The Multiverse

Abstract from organizers:

The presentation is expected to describe the idea of the multiverse paradigm and report on the implications and signatures for particle physics, in particular on the issue of the Scalar boson mass, and cosmology

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
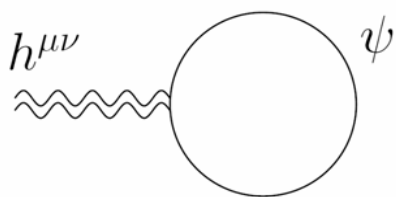## of the view on spacetime and gravity

• Holographic principle

• Horizon complementarity

• Multiverse as quantum many worlds

• …

… implications on particle physics and cosmology

Shocking news in 1998

Expansion of the universe
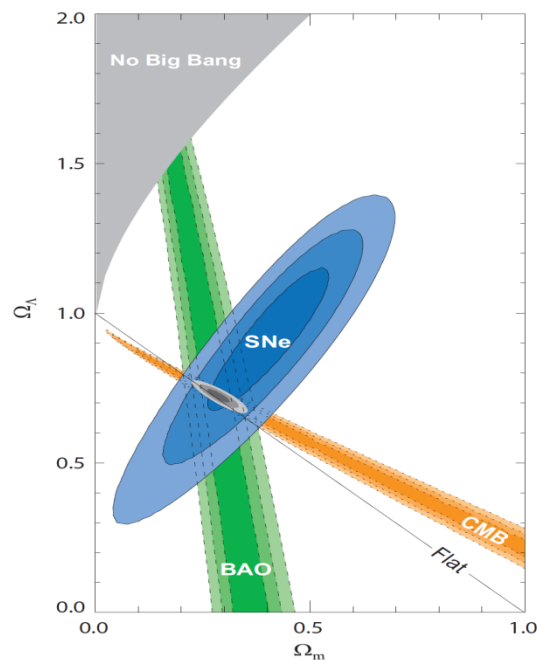is accelerating!

$$\Lambda \neq 0 \ !$$

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

Observationally,

$$\rho_\Lambda \sim (10^{-3} \text{ eV})^4 \qquad \text{Naïve estimates } O(10^{120}) \text{ too large}$$
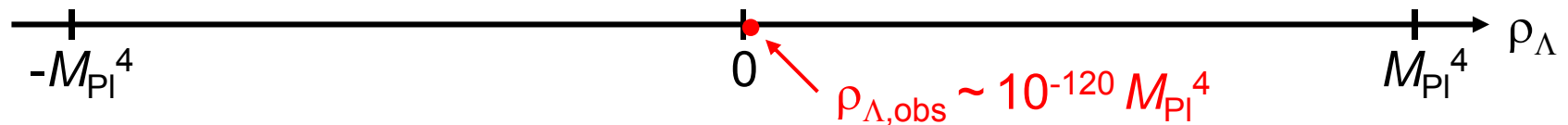
Also, $\rho_\Lambda \sim \rho_{matter}$ — Why now?

Nonzero value completely changes the view!

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

$-M_{Pl}^4$ 0 $\rho_{\Lambda,obs} \sim 10^{-120} M_{Pl}^4$ M_{Pl}^4 ρ_Λ

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

$\Longrightarrow$ Wait!

Is it really unnatural to *observe* this value?

No observer   0   No observer ρ_Λ
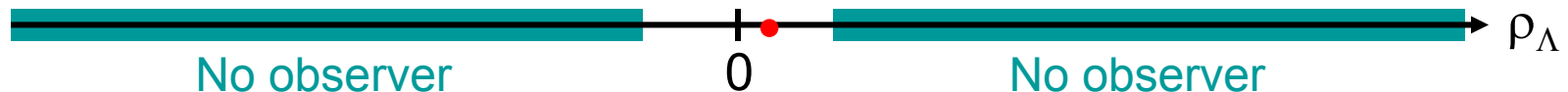
It is quite "natural" to observe $\rho_{\Lambda,obs}$,
     as long as different values of ρ_Λ are "sampled"

Weinberg ('87); also Banks, Linde, …
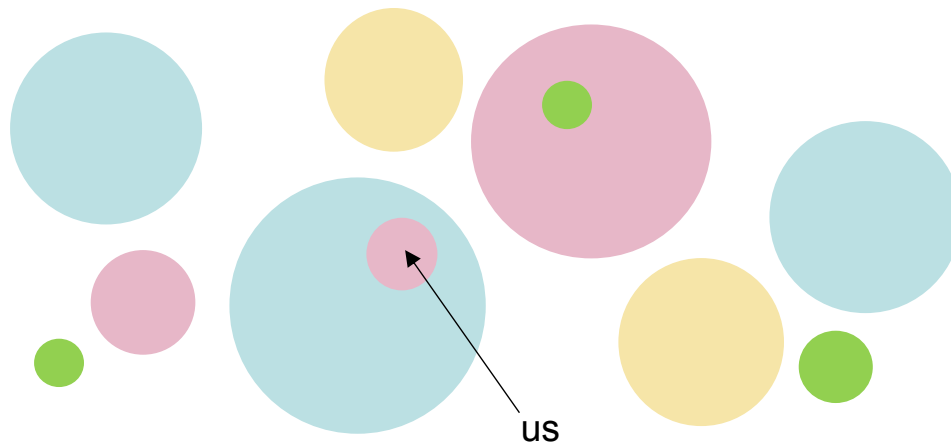
Theory also suggests

- ## String landscape

  Compact (six) dimensions   ex. $O(100)$ fields with $O(10)$ minima each

     $\rightarrow$ huge number of vacua $\rightarrow O(10^{100})$ vacua

- ## Eternal inflation

  Inflation is (generically) future eternal $\rightarrow$ populate all the vacua

us

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

$\Longrightarrow$ 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?

- Observational / experimental (test, new scenarios, …)
- Fundamental physics (spacetime, gravity, …)

  Multiverse = Quantum many worlds   Y.N., arXiv:1104.2324; Bousso, Susskind, arXiv:1105.3796

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Implications
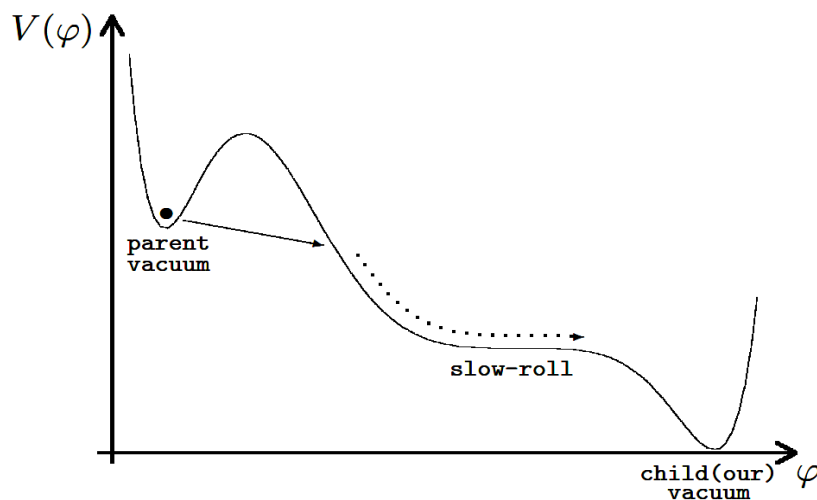## —cosmology / particle physics —
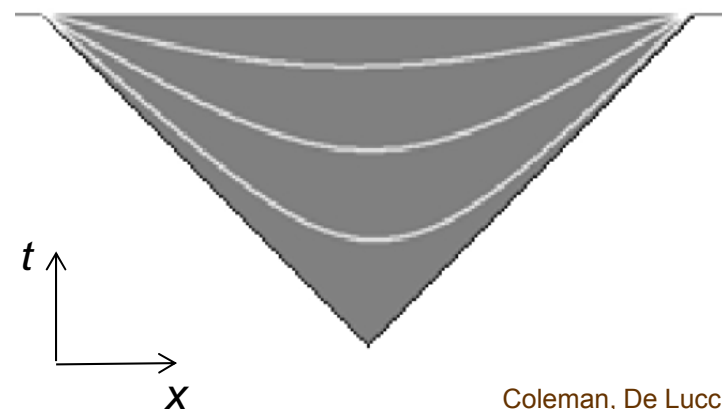
... new ways of thinking physics

What observations?

In Cosmology

Our universe is a bubble formed in a parent vacuum:

… Infinite **open** universe

(negative curvature)

Coleman, De Luccia ('80)

Why is our universe so flat?

If it is curved a bit more, no structure / observer

→ anthropic !

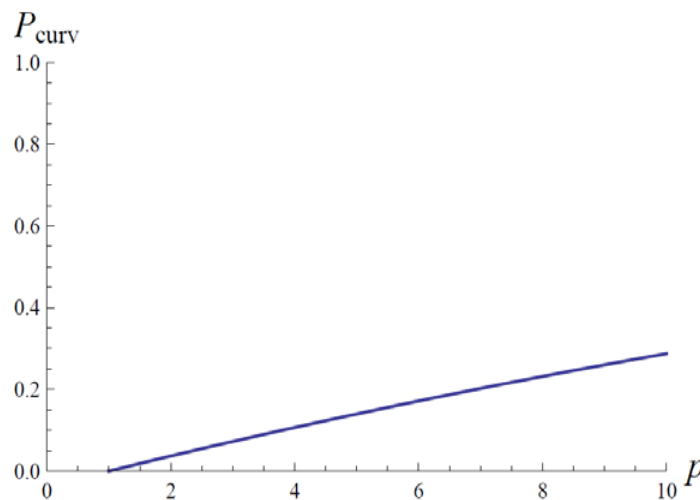## What is the "cheapest" way to realize the required flatness?

- Fine-tuning initial conditions
- Having a (accidentally) flat portion in the scalar potential

→ (Observable) inflation

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

"difficulty" of realizing a flat potential

$f(N) \sim 1/N^p$

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

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

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

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)

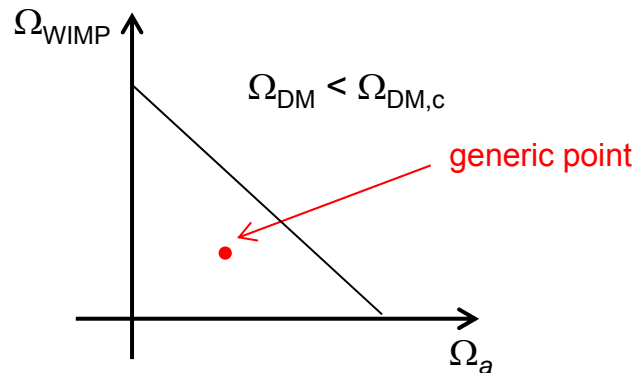## Implication for Dark Matter (DM)

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 (see later)

WIMP?
— possible

Ω_{WIMP}

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

generic point

Ω_a

⟹ Multi-component DM !

Particle Physics

Anthropic (could) affects how our universe looks

→ 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 $v > 2\, v_{obs}$ Damour, Donoghue ('07)

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

Must weak scale supersymmetry (not) exist?

… the scale of SUSY masses $\tilde{m}$ determined by statistics

$$d\mathscr{P} \sim f(\tilde{m})\, \frac{v^2}{\tilde{m}^2}\, d\tilde{m}$$

… probability function

ex. Under simple assumptions

— EW scale selected environmentally
— SUSY breaking field not singlet
— no mechanism to suppress μ
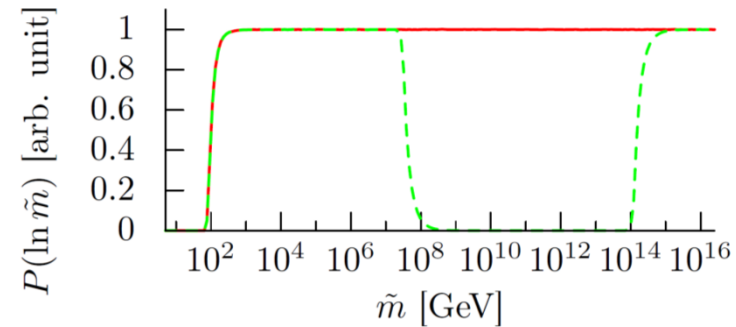
Y.N., Shirai, arXiv:1407.3785

$\tilde{m}$ ~ (10 – 1000) TeV
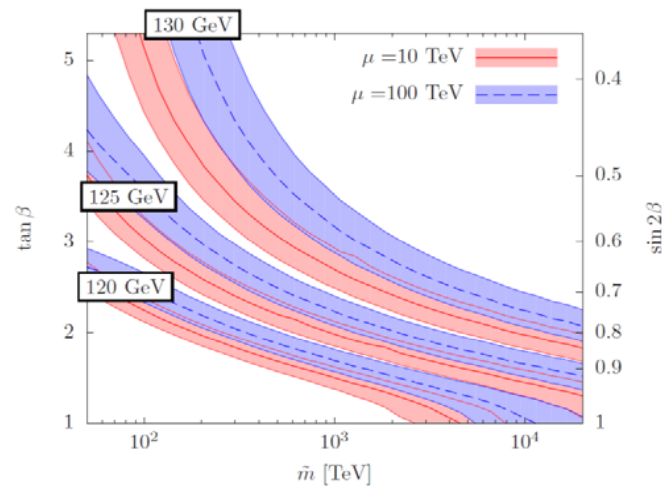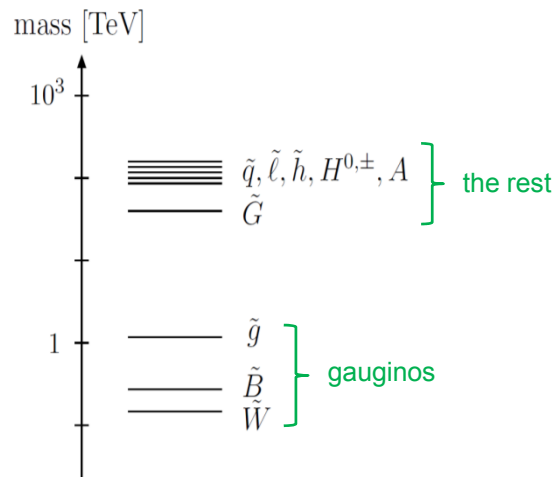
Spread / mini-split supersymmetry

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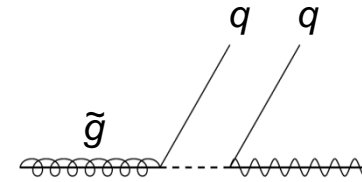Villadoro ('12); Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski ('12)

M_H ~ 126 GeV
"automatic"

… preserves successful gauge coupling unification, $\tilde{W}$ (a component of) the DM

Gluino signals

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

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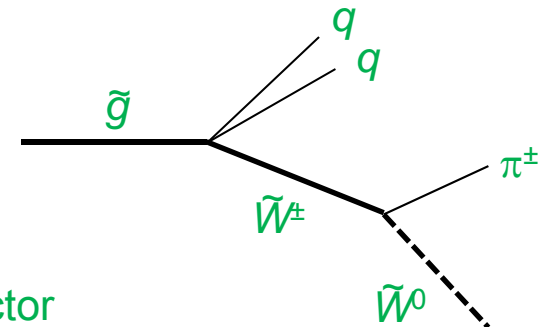

… $r_* \gtrsim O(10) \rightarrow$ long-lived (displaced) gluino signatures

Winos are (nearly-degenerate) co-LSPs

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

$\Longrightarrow$ Decay chain with two long-lived particles

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

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

Other signals include

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

Implications
—*future experiments* —

... new places to search new physics

(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 $\Omega_{curv} \sim 10^{-4}$
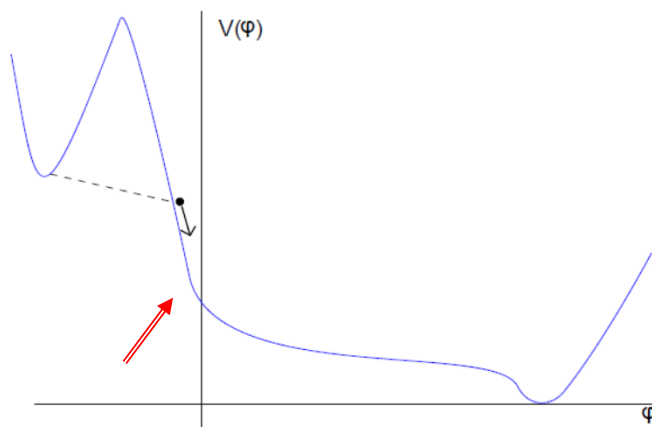
- ## Cosmic bubble collisions   e.g. Kleban, arXiv:1107.2593
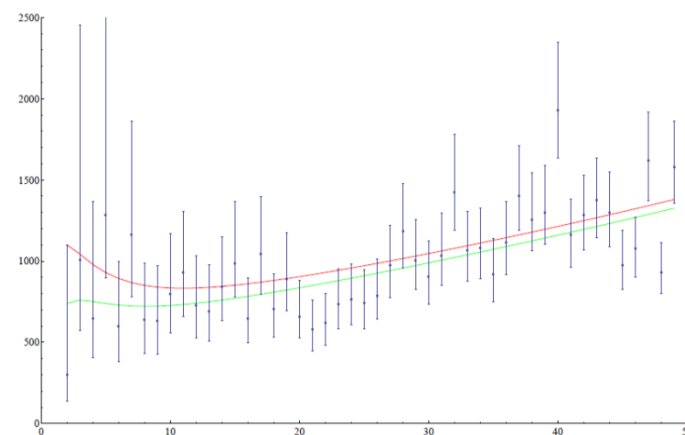
  … may leave signals in CMB and large scale structure

- ## Suppressions of low ℓ Freivogel, Kleban, Rodriguez Martinez, Susskind ('05,'14); Bousso, Harlow, Senatore ('13,'14)

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

In PLANCK data?

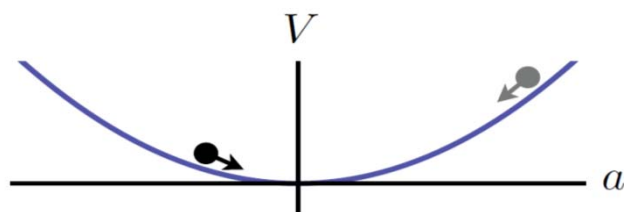(significance will increase if BICEP2 data is confirmed)

Axion (DM) with Planck/GUT scale f_a

… attractive possibility suggested by string theory   e.g. Svrček, Witten, hep-th/0605206
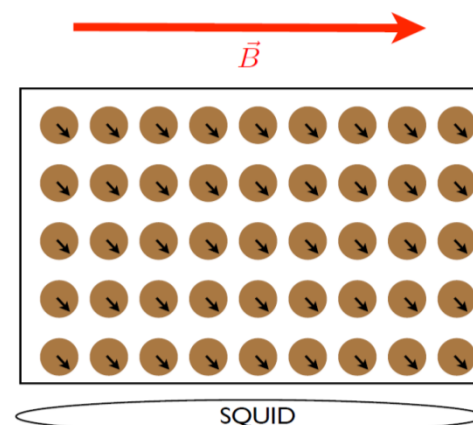
(outside the standard "axion window")

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

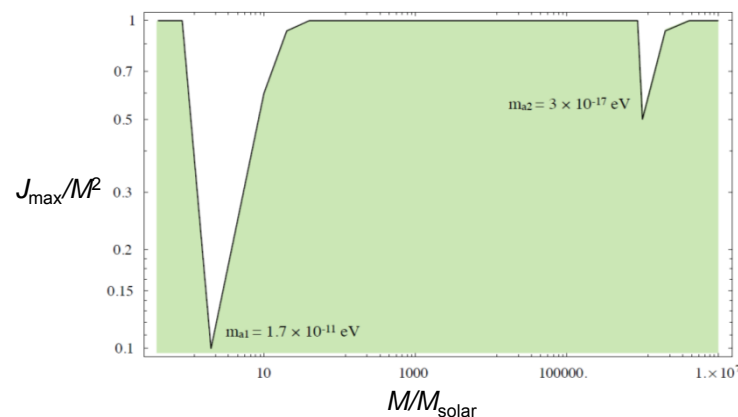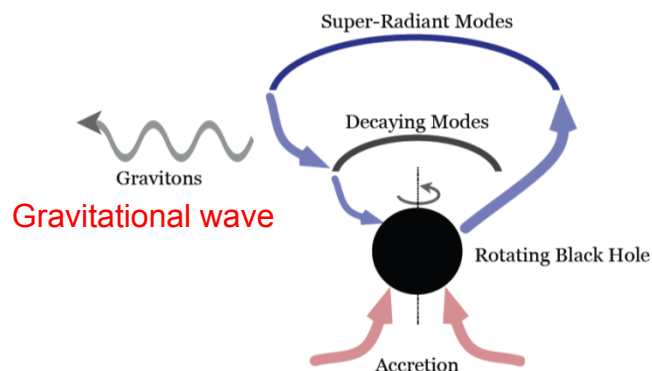Axion DM

$\rightarrow$ time-dependent EDMs

talk by Rajendran ('13)

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

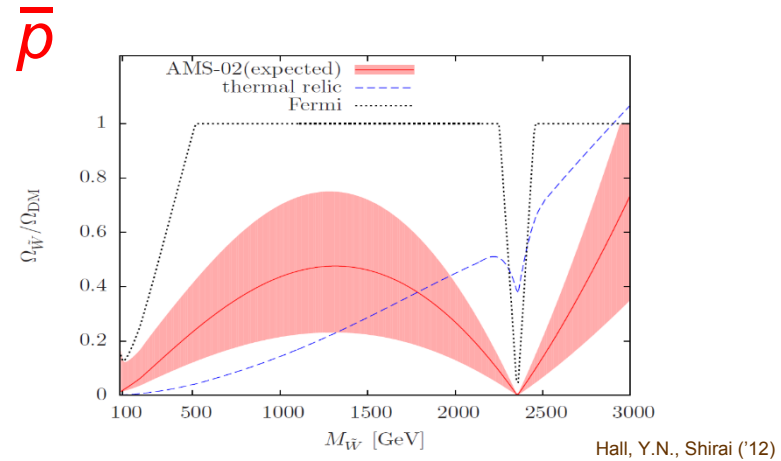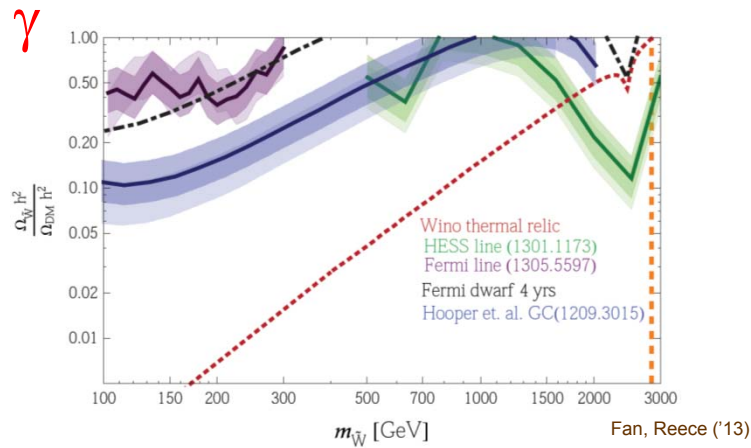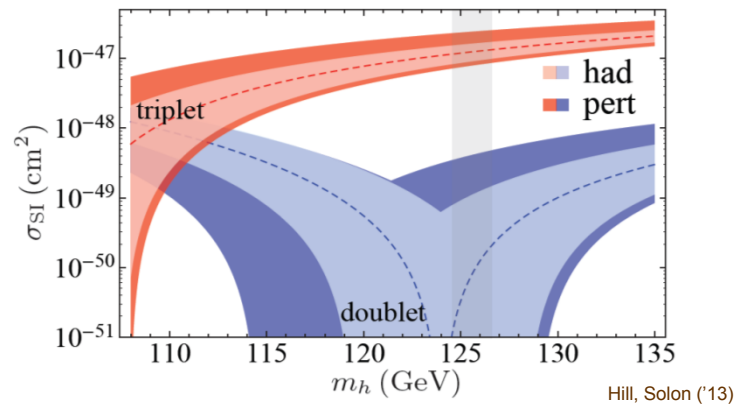Super-radiance (black hole-axion "bound state")

Gravitational wave

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)
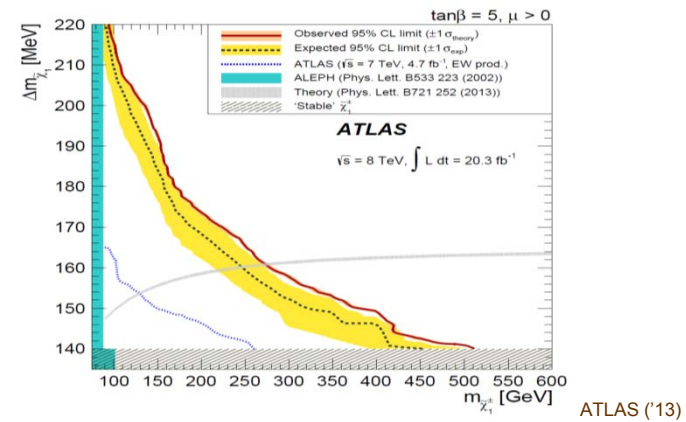
Summary

The revolutionary change of our view in the 21st century

Our universe is a part of the multiverse

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

Possible to have wide range of implications

cosmology, particle physics, quantum gravity, …

black hole physics, eternal inflation, …

~~Naturalness~~ $\Longrightarrow$ 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