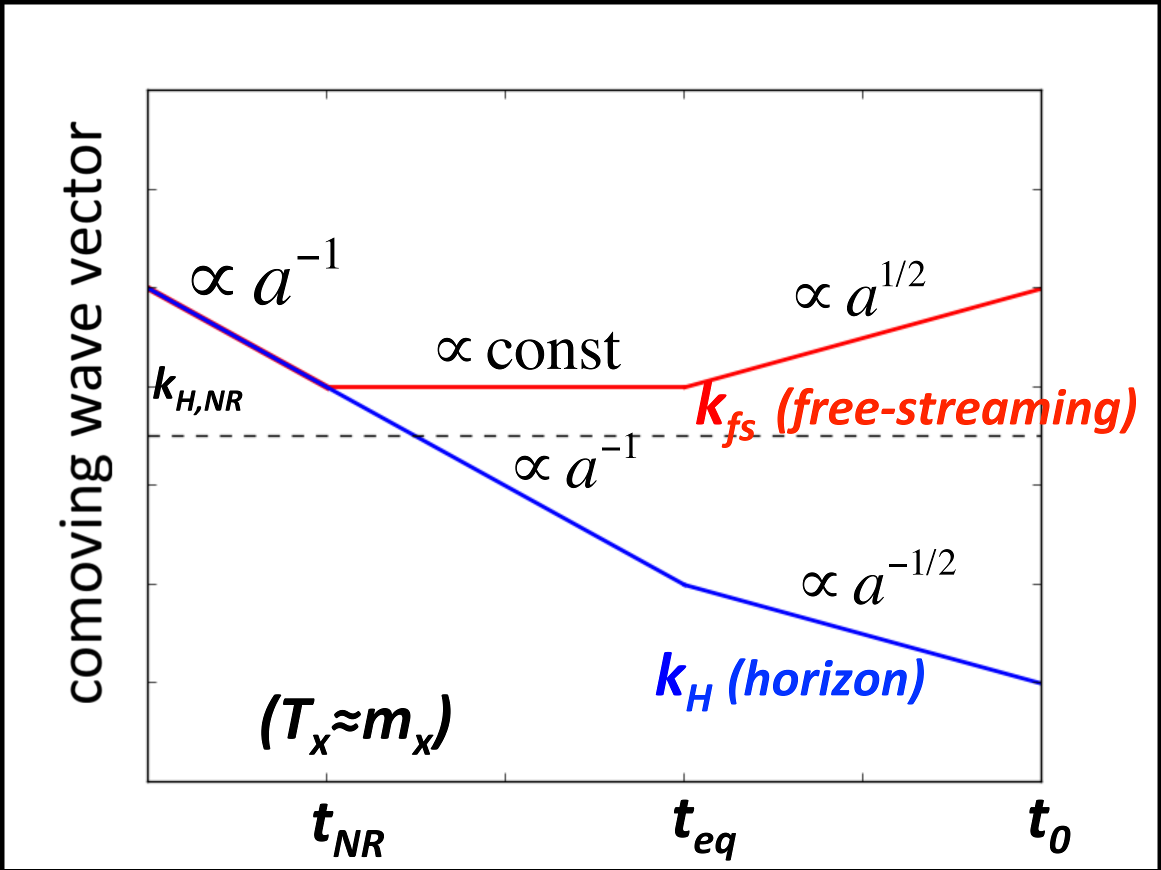
Density modes smaller than the horizon when WDM becomes non-relativistic are strongly suppressed

Free-streaming wave vector $\boldsymbol{k_{fs}(a) \approx \pi/\lambda_{fs}(a) \approx (aH)/v_{rms}(a)}$



Density modes smaller than the horizon when WDM becomes non-relativistic are strongly suppressed

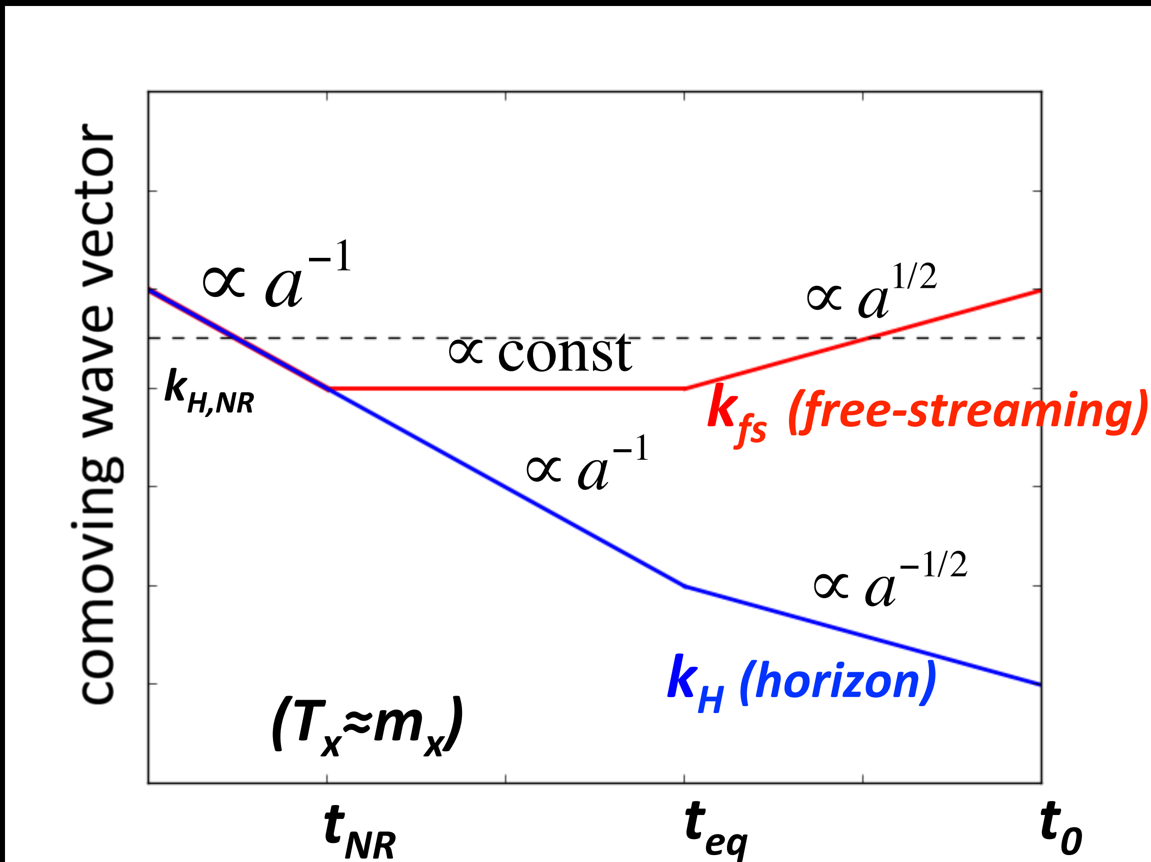
Free-streaming wave vector ***$k_{fs}(a) \approx \pi/\lambda_{fs}(a) \approx (aH)/v_{rms}(a)$***



standard growth for any ***$k < k_{fs,eq} \approx k_{H,NR}$***

Density modes smaller than the horizon when WDM becomes non-relativistic are strongly suppressed

Free-streaming wave vector $k_{fs}(a) \approx \pi/\lambda_{fs}(a) \approx (aH)/v_{rms}(a)$

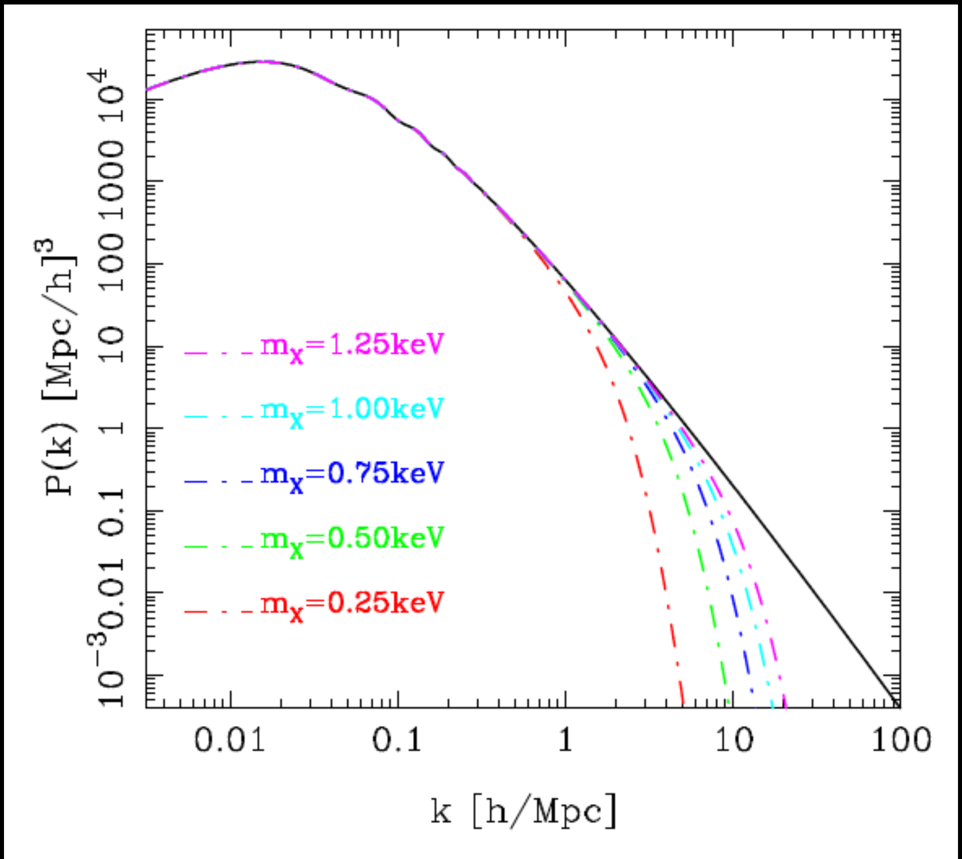


Strong suppression for any $k > k_{fs,eq} \approx k_{H,NR}$

Suppression of WDM power spectrum can be used to constrain mass m_x, but we need to probe small scales

Suppression scale:

$$k_{\rm supp} \sim 5\,{\rm Mpc}^{-1}\left(\frac{m_x}{1{\rm keV}}\right)\left(\frac{T_{\nu,0}}{T_{x,0}}\right)$$

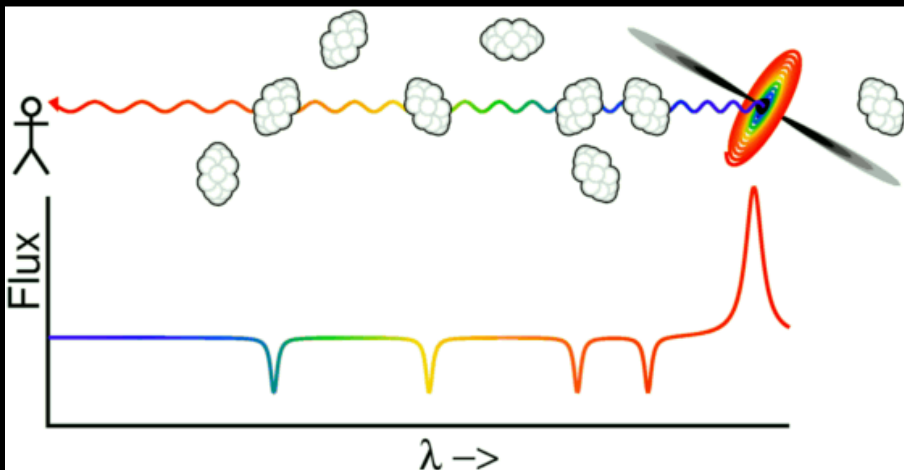


Strong Probes:

- **Lyman-alpha Forest**
- Weak Gravitational Lensing
- (Galaxy Clustering)

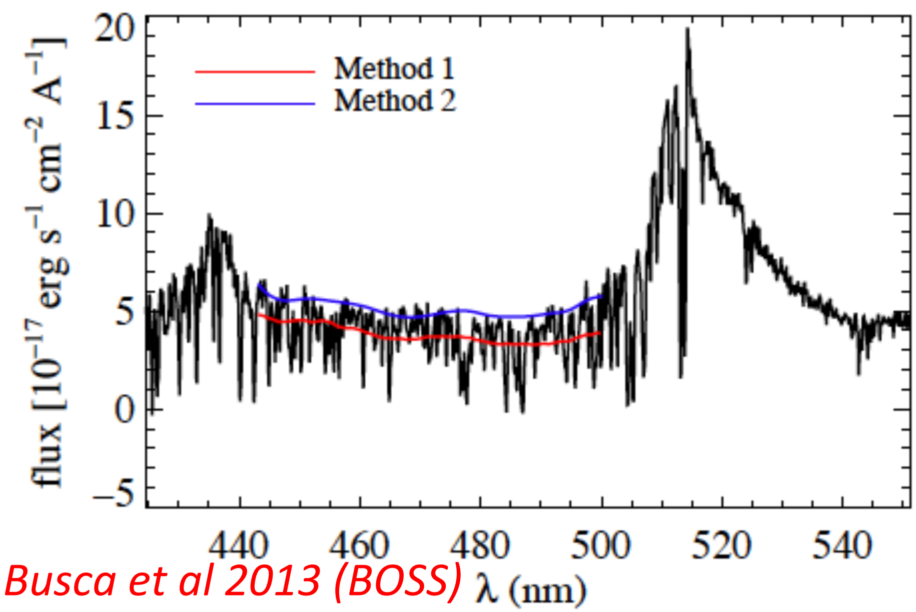
Smith & Markovic 2011
assumes thermal relic

Absorption by neutral hydrogen in IGM creates **Lyman-α forest** in quasar spectra

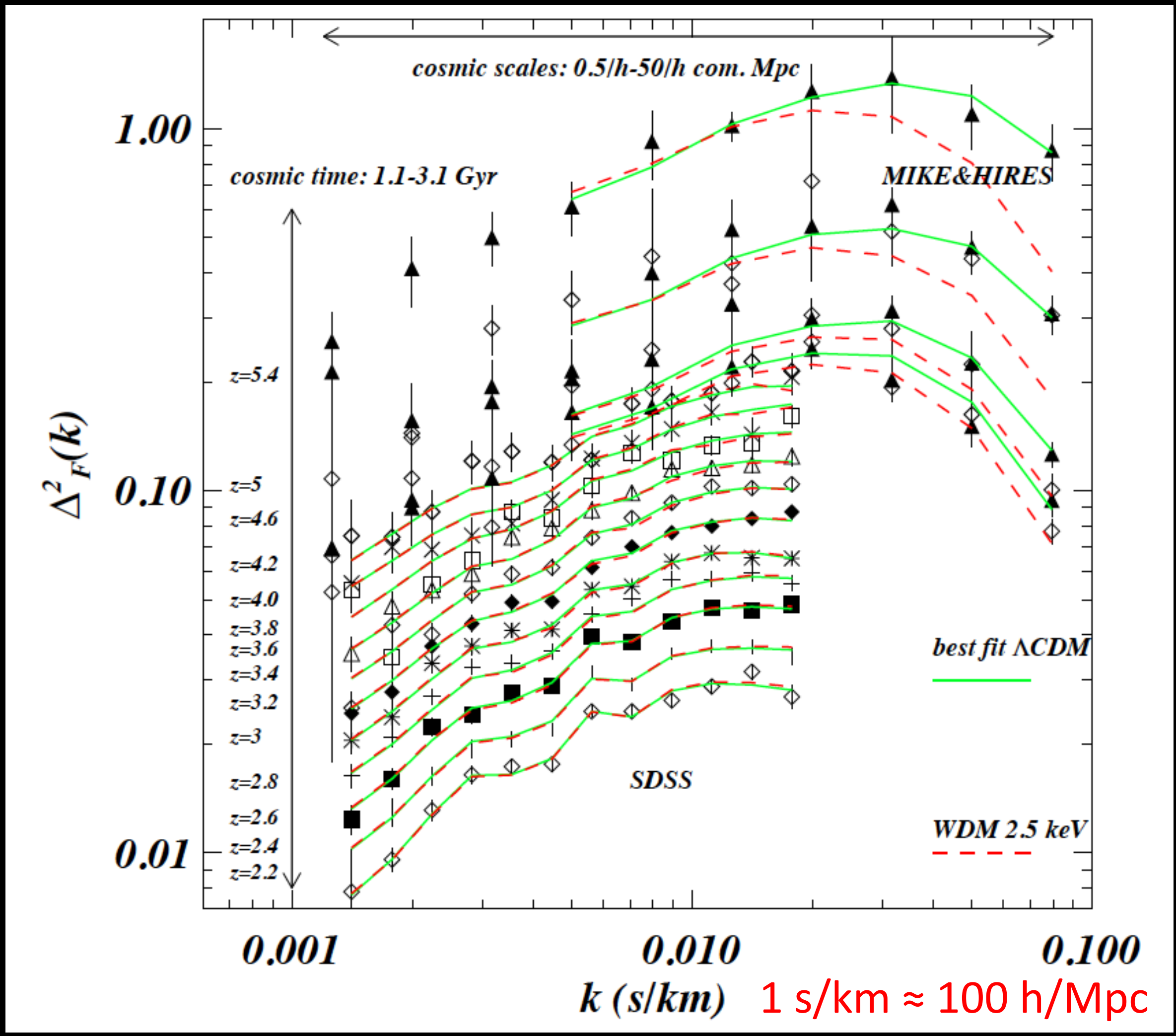


cartoon from website E. Wright (UCLA)

- probes ***z* = 2 – 5**
- can be modeled to small scales (***k* = 0.1 - 10 *h*/Mpc**)



Busca et al 2013 (BOSS)



Viel et al 2013

(HIRES+MIKE+SDSS+Planck priors)

- thermal: m_x *> 3.3 keV (95% CL)*
- NRP neutrino: m_x *> 20 keV*

Lyman-α studies help rule out many astrophysically interesting WDM models

Viel et al 2013

(HIRES+MIKE+SDSS+Planck priors)

- thermal: m_x > *3.3 keV (95% CL)*
- NRP neutrino: m_x > *20 keV*

Seljak et al 2006

(high-res+SDSS+WMAP +SDSS galaxies)

- thermal: m_x > *2.5 keV (95% CL)*
- NRP neutrino: m_x > *14 keV*

Boyarsky et al 2009

(SDSS+WMAP)

- resonantly produced neutrino: m_x > *2 keV*

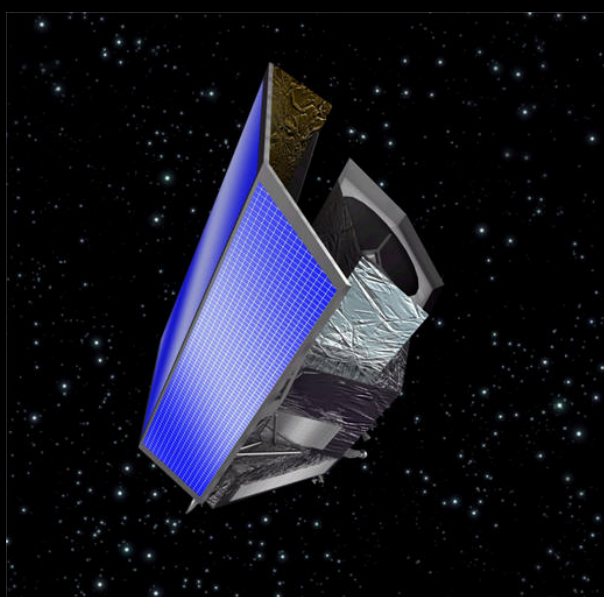
Tension with:

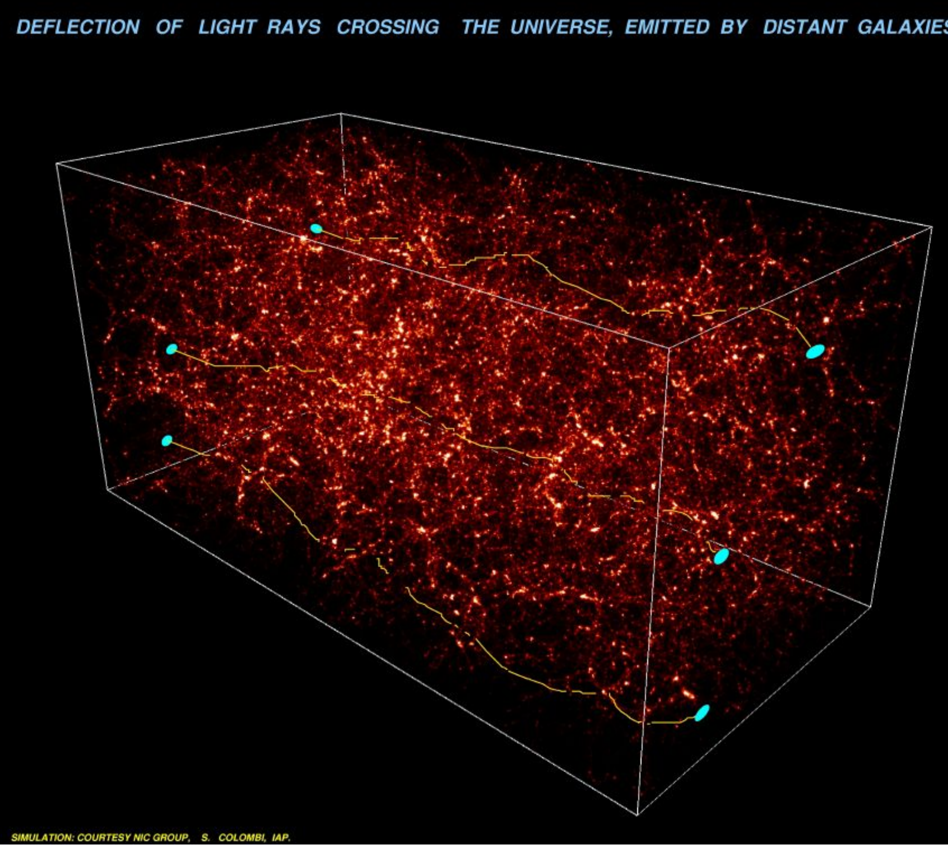
- WDM explanation anomaly Local Group satellites
- Upper limits neutrino WDM mass from X-rays

Weak gravitational lensing can reach constraints similar to Lyman-α in the future

Smith & Markovic 2011:

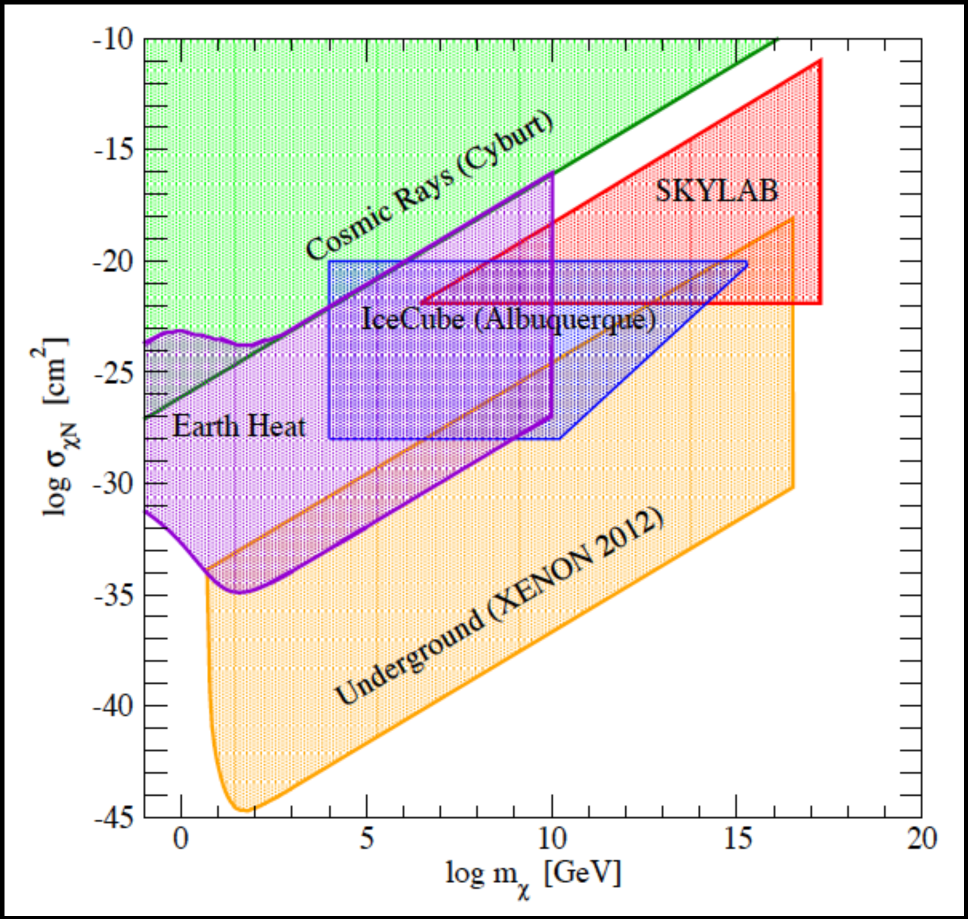
EUCLID/LSST + Planck → *$m_x > 2.6$ keV (thermal), $m_x > 16$ keV (NRP neutrino)*





2: Strongly interacting massive particles (***SIMP***) defined by large scattering cross-section with proton/neutron

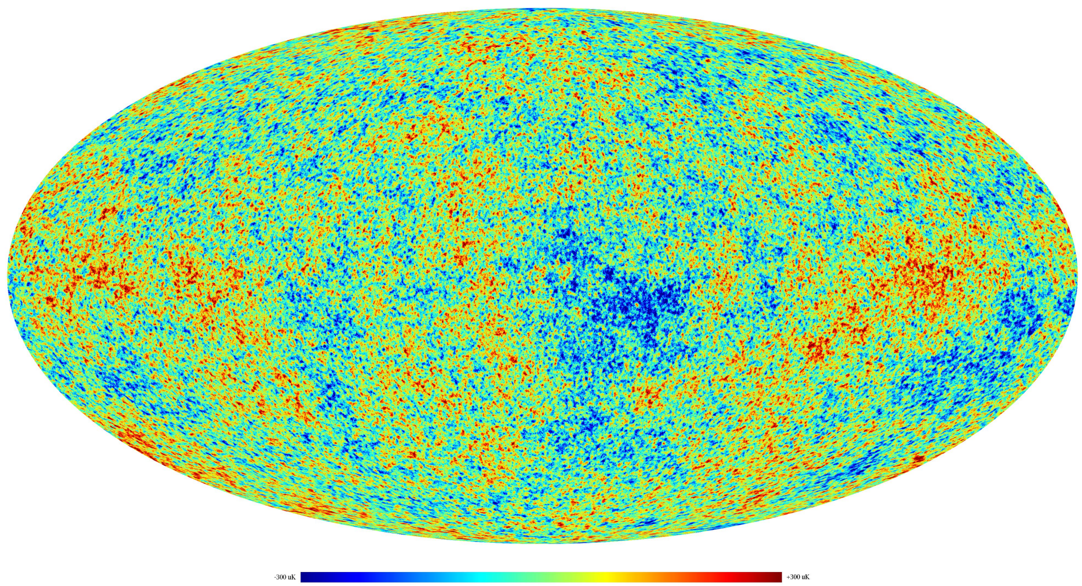
- Need large cross-sections:
  $\sigma \approx 1$ bn $= 10^{-24}$ cm^2
- Not ruled out by direct-detection experiments



Mack & Manohar 2012

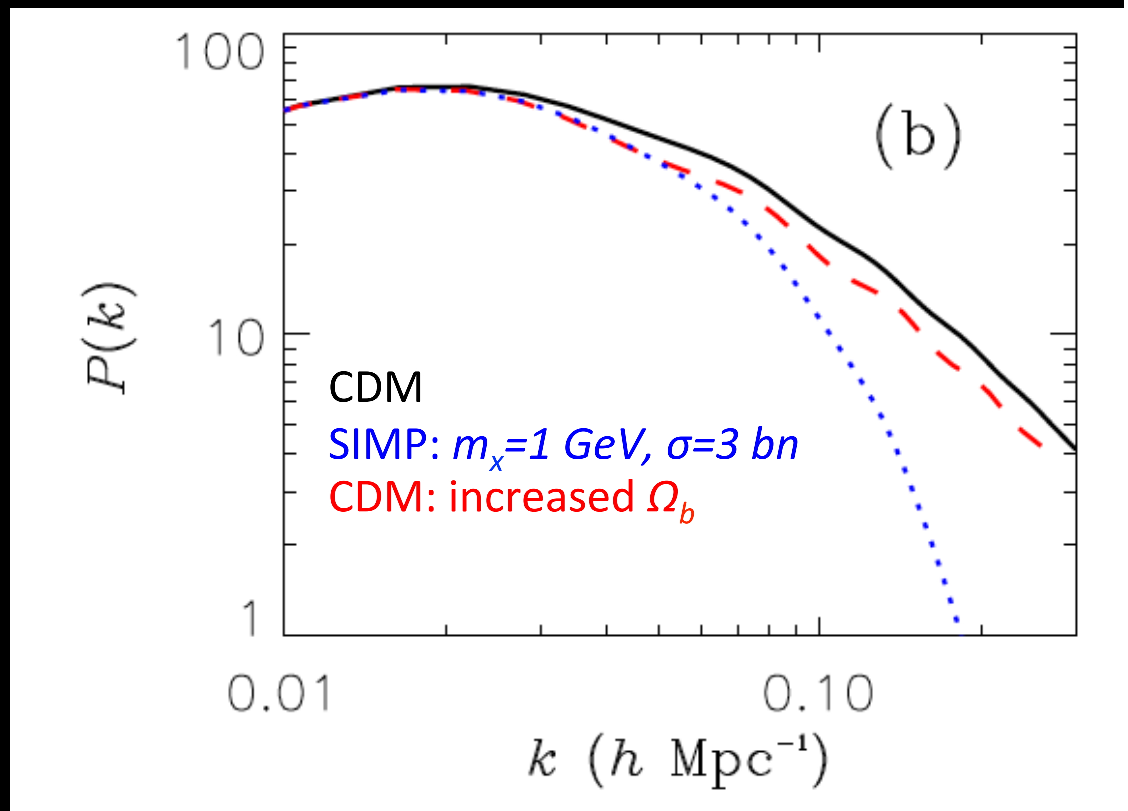
SIMP dark matter is coupled to baryon-photon plasma at early times

- Early: SIMP's participate in acoustic oscillations
- Only modes affected on scales smaller than sound horizon at time of SIMP-baryon decoupling



For $\boldsymbol{\sigma/m_x \approx 1}$ ***bn/GeV***, decoupling late enough that affected modes observable with CMB, LSS

Coupling to baryons leads to suppression of matter power spectrum



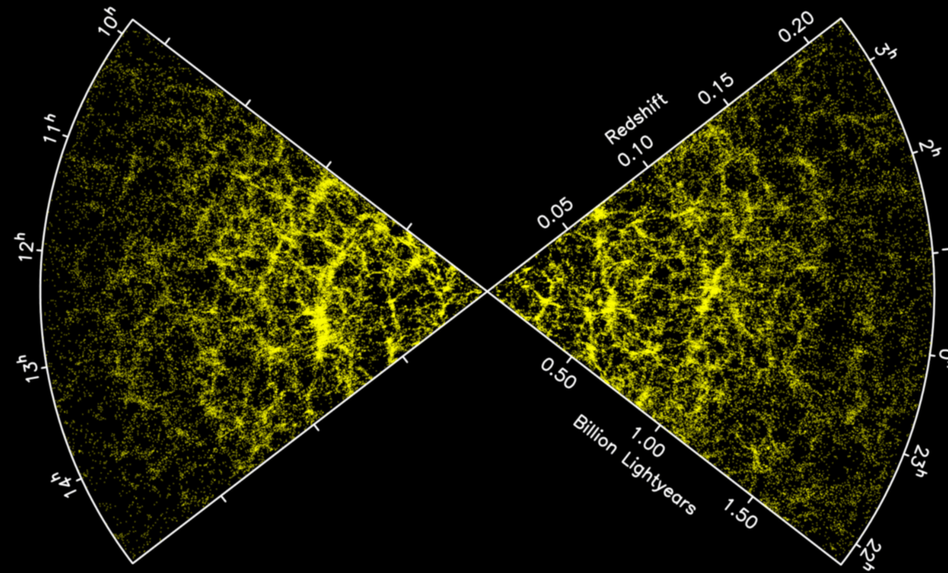
Chen, Hannestad & Scherrer 2002

Effect on matter power spectrum can be probed with galaxy clustering

- *galaxies trace the matter density on large, linear scales:*

$$P_g(k) = b^2 P_m(k) + N$$

- *b galaxy bias, free parameter → amplitude information lost*
- *difficult to model at $k > 0.2$ h/Mpc*



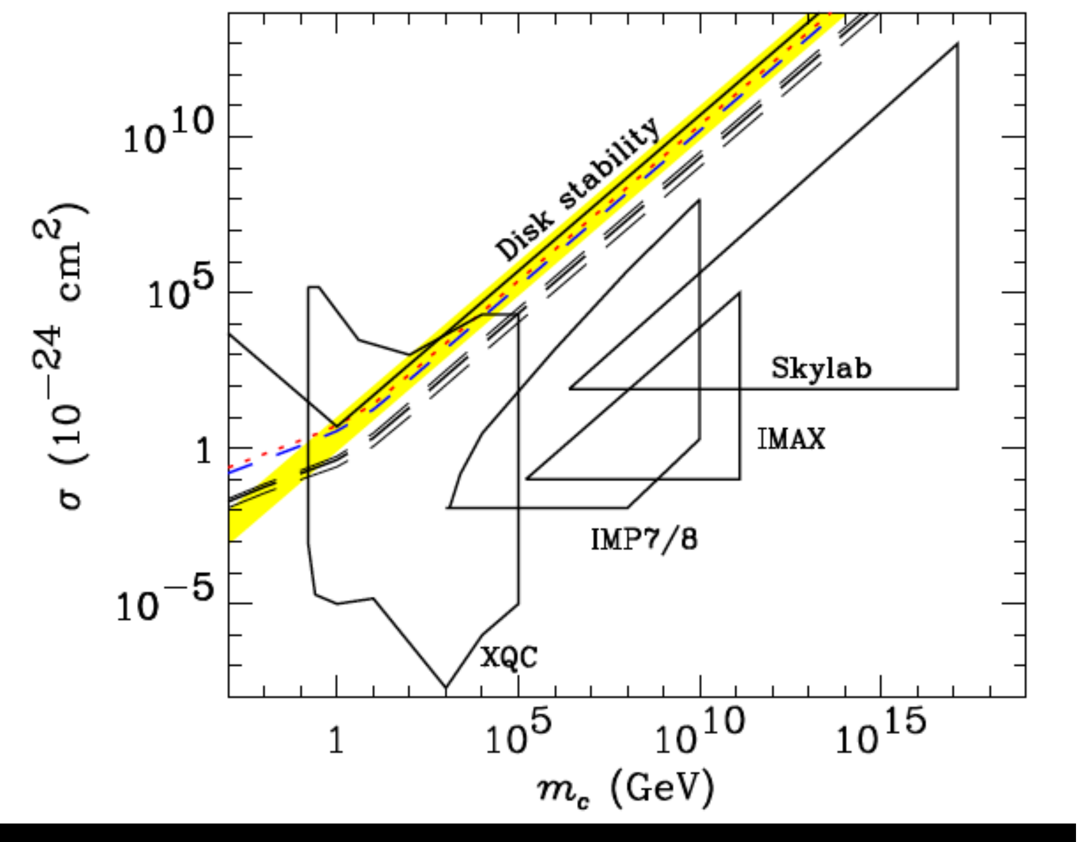
2dF Galaxy Redshift Survey

Cosmological large scale structure places interesting upper bound on σ

Chen, Hannestad & Scherrer 2002

$$\frac{\sigma}{10^{-24}\mathrm{cm}^2} < \frac{0.63x^{1/2} + 0.22x^{3/2}}{1 + x^{1/2}}$$

(95 % CL), ***x = m$_x$[GeV]***



Data:

- pre-WMAP CMB
- 2dF Galaxy Power Spectrum
- H_0
- BBN

3: Partially interacting dark matter ***(PIDM)***: a fraction of dark matter couples to dark photon

Atomic Dark Matter: *Goldberg & Hall 1986, Cyr-Racine & Sigurdson 2013, etc*

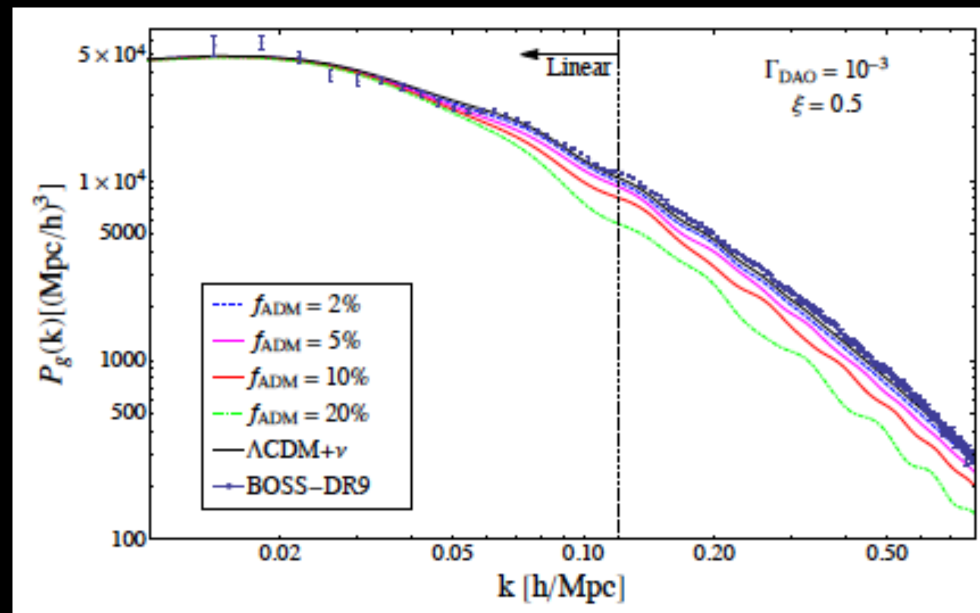
- dark proton, dark electron
- charged under $U_D(1)$

has been proposed as "double-disk" dark matter *Fan et al 2013 (x2)*
McCullough & Randall 2013

for details, see talk by
Francis-Yan

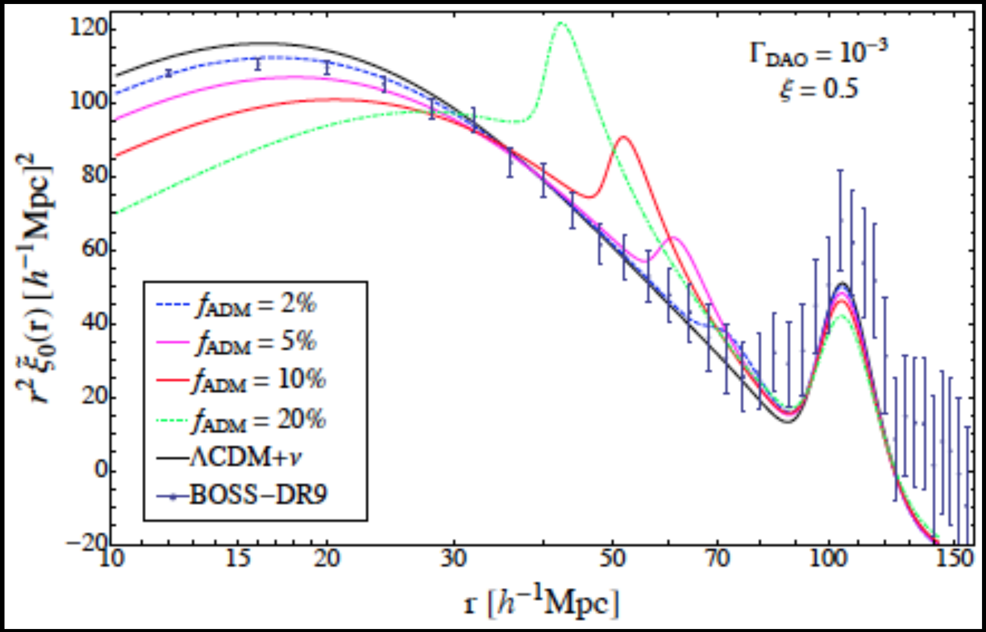
Dark acoustic oscillations (DAO) suppress the growth of structure

- When dark matter – dark radiation tightly coupled: dark acoustic oscillations
- After dark recombination/kinetic decoupling, behaves like cold dark matter
- Formation of non-linear structure can reionize DM



Cyr-Racine et al, in prep

Dark acoustic oscillations (DAO) imprint DAO peak in correlation function



Cyr-Racine et al, in prep

Galaxy power spectrum from ***BOSS*** constrains PIDM clustering

Cyr-Racine et al, in prep

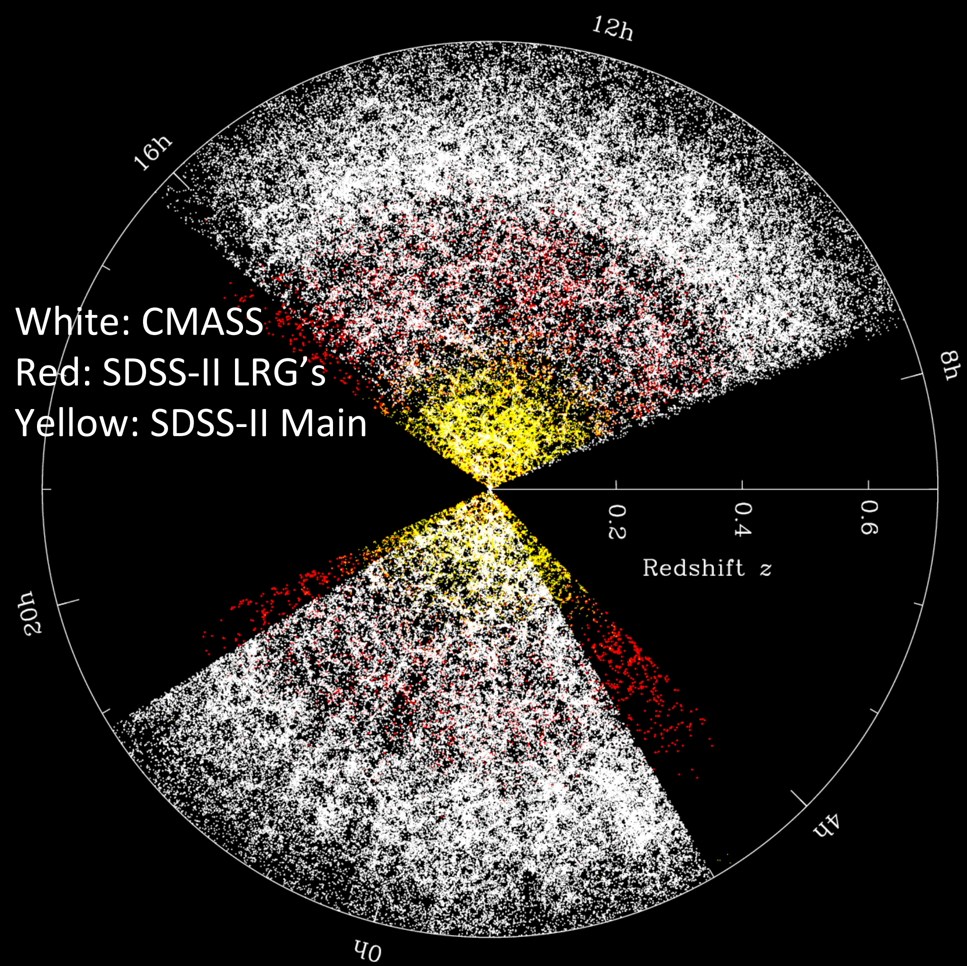


Image: Michael Blanton

CMASS sample:

Volume ≈*4 $(h^{-1}$ Gpc$)^3$/3*

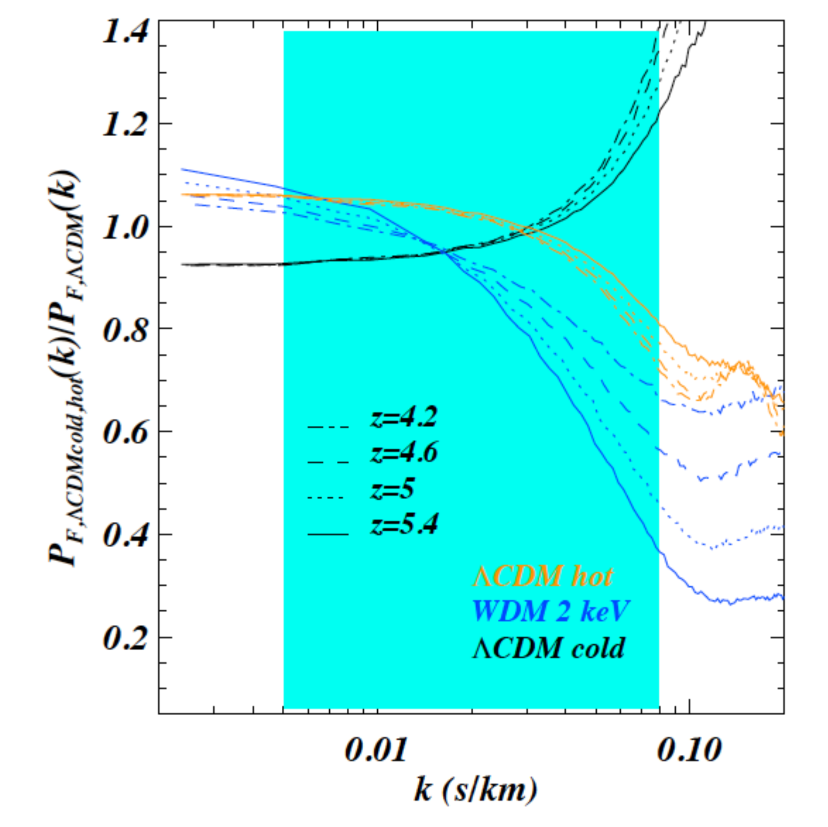
SDSS III

Cosmological data place strong constraints on double-disk dark matter

see talk by Francis-Yan

4. All three probes have systematics that might mimic effects of dark matter

- **Lyman-α** *transmission $F(\lambda) = e^{-\tau(z)}$*
  - *non-linearities -> need hydrodynamic simulations*
  - ***thermal state of IGM (e.g. inhomogeneous heating)***
  - *QSO continuum emission*
  - *etc*



Effect of change in temperature - density relation
Viel et al 2013

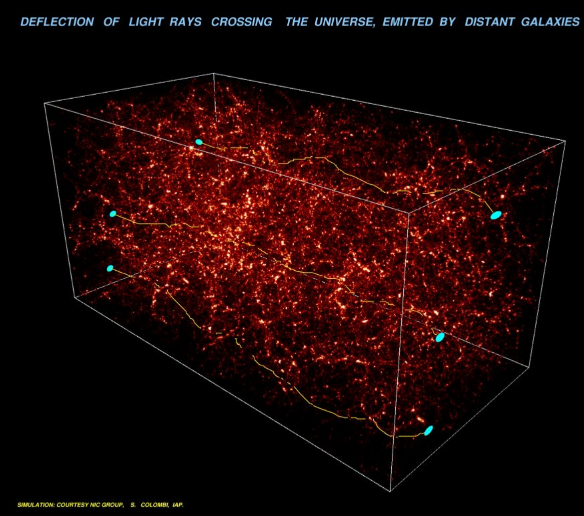
• Weak Lensing

forecasts in literature assume* we can model
P(k) to *k = 4 h/Mpc – 15 h/Mpc*

- *non-linear clustering*
- *baryonic effects*

Need hydrodynamic simulations

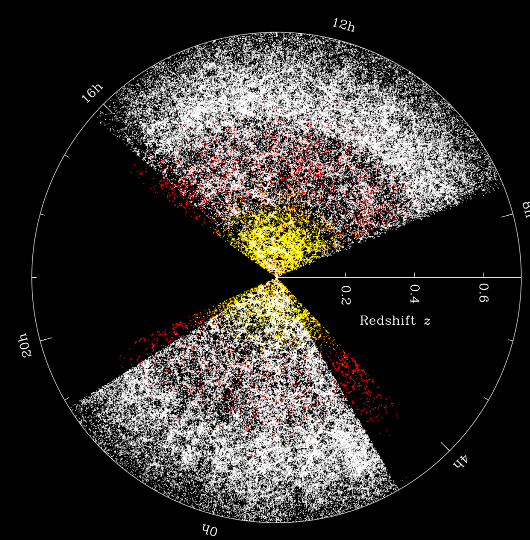
**Markovic et al 2011, Smith & Markovic 2011*



Semboloni et al 2011

• Galaxy Clustering

$$P_g(k) \approx b^2 P_m(k) + N$$



- *non-linear clustering*
- *scale-dependent galaxy bias*

Does not probe scales as small as WL or Ly-α:
k_{max} = *0.2 h/Mpc* optimistic

Jeong & Komatsu 2009

Summary

- *Lyman-α*, *weak lensing* & *galaxy clustering* useful probes of dark matter
- Strong constraints found/forecasted on *warm dark matter*, *dark matter-baryon interaction*, *dark matter-dark radiation interaction*
- (Typical large scale structure signature is small-scale suppression: confusion with modeling/observational systematics is a risk)