Dark Matter and Dark Energy interaction models

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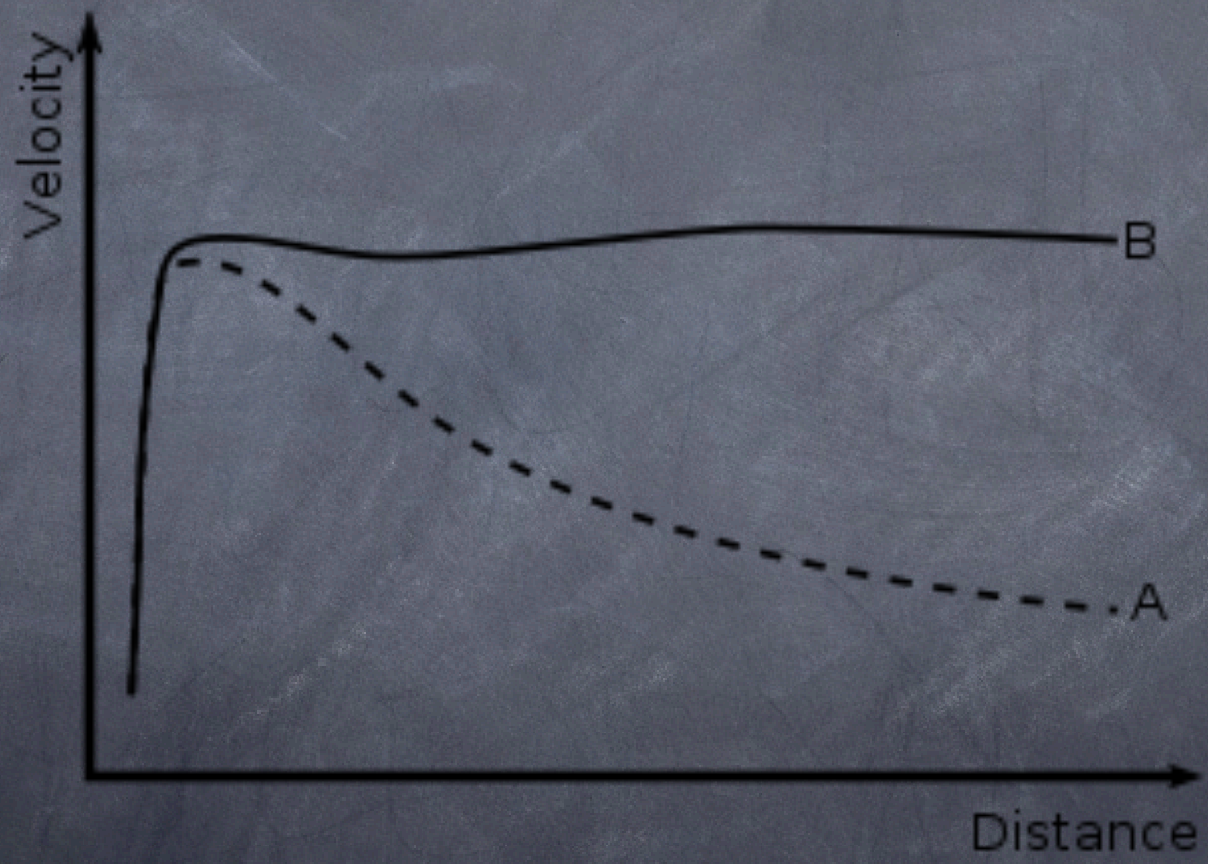
Dark Matter

- Since Zwicky (in the thirties Coma Cluster)

$$\boxed{V^2 = \frac{GM}{R}}$$

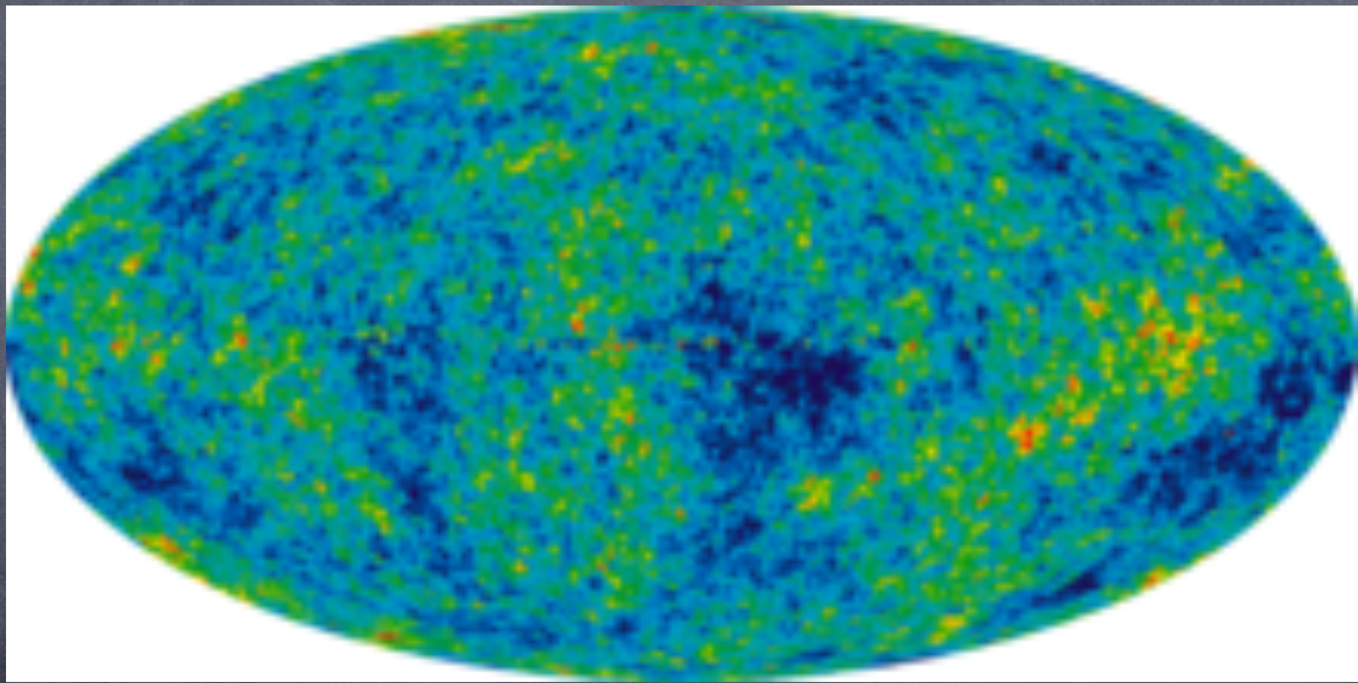
Dark Matter



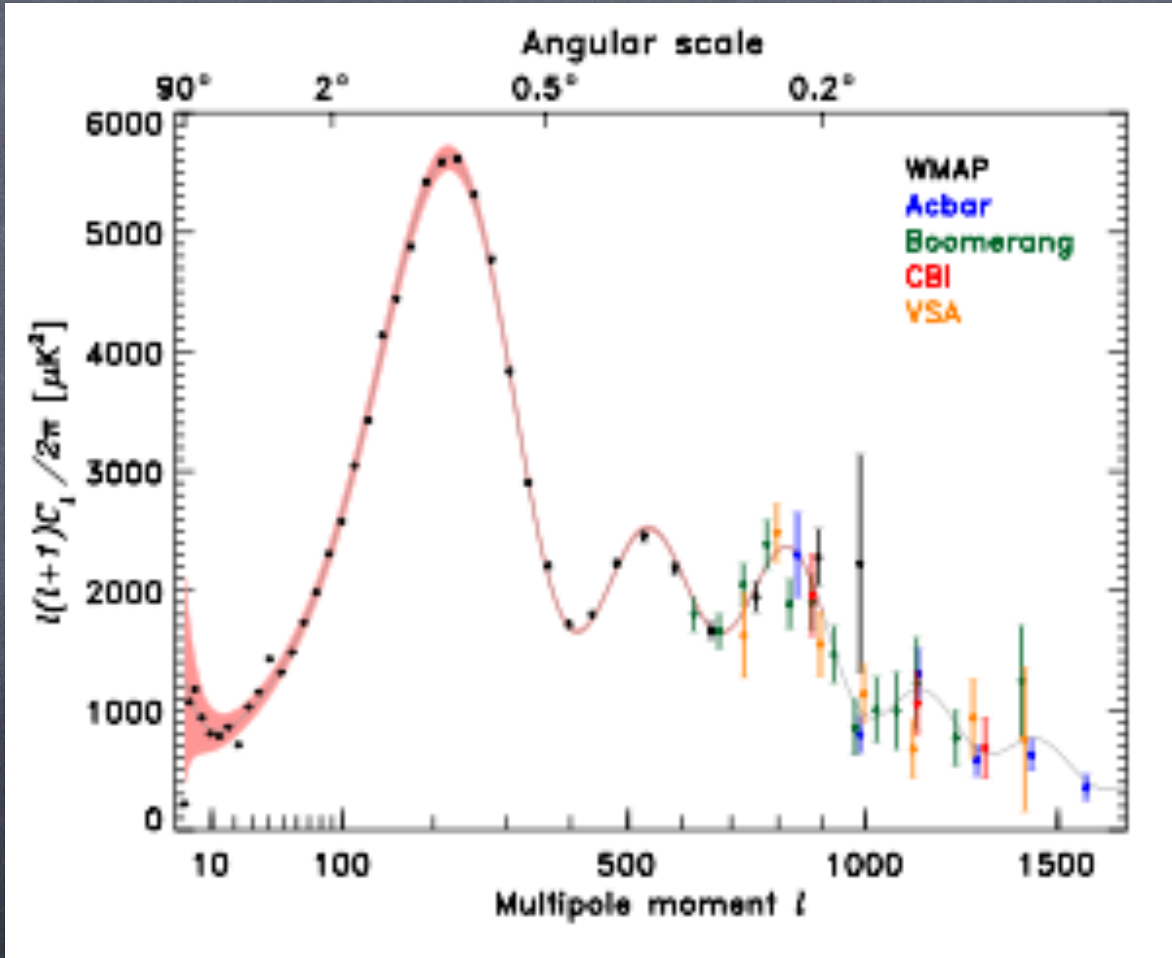
Dark Energy

- Todays accelerated phase
- IA Supernovae (white dwarfs implosion): standard candles.
- CMB spectrum

CMB satellite WMAP

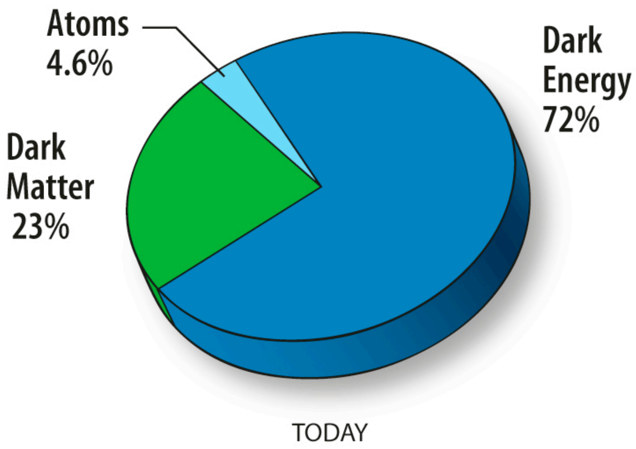


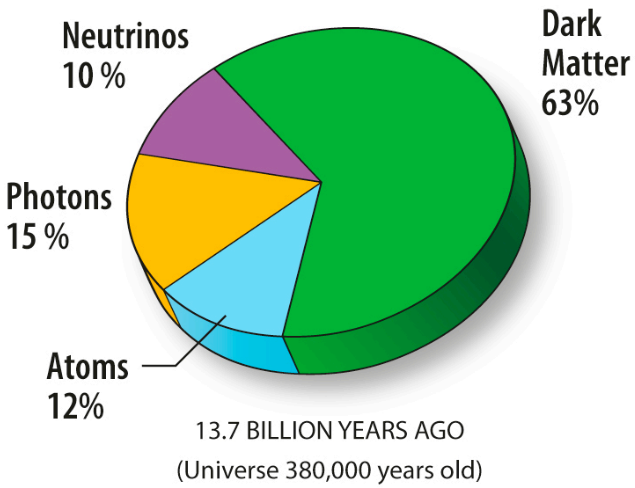
CMB

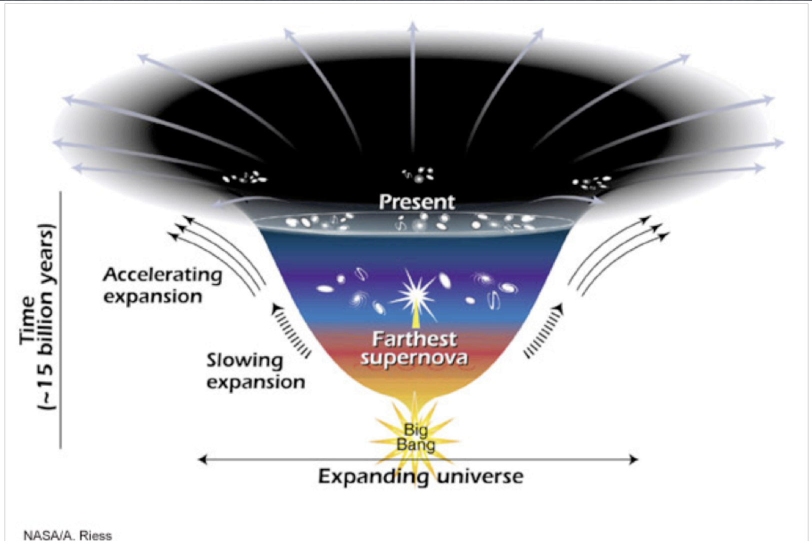


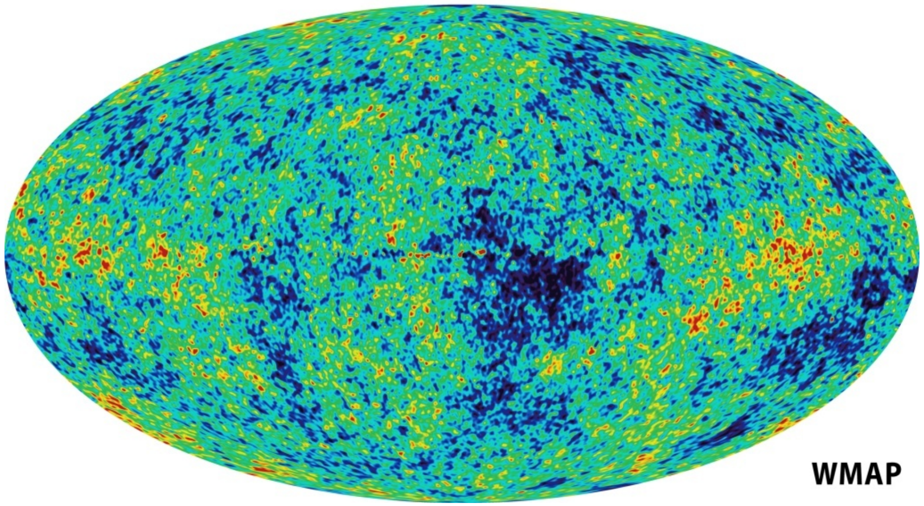
Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
WMAP
Acbar
Boomerang
CBI
VSA
$l(l+1)C_l/2\pi\ [\mu K^2]$
10
100
500
1000
1500
Multipole moment l

The standard "model" for cosmology









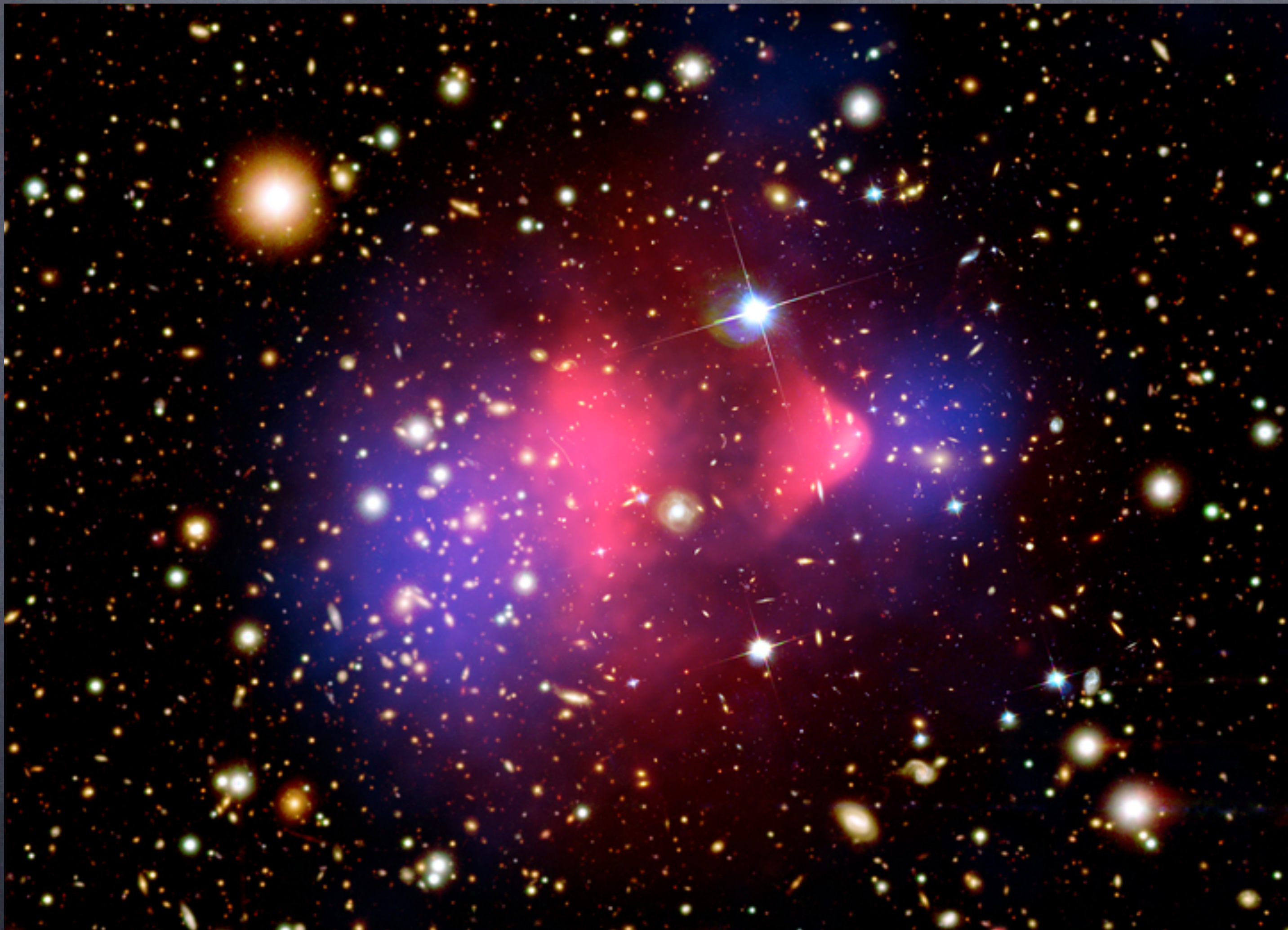
All observations consistent with DM and DE, where:

✓Total Energy density given by the critical value.

✓Clustering Matter (baryons plus DM) represent 1/3 of total Energy.

✓Strange (very strange) object responsable for 2/3 of Universe energy content!

Bullet Cluster



Essence of Dark Energy

- What is it?
- Simple?
- A new Particle/Field?
- Cosmological Constant?

How to get acceleration?

- Friedmann Equation

$$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)}$$

- Thus, to have acceleration:

$$\boxed{p < -\frac{\rho}{3} \Leftrightarrow \omega < -\frac{1}{3}}$$

How to get acceleration?

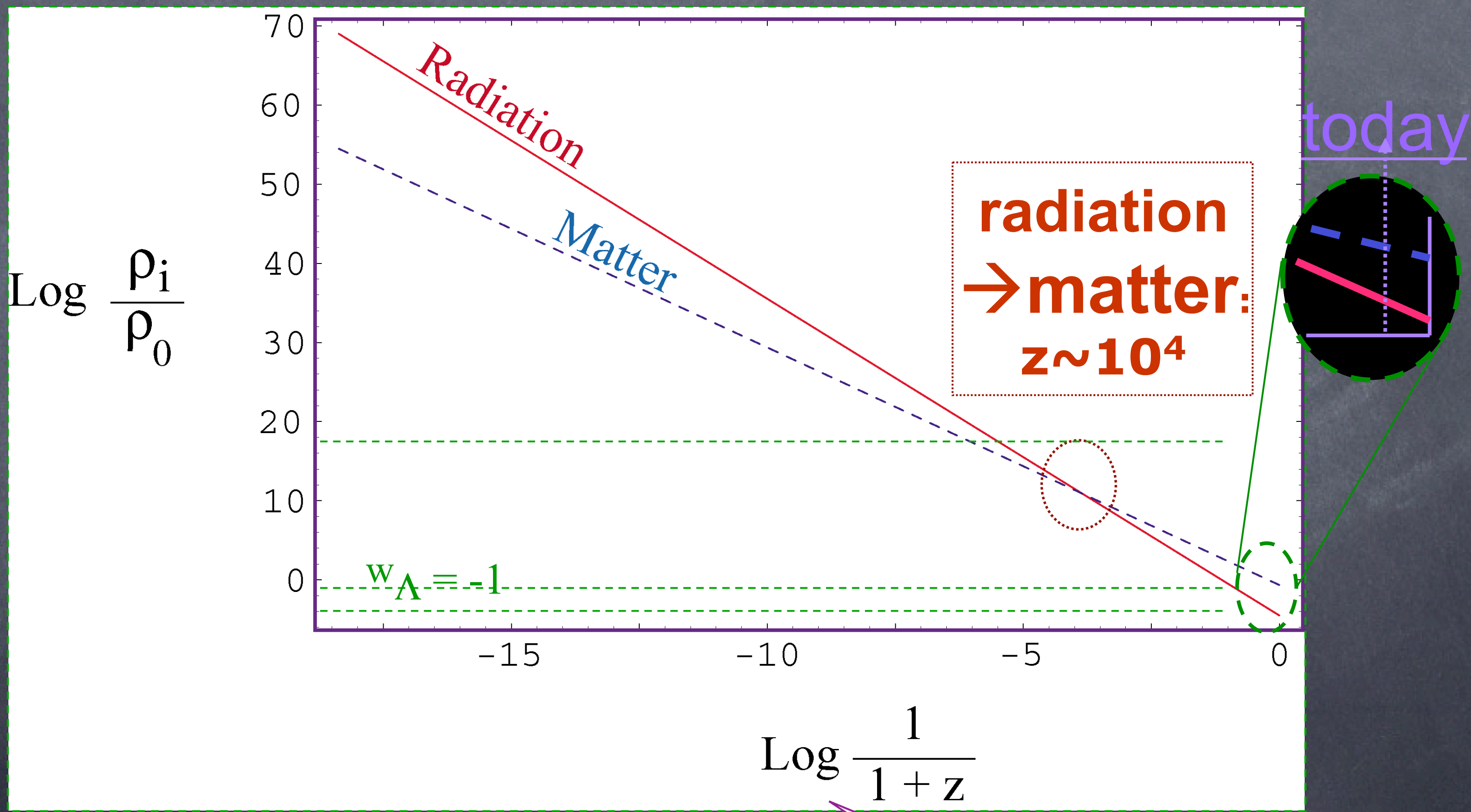
The first hypothesis was the cosmological constant. Is a simple solution, providing $\omega = -1$.

However, there are some problems :

— The energy density consistent with the observations is such that the cosmological constant must be of the order of $1(MeV)^4$, 120 orders of magnitude less than the value obtained from field theory.

— The fact that the cosmological constant is important at this stage of evolution of the Universe is a mystery.

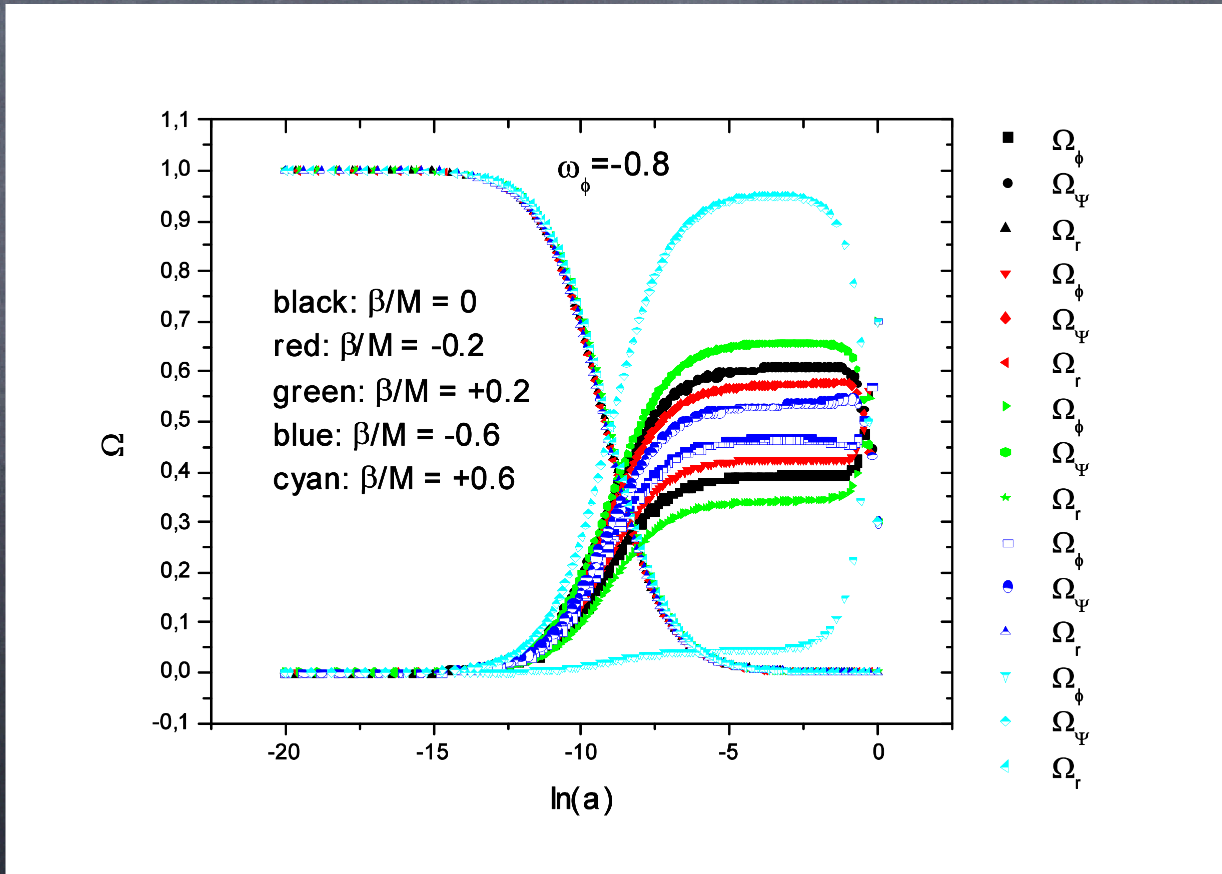
The Coincidence Problem



$1+z = a_0/a$

The Coincidence Problem and the interaction DE/DM

- Why DE and DM have the same order of magnitude today (Micheletti, E.A., Wang)?



The Coincidence Problem and the interaction DE/DM

- The decay of DE into DM alleviates the coincidence problem.
- Question: These ideas can be tested with observations?

Interaction DE/DM: Preliminary

- Question of the suppression of lower multipoles of CMB power spectrum.
- Cosmic Holography (E.A., Wang, et al).
- Holographic idea (DE proportional to the square of the scale factor) is good for various non trivial models (without cosmological constant).

Interacting Holographic Model

- The simplest interacting model for DE/DM is given by two fluids interacting

$$\boxed{\begin{aligned}&\dot{\rho}_{DM} + 3H\rho_{DM} = Q\\ &\dot{\rho}_{DE} + 3H(1+\omega)\rho_{DE} = -Q\end{aligned}}$$

Interacting Holographic Model

- The simplest interaction is proportional to the density of dark energy

$$\boxed{Q = 3b^2 H \rho}$$

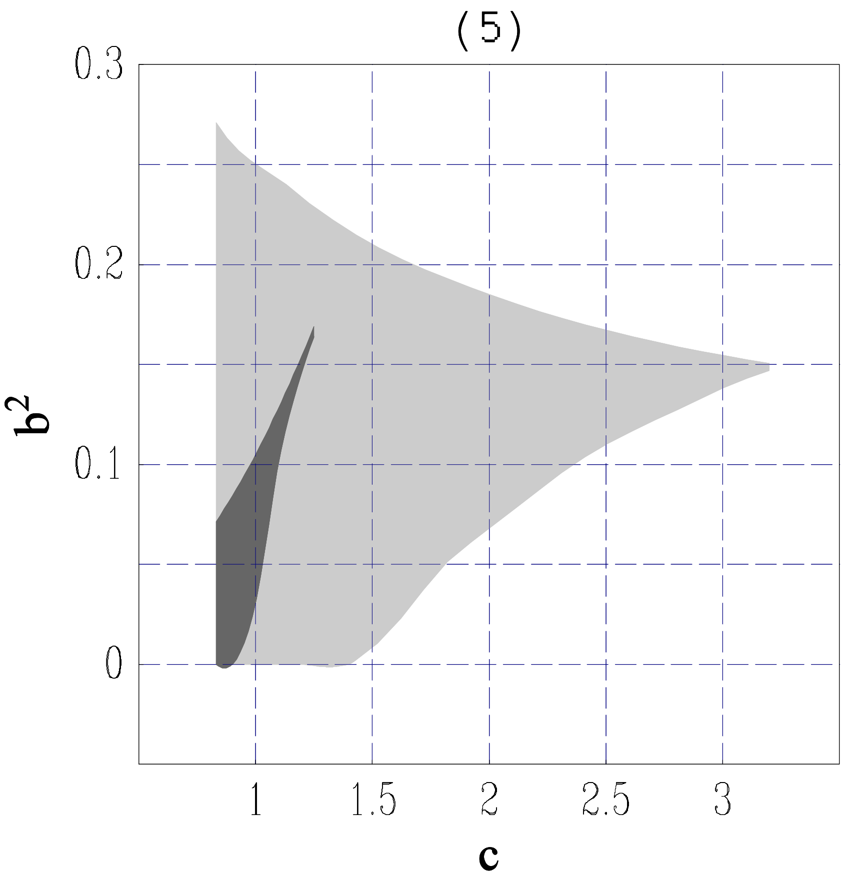
Interacting Holographic Model

- Comparing with the supernovae data lead us to the following results (Wang, E.A. et al)

$$\boxed{\begin{aligned} b^2 &= 0.00^{+0.12}_{-0.00} \\ c &= 0.40^{+0.75}_{-0.05} \end{aligned}}$$

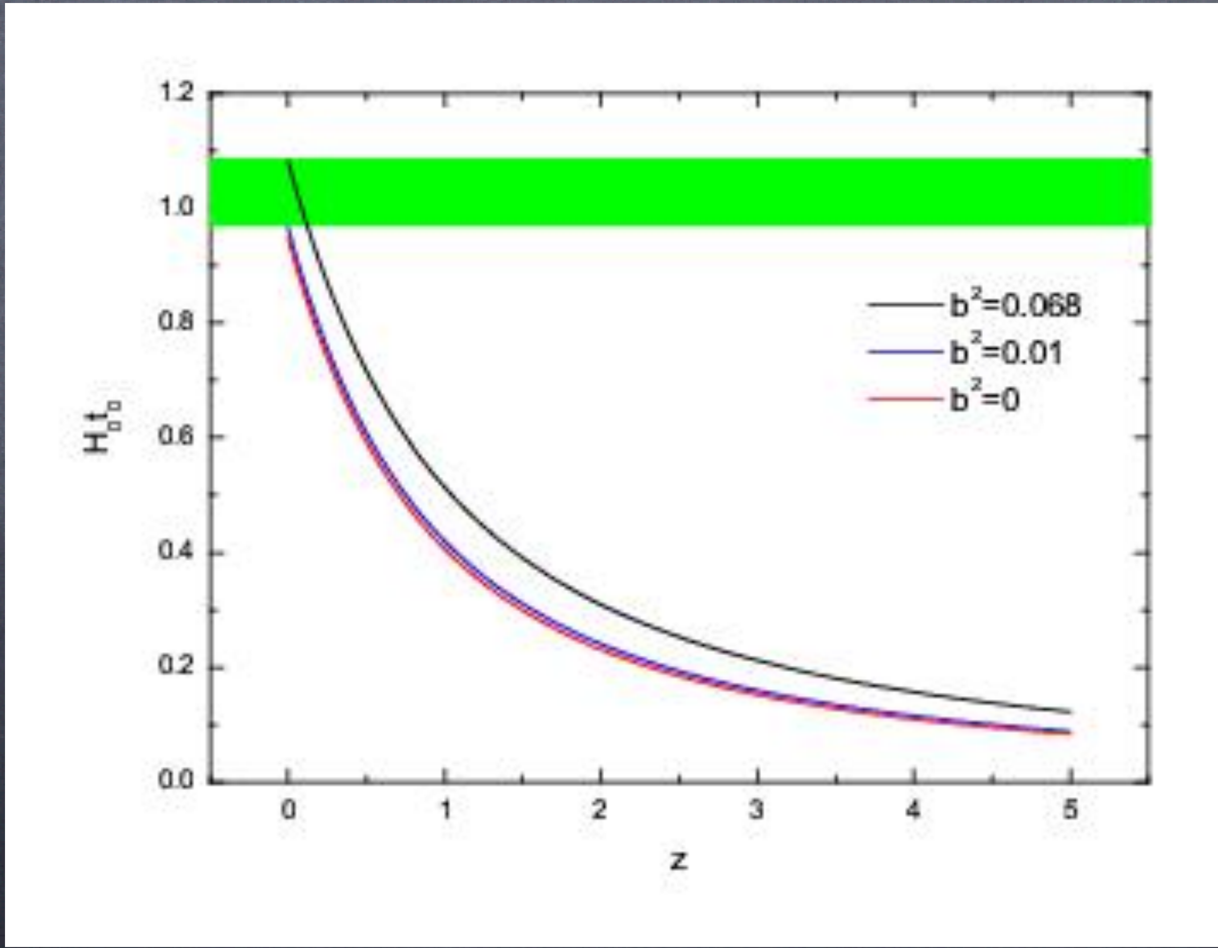
Interacting Holographic Model

- Regarding to the equation of state, the comparison with observational data tell us



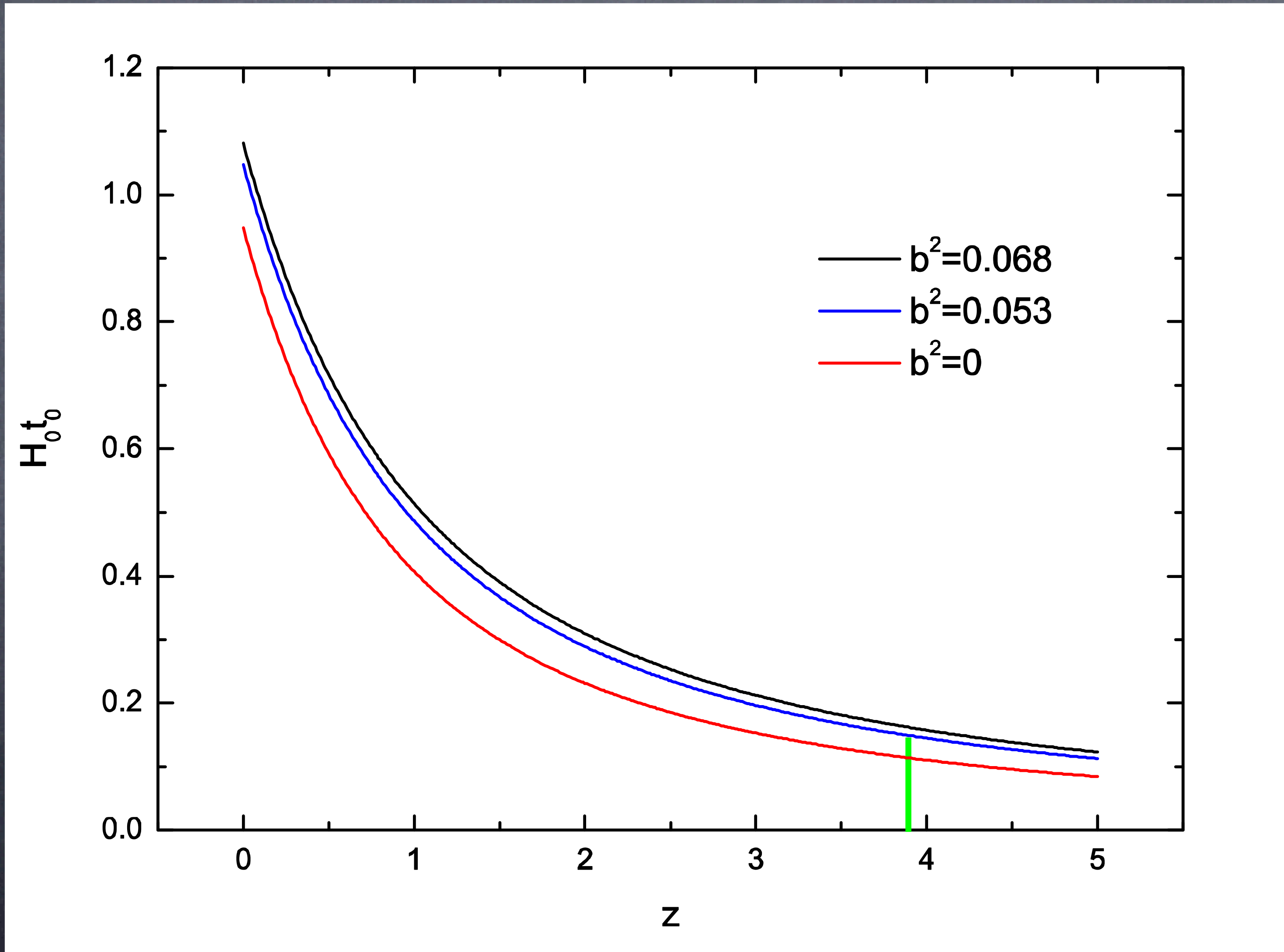
Further on Phenomenology

- Age of Universe



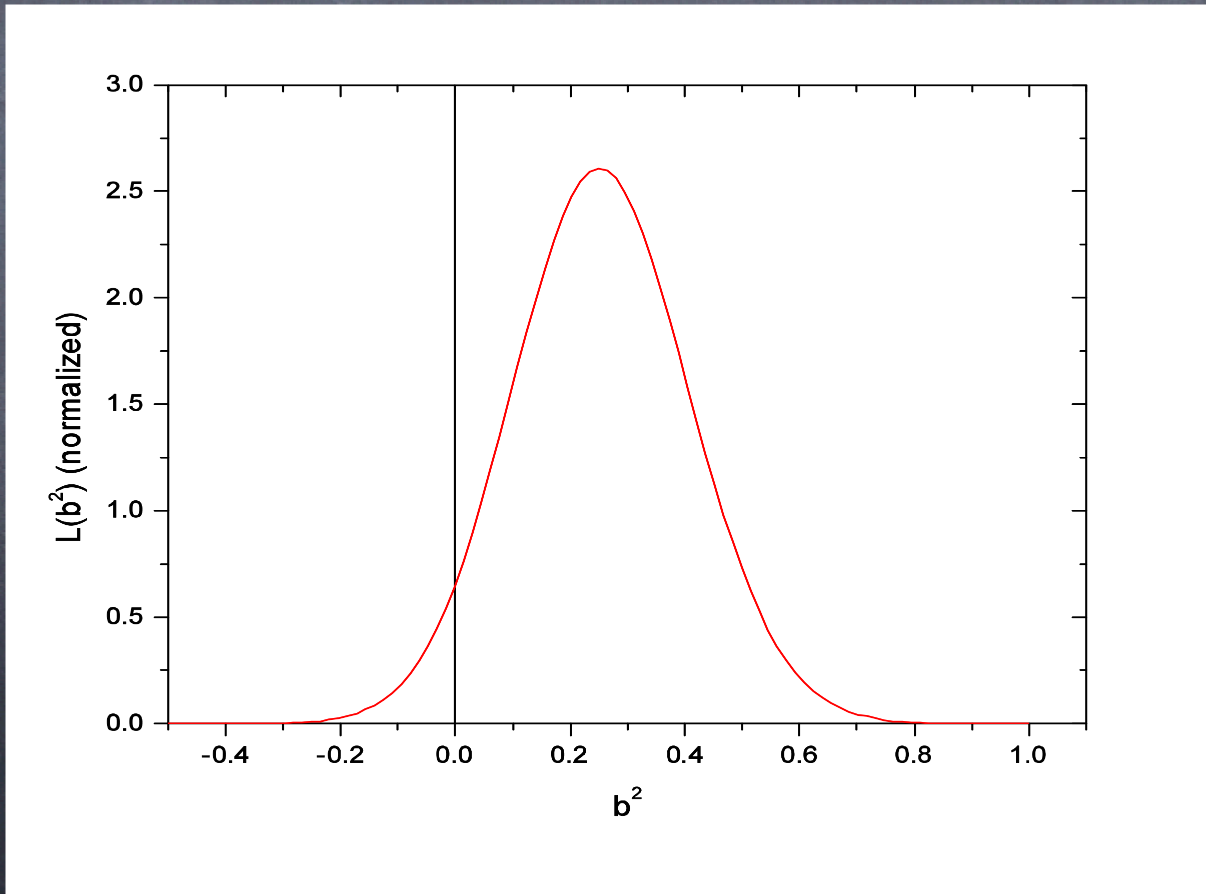
Further on Phenomenology

- Age of Quasar APM 08279+5255



Further on Phenomenology

- Lower multipoles in CMB spectrum



Further on Phenomenology

- Order of magnitude estimate for b^2 (with some dependence on the DE equation of state) :

$$\star\ 1\sigma : \qquad 0.10 < b^2 < 0.2$$

$$\star\ 2\sigma : \qquad -0.10 < b^2 < 0.24$$

Probability of b^2 positive: 95%

Thermodynamics?

- The interaction must be DE --> DM in order to preserve the second law of thermodynamics (Wang, Pavon)

Galaxy clusters and the Virial theorem

- Only baryonic matter is observed.
- Suppose that Dark Matter follows the pattern of baryonic matter.
- The interaction with Dark Energy works as an effective potential.
- Then, the Virial theorem has a correction (O. Bertolami et al).

Galaxy clusters and the Virial theorem

- Virial theorem :

$$2K + U = 0$$

- General Relativity: Layser-Irvine equation

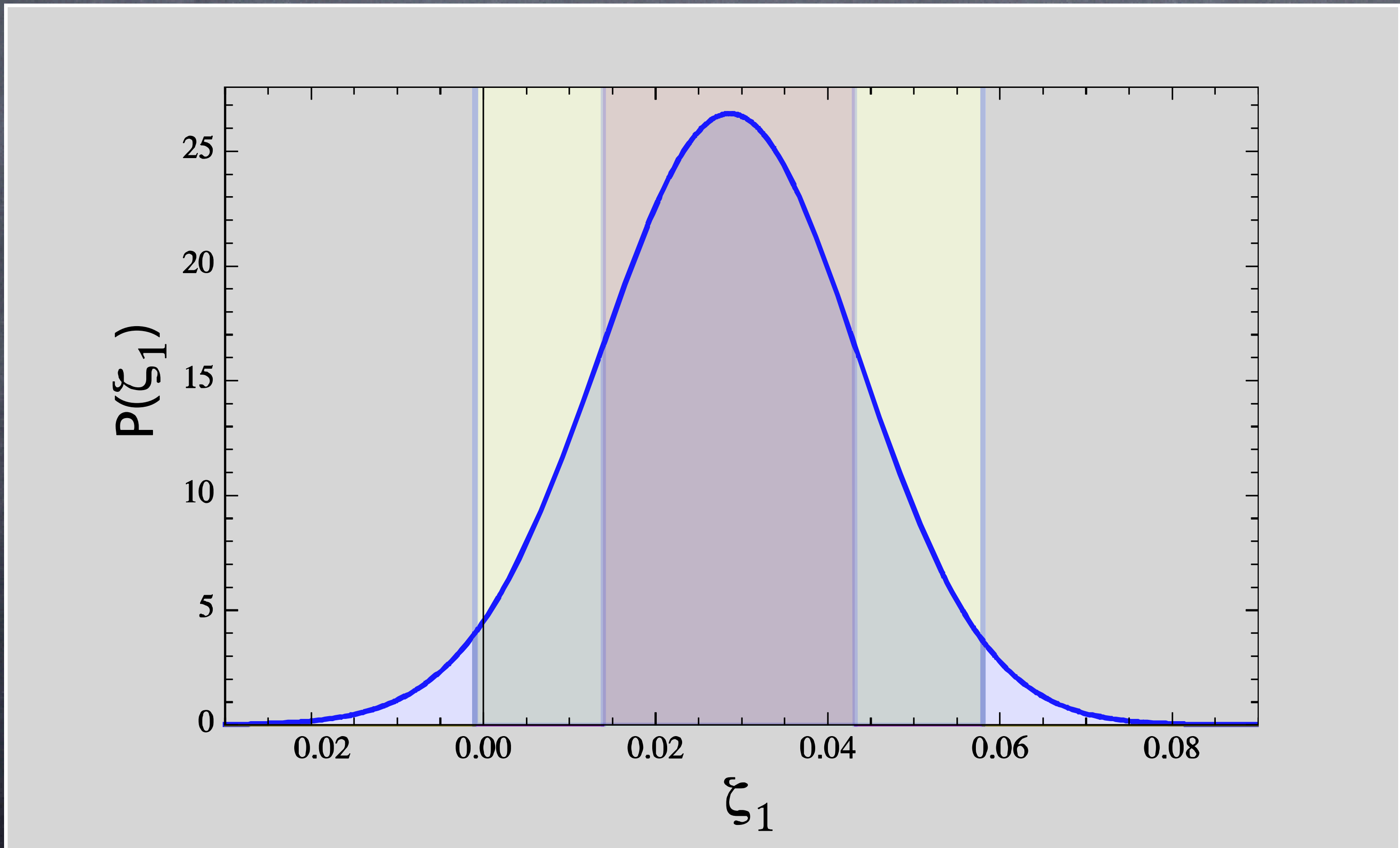
Galaxy clusters and the Virial theorem

- Layser-Irvine equation with interaction (Virial Theorem)

$$\boxed{\begin{aligned} M_{vir} &= \frac{(1-\frac{\zeta}{2})}{(1-2\zeta)} M_X \\ M_{vir} &= \frac{(1-\frac{\zeta}{2})}{(1-2\zeta)} M_{WL} \\ M_X &= M_{WL} \end{aligned}}$$

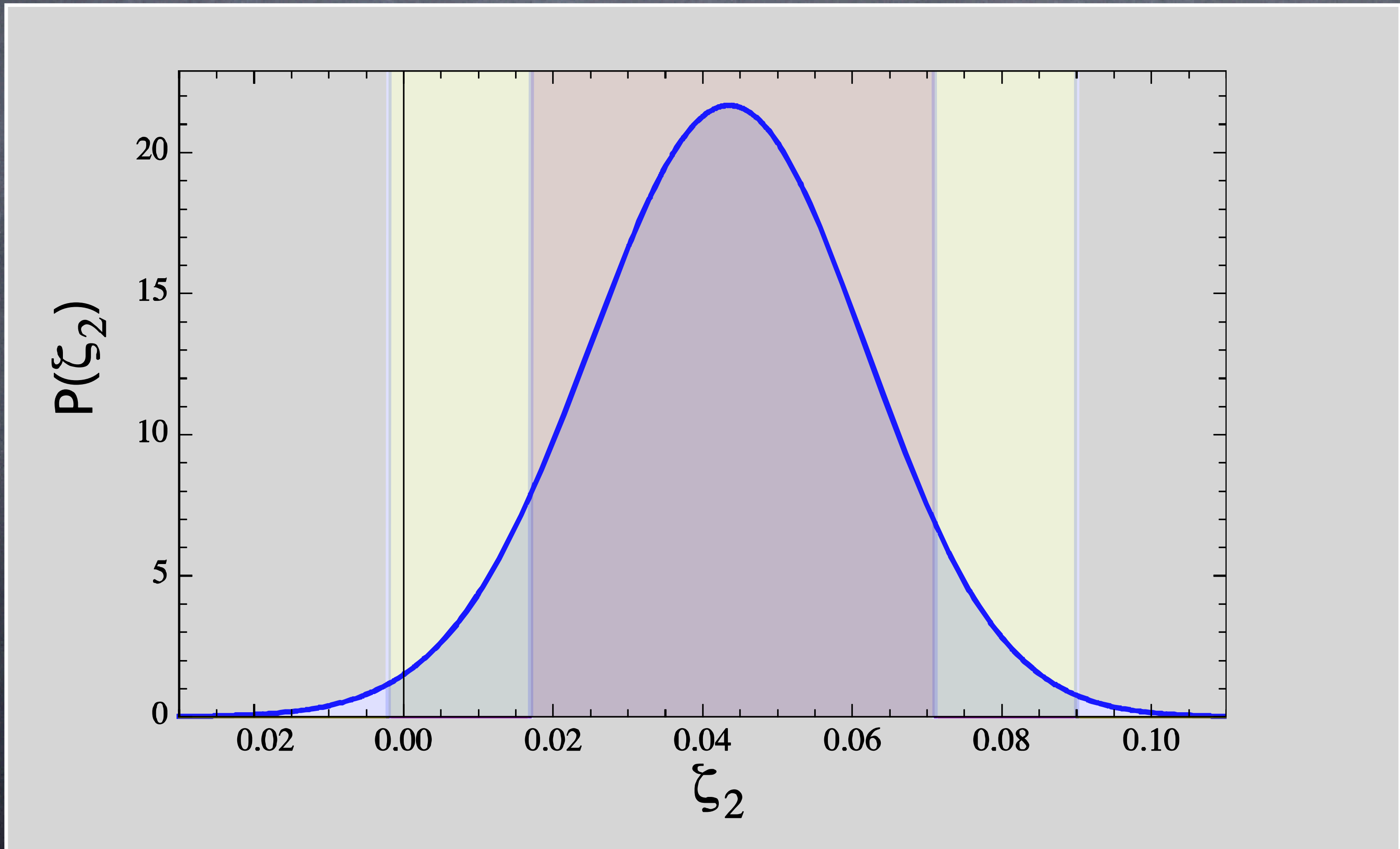
Galaxy clusters and the Virial theorem

- Results (E.A., Abramo, Sodre, Wang, Campos)



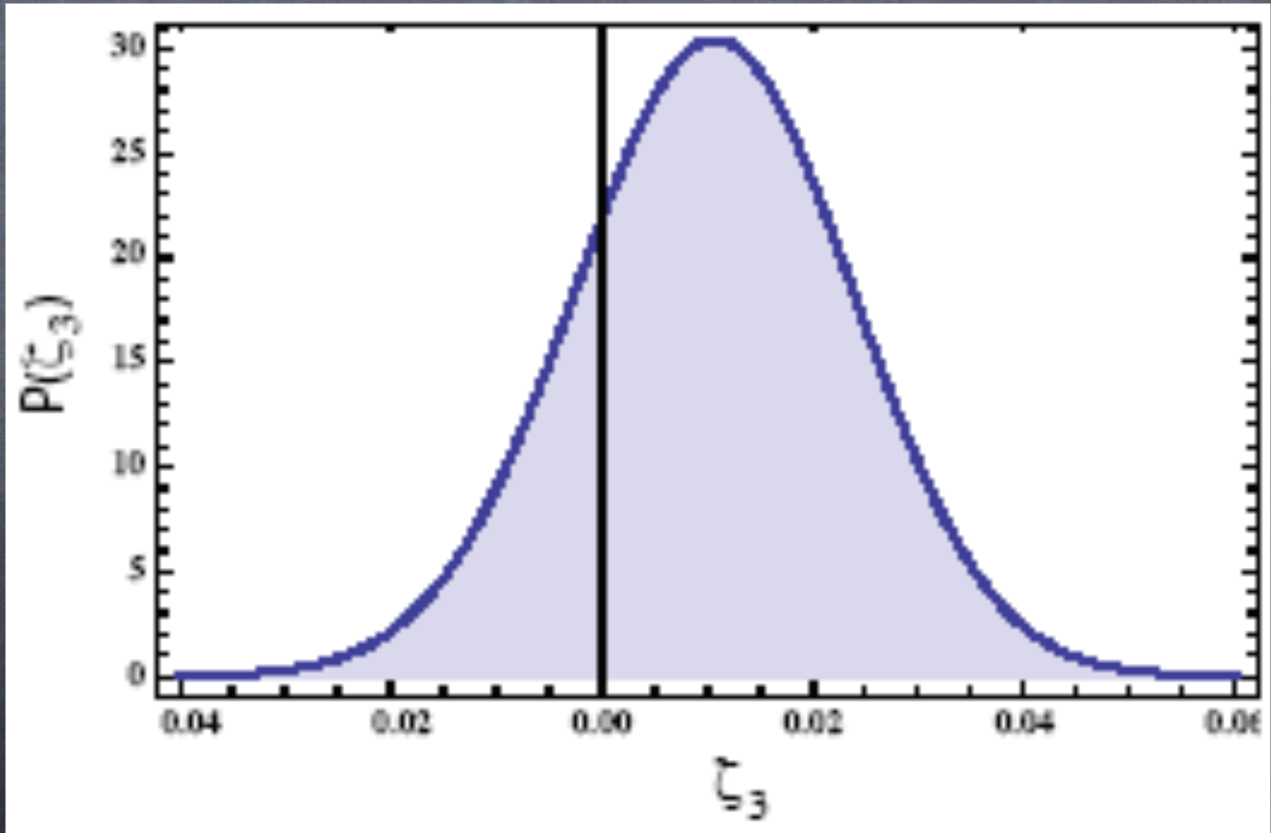
Galaxy clusters and the Virial theorem

- Results

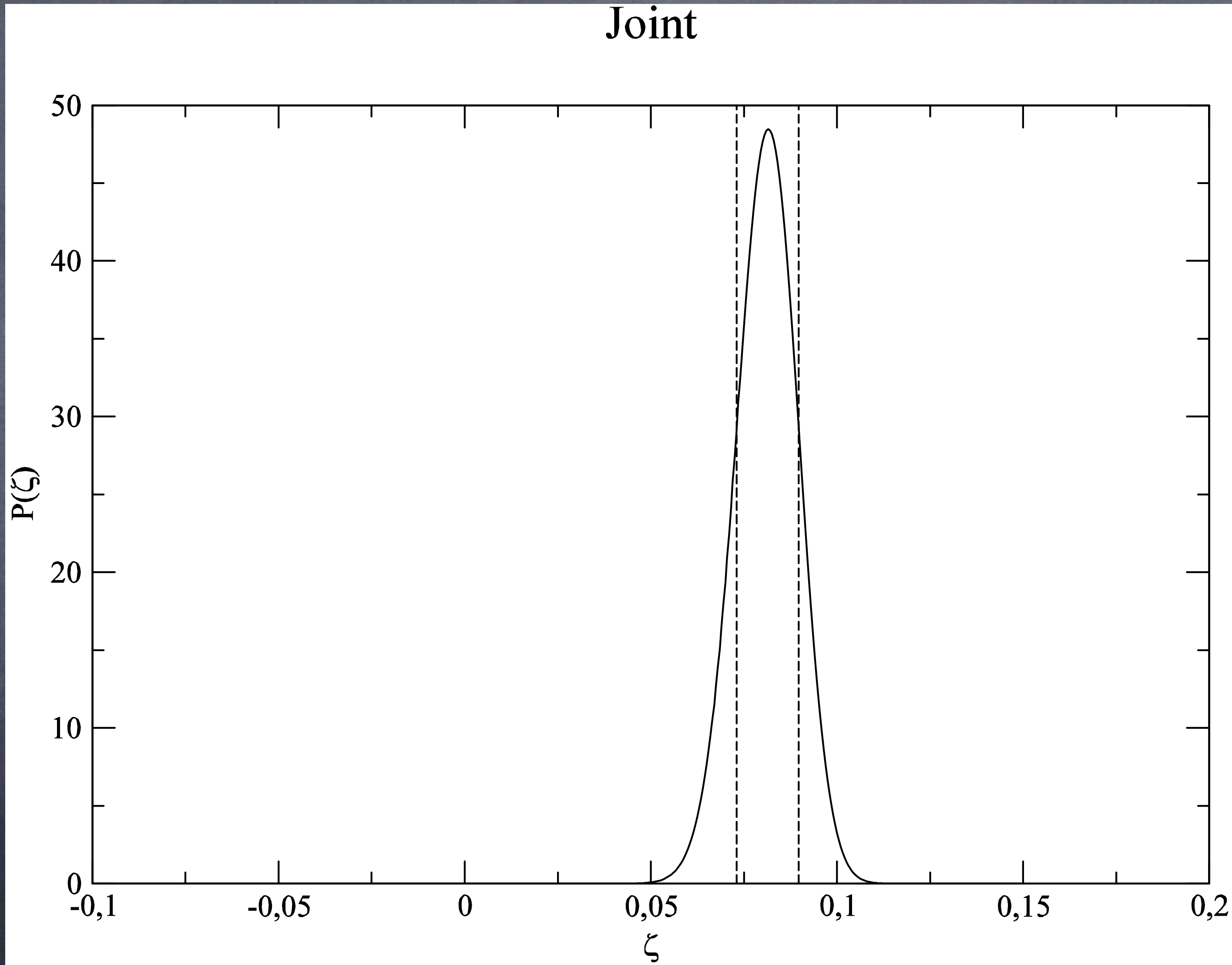


Signature in Galaxy Clusters: an apparent correction of the Virial Theorem

- Results



Clusters (~ 100)



Perturbations

- The interaction $\zeta\rho_{dm}$ gives rise to very strong non perturbative effects (He, Wang, E.A.).
- They come from classical solutions of equations of motion of order $\frac{1}{\zeta}$.
- So, the perturbative methods fail.
- The interaction $\zeta\rho_{de}$ behaves differently.
- Alternative methods are needed.

Modeling the interaction

- Suppose DE/DM are interacting parts (E.A., Wang).
- Suppose that there is a "Thompson scattering amplitude".
- Existence of galaxies with M_{dm} of order $10M_{baryons}$ leads to a coupling constant $b^2 \sim 3\alpha_{QED}$.
- According to previous calculations.

Modeling the interaction

- Suppose DM and baryons are at equilibrium after the Big Bang.
- In the balance between the expansion rate and the self annihilation into ordinary matter, we have a relation between the DM interaction constant and the fine structure constant

Theoretical model to DE/DM (Micheletti, Wang, E.A.)

For $g_{\mu\nu} = diag(1, -a(t)^2, -a(t)^2, -a(t)^2)$ one finds

$$\ddot{\varphi} \; = \; -(1-\alpha\dot{\varphi}^2)\left[\frac{1}{\alpha}\frac{dlnV(\varphi)}{d\varphi} + 3H\dot{\varphi} - \frac{\beta\bar{\Psi}\Psi}{\alpha V(\varphi)}\sqrt{1-\alpha\dot{\varphi}^2}\right] ,$$

with $H = \frac{\dot{a}}{a}$. We also find

$$\frac{d(a^3\Psi^\dagger\Psi)}{dt} \; = \; 0 ,$$

$$\frac{d(a^3\bar{\Psi}\Psi)}{dt} \; = \; 0 .$$

From the latter, $\bar{\Psi}\Psi = \frac{\bar{\Psi}_0\Psi_0 a_0^3}{a^3}$.

Theoretical model to DE/DM

Moreover,

$$\begin{aligned}
\rho_\varphi &= \frac{V(\varphi)}{\sqrt{1-\alpha\dot{\varphi}^2}} \,, \\
P_\varphi &= -V(\varphi)\sqrt{1-\alpha\dot{\varphi}^2} \,, \\
\rho_\Psi &= M^*\bar{\Psi}\Psi \\
P_\Psi &= 0 \,,
\end{aligned}$$

where $M^* \equiv M - \beta\varphi$. Note that $\omega_\varphi \equiv P_\varphi/\rho_\varphi = -(1-\alpha\dot{\varphi}^2)$. Using time derivatives and equations of motion, we also find

$$\begin{aligned}
\dot{\rho_\varphi} + 3H\rho_\varphi(\omega_\varphi + 1) &= \beta\dot{\varphi}\frac{\bar{\Psi}_0\Psi_0 a_0^3}{a^3} \\
\dot{\rho_\Psi} + 3H\rho_\Psi &= -\beta\dot{\varphi}\frac{\bar{\Psi}_0\Psi_0 a_0^3}{a^3} \,.
\end{aligned}$$

Theoretical model to DE/DM

Similar to eq. for the interaction of Dark Matter and Dark Energy. The right hand side does not contain the Hubble parameter H explicitly, but it does contain the time derivative of the scalar fields, which should behave as the inverse cosmological time, replacing thus the Hubble parameter.

Friedmann equation for a flat universe reads

$$H^2 = \frac{1}{3M_{pl}^2}\left[M^* \frac{\bar{\Psi}_0 \Psi_0 a_0^3}{a^3} + \frac{V(\varphi)}{\sqrt{1-\alpha\dot{\varphi}^2}}\right] ,$$

where $M_{pl}^2 = (8\pi G)^{-1}$ e $H = \frac{\dot{a}}{a}$.

Some analytic solutions in the pure bosonic case have been found elsewhere for the potential

$$V(\varphi) = \frac{m^{4+n}}{\varphi^n} \, , n > 0 \, .$$

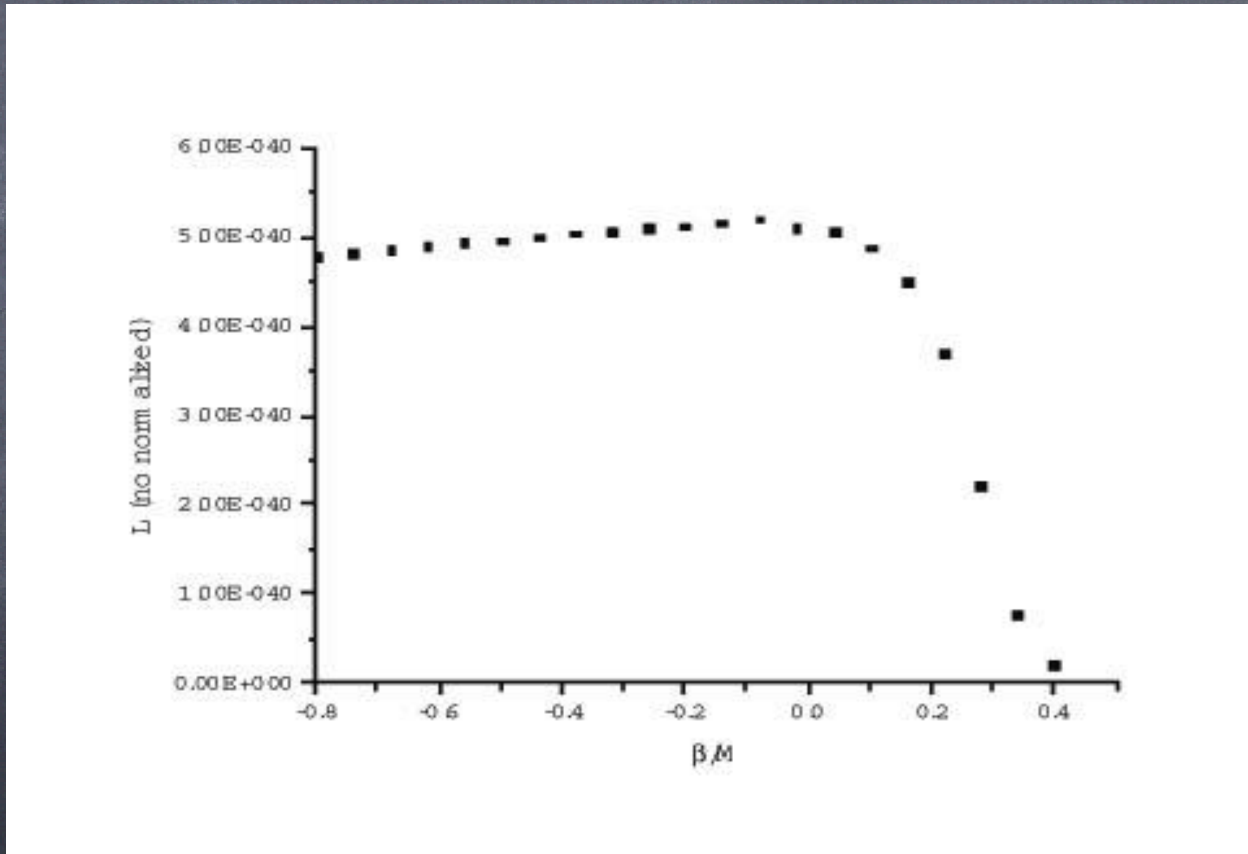
Theoretical model to DE/DM

$$
\begin{aligned}
\frac{d\omega}{dz} &= \frac{4\omega\sqrt{\omega+1}}{H_0E(z)\phi(1+z)} - \frac{6\omega(\omega+1)}{1+z} \\
&+ \frac{2\left(\frac{\beta}{M}\right)\frac{\Omega_{\Psi 0}}{\sqrt{\alpha}}}{(1-\Omega_{\Psi 0})(1-\frac{\beta}{M}\frac{\phi_0}{\sqrt{\alpha}})}\frac{\omega\sqrt{|\frac{\omega}{\omega_0}|(\omega+1)}\left(\frac{\phi}{\phi_0}\right)^2}{H_0E(z)}(1+z)^2 , \\
\frac{d\phi}{dz} &= -\frac{\sqrt{\omega+1}}{H_0E(z)(1+z)} , \\
\frac{dt}{dz} &= -\frac{1}{(1+z)H_0E(z)} ,
\end{aligned}
$$

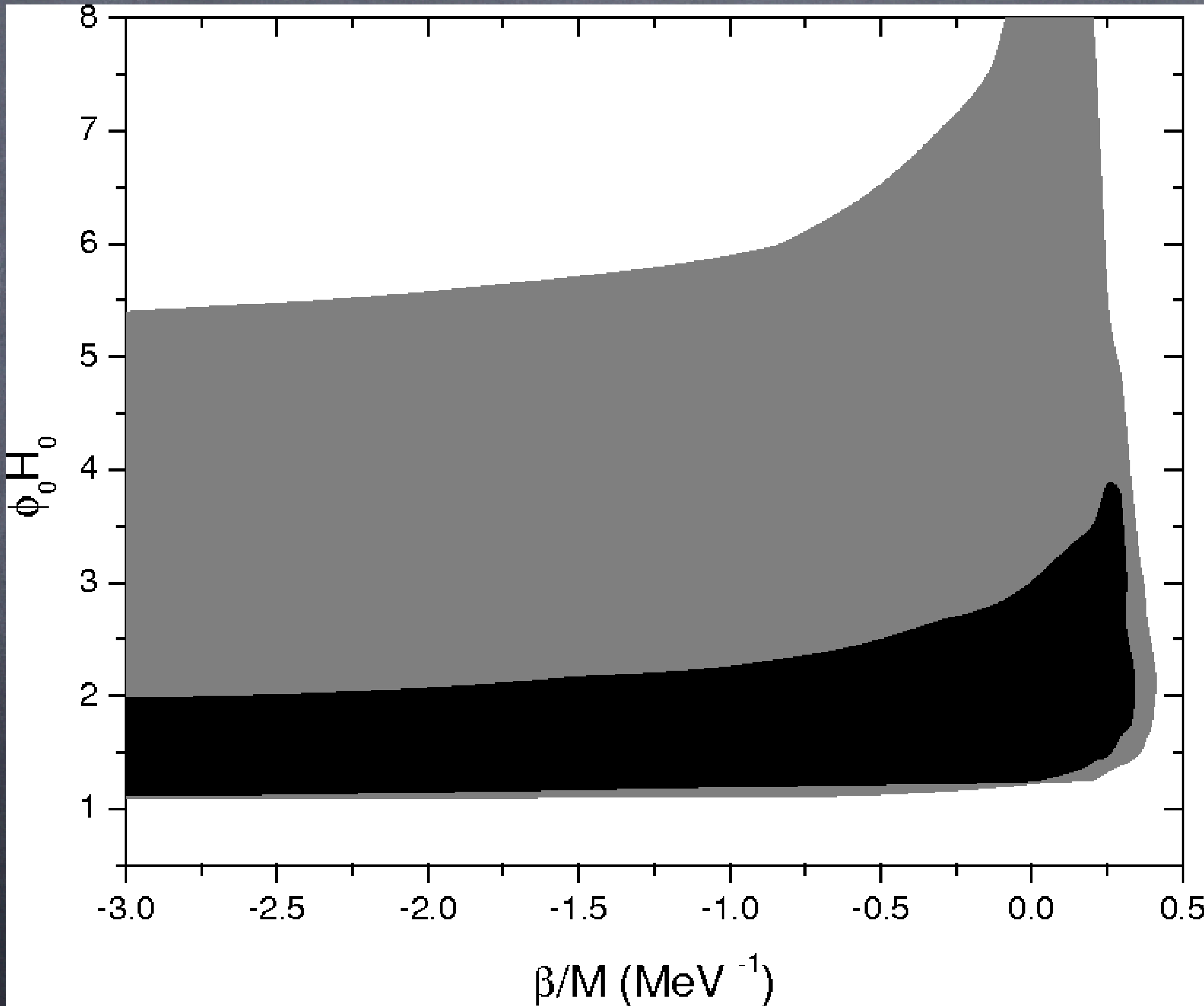
where $H_0 = 2.133h \times 10^{-39} MeV$ is the value of the Hubble parameter, $\Omega_{\Psi 0} = \frac{\rho_\Psi}{3M_{pl}^2H_0^2}$ and

$$
E(z) = \sqrt{\frac{1-\frac{\beta}{M}\frac{\phi}{\sqrt{\alpha}}}{1-\frac{\beta}{M}\frac{\phi_0}{\sqrt{\alpha}}}\Omega_{\Psi 0}(1+z)^3 + \left(\frac{\phi_0}{\phi}\right)^2\sqrt{|\frac{\omega_0}{\omega}|}(1-\Omega_{\Psi 0})} .
$$

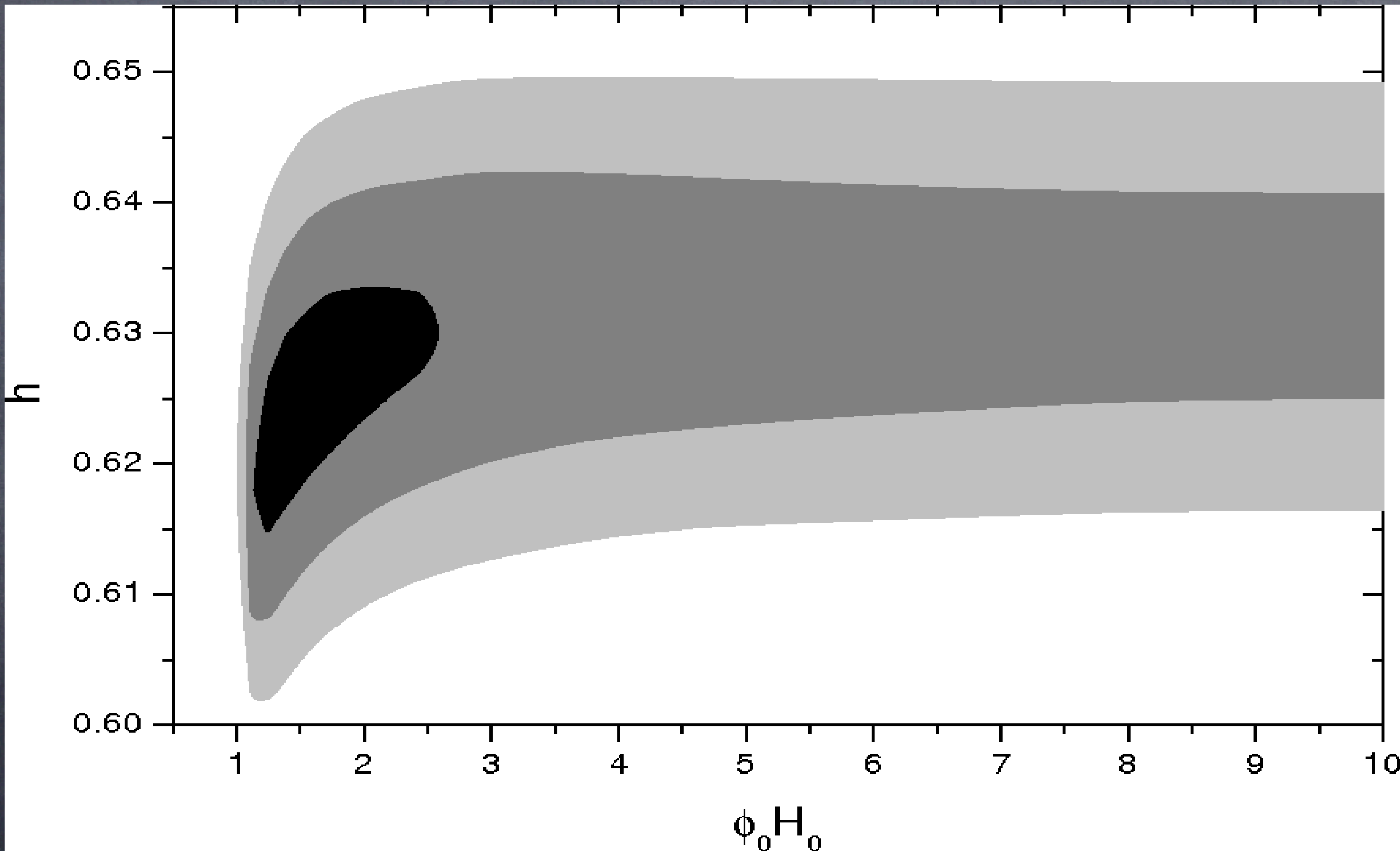
Likelihood β



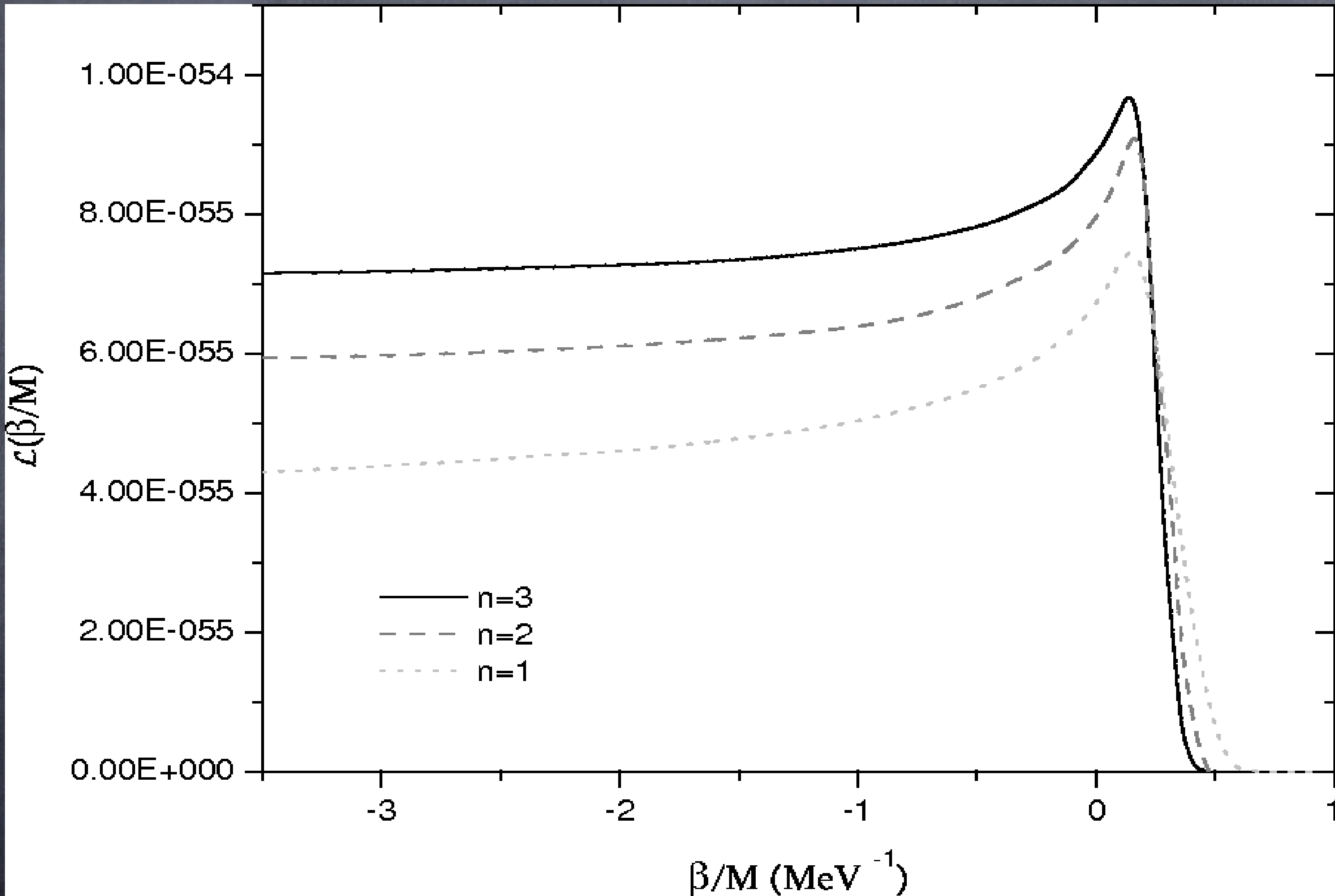
2D-Likelihood $\Phi_0\beta$



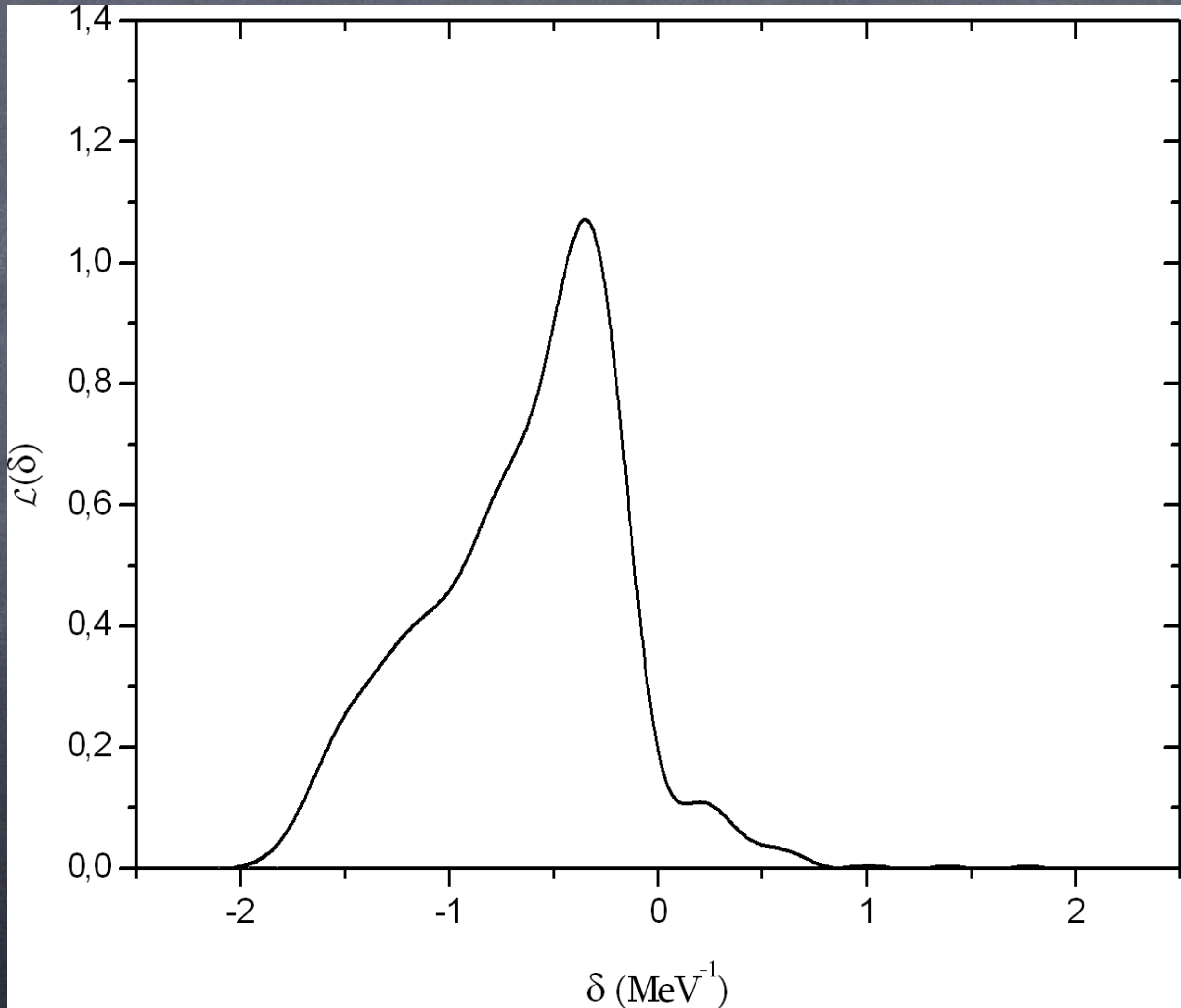
2D-Likelihood $\Phi_0 H_0$



Likelihood n = 1,2,3



Likelihood δ (effective interaction)



Theoretical model to DE/DM

- Are there standard model particles that constitute a natural candidate for DM?
- Neutralinos: candidate for lighter supersymmetric particle (LSP), would be stable, heavy enough, it interacts very weakly with ordinary matter.
- Gravitinos : candidate for LSP, stable, it interacts almost exclusively by gravitation.

Theoretical model to DE/DM

- Are there standard model particles that constitute a natural candidate for DE?
- Such particle must be very stable (τ of order of 10 billions years) interacting very weakly.
- The standard model can have multiple scalar particles, the stability condition is quite strong. There are uncertainties.

We compute now the likelihood of the function $\delta \equiv \frac{\frac{\beta}{M\sqrt{\alpha}}}{1-\frac{\beta}{M\sqrt{\alpha}}\dot{\phi}_0}$

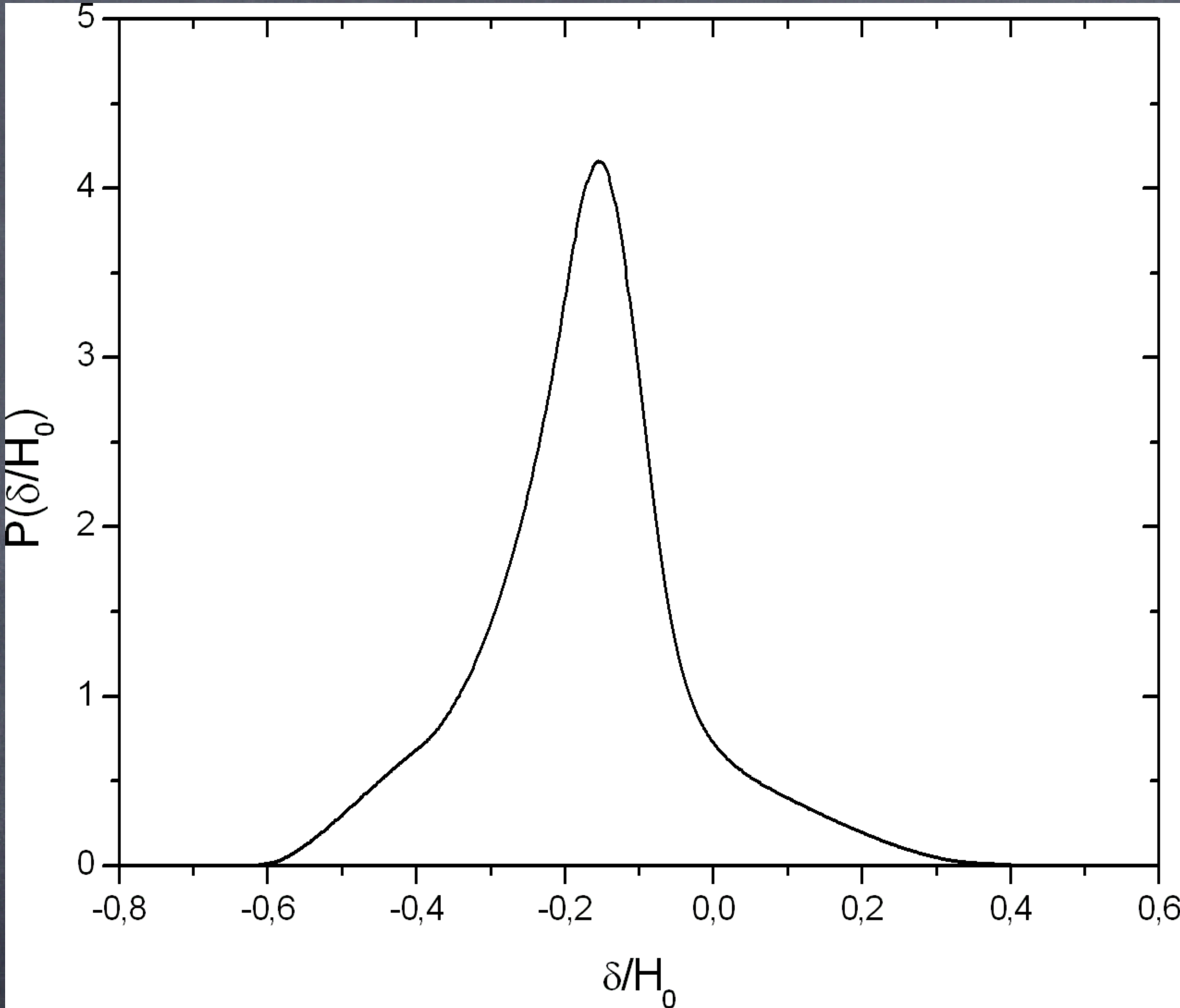
The likelihood of δ is determined from the likelihood of $\frac{\beta}{M\sqrt{\alpha}}$ and ϕ_0 according to

$$P(u') = \int\int \delta(u' - \delta) P(\frac{\beta}{M\sqrt{\alpha}}, \phi_0) d(\frac{\beta}{M\sqrt{\alpha}}) d\phi_0 \quad ,$$

where

$$P(\frac{\beta}{M\sqrt{\alpha}}, \phi_0) \sim prior(\frac{\beta}{M\sqrt{\alpha}}, \phi_0) \mathcal{L}(\frac{\beta}{M\sqrt{\alpha}}, \phi_0)$$

for some prior we choose for $\frac{\beta}{M\sqrt{\alpha}}$ and ϕ_0 .



The likelihood function

Calculation of the Decay Rate of the Dark energy

We know that the decay rate (per unit time and volume) of a scalar particle in a meta stable vacuum is given by the formula (Coleman 77):

$$\boxed{\frac{\Gamma}{V} = \frac{S(\phi_b)^2}{(2\pi\hbar)^2} . e^{-(\frac{S_e}{\hbar} - \frac{S_\Lambda}{\hbar})} . \left(\frac{det'(-\partial_\mu\partial_\mu + V''(\bar{\phi}(\rho))}{det(-\partial_\mu\partial_\mu + V''(2m/3\lambda))}\right)^{-\frac{1}{2}}}$$

We will calculate the decay rate of dark energy scalar field described by the Wess-Zumino potential (E.A. Graeff, Wang)

$$U = |2m\phi - 3\lambda\phi^2|^2$$

with a term of supersymmetry breaking equal to

$$\xi\phi = \epsilon = 10^{-47} GeV^4$$

This potential corresponds to that of dark energy, which currently is at the metastable minimum corresponding to the cosmological constant, that has the value

$$10^{-47} GeV^4$$

We wish to calculate the decay's time of the metastable minimum to the true stable minimum, which corresponds to a decay of dark energy in dark matter. The dominant term of the formula of the decay's rate is the term $e^{-Se/\hbar}$. So, we compute calculate it first.

The classical solution follows the equation

$$\frac{\delta Se}{\delta\phi} = (-\frac{\partial^2\phi}{\partial\rho^2} + V'(\phi)) = 0$$

S_e = euclidean action

Due to the $O(4)$ invariance of the field ϕ , this equation can be written as:

$$\frac{\partial^2\phi}{\partial\rho^2} + \frac{3}{\rho}.\frac{\partial}{\partial\rho}\phi - V'(\phi) = 0$$

This equation of motion can be interpreted similarly to the equation of motion of a particle at position ϕ moving in time ρ , subject to a force= $-V'$, and a frictional force with a coefficient depending on ρ. The classic solution of minimal action is the oscillatory solution that satisfies this equation, which in analogy corresponds to a particle oscillating between the two maxima in the potential- $V(\phi)$. Due to the invariance $O(4)$ we can interpret the solution as a bubble of true vacuum separated by a wall of the false vacuum.

$m > 10^{-13} GeV$

Conclusions

- At level of 1σ there are good reasons to believe that DE and DM are interacting fields.
- At level of 2σ the results are still reliable.
- There are some solid indications from galaxy clusters
- There would be models of particles/fields describing DE/DM interaction ? (we are working)

Conclusions

- The QFT can give us some convincing models, however, more constraints are needed. The models are still very poor, lacking a strong phenomenology, and the results so far are still compatible with no interaction.
- The problem comes form the DE sector: the quintessence described is somewhat sensitive to various parameters.

Conclusions

- QFT models could describe correctly the interaction DE/DM? (work in progress)
- Neutralinos and gravitinos seem to be good candidates to DM.
- Indeed, fermions seems to be good candidates to DM. What about DE?
- What happens to String theory claims about anthropic principle and all that?