Lethal radiation from nearby supernovae helps explain the small cosmological constant

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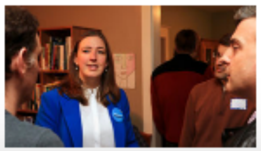

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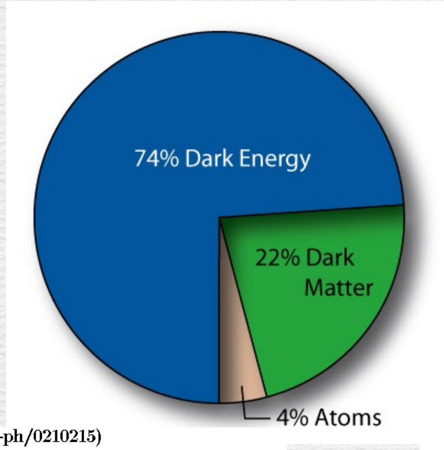
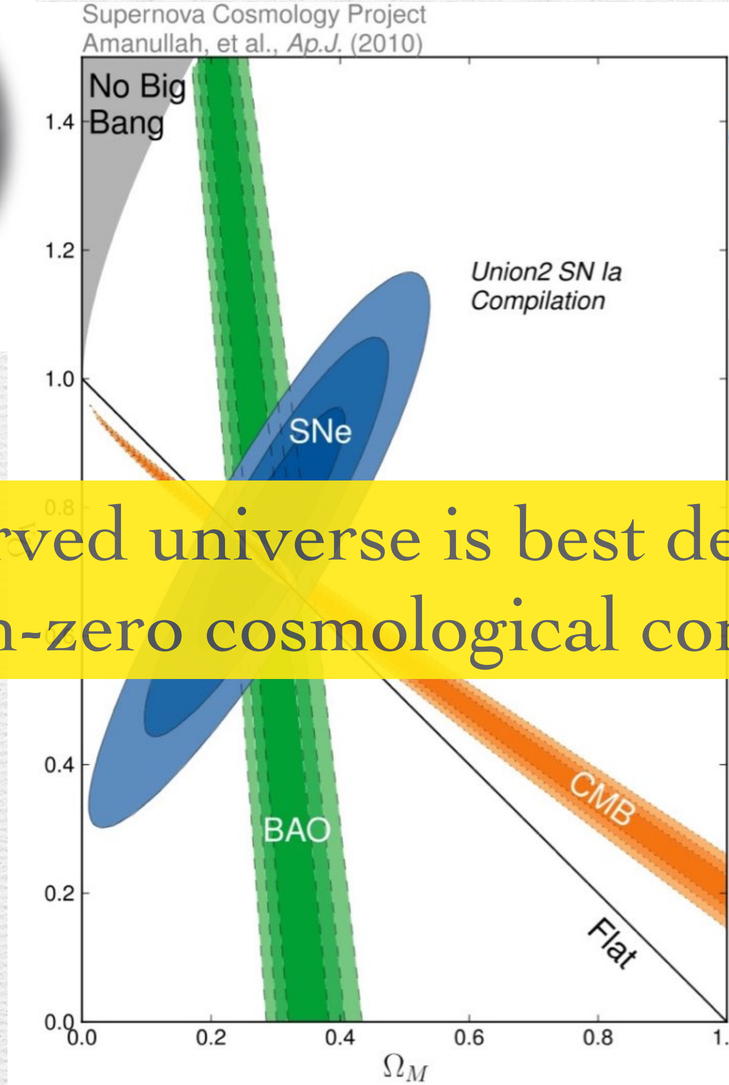
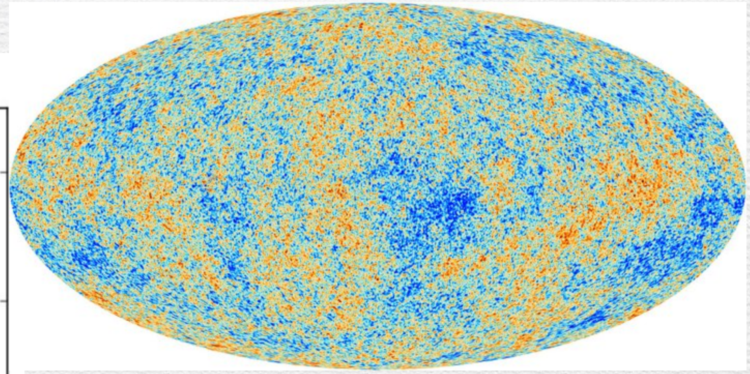
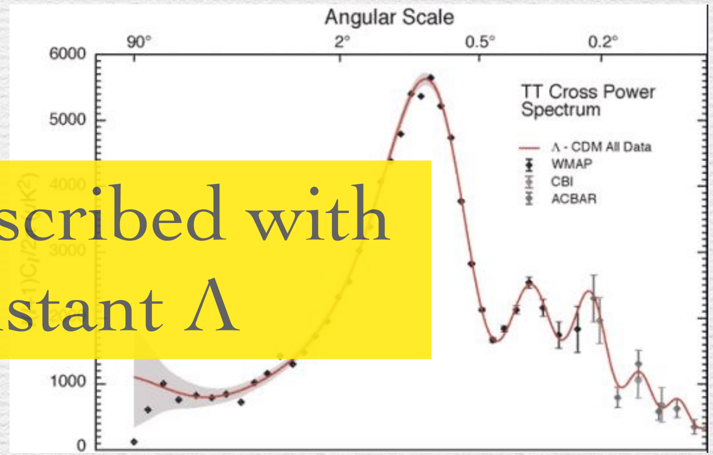
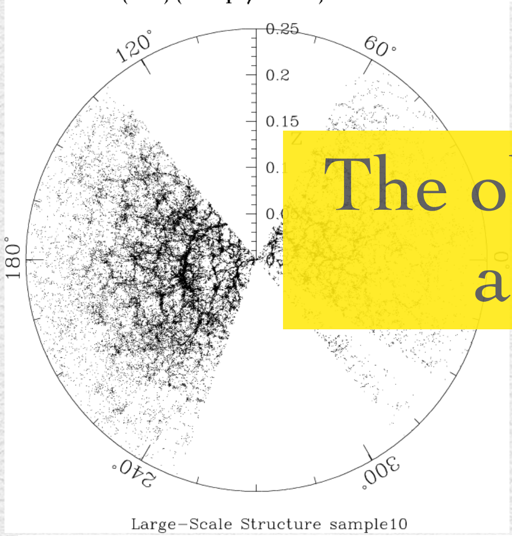


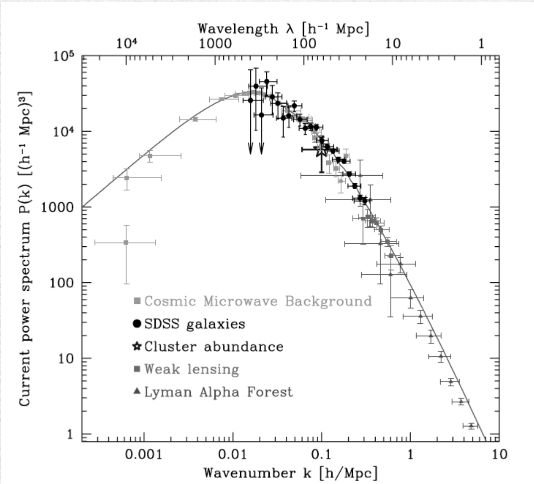


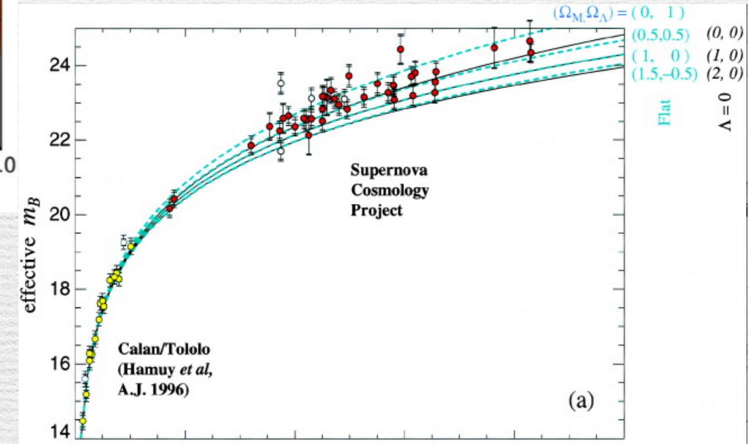




Blanton et al. (2003) (astro-ph/0210215)







The observed universe is best described with a non-zero cosmological constant Λ

Thoeretical Problem of Cosmological Constant

- the smallness
  - Λ is vacuum energy density $\rho_{vac} \sim (\text{energy})^4$ in the natural units from the viewpoint of quantum field theory
  - observed $\rho_\Lambda \sim \rho_{matter} \sim (\text{meV})^4$ in the present time we exist
  - $\rho_{vac} \sim (\text{Planck scale} = 10^{19}\ \text{GeV})^4 \sim 10^{120}\ \rho_{matter}$
  - $\rho_{vac} \sim (\text{electroweak scale} = 100\ \text{GeV})^4 \sim 10^{50}\ \rho_{matter}$

- the coincidence
  - There may be some mechanisms to cancel Λ, but its observed value is not exactly zero!
  - furthermore, somehow $\rho_\Lambda \sim \rho_{matter}$ just in our present time
  - no known first-principle-based explanation about this

Proposed models/explanations

- Proposed solutions?
  - the cosmological constant Λ
  - dark energy, a generalized form of vacuum energy
    - e.g. a potential energy of a particle field (like inflation)
    - not necessarily constant, but variable in time
  - modified theory of gravity

- no persuasive solution based on the first principle
  - energy scale too low
  - difficult to explain coincidence

- anthropic argument?

the anthropic argument for Λ

- Λ may be stochastically determined when the universe is born
  - theoretically possible, e.g. multiverse motivated by string theory
  - other fundamental constants may also change, but let's think that Λ is the only variable for simplicity

- galaxies do not form when $\Lambda >> \Lambda_{obs}$, so no observer
  - Barrow and Tipler 1986; Weinberg 1987; Efstathiou 1995; Martel et al. 1998; Garriga et al. 2000; Peacock 2007; …

- universe will collapse within 10 Gyr when $\Lambda < -\Lambda_{obs}$, so no observer

- so $|\Lambda| <\sim \Lambda_{obs}$ is expected.
  - perhaps the only one explanation of the smallness & coincidence problem without fine tuning

Probability Distribution of Λ?

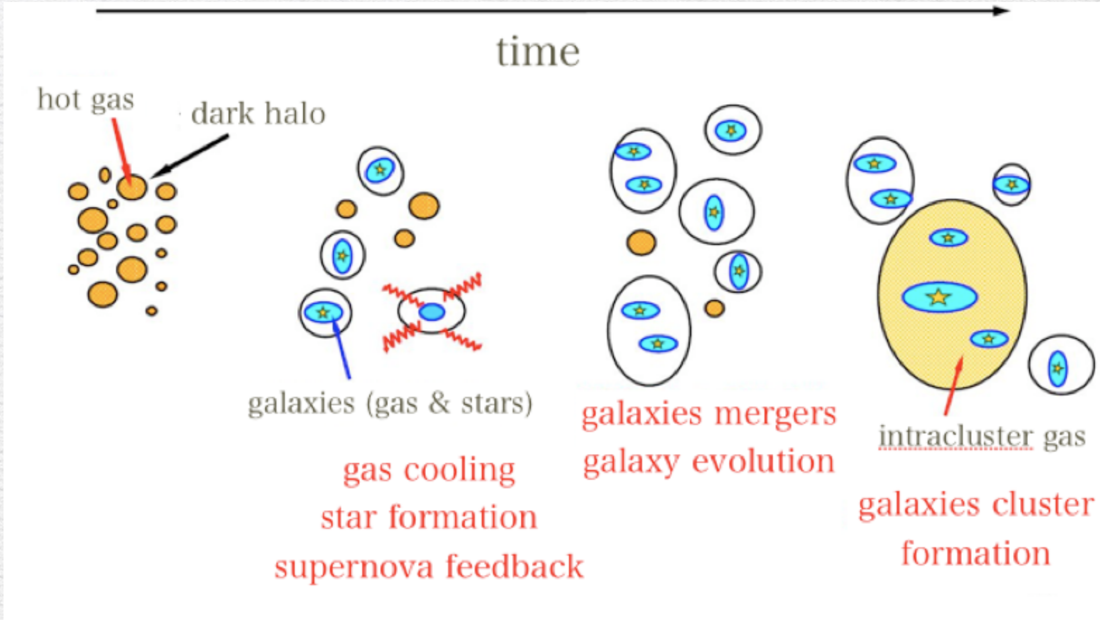
- a natural prior probability distribution of Λ: "flat" about Λ
  - $dP_{pri}/d\Lambda$ = const. around $\Lambda=0$
  - because physically natural scale of $\Lambda >>>>>>>>> \Lambda_{obs}$
  - assumed in most previous studies
  - coincidence problem solved: $\Lambda << \Lambda_{obs}$ is statistically disfavored because $P(<\Lambda) \propto (\Lambda/\Lambda_{obs})$

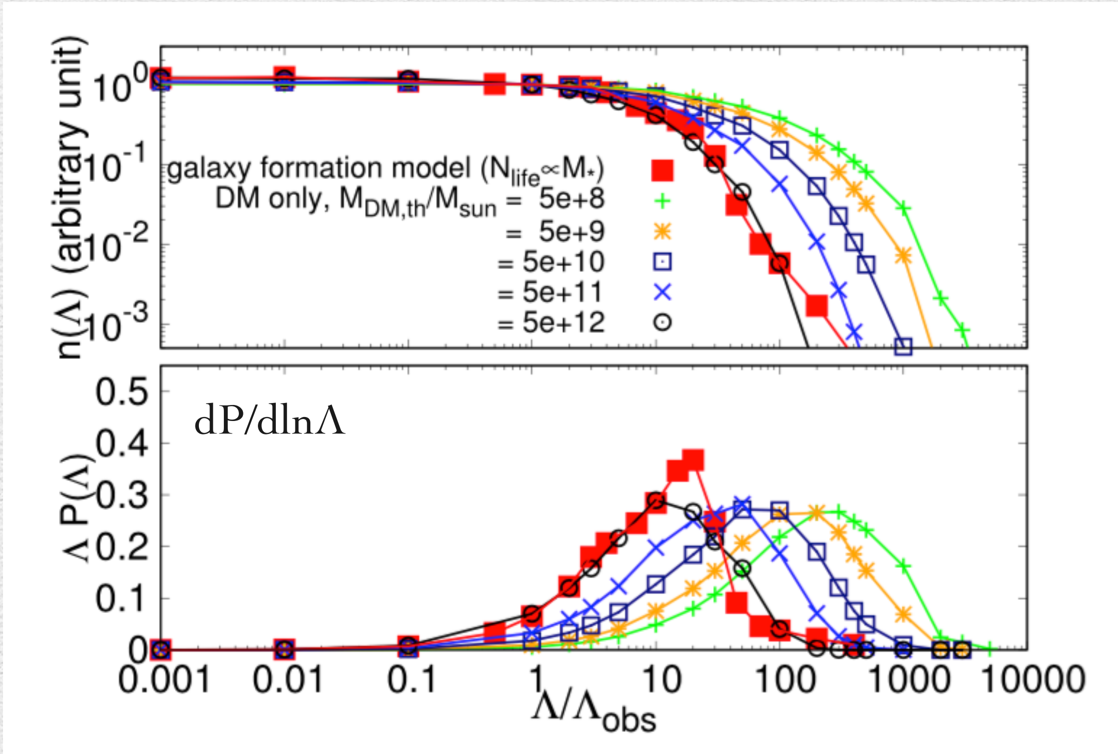
- $dP_{pri}/d(\ln\Lambda)$ = const. may also be possible, if Λ is positive bound, but we need to introduce a very low energy cut off at $\Lambda << \Lambda_{obs}$

- observable distribution $dP_{obs}/d\Lambda \propto n(\Lambda) \times dP_{pri}/d\Lambda$
  - $n(\Lambda)$: number of observers appearing in the universe
  - observable distribution can be calculated by astrophysics!

Λ distribution from galaxy formation theory

- Sudoh, TT+17
  - using a semi-analytic model of galaxy formation
    - ΛCDM structure formation theory
    - gas cooling, star formation, supernova feedback, galaxy mergers
    - reproduce a variety of observations (e.g. galaxy luminosity functions)
  - assuming $n(\Lambda) \propto$ stellar mass produced up to 15 Gyr, we found $P(\Lambda<\Lambda_{obs}) = 6.7\%$, with the distribution peak at $\Lambda/\Lambda_{obs} \sim 20$
- Barnes+'18
  - using the EAGLE numerical simulation of galaxy formation, they found $P(\Lambda<\Lambda_{obs}) = 2\%$ and peak at $\Lambda/\Lambda_{obs} \sim 60$





$P(\Lambda<\Lambda_{obs})$ to small?

- If we assume that all stars produce an observer equally, the probability of finding the small Λ as observed is small: $P(\Lambda<\Lambda_{obs}) \sim 2\%$

- What options do we have?
  - Forget the anthropic argument. Search other explanations for Λ.
  - Well, it is not surprising even if an event of 2% probability happened to us.
  - There are many effects affecting the number of observers (habitability) in the universe. Perhaps we may have missed some effects to change the Λ distribution?
    - Piran+'16 considered extinction of an observer by a GRB in nearby dwarf galaxies, which disfavors high galaxy number density → disfavoring low $\Lambda < \Lambda_{obs}$. Not useful to solve small $P(\Lambda<\Lambda_{obs})$, but useful to explain non-zero Λ if $dP_{pri}/d(\ln\Lambda)$ = const.
    - Here we consider extinction by a nearby supernova within a galaxy, disfavoring high stellar density → disfavoring large $\Lambda > \Lambda_{obs}$

$P(\Lambda < \Lambda_{obs})$ to small?

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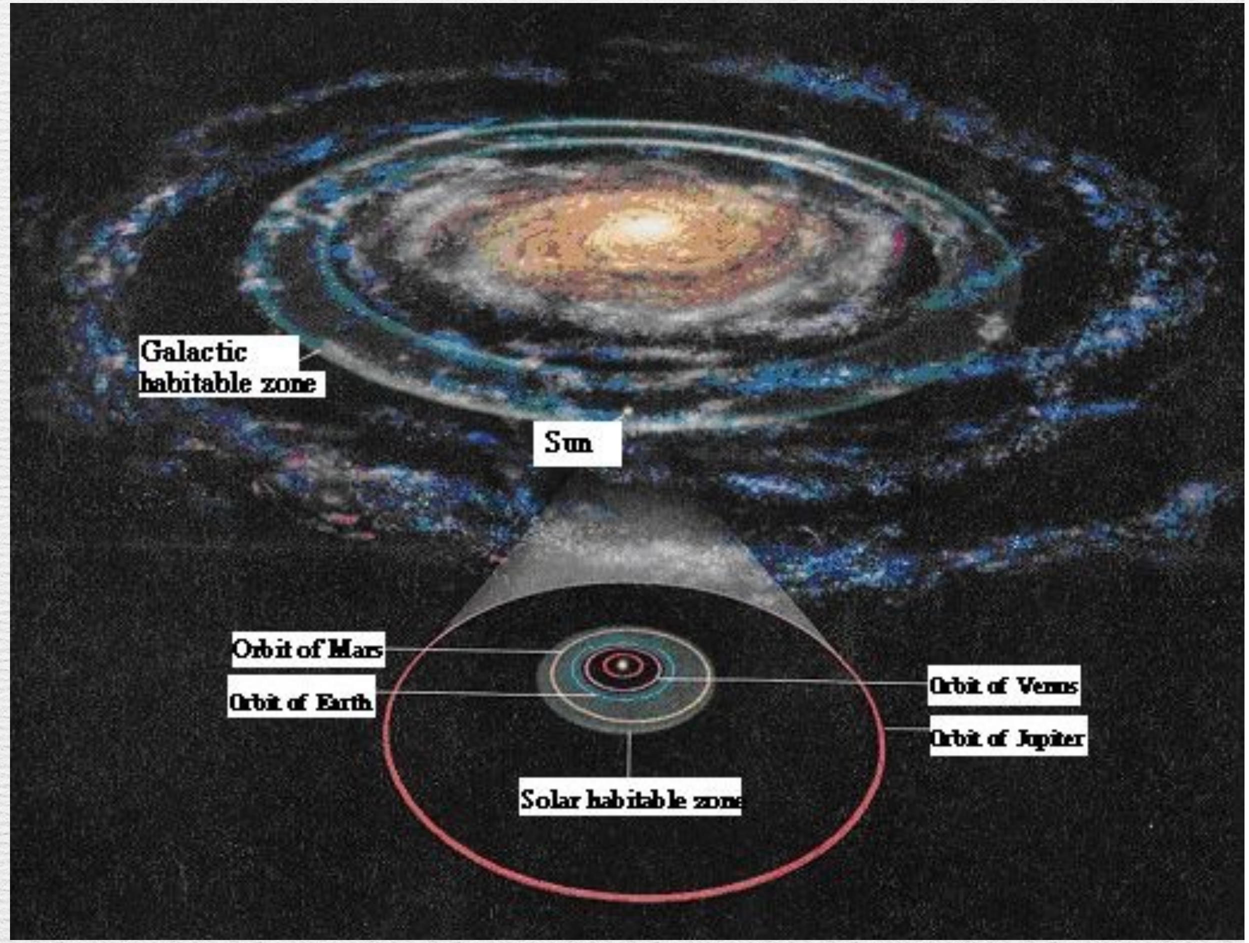
the Galactic habitable zone

- habitability depends on:
  - amount of stars
  - sufficient age for evolution of life
  - sufficient metal abundance for rocky planet formation
  - no hazardous supernovae / gamma-ray bursts
  - …

Gonzalez+'01; Lineweaver+'04; …



effect on life by a nearby supernova

Ruderman 74; Whitten+'76; Reid+'78; Gehrels+'03; …

- a supernova within ~10 pc would have a significant impact on the ozone layer of Earth
  - gamma-ray/cosmic-ray radiation produces free N atoms, subsequently producing nitrogen oxides (NOx) in the atmosphere
  - nitrogen oxides catalytically destroy ozones

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

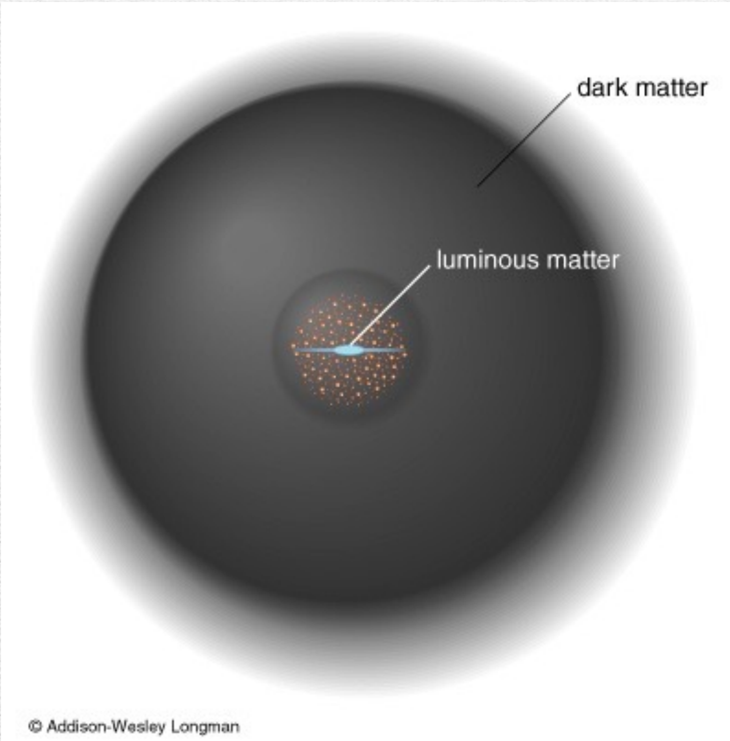
$$\text{net}: \quad O_3 + O \rightarrow O_2 + O_2 \,.$$

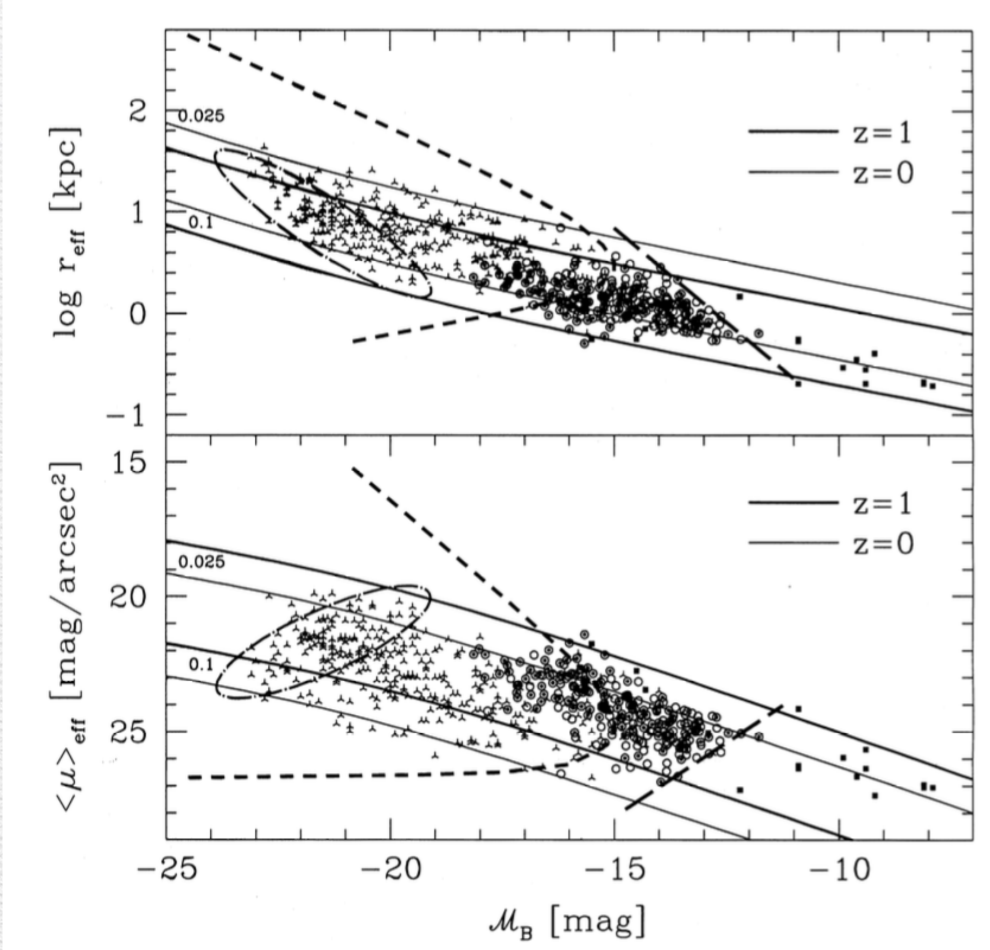
  - terrestrial life could be significantly damaged

- the number of SNe within 10 pc from the Sun?
  - about one in 0.5 Gyr (time after the complex terrestrial life emerged on Earth)
  - a coincidence! — we are living on the edge of habitable region about stellar density, implying that the supernova effect is actually working?

Stellar density in galaxy formation

- virial radius of dark halos is a good indicator of stellar disk radius of galaxies
  - $R_{disk} \sim \lambda R_{vir}$
  - halo spin parameter is roughly universal: $\lambda \sim 0.05$
    - $\lambda = JE^{1/2}/GM^{5/2} \sim J/(MR_{vir}V_{rot})$
  - so roughly we expect $\rho_{star} \propto \rho_{vir}$ (virial density of dark halo)

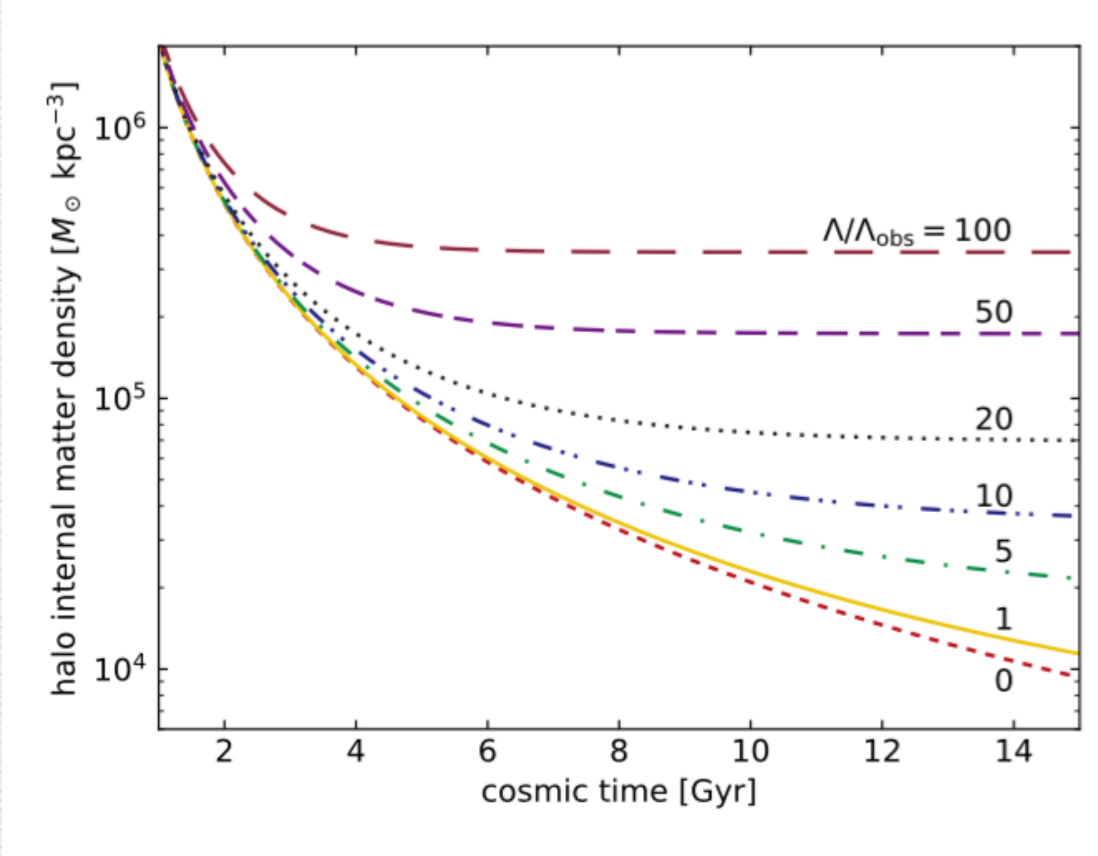




Mao+'98

halo density in structure formation

- the spherical collapse model predicts:
  - ρ_{vir} does not depend on M_{halo}
  - ρ_{vir} decreases with time when Λ effect is not significant
    - stars formed earlier should be located in higher density regions
  - after Λ becomes dominant,
    - ρ_{vir} becomes constant
    - halo formation rate rapidly drops by accelerated cosmic expansion



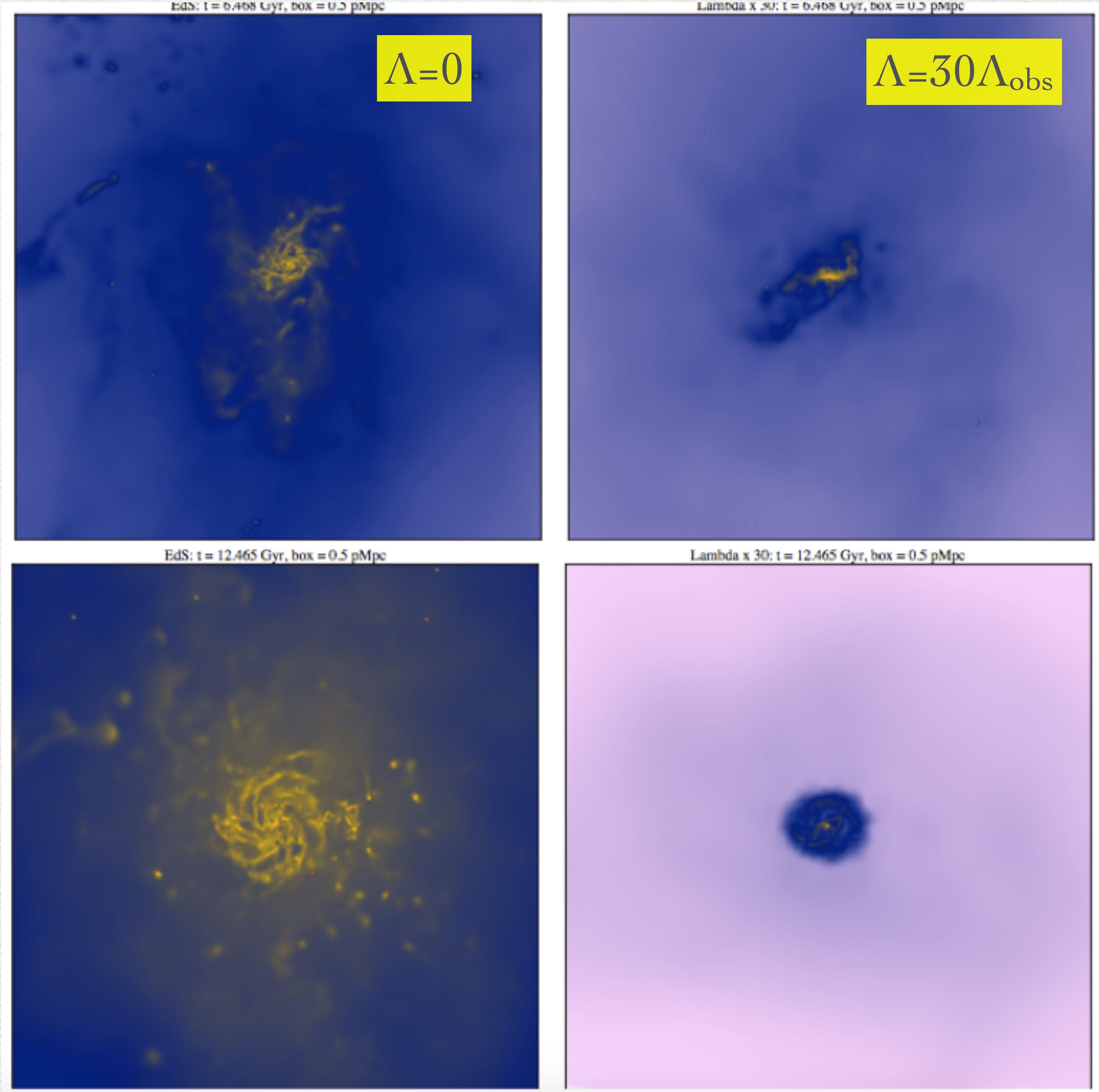
Totani+ '18

- If Λ/Λ_{obs} = 50, internal density of any halo is more than 10 times larger than the halo forming at ~10 Gyr in our universe.

galaxy formation simulation in high Λ universe

t=6.5 Gyr

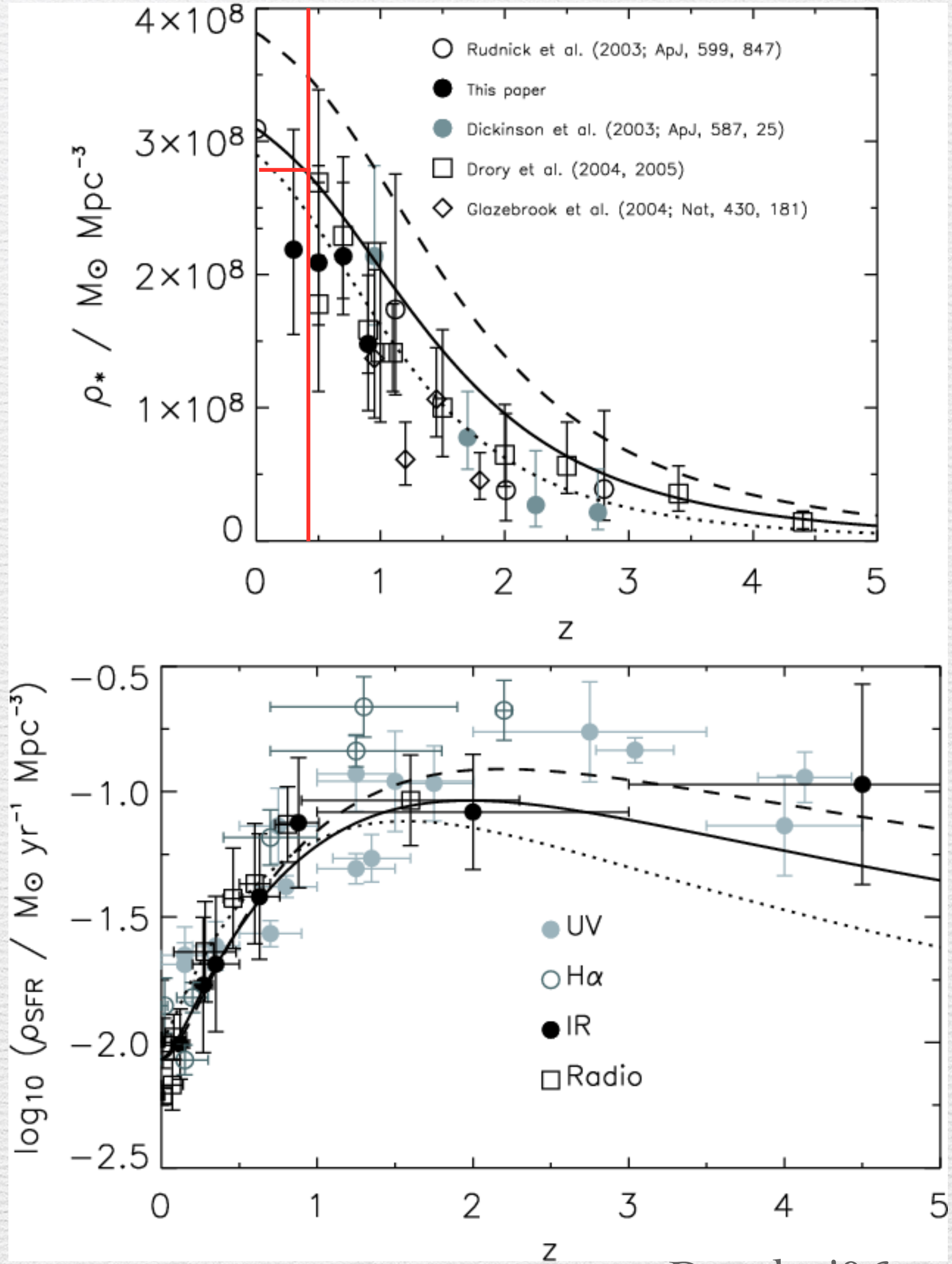
t=12.5 Gyr



Barnes+'18

the Sun in cosmic star formation history

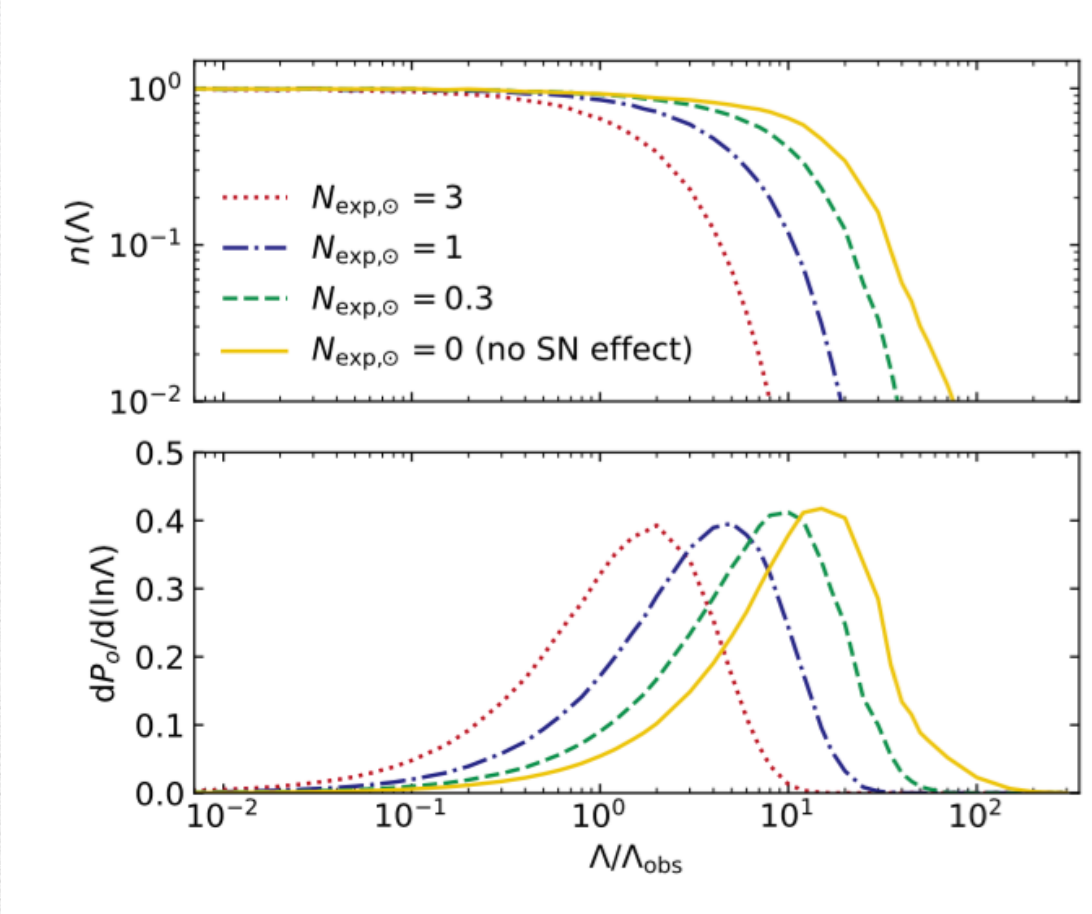
- the Sun formed 4.6 Gyr ago (z=0.44)
- 90% of all stars formed by now are older than the Sun
    - they are in higher density regions
    - they have more time for evolution of life
- We are living in the low tail end of stellar density distribution
    - implying that an observer avoids high stellar density regions?



Borch+'06

probability distribution of Λ with the nearby SN effect

- using the semi-analytic galaxy formation model of Sudoh+'17
- N_{exp}: the expected number of lethal supernova around a star during the time of evolution of life to an observer
    - assuming $N_{exp} \propto \rho_{star} \propto \rho_{vir}$
    - core-collapse SNe occur only in young stellar populations, but type Ia occurs also in old populations
    - life survival probability: $\exp(-N_{exp})$
- controlling model parameter: $N_{exp,\odot}$ (N_{exp} for the Sun)
- with $N_{exp,\odot}$ = 1 or 3,
    - distribution peaks at Λ/Λ_{obs} ~ 4 or 2
    - $P(\Lambda<\Lambda_{obs})$ increases to 19% and 41%



Totani+'18

Conclusions and Discussions

- extinction of an observer by a nearby supernova has an effect to make the expected Λ value smaller, which may be important for the anthropic argument
- similar effects by other phenomena than SNe to disfavor high stellar density?
  - comet bombardment by a field star passage?
  - wide binary system affected by the Galactic potential?
  - gamma-ray bursts?
    - much brighter but less frequent than SNe, critical distance comparable to a galaxy size
    - long GRBs only in young stellar populations, short GRBs much less energetic
      - our scenario requires lethal events in old stellar populations as well
    - low metallicity preference of long GRBs → not important in high density regions?
- Prediction?
  - Stellar density around Sun is close to the critical value, beyond which terrestrial life do not exist
  - Future exoplanet studies would find less probability of biomarker detection in regions of higher stellar density than the solar neighborhood