IPMU
November 2008

Predictions from the Multiverse

Lawrence Hall
University of California
Berkeley

Where are we?

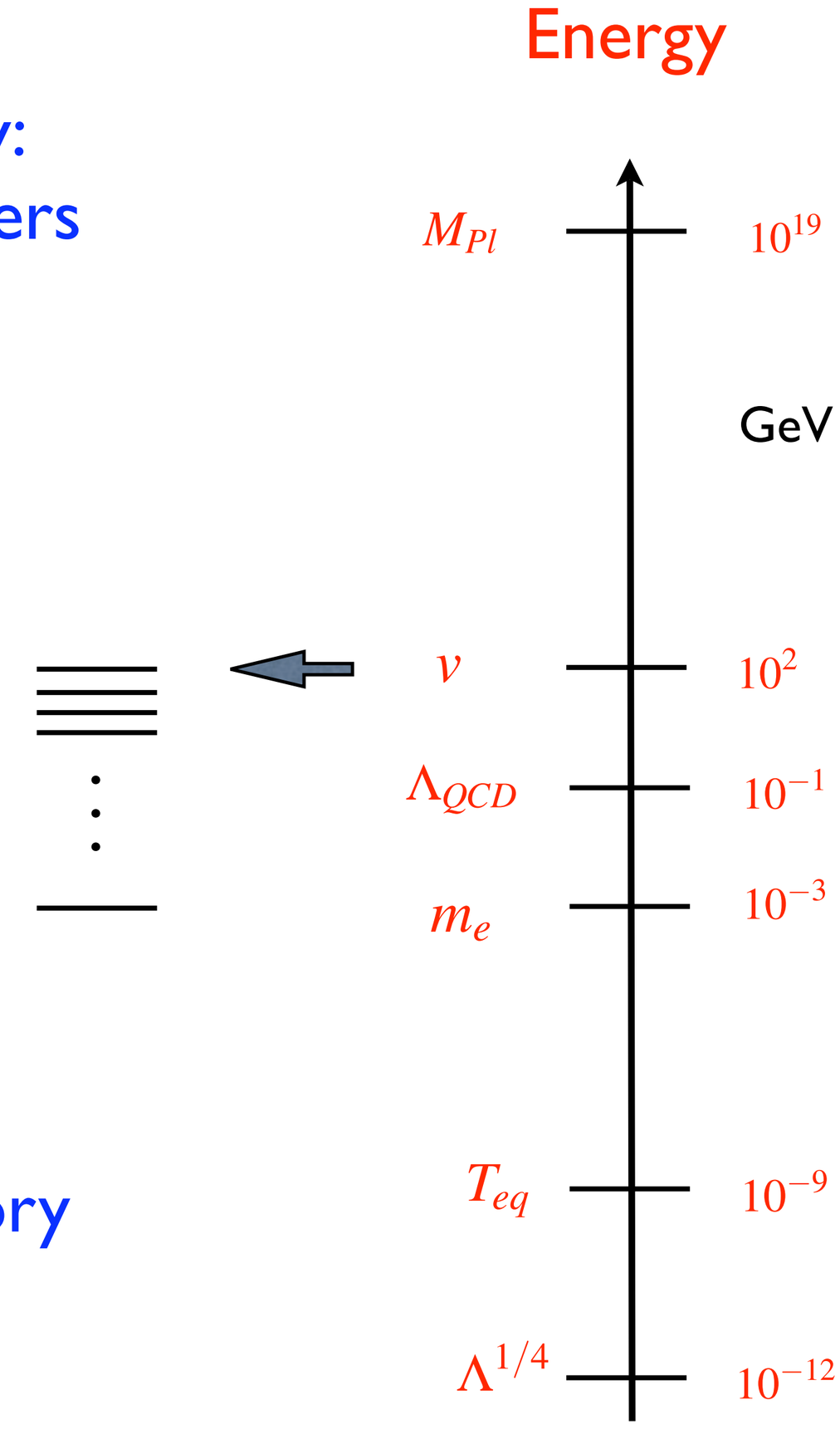
- Particle Physics and Cosmology:
  Standard Model with 30 parameters

- Why this theory?
  Why these numerical values?

- The conventional argument:

  Eventually all determined by
  symmetries of the unique theory

  I'm not so sure!!



- Why this theory?
  Why these numerical values?

The Anthropic Principle of Old

"The Laws of Physics take their form
because they must allow us,
the observer of these laws,
to exist."

This is giving up!

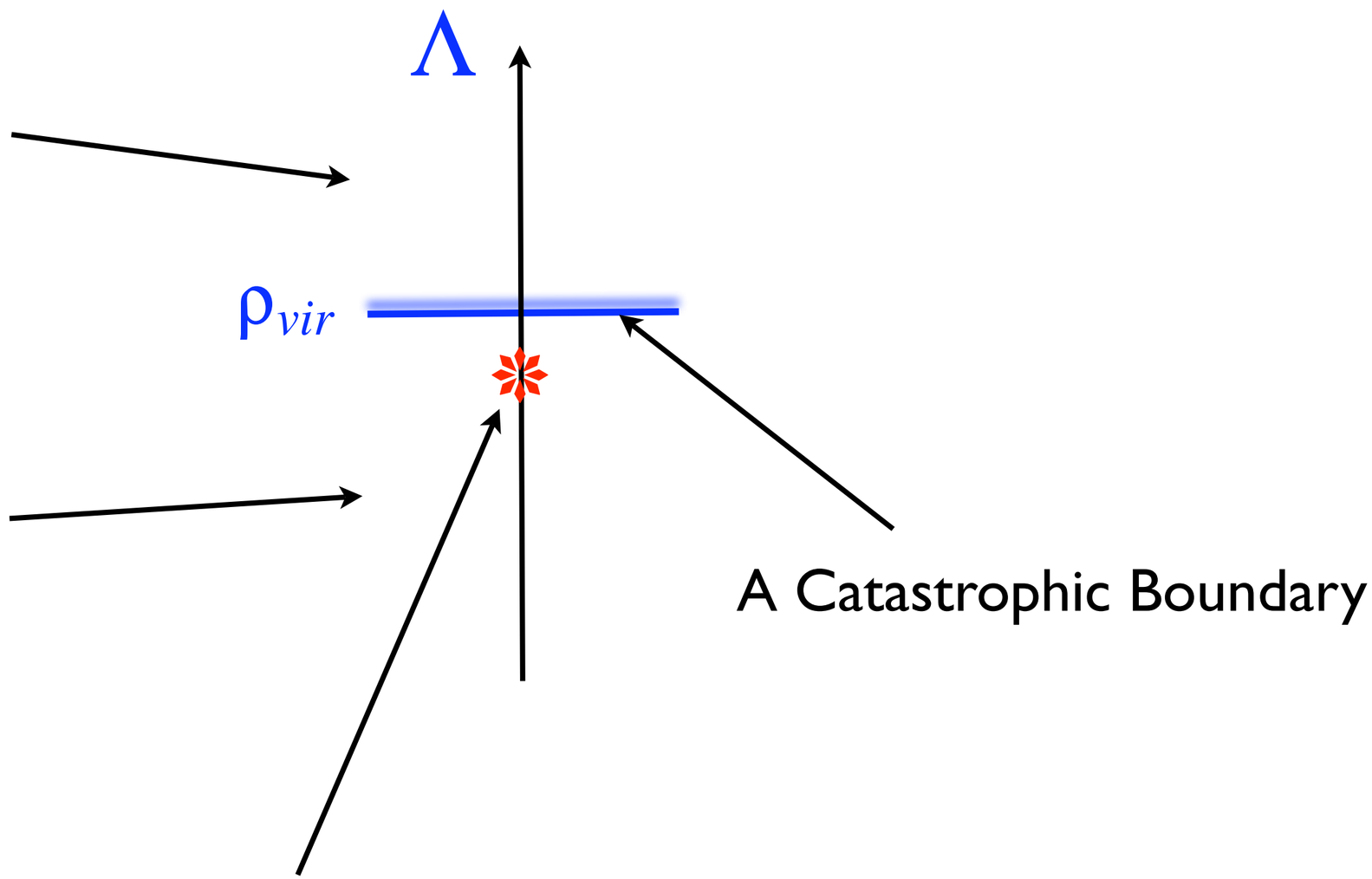
The Cosmological Constant

Weinberg PRL 1987:

Why so small? An anthropic argument:

Universe becomes a structureless, dilute, inflating gas

Galaxies, and therefore observers, are able to form



Martell, Shapiro, Weinberg astro-ph/9701099:

Predicted Dark Energy

Need Theory of a Multiverse!

A Preview of Results

Successful Prediction	Level of accuracy
$v = N_1 \ \Lambda_{QCD}^{3/4} M_{Pl}^{1/4}$	2
$m_e = N_2 \ \alpha \Lambda_{QCD}$	2
$T_{eq} = N_3 \ \frac{m_e^{1/4} \Lambda_{QCD}^{5/4}}{\alpha M_{Pl}^{1/2}}$	100
$\Lambda^{1/4} = N_4 \frac{m_e \Lambda_{QCD}^{1/2}}{\alpha M_{Pl}^{1/2}}$	3

$$N_4^4 = \frac{3^6 \pi c f_{rad}^2}{2^7 f_\rho^2 K^2 f_b^2}$$

Also $m_u, m_d; m_t, m_H;\ Q_0, M_{gal}$

Outline

I. Predictions from the Multiverse

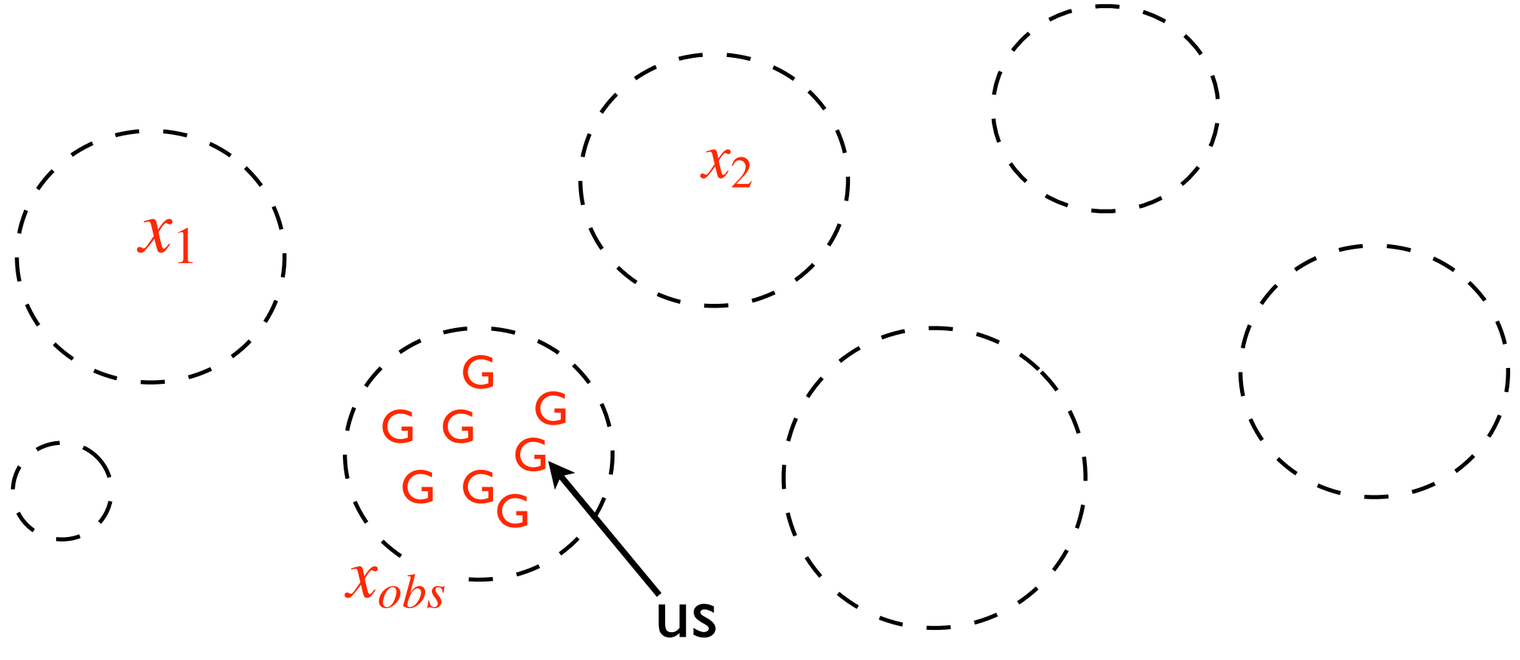
II. The Higgs Boson Mass

III. Nuclear Physics and the Weak Scale

IV. Cosmological Coincidences

1. Predictions from The Multiverse

- Many universes



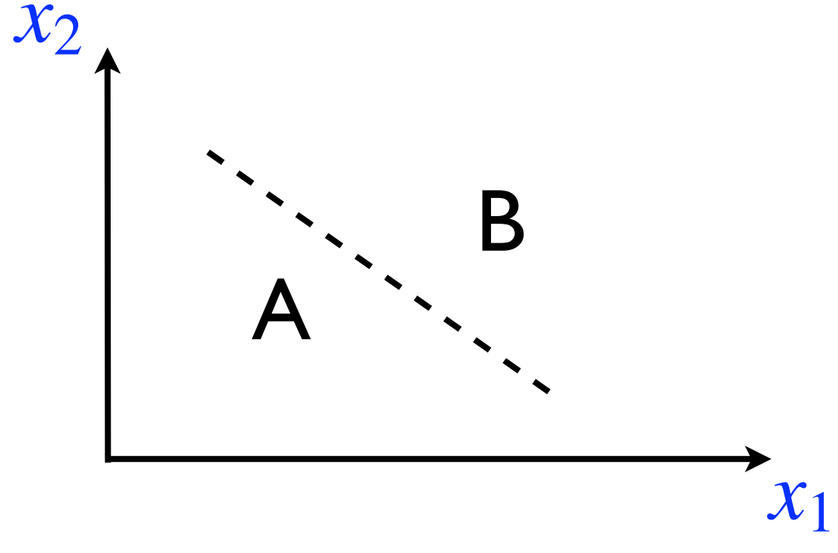
- x Parameters of low energy field theory;
  or important physical quantities, eg T_{eq}

- Environmental selection

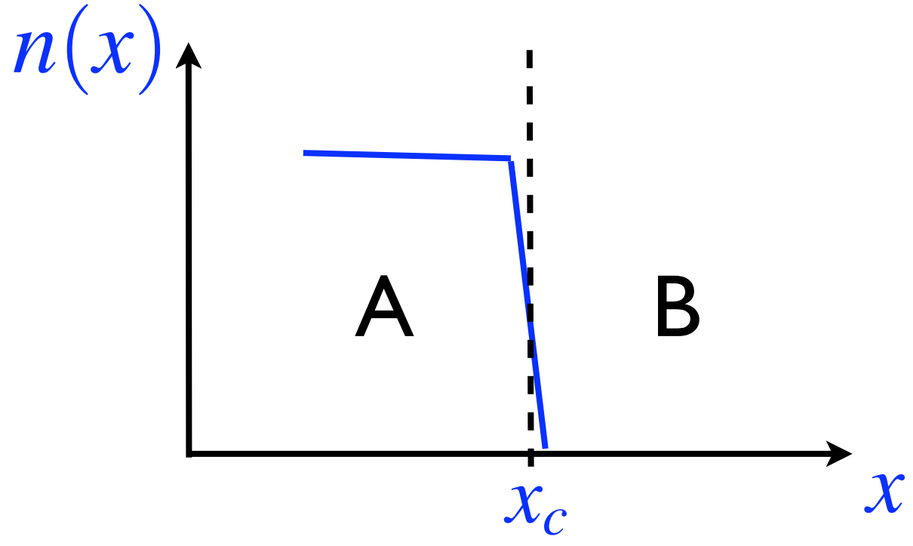
$$dN_{obs} = \tilde{f}(x)\, n(x)\, d\ln x = f(x)\, d\ln x$$

Catastrophic Boundaries

- In many situations there are catastrophic boundaries -- physics makes a sudden transition

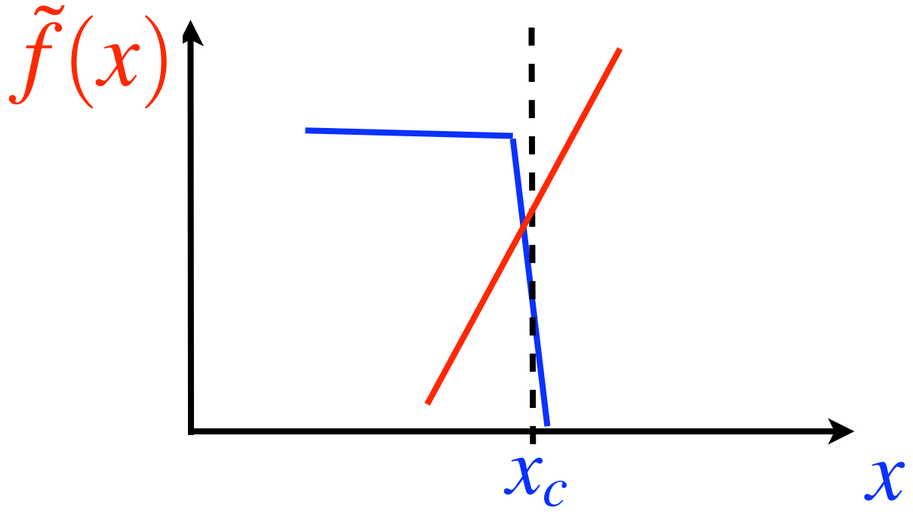


- This regime change induces a sudden change in $n(x)$



- The crucial assumption:

$\tilde{f}(x)$ is peaked towards the boundary



→ Most observers near boundary

A Comparison

- Symmetries

symmetries restrict the parameter space.

Assumptions:

symmetries, representations, symmetry breaking

- Multiverse

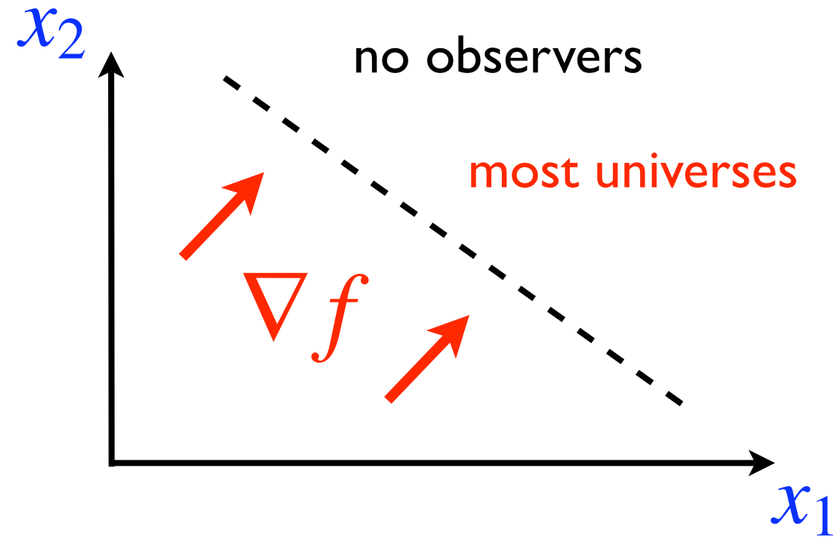
physics of catastrophic boundaries:

eg nuclear stability, formation of galaxies.

Assumptions:

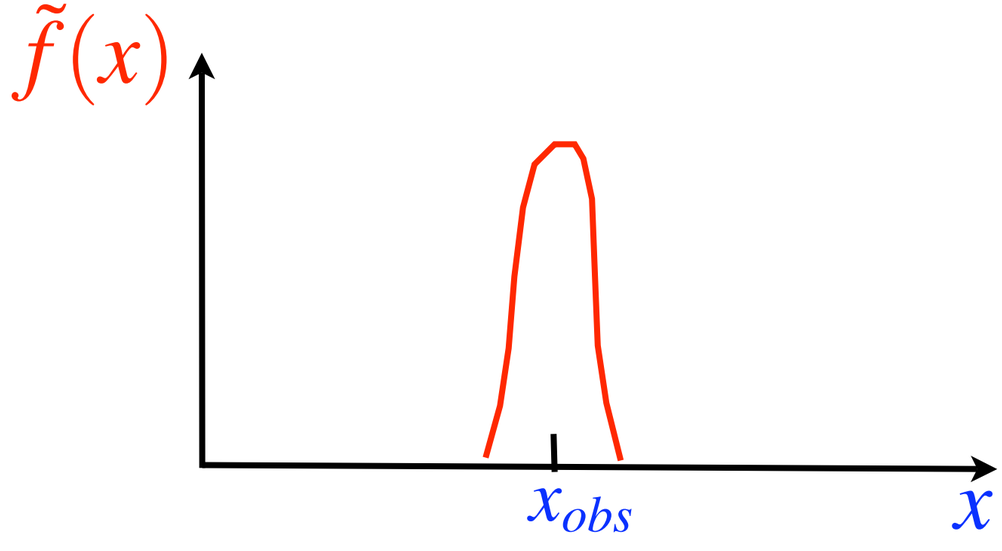
a multiverse force towards the boundary

catastrophic nature of boundary

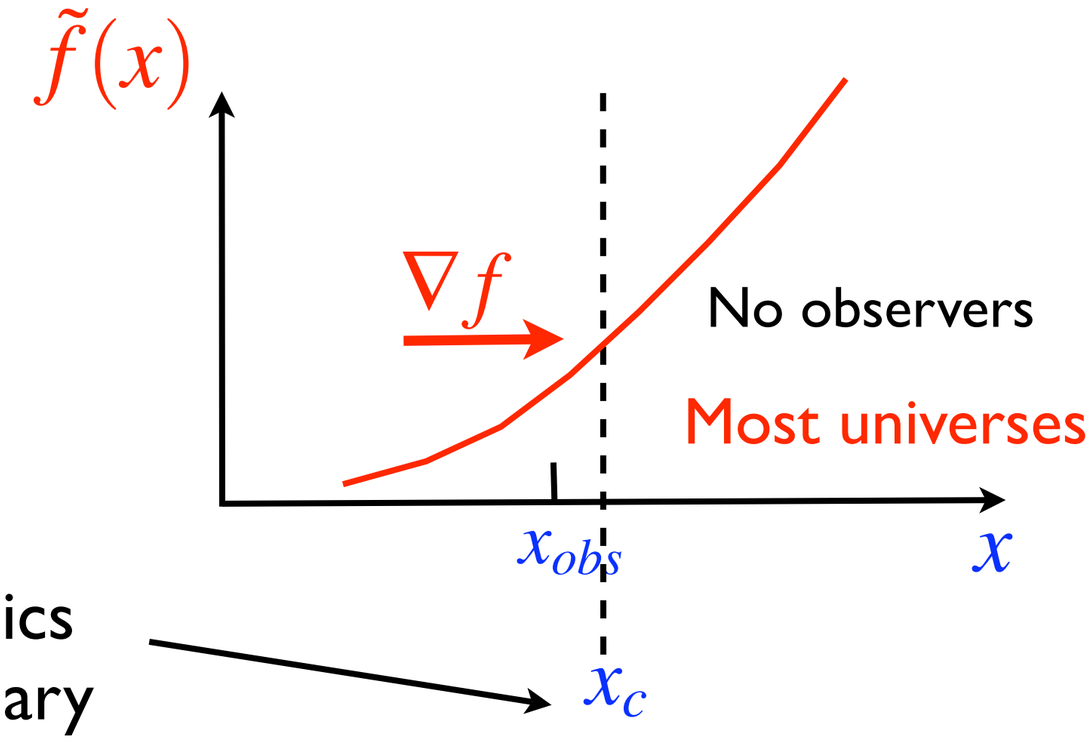


Fake and Real Predictions

- A fake prediction:



- A real prediction:

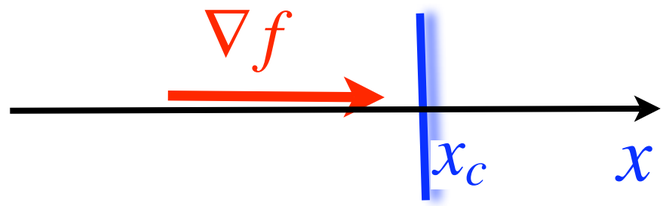


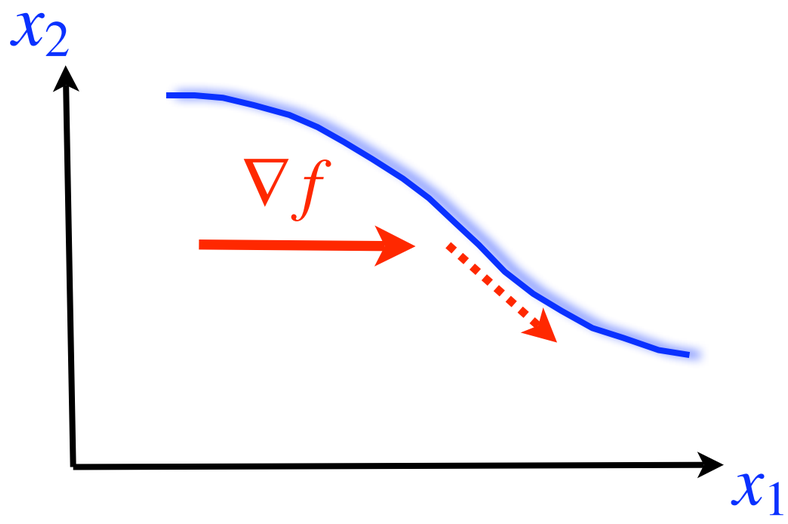
Calculated from the physics
of the catastrophic boundary

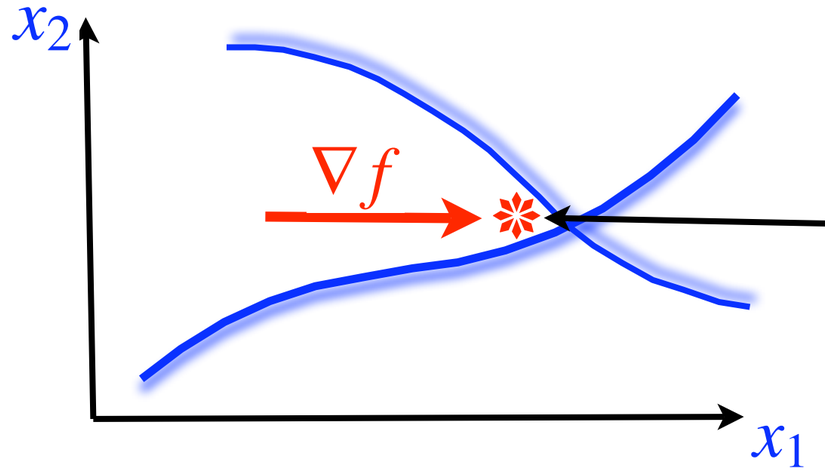
- Assume ∇f sufficiently large

"Tip of the Cone"

N_b \ N_x	1	2	n
1	1 prediction	1 prediction, 1 runaway	
2		2 predictions	
n			n predictions





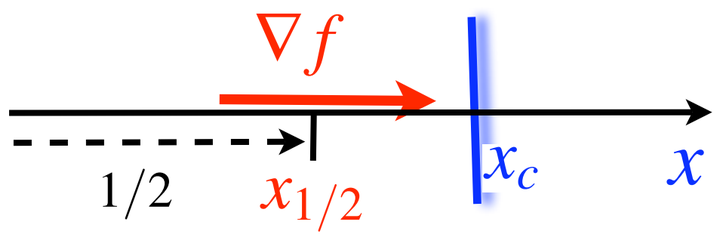


Tip of the Cone

How close to the Boundary?

- Define f(x): $dN_{obs} = f(x)\, d\ln x$ Define force: $F = \nabla f = \dfrac{\partial \ln f}{\partial \ln x}$

- Power law: $f \propto x^p$ Gives: $F = p$

- 

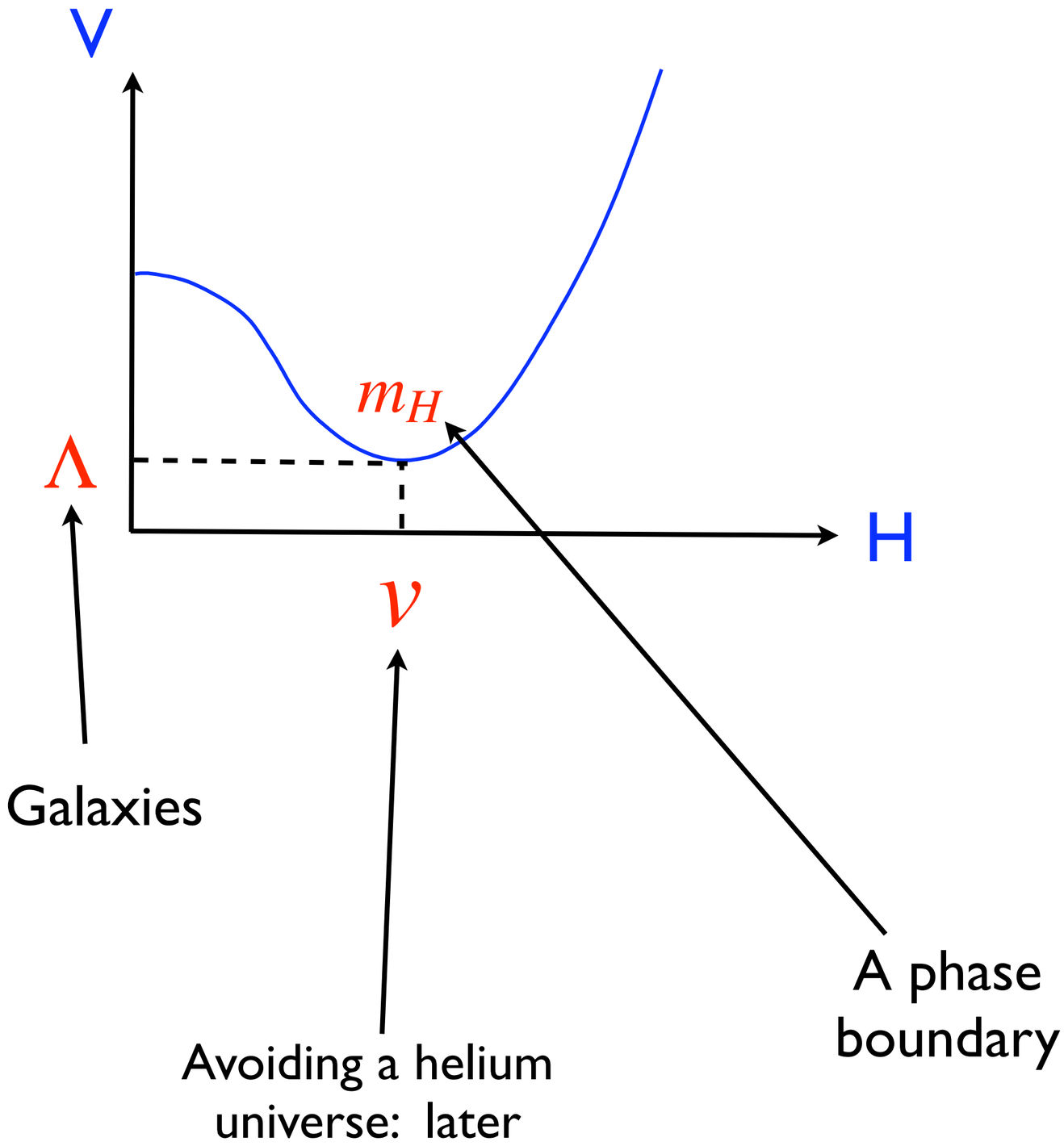
$$\frac{x_c}{x_{1/2}} = 2^{1/p}$$

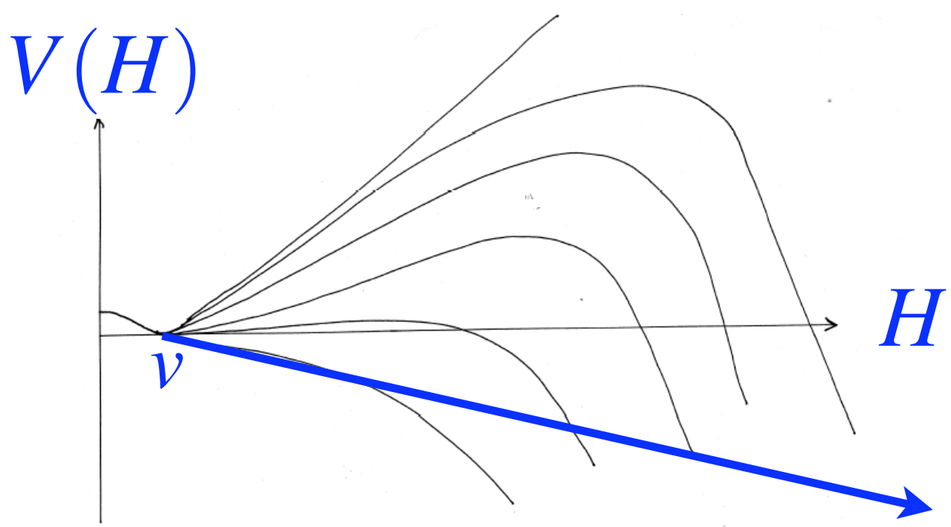
- $F = p$: 5 3 2 1 1/2 1/3 1/5

  $\dfrac{x_c}{x_{1/2}}$ 1.15 1.26 1.41 2 4 8 16

II) The Higgs Mass

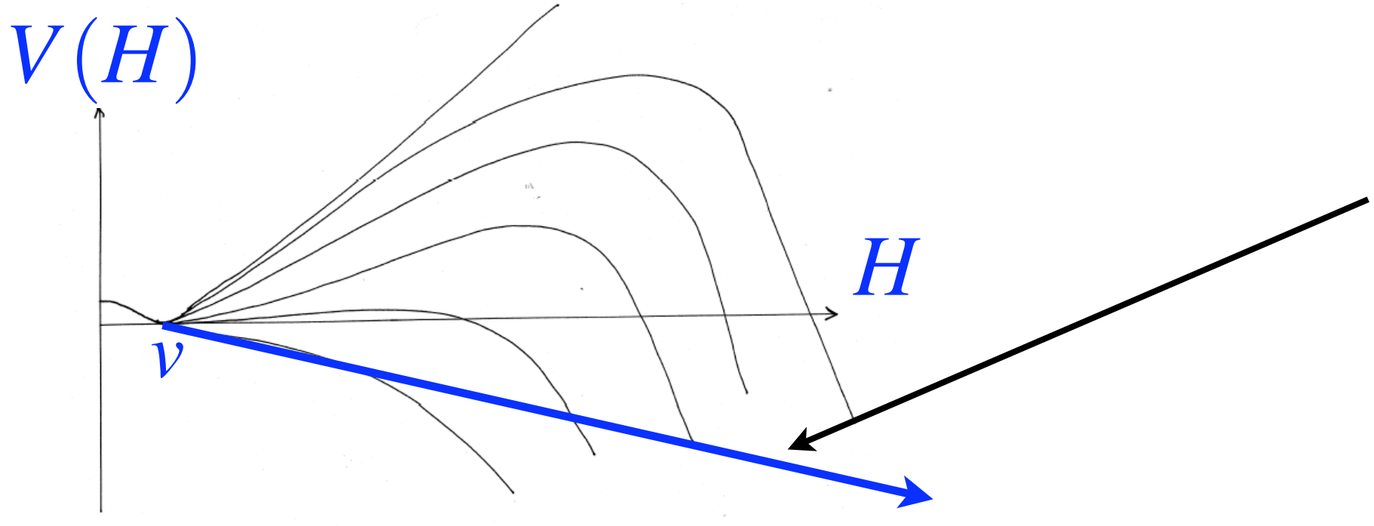
Brian Feldstein, LJH,
Taizan Watari;
hep-ph/0608121





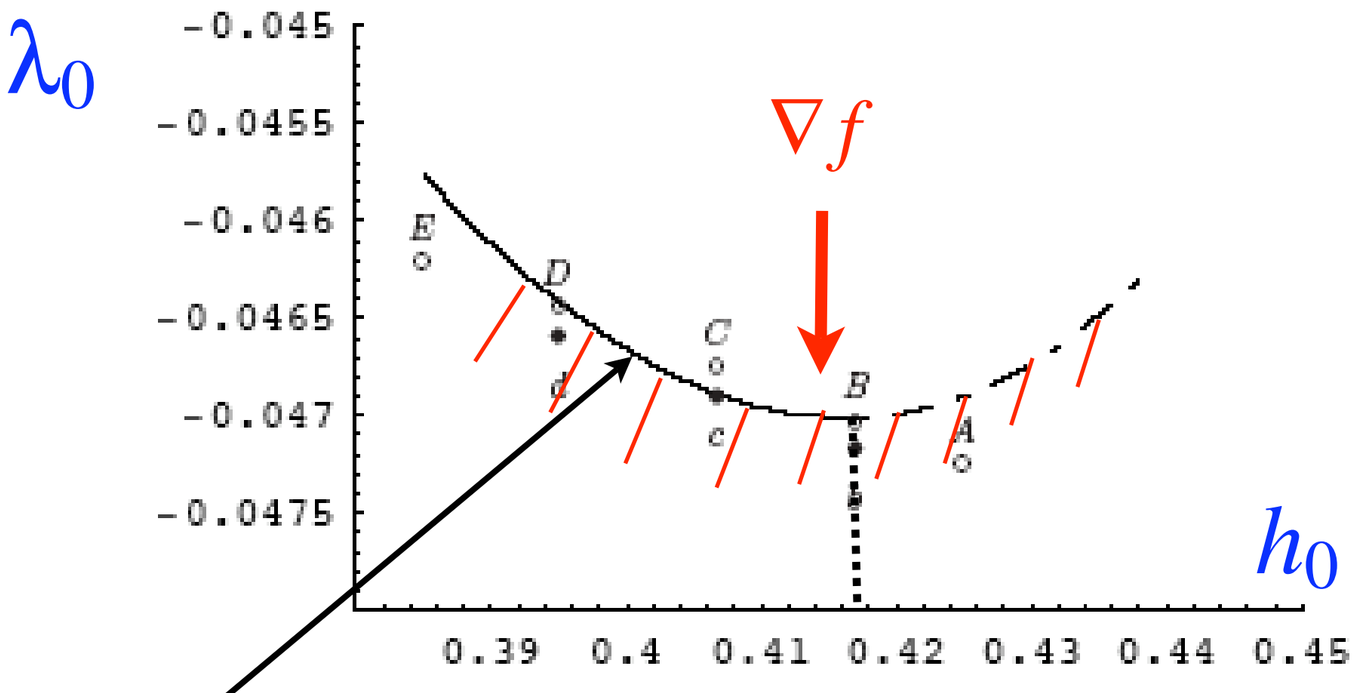
The Phase Boundary

Assume: SM up to some large scale Λ_{SM}



$$\lambda(\Lambda_{SM}) = \lambda_0$$

$$h_t(\Lambda_{SM}) = h_0$$



EW phase boundary is catastrophic boundary

Environmental predictions for m_t , m_H

Higgs and Top Mass Predictions

$$m_H = \left[110.5 + 4.4\left(\frac{m_t - 172.6\,\text{GeV}}{1.4\,\text{GeV}}\right) - 2.6\left(\frac{\alpha_s - 0.1176}{0.002}\right) \pm 6\right]\text{GeV} + \frac{25\,\text{GeV}}{p}$$

2 loop running

3 loop: $\rightarrow$ 109 Arkani-Hamed, Dobovsk Senatore, Villadoro 0808.2399

Top and QCD contributions to running

running to pole

$$m_t = \left[176.7 + 2.2\log_{10}\left(\frac{\Lambda_{SM}}{10^{18}\,\text{GeV}}\right) \pm 3\right]\text{GeV} - \frac{35\,\text{GeV}}{\sqrt{p}}$$

relatively insensitive to SM cutoff

p sufficiently large for a tight Higgs mass prediction

Suppose LHC finds only a SM Higgs

$m_H \sim (120 - 130)\,\text{GeV} \rightarrow p \sim 1 - 2$!

$m_H \sim 115\,\text{GeV} \rightarrow p \sim 10$!!

III) Nuclear Boundaries

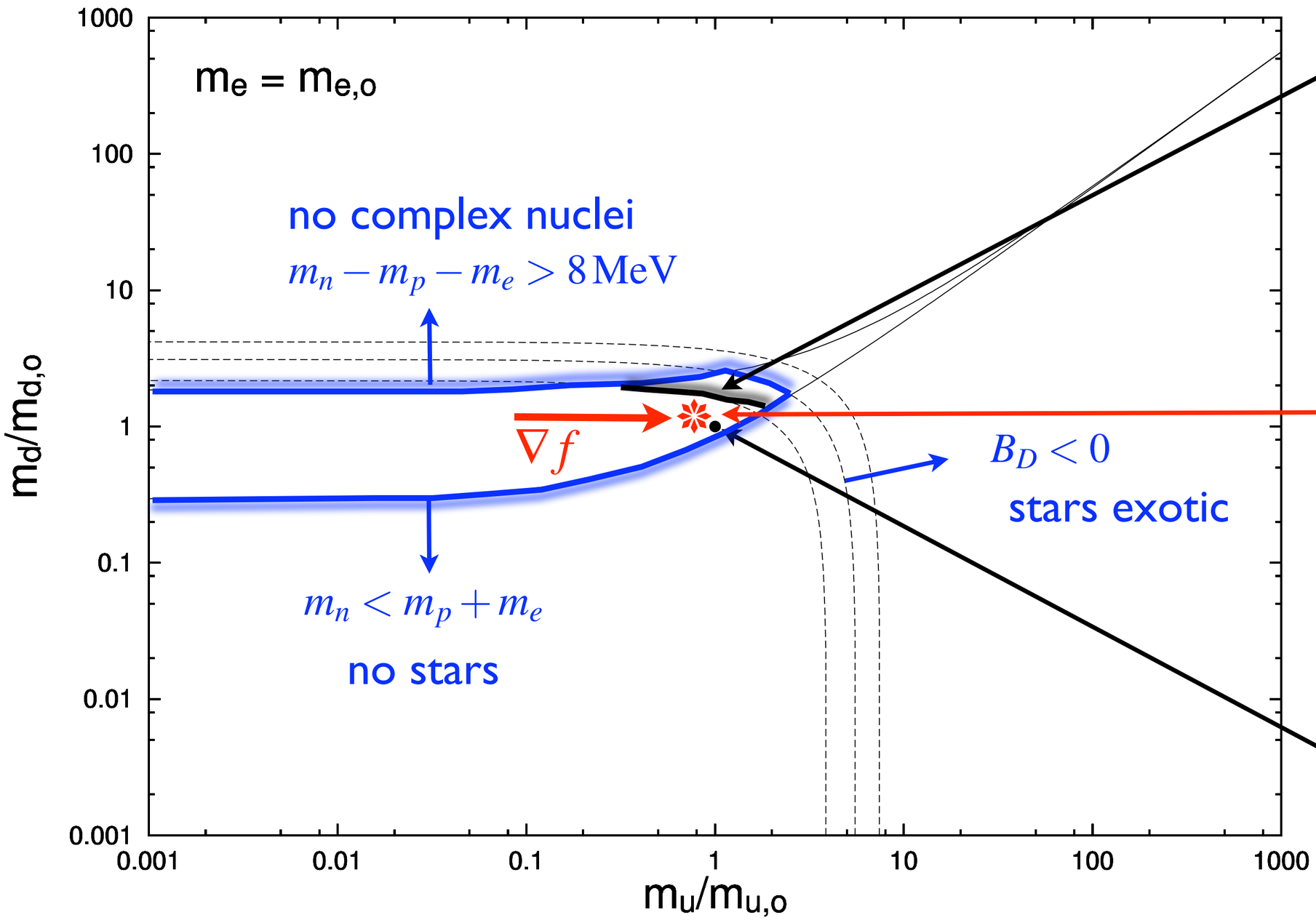
- Stability of Nuclei
- BBN

Nuclear Stability Boundaries

Relevant parameters $\left(\alpha, \frac{m_e}{m_p}, \frac{m_u}{m_p}, \frac{m_d}{m_p}\right)$

Yasunori Nomura, LJH
arXiv:0712.2454

2d slice



Damour
Donoghue
arXiv:0712.2968

Tip of theCone!

$m_{u,d,e}$
determined by nuclear physics of boundaries

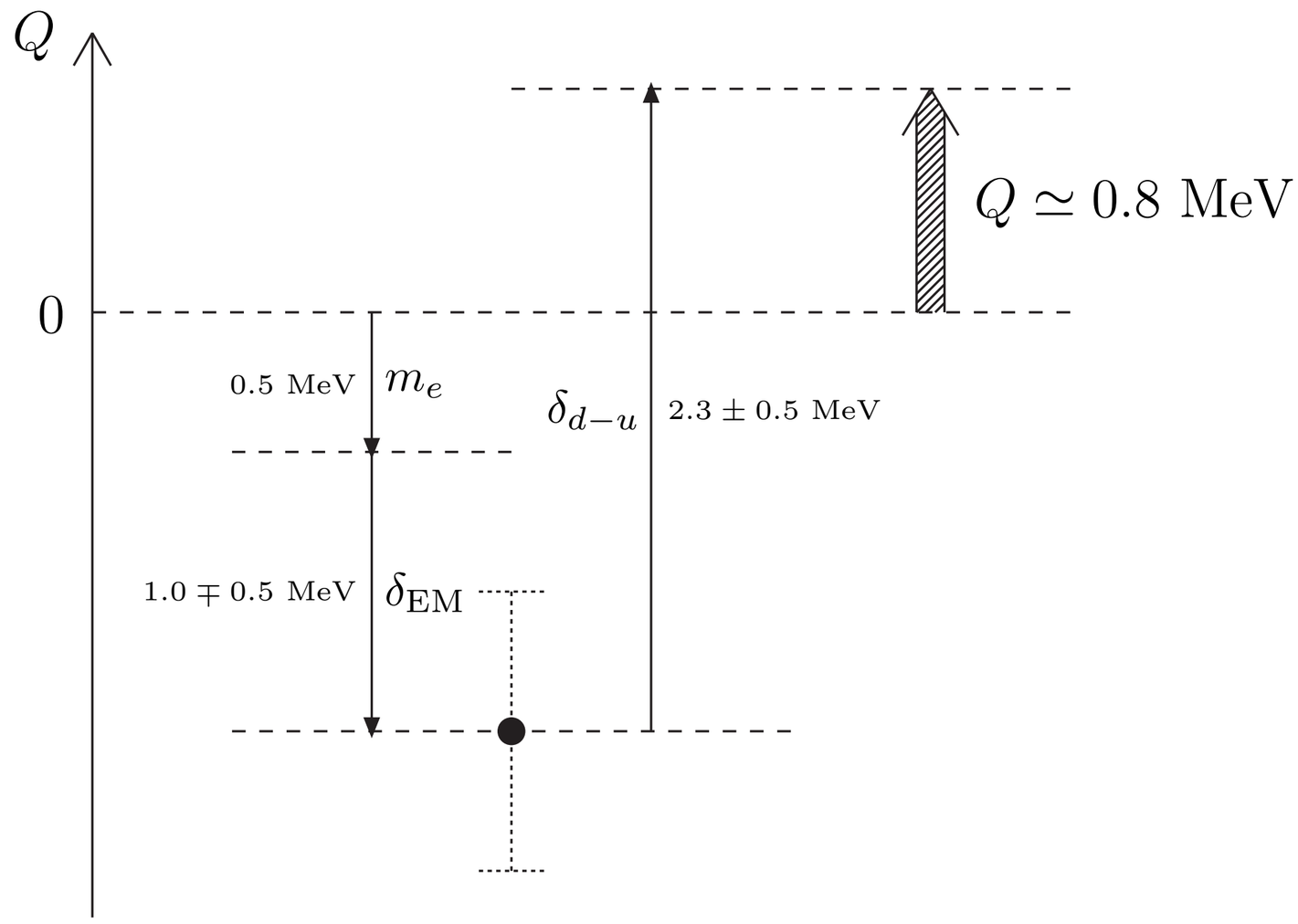
Closeness to n boundary

(10 - 30)%

Understanding Coincidences

- Why are the three contributions to $Q(n \to pe\nu)$ comparable?

- m_e, m_u, m_d are determined by the physics of the boundary



- Simple distributions give

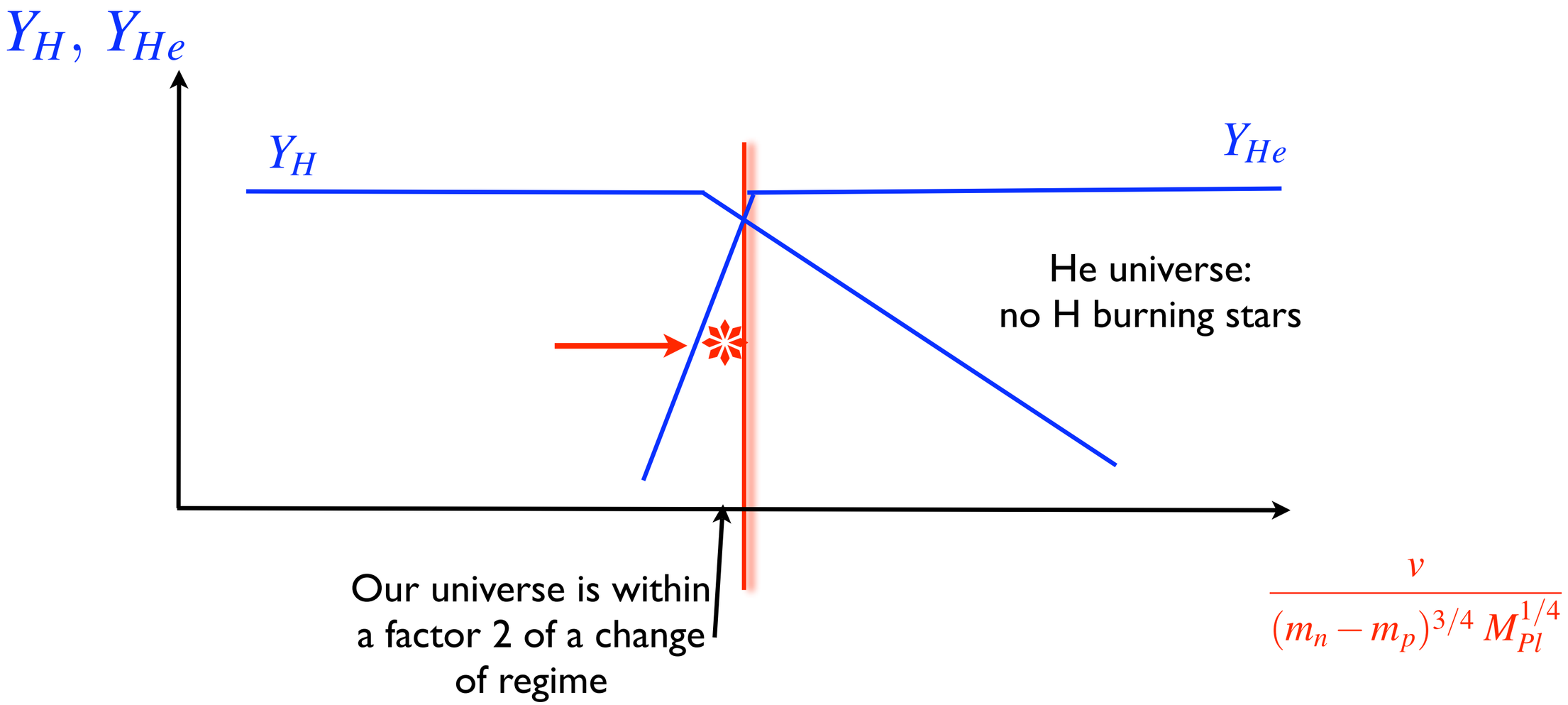
  - $m_e \simeq \delta_{EM}$

  - $m_{u,d} \simeq \dfrac{B}{N}, B_D$

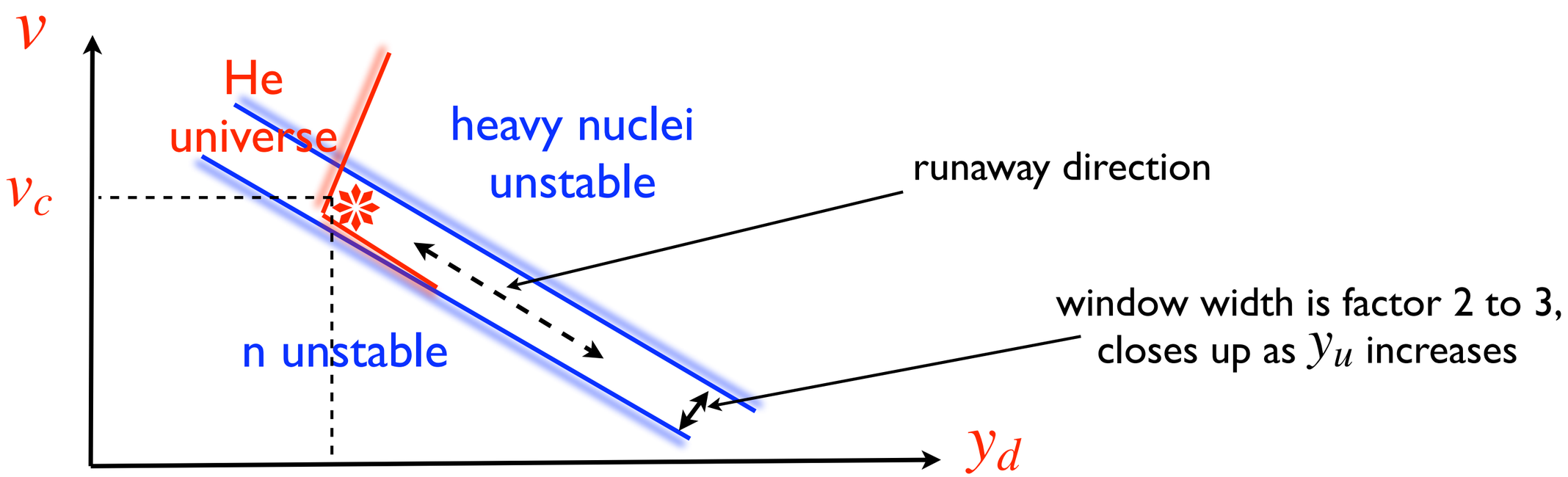
The BBN Boundary

Relevant quantities:

- $m_n - m_p \propto \Lambda_{QCD}$ — 1.3 MeV
- $T_f(v)$ — 0.8 MeV



The Weak Scale



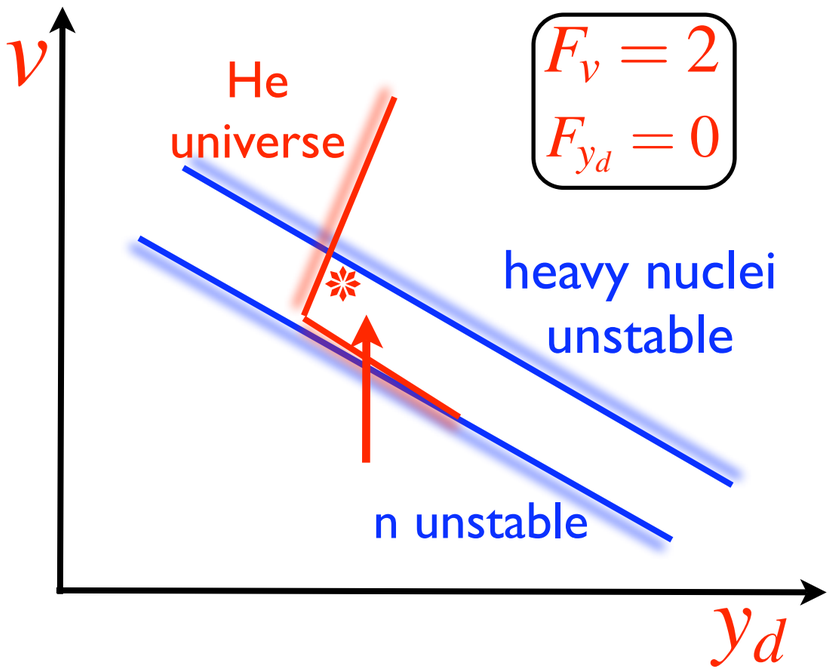
- Our universe is within a factor of 2 of the critical point

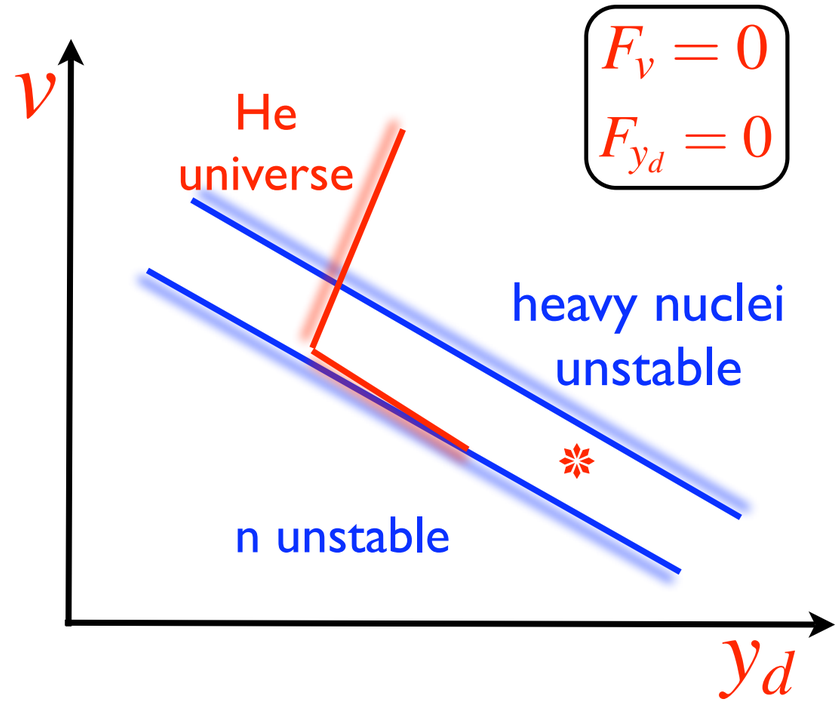
$$v_c \sim \Lambda_{QCD}^{3/4} M_{Pl}^{1/4}$$

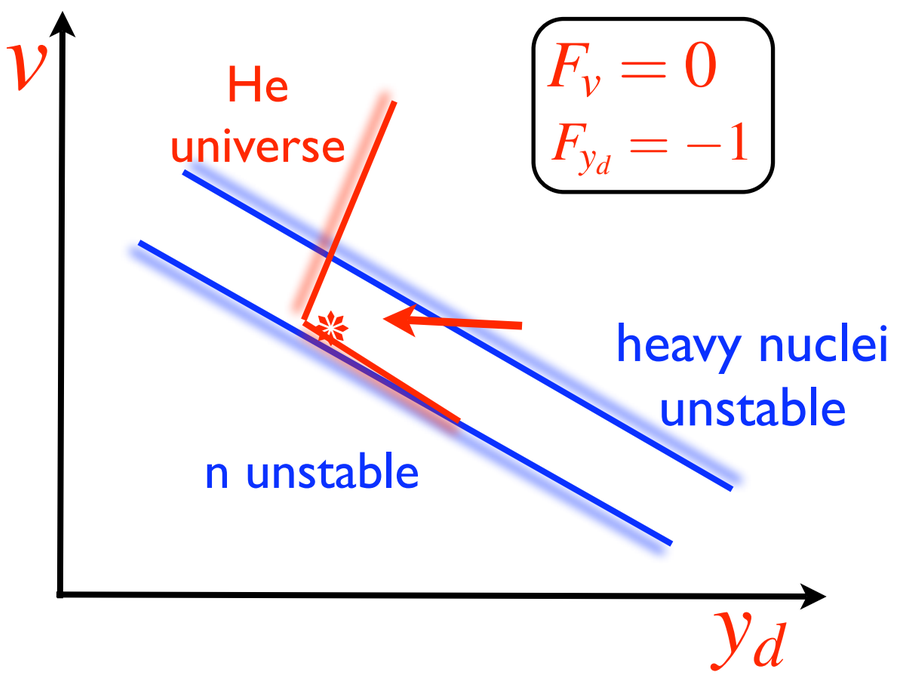
$$y_{d_c} \sim \left(\frac{\Lambda_{QCD}}{M_{Pl}}\right)^{\frac{1}{4}}$$

- Does this require a strong force on v?
  ie does it exclude dynamical EWSB !?!

The Force on v

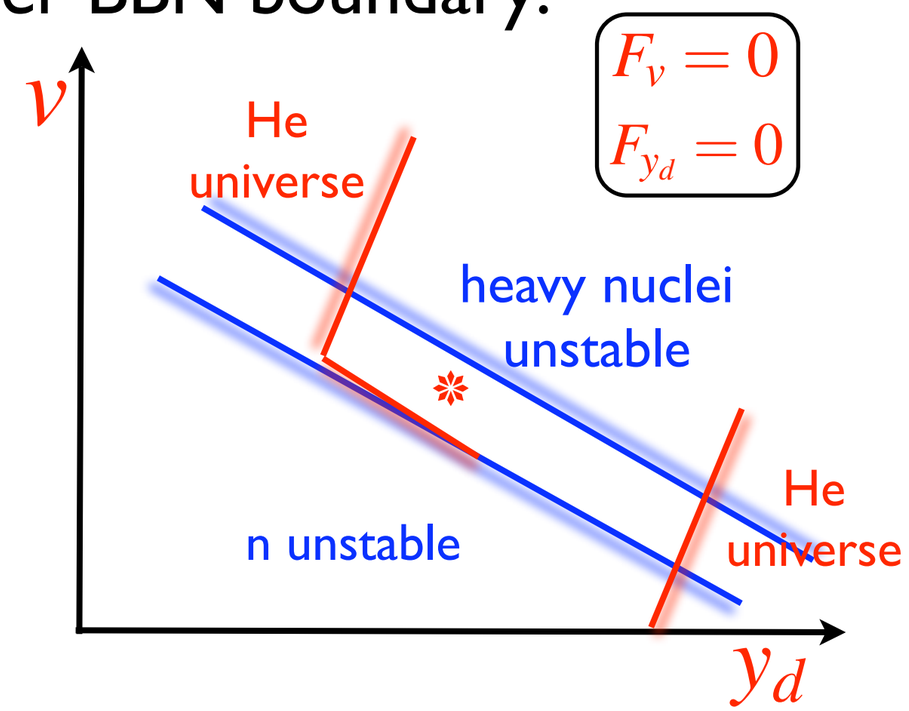






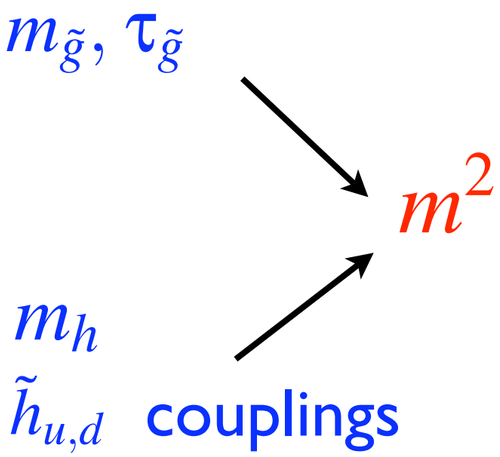
Perhaps preferred

Another BBN boundary:



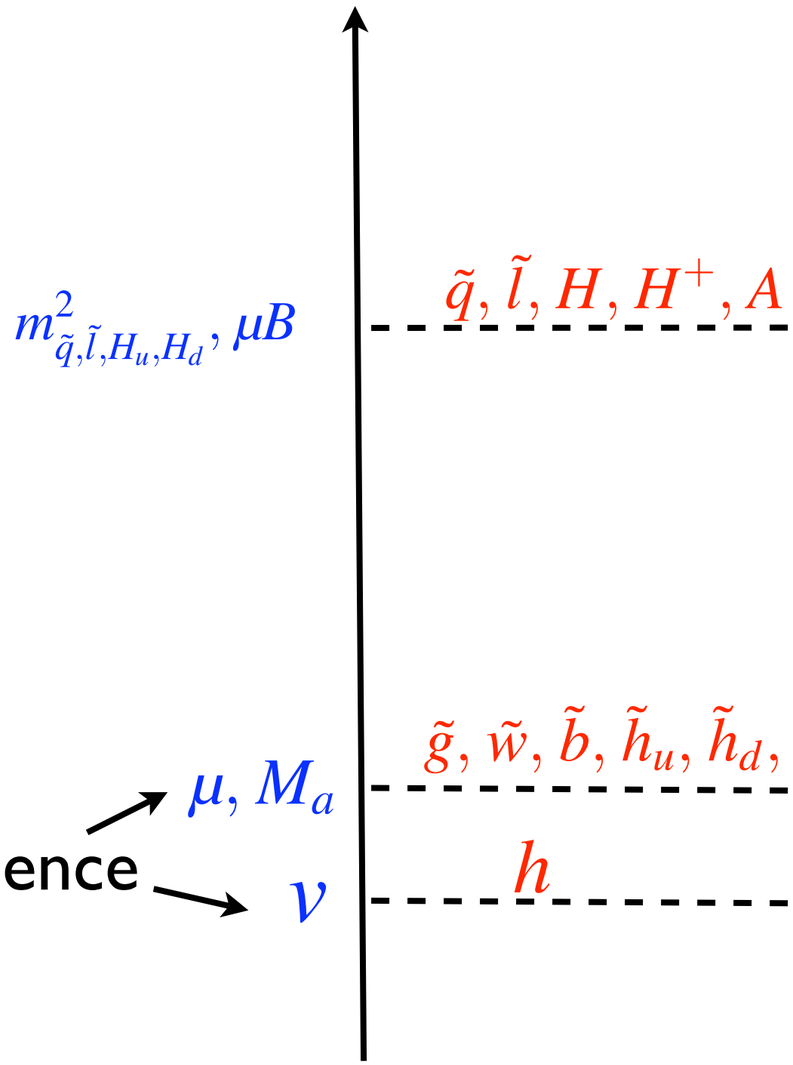
Split Supersymmetry

Arkani-Hamed, Dimopoulos
th/0405159



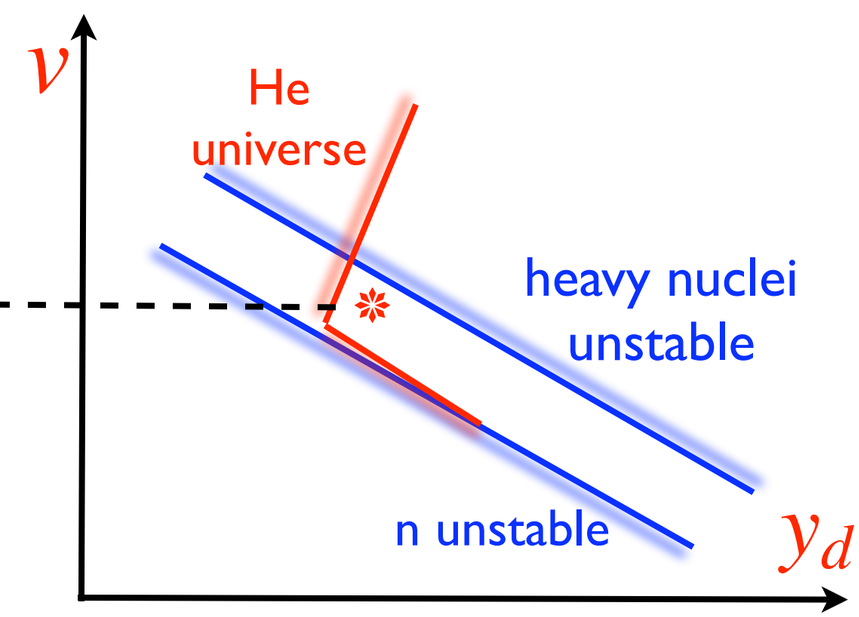
Compelling evidence for an amount of fine tuning of

$\frac{m^2}{v^2}$ e.g. 10^{15}



Works even if Yukawas scan:

$v \simeq \Lambda_{QCD}^{3/4} M_{Pl}^{1/4}$



Implication:

Certain crucial parameters are being related by environmental selection

- $m_e \simeq \delta_{EM}$
- $m_{u,d} \simeq \frac{B}{N}, B_D$
- $y_d \sim \left(\frac{\Lambda_{QCD}}{M_{Pl}}\right)^{\frac{1}{4}}$
- $v \sim \Lambda_{QCD}^{3/4} M_{Pl}^{1/4}$

At the factor of 2 level

These parameters are not determined by symmetries or by accidents

IV) Cosmological Coincidences

Raphael Bousso, Yasunori Nomura, LJH

- Well separated cosmic eras: $t_{infl} \ll t_{EWSB} \ll t_{QCD} \ll t_{eq}$
- Broken down recently:

$$t_\Lambda \simeq t_{vir} \simeq t_{rad} \simeq t_{Comp}$$

Amount of Dark Energy

Amount of Dark Matter & Size of primordial density perturbations

eg, QED bremsstrahlung

Inverse Compton scattering from CMB

Why are these time scales all 10^{9-10} years?

Hard to imagine a symmetry explanation

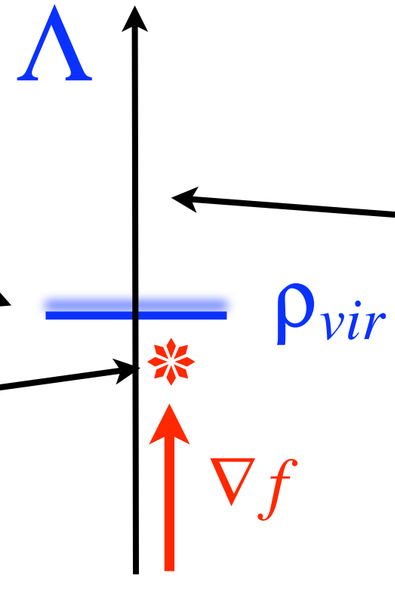
- Seek order of magnitude understanding!!

The Cosmological Constant

Weinberg PRL 1987

Catastrophic boundary:
must form non-linear proto-galaxies before CC fuels inflation

Most universes a dilute inflating homogeneous gas



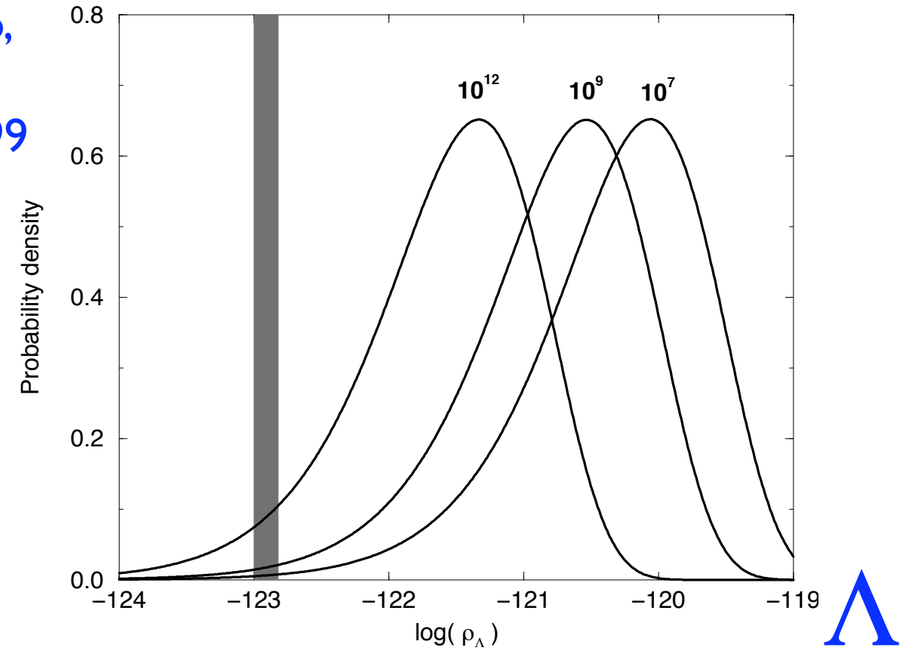
CC problem solved

Amount of Dark Energy predicted

$\Lambda \sim \rho_{vir}$ *i.e.* $t_\Lambda \sim t_{vir}$

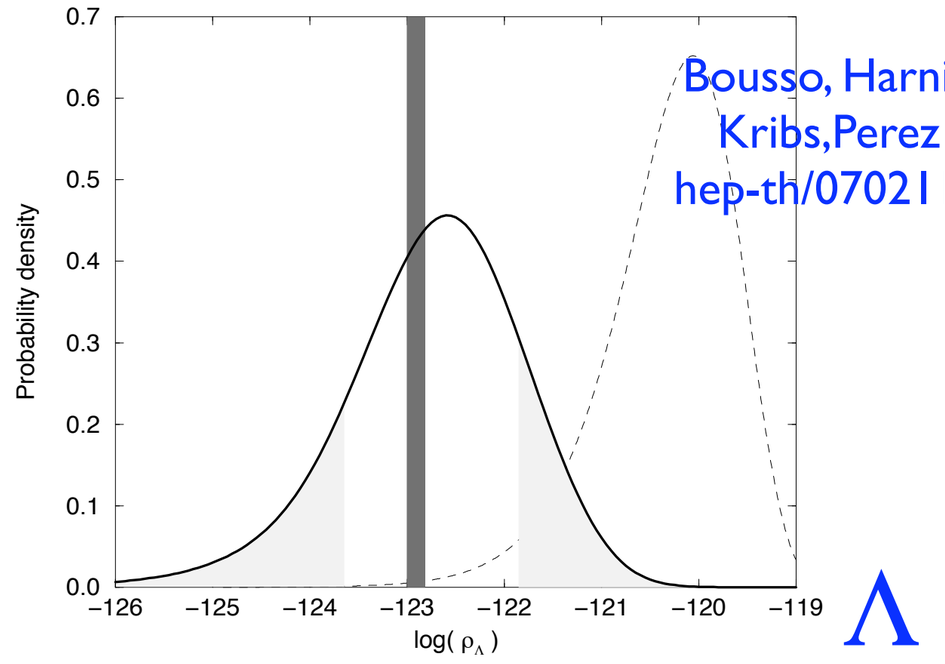
❋ $n_{obs} \sim n_{vir\,B}$

Martell, Shapiro, Weinberg
astro-ph/9701099



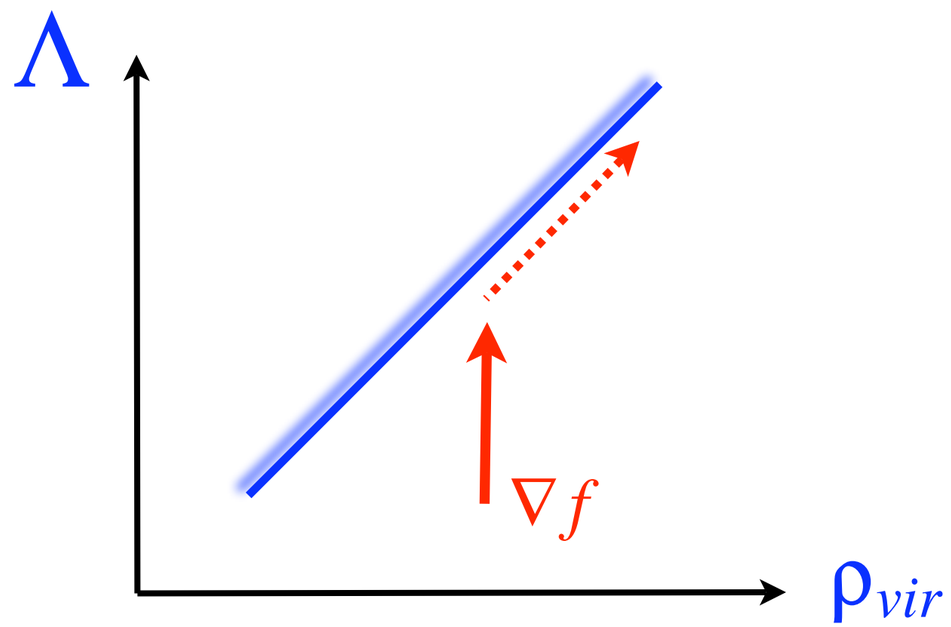
❋ $n_{obs} \sim S_{causal\ diamond}$

Bousso, Harnik
Kribs,Perez
hep-th/0702115



The CC Runaway Problem

- Suppose ρ_{vir} scans



- $f(\rho_{vir}, \Lambda)$ might reach a maximum at some point

  This preserves $\Lambda \sim \rho_{vir}$ but the value cannot be predicted

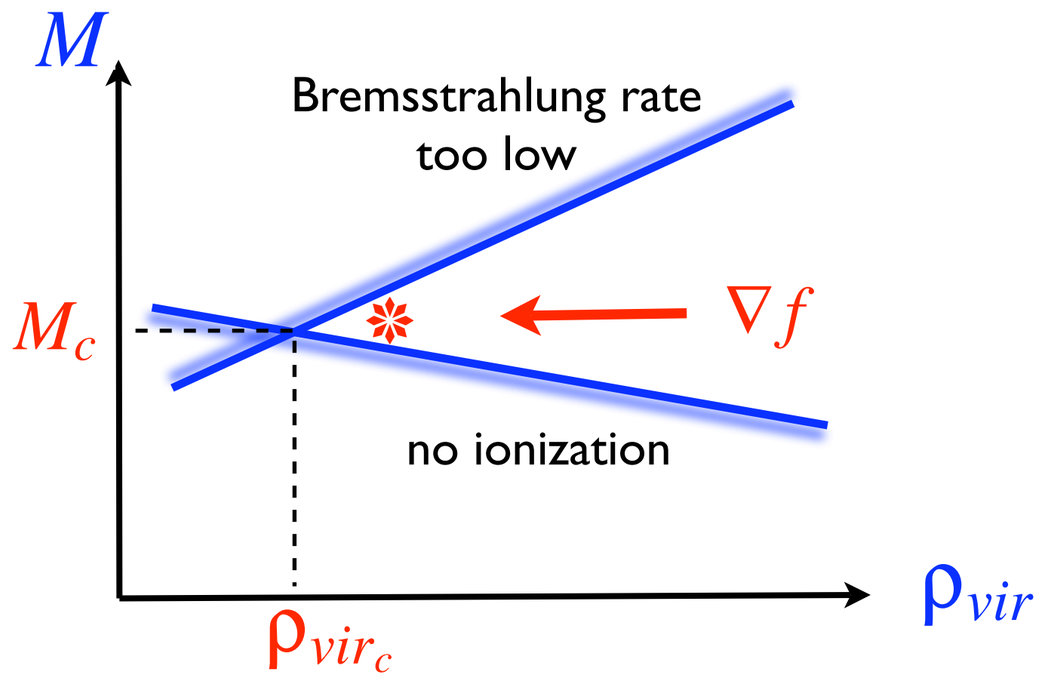
- Need a second catastrophic boundary

The Galaxy Cooling Catastrophe

- Compute ionization and cooling boundaries

Relevant parameters

$$\alpha,\ m_e,\ m_p;\ \rho_{vir},\ M_{Pl},\ M$$



- ρ_{vir_c} predicted from proto-galaxy cooling physics:

$$\rho_{vir_c} \sim \frac{m_e^4 m_p^2}{\alpha^4 M_{Pl}^2} \sim (8 \times 10^{-3}\,\mathrm{eV})^4$$

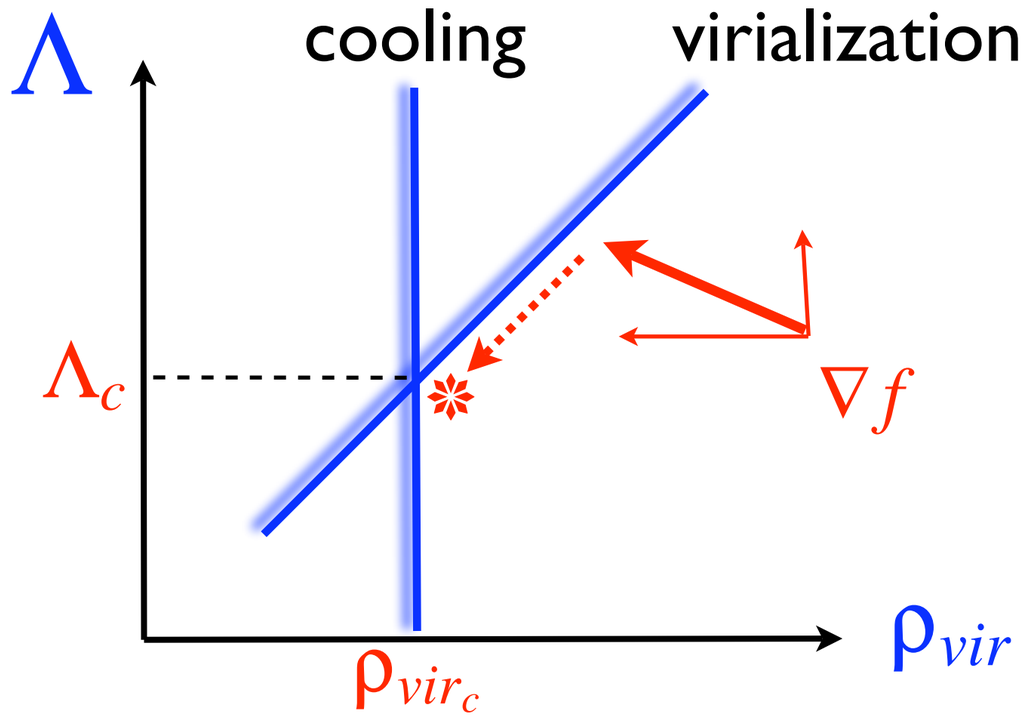
explaining the coincidence $t_{rad} \sim t_{vir}$

and as a bonus:

$$M_c \sim \frac{\alpha^5 M_{Pl}^4}{m_e^{1/2} m_p^{5/2}} \sim 10^{67}\,\mathrm{GeV} \sim 10^{10}\,M_\odot$$

Solving the CC Runaway Problem

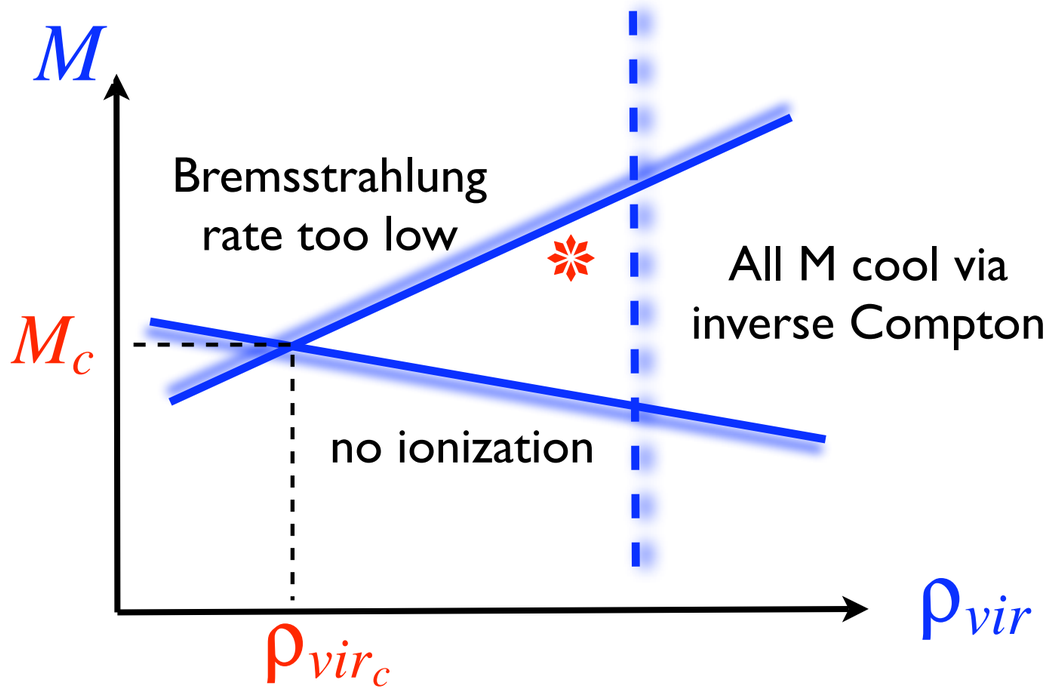
2 scanning parameters
and
2 catastrophic boundaries



✻ $$\Lambda_c \sim \frac{m_e^4 m_p^2}{\alpha^4 M_{Pl}^2} \sim (2 \times 10^{-3}\,\mathrm{eV})^4$$

Inverse Compton Cooling

- Why is our galaxy so close to inverse Compton cooling?



- Assume Compton cooling is catastrophic

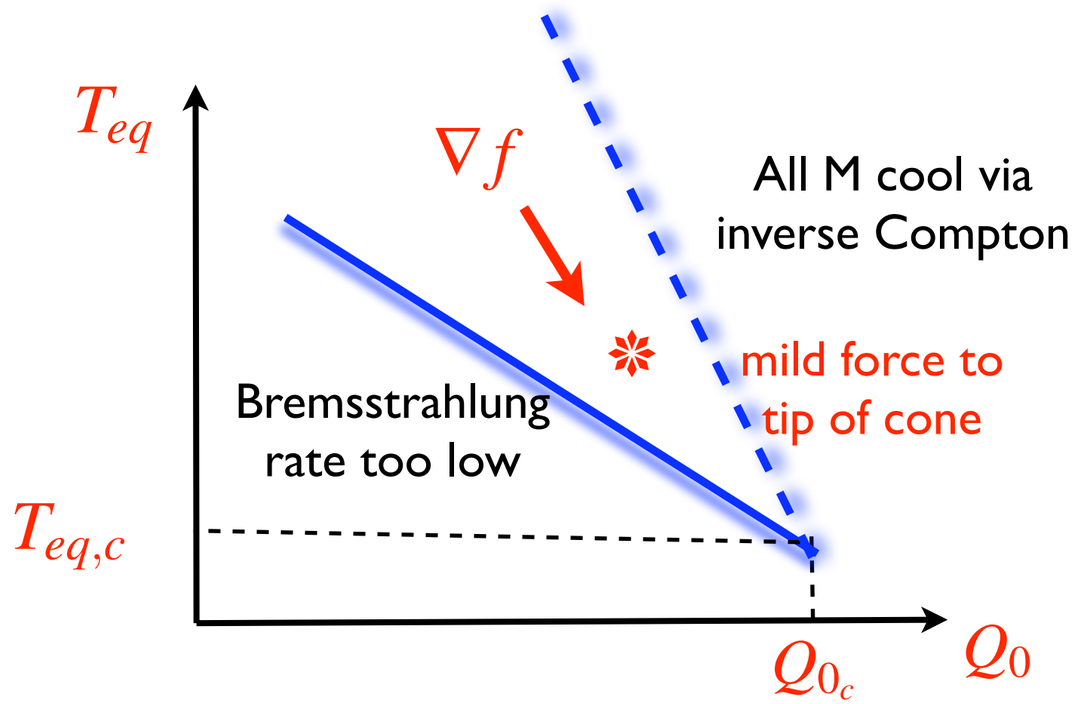
- This radically changes the scanning analysis

- Small region in ρ_{vir} is tip of higher dimensional cone!

$$\rho_{vir} \sim Q_0^3 T_{eq}^4 \Rightarrow (Q_0, T_{eq})$$

Scanning Q_0, T_{eq}

$\rho_{vir} \sim Q_0^3 T_{eq}^4 \Rightarrow (Q_0, T_{eq})$



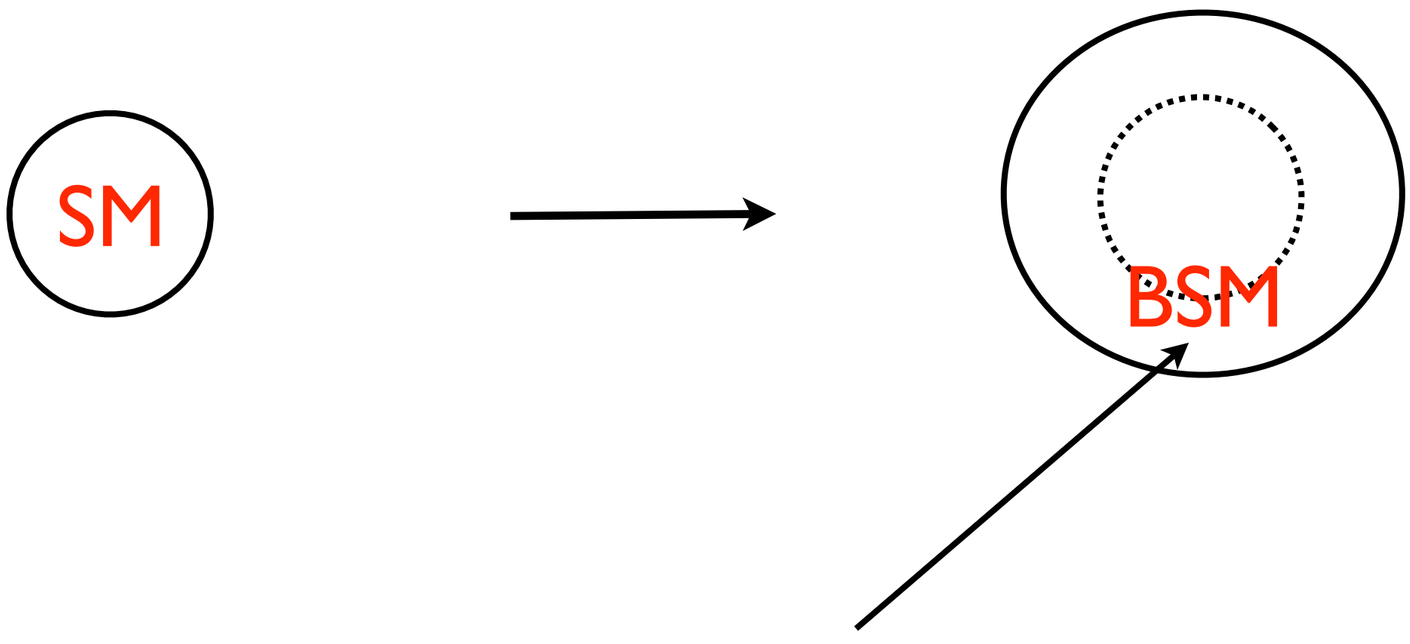
- Explains the coincidence $t_{Comp} \sim t_{rad}$
- Two predictions $Q_{0_c} \sim \frac{m_e}{m_p}$ $T_{eq,c} \sim \frac{m_e^{1/4} m_p^{5/4}}{\alpha M_{Pl}^{1/2}}$
- Q_0, T_{eq} are each factor 100 from the critical point; e.g.

$f(Q_0, T_{eq}) \sim Q_0 / T_{eq}^{1/2}$

Symmetries & The Multiverse

- Standard Model → Beyond Standard Model

- Environmental selection does not care what the underlying theory is



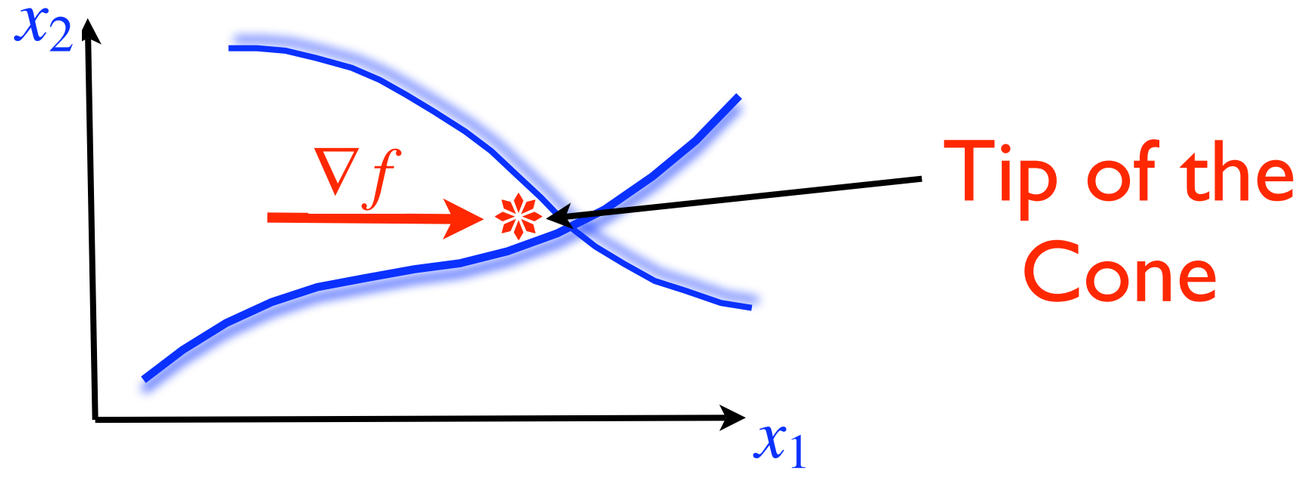
- Independent parameters that allow for the variation of

$m_e, m_u, m_d, v, \Lambda, Q_o, T_{eq}$

(Lose Higgs prediction)

Conclusions: A Complete Scheme

- The idea:
  assume multiverse force
  towards catastrophic edges



- Nuclear stability — $\frac{m_e}{\Lambda_{QCD}}, \frac{m_u}{\Lambda_{QCD}}, \frac{m_d}{\Lambda_{QCD}}$
- BBN — $\frac{v}{\Lambda_{QCD}}, y_{e,u,d}$
- Virialization — Λ
- Proto-galaxy cooling: — T_{eq}, Q_0 — M_{gal}

What determines $\frac{\Lambda_{QCD}}{M_{Pl}}$?

- A missing boundary?
- Multiverse distribution?
- The discretuum?

- Will LHC discover unnatural EWSB?