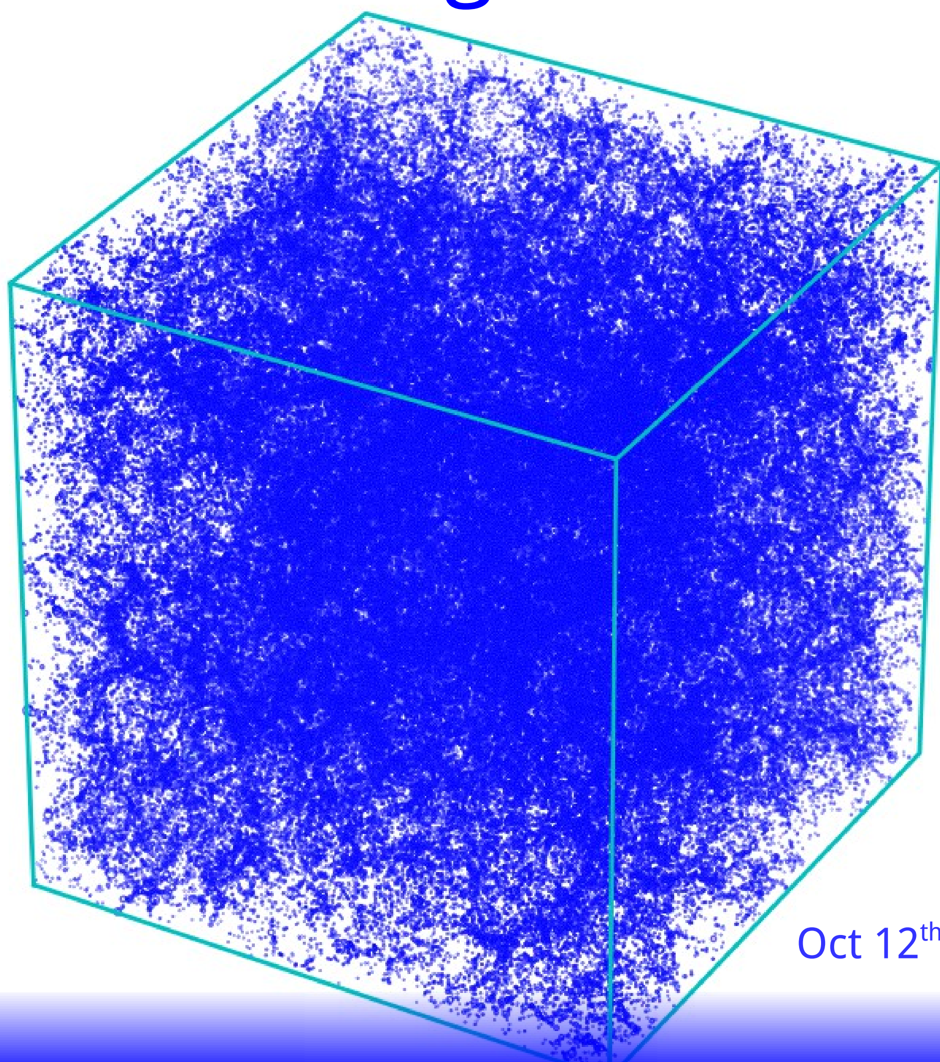
The impact of massive neutrinos on the large-scale structure of the Universe



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First Year Ph.D. student workshop

Oct 12th 2015 – Università degli Studi di Milano

Neutrinos and Cosmology

- Neutrino total mass from beta-decay experiments

$$0.05\mathrm{eV} \lesssim \sum_i m_{\nu_i} \lesssim 2\,\mathrm{eV}$$

[T. Thummler et al. (2010)]
ArXiv:1012.2282

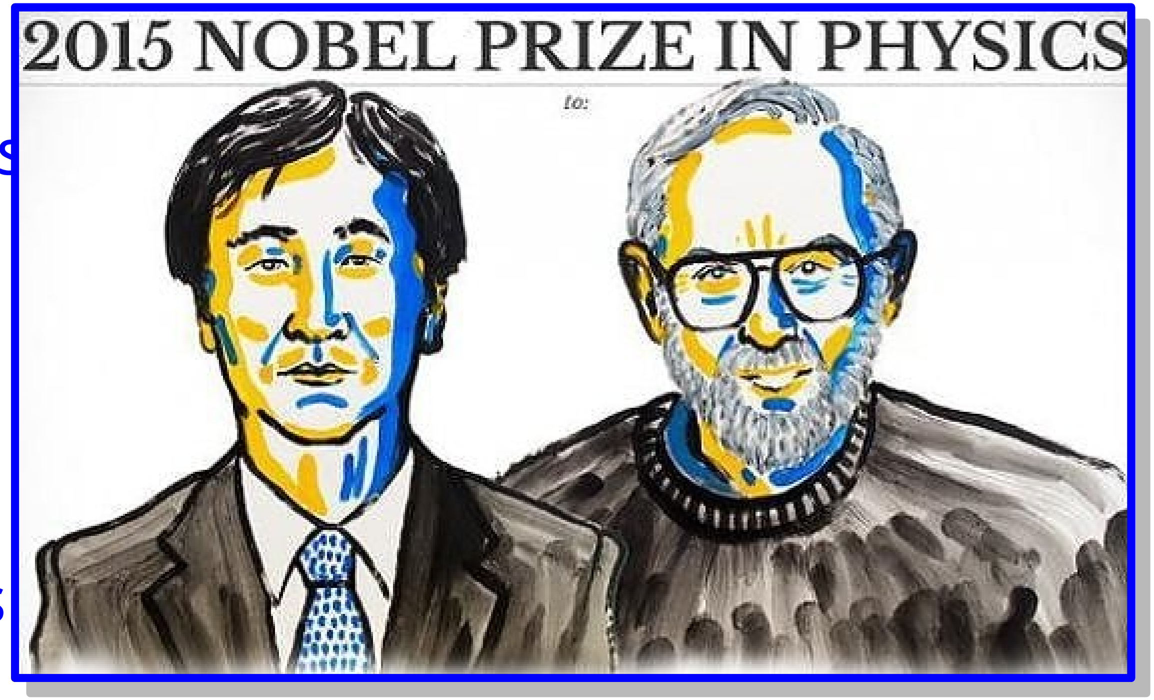
- Massive neutrinos have an impact on cosmological observables

- Cosmology can help in tightening the constraints on the neutrino total mass

Neutrinos and Cosmology

- Neutrino total mas

$$0.05\text{eV} \lesssim$$



- Massive neutrinos
observables

- Cosmology can help in tightening the constraints on the neutrino total mass

Neutrinos and Cosmology

- Neutrino total mass from beta-decay experiments

$$0.05\mathrm{eV} \lesssim \sum_i m_{\nu_i} \lesssim 2\,\mathrm{eV}$$ [T. Thummler et al. (2010)]

- Massive neutrinos have an impact on cosmological observables

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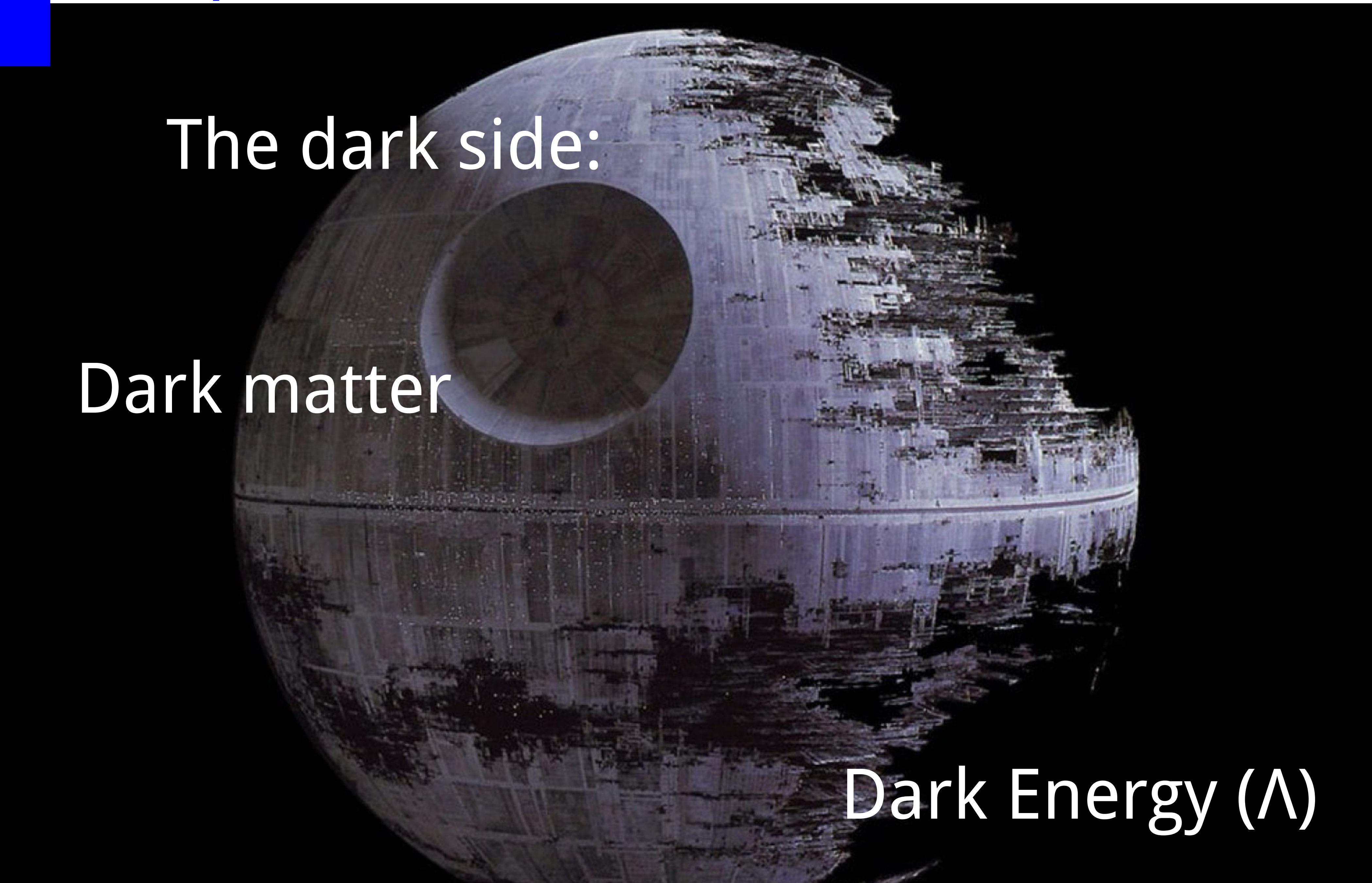
Components of the Universe

Radiation

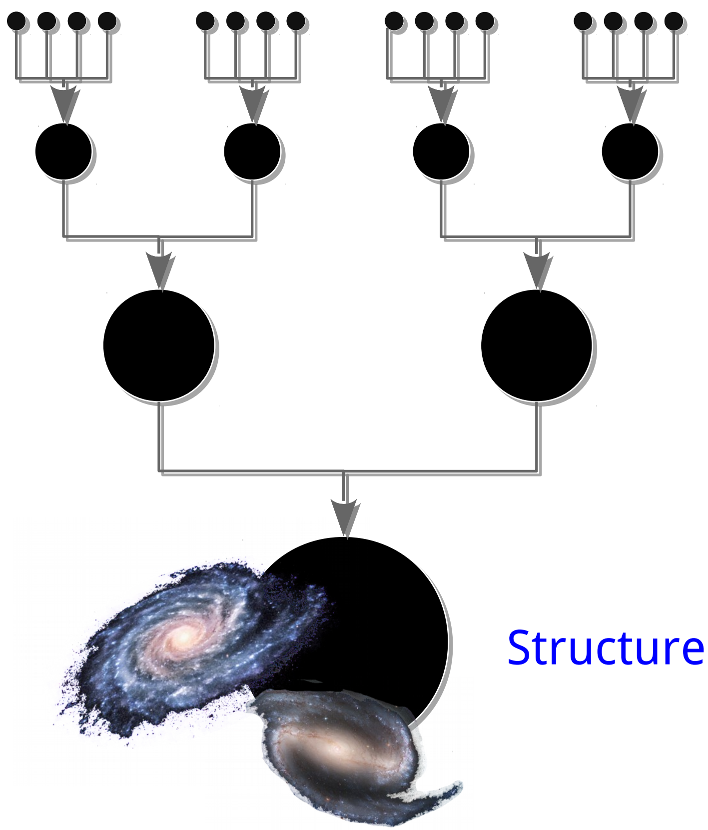
Components of the Universe

Components of the Universe



ΛCDM model

- Expanding universe
- We describe Cold Dark Matter as an expanding <u>pressureless</u> fluid:

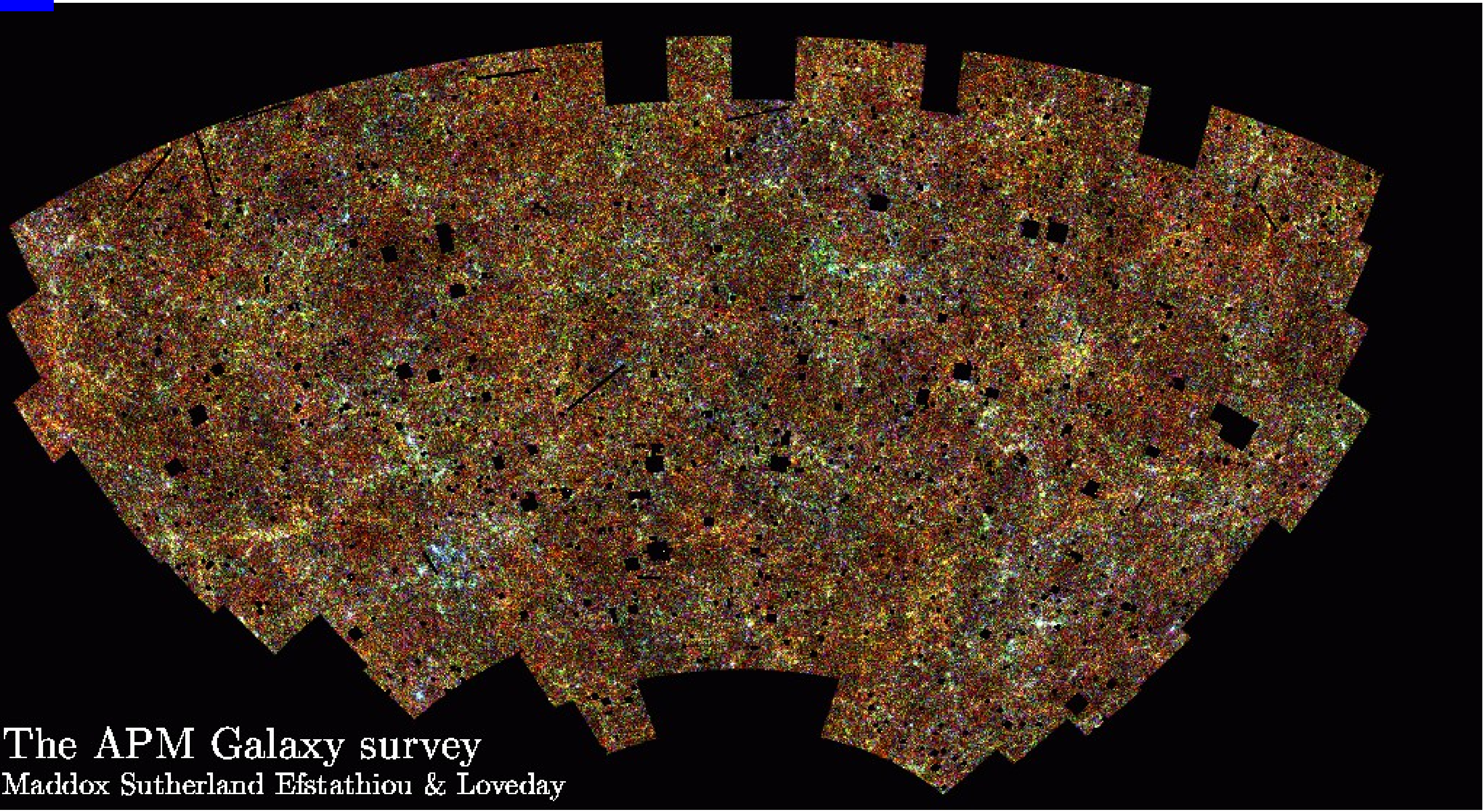


Otherwise pressure would prevent gravitational collapse!

(another reason for having CDM...)

Structures form! Stars, galaxies...

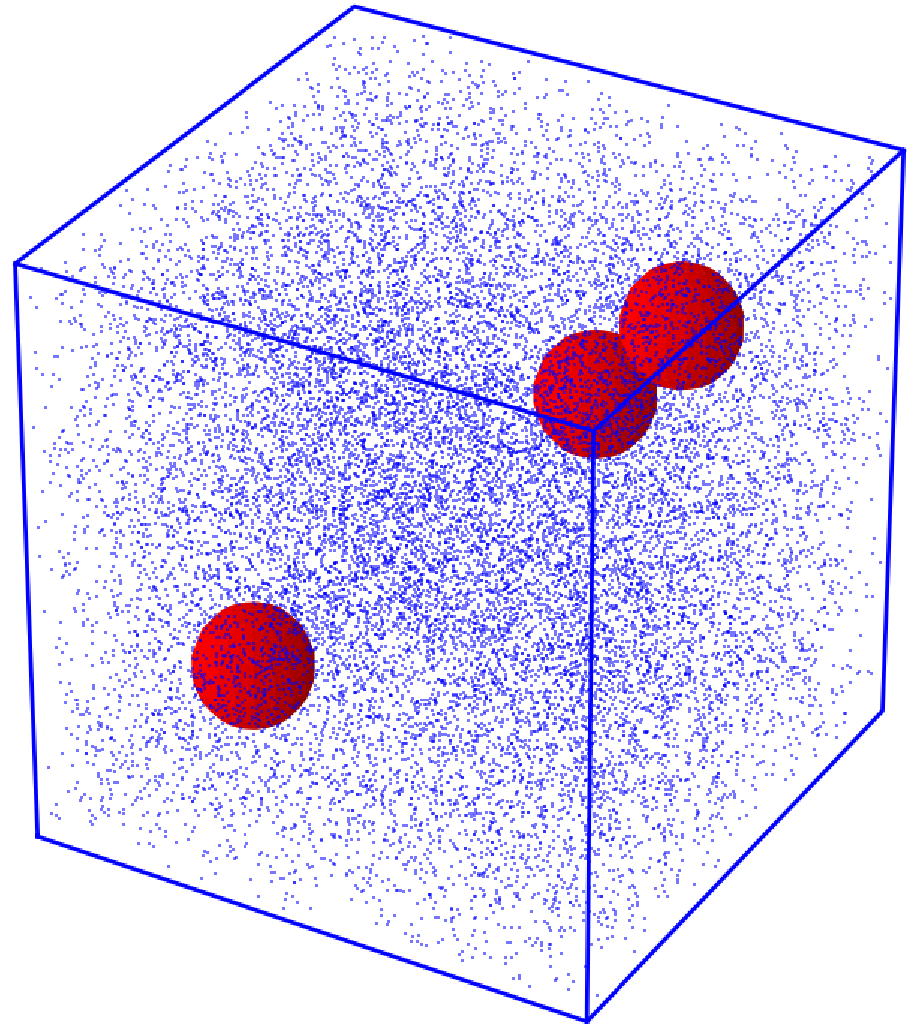
Isotropy and homogeneity



Statistical properties

- Count number of objects (N) in spheres of radius R
- Define an overdensity field

$$\delta_R \equiv N/\bar{N} - 1$$



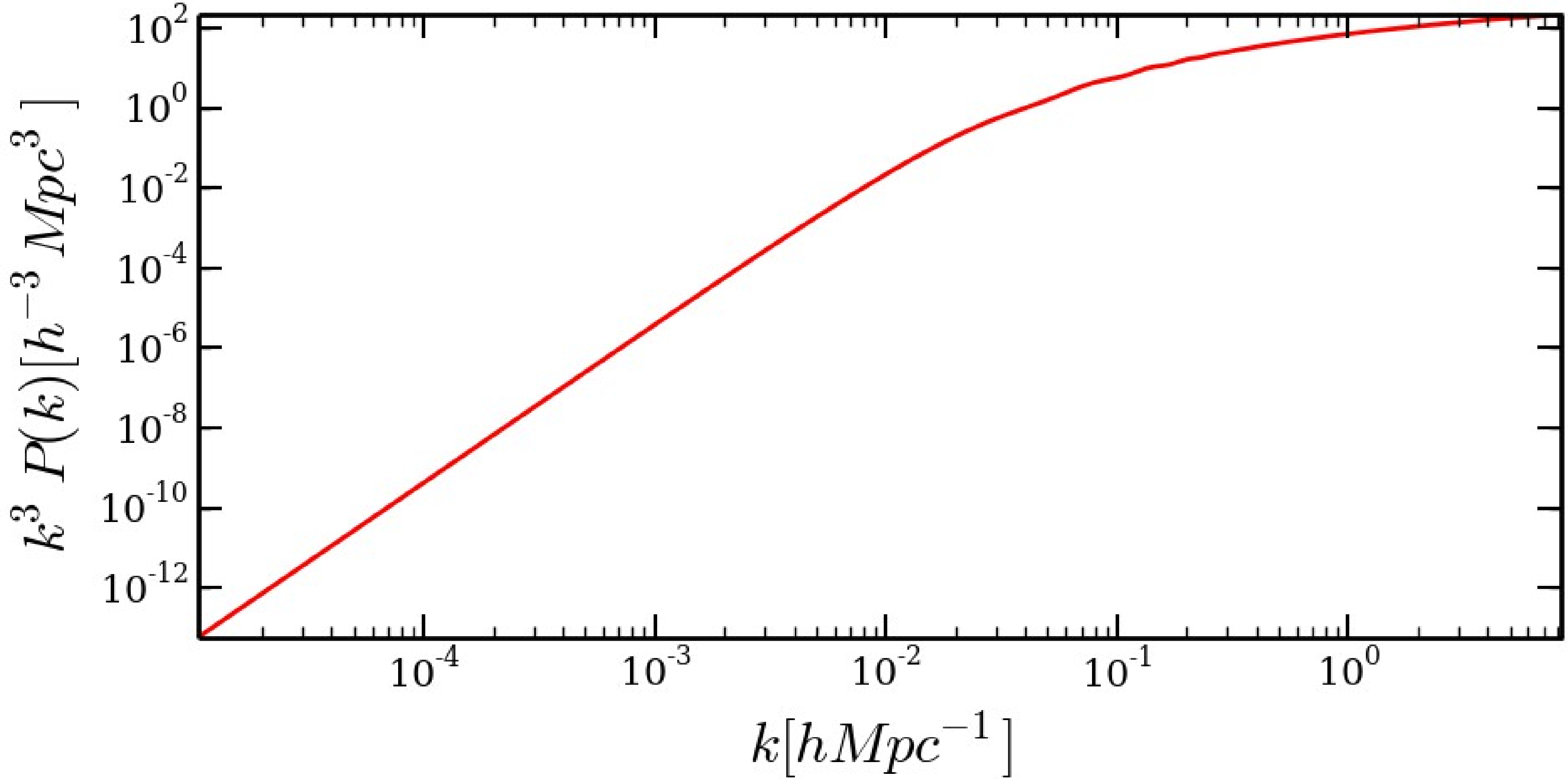
- Autocorrelation:

$$\xi_R(r) = \langle \delta_R(\mathbf{x}) \delta_R(\mathbf{x} + \mathbf{r}) \rangle$$

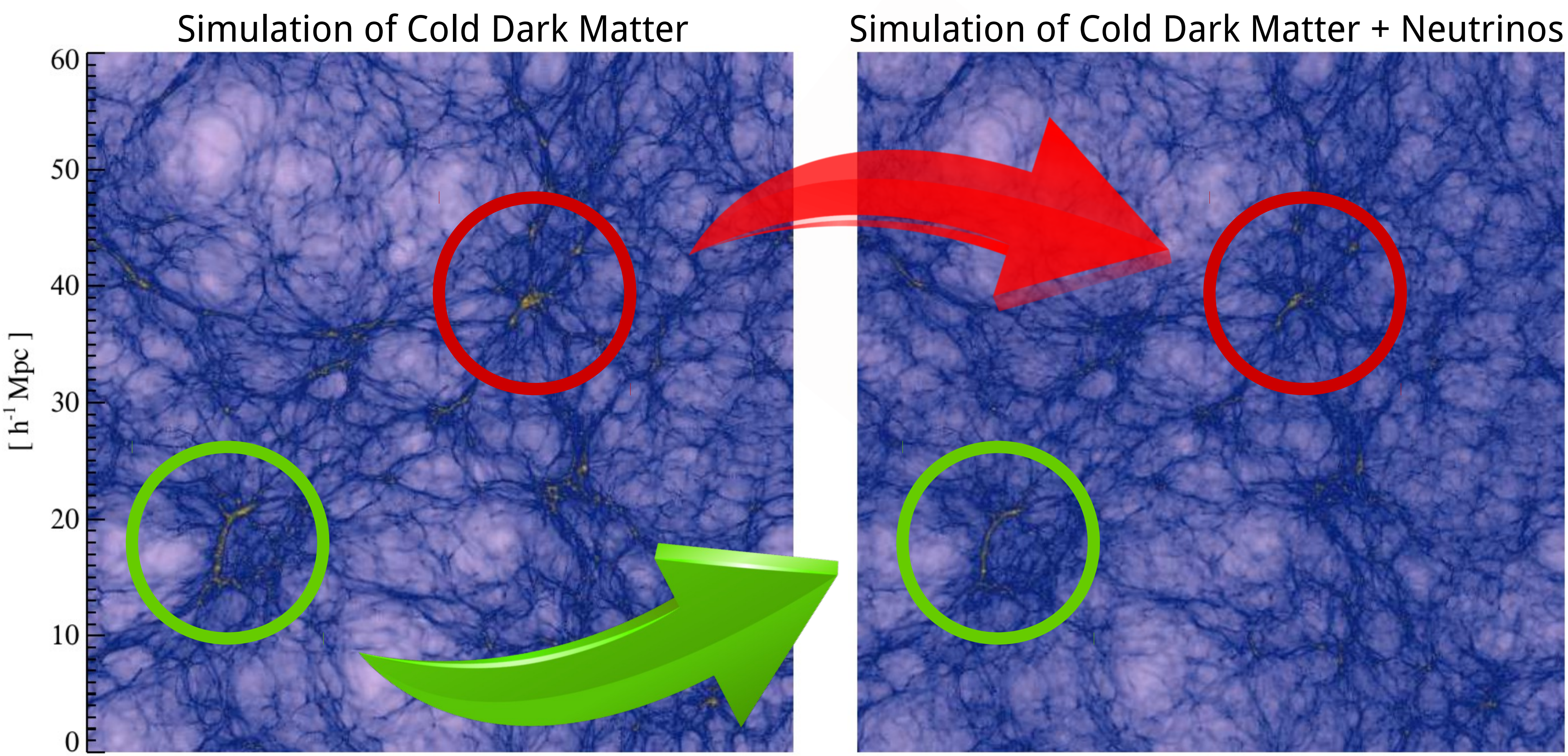
- Power Spectrum:

$$P(k_1)\delta_D(\mathbf{k}_1 + \mathbf{k}_2) = \langle \delta_{\mathbf{k}_1} \delta_{\mathbf{k}_2} \rangle$$

The Power Spectrum

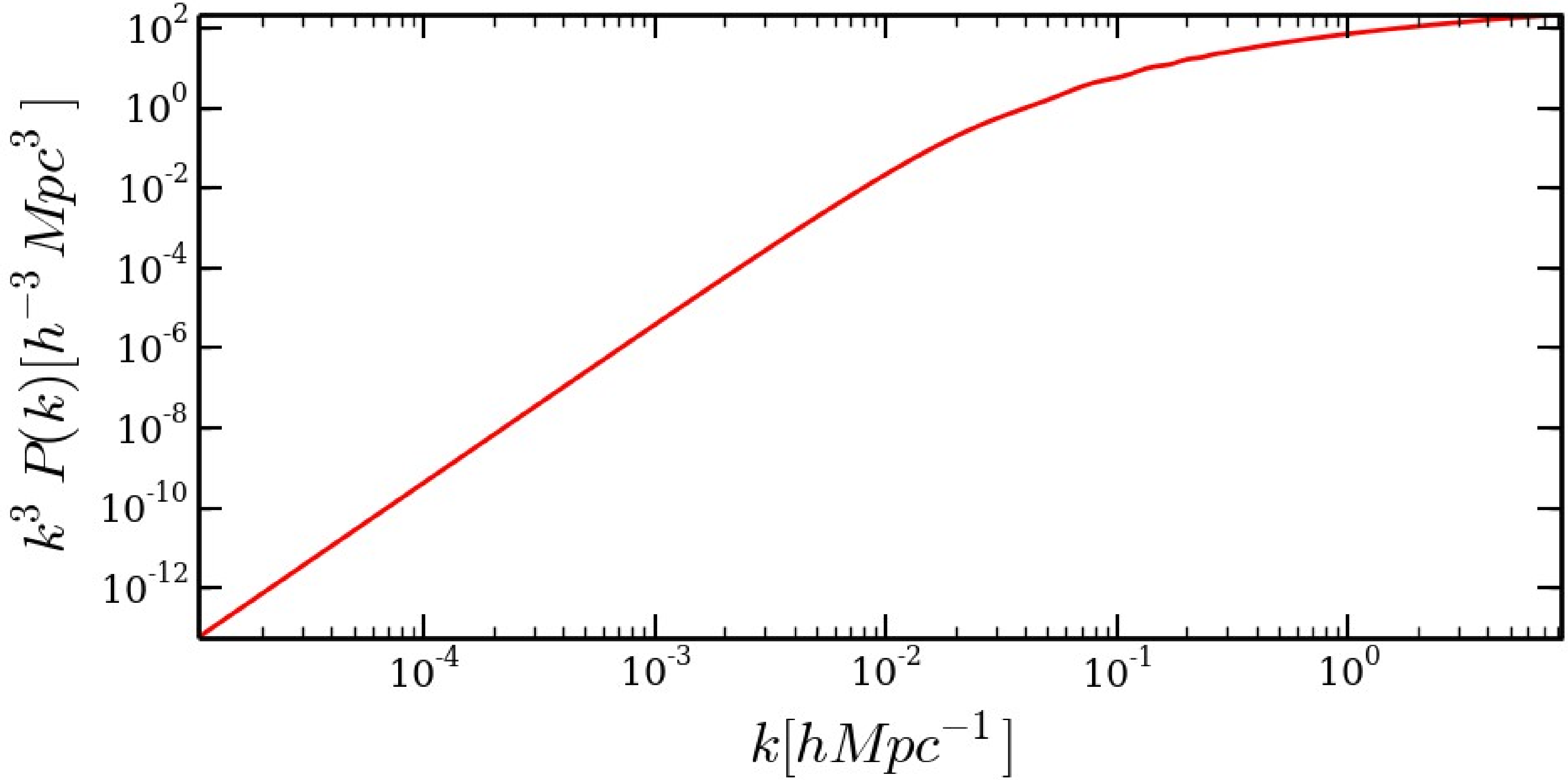


Massive neutrinos
Effects on the clustering properties

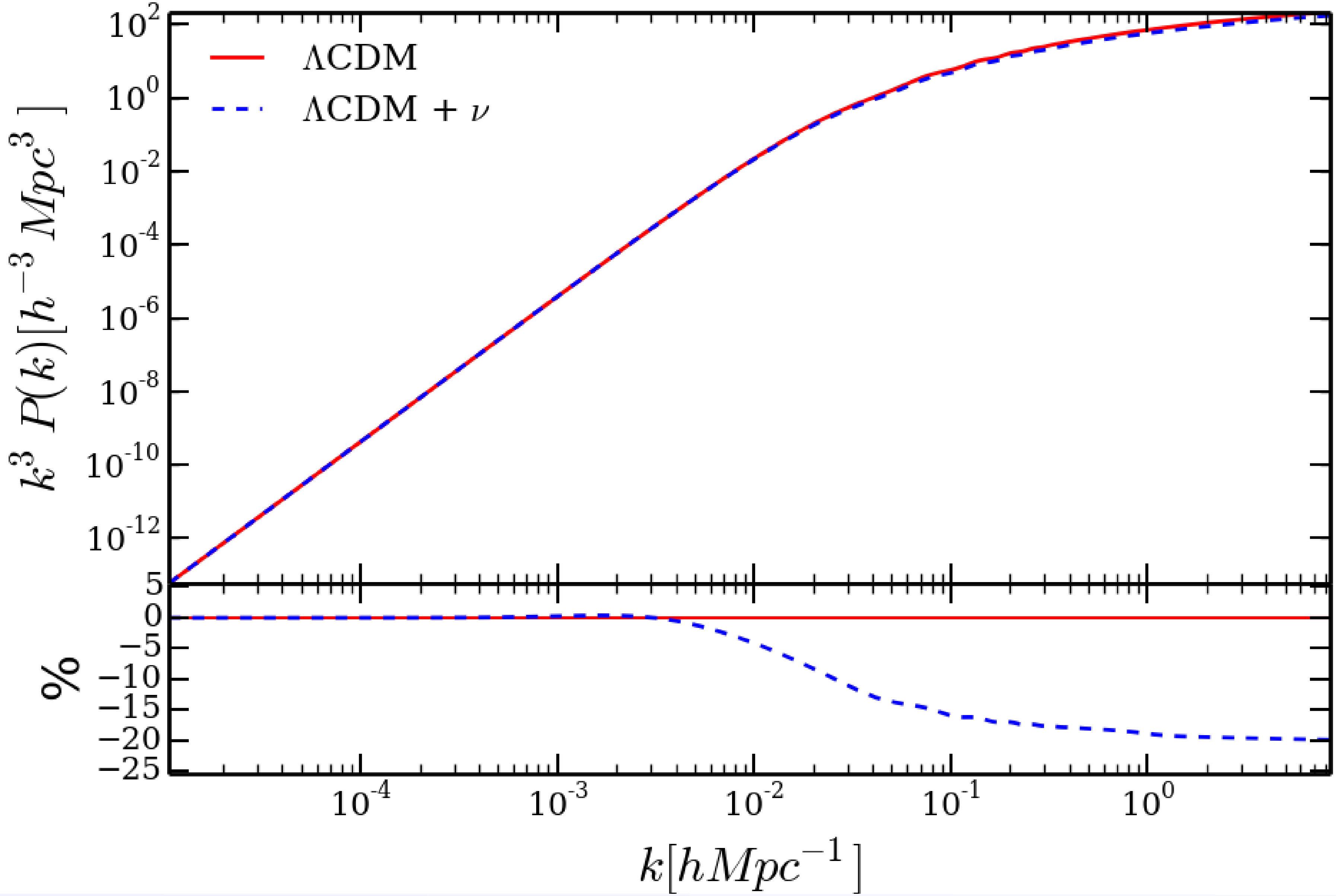


Viel et al, JCAP (2010)

Massive neutrinos
Effects on the power spectrum



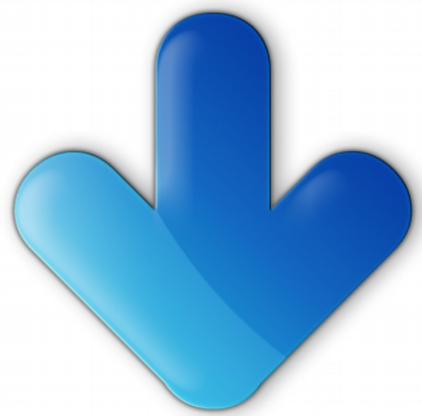
Massive neutrinos
Effects on the power spectrum



Massive neutrinos
Effective pressure at work

- Fermi-Dirac phase-space distribution → **effective** pressure

- Effective neutrino pressure **contrasts** the gravity-driven collapse at all scales smaller than a characteristic 'free streaming scale', $\lambda_{\rm fs}$, corresponding to a wavenumber $k_{\rm fs}$



- Damping of neutrino clustering at small scales → reflected also on CDM and galaxy clustering

Massive neutrinos
Constraining their mass

- We could use the shape of the measured galaxy power spectrum but...

Galaxies are not all that 'matters'!!!

- Galaxy form only in the densest regions → they are a biased sampling of the total matter distribution

$$P_{\rm gal}(k) = F(P_{\rm tot\,matter}(k))$$

Massive neutrinos
Constraining their mass

- We can optimally choose to probe scales where non linearities (i.e. small scale physics) are not important

- The relation becomes a simple one!

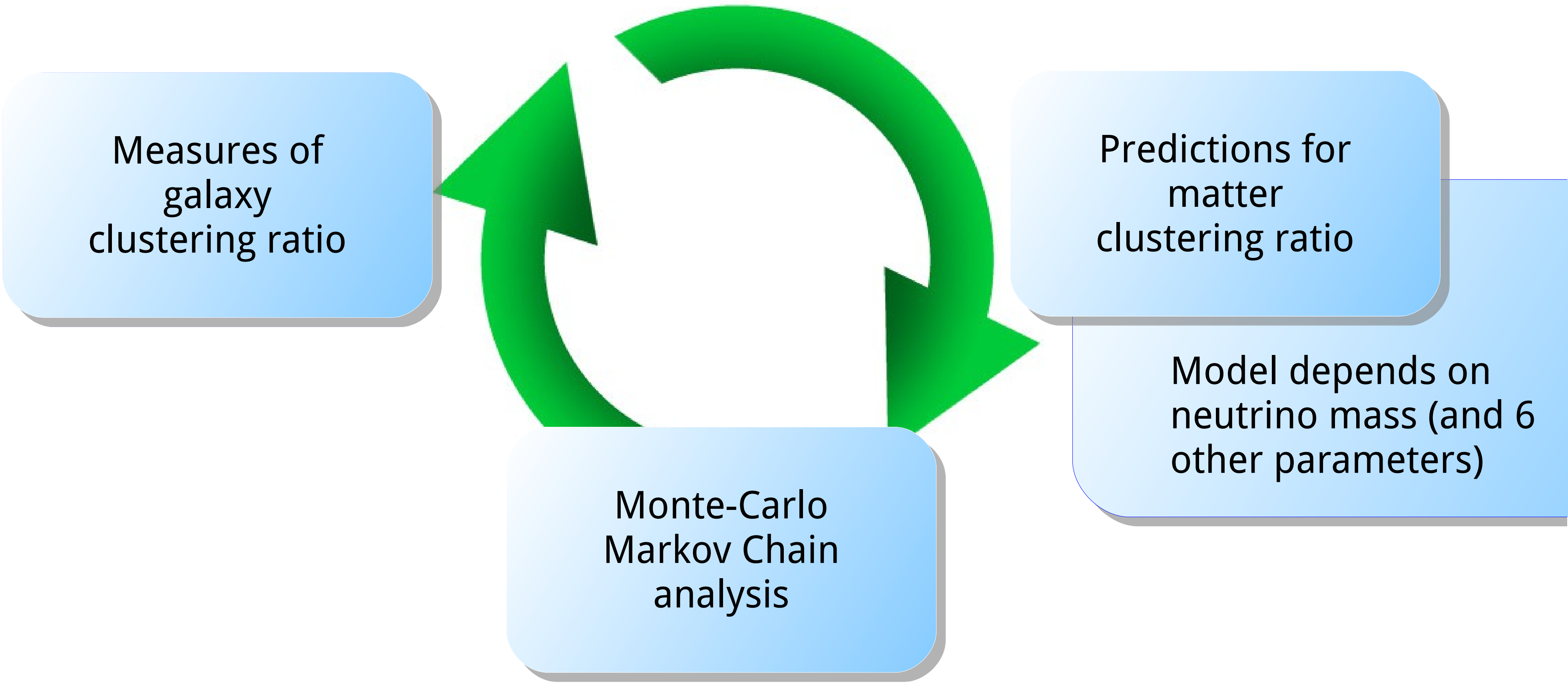
$$P_{\rm gal}(k) = b_{\rm lin}^2 \, P_{\rm tot\ matter}(k)$$

- An observable designed specifically to exploit this, the **clustering ratio**, depends on the power spectrum and is unbiased at linear scales:

[Bel et al, A&A (2014)]

$$\eta_{\rm gal} \equiv \eta_{\rm tot\ \ matter}$$

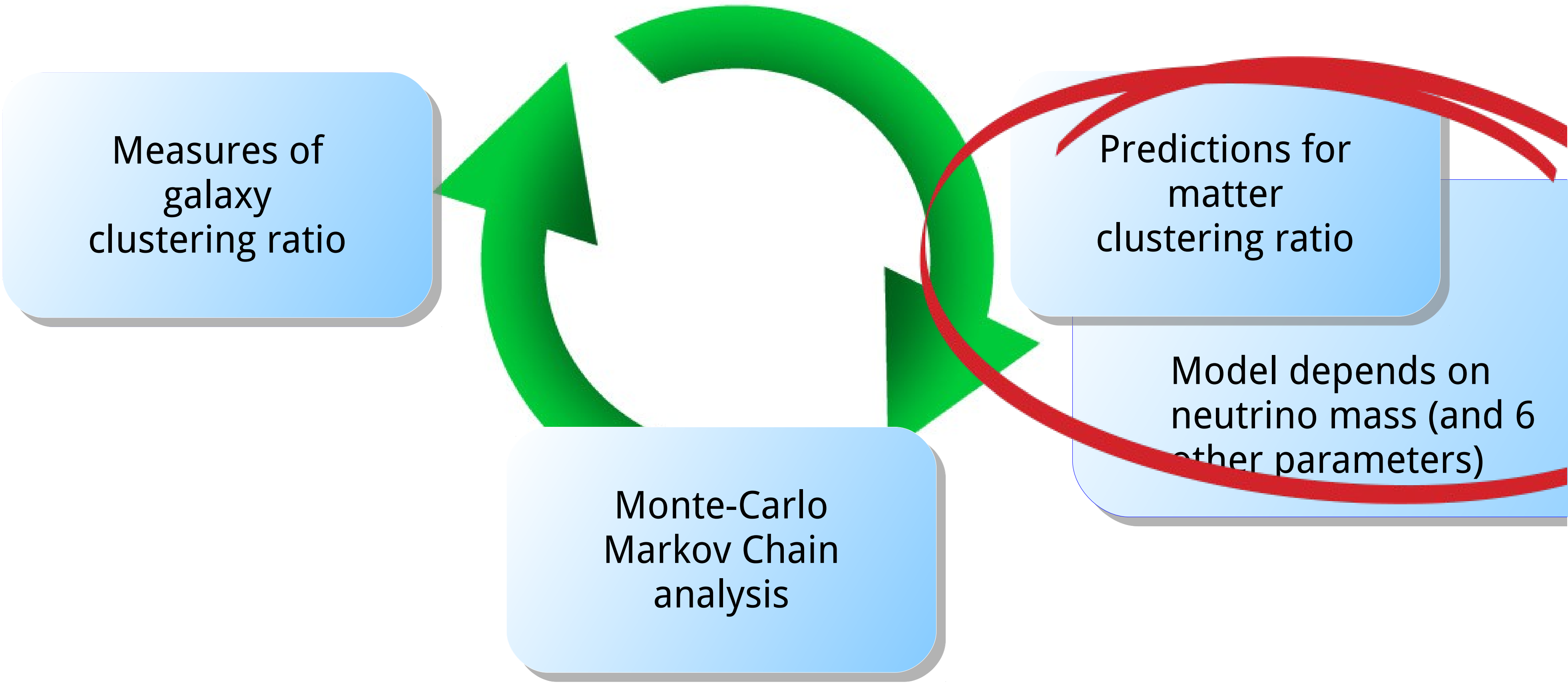
Massive neutrinos
What I'm currently doing!



Search for the set of parameters of the model that maximises the likelihood

→ constraints on total neutrino mass

Massive neutrinos
What I'm currently doing!



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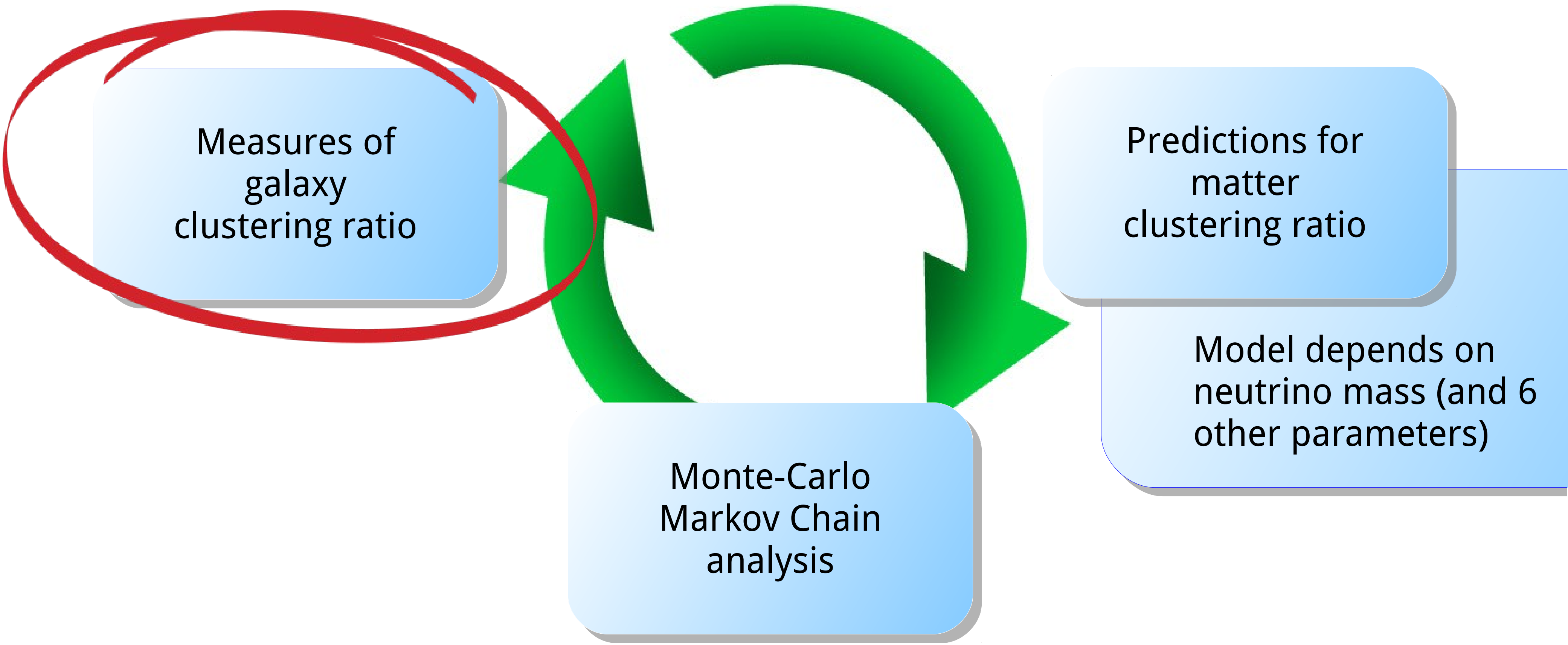
Massive neutrinos

What I'm currently doing!



Search for the set of parameters of the model that maximises the likelihood

→ constraints on total neutrino mass

Massive neutrinos
What I'm currently doing!

Measures of galaxy clustering ratio

Predictions for matter clustering ratio

Model depends on neutrino mass (and 6 other parameters)

Monte-Carlo Markov Chain analysis

MZ, Bel J., Carbone C., Dossett J., Guzzo L., 2015, in prep

Stay tuned!

Conclusion

- Cosmology can help in tightening the constraints on neutrino mass

- The distribution of galaxies can be used for this purpose

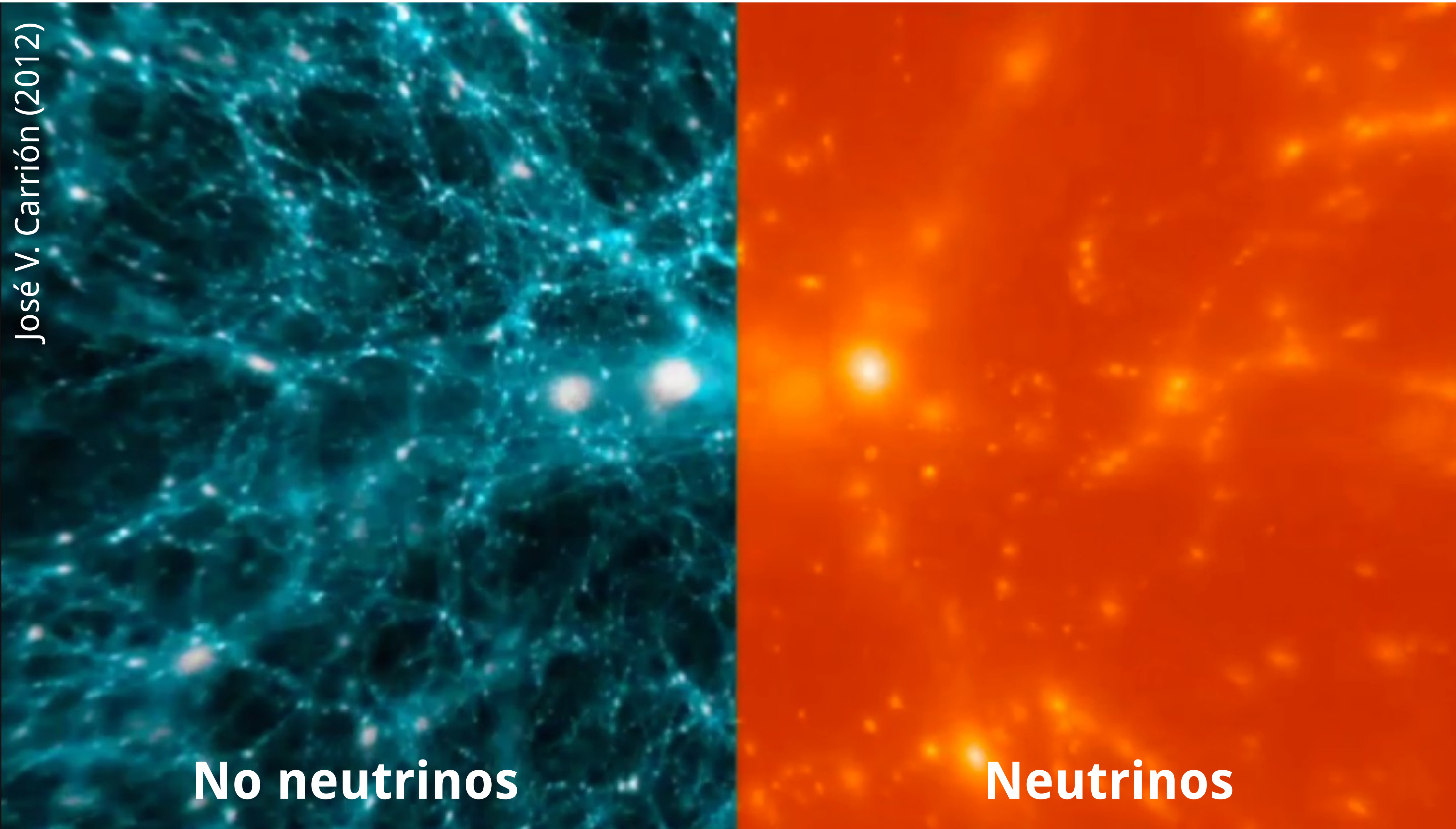
  Measuring its power spectrum (bias!!)

  Using some smart observable (clustering ratio)

- What to do?

  Theoretical characterisation of clustering ratio
  Measures of clustering ratio
  Monte-Carlo Markov Chain runs
  ...

Massive neutrinos
Effects on the clustering properties



Matter clustering
Fluid description

- Matter can be modelled as an expanding fluid, governed by:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \nabla_{\mathbf{r}}(\rho \mathbf{u}) = 0 \\ \dfrac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla_{\mathbf{r}})\mathbf{u} = \dfrac{1}{\rho}\nabla_{\mathbf{r}} P + \nabla_{\mathbf{r}} \phi \\ \nabla^2_{\mathbf{r}} \phi = 4\pi G \rho \end{cases}$$

- With (a bit more than) some algebra, these can be arranged into the linear equation of growth of fluctuations in an expanding fluid:

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta + \frac{c_s^2}{a^2}\nabla^2\delta$$

Matter clustering
Fluid description

- Cold Dark Matter is supposed to be pressureless, so we can safely neglect the speed of sound here...

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta + \frac{c_s^2}{a^2}\nabla^2\delta$$

- ...but is it the same for neutrinos?

[spoiler: no!]

Massive neutrinos
Effective pressure at work

- They are characterised by a Fermi-Dirac phase-space distribution:

$$f(\mathbf{x},\mathbf{p},t) = \frac{1}{e^{-\frac{\mathbf{p}}{T_\nu}}+1}$$

- Their density is

$$E = \sqrt{|\mathbf{p}|^2 + m_\nu^2}$$

$$\rho(\mathbf{x},t) = \frac{g}{(2\pi)^3}\int \mathrm{d}^3\mathbf{p}\, f(\mathbf{x},\mathbf{p},t)\, E(\mathbf{p})$$

- And their pressure

$$P(\mathbf{x},t) = \frac{g}{(2\pi)^3}\int \mathrm{d}^3\mathbf{p}\, f(\mathbf{x},\mathbf{p},t)\, \frac{|\mathbf{p}|^2}{E(\mathbf{p})}$$

Massive neutrinos
Effective pressure at work

- From density and pressure one can find their effective sound speed

$$c_s = 134.423(1+z)\left[\frac{1\,\mathrm{eV}}{m_\nu}\right]\ \mathrm{km/s}$$

- This is not negligible! When considering massive neutrinos, we will have to solve a system of equations, one for CDM and one for neutrinos → **2 fluid approximation**

Massive neutrinos
Effective pressure at work

- **2 fluid approximation**:

$$\begin{cases} \ddot{\delta}_{\rm c} + 2H\dot{\delta}_{\rm c} - \frac{3}{2}H^2\Omega_m\left\{[1-\nu]\delta_{\rm c} + \nu\delta_\nu\right\} \\ \ddot{\delta}_\nu + 2H\dot{\delta}_\nu - \frac{3}{2}H^2\Omega_m\left\{[1-\nu]\delta_{\rm c} + [\nu - (k/k_{\rm fs})^2]\delta_\nu\right\} \end{cases}$$

where we defined

$$k_{\rm fs} = \sqrt{\frac{4\pi G\rho_{\rm tot}}{c_s^2(1+z)^2}}$$

collapse induced by gravity

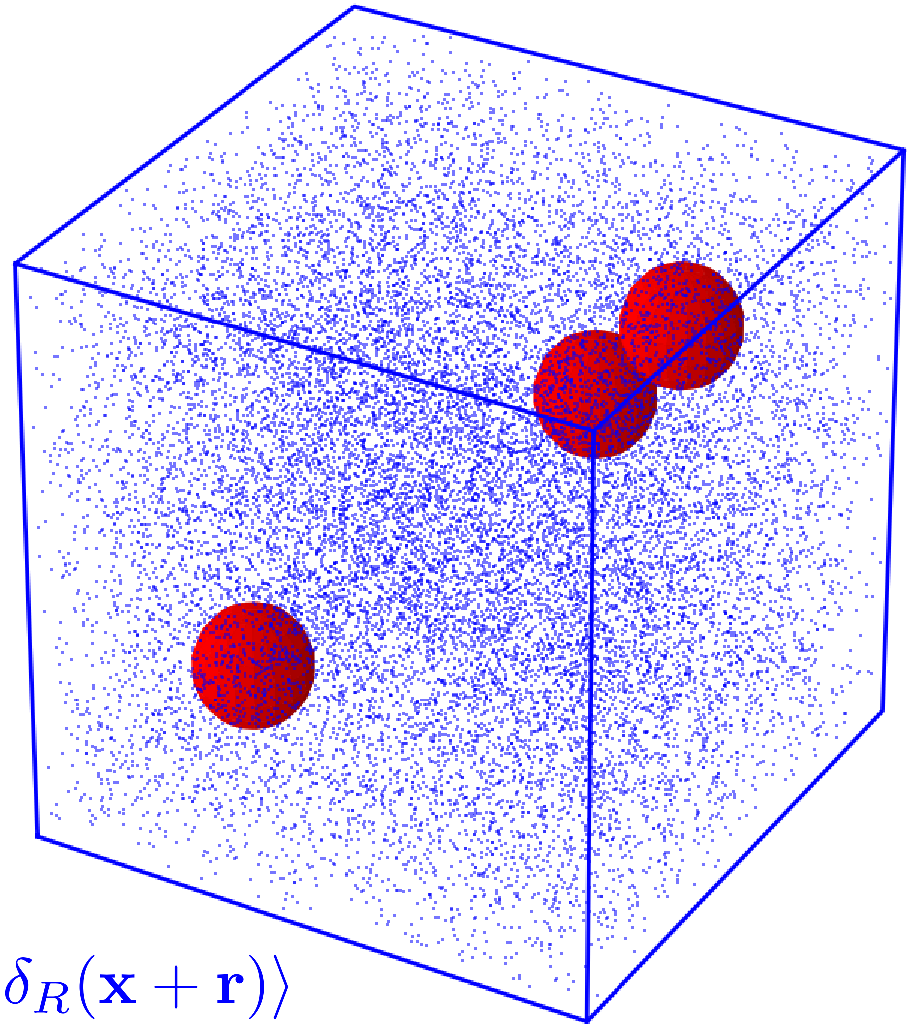
effective pressure support

scale of dissipation of neutrino density perturbations (free streaming scale)

Statistical properties

- Count number of objects (N) in spheres of radius R
- Define an overdensity field

$$\delta_R \equiv N/\bar{N} - 1$$



- Spatial average $\langle \delta_R \rangle = 0$
- Variance $\sigma_R^2 = \langle \delta_R^2 \rangle$
- Autocorrelation $\xi_R(r) = \langle \delta_R(\mathbf{x}) \delta_R(\mathbf{x}+\mathbf{r}) \rangle$

The Clustering Ratio
Motivation

Matter density field	Galaxy distribution
$\rho_R(\mathbf{x})$	$N_R(\mathbf{x})$
$\delta_{m,R}(\mathbf{x}) = \frac{\rho_R(\mathbf{x})}{\bar{\rho}} - 1$	$\delta_{g,R}(\mathbf{x}) = \frac{N_R(\mathbf{x})}{\bar{N}} - 1$
$\xi_{m,R}(r) = \langle \delta_{m,R}(\mathbf{x}) \delta_{m,R}(\mathbf{x}+\mathbf{r}) \rangle$	$\xi_{g,R}(r) = \langle \delta_{g,R}(\mathbf{x}) \delta_{g,R}(\mathbf{x}+\mathbf{r}) \rangle$
$\sigma^2_{m,R} = \langle \delta^2_{m,R}(\mathbf{x}) \rangle$	$\sigma^2_{g,R} = \langle \delta^2_{g,R}(\mathbf{x}) \rangle$

what we can predict ↑ (Matter density field)

what we can measure ↑ (Galaxy distribution)

The Clustering Ratio
Motivation

- But they are not scorrelated!

$$\delta_{g,R}(\mathbf{x}) = F[\delta_{m,R}(\mathbf{x})]$$

- Smoothing on linear scale (and assuming this function to be local)

$$\delta_{g,R}(\mathbf{x}) = b_{lin}\delta_{m,R}(\mathbf{x})$$

$$\xi_{g,R}(r) = \boxed{b_{lin}^2}\xi_{m,R}(r)$$

$$\sigma_{g,R}^2 = \boxed{b_{lin}^2}\sigma_{m,R}^2$$

The Clustering Ratio
Definition

- Therefore, if we define the clustering ratio as...

$$\eta = \frac{\xi(r)}{\sigma^2}$$

[Bel et al.(2014)]

- ...it ends up having this very good property:

$$\eta_{g,R}(r) \equiv \eta_{m,R}(r)$$

Measured in galaxy redshift surveys

Predicted from the cosmological model

The Simulations
DEMNUni

- **D**ark **E**nergy and **M**assive **N**eutrino **Uni**verse
  [**C. Carbone** et al. (2015) in prep, E. Castorina et al, JCAP (2015)]

- Set of 4 simulations with Planck13 cosmology and neutrino mass = { 0, 0.17, 0.30, 0.53 } eV

- CDM mass resolution: $\sim 8\times10^{10}\ h^{-1}\ M_{sun}$
- Number of CDM particles: 2048^3
- Number of neutrino particles: 2048^3
- Cubical box of side: $2000\ h^{-1}$ Mpc

- Run at CINECA by C. Carbone (5×10^6 cpu hours) using the `gadget-III` code [Springel et al. (2005), Viel et al. (2010)]