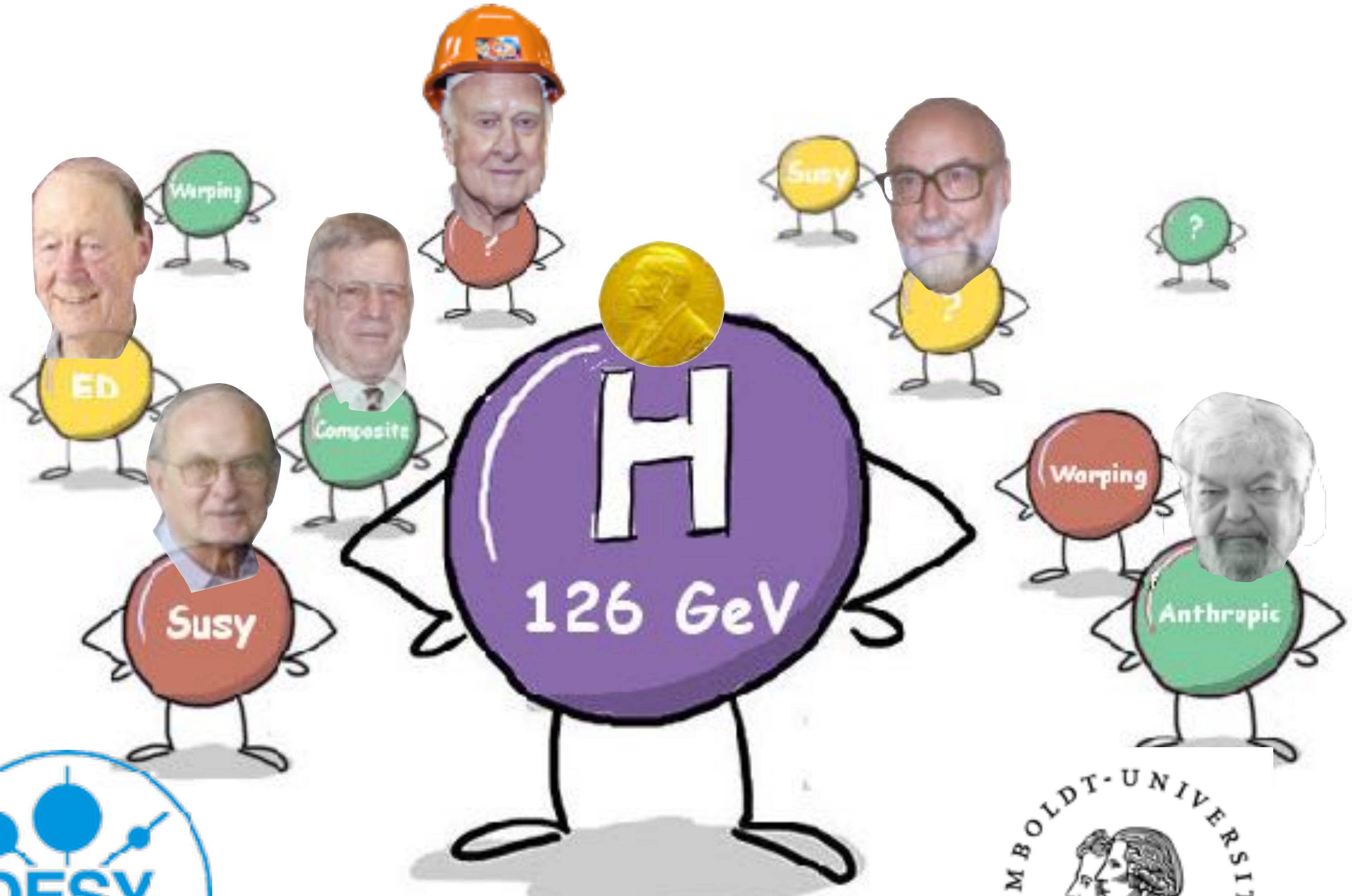
Beyond the Standard Model

CERN summer student lectures 2018



Lecture 4/4

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Outline

- ☐ Monday
  - ○ General introduction
  - ○ What kind of physics can be probed at colliders?
  - ○ Higgs physics as a door to BSM
- ☐ Tuesday
  - ○ Naturalness
  - ○ Supersymmetry
  - ○ Grand unification, proton decay
- ☐ Wednesday
  - ○ Composite Higgs
  - ○ Extra dimensions
  - ○ (Quantum gravity)
- ☐ Thursday
  - ○ Cosmological relaxation
  - ○ Beyond colliders searches for new physics

Cosmological relaxation

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- $m_H(t)$: $m_H^2(t=-\infty)=\Lambda^2_{\rm cutoff}\to m_H^2({\rm now})=-(125\,{\rm GeV})^2$
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But "Why/How/When does it stop evolving?"
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking back-reacts on the relaxion field and stops the time-evolution of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

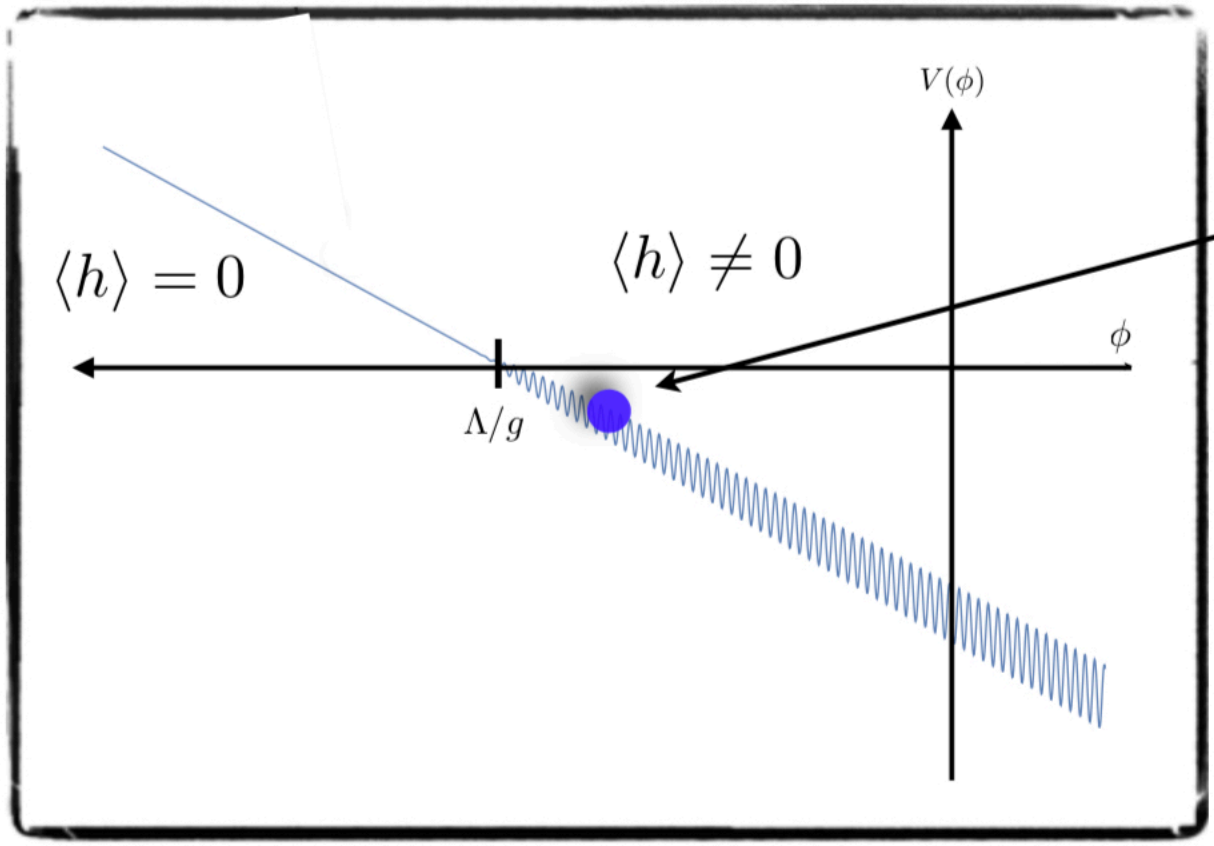
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

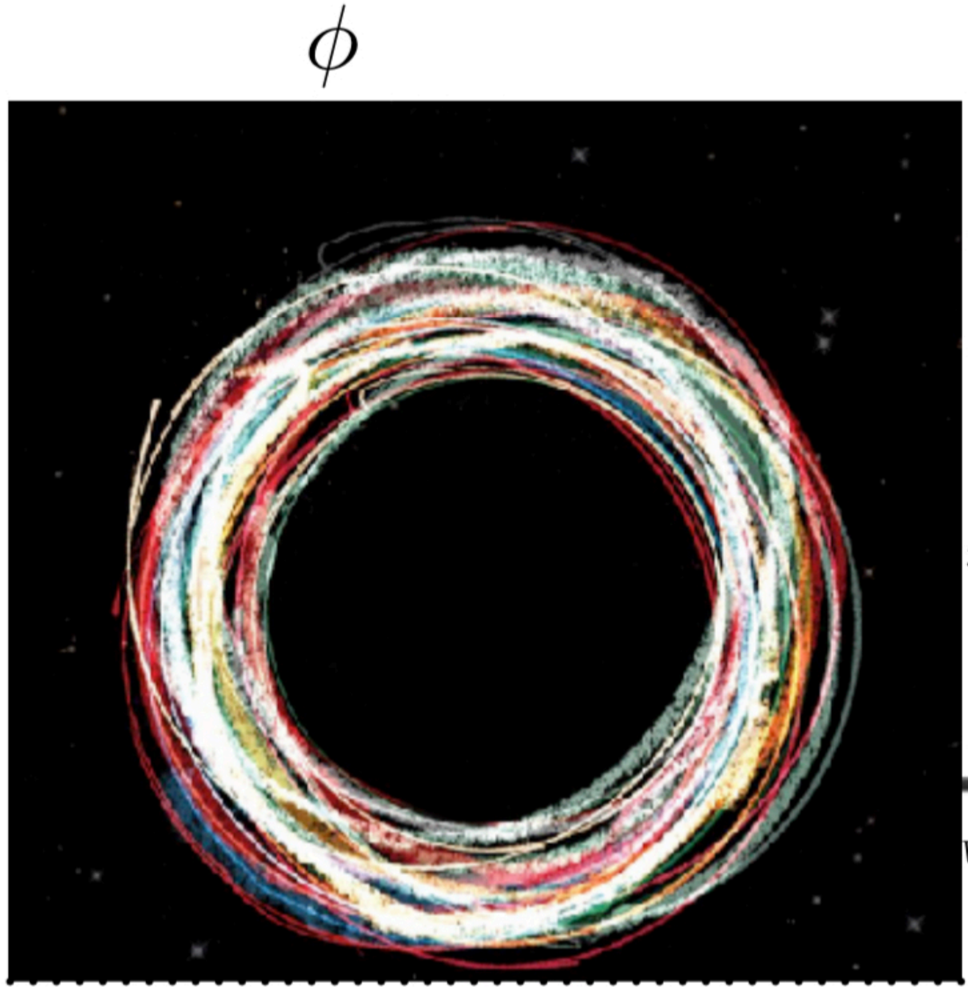
axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

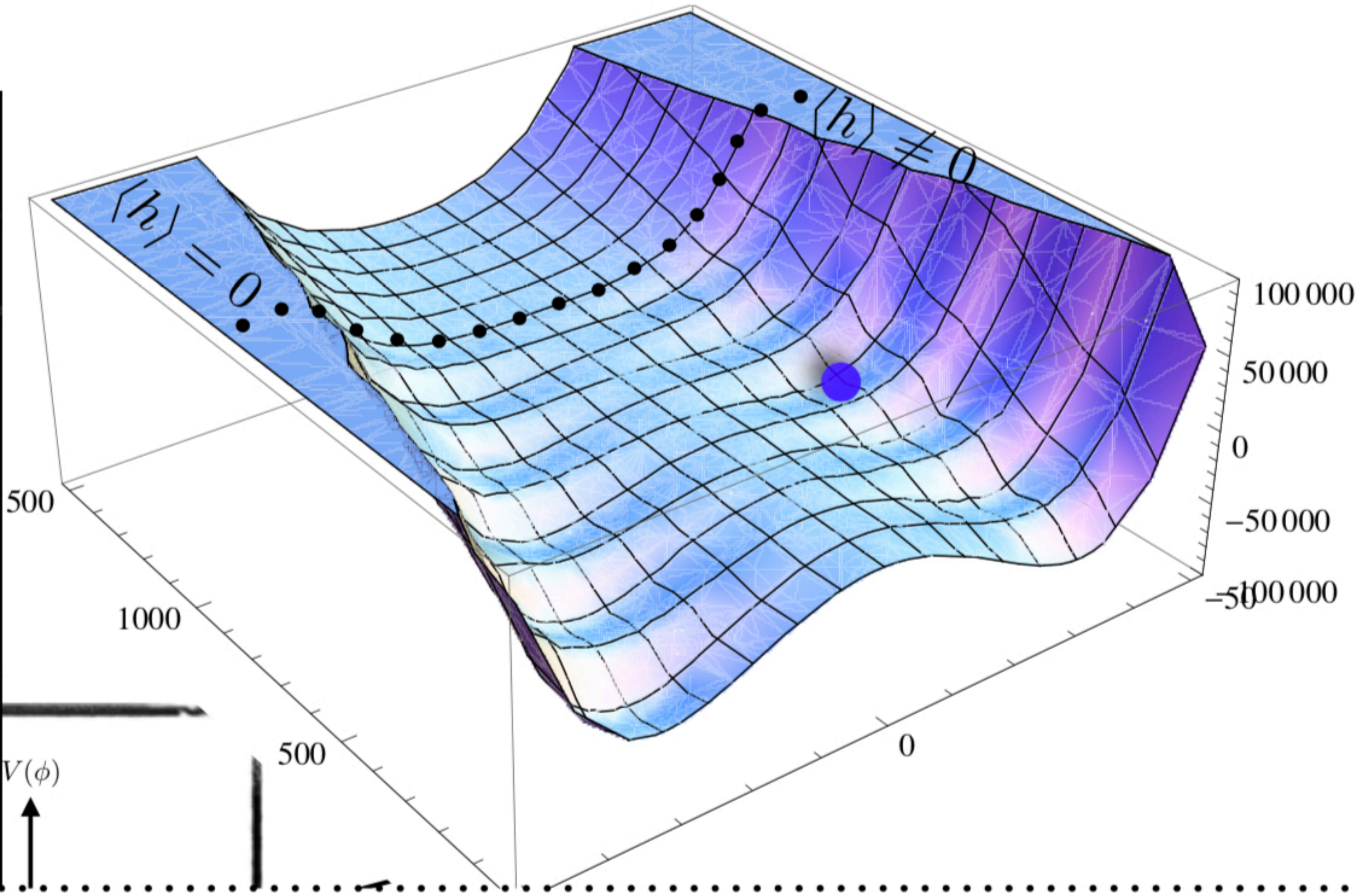
$$\Lambda_{\rm QCD}^3\, h \cos\frac{\phi}{f}$$



Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

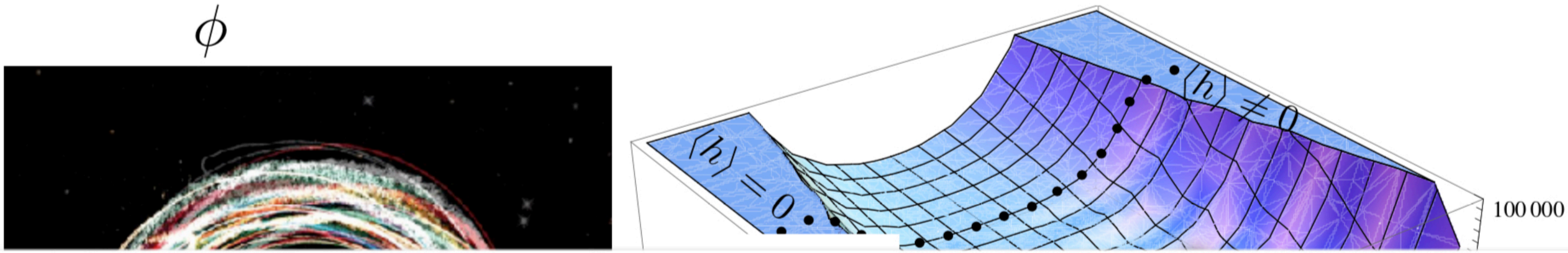


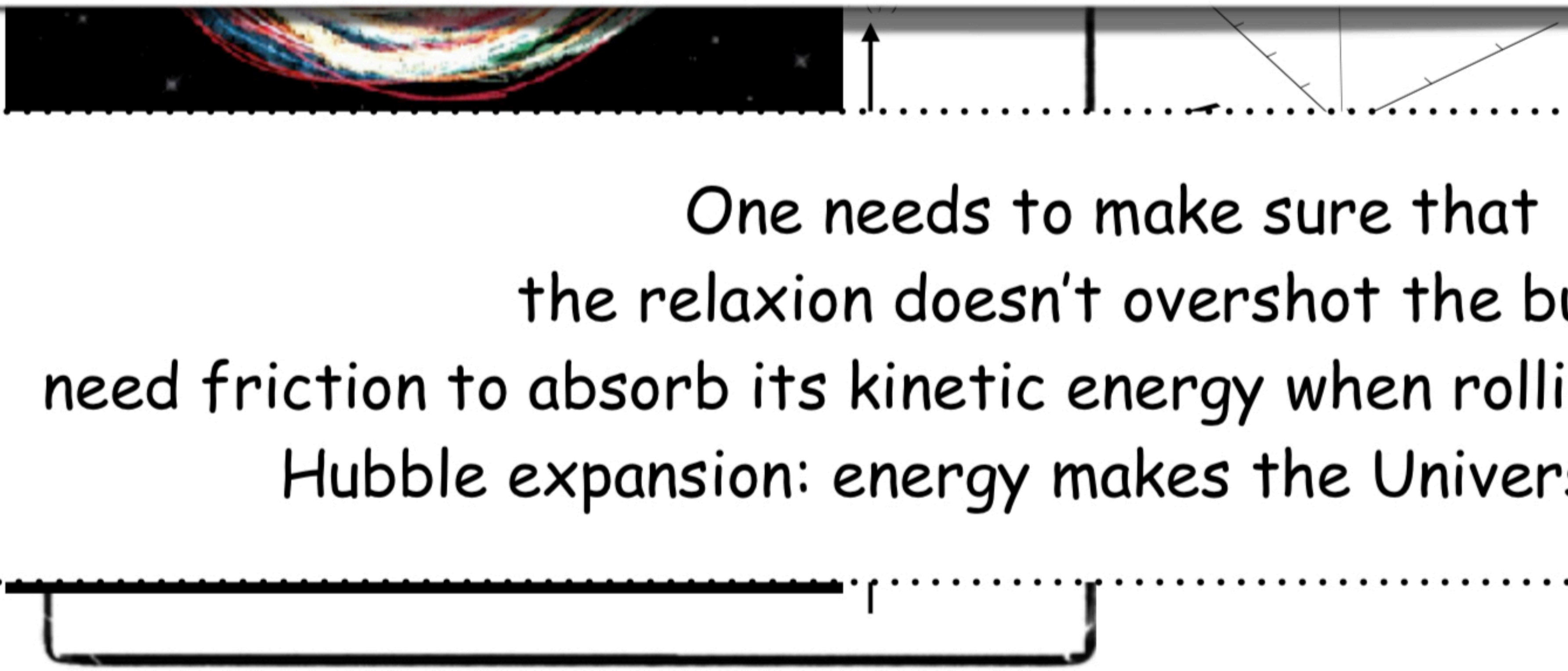


One needs to make sure that
the relaxion doesn't overshot the bumps
need friction to absorb its kinetic energy when rolling down its potential
Hubble expansion: energy makes the Universe expanding

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15





Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

One needs to make sure that
the relaxion doesn't overshot the bumps
need friction to absorb its kinetic energy when rolling down its potential
Hubble expansion: energy makes the Universe expanding

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology

Phenomenological signatures

~interesting cosmology signatures~

- ◎ BBN constraints
- ◎ decaying DM signs in γ-rays background
- ◎ ALPs
- ◎ superradiance (BH losing angular momentum by accelerating relaxion)

~ interesting signatures @ beam dump experiments (e.g. SHiP) ~

- ◎ production of light scalars by B and K decays

~connections with DM~

- ◎ coherent oscillations of the relaxion around its minimum ≈ DM

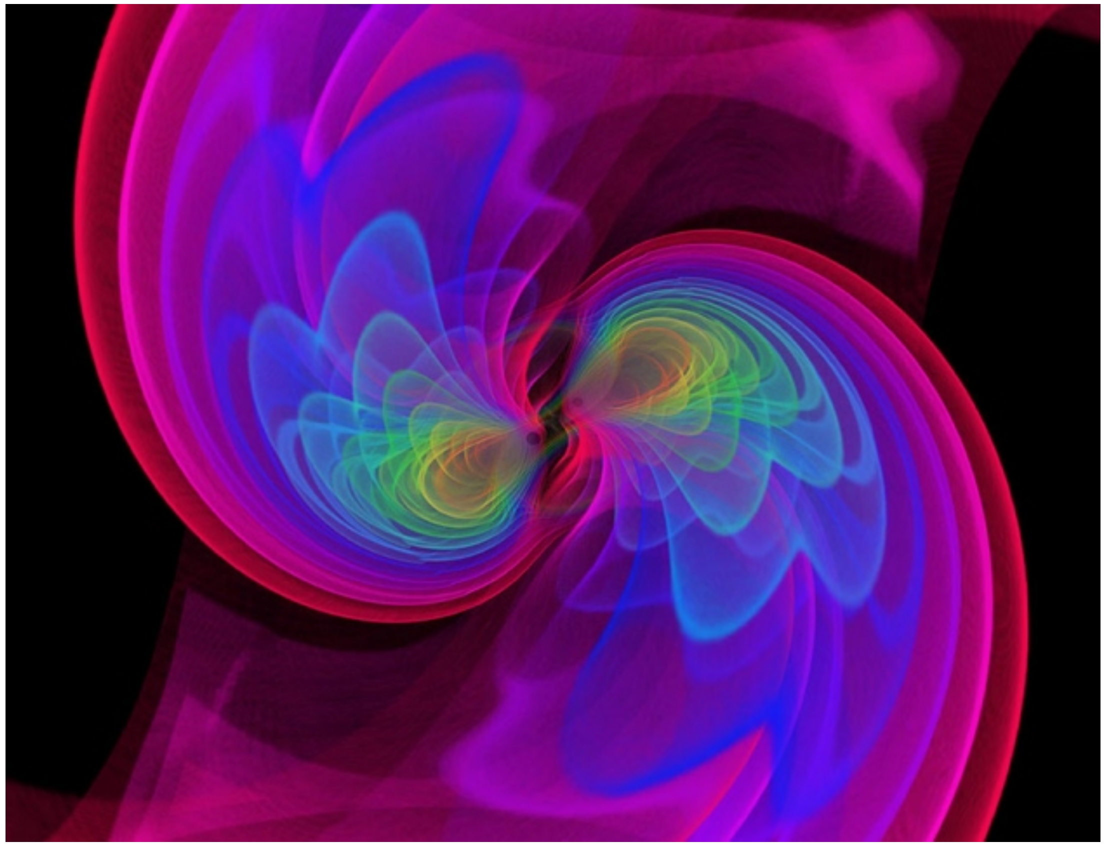
~interesting signatures in atomic physics~

- ◎ oscillations of the relaxion around its minimum
  ⇛ oscillations of the Higgs vev
  ⇛ oscillations of the mass of the proton, of the size of the atoms
- ◎ isotope shifts, piezo-electric atoms...

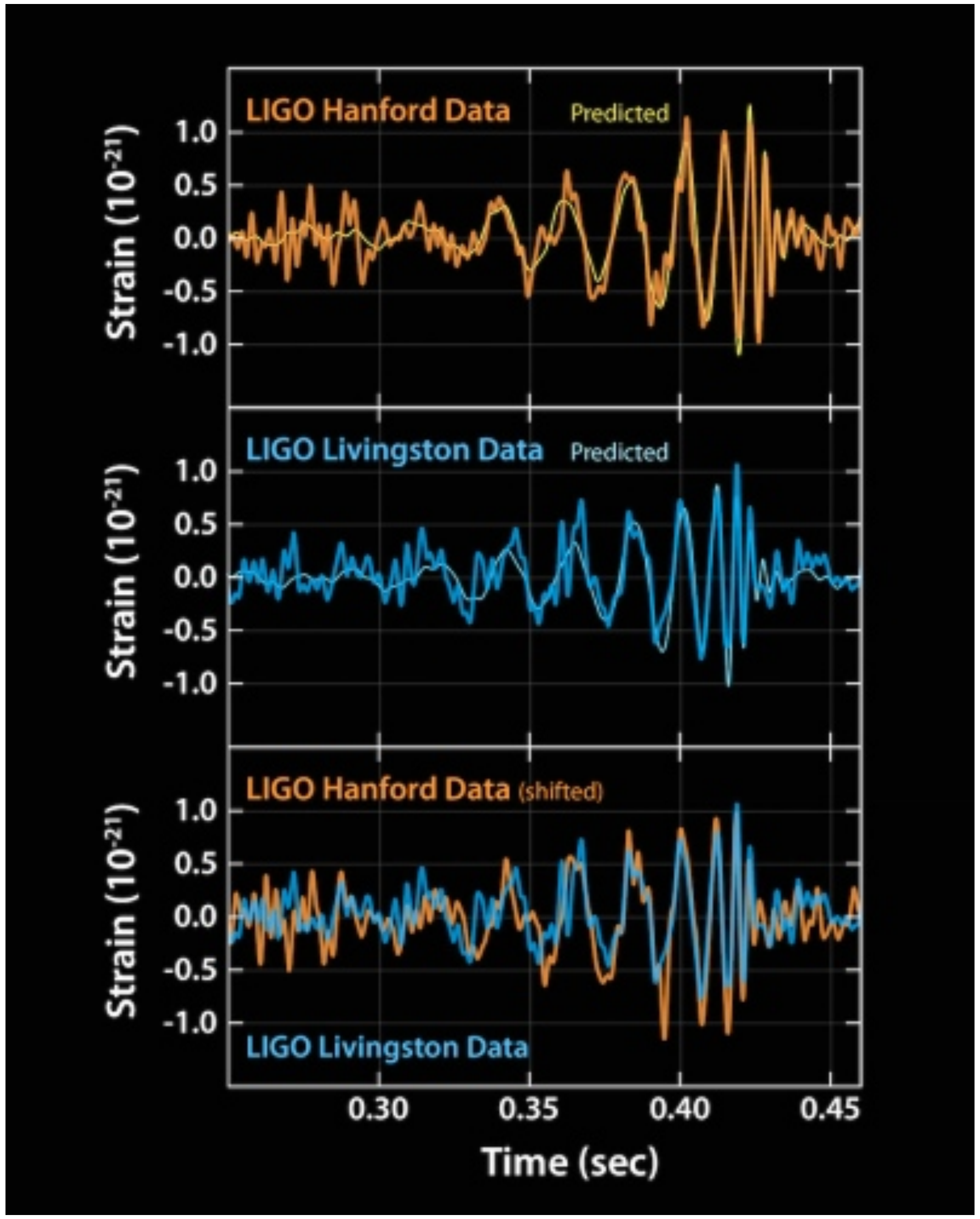
Gravitational waves

The pictures that shook the Earth

GW150914



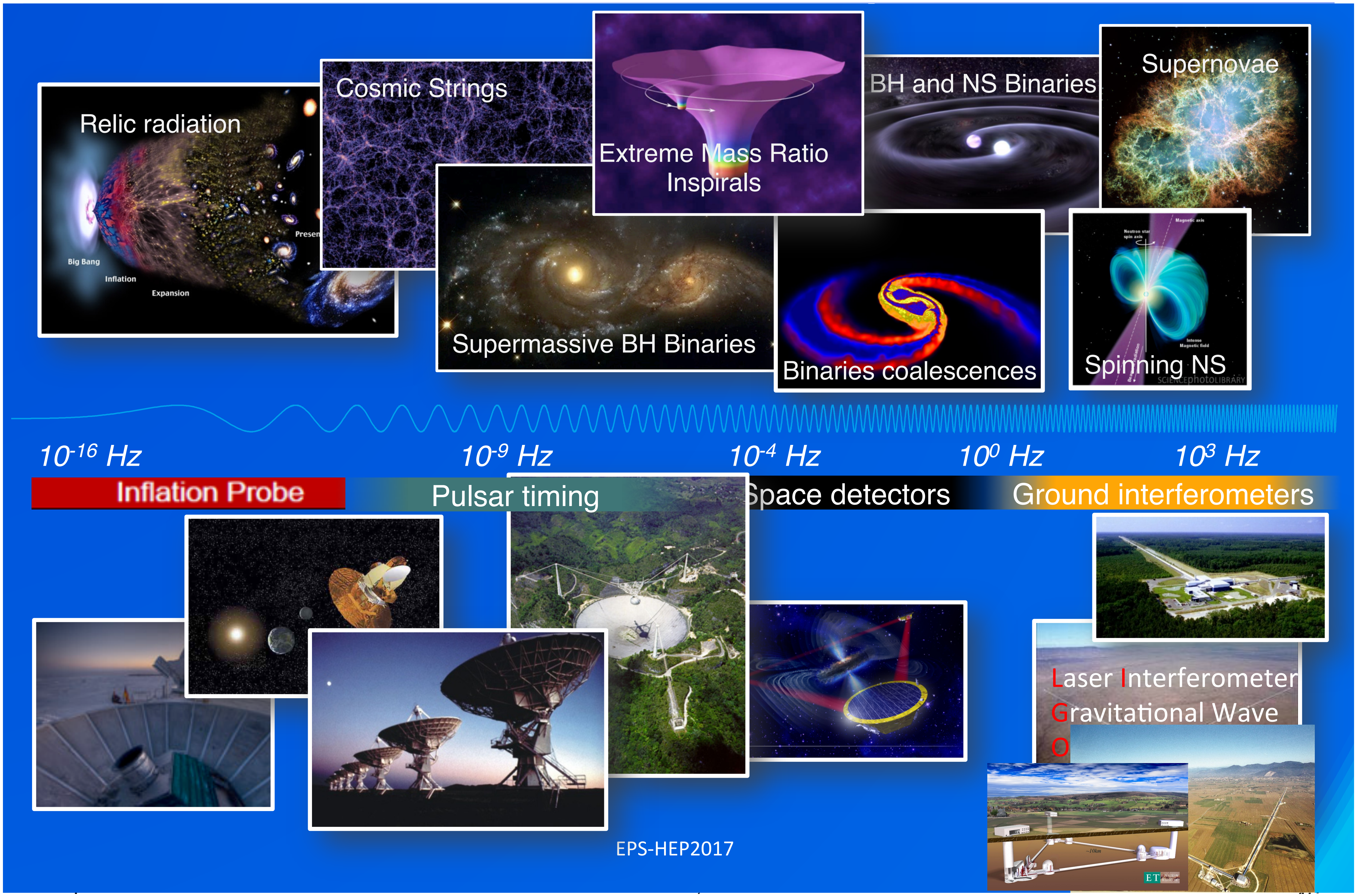
1.3 billion years later on earth



what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity > 100 keV

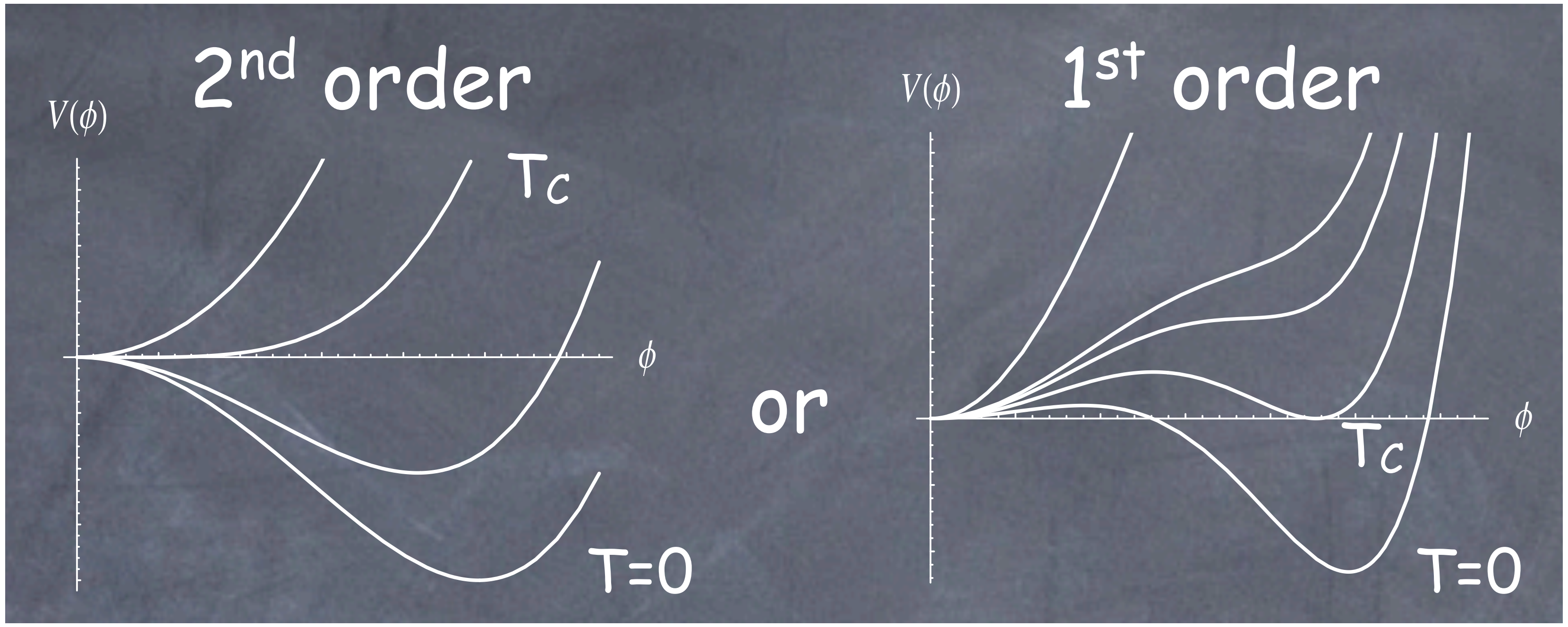
GW and astrophysics/cosmology



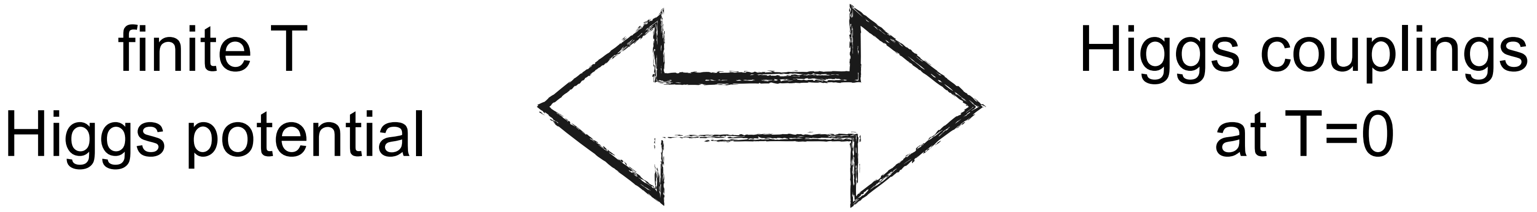
Dynamics of EW phase transition

The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

An appealing idea is EW baryogenesis associated to a first order EW phase transition



the dynamics of the phase transition is determined by Higgs effective potential at finite T
which we have no direct access at in colliders (LHC≠Big Bang machine)


finite T
Higgs potential

Higgs couplings
at T=0

SM: first order phase transition iff mH < 47 GeV

BSM: first order phase transition needs some sizeable deviations in Higgs couplings

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

direct probe of physical process of the very early universe

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1st order)

typical freq. ~ (size of the bubble)$^{-1}$ ~ (fraction of the horizon size)$^{-1}$

$$@\ T = 100\ \text{GeV}, \qquad H = \sqrt{\frac{8\pi^3}{45}\frac{T^2}{M_{Pl}}} \sim 10^{-15}\ \text{GeV}$$

redshifted freq.

~ today ~

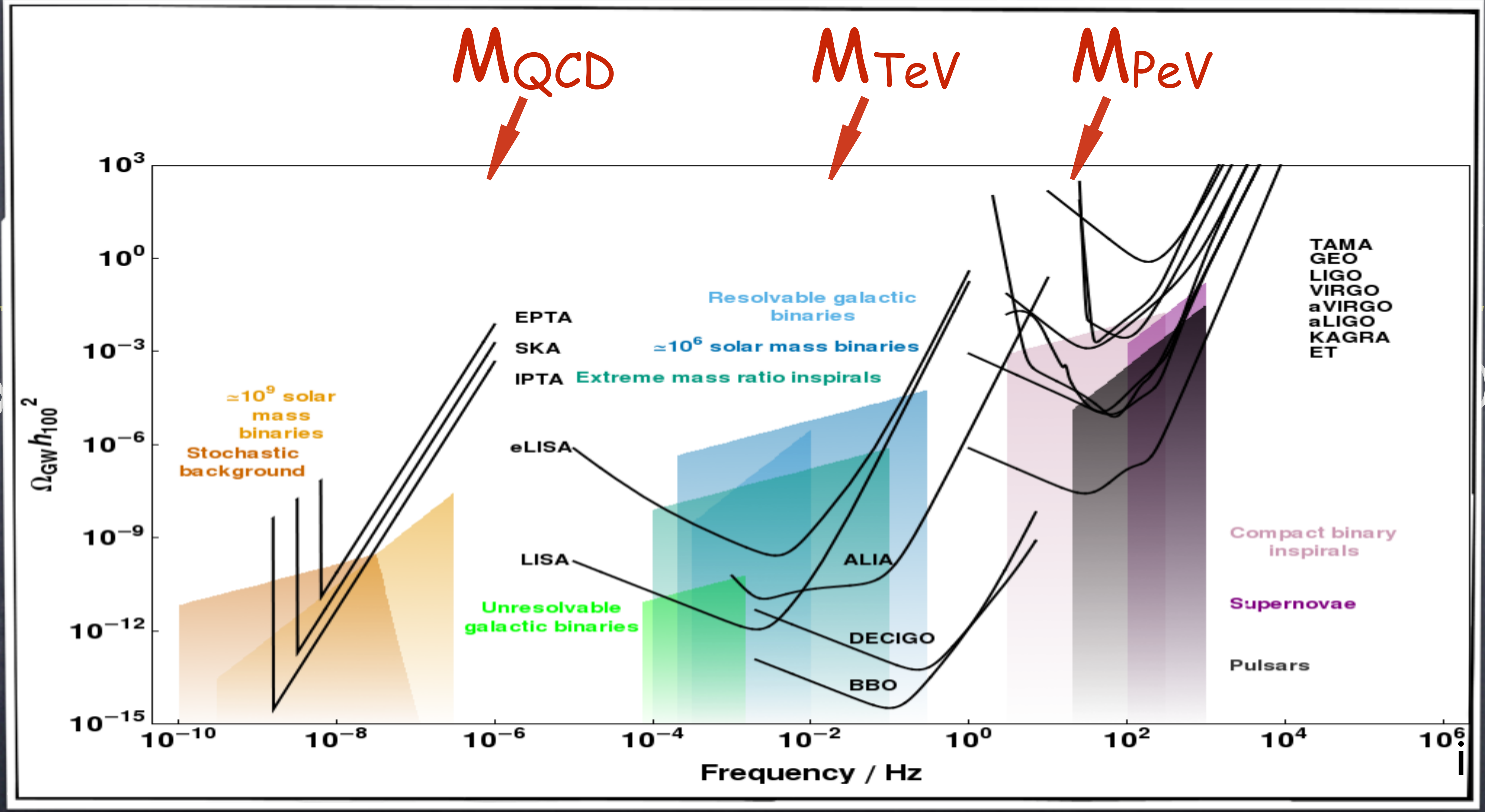
$$f \sim \# \frac{2\cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\, 10^{-15}\ \text{GeV} \sim \# 10^{-5}\ \text{Hz}$$

Grojean, Servant '06

The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency

GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed



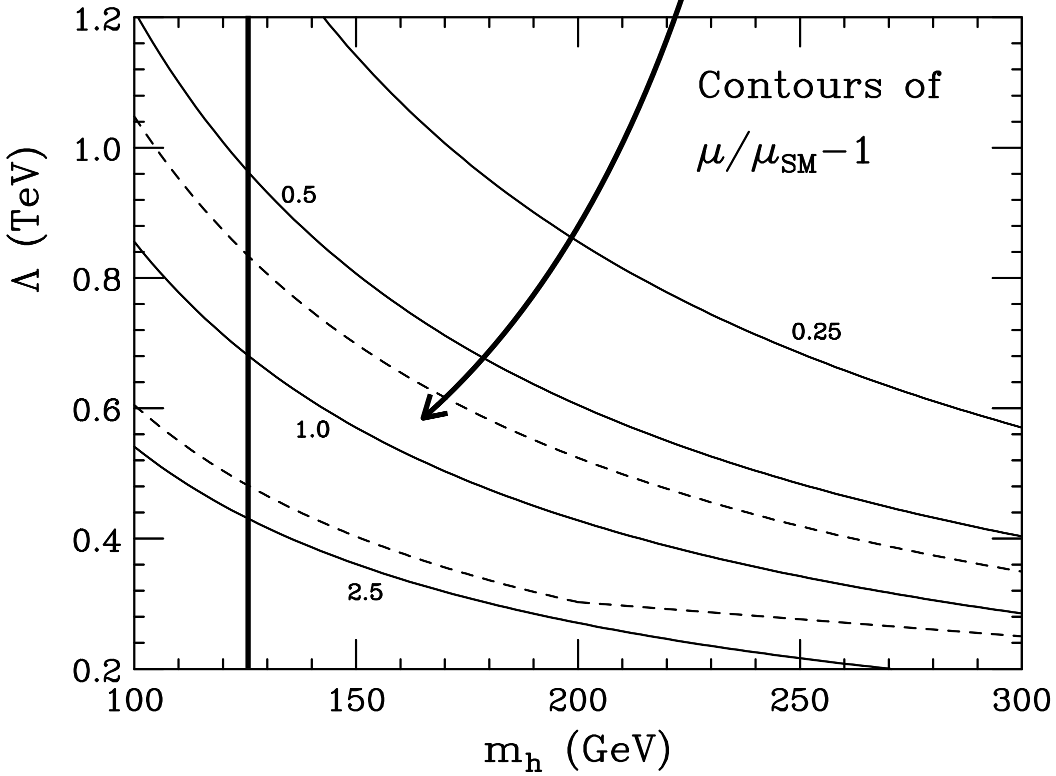
M_{QCD} M_{TeV} M_{PeV}

Grojean, Servant '06

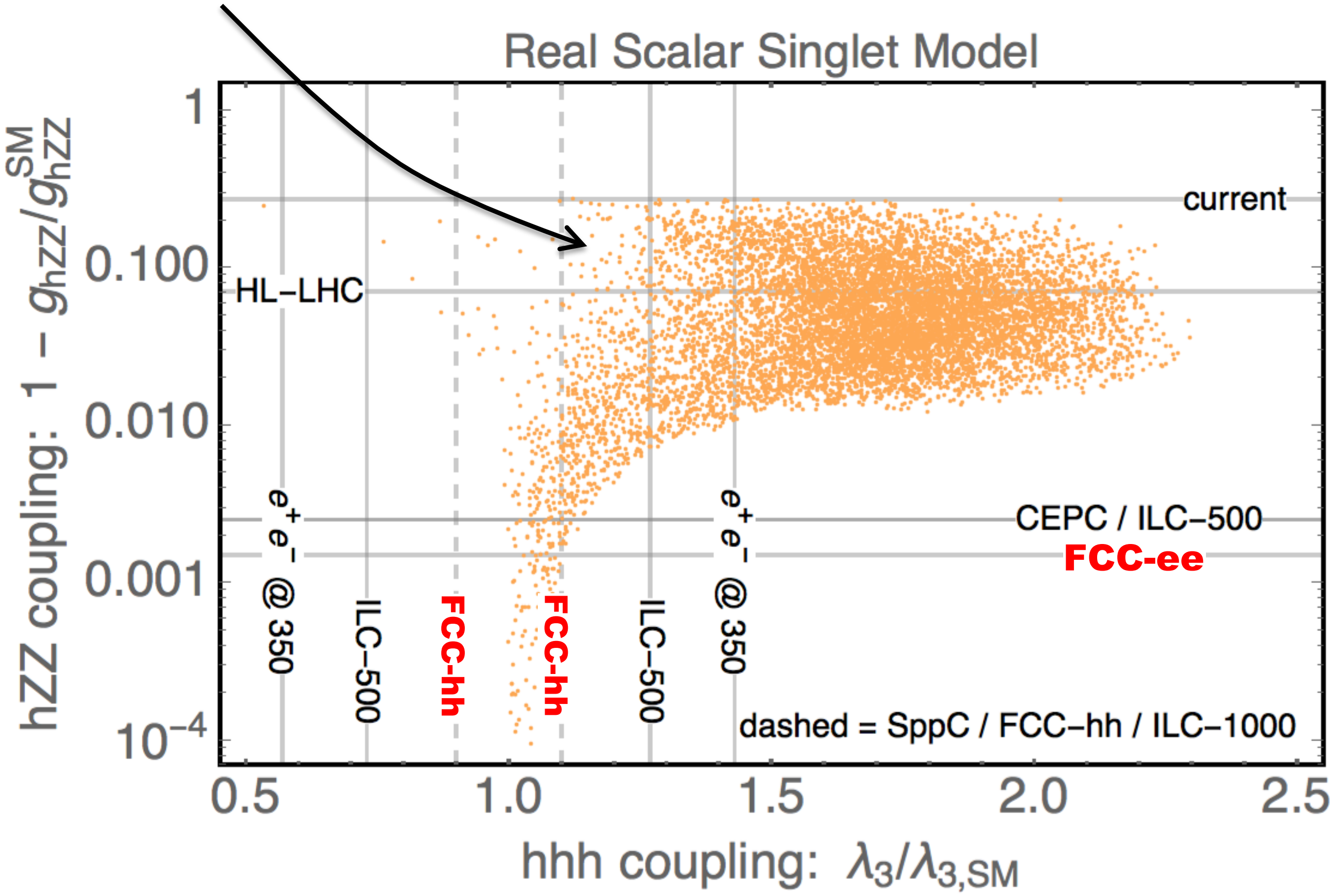
The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency

Complementary GW - Colliders

EWPT is 1st order and gives rise to GW stochastic background



Grojean, Servant, Wells ’04

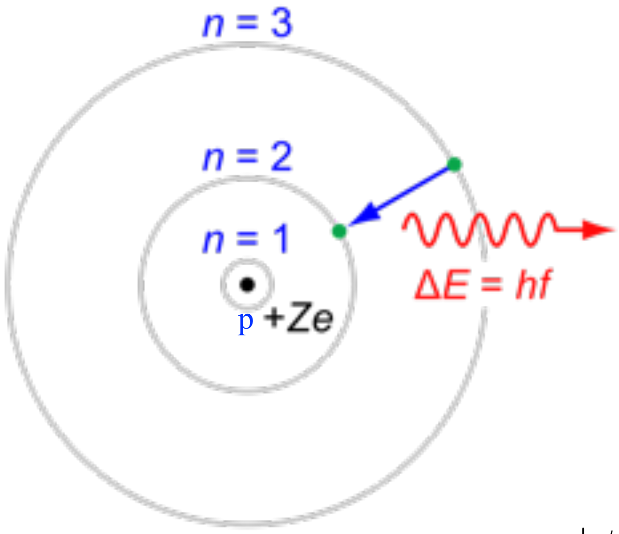


Huang, Long, Wang ’16

“Large" deviations of the Higgs (self-)couplings expected to obtain a 1st order phase transition

BSM and Atomic Physics

Atomic Clocks as a BSM probe



Physics beyond QED contributes to

the frequency of the radiation

$$\frac{1}{\lambda} = R\,Z^2\left(\frac{1}{n^2} - \frac{1}{n'^2}\right)$$

$|\psi(0)|^2/n^3$ is the wave-function-density at the origin.

$$V_{\mathrm{weak}}(r) = -\frac{8G_{\mathrm{F}}m_{Z^0}^2}{\sqrt{2}}\frac{g_e g_A}{4\pi}\frac{e^{-rm_{Z^0}}}{r} \quad \Longrightarrow \quad \delta E_{nlm}^{\mathrm{weak}} = -\frac{8G_F m_Z^2}{\sqrt{2}}\frac{g_e g_A}{4\pi m_Z^2}|\psi(0)|^2\frac{\delta_{l,0}}{n^3}$$

fifth force → ?

Exp sensitivity in atomic clock measurements $O(10^{-18})$

(ms over one billon years)

Not all transitions can be used (yet) for BSM

frequency shifts O(1-100 Hz) over frequencies O(1THz): still a sensitivity $O(10^{-6:-9})$

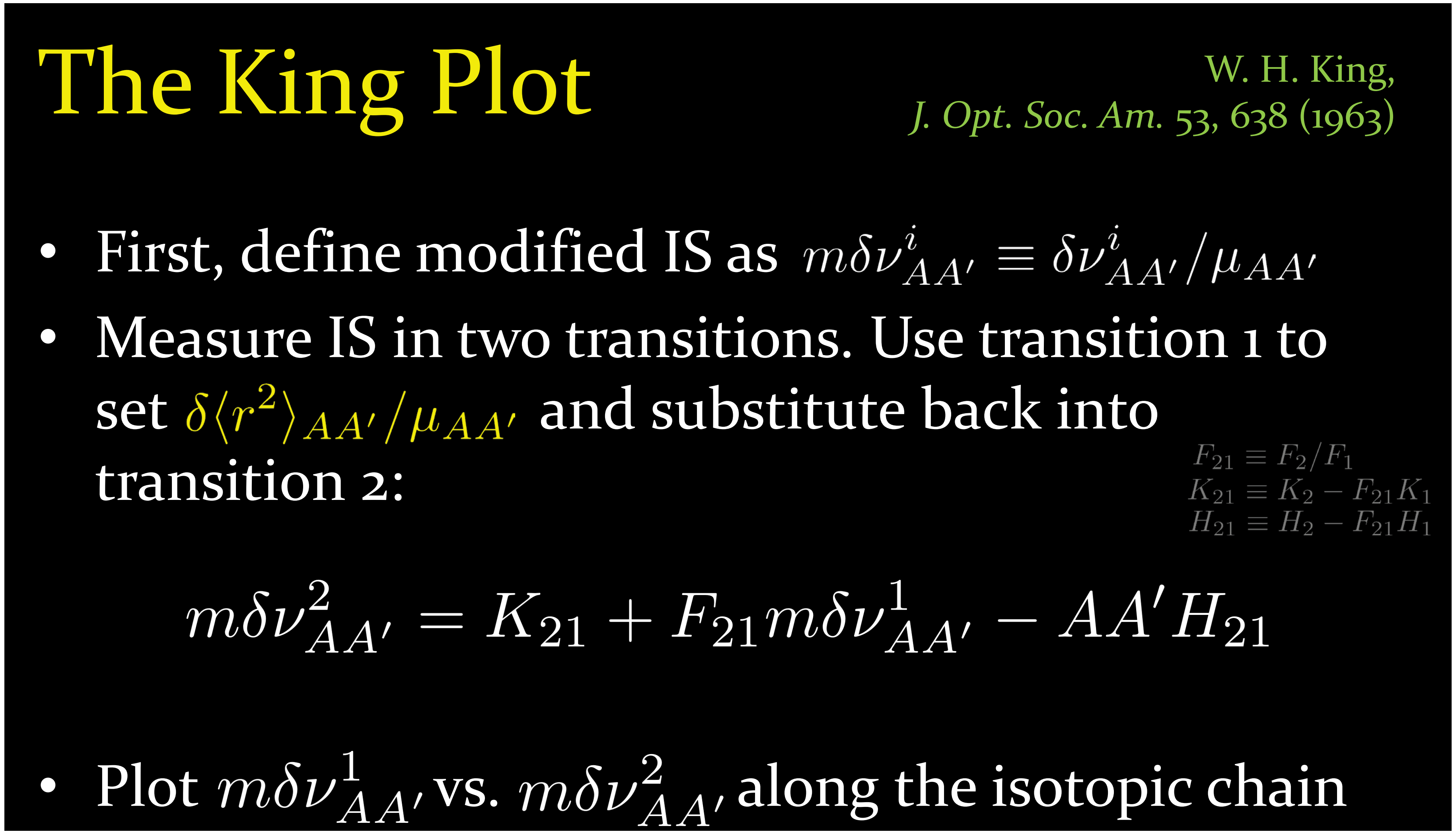
can be used to detect new (long range) forces

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

$$\delta\nu^i_{AA'} = \underbrace{K_i\,\mu_{AA'}}_{\text{mass shift}} + \underbrace{F_i\delta\langle r^2\rangle_{AA'}}_{\text{field shift}} + \underbrace{H_i(A-A')}_{\text{BSM or NLO SM/QED}}$$

K_i and F_i are difficult to compute to the accuracy needed
but they are the same for different isotopes



The King Plot

W. H. King,
J. Opt. Soc. Am. 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$
- Measure IS in two transitions. Use transition 1 to set $\delta\langle r^2\rangle_{AA'}/\mu_{AA'}$ and substitute back into transition 2:

$F_{21} \equiv F_2/F_1$
$K_{21} \equiv K_2 - F_{21}K_1$
$H_{21} \equiv H_2 - F_{21}H_1$

$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Isolating the signal: isotope shifts

$$\nu_i^{AA'} = \nu_i^A - \nu_i^{A'}$$

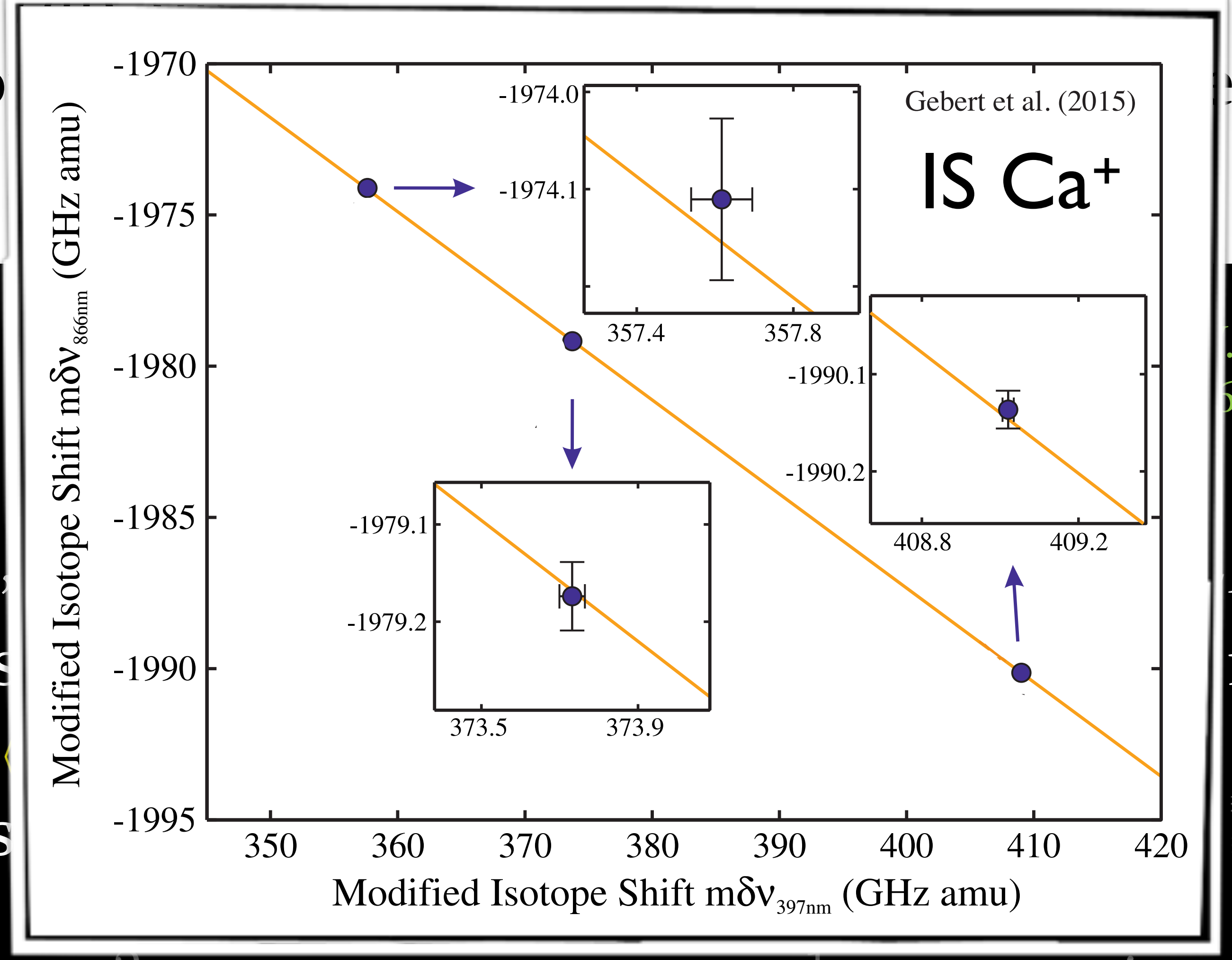
$$\delta\nu^i_{AA'} = K_i\,\mu_{AA'} + F_i\delta\langle r^2\rangle_{AA'} + H_i(A-A')$$

mass shift field shift BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed

b

es



The

. H. King,

638 (1963)

- First, AA'
- Meas 1 to

set δ

trans

$\equiv F_2/F_1$

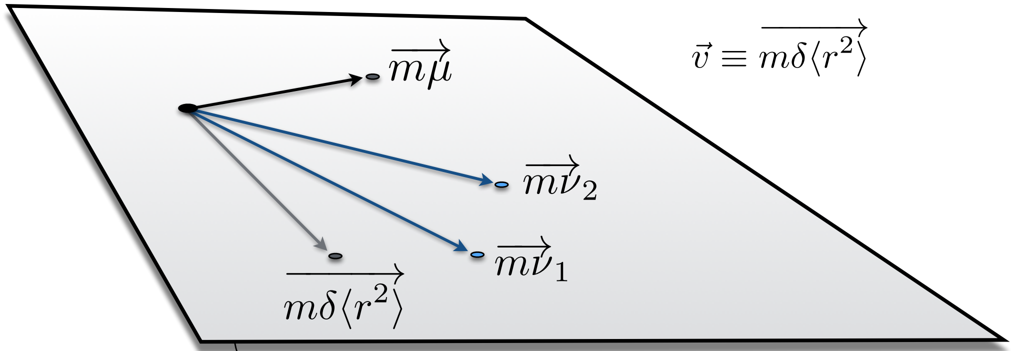
$\equiv K_2 - F_{21}K_1$

$\equiv H_2 - F_{21}H_1$

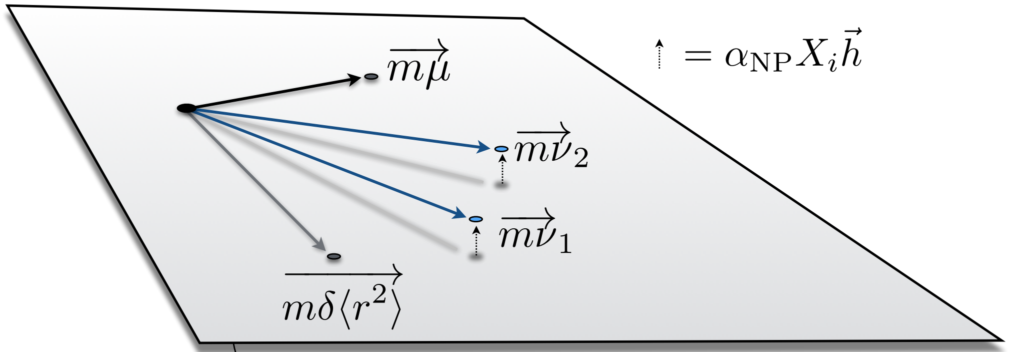
$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Constraining light NP

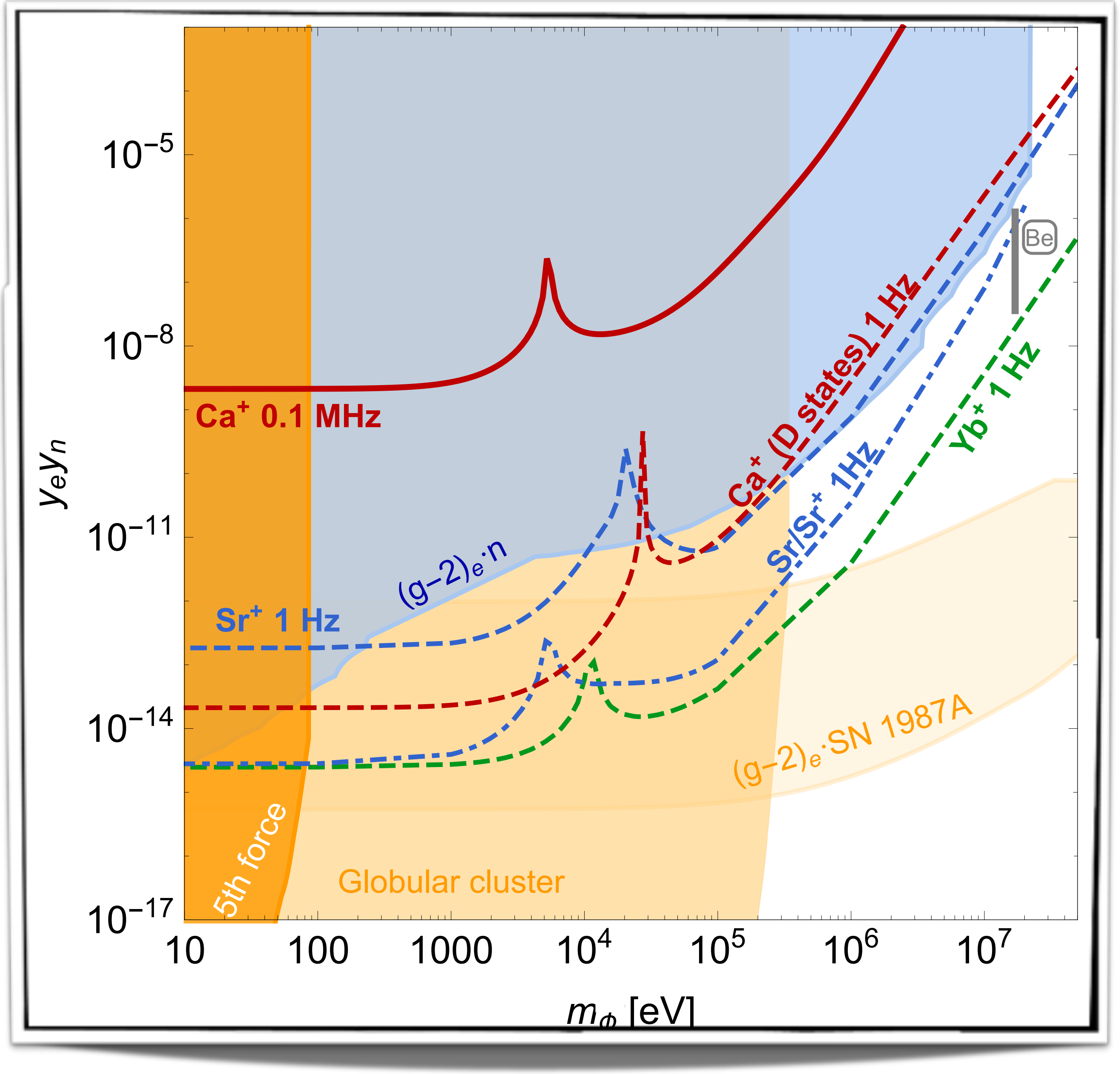


the plane spanned by $\overrightarrow{m\mu}$ and $\overrightarrow{m\delta\langle r^2\rangle}$



the plane spanned by $\overrightarrow{m\mu}$ and $\overrightarrow{m\delta\langle r^2\rangle}$

As long as
King linearity deviation
is not observed,
one can bound
new physics sources
More tricky to interpret
if a signal is observed



arXiv:1704.05068v1 [hep-ph]

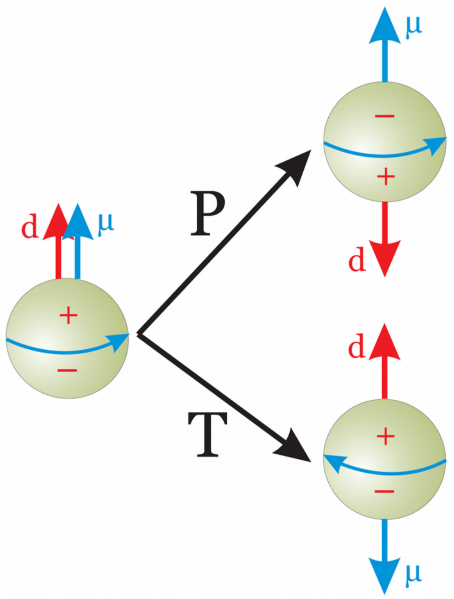
EDM

Electric Dipole Moment

$$\mathcal{L}_{dipole} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$

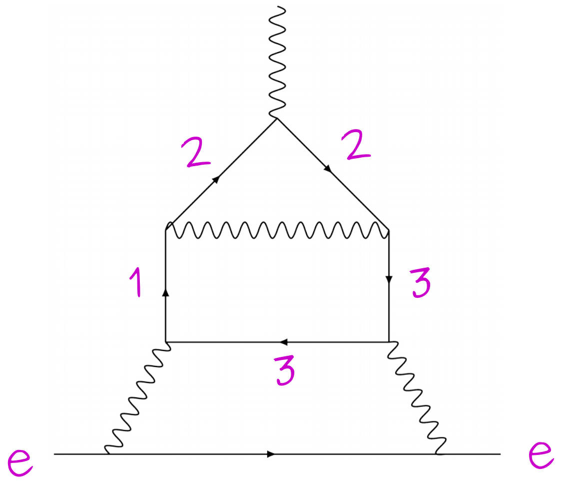
$\downarrow$ Non-relativistic limit

$$H = -\mu\,\vec{B}\cdot\frac{\vec{S}}{S} - d\,\vec{E}\cdot\frac{\vec{S}}{S}$$



Nonvanishing EDM breaks CP

SM predictions



$\rightarrow\ d_e/e \sim 10^{-40}\ \ cm$

SM contribution is ridiculously small
EDM is clear signal of New Physics

EDM - experimental status

Science 343, p. 269-272 (2014)

$|d_e| < 9.4 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad \text{at} \;\; 90\% \text{ CL}$

$|d_e| \lesssim 0.5 \cdot 10^{-29}\, e\,\mathrm{cm} \qquad \text{(ACME II)}$

$|d_e| \lesssim 0.3 \cdot 10^{-30}\, e\,\mathrm{cm} \qquad \text{(ACME III)}$

$|d_e| \lesssim 10^{-30}\; e\; cm$ arXiv:1704.07928

$|d_e| \lesssim 5 \cdot 10^{-30}\; e\; cm$ arXiv:1804.10012

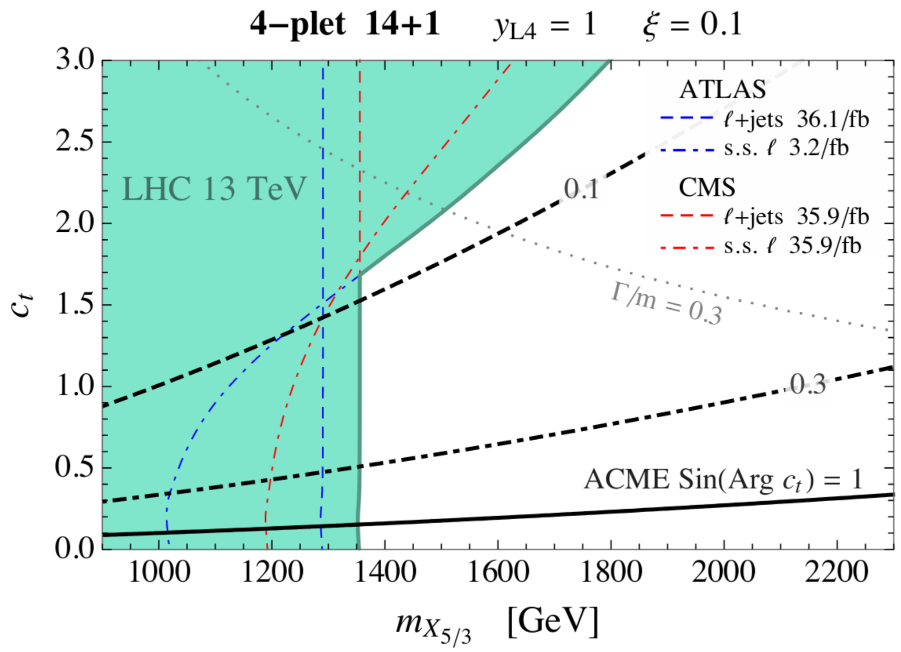
$|d_e| \lesssim 10^{-35}\; e\; cm$ arXiv:1710.08785

EDM as a BSM probe

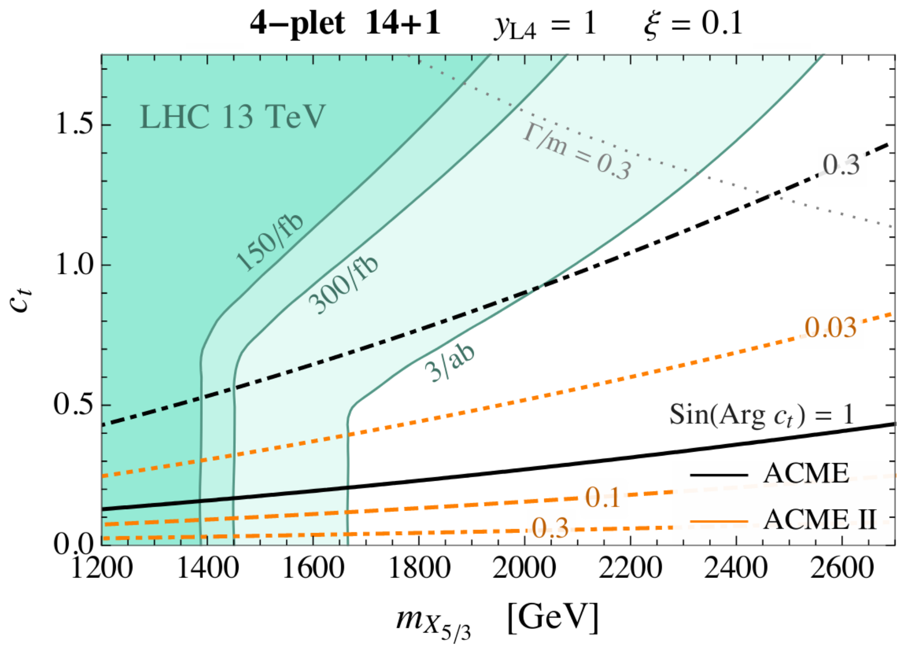
Panico, Riembau, Vantalon '17

e.g., EDM can help testing the presence of top partners in composite Higgs models

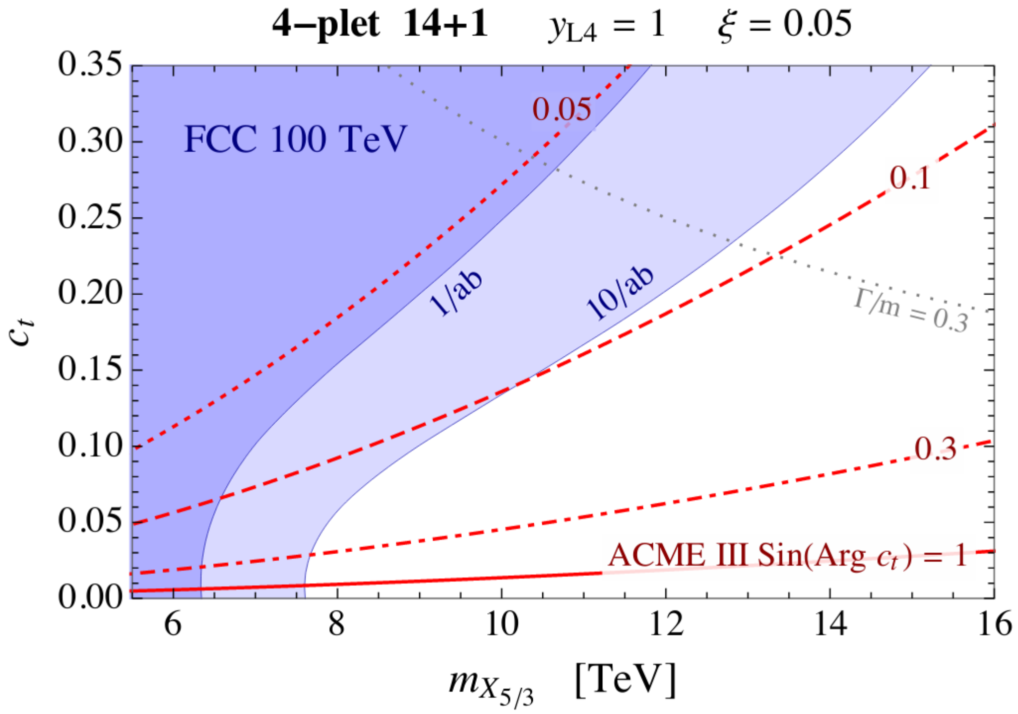
LHC



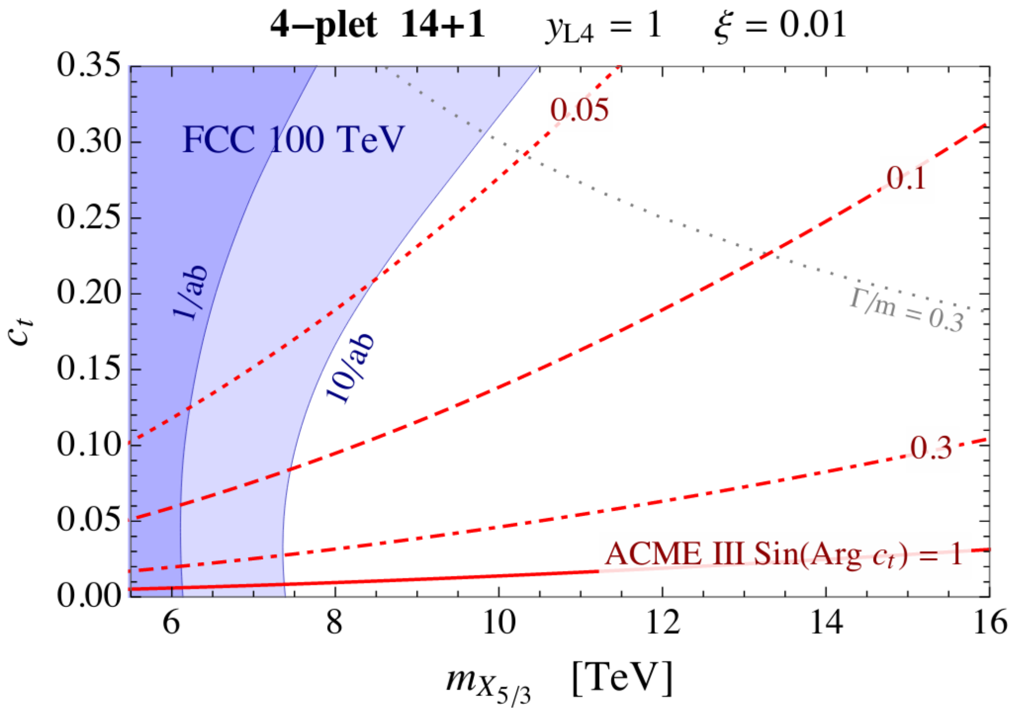
HL-LHC



FCC-hh

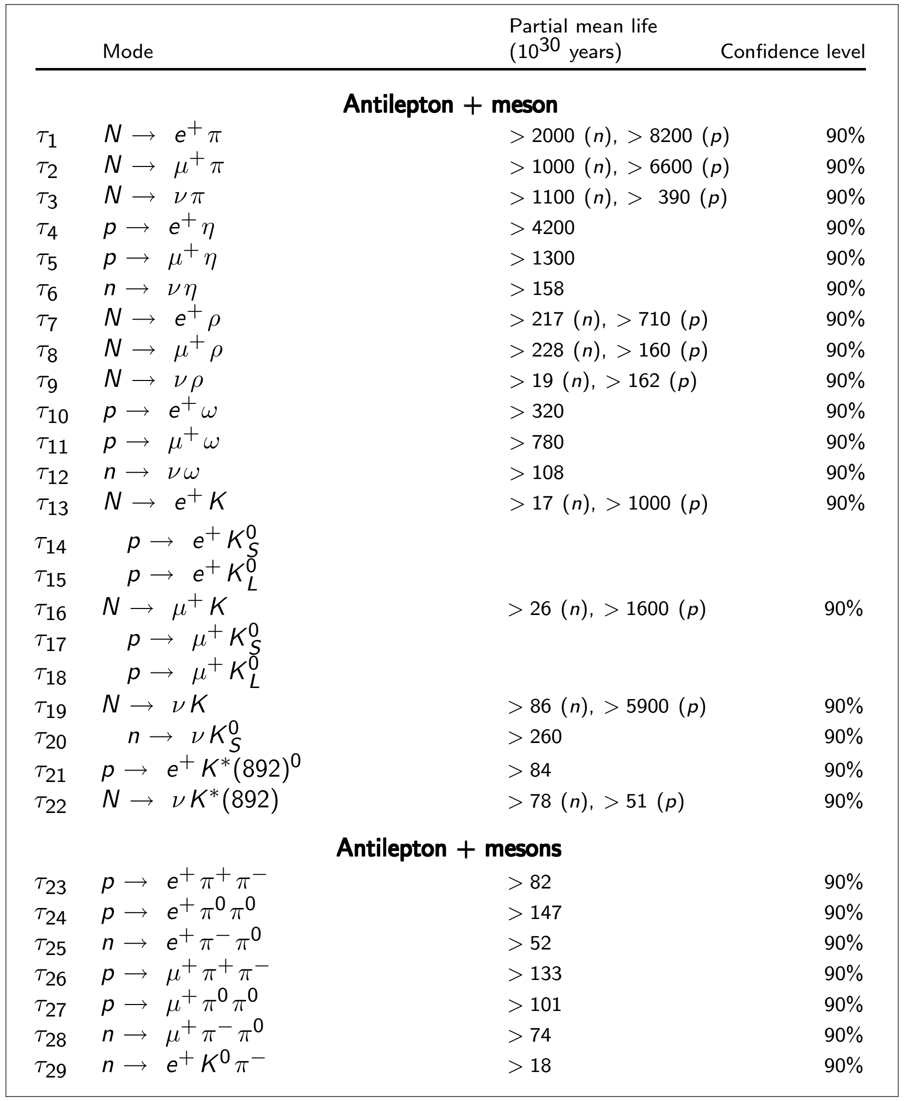


FCC-hh



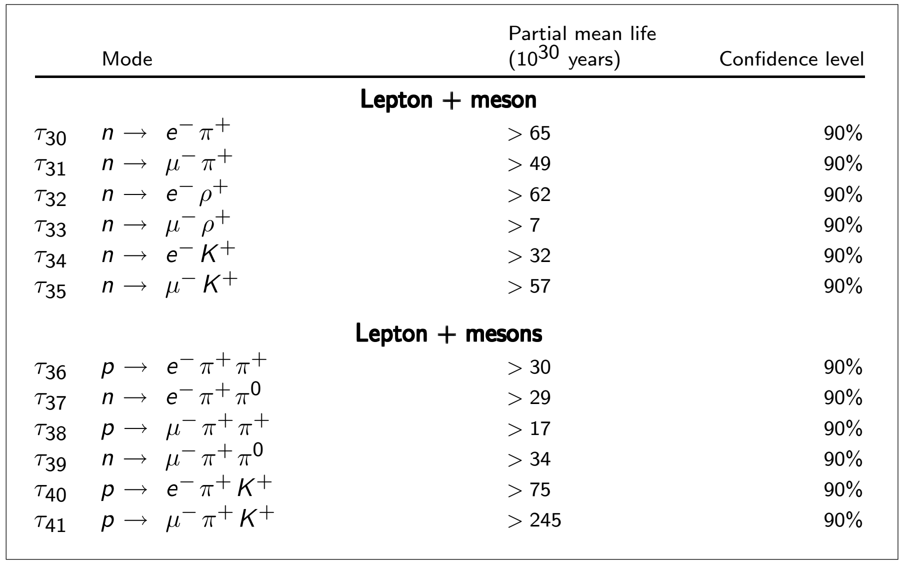
Neutron-antineutron oscillations

Constraints on Baryon # violation



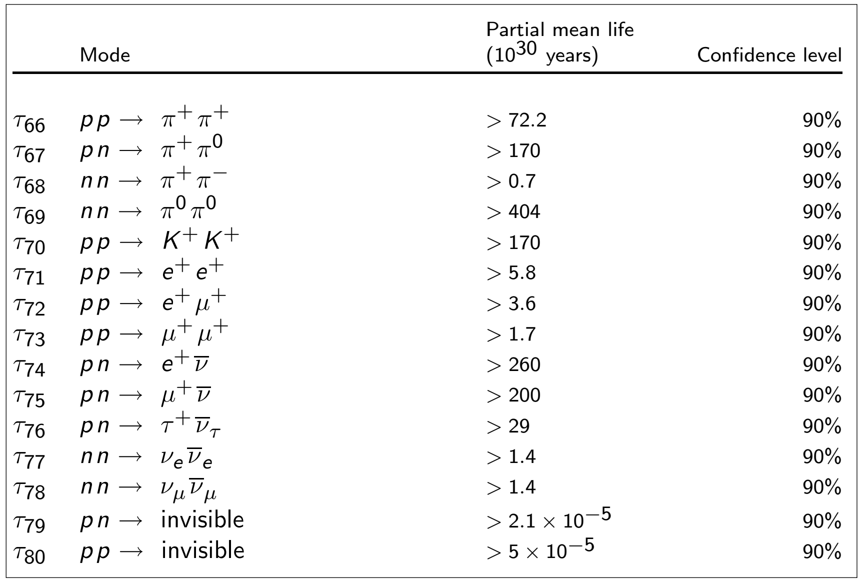
	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 2000 (n), > 8200 (p)	90%
τ_2	$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
τ_3	$N \to \nu\pi$	> 1100 (n), > 390 (p)	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 710 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 160 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	> 17 (n), > 1000 (p)	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	> 26 (n), > 1600 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	> 86 (n), > 5900 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%

ΔB=ΔL=1 decay bounds



	Mode	Partial mean life (10^{30} years)	Confidence level
	Lepton + meson		
τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%

ΔB=-ΔL=1 decay bounds

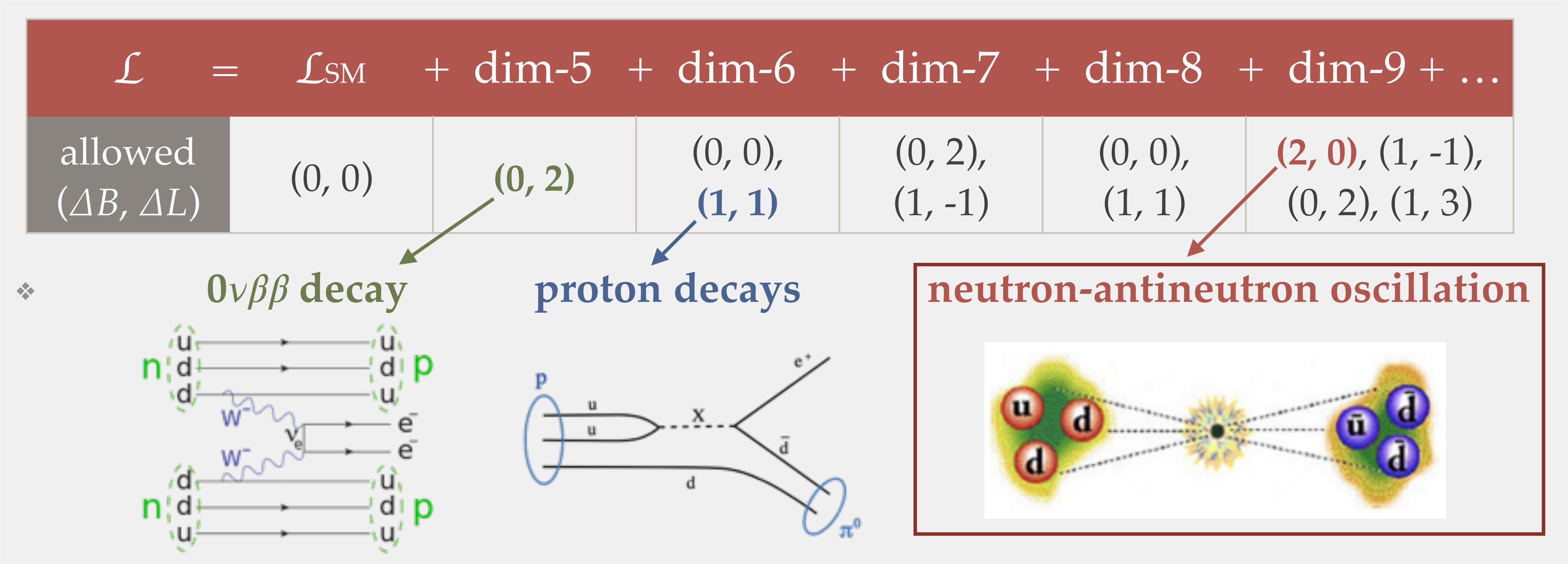


	Mode	Partial mean life (10^{30} years)	Confidence level
τ_{66}	$pp \to \pi^+\pi^+$	> 72.2	90%
τ_{67}	$pn \to \pi^+\pi^0$	> 170	90%
τ_{68}	$nn \to \pi^+\pi^-$	> 0.7	90%
τ_{69}	$nn \to \pi^0\pi^0$	> 404	90%
τ_{70}	$pp \to K^+K^+$	> 170	90%
τ_{71}	$pp \to e^+e^+$	> 5.8	90%
τ_{72}	$pp \to e^+\mu^+$	> 3.6	90%
τ_{73}	$pp \to \mu^+\mu^+$	> 1.7	90%
τ_{74}	$pn \to e^+\overline{\nu}$	> 260	90%
τ_{75}	$pn \to \mu^+\overline{\nu}$	> 200	90%
τ_{76}	$pn \to \tau^+\overline{\nu}_\tau$	> 29	90%
τ_{77}	$nn \to \nu_e\overline{\nu}_e$	> 1.4	90%
τ_{78}	$nn \to \nu_\mu\overline{\nu}_\mu$	> 1.4	90%
τ_{79}	$pn \to$ invisible	$> 2.1 \times 10^{-5}$	90%
τ_{80}	$pp \to$ invisible	$> 5 \times 10^{-5}$	90%

ΔB=2/ΔL=0 decay bounds*

*For flavour universal models, nn gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might be win

Pattern of B violation in SM(EFT)



$\mathcal{L}$ =	$\mathcal{L}_{\rm SM}$	+ dim-5	+ dim-6	+ dim-7	+ dim-8	+ dim-9 + …
allowed $(\Delta B, \Delta L)$	(0, 0)	**(0, 2)**	(0, 0), **(1, 1)**	(0, 2), (1, -1)	(0, 0), (1, 1)	**(2, 0)**, (1, -1), (0, 2), (1, 3)

$0\nu\beta\beta$ decay

proton decays

neutron-antineutron oscillation

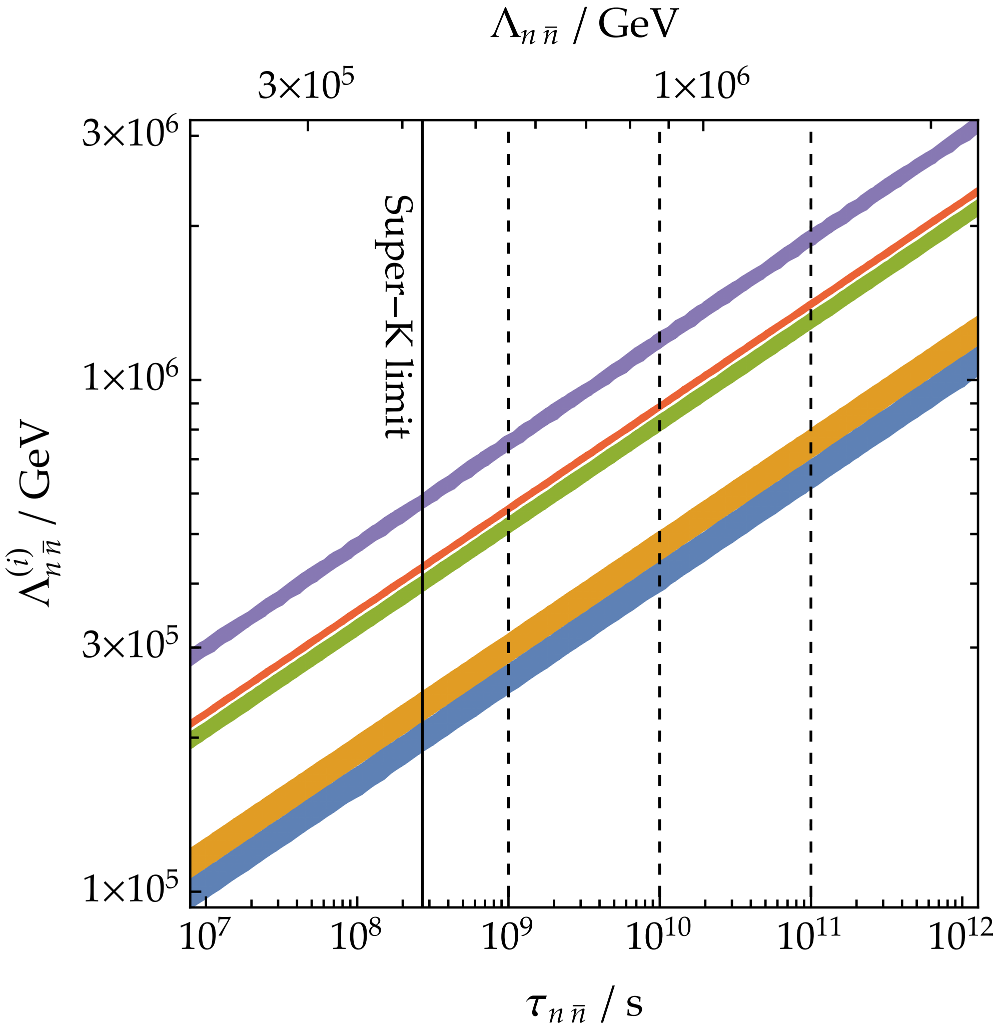
A. Kobach '16

Slide stolen to Z. Zhang @ Pascos'18

12 operators (of the type 'uudddd')

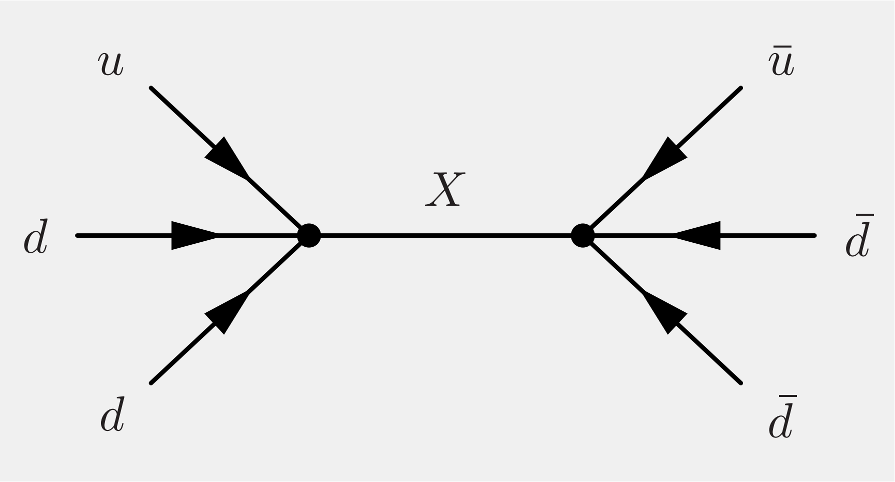
$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n}|\mathcal{H}_{\rm eff}|n\rangle\right|$$

SuperK/ESS, DUNE is/will probe scales 10^5-10^6 GeV



$n\bar{n}$ oscillations and baryogenesis

Grojean, Shakya, Wells, Zhang ‘18



Mediator X

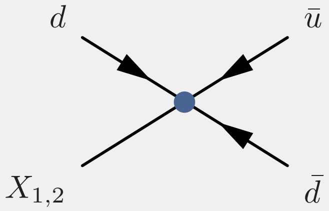
Single mediator X decays cannot generate a baryon asymmetry at leading order in the B violating coupling (Nanopoulos-Weinberg theorem ‘1979)

Two mediators X_1, X_2 ($M_{X1}<M_{X2}$)

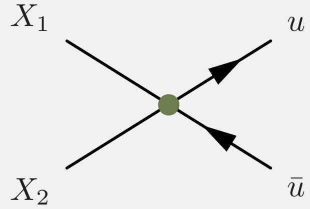
$$\begin{aligned}\mathcal{L} \supset\ & \eta_{X_1}\, \epsilon^{ijk} (\bar{u}^c_i P_R d_j)(\bar{d}^c_k P_R X_1) \\ & + \eta_{X_2}\, \epsilon^{ijk} (\bar{u}^c_i P_R d_j)(\bar{d}^c_k P_R X_2) \\ & + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}\end{aligned}$$

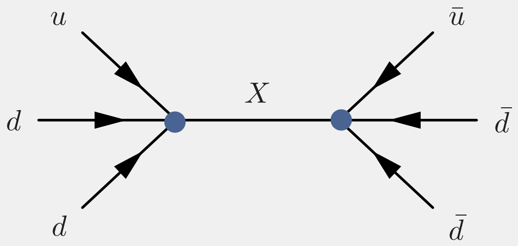
$$|\eta_{X_1}| \equiv \Lambda^{-2}_{X_1}\,,\ |\eta_{X_2}| \equiv \Lambda^{-2}_{X_2}\,,\ |\eta_c| \equiv \Lambda^{-2}_c\,.$$

- 2 ***B*-violating** operators



- 1 ***B*-conserving** operator





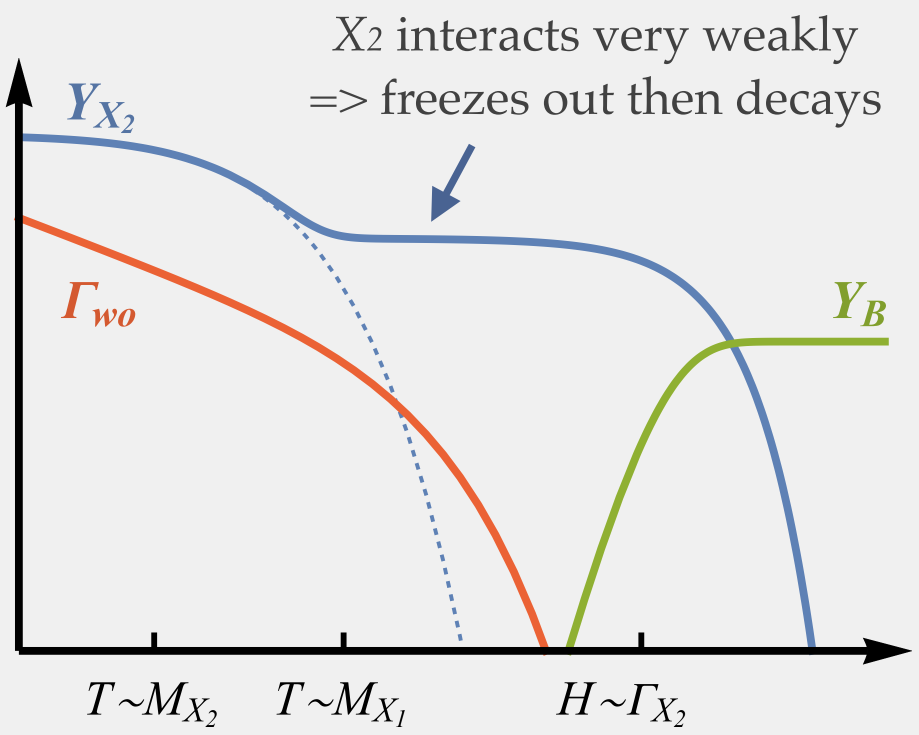
$$c_1 = \frac{1}{\left(\Lambda^{(1)}_{n\bar{n}}\right)^5} = \frac{1}{M_{X_1}\Lambda^4_{X_1}} + \frac{1}{M_{X_2}\Lambda^4_{X_2}}$$

Two mediators with both B and $\not{B}$ couplings are enough to evade Nanopoulos-Weinberg

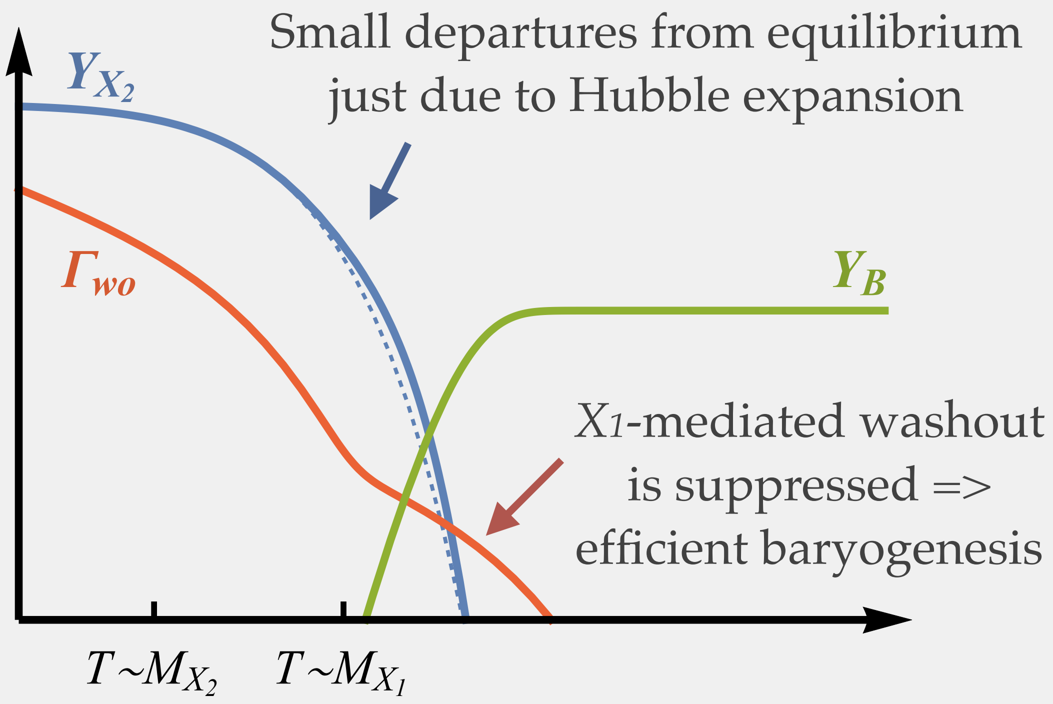
Baryogenesis

Grojean, Shakya, Wells, Zhang '18

Late decay scenario	Early decay scenario
$\Lambda_{X_2} \sim \Lambda_c \gg \Lambda_{X_1}$	$\Lambda_{X_1} \gg \Lambda_{X_2} \gtrsim \Lambda_c$



X_2 interacts very weakly
=> freezes out then decays



Small departures from equilibrium
just due to Hubble expansion

X_1-mediated washout
is suppressed =>
efficient baryogenesis

-

Baryogenesis

Grojean, Shakya, Wells, Zhang ‘18

Late decay scenario	Early decay scenario
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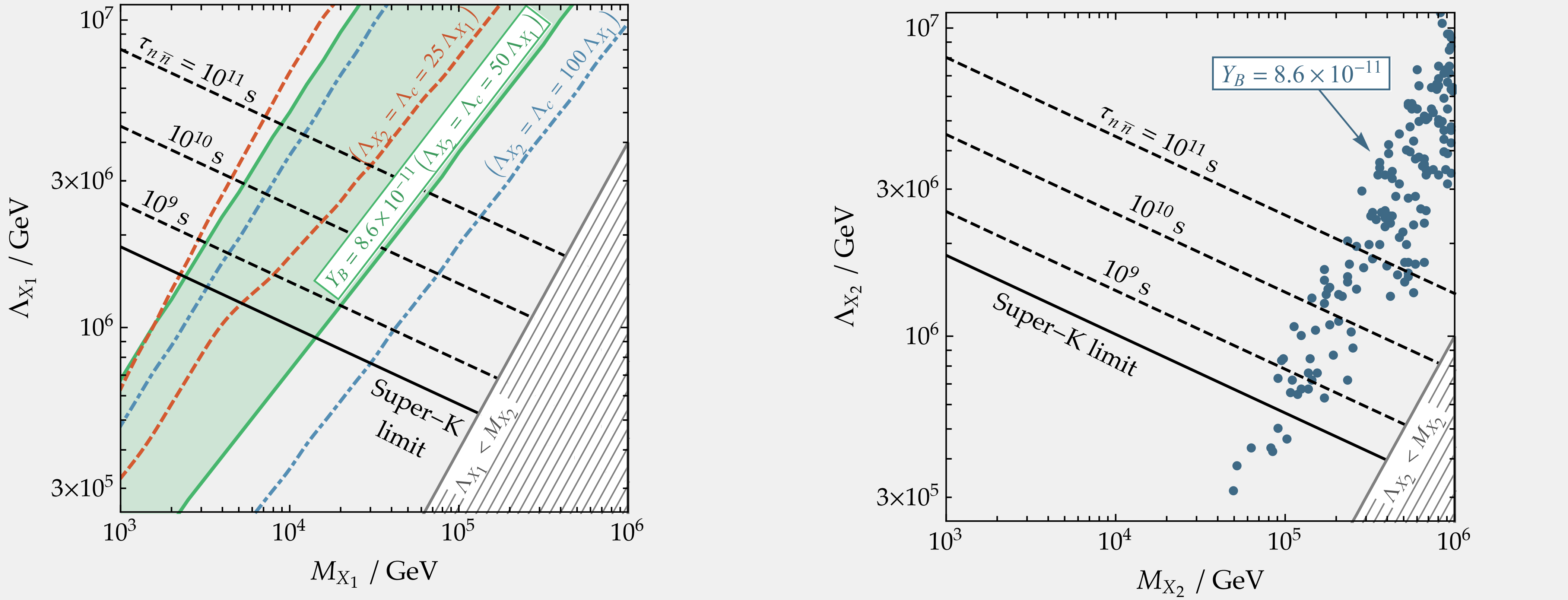
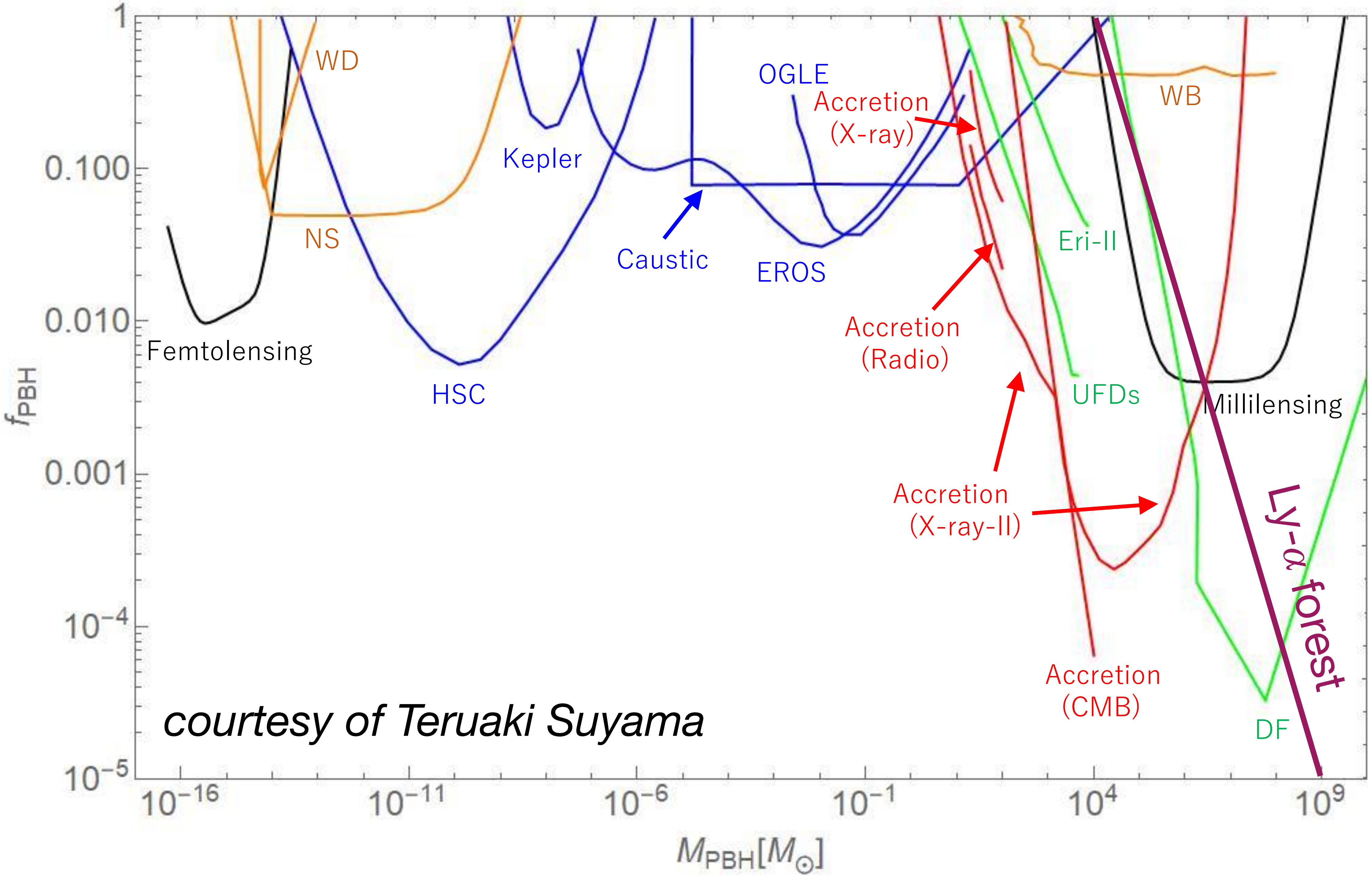


Explicit realisation of late decay scenario:
RPV SUSY with late decays of the bino in presence of a wino/gluino
[F.Rompineve, 1310.0840] [Y.Cui, 1309.2952] [G.Arcadi, L.Covi, M.Nardecchia, 1507.05584]

$n\bar{n}$ oscillations can probe direct baryogenesis scenarios @ $10^{5\text{-}6}$ GeV

Searching for a black moon

PBHs as DM



courtesy of Teruaki Suyama

PBH abundance

Details depends on production mode, but various mechanisms agree upon estimate

$M_{PBH} \simeq 10^{-16} M_{\odot}$ (~ asteroid)

$R_{PBH} \simeq 10^{-13}$ m (subatomic size)

Assuming they give all DM

$\rho_{DM} \sim 0.3 \text{ GeV/cm}^3 \Rightarrow \Delta x \sim 10^{12}$ m

(~ a few in our solar system)

$N_{Galaxy} \sim 10^{27}$

JR Espinosa @ Benasque 2018

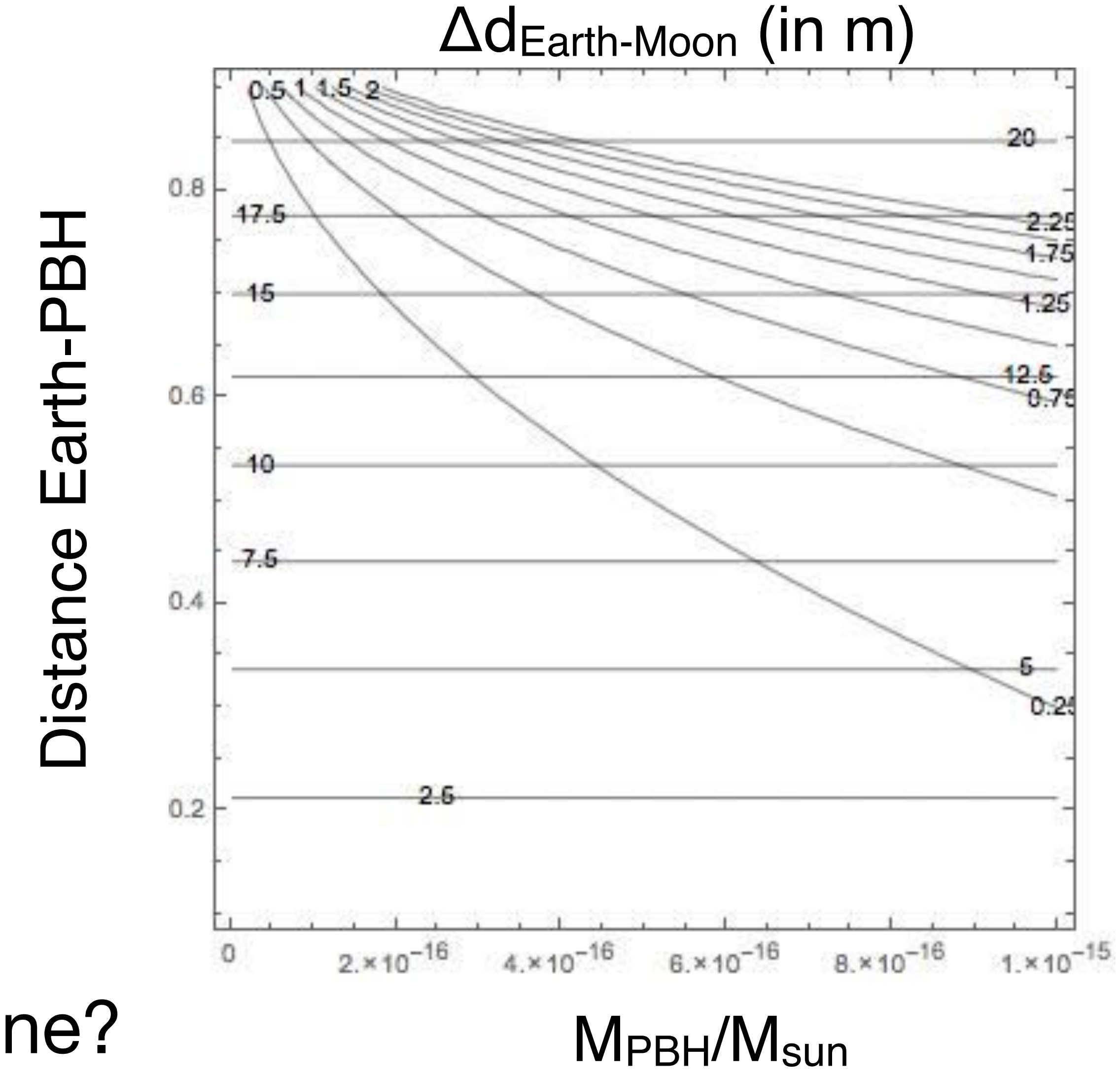
How can we detect PBHs in the Solar system?

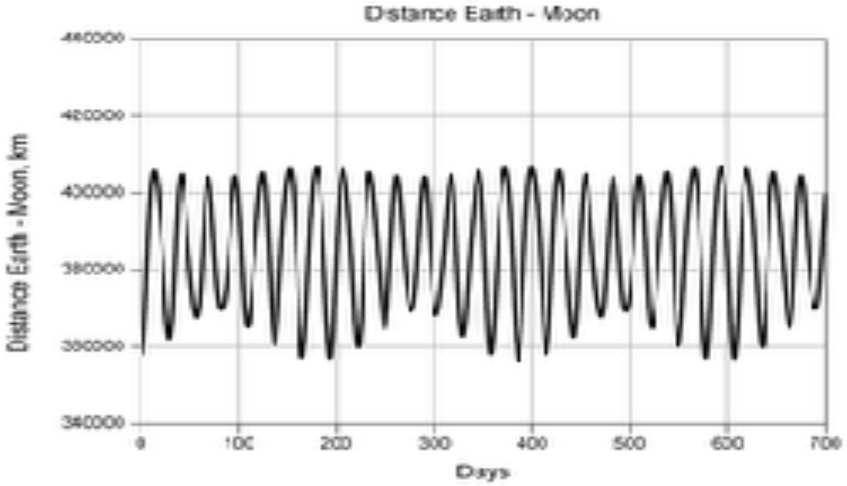
A PBH orbiting around Earth

Grojean, Riembau, Ruderman et al, in progress

Is there a black moon around Earth interacting only gravitationally?

A black moon between the Earth and the Moon will induce a various of the distance Earth-Moon, which is measured with an accuracy of 1mm (10^{-11} relative accuracy)





Can also use GPS measurements…
Looking for a black moon with your cell-phone?

Conclusion(s)

The hierarchy problem made easy

only a few electrons are enough to lift your hair (~ 10^{25} mass of e^-)

the electric force between 2 e^- is 10^{43} times larger than their gravitational interaction

we don't know why gravity is so weak?

we don't know why the masses of particles are so small?

Several theoretical hypothesis

new dynamics? new symmetries? new space-time structure?

modification of special relativity? of quantum mechanics?

One day, one of you might be in his position...

B. Clinton, Davos 2011

Hopefully, that day you'll remember
what you have learnt during your stay at CERN

Thank you for your attention.
Good luck for your studies!

if you have question/want to know more

do not hesitate to send me an email

christophe.grojean@desy.de