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Warm dark matter with future cosmic shear data

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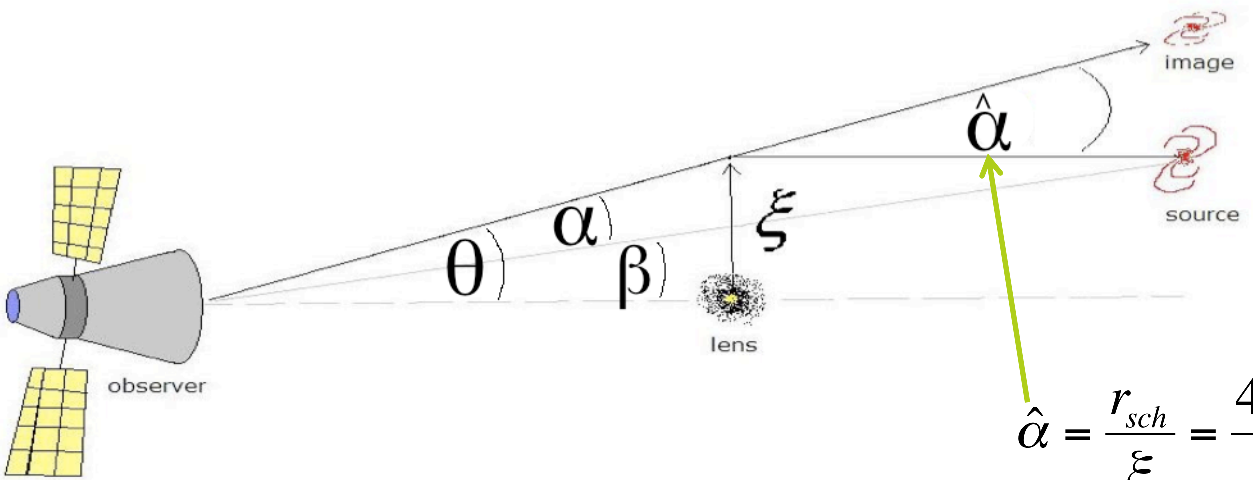
Warm dark matter with future cosmic shear data

- Gravitational lensing
  - Quick introduction
  - Shear power spectrum
  - 3D-mapping with Euclid
- Non-linear WDM strucure
  - Free-streaming
  - HALOFIT
  - Halo model
  - WDM Halo model
- Forecasts

Gravitational lensing as a probe of dark matter structure

- The (so far) only observable dark matter interaction is gravitational.
- Light follows the shortest paths through spacetime (geodesics) => is deflected around massive objects.
- Therefore we can probe the distribution of dark matter by observing this deflection called *gravitational lensing*.
- Einstein deflection law for a circularly symmetric lens:

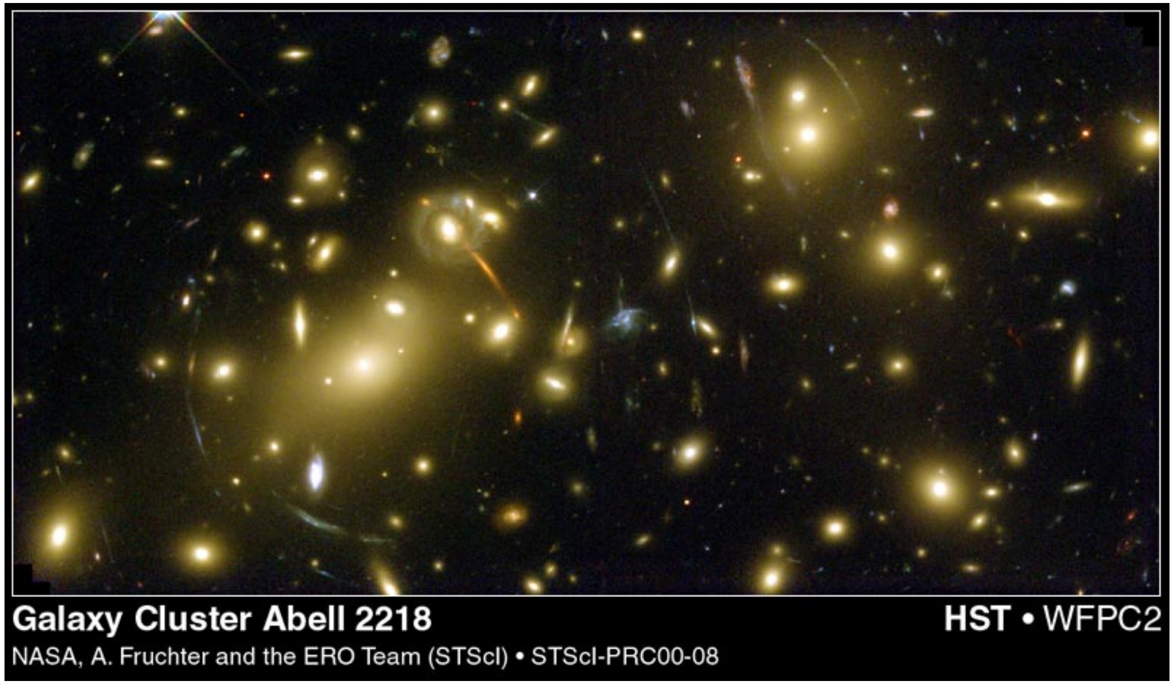


$$\hat{\alpha} = \frac{r_{sch}}{\xi} = \frac{4GM}{c^2 \xi}$$

Gravitational lensing as a probe of dark matter structure

Strong gravitational lensing:

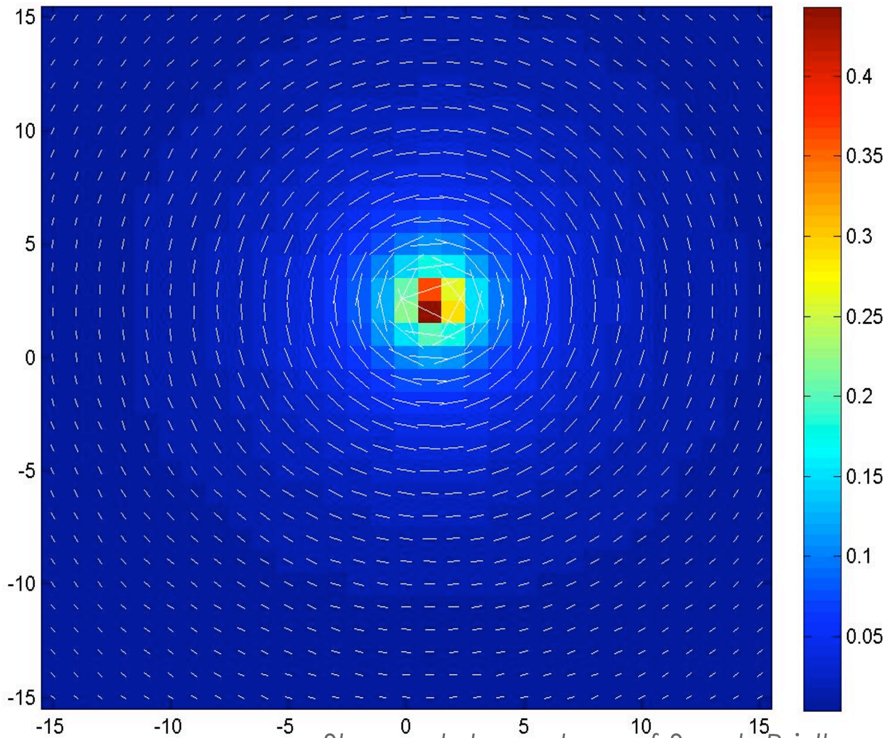
- Very massive lens – large clusters of galaxies, superclusters
- Magnification of background galaxies
- Distortion
- Multiple images
- Probes the substructure of massive objects
- Can measure the mass of the lens very accurately



Gravitational lensing as a probe of dark matter structure

Weak gravitational lensing:

- Weak lensing distorts background images in two ways:
  ~ it stretches them - *shear*
  ~ it bends them - *flexion*
- Traces the mass distribution even for weaker lenses and to larger radii.
- Get weak lensing even from individual galaxies and can estimate the large scale mass distribution – statistical studies.



Shear plot courtesy of Sarah Bridle

Gravitational lensing as a probe of dark matter structure

Weak gravitational lensing:

- Scaled deflection angle: $$\vec{\alpha}\left(\vec{\theta}\right) = \frac{1}{\pi}\int d^2\vec{\theta}'\kappa\left(\vec{\theta}'\right)\frac{\vec{\theta}-\vec{\theta}'}{\left|\vec{\theta}-\vec{\theta}'\right|^2} = \nabla\psi$$
- $\kappa(\theta)$ is the dimensionless surface mass density or *convergence*, which quantifies the distortion in the size of the image, Ψ is the lensing potential.
- For an extended source image (but still with much smaller angular size than the lens) use the Jacobian matrix to describe the distortion:

$$A(\vec{\vartheta}) = \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

- γ_1 and γ_2 are the shear components, describing the magnitude and direction of the stretching of the image.
- The statistics of $\kappa(\theta)$ and $\gamma(\theta)$ are directly related.

Gravitational lensing as a probe of dark matter structure

Cosmic shear:

- Photons propagate through the universe and are constantly deflected by the gravitational field of the inhomogeneous 3D cosmic mass distribution.
- This lensing by Large Scale Structure is called *cosmic shear*.
- We now need a modified description of our lensing optics.
- The lowest order approximation takes sources at a single redshift and integrates over all lenses along the line of sight the [geometric factor from the lens equation] x [density contrast]:

$$\kappa(\theta) = \int_0^{\chi_s} d\chi_l W(\chi_l)\delta(\chi_l, \chi_l\theta)$$

- We can measure 2nd order statistics in κ .
- It can be shown that they are directly related to 2nd order statistics in γ .

Measuring the shear power spectrum

- The power spectrum of this effective κ is actually the same as the shear power spectrum and is defined as:

$$\left\langle \kappa_l \kappa_{l'}^* \right\rangle = (2\pi)^2 \delta_D (l - l') C_\kappa (l)$$

- Therefore we can write:

$$C_\kappa(l) = \int_0^{\chi_H} d\chi_l W^2(\chi_l) \chi^{-2} P_{nlin}\left(k = \frac{l}{\chi_l}, \chi_l\right)$$

- With the lensing weight:

$$W(\chi_l) = \overline{\rho}_m (z_l) \Sigma_{crit}^{-1} (\chi_l, \chi_s)$$

- with all sources assumed to lie on a single plane.
- $P_{nlin}(k)$ is the non-linear matter power spectrum at the redshift of the lens.

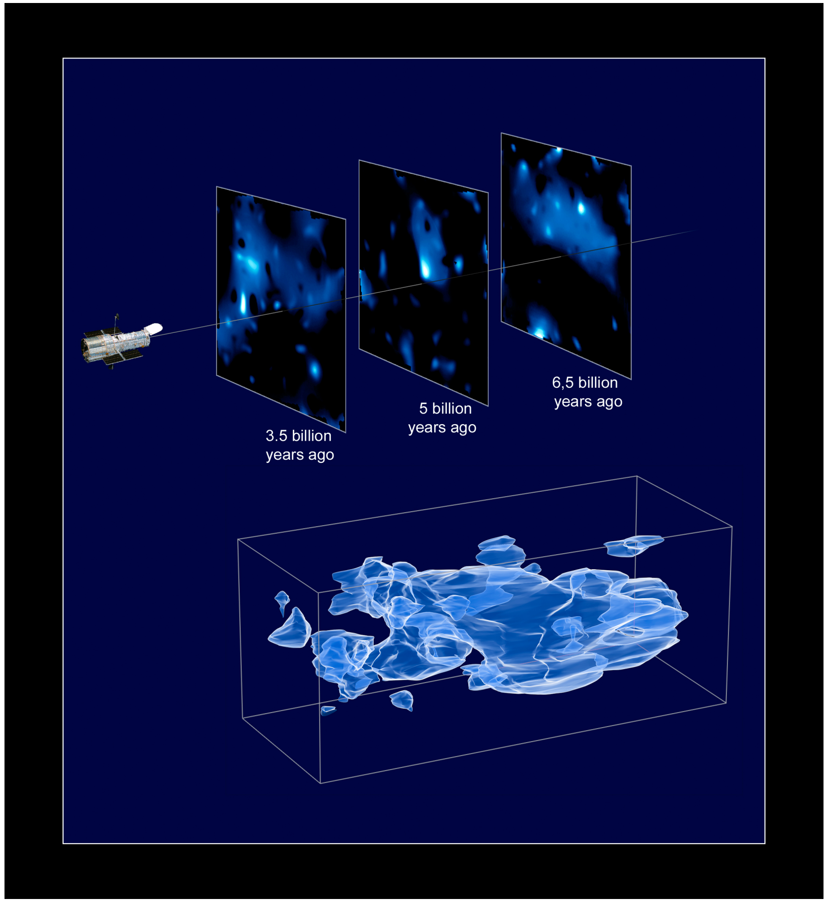
Measuring the shear power spectrum

- Cosmic shear is the only way to map out the dark matter distribution without making any assumptions about the relation between dark matter and baryonic matter.
- Cosmic shear measures the non-linearly evolved mass distribution.
- Cosmic shear measurements can be combined with measurements of linear power spectra from CMB data.
- Therefore it can provide a powerful probe of the gravitational growth of structure.
- Cosmic shear probes smaller scales than CMB data and so combining these breaks parameter degeneracies.
- In addition, in order to probe the dark energy equation of state, we need low redshift measurements (recent in time)!

Measuring the shear power spectrum

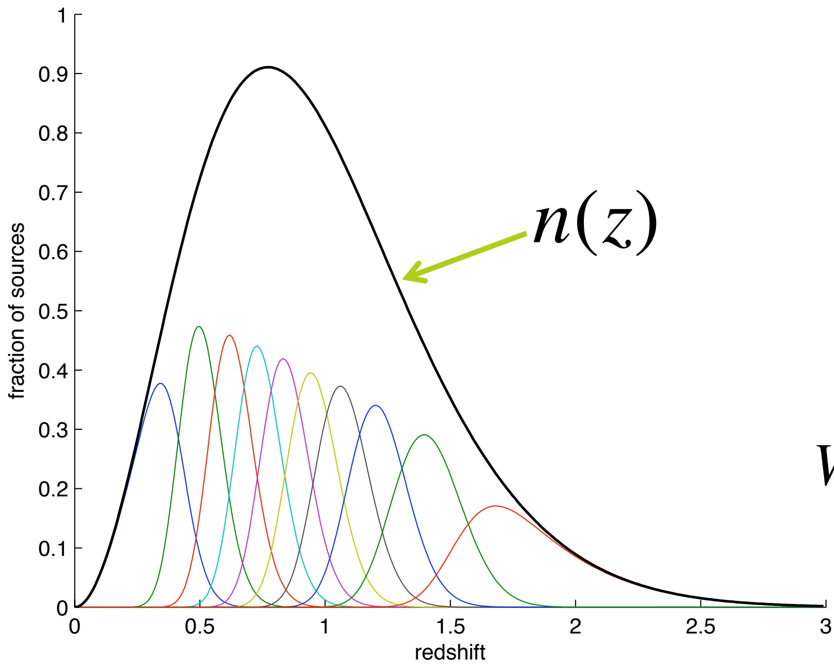
EUCLID: an ESA Cosmic Vision proposal

- 20,000 deg – half the sky!
- WEAK LENSING with photometric redshifts
- spectroscopic redshifts (NIR) for 33% of all galaxies brighter than 22 mag
- Constraints:
  aperture: max 1.2 diameter
  limited numbers of NIR detectors
  mission duration: max ~5 years



WL reconstruction from the HST COSMOS survey (source: ESA)

Measuring the shear power spectrum



Tomography:

- Convergence from redshift bin i:

$$\kappa_i(\theta) = \int_0^{\chi_H} d\chi W_i(\chi)\delta(\chi,\chi\theta)$$

- Lensing weight:

$$W_i(\chi_l) = \bar{\rho}_{m,0} \int_{z_l}^{z_{\max}} \left[\frac{n_i(z_s)}{\Sigma_{crit}(\chi_l,\chi_s)} \right] dz_s$$

- The lensing power spectrum - correlation of bins i & j:

$$\bar{C}_{ij}(l) = \left[\int_0^{\chi_H} d\chi W_i(\chi) W_j(\chi) \chi^{-2} P_{nlin}\left(l = \frac{k}{\chi}, \chi \right) \right] + \delta_{ij} \frac{\sigma_\gamma}{\bar{n}_i}$$

Free-streaming of WDM

- Energetic DM particles free-stream. This means that they are able to escape some gravitational potential wells.
- The free-streaming is limited by their velocity and the size of the cosmological horizon at each time point.
- WDM particles had “large” (compared to CDM) velocities in the early universe.
- In the early universe have forming gravitational potential wells, due to the perturbations in the matter density field (caused by inflation).
- Free-streaming of energetic DM particles (i.e. WDM) suppresses formation of gravitational wells smaller than the free-streaming length of WDM.
- As the universe expanded DM particles “cooled-down”.
- WDM stayed relativistic longer than CDM.
- If initial velocity (or temperature) of DM particles relatively low (compared to HDM, neutrinos), CMB observations unaffected…
- Today: “missing dwarf galaxy problem” etc. – observations vs. CDM simulations

Free-streaming of WDM

- A DM candidate particle must be neutral and very stable.
- We take a thermalised, light (keV mass), neutrino-like DM particle.
- E.g. supersymmetric gravitino: m~keV
- We forecast a limit on this particle mass for the Euclid survey (proposed to the ESA).
- Can convert our limit to a limit on the mass of a standard model sterile neutrino (simple model of sterile ν pretty much ruled out by Lyα & X-ray data)
- This particle stays relativistic long enough to erase small structure in the early universe, but not long enough to affect the scales probed by the CMB (these are consistent with CDM).
- If DM decouples while in thermal eqm. in the early universe, we can calculate its free streaming length and effective temp. (Viel et al (2005), Bode, Ostriker & Turok (2001)):

$$R_{\rm fs} = 0.11\left(\frac{\Omega_{WDM}h^2}{0.15}\right)^{1/3}\left(\frac{m_{WDM}}{1\rm keV}\right)^{-4/3}\rm Mpc \qquad \frac{T_{WDM}}{T_\nu} = \left(\frac{10.75}{g*(T_D)}\right)^{1/3} = \left(\Omega_{WDM}h^2\frac{94eV}{m_{WDM}}\right)^{1/3}$$

Free-streaming of WDM

- From Boltzmann codes like CAMB or CMBFAST can calculate modification of matter power spectra due to WDM.

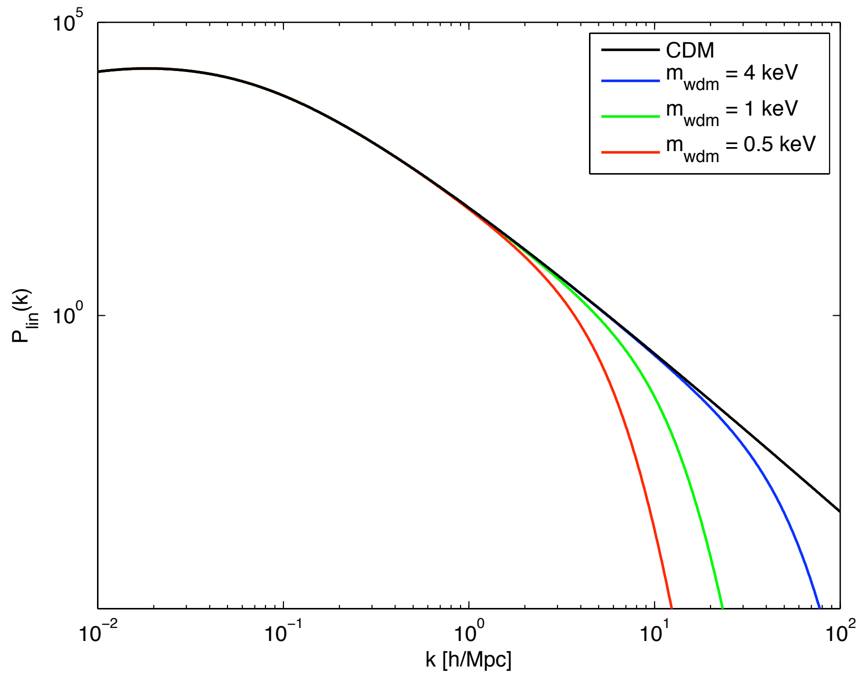
- Small scales become suppressed.

- Have a simple fitting function from Viel et al (2005):

$$T_{wdm}(k) = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

- where:

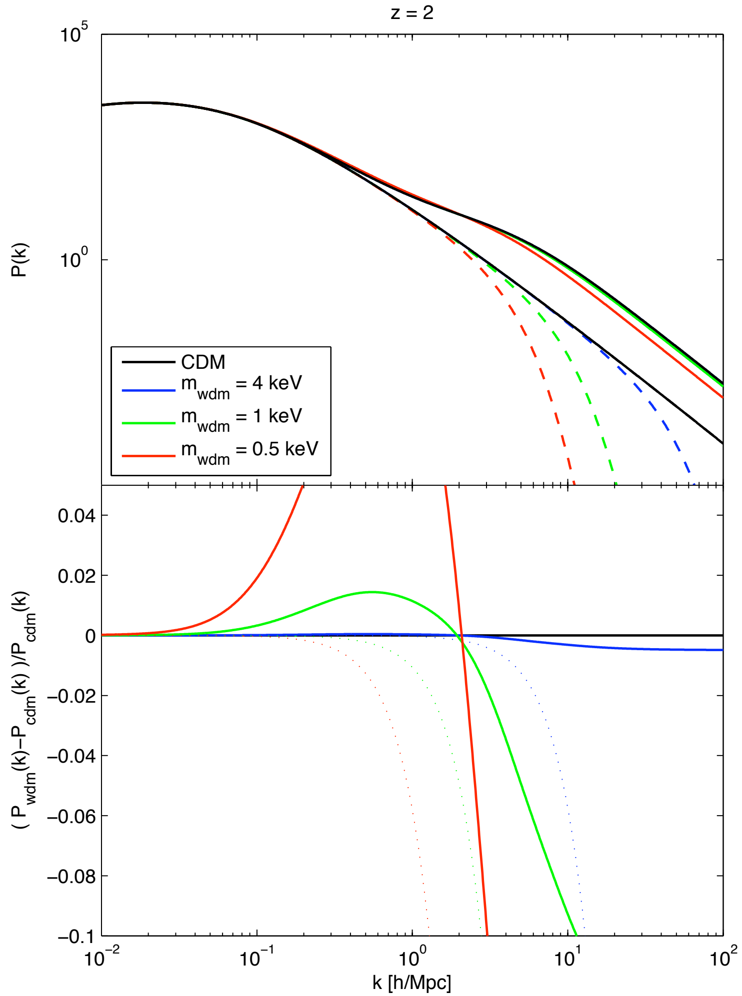
$$\alpha = 0.049 \left(\frac{m_{wdm}}{1\mathrm{keV}}\right)^{-1.11} \left(\frac{\Omega_{wdm}}{0.25}\right)^{0.11} \left(\frac{h}{0.7}\right)^{1.22} h^{-1}\mathrm{Mpc}$$



Non-linear WDM structure

HALOFIT

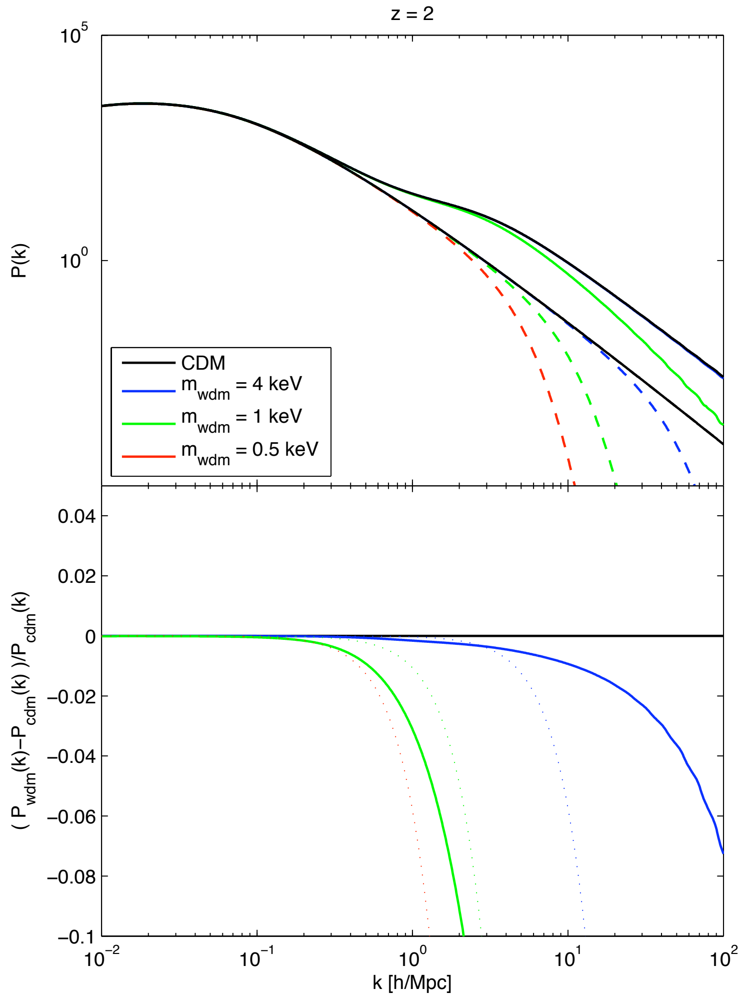
- Naïve/brute force application of HALOFIT (Smith et al. 2003)
- Regeneration of small scale power => information loss
- But HALOFIT is based on CDM simulations!
- If go higher in redshift, see more of a suppresion effect



Non-linear WDM structure

HALO MODEL

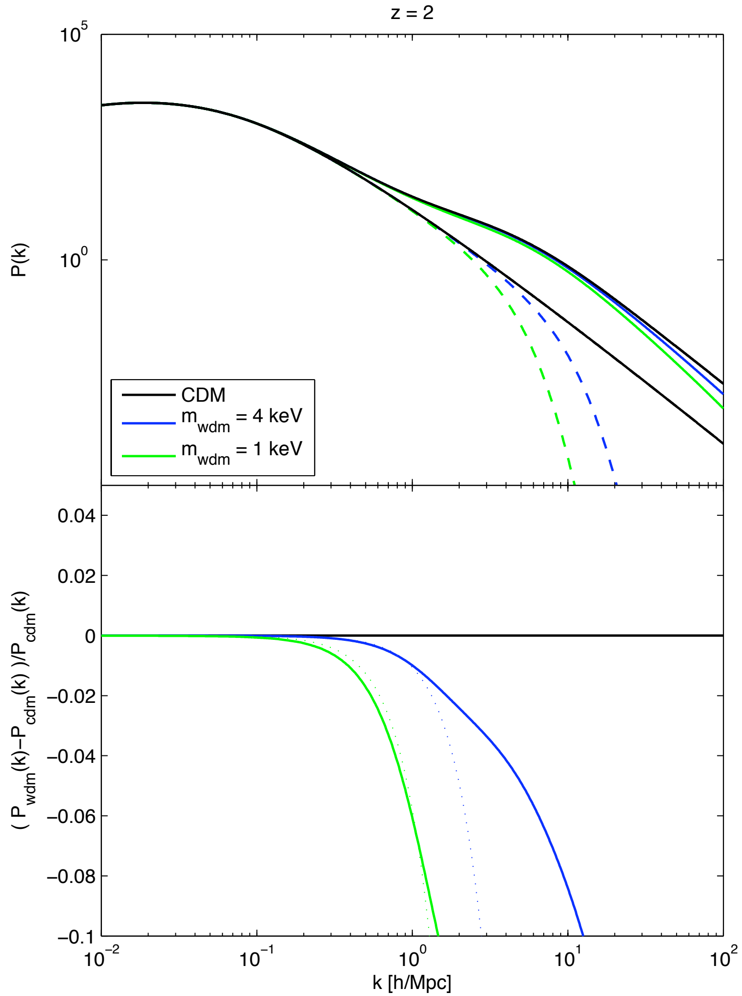
- Naïve/brute force application of the HALO MODEL
- Regeneration of small scale power
  => information loss
- But HALO MODEL is based on CDM simulations!
- If go higher in redshift, see more of a suppresion effect



Non-linear WDM structure

WDM HALO MODEL

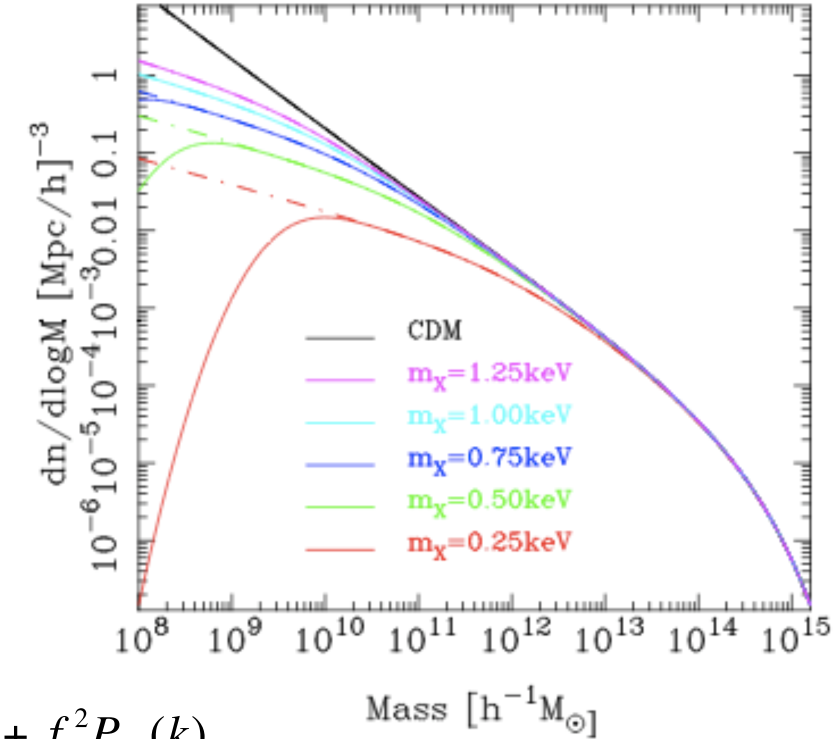
- Modified halo model
- Modification is mostly ad hoc:



Non-linear WDM structure

WDM HALO MODEL

Smith & Markovic 2011



- Modified halo model
- Modification is mostly ad hoc:
  - step function applied to the mass functions to further suppress the abundance of small haloes
  - not all DM is within haloes: there is a smooth component of the density field:

$$P_{\delta\delta}(k) = (1-f)^2 P_{ss}(k) + 2(1-f) f P_{sh}(k) + f^2 P_{hh}(k)$$

  - f is the fraction of mass within haloes:

$$f = \frac{1}{\bar{\rho}} \int_{M_{cut}}^{\infty} M dM n(M)$$

Non-linear WDM structure

WDM HALO MODEL

- Modified halo model

$$P_{ss}(k) = b_s^2 P_{NL,R}(k)$$

$$P_{sh}(k) = \frac{b_s P_{NL,R}(k)}{f\bar{\rho}} \int_{M_{cut}}^{\infty} M dM b(M) n(M) \tilde{U}(k|M)$$

$$P_{hh}(k) = \frac{P_{NL,R}(k)}{(f\bar{\rho})^2} \left[\int_{M_{cut}}^{\infty} M dM b(M) n(M) \tilde{U}(k|M) \right]^2 + \\ + \frac{1}{(f\bar{\rho})^2} \int_{M_{cut}}^{\infty} M dM n(M) \tilde{U}(k|M)$$

Non-linear WDM structure

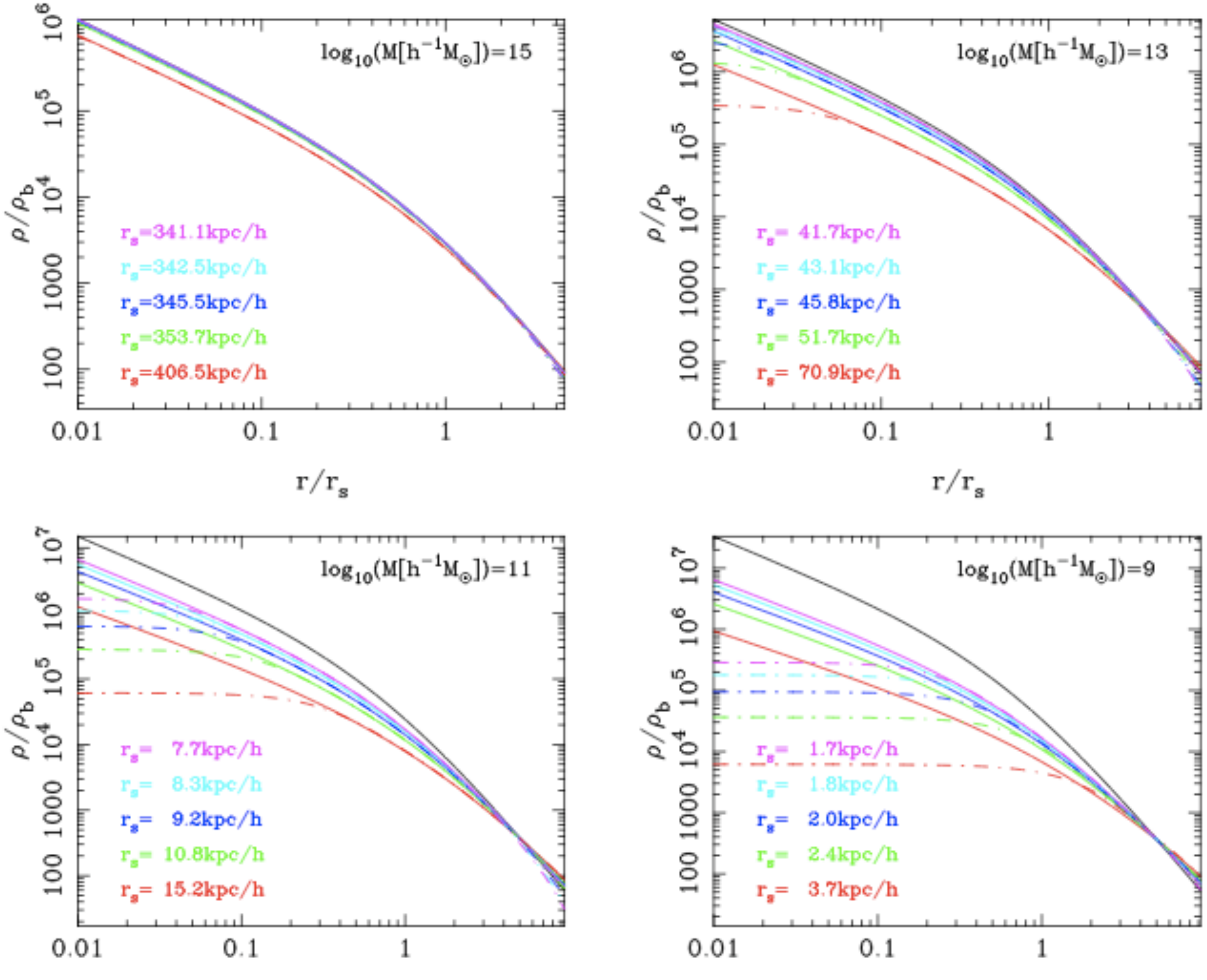
- Relic thermal velocity effect
- Assumed Fermi-Dirac distribution
- Decoupled when relativistic.
- Convolved the NFW halo profile with a Gaussian with the scale determined by the remnant velocity…

TABLE I: Variation of the present day ($z = 0$) relic velocity statistics with WDM particle mass. Columns are: particle mass, characteristic velocity of FD gas, mean velocity, rms velocity and the smoothing scale for profiles.

$m_{\rm WDM}$ [keV]	v_0 [km s^{-1}]	$\overline{v_{\rm r}}$ [km s^{-1}]	$\sqrt{\overline{v_{\rm r}^2}}$ [km s^{-1}]	$l_{v_{\rm r}}$ [h^{-1}kpc]
0.25	0.065	0.204	0.234	2.04
0.50	0.026	0.082	0.094	0.82
0.75	0.015	0.047	0.054	0.47
1.00	0.010	0.032	0.036	0.32
1.25	0.008	0.025	0.029	0.25

Smith & Markovic 2011

Non-linear WDM structure



Smith & Markovic 2011

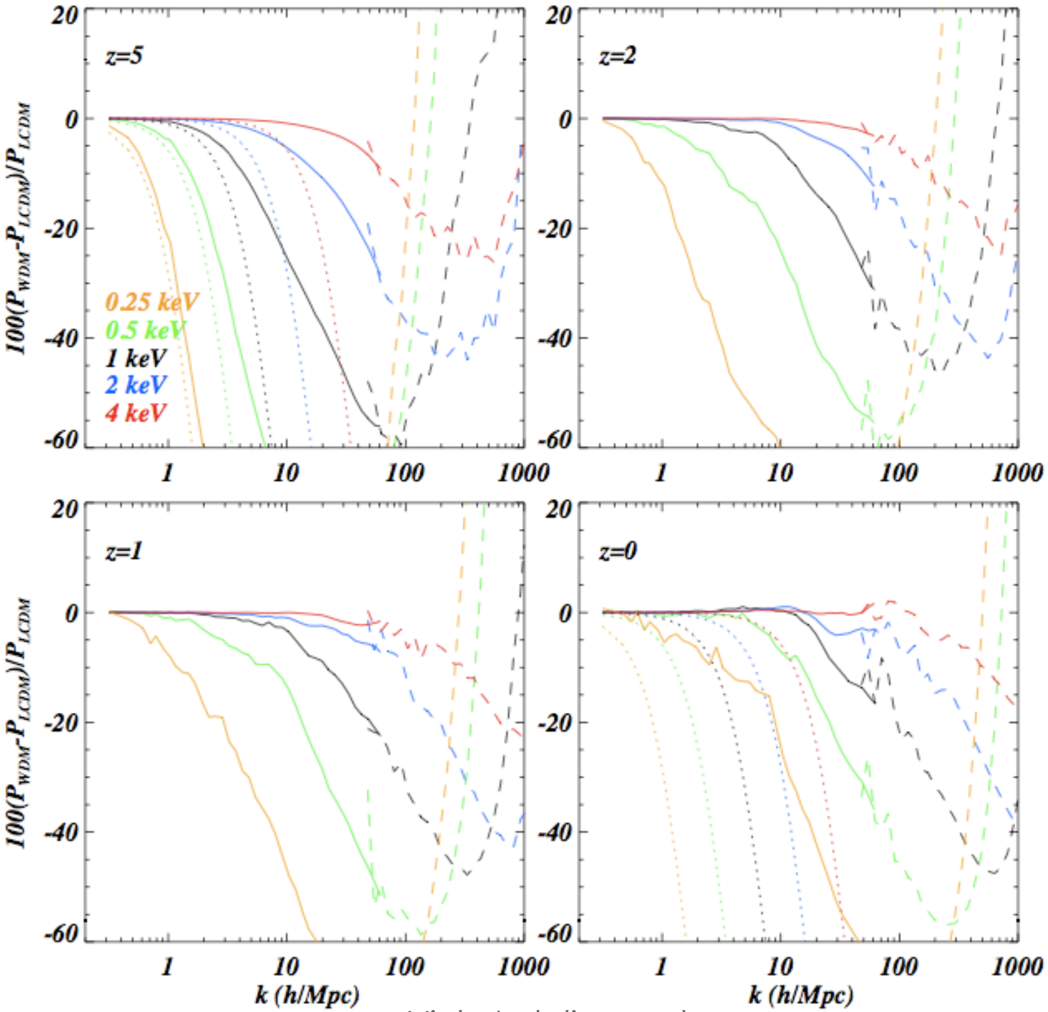
Non-linear WDM structure

- Relic thermal velocities have minimal impact on the power spectrum!
- Suppression in the spectrum comes from a lack of small objects!
- Want to explore this further with simulations!

Non-linear WDM structure

SIMULATIONS

- … want to check WDM halo model with simulations.
- Want to have the right evolution and k-dependence.
- For now running cosmological simulations with 25 Mpc & 512 particles cubed.
- Eventually want to check degeneracies with Coupled Dark Energy, Baryonic effects etc.

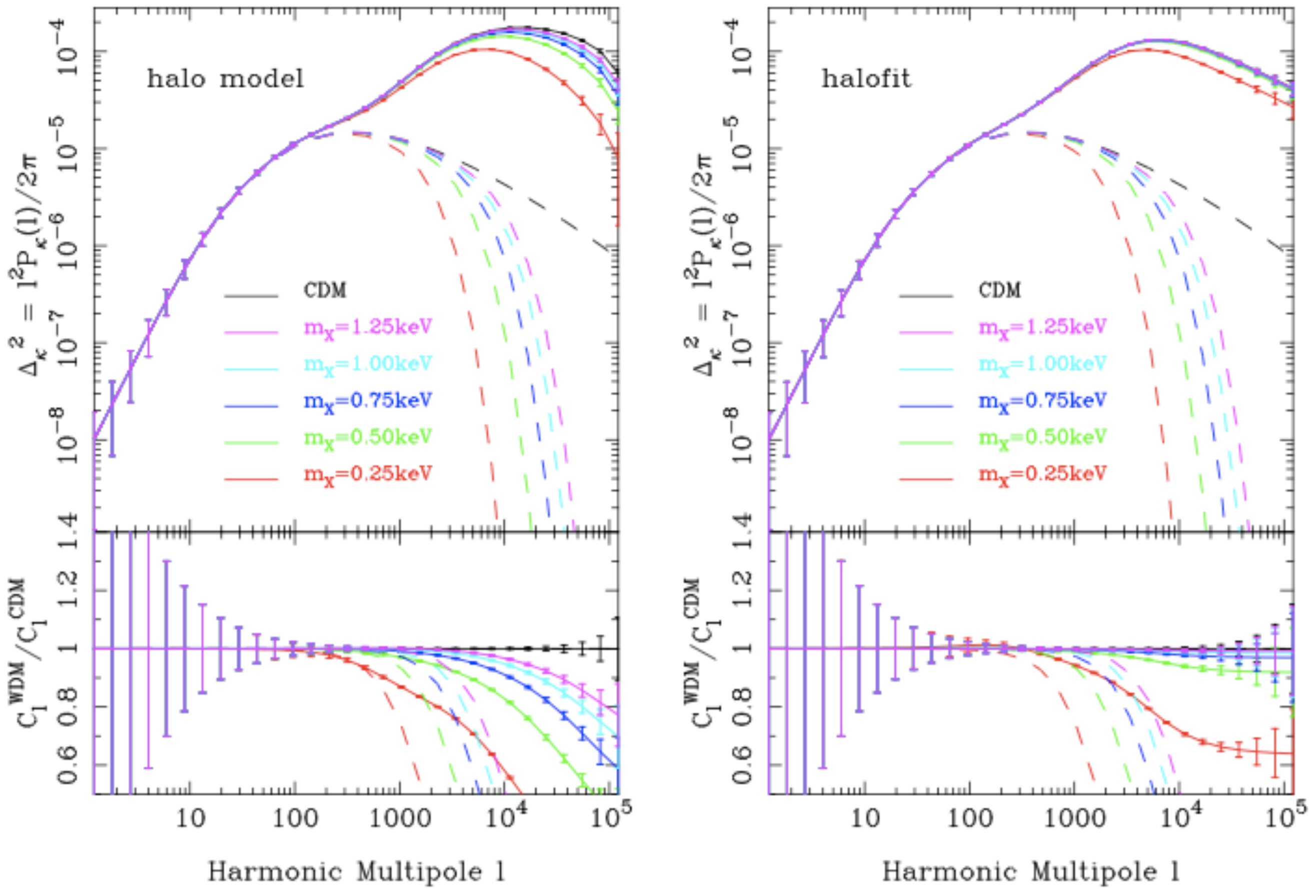


Viel et al. (in prep)

Non-linear WDM structure

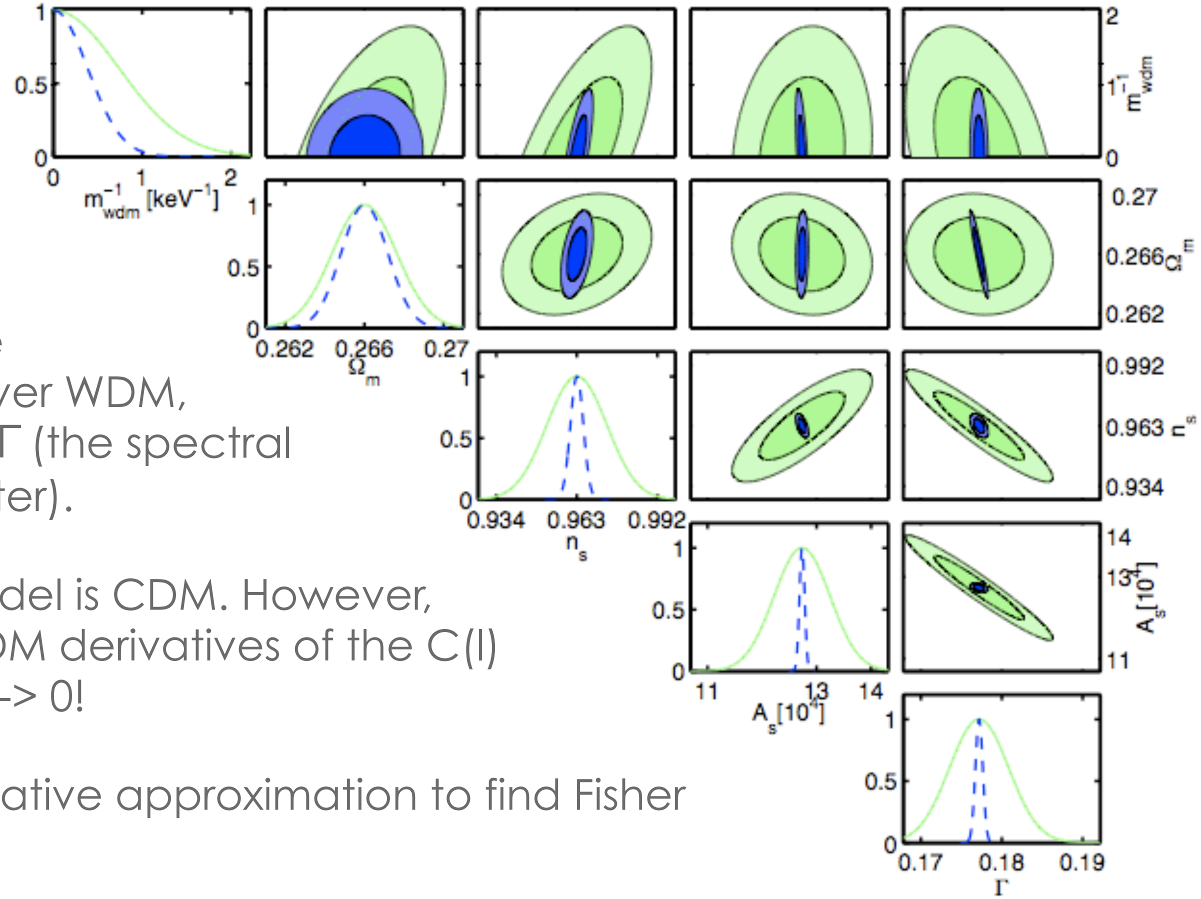
SHEAR POWER SPECTRUM:

Smith & Markovic 2011



Forecasts for Euclid

Smith & Markovic 2011



- Used Fisher matrices to marginalise over several parameters.
- In plot we have marginalised over WDM, Ω_m, n_s, A_s and Γ (the spectral shape parameter).
- The fiducial model is CDM. However, cannot find WDM derivatives of the C(l) at CDM, since -> 0!
- Used a conservative approximation to find Fisher matrices.
- Plot: Euclid only (green) & Euclid + Planck (blue)

In conclusion…

- Predicted limit for Euclid+Planck:
  $m_{WDM} > 2.5$ keV ($m_{\nu s} > 15.5$ keV)
- When have data, need to have a better model for non-linear structure in WDM scenario.
- Lensing probes different scales and redshifts than CMB experiments!
- More linear signal at high redshift, so deep surveys will give a better constraint! Tomography significantly improves result!
- Cannot use Fisher matrices for CDM as fiducial model!

Thank you!

In conclusion...

- Predicted limit for Euclid+Planck:
  m_{WDM} > 2.5 keV for thermal relic
  $m_{\nu s}$ > 15.5 keV for sterile neutrino
- When have data, need to know which model for non-linear structure works for the WDM scenario.
- Cannot use Fisher matrices for CDM as fiducial model!
- More linear signal at high redshift, so deep surveys will give a better constraint! Tomography significantly improves result!

Extra: EUCLID

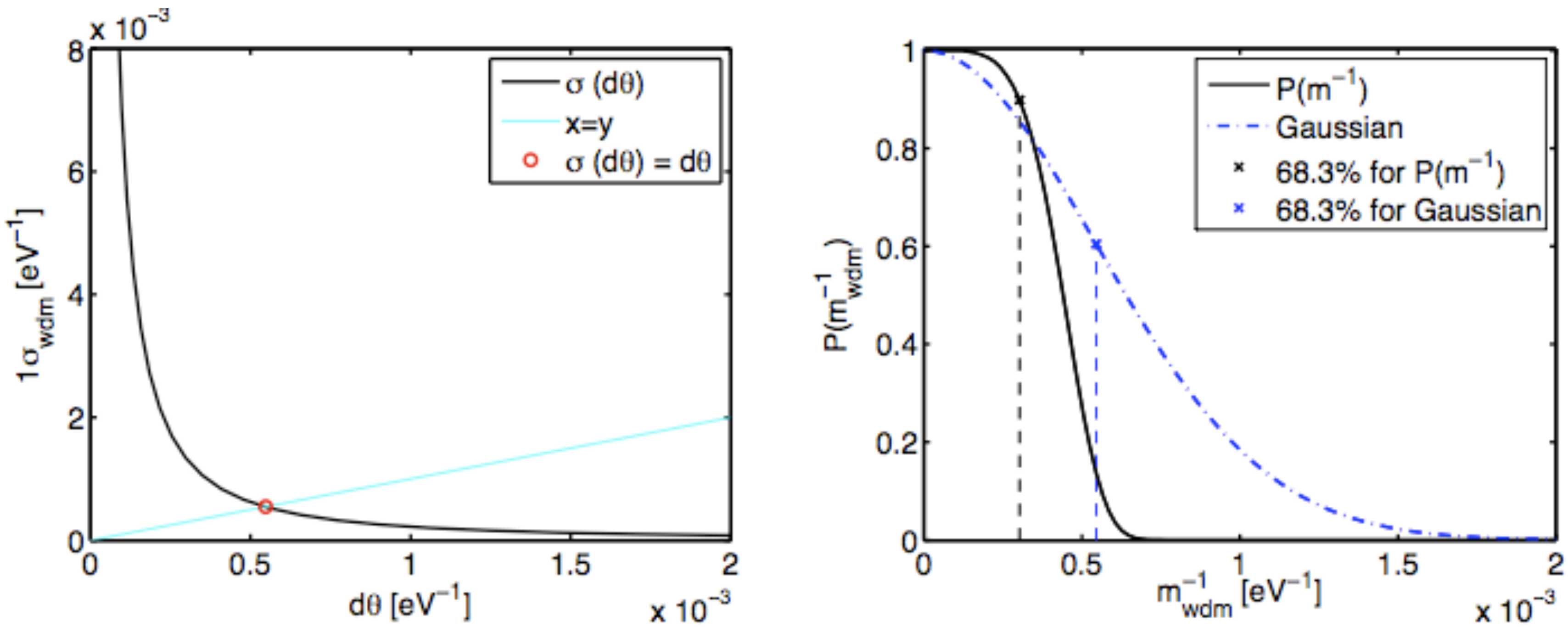
EUCLID: an ESA Cosmic Vision proposal

- WEAK LENSING:
  - diffraction limited galaxy shape measurements in one broad visible R/I/Z band
  - redshift determination by photo-z measurements in 3 YJH NIR bands to H(AB) = 24mag
- BAO:
  - spectroscopic redshifts (NIR) for 33% of all galaxies brighter than H5AB)=22 mag, sigma_l<0.001

- shear error = 0.35/√2
- 35 gal. per sq. arcmin
- sky fraction = 0.5
- photo-z error = 0.05(1+z)
- no catastrophic outliers
- use Smail et al. perscription to find n(z), with median z = 0.9 use 10 redshift bins

Extra: Fisher Matrices

- Cannot find Fisher matrices => used a conservative approximation.



Markovic et al. 2011

Extra: Fisher Matrices

- Fisher matrices: assume Gaussian Likelihoods centered on fiducial values of parameters.
- Can marginalize easily over many parameters.

$$\mathrm{Cov}\left[C^{\mathrm{obs}}_{(ij)}(l), C^{\mathrm{obs}}_{(op)}(l')\right] = \frac{1}{f_{\mathrm{sky}}} \frac{1}{N(l_m, l_n)} \delta^K_{l,l'} \times \left[C^{\mathrm{obs}}_{(io)}(l) C^{\mathrm{obs}}_{(jp)}(l) + C^{\mathrm{obs}}_{(ip)}(l) C^{\mathrm{obs}}_{(jo)}(l)\right]$$

$$\mathcal{F}_{\alpha\beta} = \sum_l \sum_{X,Y} \frac{\partial C_{(X)}(l)}{\partial \alpha} \mathrm{Cov}^{-1}\left[C^{\mathrm{obs}}_{(X)}(l), C^{\mathrm{obs}}_{(Y)}(l)\right] \frac{C_{(X)}(l)}{\partial \beta}$$