DARK ENERGY MODELS AND ANTHROPIC SELECTION.

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COSMOLOGICAL CONSTANT PROBLEMS:

- WHY IS ρ_v NOT HUGE?
- WHY IS $z_v \sim z_G \sim 1$?

(z_v: VACUUM DOMINATION; z_G: GALAXY FORMATION)

ANTHROPIC SELECTION IS THE ONLY APPROACH THAT ADDRESSES BOTH PROBLEMS.

COMPLAINTS:
- UNPREDICTIVE
- ROBS US OF CHALLENGES

THIS TALK:

- ANTHROPIC MODELS FOR ρ_v
- EXTRACTING QUANTITATIVE PREDICTIONS
- THE IMPORTANCE OF $\mathcal{P}_{prior}$
- ANTHROPIC PREDICTIONS FOR m_ν
- CHALLENGES FOR FUNDAMENTAL PHYSICS.

ANTHROPIC BOUND ON ρ_v:

Weinberg 87
Linde 86
Barrow +Tipler 86

SUPPOSE ρ_v TAKES DIFFERENT VALUES IN DIFFERENT PARTS OF THE UNIVERSE.

STRUCTURE FORMATION STOPS AT $z \sim z_v$.

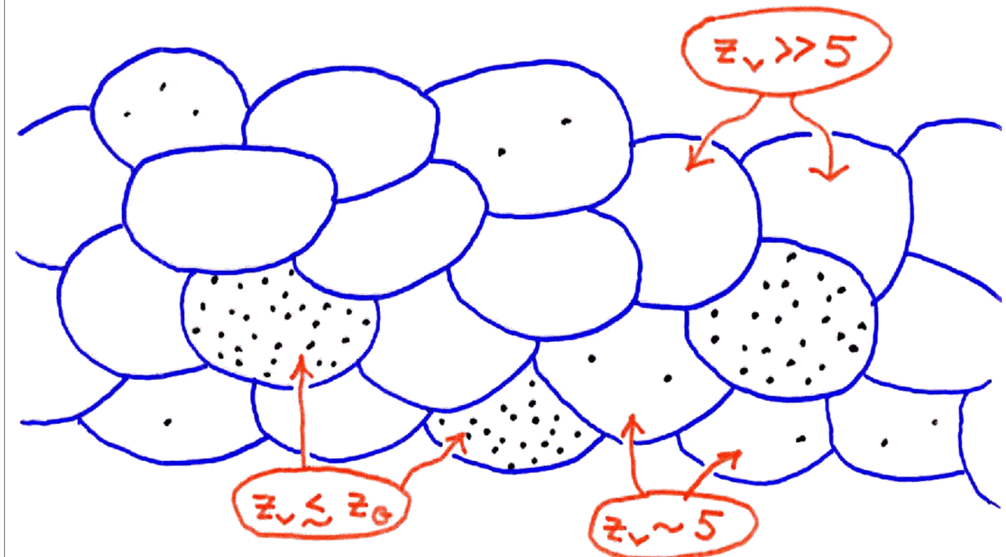
$\Rightarrow$ NO GALAXIES IN REGIONS WHERE $z_v \gtrsim 5$.

$\Rightarrow$ $\rho_v = (1+z_v)^3 \rho_m \lesssim 200\, \rho_m$. ANTHROPIC RANGE

"ANTHROPIC PRINCIPLE":

THEREFORE, VALUES OF $\rho_v > 200\, \rho_m$ ARE NOT GOING TO BE OBSERVED.

(TRIVIALLY TRUE).



MOST GALAXIES ARE IN REGIONS WHERE $z_v \lesssim z_G$.

SOLVES THE COINCIDENCE PROBLEM

GIANT GALAXIES FORM AT $z_G \sim 1$.

$$\Rightarrow \rho_v = (1+z_v)^3 \rho_m \lesssim 8\, \rho_m$$

A.V. 95
Efstathiou 95

OBSERVED: $\rho_v \sim (2-3)\, \rho_m$.

SIMILAR BOUND FOR $\rho_v < 0$.

Kallosh + Linde 03

PROBABILITY DISTRIBUTION FOR ρ_v.

$\mathcal{P}(\rho_v)\,d\rho_v \propto$ # OF OBSERVERS WHO WILL MEASURE ρ_v IN THE INTERVAL $d\rho_v$.

$$\mathcal{P}(\rho_v)\,d\rho_v = n_{obs}(\rho_v)\,\mathcal{P}_{prior}(\rho_v)\,d\rho_v$$

$n_{obs}(\rho_v)$: # OF OBSERVERS PER UNIT VOLUME

$\mathcal{P}_{prior}(\rho_v)$: FRACTION OF VOLUME

A.V. 95

$n_{obs}(\rho_v) \propto$ FRACTION OF MATTER IN GIANT GALAXIES $(M \sim 10^{12} M_\odot)$ $- f(\rho_v)$.

$\mathcal{P}_{prior}(\rho_v)$ – FROM INFLATION.

IN A WIDE CLASS OF MODELS,

$$\mathcal{P}_{prior}(\rho_v) \approx \text{const}$$

Weinberg 96

IN THE ANTHROPIC RANGE.

$$\Rightarrow \mathcal{P}(\rho_v) \propto f(\rho_v).$$

CALCULATION OF $f(\rho_v)$ IS A STANDARD ASTROPHYSICAL PROBLEM.

Press+Schechter 74, Martel, Shapiro +Weinberg 98, Efstathiou 95.

$$\mathcal{P}(\rho_v) \propto \text{erfc}\left[0.8\left(\frac{\rho_v}{\rho_m\sigma^3}\right)^{1/3}\right]$$

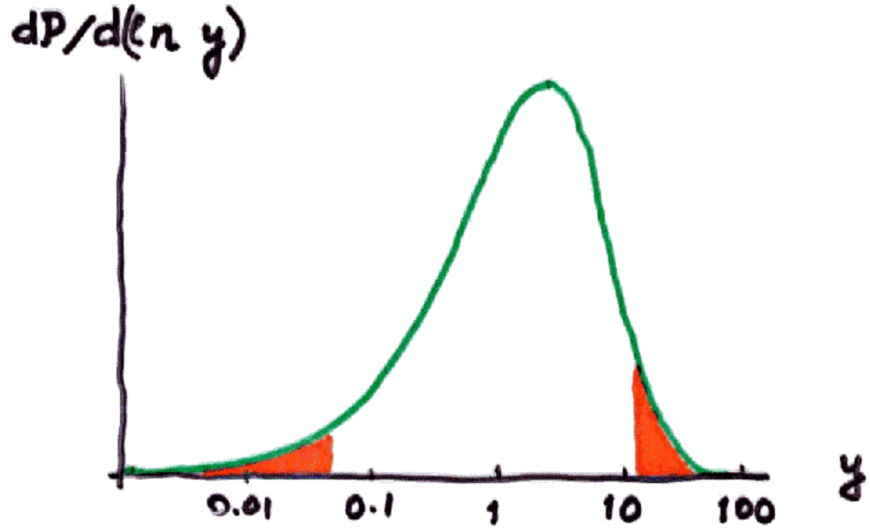
$\sigma = \delta\rho/\rho$ ON GALACTIC SCALE.

$\rho_m\sigma^3 \approx \text{const}$ DURING MATTER ERA.

NO NEW "PRINCIPLE":
JUST ACCOUNTING FOR
OBSERVATIONAL SELECTION
EFFECTS.

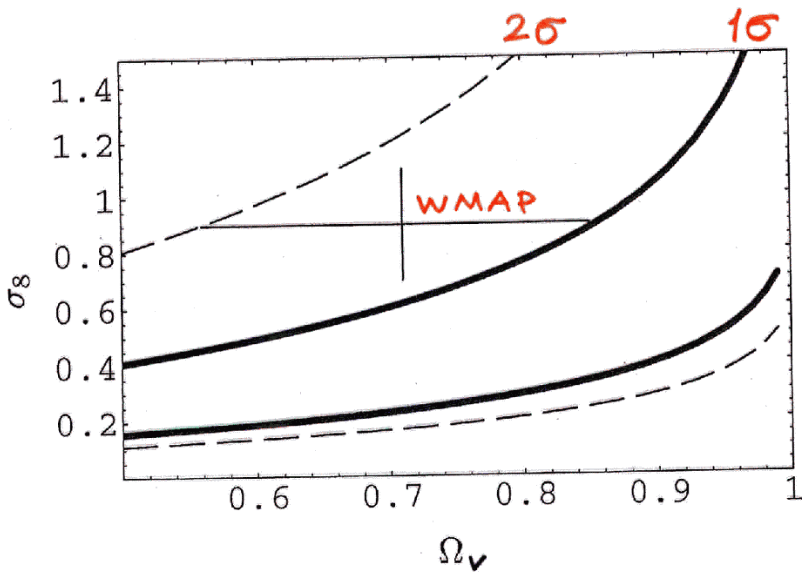
"PRINCIPLE OF MEDIOCRITY":
WE SHOULD BE IN THE 2σ
RANGE OF THE DISTRIBUTION.

$$y = \frac{\rho_v}{\rho_m \sigma^3}$$



MEDIOCRITY: $0.043 < y < 16.$

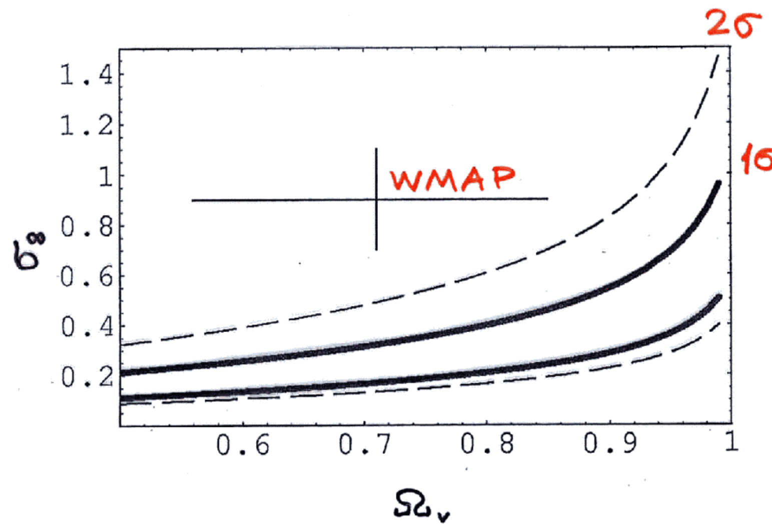
GARRIGA + A.V. (2003)
GARRIGA, LINDE + A.V. (2003)



$\mathcal{P}_{prior} = const$

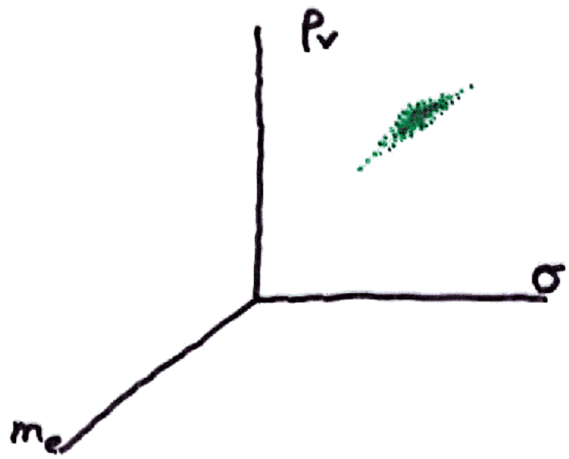
$h = 0.72, \ \Omega_b = 0.47$

$n = 0.99, \quad w = -1.$



$\mathcal{P}_{prior}(\rho_v) \propto \rho_v.$

WHAT IF OTHER PARAMETERS VARY ?



- NO MODEL
  — NO PREDICTIONS.
- NEED BETTER MODELS FOR n_{obs}.
- FOCUS ON PARAMETERS THAT DO NOT DIRECTLY AFFECT LIFE PROCESSES:

  ρ_v, σ, m_ν, ρ_B/ρ_{CDM}, etc.

ANTHROPIC APPROACH NATURALLY RESOLVES BOTH CCPs.

BUT IT REQUIRES:

- A PARTICLE PHYSICS MODEL WITH A VARIABLE ρ_v.
- A COSMOLOGICAL MODEL FOR THE CALCULATION OF $\mathcal{P}_{prior}$.

  [NEED $\mathcal{P}_{prior}(\rho_v) \sim const.$]

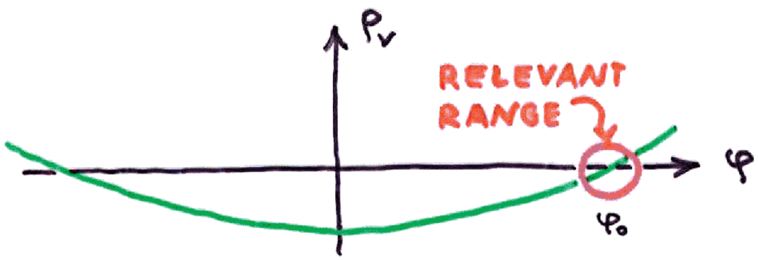
SCALAR FIELD MODELS

Banks 85
Linde 86
Garriga + A.V. 00.

$\rho_V = \rho_\Lambda + V(\varphi)$

A SIMPLE EXAMPLE: $V(\varphi) = \frac{1}{2} m^2 \varphi^2$,

$\rho_\Lambda < 0$.



$V(\varphi)$ IS VERY FLAT ⇒ SLOW ROLL:

$M_P V' \ll \rho_V \sim \rho_m \Rightarrow m \lesssim 10^{-90} M_P$.

$\varphi_0 \sim |\rho_\Lambda|/m \gtrsim 10^{60} M_P$.

VOLUME DISTRIBUTION $\mathcal{P}_{prior}(\varphi)$

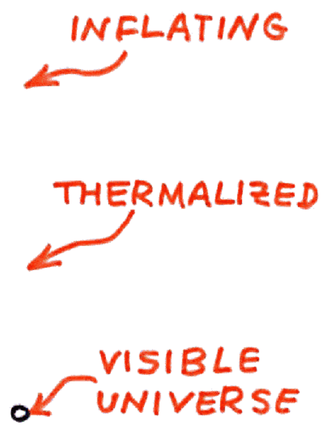
— FROM THEORY OF INFLATION.

$$\mathcal{P}_{prior}(\rho_V) = \frac{\mathcal{P}_{prior}(\varphi)}{V'(\varphi)}$$

⇒ NEED $\mathcal{P}_{prior}(\varphi) \simeq const.$

ETERNAL INFLATION

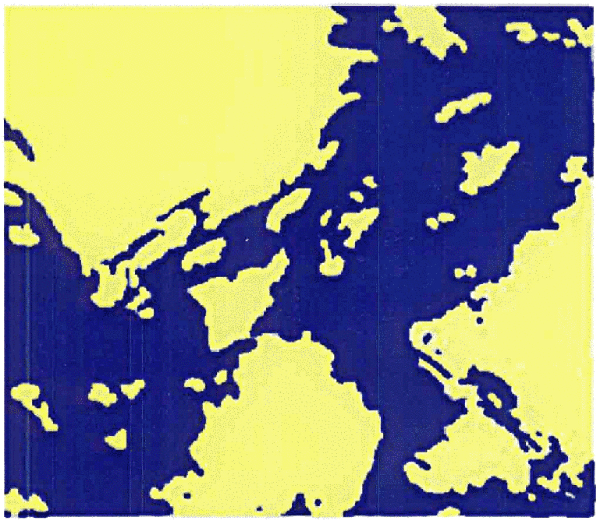
AV 83
Linde 86



φ IS RANDOMIZED BY QUANTUM FLUCTUATIONS ⇒ ρ_V TAKES ALL POSSIBLE VALUES IN EACH THERMALIZED REGION.

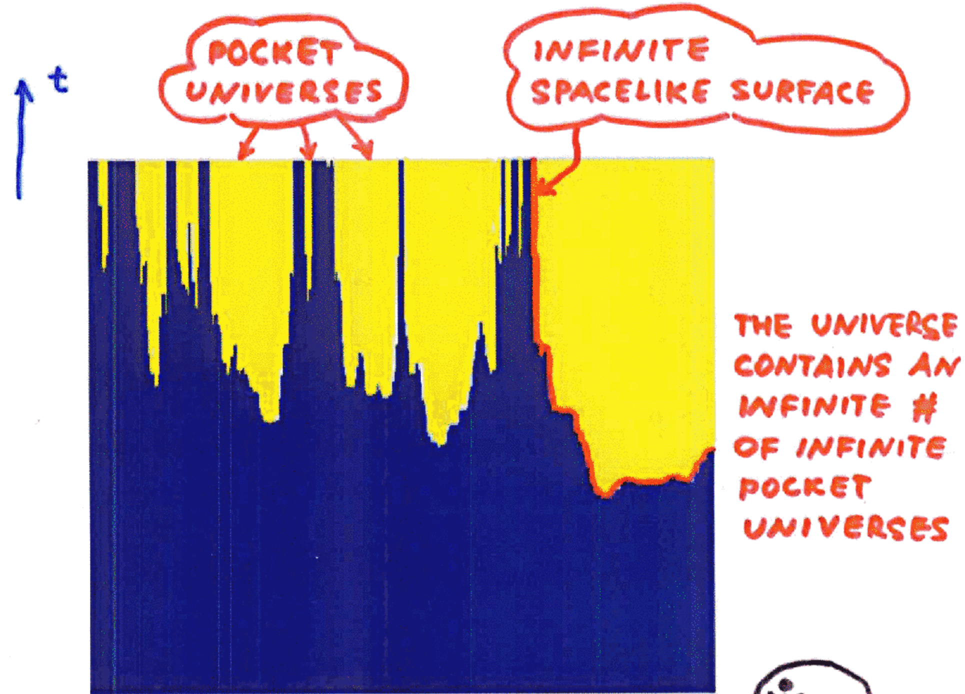
- $\mathcal{P}_{prior}(\rho_V)$ CAN BE CALCULATED. AV 98

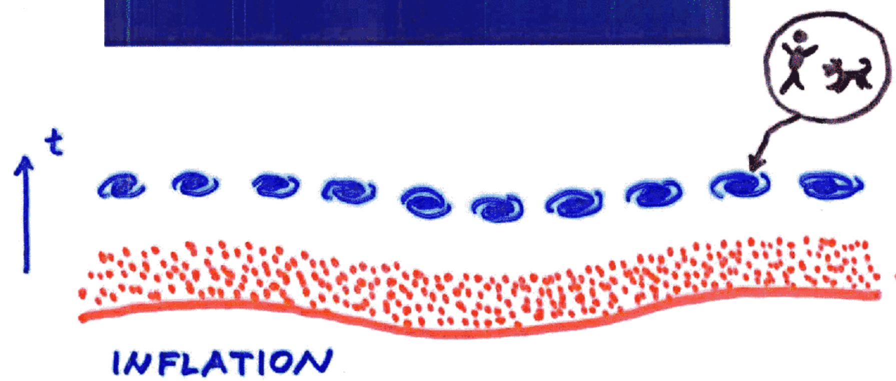
$\mathcal{P}_{prior}(\rho_V) \approx const$ IF $10^{-137} \lesssim \frac{m}{M_P} \lesssim 10^{-90}$.



SPACETIME STRUCTURE

(EXPANSION OF THE UNIVERSE IS FACTORED OUT)





4-FORM MODELS

$$F^{\mu\nu\sigma\tau} = F\epsilon^{\mu\nu\sigma\tau},$$

$$\partial_\mu F = 0,$$

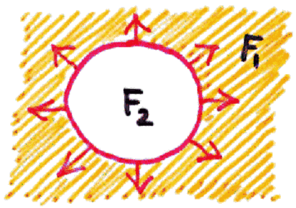
$$\rho_v = -\Lambda + \frac{1}{2}F^2.$$

Brown + Teitelboim 88
Bousso + Polchinski 00
Donoghue 00
Banks, Dine + Motl 00
Feng, March-Russell, Sethi + Wilczek 00
Garriga + AV 01

BUBBLE NUCLEATION:

$\Delta F = q$ ← 'CHARGE'

$$\Delta\rho_v = F\Delta F \approx (2\Lambda)^{1/2} q$$



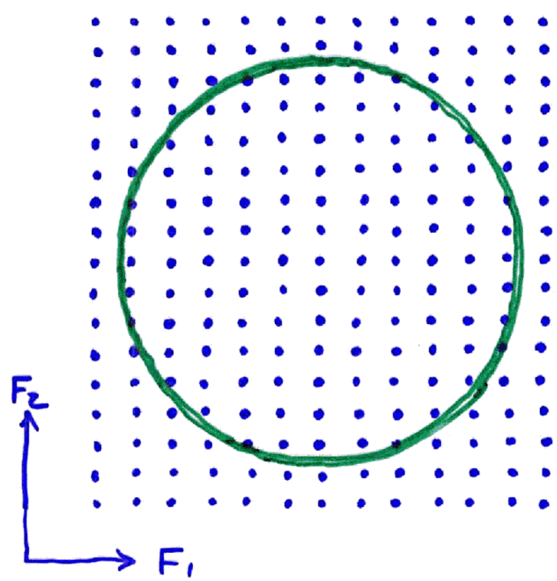
BUBBLE NUCLEATION DURING INFLATION

⇒ F IS RANDOMIZED.

$$\Delta\rho_v \lesssim \rho_m \Rightarrow q \lesssim 10^{-90} M_P^2.$$

$\mathcal{P}_{prior} \approx$ const FOR A WIDE RANGE OF PARAMETERS.

BOUSSO + POLCHINSKY (2000)

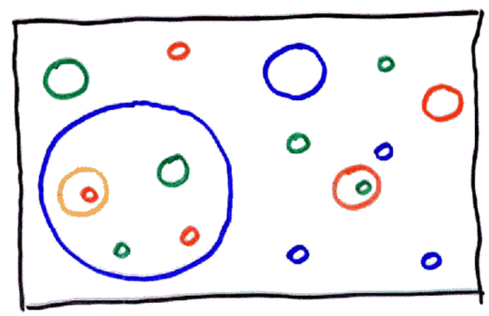


$N \gg 1$ FLUXES

⇒ DENSE SPECTRUM FOR ρ_v.

BUT: NEARBY VALUES OF ρ_v CORRESPOND TO VERY DIFFERENT F_i

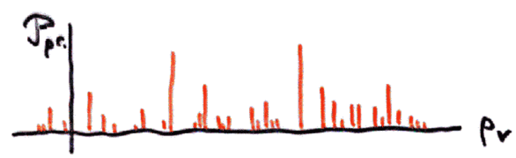
⇒ DIFFERENT $\mathcal{P}_{prior}$.



DIFFERENT F_i IN DIFFERENT BUBBLES.

EACH BUBBLE — AN INFINITE OPEN UNIVERSE.

NOT CLEAR HOW TO CALCULATE $\mathcal{P}_{prior}$.



SMALL BRANE CHARGES FROM SYMMETRY BREAKING

$a \;|\; a+2\pi$

$F \;|\; F+q$

a – pseudo-Goldstone

$$F_{\mu\nu\sigma\tau} = \epsilon_{\mu\nu\sigma\tau} F$$

MIXING: $\kappa a F$

$$\Rightarrow \Delta F \equiv q = 2\pi\kappa$$

$$m_a = \kappa/\eta_a$$

q CAN BE SUPPRESSED BY A SYMMETRY:

$$\Phi \to e^{i\pi/N}\Phi, \quad a \to -a.$$

$$\Rightarrow \frac{\langle\Phi\rangle^N}{M_p^N} a F$$

$$\Rightarrow q \propto \frac{\langle\Phi\rangle^N}{M_p^N}.$$

(CAN BE EMBEDDED INTO AN EXTENSION OF THE STANDARD MODEL.)

CHALLENGE TO FUNDAMENTAL THEORY:

EXPLAINING THE SMALL PARAMETERS m, q.

- LARGE SCALAR FIELD RENORMALIZATION

$$L = \frac{1}{2} Z (\partial_\mu \varphi)^2 - V(\varphi), \quad Z \gg 1.$$

Weinberg 01, Donoghue 01, Dimopoulos + Thomas 03.

- MIXING OF A 4-FORM WITH A (PSEUDO) GOLDSTONE, $F \cdot a$.

m OR q SUPPRESSED BY A SPONT. BROKEN DISCRETE SYMMETRY. Dvali + A.V. 01.

NEXT SUPERSTRING REVOLUTION?

MODELS WITH SEVERAL SCALAR FIELDS

BOTH $\rho_v = V(\varphi_a)$ AND $s = \left|\frac{\partial V}{\partial \varphi_a}\right|$ ARE VARIABLE.

$\Rightarrow \mathcal{P}_{prior}(\rho_v, s)$.

IF $\mathcal{P}_{prior}$ FAVORS SMALL s,

$w \equiv P_v/\rho_v \approx -1$.

Garriga + AV 03
Dimopoulos + Thomas 03

IF IT FAVORS LARGE s, THE SLOW ROLL CONDITION IS ONLY MARGINALLY SATISFIED

$\Rightarrow$ RECOLLAPSE ON A TIMESCALE

$t \sim t_0$.

$\Rightarrow$ OBSERVATIONAL PREDICTIONS

Dimopoulos + Thomas 03
Kallosh, Kratochvil, Linde, Linder + Shmakova 03

BOTH TYPES OF MODELS CAN BE CONSTRUCTED.

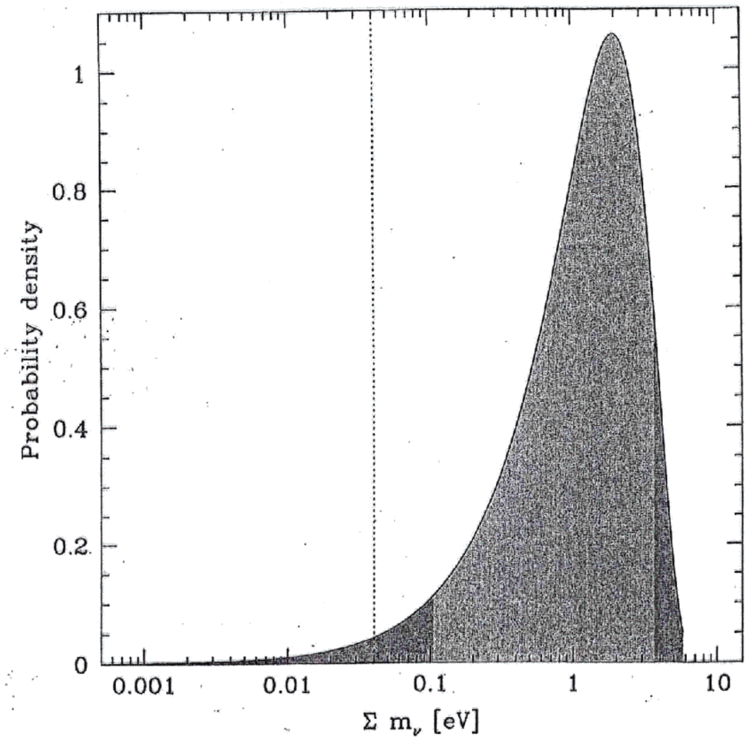
Garriga, Linde + AV 03.

PREDICTIONS FOR NEUTRINO MASSES

$$m_\nu \equiv \sum_{i=1}^{3} m_\nu^{(i)}, \qquad \Omega_\nu = \left(\frac{m_\nu}{94\,eV}\right) h^{-2}.$$

SUPPOSE m_ν IS A STOCHASTIC VARIABLE WITH $\mathcal{P}_{prior}(m_\nu) \approx$ const.

$$\mathcal{P}(m_\nu) \propto f(m_\nu) \approx f^{(0)} \exp\left(-4\frac{\Omega_\nu}{\Omega_m}\right).$$



PREDICTIONS: Tegmark + A.V.

$0.1\,eV < \Sigma m_\nu < 4\,eV$ (90% c.l.)

Allen et.al.: (2003) $\Sigma m_\nu = 0.64^{+0.40}_{-0.28}$ eV.

[ν OSCILLATIONS: $\Sigma m_\nu \gtrsim 0.04\,eV$.]

CONCLUSIONS

ANTHROPIC APPROACH:

- NATURALLY RESOLVES BOTH CCPs.
- PREDICTIONS FOR ρ_v IN GOOD AGREEMENT WITH OBSERVATION — ASSUMING A FLAT $\mathcal{P}_{prior}$.
- SCALAR FIELD AND BRANE NUCLEATION MODELS GIVE A FLAT PRIOR, BUT THE CHALLENGE IS TO EXPLAIN THE SMALL m OR q.
- IN BP-TYPE MODELS, WE HAVE TO FIGURE OUT HOW TO CALCULATE $\mathcal{P}_{prior}$.
- ANTHROPIC APPROACH OPENS A WINDOW TO SUPER-LARGE SCALES BEYOND THE VISIBLE UNIVERSE.