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Predictions from Star Formation in the Multiverse

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Predictions from Star Formation in the Multiverse

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In preparation, Raphael Bousso and S.L.

Outline

- Motivation
- Developing a star formation model
- Calculating probabilities

Solving the Measure Problem

- We use the scientific method when addressing the measure problem:

1. Propose a measure
2. Compute its predictions
3. Compare to experiment

Solving the Measure Problem

- The multiverse poses a challenge here:

1. Only statistical predictions possible
2. Only one measurement can be made, so there is no way to really test the statistics

Solving the Measure Problem

- We can still make progress: if a measure predicts $T_{CMB} > 2.7$ K with 99.99…99% confidence, then that measure is ruled out with the same level of confidence
- Detailed models are not necessary for making such arguments

Making Real Predictions

- To make precise predictions, or to decide between two alternative viable measures, more comprehensive tools are needed
- Here we present a model for star formation which is unprecedented in its level of detail and broad applicability in the landscape

Making Real Predictions

- Cline, Frey, Holder (2007) and Bozek, Albrecht, Phillips (2009) use the star formation model of Hernquist & Springel (2003)
- That model is not applicable over a wide range of landscape parameters; it has unphysical features which give false conclusions

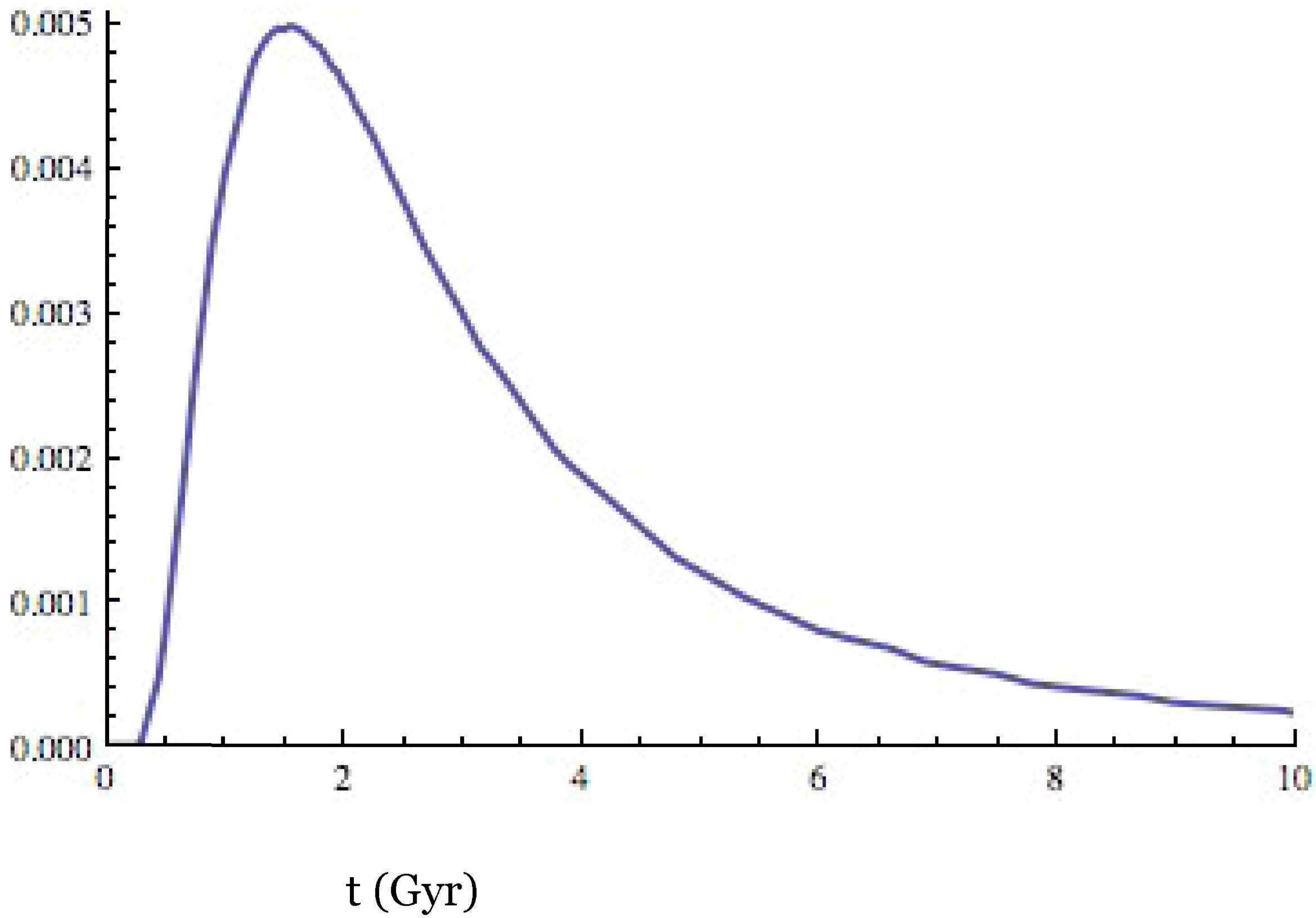
Star formation is a tool

- After a measure regulates the infinities, the star formation model helps us quantify how many observers there are and the time at which they exist
- We must also choose a way to go from stars to observers

The Star Formation Rate

- The SFR is the mass per unit comoving volume per unit time which is forming stars, as a function of time
- We explore a three dimensional region of the landscape parametrized by Λ, Q, and ΔN
- Straightforward generalization to more parameters is possible

The Star Formation Rate



Λ is the cosmological constant

- Known to be amenable to anthropic arguments
- Can be positive or negative
- $\sim +10^{-123}$ in our universe
- For star formation, important because it halts structure growth

ΔN parametrizes curvature

- N is the number of efolds of inflation, and ΔN is the difference between N and N_0
- Affects structure growth
- $1/N^4$ prior probability means inflation is suppressed in the landscape (Freivogel, Kleban, Martinez, Susskind (2005))

Q is the perturbation strength

- $Q = \delta\rho/\rho$ is the amplitude of primordial density perturbations
- $\sim 10^{-5}$ in our universe, these small perturbations become galaxies
- Changing Q changes how long it takes to form structure
- We assume a prior flat in Log Q

Some things we don't vary

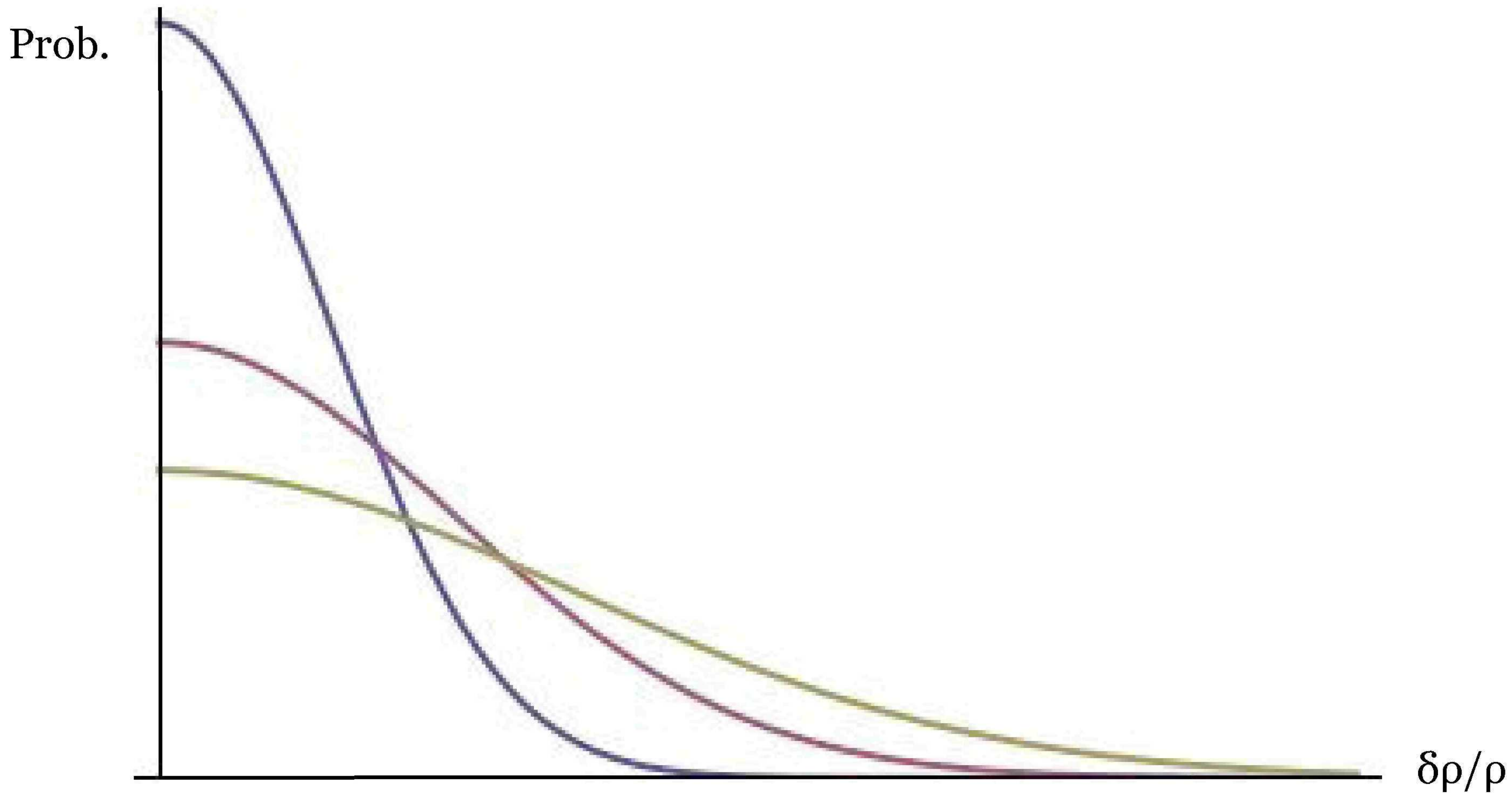
- Microscopic physics is held fixed
- Matter-radiation ratio fixed (start calculations at matter-radiation equality)
- Dark matter fixed

Structure Formation Overview

- Initial perturbations are set by inflation, grow, and eventually collapse
- Collapse time determines the density of the resulting halo
- Halo mass distribution is determined by PS formalism

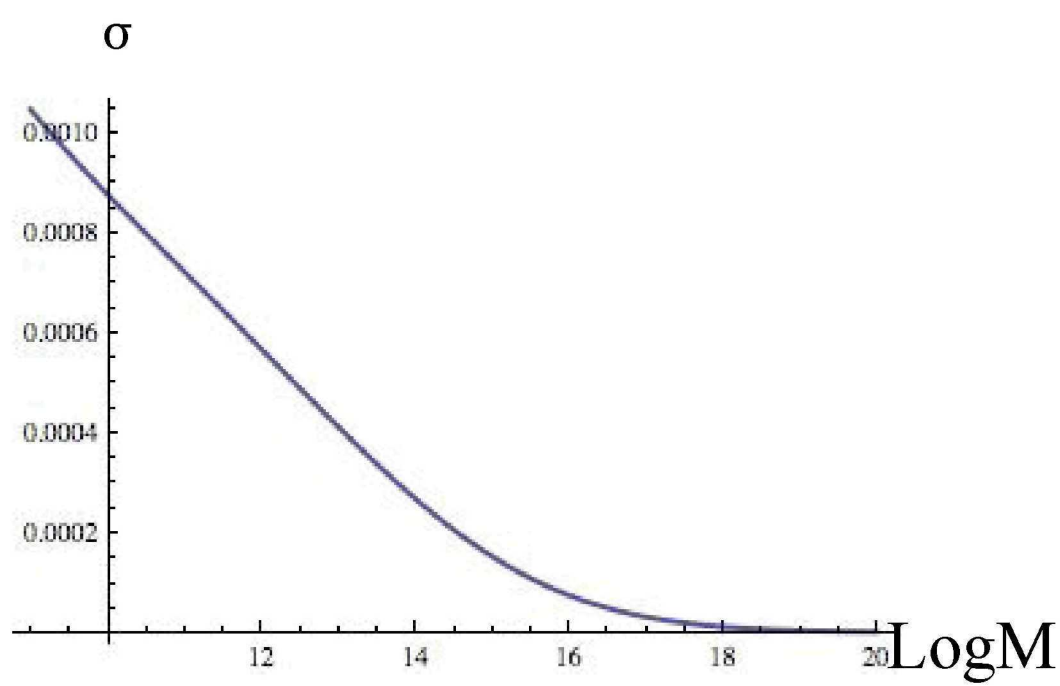
Each mass scale has a Gaussian

- The perturbation amplitude is the width



Primordial Perturbations

- Shape as a function of mass set by inflation and radiation era
- We vary the overall amplitude



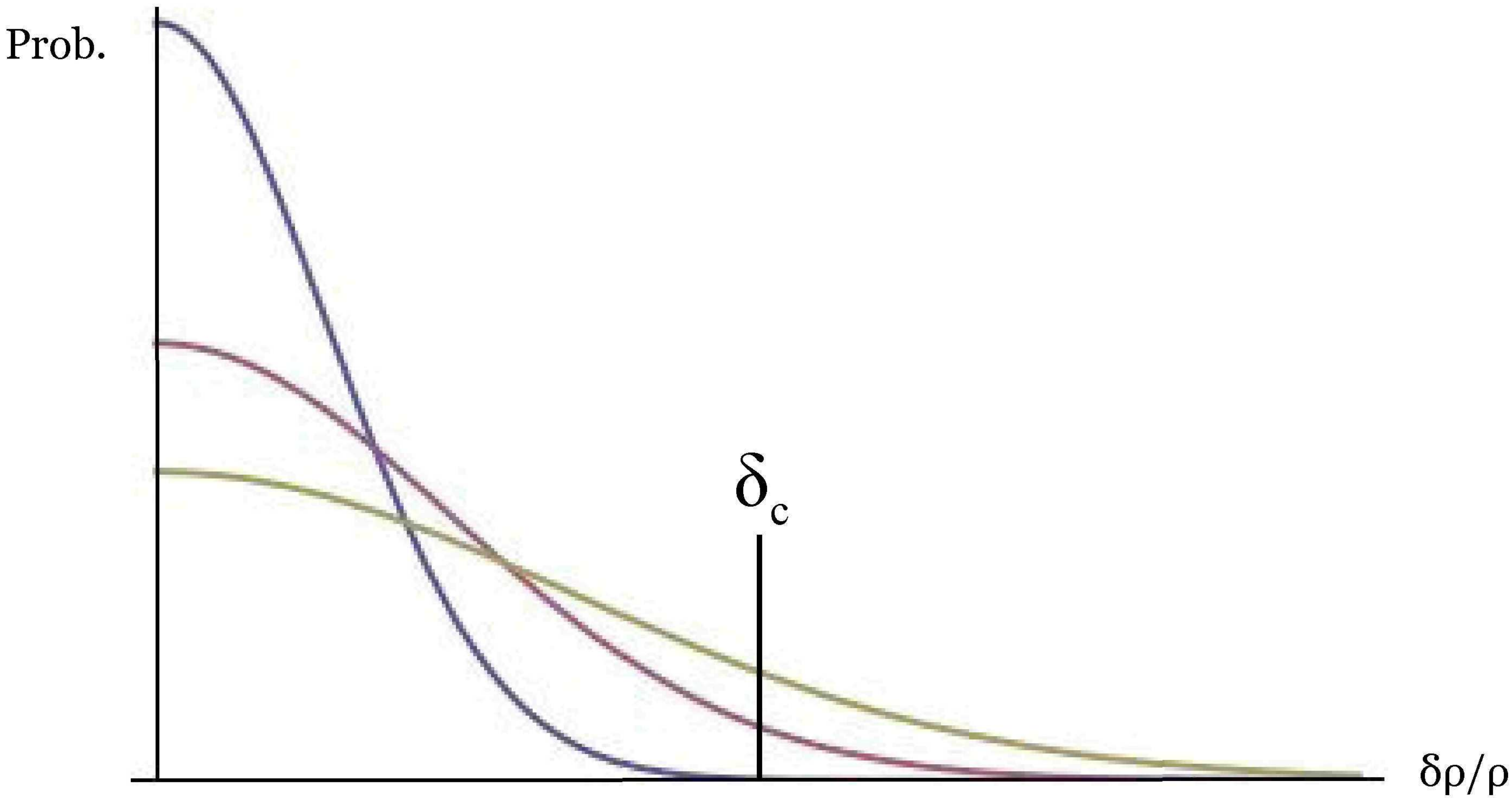
$$\sigma(M,t)=Q\,s(M)\,G(t)$$

Gravitation causes growth

- For small perturbations, a linear approximation suffices
- Linear growth rate G(t) slowed by Λ, curvature
- Perturbations which reach a certain amplitude in the linear theory are said to have collapsed.

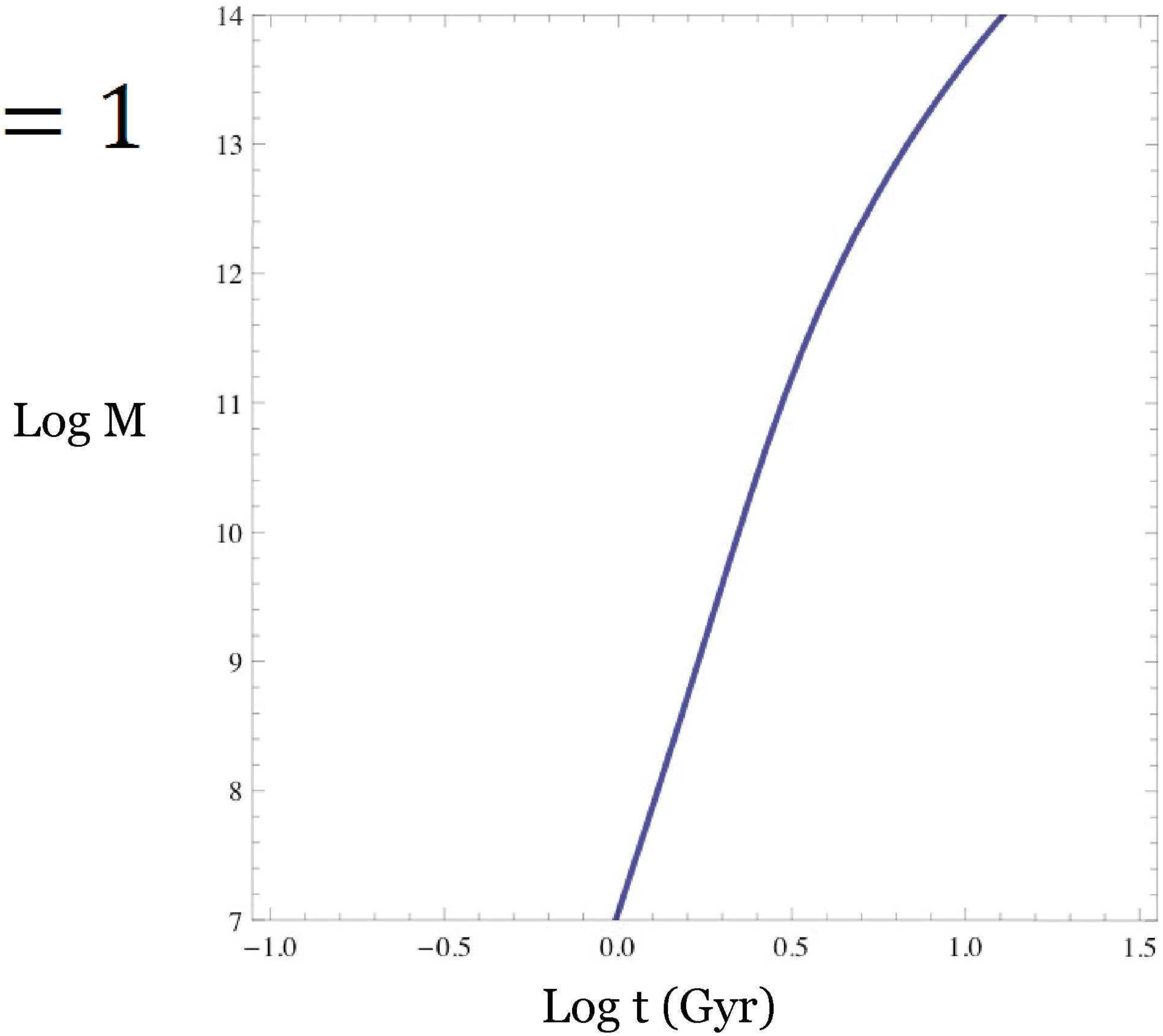
Tail area is collapsed fraction

- Press-Schechter formalism



Typical mass collapsing at t

$$\frac{\delta_c}{\sqrt{2}\sigma(M_{typ}(t),t)} = 1$$



Collapse time determines density

- Controls the gravitational timescale
- All gravitational processes (like star formation) in the halo proceed on this timescale

$$t_{\mathrm{grav}} = \rho_{\mathrm{vir}}^{-1/2}$$

Cooling

- Newly collapsed halos are very hot (virial theorem) and baryons need to cool before collapsing further
- Bremsstrahlung, line cooling, Compton cooling
- Need ionized gas

Lower limit on mass

- Masses below 10^4 K won't cool (efficiently)

Log M

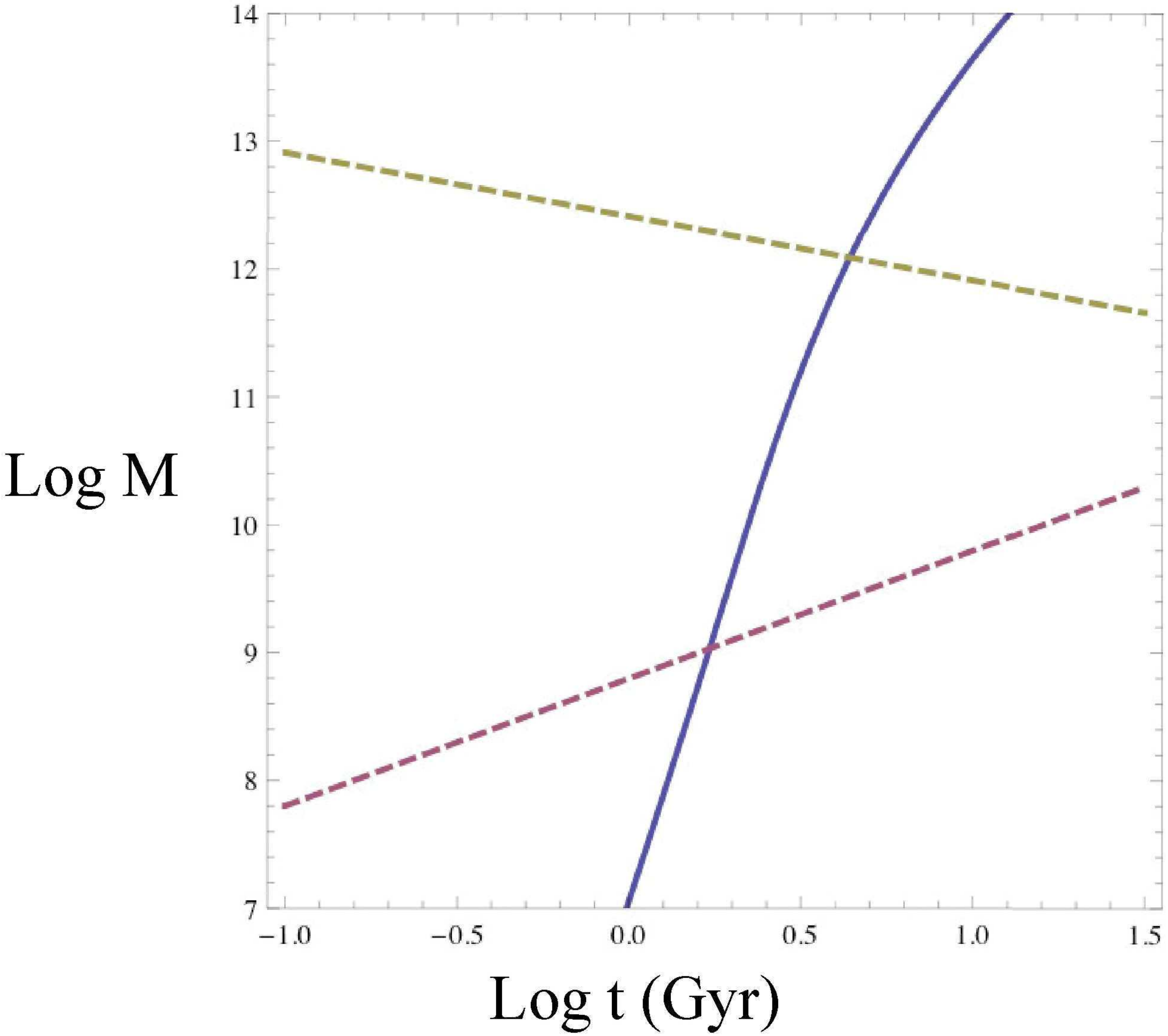
Log t (Gyr)

Cooling timescale

- The cooling efficiency defines a cooling timescale t_{cool} ~ Energy/(Energy Loss Rate)
- This timescale increases for large temperature
- Setting $t_{grav} = t_{cool}$ gives a maximum mass

Upper limit on mass

- A window of opportunity for cooling



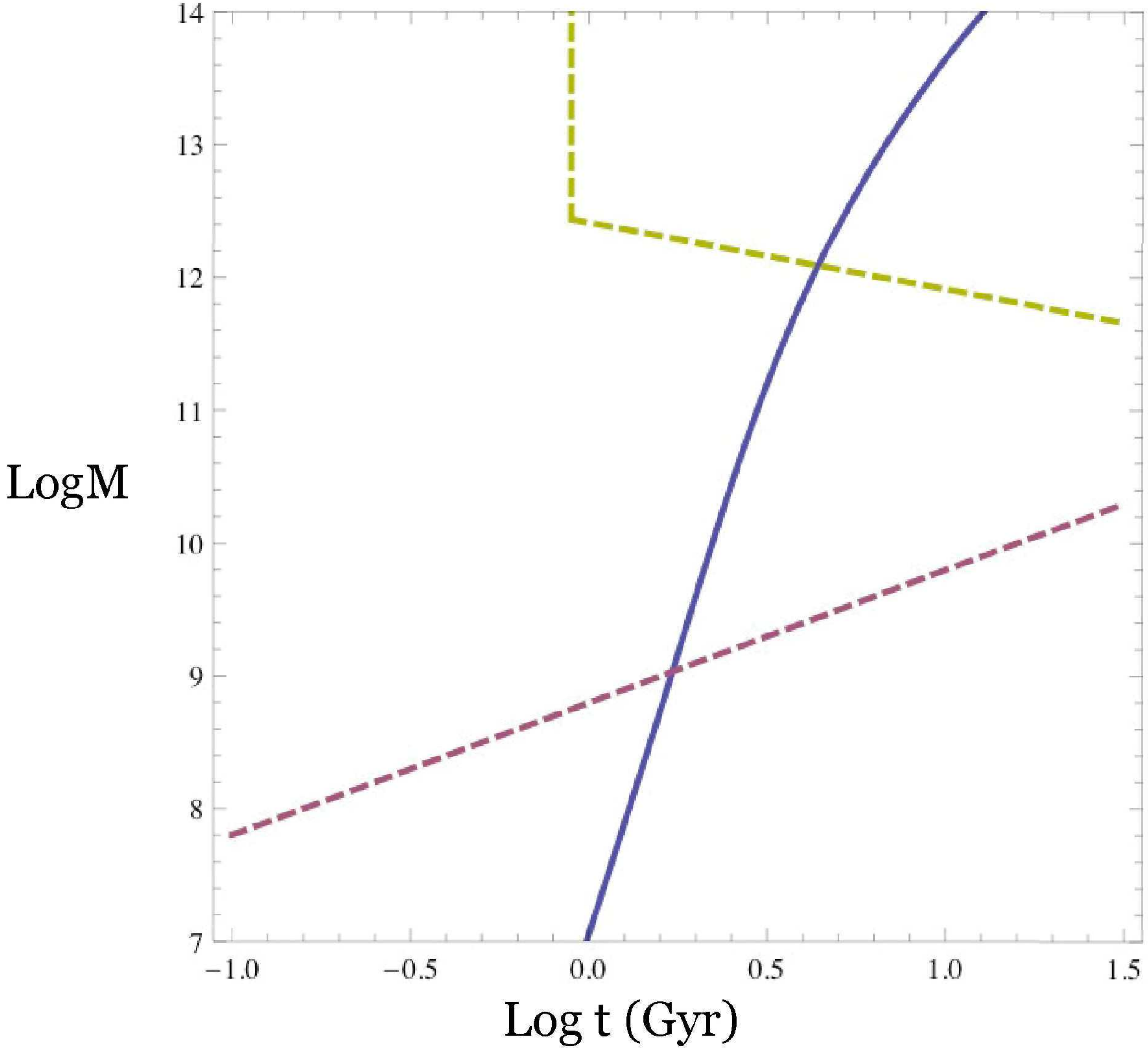
Cooling by Compton scattering

- Scatter with the CMB photons, lose energy
- As long as a gas is ionized (10^4 K), Compton cooling depends only on the CMB temperature
- Effective early on, before CMB gets too cold
- Unimportant in our universe

$$t_{comp} = \frac{45 m_e}{4\pi^2 \sigma_T (T_{CMB})^4}$$

Upper limit on mass

- A window of opportunity for cooling



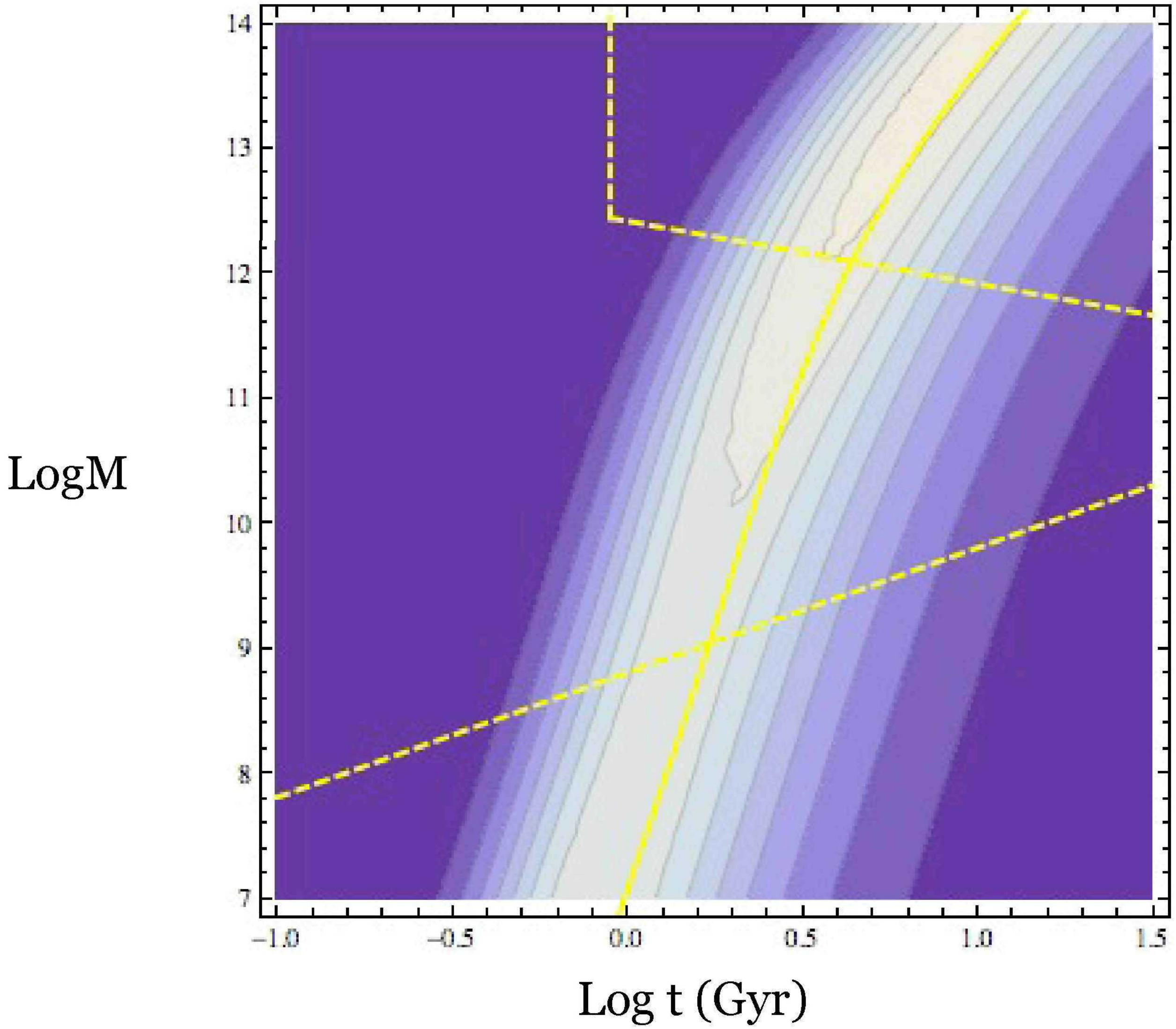
Star formation is very nonlinear

- Detailed physics is hard to understand (unsolved problem)
- The only timescale comes from the density, so we say stars form on that timescale
- We also stipulate that only a certain fraction (about one third) of the gas of an individual halo is processed before an unknown feedback mechanism halts star formation

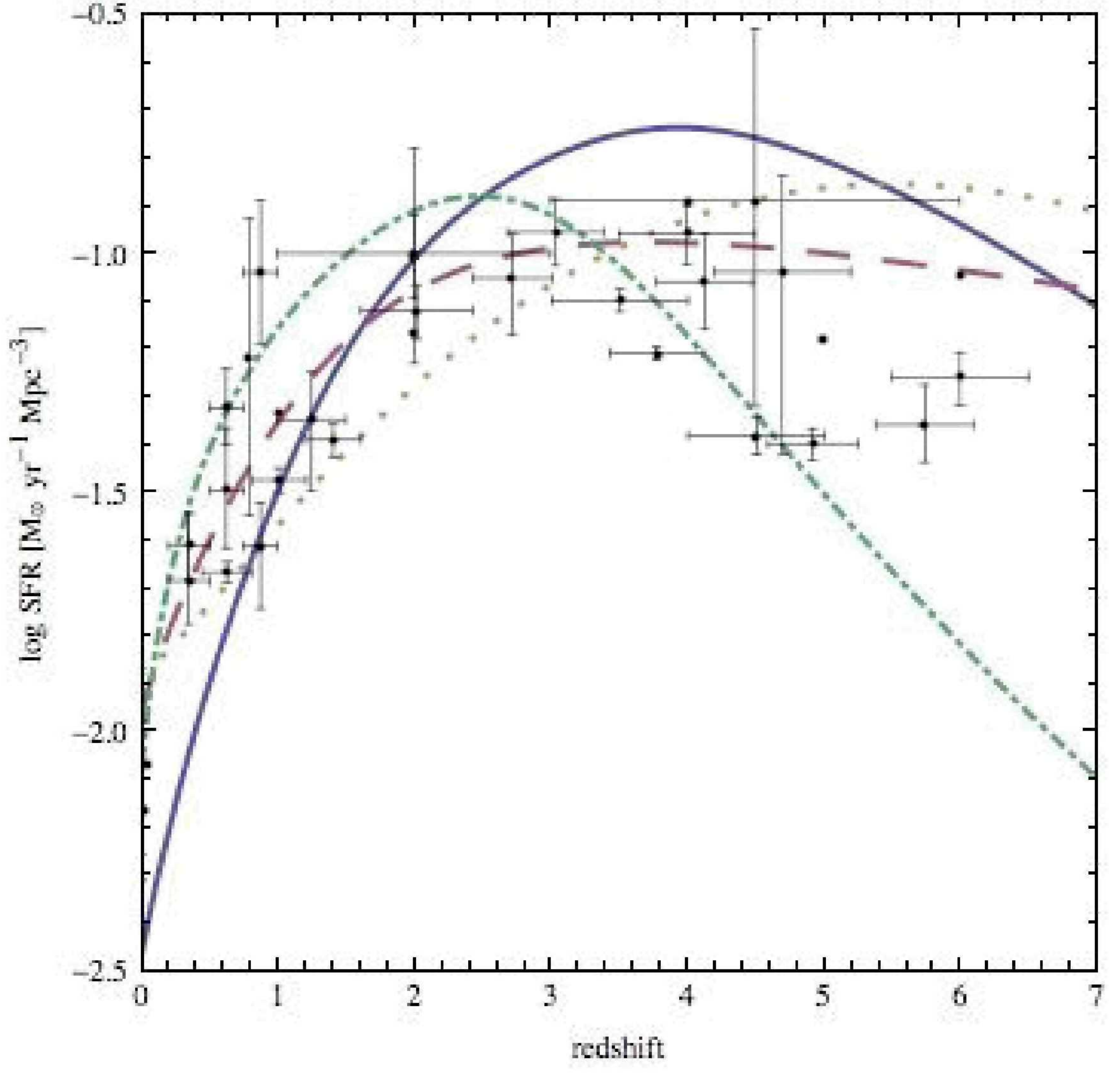
The Whole Picture

- Perturbations grow and collapse
- Ordinary matter cools (if it can)
- Cooled matter will form stars according to the graviational timescale of the halo
- Now just average over everything (EPS formalism helps you here)

The Whole Picture

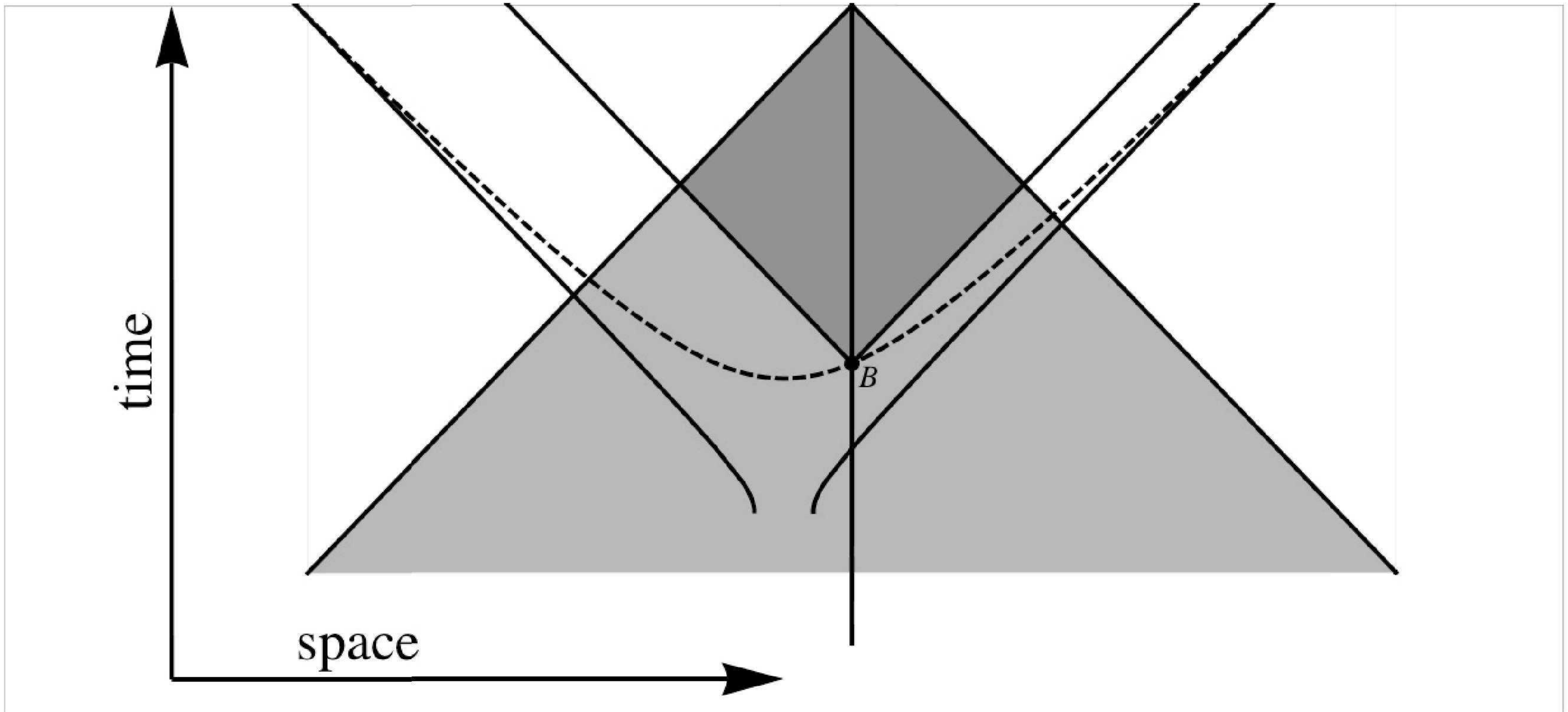


It also matches observation

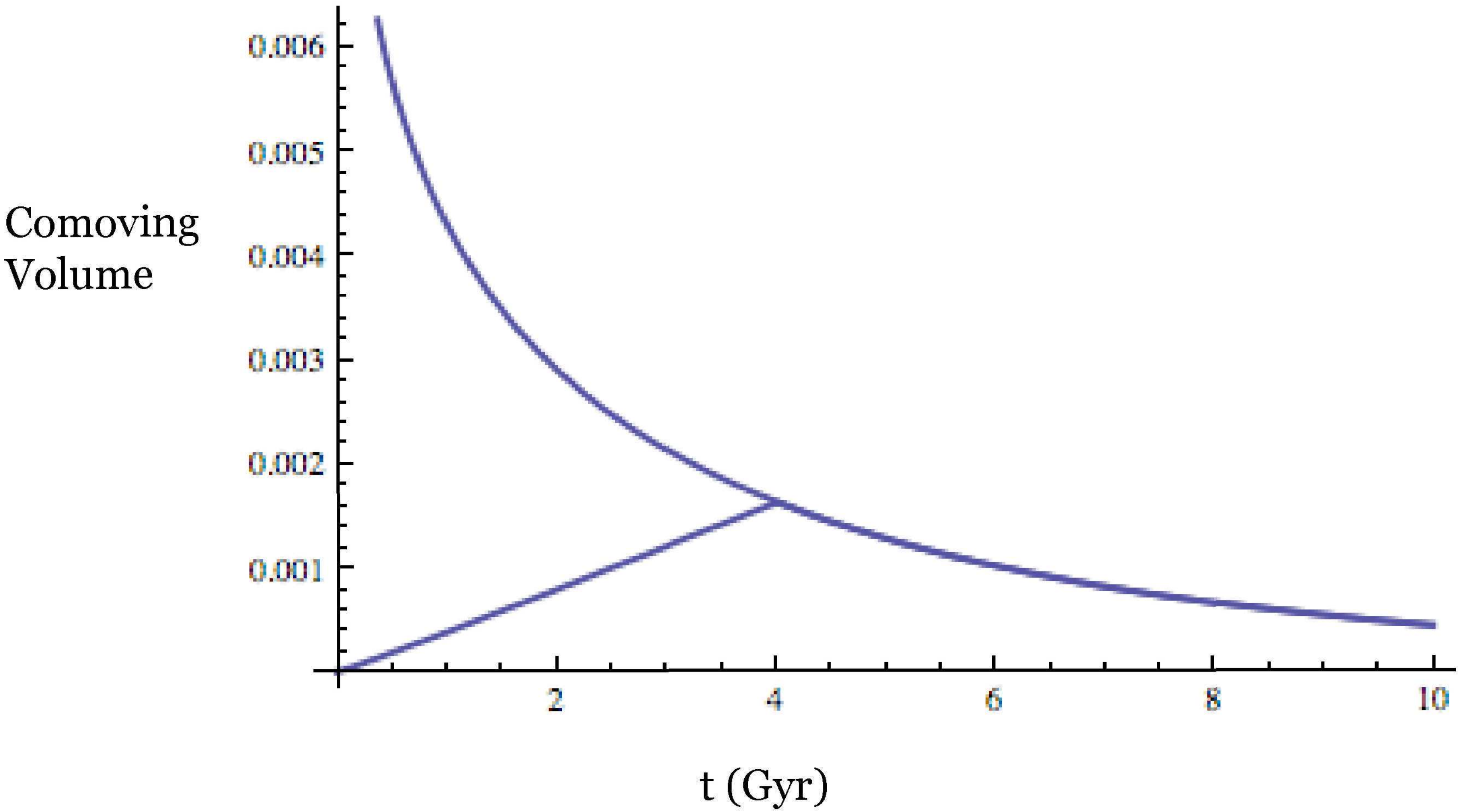


The Causal Diamond Measure

- Regulate by counting observations in a causally connected region of spacetime
- Pathology-free

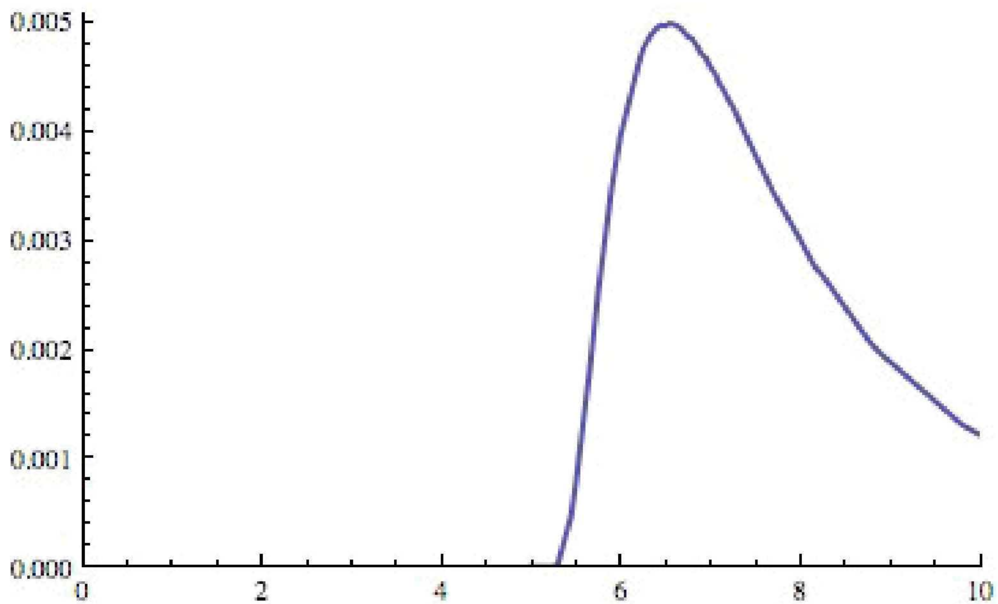


The Causal Diamond Measure



Observer model

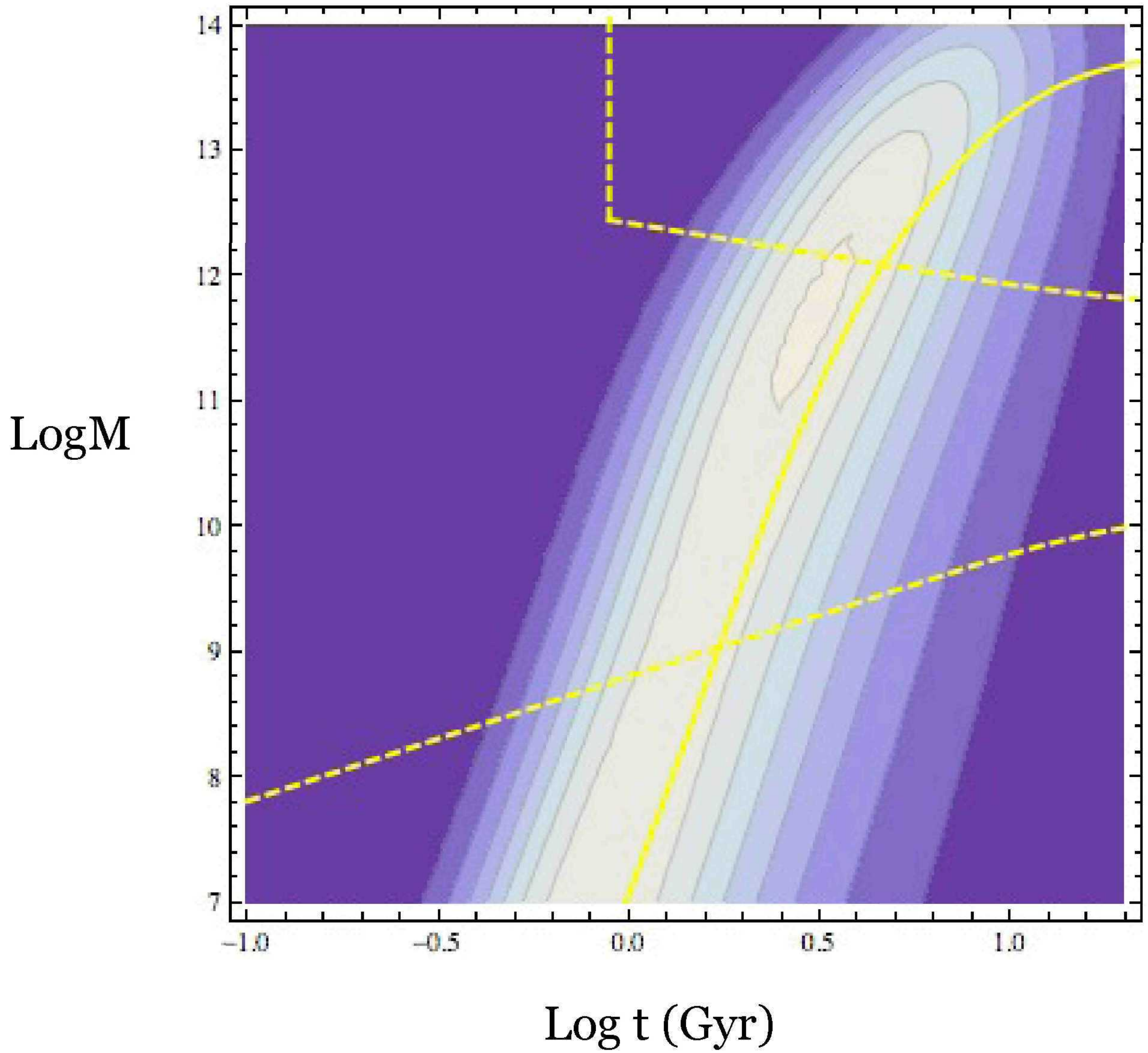
- Star formation is not the same as observer formation
- One choice is to shift the star formation rate by an evolutionary delay time



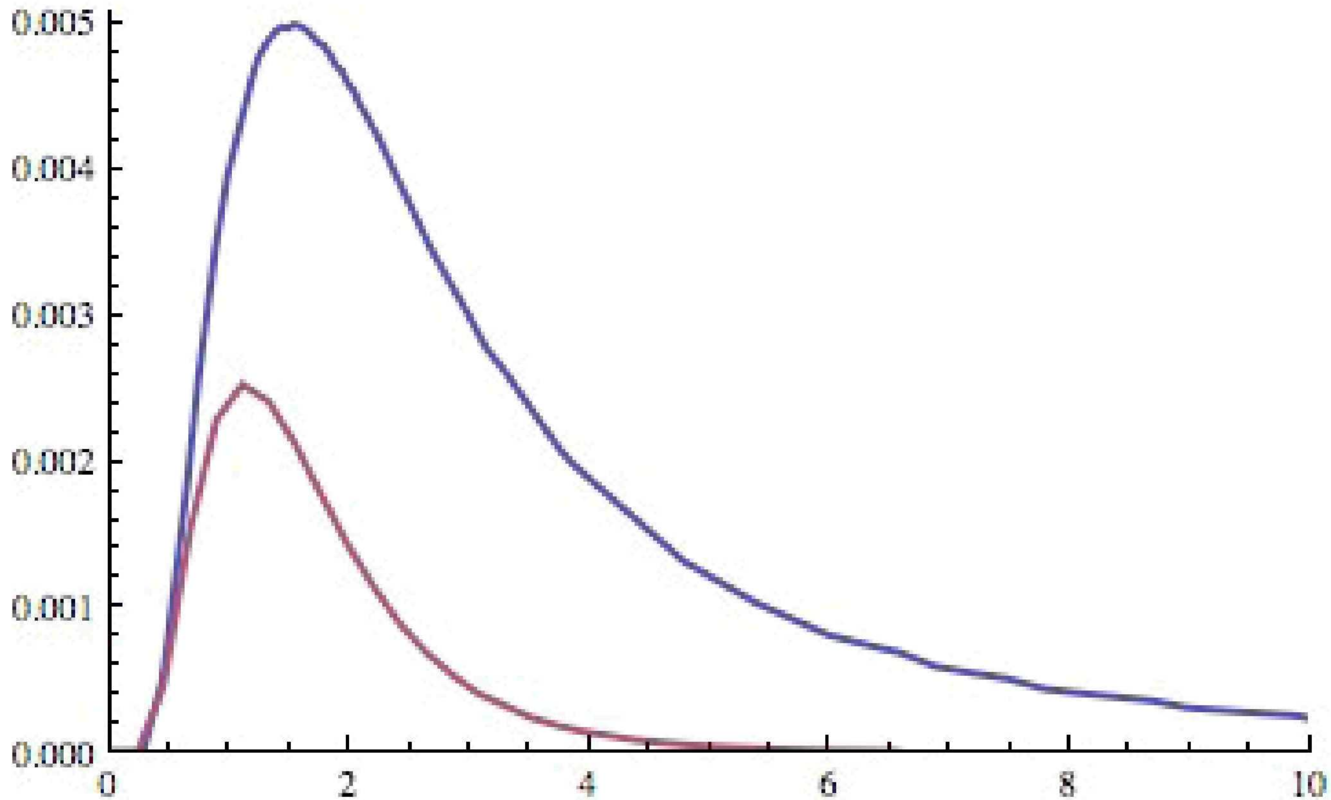
Observer model

- Another possibility is to use entropy production
- Entropy production is well-defined
- Stars are the main source of entropy (at least in our universe)
- Entropy production requires knowledge of interstellar dust temperature
- Bousso, Harnik, Kribs, Perez (2007)

Changing Λ



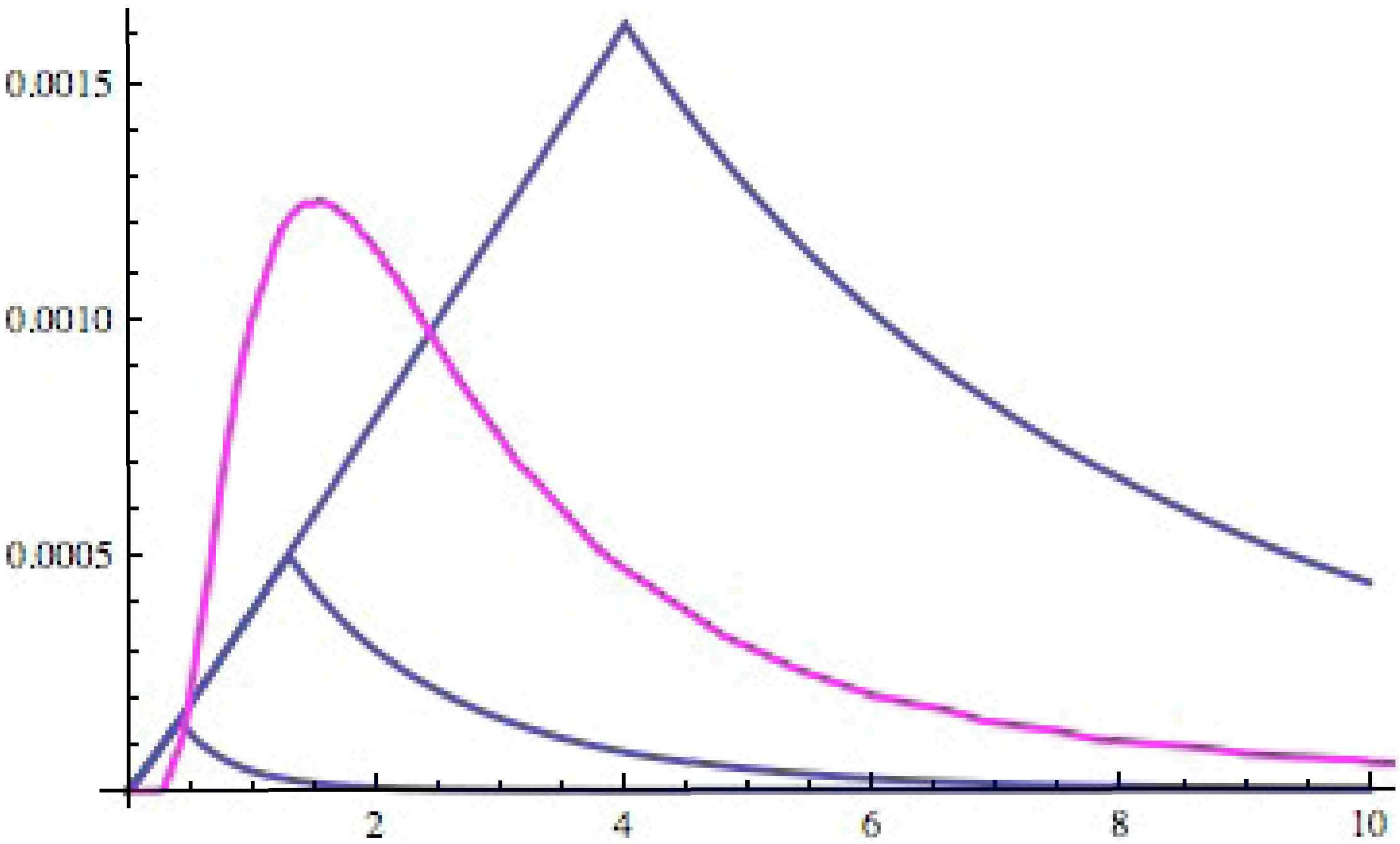
Changing Λ



t (Gyr)

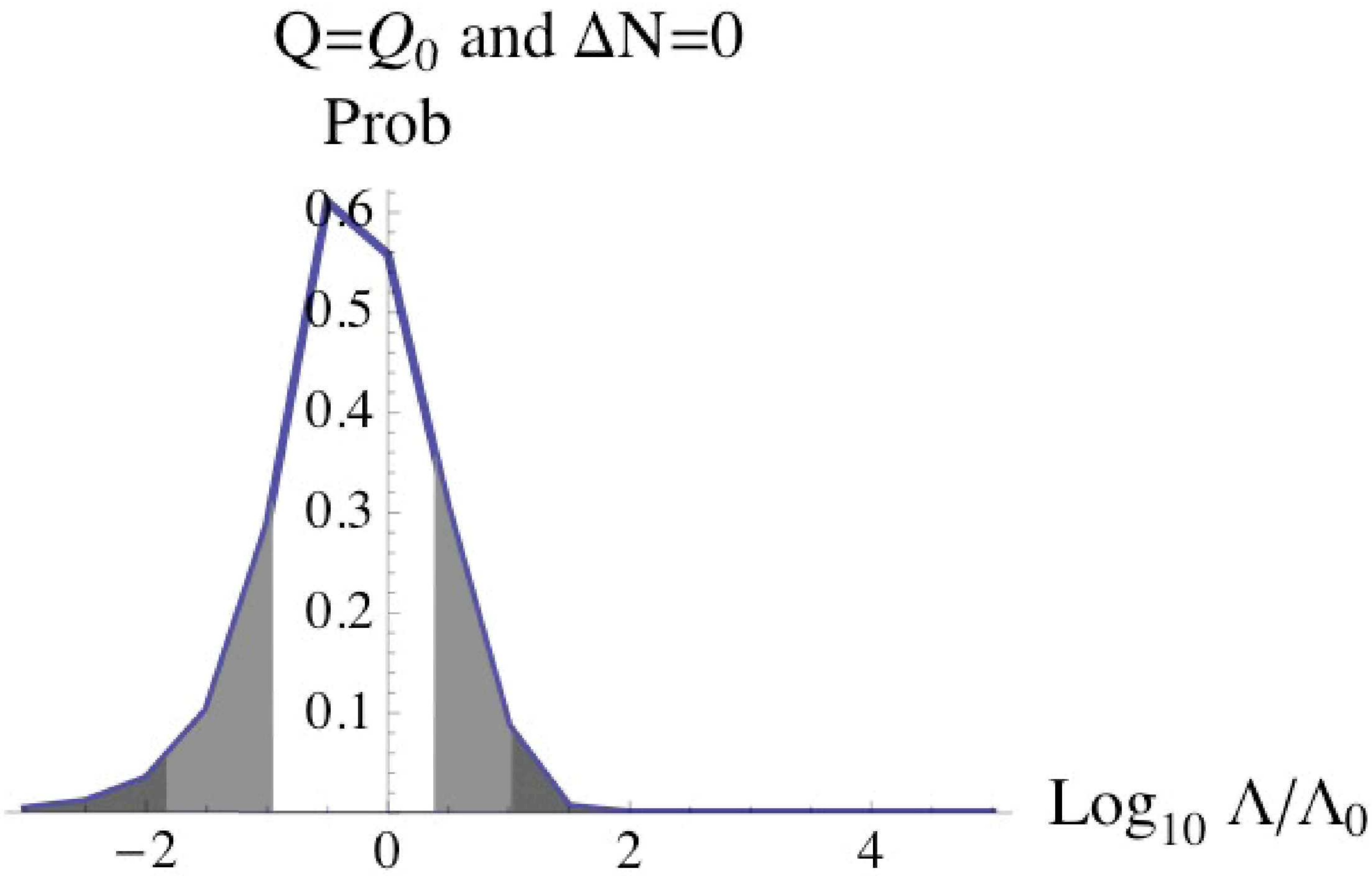
The Causal Diamond selects Λ

- $t_\Lambda = t_{peak} + t_{delay}$

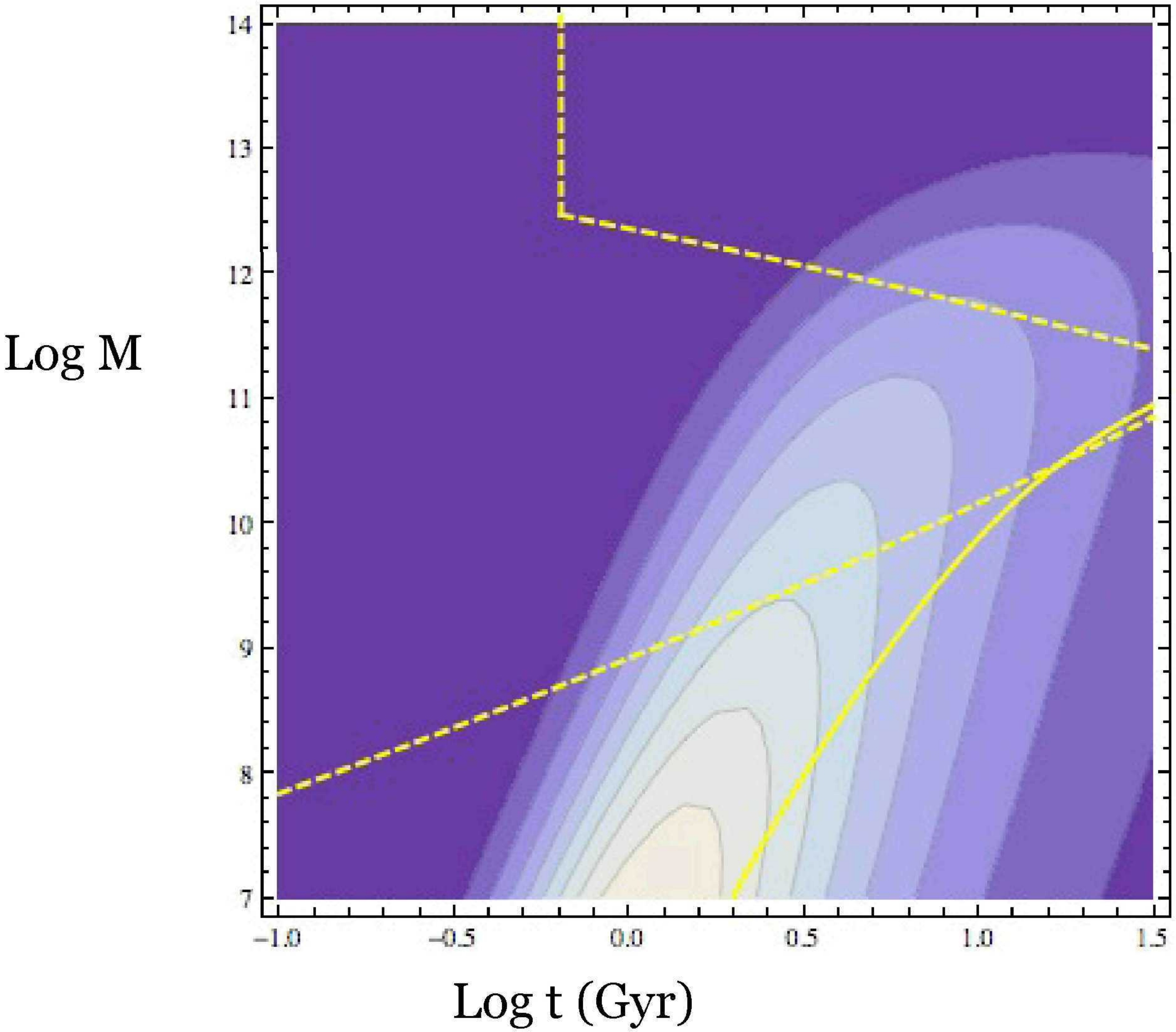


Changing Λ

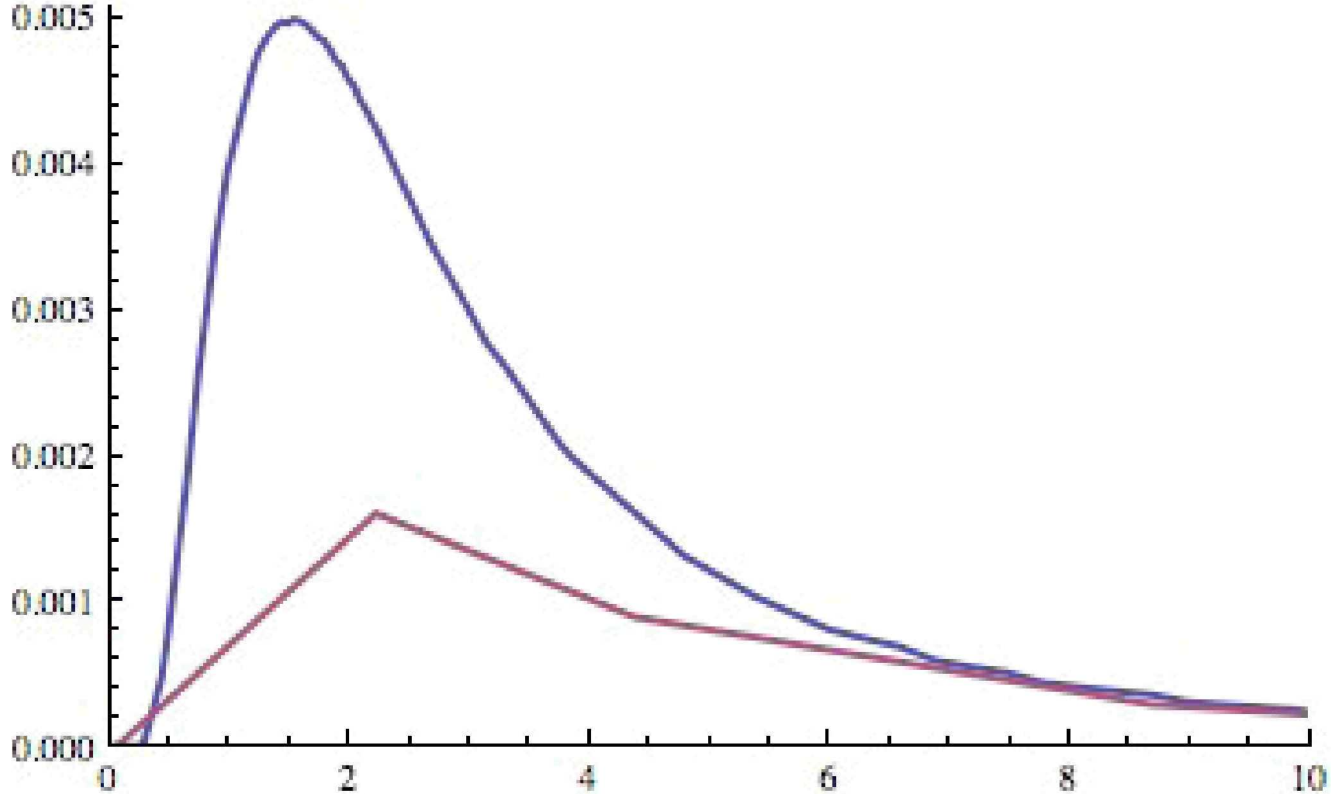
- t_{delay} shifts the center of the distribution



Changing Curvature

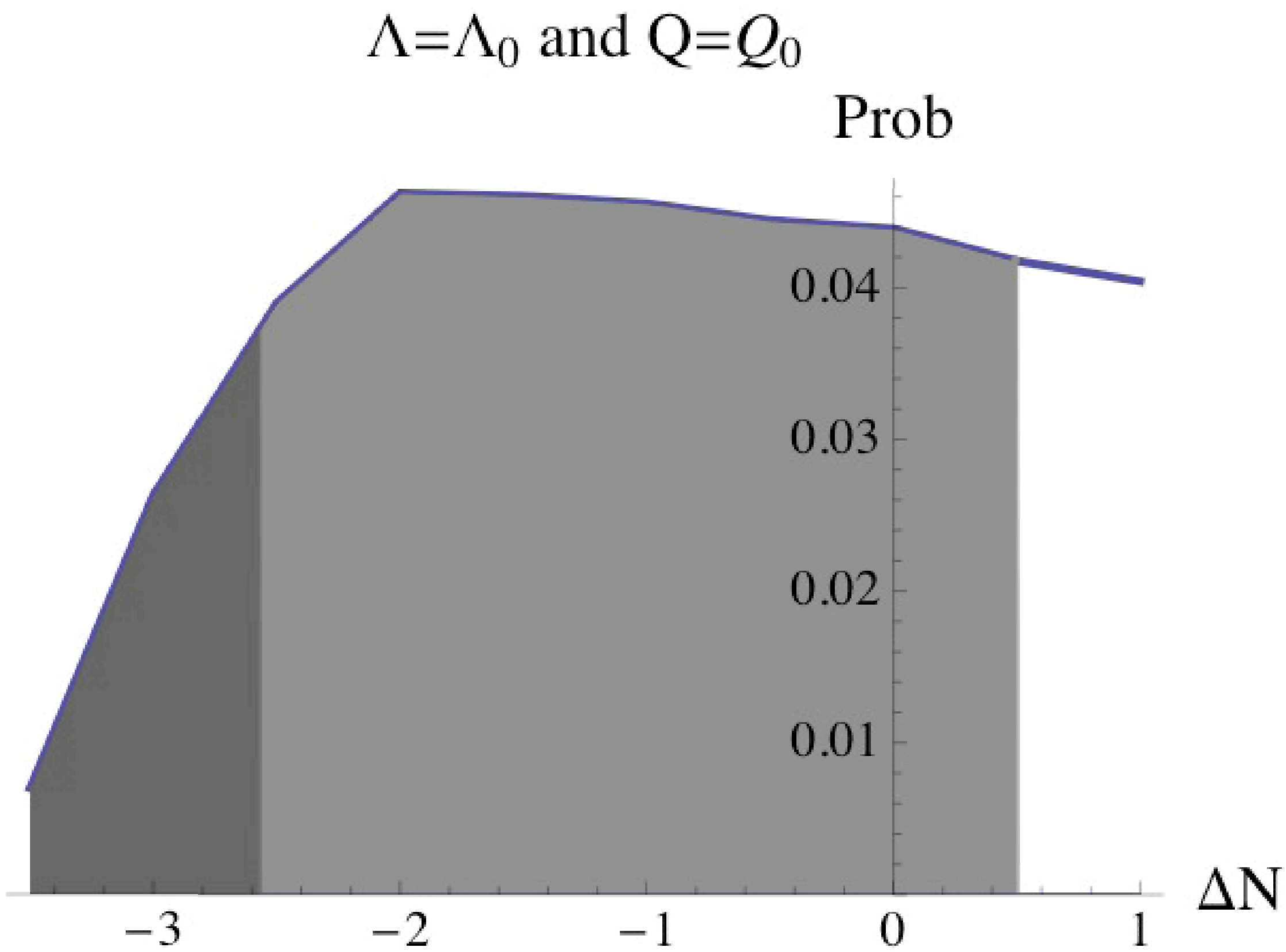


Changing Curvature

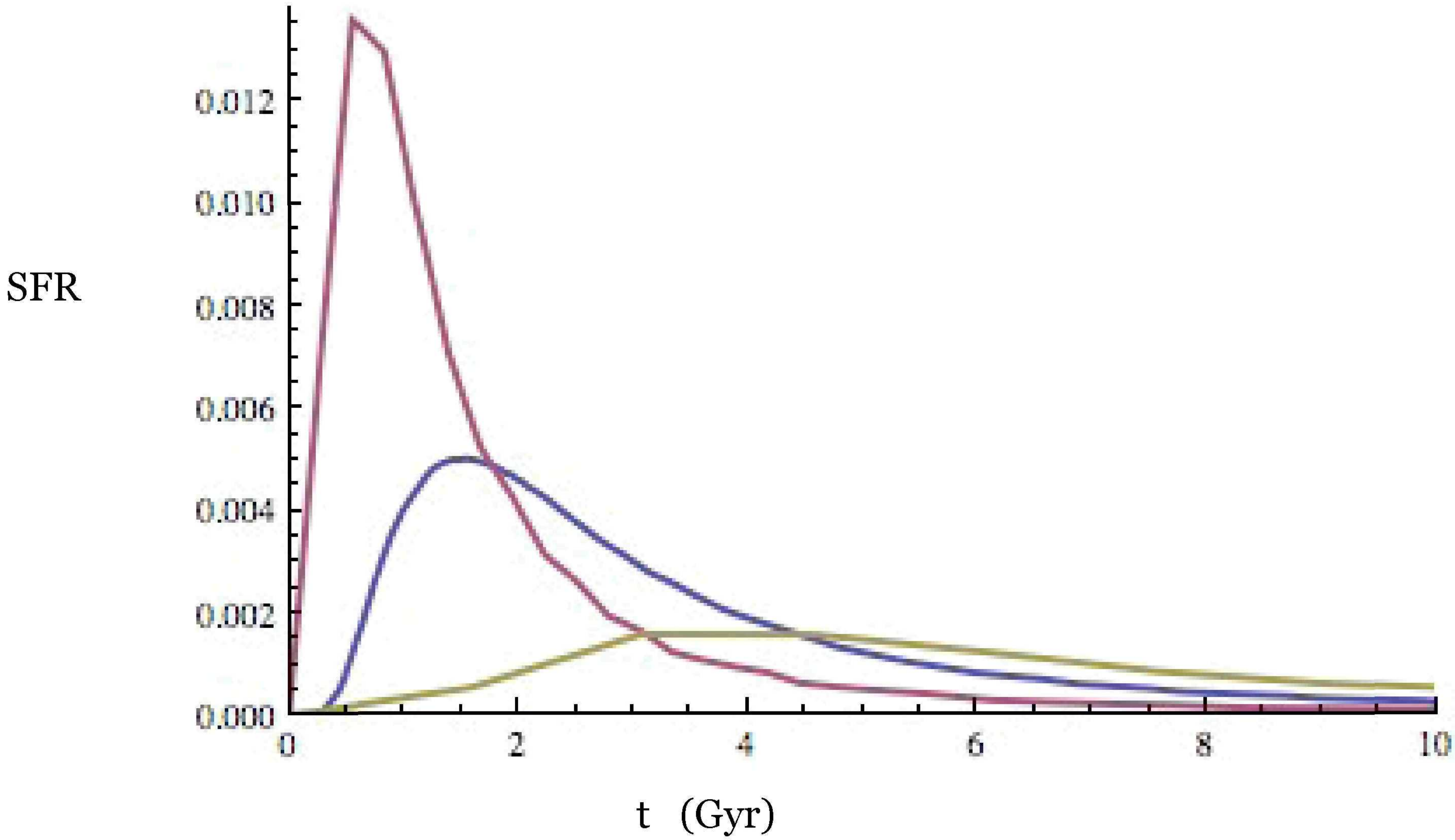


t (Gyr)

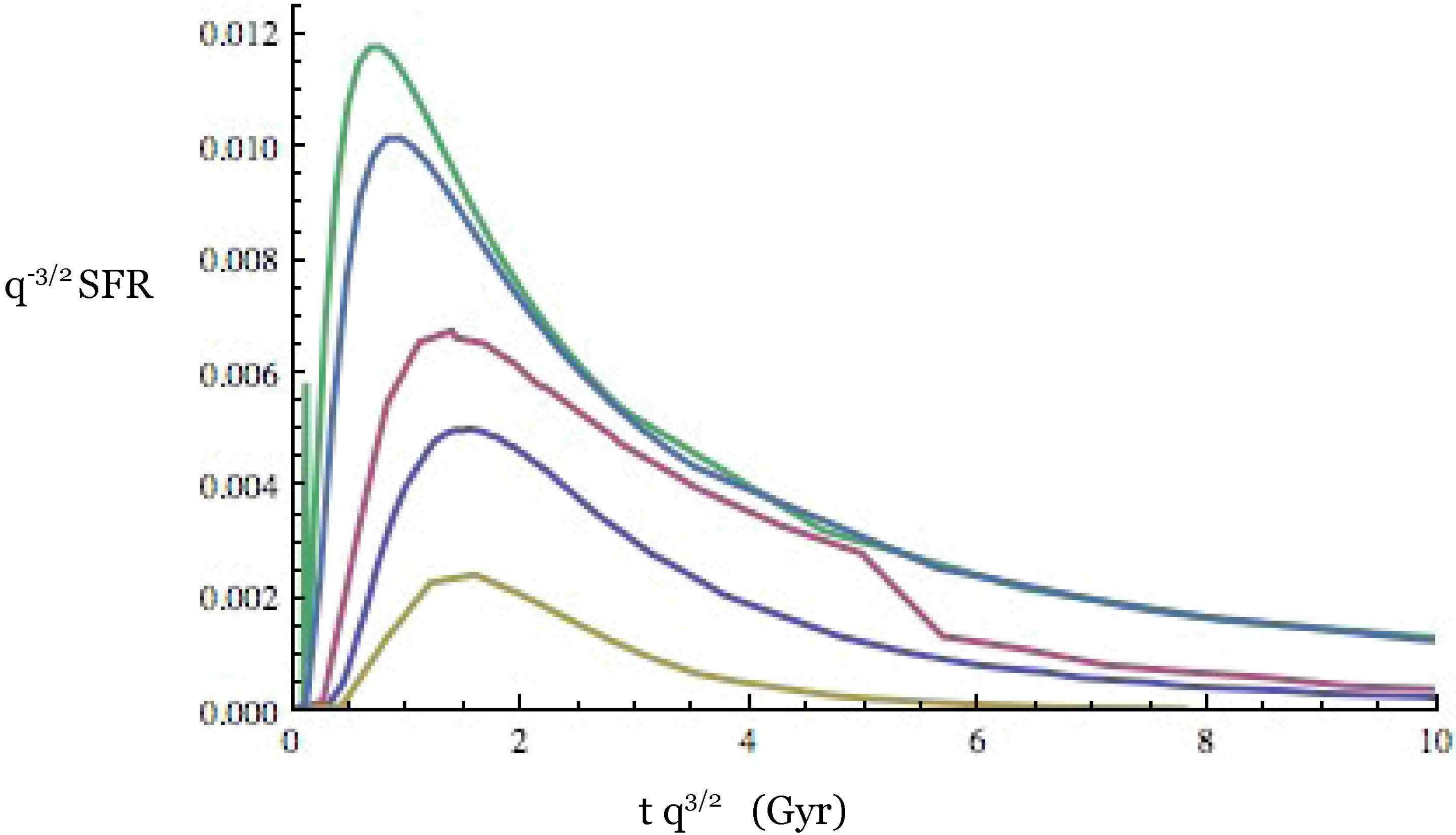
Changing Curvature



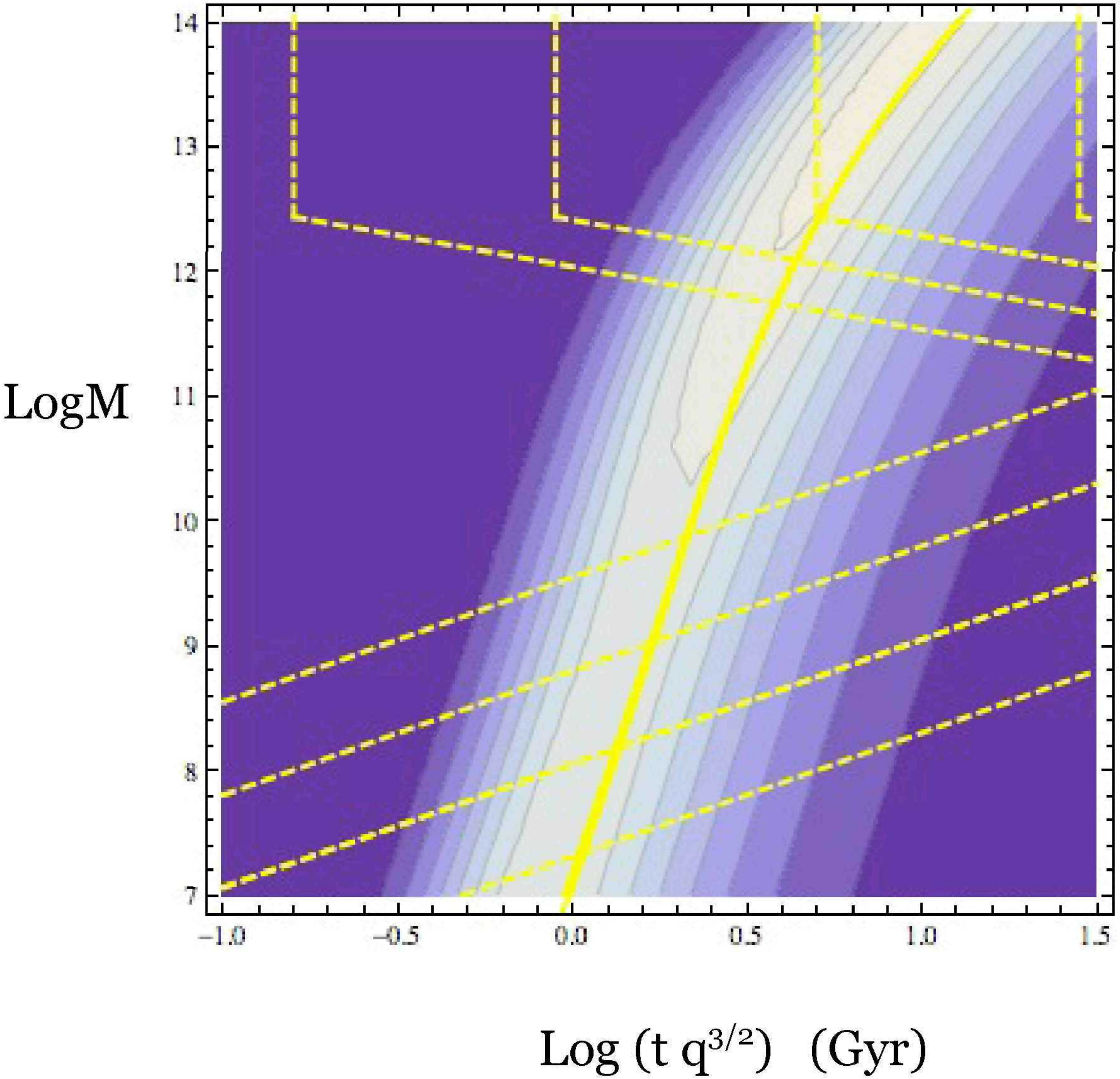
Changing Q



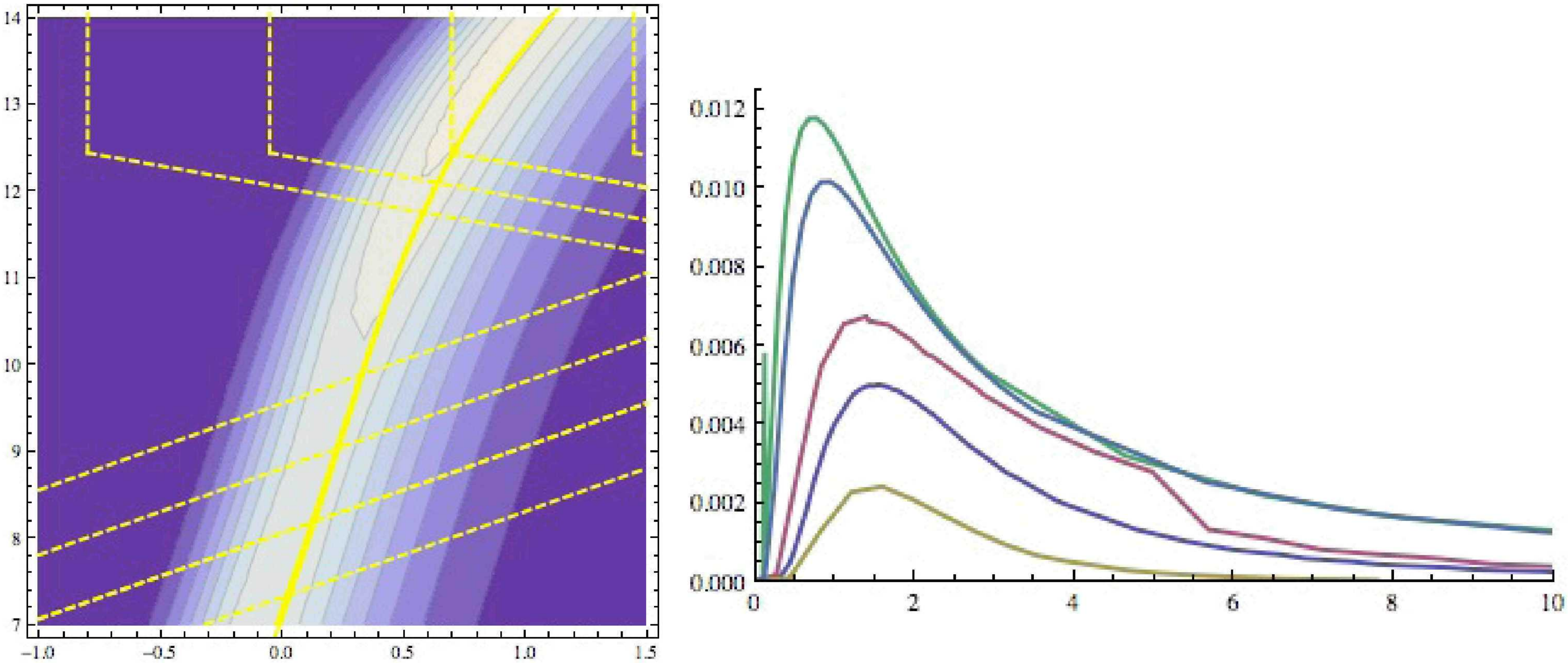
Changing Q



Changing Q

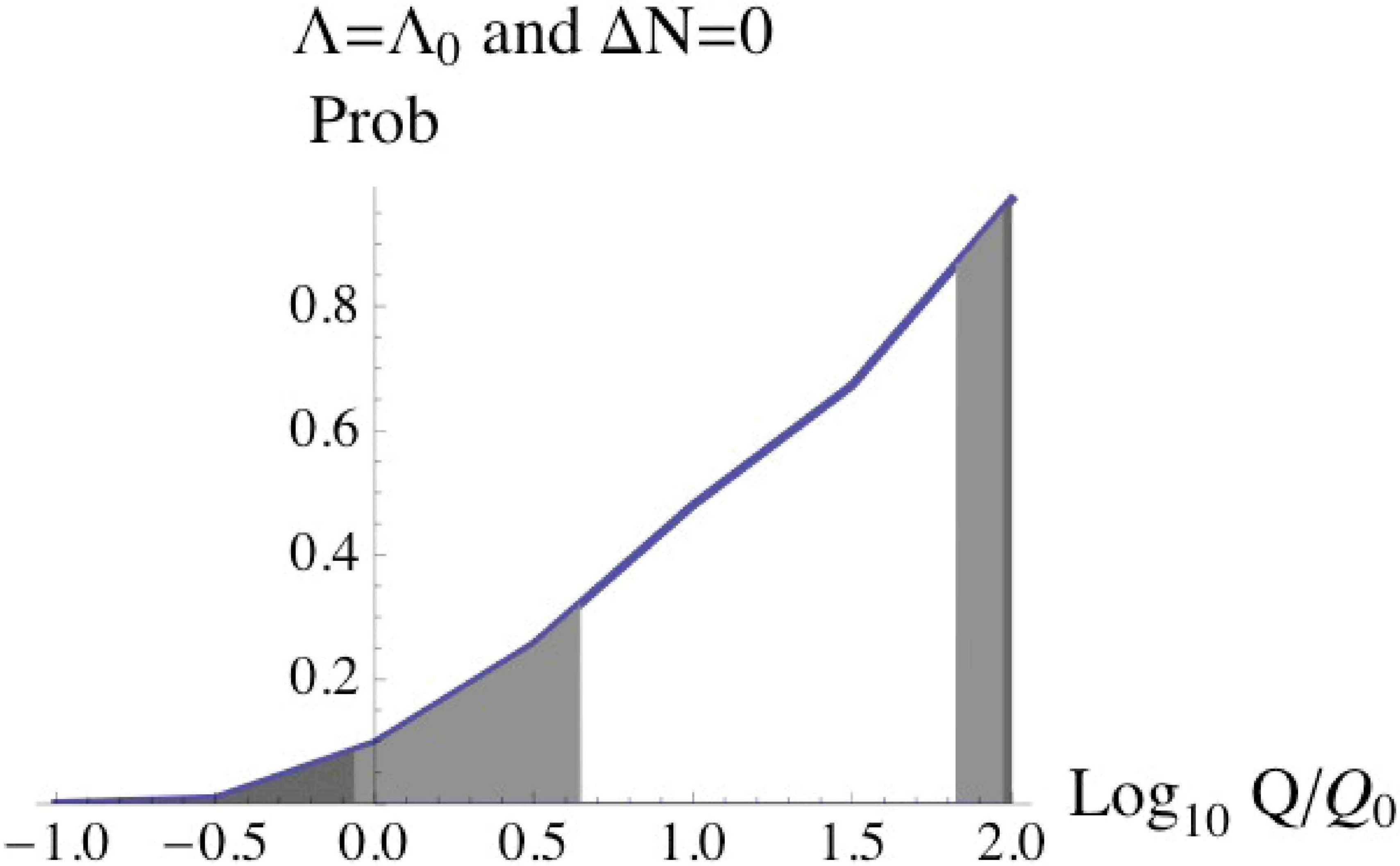


Changing Q

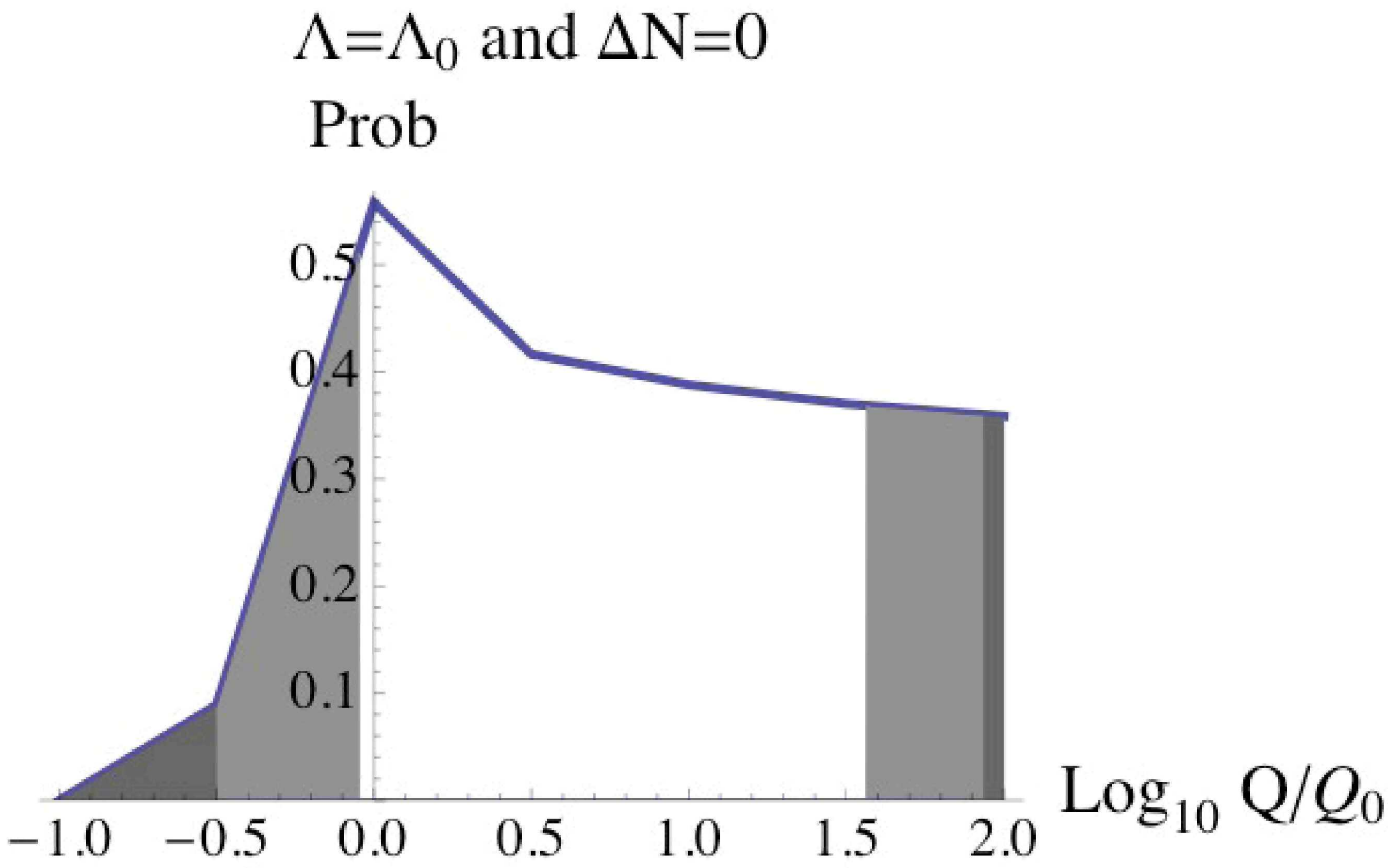


14
13
12
11
10
9
8
7
−1.0
−0.5
0.0
0.5
1.0
1.5
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0
2
4
6
8
10

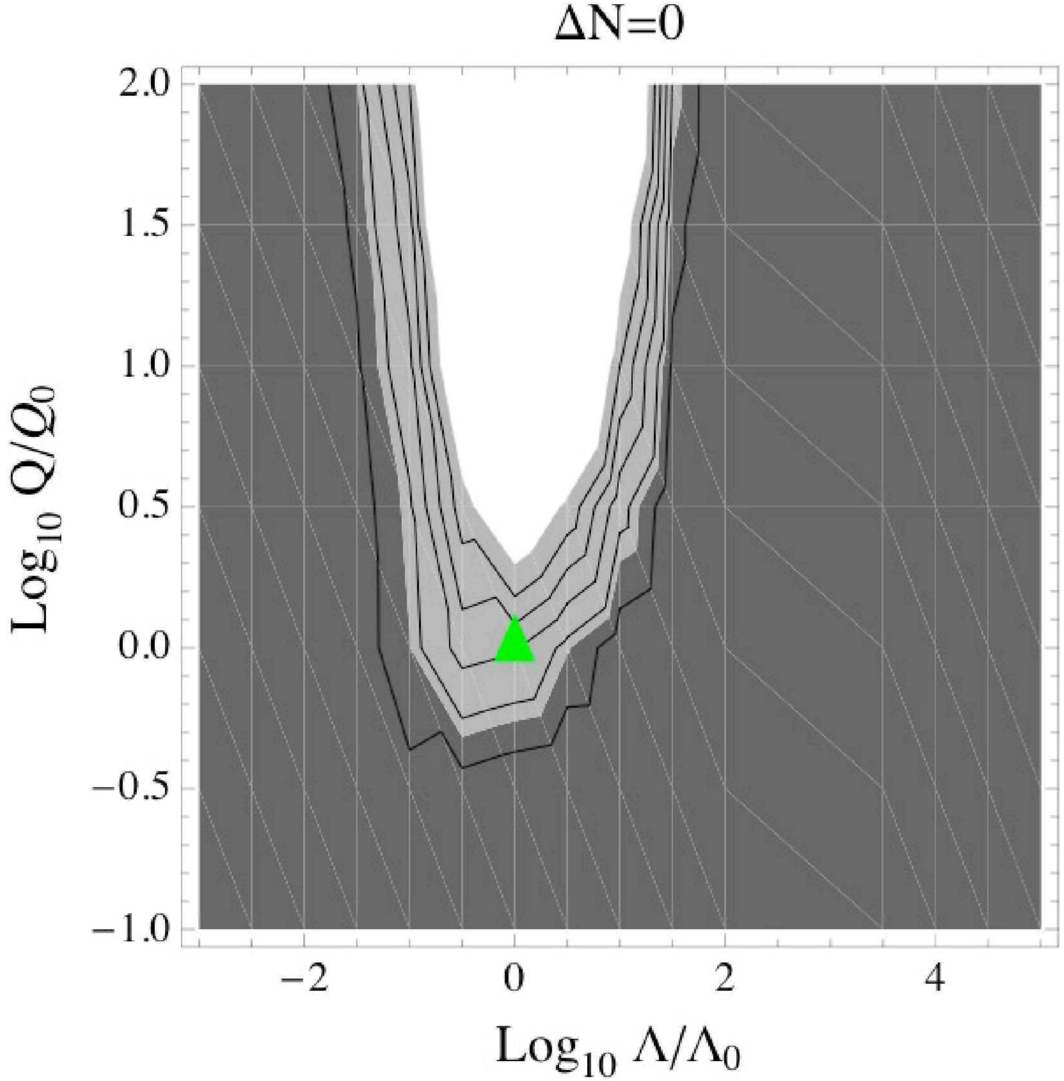
Delay model has growth in LogQ



Entropy is complicated



Multiple parameters



Λ<0 with negative curvature

$$ds^2 = -dt^2 + a^2(t)\,d\chi^2 + a^2(t)\sinh^2(\chi)\,d\Omega_2^2$$

$$a(t) = t_\Lambda \sin(t/t_\Lambda)$$

$$\chi(t_{obs}) = \int_{t_{obs}}^{t_{crunch}} a^{-1}(t)\,dt$$

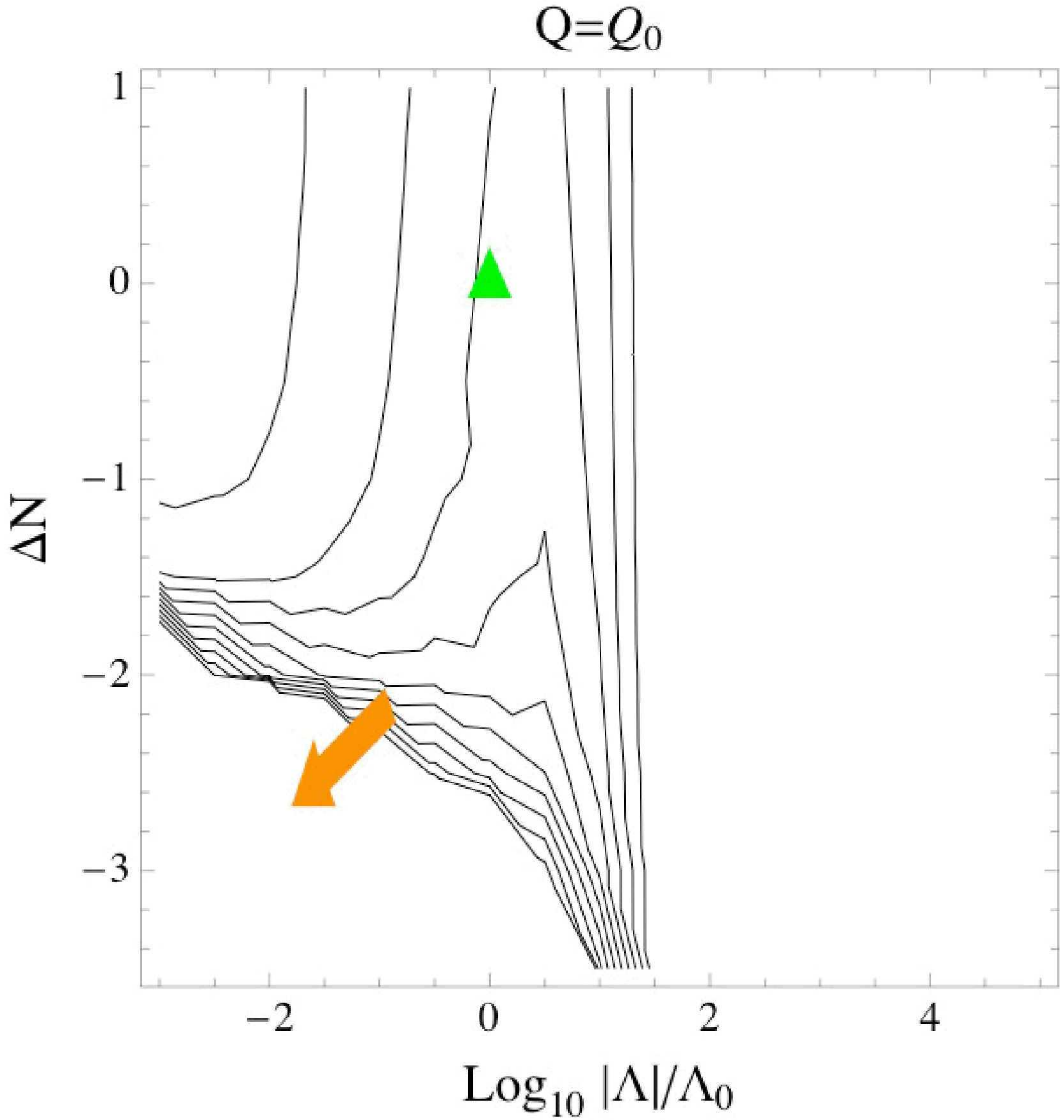
$$\chi(t_{obs}) > \int_{\epsilon}^{t_{crunch}-\epsilon} t_\Lambda^{-1} \sin(t/t_\Lambda)^{-1}\,dt$$

$$\chi(t_{obs}) \sim 2\log(t_\Lambda/\epsilon)$$

$$V_c(t_{obs}) \sim \exp(2\chi(t_{obs})) \sim t_\Lambda^4 \sim \Lambda^{-2}$$

Multiple parameters

$1/\Lambda$ pressure toward small Λ in the causal patch measure



Future

- This tool should be used for more measures
- Extending to other parameters is straightforward in principle