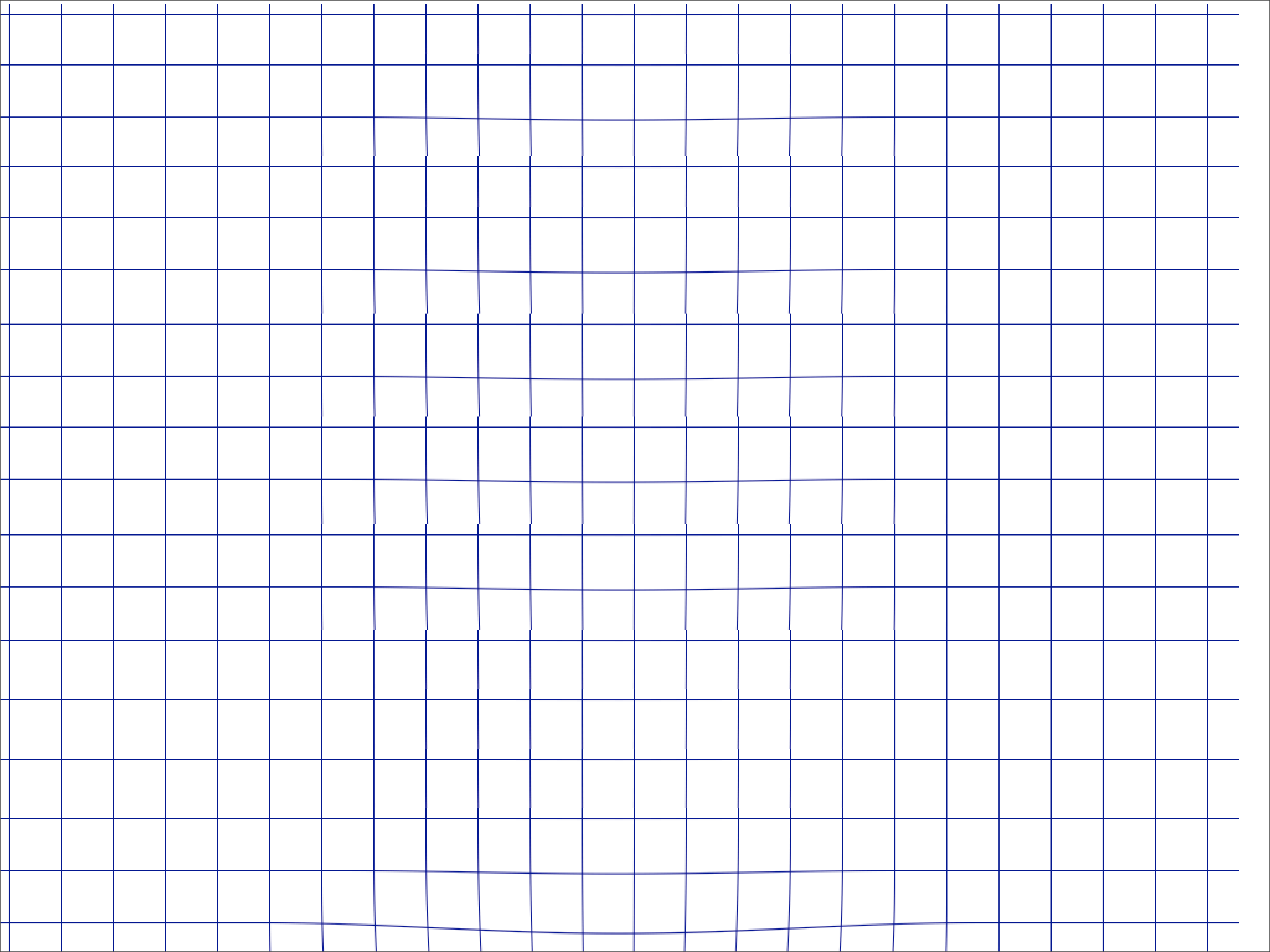


OLGA MENA,
THEORETICAL
PHYSICS DEPARTMENT

OLGA MENA,

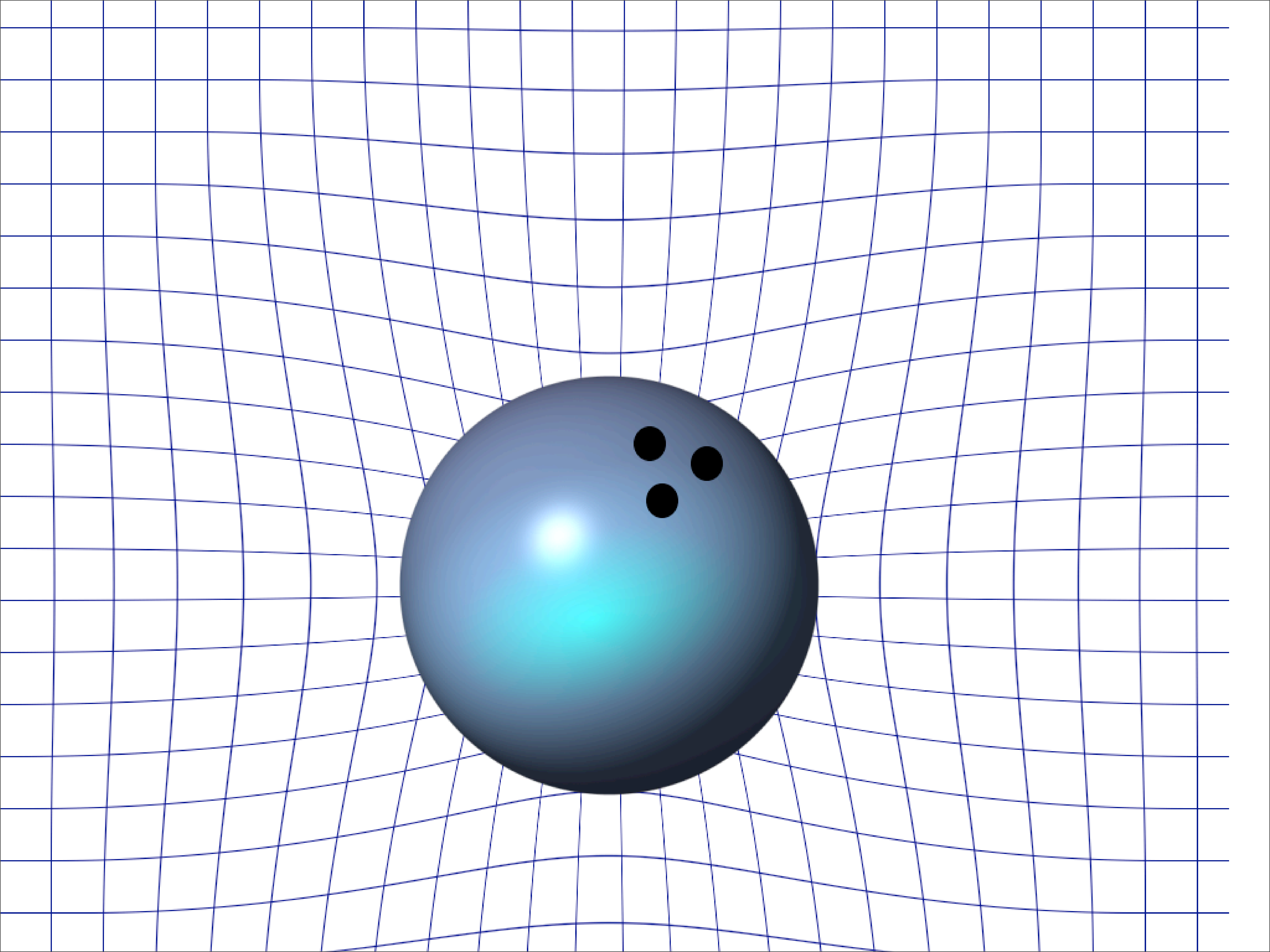
THEORETICAL

PHYSICS DEPARTMENT

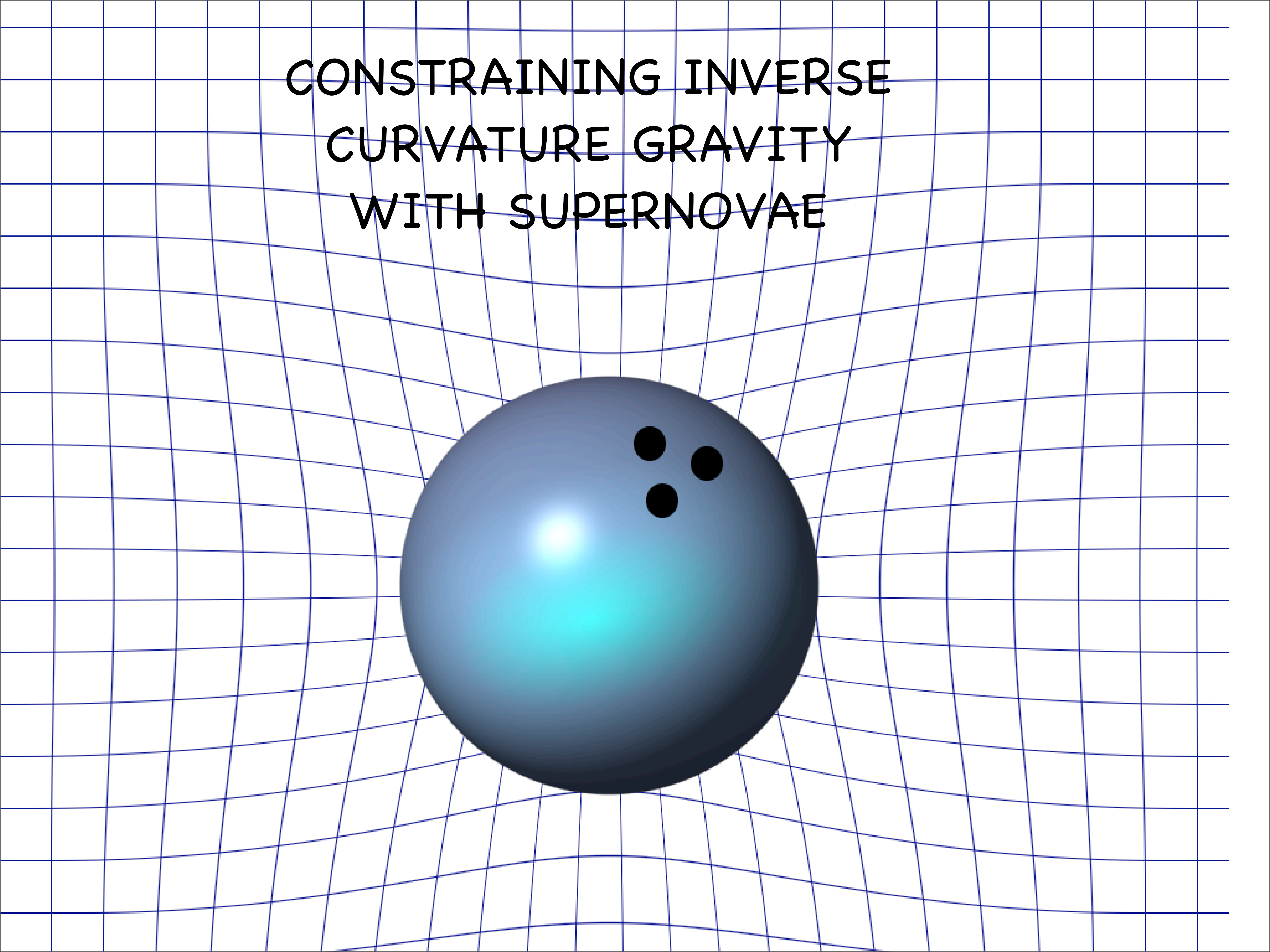
"Recent developments

on Theoretical

ASTRO(!!)PHYSICS"



CONSTRAINING INVERSE CURVATURE GRAVITY WITH SUPERNOVAE



CONSTRAINING INVERSE CURVATURE GRAVITY WITH SUPERNOVAE

In Collaboration with J. Santiago and J. Weller

PRL96 (2006)

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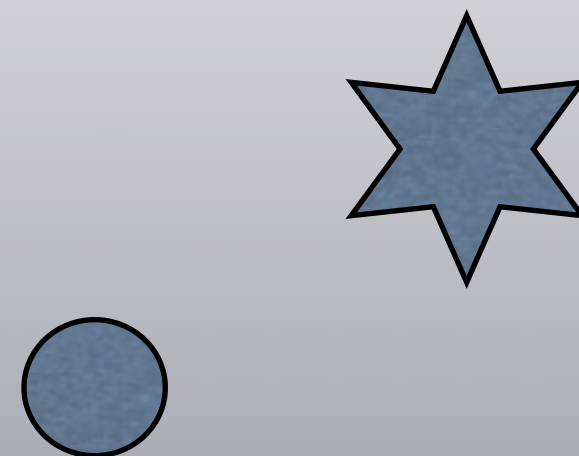
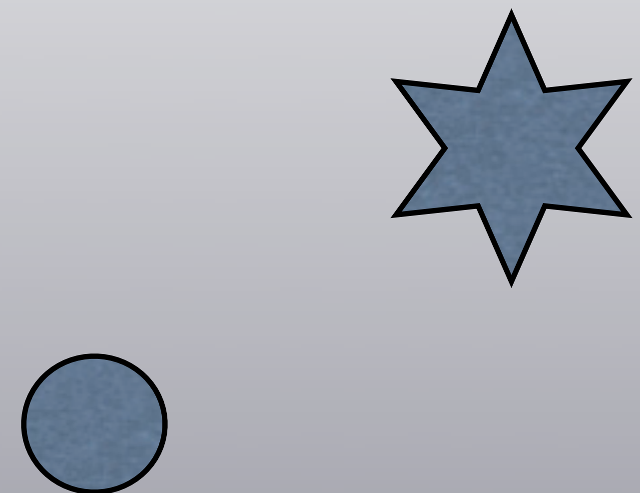
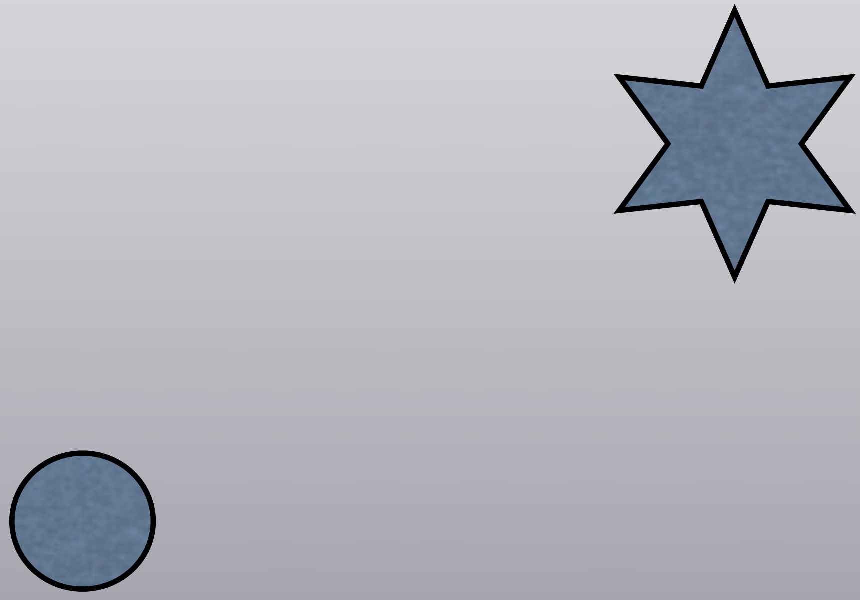
The universe is expanding at an accelerating pace.



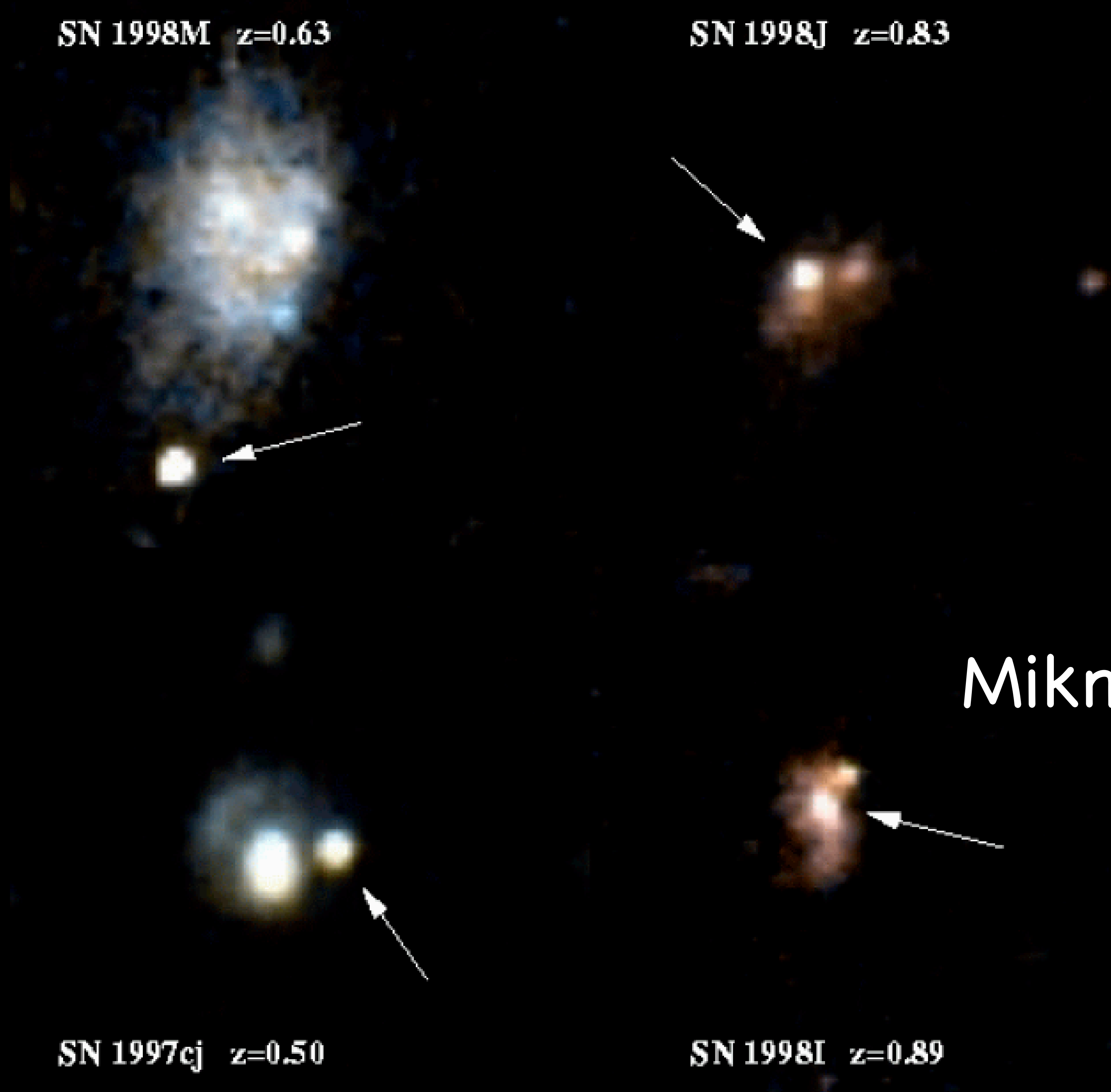




The universe is expanding at an accelerating pace.

Probes: SNIa luminosity distances, CMB, LSS

SNIa are excellent standard candles, bright enough to test the geometry of the universe



Miknaitis' talk!

For a given SNIa of fixed luminosity
at a certain redshift, its distance from us
will depend on the cosmological model.

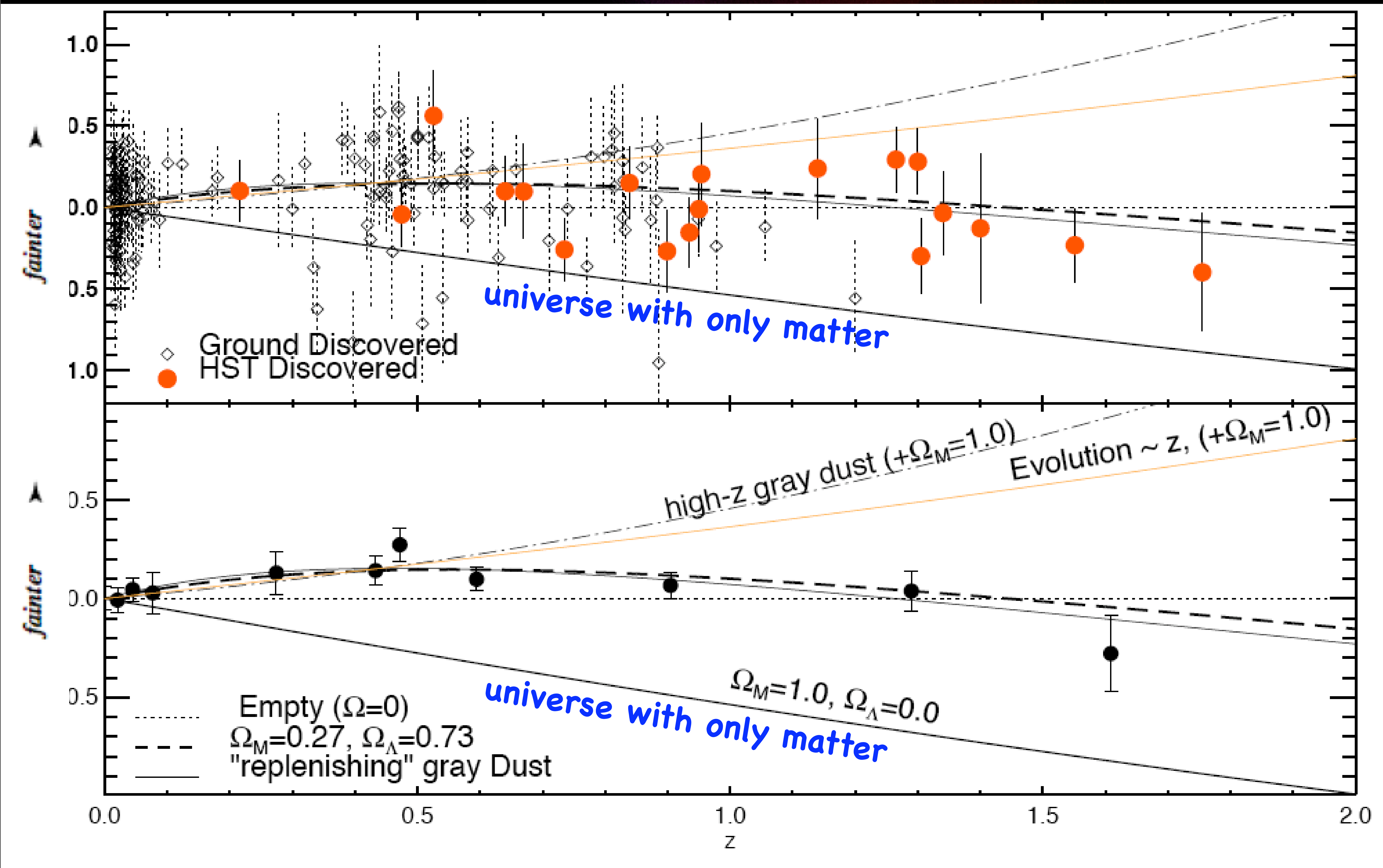
By comparing the apparently magnitude:

observed Flux∝Luminosity/d_L^2

to what is expected from different cosmologies,

$$d_L \propto \int H^{-1}(z)dz$$

one CAN EXTRACT the cosmological model



1.0
0.5
0.0
0.5
1.0
fainter
Ground Discovered
HST Discovered
universe with only matter
high-z gray dust (+Ω_M=1.0)
Evolution ~ z, (+Ω_M=1.0)
Ω_M=1.0, Ω_Λ=0.0
Empty (Ω=0)
Ω_M=0.27, Ω_Λ=0.73
"replenishing" gray Dust
0.0
0.5
1.0
1.5
2.0
z

The universe is expanding at an accelerating pace.

Probes: SNIa luminosity distances, CMB, LSS

Why is the universe accelerating?

Is General Relativity Correct? YES!

Is the strong energy condition violated?

$$\rho + 3p \geq 0$$

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Is the strong energy condition violated? YES!

DARK ENERGY

Krauss and Turner, Gen. Rel. Grav. 27, (1995);
Caldwell, Dave and Steindhardt, Phys. Rev. Lett. 80 (1998).

DARK ENERGY

$$w = \frac{p}{\rho}$$

$w < -1/3$

Krauss and Turner, Gen. Rel. Grav. 27, (1995);
Caldwell, Dave and Steindhardt, Phys. Rev. Lett. 80 (1998).

COSMOLOGICAL CONSTANT Λ $w = -1$

COSMOLOGICAL CONSTANT Λ w =-1

PLANCK SCALE FUNDAMENTAL CUTOFF

0.000000000000000000000000000000000000
00000000000000000000000000000000000000
00000000000000000000000000000000000000
000000000000000000000000000000001

123 orders of magnitude larger than the value of Λ observed

$$\rho_V^{th} \simeq 1.4 \times 10^{74}\ \mathrm{GeV}^4 \qquad \rho_V^{obs} \simeq 10^{-47}\mathrm{GeV}^4$$

Dynamical alternatives

Quintessence

$w = f(z)$

Is General Relativity Correct? YES!

Is the strong energy condition violated? NO!

Backreaction of subhorizon homogeneities

Kolb, Matarrese, Notari and Riotto, hep-th/0503117;
Kolb, Matarrese and Riotto, astro-ph/0506534.

Is General Relativity Correct?

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Extremely very well tested in Solar System and in binary systems < 100 AU = 10^{13} m

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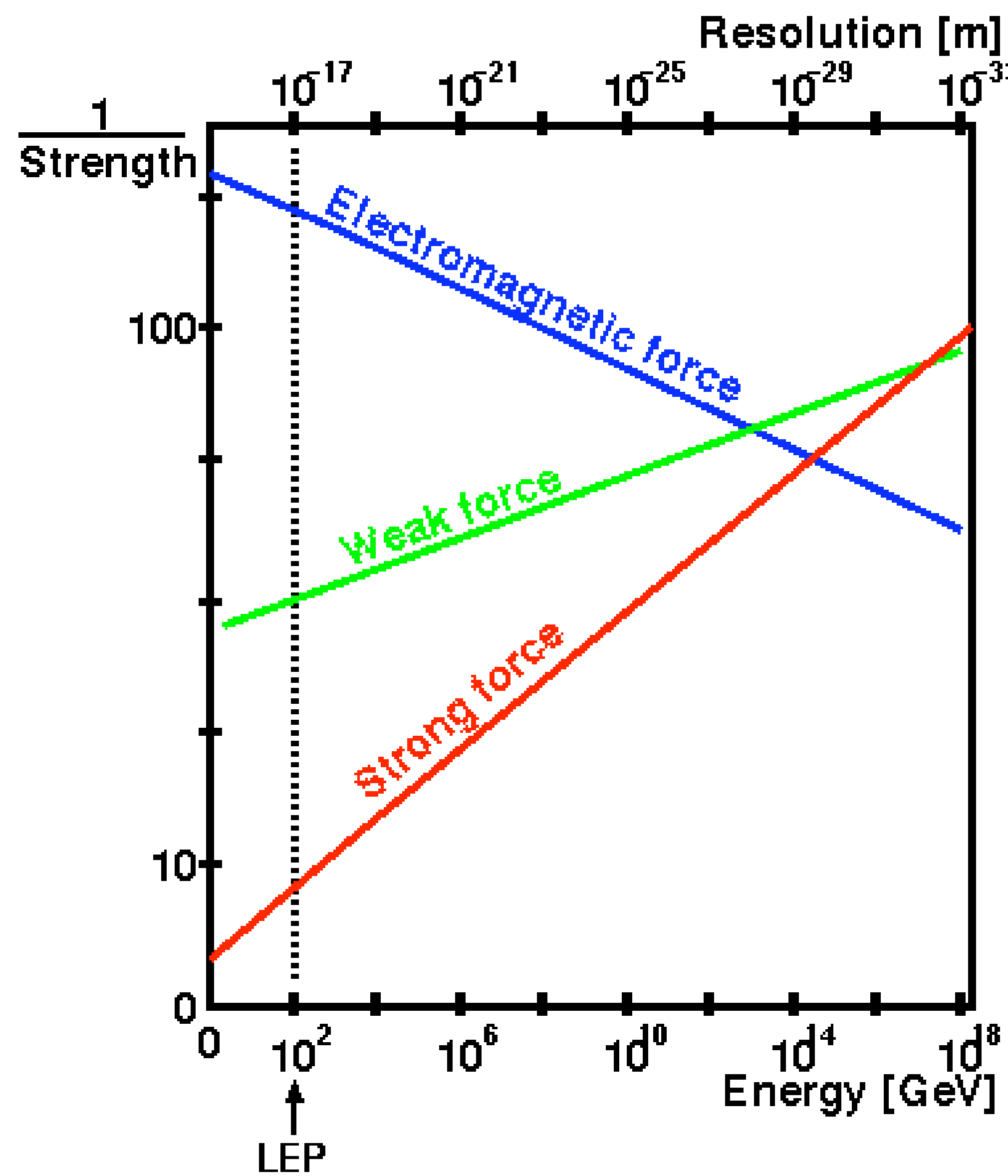
Extremely very well tested in Solar System and in binary systems < 100 AU = 10^{13} m

We are applying it to COSMOLOGICAL DISTANCES, galaxies, clusters, superclusters..
10^{7}-10^{13} times larger!

Distance to a SN @ z=1.7 is 7 x 10^{24} m

“The running coupling constants team at CERN”



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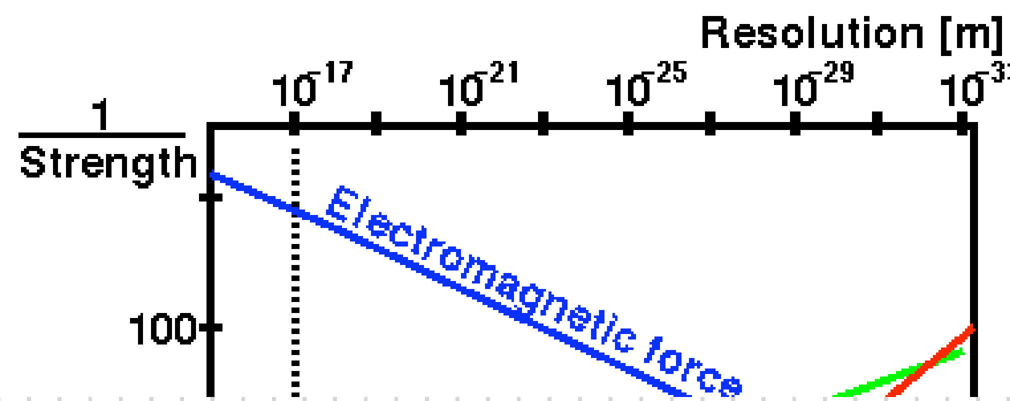
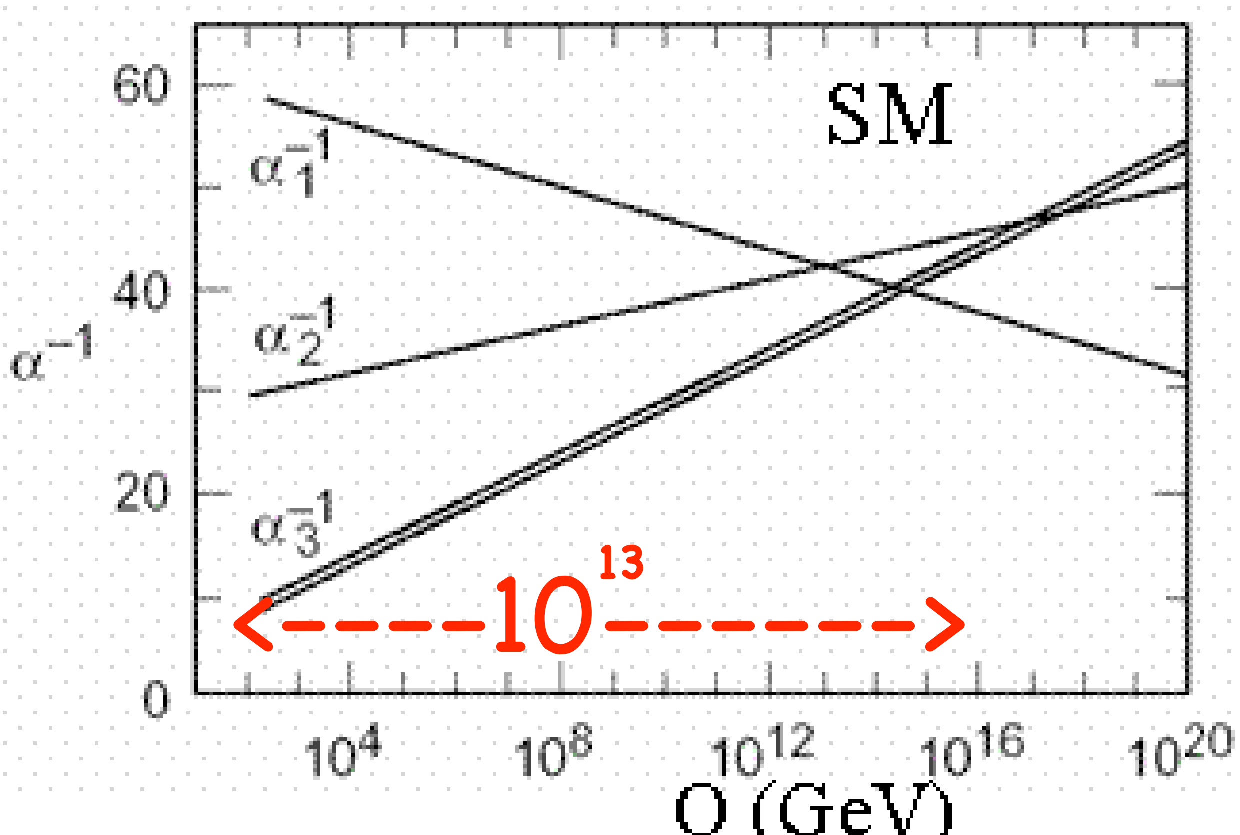
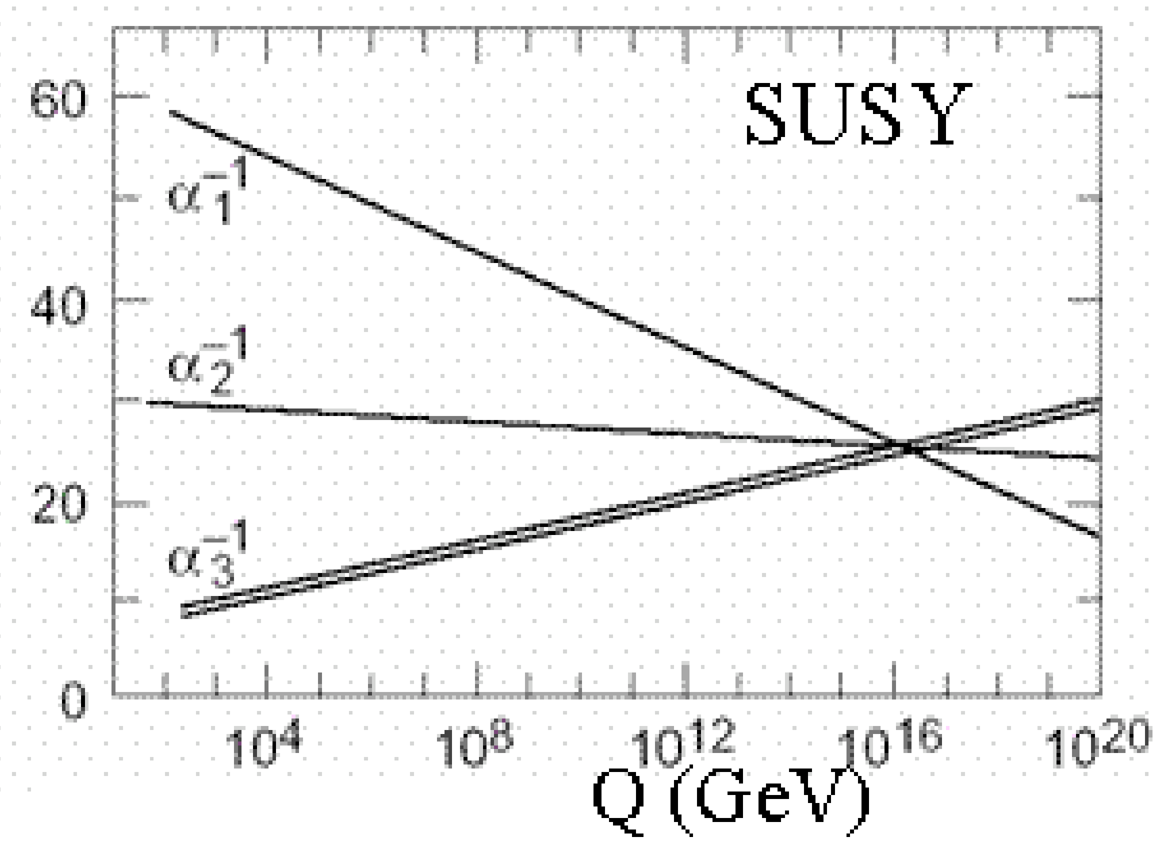






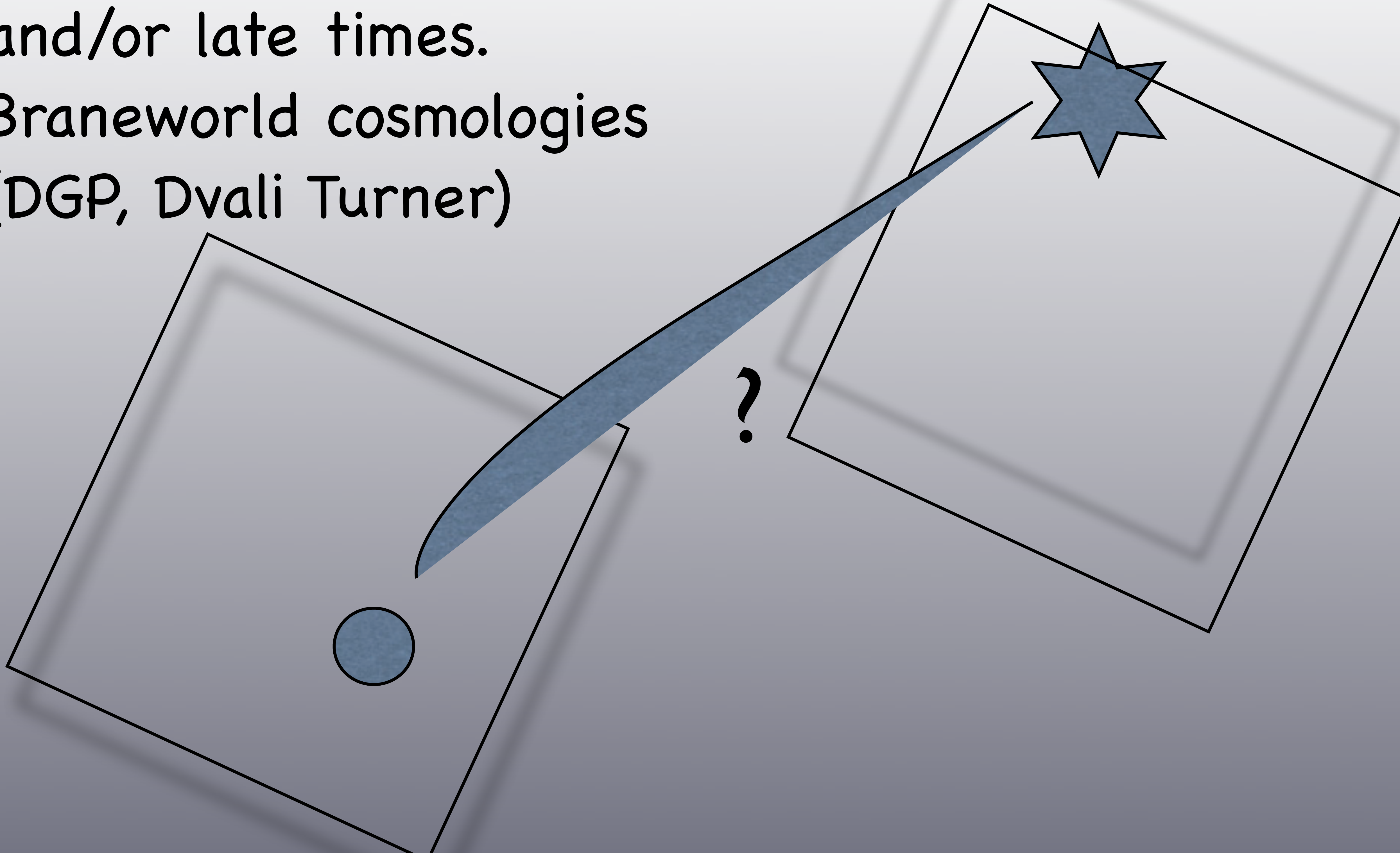
Is General Relativity Correct? NO!

(it might be modified at ultra large length scales)

Modified Gravity on ultra large length scales and/or late times.

Braneworld cosmologies

(DGP, Dvali Turner)



Dvali, Gabadadze, Porrati, Deffayet; Gabadadze, hep-th/0408118;
Carroll, Duvvuri, Trodden and Turner, PRD70 (2004);
Capozziello, Carloni and Troisi, astro-ph/0303041; Vollick, PRD68 (2003).

An Historical Note

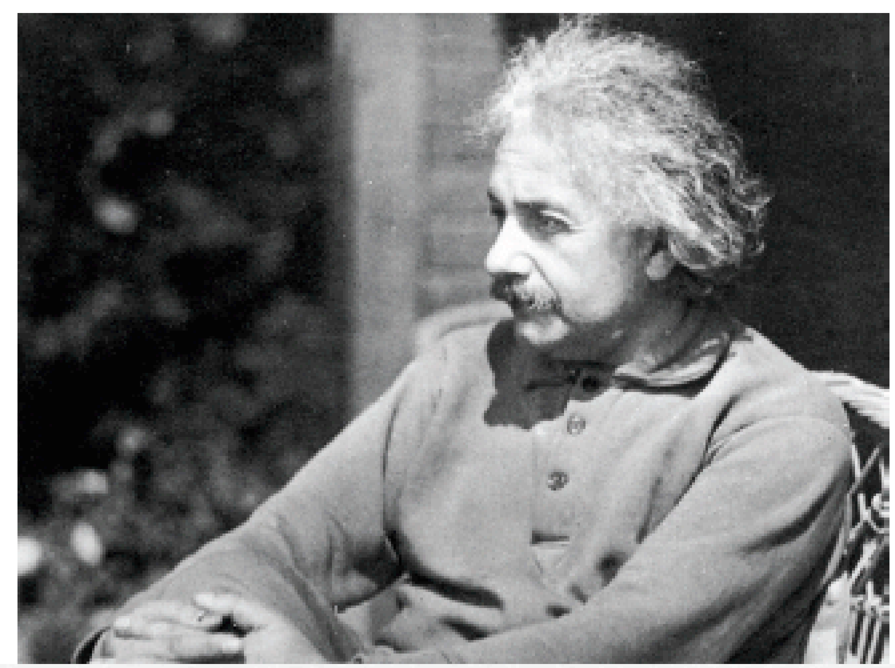
or....

Precedent?

Annales de l'Observatoire Impérial de Paris. Publiées par U. J. Leverrier, Directeur de l'Observatoire, tom. v. 4to, Paris, 1859.

This volume contains the theory and tables of *Mercury* by M. Leverrier; the discrepancy as regards the secular motion of the perihelion which is found to exist between theory and observation, led, as is well known, to the suggestion by M. Leverrier of the existence of a planet or group of small planets interior to *Mercury*. The volume contains also a memoir by M. Foucault, on the " Construction of Telescopes with Silvered

"[General Relativity] explains ... quantitatively ... the secular rotation of the orbit of Mercury, discovered by Le Verrier, ... without the need of any special hypothesis.",
SPAW, Nov 18, 1915



“Once bitten, twice shy”=

“El Hombre es el unico animal
que tropieza dos veces
con la misma piedra”

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and it is dark out there.

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$$R - \frac{\mu^{4n+2}}{(aR^2 + bR_{\mu\nu}R^{\mu\nu} + cR_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma})^n}$$

Carroll, De Felice, Duvvuri, Easson, Trodden, Turner, PRD71 (2005).

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Simplest model ~ 1/R ruled out by solar system data

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General model is OK with solar tests if

$$b = 4c \neq 0$$

Navarro and Van Acoleyen, PLB622 (2005); gr-qc/0511045.

Modifications of gravity may provide the explanation for the current accelerated expansion.

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Identify the distinguishing features and data fits are absolutely necessary.

Knox, Song and Tyson, astro-ph/0503644; Song, PRD7 (2005);
Upadhye and Spergel, astro-ph/0507184;
Amarzguioui, Elgaroy, Mota and Multamaki, astro-ph/0510519;
Sawicki and Carroll, astro-ph/0510364;
Alam and Sahni, astro-ph/0209443: astro-ph/0511473;
Fairbairn and Goobar, astro-ph/0511029;
Szydlowski and Godlowski, astro-ph/0511259;
Nesseris and Perivolaropoulos, astro-ph/0511040;
Zhang, astro-ph/0511218.

Bento et al, astro_ph/0512076;
Koyama, astro_ph/0601220;
Song, astro_ph/0602598;
Moffat, astro_ph/0602607;
Koyama, astr_ph/0601220;
de Felice et al, astro_ph/0604154;
Basset et al, astro_ph/0605278;
Carneiro et al, astro_ph/0605607;

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Geometrical technique of measuring distances!

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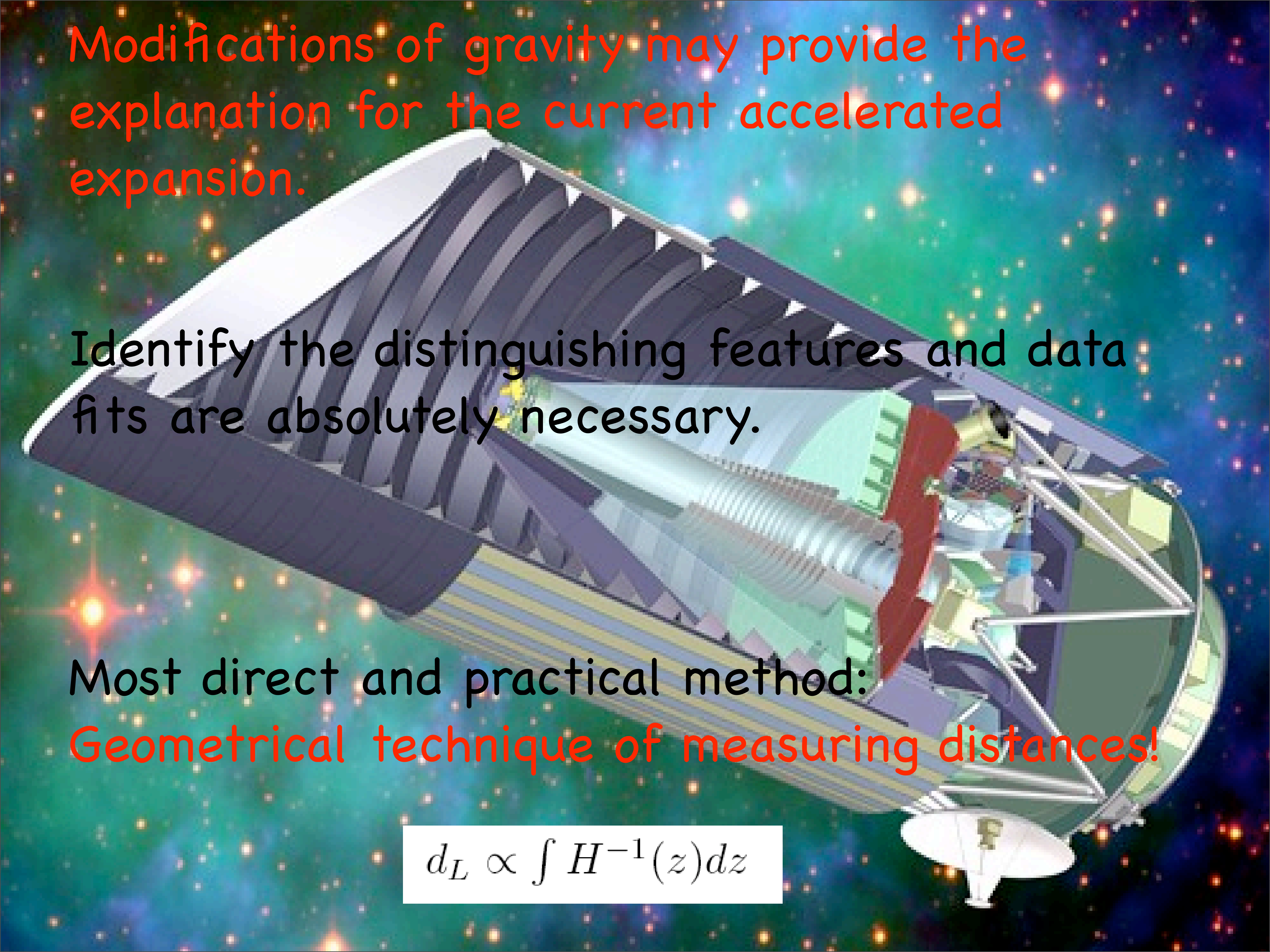

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We need to solve the Friedmann Equation

$$H^2 = \frac{8\pi G}{3}\rho$$

We need to solve the modified Friedmann Equation

$$\frac{H'' F_1(H,H') + F_2(H,H')}{F_3(H,H')} \frac{\mu^6}{H^4} + H^2 = \frac{8\pi G}{3}\rho$$

Non linear second order differential equation

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Non linear second order differential equation

$$\frac{8\pi G}{3}\rho = \frac{8\pi G}{3}\left(\frac{\rho_{r0}}{a^4} + \frac{\rho_{m0}}{a^3}\right) \equiv \frac{\omega_{r0}}{a^4} + \frac{\omega_{m0}}{a^3}$$

Numerical codes can NOT solve the modified equation due to STIFFNESS

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Matching to a perturbative analytical solution

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$$H_{\mathrm{approx}} = \bar{H}\left(1 - \frac{1}{2}\,\frac{\bar{H}''F_1(\bar{H},\bar{H}') + F_2(\bar{H},\bar{H}')}{F_3(\bar{H},\bar{H}')}\,\frac{\mu^6}{\bar{H}^4}\right)$$

$\bar{H}$ is the standard Einstein solution

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z≥5 Very accurate solution (better than 0.1%)

z≈5 Initial conditions

z<5 Numerical solution until today (z=0)

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NUMERICAL INTEGRATION WORKS!

We are ready to fit SN Ia data,

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In principle....

$$\hat{\mu} \equiv \mu/|12a + 3b + 2c|^{1/6} \qquad \sigma \equiv \mathrm{sign}(12a + 3b + 2c)$$

$$\bar{\omega}_m \equiv \frac{8\pi G}{3}\frac{\rho_{m0}}{\hat{\mu}^2} \qquad \alpha \equiv \frac{12a + 4b + 4c}{12a + 3b + 2c}$$

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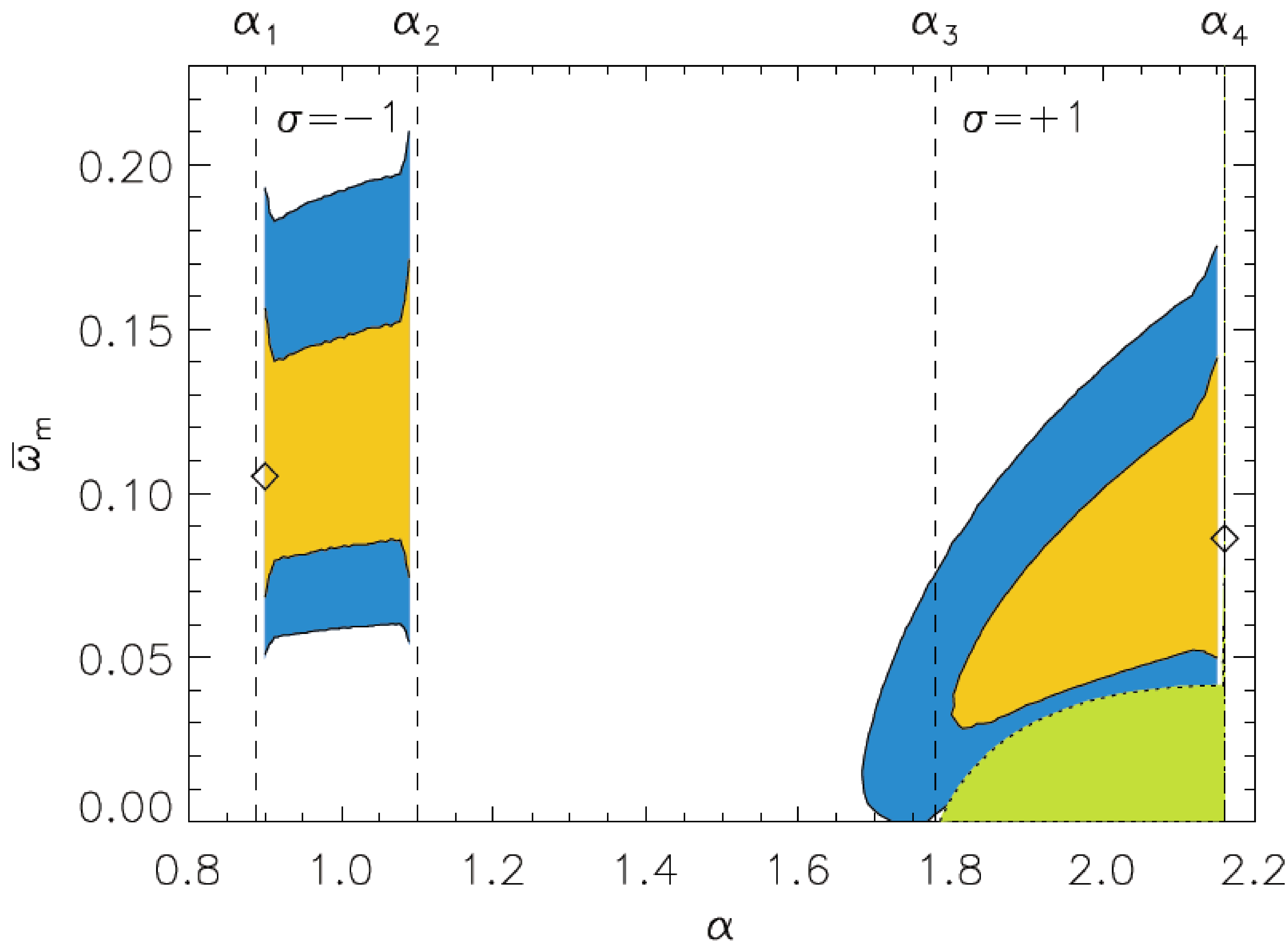
There are four parameters. In practice...

SN Ia data insensitive to the absolute scale of H(z)

$\hat{\mu} d_L$ IN TERMS OF α AND $\bar{\omega}_m$ ONLY!

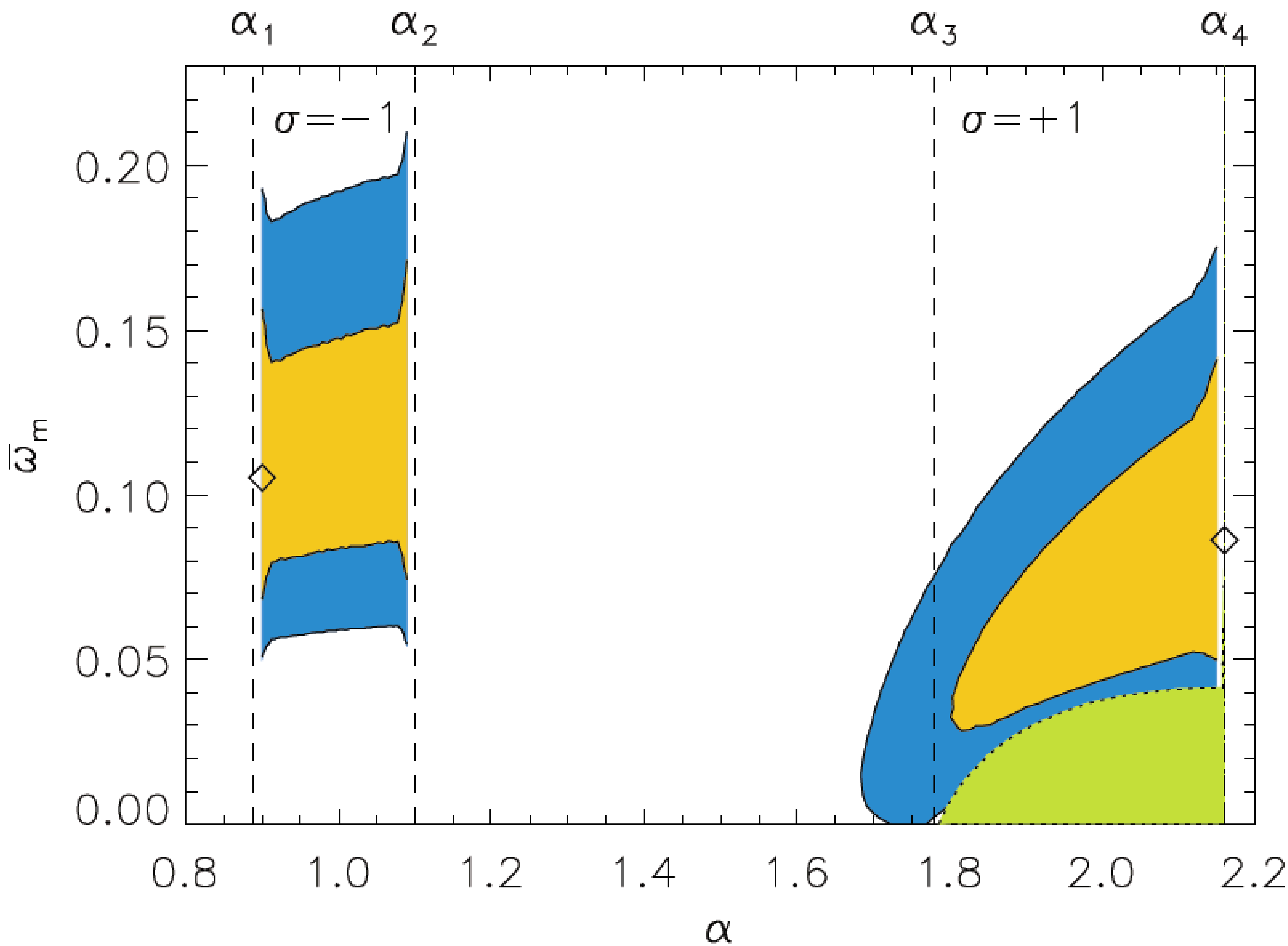
What about σ

What about σ



Fit to SN Ia Golden data set of HST (Riess et al'04)

What about σ



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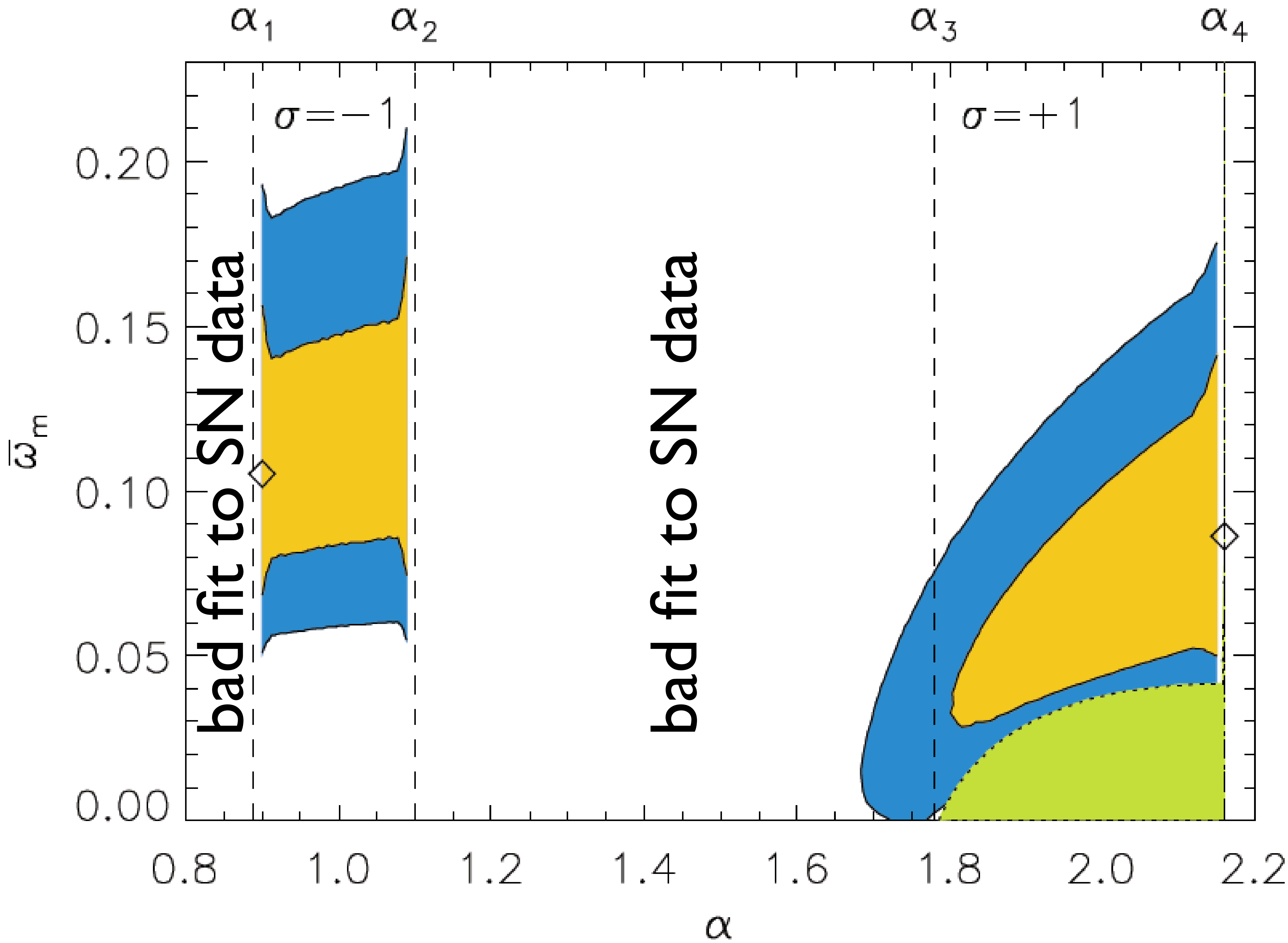

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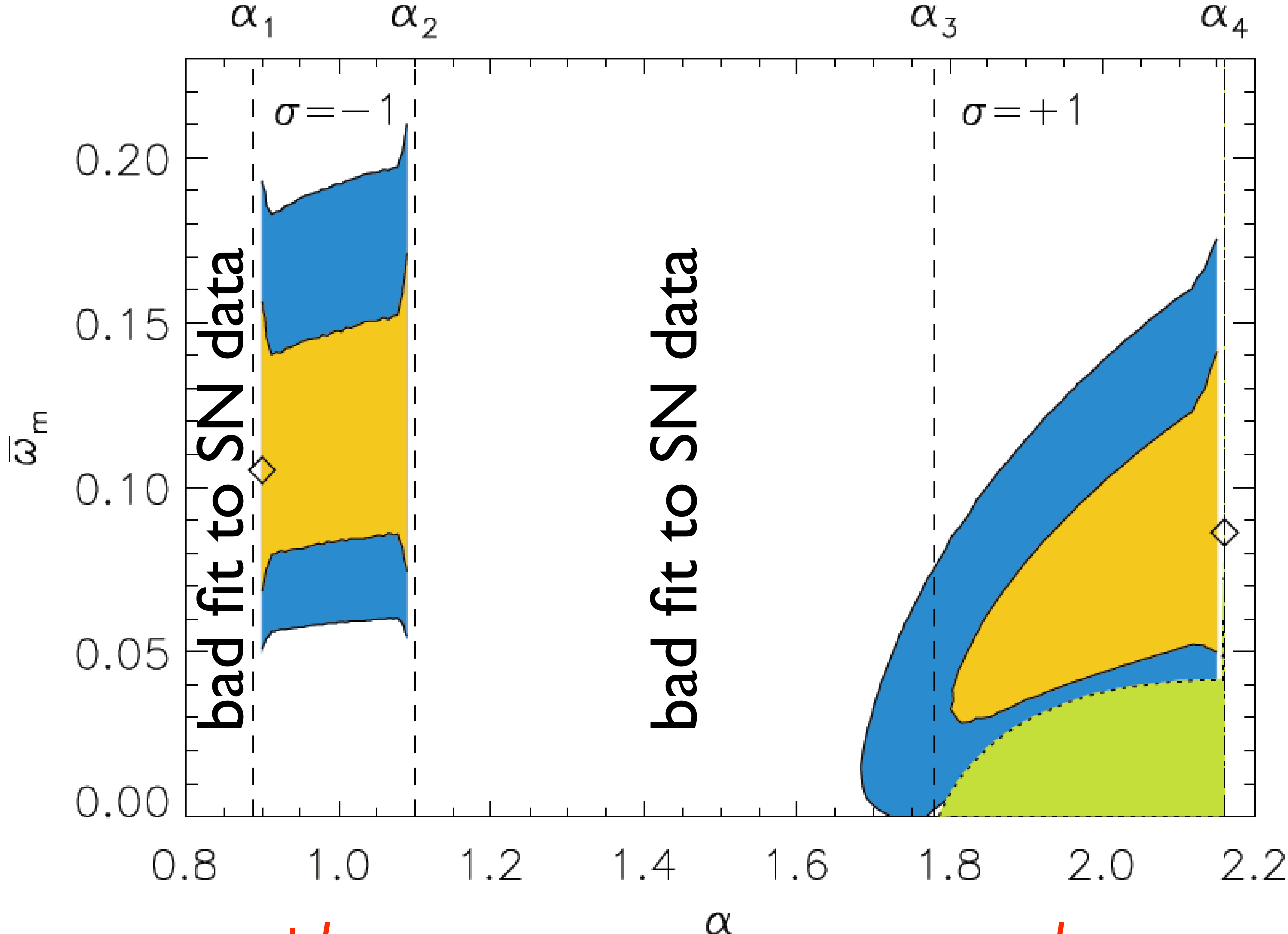
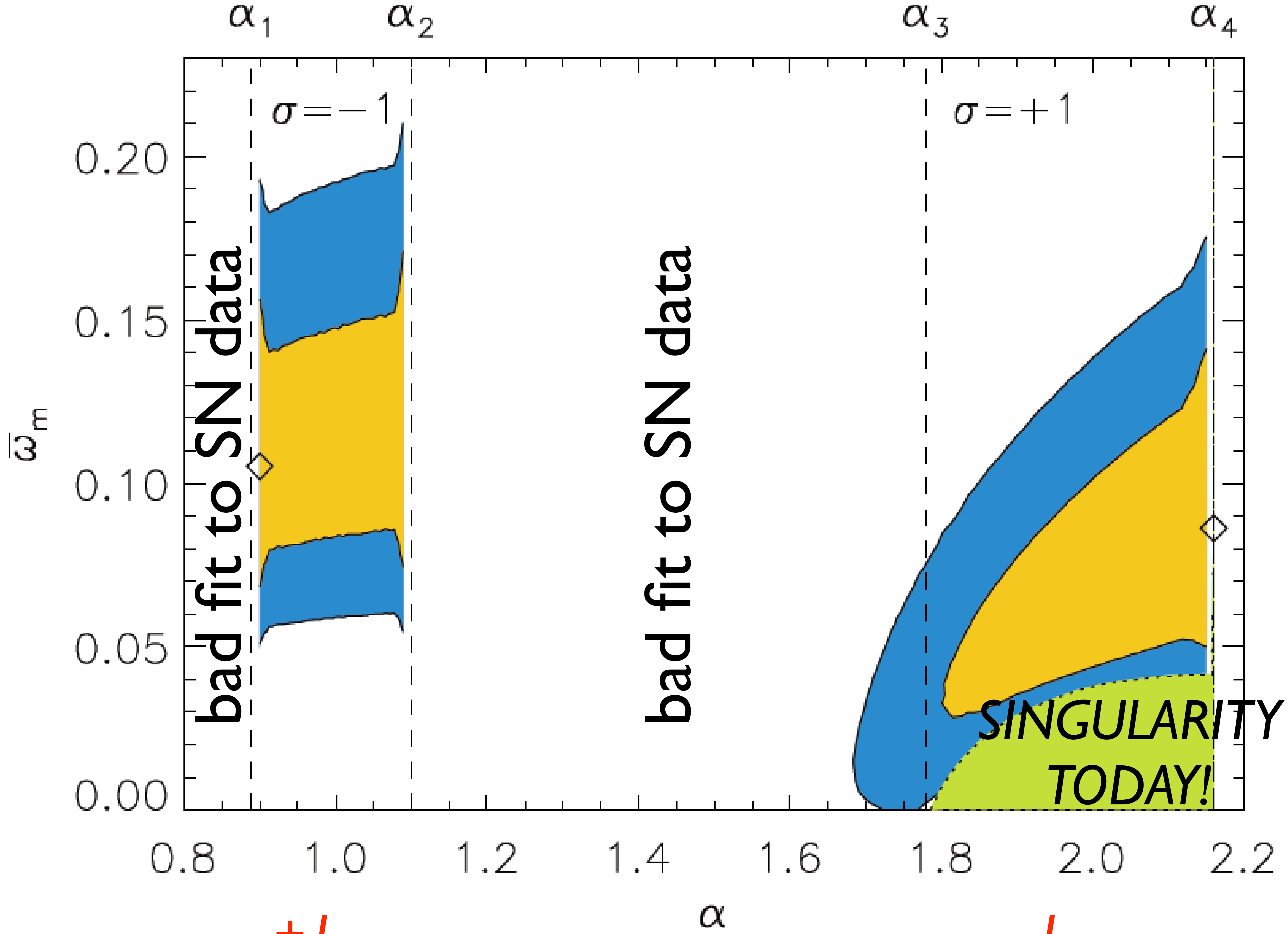


+1

-1

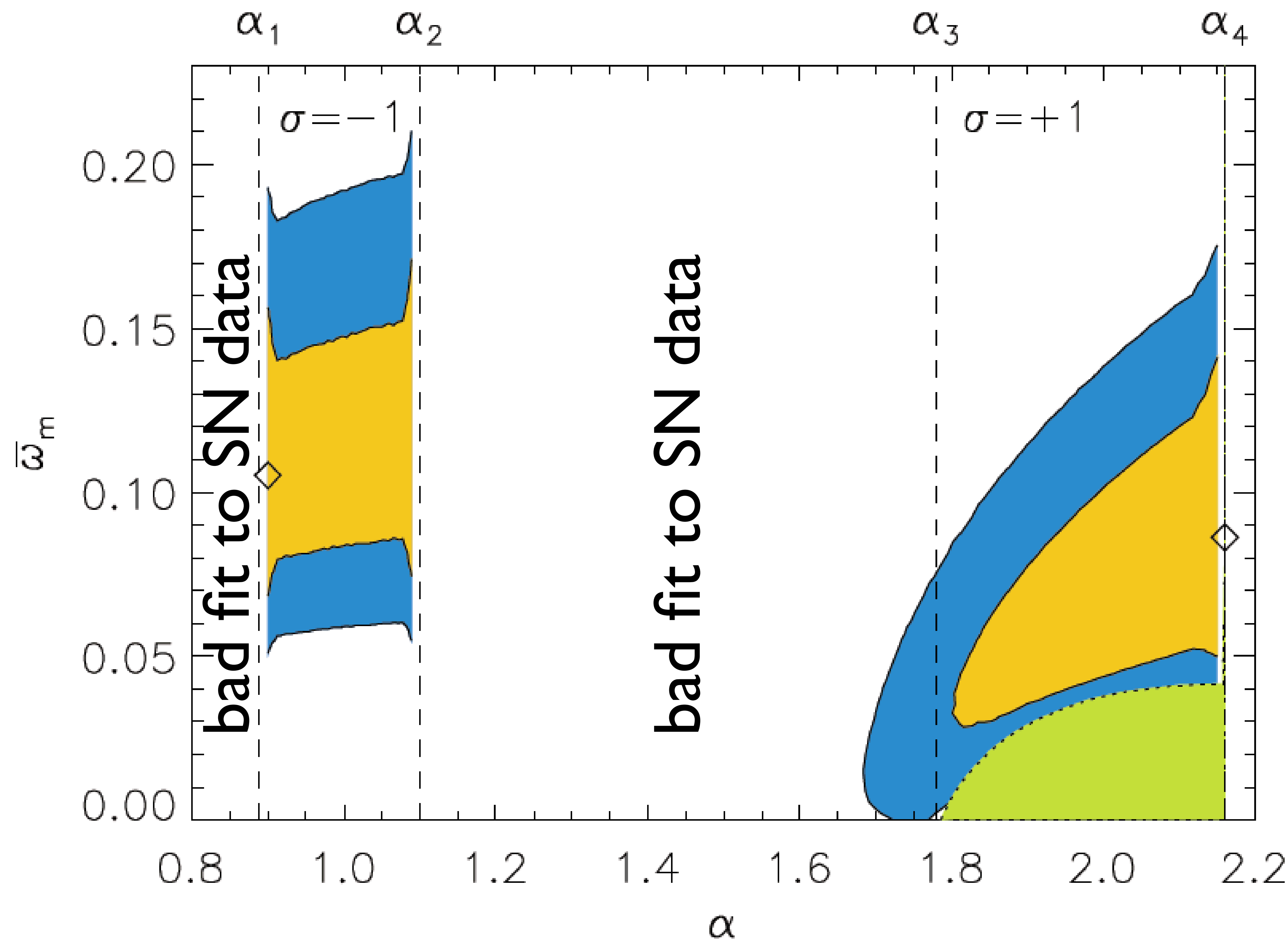
SINGULARITY IN THE PAST

What about σ



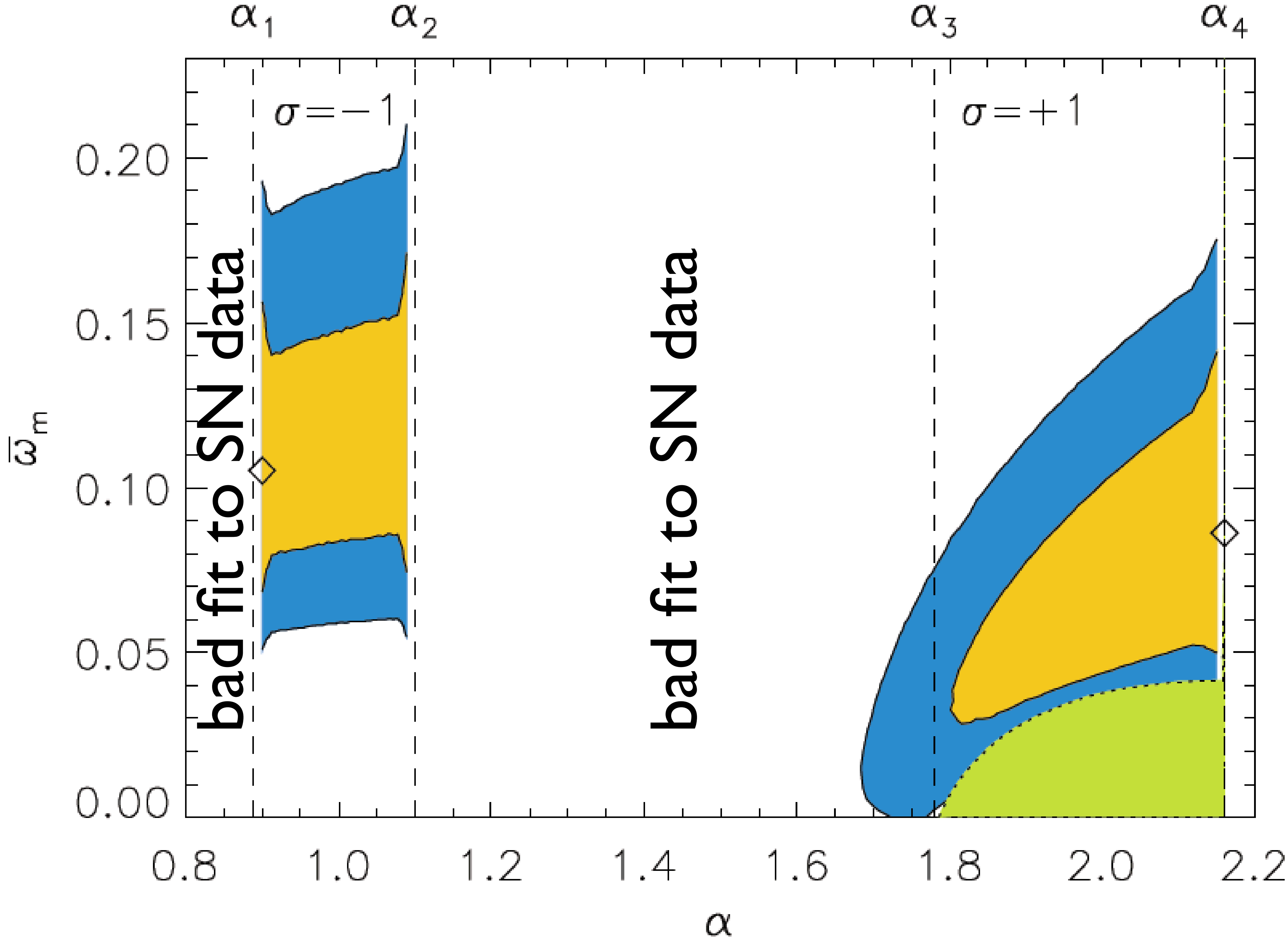
+1 -1

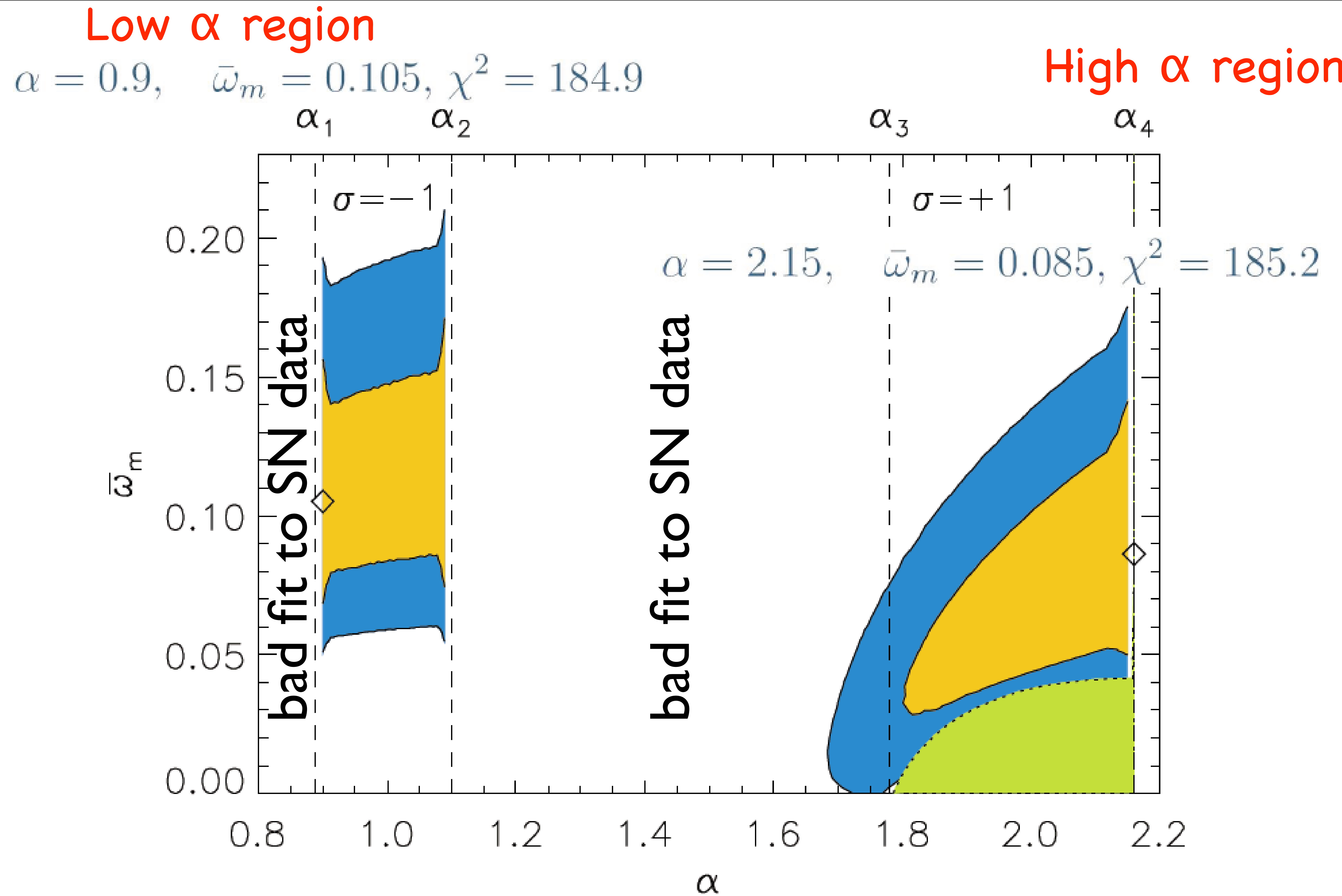
SINGULARITY IN THE PAST


α1
α2
α3
α4
σ=−1
σ=+1
bad fit to SN data
bad fit to SN data
0.20
0.15
0.10
0.05
0.00
ω̄m
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
α

Low α region

$\alpha = 0.9, \quad \bar{\omega}_m = 0.105, \chi^2 = 184.9$




Low α region
$\alpha = 0.9, \quad \bar{\omega}_m = 0.105, \chi^2 = 184.9$
High α region
α_1
α_2
α_3
α_4
$\sigma = -1$
$\sigma = +1$
$\alpha = 2.15, \quad \bar{\omega}_m = 0.085, \chi^2 = 185.2$
bad fit to SN data
bad fit to SN data
$\bar{\omega}_m$
0.20
0.15
0.10
0.05
0.00
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
α

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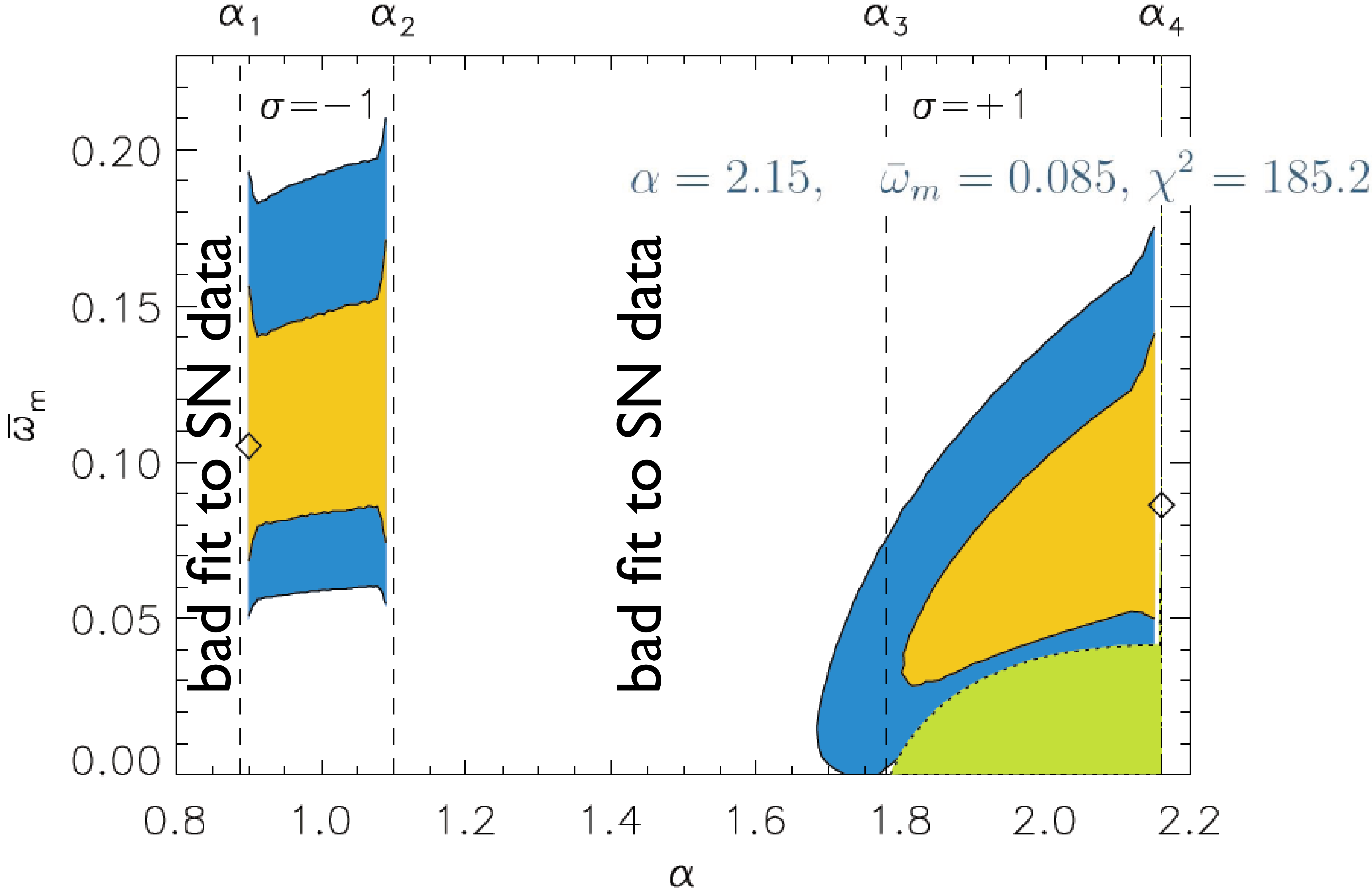

Very good fits!

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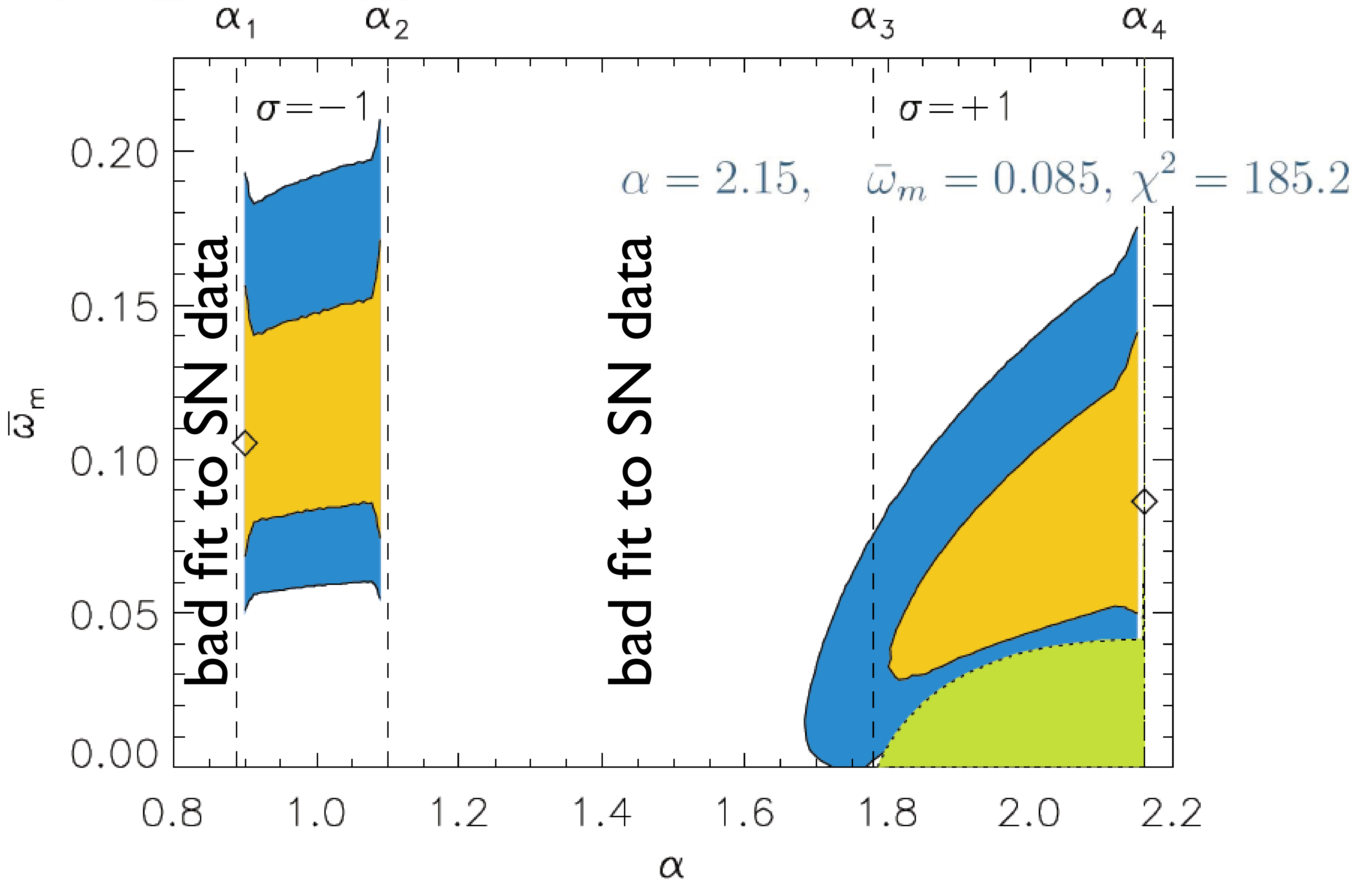

Very good fits! $\Lambda\mathrm{CDM}\ (\chi^2 = 183.3)$

SETTING SCALES! We impose two priors:

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$H_0 = 72 \pm 8$ Km s^{-1} Mpc^{-1} HKP (Freedman et al'01)

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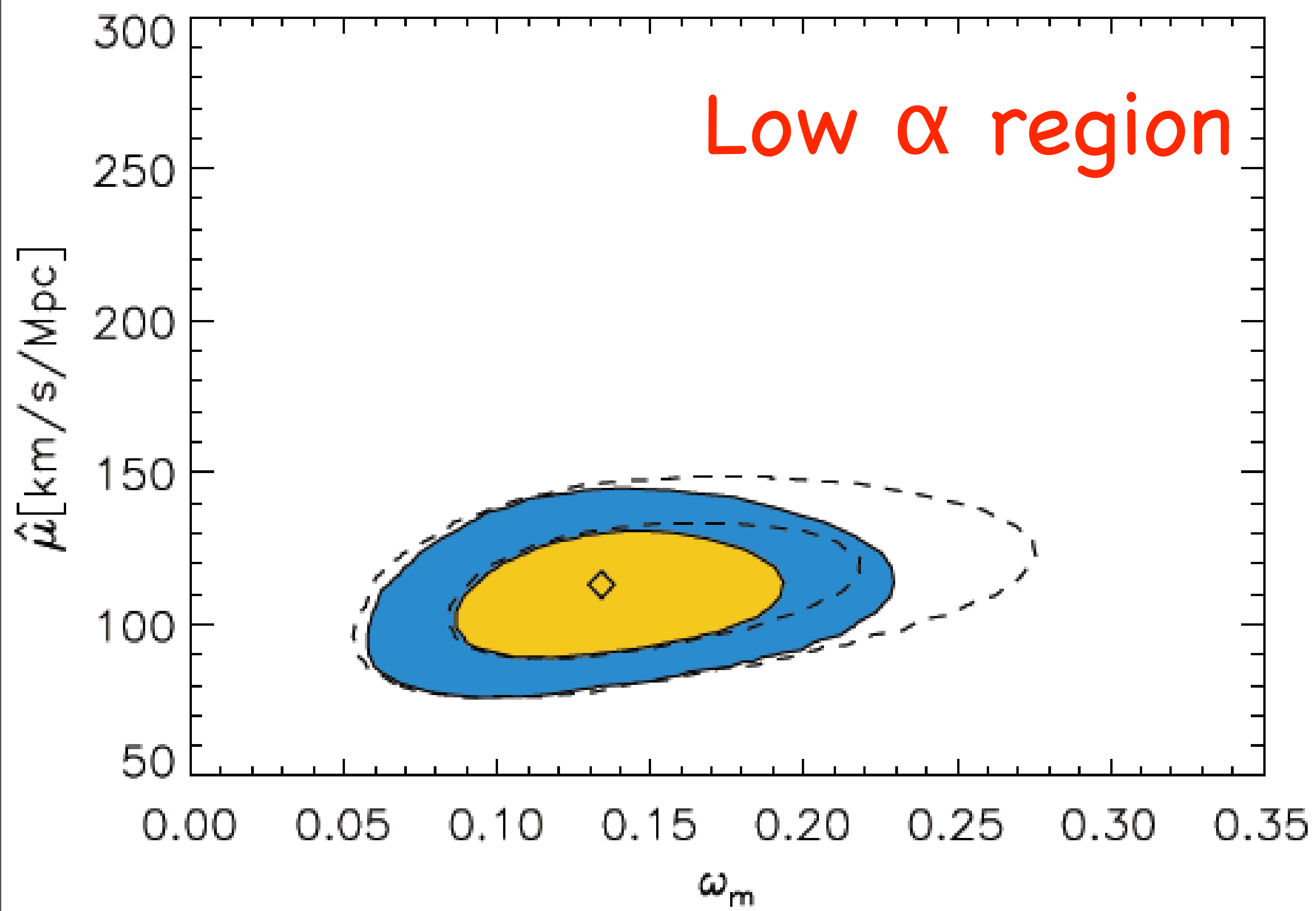

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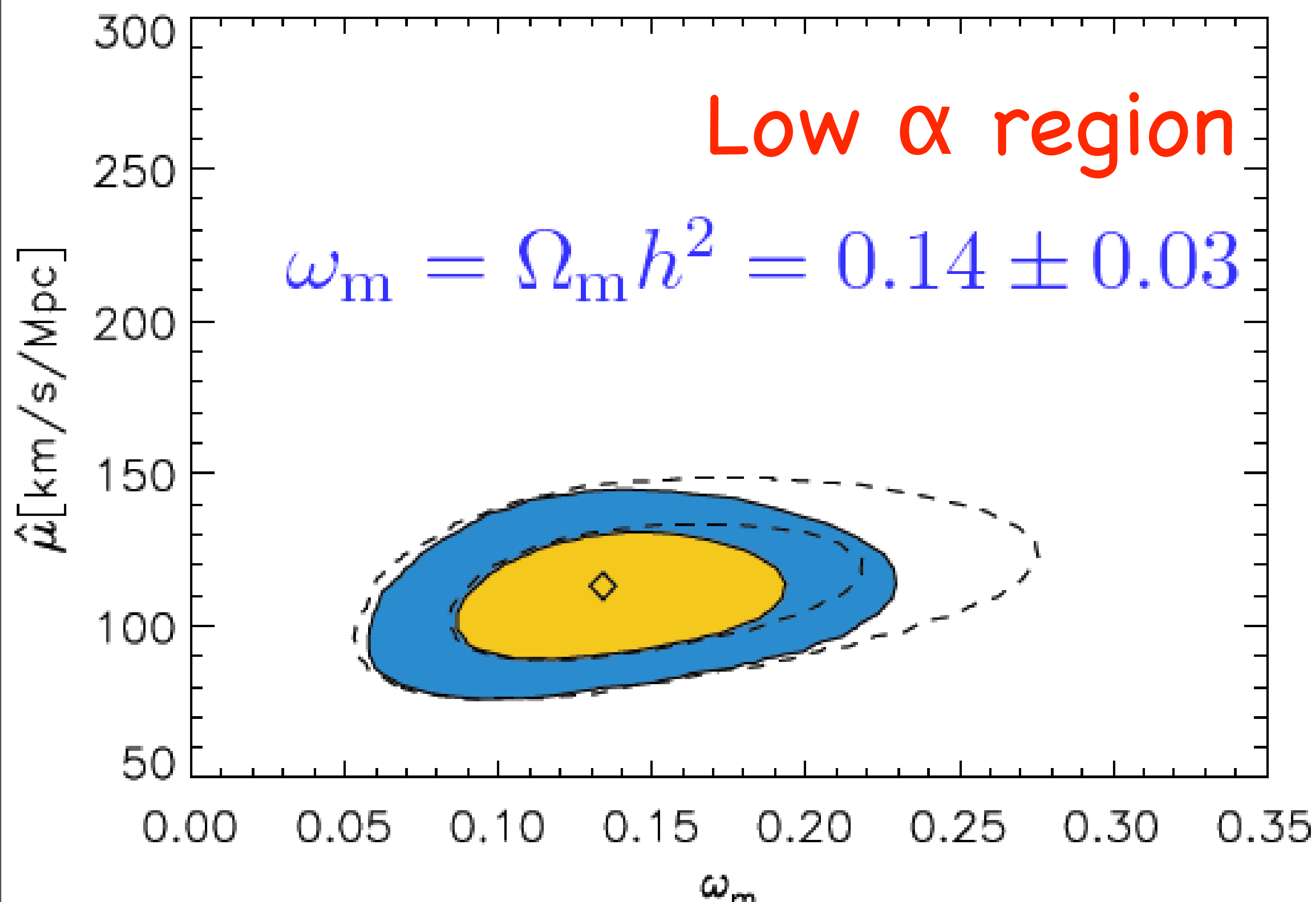

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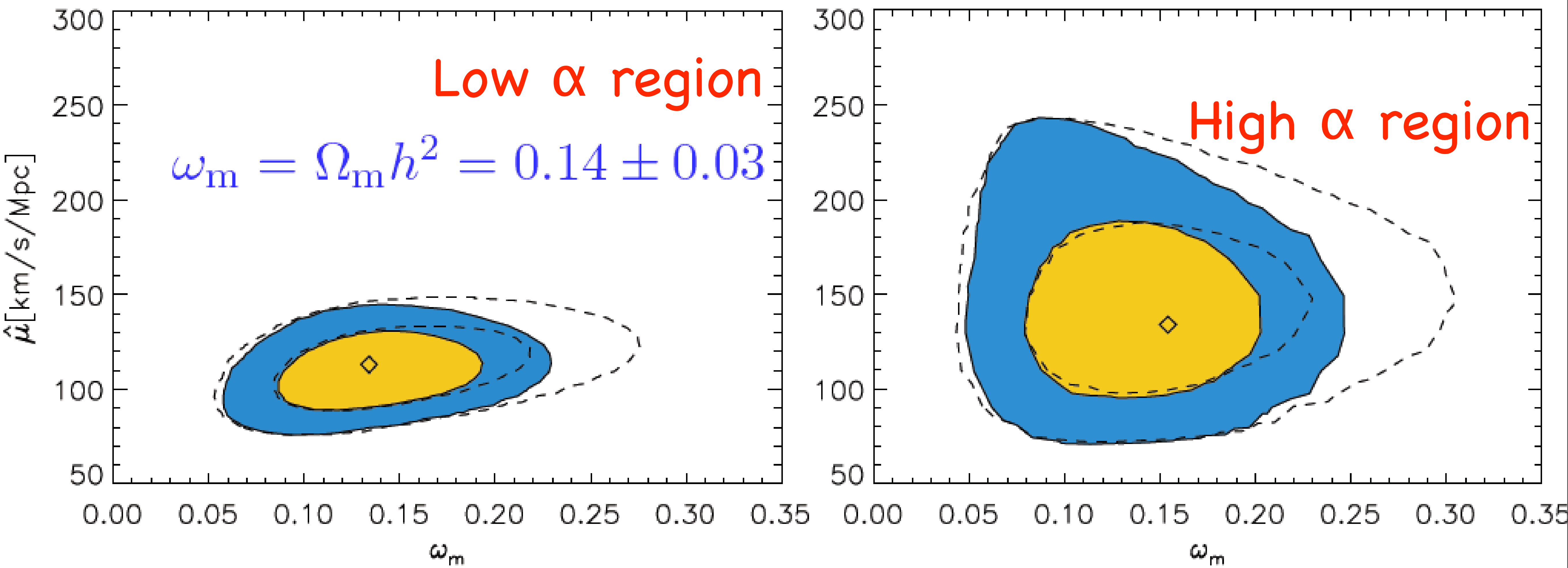
$t_0 > 11.2$ Gyrs at 95% CL (Kraus, Chaboyer'03)

After marginalization over α



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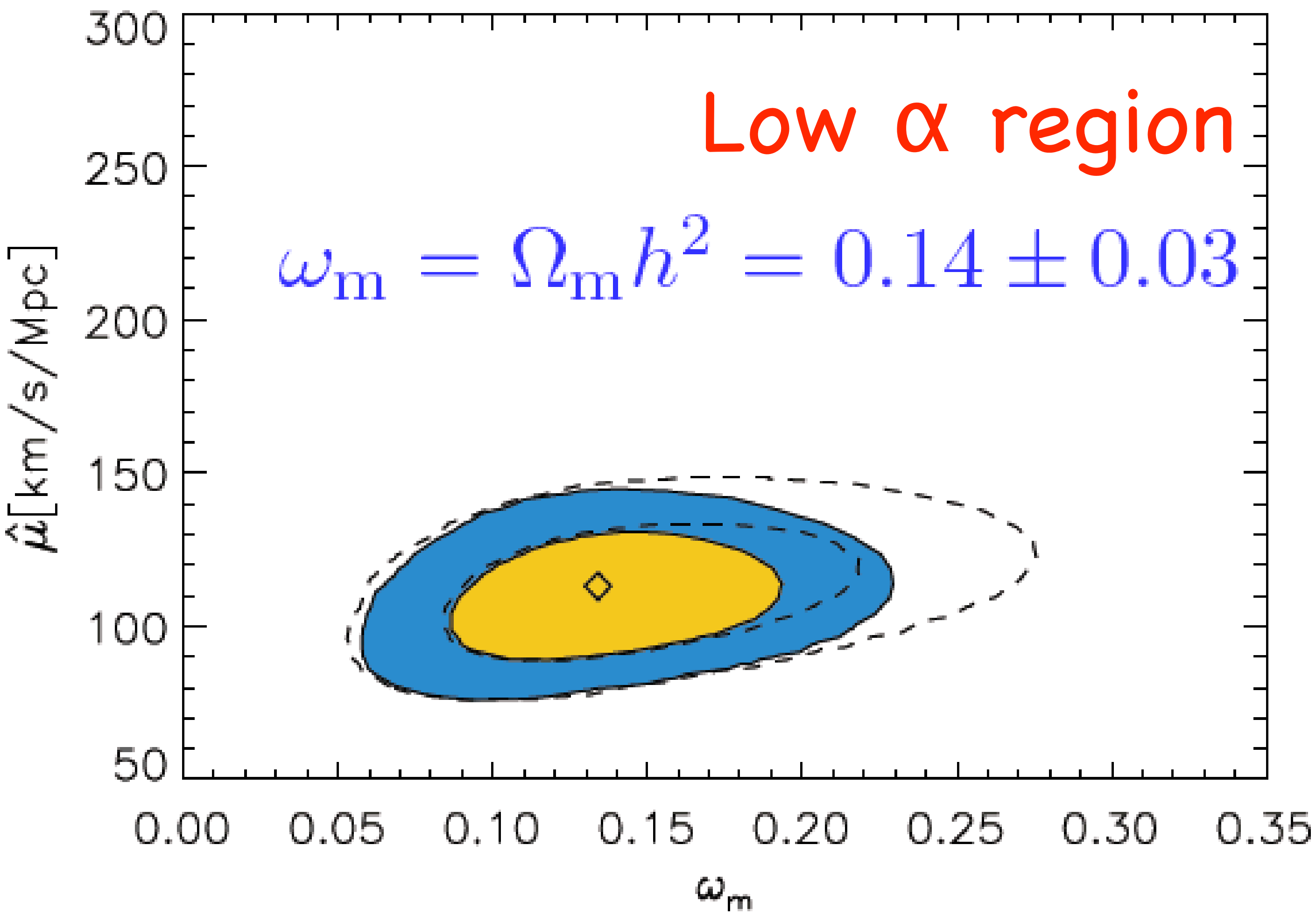
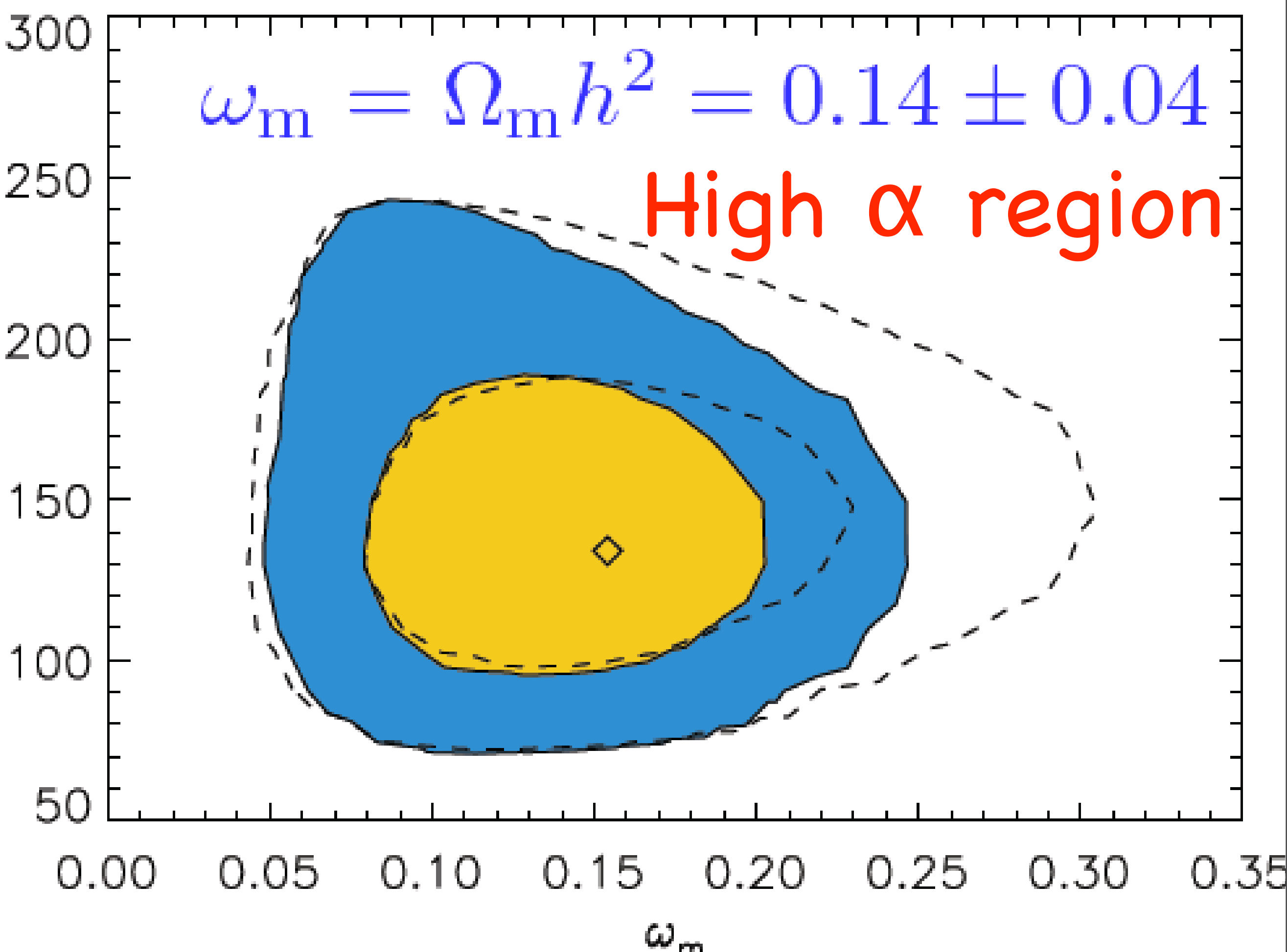
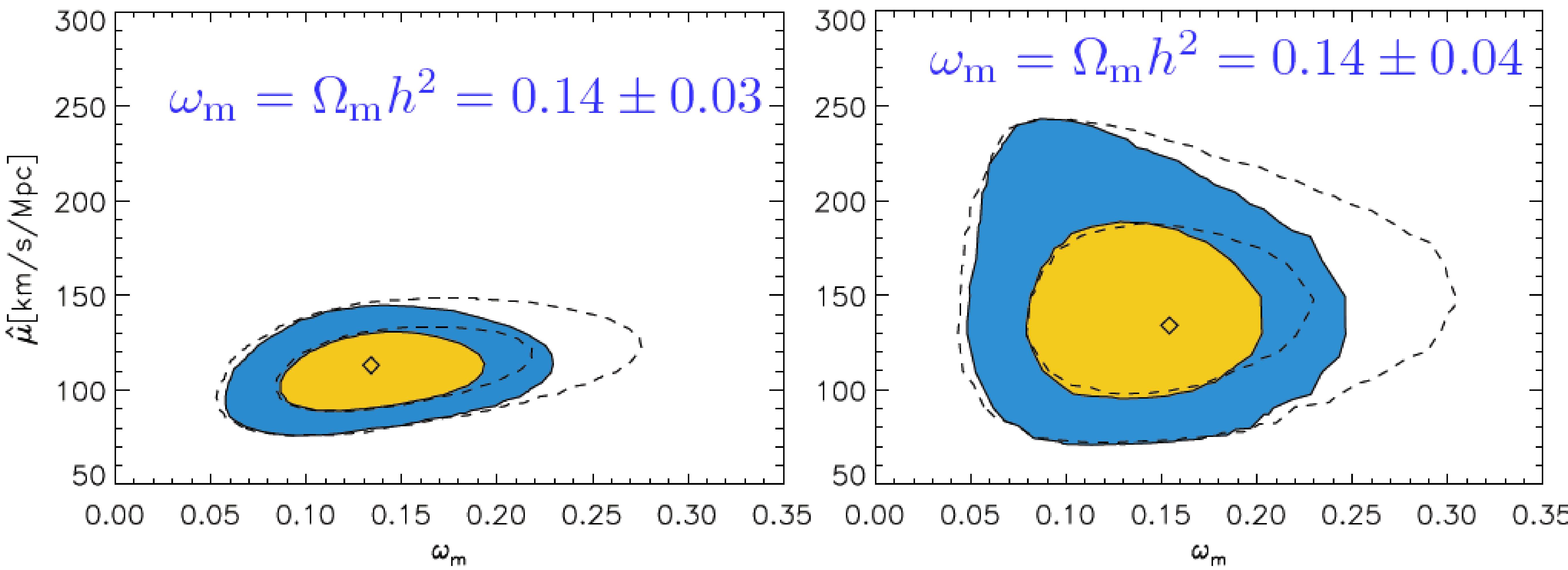




We find

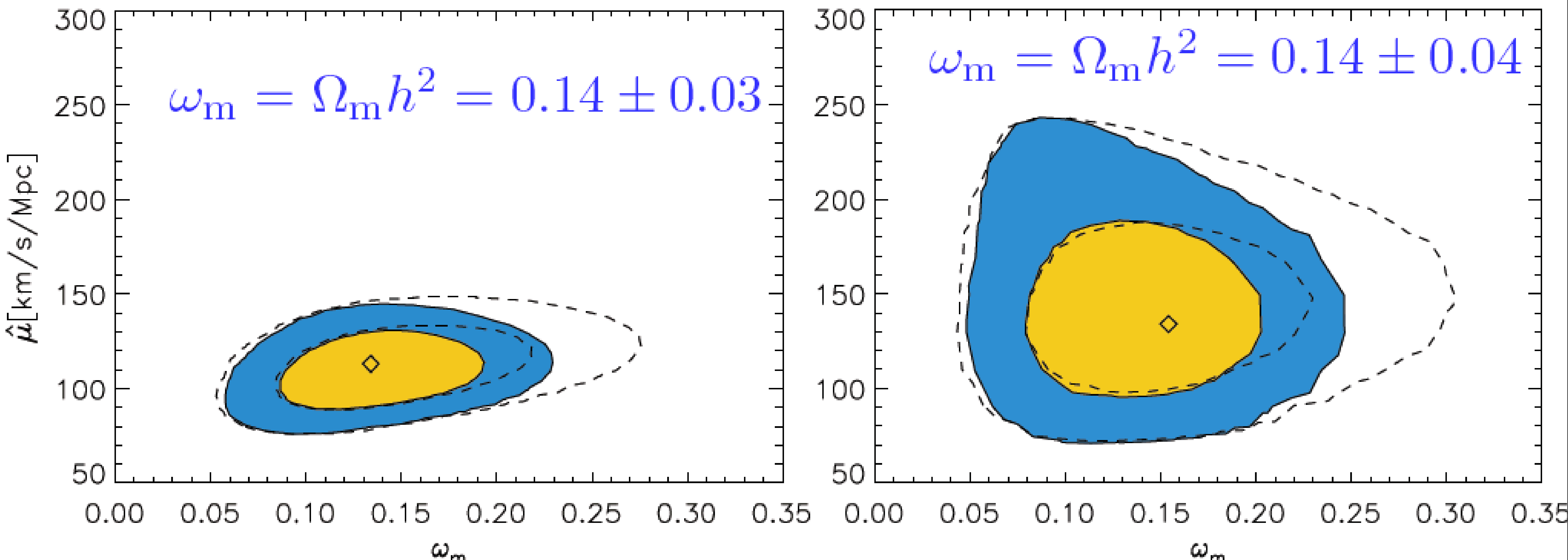


$\omega_m = \Omega_m h^2 = 0.14 \pm 0.03$
$\omega_m = \Omega_m h^2 = 0.14 \pm 0.04$
$\hat{\mu}$[km/s/Mpc]
ω_m
300
250
200
150
100
50
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

We find

$0.07 \leq \omega_{\rm m} \leq 0.21$ @ 95% CL, that compare to:

$$\omega_{\rm b} = 0.0214 \pm 0.0020$$



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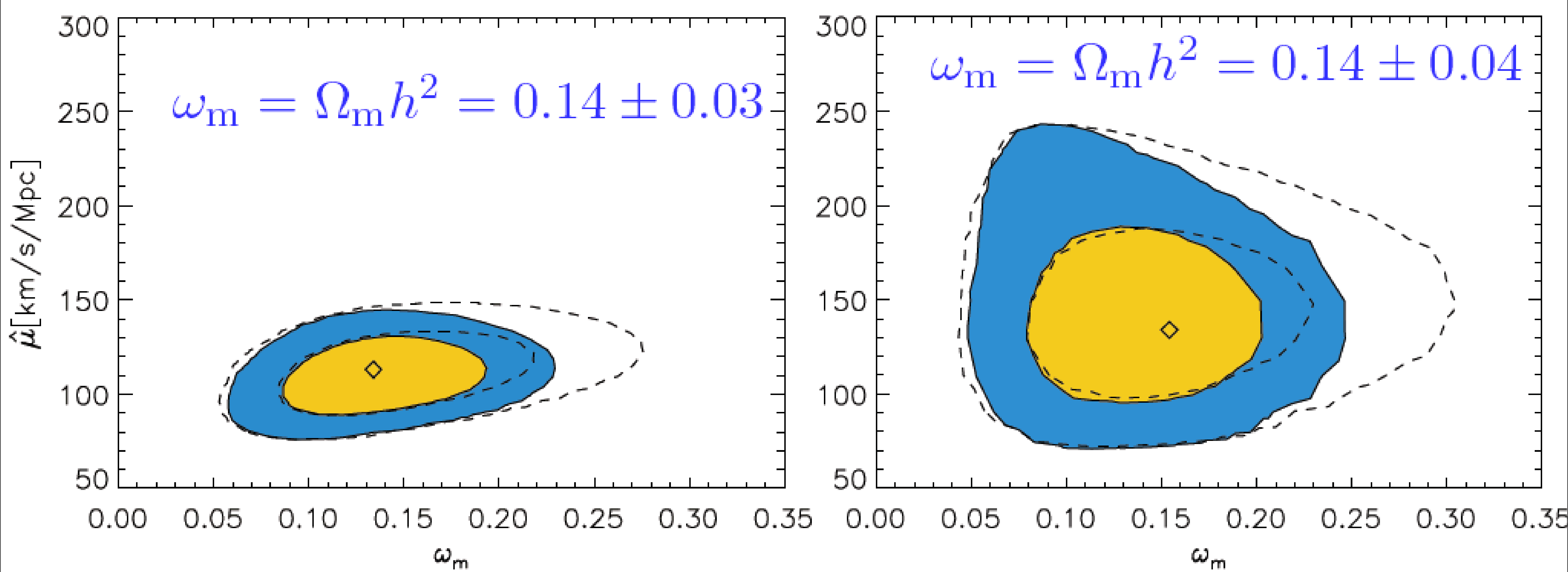
We still require "dark matter" to fit SNIa data



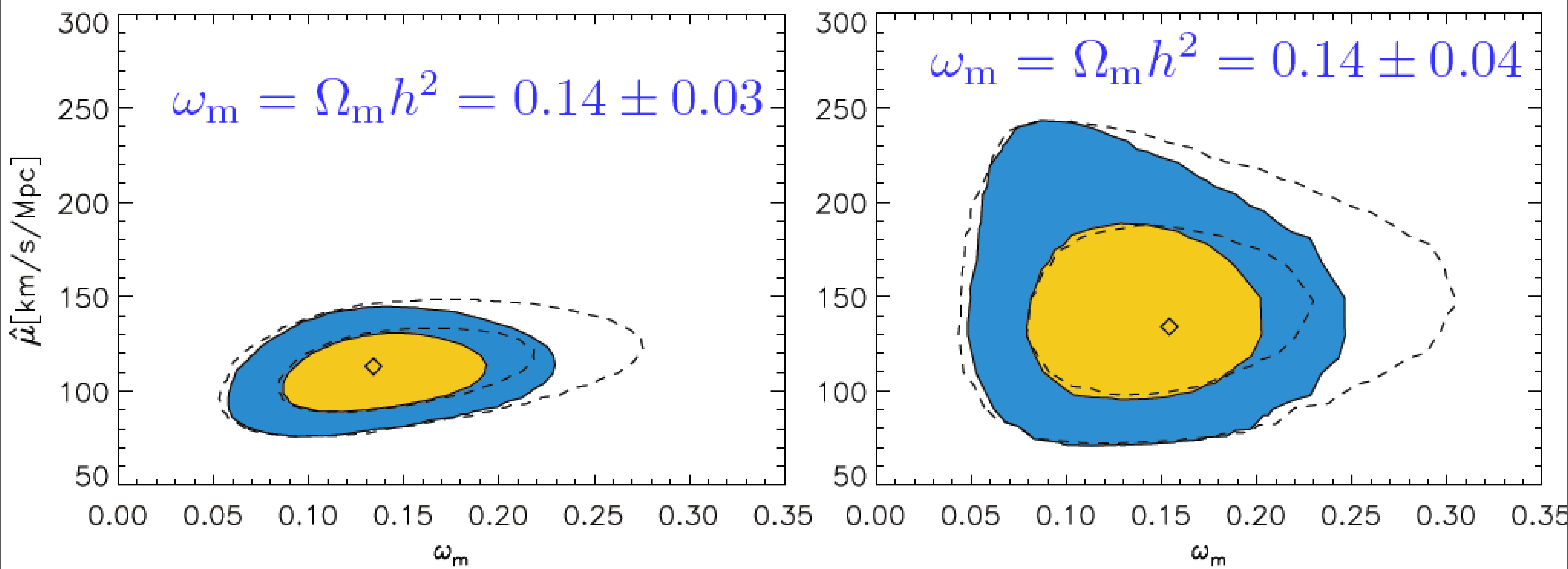
We find

$0.07 \leq \omega_{\rm m} \leq 0.21$ @ 95% CL, that compare to:

$$\omega_{\rm b} = 0.0214 \pm 0.0020$$

However, other modifications (for instance $n \neq 1$)

might also account for the "dark matter"



FINAL REMARKS!

We might be missing something really important in our picture of the universe.

Future SN surveys may identify the new physics responsible for the current accelerated expansion:

Modifications of Gravity at small curvatures are a possible geometrical explanation and should be considered among the models fitted to the data

Extend the analysis to CMB and cluster datasets

SN Ia data insensitive to the absolute scale of H(z)

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$$m(z) = \mathcal{M} + 5 \log \hat{\mu} d_L$$

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Nuisance parameter!

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$$\hat{\mu} d_L$$

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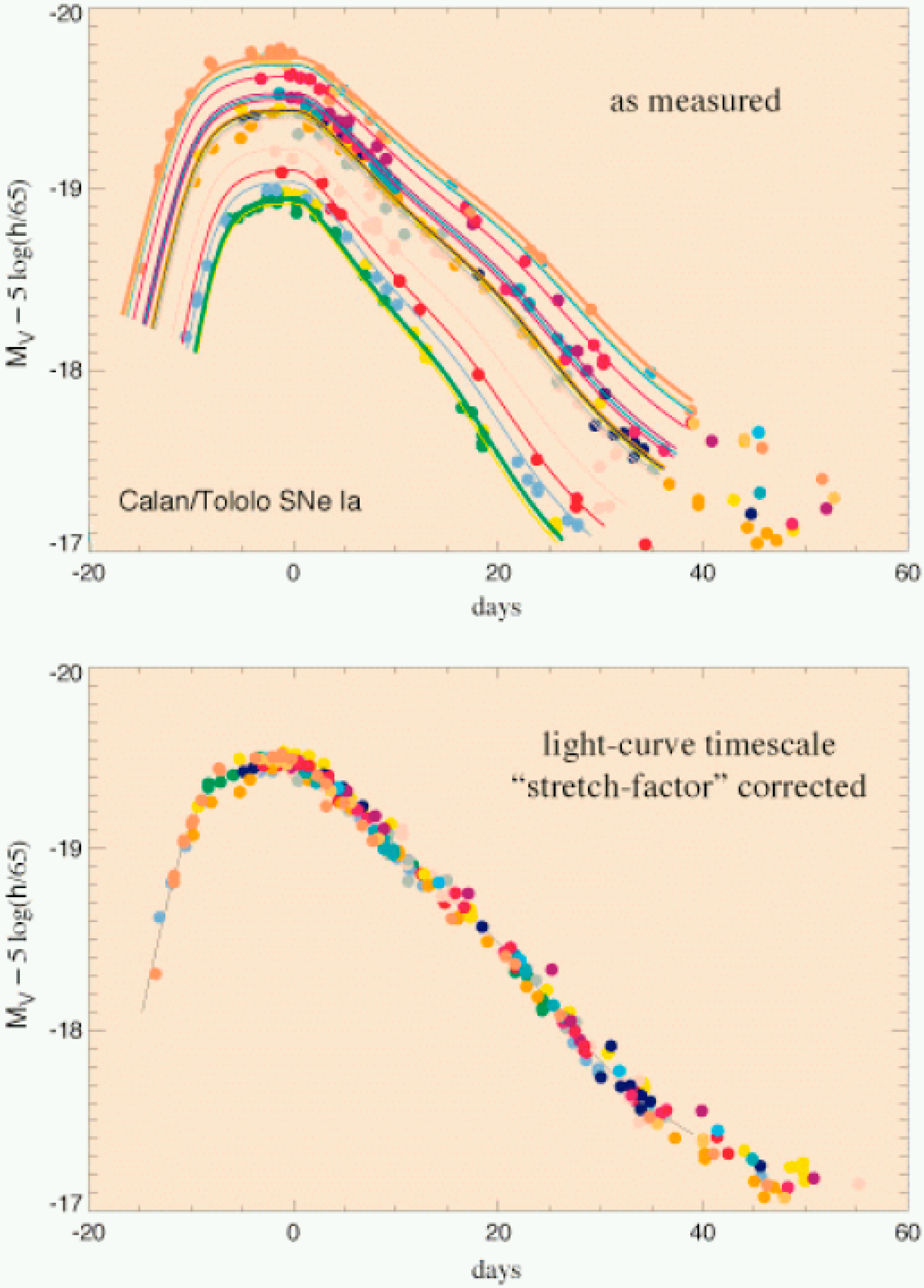
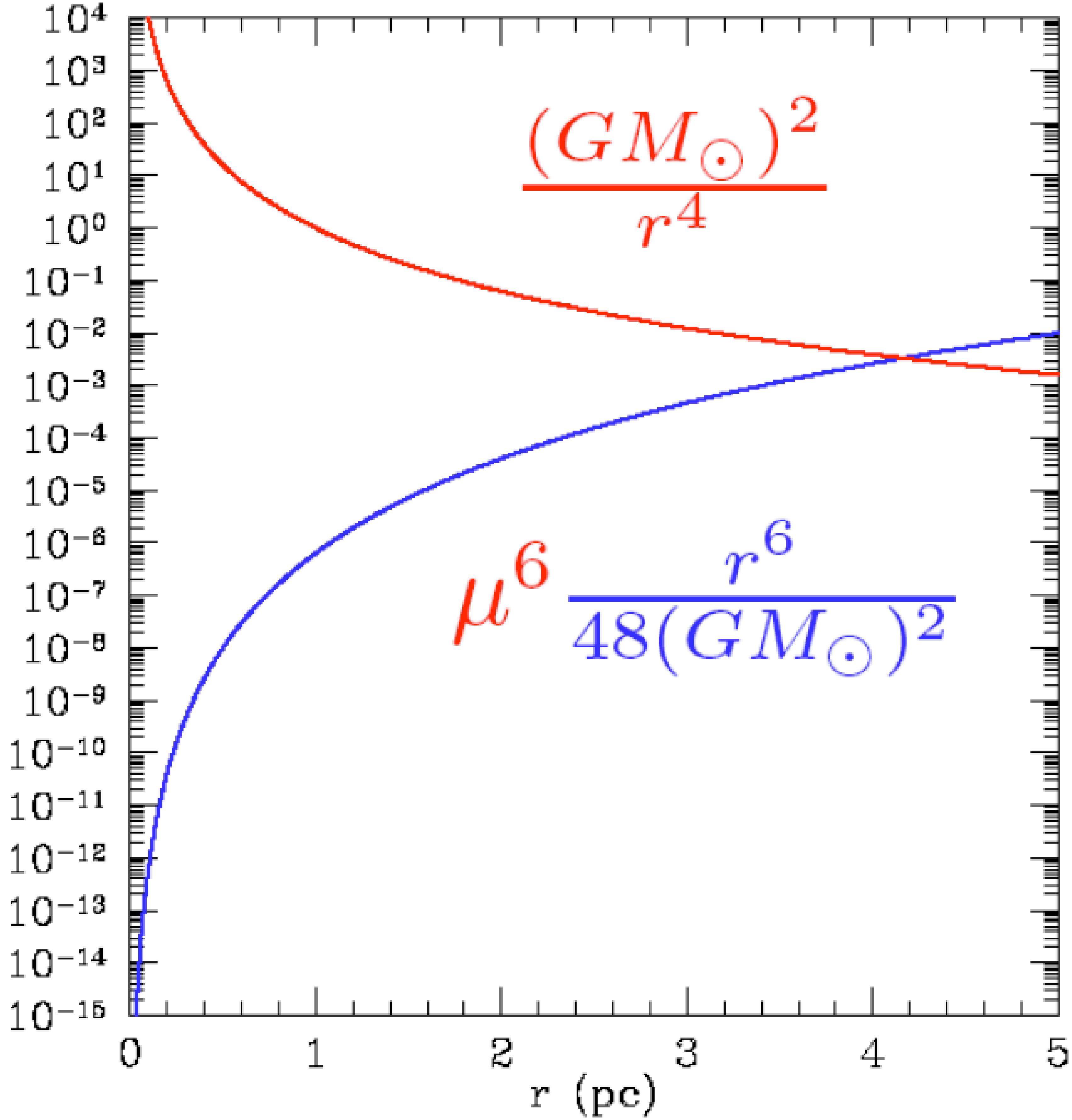
Nuisance parameter!

$\hat{\mu} d_L$ IN TERMS OF α AND $\bar{\omega}_m$ ONLY!

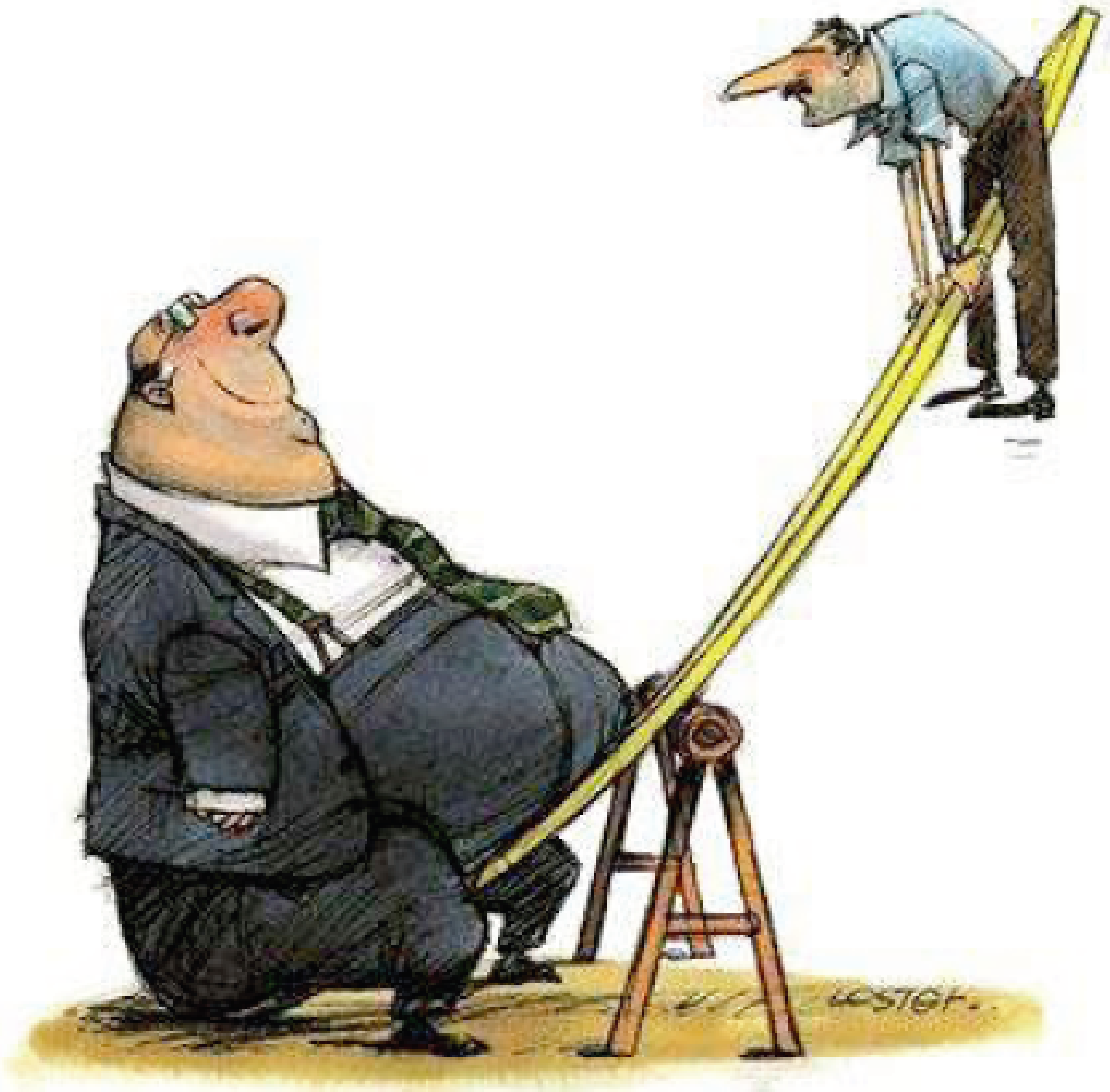
$$\bar{\omega}_{r,m} \equiv \frac{8\pi G}{3}\frac{\rho_{r,m\,0}}{\hat{\mu}^2}$$

V Band

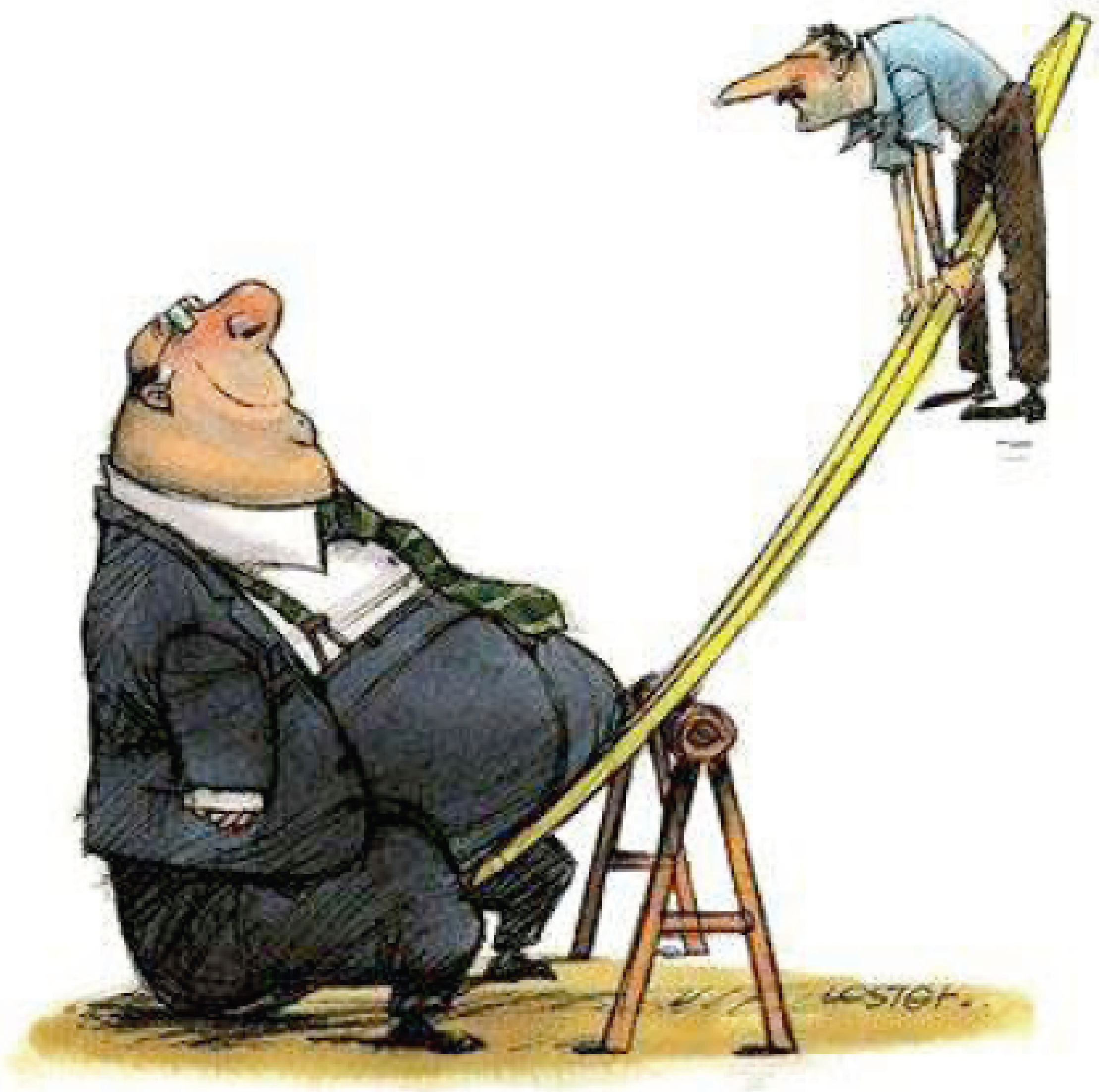

as measured
Calan/Tololo SNe Ia
$M_V - 5\log(h/65)$
days
light-curve timescale
"stretch-factor" corrected
$M_V - 5\log(h/65)$
days



$\frac{(GM_\odot)^2}{r^4}$
$\mu^6 \frac{r^6}{48(GM_\odot)^2}$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0
1
2
3
4
5
r (pc)



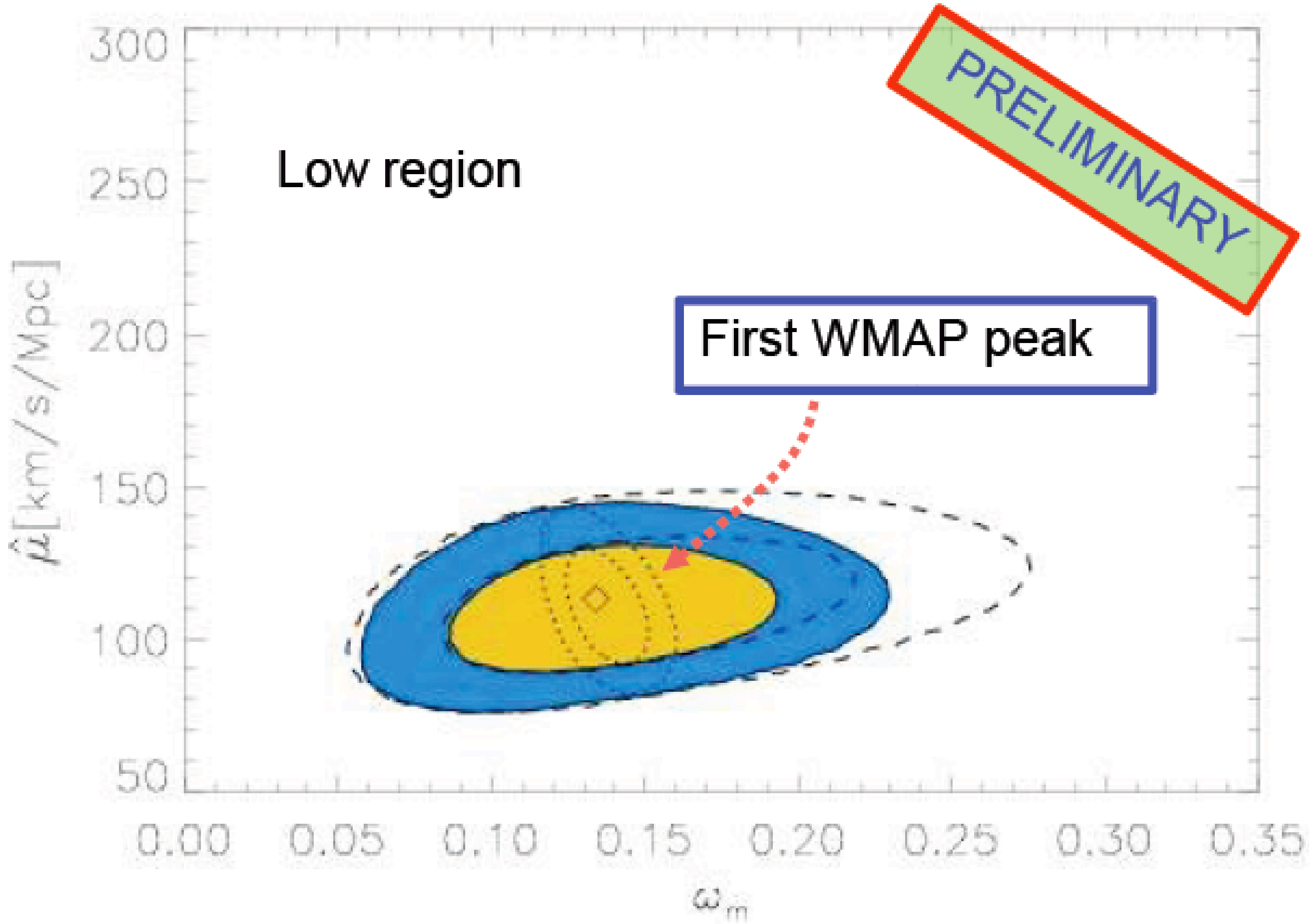
Short distances



Short distances

Ultra large distances

Asuming perturbations behave in the standard way...



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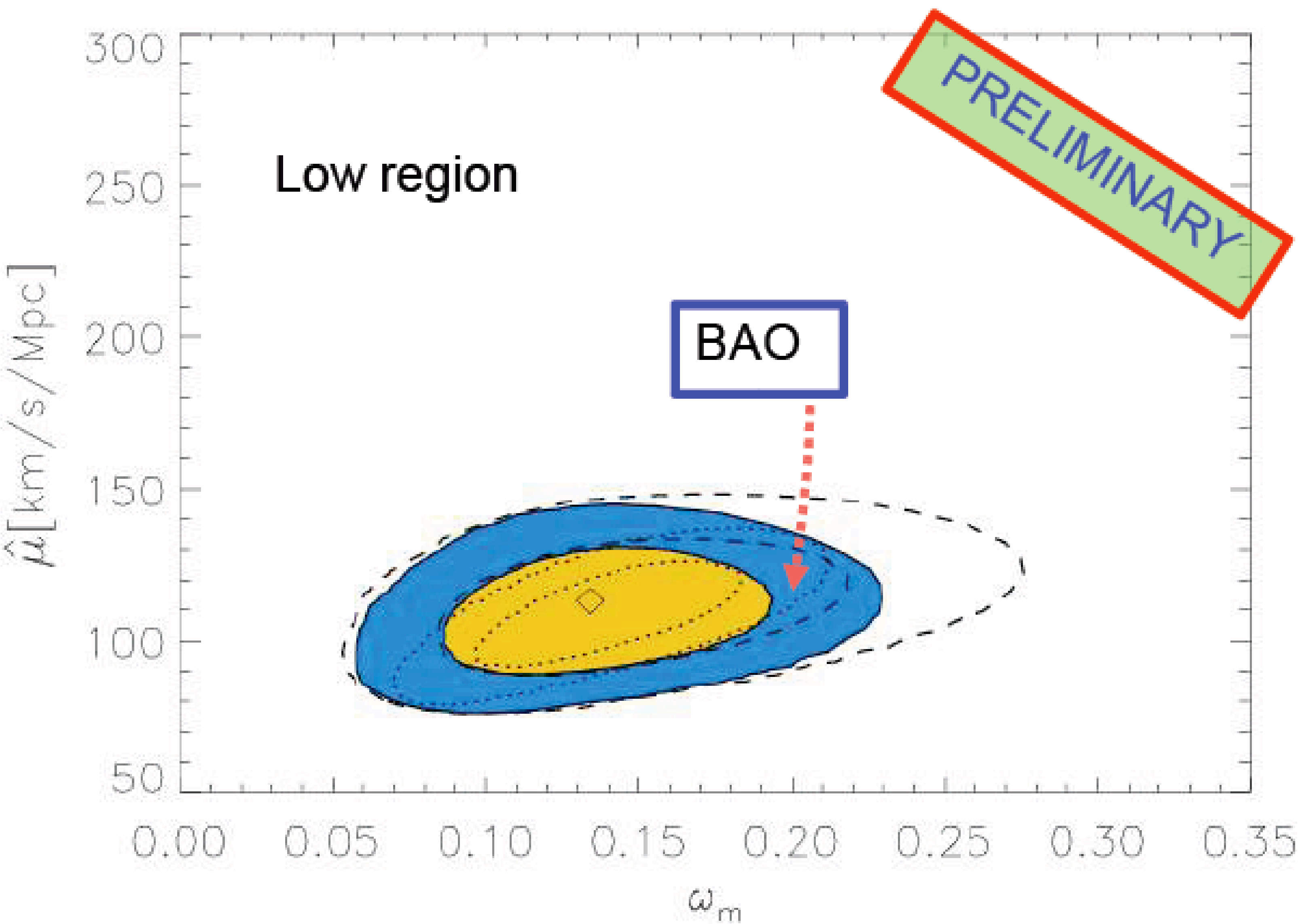

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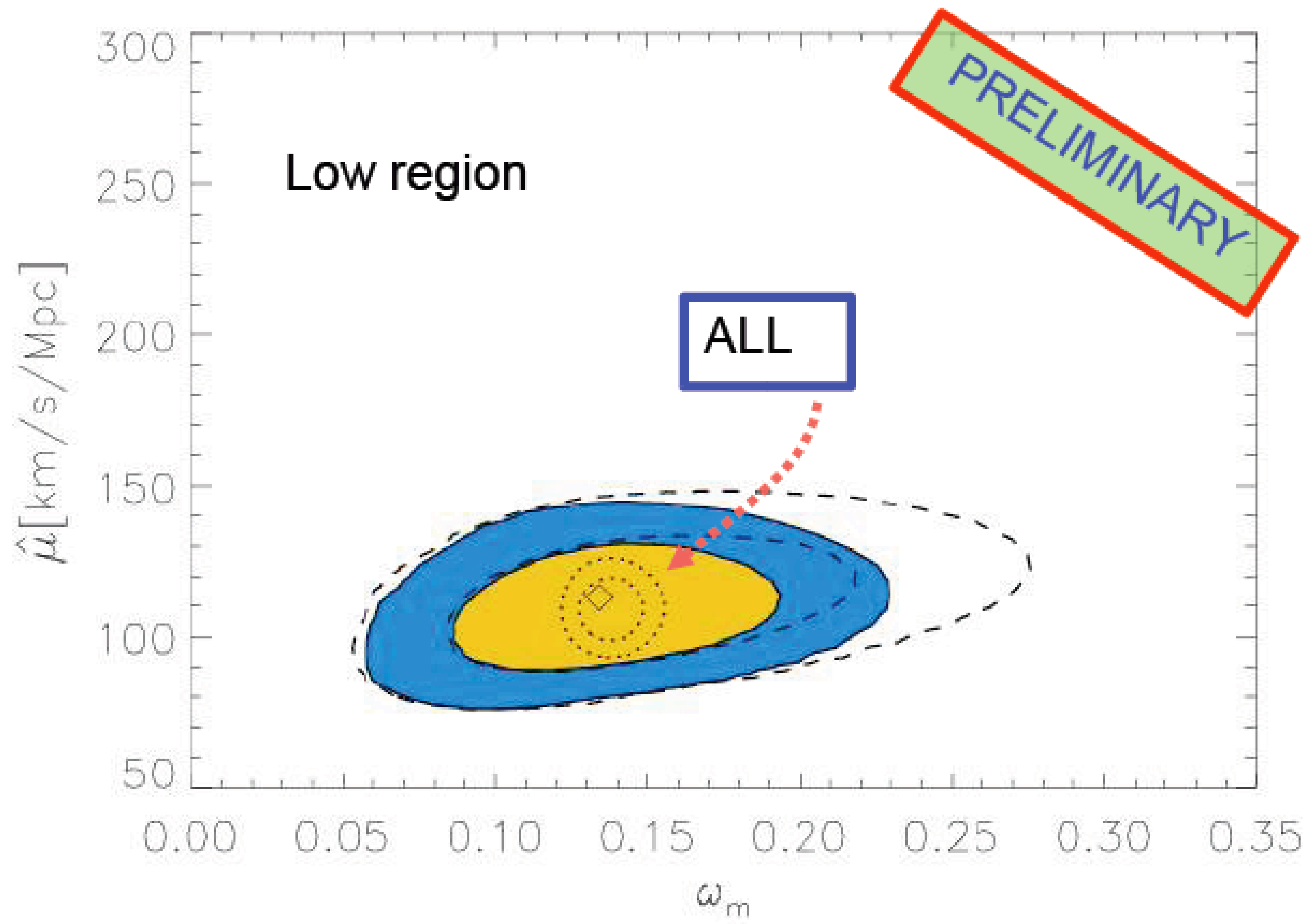
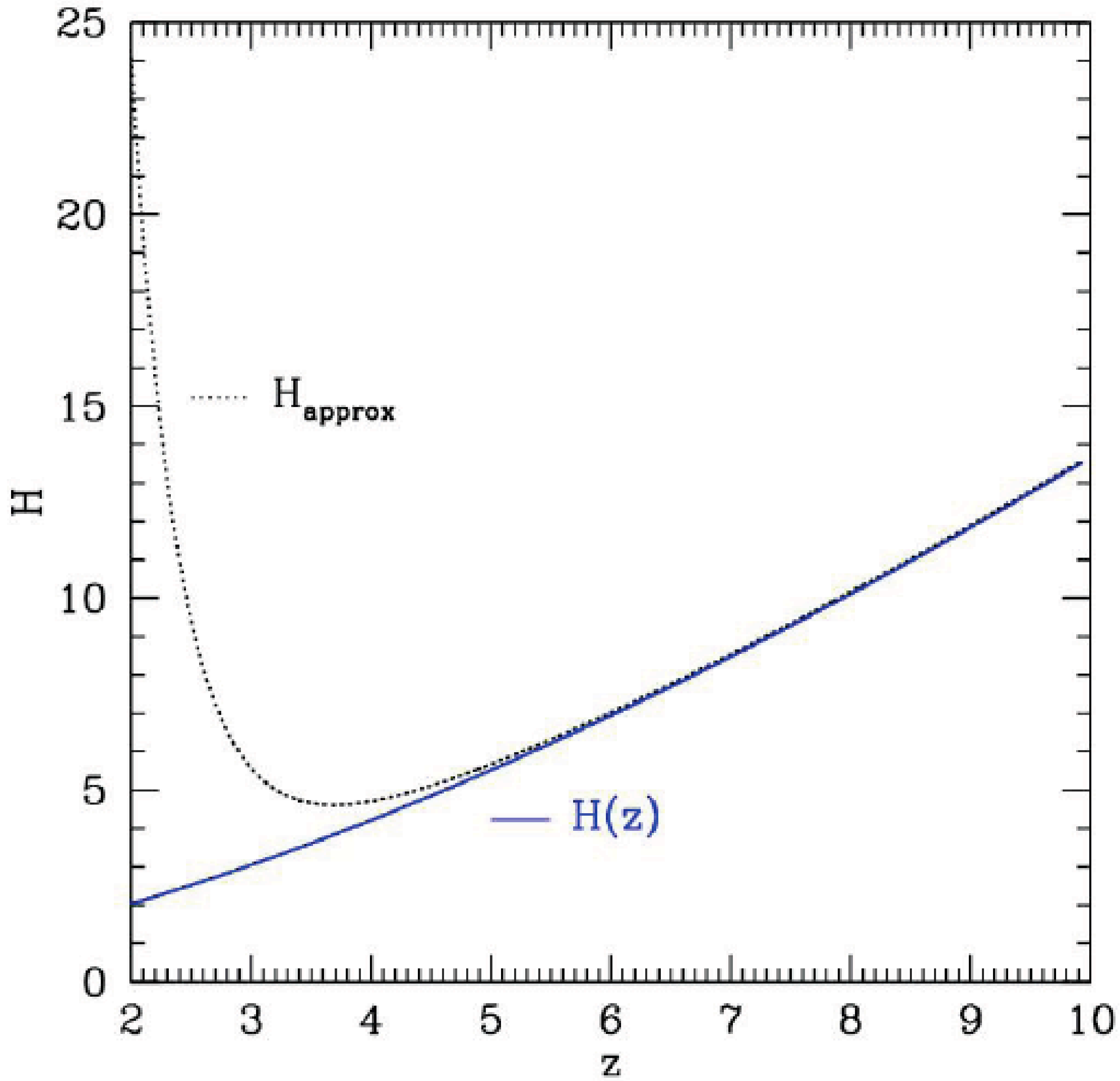


Numerical codes can NOT solve the modified equation due to STIFFNESS



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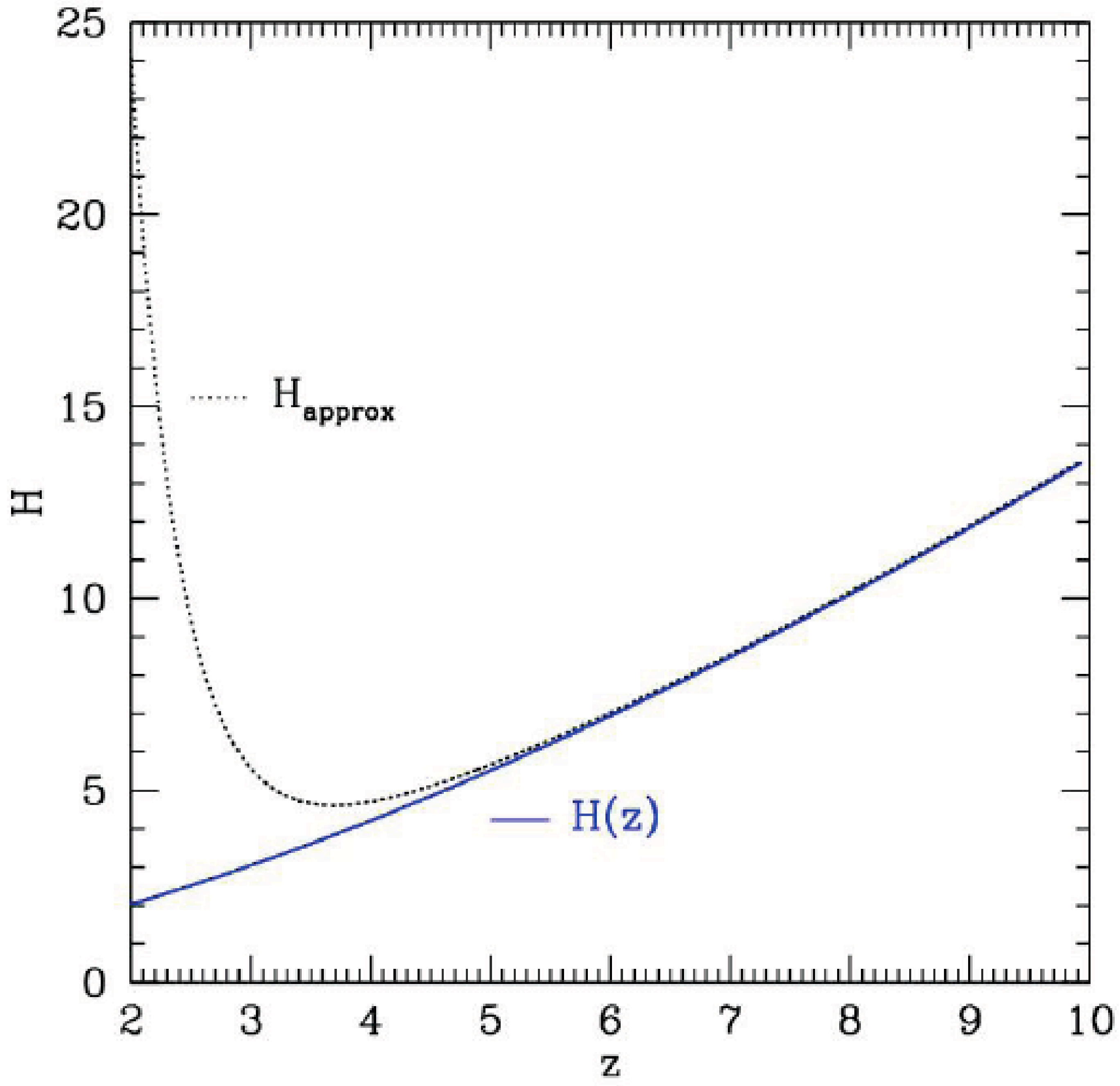
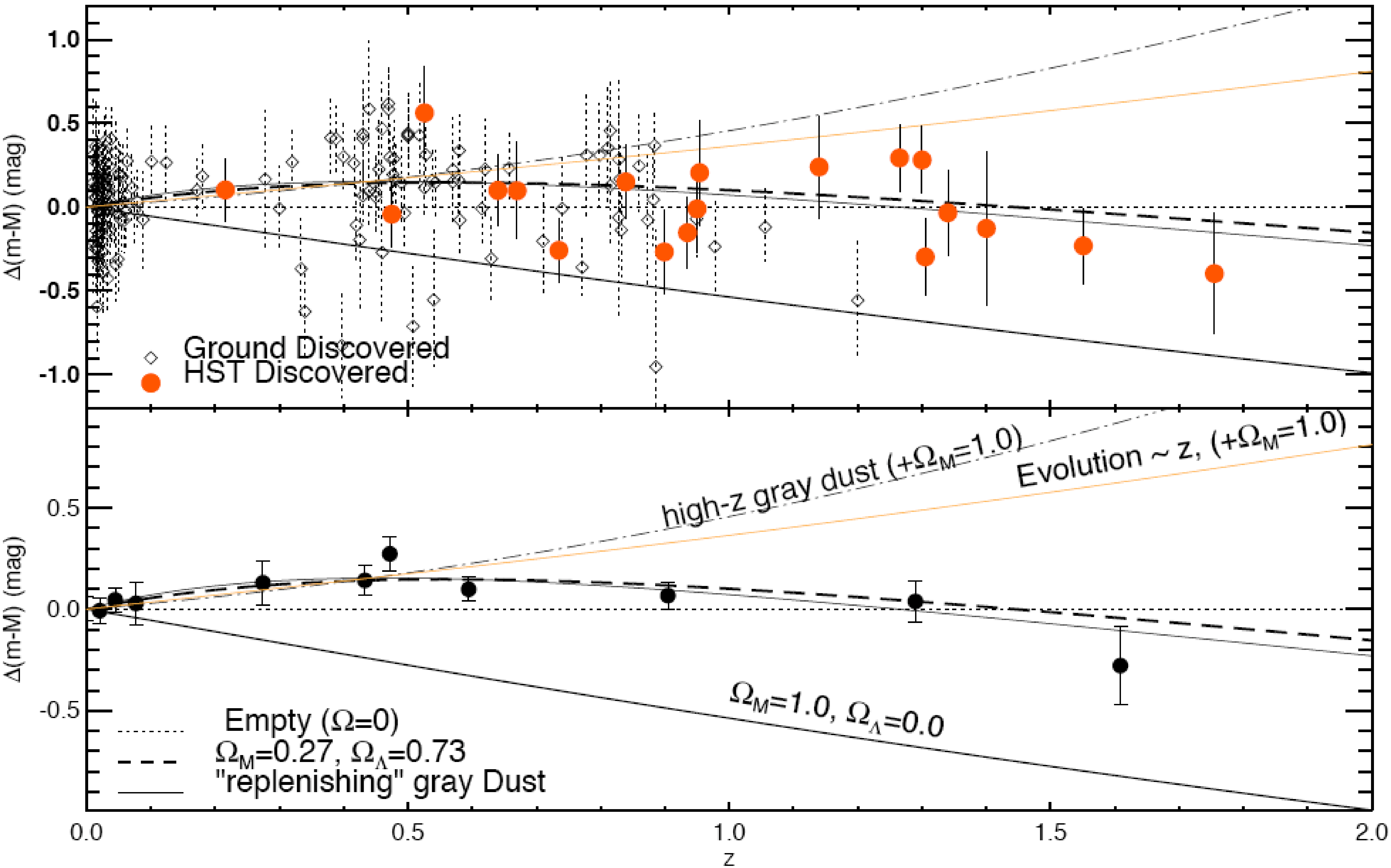
Matching to a perturbative analytical solution





1.0
0.5
0.0
-0.5
-1.0
Δ(m-M) (mag)
Ground Discovered
HST Discovered
high-z gray dust (+Ω_M=1.0)
Evolution ~ z, (+Ω_M=1.0)
0.5
0.0
-0.5
Δ(m-M) (mag)
Ω_M=1.0, Ω_Λ=0.0
Empty (Ω=0)
Ω_M=0.27, Ω_Λ=0.73
"replenishing" gray Dust
0.0
0.5
1.0
1.5
2.0
z