Naturalness or Typicality?

Yasunori Nomura

UC Berkeley; LBNL

Why is the universe as we see today?

— Mathematics requires

— “We require”

Dramatic change of the view

Our universe is only a part of the “multiverse”

… suggested **both** from observation **and** theory

This comes with revolutionary change of the view of spacetime and gravity

- Holographic principle / complementarity
- Multiverse as quantum many worlds
- …

… implications on particle physics and cosmology

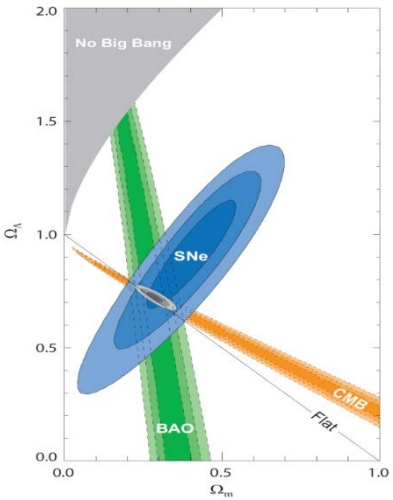
- What is naturalness?
- …

Shocking news in 1998

Supernova cosmology project; Supernova search team

Expansion is accelerating!

$$\Lambda \neq 0 \,!$$



Particle Data Group (2010)

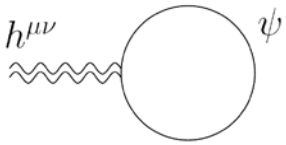
Observationally,

$$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$$

Its smallness is already hard to understand

… natural size of $\rho_\Lambda \equiv \Lambda^2 M_{\mathrm{Pl}}^2 \sim M_{\mathrm{Pl}}^4$ (at the very least ~ TeV^4)

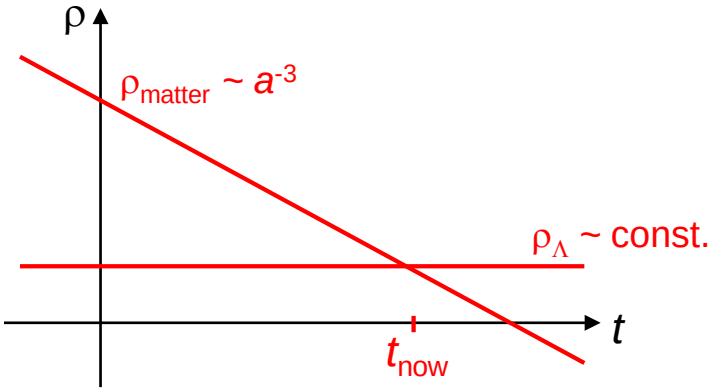
… Naïve estimates $O(10^{120})$ too large



Moreover

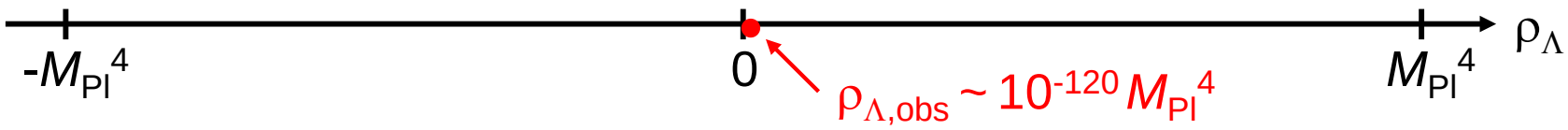
$$\rho_\Lambda \sim \rho_{\mathrm{matter}}$$

— Why now?



Nonzero value completely changes the view!

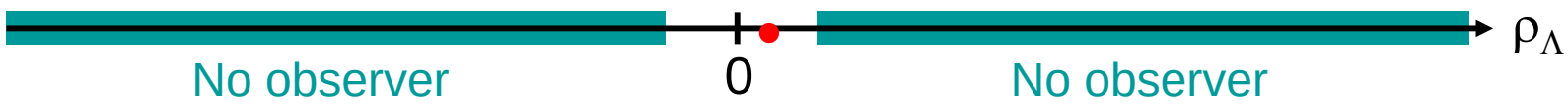
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



Unnatural (Note: $\rho_\Lambda = 0$ is NOT special from theoretical point of view)

⟹ Wait!

Is it really unnatural to *observe* this value?



It is quite "natural" to observe $\rho_{\Lambda,obs}$,

as long as different values of ρ_Λ are "sampled"

Weinberg ('87)

Theory also suggests

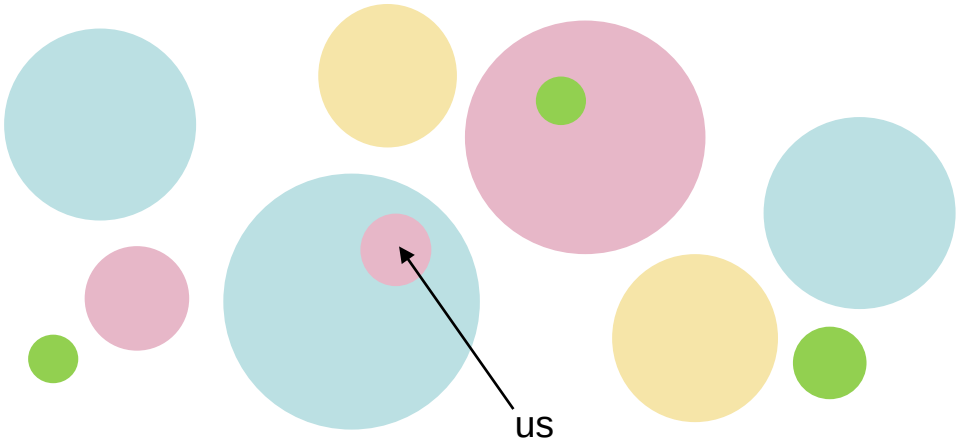
- String landscape

Compact (six) dimensions
→ huge number of vacua

ex. $O(100)$ fields with $O(10)$ minima each
→ $O(10^{100})$ vacua

- Eternal inflation

Inflation is (generically) future eternal → populate all the vacua



… Anthropic considerations **mandatory** (not an option)

⟹ Eternally inflating multiverse

Full of “fine-tunings”

Examples:

- $y_{u,d,e} v \sim \alpha \Lambda_{QCD} \sim O(0.01) \Lambda_{QCD}$

  … otherwise, no nuclear physics or chemistry

(Conservative) estimate of the probability: $P \ll 10^{-3}$

- $\rho_{Baryon} \sim \rho_{DM}$

....

Some of them could be anthropic (and some may not)

$\Longrightarrow$ Implications?

- Particle physics / cosmology (naturalness, observations, …)
- Quantum gravity (spacetime, gravity, …)

Implications

—particle physics / cosmology —

... new ways of thinking physics

Particle Physics

Could anthropic lead to any change in our thinking?

Weak scale *does* affect environment Agrawal, Barr, Donoghue, Seckel ('97)

ex. Stability of complex nuclei

For fixed Yukawa couplings,

no complex nuclei for $v > 2\, v_{\rm obs}$ Damour, Donoghue ('07)

Possible that $v_{\rm obs}$ arises as a result of environmental selection

Does this mean that there is no weak scale supersymmetry?

— No !

The scale of superparticle masses determined by statistics

… Typicality !

$$\boxed{d\mathscr{N} \sim f(\tilde{m})\, \frac{v^2}{\tilde{m}^2}\, d\tilde{m}} \qquad f(\tilde{m}) \sim \tilde{m}^{p-1}$$

For $p < 2$, weak scale SUSY results, but for $p > 2$, $\tilde{m}$ prefers to be large…

What is the simplest scenario in this case?

We assume the "simplest": MSSM + *R* parity

(I) The simplest high scale mediation

SUSY breaking mediated at the field-theoretic "cutoff" scale M_* ($\gtrsim M_{\rm unif}$)

— no (need of) flavor symmetry, *CP*, sequestering, …

e.g. the string scale

SUSY breaking field $X = \theta^2 F$ is **not** neutral

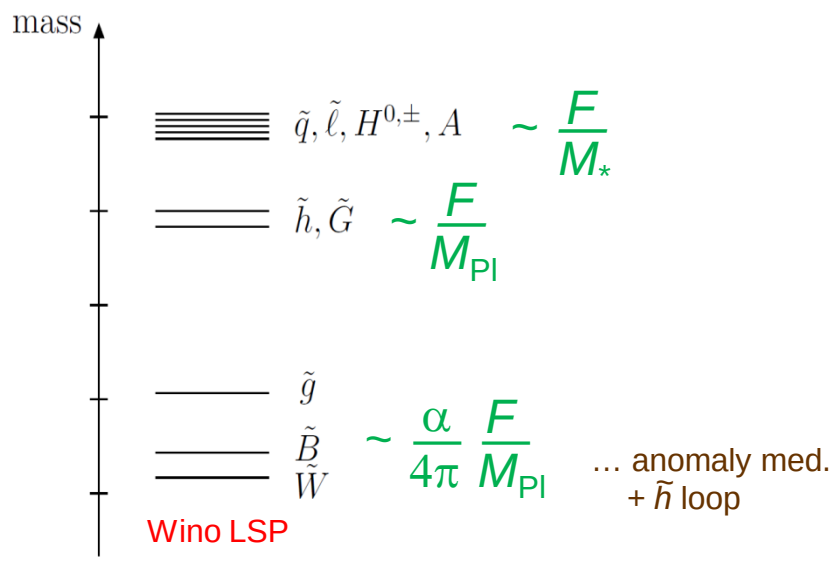
… scalar masses: $X^+X\,Q^+Q$, B_μ term: $X^+X\,H_uH_d$

~~gaugino mass: $XW^\alpha W_\alpha$~~, ~~A term: XQ^+Q~~, ~~μ term: $X^+H_uH_d$~~

… supergravity or loop effects

→ "Spread" / mini-split superparticle spectrum

Giudice, Luty, Murayama, Rattazzi ('98); Wells ('03,'04);
….
Hall, Y.N. ('11); Ibe, Yanagida ('11); Arvanitaki, Craig, Dimopoulos, Villadoro ('12);
Hall, Y.N., Shirai ('12); Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski ('12)

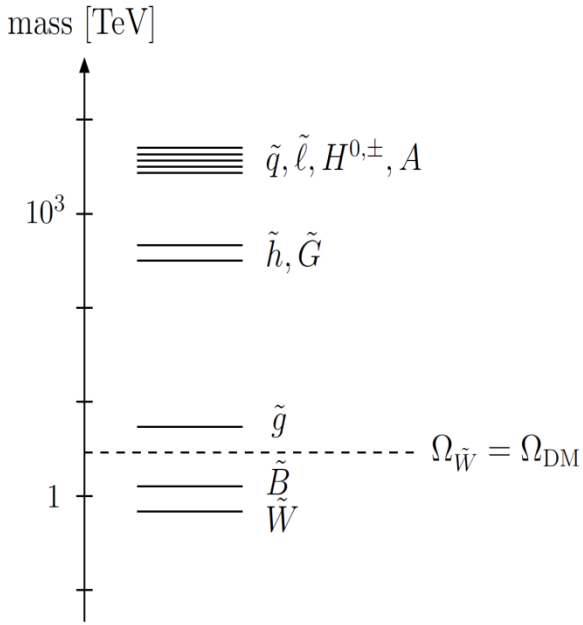


Write down all the possible terms with $O(1)$ couplings in units of M_*, including $K = H_uH_d$

What stops "drifting-up" of the spectrum?

(II) The existence of the environmental boundary

$$\Omega_{DM} < \Omega_{DM,max}$$



If thermal & $\Omega_{\tilde{W}} = \Omega_{DM}$,
$M_{\tilde{W}} \sim 3$ TeV … generally **not** the case

Note: This is the same boundary used to argue for axion DM

Linde ('88); Tegmark, Aguirre, Rees, Wilczek ('05)

In general,

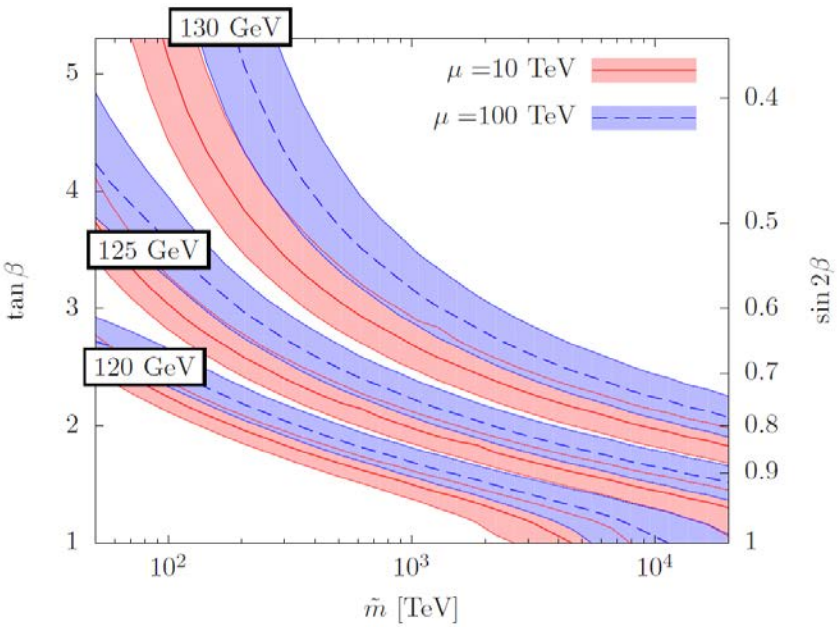
$$\Omega_a + \Omega_{WIMP} < \Omega_{DM,max} \longrightarrow \text{Multi-component DM!}$$

Immediate bonus

The two-step hierarchy implies

$$\tilde{m} \sim (10^2 - 10^4)\ \text{TeV}$$

- Higgs boson mass



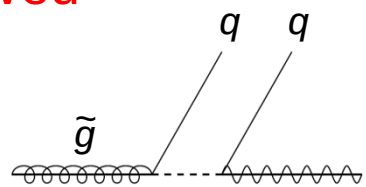
- Unsuppressed B_μ term
  $\rightarrow$ $\tan\beta \sim O(1)$
- $|A_t| \ll m_{\tilde{t}}$

- No SUSY flavor or *CP* problem (but still have a chance to see signals in the future)
- No gravitino problem ($m_{3/2} \sim 10 - 100\ \text{TeV}$)

Gluino signals

Because of large $\tilde{m}$, the gluino can be "long-lived"

$$c\tau_{\tilde{g}} = O(1\ \mathrm{cm}) \left(\frac{M_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^{-5} \left(\frac{\tilde{m}}{1000\ \mathrm{TeV}}\right)^{4}$$



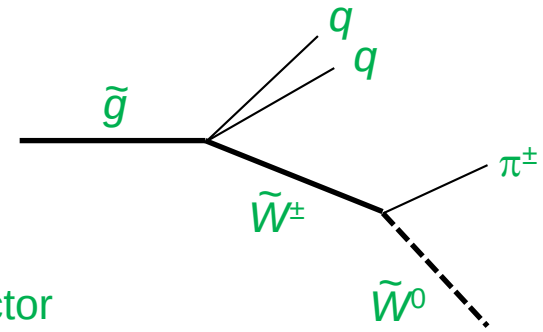
… $r_* \gtrsim O(10)$ → long-lived (displaced) gluino signatures

Winos are (nearly-degenerate) co-LSPs

$$M_{\tilde{W}^\pm} - M_{\tilde{W}^0} \simeq 160\ \mathrm{MeV} \longrightarrow c\tau_{\tilde{W}^\pm} = O(10\ \mathrm{cm})$$

⟹ Decay chain with two long-lived particles

$$\boxed{\tilde{g} \xrightarrow[\text{long-lived}]{} q\bar{q}(\tilde{W}^\pm \xrightarrow[O(10\ \mathrm{cm})]{} \tilde{W}^0\pi^\pm)}$$



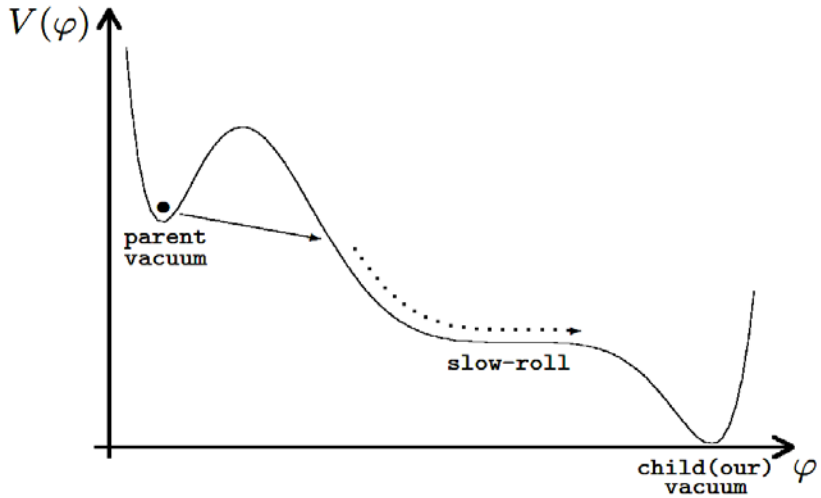
… may be able to probe the flavor structure of the squark sector

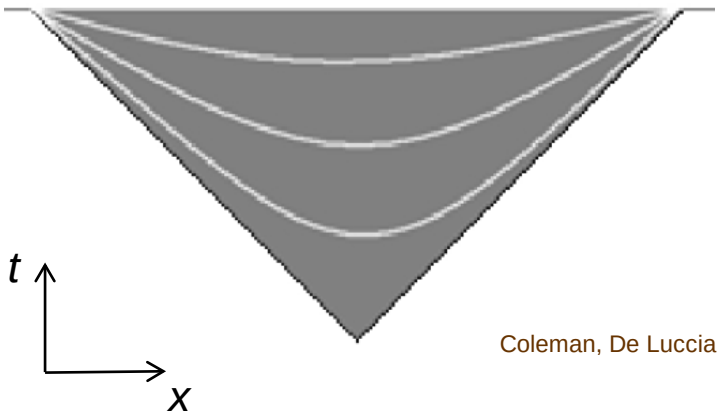
Other signals include

indirect DM detection, CMB, EDMs, flavor / CP, *p* decay, …

Cosmology

Our universe is a bubble formed in a parent vacuum:





Coleman, De Luccia ('80)

… Infinite open universe

(negative curvature: $\Omega_{curvature} > 1$)

- Finding $\Omega_{curvature} < 0$ will **exclude** the framework!

  … The eternally inflating multiverse **is** falsifiable Guth, Y.N. ('12); Kleban, Schillo ('12)

- Finding $\Omega_{curvature} > 0$ will be suggestive

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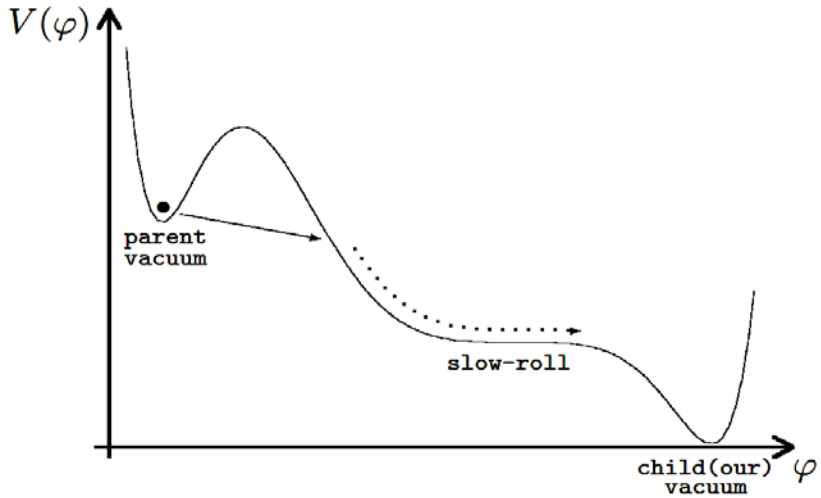

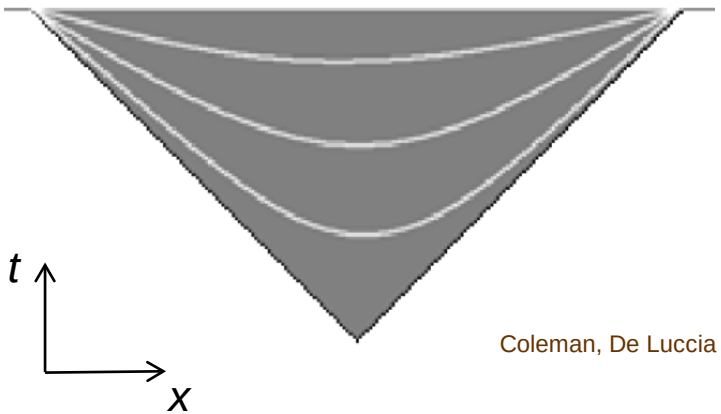

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- Finding $\Omega_{curvature} > 0$ will be suggestive … Can we expect?

A possible scenario

Why is our universe so flat?

If it is curved a bit more, no structure/observer → could be anthropic!

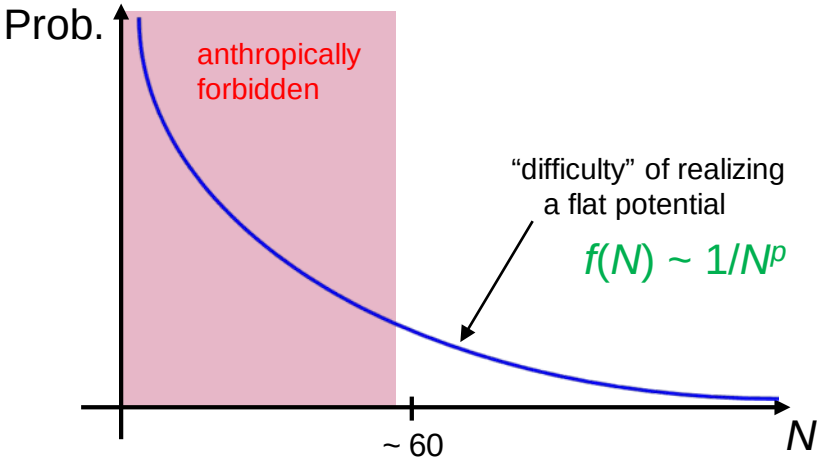
Does this mean there is no slow-roll inflation? ⟹ No!

What is the "cheapest" way to realize the required flatness?

– Fine-tuning initial conditions **or**

– Having (accidentally) a flat portion in the potential → (observable) inflation

⟹ The flatness will not be (much) beyond needed!



$\Omega_{\text{curvature}} > 0$ may be seen

Freivogel, Kleban, Rodriguez Martinez, Susskind ('05)
....
Guth, Y.N. ('12)
....

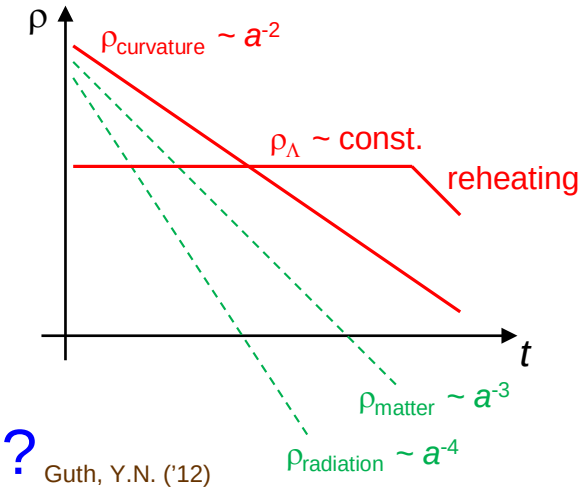
Slow-roll inflation may be "just-so"

- A coherent picture for the early universe *e.g.* Guth, Kaiser, Y.N. ('13)

Problems in small-field (low energy) inflation avoided:

$|\nabla\phi|^2 \to 0$ … Coleman-De Luccia instanton (homogeneity by tunneling)

$|\dot{\phi}|^2 \to 0$ … Early curvature domination (damping effect)



The almost only way to get
a nontrivial universe after bubble nucleation

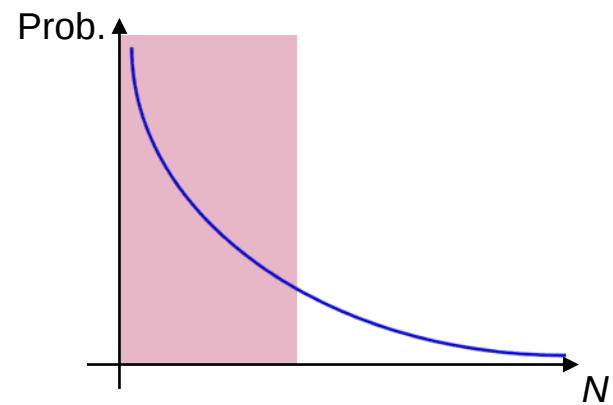
- What can we learn if $\Omega_{curvature} > 0$ is found? Guth, Y.N. ('12)

– Our universe begins with bubble nucleation

– Slow-roll inflation occurs "accidentally"

(without e.g. a shift symmetry over a wide field range)

– No volume weighting in probability



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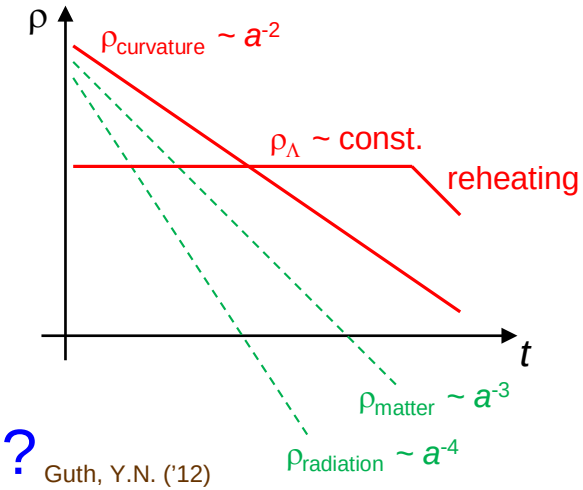

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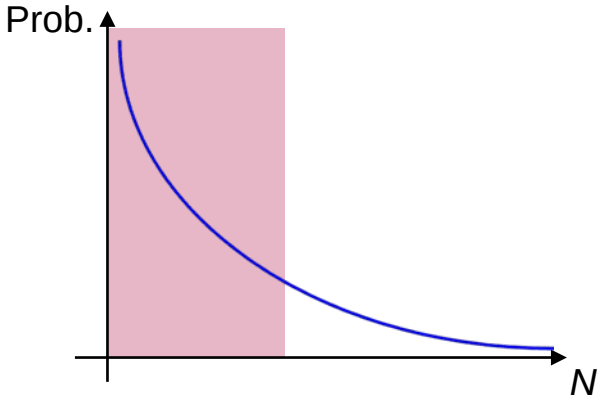


will come back …

Implications

—fundamental physics —

... the multiverse as quantum many worlds

Eternally Inflating Multiverse

Far-reaching implications

… The multiverse is “infinitely large”!

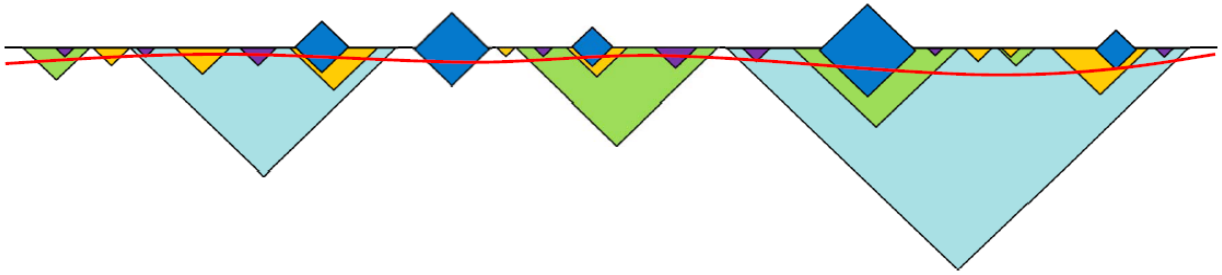
Predictivity crisis!

In an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times. Guth (‘00)

ex. Relative probability of events *A* and *B*

$$P = \frac{N_A}{N_B} = \frac{\infty}{\infty} \;!!$$

Why don’t we just “regulate” spacetime at $t = t_c$ ($\rightarrow \infty$)



… highly sensitive to regularization!! (The measure problem)

The problem consists of several elements

— Problem of infinity

… How is the infinity regulated?

— Problem of arbitrariness

… What is the principle behind the regularization?

— Problem of selecting the state

… What is *the* initial condition of the multiverse? … What is time?

— …

Work addressing various aspects:

Aguirre, Albrecht, Bousso, Carroll, Guth, Linde, Nomura, Page, Susskind, Tegmark, Vilenkin, …

This can be a great opportunity !

Below, my view

Quantum mechanics is essential to answer these questions.

Multiverse = Quantum many worlds

… Breakdown of the general relativistic spacetime picture **at long distances**

Multiverse = Quantum Many Worlds

Y.N., "Physical theories, eternal inflation, and the quantum universe," JHEP 11, 063 ('11) [arXiv:1104.2324]

(see also Bousso, Susskind, PRD 85, 045007 ('12) [arXiv:1105.3796])

— in what sense?

Quantum mechanics is **essential**

The basic principle:

The basic structure of quantum mechanics persists when an appropriate description of physics is adopted

→ Quantum mechanics plays an important role even at largest distances:

The multiverse lives (only) in probability space

Probability in cosmology has the same origin as the quantum mechanical probability

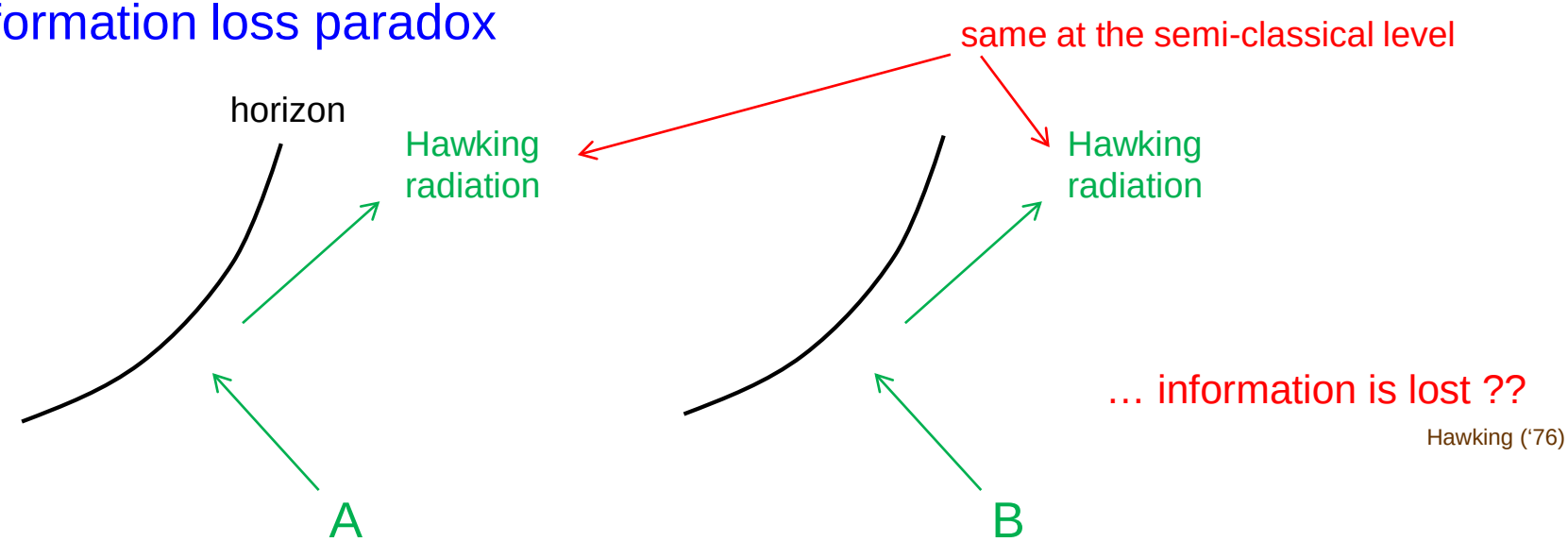
… provide simple regularization

(Anything that can happen will happen *but not with equal probability*.)

Quantum mechanics in a system with gravity

Black Hole

Information loss paradox



… information is lost ??

Hawking ('76)

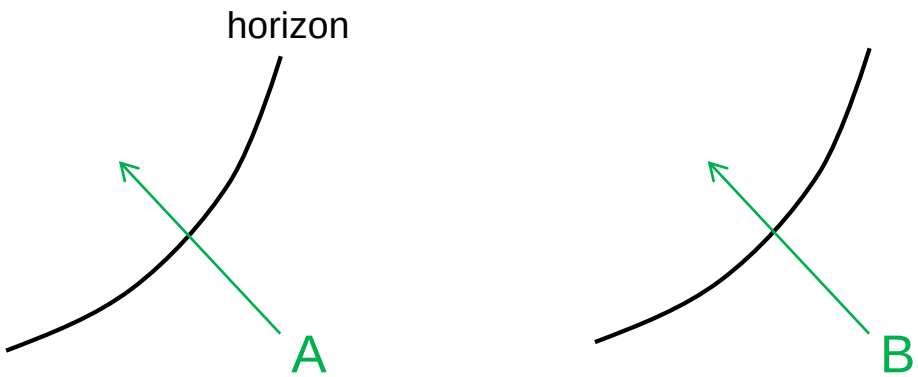
⟹ No

… Quantum mechanically different final states

The whole information is sent back in Hawking radiation (in a form of quantum correlations)

cf. AdS/CFT, classical "burning" of stuffs, …

From a falling observer's viewpoint:



… Objects simply fall in

cf. equivalence principle

- Distant observer:

  Information will be *out*side at late times.

  (sent back in Hawking radiation)

- Falling observer:

  Information will be *in*side at late times.

  (carried with him/her)

Which is correct?

Note: Quantum mechanics prohibits
faithful copy of information (no-cloning theorem)

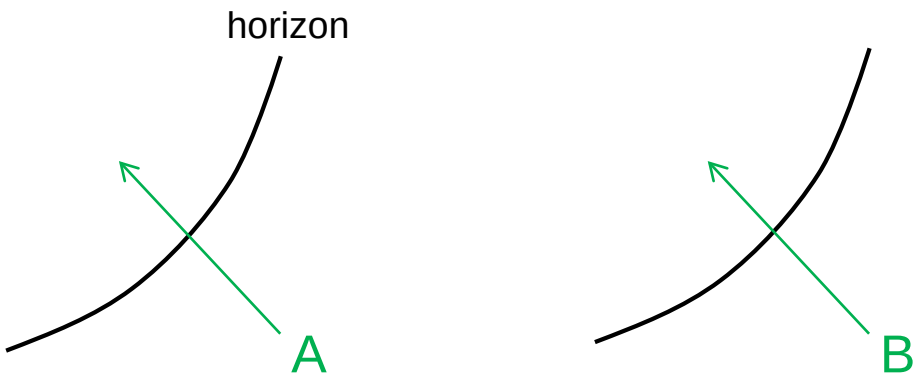
$|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

$|\downarrow\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$

$|\uparrow\rangle+|\downarrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle+|\downarrow\rangle|\downarrow\rangle$ (superposition principle)

$\neq (|\uparrow\rangle+|\downarrow\rangle)(|\uparrow\rangle+|\downarrow\rangle)$

From a falling observer's viewpoint:



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Which is correct?

$\Longrightarrow$ **Both are correct !**

There is no contradiction !

One cannot be *both* distant and falling observers *at the same time*.

… "Black hole complementarity"

Susskind, Thorlacius, Uglum ('93);
Stephens, 't Hooft, Whiting ('93)

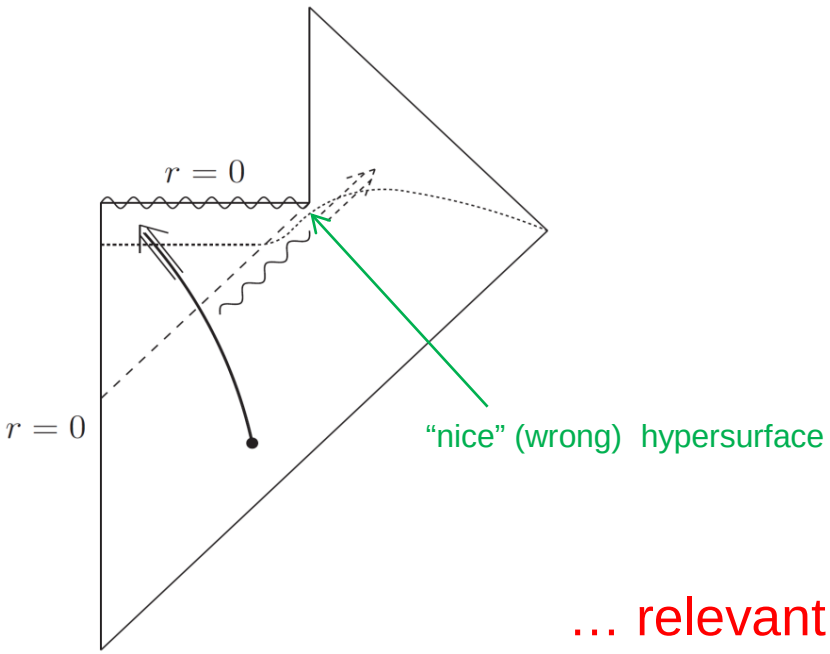
A Lesson:

Including both Hawking radiation and
interior spacetime in a single description is **overcounting** !!

To keep our description of nature to be **local** in space at long distances

(or, at least, to keep approximate locality in the description)

… Equal time hypersurface must be chosen carefully.



… relevant for formulating "measurements"

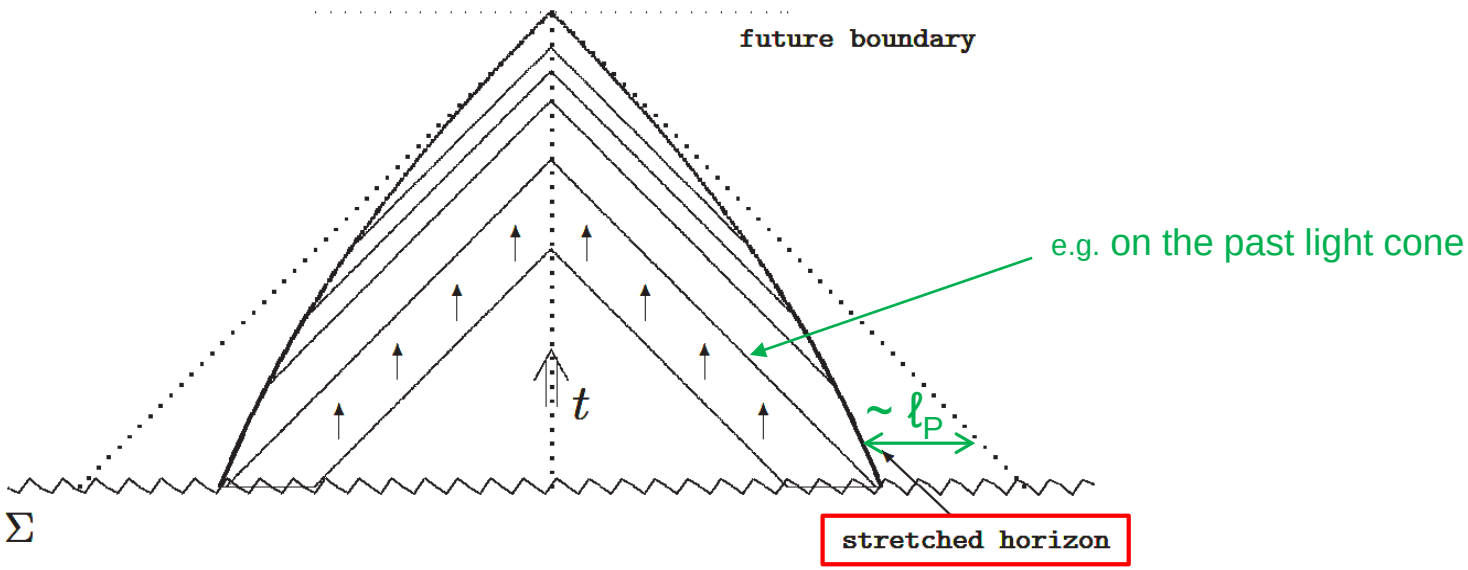
separating into subsystems, the basis for information amplification, …

Now, cosmology (eternal inflation)

… simply “inside-out” !

Including Gibbons-Hawking radiation, there is **no outside spacetime** !!

Specifically, the state can be defined to represent **only**
the spatial region **in and on the stretched (apparent) horizons**
as viewed from a freely falling reference frame. Y.N. (’11)



What is the multiverse? $\longrightarrow$ probability !!

Bubble nucleation … probabilistic processes

usual QFT: $\Psi(t=-\infty) = \left|e^+e^-\right\rangle \quad \to \quad \Psi(t=+\infty) = c_e \left|e^+e^-\right\rangle + c_\mu \left|\mu^+\mu^-\right\rangle + \cdots$

multiverse: $\Psi(t=t_0) = \left|\Sigma\right\rangle \quad \to \quad \Psi(t) = \cdots + c\left|\overset{321}{\underset{\rho_\Lambda}{\bigcirc}}\right\rangle + c'\left|\overset{321}{\underset{\rho'_\Lambda}{\bigcirc}}\right\rangle + \cdots + d\left|\overset{41}{\bigcirc}\right\rangle + \cdots$

eternally inflating

each term representing only the region within the horizon

- Probability in cosmology has the origin in quantum mechanics

  … (a suitable generalization of) the Born rule will give the probability

Multiverse = Quantum many worlds

- Global spacetime is an emergent (and "redundant") concept

  … probability is more fundamental

  — counting observers (with equal weight) may vastly overcount d.o.f.

→ provides natural and effective "regularization"

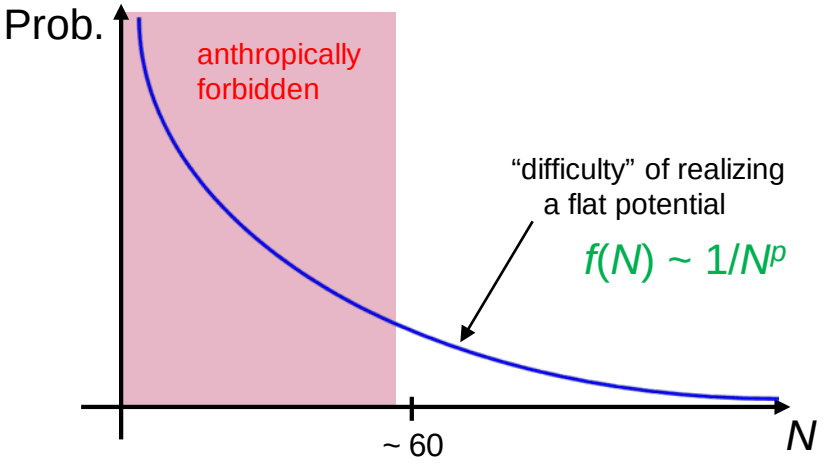
⟹ The multiverse lives **only** in probability space !!

Implications

—future experiments —

... new places to search for new physics

- Argument for “just-so” inflation



- What can we learn if $\Omega_{\text{curvature}} > 0$ is found ? Guth, Y.N., arXiv:1203.6876
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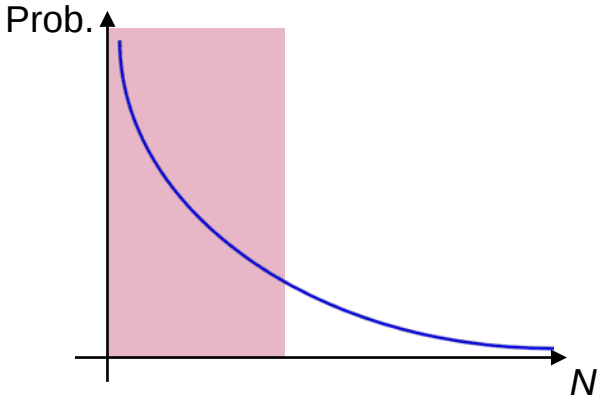

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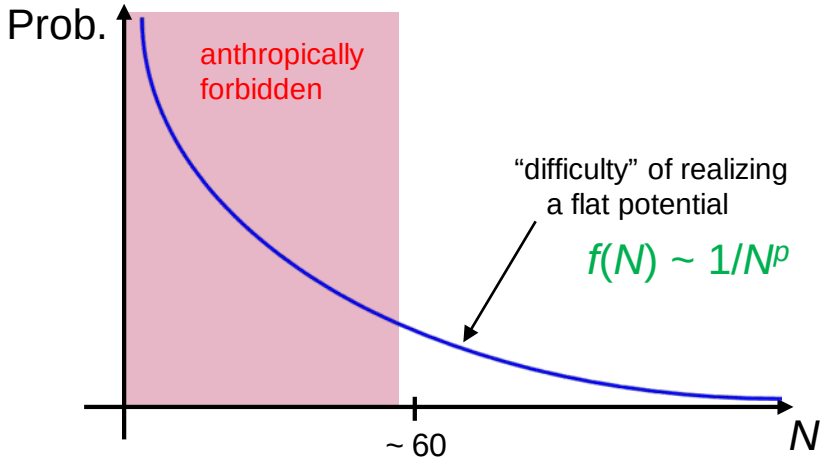

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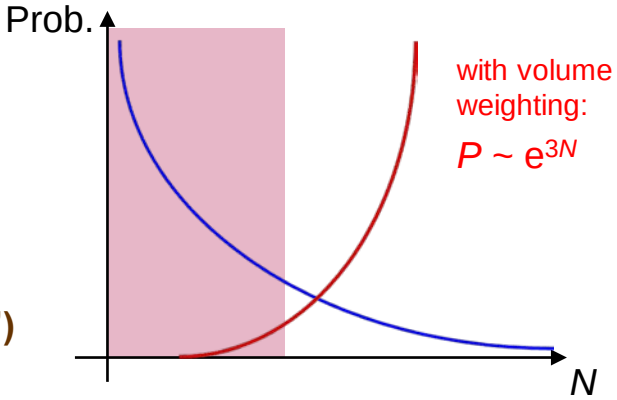
  – No volume weighting in probability

  (→ Global spacetime in general relativity is an "artifact")



… nontrivial connection between quantum gravity and observation

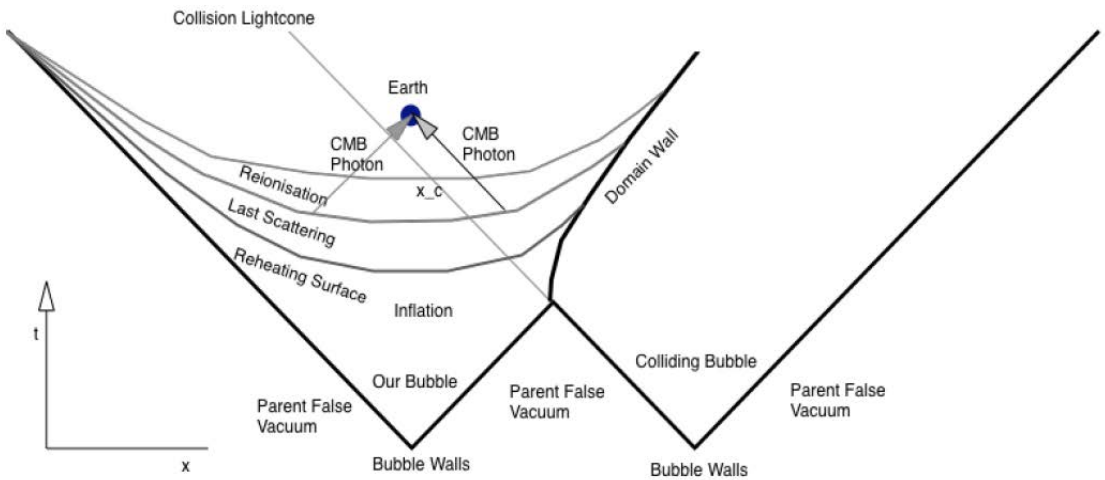
(Slow-roll) Inflation may be "just so"

… opens the possibility of many dramatic signals

- Nonzero spacetime curvature

  e.g. 21 cm might probe down to $\Omega_{curv} \sim 10^{-4}$

- Cosmic bubble collisions e.g. Kleban, arXiv:1107.2593



Note: the number of relevant collisions ~ e^{-N}

… may leave signals in CMB and large scale structure

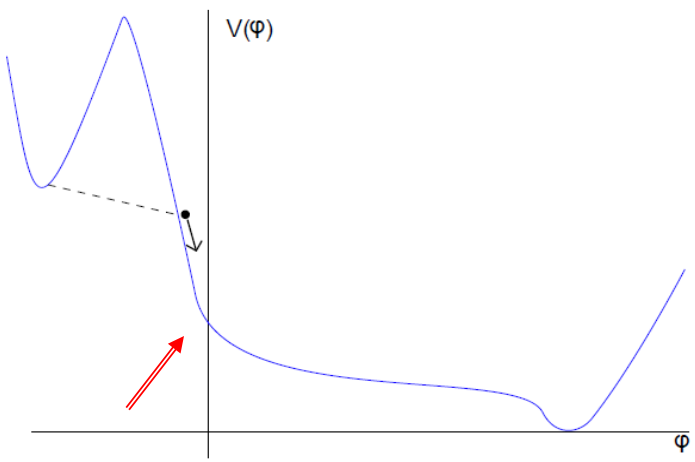
- Tunneling from a lower dimensional vacuum Graham, Harnik, Rajendran, arXiv:1003.0236

  … may lead to signals in CMB through anisotropic curvature

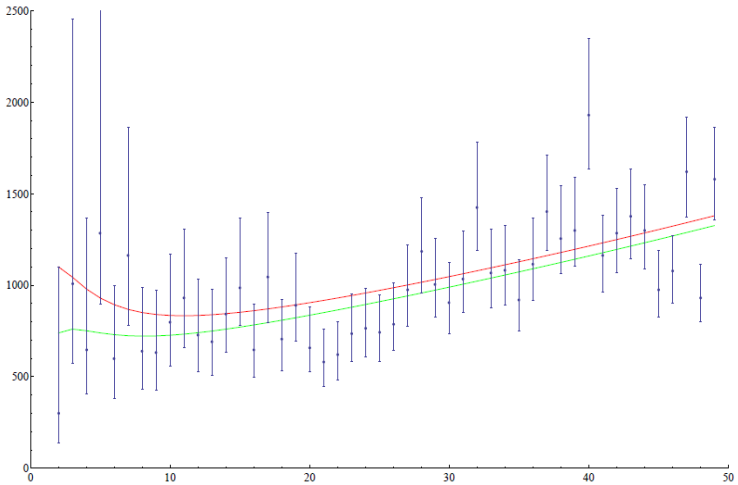
- Suppressions of low ℓ

Freivogel, Kleban, Rodriguez Martinez, Susskind, hep-th/0505232, arXiv:1404.2274;
Bousso, Harlow, Senatore, arXiv:1309.4060, arXiv:1404.2278; …

… may be able to probe a faster-roll phase during the onset of inflation



In PLANCK data?



- Remnants of the pre-inflationary history

ex. Peccei-Quinn phase transition before inflation

→ may lead to a tilt between the rest frames of CMB and matter

D.B. Kaplan, Nelson, arXiv:0809.1206

Detection of any of these signals would provide
evidence for the multiverse & information about the structure of spacetime

Can anthropic explain *everything*?

⟹ **No !**

ex. Strong CP problem in QCD

θ_{QCD} already way too small ($< 10^{-10}$)

… mechanism needed → "axion"

(more "robust" problem than the hierarchy problem)

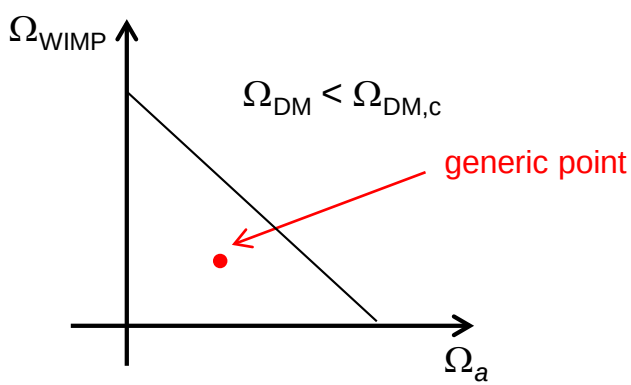
Implication for Dark Matter (DM)

Axion DM with *any* values of $f_a > 10^{10}$ GeV … controlled by $\Omega_{DM} < \Omega_{DM,c}$

Linde ('88); Tegmark, Aguirre, Rees, Wilczek ('05)

→ motivates new experiments

WIMP?
— possible



⟹ Multi-component DM!

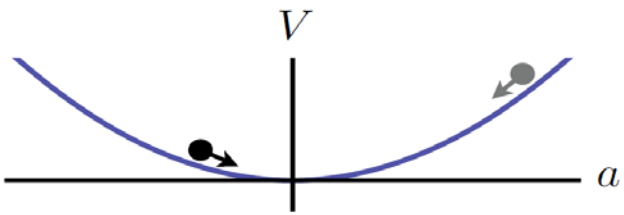
Axion (DM) with Planck/GUT scale f_a

… attractive possibility suggested by string theory e.g. Svrček, Witten, hep-th/0605206

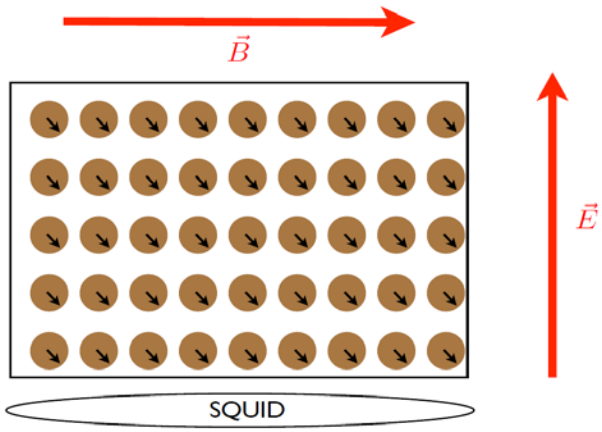
(outside the standard "axion window")

- Solid state magnetometry Budker, Graham, Ledbetter, Rajendran, Sushkov ('13)

Axion DM

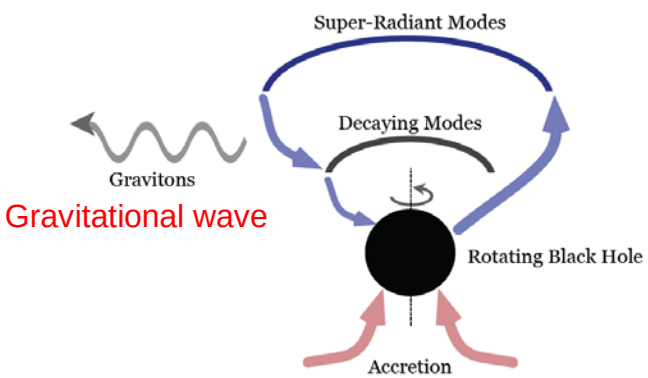


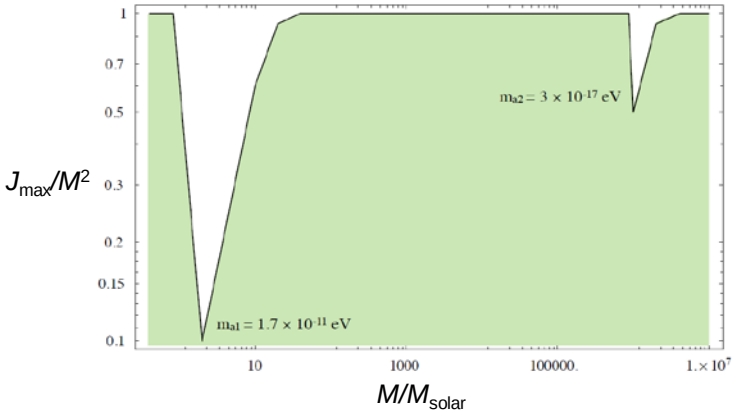
→ time-dependent EDMs



- Cosmic (black hole) detector Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ('09)

Super-radiance (black hole-axion "bound state")



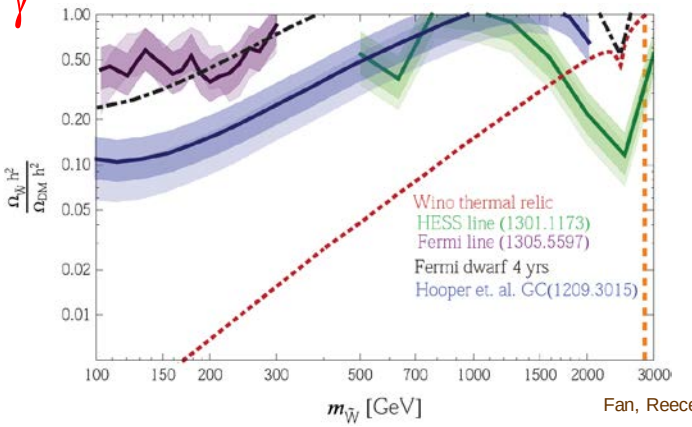


Wino DM (as a component)

… opportunity for discoveries in “conventional” searches

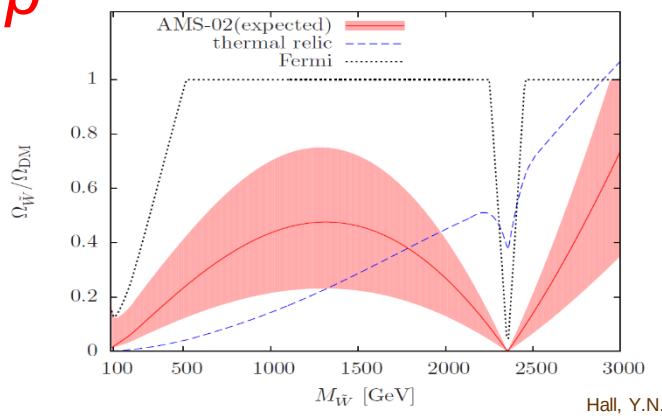
- Indirect detection

γ



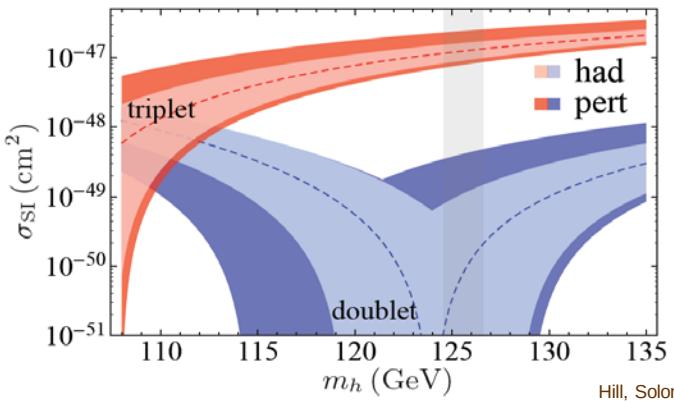
Fan, Reece ('13)

$\bar{p}$



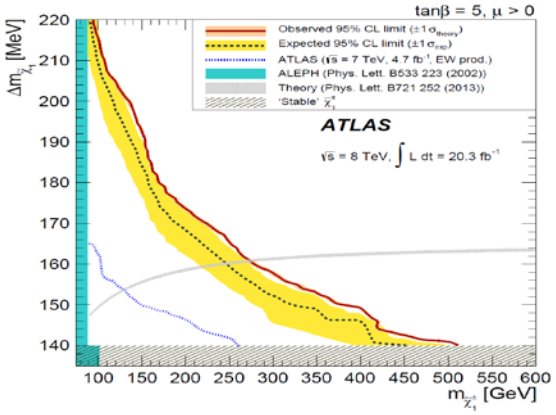
Hall, Y.N., Shirai ('12)

- Direct detection



Hill, Solon ('13)

- Colliders (HL LHC, 100 TeV coll., …)



ATLAS ('13)

Summary

The revolutionary change of our view

Our universe is a part of the multiverse

(suggested by **both** observation **and** theory)

Possible to have wide range of implications

particle physics, cosmology, quantum gravity, …

black hole physics, eternal inflation, …

~~Naturalness~~ ⟹ Typicality

Does this affect our considerations of new physics?

… depends on the distribution of parameters in the multiverse

The LHC results (so far) seem to suggest that it does.

This does **not** mean that we cannot make progress

or there is no new physics at the TeV scale

Crucial to have a wide range of (unprejudiced) experimental programs