Cosmology W13

Lecture 11: February 27 2013

Finally, dark matter!!

- What is Dark Matter?
  - Hot/Warm/Cold dark matter
  - Dark matter candidates
  - Limits on dark matter
- Free streaming
- Cold dark matter scenario

What is dark matter?

Hot Dark Matter

- Neutrinos are a good example… mass required is too high for standard neutrinos (see homework)
- Does not work from the point of view of Large Scale Structure

Cold Dark Matter

- WIMP is a good example. Decoupled when non-relativistic (hence cold)
- See homework
- Consistent with current observations. Leading model at the time

Warm Dark Matter

- Intermediate case. E.g. sterile neutrinos
- Generically distribution function can be described by

$$f(v) \propto \frac{\beta}{e^{pc/\alpha k T_\gamma} + 1}$$

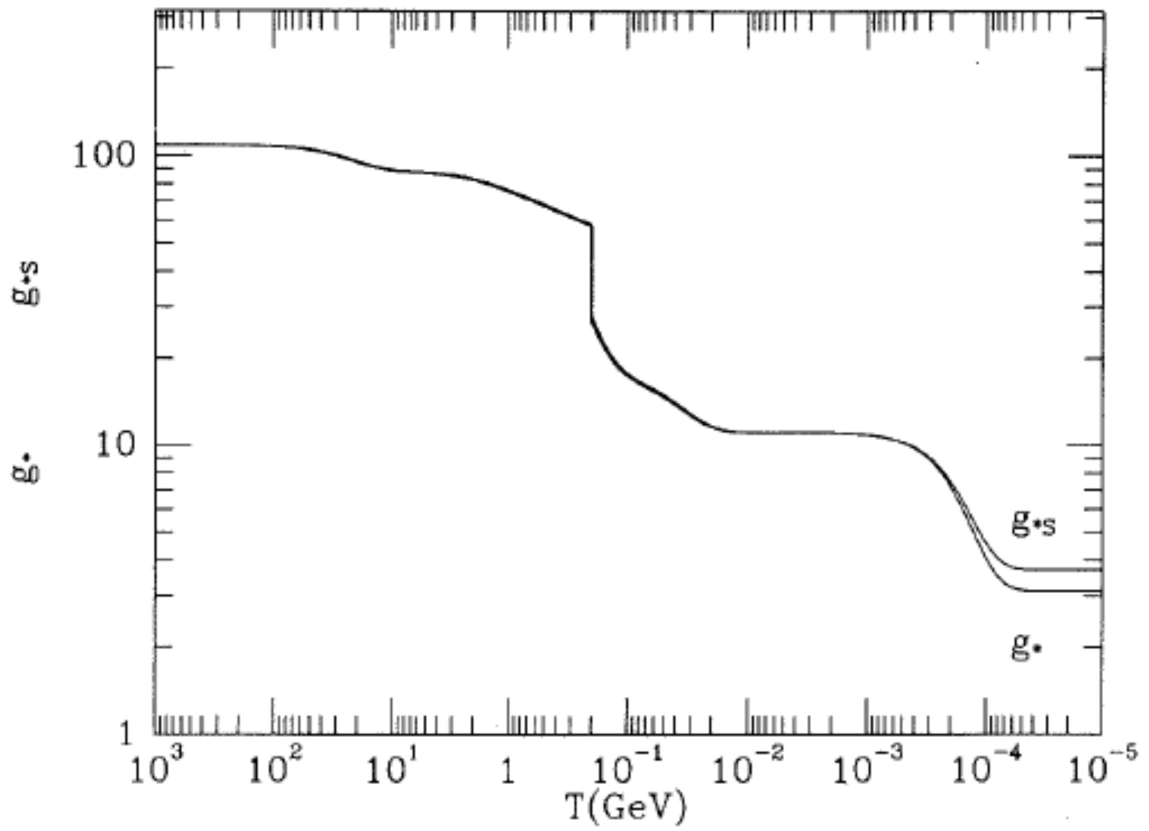
$$\mathrm{Neutrino\ HDM:}\ \ \alpha = (4/11)^{1/3}, \beta = 1$$

$$\mathrm{CDM:}\ \ \alpha \to 0 m \to \infty$$

$$\mathrm{thermal\ WDM:}\ \ \alpha < 1$$

$$\mathrm{non-thermal\ WDM:}\ \ \beta < 1$$

Number of rel. degrees of freedom



$$\chi = g_*/2 \quad \epsilon = \chi a T^4$$

$$g_{*,s} = \sum_{bose} g_i (T_i/T)^3 + 7/8 \sum_{fermi} g_i (T_i/T)^3$$

Kolb & Turner

Warm Dark Matter

- Since WDM decouples when it's relativistic its abundance is given by

$$\Omega_{\mathrm{WDM}}h^2 = \beta\left(\frac{\alpha^3 11}{4}\right)\left(\frac{m_{WDM}}{93eV}\right)$$

- Thermal relic is for beta=1 and T can be much lower than TCMB if decoupling happens early on

Free streaming

- Dark matter is weakly interacting – long mean free path - fluid approximation is only valid for scales much larger than the mean free path
- Free streaming length sets a minimum scale for perturbation in collisionless dark matter [blackboard]

For a relativistic thermal relic

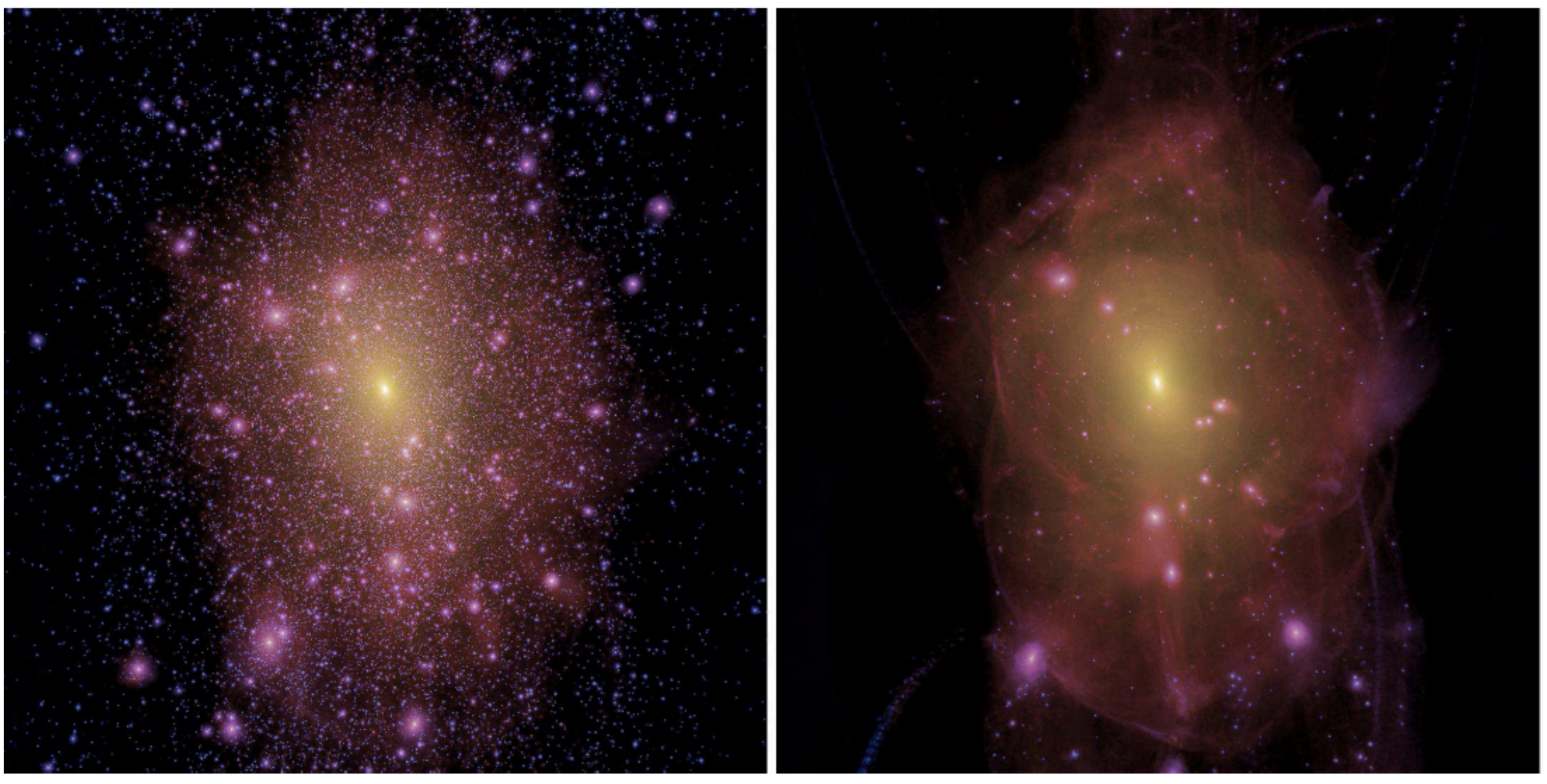
$$\Omega_{\rm DM} h^2 \approx 30 \left(\frac{m_{\rm DM}}{1{\rm keV}}\right) \left(\frac{T_{\rm DM}}{T_{\rm CMB}}\right)^3$$

$$\lambda_{\rm FS} = 0.5{\rm Mpc} \left(\Omega_{\rm DM} h^2\right)^{1/3} \left(\frac{m_{\rm DM}}{1{\rm keV}}\right)^{-4/3}$$

$$\approx 0.25{\rm Mpc} \left(\frac{m_{\rm DM}}{1{\rm keV}}\right)^{-4/3} [\text{for WDM}]$$

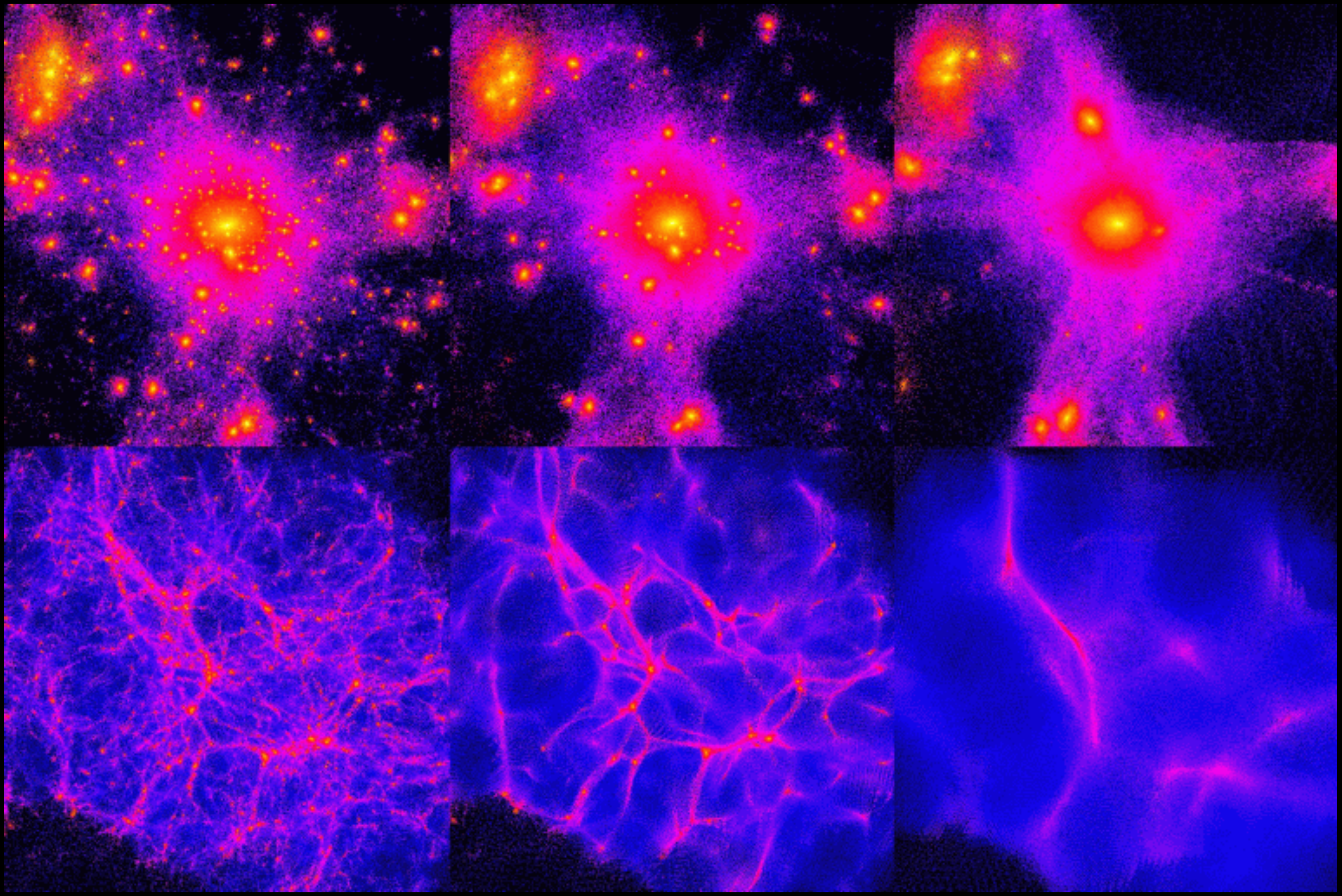
$$\rightarrow M_{\rm FS} \propto \Omega_{\rm DM} \lambda_{\rm FS}^3 \propto \Omega_{\rm DM}^2 m_{\rm DM}^{-4} \sim 10^9 [\text{for KeV WDM}]$$

Warm Dark Matter



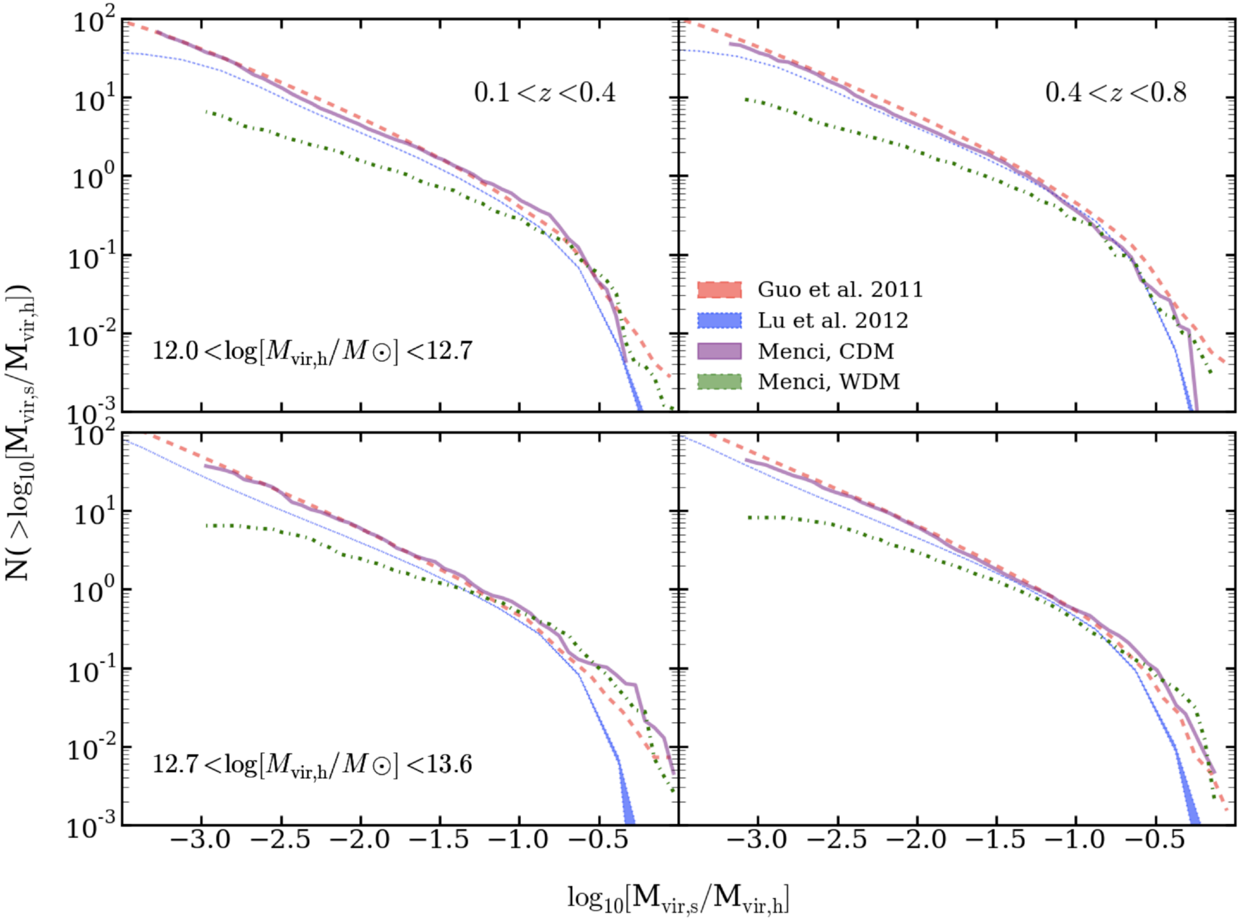
Lovell et al. 2012

Cold Warm and Hot Dark Matter



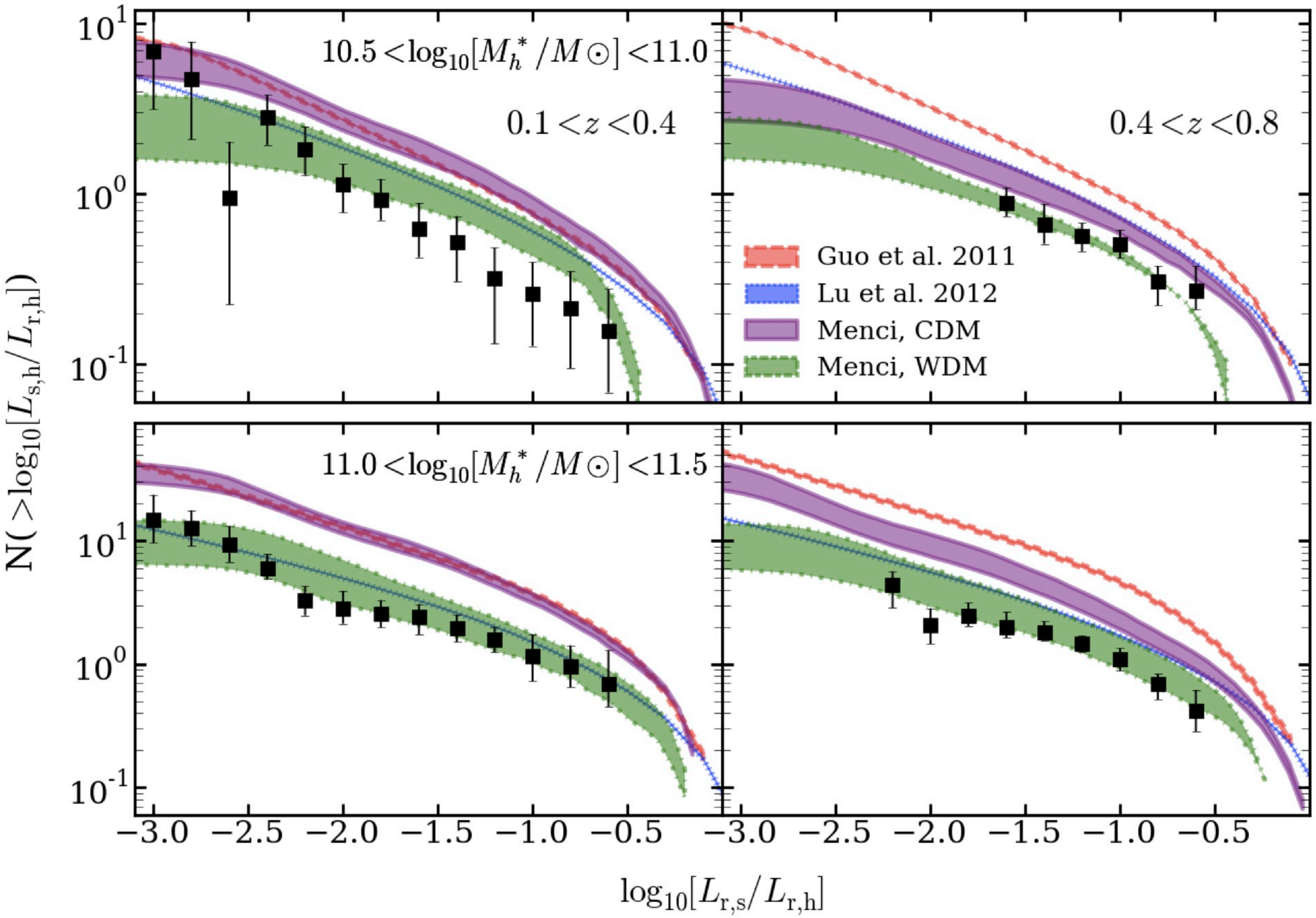
ITP Zurich

Satellites in CDM vs WDM



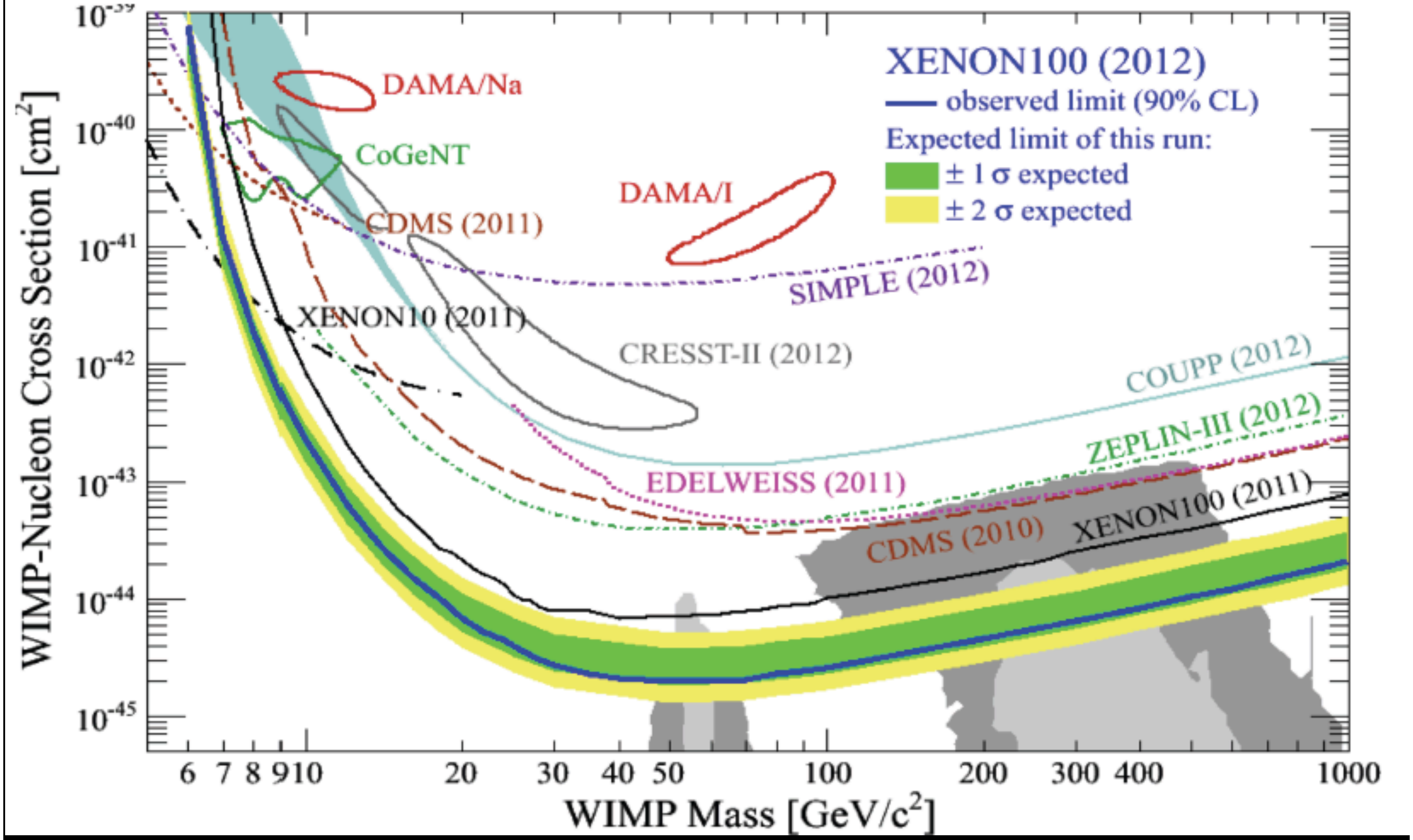
Nierenberg et al. 2013

Satellites in CDM vs WDM

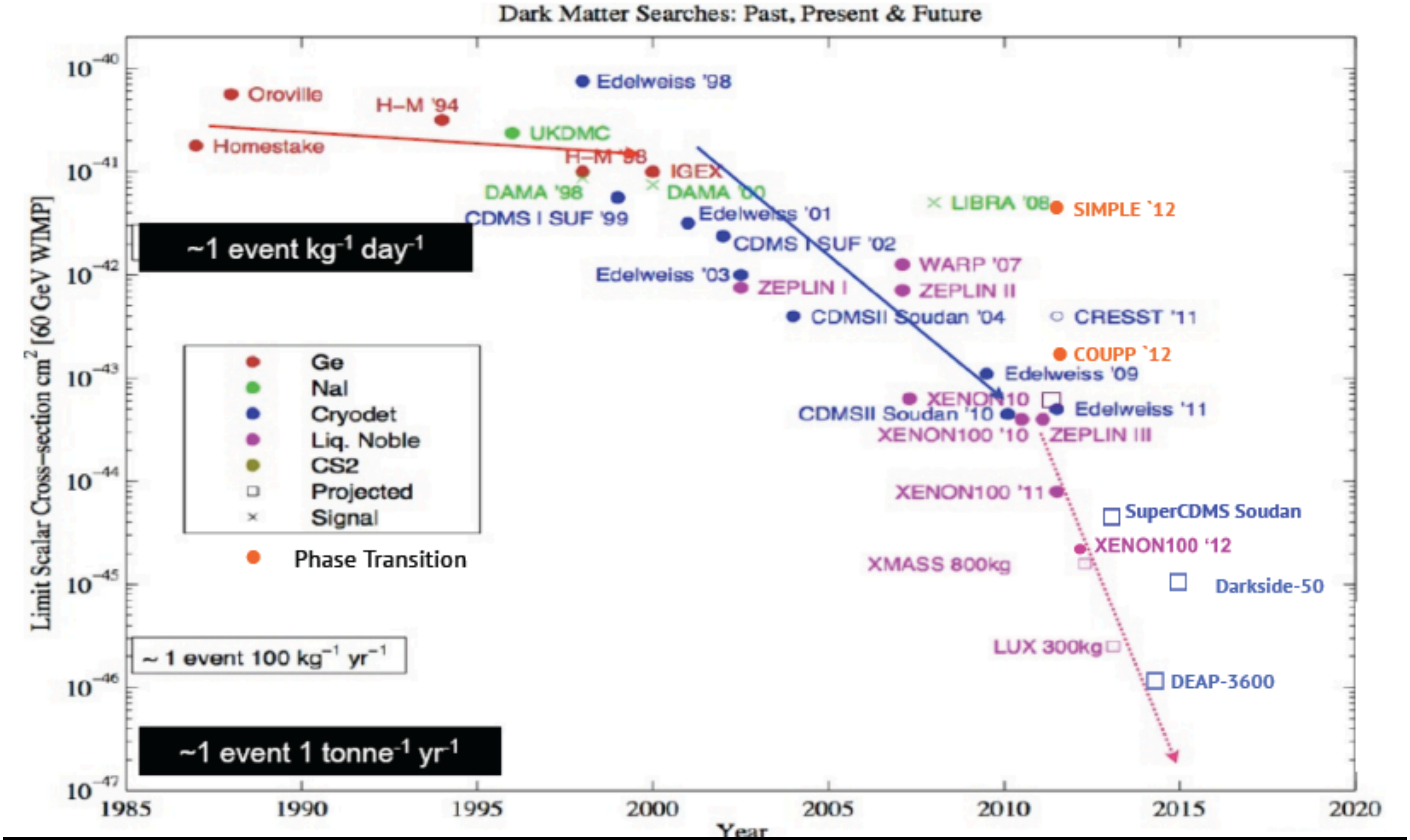


Nierenberg et al. 2013

WIMP SI Parameter Space “race to the bottom”



From Harry Nelson’s talk at DAMASC



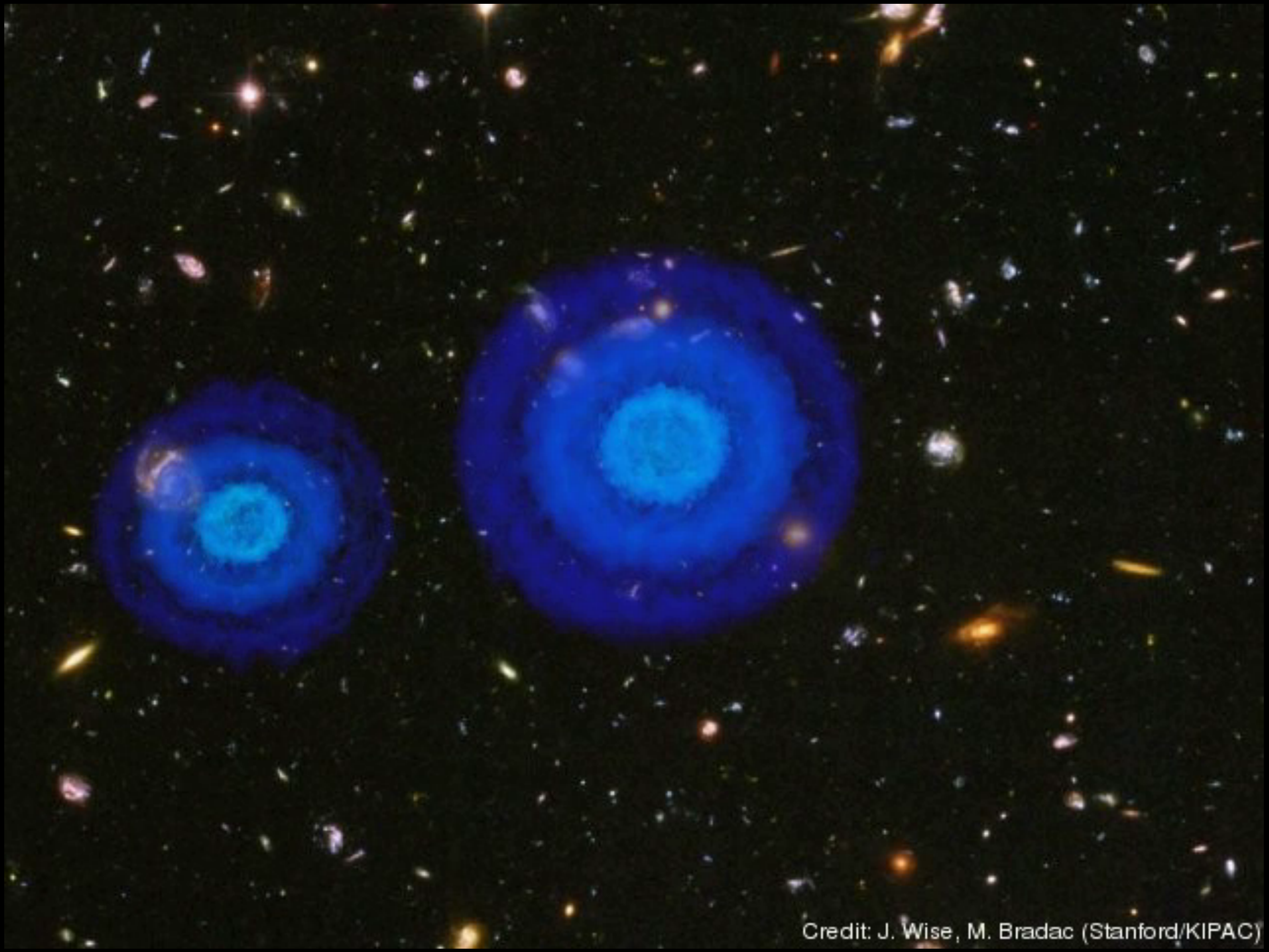
Dark Matter Searches: Past, Present & Future

From Harry Nelson’s talk at DAMASC

Other limits on dark matter

- LHC
- Astronomical limits on self-interaction cross-section (claim of a marginal detection; Dawson et al. 2012)
- Limits on cross section for self-annhilation and decay into standard model particles, e.g. from Fermi Gamma Ray Telescope. Recent claim of line detection at ~130 GeV

One example



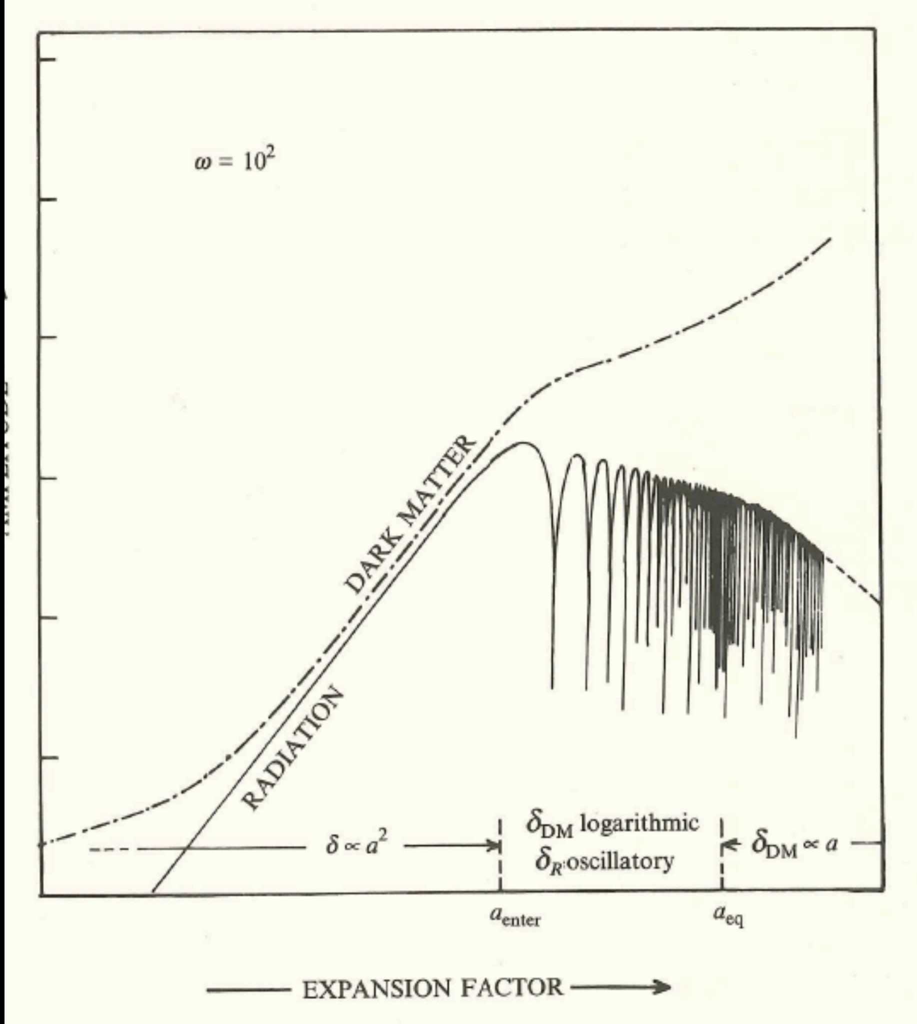
Credit: J. Wise, M. Bradac (Stanford/KIPAC)

Perturbations in W/CDM

Perturbations with Dark Matter

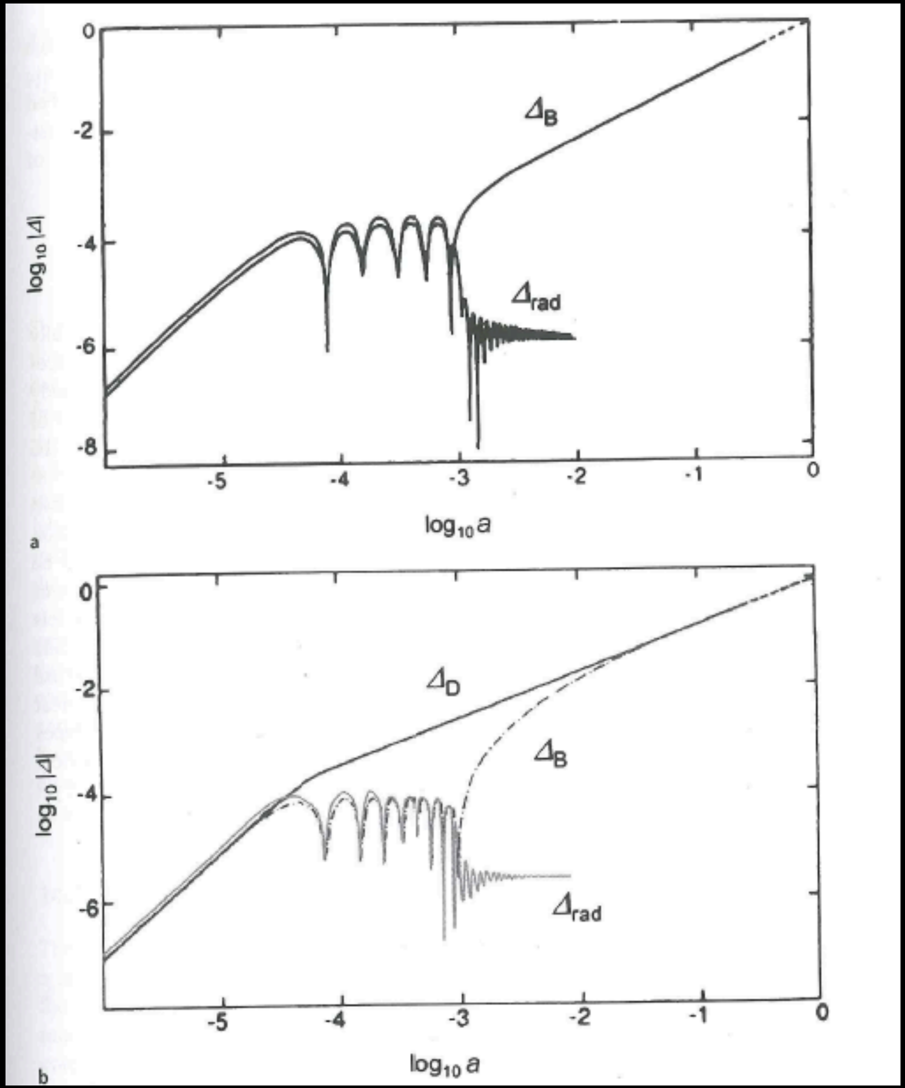
- Dark matter is collisionless and interactions with photon-baryon gas are negligible
- Subhorizon scale dark matter perturbations grow even while baryon perturbations are stabilized by radiation pressure or damped by Silk damping
- At the time of decoupling of baryons from radiation, baryons find larger fluctuations in dark matter density field and quickly “catch up”

Evolution of perturbations



Padmanabhan

Evolution of perturbations



Padmanabhan

Perturbations with Dark Matter

Epoch **Scale**	δ_R	δ_{DM}	δ_B
$z<z_{enter}<z_{eq}$ λ>horizon	Grow as a^2	Grow as a^2	Grow as a^2
$z_{enter}<z<z_{eq}$ λ<horizon	Oscillates; Silk Damping	Grows as ln a; Free streaming	Oscillates; Silk Damping
$z_{eq}<z<z_{dec}$ λ<horizon	Oscillates; Silk Damping	Grows as a; Free streaming	Oscillates; Silk Damping
$z_{dec}<z$ λ<horizon	Oscillates; Silk Damping	Grows as a; Free streaming	Grows as a;

z_{eq}~3500; Z_{dec}~400: dark matter fluctuations x10 baryons between the two times

Type of perturbations

- Curvature modes:
  - Initial perturbations are set in all components

$$\frac{1}{3}\Delta_B = \frac{1}{3}\Delta_D = \frac{1}{4}\Delta_{\mathrm{rad}} = \frac{1}{4}\Delta_C$$

  - Curvature modes arise naturally in inflation (we cannot conver this unfortunately)
- Isocurvature modes:
  - Perturbations are such that curvature is not perturbed

Growth of perturbations in baryons

- Imagine you have much stronger perturbations in DM than in baryons, during the matter dominated era.
  - Before decoupling DM fluctuations grow linearly
  - Baryon fluctuations are stabilized by coupling with photons
- As soon as the coupling stops

$$\ddot{\Delta}_B + 2\frac{\dot{a}}{a}\dot{\Delta}_B = 4\pi G\rho_D \Delta_{\mathrm{D,dec}} a$$

Growth of perturbations in baryons

- But universe is effectively EdS (no lambda, no photons in this range) so one can simplify to

$$a = (3H_0t/2)^{\frac{2}{3}}$$

$$\rightarrow \Delta_B = \Delta_{\mathrm{D}}\left(1 - \frac{z}{z0}\right)$$

- Where z0 is redshift at which there are no baryonic fluctuations.
- So baryons catch up very quickly with dark matter

The cold dark matter model

The next challenge is taking baryons into account realistically…

The end