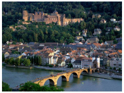
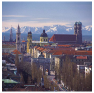
Dark Matter in the sky and in the lab

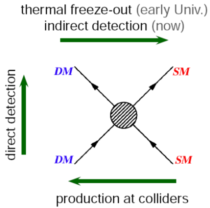
Mathias Garny (CERN)

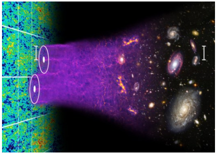
TH division retreat, Les Houches, 04.11.15

Topics

- Interplay of dark matter searches (mainly indirect detection; γ-ray spectral features; electroweak effects)



- Large-scale structure (perturbation theory)



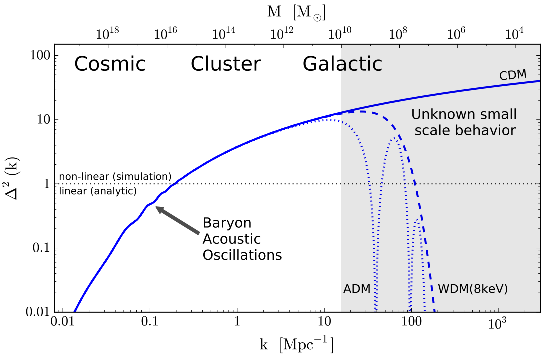
- Physics of the Early Universe (leptogenesis, nonequilibrium QFT)

Can we understand the weakly non-linear regime?

Power spectrum of density contrast $\delta(\mathbf{x}, z) = \rho(\mathbf{x}, z)/\bar{\rho}(z) - 1$

$$\langle \delta(\mathbf{k}, z)\delta(\mathbf{k}', z)\rangle = \delta^{(3)}(\mathbf{k} + \mathbf{k}')P(k, z)$$

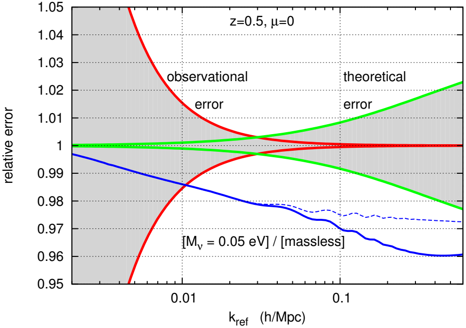
$$\Delta^2(k, z) = 4\pi k^3 P(k, z)$$



Kuhlen, Vogelsberger, Angulo 1209.5745

What can we learn? (for example)

Euclid forecast vs theoretical errors *Audren, Lesgourgues, Bird et. al. 1210.2194*

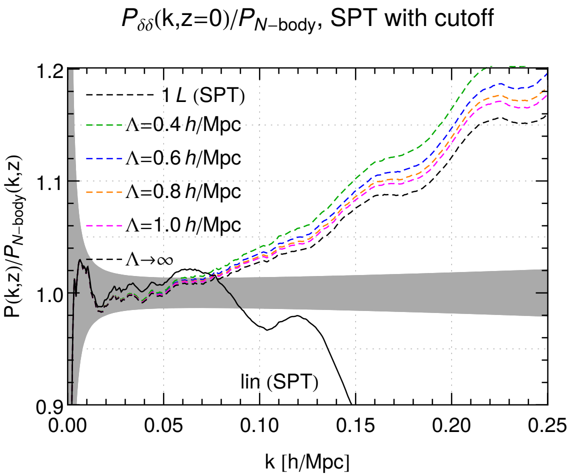


$$\sigma(M_\nu) \simeq \begin{cases} \text{25meV} & \text{fiducial (2\%th. err. at } k = 0.4h/Mpc, z = 0.5) \\ \text{14meV} & \text{th. err. } / = 10, k_{max} = 0.6h/Mpc \end{cases}$$

$$M_\nu = \sum m_\nu \geq \begin{cases} 0.056\text{eV (nh)} \\ 0.095\text{eV (ih)} \end{cases}$$

theoretical uncertainties from bias, RSD, non-linear evolution, . . .

Perturbation theory for large scale structure



Idea: expand in density contrast $\delta = \rho/\bar{\rho} - 1$

- Solve coupled continuity, Euler, Poisson equation, ideal fluid (SPT)
- Initial $\delta(\mathbf{x}, t_0)$ Gaussian random field with two-point corr. $P_0(k)$

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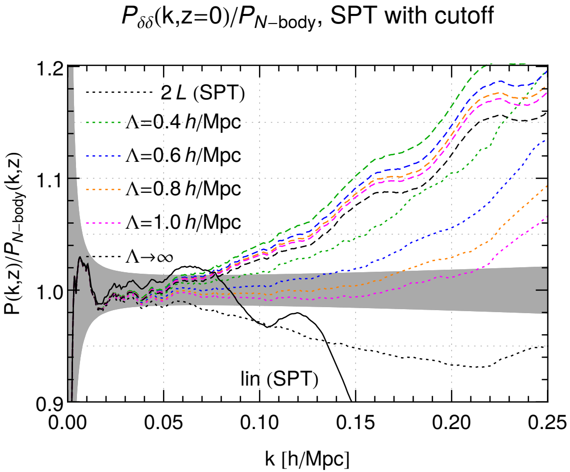

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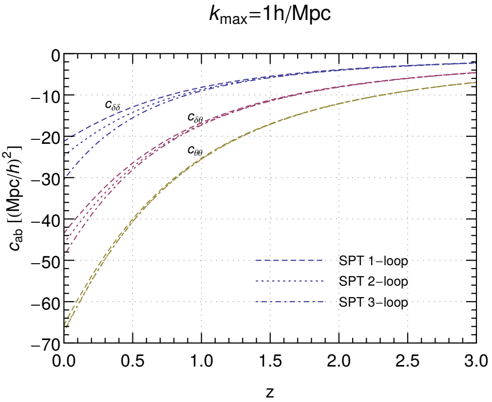
Power spectrum on large scales: SPT

Power spectrum for $q \to 0$, for density contrast δ and velocity div. θ

$$P_{ab}(q,z) \to \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} P_{lin}(q,z) + c_{ab}(z) q^2 P_{lin}(q,z) + \cdots + d_{ab} q^4 + \ldots$$



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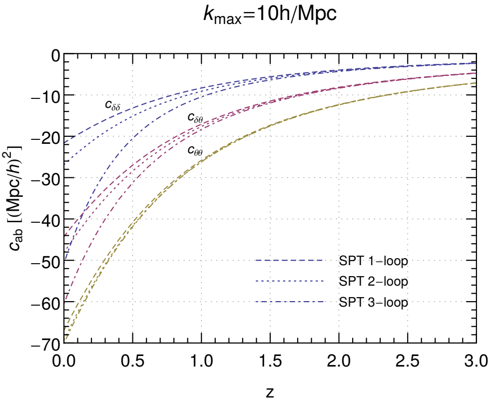

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$$c_{ab}^{1-loop} = -\begin{pmatrix} \frac{61}{105} & \frac{25}{21} \\ \frac{25}{21} & \frac{9}{5} \end{pmatrix} \frac{4\pi}{3} \int_{k<\Lambda} dk P_{lin}(k,z)$$

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$$\begin{aligned} c_{ab}^{L-loop} &\sim -\int_{k<\Lambda} dk P_{lin}(k,z) \left[\int_{p<k} dp p^2 P_{lin}(p,z) \right]^{2L-2} \\ &\sim -\int_{k<\Lambda} dk P_{lin}(k,z) \left[D_+(z)^2 \ln^3(k/k_{eq}) \right]^{2L-2} \quad \text{Eisenstein-Hu} \\ &\sim -k_{eq}^2 \frac{(3L)!}{2^{3L}} D_+(z)^{2L} \quad \text{where } D_+ \sim 1/(1+z) \end{aligned}$$

Asymptotic series

Power spectrum on large scales: SPT

Possible strategies

- Truncate series at smallest term $\Rightarrow \mathcal{O}(25\%)$ uncertainty at $z = 0$

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What do we expect?

- Decoupling arguments of virialized structures (Peebles '80): small UV sensitivity
- Response fctn from N-body support this *Nishimichi, Bernardeau, Taruya 1411.2970*

Wilsonian approach I

Power spectrum for $q \to 0$

$$P_{ab}(q,z) \to \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} P_{lin}(q,z) + c_{ab}(z) q^2 P_{lin}(q,z) + \dots + d_{ab} q^4 + \dots$$

Wilsonian picture

$$c_{ab}(z) = \int d\Lambda \frac{\delta c_{ab}}{\delta \Lambda}$$

... if we would expand perturbatively

$$\frac{\delta c_{ab}^{L-loop}}{\delta \Lambda} \quad \sim \quad -P_{lin}(\Lambda, z) \left[\ln^3(\Lambda / k_{eq}) \right]^{2L-2}$$

$\Rightarrow$ Goal: non-perturbative equation

Non-perturbative equation for the long-wave power spectrum

$$(\partial_\eta + 2)\, c \quad = \quad \{\Omega, c\} - \begin{pmatrix} 0 & 1 \\ 1 & 2 \end{pmatrix} C_{\theta\theta}(z) - \begin{pmatrix} 2 & 1 \\ 1 & 0 \end{pmatrix} C_{\delta\theta}(z)\,,$$

where

$$\begin{aligned} C_{\theta\theta}(z) &= 4\pi \int dk\, f_{\theta\theta}^{\mathcal{O}_0}(k, z) \\ &= \frac{4\pi}{3} \left(-4 - \frac{\partial}{\partial\eta} + 5\frac{\partial}{\partial\kappa}\right) \int dk\, P_{\theta\theta}^{\kappa}(k, z)\Big|_{\kappa=0} \end{aligned}$$

$P_{\theta\theta}^{\kappa}(k, \eta)$ is the full non-perturbative velocity power spectrum in the presence of (hypothetical) spatial curvature $K = \mathcal{H}^2\kappa$.

MG, Konstandin, Porto, Sagunski 1508.06306

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MG, Konstandin, Porto, Sagunski 1508.06306

$$\Rightarrow \frac{\delta c_{ab}}{\delta\Lambda} \sim [-4 - \partial_\eta + \partial_\kappa] P^{\kappa}_{\theta\theta}(\Lambda, z) + [...] P^{\kappa}_{\delta\theta}(\Lambda, z)|_{\kappa=0}$$

Using $P^{\kappa}_{\theta\theta}$ from small-scale N-body $\Rightarrow$ small UV sensitivity

Derivation

- OPE ($\psi = (\delta, \theta)$ at time $\eta = \log(D)$, Φ = grav. potential)

$$\psi_a(\mathbf{x}, \eta)\psi_b(\mathbf{y}, \eta) \xrightarrow{\mathbf{x} \to \mathbf{y}} \sum_{\mathcal{O}} f_{ab}^{\mathcal{O}}(|\mathbf{x} - \mathbf{y}|, \eta)\ \mathcal{O}[\Phi, \partial\Phi, \cdots]\left(\tfrac{1}{2}(\mathbf{x} + \mathbf{y}), \eta\right),$$

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- Response to long mode $\delta_L \Rightarrow$ response to bkg curvature $\kappa = \frac{5}{3}\delta_L$

e.g. Baldauf et al 1106.5507, Sherwin, Zaldarriaga 1202.3998

$$f_{\theta\theta}^{\mathcal{O}_0}(k, \eta) \quad = \quad \left(-\frac{5}{3} - \frac{1}{3}k\ \frac{\partial}{\partial k} - \frac{1}{3}\frac{\partial}{\partial \eta} + \frac{5}{3}\frac{\partial}{\partial \kappa}\right) P_{\theta\theta}^{\kappa}(k, \eta)\big|_{K=0}$$

$\rightarrow$ closely related to ‘equal-time consistency relations’

Valageas 1311.4286, Kehagias, Perrier, Riotto 1311.5524, Konstandin, Porto, Sagunski 1411.3225

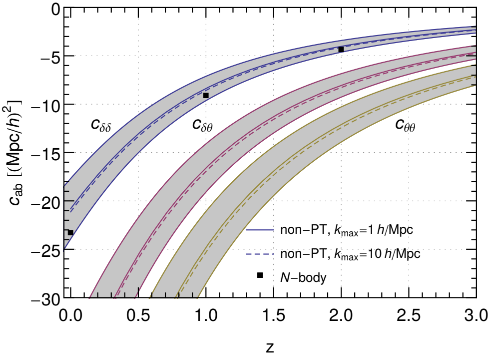
- Directional long mode can be absorbed in Bondi-type bkg

Numerical check

Solution of non-pt eq for the long-wave power spectrum (lines)

$$P_{ab}(q,z) \to \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} P_{lin}(q,z) + c_{ab}(z) q^2 P_{lin}(q,z) + \ldots$$

compared to direct measurements of $c_{\delta\delta}$ from N-body (black squares)



Bands = error estimate due to VKPR approx. for curvature response

MG, Konstandin, Porto, Sagunski 1508.06306

Wilsonian approach II

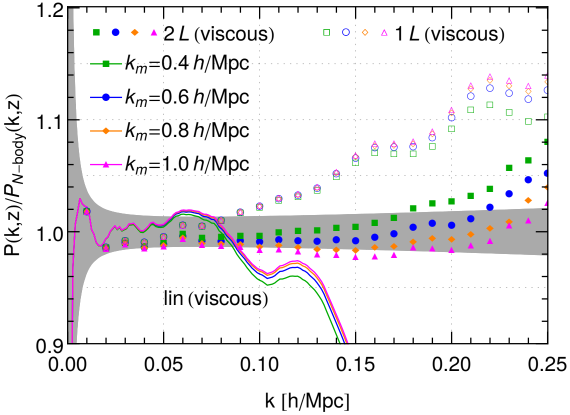
- Coarse-grained (Navier-Stokes) theory where modes below $k < k_m$ are included
- Effective viscosity and pressure which depend on k_m in such a way that

$$\begin{aligned} c_{ab}(z) &= \int d\Lambda \frac{\delta c_{ab}}{\delta \Lambda} \\ &\stackrel{!}{=} \int_0^{k_m} d\Lambda \frac{\delta c_{ab}}{\delta \Lambda} + c_{ab}^{visc/pressure}(z) \end{aligned}$$

- The scale k_m is an artificial matching scale, and the physical result should be independent
- Any residual dependence on k_m quantifies the theoretical error due to perturbative approximations

Wilsonian approach II

$P_{\delta\delta}(\text{k,z=0})/P_{N\text{-body}}$, viscous theory

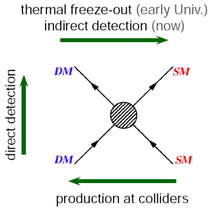


Effective viscosity/pressure from integrating out modes $k > k_m$
Residual dependence on k_m is an estimate for the theoretical error

Blas, Floerchinger, MG, Tetradis, Wiedemann 1507.06665

Topics

- Interplay of dark matter searches (mainly indirect detection; γ-ray spectral features; electroweak effects)



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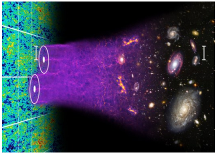
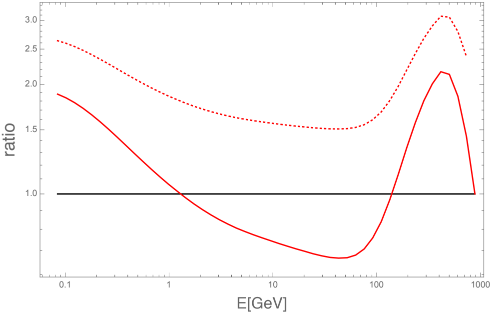


- Physics of the Early Universe (leptogenesis, nonequilibrium QFT)

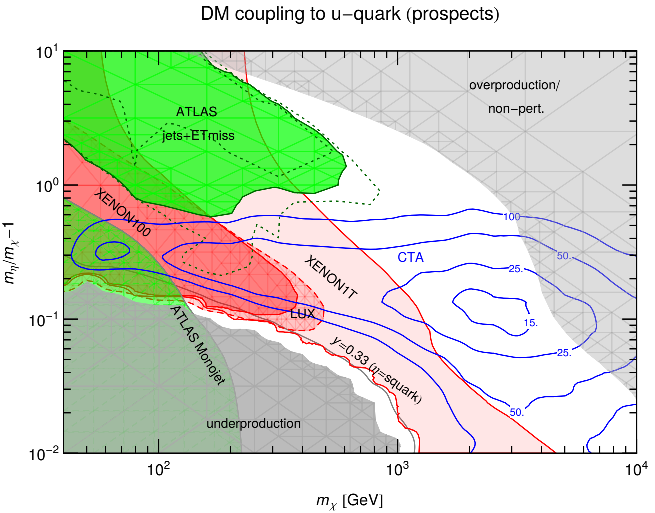
$\chi\chi \to f\bar{F} + \gamma, Z, W, h, H, A, H^{\pm}$

Modification of ν_μ spectrum (MSSM)



Preliminary – Bringmann, Calore, Galea, MG

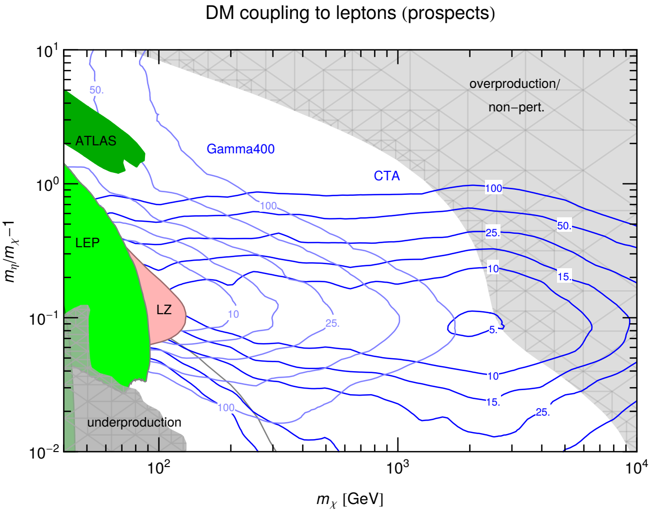
Prospects (coloured t-channel mediator)



MG, Ibarra, Vogl 1503.01500


250 mL

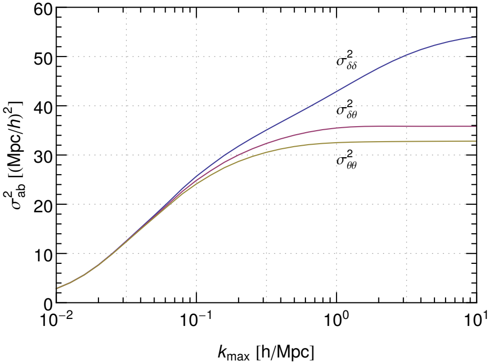
Prospects (uncolored t-channel mediator)



MG, Ibarra, Vogl 1503.01500

UV dependence

- Variance $\sigma^2_{ab} = 4\pi/3 \int_0^{k_{max}} dk P_{ab}$
- For velocity and cross spectrum, saturation around few$\times k_{nl}$
- $\Rightarrow$ small dependence on UV modes with $k >$ few$\times k_{nl}$



MG, Konstandin, Porto, Sagunski 1508.06306