Title: Observational constraints on the future lifetime of the universe

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Abstract: We place bounds on the future lifetime of the universe based on present and future Type Ia supernovae and CMB observations, and explain features in the constraints on the past. We give a review of our work done in the last few years and present mainly our current work using a new Markov Chain Monte Carlo (MCMC) code. The resulting constraints exhibit features which have been observed by other groups previously, but which have not been explained so far. Using our new code, we are able to explain them and show that the new first-year data of the Supernova Legacy Survey (SNLS) prefer the cosmological constant, despite the fact that probability distributions for model parameters generically seem to favor dark energy models with non-trivial dynamics. We also calculate the future lifetime of the universe in a model derived from supergravity and discuss the proper interpretation of the results

Constraints on the Future Lifetime of the Universe

Jan Michael Kratochvil

Stanford University and CITA

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astro-ph/0312183: JCAP 0407, 001 (2004)

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astro-ph/0602xxx: MCMC constraints for high-energy theory

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COLLABORATORS

Andrei Linde

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Eric Linder

Yun Wang

Marina Shmakova

Renata Kallosh

Pascal Vaudrevange

ACHIEVEMENTS

Calculating the Future Lifetime of the Universe:

- After discovery of dark energy, situation hopeless: not enough SNe data to know future lifetime with all the non-trivial dark energy possibilities.
- Use future observations to constrain a simple fit to a dark energy potential.
- Use present data to constrain directly theory coming from fundamental particle physics.

ACHIEVEMENTS (CONTINUED)

Data analysis improvements:

- $\Omega_D = 0.7$, $H_0 = 1$
- Fisher matrix
- Markov Chain Monte Carlo (MCMC) code

Mathematical/Methodological advancements:

- Even in the absence of precise knowledge of nature of dark energy, technique developed to calculate future lifetime and interpret results correctly.
- Given a particle physics theory, we know how to obtain precise results from observations.

CONTENTS

Part I: Review (earlier work)

- Introduction: scalar field dark energy
- Peculiarities of calculating future lifetime
- Using future data to constrain the linear potential: 30-40 Gyr
- Present observations and constraints (Riess 2004 sample)
- Cosmological constant or not?

Part II: Present work (J.M.K., Pascal Vaudrevange)

- New MCMC code for study of dark energy
- Supernova Legacy Survey (SNLS)
- Probability distributions of dark energy parameters peak at non-cosmological-constant values
- But: SN Ia data prefer cosmological constant
- Future Lifetime of gauged N=8 SUGRA: 8-55 Gyr
- Future lifetime vs present age

SCALAR FIELD DARK ENERGY

Equation of motion for scalar field ϕ (in FRW background):

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

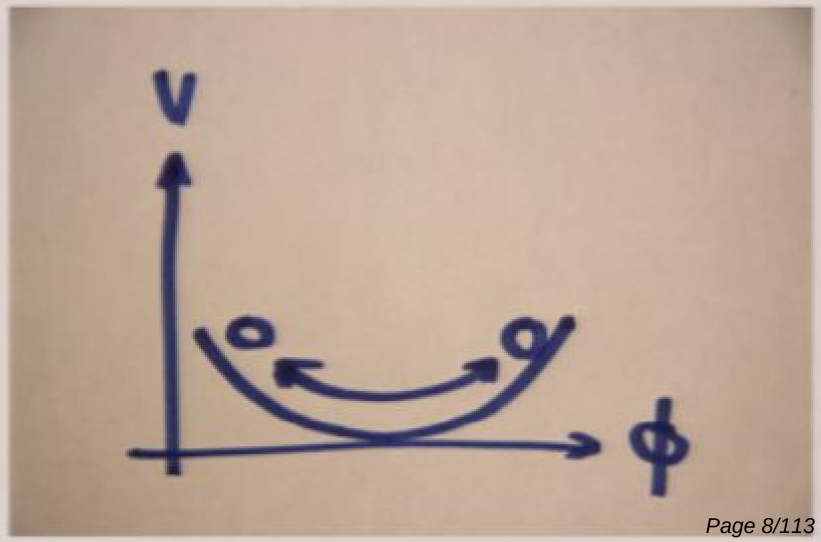
Energy density and pressure:

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi), \qquad p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi)$$

Equation of state:

$$p_\phi = w\rho_\phi$$

$$w = \frac{\frac{\dot{\phi}^2}{2} - V(\phi)}{\frac{\dot{\phi}^2}{2} + V(\phi)}$$

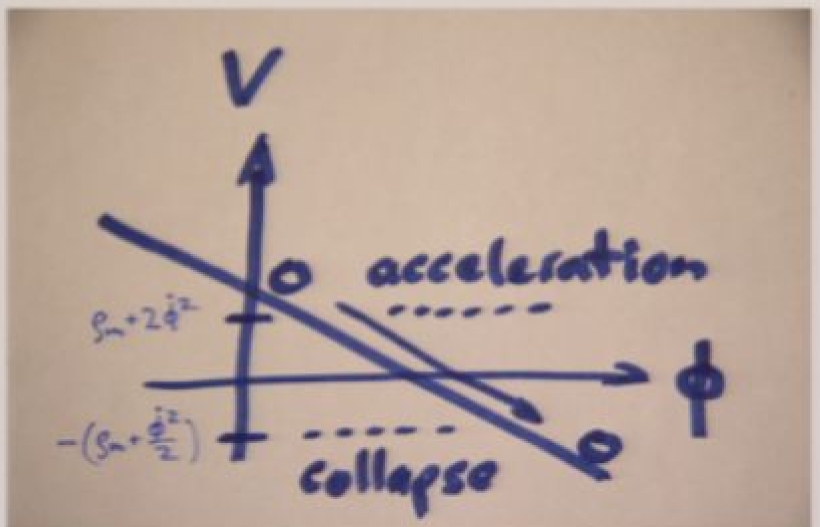


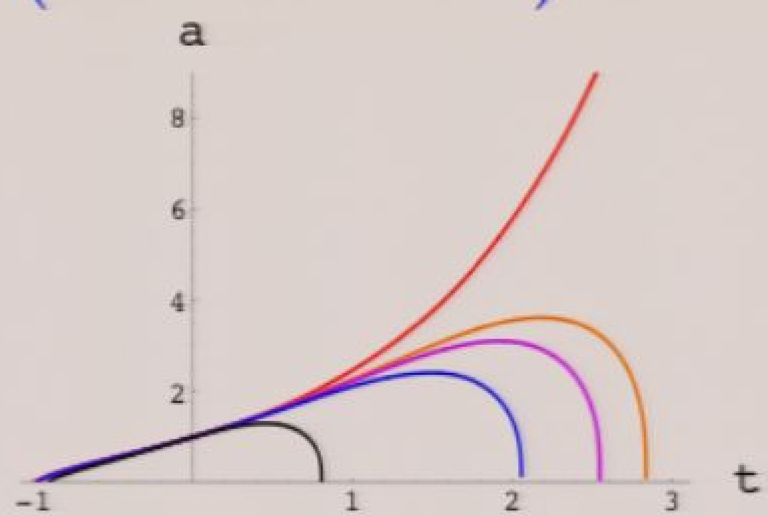
TIME EVOLUTION OF SCALE FACTOR $a(t)$

Friedmann equations:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\frac{\rho_m^{(1)}}{a^3} + 3\underbrace{p_m}_{=0} + 2\dot{\phi}^2 - 2V(\phi)\right)$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{\rho_m^{(1)}}{a^3} + V(\phi) + \frac{\dot{\phi}^2}{2}\right)$$





Generic scalar field dark energy behavior!

Why use a specific Potential?

- Model (potential)- and fit-independent reconstructions of the past, of
  $X(z) \equiv \rho(z)/\rho(z=0)$ and $w(z)$,
  where $X(z)$ defined by $H^2(z) = H_0^2(\Omega_m(1+z)^3 + \Omega_X X(z))$,
  useful and have been done. However:
- Must resist urge to extrapolate from this to the future!

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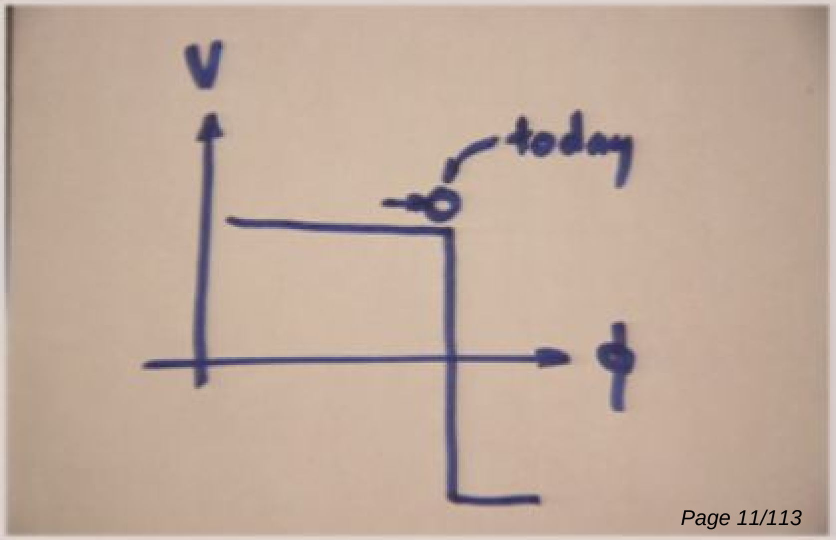

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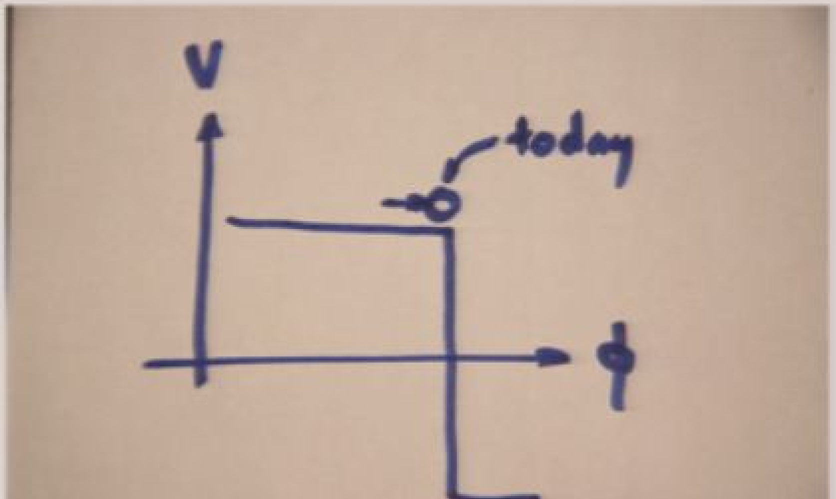
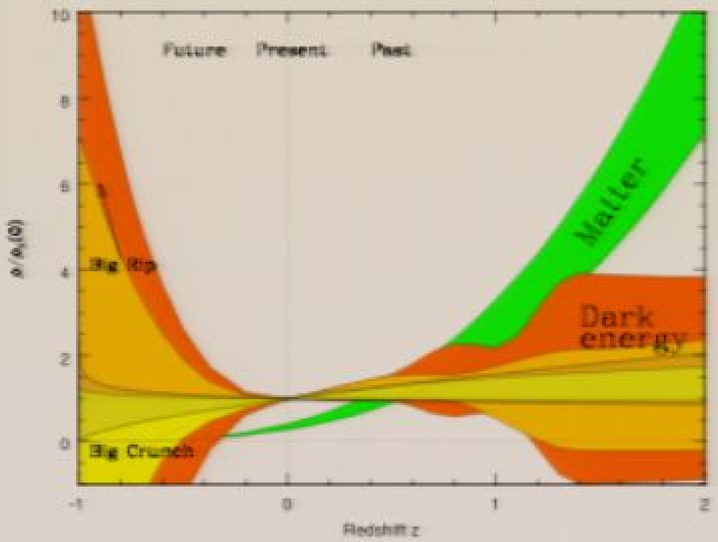


MODEL INDEPENDENT ANALYSIS



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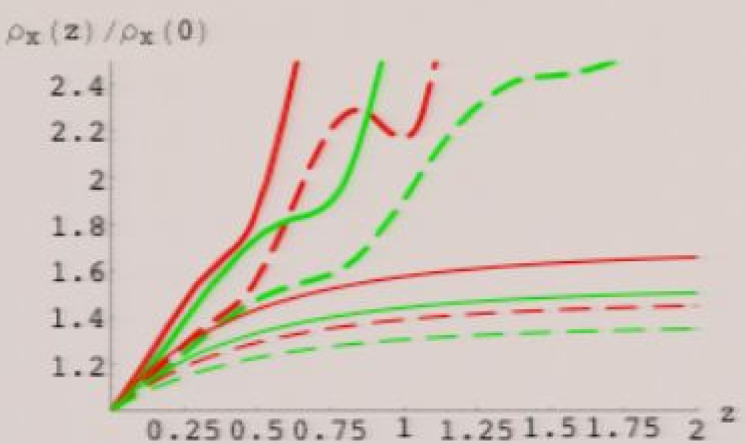
Wang & Tegmark (2004)



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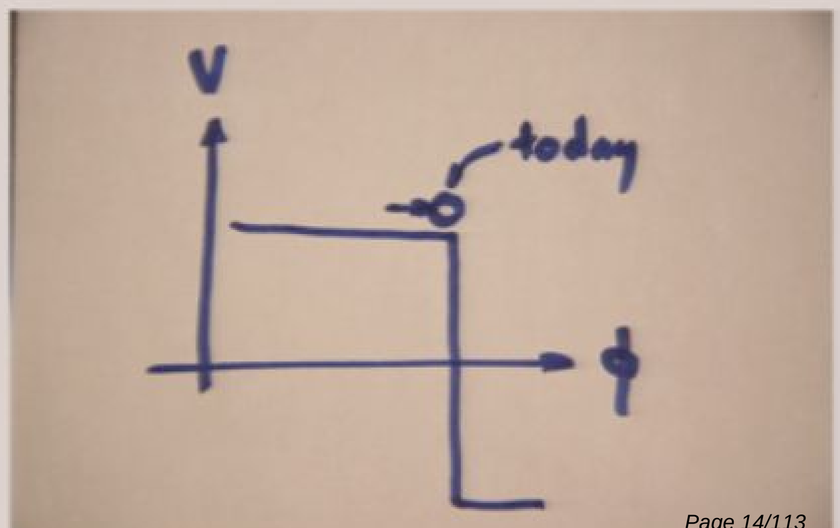

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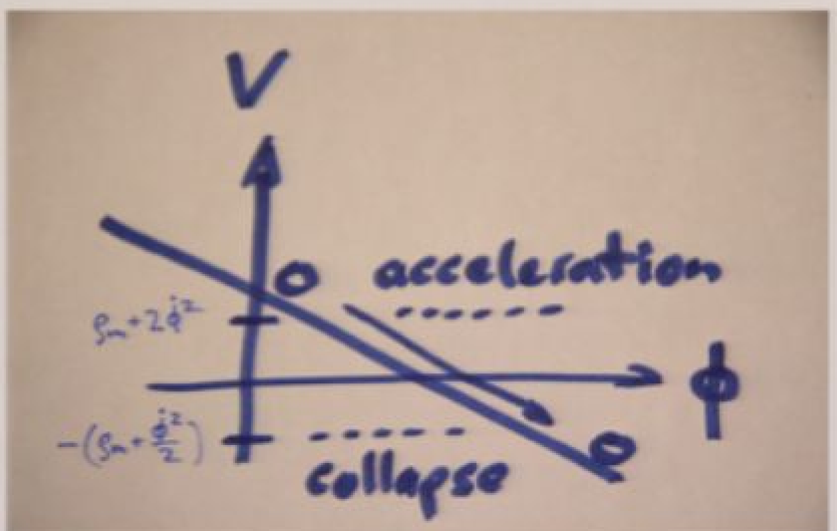
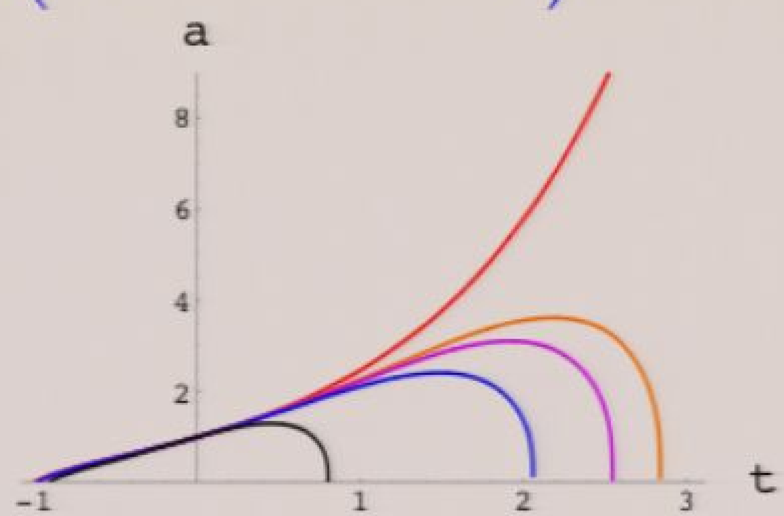
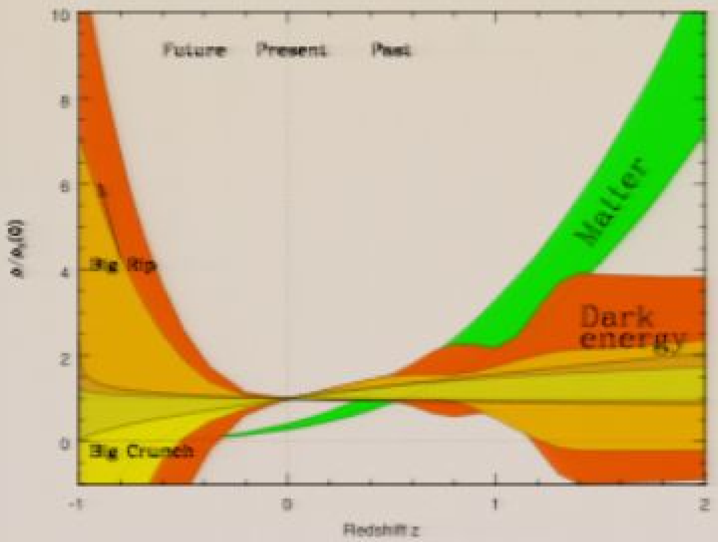




Generic scalar field dark energy behavior!

Model independent Analysis



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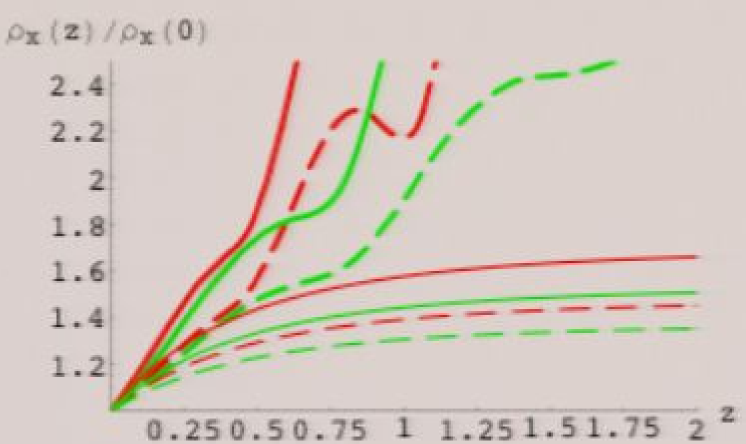

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- Measures luminosity distances to some 2000 Type Ia supernovae.
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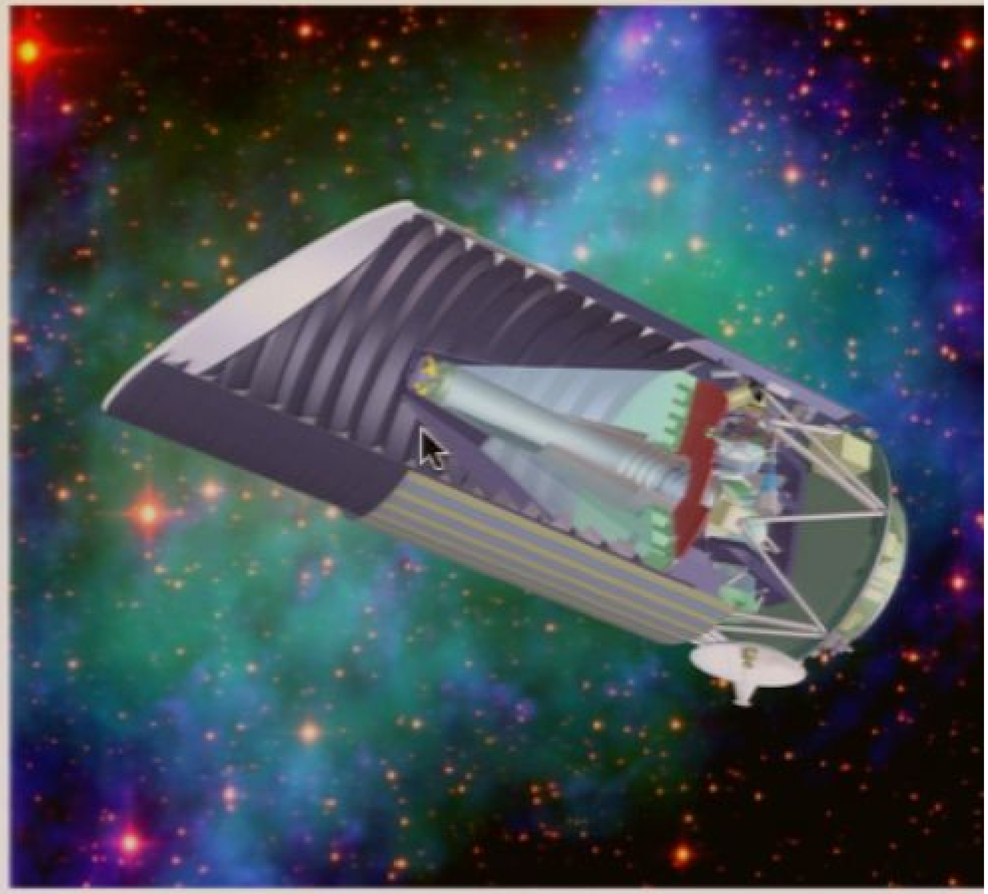

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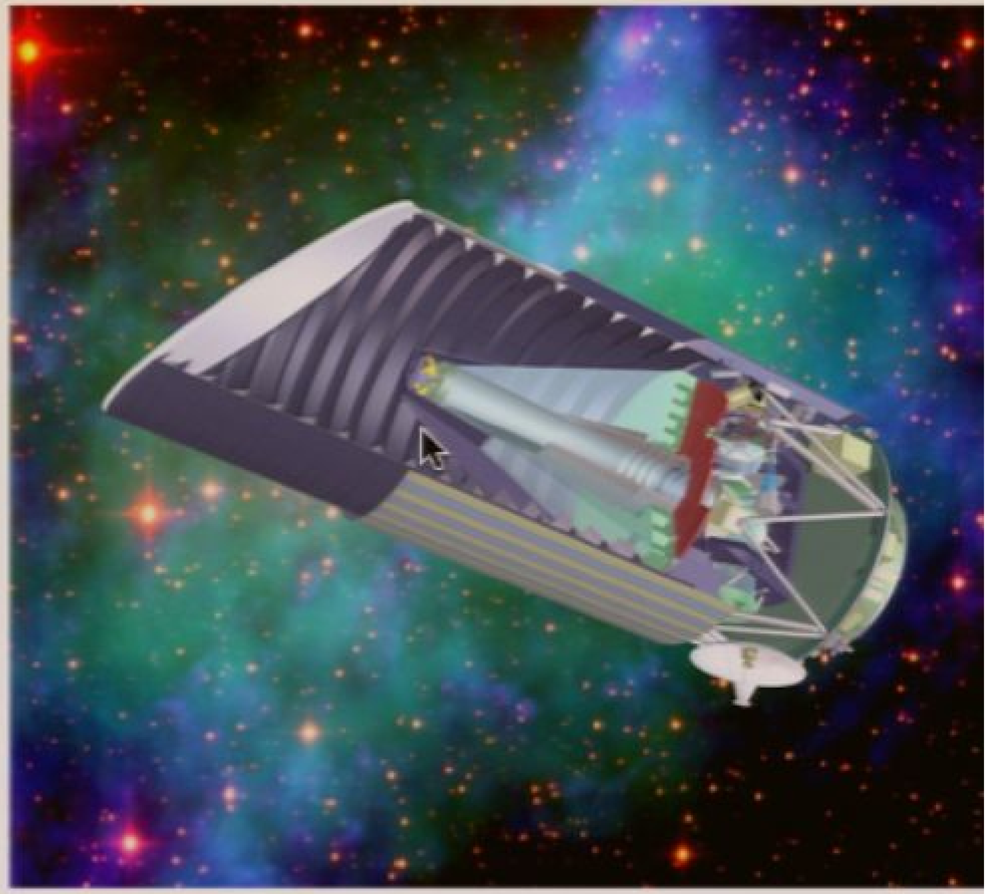

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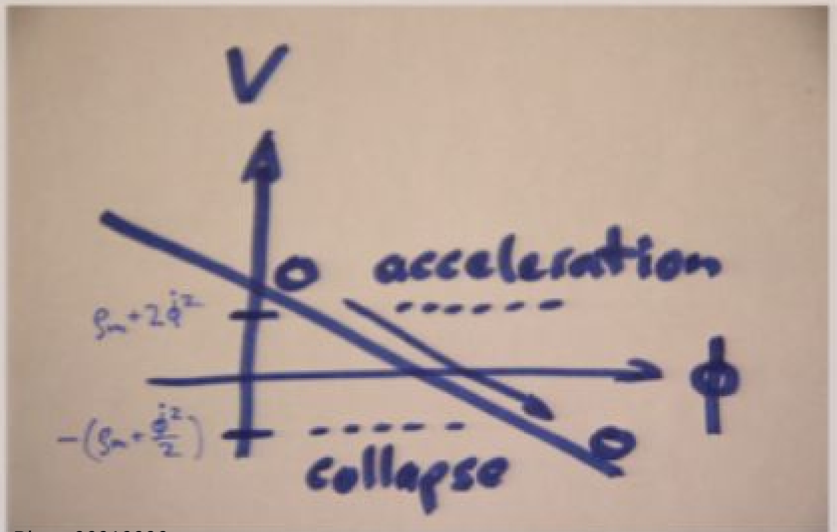

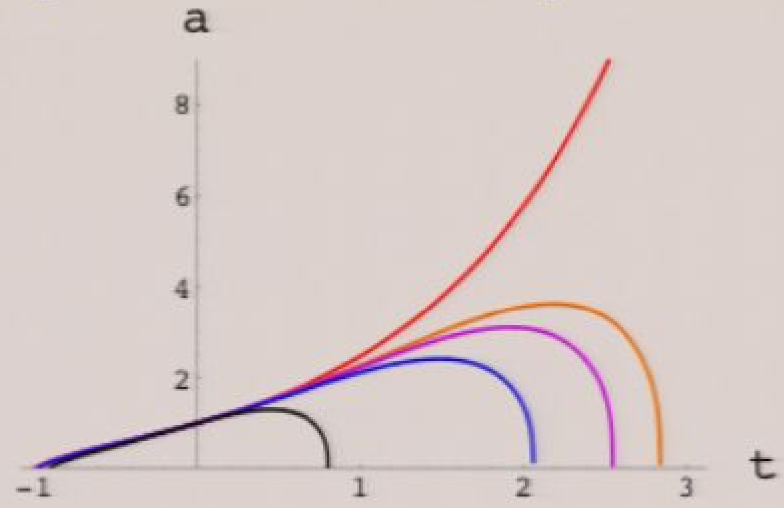

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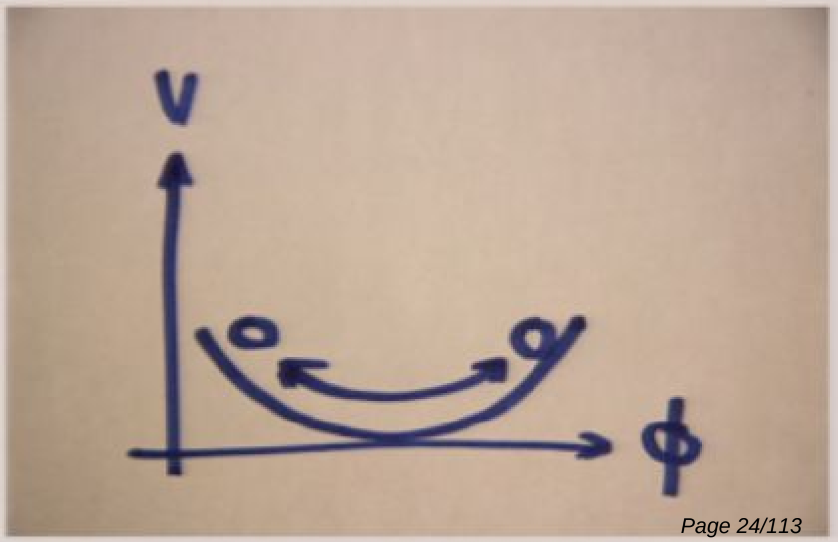

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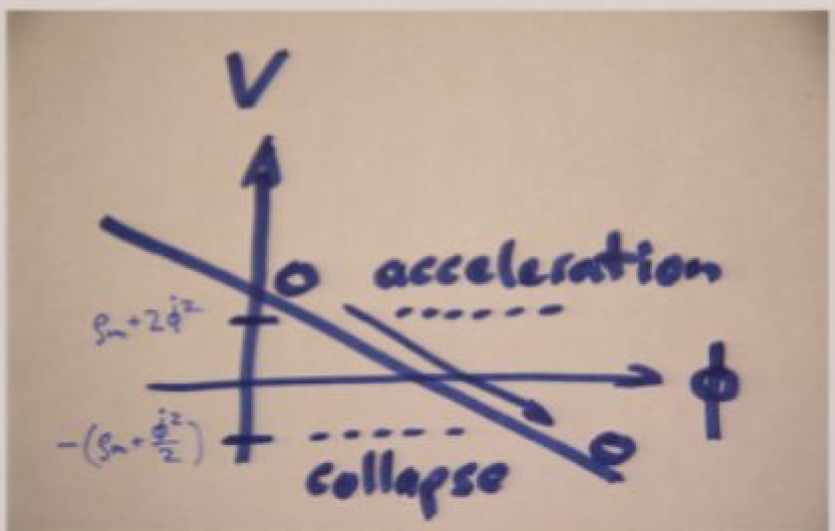

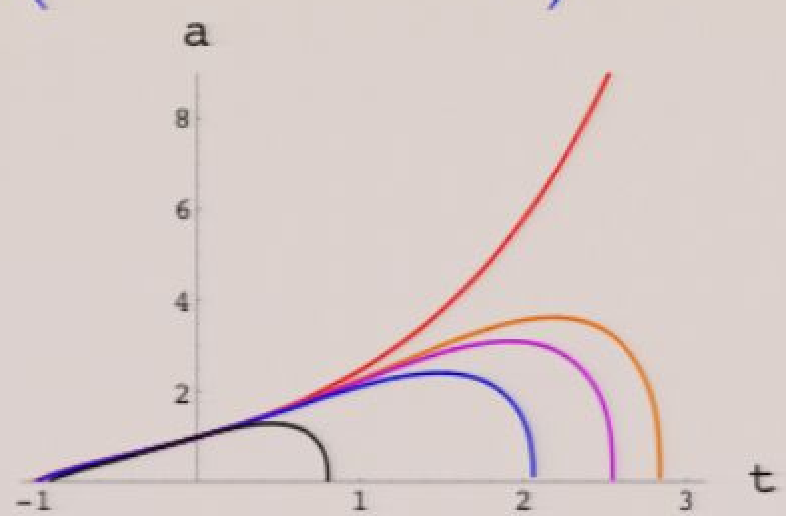

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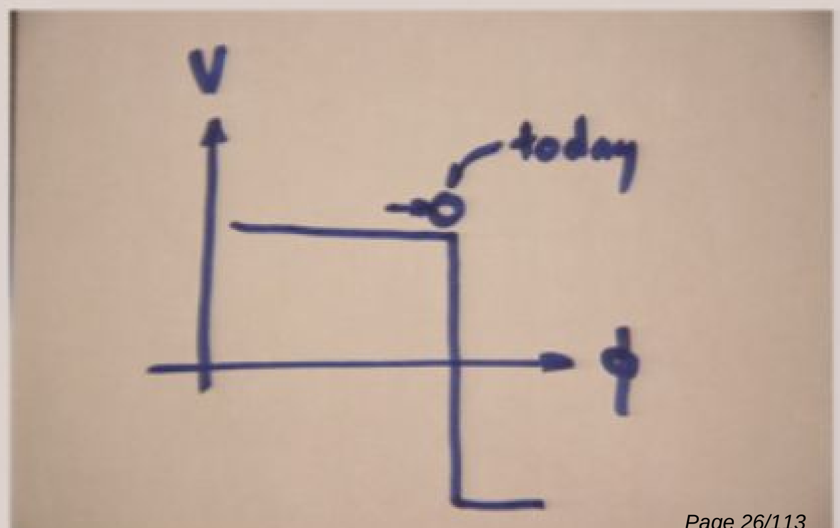

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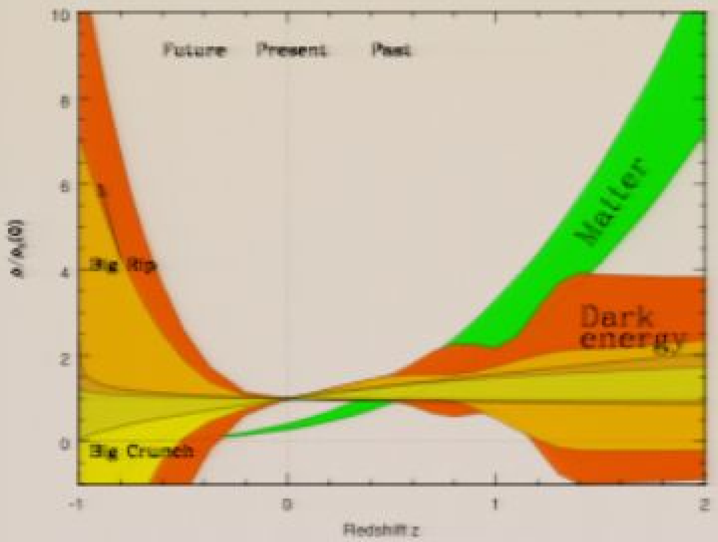

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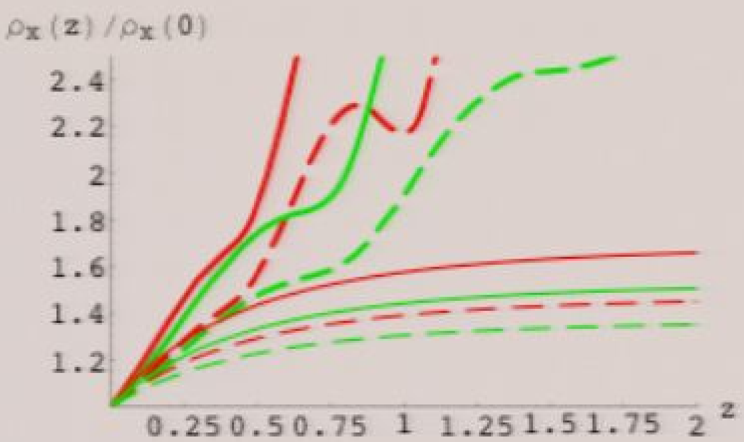

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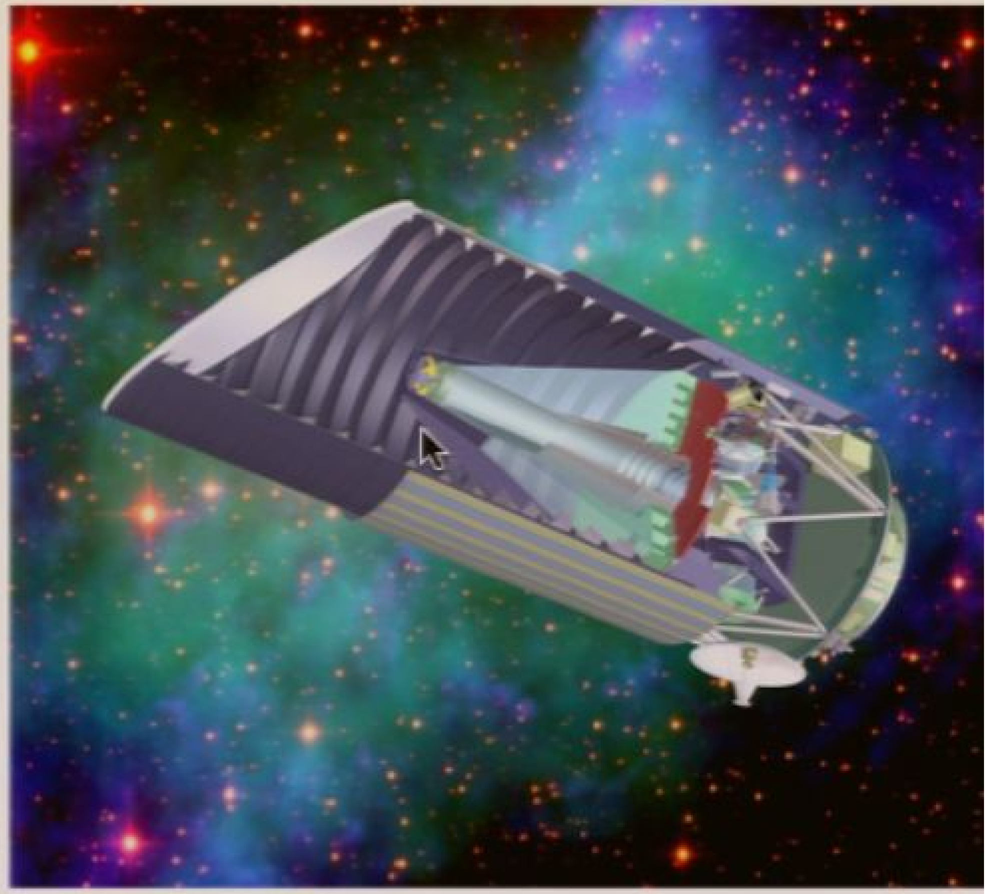

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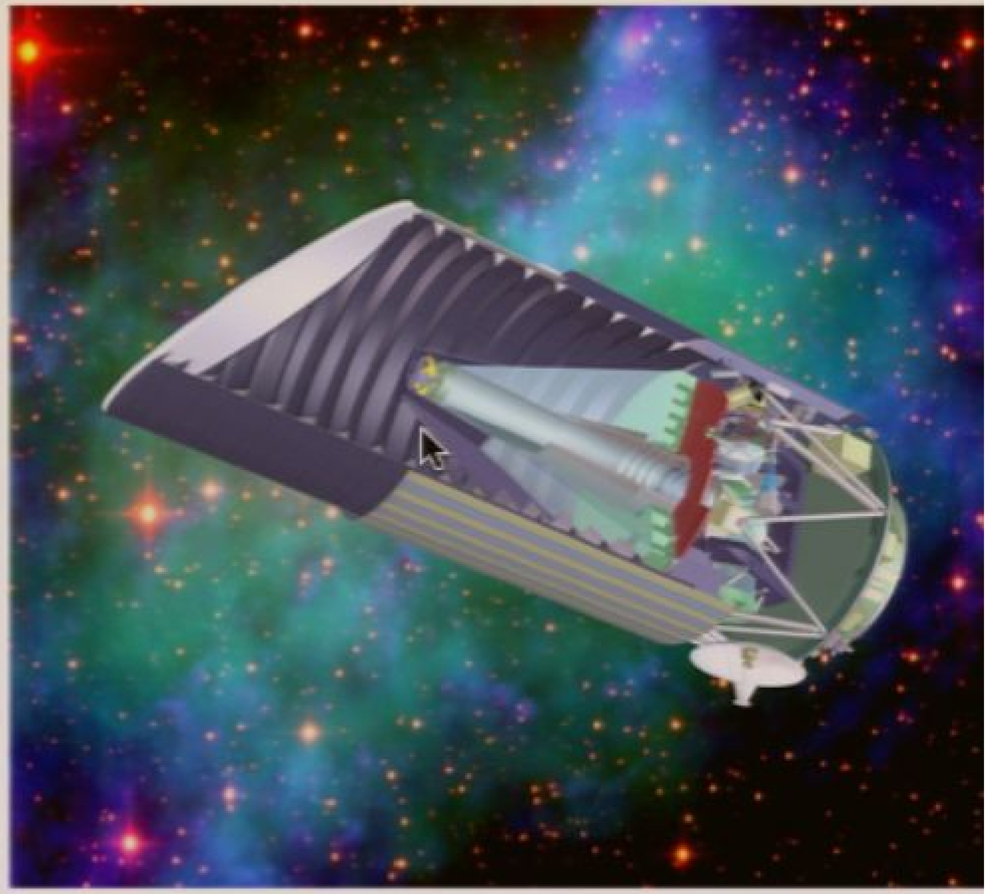

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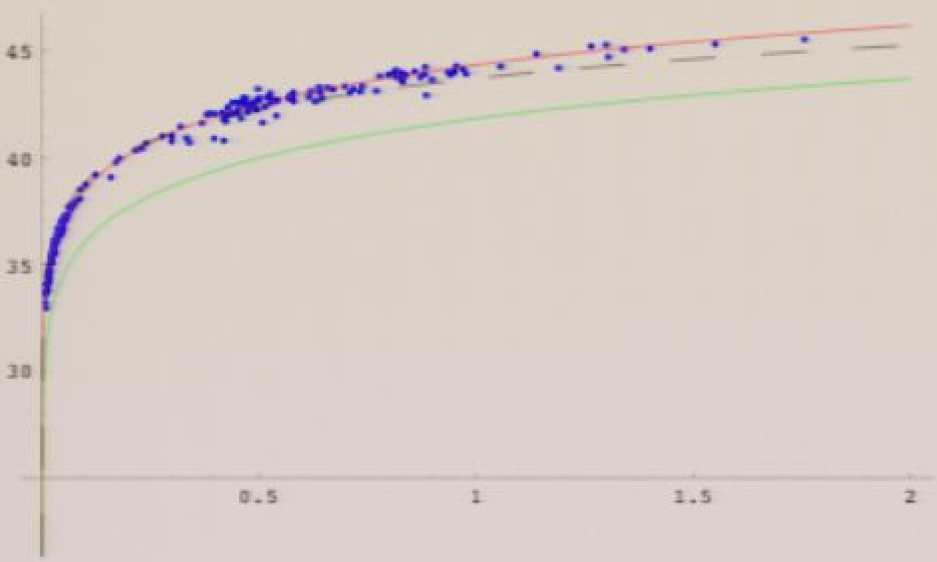
Magnitude-Redshift Relation of SNe

Apparent SNe magnitude as function of redshift z:

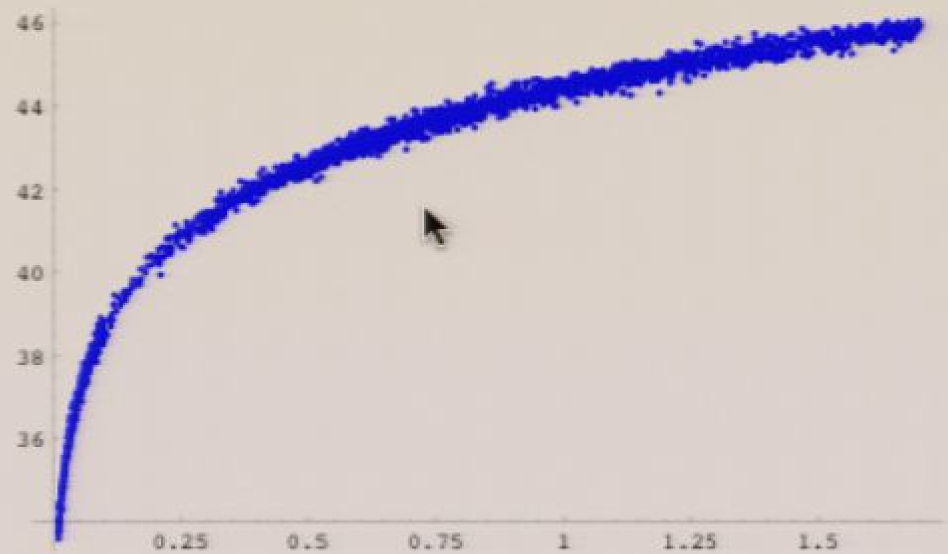
$$
\begin{aligned}
m(z) &= 5\log_{10}\left[(1+z)\int_0^z dz'\left[(1-\Omega_D)(1+z')^3\right.\right. \\
&+ \left.\left.\Omega_D e^{3\int_0^{\ln(1+z')} d(\ln(1+z''))[1+w(z'')]}\right]^{-1/2}\right] + \mathcal{M}
\end{aligned}
$$

and $\mathcal{M} = M + 25 - 5\log_{10}(H_0/100\mathrm{km/s/Mpc})$,
where M is the supernova absolute magnitude.

MAGNITUDE-REDSHIFT RELATION OF SNE



Riess *et al.* 2004 gold/silver sample



Simulated dataset for SNAP

(2298 SNe, $\sigma_0 = 0.15\,\mathrm{mag}$ statistical uncertainty)

PLANCK

Planck Surveyor cosmic microwave background satellite: Measurement of angular diameter distance to the CMB LSS at $z = 1089$.

$$\tilde{d} = \int_0^{z_{LSS}} dz\, f(z)^{-1/2},$$

$$f(z) = \Big[(1+z)^3 + \\ + \frac{\Omega_D}{1-\Omega_D}(1+z)^{3(1+w_0+w_a)} e^{-3w_a \frac{z}{1+z}}\Big]$$

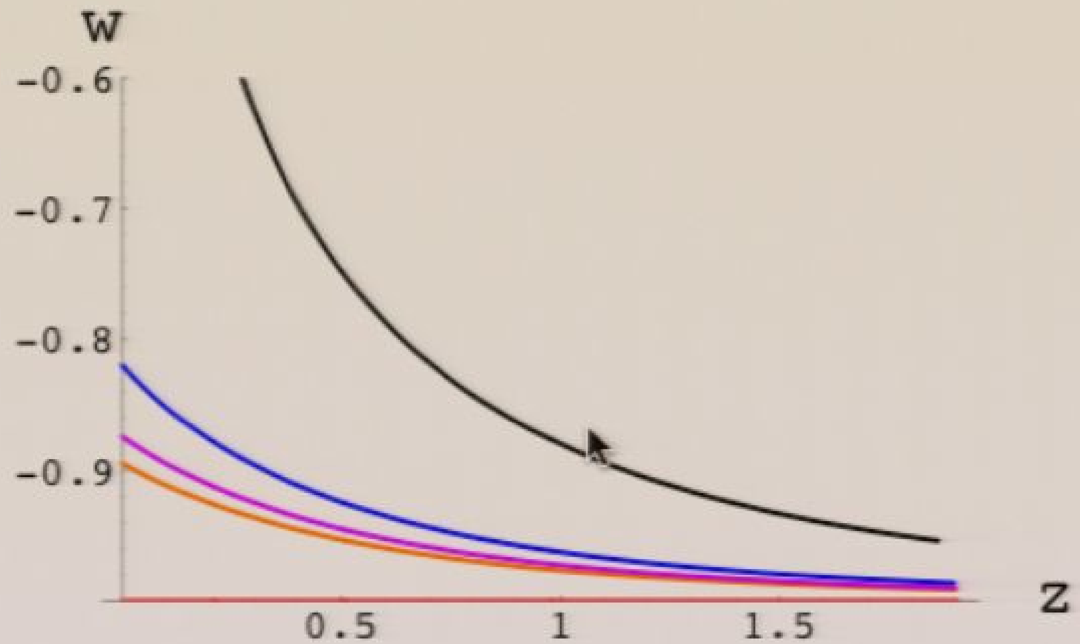
Measurement error:

$$\sigma_{\tilde{d}} = 0.007 \cdot \tilde{d}.$$

http://www.planck.fr/

$w(z)$

$w(z)$ for different slopes of the linear potential in the relevant redshift range of SNAP:



So use fit (introduced by Linder):

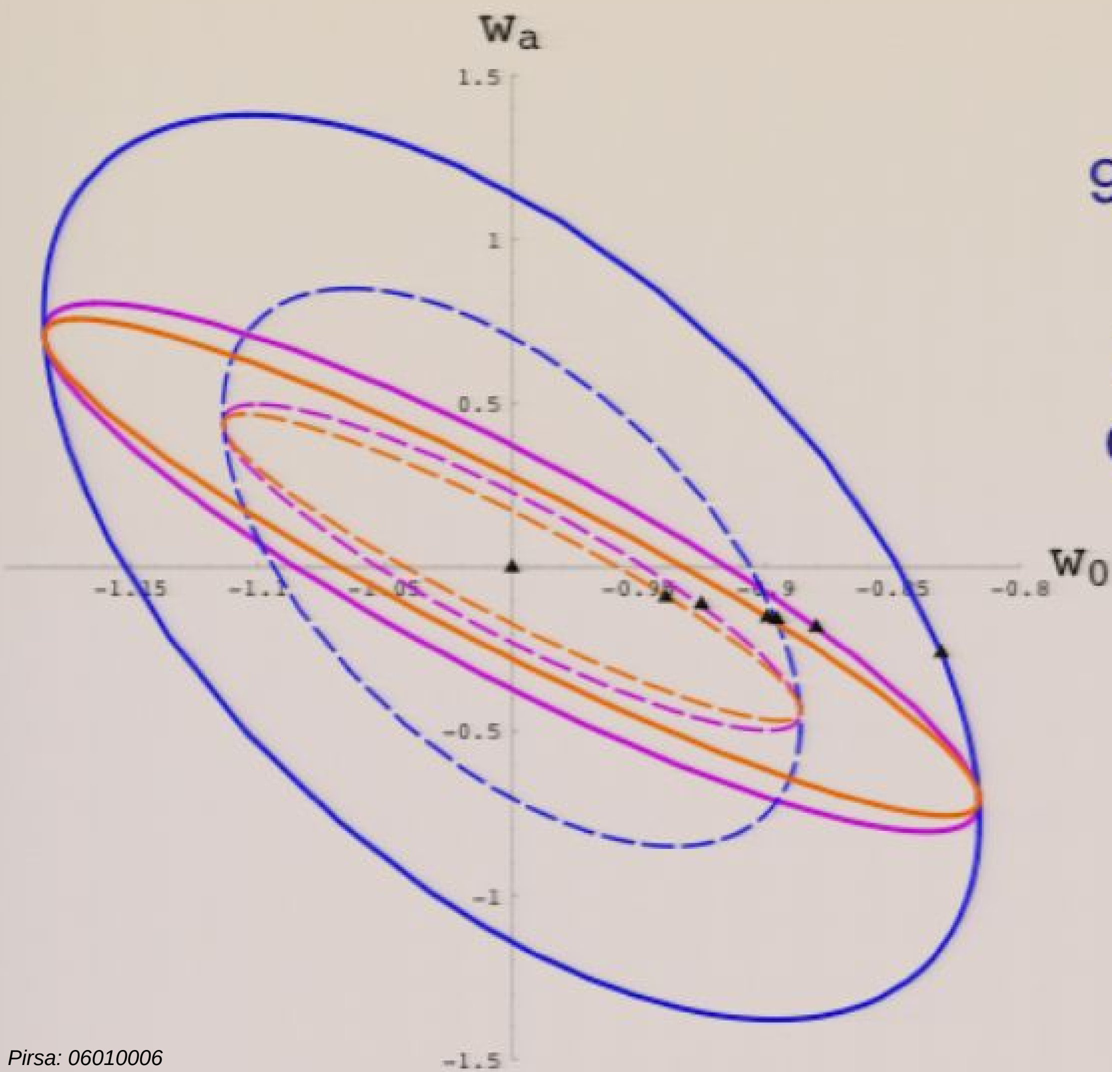
$$w(z) = w_0 + w_a(1 - a) = w_0 + w_a \frac{z}{1 + z}$$

In general a good fit for many potentials.

Fits shape of $w(z)$ from linear potential particularly well.

CONSTRAINTS ON $w(z)$

Constraints from SNAP and Planck:



Confidence contours at 95% confidence level (solid).
Blue: SNAP[SN]
Purple: SNAP[SN]+Planck
Orange: SNAP[SN]+Planck +SNAP[WL]

Black triangles: intersections with one-parameter line of linear potential.

Constraints on the Linear Potential

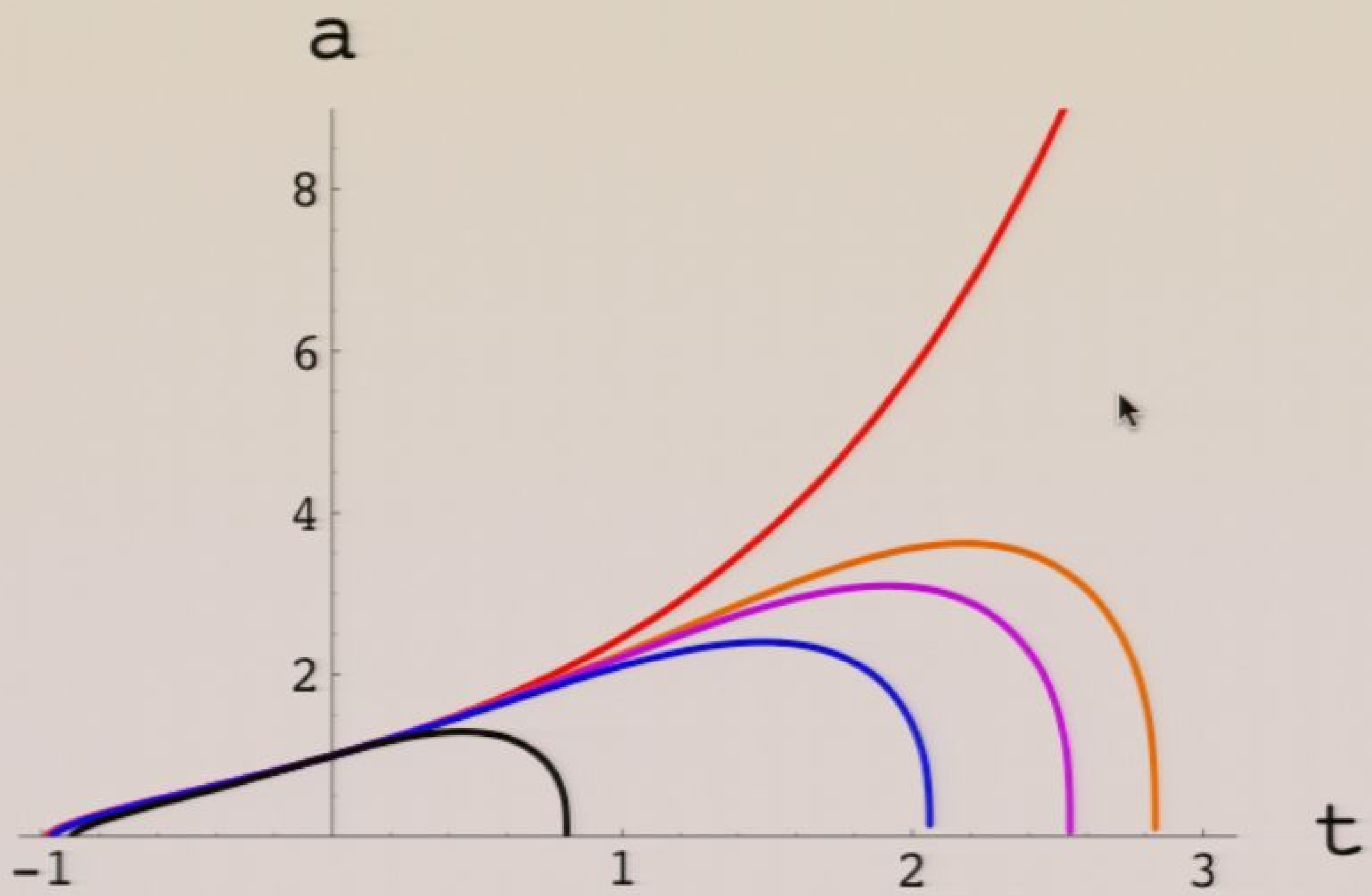
Parameter (95% cl)	Cosm. Const.	SNAP[SN] + Planck + SNAP[WL]	SNAP[SN] +Planck	SNAP[SN] $+\sigma_\Omega$	Minimum Lifetime Model
color	red	orange	purple	blue	black
α	0	0.71	0.76	0.86	1.13
V_0	0.72 ρ_0	0.83 ρ_0	0.85 ρ_0	0.91 ρ_0	1.77 ρ_0
αV_0	0	0.72 ρ_0/M_p	0.79 ρ_0/M_p	0.96 ρ_0/M_p	2.46 ρ_0/M_p
$w(0)$	-1	-0.89	-0.87	-0.82	-0.0001
t_c	∞	39.5 Gyr	35.5 Gyr	28.7 Gyr	11.3 Gyr

where

$$\rho_0 \sim 10^{-120} M_p^4 \sim 10^{-29} \mathrm{g/cm}^3$$

is the total energy density of the universe today, and t_c is the time from now until collapse.

SCALE FACTOR EVOLUTION



Kallosh, J.M.K., Linde, Linder, Shmakova (2003)

OTHER POSSIBLE SNAP RESULTS

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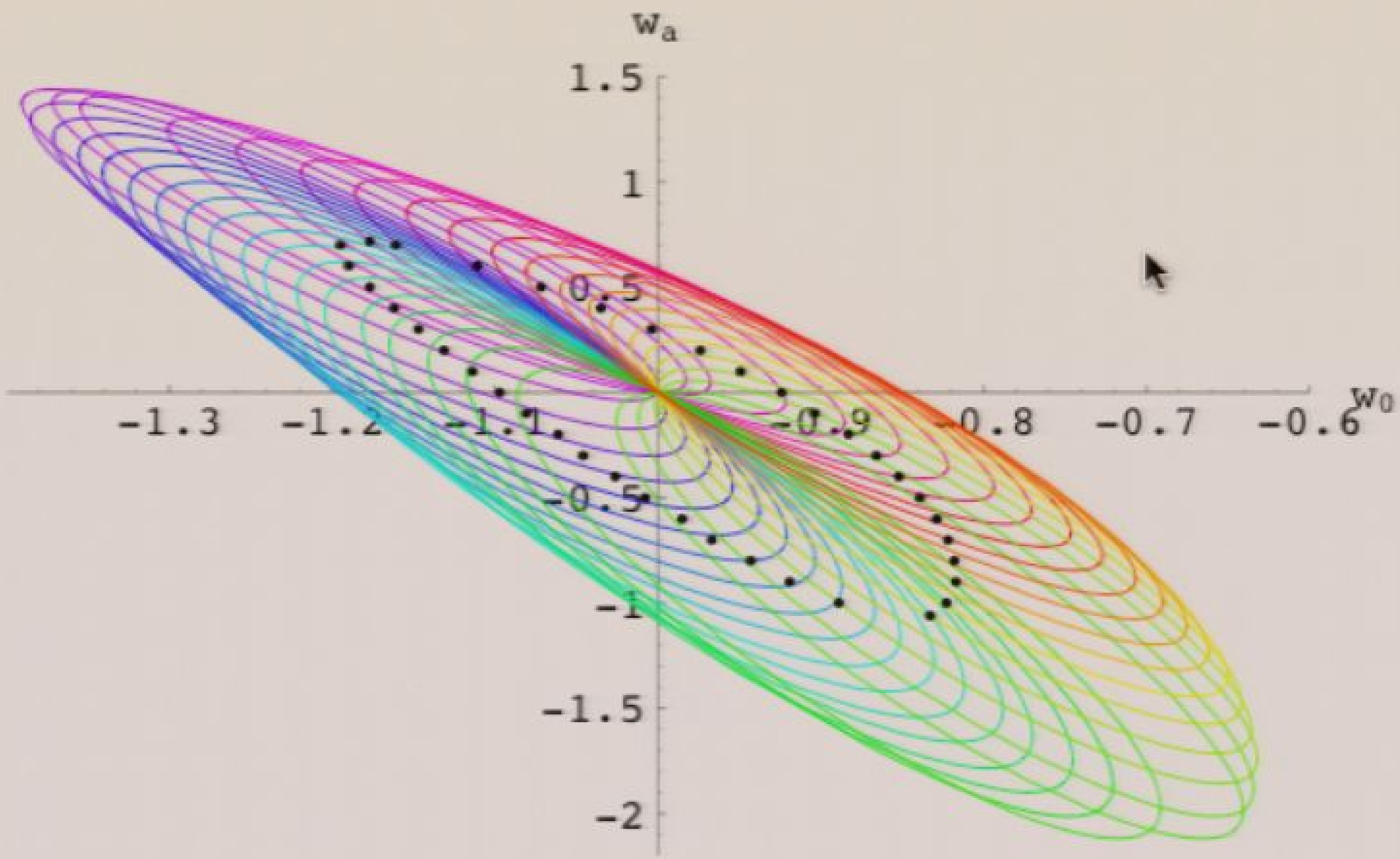

CC excluded if SNAP outside dotted contour. *J.M.K., Linde, Linder, Shmakova (2003)*

Excluding CC with SNAP + Planck

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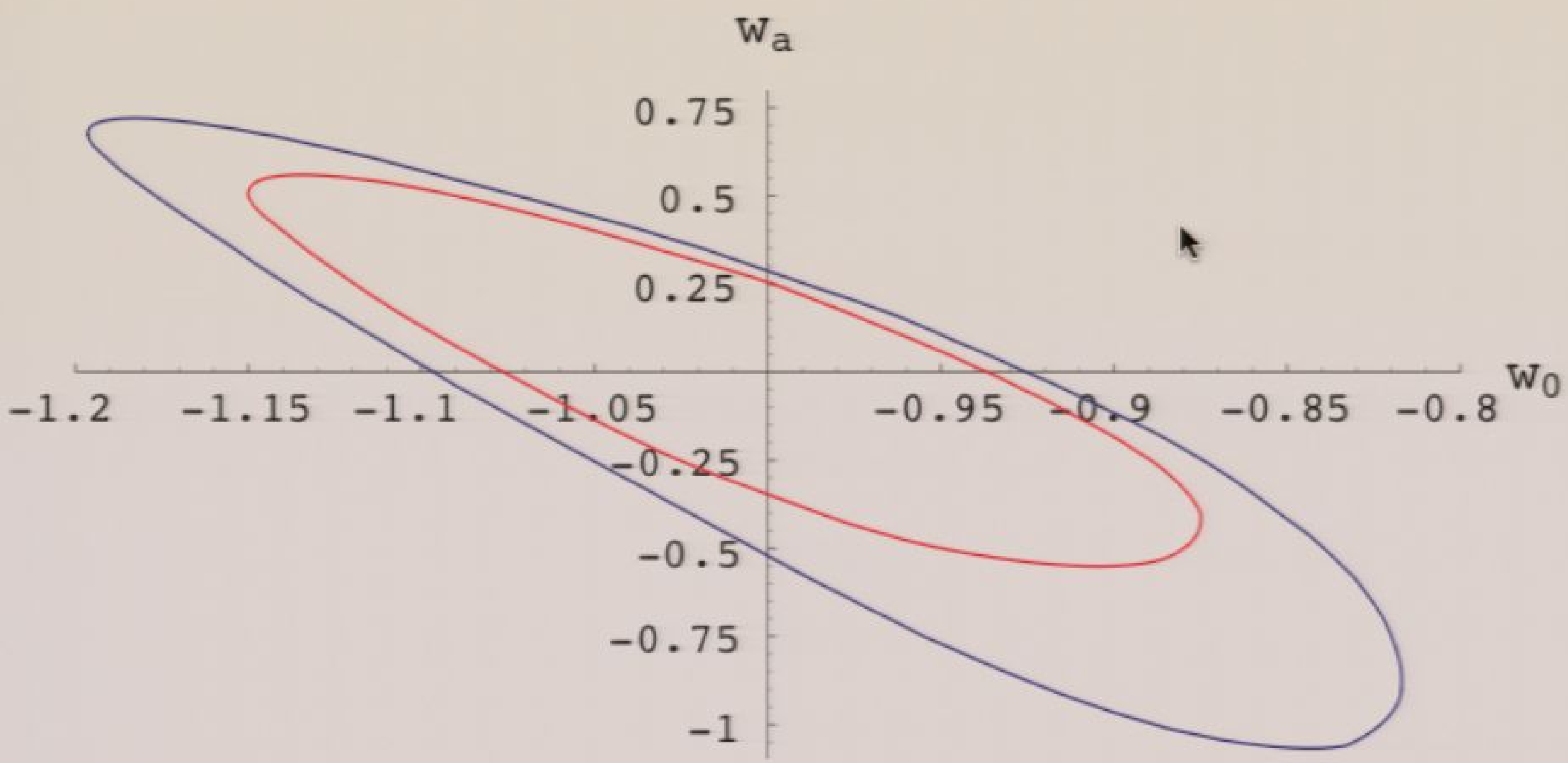

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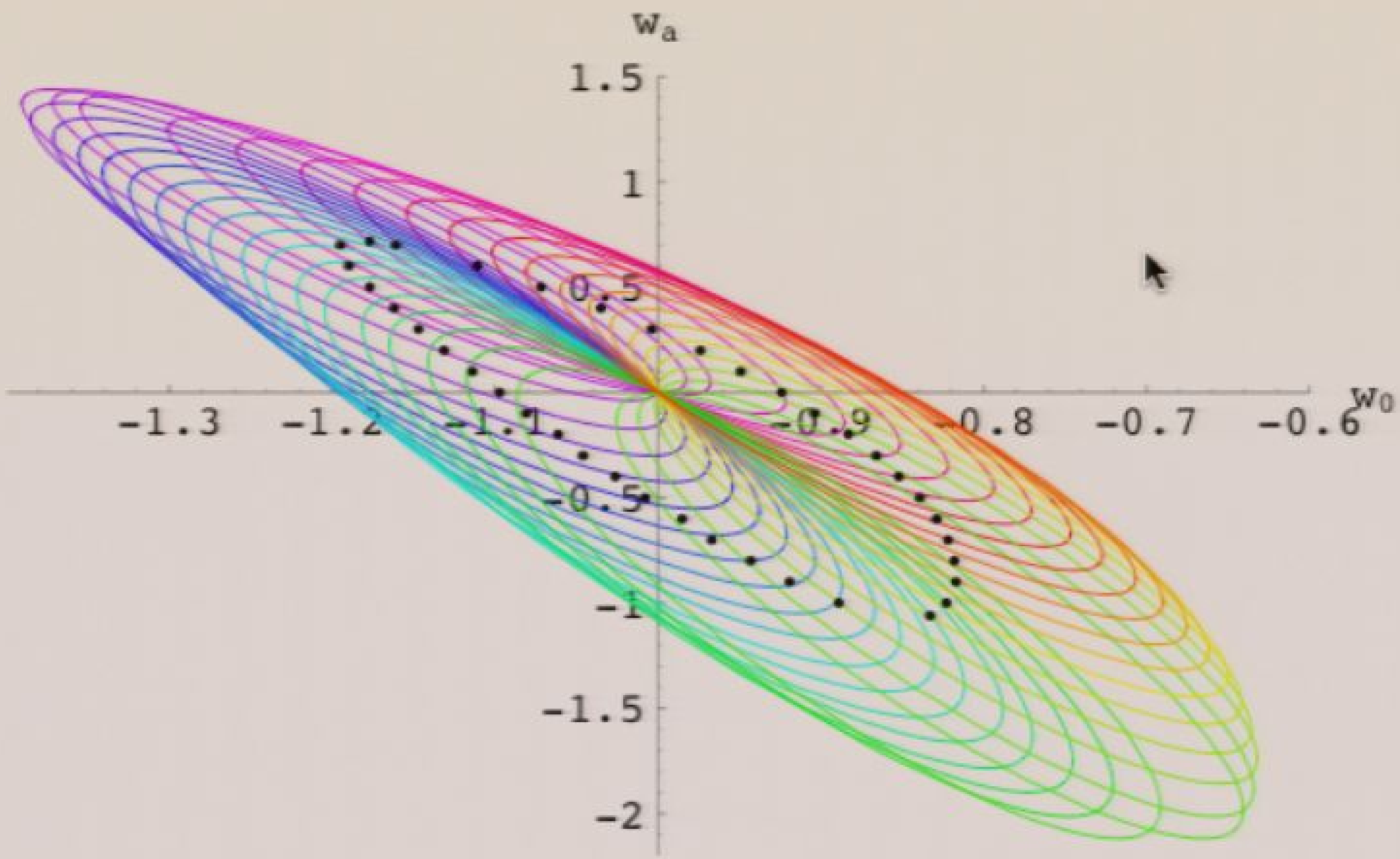

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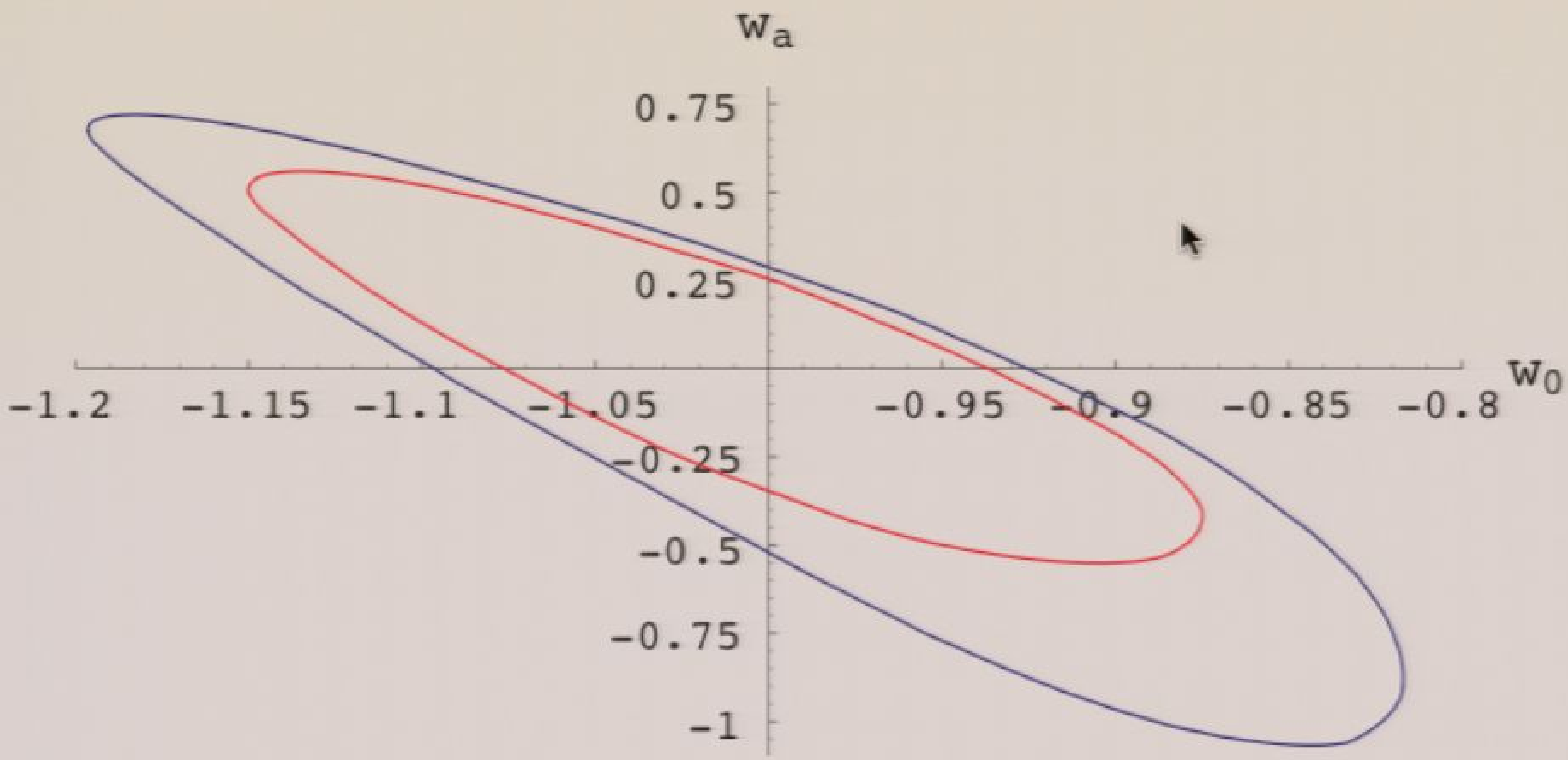

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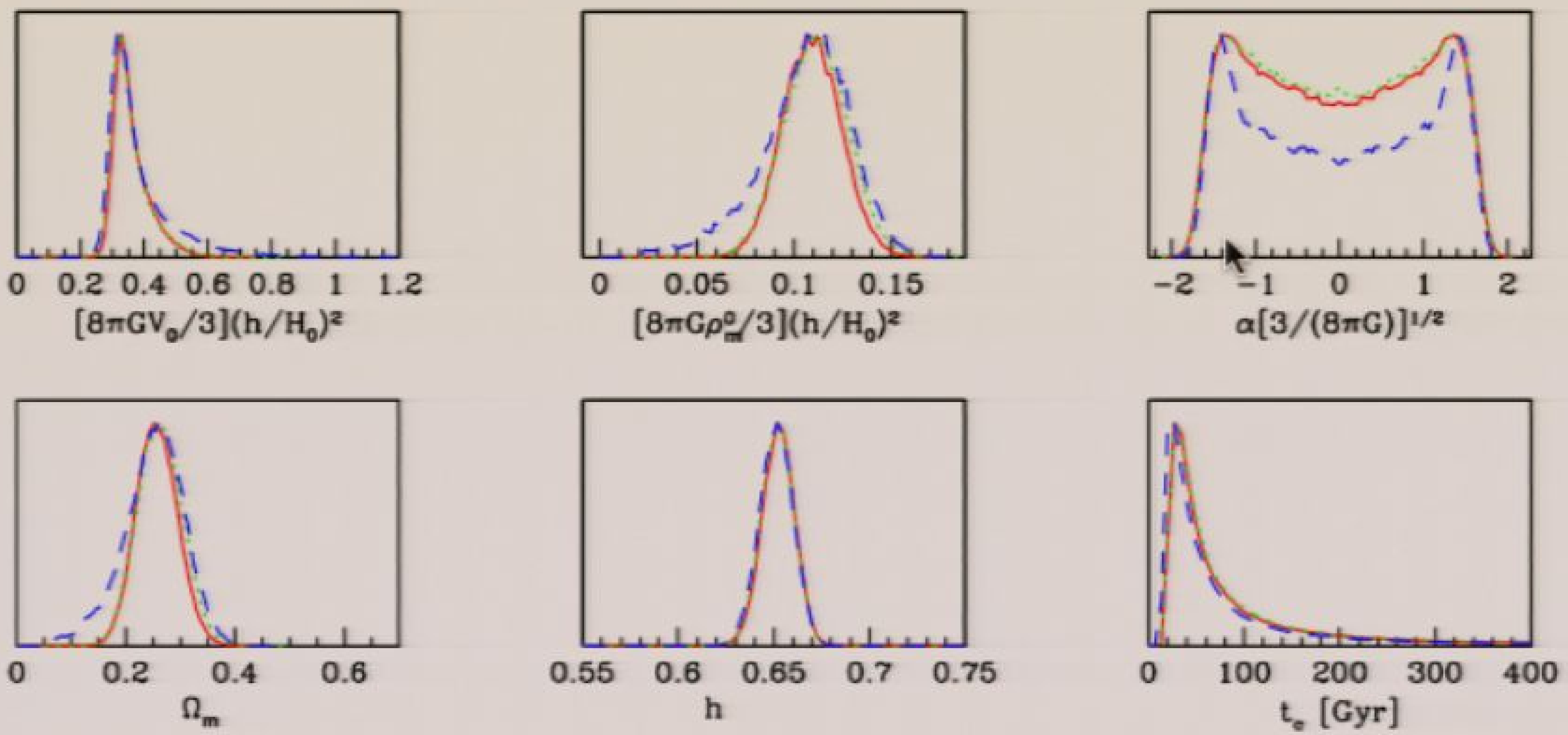

➠ t_c: 24 Gyr (at 95% cl)

Wang, J.M.K., Linde, Shmakova (2004)

Introducing new MCMC code

J.M.K., Pascal Vaudrevange

Markov Chain Monte Carlo code for the study of Dark Energy

- Originally based on CosmoMC MCMC engine (by Lewis & Bridle).
- Designed specifically to study time-varying dark energy.
- CosmoMC does not have a dark energy extension: the quintessence module provided by Lewis runs only with CAMB, not in connection with the MCMC core.
- Parallelized to run on CITA's McKenzie cluster.
- Easy modular design: Arrays of arbitrary input and output variables.
- Eventually publicly available, with support for theorists in other fields.

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First-year dataset now available!

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- SNLS: 5-year program.
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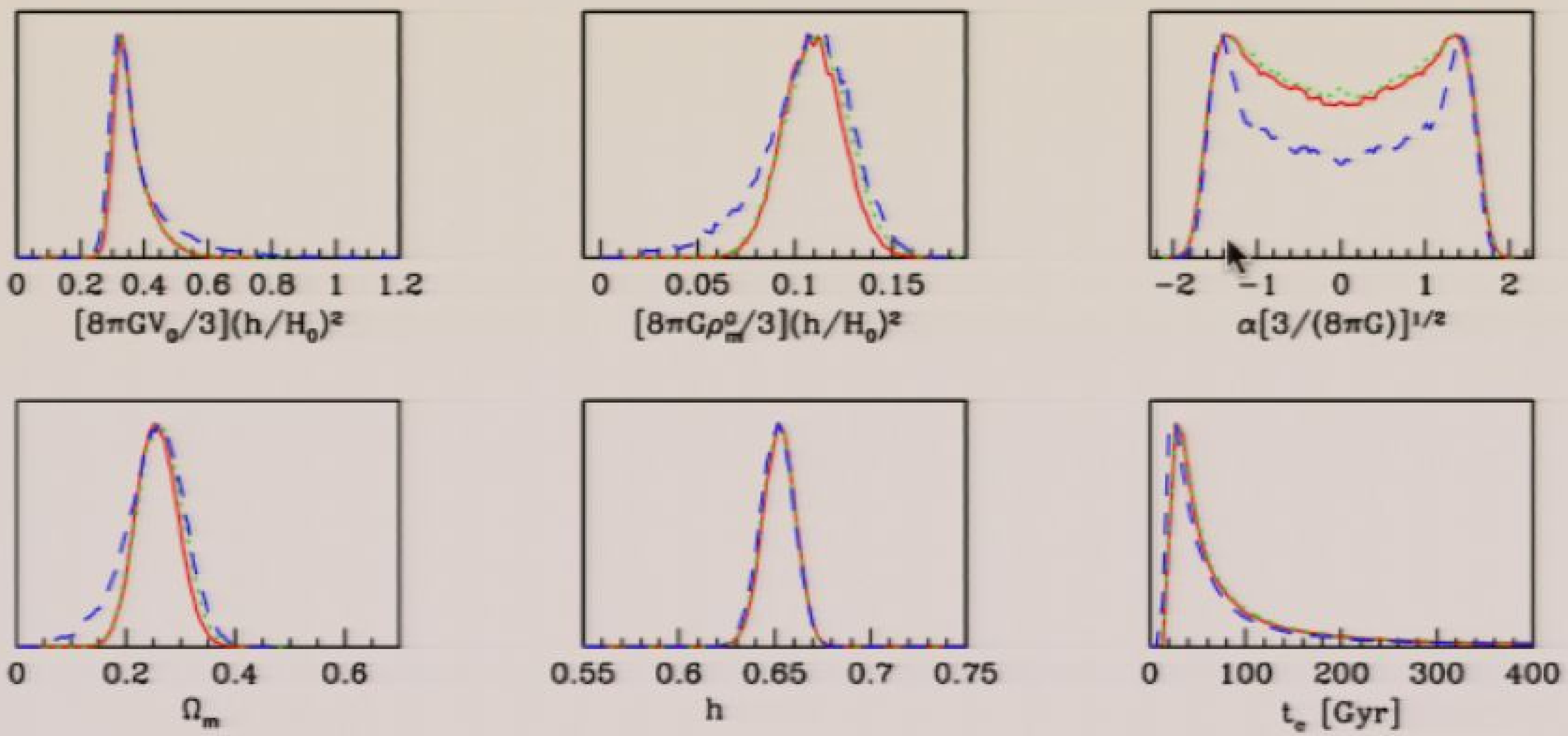

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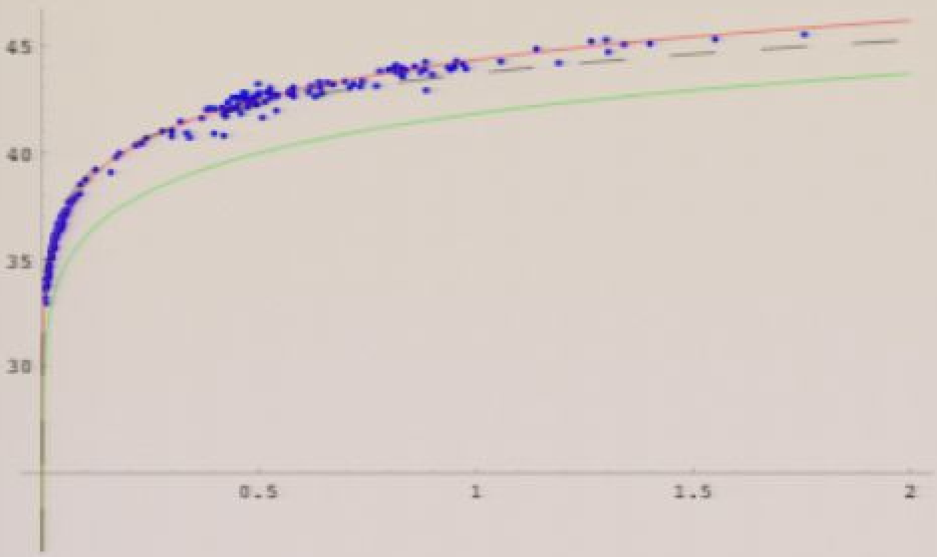
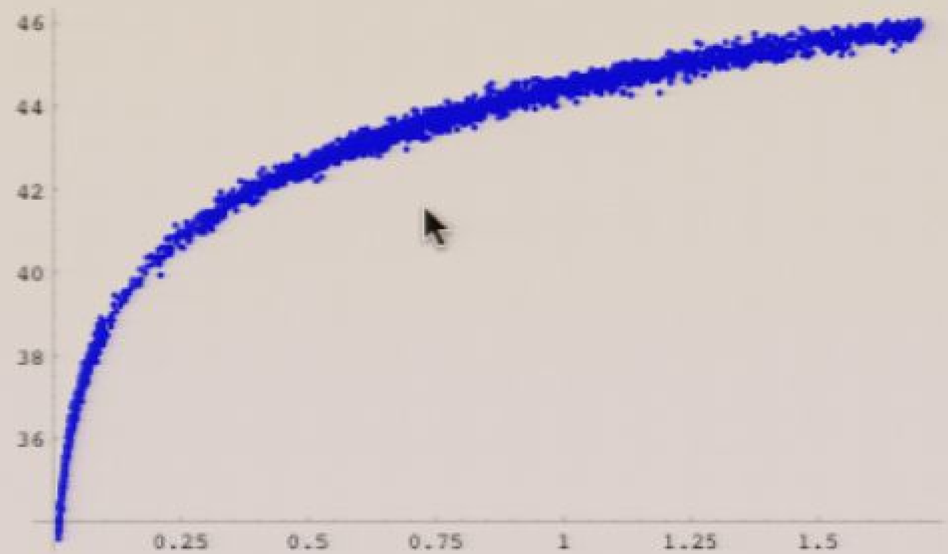
Wang, J.M.K., Linde, Shmakova (2004)

MAGNITUDE-REDSHIFT RELATION OF SNE



Riess *et al.* 2004 gold/silver sample



Simulated dataset for SNAP

(2298 SNe, $\sigma_0 = 0.15\,\mathrm{mag}$ statistical uncertainty)

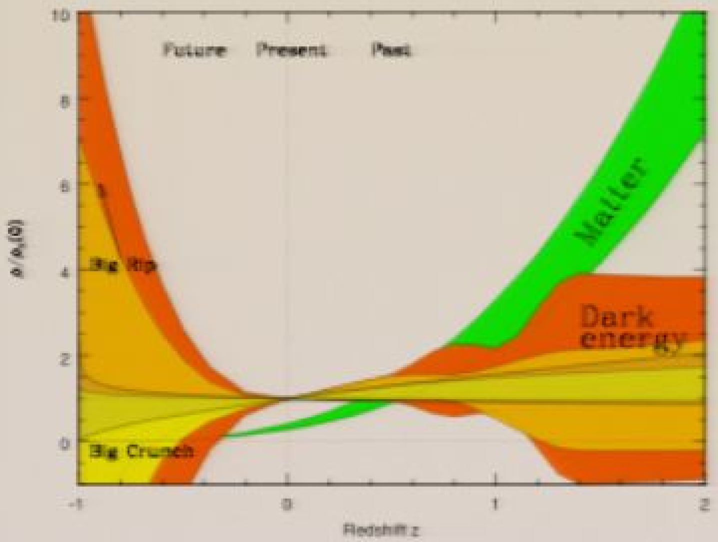
Magnitude-Redshift Relation of SNe

Apparent SNe magnitude as function of redshift z:

$$
\begin{aligned}
m(z) &= 5\log_{10}\Bigg[(1+z)\int_0^z dz'\Big[(1-\Omega_D)(1+z')^3 \\
&+ \Omega_D e^{3\int_0^{\ln(1+z')} d(\ln(1+z''))[1+w(z'')]}\Big]^{-1/2}\Bigg] + \mathcal{M}
\end{aligned}
$$

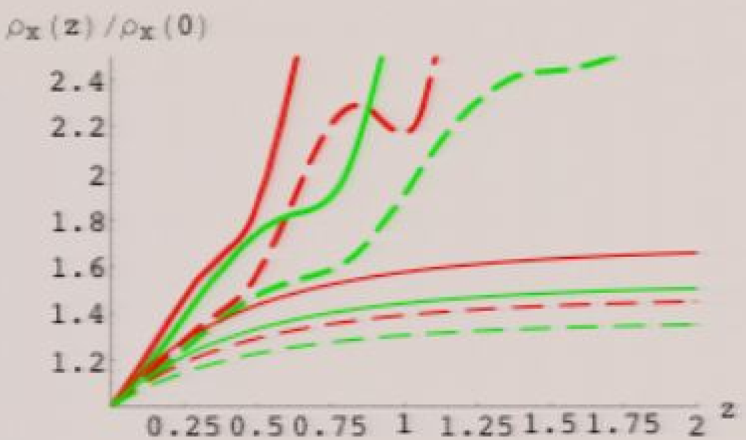
and $\mathcal{M} = M + 25 - 5\log_{10}(H_0/100\mathrm{km/s/Mpc})$,
where M is the supernova absolute magnitude.

MODEL INDEPENDENT ANALYSIS



Model independent: splines still depend on the number of parameters used for the splines. One should not extrapolate from this analysis into the future.

Wang & Tegmark (2004)



Model independent boundaries constrain $\rho_X(z)/\rho_X(z=0)$ of linear potential at redshift $z < 0.003$, where there are no supernovae.

Wang, J.M.K., Linde, Shmakova (2004)

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Scalar Field Dark Energy

Equation of motion for scalar field ϕ (in FRW background):

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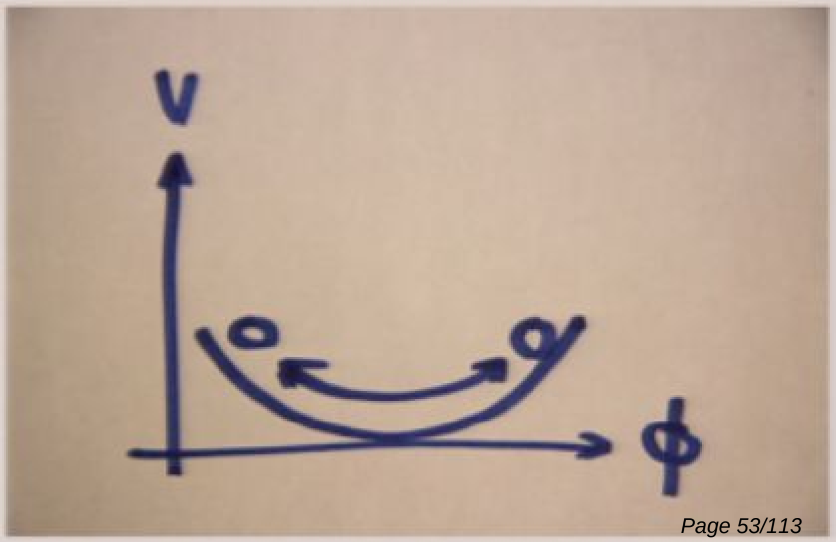

TIME EVOLUTION OF SCALE FACTOR $a(t)$

Friedmann equations:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\frac{\rho_m^{(1)}}{a^3} + 3\underbrace{p_m}_{=0} + 2\dot{\phi}^2 - 2V(\phi)\right)$$

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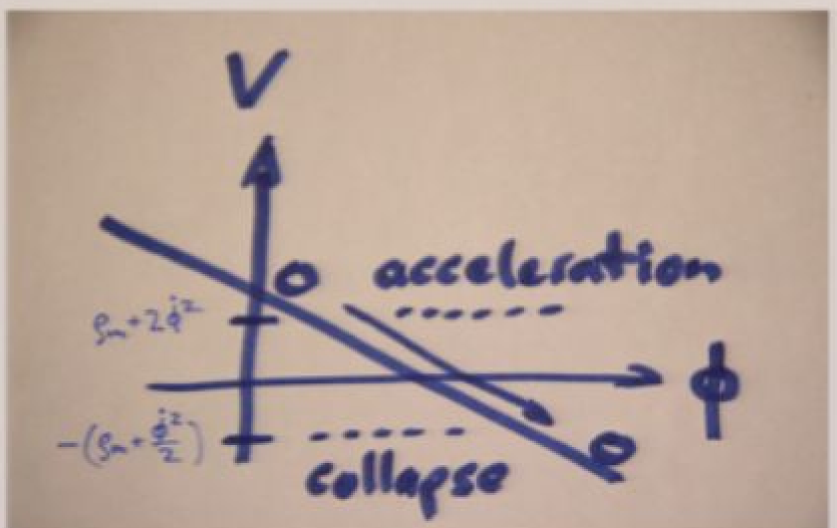

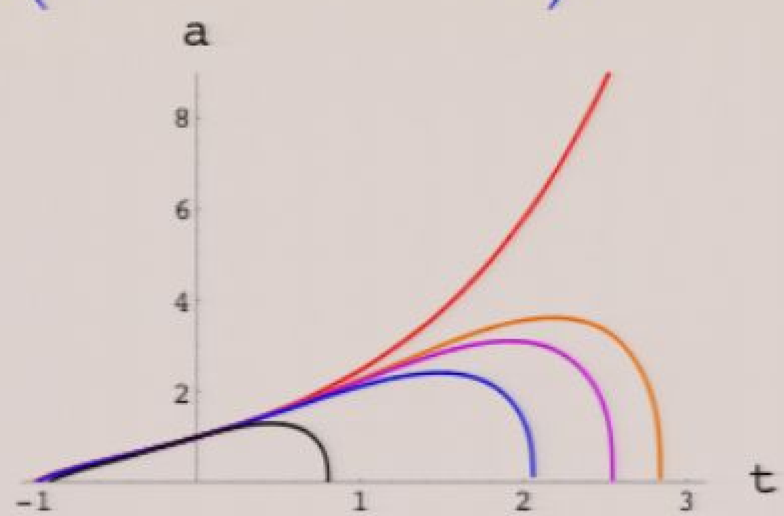

Generic scalar field dark energy behavior!

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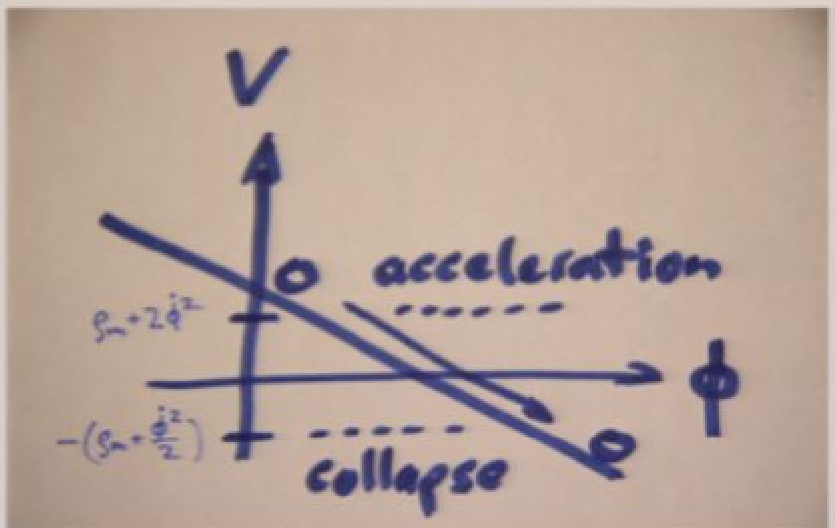

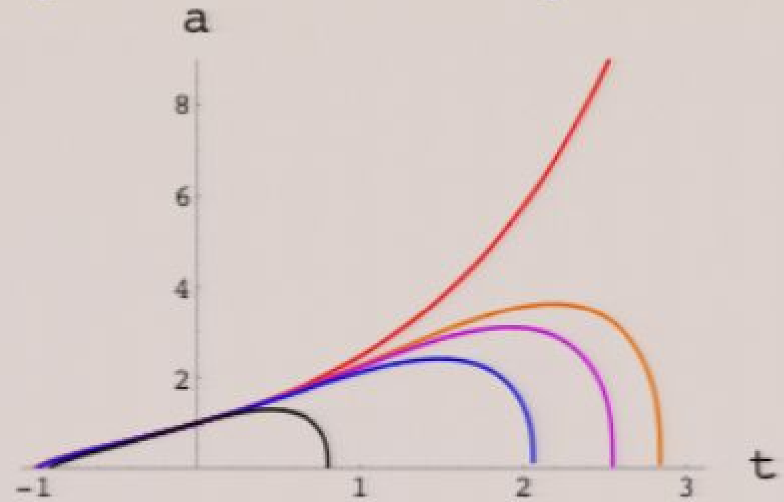

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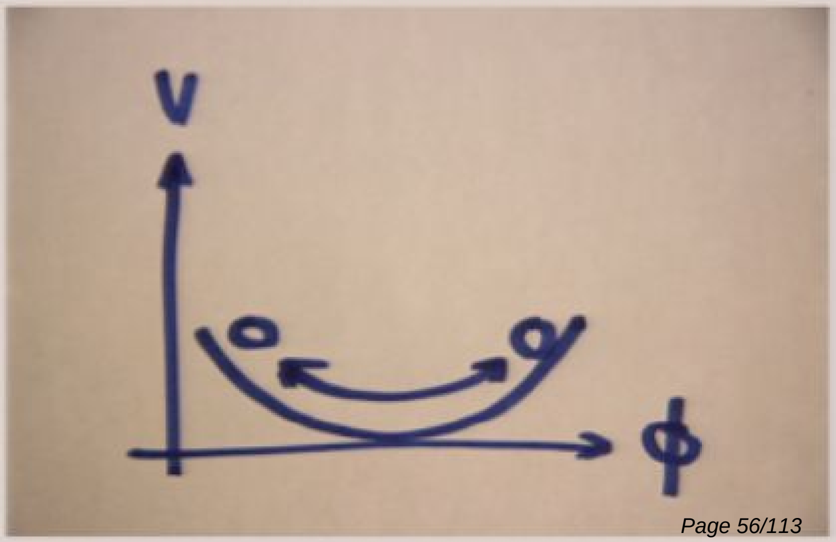

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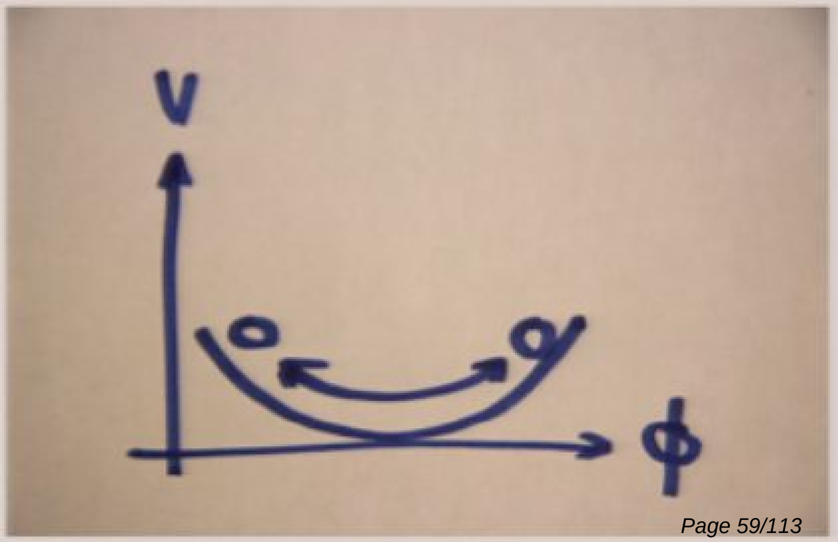

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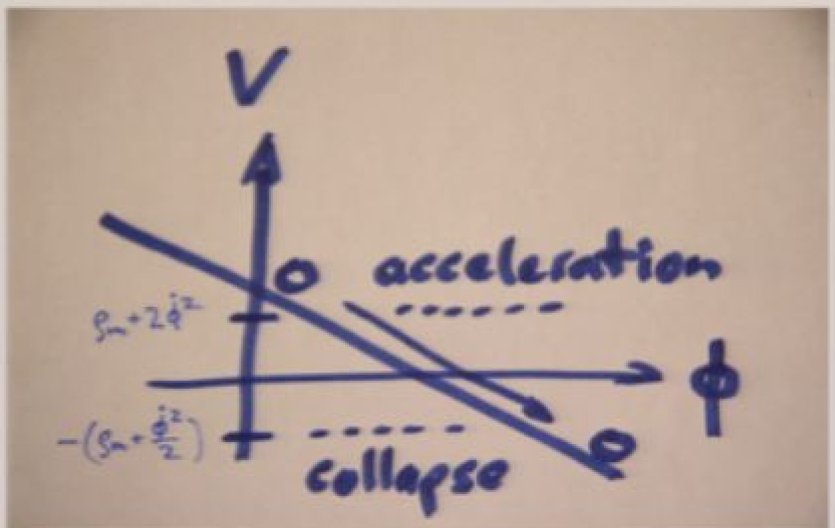

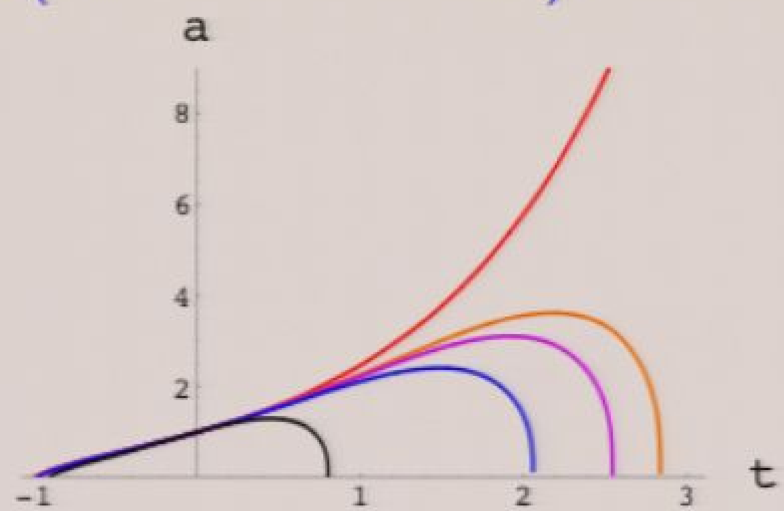

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Spectroscopic Follow-up

- Obtain redshift of SNe
- Identify if SN is of Type Ia
- Requires 8-10 m class telescopes due to faintness of distant SNe:
  - European Southern Observatory Very Large Telescope
  - Gemini-North and South
  - Keck-I and -II
- Imaging Survey: more candidates that can be followed up:
  - Photometric selection tool: real-time light-curve fits
  - Database of variable objects (remove AGN, variable stars)
- Determines SN Ia (secure) and SN Ia* (probable)

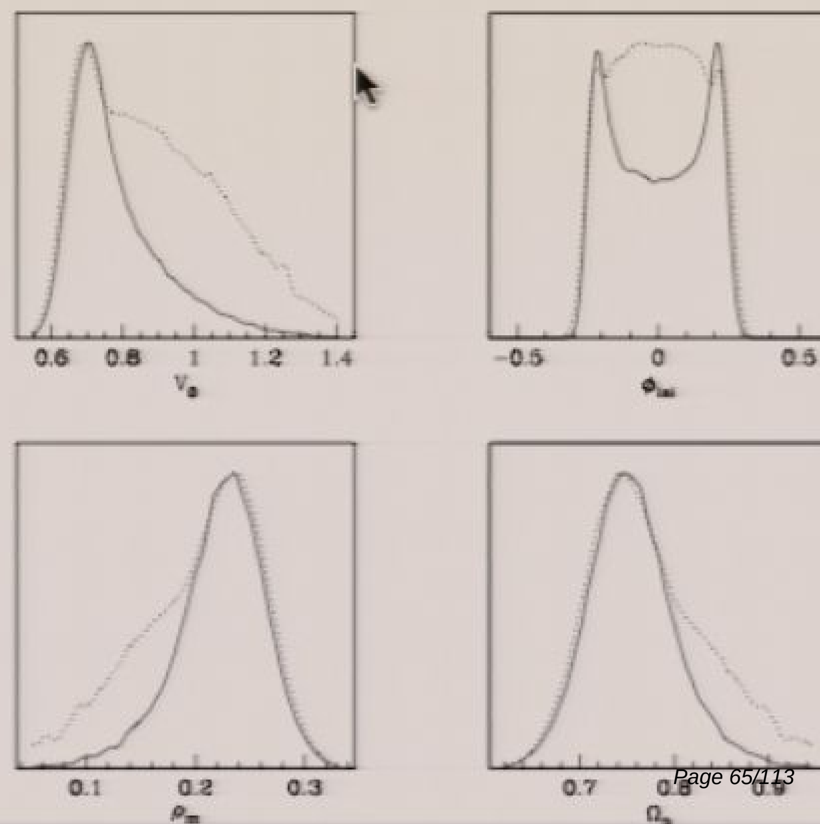
GAUGED N=8 SUPERGRAVITY

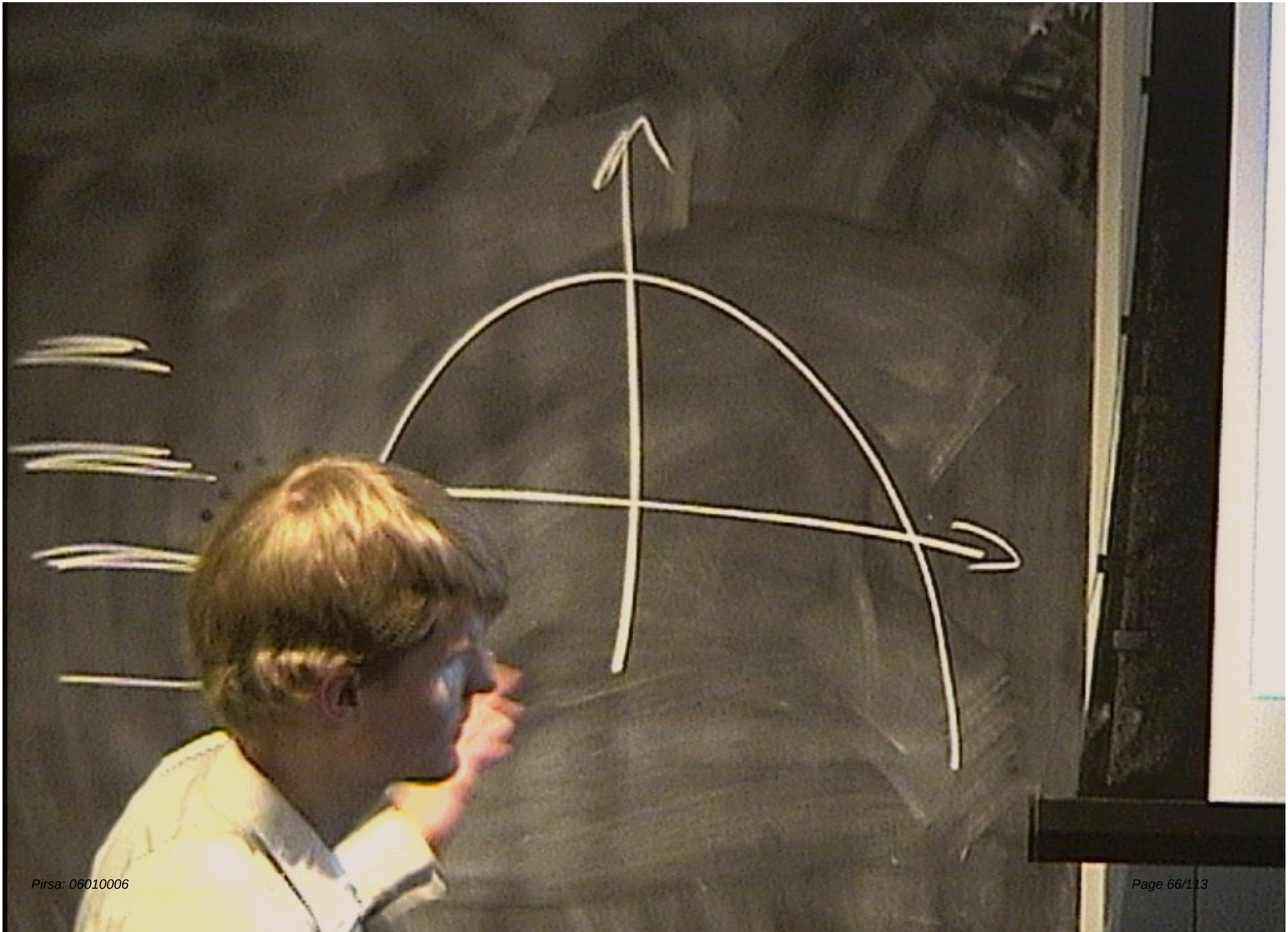
Gauged N=8 SUGRA
dark energy potential:

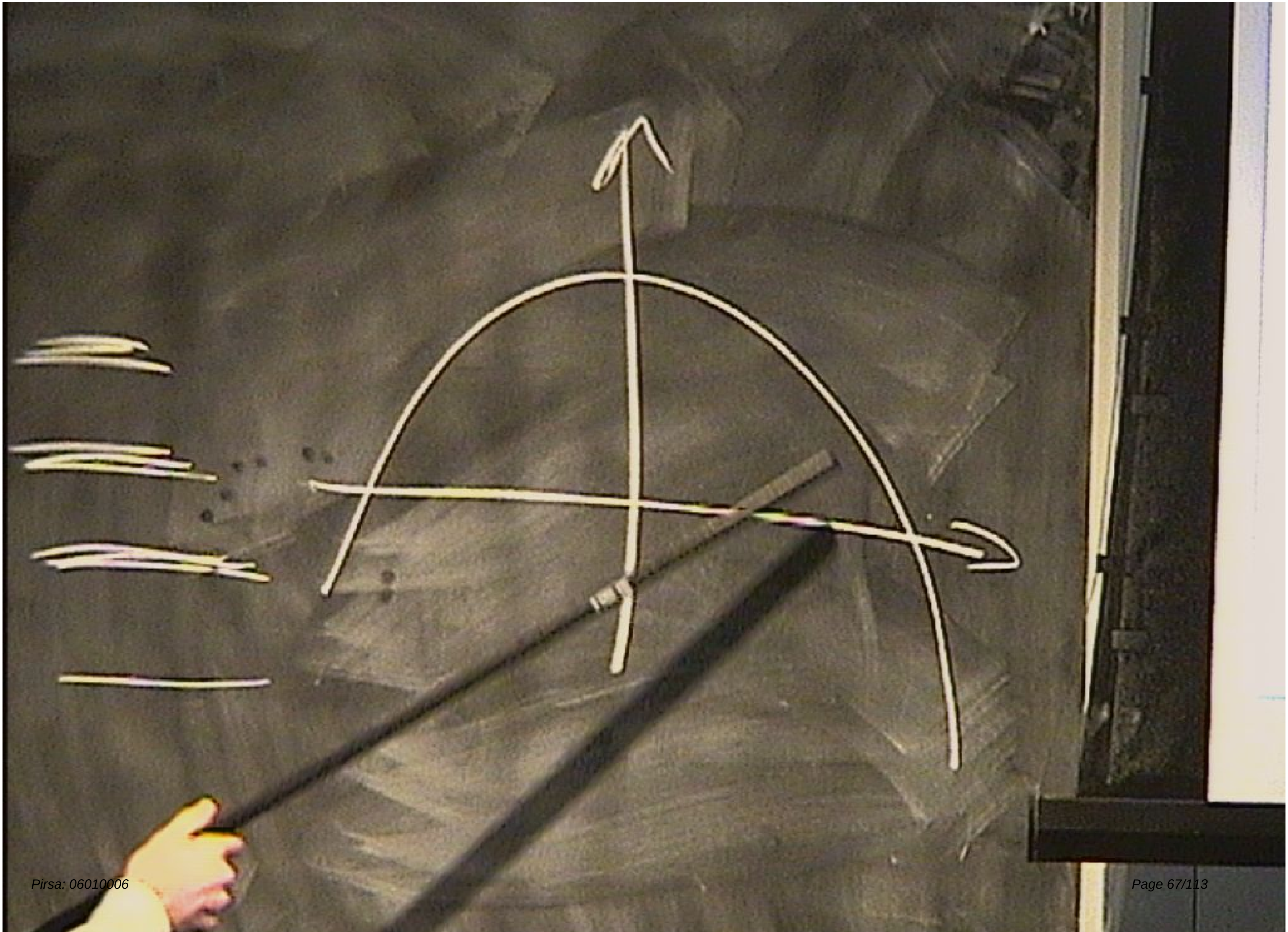
$$V(\phi) = V_0\left(2 - \cosh(\sqrt{2}\phi)\right)$$

- Derived from fundamental particle physics
- Generic shape
  ➠ Features generic.
- Rapidly collapsing
  ➠ Shows features more prominently.

Likelihood (dotted) and marginalized probability distribution (solid) of model parameters:







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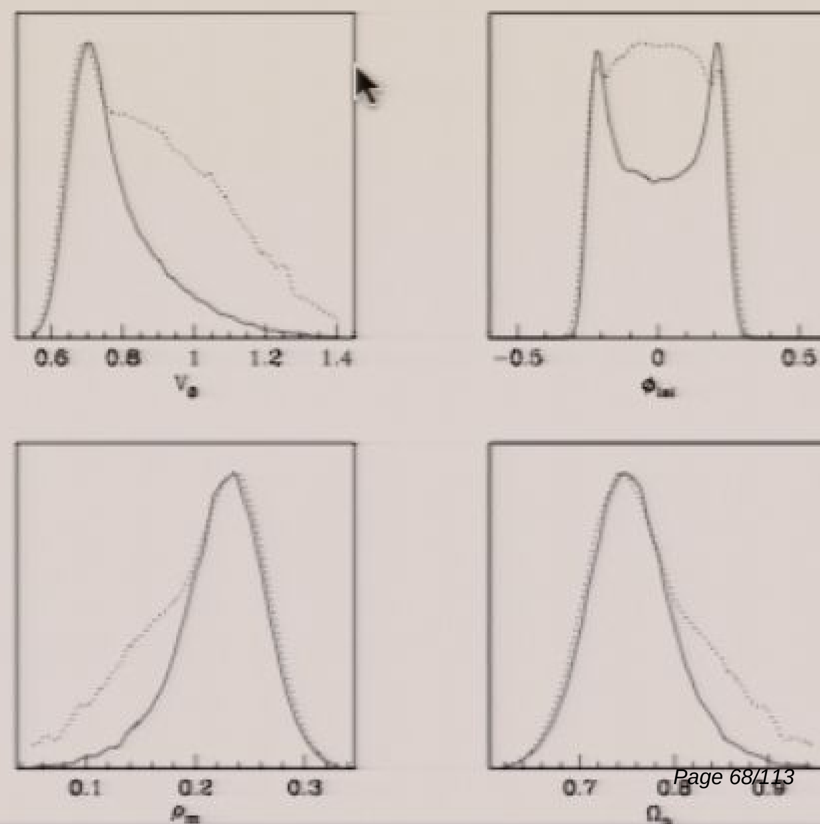

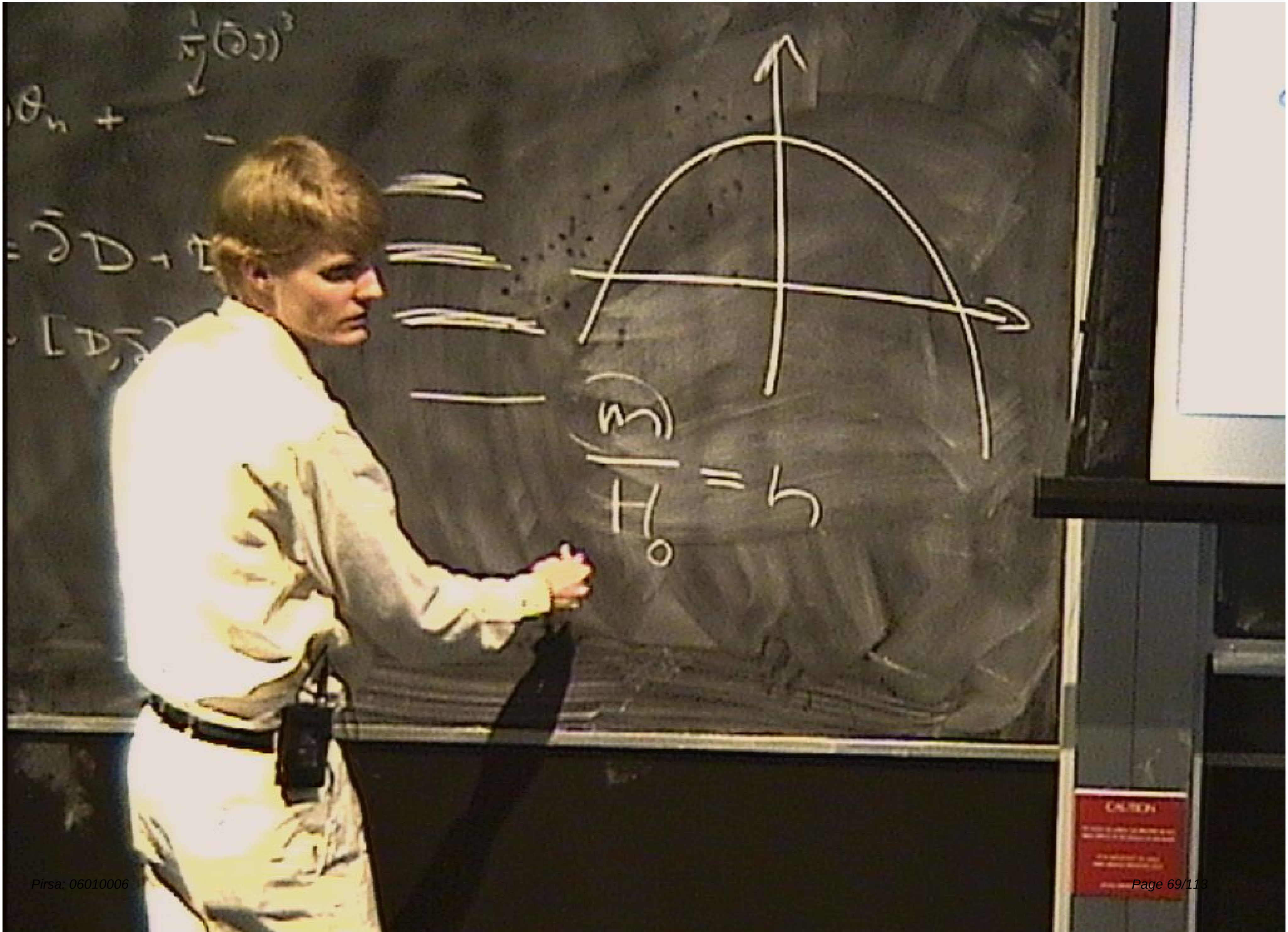

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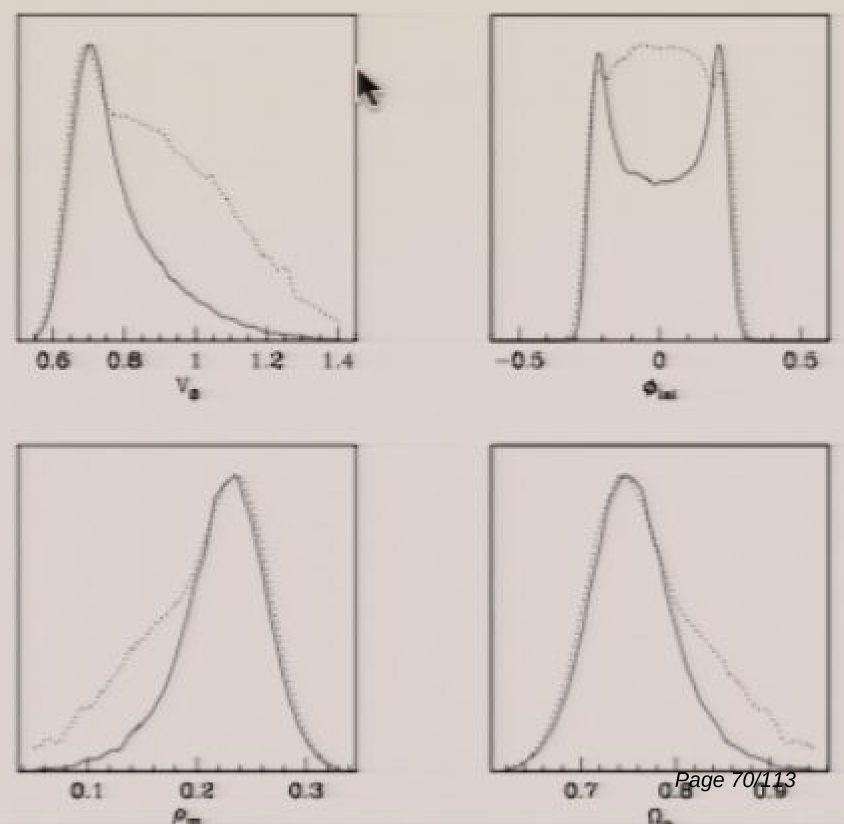

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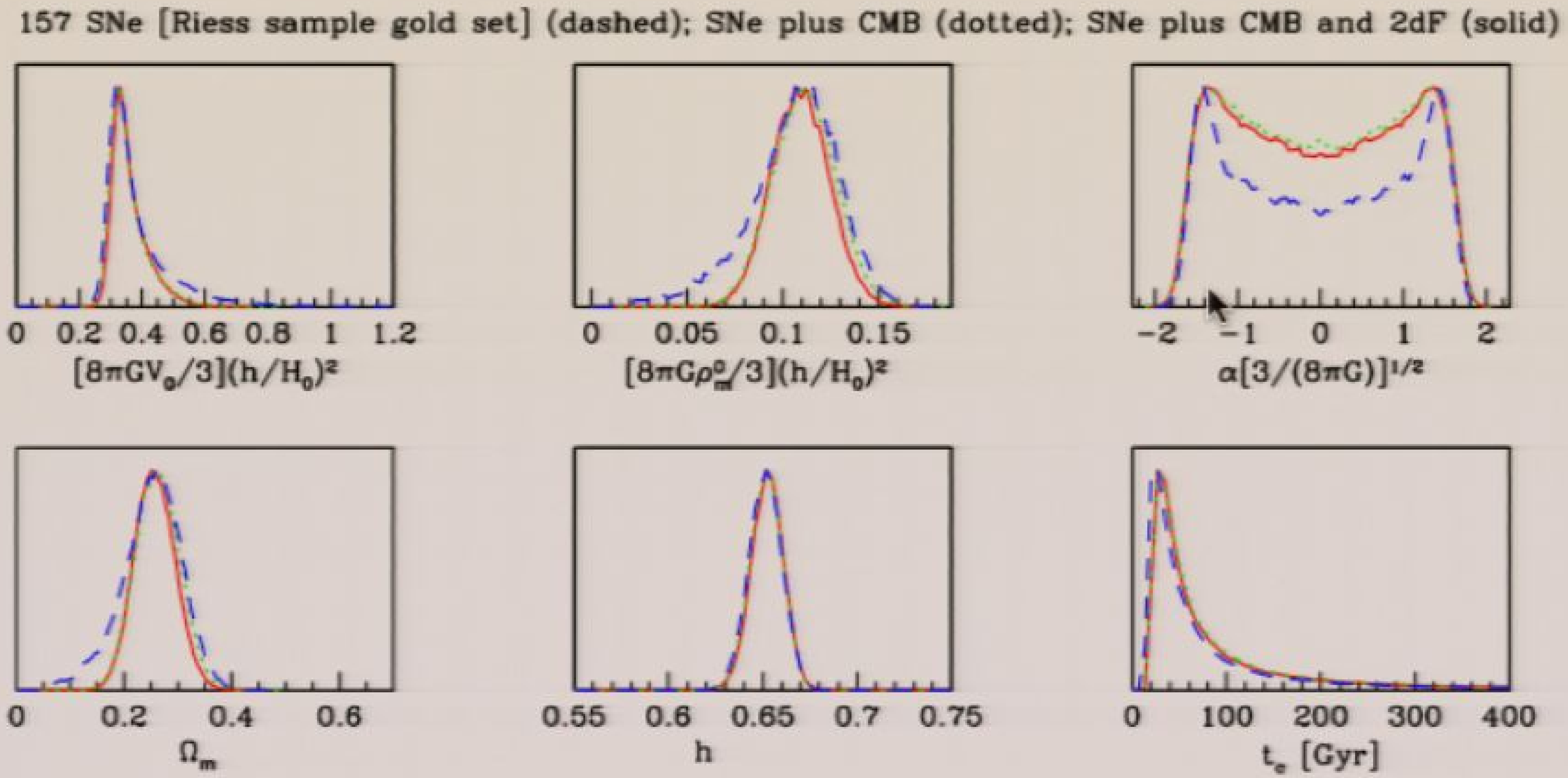

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Wang, J.M.K., Linde, Shmakova (2004)

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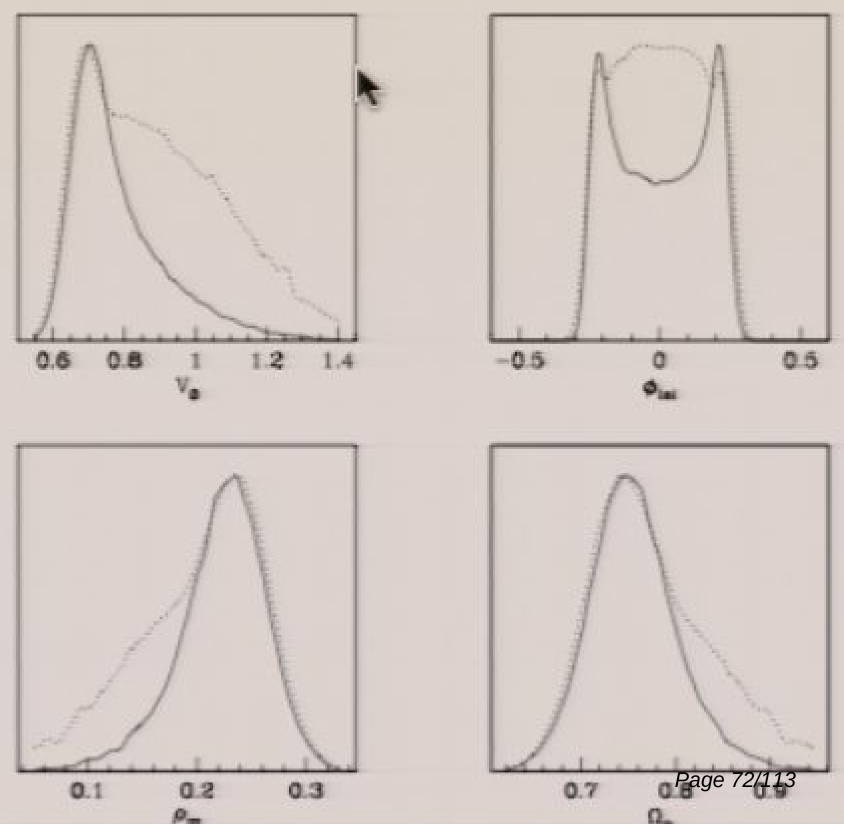
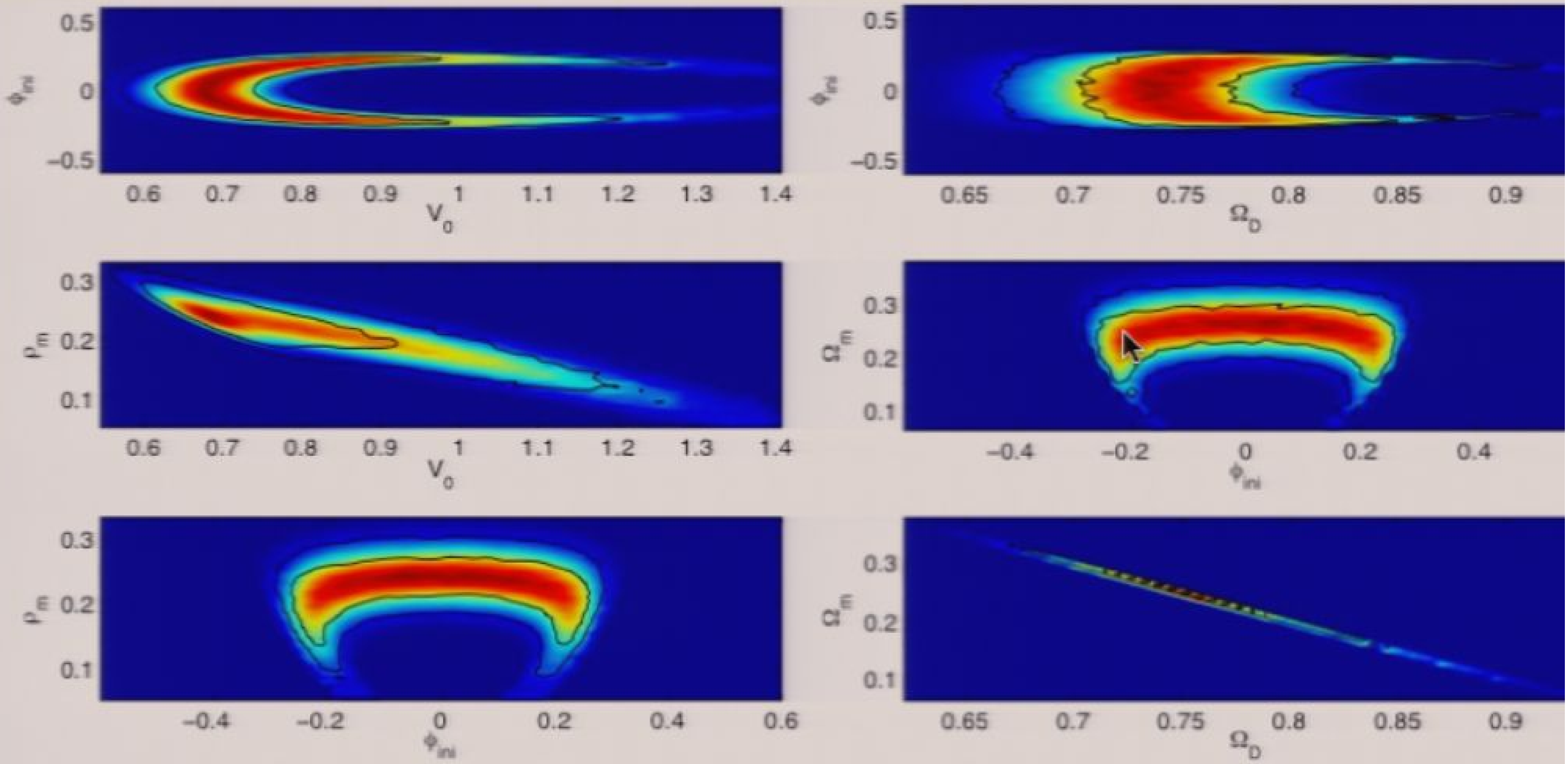


3D Parameter Space



color: likelihood, contour: marginalized probability

Cosmological parameters (H_0^2 divided out)

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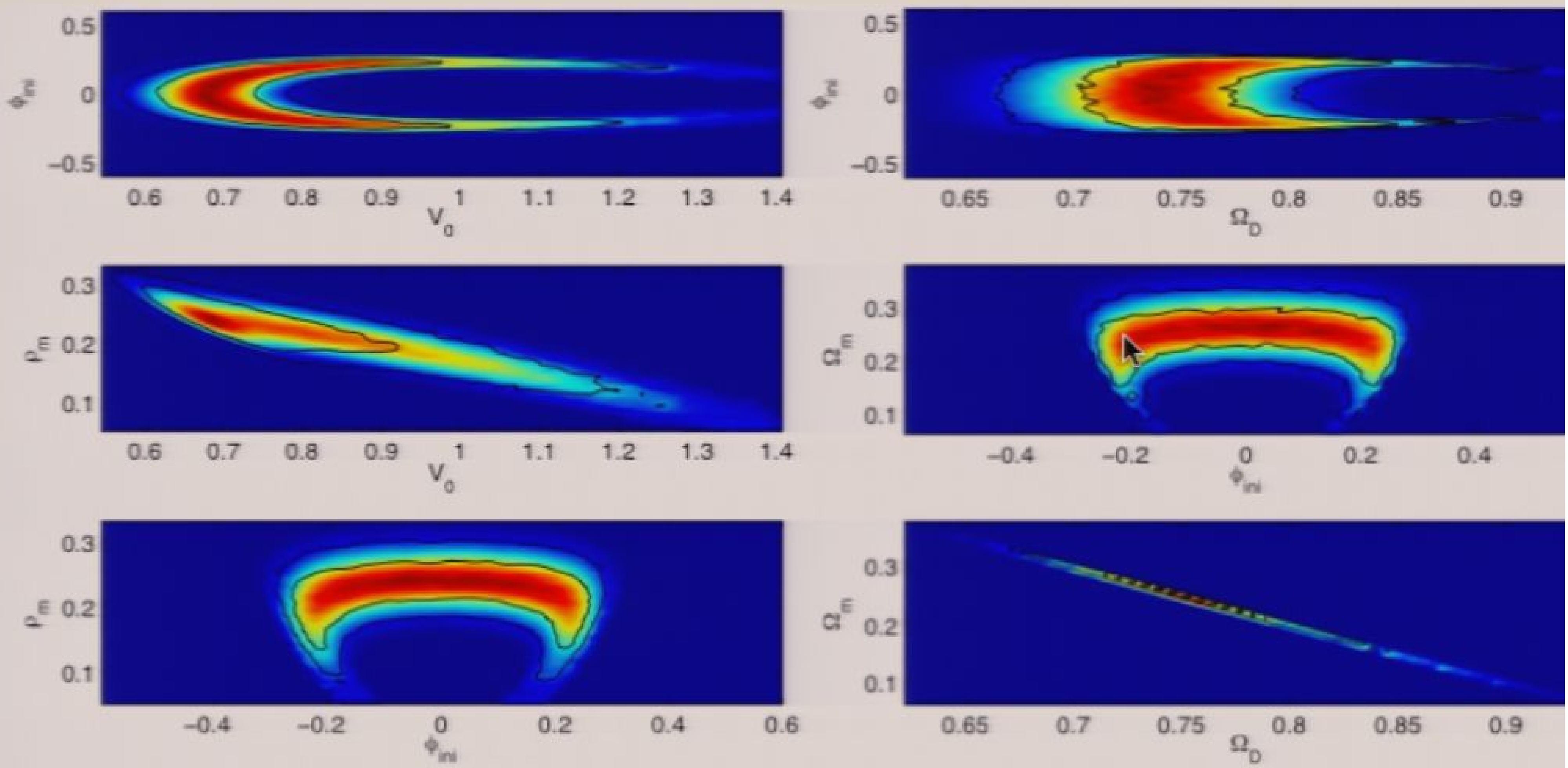

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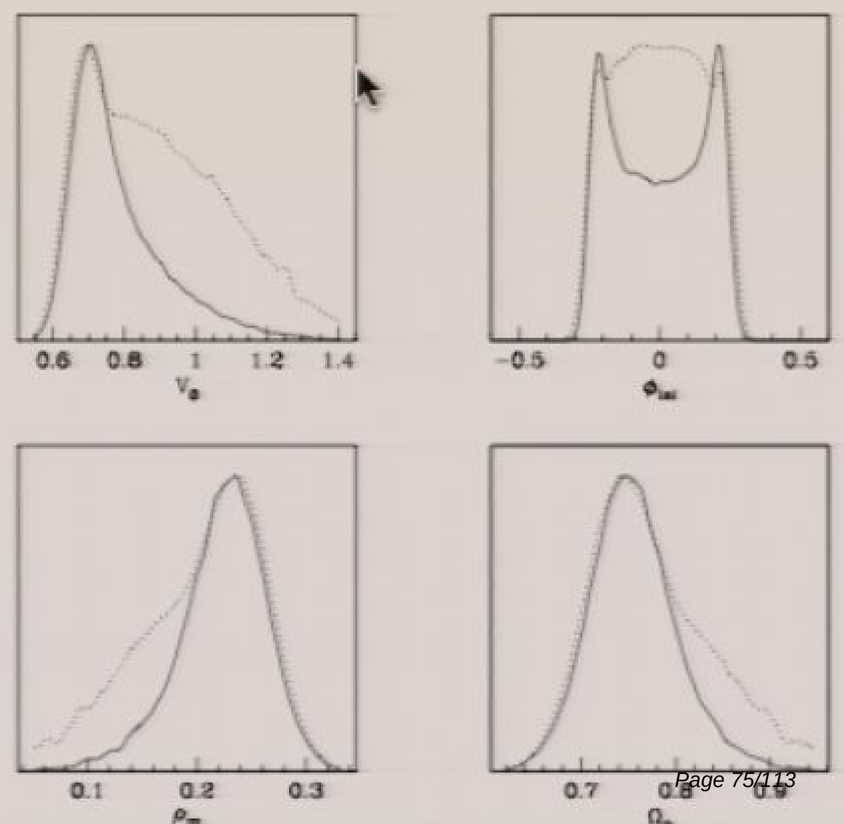

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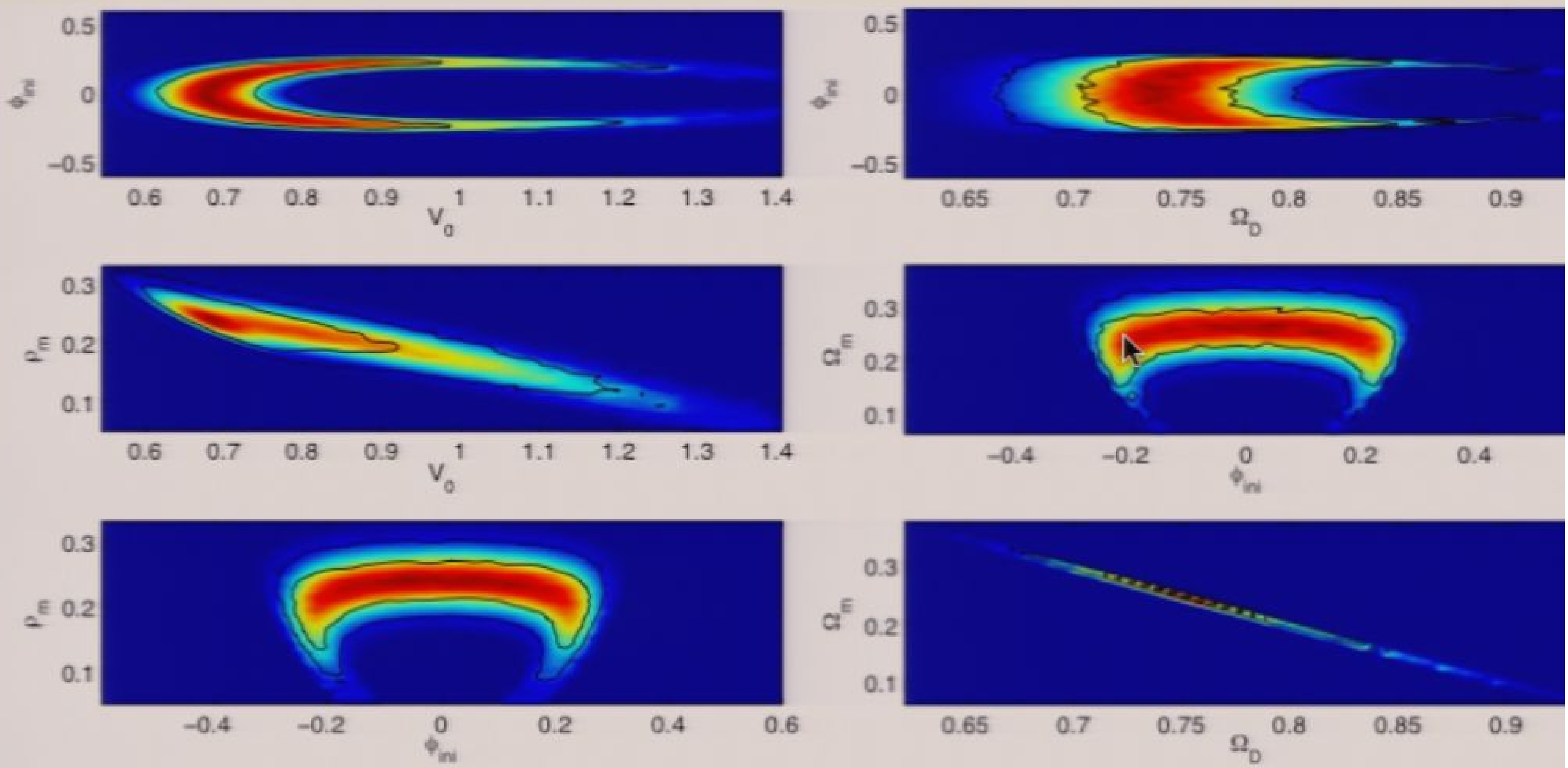

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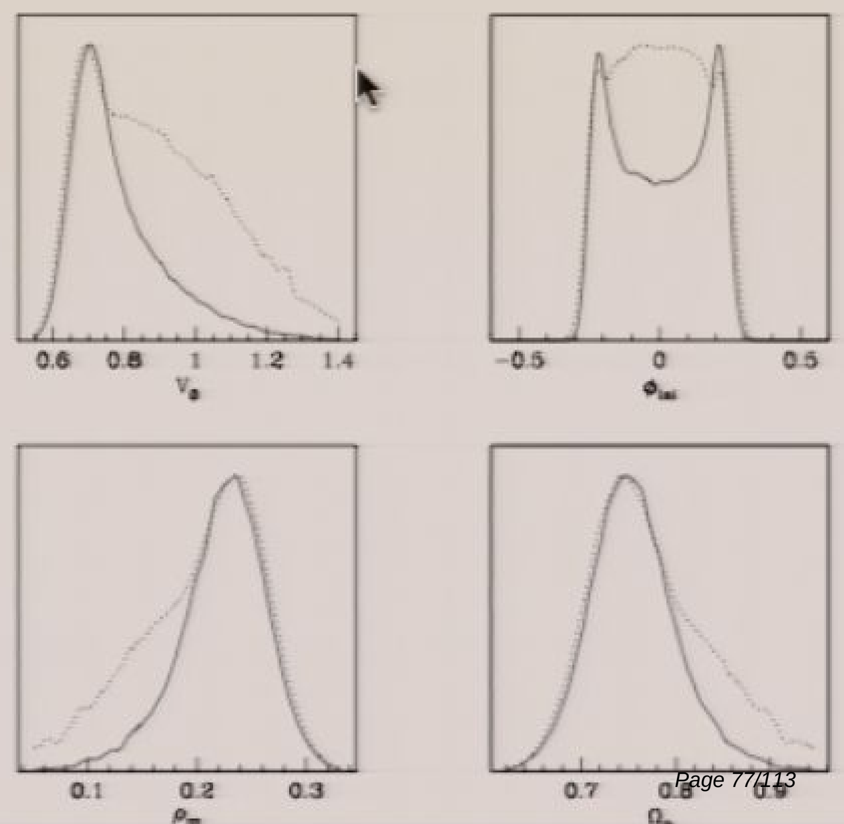

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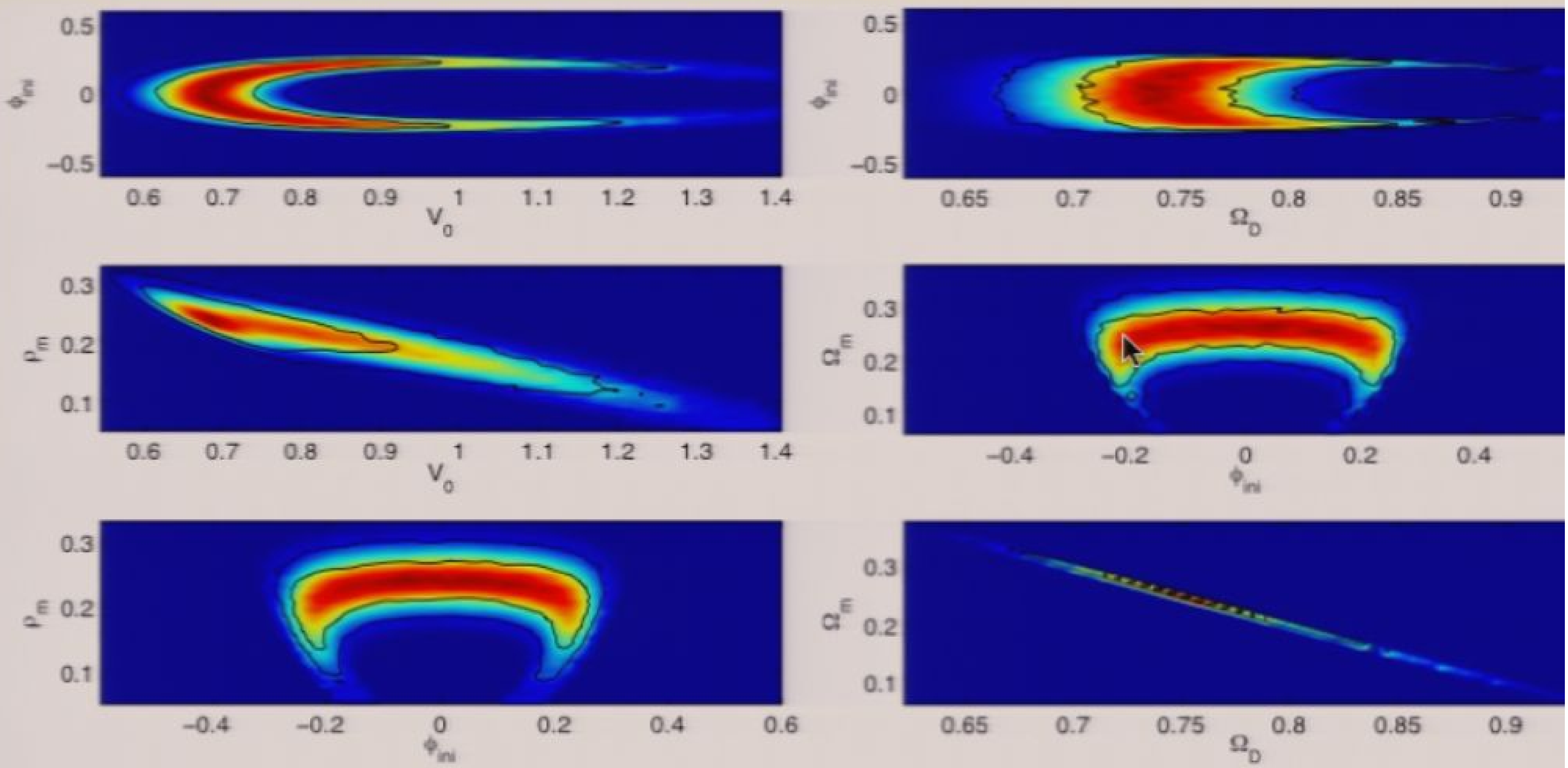

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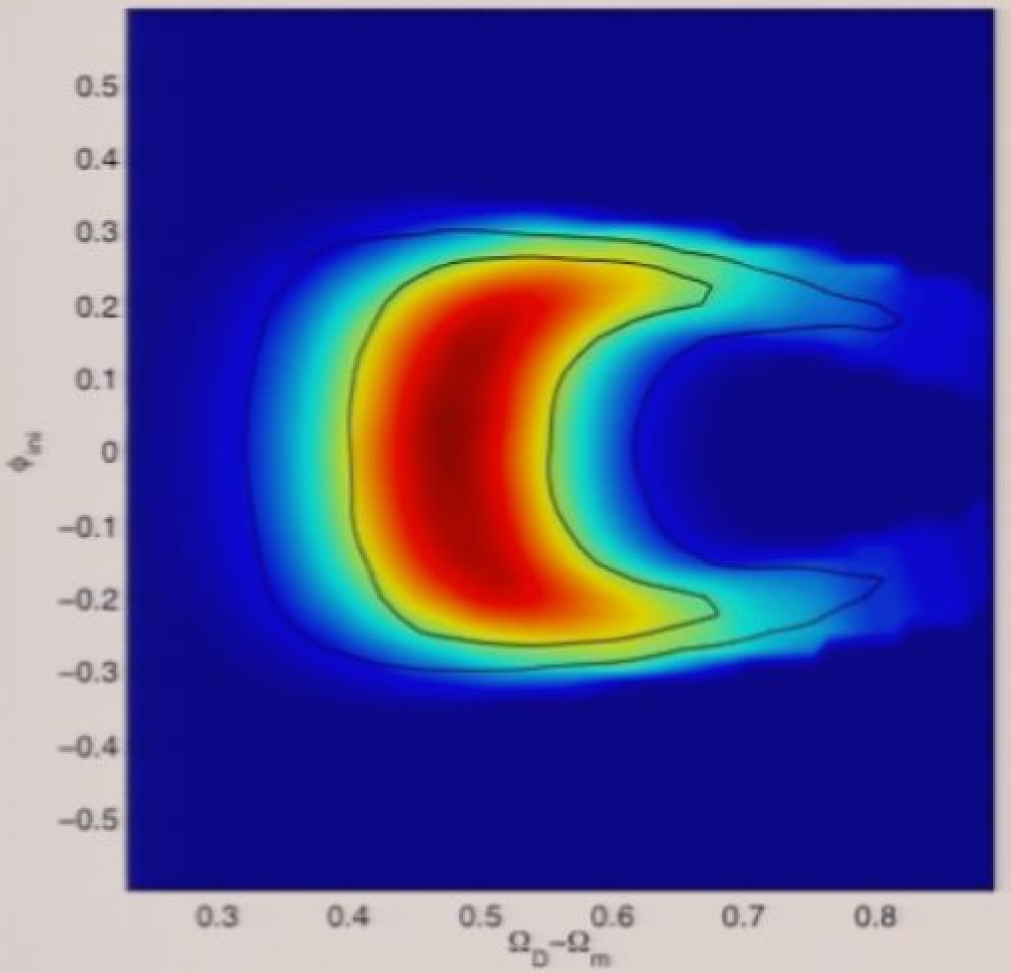
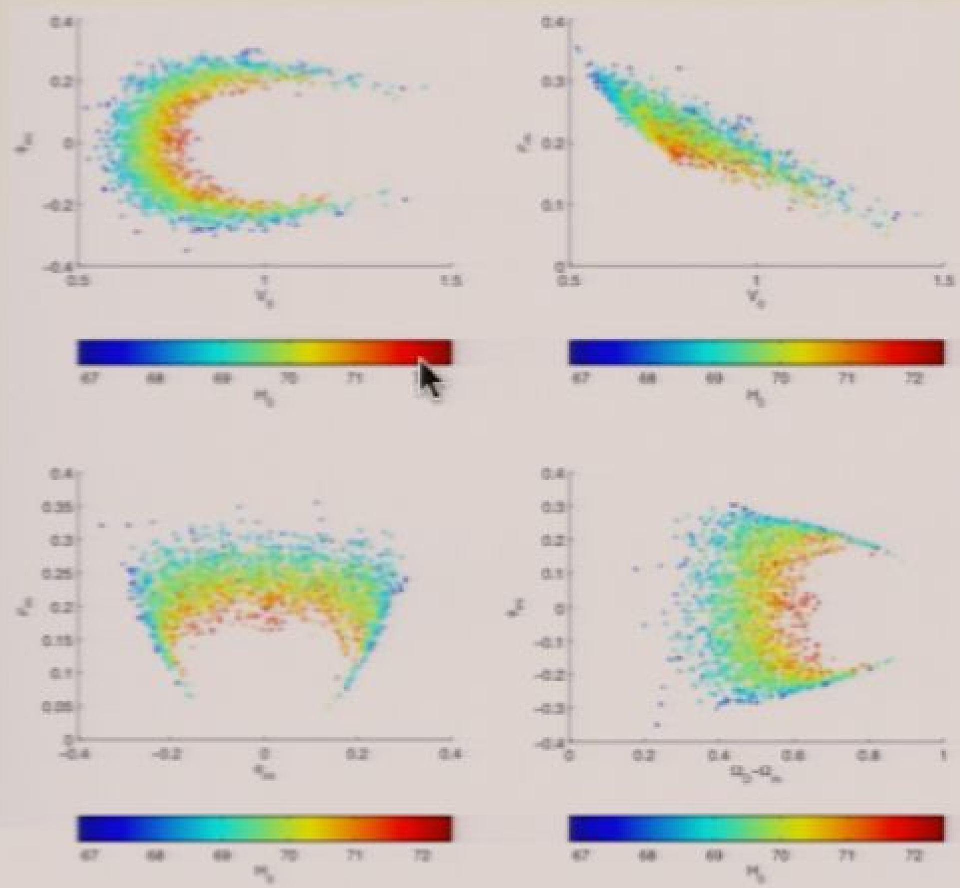
2D MARGINALIZED DISTRIBUTION



color: mean likelihood
black contours: marginalized probability
(68% and 95% c.l.)



Removing H_0 dependence from model parameters.

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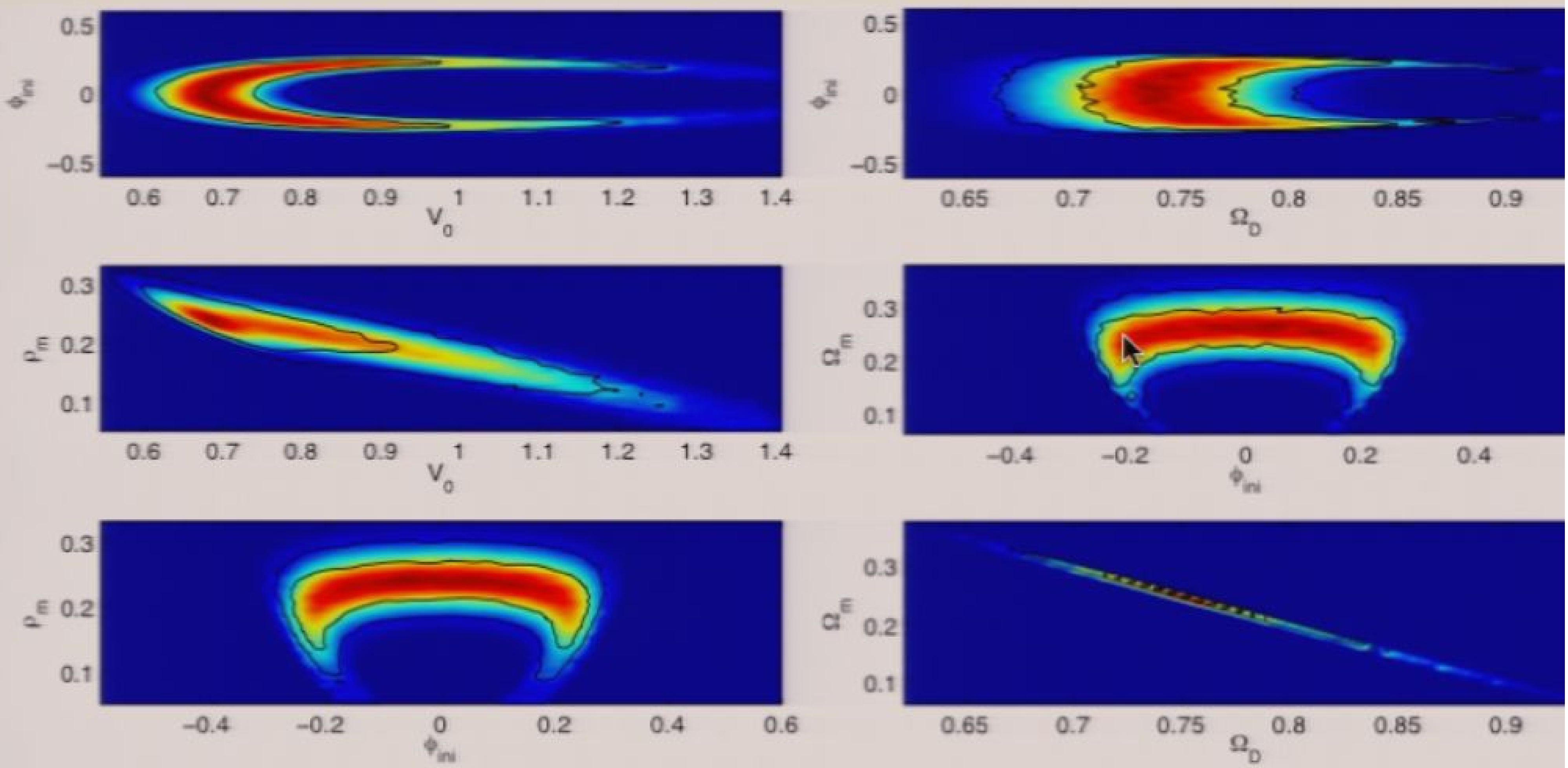

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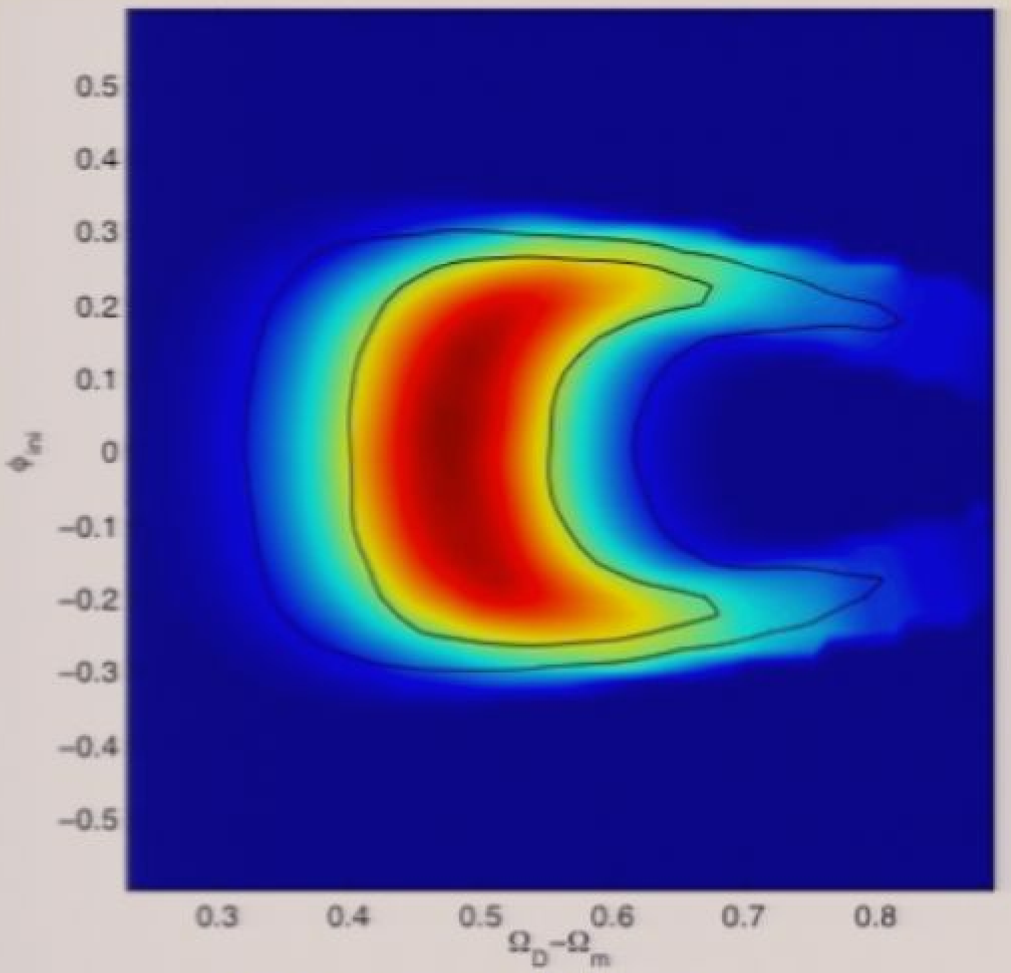
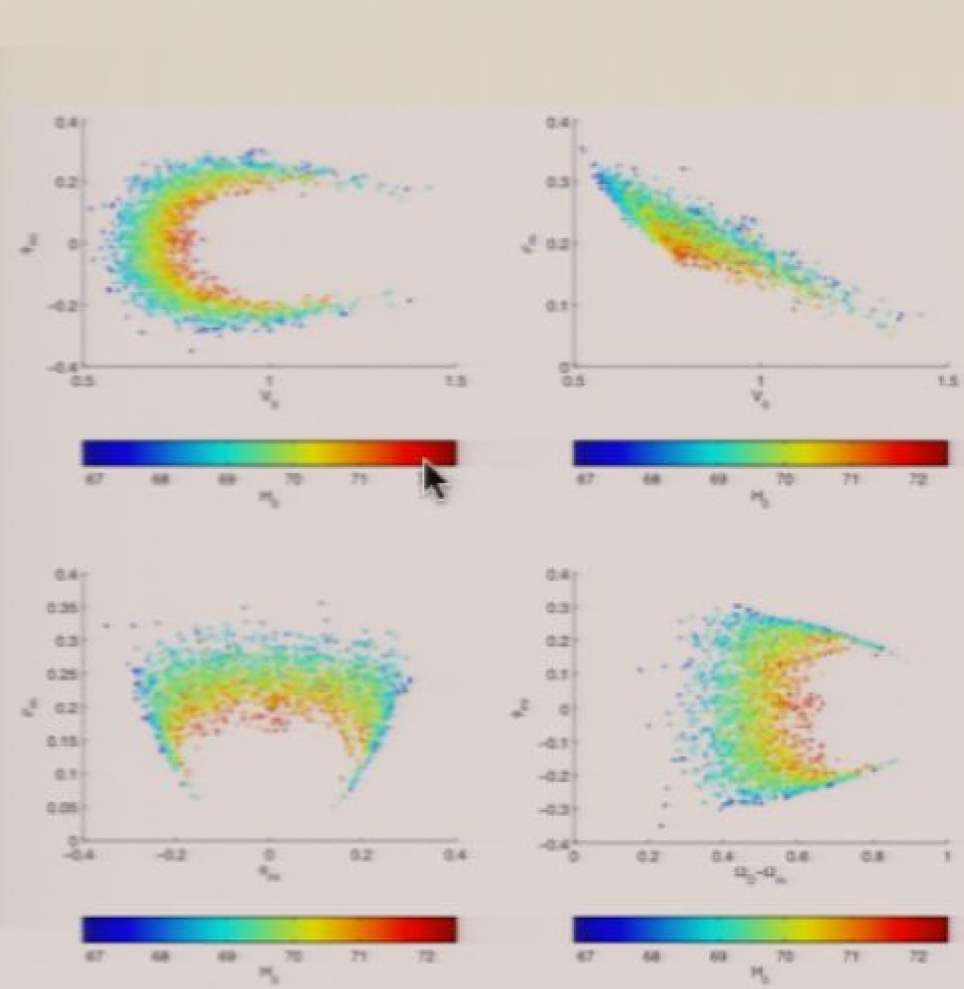
2D MARGINALIZED DISTRIBUTION





color: mean likelihood

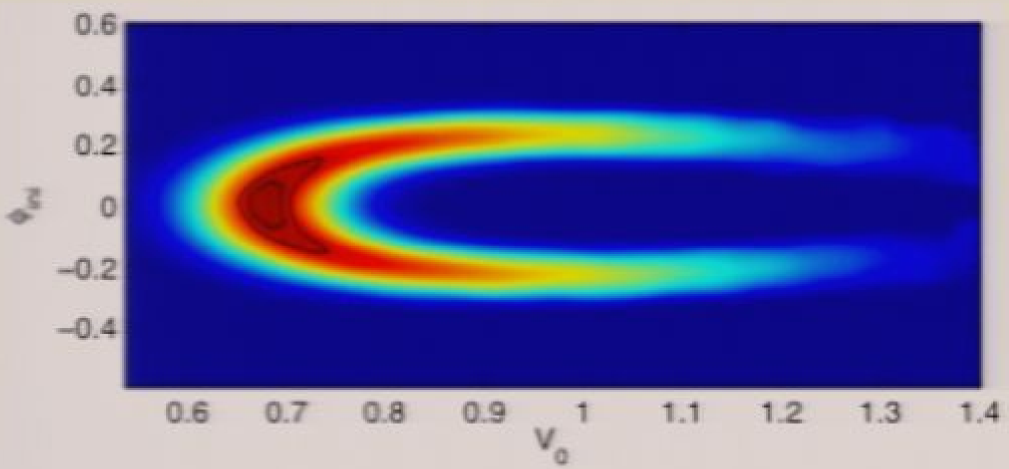
black contours: marginalized probability

(68% and 95% c.l.)

Removing H_0 dependence from model parameters.

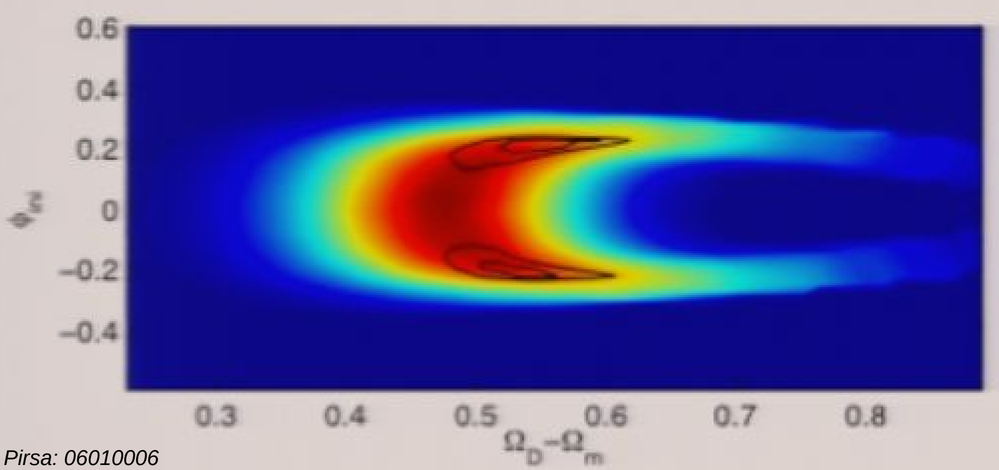
Peak Shift due to Marginalization

Marginalization over H_0 causes shift in peaks of probability distribution.



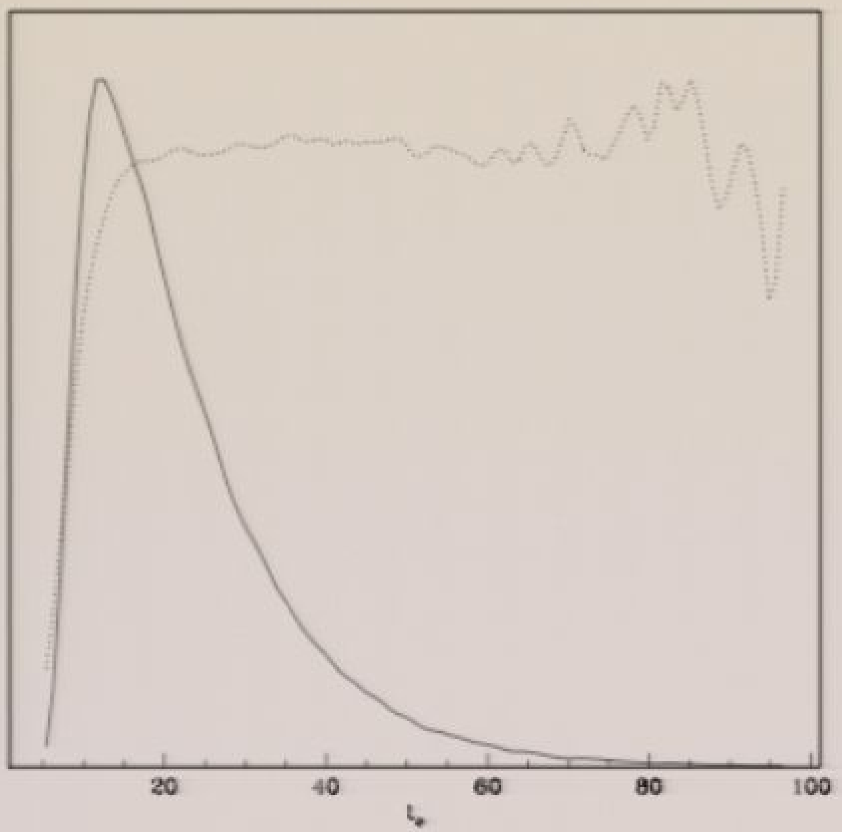
$\leftarrow$ Original parameter space

Color: mean likelihood.
Black contours: 5% and 15% marginalized probability.

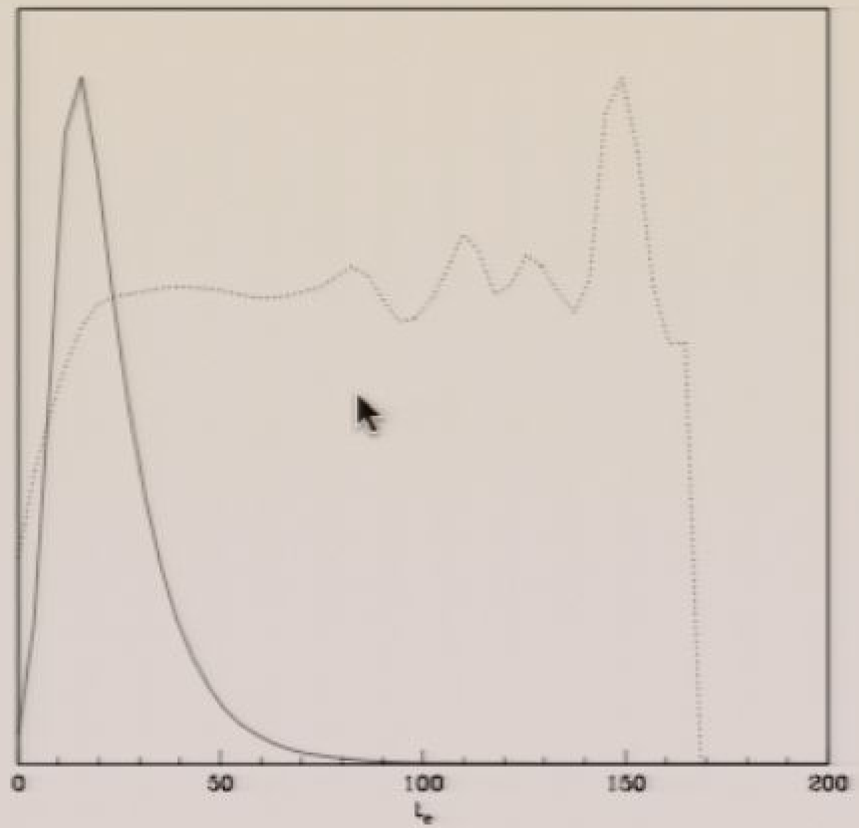


$\leftarrow$ H_0 marginalized parameter space.

Future Lifetime

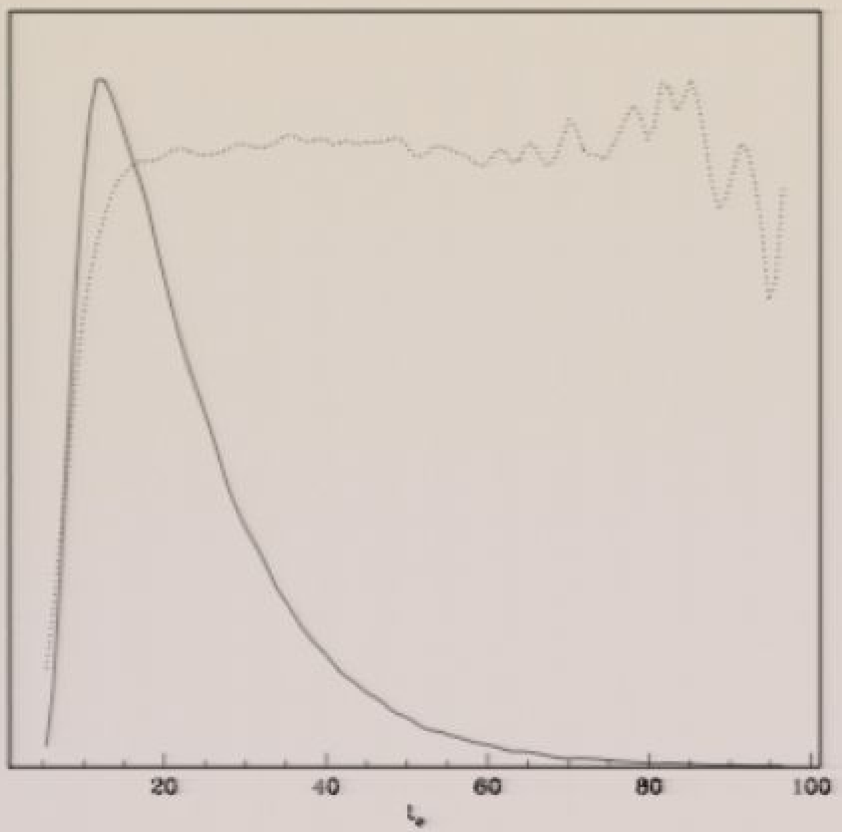


8–55 Gyr at 95% c.l.



Cut-off due to quantum fluctuations / numerical accuracy.

FUTURE LIFETIME



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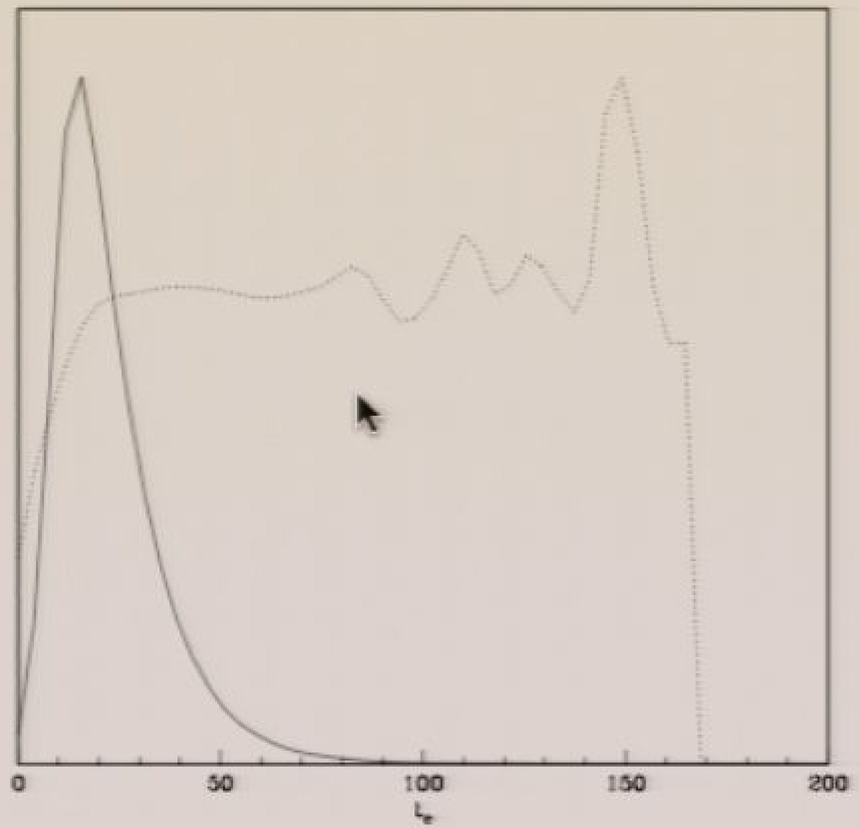

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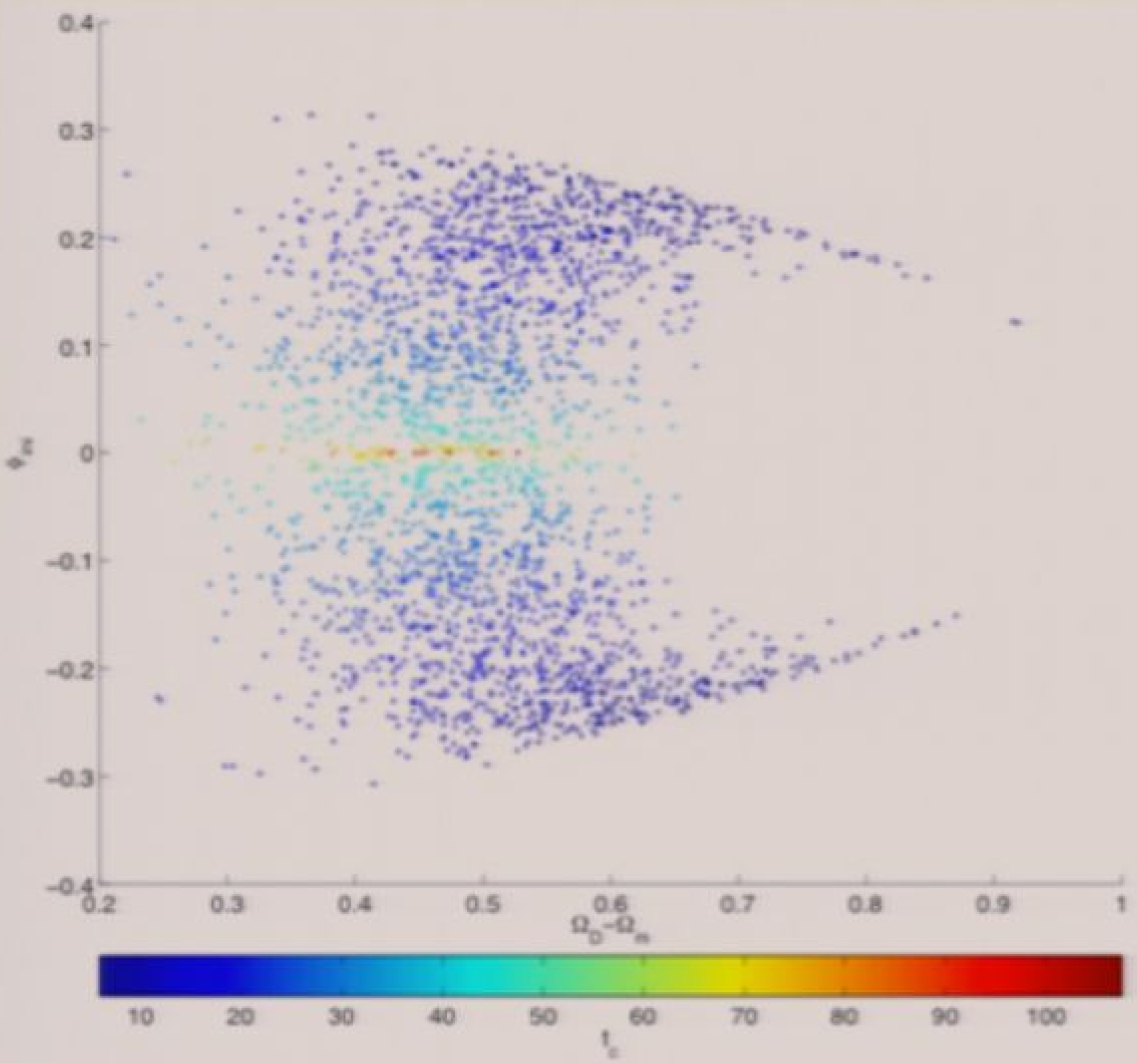
LIFETIME DISTRIBUTION

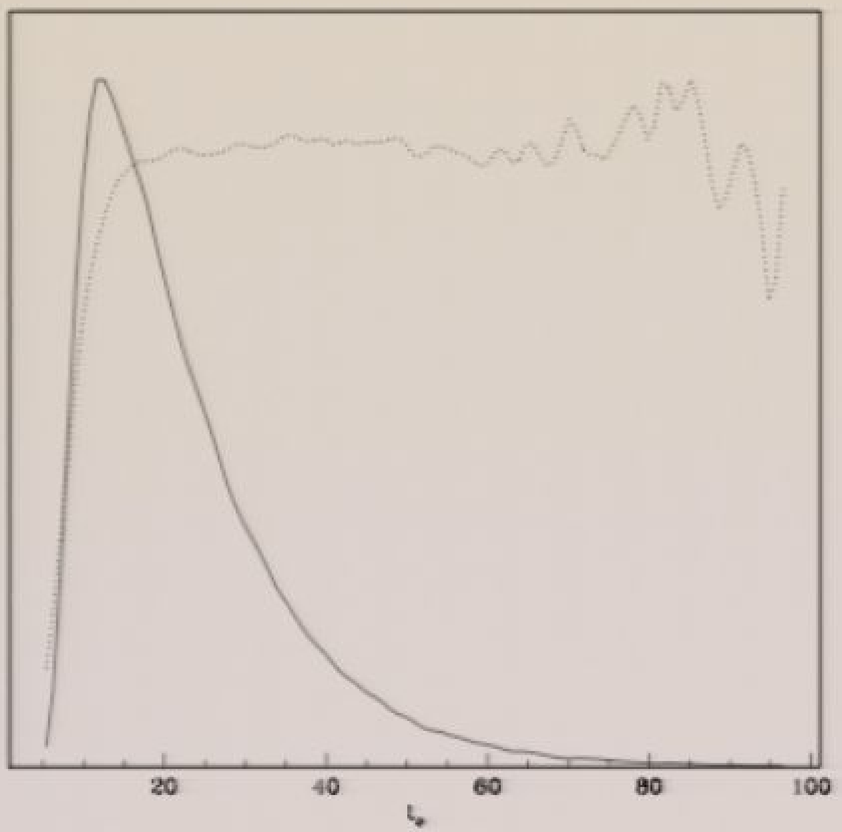


Much of the parameter space volume is occupied by short lifetimes (dark blue).

Lifetimes longer than 100 Gyr only near the very center.

➠ Volume suppression of long lifetimes. Has nothing to do with data. SNe data prefer cosmological constant (see likelihood).

FUTURE LIFETIME



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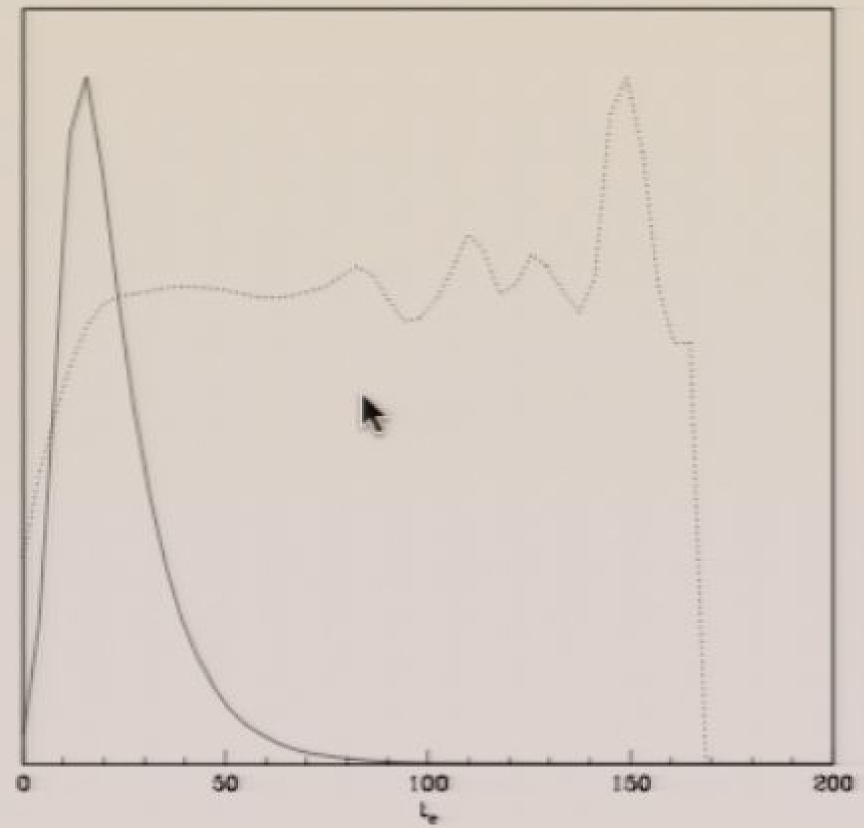

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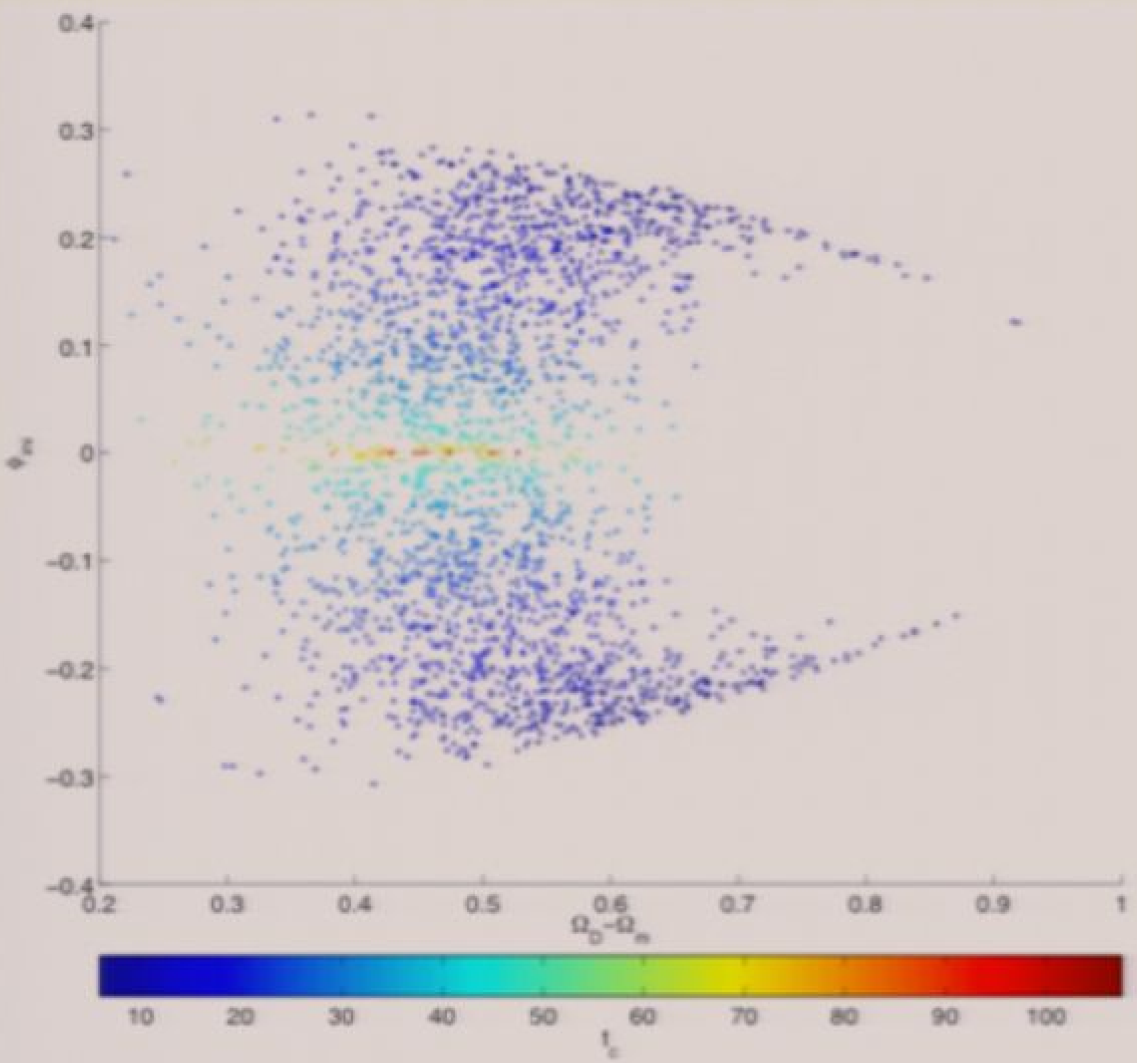

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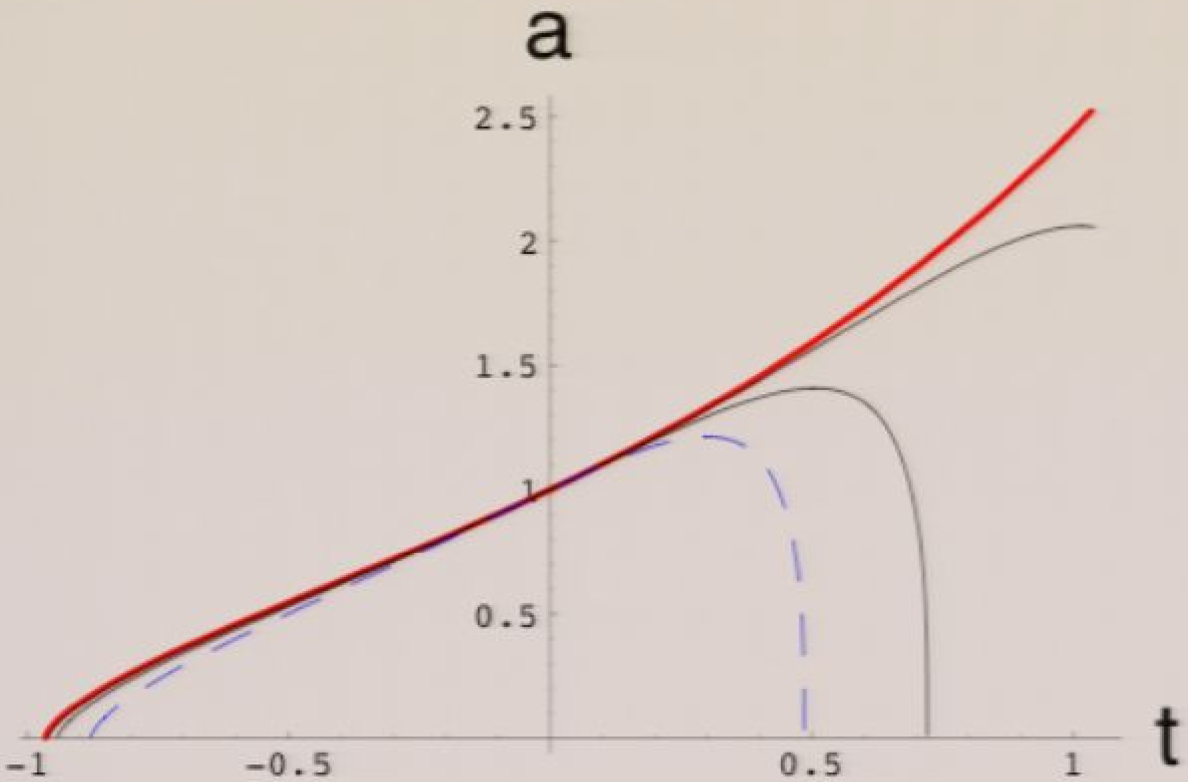
ARE MODELS COLLAPSING EARLIER YOUNGER?

Does smaller t_c (time until collapse) indeed imply smaller t_0 (age today)?



"Observations:"

$\Omega_D = 0.7,$

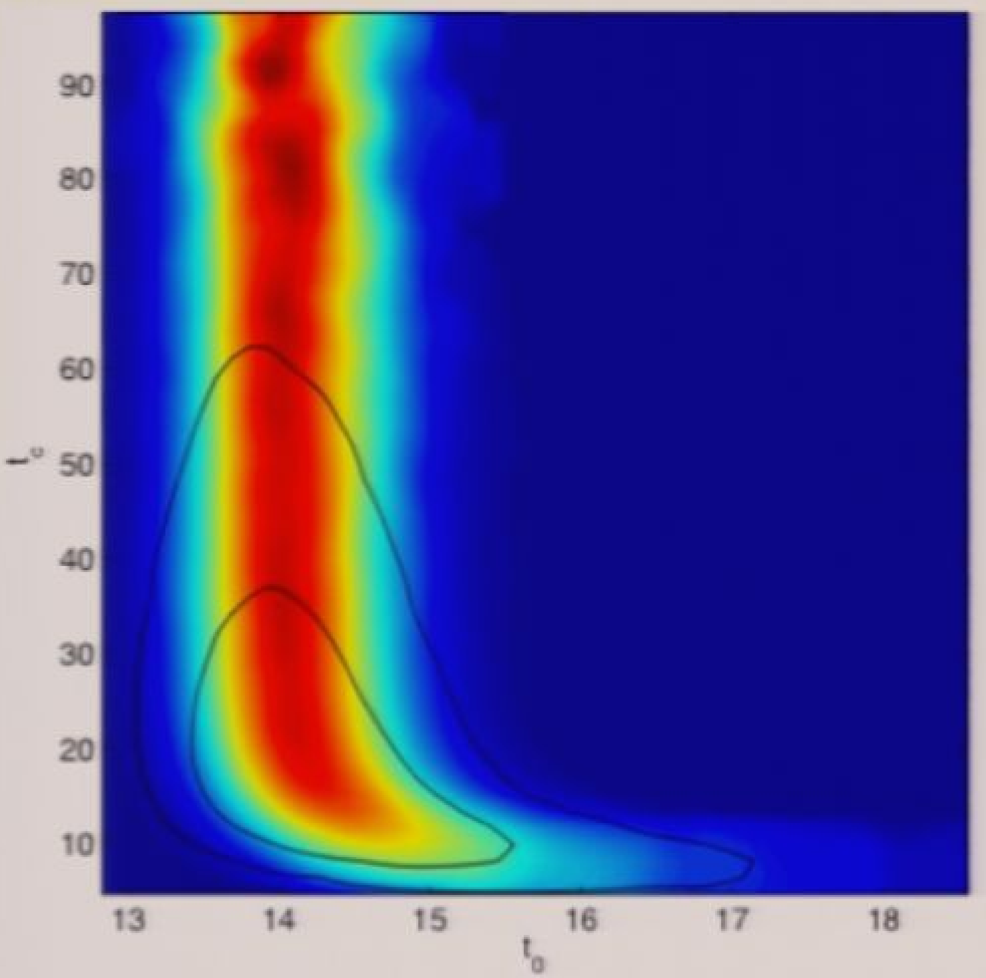
$H_0 = 1.$

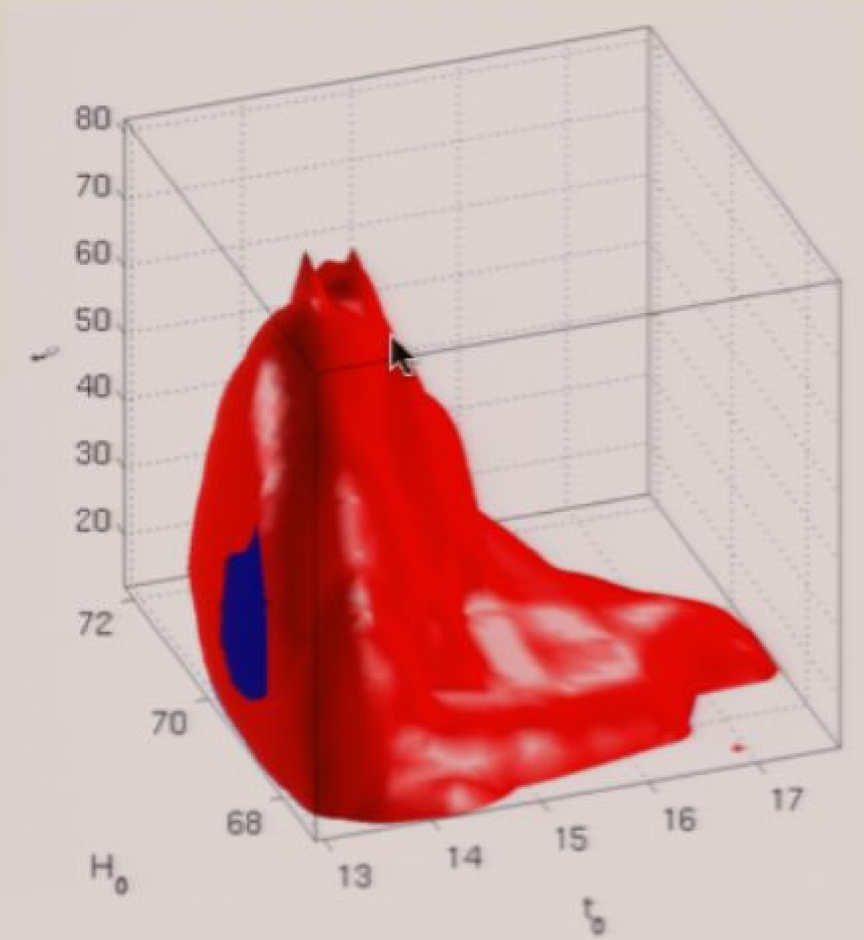
No error bars.

Kallosh, Linde (2003)

FUTURE LIFETIME – AGE RELATION

Real SN Ia observations tell a different story:





Color band (likelihood, data preference) shows: small t_c ➠ large t_0.

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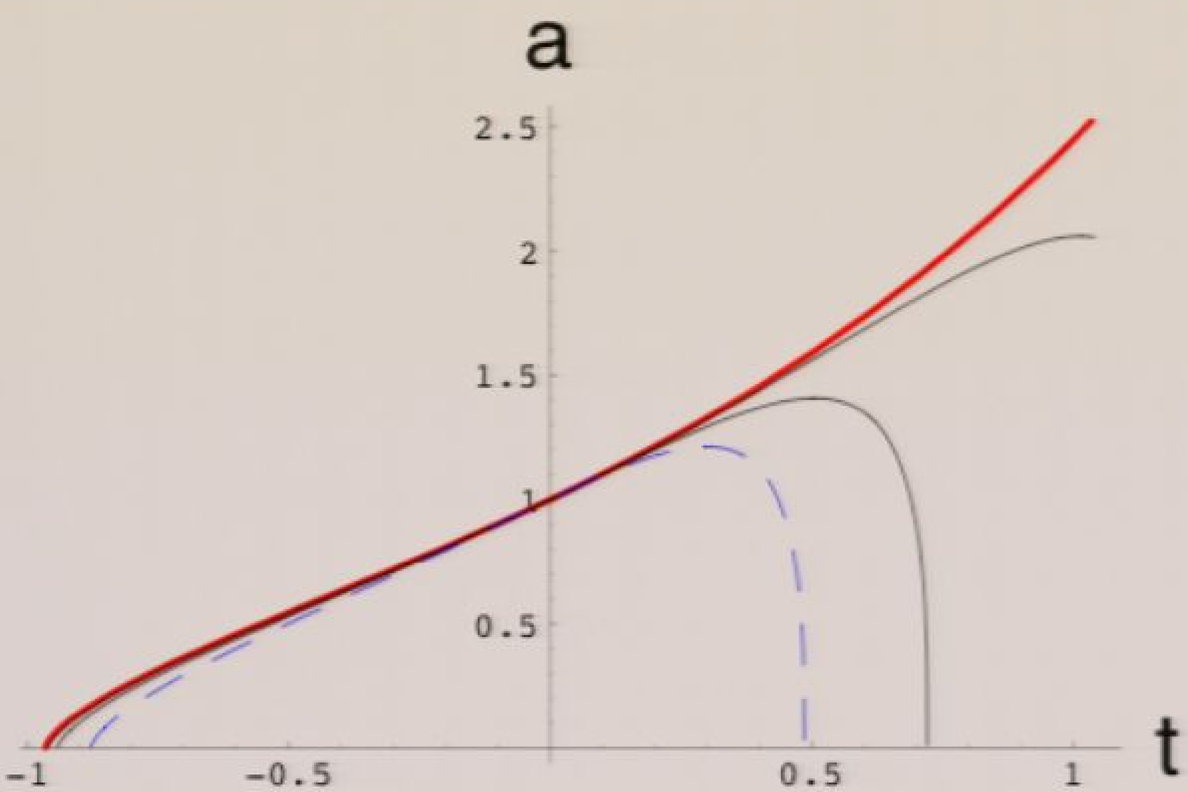

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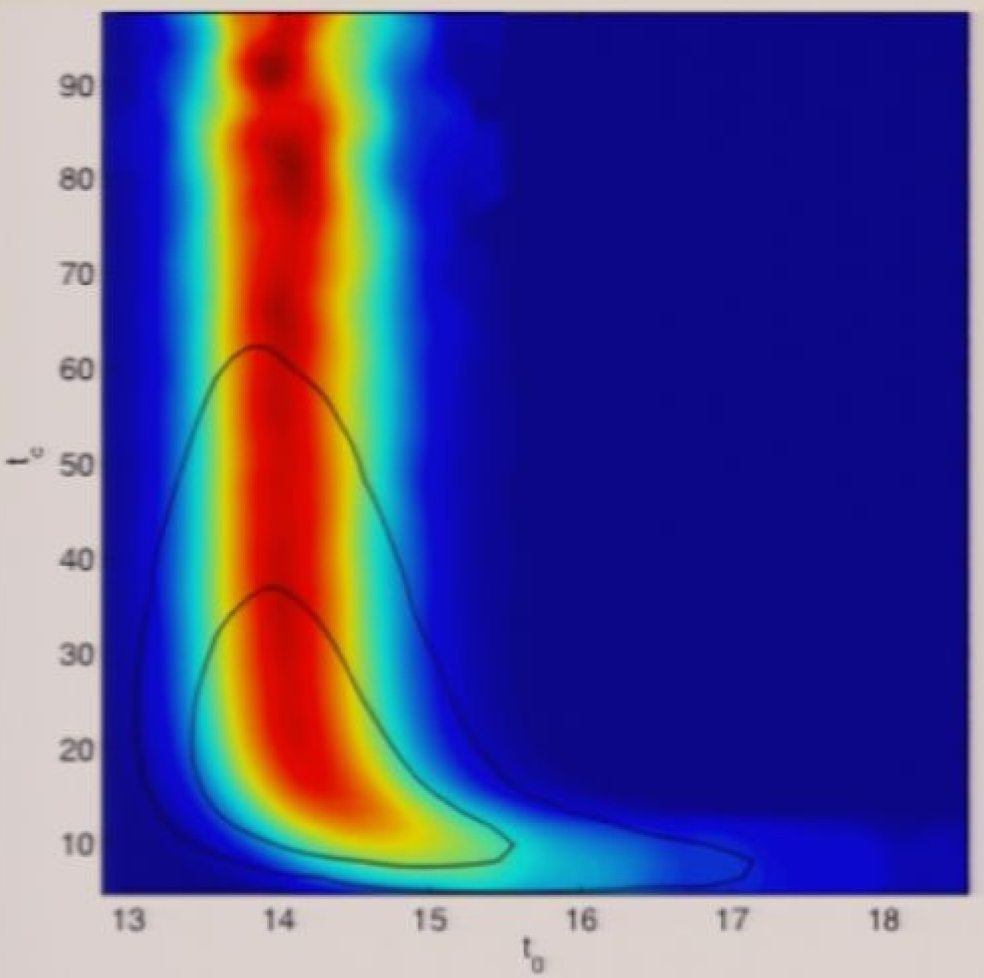

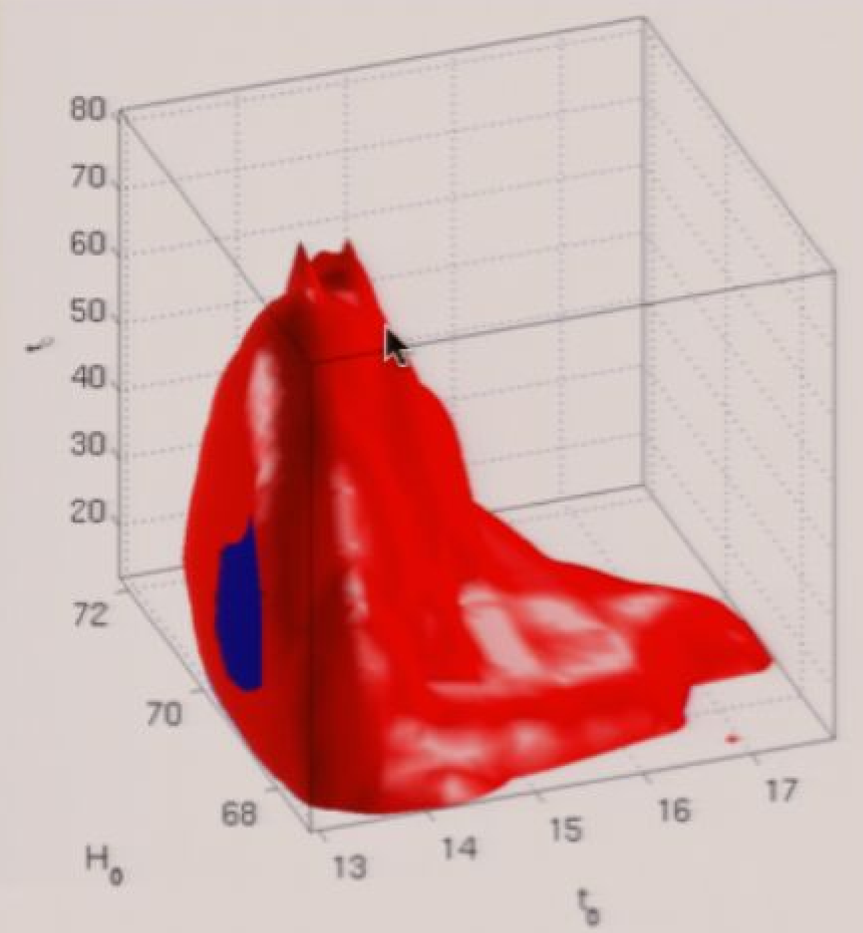

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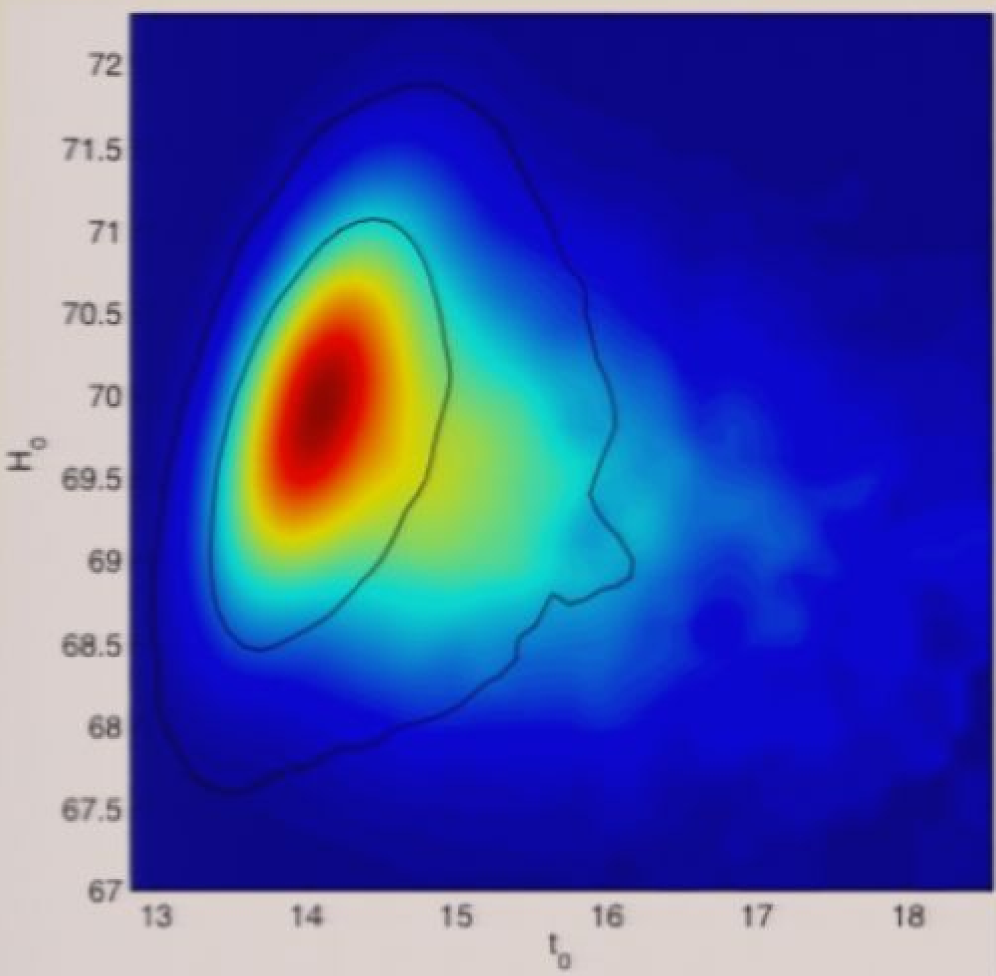
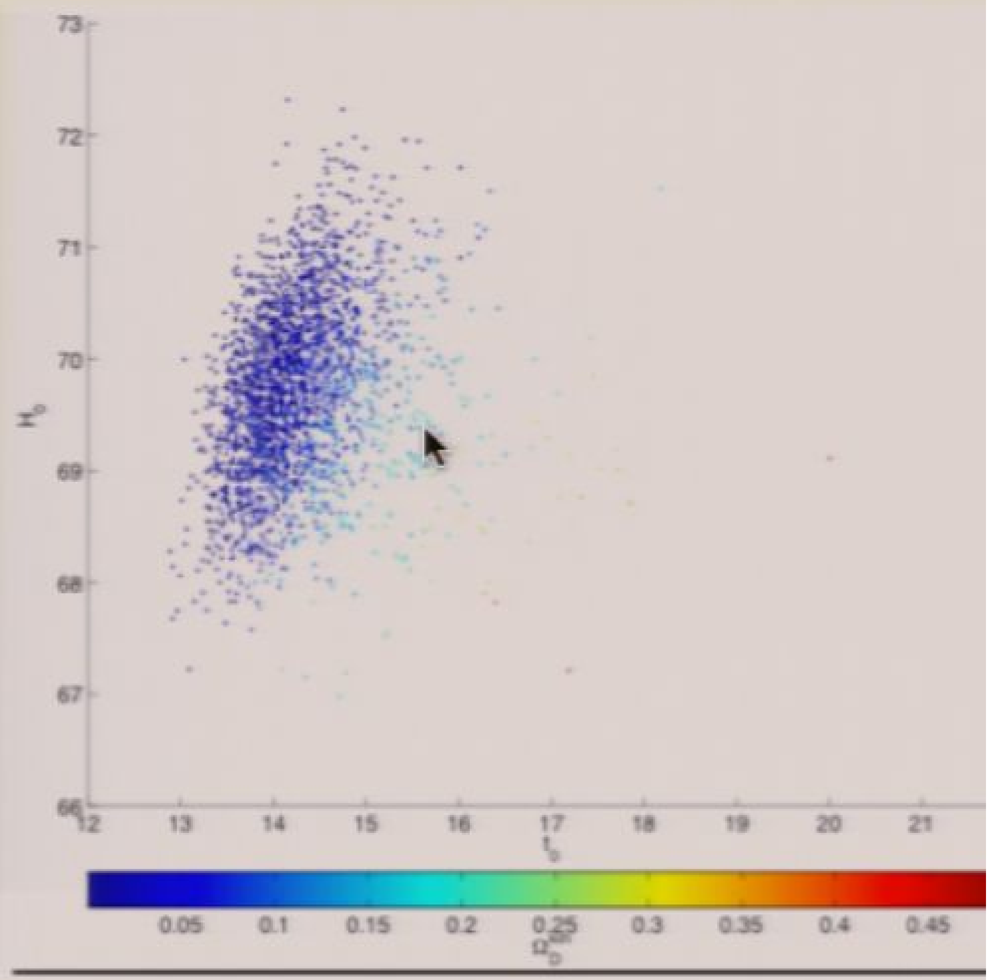
Age and Hubble





1 o'clock axis from SNe observation uncertainty. 4 o'clock spread from dynamics of scalar field.

Conclusions

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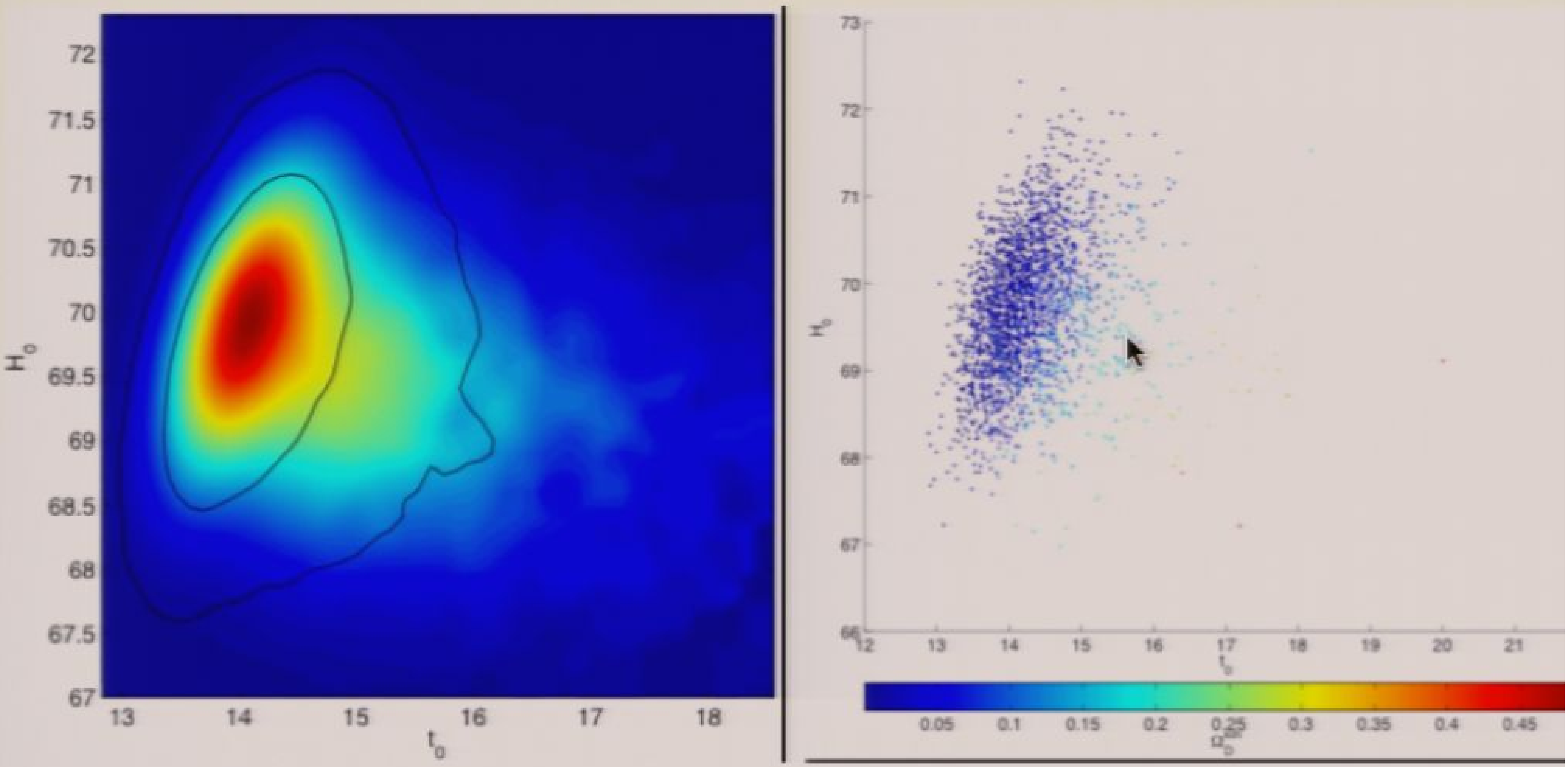

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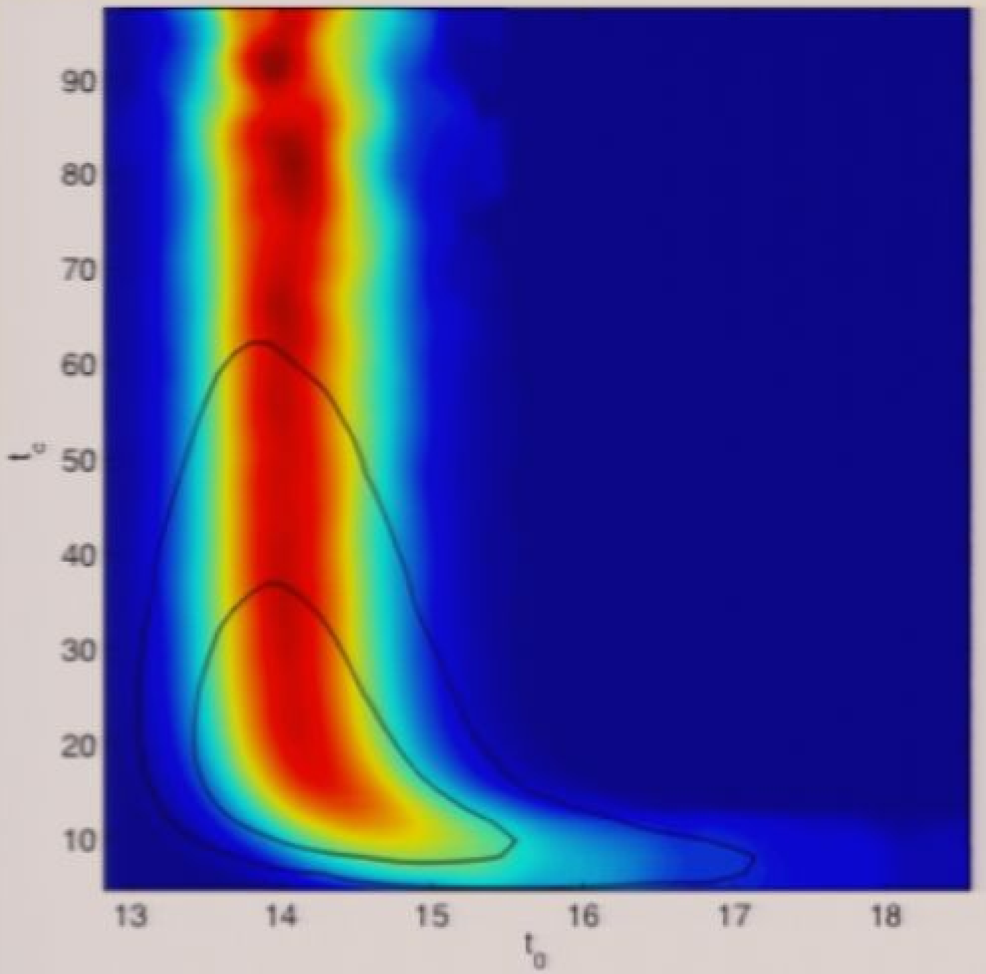

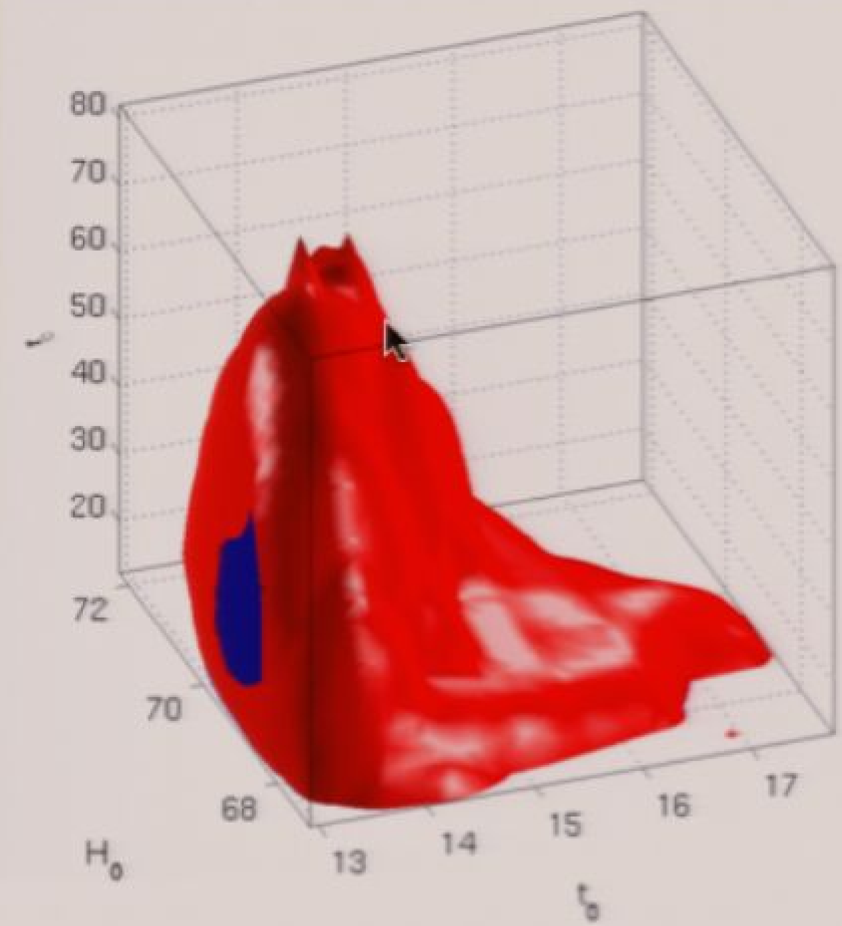

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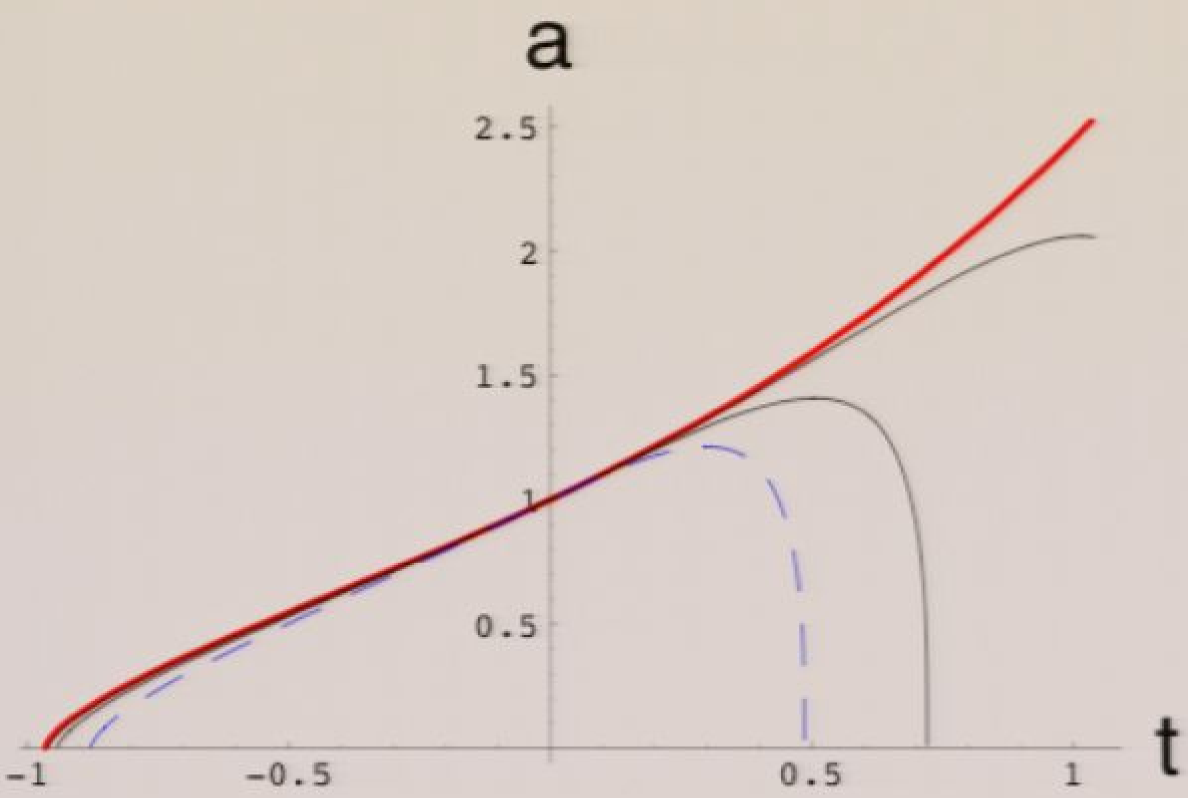

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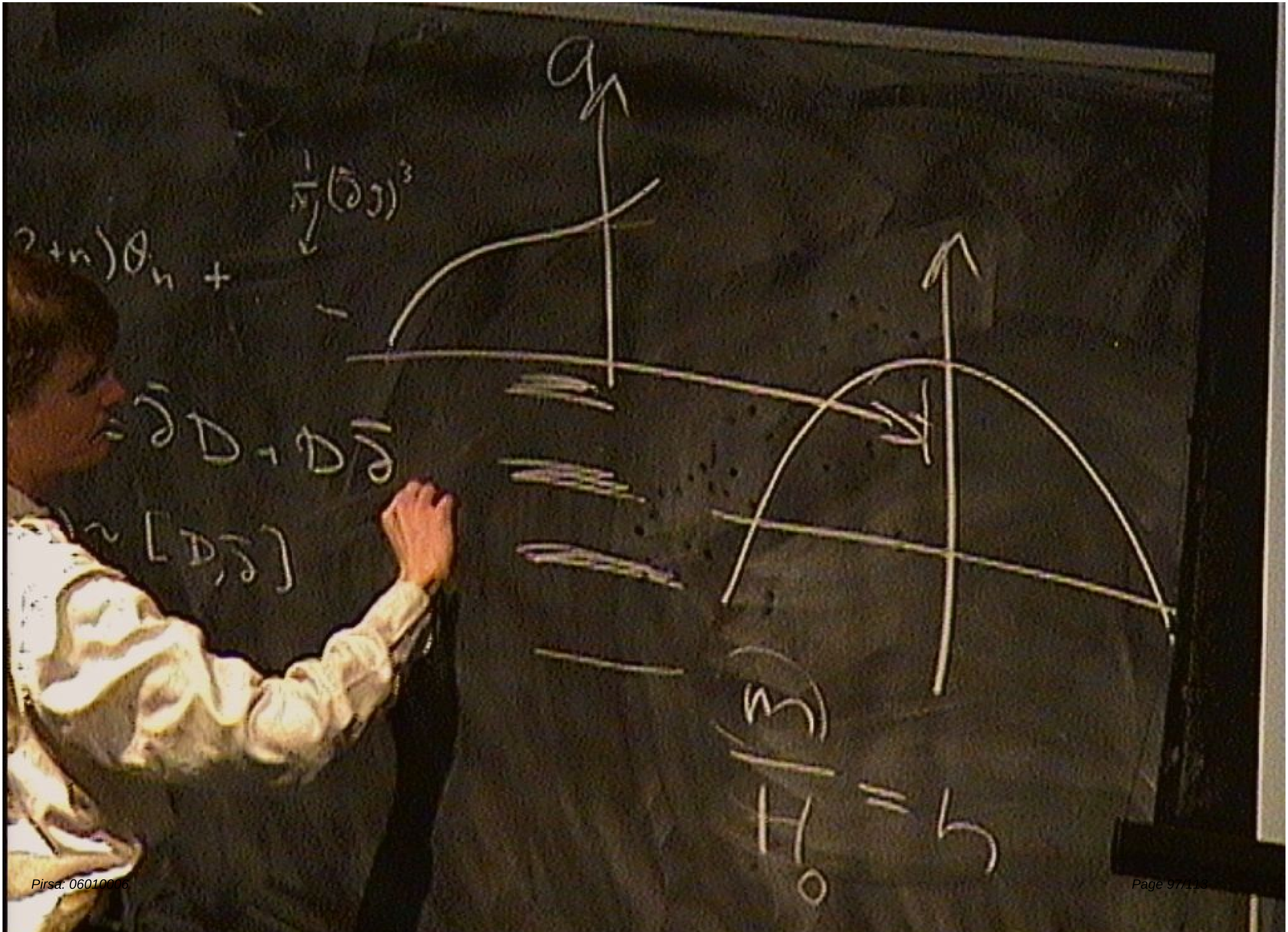

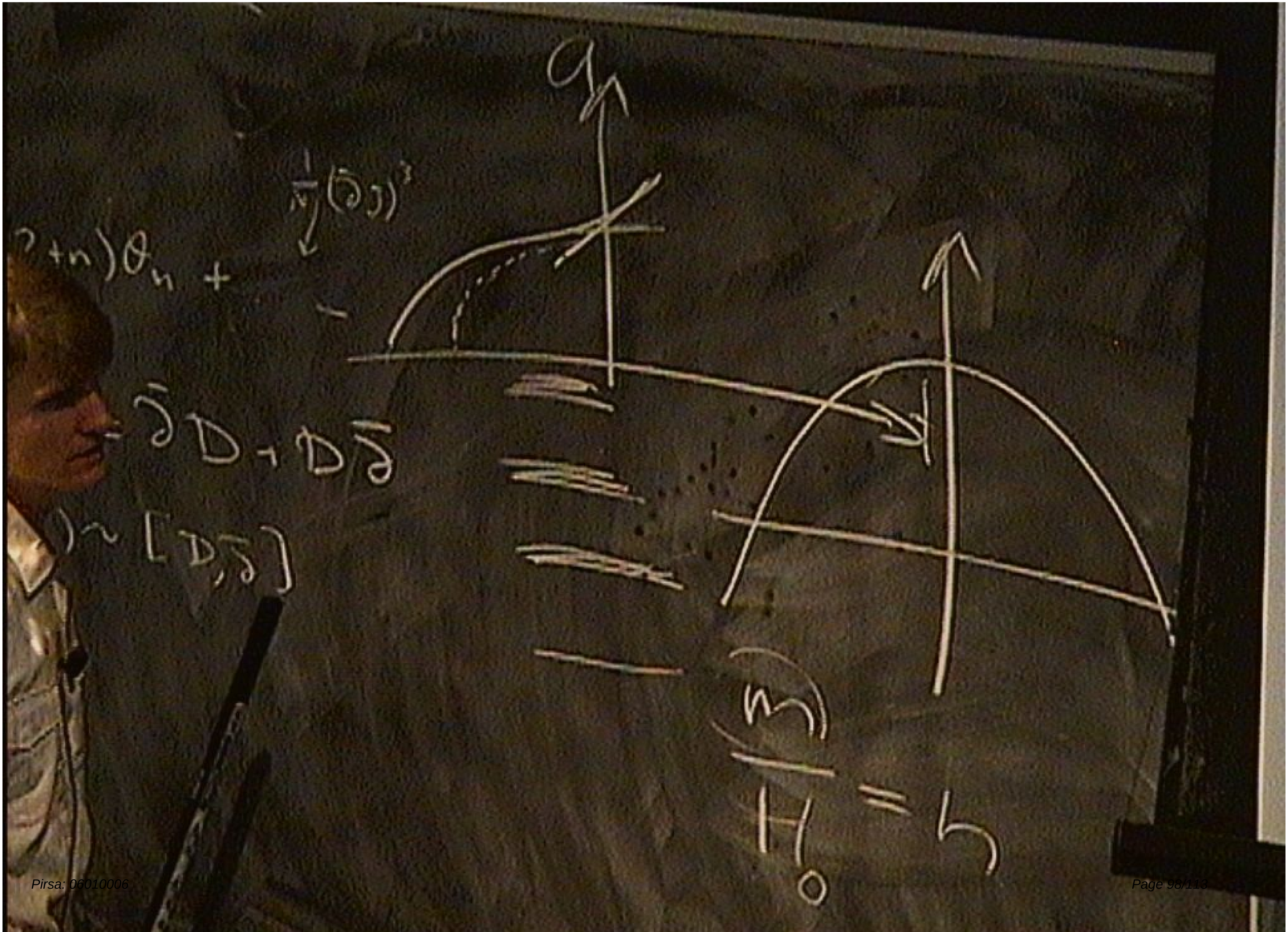

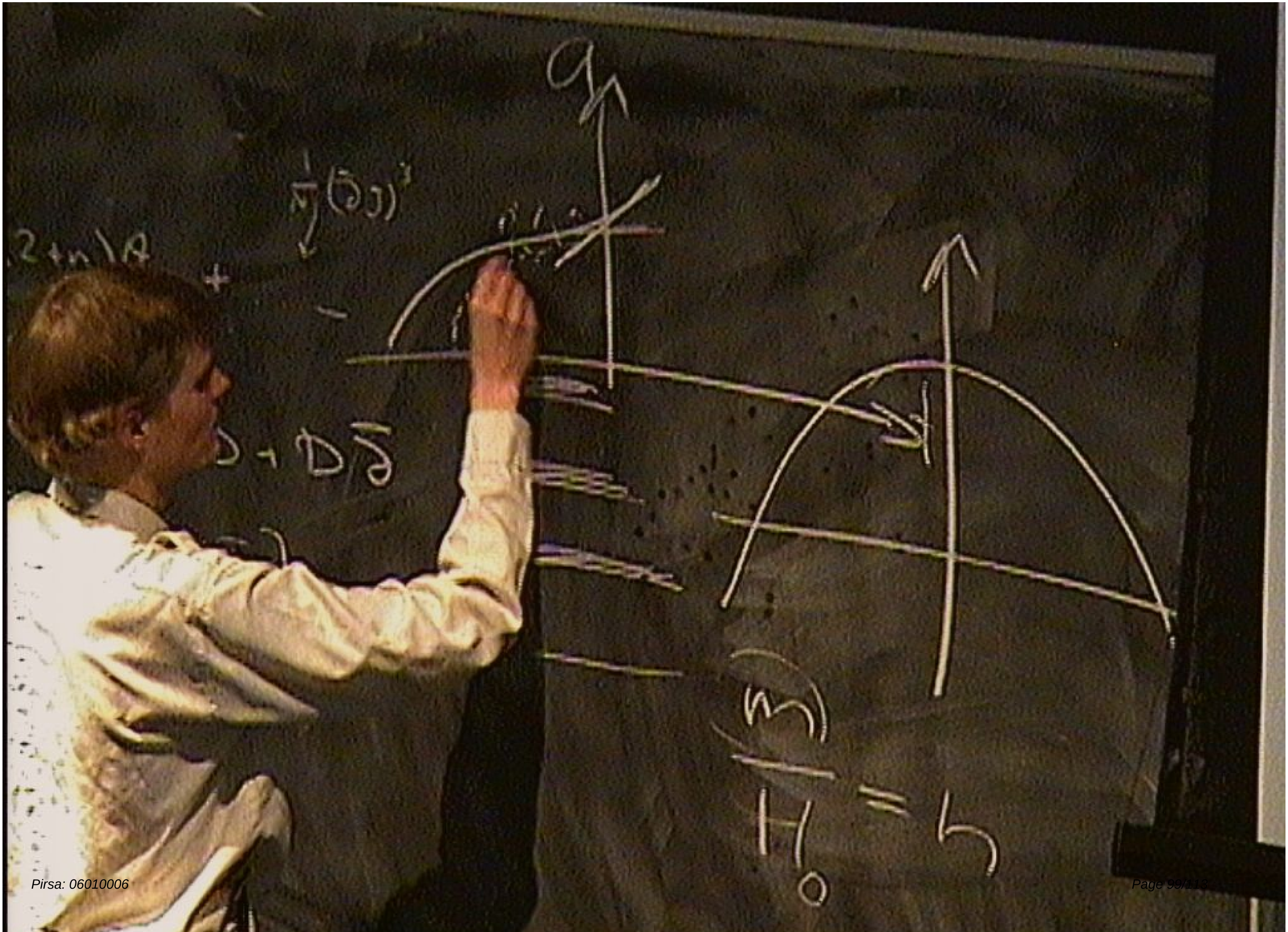

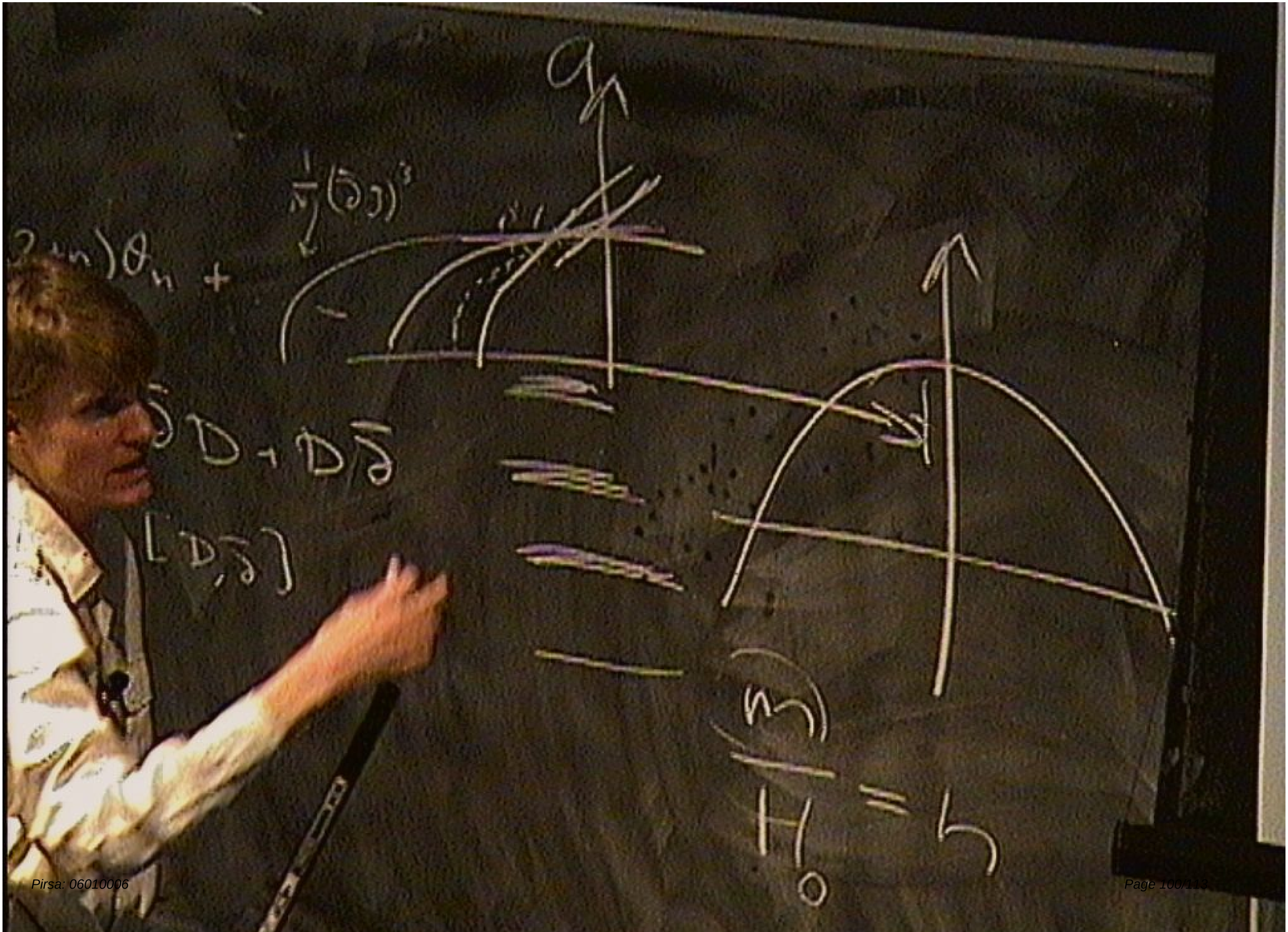
$\bar{\partial} D + D \bar{\partial}$
$[D, \bar{\partial}]$
$H_0 = h$

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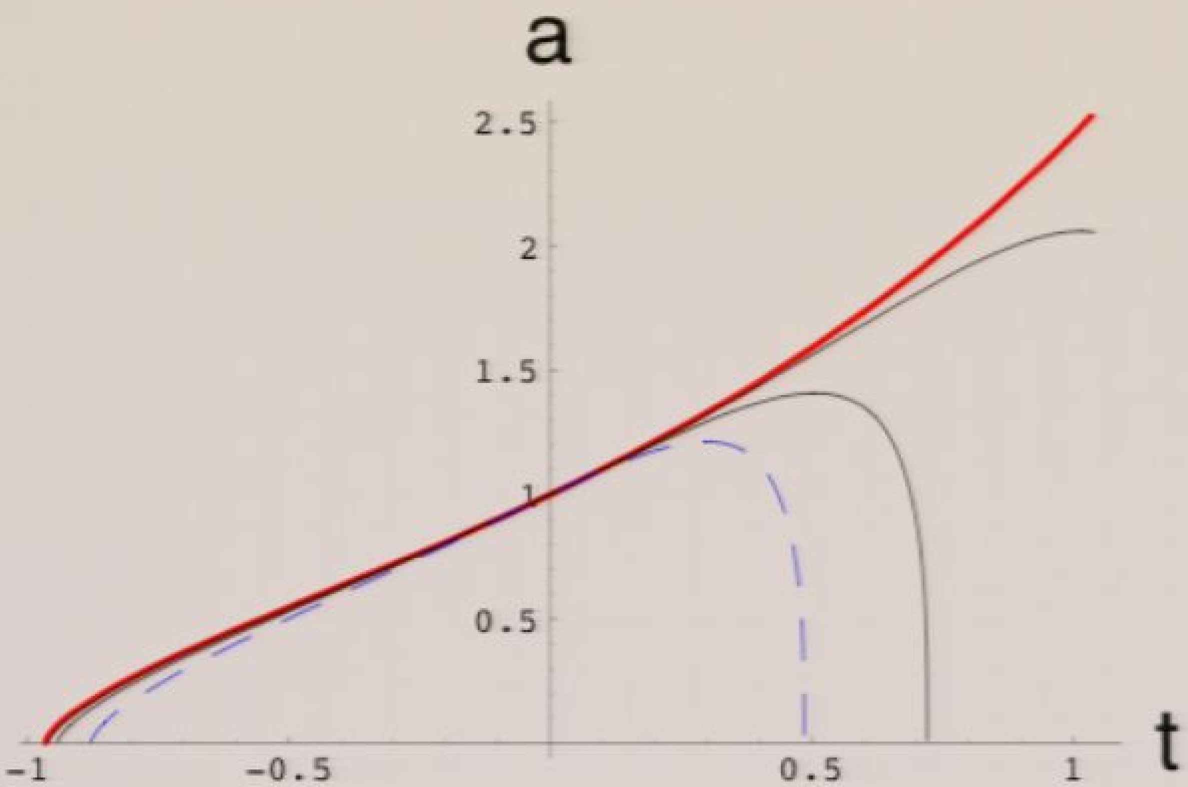

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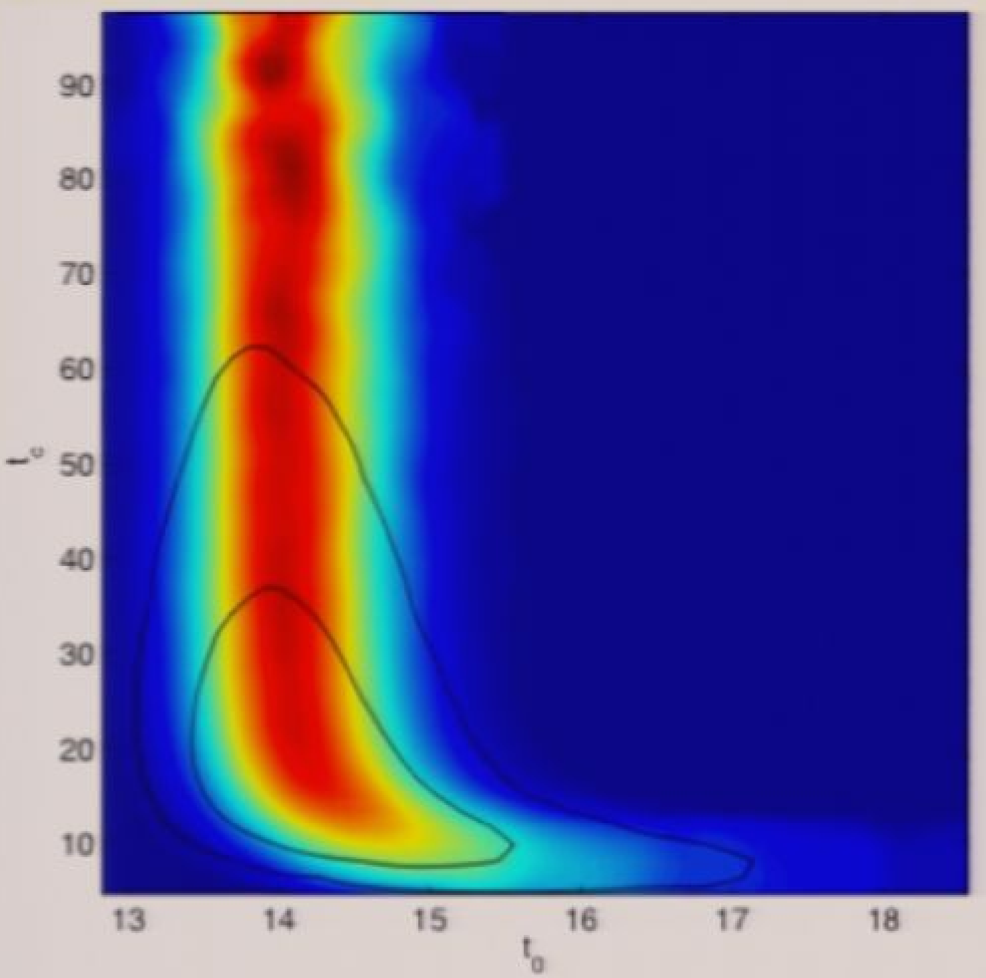

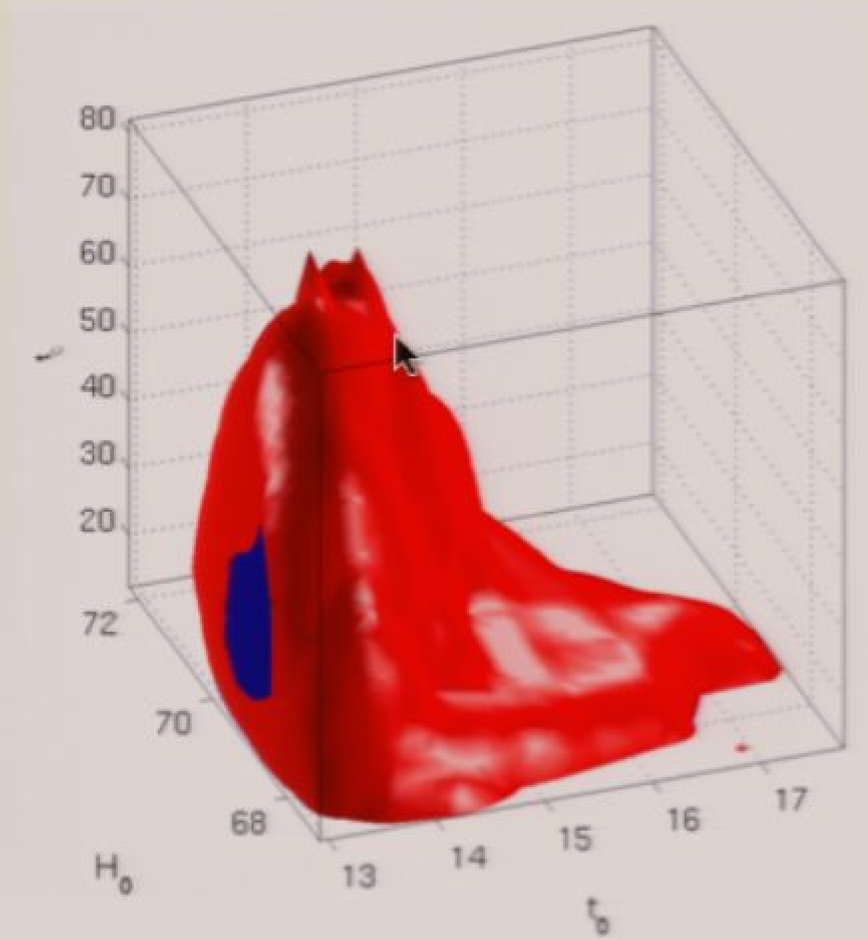

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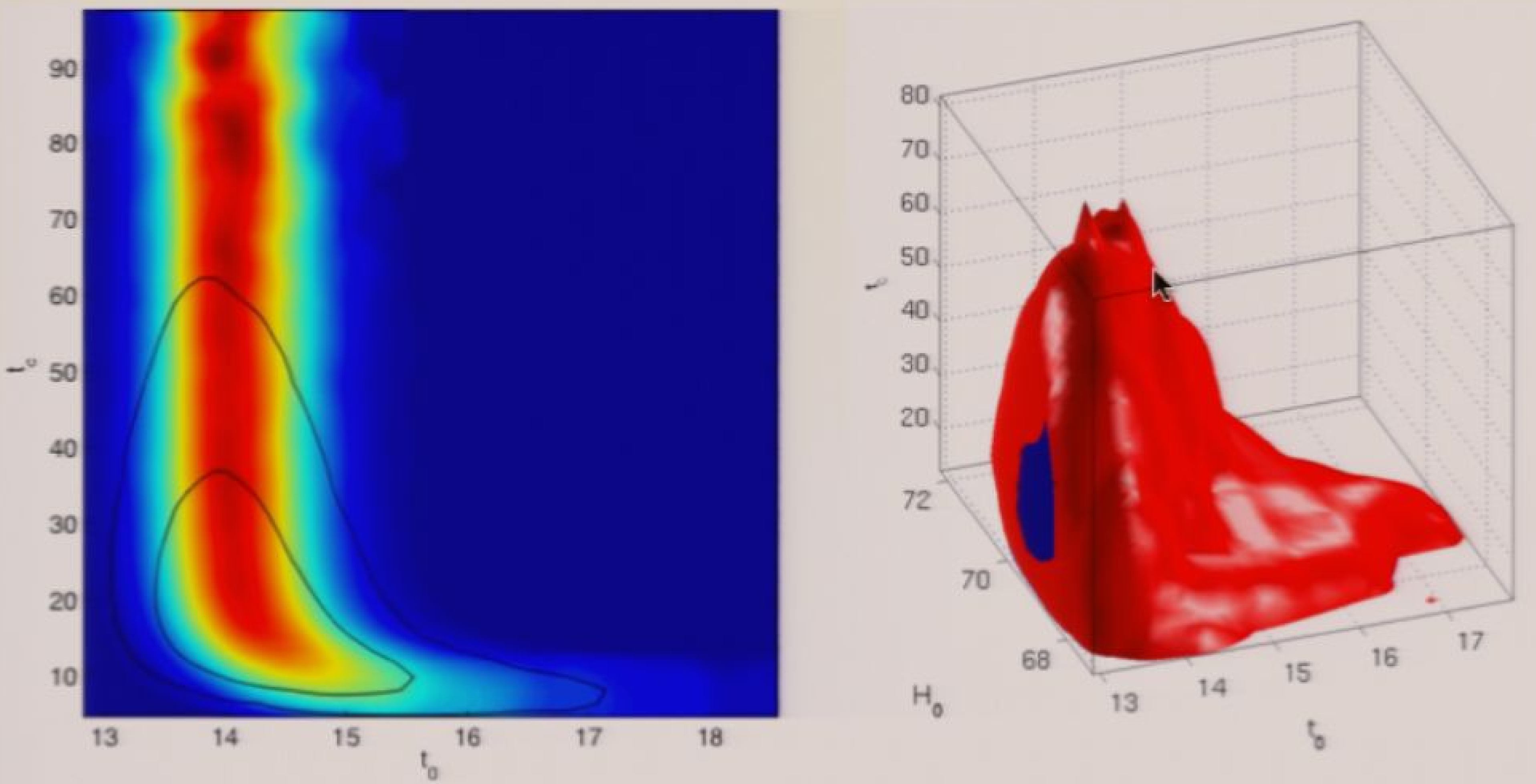

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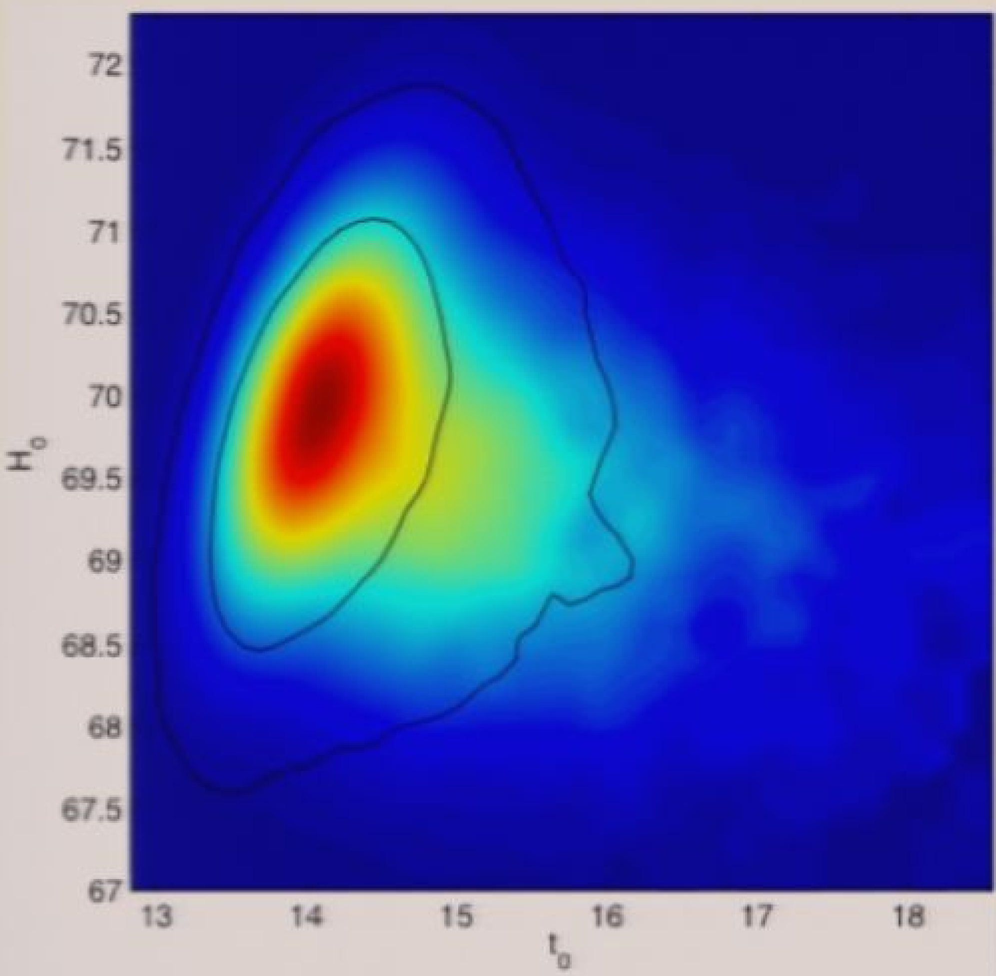
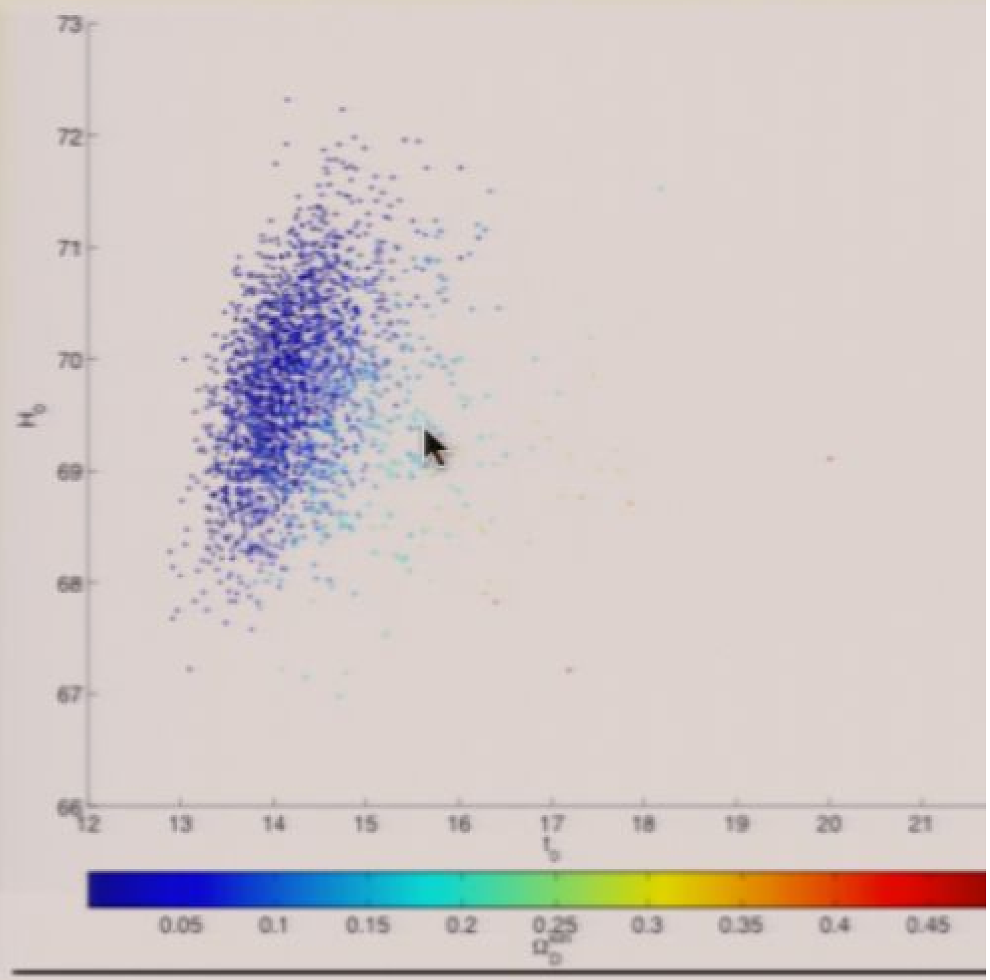
AGE AND HUBBLE





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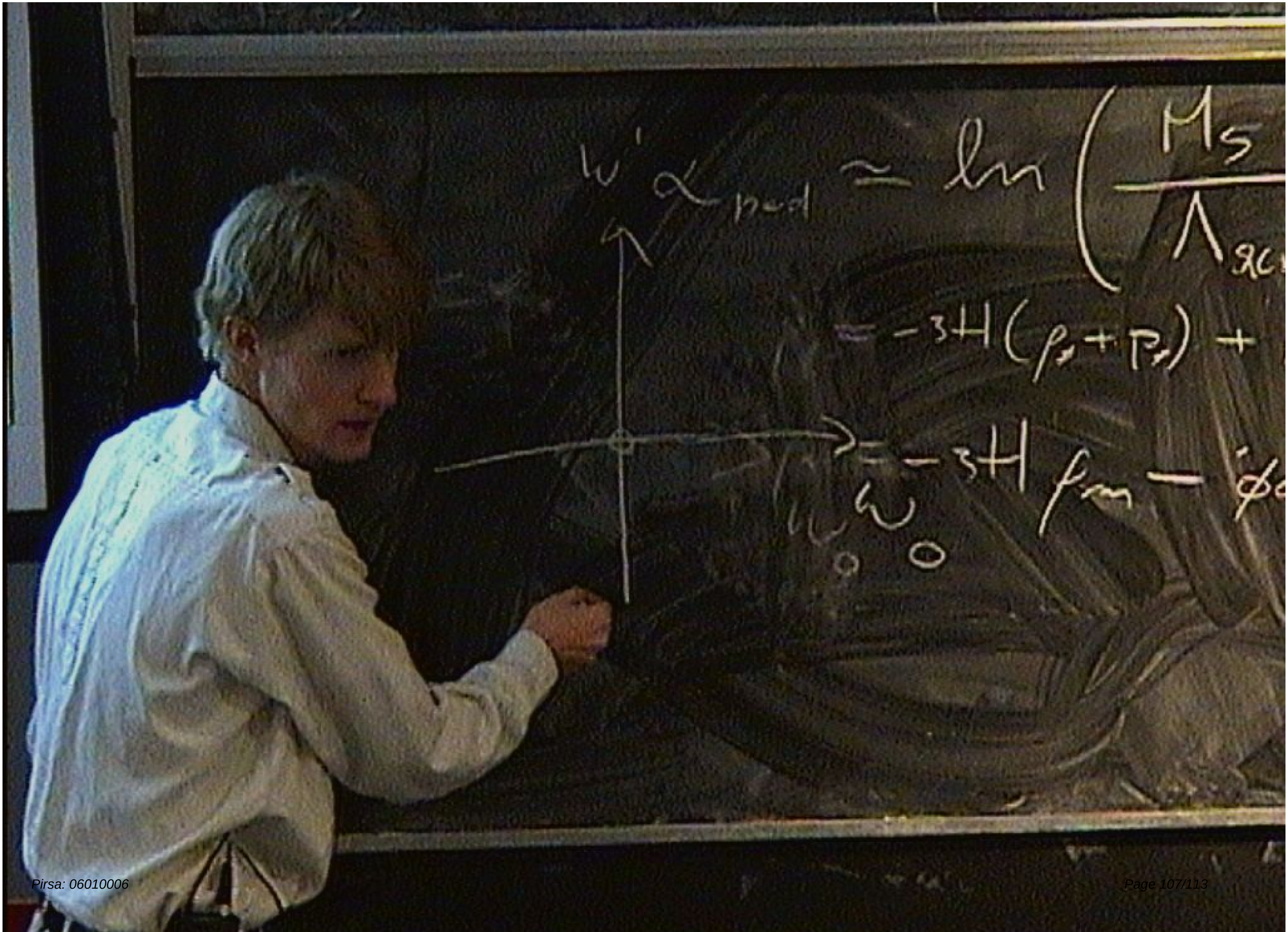
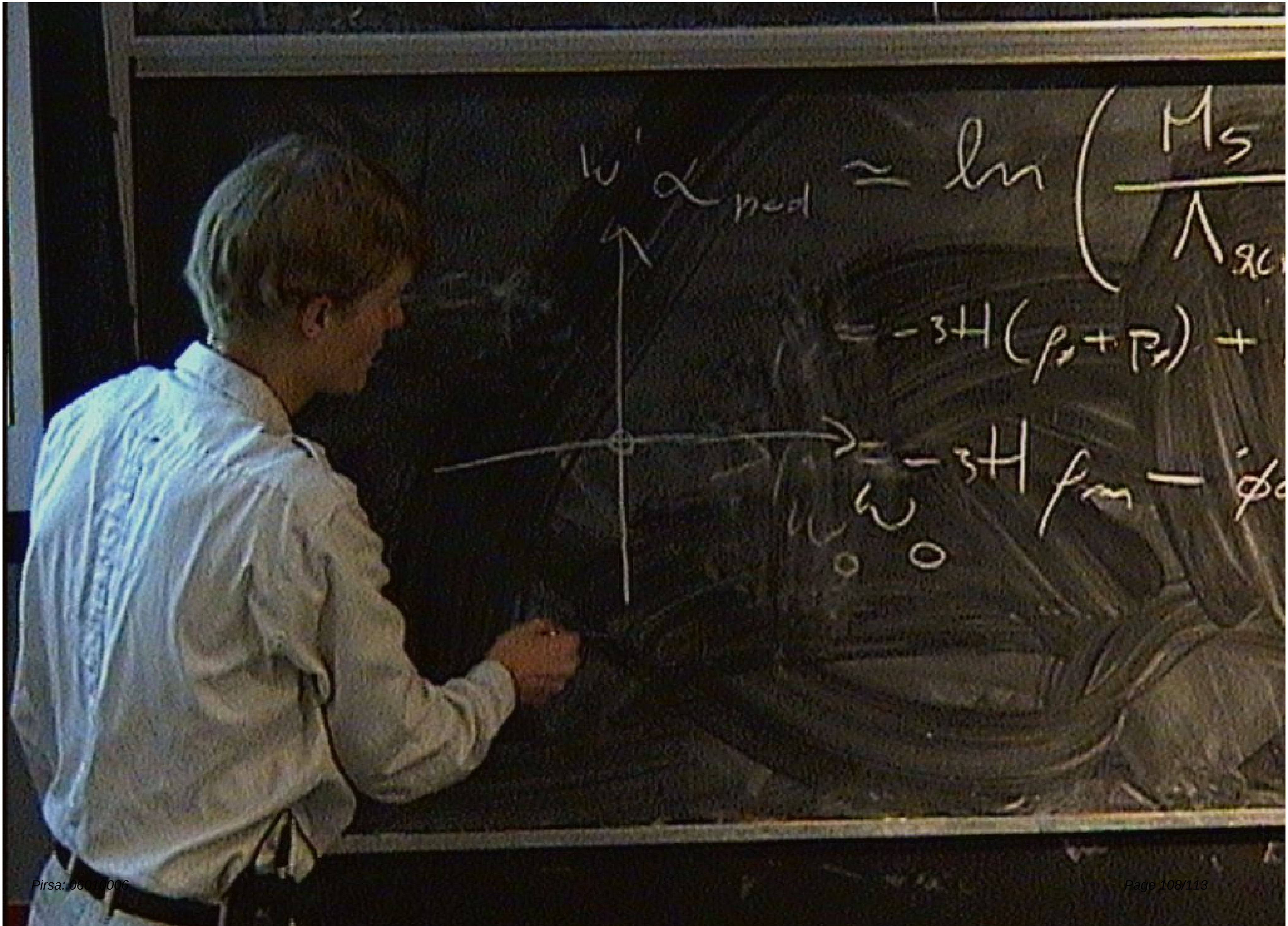
CONCLUSIONS (EARLIER WORK)

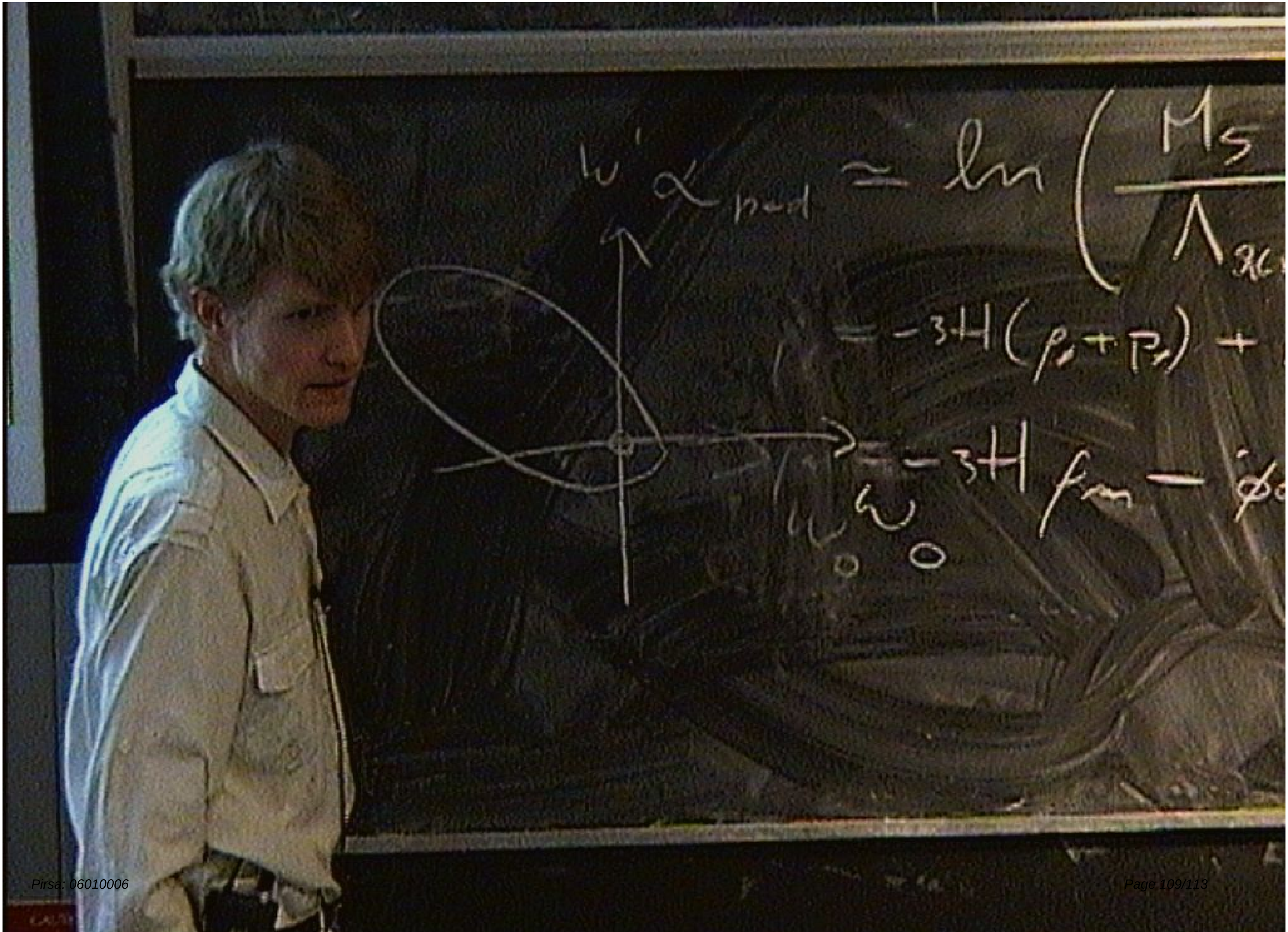
Future lifetime calculation must be done model-dependently.

Future lifetime constraints on the linear potential:

- Our universe will not collapse for at least another 24 Gyr according to the Riess 2004 Type Ia SNe dataset (at 95% cl).
- Future SN observations with SNAP may push this frontier to 30 Gyr.
- Adding CMB observations (Planck) improves this to 35 Gyr.
- Including also SNAP[WL] raises lifetime to 40 Gyr.



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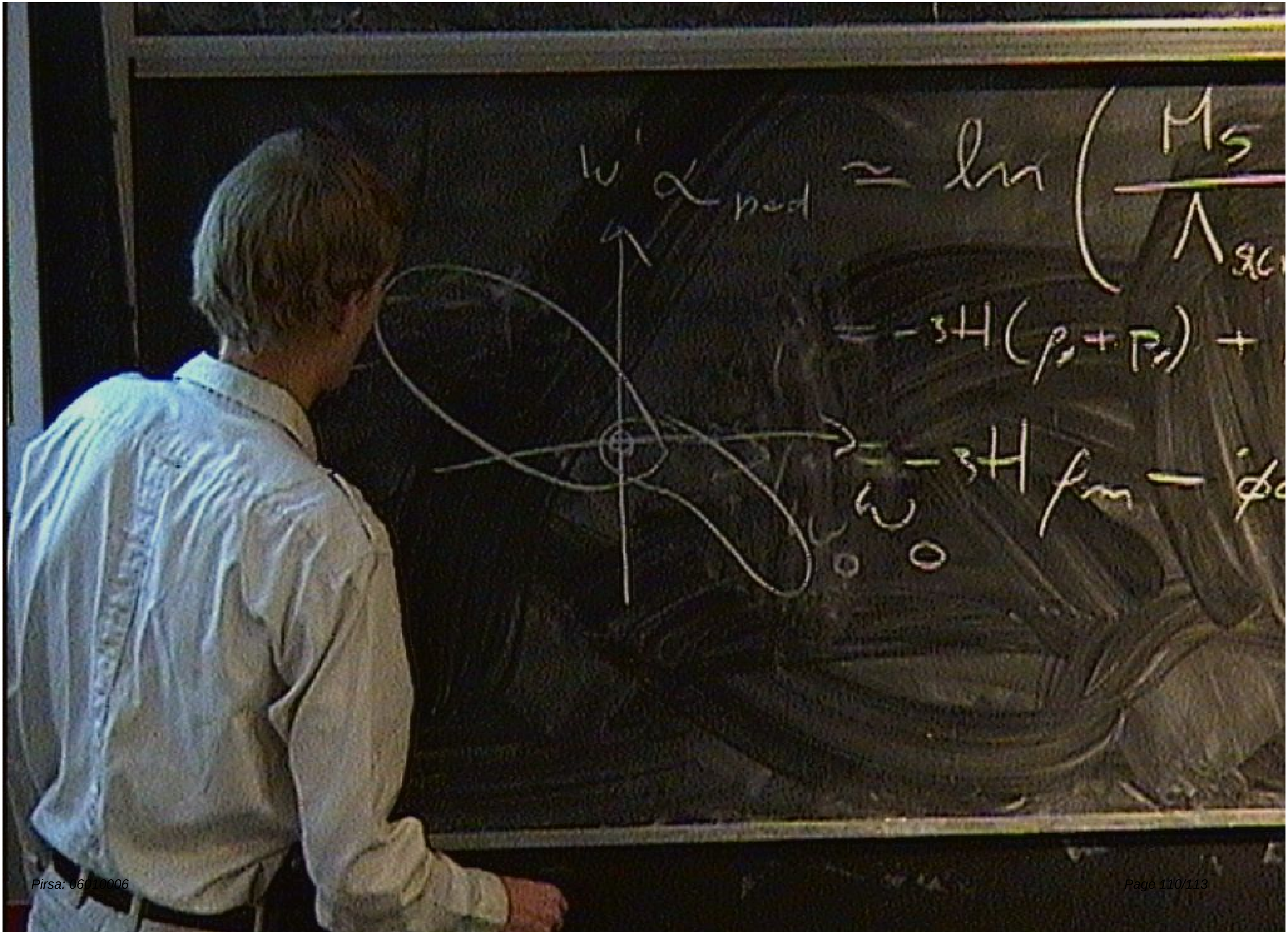
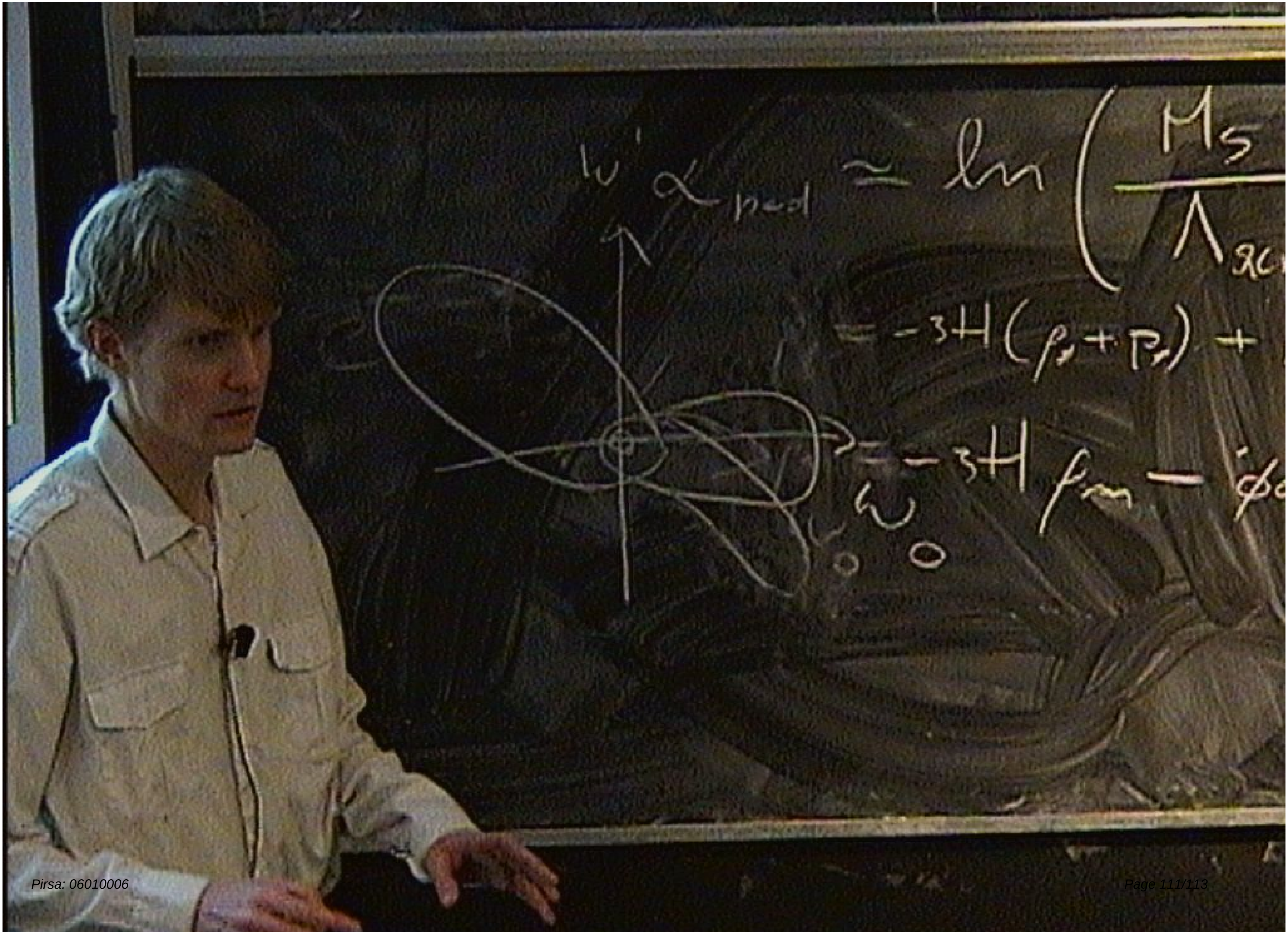
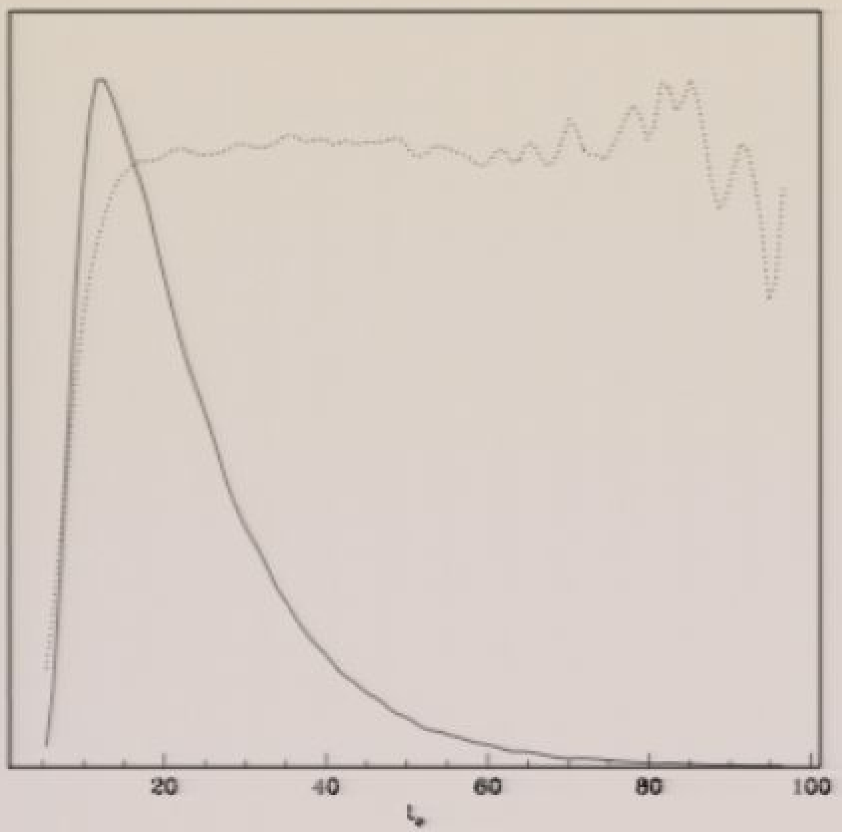




FUTURE LIFETIME



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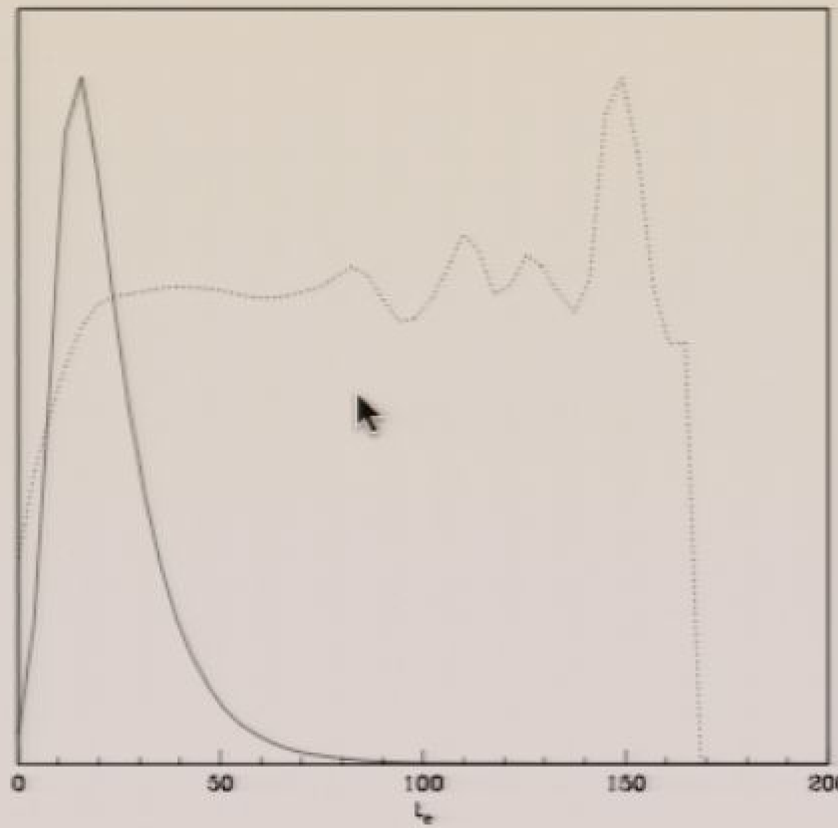
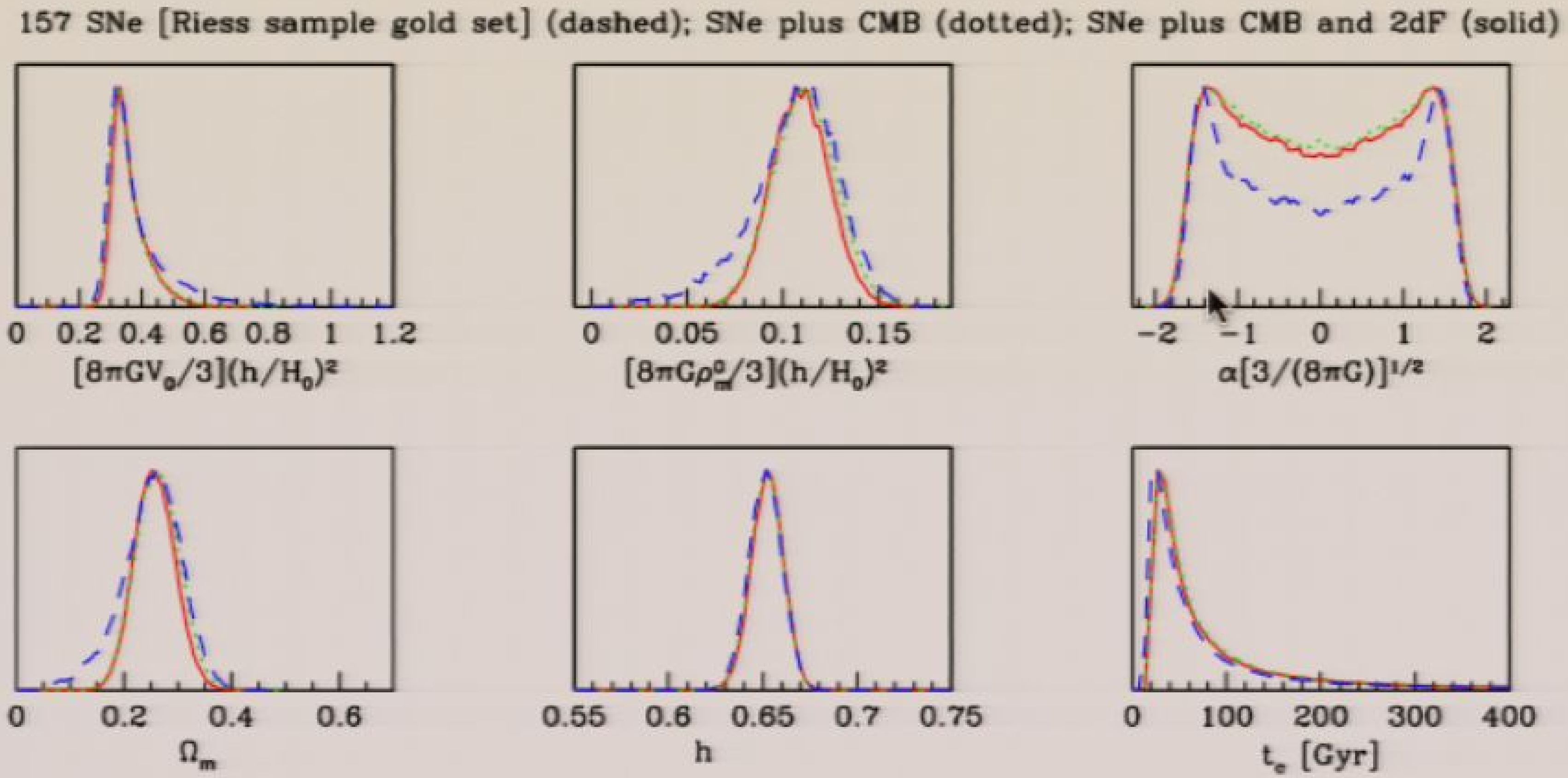


Cut-off due to quantum fluctuations / numerical accuracy.

Cosmological Constant or not?

Parameter constraints using Riess 2004 gold dataset:



- t_c: 24 Gyr (at 95% cl)

Wang, J.M.K., Linde, Shmakova (2004)