Title: Dark Energy and Neutrino Mass

Date: May 18, 2007 05:00 PM

URL: http://pirsa.org/07050032

Abstract: One of the possible explanations for the current acceleration of the universe comes from a coupling between the Dark Energy and the Neutrino sectors. This coupling causes the neutrino mass to vary with cosmic time, what opens a new window to constrain this dark energy candidate. In this work, we analyze the mass-varying neutrino scenario in a model independent way, focusing on its effects for the Cosmic Microwave Background and Large Scale Structure.

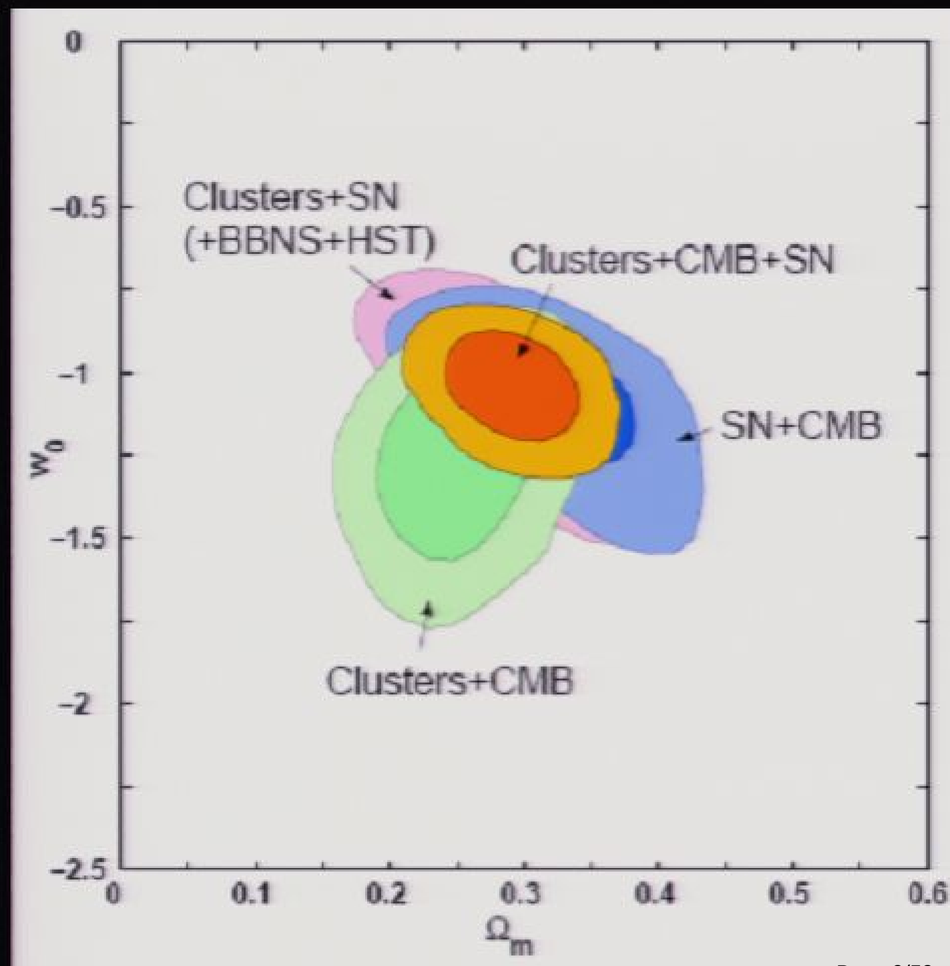
Cosmological status in a nutshell

Set of cosmological observations give nowadays very strong evidence for a flat ΛCDM like cosmological model

parameter	ALL DATA
ω_b	$0.0230^{+0.0006+0.0011+0.0017}_{-0.0006-0.0011-0.0019}$
ω_{dm}	$0.117^{+0.003+0.005+0.007}_{-0.002-0.005-0.008}$
h	$0.705^{+0.013+0.025+0.038}_{-0.013-0.023-0.038}$
τ	$0.108^{+0.010+0.039+0.063}_{-0.010-0.043-0.069}$
n_s	$0.964^{+0.012+0.025+0.037}_{-0.012-0.026-0.038}$
σ_8	$0.847^{+0.022+0.042+0.070}_{-0.022-0.045-0.062}$
Ω_k	$-0.003^{+0.0060+0.0109+0.0157}_{-0.0061-0.0122-0.0180}$
w	$-1.040^{+0.063+0.124+0.178}_{-0.063-0.130-0.208}$
$\sum m_\nu$	$< 0.17\text{eV}\ (< 0.32\text{eV})$

Rapetti, Allen, Weller 05

Seljak, Slosar and McDonald 07



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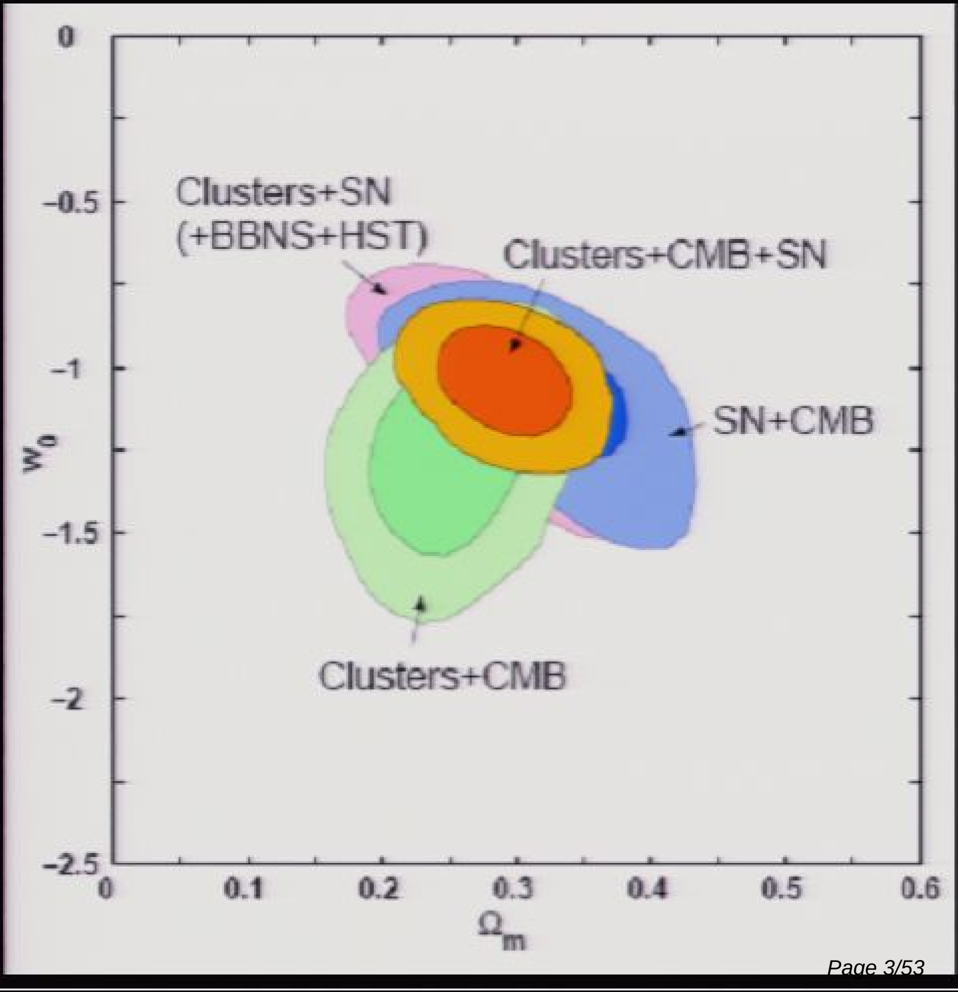
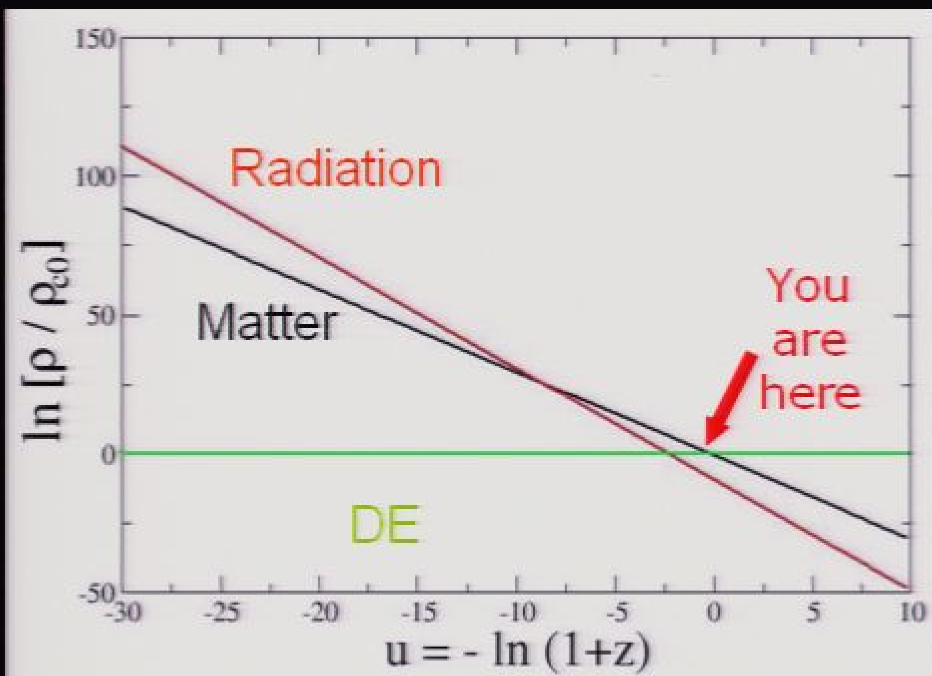
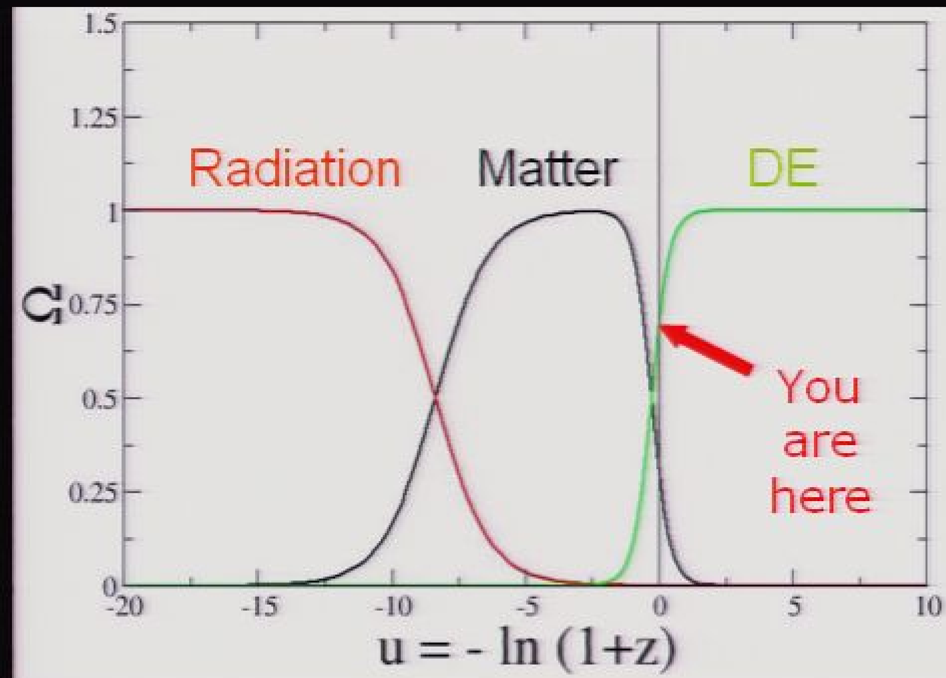


Model leads to some coincidences...

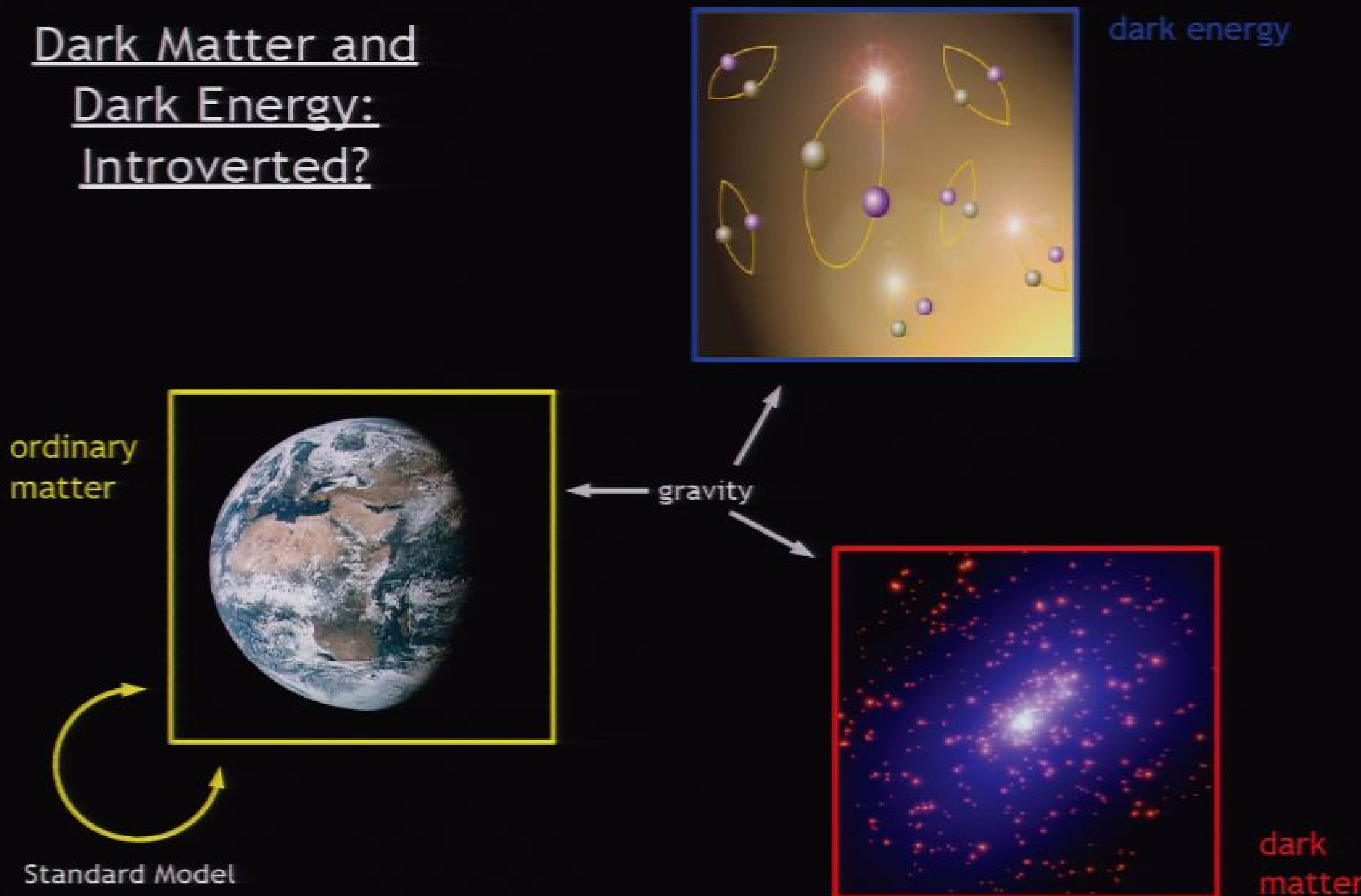




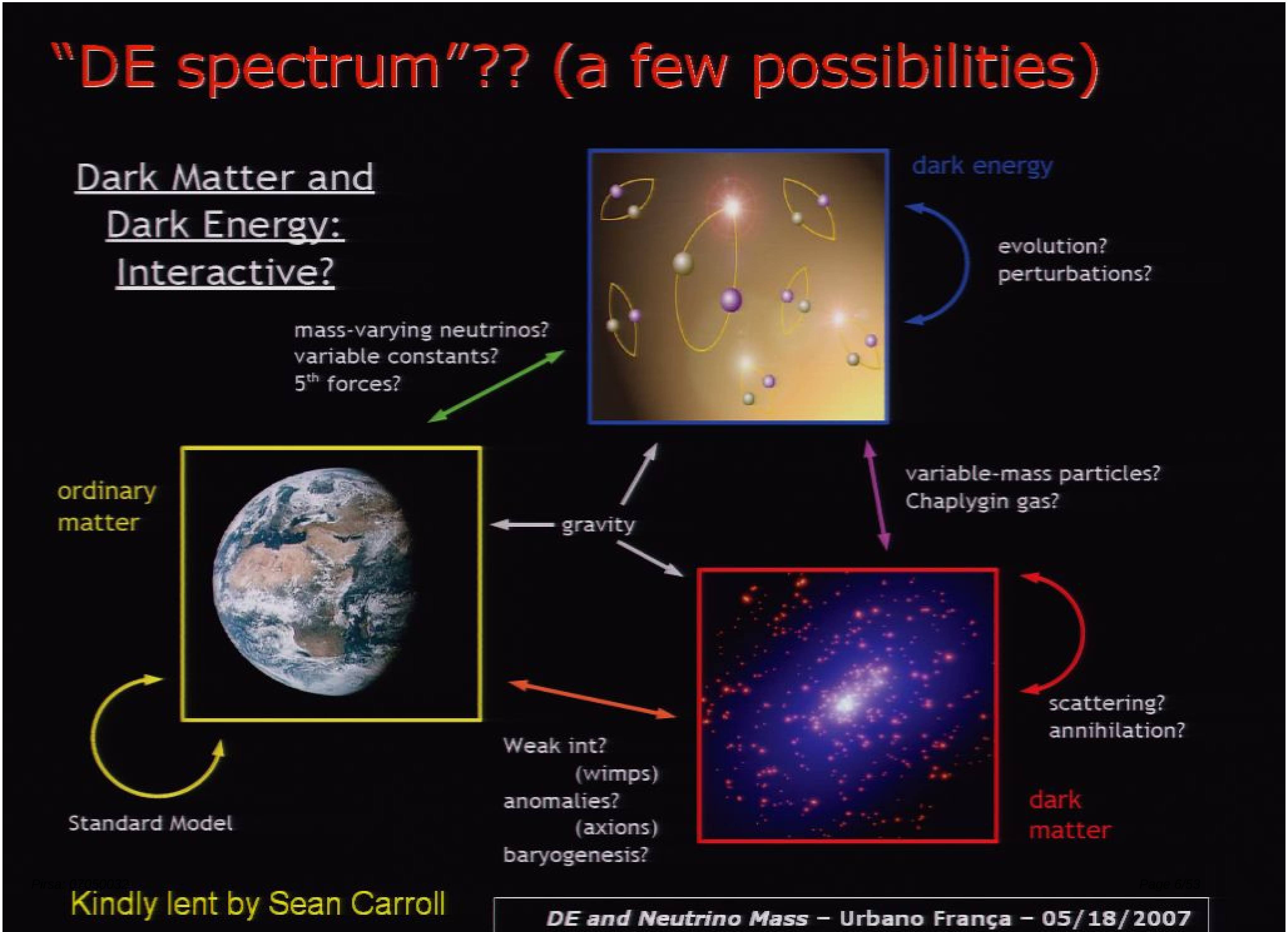
But that is only the simplest model that you can think of!

"DE spectrum"?? (a few possibilities)

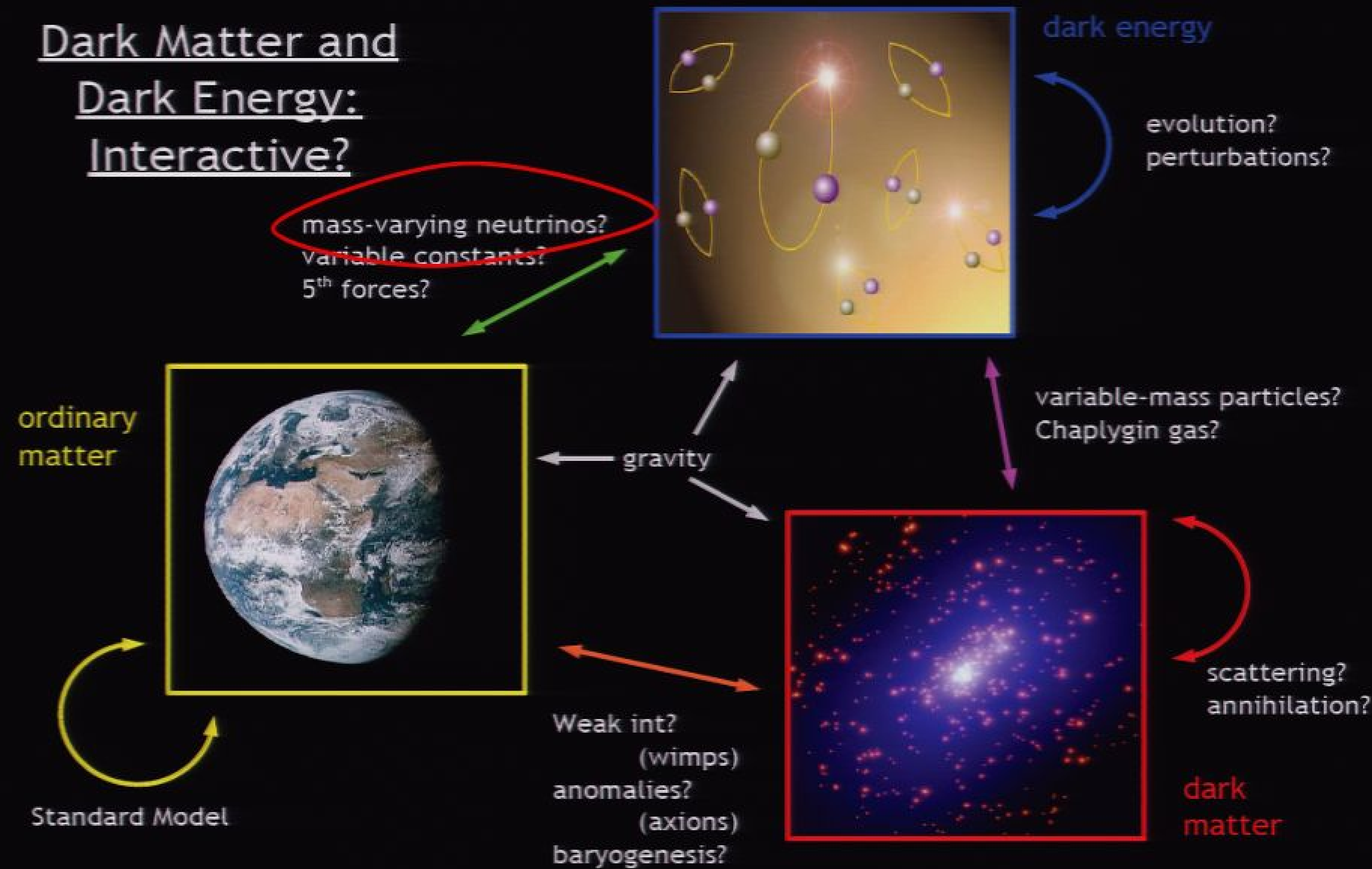
Dark Matter and
Dark Energy:
Introverted?



Kindly lent by Sean Carroll


"DE spectrum"?? (a few possibilities)
Dark Matter and
Dark Energy:
Interactive?
dark energy
evolution?
perturbations?
mass-varying neutrinos?
variable constants?
5th forces?
ordinary
matter
gravity
variable-mass particles?
Chaplygin gas?
scattering?
annihilation?
Weak int?
(wimps)
anomalies?
(axions)
baryogenesis?
dark
matter
Standard Model
Kindly lent by Sean Carroll
DE and Neutrino Mass – Urbano França – 05/18/2007

Where are MaVaNs in the "DE spectrum"??



Kindly lent by Sean Carroll

Why neutrinos?

- They are light
  - Small QC to the DE potential
- They almost do not interact
  - Avoid 5th force problems
- Coincidence of scales (~m/33 eV)
  - numerology??
- Why not?

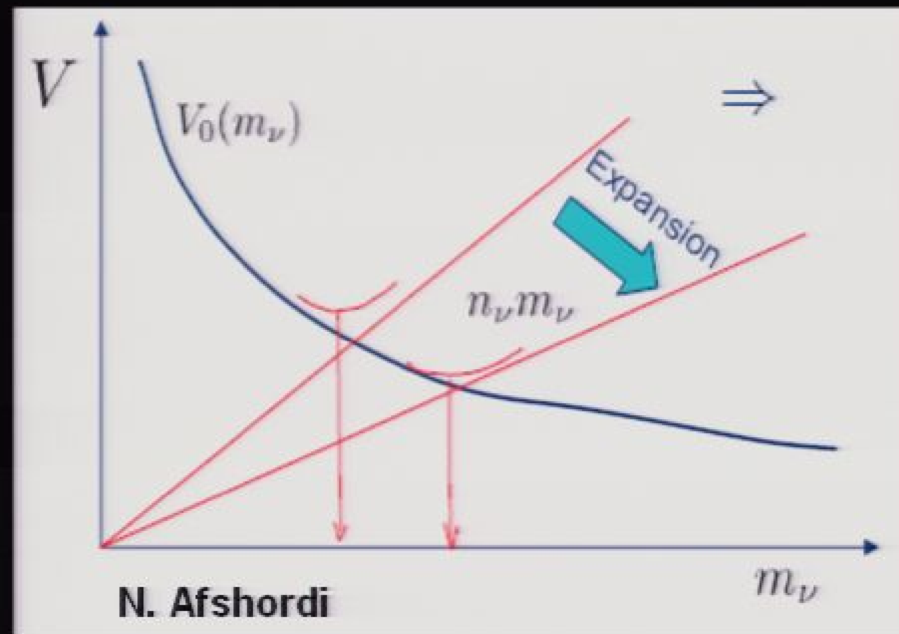
MaVaNs (Mass Variable Neutrinos)

"Original" model Fardon, Nelson & Weiner 04, 06

$$V = n_\nu m_\nu(\mathcal{A}) + V_0(\mathcal{A})$$

$$\frac{\partial V}{\partial \mathcal{A}} = \left(n_\nu + \frac{\partial V_0}{\partial m_\nu}\right)\frac{\partial m_\nu}{\partial \mathcal{A}} = 0 \Rightarrow n_\nu = -\frac{\partial V_0}{\partial m_\nu}.$$

$$w \equiv \frac{\text{Pressure}}{\text{Density}} \simeq -\frac{V_0(\mathcal{A})}{V} = -1 + \frac{n_\nu m_\nu(\mathcal{A})}{V},$$



* Only treating nonrelativistic neutrinos (p ~ 0)

* DE mass could be very "large", m ~ 0.0001 eV (you don't even need scientific notation!!)

* Neutrino pert. unstable: TO BE (Afshordi, Kohri, Zaldarriaga 05) or NOT TO BE (Bjaelde et al. 2007 – Lily Schrempp's talk)?

MaVaNs (Mass Variable Neutrinos)

Peccei 05

Brookfield, et al. 05, 06

Including the "relativistic nature" of neutrino (and dynamics for the field)

$$\dot{\rho}_\nu + 3H(\rho_\nu + p_\nu) = \frac{\partial \ln m_\nu}{\partial \phi}\dot{\phi}(\rho_\nu - 3p_\nu)$$

$$\ddot{\phi} + 2H\dot{\phi} + a^2\frac{\partial V}{\partial \phi} = -a^2\frac{\partial \ln m_\nu}{\partial \phi}(\rho_\nu - 3p_\nu),$$

Mass variation only starts when the neutrinos become nonrelativistic!

MaVaNs (Mass Variable Neutrinos)

It leads to well behaved ΛCDM-like background solutions

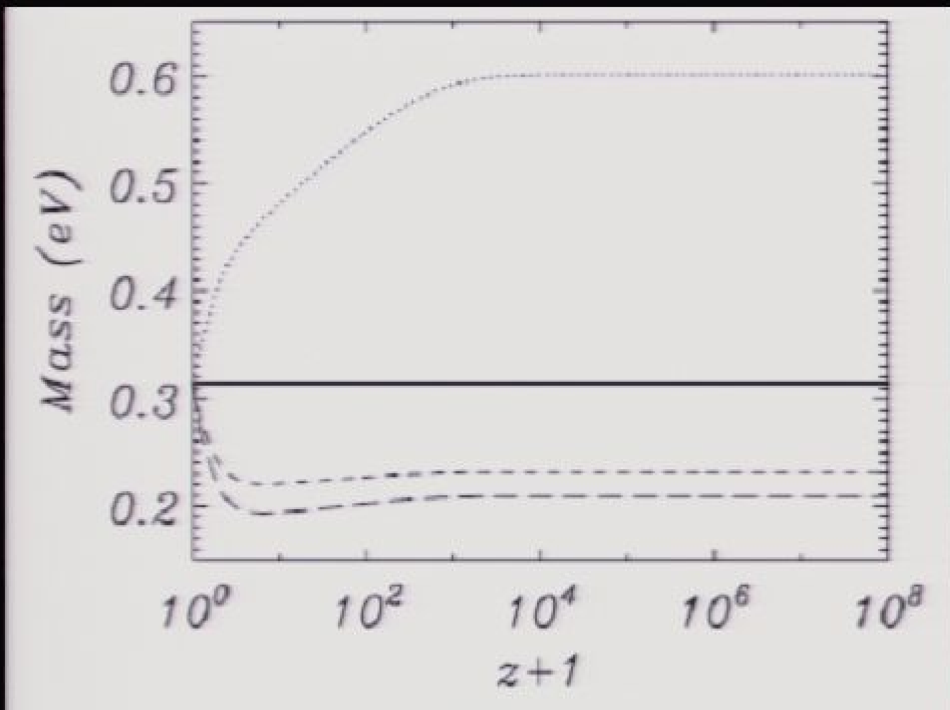
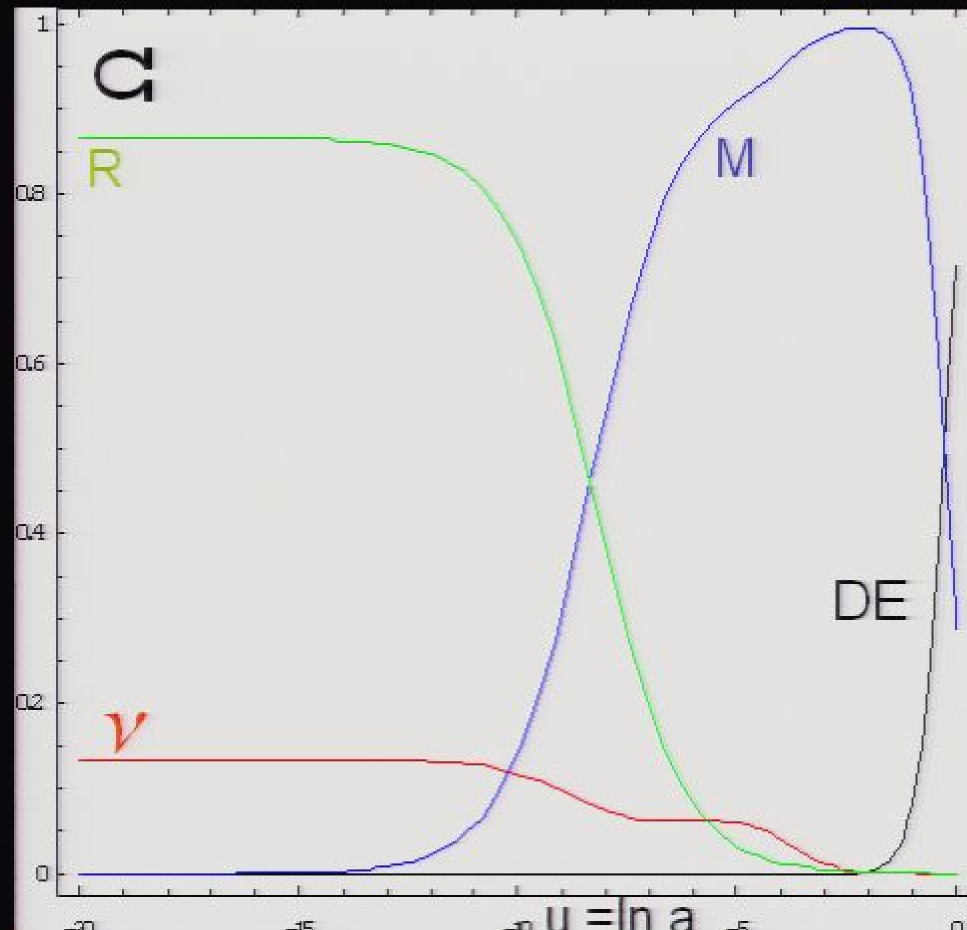


FIG. 8. The evolution of the neutrino mass for the inverse power-law potential with $m_\nu(\phi) = m_0 e^{\beta\phi^2}$ (solid line: $\beta = 0$; short-dashed line: $\beta = 0.2$; dotted line: $\beta = -0.2$; long-dashed line $\beta = 0.27$.)



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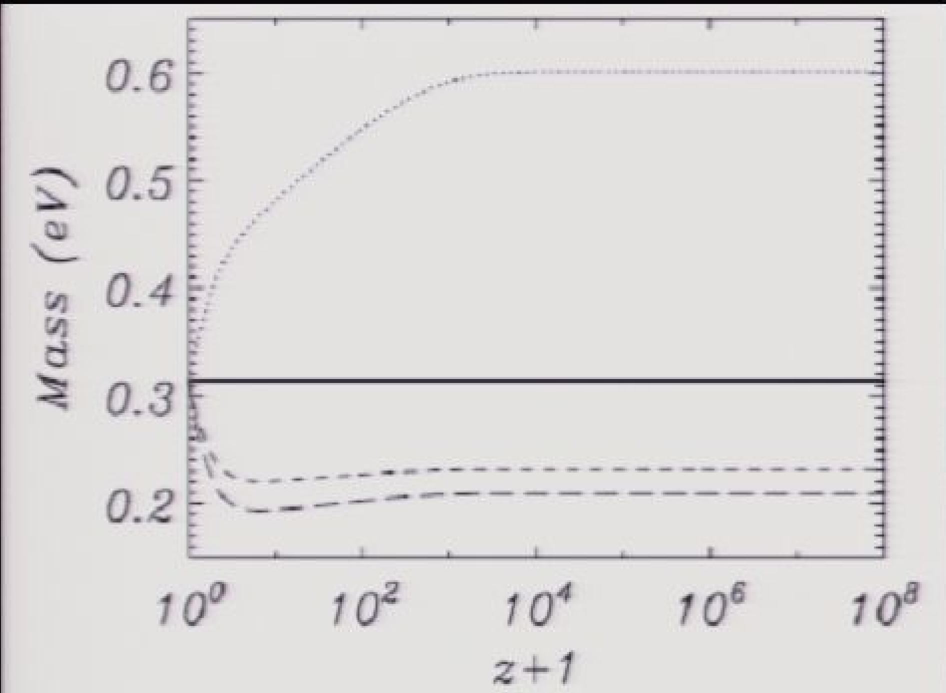

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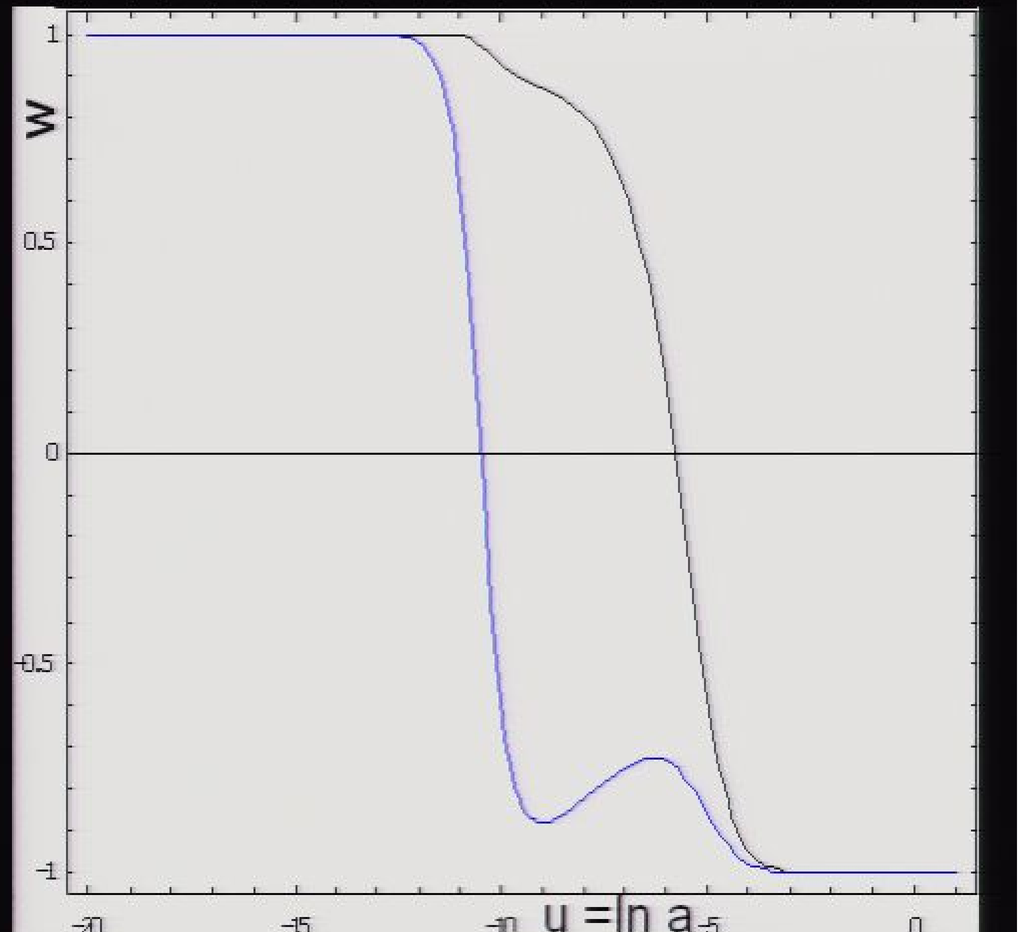


Our goal: to verify, in a **<u>model independent way</u>**, if it is possible to constrain such models using cosmological implications of the variation of the neutrino mass.

Outline

I. Mass Varying Neutrinos

II. Parameterizations

III. Model

IV. Results

V. Summary

For the DE equation of state…

* $w \equiv p_X/\rho_X$ — Turner and White 97
* $w(a) = w_0 + w_a(1-a)$ — Linder 03, DETF 06

+ Exp[32456786898320] other ones...

For the DM mass…

* $\rho_m = \rho_{m0} a^{-3} e^{\int \delta d\alpha}$ — Amendola 05, Amendola 06, Amendola, Camargo, Rosenfeld 07

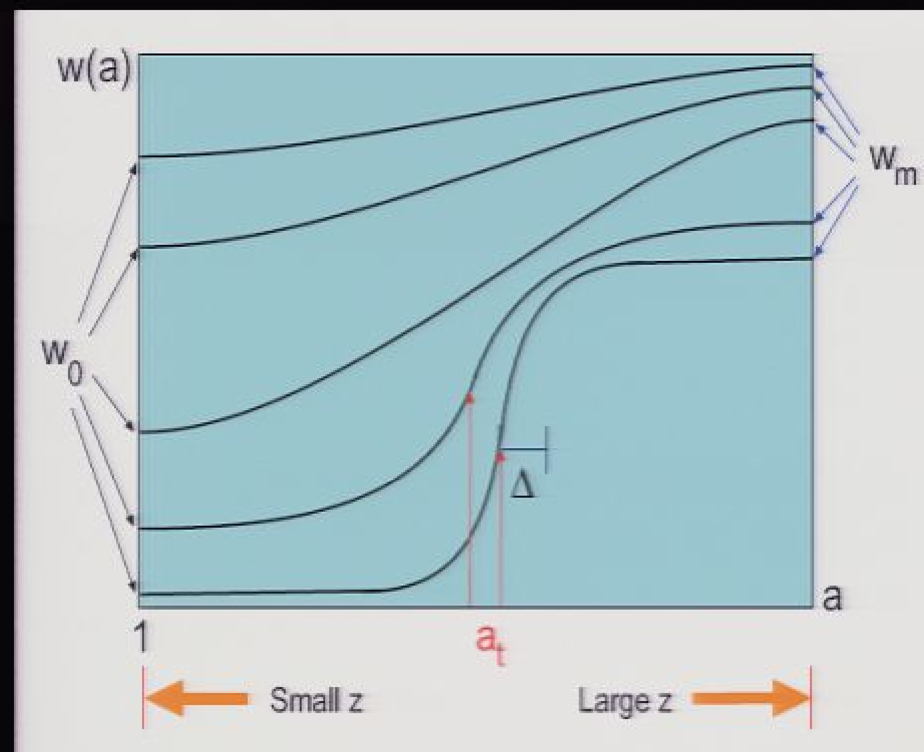
$$\delta(a) = \frac{d\ln m_\psi(a)}{d\ln a}$$

One particular parameterization

$$w(a) = w_0 + (w_m - w_0)\Gamma(a, a_t, \Delta)$$

Corasaniti, Copeland and collaborators 03, 04

$$\Gamma(a, a_t, \Delta) = \frac{1 + e^{\frac{a_t}{\Delta}}}{1 + e^{-\frac{a - a_t}{\Delta}}} \times \frac{1 - e^{-\frac{a-1}{\Delta}}}{1 - e^{\frac{1}{\Delta}}}$$

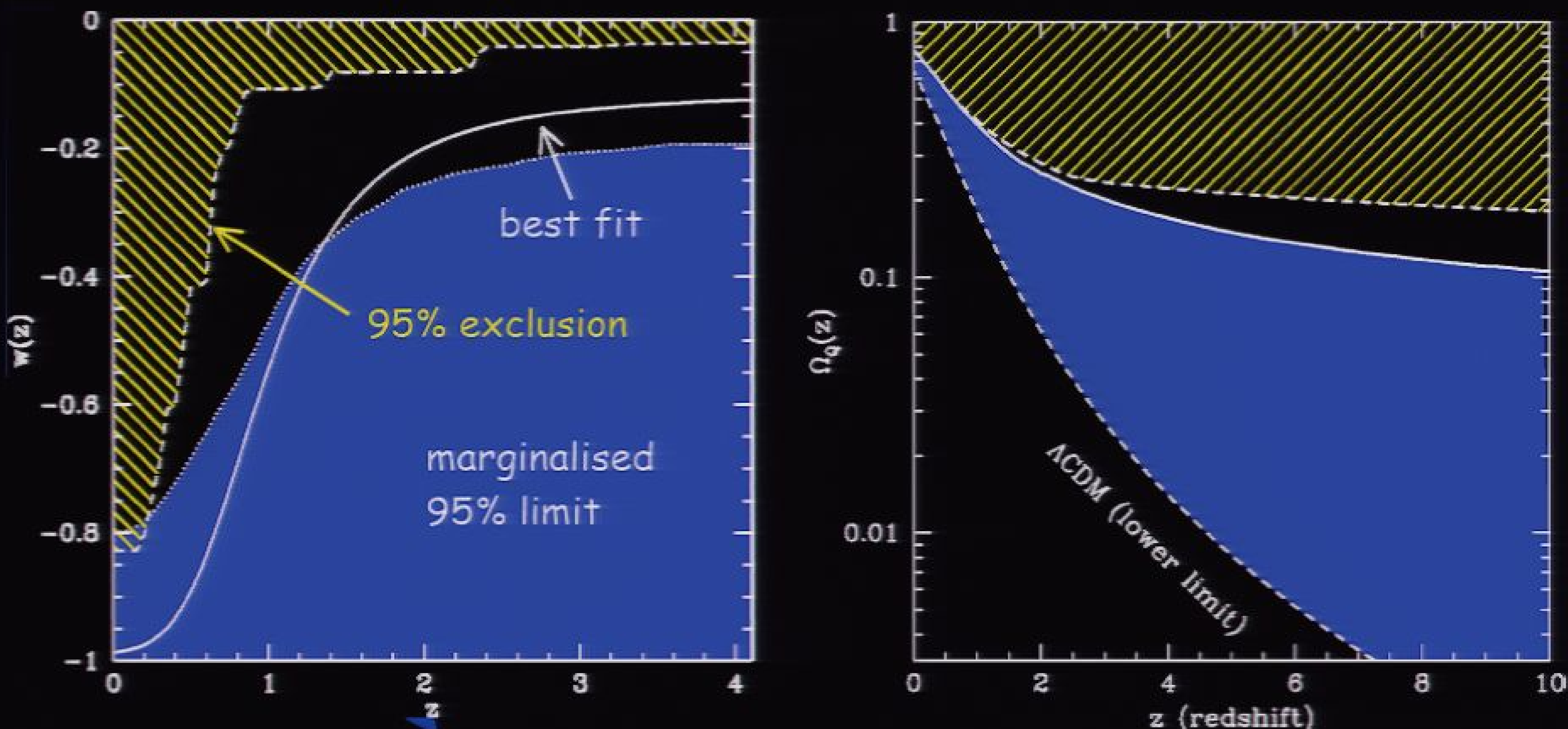


Allows for different (smooth) behaviors for the DE e.o.s. using 4 parameters.

Constraints

Corasaniti, Copeland and collaborators 03, 04

WMAP1+2dF+ SN (2004)



Could one get something similar for the variation of the mass??

Outline

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Goal: to verify, in a **model independent way**, if it is possible to constrain such models using cosmological implications of the variation of the neutrino mass.

- Variation starts when the trace of the neutrinos EM tensor is different from zero.
- smooth behavior
- nice for perturbations

Our approach

Parameterize "a la Corasaniti-Copeland" the varying mass of the neutrino

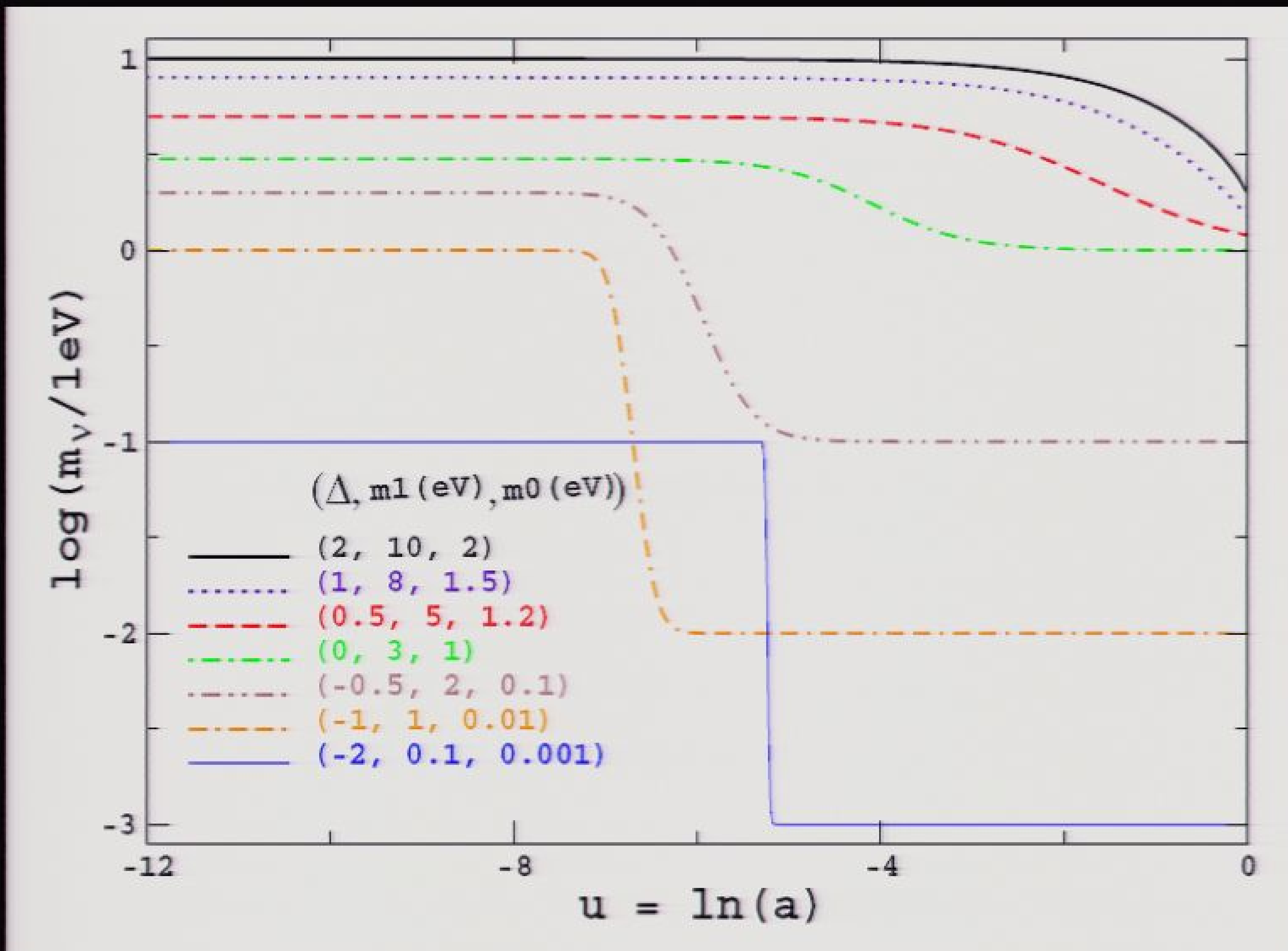
$$m_\nu = m_0 + (m_1 - m_0) \times \Gamma(u, u_{nr}, \Delta)$$

$$\Gamma(u, u_{nr}, \Delta) = \left[1 - \frac{1 + e^{u_{nr}/10^\Delta}}{1 + e^{-[u\ (1+10^\Delta) - u_{nr}]/10^\Delta}}\right]$$

$$u \equiv \ln(a)$$

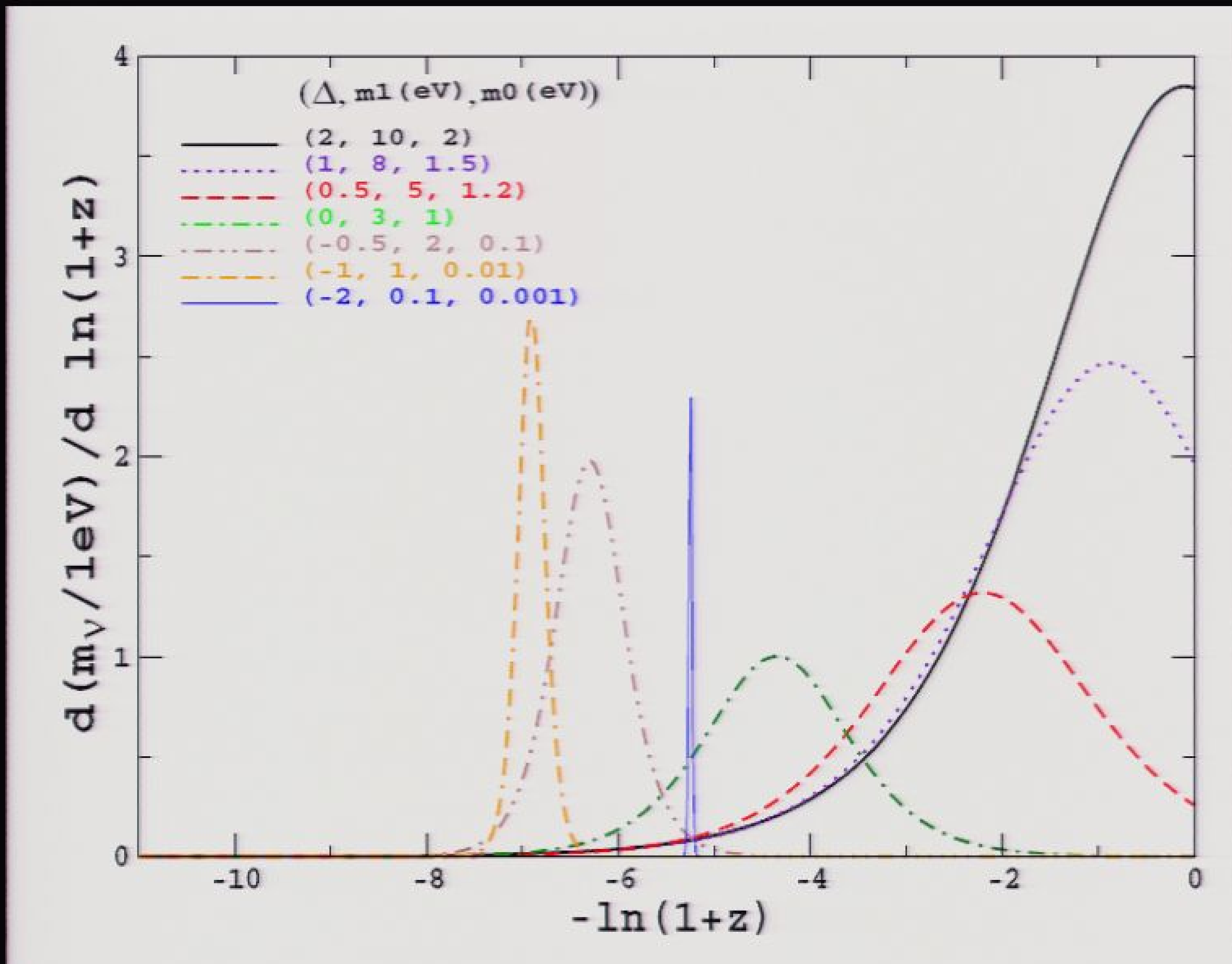
$$z_{nr} \approx \left(\frac{11}{4}\right)^{1/3} \left(\frac{1\ \mathrm{eV}}{3\, T_{\gamma 0}}\right) \left(\frac{m_1}{1\ \mathrm{eV}}\right) \approx 2 \times 10^3 \left(\frac{m_1}{1\ \mathrm{eV}}\right)$$

Weight loss



1
0
-1
-2
-3
-12
-8
-4
0
log(m_ν/1eV)
u = ln(a)
(Δ, m1(eV), m0(eV))
(2, 10, 2)
(1, 8, 1.5)
(0.5, 5, 1.2)
(0, 3, 1)
(-0.5, 2, 0.1)
(-1, 1, 0.01)
(-2, 0.1, 0.001)

Slow and fast mass variations



Perturbations

Ma, Bertschinger 95
Brookfield et al. 05, 06

For the neutrinos:

$$\beta \equiv \frac{d\ln m_\nu}{d\rho_\phi} = \frac{d\ln m_\nu}{d\ln a}\left(\frac{d\rho_\phi}{d\ln a}\right)^{-1}$$

$$\delta\rho_\nu = \frac{1}{a^4}\int q^2 dq\, d\Omega\, \epsilon f^0(q)\Psi + \delta\rho_\phi\, \beta\, (\rho_\nu - 3p_\nu)$$

$$\delta p_\nu = \frac{1}{3a^4}\int q^2 dq\, d\Omega\, f^0(q)\left(\frac{q^2}{\epsilon}\Psi - \delta\rho_\phi\, \beta\, \frac{q^2 m_\nu^2 a^2}{\epsilon^3}\right)$$

Perturbations

Hu 98
Weller, Lewis 03
Bean, Doré 04
Hannestad 05

For the DE (as a fluid, not SF):

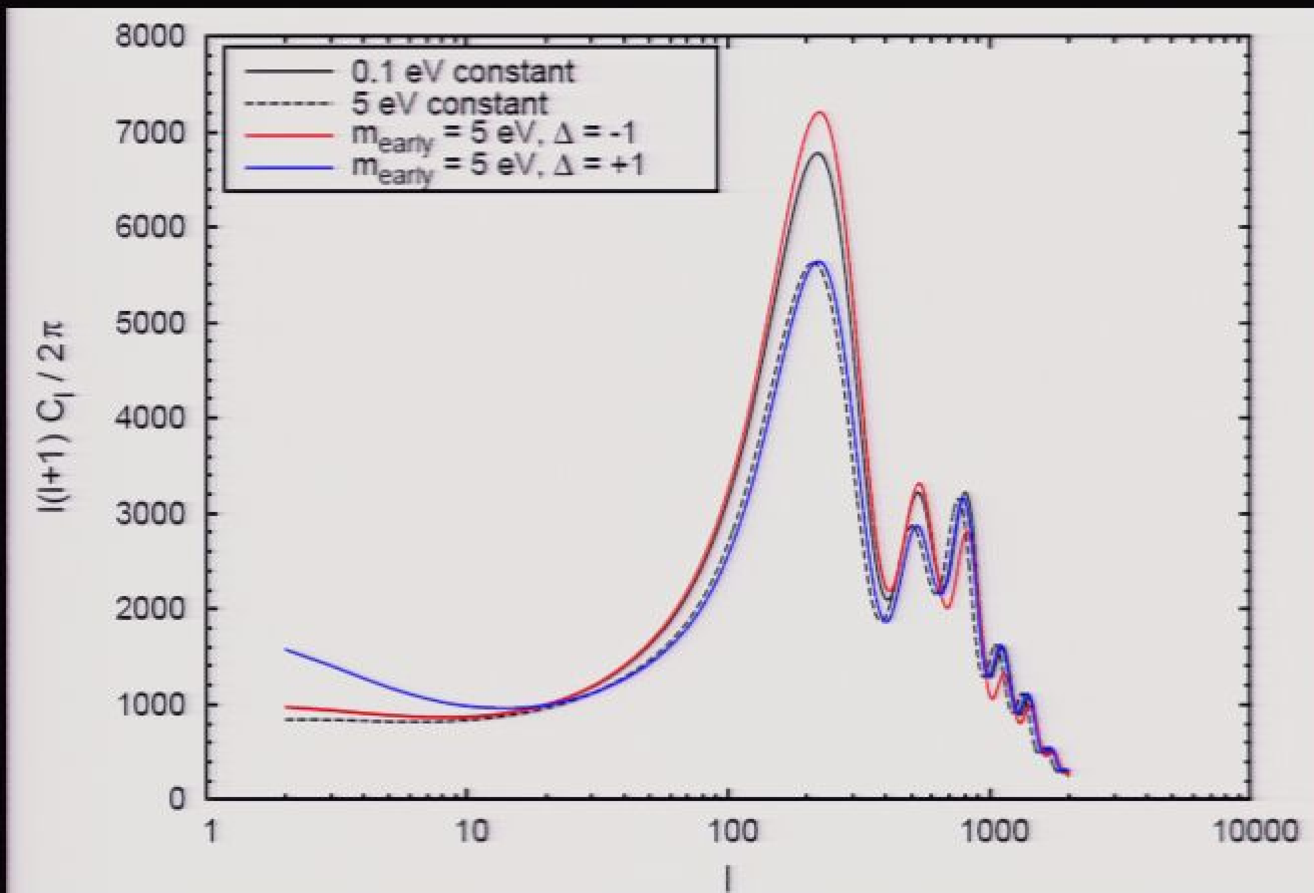
$$\beta \equiv \frac{d\ln m_\nu}{d\rho_\phi} = \frac{d\ln m_\nu}{d\ln a}\left(\frac{d\rho_\phi}{d\ln a}\right)^{-1}$$

$$c_a^2 = \omega_\phi - \frac{1}{3H}\frac{\dot\omega_\phi}{1+\omega_\phi}$$

$$\begin{aligned}\dot\delta_\phi\left[1+\beta(1-3\omega_\nu)\rho_\phi\right] = &- (1+\omega_\phi)\left[k^2+9H^2\left(1-\omega_\phi+\frac{1}{3H}\frac{\dot\omega_\phi}{1+\omega_\phi}\right)\right]\frac{\theta_\phi}{k^2} - 3H(1-\omega_\phi)\delta_\phi \\ &- \frac{\beta\dot\rho_\phi}{3H}\left(\frac{\dot\omega_\nu}{1+\omega_\nu}\right)\delta_\nu - (1-3\omega_\nu)\dot\rho_\phi\left(\beta+\frac{d\beta}{d\rho_\phi}\rho_\phi\right)\delta_\phi\,,\end{aligned}$$

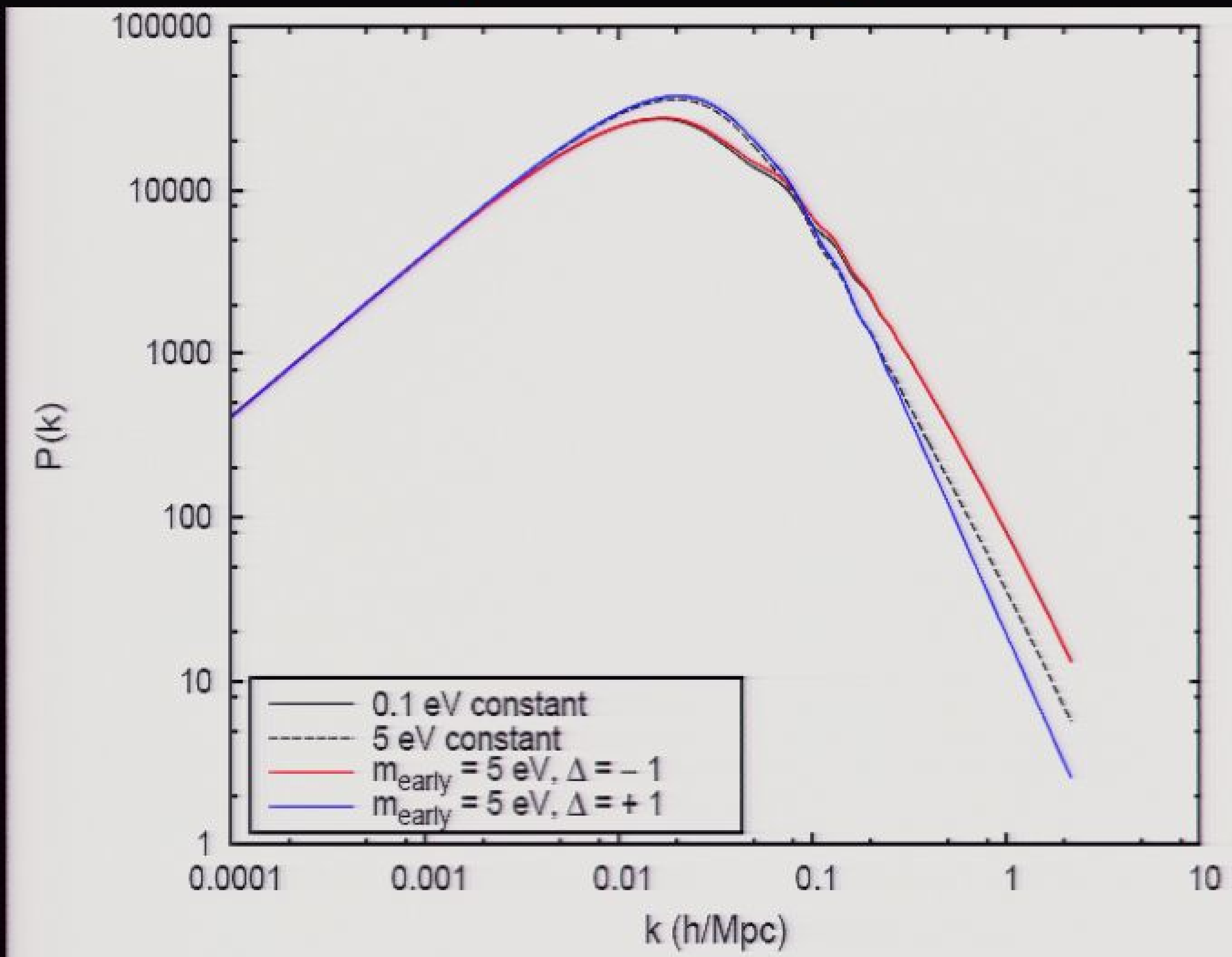
$$\begin{aligned}\dot\theta_\phi = &- H(1-3\omega_\phi)\theta_\phi - \left(\frac{\dot\omega_\phi}{1+\omega_\phi}\right)\theta_\phi + \left(\omega_\phi - \frac{1}{3H}\frac{\dot\omega_\phi}{1+\omega_\phi}\right)\frac{1}{1+\omega_\phi}k^2\delta_\phi \\ &- \beta\left(\frac{1-3\omega_\nu}{1+\omega_\nu}\right)k^2\rho_\phi\delta_\phi + \beta(1-3\omega_\nu)\dot\rho_\phi\theta_\phi\,,\end{aligned}$$

CMB spectra



0.1 eV constant
5 eV constant
m_early = 5 eV, Δ = -1
m_early = 5 eV, Δ = +1
l(l+1) C_l / 2π
l

Matter power spectra



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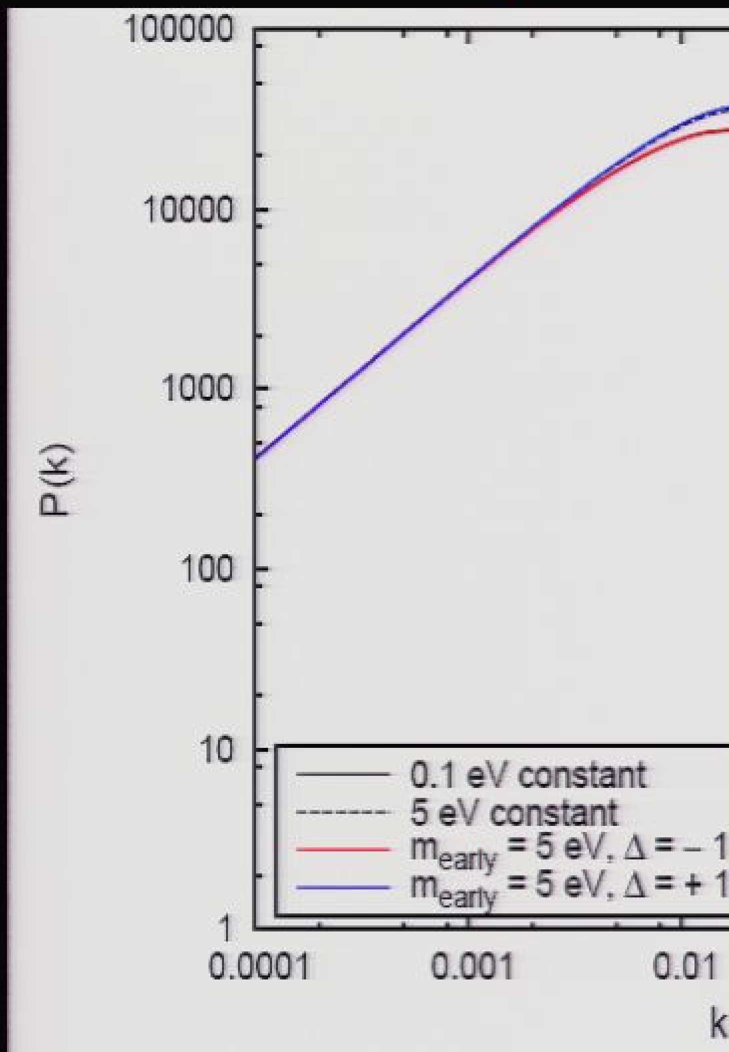
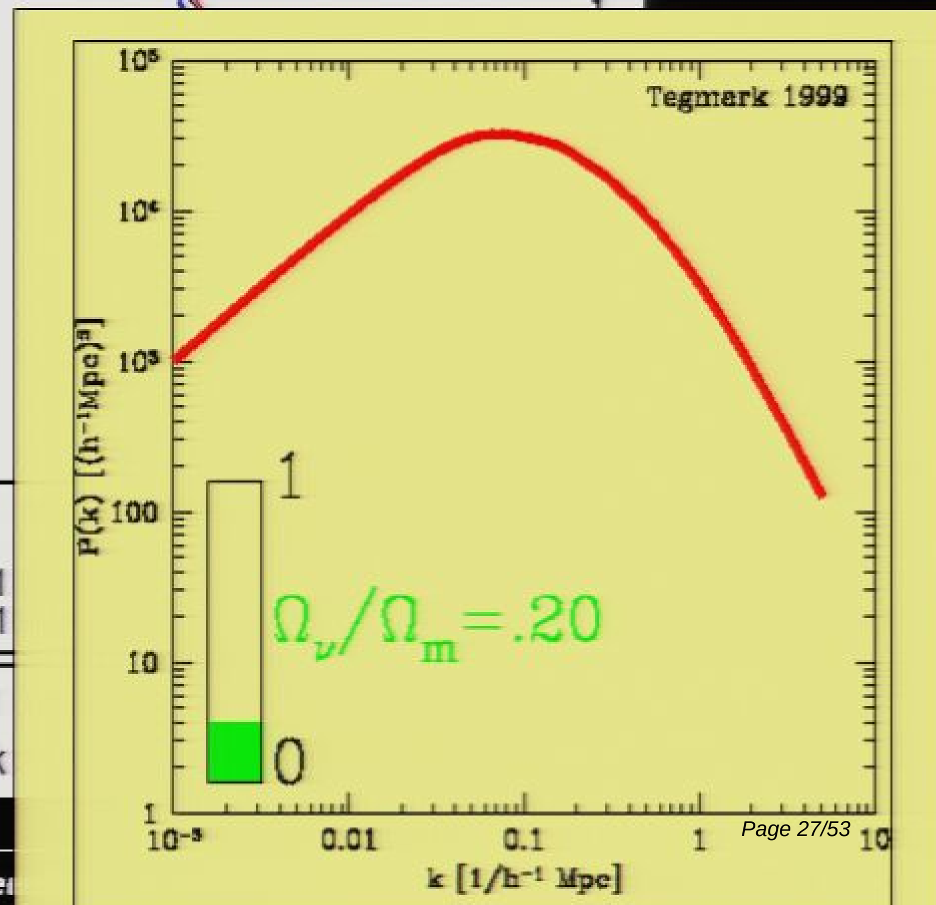
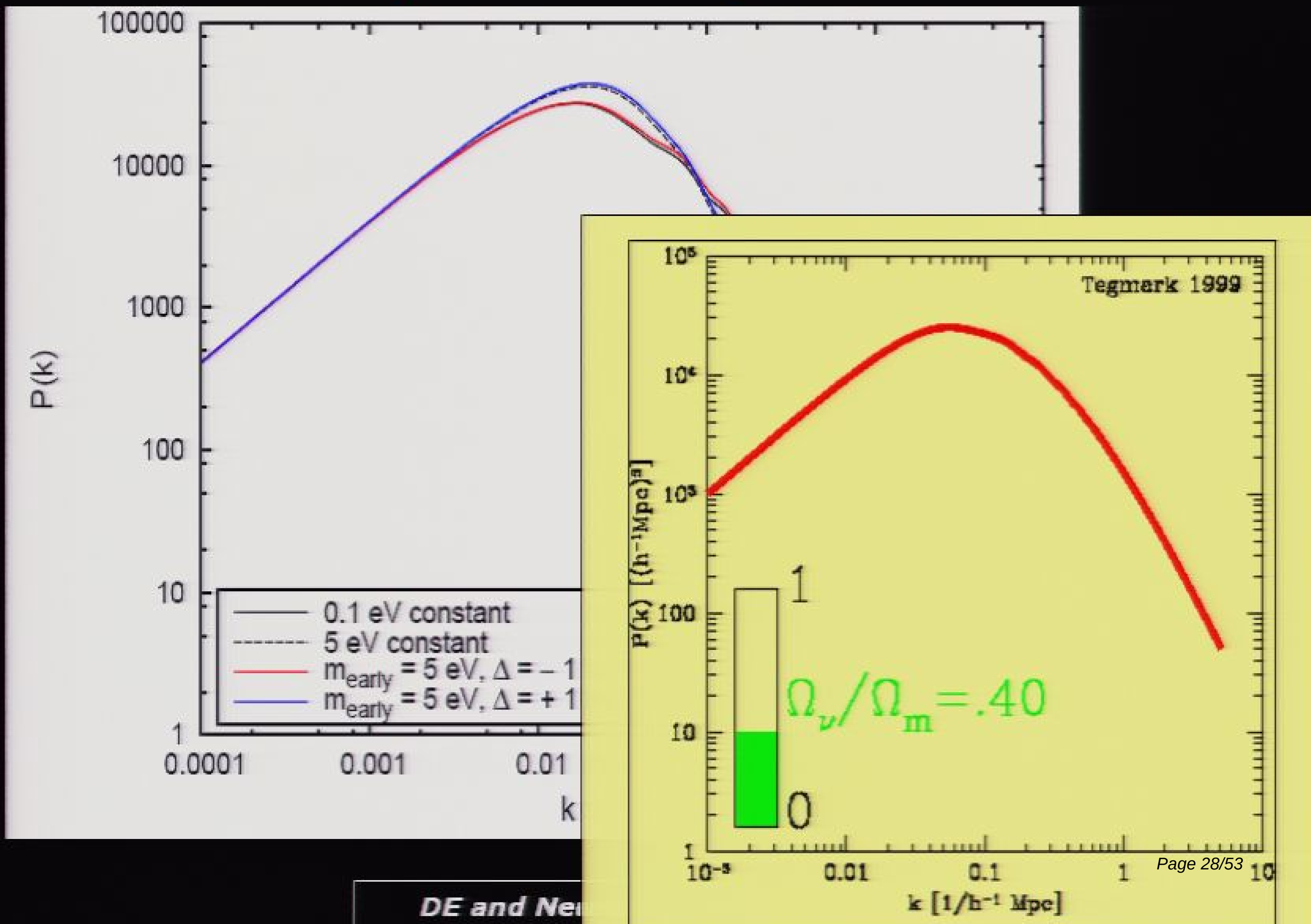




DE and Ne

Matter power spectra



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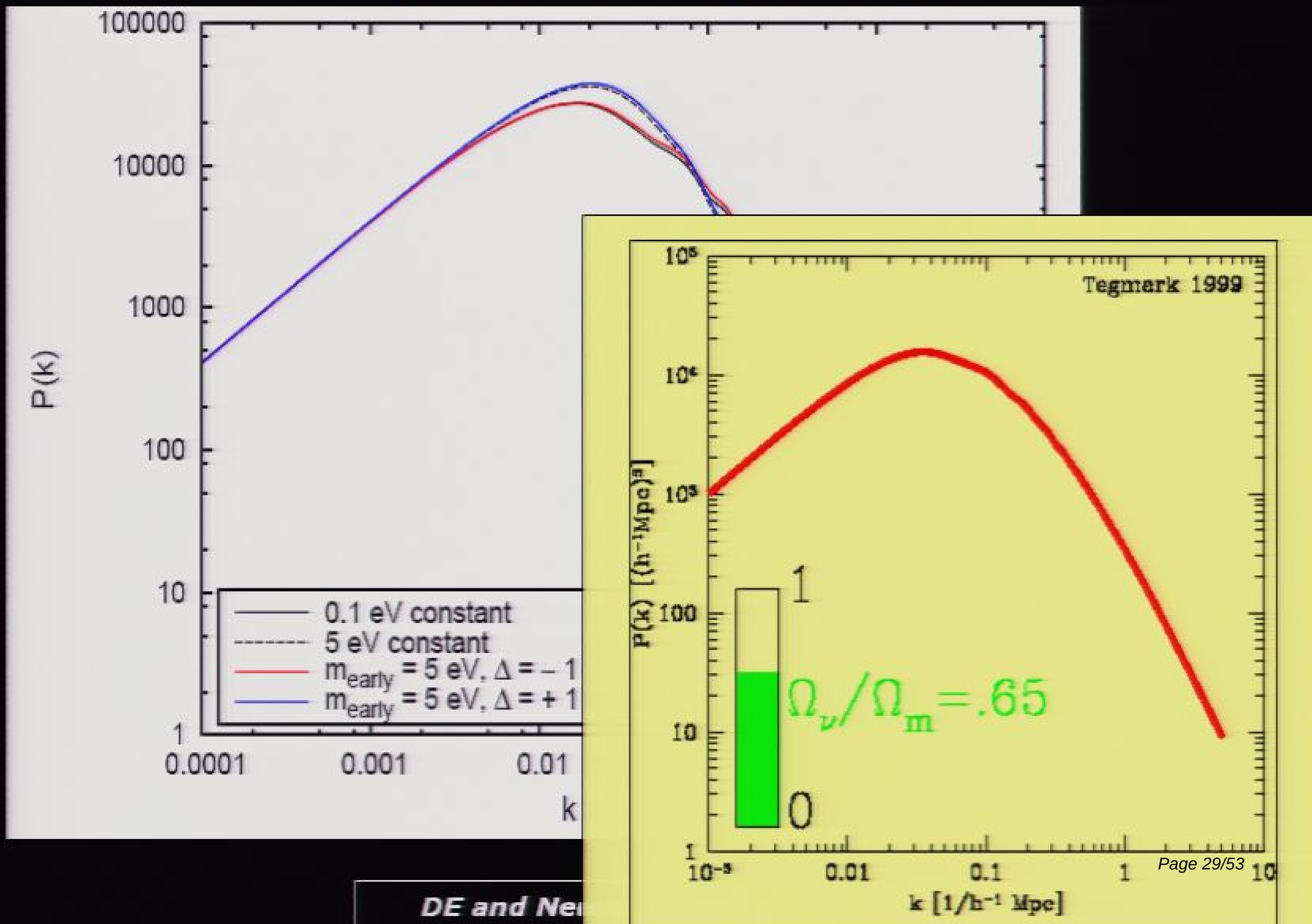

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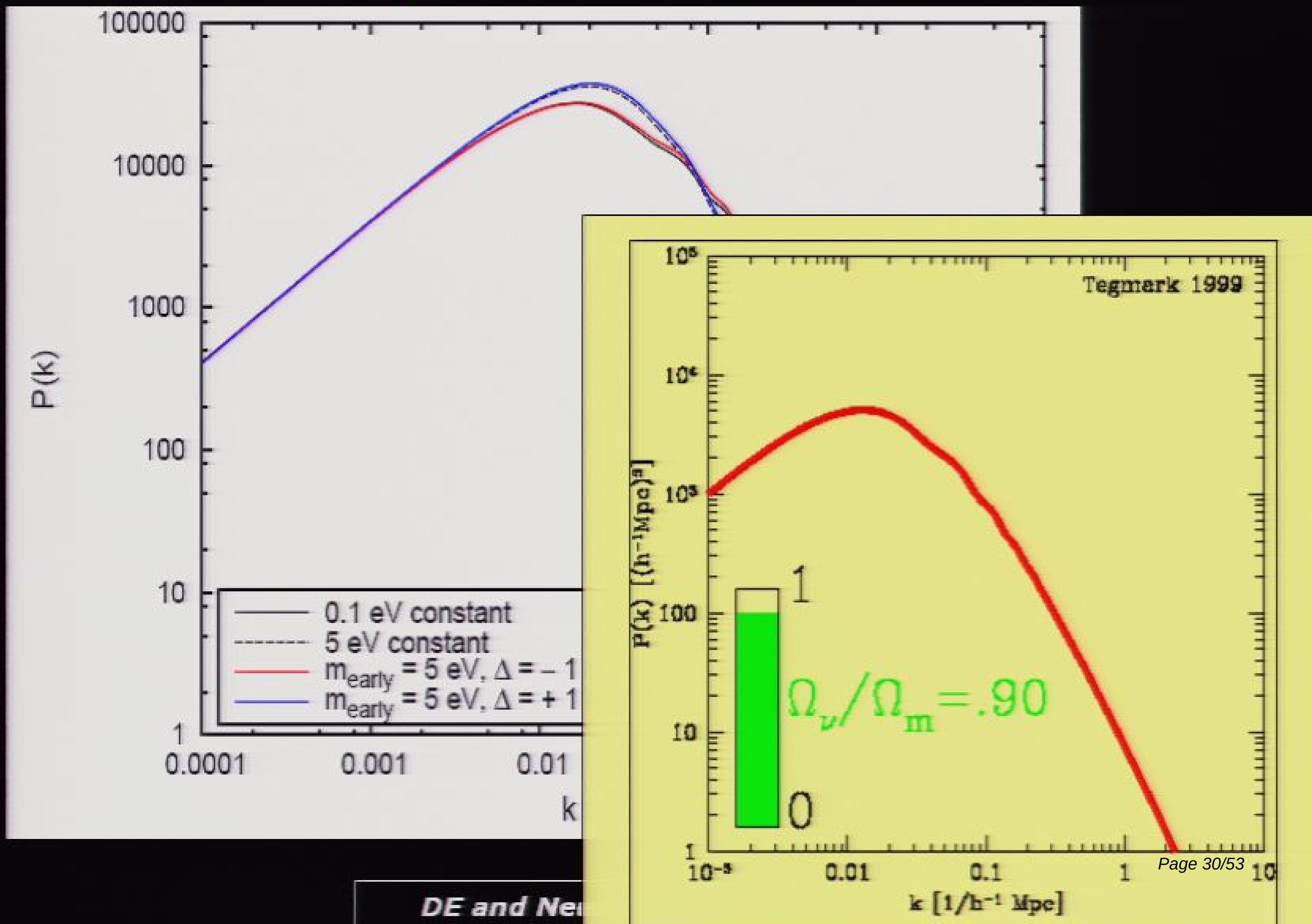
Matter power spectra



DE and Ne

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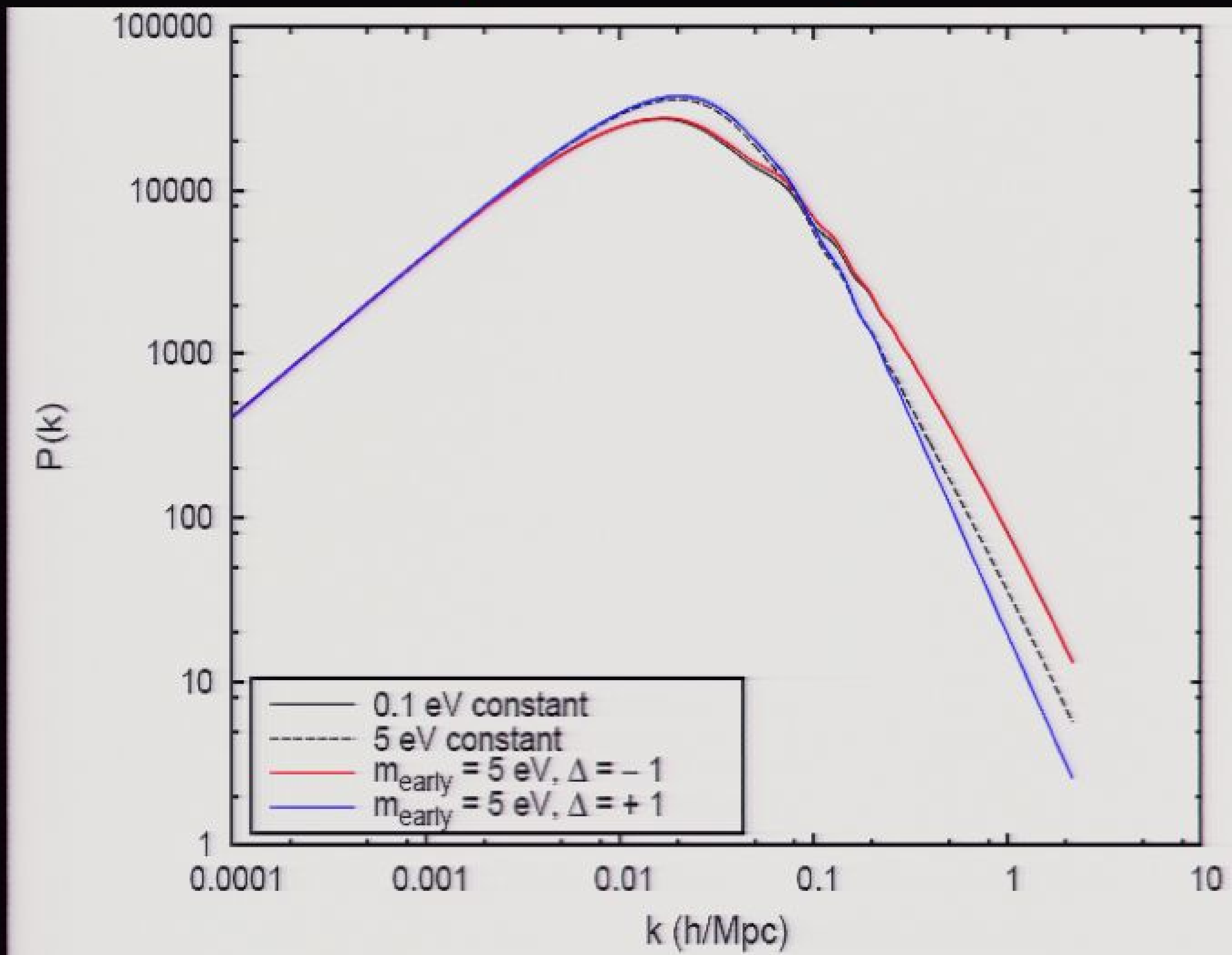

Outline

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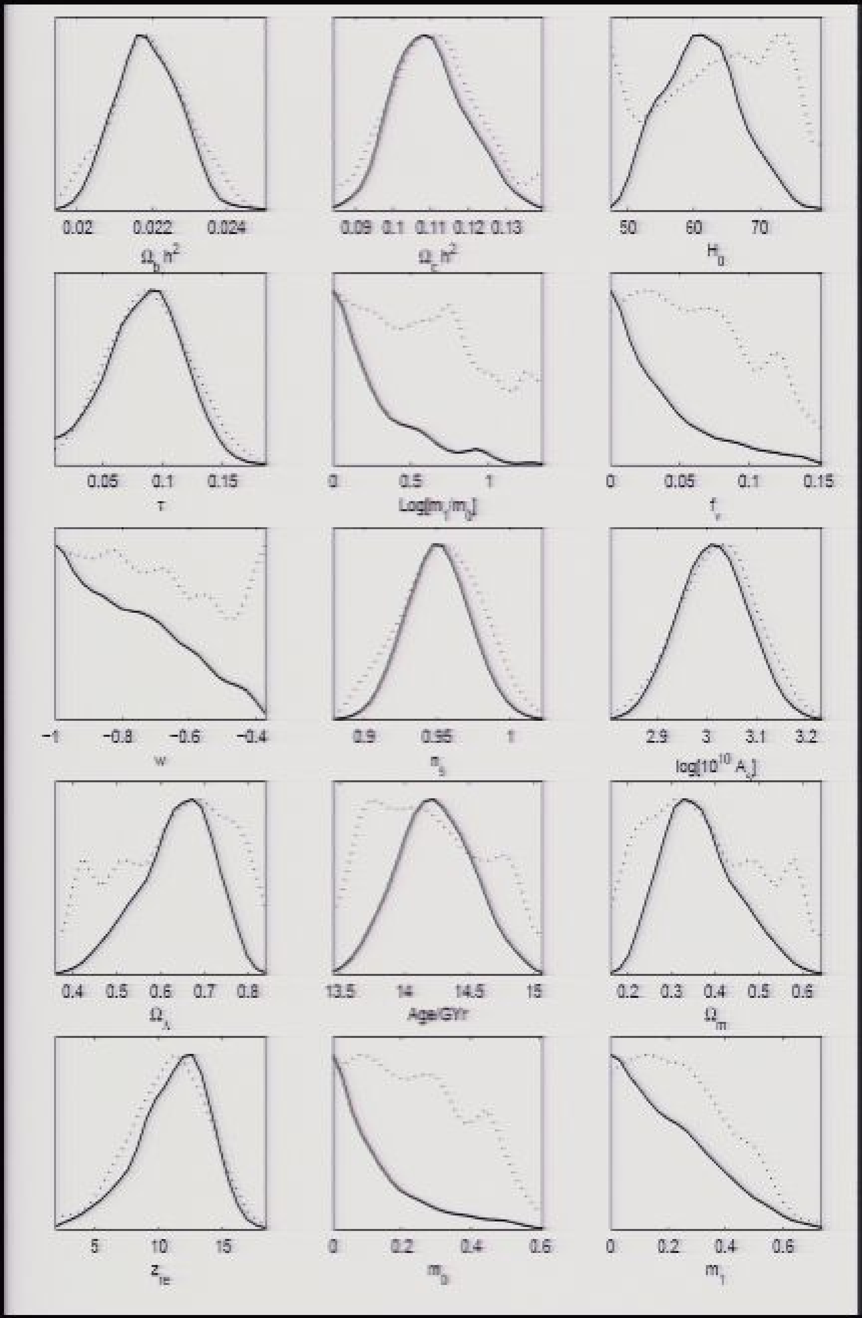
III. Model

IV. (Preliminary) Results

V. Conclusions

Recipe for a MCMC

1. $\Omega_{b0}\ h^2$
2. $\Omega_{dm0}\ h^2$
3. h
4. τ
5. ns
6. σ_8
7. **w -> const** (no free lunch...)
8. **f_ν**
9. **$Log(m_1/m_0)$**



Get everything together…

Fiducial cosmological model:

$(\Omega_b h^2,\ \Omega_m h^2,\ h\ ,\ n_s\ ,\ \sigma 8,\ \tau,\ w,\ f\nu,\ m1)$

Get everything together…

Fiducial cosmological model:
($\Omega_b h^2$, $\Omega_m h^2$, h, n_s, $\sigma 8$, τ, w, $f\nu$, $m1$)

Get everything together…

Fiducial cosmological model:

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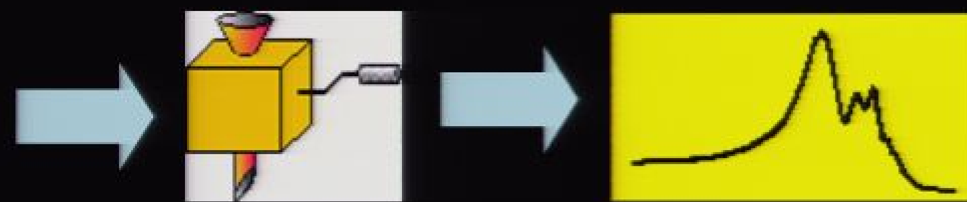
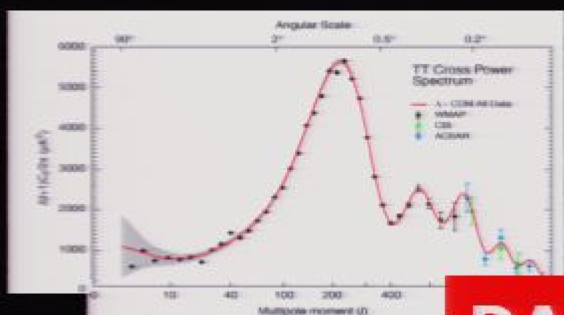
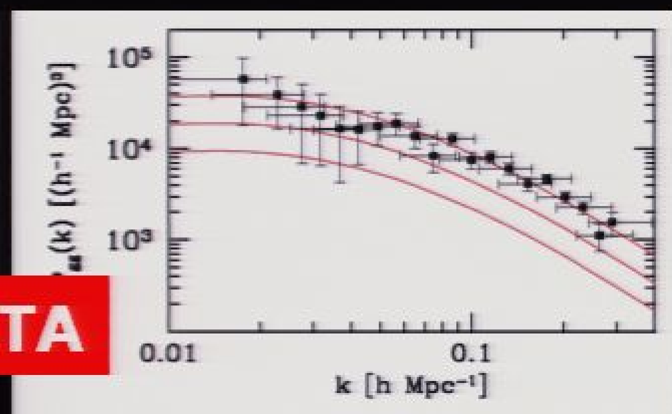


Get everything together…

Fiducial cosmological model:
($\Omega_b h^2$, $\Omega_m h^2$, h , n_s , σ8, τ, w, $f\nu$, m1)





DATA

Get everything together…

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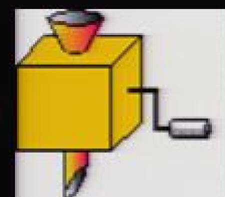
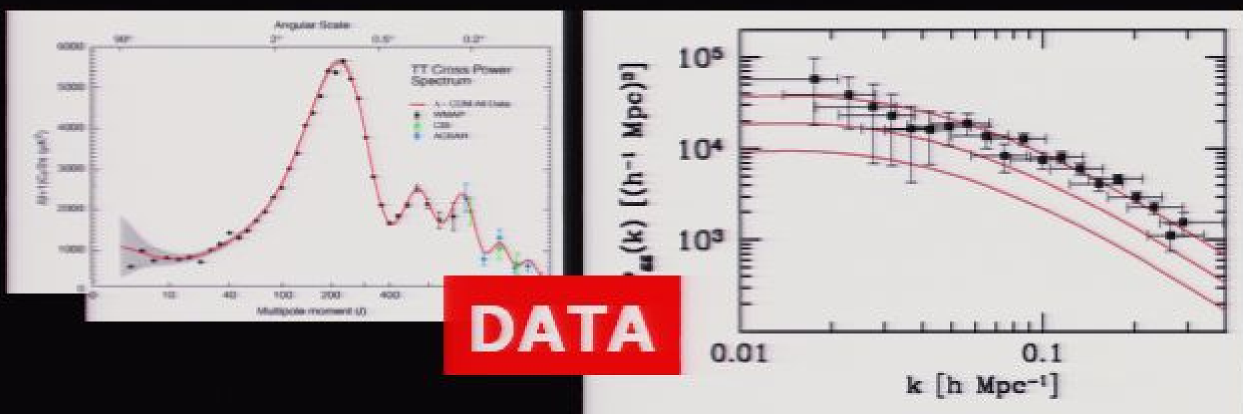
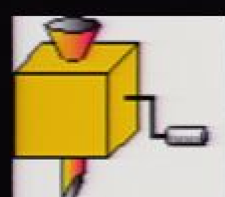
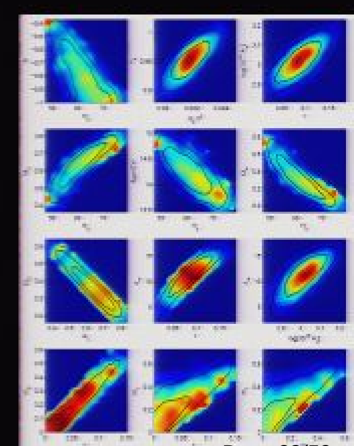




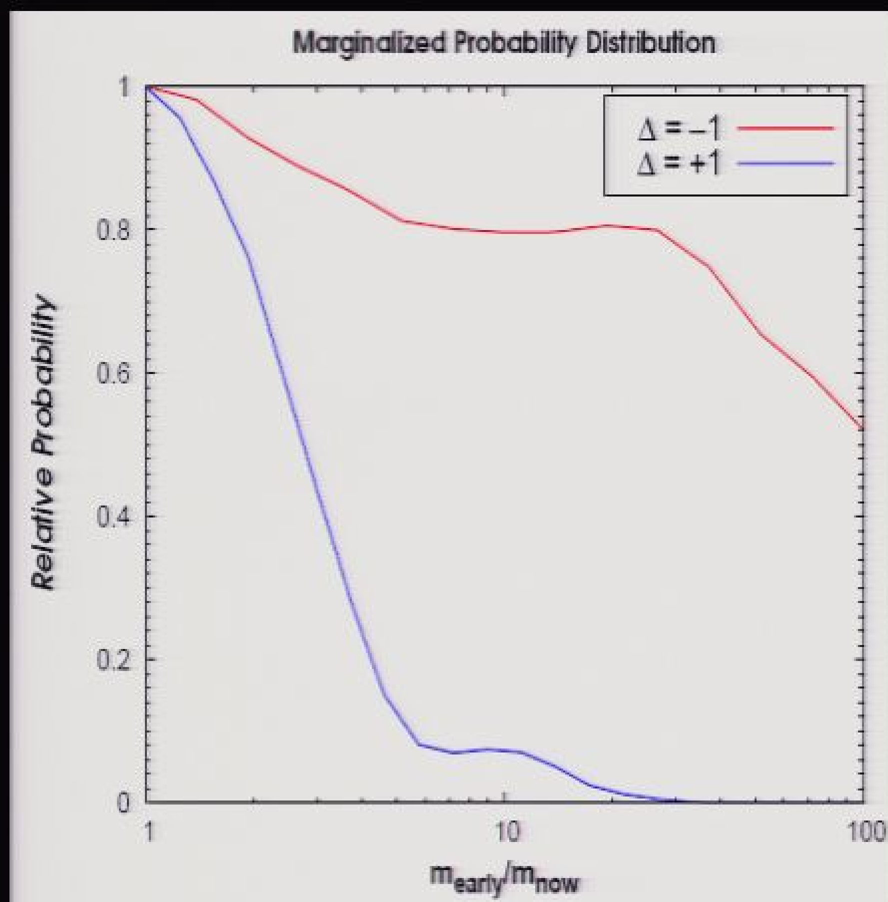




How varying the mass can be??

UF, M. Lattanzi, J. Lesgourgues & S. Pastor
(Coming soon to an arXiv server near you!!)

Preliminary results



WMAP(+ small scales)
+ HST + SNLS

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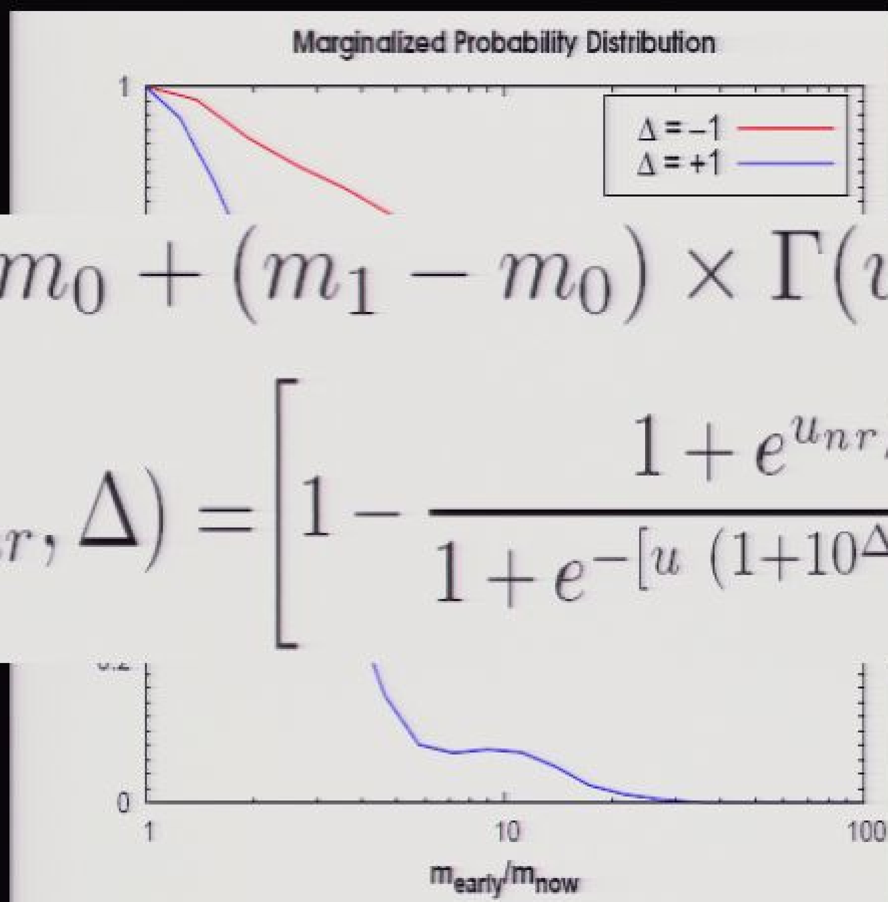

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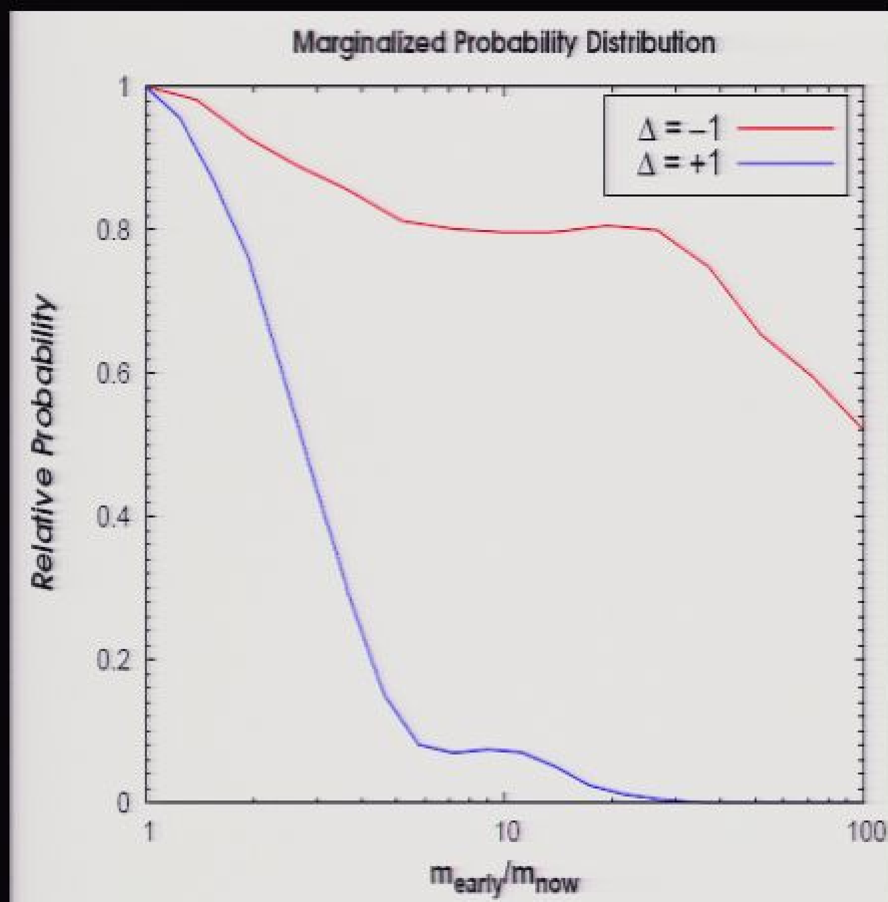

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Preliminary results

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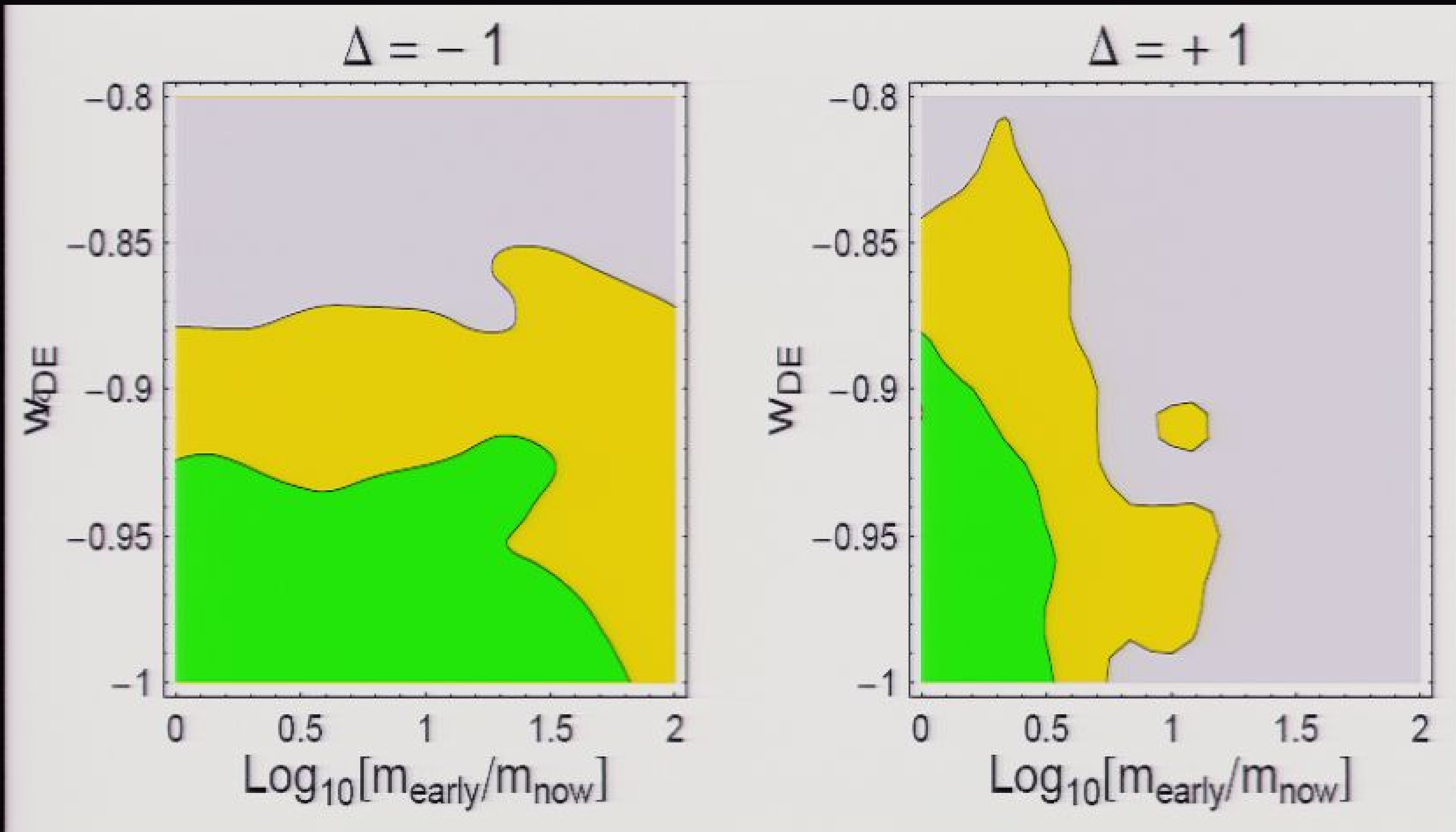
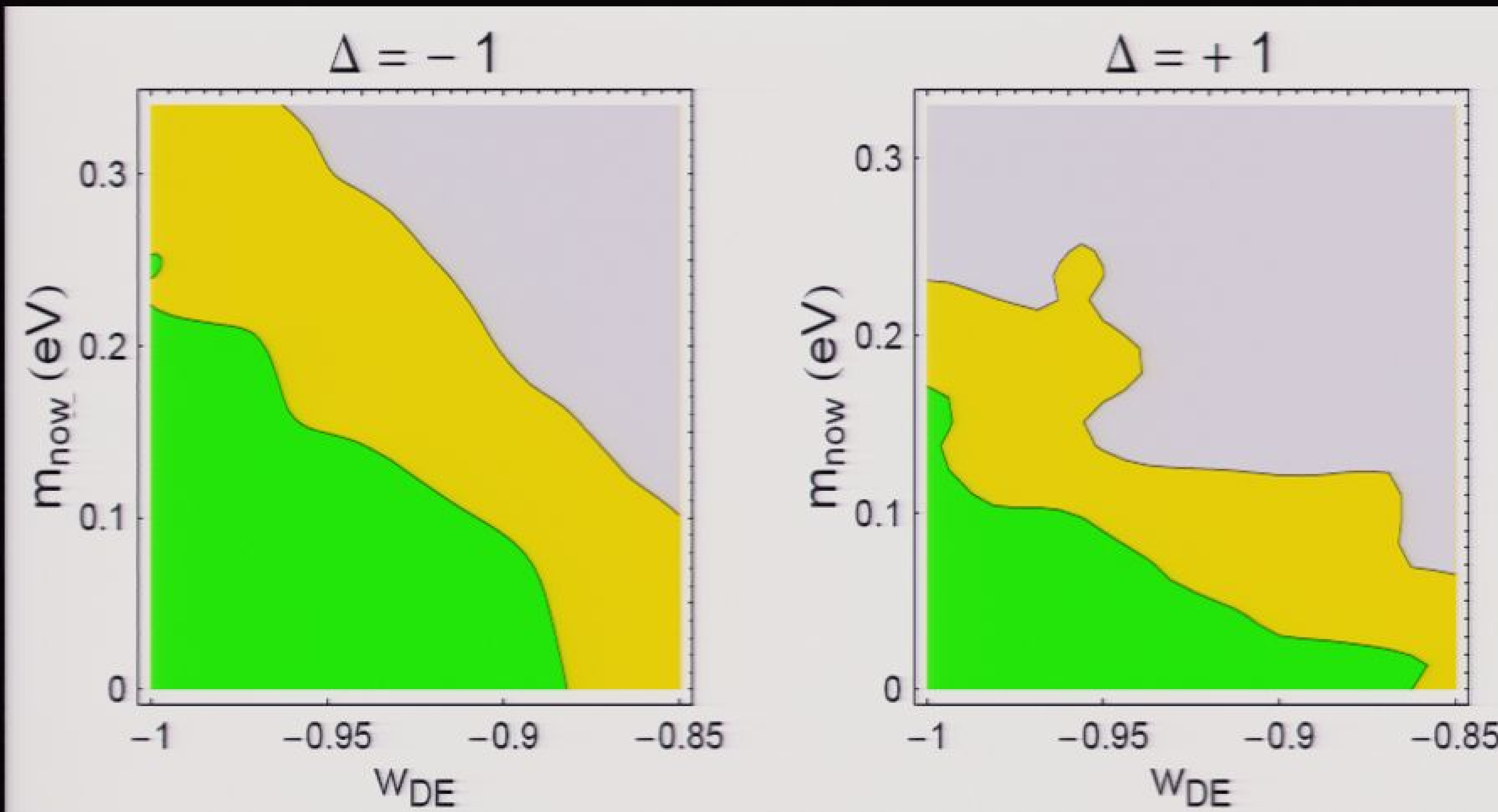


Late mass changes well constrained, but early ones not.

DE and Neutrino Mass – Urbano França – 05/18/2007

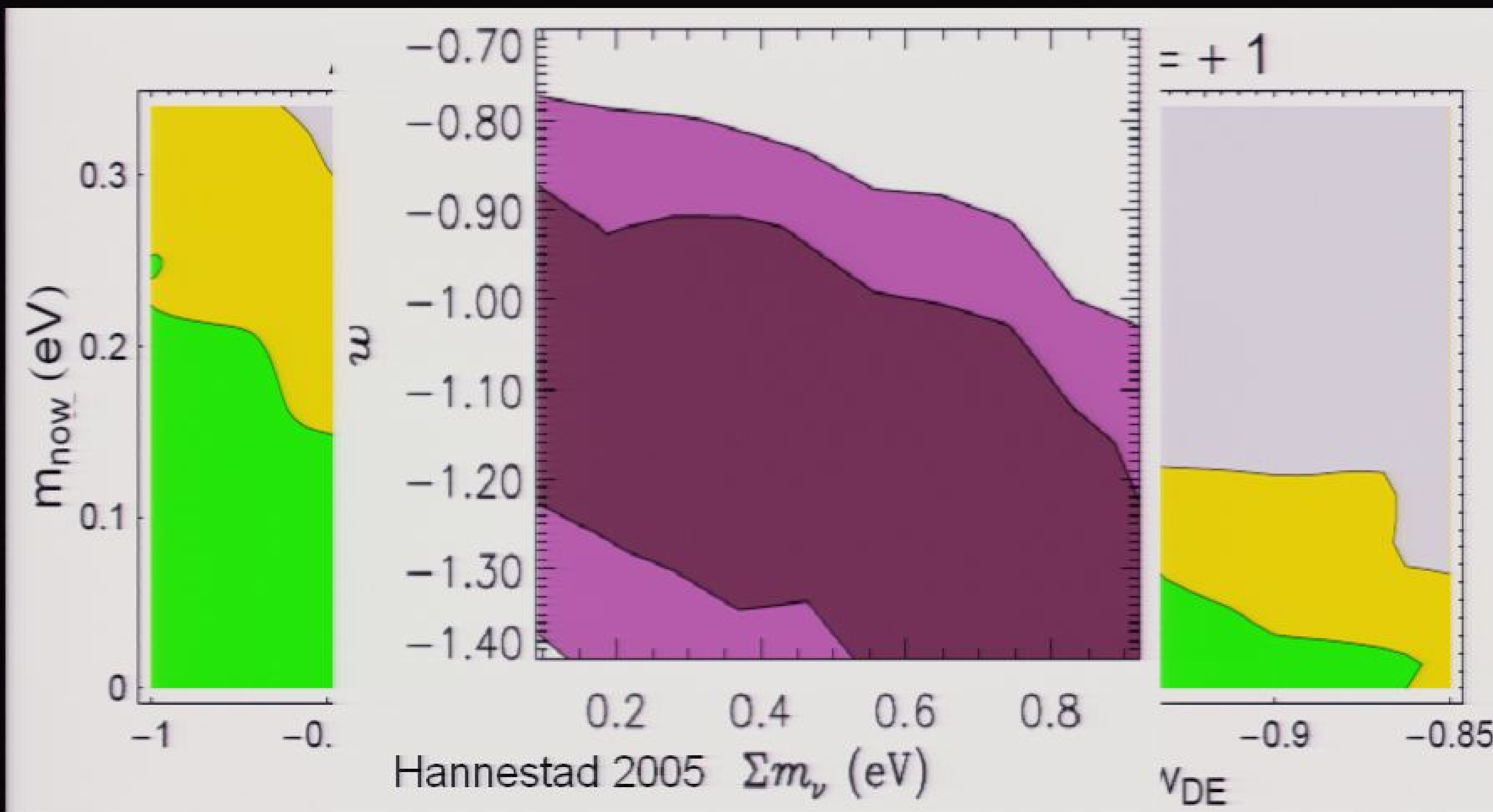
Old and new correlations

WMAP(+ small scales)+ HST + SNLS



Old and new correlations

WMAP(+ small scales)+ HST + SNLS



DE and Neutrino Mass – Urbano França – 05/18/2007

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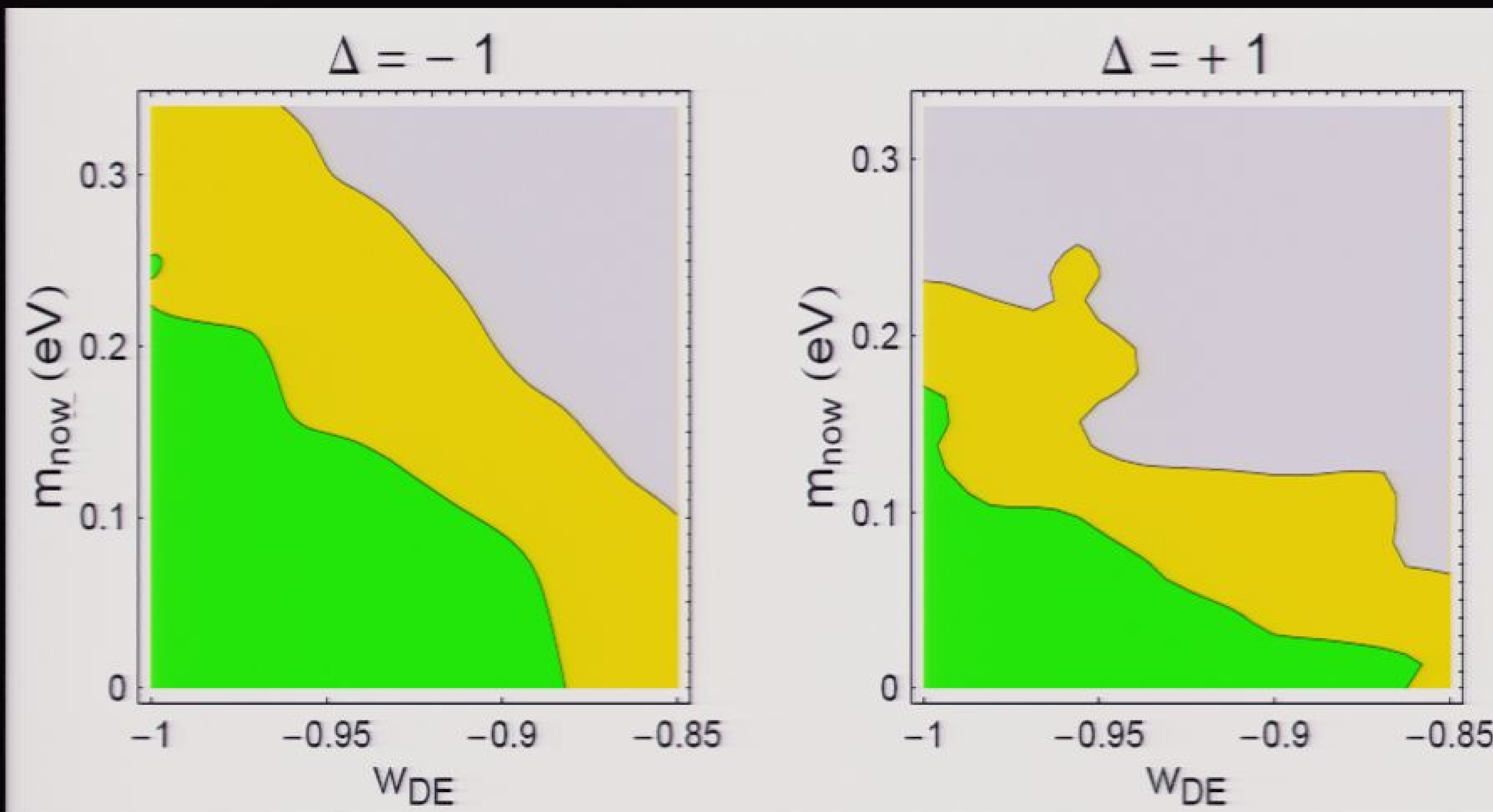

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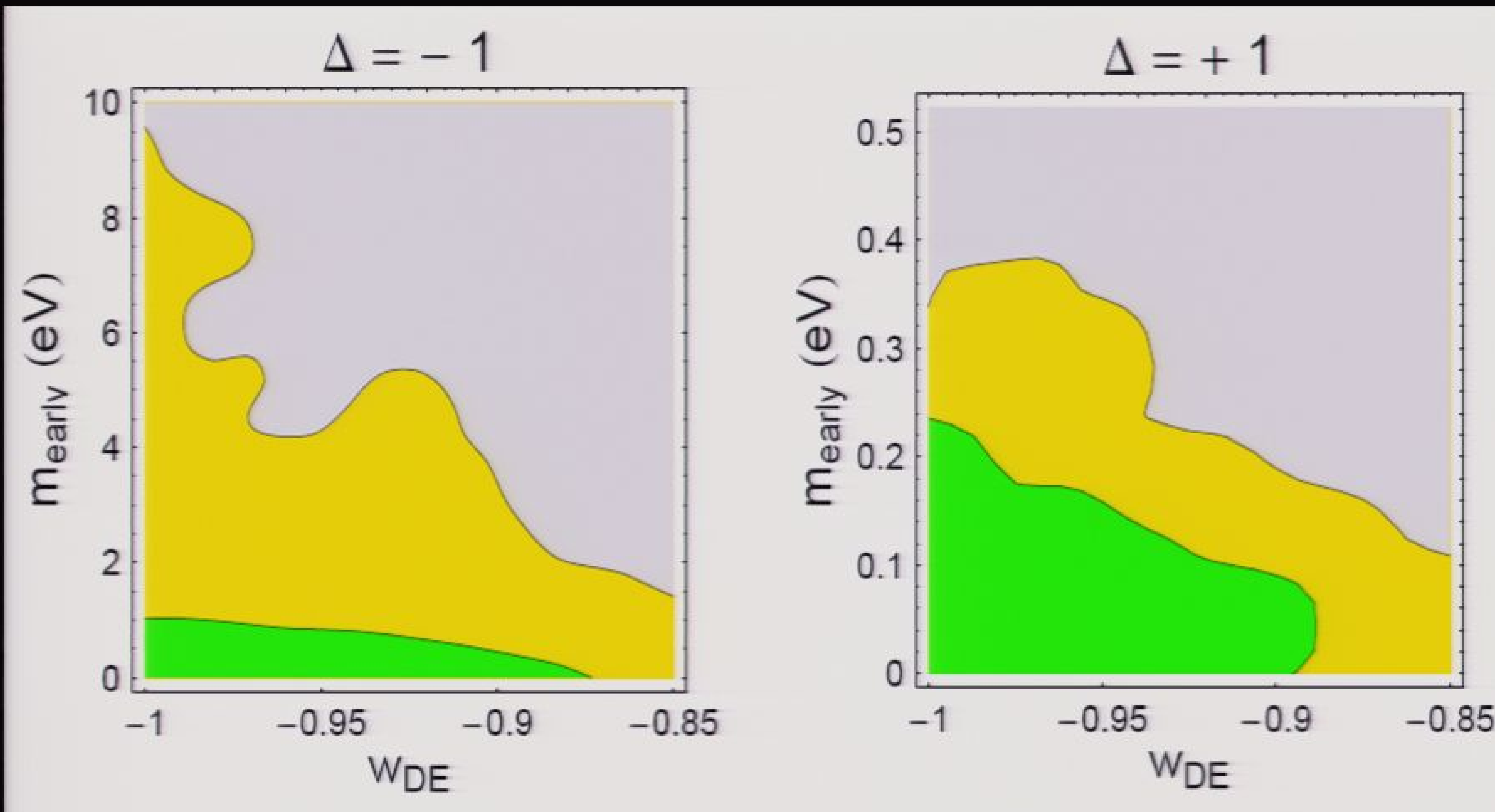
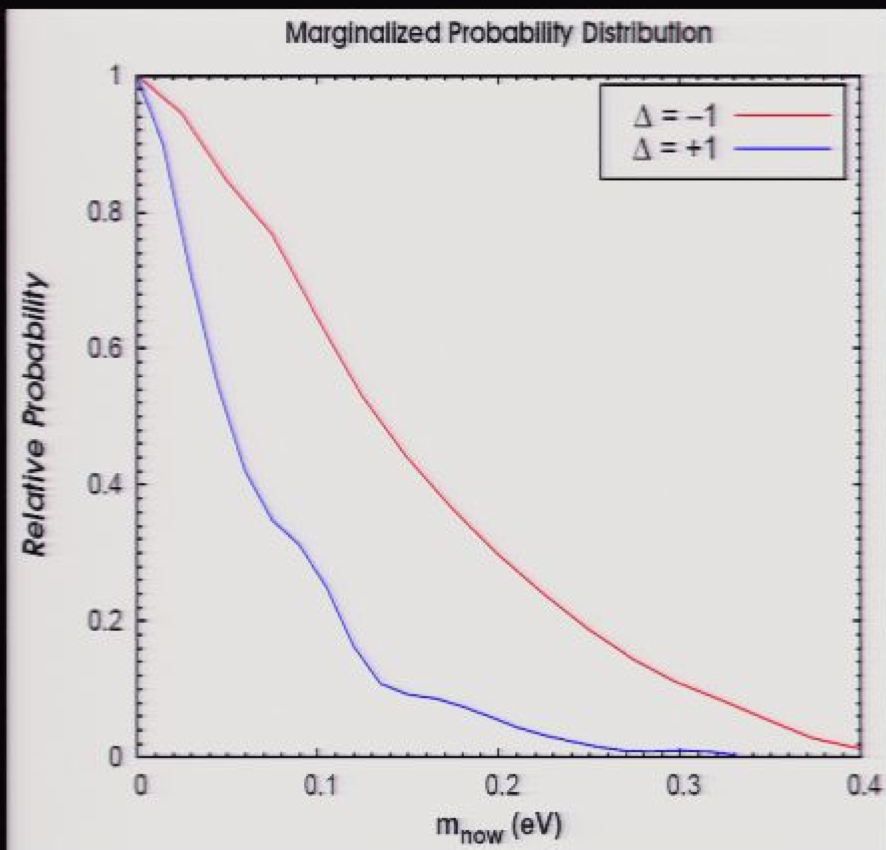
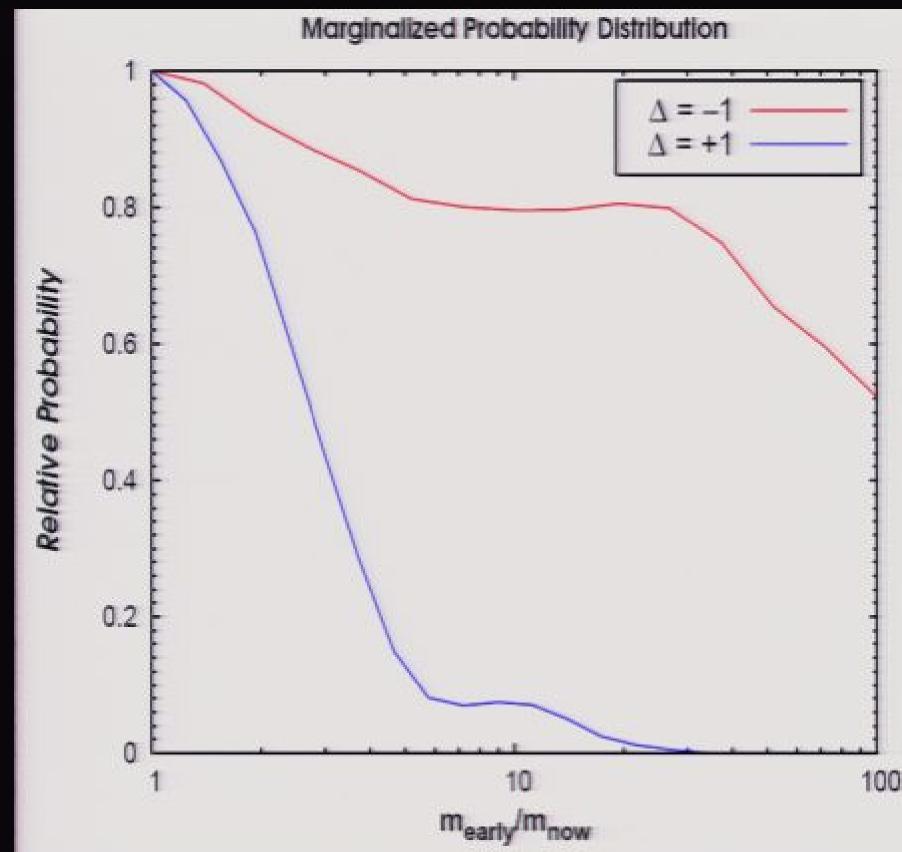


Preliminary results

WMAP(+ small scales)+ HST + SNLS





Early mass variations very poorly constrained.

Present and future

- Full MCMC calculation
- Goal: obtain a "region" for m(z)
- Find the most sensitive z for mass variations
- Bonus Q: can the same be done to DM? Worth?

Summary

- MaVaN's models are somehow attractive, since they can provide a nice framework to "explain" some features (fine-tunings) needed for DE models.
- In this work, we parameterized the mass variation of the neutrino aiming to derive constraints on it, instead of using DE e.o.s only.
- Our preliminary results show that while recent mass variations can be well constrained by the data, "early" (=fast) large mass variations are completely in agreement with the data.
- More on that coming soon!

Dark Energy and Neutrino Mass

Urbano França
Astroparticle and High Energy Physics Group
Instituto de Física Corpuscular

with
Massimiliano Lattanzi (Oxford)
Julien Lesgourgues (LAPTH- Annecy)
Sergio Pastor (AHEP-IFIC)

AHEP
Astroparticle and High Energy Physics Group

IFIC
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VNIVERSITAT DE VALÈNCIA

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ORIGINS OF DARK ENERGY

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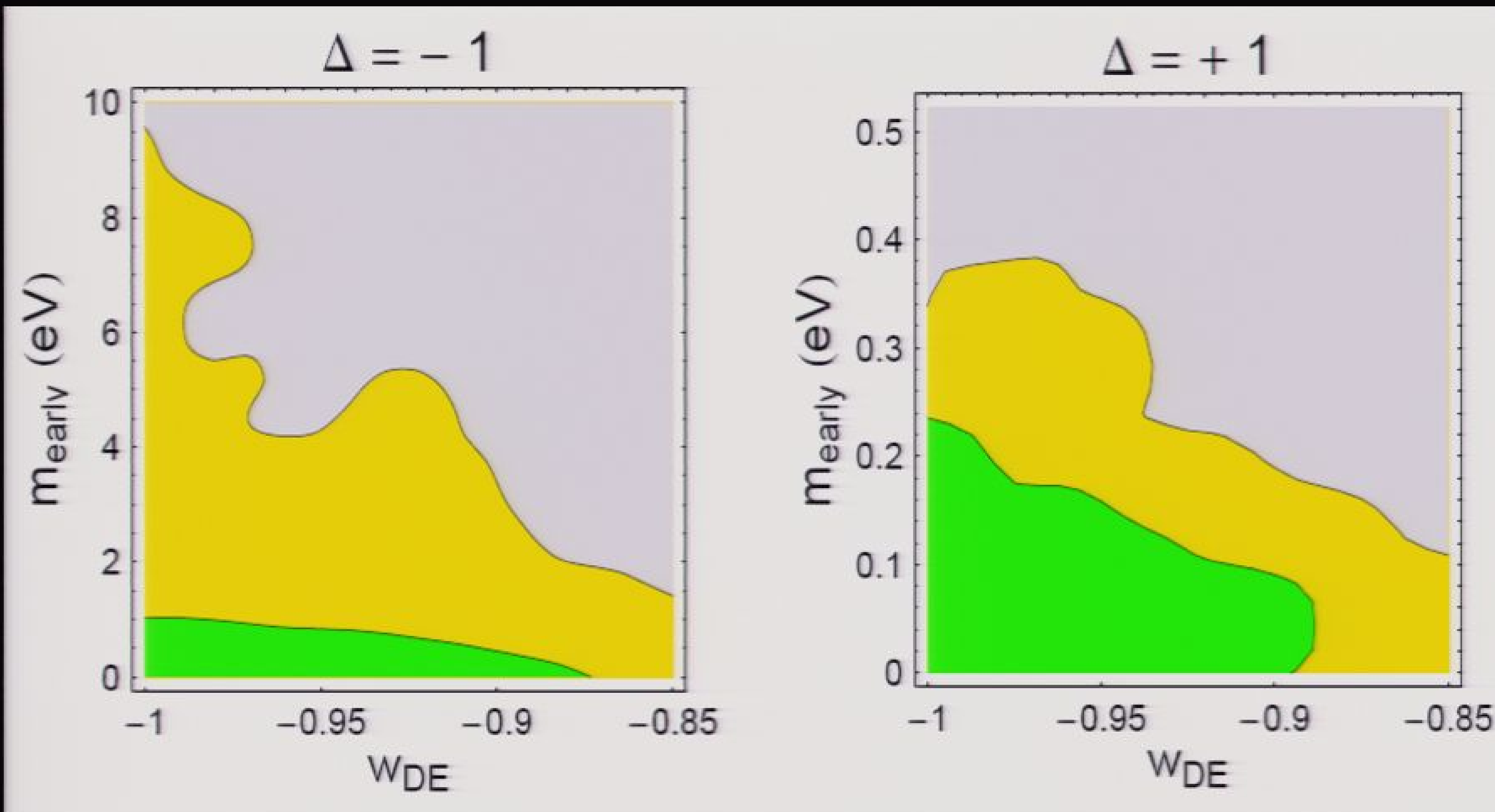
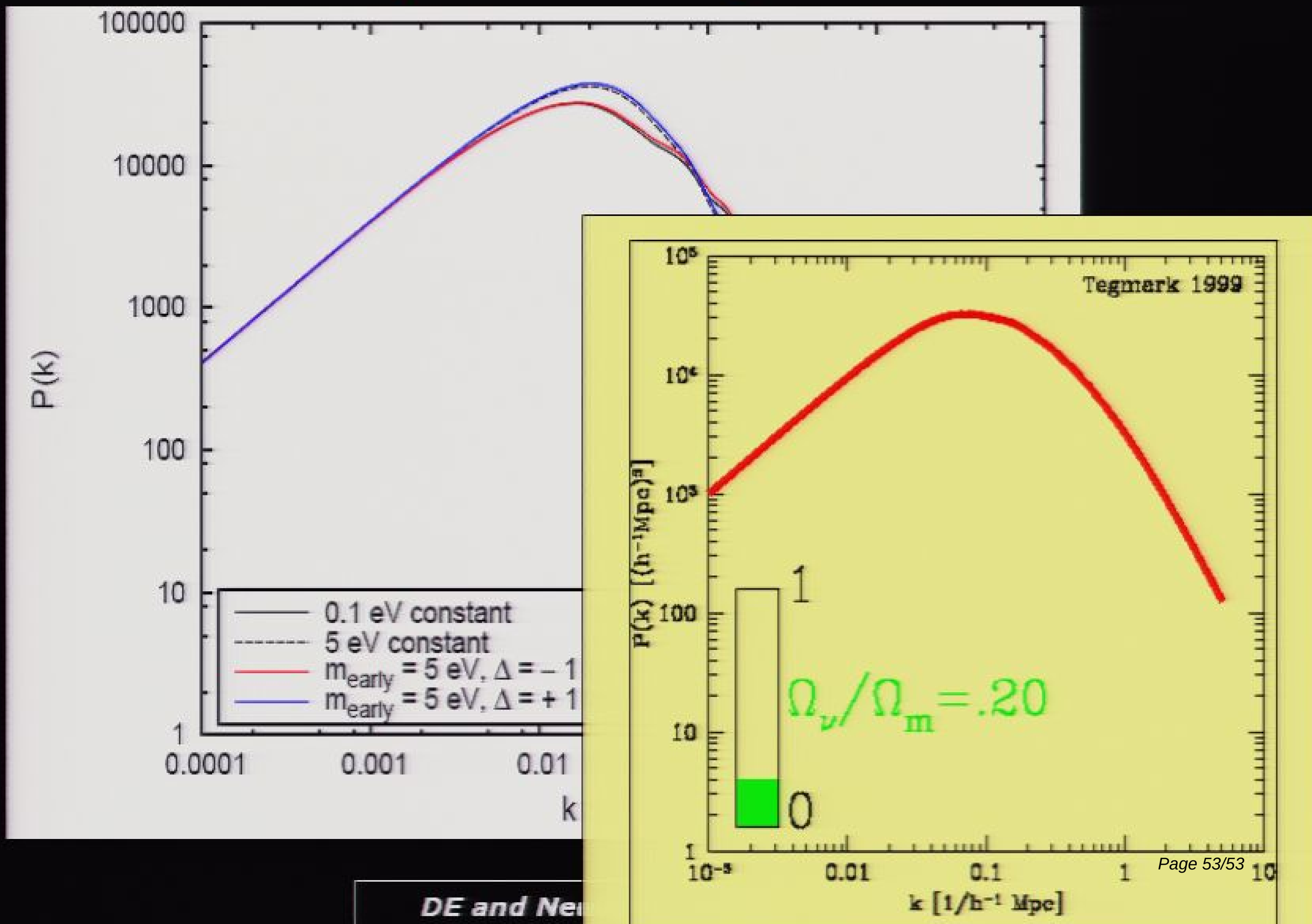


Matter power spectra



DE and Ne