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Viscous Cosmology — Is the dark sector perfect?

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- Cosmic expansion and dissipation
- A unified dark sector?
- Viscous dark matter?
- Observables (focus on bulk viscosity)

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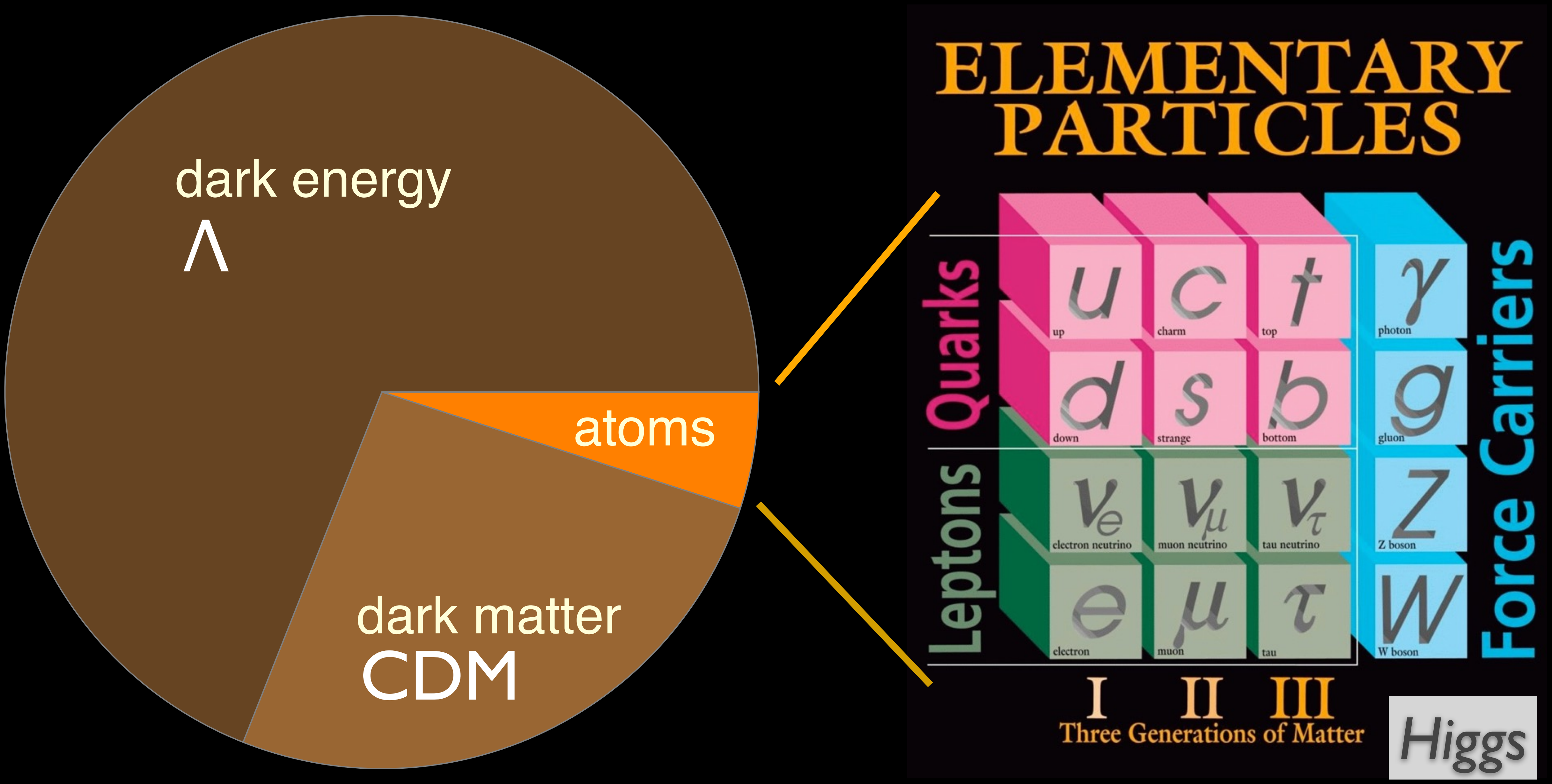
Basic observations

1- expansion history (SN1a, BAO, ...)
   ➜ accelerated expansion of the Universe
2- geometry (CMB)
   ➜ spatial flatness
3- growth of structures (CMB, LSS surveys)
   ➜ non-relativistic (cold/warm) dark matter

Composition of the Universe



dark sector:
cosmological constant & cold dark matter

Why does vanilla cosmology model the cosmic substratum as perfect fluids?

hydrodynamic limit: $1/\tau_{\mathrm{relax}} \gg H \equiv \frac{\mathrm{d}\ln V}{\mathrm{d}t}$

cosmological constant o.k.
but for dark matter ?

Physical Cosmology

1- equations of motion

➜ general relativity & energy/matter content

(or modification of GR)

2- initial/boundary conditions

➜ ??? (inflation?, QG???)

instead

extra symmetry principles to avoid initial/boundary data

➜ cosmological principle(s) !!!

Cosmological principle(s)

Exact: The Universe is spatially isotropic and homogeneous.
ruled out by the fact that we see cosmic structures, reasonable 1st approximation

Statistical: The distribution of mass and light in the Universe is statistically isotropic and homogeneous.

now:
consider comoving cells of volume V,
large enough that statistical averages are useful,
but much smaller than scales of interest

Isotropic & Homogeneous Universe

$$T^{\mu}_{\nu} = (\epsilon + P)u^{\mu}u_{\nu} + \delta^{\mu}_{\nu}P, \qquad \epsilon = \epsilon(t), P = P(t), u^{\mu} = u^{\mu}(t)$$

$$V\mathrm{d}\epsilon = -(\epsilon + P)\mathrm{d}V + \delta' Q$$

1st law of TD for each voxel

$\delta' Q$ heat flow:
must vanish if no direction is preferred
⇒ isotropic & homogeneous fluid

But does that mean that there is no dissipation?

$\mathrm{d}S \geq 0$ does allow for bulk viscosity:

Eckart 1940;
Landau & Lifshitz 1958

$$P = p + \Pi = p - 3H\zeta, \quad \zeta = \zeta(t) \geq 0$$

1st or 2nd order?

Müller 1967; Israel & Stewart 1976

Interest in cosmic bulk viscosity arose in the in the context of cosmological inflation (acceleration of the expansion!)

see e.g. review by Maartens 1995

$$\Pi + \tau\dot{\Pi} = -3H\zeta - \frac{1}{2}\tau\Pi\left(3H + \frac{\dot{\tau}}{\tau} - \frac{\dot{\zeta}}{\zeta} - \frac{\dot{T}}{T}\right)$$

$$t \gg \tau : \qquad \Pi = \frac{-3H\zeta}{1 + \frac{3}{2}H\tau} \approx -3H\zeta_{\mathrm{eff}}$$

If relaxation time is comparable or larger than Hubble time, 2nd order required, but then fluid assumption is very questionable

Causality issue?

Disconzi, Kephart & Scherrer 2015
based on Lichnerowitz 1944, 1957

Why should we expand in gradients of u^μ?

claim:
gradient expansion in u^μ is reason for violation of causality,
instead expand in

$$F u^\mu \equiv \frac{\epsilon + p}{\mu} u^\mu, \quad \nabla_\nu (\mu u^\nu) \equiv 0$$

for dissipationless fluids $\mu = \epsilon + p$

now: $\Pi = -\dot{F}\zeta - F 3 H \zeta$

causal at 1st order,
promising idea!

Standard model or unified dark matter

SM assumes no dissipation:

1- cosmological constant $p = -\epsilon$ no fluctuations

2- cold dark matter thermal origin (?), free fall

$p = 0$

3- atoms (visible matter) gas,

viscosity in astrophysics

Could the dark sector be unified?

Generalized Chaplygin gas: $p = -A\epsilon_0(\epsilon_0/\epsilon)^\alpha$ Kamenshchik, Moschella & Pasquier 2001

Viscous dark fluid: $p = -3H\zeta, \quad \zeta = \zeta_0(\epsilon_0/\epsilon)^\nu, H = H_0(\epsilon_0/\epsilon)^{1/2}$

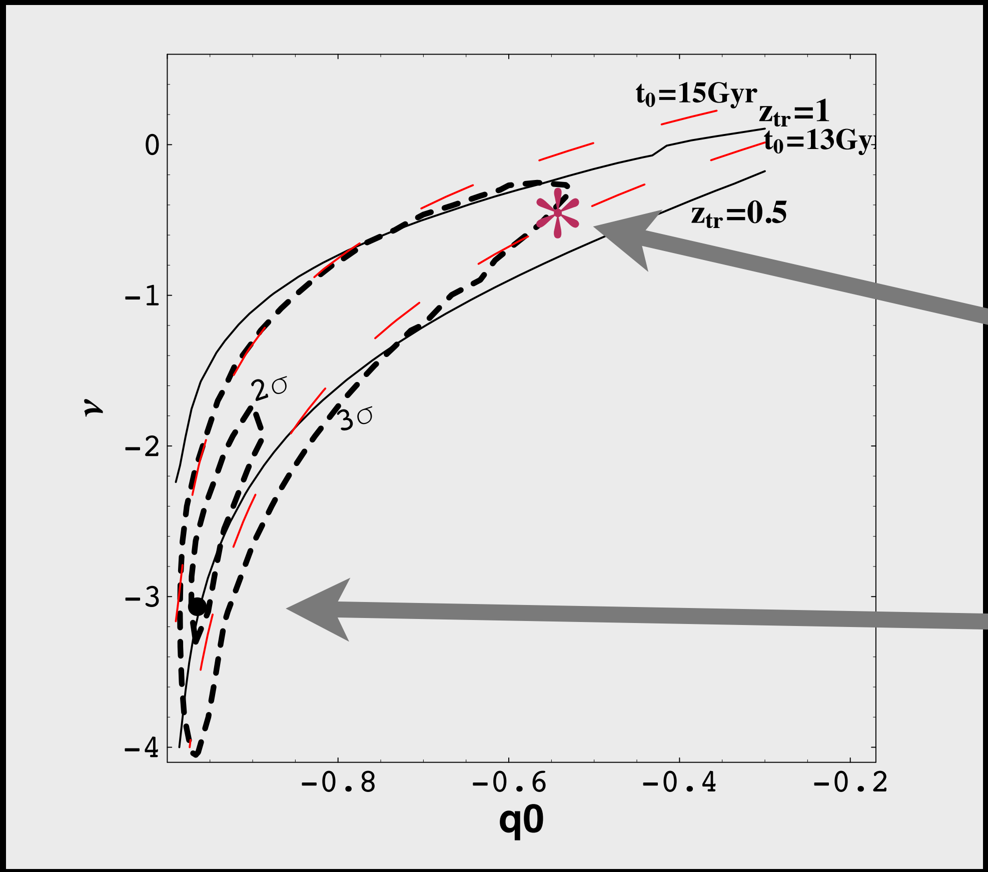
Zimdahl, Schwarz, Balakin & Pavon 2001; Fabris, Goncalves & de Sa Ribeiro 2006

Unified dark matter

At background level, both models are equivalent and include the standard model ($\alpha = 0$; $\nu = -1/2$)

$p = -A\epsilon_0(\epsilon_0/\epsilon)^\alpha$ becomes with $A = 3H_0\zeta_0, \quad \alpha = \nu + 1/2$

$p = -3H_0\zeta_0(\epsilon_0/\epsilon)^{\nu+1/2}$ and $w_{\rm v} = \dfrac{-1}{1 + (\frac{\epsilon_0}{3H_0\zeta_0} - 1)(1+z)^{3(1/2-\nu)}}$



ΛCDM

best-fit VDF to SN1a and H(z) data

Velten & Schwarz 2011

Dissipative fluctuations

But dissipative terms in VDF model are different from (dissipationless) GCG perturbations.

Velten & Schwarz 2011

$$\psi'' + 3\mathcal{H}\psi' =$$

$$w_{\rm v}\left[\left[-\frac{1}{2} + \frac{k^2}{(1+w_{\rm v})9\mathcal{H}^2}\right]3\mathcal{H}\psi' + \left[\frac{3\mathcal{H}^2}{2} + \frac{k^2}{1+w_{\rm v}}\right]\psi + \frac{3\mathcal{H}^2}{2}\frac{\delta\zeta}{\zeta}\right]$$

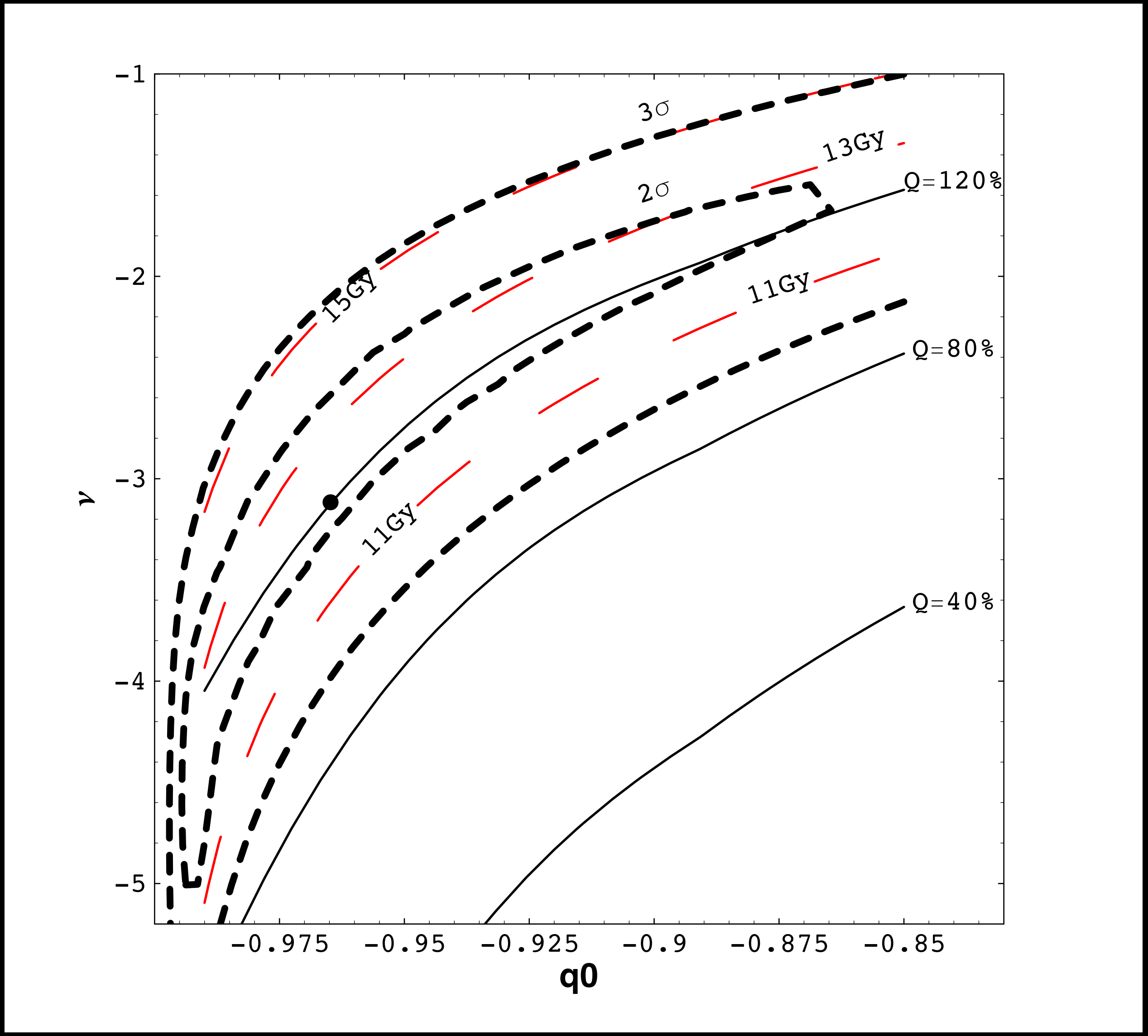
equation for metric potential at z ≪ 1000

rhs gives rise to observable modifications wrt ΛCDM and allows us to distinguish VDF ($\delta\zeta \neq 0$) from GCG ($\delta\zeta = 0$)

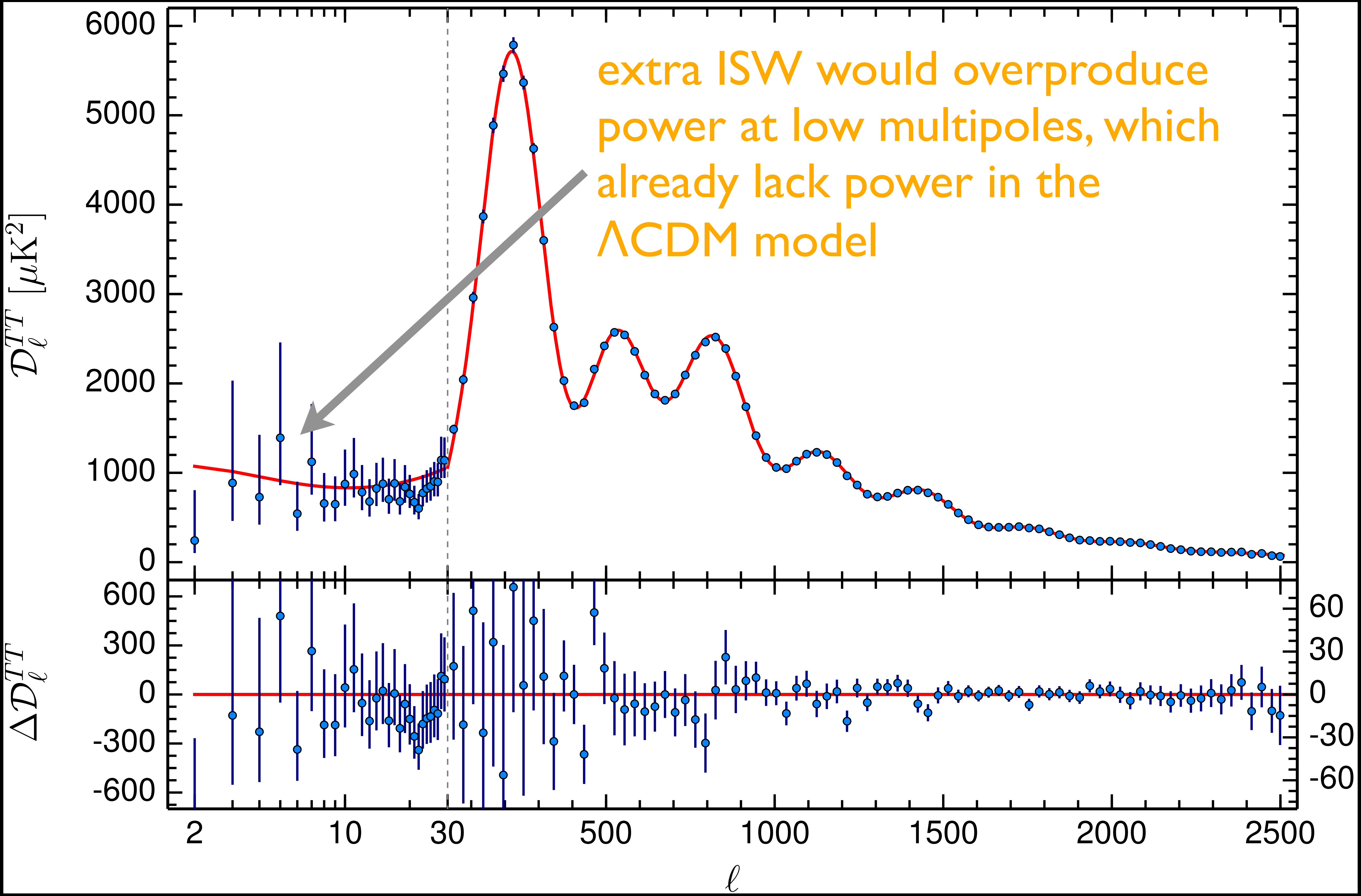
Observable effects I

Both models give rise to a modification of the late time integrated Sachs-Wolfe effect

Li & Barrow 2009, Velten & Schwarz 2011



$$\left(\frac{\delta T}{T}\right)_{\rm ISW} = 2\int_{\rm dec}^{\rm today} {\rm d}\eta\, \partial_\eta \psi$$

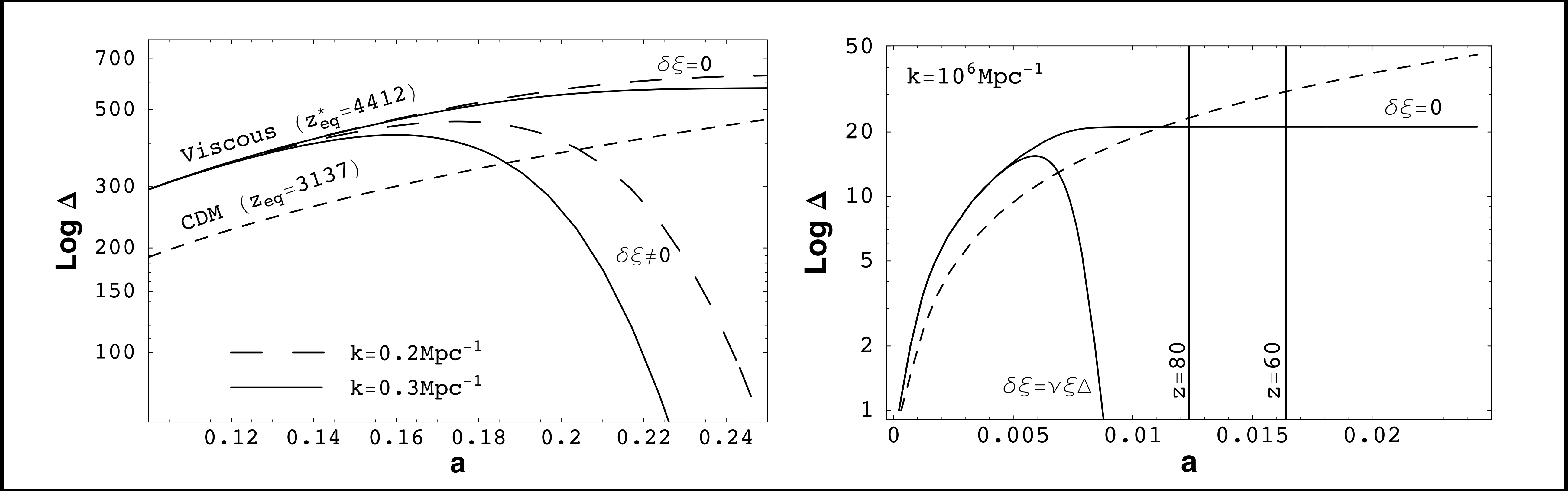


extra ISW would overproduce power at low multipoles, which already lack power in the ΛCDM model

Planck 2015

Observable effects II

The VDF gives also rise to an extra damping of small scale structure at late times Velten & Schwarz 2011



Sub-galactic scales are damped exponentially

might be useful to smooth galactic cores and to reduce number of satellites and dwarfs

Viscous dark matter

Hot and cold dark matter behave differently:

relativistic neutrinos:

Weinberg 1971, Straumann 1976

$$c_{\rm s}^2 = \frac{1}{3}, \quad \eta \approx \frac{4}{15}\epsilon\tau, \quad \zeta \approx 0, \quad \chi \approx \frac{4}{3}\frac{\epsilon}{T}\tau, \quad \tau \approx \tau_{\rm coll}$$

WIMPs in radiation background:

Hofmann, Schwarz & Stoecker 2001;
Green, Hofmann & Schwarz 2004,2005;
Bringmann & Hofmann, 2006

$$c_{\rm s}^2 \approx \frac{5}{3}\frac{T}{m}, \quad \eta \approx nT\tau, \quad \zeta \approx \frac{3}{5}nT\tau, \quad \chi \approx 0; \quad \tau \approx \sqrt{\frac{2}{3}\frac{m}{T}}\tau_{\rm coll}$$

$$\Rightarrow L \approx \frac{3}{2}\frac{T}{m}\tau$$

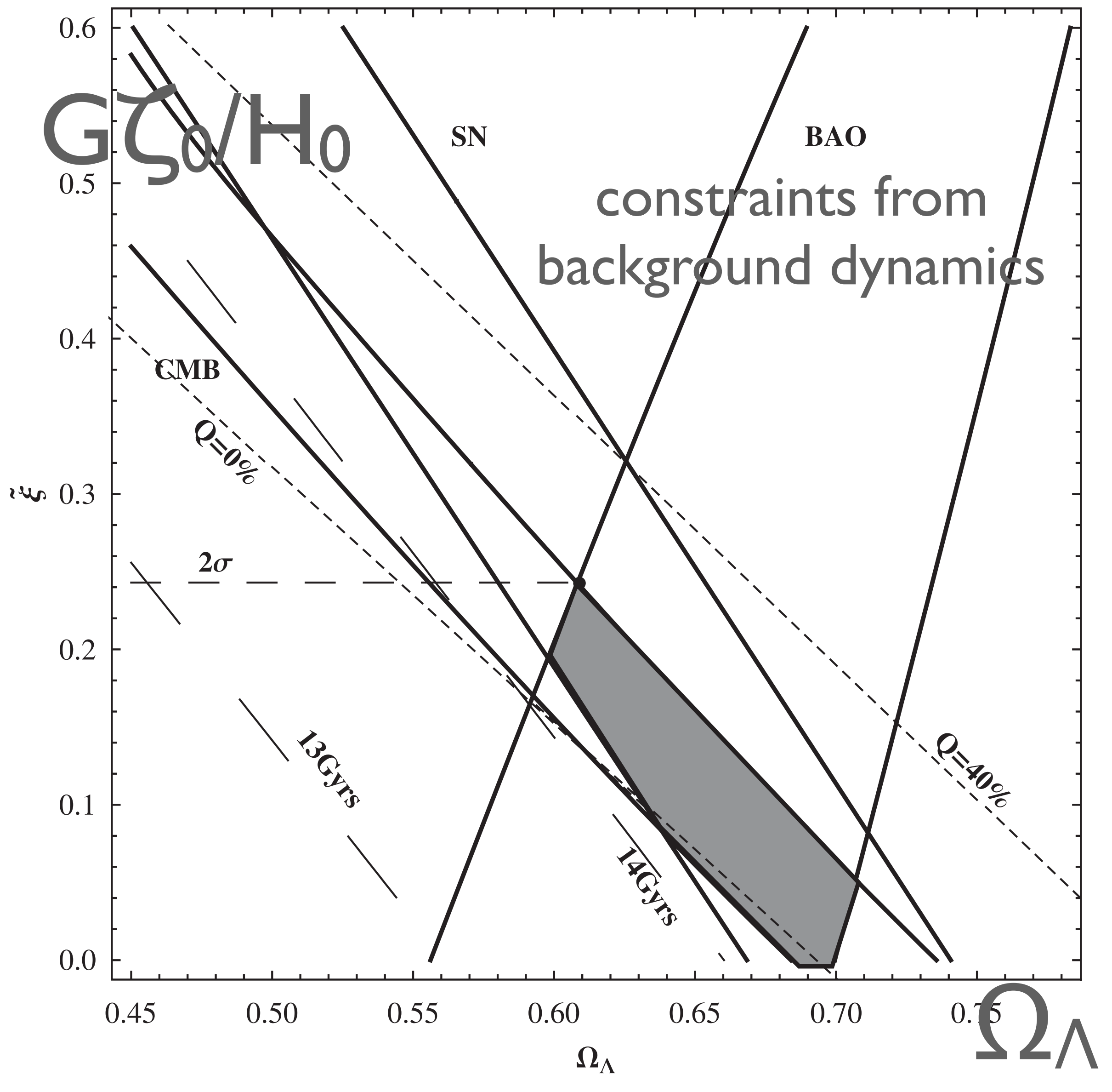
damping length

both examples relevant in early universe

Viscous dark matter

study a ΛvCDM model

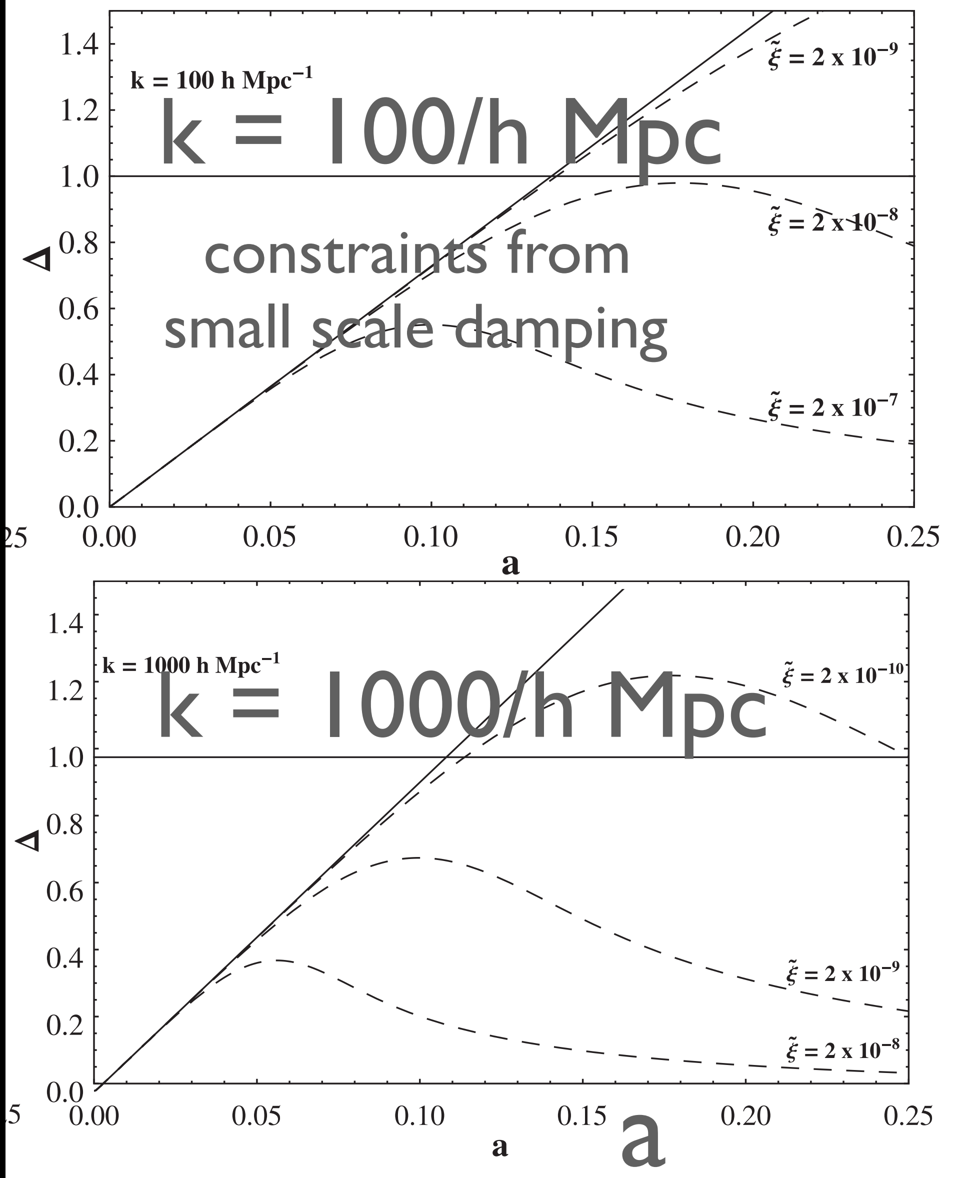
viscosity in todays universe?



$G\zeta_0/H_0$

constraints from background dynamics

Ω_Λ



k = 100/h Mpc

constraints from small scale damping

k = 1000/h Mpc

a

Velten & Schwarz 2012;
Velten, Schwarz, Fabris & Zimdahl 2013

Viscous dark matter

subhorizon vCDM equation: scale dependent terms !

$$a^2\frac{d^2\Delta_\mathrm{v}}{da^2}+\left[\frac{a}{H}\frac{dH}{da}+3+A(a)+B(a)k^2\right]a\frac{d\Delta_\mathrm{v}}{da}+\left[+C(a)+D(a)k^2-\frac{3}{2}\right]\Delta_\mathrm{v}=P(a),$$

$$A(a)=-6w_\mathrm{v}+\frac{a}{1+w_\mathrm{v}}\frac{dw_\mathrm{v}}{da}-\frac{2a}{1+2w_\mathrm{v}}\frac{dw_\mathrm{v}}{da}+\frac{3w_\mathrm{v}}{2(1+w_\mathrm{v})}$$

$$B(a)=-\frac{w_\mathrm{v}}{3a^2H^2(1+w_\mathrm{v})}$$

$$C(a)=\frac{3w_\mathrm{v}}{2(1+w_\mathrm{v})}-3w_\mathrm{v}-9w_\mathrm{v}^2-\frac{3w_\mathrm{v}^2}{1+w_\mathrm{v}}\left(1+\frac{a}{H}\frac{dH}{da}\right)-3a\left(\frac{1+2w_\mathrm{v}}{1+w_\mathrm{v}}\right)\frac{dw_\mathrm{v}}{da}+\frac{6aw_\mathrm{v}}{1+2w_\mathrm{v}}\frac{dw_\mathrm{v}}{da}$$

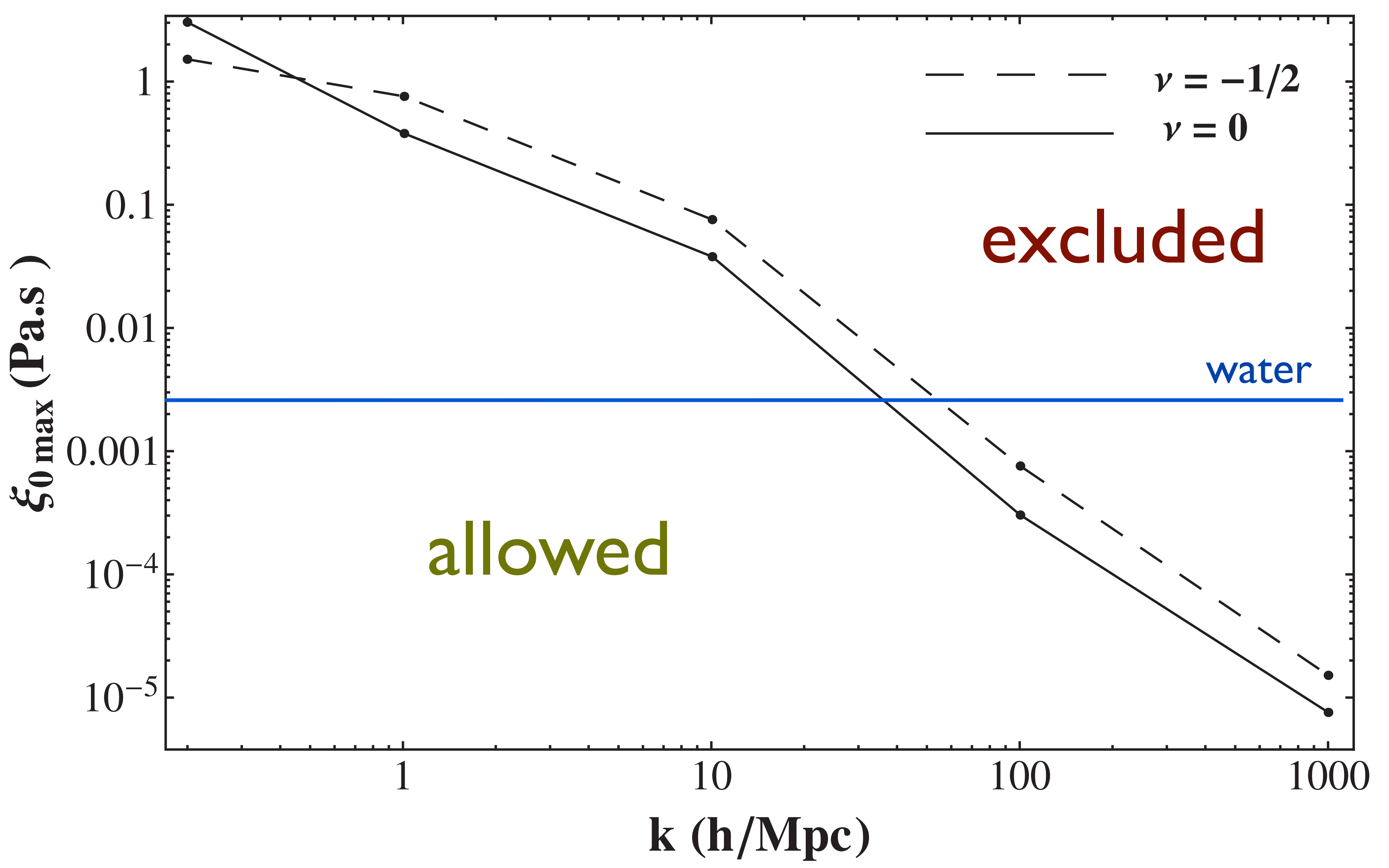
$$D(a)=\frac{w_\mathrm{v}^2}{a^2H^2(1+w_\mathrm{v})}$$

$$P(a)=-3\nu w_\mathrm{v}a\frac{d\Delta_\mathrm{v}}{da}+3\nu w_\mathrm{v}\Delta_\mathrm{v}\left[-\frac{1}{2}+\frac{9w_\mathrm{v}}{2}+\frac{-1-4w_\mathrm{v}+2w_\mathrm{v}^2}{w_\mathrm{v}(1+w_\mathrm{v})(1+2w_\mathrm{v})}a\frac{dw_\mathrm{v}}{da}-\frac{k^2(1-w_\mathrm{v})}{3H^2a^2(1+w_\mathrm{v})}\right],$$

CDM: Meszaros equation for A= B = C = D = P = 0

Velten & Schwarz 2012

Constrain on dark matter bulk viscosity



existance of dwarf galaxies excluded unless

$\zeta_0 < 10^{-14}\, H_0/G$

consistency check:

$\zeta_0 \sim \epsilon_v \tau \ll H_0/G$

thus

$\tau H_0 \ll \epsilon_0/\epsilon_v \sim 1$

Velten & Schwarz 2012

Open issues

study the more general cases $\zeta = \zeta(\varepsilon, \mathrm{S}, \ldots)$

- could huge ISW contribution be avoided?

- put quantitative limits on unified dark matter from final Planck release and LSS surveys

update limits on ζ and η of dark matter from final Planck release and LSS surveys

calculate ζ and η for realistic dark matter candidates (so far done for generic WIMP and SDM)

Conclusion

Unified dark matter/viscous inflation require unrealistic assumptions on bulk viscosity/relaxation times

Alternative solution to causality problem?

Viscous dark matter is a real option, but bulk viscosity must be small and is in accord with hydrodynamic assumption

Constraints on viscous cosmology from
ISW (CMB - LSS xcorrelation) and dwarf galaxies

Is there a good candidate for VDM? Not WIMPs!