Concluding Remarks — Cosmology (Neutrino, Gravity and Black Holes)

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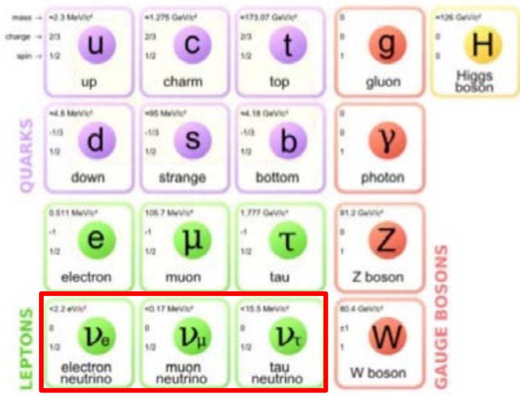
Plan

- Standard Model ($\supset$ Neutrinos)
- Beyond the Standard Model
- Black Holes
- Cosmology

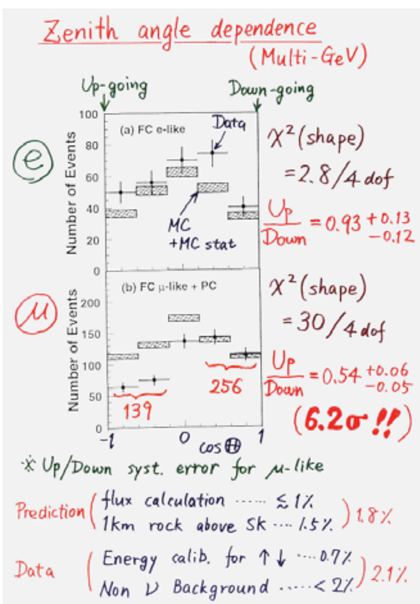
apologies for omissions…

Standard Model (⊃ Neutrinos)

The parameters are determined (almost) completely, except for



Dramatic progress in the past 20 years



Kajita 1998

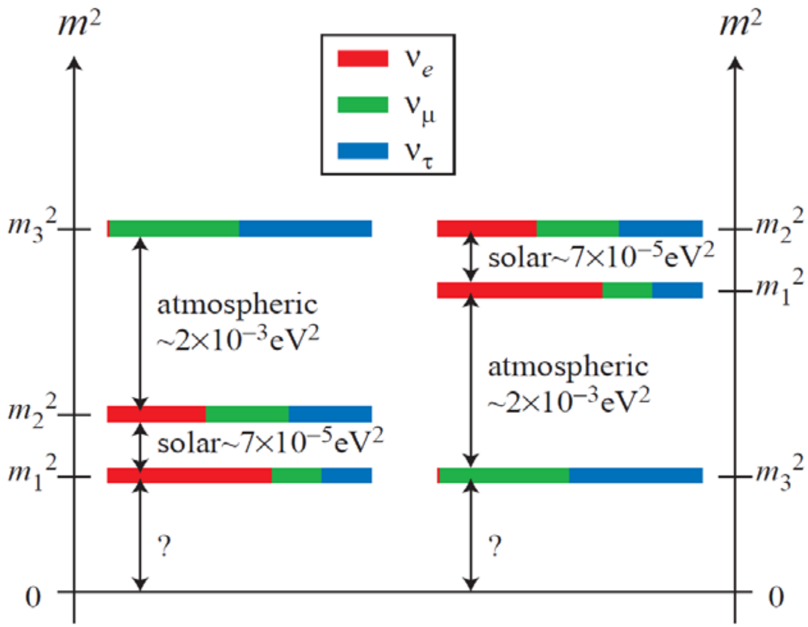
⟹

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

PDG 2018

Some basic properties are still unknown

- Dirac or Majorana
- absolute masses
- mass ordering
- *CP* violation or not
- 3 neutrinos or more (sterile neutrinos)
- …



Petcov's talk

Oscillation experiments are sensitive only to mass differences

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

Other experiments, including cosmological observations, are crucial

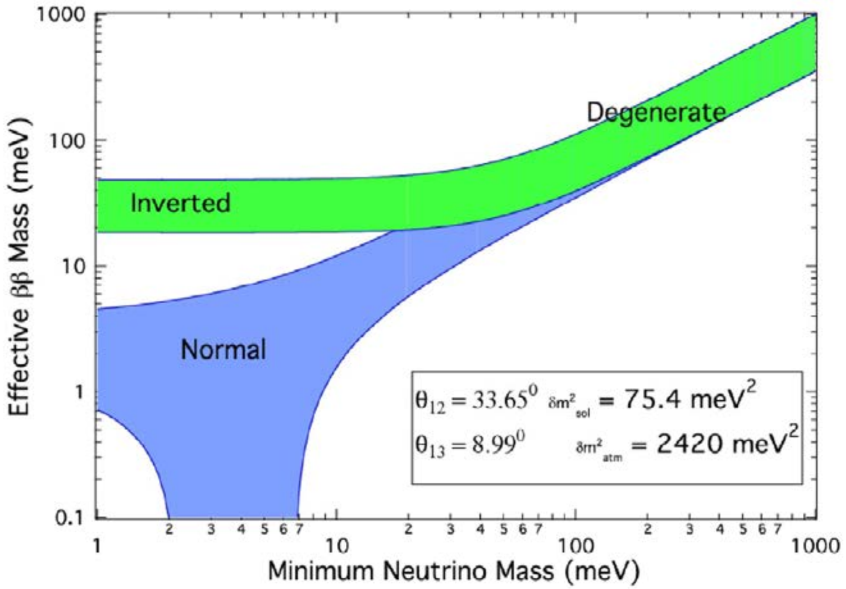
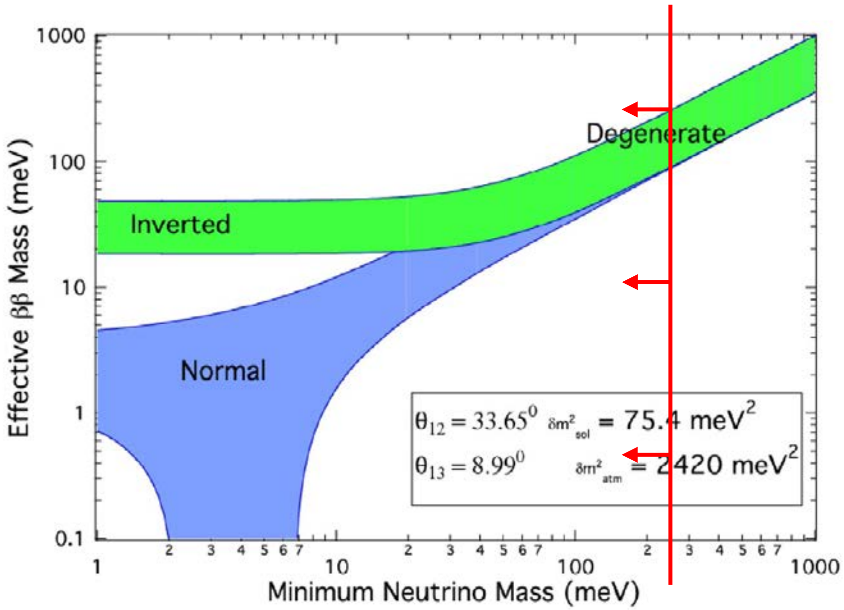


image: IceCube PINGU Collaboration

Other experiments, including cosmological observations, are crucial



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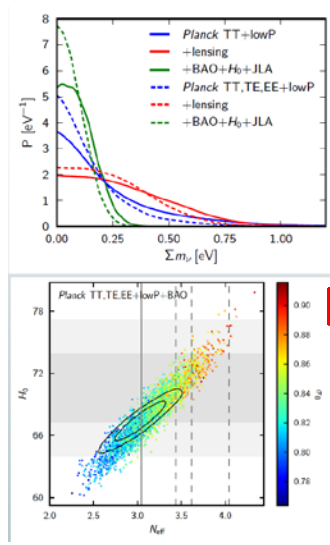


$\sum m_\nu < 0.23\,\mathrm{eV}$
(95%) is from
TT+lowP+lensing
+ext *[P15 XIII]*

$\Omega_\nu h^2 < 0.0025$
(slight tightening
With TE & EE)

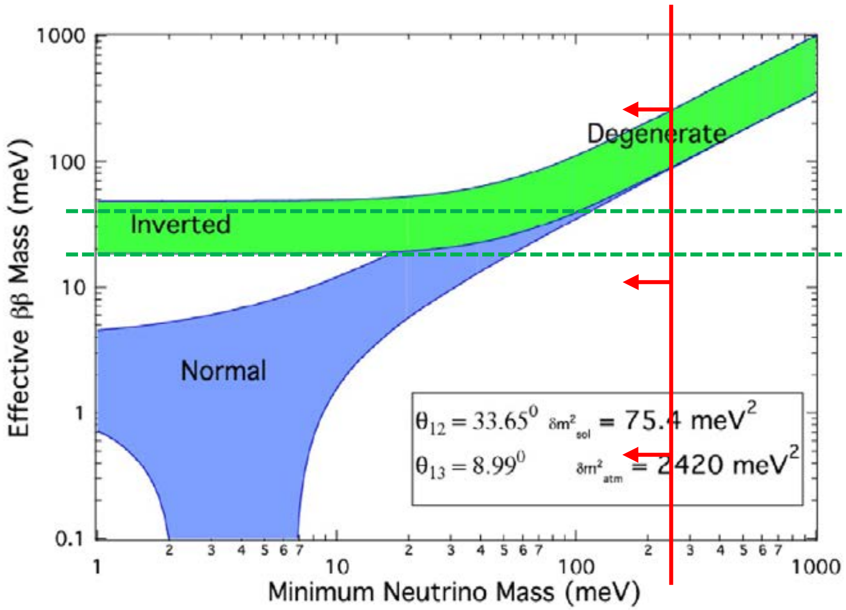
$N_{eff} = 3.15 \pm 0.23$ → constrains extra neutrinos

$N_{eff} > 0$ at ~ 15σ
$N_{eff} = 4$ excluded at 3-5 σ (P)

Large N_{eff} would allow larger H_0 & alleviate tension with direct measurement, but would require large σ_8

Bouchet's talk
also Hoeneisen's talk

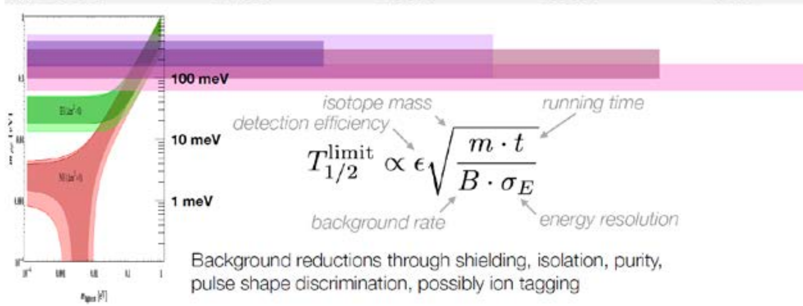
Other experiments, including cosmological observations, are crucial



Next generation experiments ~ 15-40 meV

image: IceCube PINGU Collaboration

	EXO PRL 120 072701 (2018)	CUORE PRL 120, 132501 (2018)	GERDA/Majorana Eur. Phys. J. C78 (2018) 388	KamLAND-Zen PRL 117, 082503 (2016)
	^{136}Xe	^{130}Te	^{76}Ge	^{136}Xe
	TPC	Bolometer	Solid state	Scintillator
Exposure [kg-yr]	175	86	82	504
σ_E [keV]	30	5	3-3.6	100
$T_{1/2}$ @ 90% CL	1.8×10^{25}	1.5×10^{25}	1.1×10^{26}	1.1×10^{26}
mββ @ 90%CL	147-398	110-520	100-300	61-165

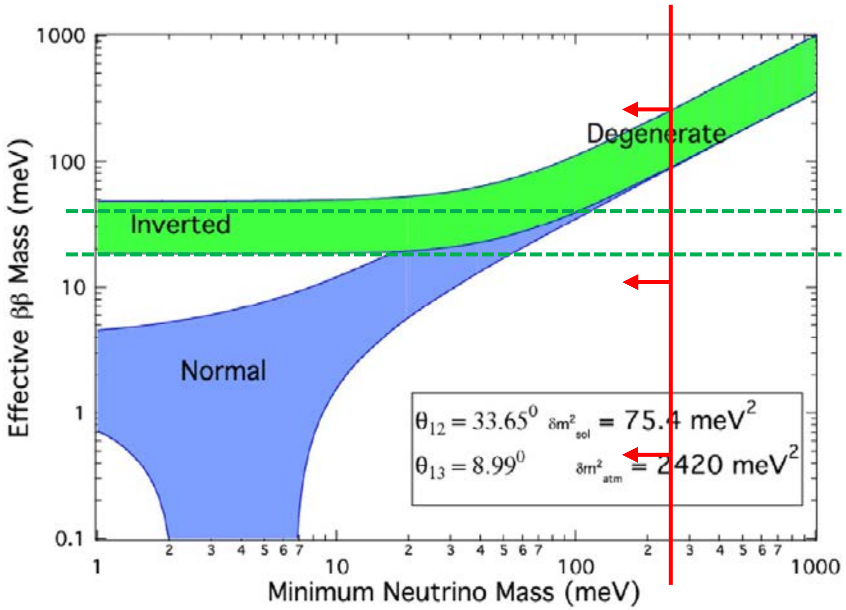


$$T^{\text{limit}}_{1/2} \propto \epsilon \sqrt{\frac{m \cdot t}{B \cdot \sigma_E}}$$

Background reductions through shielding, isolation, purity, pulse shape discrimination, possibly ion tagging

Messier's talk

Other experiments, including cosmological observations, are crucial



Next generation experiments ~ 15-40 meV

image: IceCube PINGU Collaboration

- Leptonic *CP* violation → Leptogenesis
- sterile neutrinos (still possible, despite constraints from BBN etc)
- …

Beyond the Standard Model

- Hierarchy problem → New physics at ~TeV
- Unification
- Dark Matter
- Dark Energy
- Strong *CP* problem → axion, …
- Inflation, or something that replaces it
- Baryogenesis
- Gravity
- ….

Beyond the Standard Model

(– Hierarchy problem → New physics at ~TeV)

(– Unification)

– Dark Matter

(– Dark Energy)

– Strong *CP* problem → axion, …

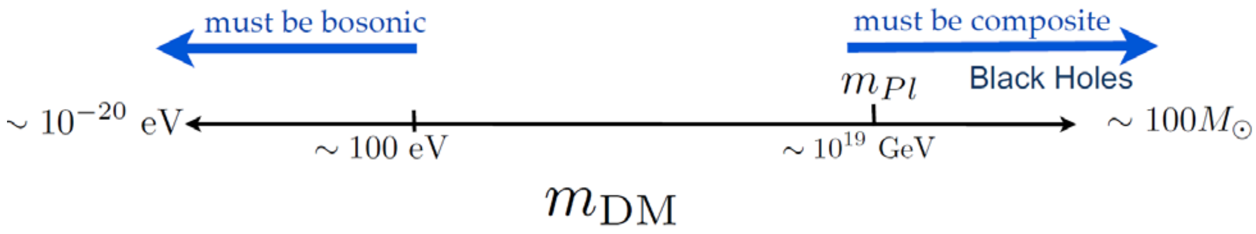
– Inflation, or something that replaces it

(– Baryogenesis)

– Gravity

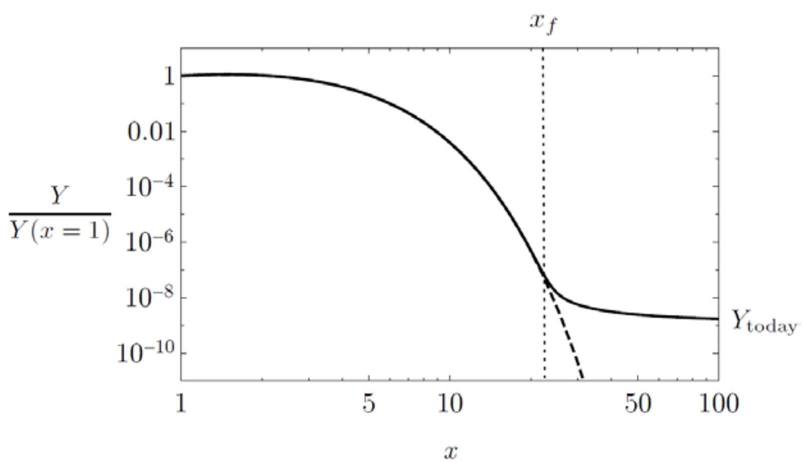
– ….

Dark Matter



Carena's talk

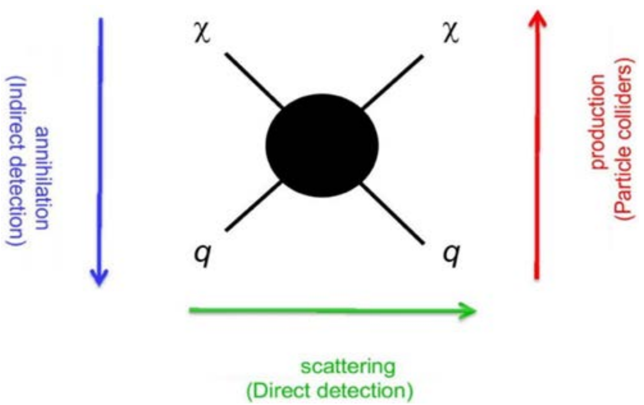
Conventional candidate … WIMP

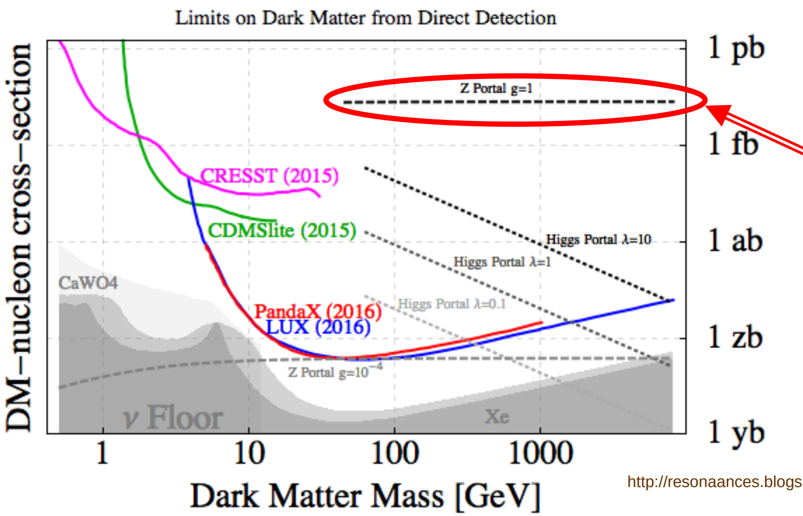


… required annihilation cross section

$$\sigma \sim \frac{1}{\mathrm{TeV}^2}$$

WIMP "miracle" … not too miraculous

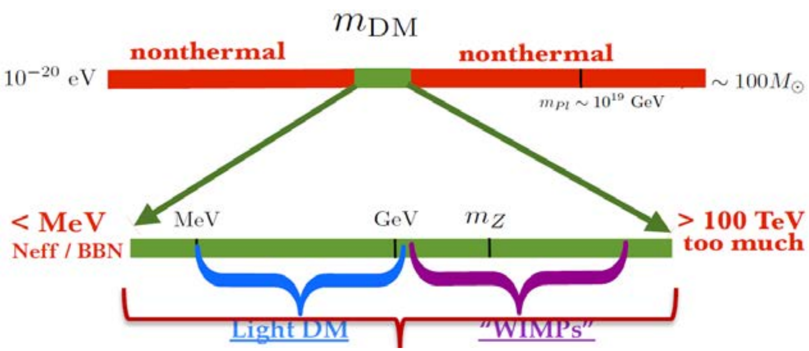




http://resonaances.blogspot.com/2016/

Also

$$\sigma \sim \frac{g^4}{m_{\rm DM}{}^2} \sim \frac{1}{\rm TeV^2}$$



Carena's talk

Moreover, the existence of new physics at the TeV scale is not guaranteed

$\rho_{matter} \sim \rho_\Lambda \neq 0$ suggests vast landscape / the multiverse

talk by Y.N.

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

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

Does this mean that there is no weak scale supersymmetry?

— No !

The scale of superparticle masses are determined by statistics

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

$f(\tilde{m}) \sim \tilde{m}^{p-1}$

It can be at the TeV scale, but could be higher (~ 100 TeV, Planck scale, …)

A simple scenario

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

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

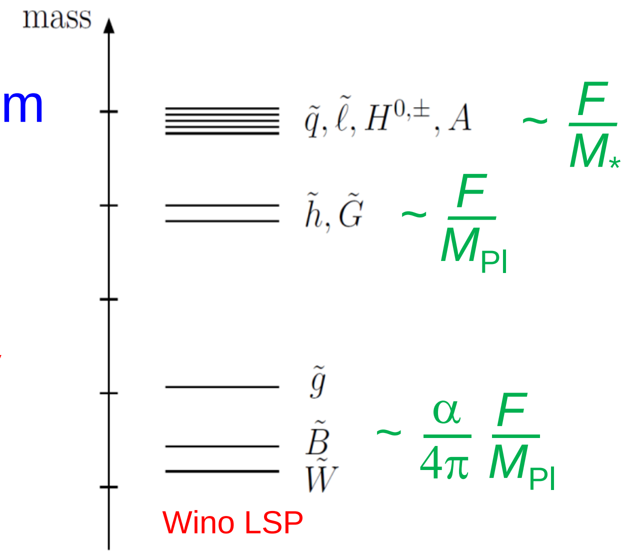
e.g. the string scale

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

⟶ "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);
….
Y.N., Shirai ('14)

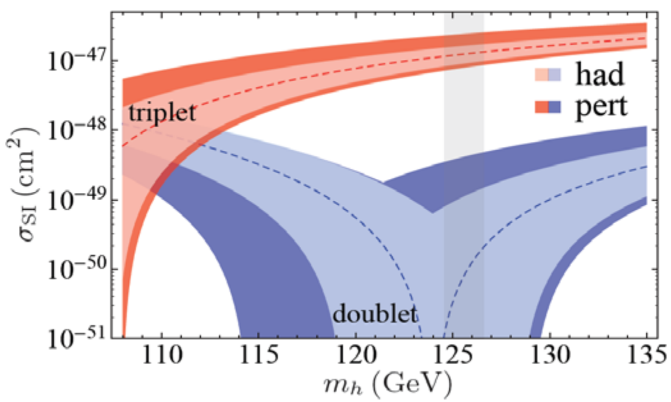
$\tilde{m} \sim (10^2 - 10^4)$ TeV



Wino LSP

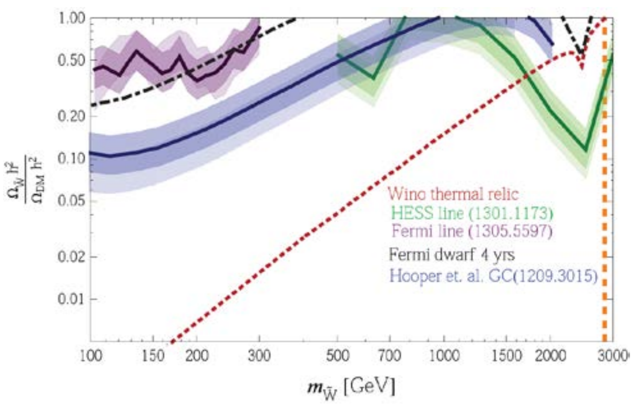
Not easy to detect WIMP (even if $\Omega_{WIMP} = \Omega_{DM}$; see later)

Direct detection



Hill, Solon ('13)

Indirect detection



Fan, Reece ('13)

Axion is more "robust"

Can anthropic explain *everything*? $\Longrightarrow$ **No!**

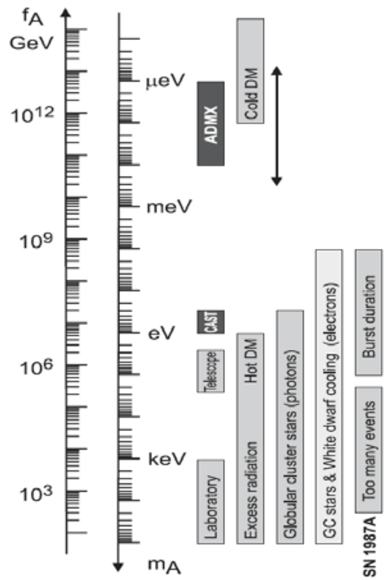
ex. Strong CP problem in QCD

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

… mechanism needed → "axion"

(more "robust" problem than the hierarchy problem)

Implication for axion dark matter



$f_a \gg 10^{12}$ GeV disfavored by cosmology (DM overabundance)

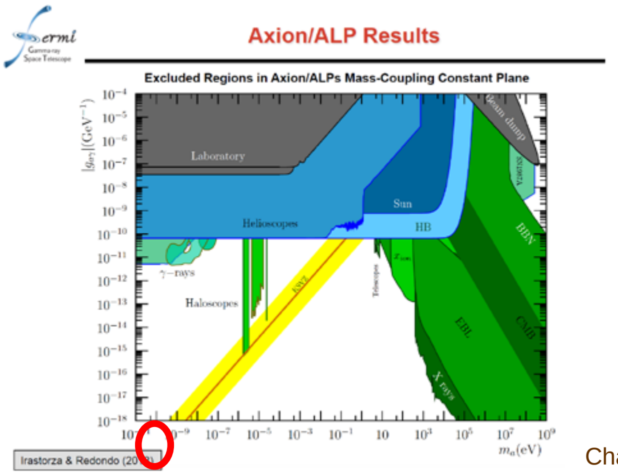
PDG review (2010)

→ Axion DM with *any* values of $f_a \gtrsim 10^{10}$ GeV possible

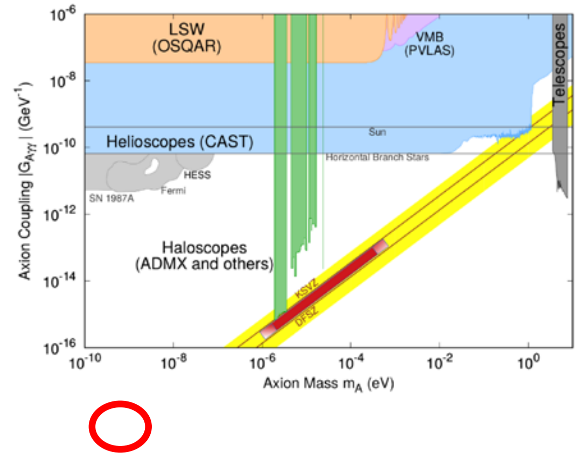
… controlled by anthropic condition $\Omega_{DM} < \Omega_{DM,max}$ Linde ('88); Tegmark, Aguirre, Rees, Wilczek ('05)

Axion (DM) with Planck/GUT scale f_a (outside the standard "axion window")

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



Charles's talk

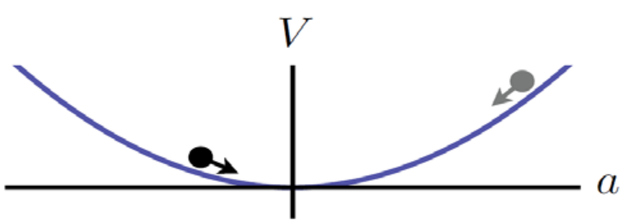


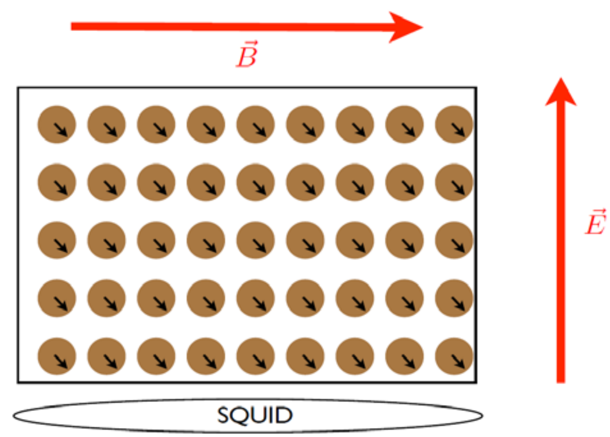
Chevarier's talk

→ motivates new experiments

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

Axion DM





→ time-dependent EDMs

Multi-component DM

… Coincidences are "generic" in the multiverse

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

also $\rho_{\text{Baryon}} \sim \rho_{\text{DM}}$, $y_{u,d,e} v \sim \alpha \Lambda_{\text{QCD}} \sim O(0.01) \Lambda_{\text{QCD}}$, …

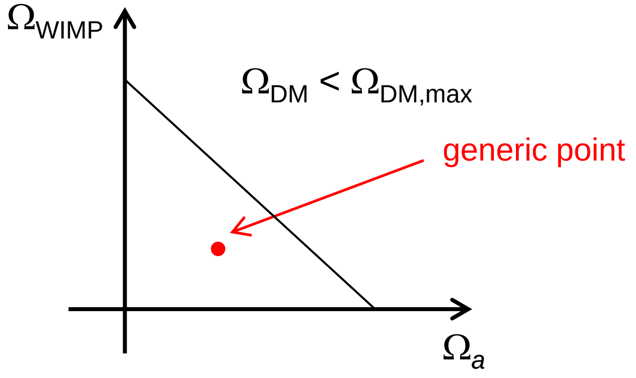
Why not $\rho_{\text{DM},1} \sim \rho_{\text{DM},2}$?

ex. Axion needed for string *CP*

DM already present $\rightarrow$ no "need" for WIMP

WIMP absent ?

$\rightarrow$ WIMP could coexist with the axion (and PBH, …)



… must be prepared for $\Omega_{\text{WIMP}} < \Omega_{\text{DM}}$

Black Holes

Supermassive black holes, (a portion of) dark matter, …

- Astrophysical black holes
- Primordial black hole (break of the power spectrum in inflation, …) Garcia-Bellido’s talk

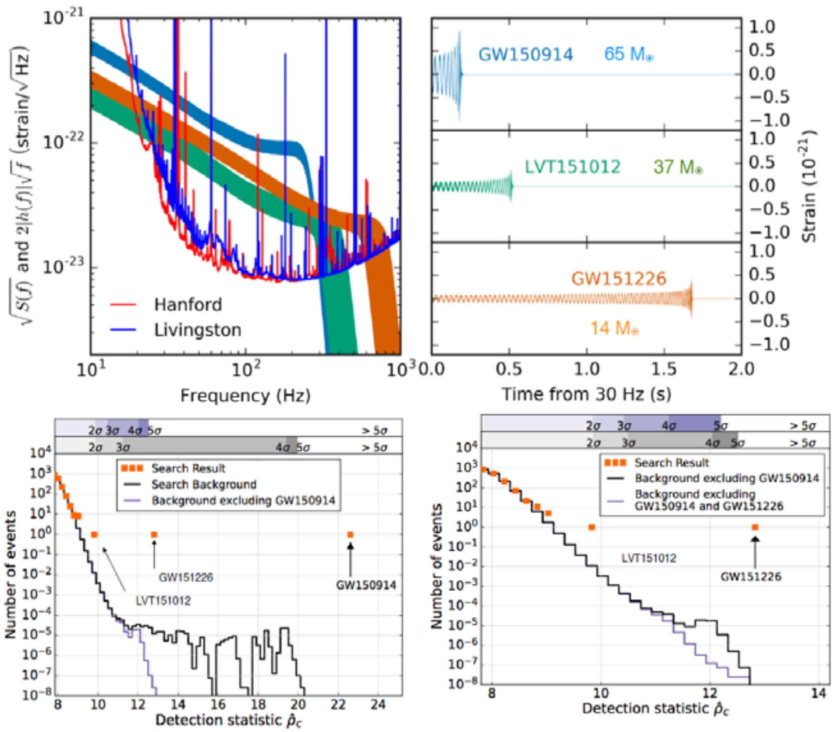
Black Holes

Supermassive black holes, (a portion of) dark matter, LIGO, …

– Astrophysical black holes

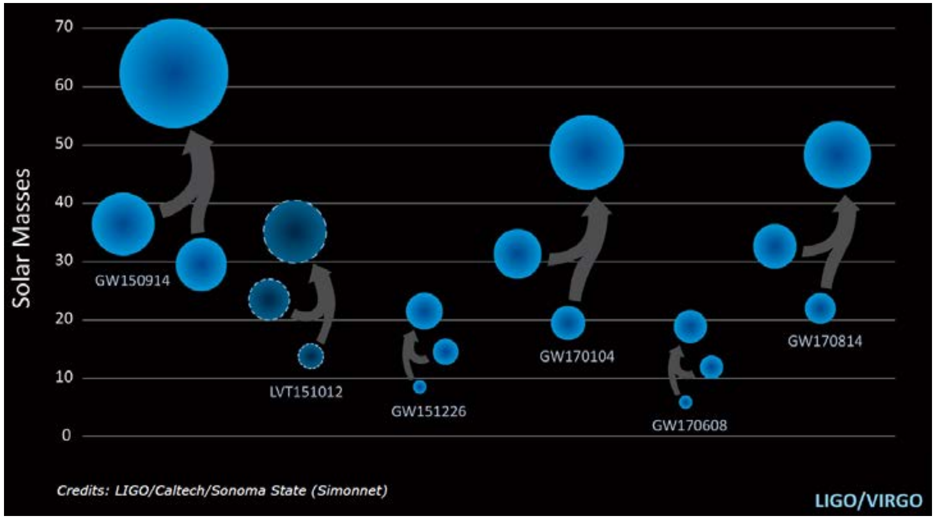
– Primordial black hole (break of the power spectrum in inflation, …) Garcia-Bellido's talk

Binary Black Hole Mergers in LIGO's First Scientific Run



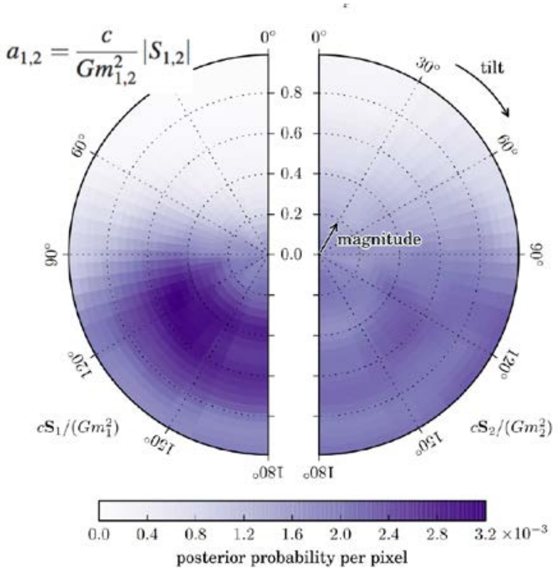
→ Multi-Messenger Astronomy, … talks by Humensky, Coutu, Aguilar, …

Masses



Cadonati's talk

Spins



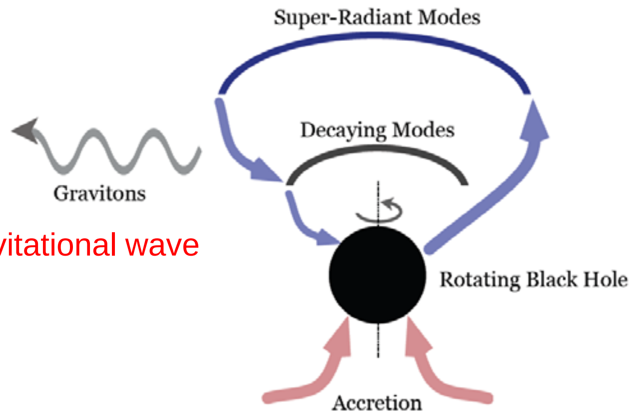
Cadonati's talk

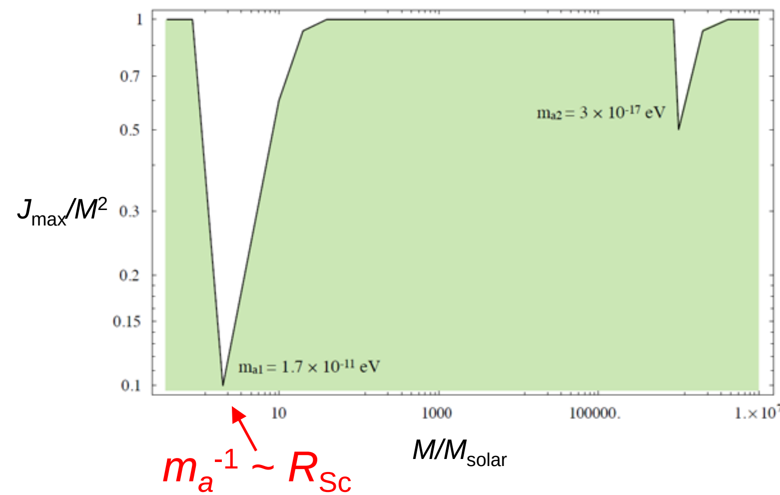
… starts exploring properties
of black holes in our universe

Using black holes as a particle detector

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ('09)

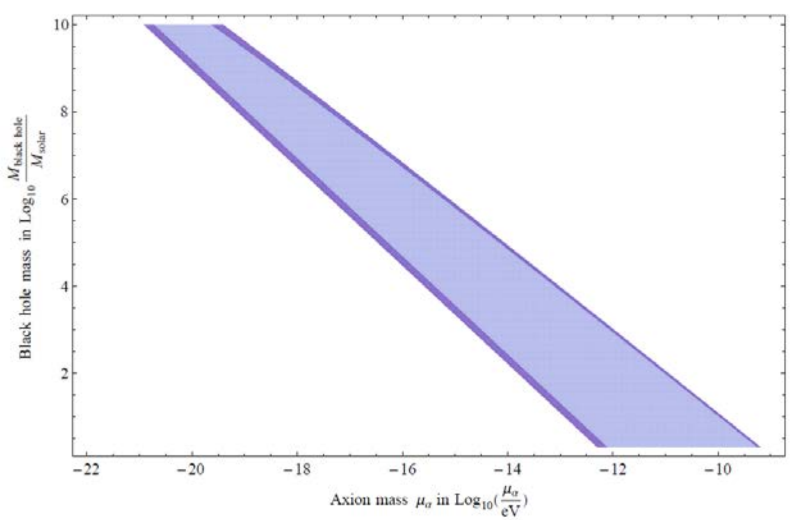
Super-radiance (black hole-axion "bound state")

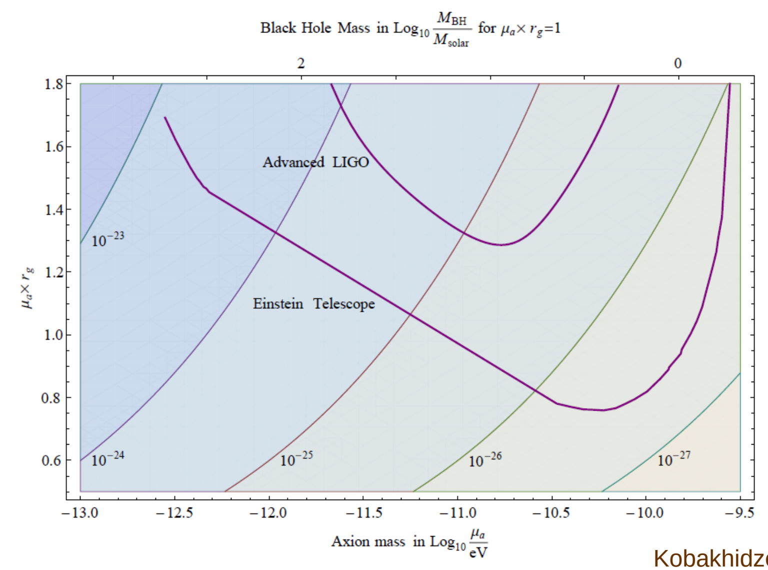




Gravitational wave signals

Arvanitaki,, Dubovsky ('10)

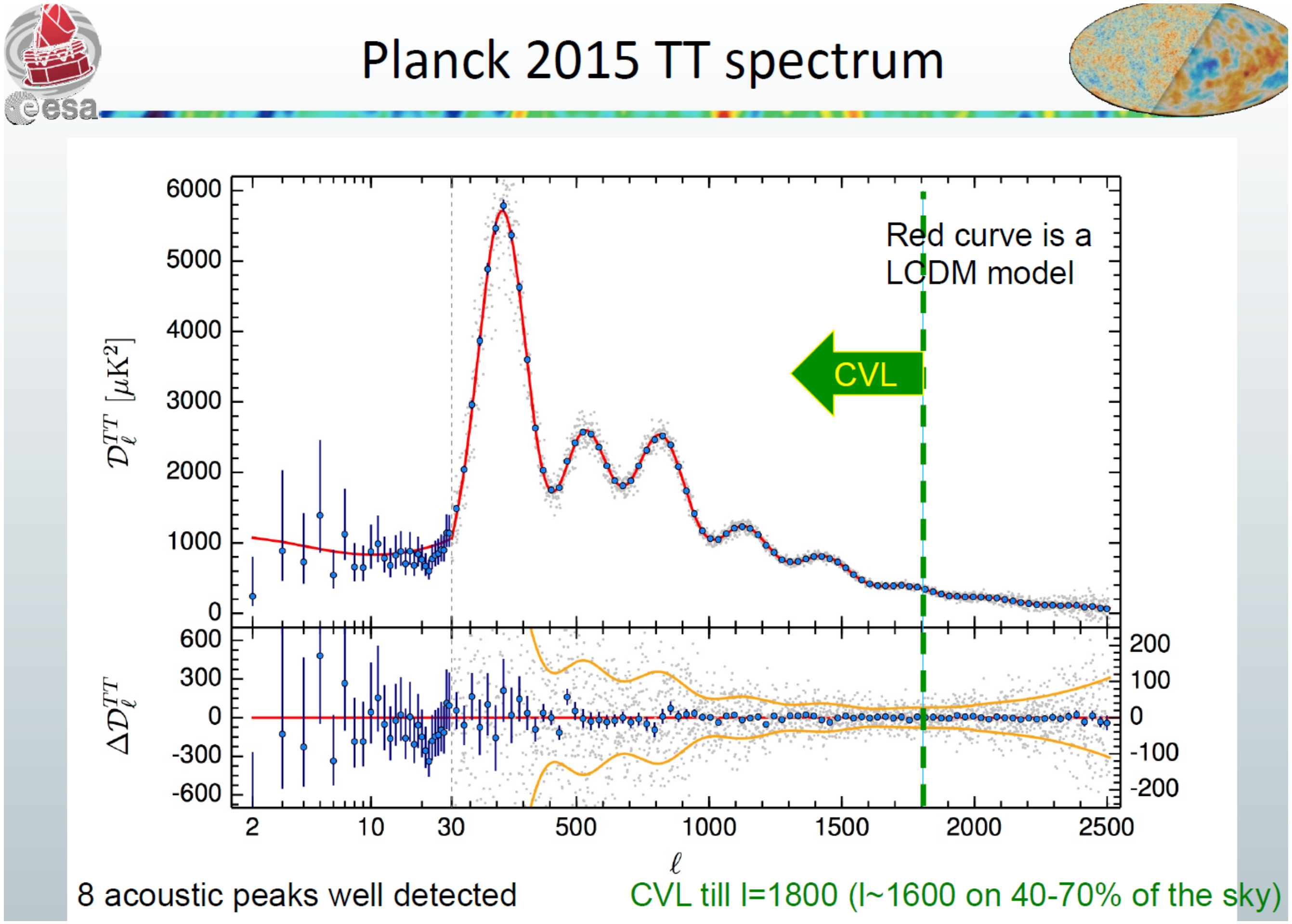




Kobakhidze's talk

Cosmology

Beautiful results in the past decades !



Bouchet’s talk

Too beautiful ?

A perfect (-ly boring) Universe?

Parameter	TT, TE, EE+lensing+ext
Ω_K	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.194
$N_{\rm eff}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.113
w	$-1.019^{+0.075}_{-0.080}$

$f^{local}_{NL} = 0.8 \pm 5.0$

$f^{equil}_{NL} = -4 \pm 43$

$f^{ortho}_{NL} = -26 \pm 21$

Defect	$G\mu/c^2$
NG	$< 1.3 \times 10^{-7}$
AH	$< 2.4 \times 10^{-7}$
SL	$< 8.5 \times 10^{-7}$
TX	$< 8.6 \times 10^{-7}$

$\alpha_{\rm ISO}$

α (Fine structure constant)

$P_{\rm ann}$

C_s (for MG)

$c^2_{\rm eff} = c^2_{\rm vis} = 1/3$ for nu's

$A_{2s\to1s}$

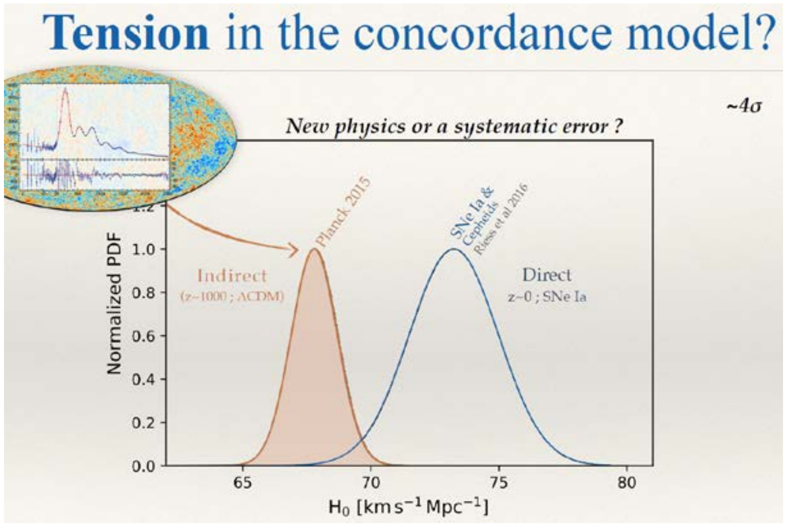
+ all others obtained by the community!
(Specific theories, specific data combinations, new data…)

Bouchet's talk

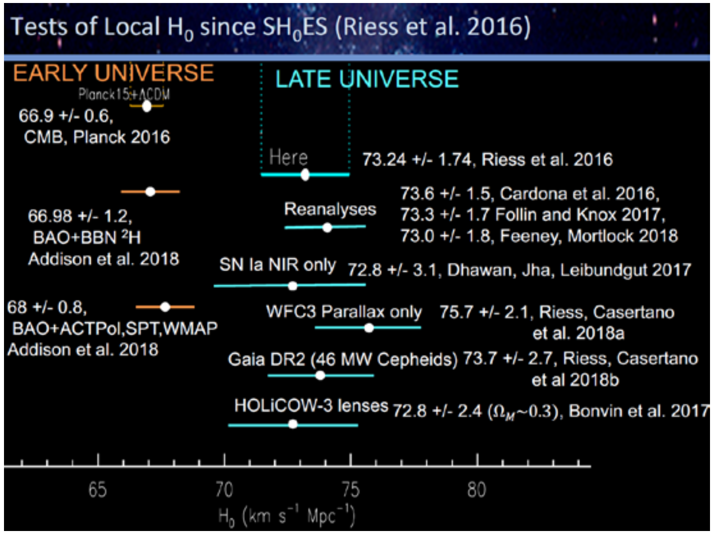
– Where should we go?

– What do/can we expect?

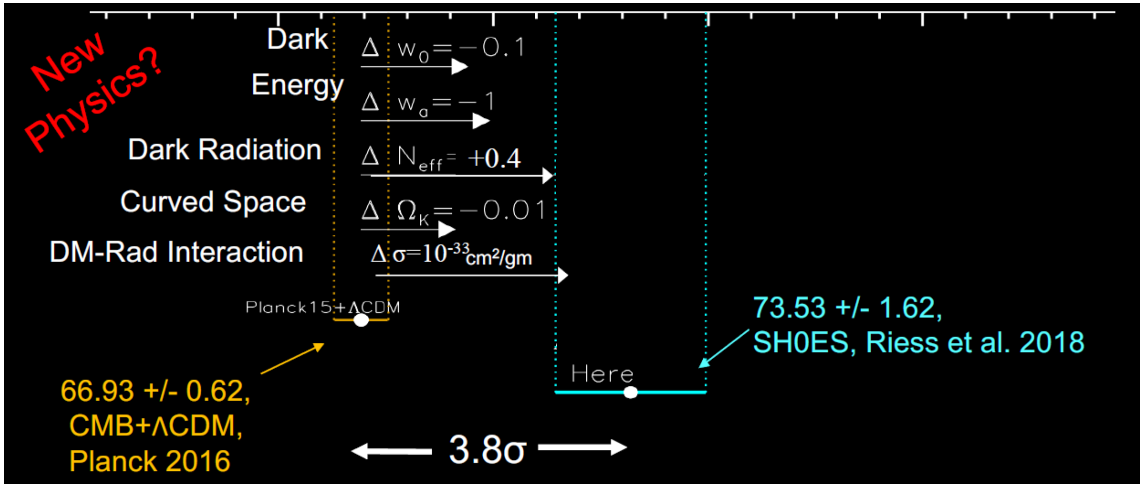
There is still a tension



Rigault's talk



Riess's talk

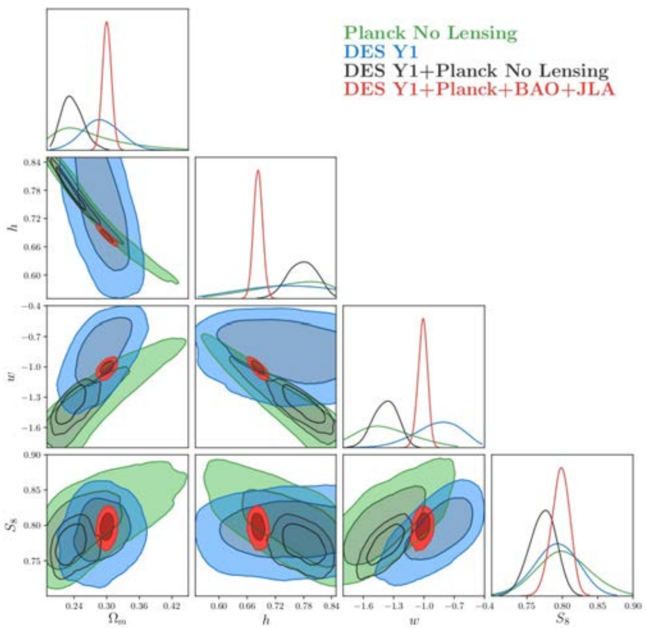


… That would be great.

What else?

– Exploring physics of inflation Linde's talk

– Deviation from w = -1 Kallosh's talk



	1	1	4	4
Ω_k	0 fixed	0.002 ± 0.007	0 fixed	-0.015 ± 0.030
$\Omega_{\rm DE} + 2.2\Omega_k$	0.719 ± 0.003	0.718 ± 0.004	0.718 ± 0.004	0.717 ± 0.004
w_1	n.a.	n.a.	0.06 ± 0.15	0.37 ± 0.61
$d_{\rm BAO} \times 100$	3.40 ± 0.02	3.39 ± 0.02	3.39 ± 0.03	3.37 ± 0.05
χ^2/d.f.	11.2/17	11.2/16	11.1/16	10.8/15

Hoeneisen's talk

$$w = -1.00^{+0.04}_{-0.05}$$

talks by Leonard, Eifler, …

– Comment on emergent gravity

We believe that spacetime and gravity are emergent (classical) concepts

… entanglement of holographic / boundary degrees of freedom

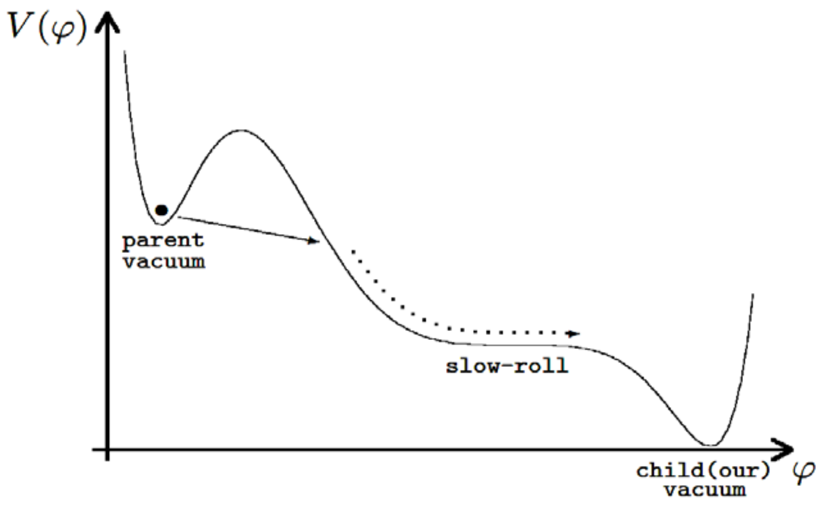
Modified gravity? – not nessecarily

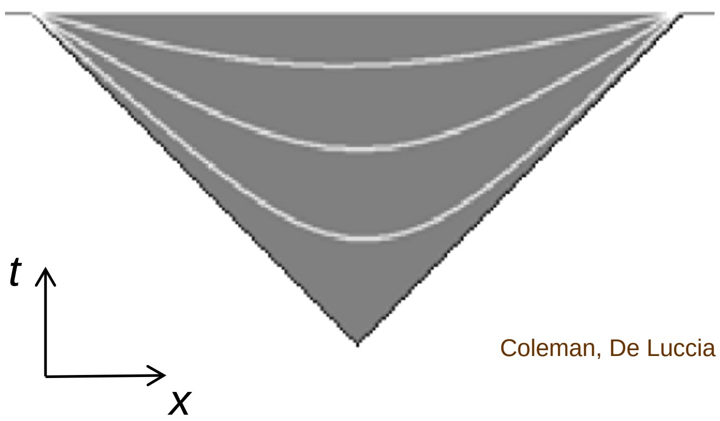
e.g. Dark universe from emergent gravity $\longleftrightarrow$ Large (~mm) extra dimensions

Verlinde ('16)

The universe in the multiverse

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

The universe in the multiverse

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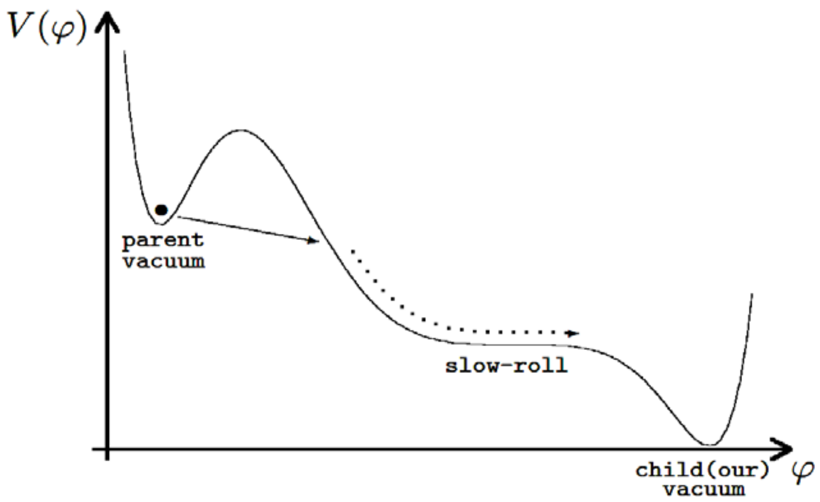

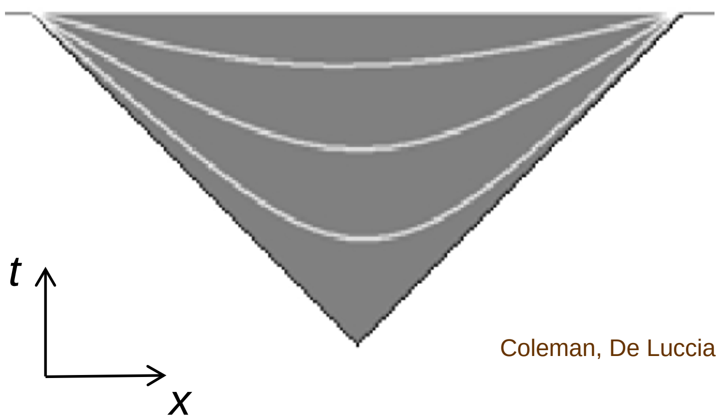

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… Can we expect?

A possible scenario

Why is our universe so flat?

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

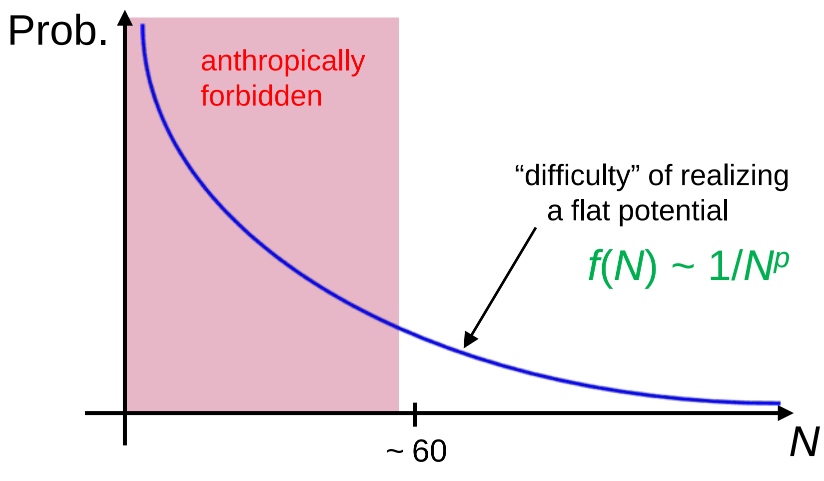
Does this mean there is no slow-roll inflation? ⟹ No!

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)
….

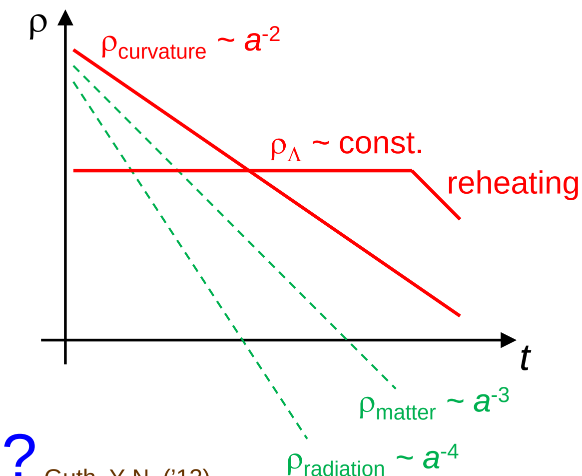
Slow-roll inflation may be "just-so"

- A new picture for slow-roll inflation (in our universe)

Problems in small-field (low energy) inflation avoided: *e.g.* Guth, Kaiser, Y.N. ('13)

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

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



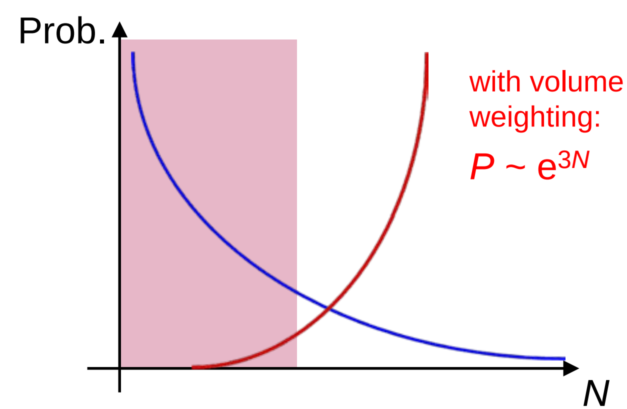
The almost only way to get
a nontrivial universe after bubble nucleation

- 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
  (→ Global spacetime in GR is an "artifact")



… nontrivial connections between cosmology and fundamental theory

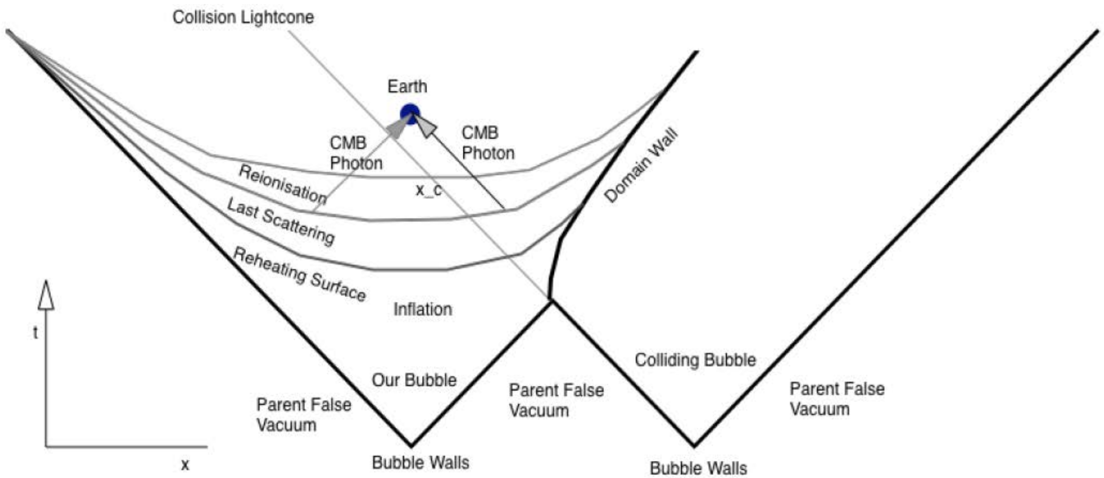
(Slow-roll) Inflation may be "just so"

… 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 ('10)

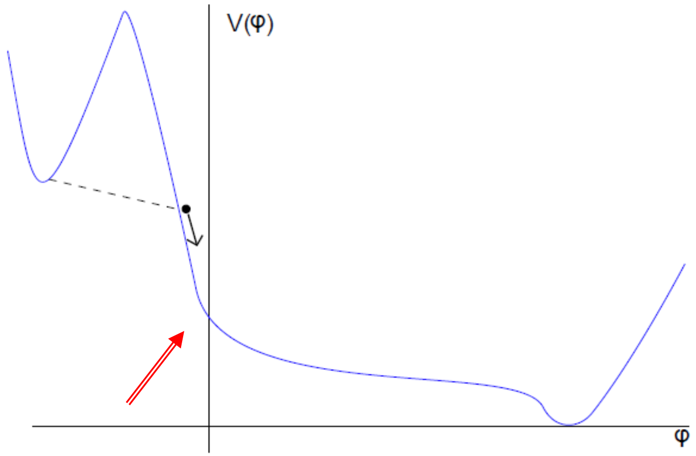
  … may lead to signals in CMB through anisotropic curvature

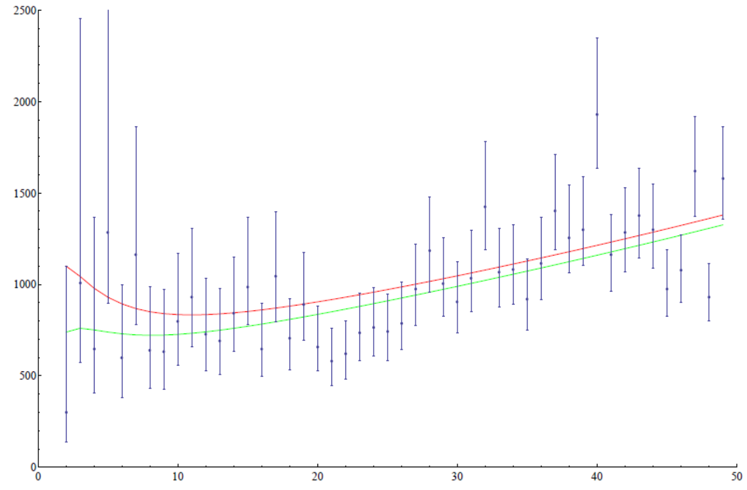
• Suppressions of low ℓ

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?





• 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, ('08)

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

Anomalies *[Planck 2015 XVI]*

- Some large scale anomalies detected pre-Planck were confirmed and significance often increased (in particular since BF model is better determined)
  - *Power deficit at low-ell*
  - *Power asymmetry between hemisphere*
  - *Low multipoles alignment*
  - *Dipolar modulation*
  - *Low variance*
  - *Cold spot*
  - *Point parity and mirror-parity asymmetry*
- Planck provides high confidence in their existence due to two independent instruments, the quality of data, the unprecedented coverage of Foregrounds…
- No compelling explanation
  - *Statistical fluke in LCDM is quite possible (NB: A_lens)*
  - *Secondary effect apparently too weak*
  - *Foregrounds are well controlled (and systematics essentially ruled out)*
  - *Of course, tantalising possibility of new physics, But CV, a posteriori, etc.*

Bouchet's talk

?

Summary (of the summary talk)

(Still) Lots of opportunities to explore fundamental physics

- Neutrinos
- Dark Matter
- Black Holes
- Cosmology
- …

Great experimental / observational perspectives

… discussed throughout this conference!

$\rho_\Lambda \sim \rho_{matter}$ leads to a new picture

Eternally inflating multiverse (surprising, quantum natures of spacetime and gravity)

→ Wide range of implications

particle physics (naturalness), cosmology, …