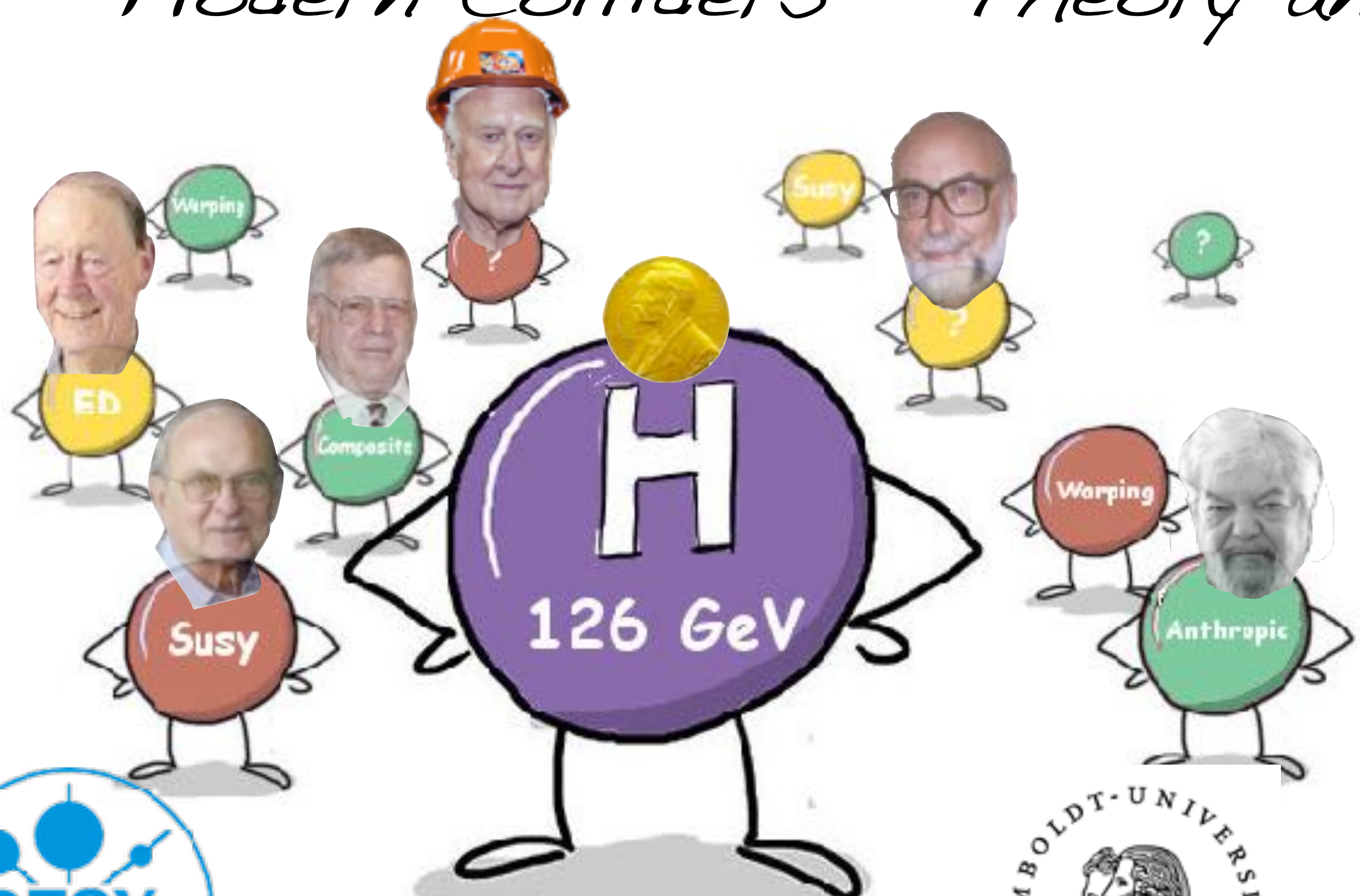
Beyond the Standard Model

Helmholtz International School

" Modern Colliders - Theory and Experiment 2018 "



Lecture 3/3

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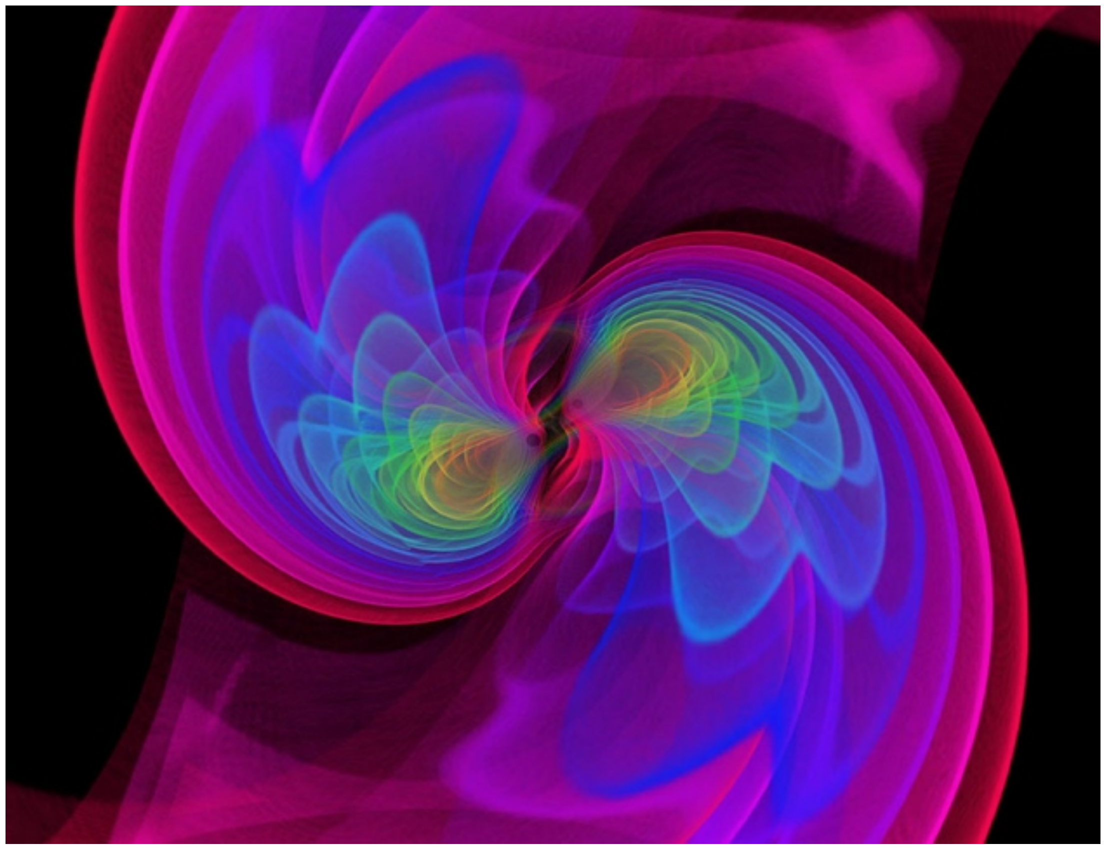
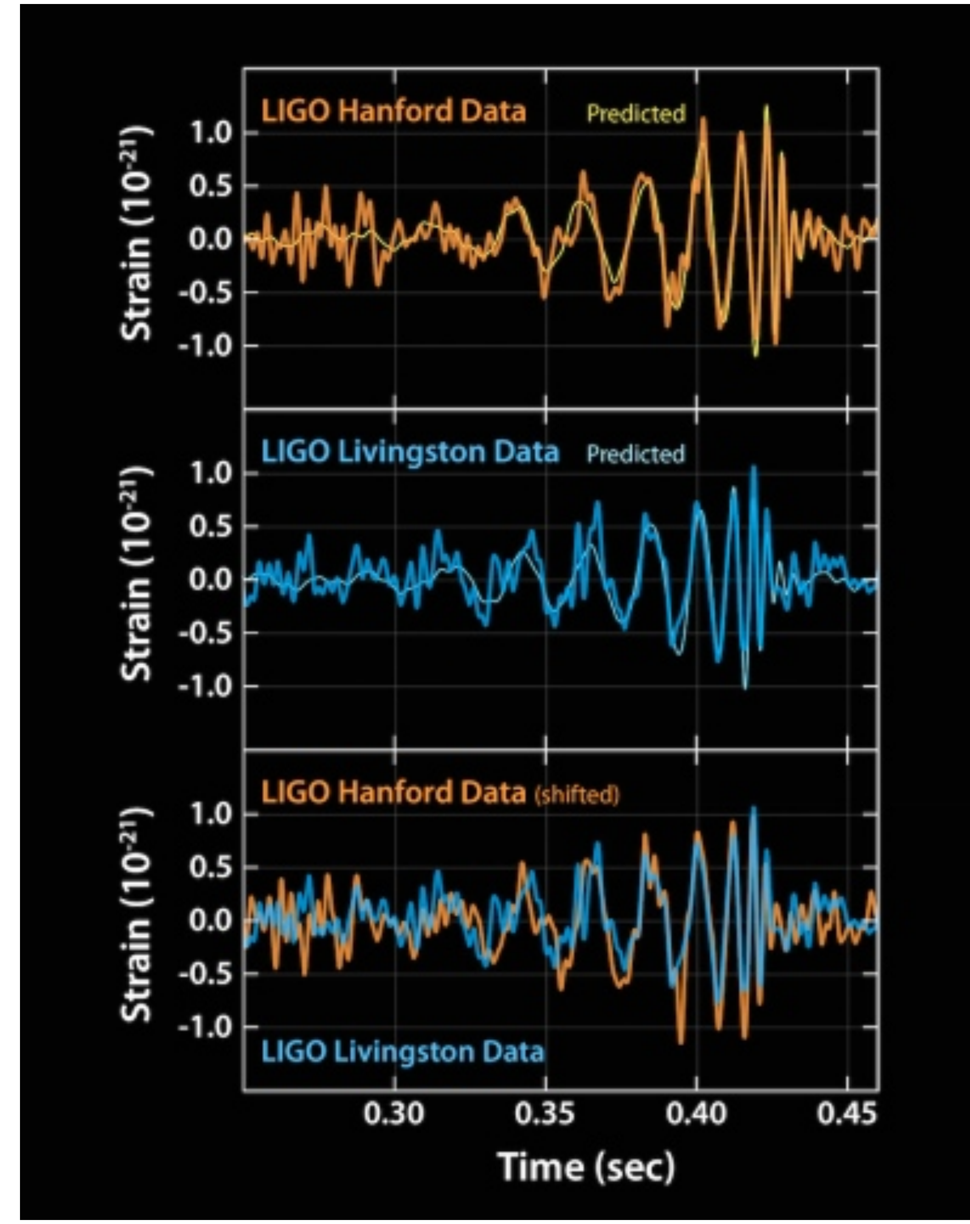
Gravitational waves

The pictures that shook the Earth

GW150914



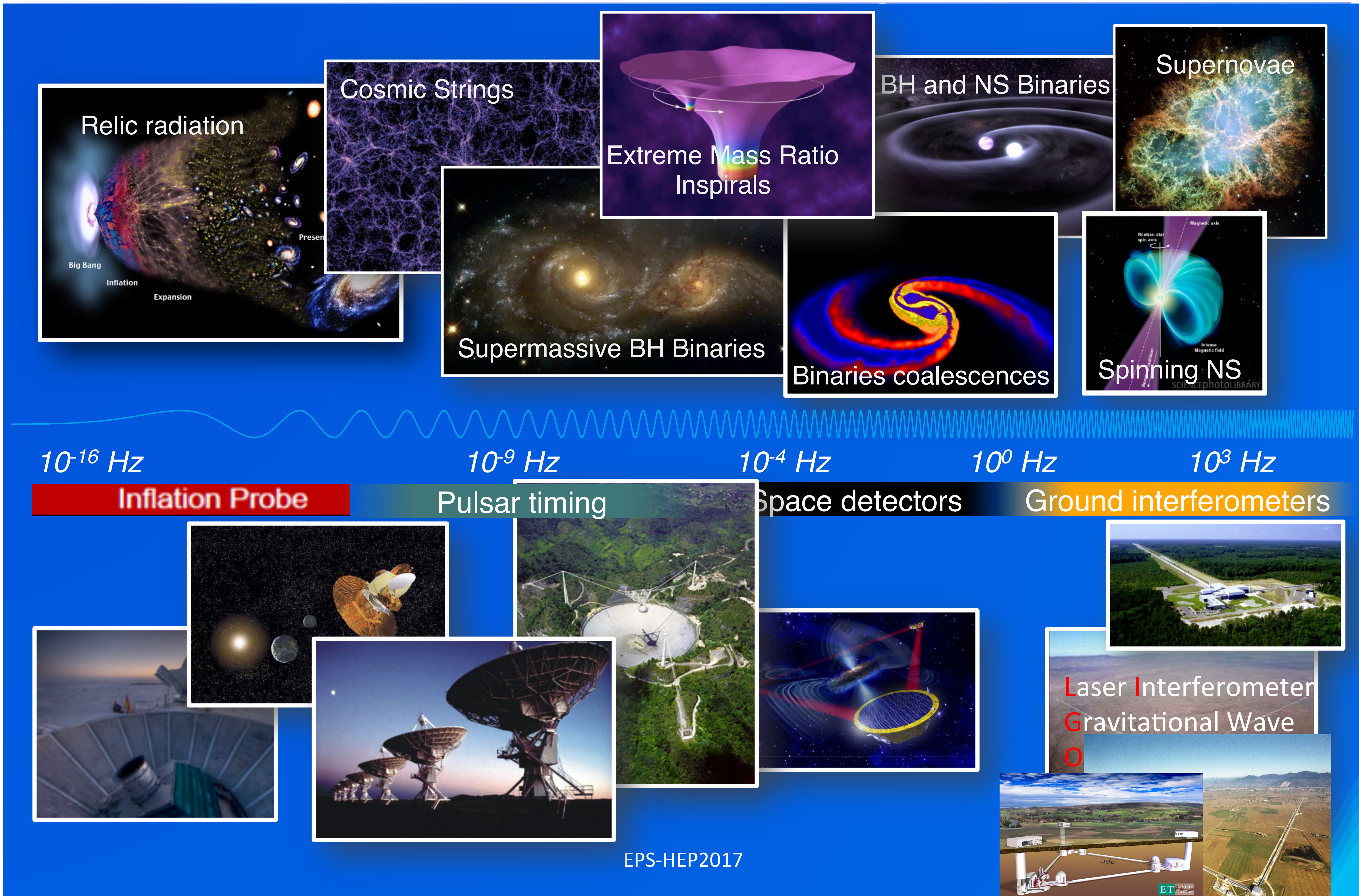
1.3 billion
years
later
on earth



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

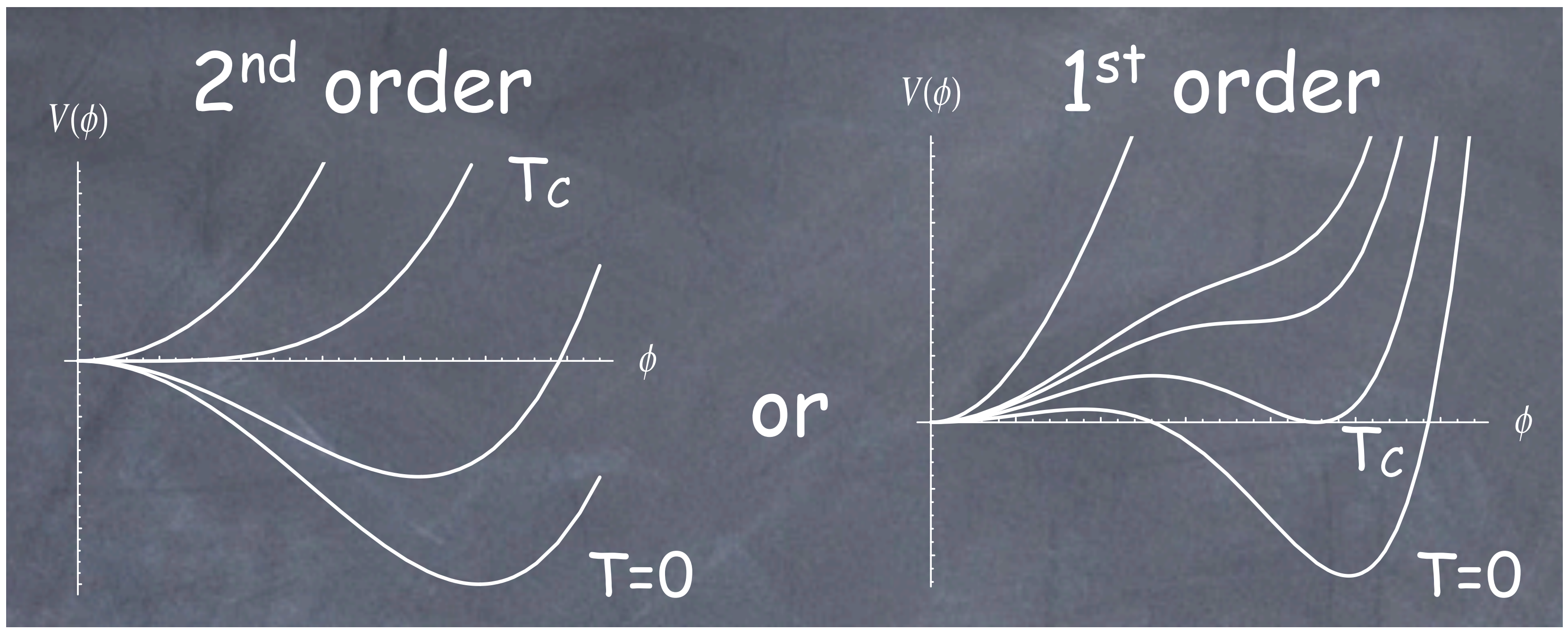
GW and astrophysics/cosmology



Dynamics of EW phase transition

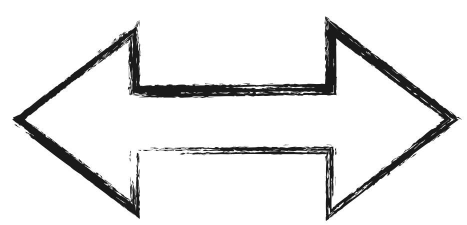
The asymmetry between matter-antimatter can be created dynamically
it requires an out-of-equilibrium phase in the cosmological history of the Universe

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 ~

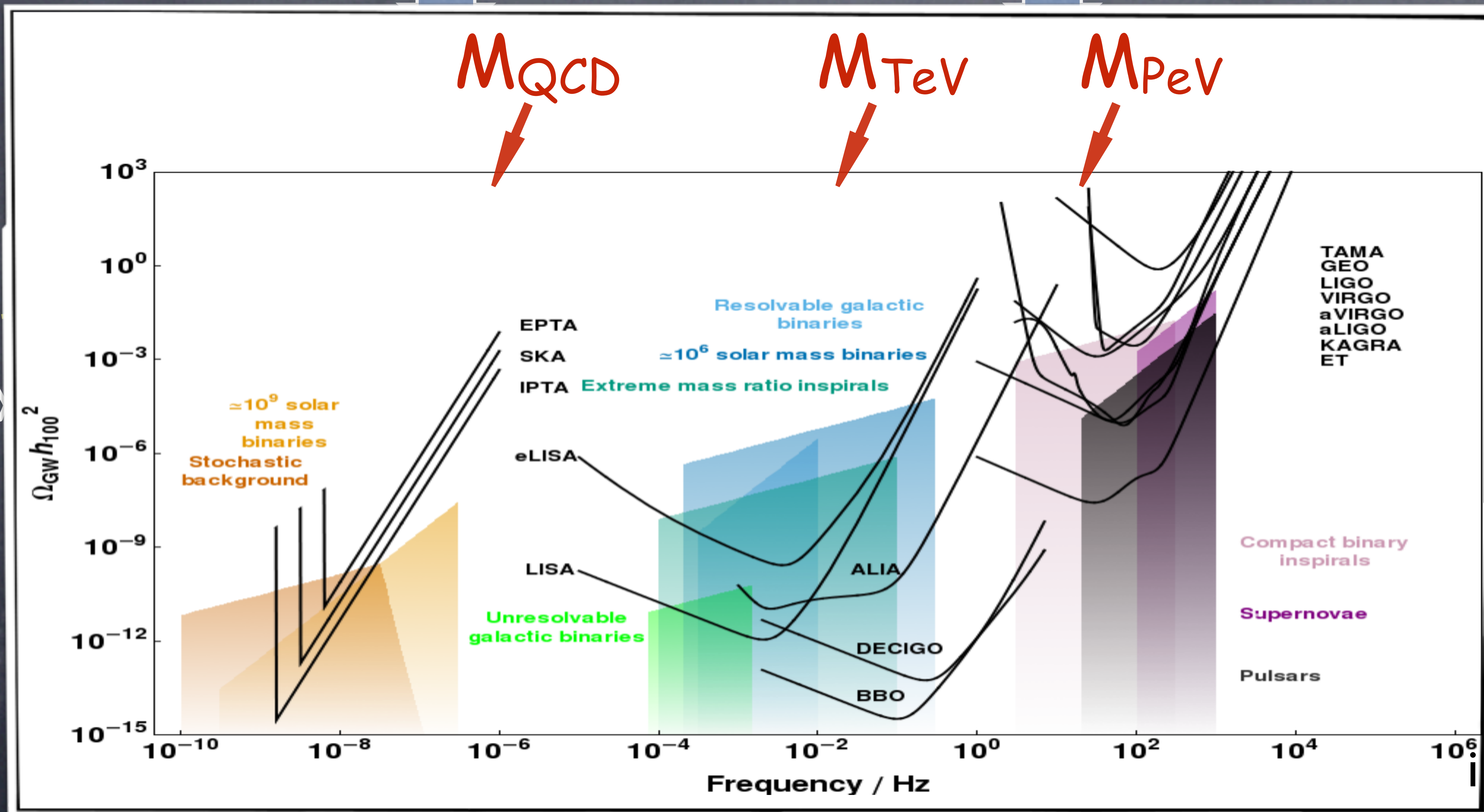
$$f \sim \# \frac{2\cdot 10^{-4}\ \text{eV}}{100\ \text{GeV}}\ 10^{-15}\ \text{GeV} \sim \#\, 10^{-5}\ \text{Hz}$$

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

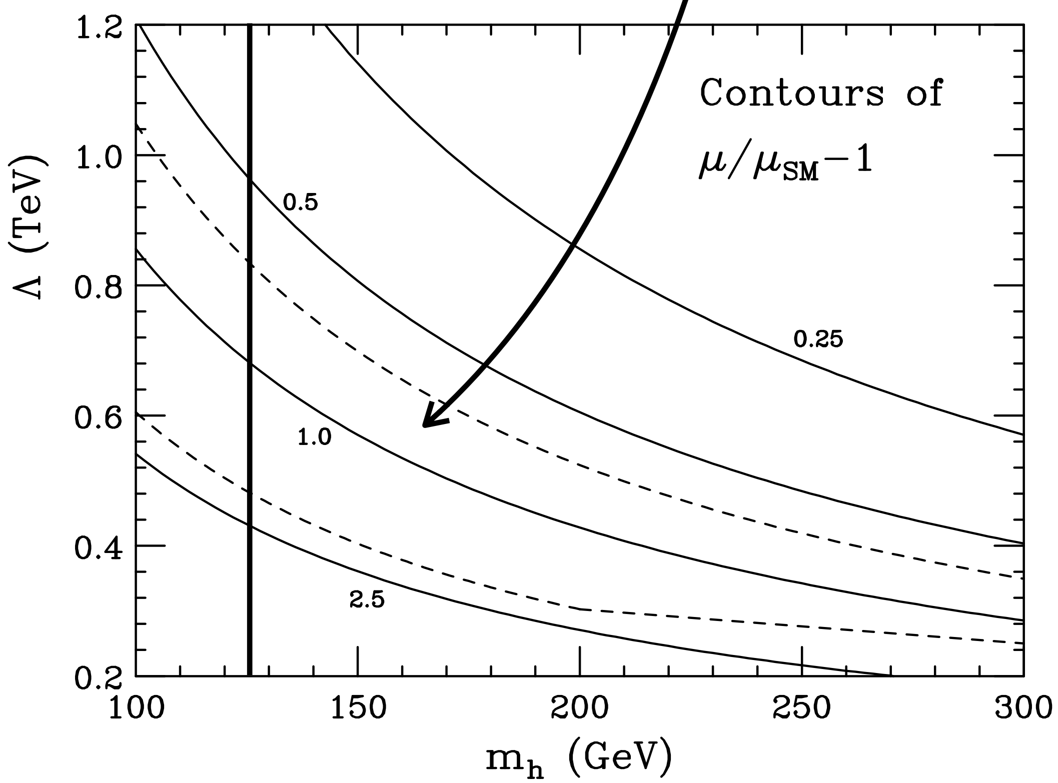


Grojean, Servant '06

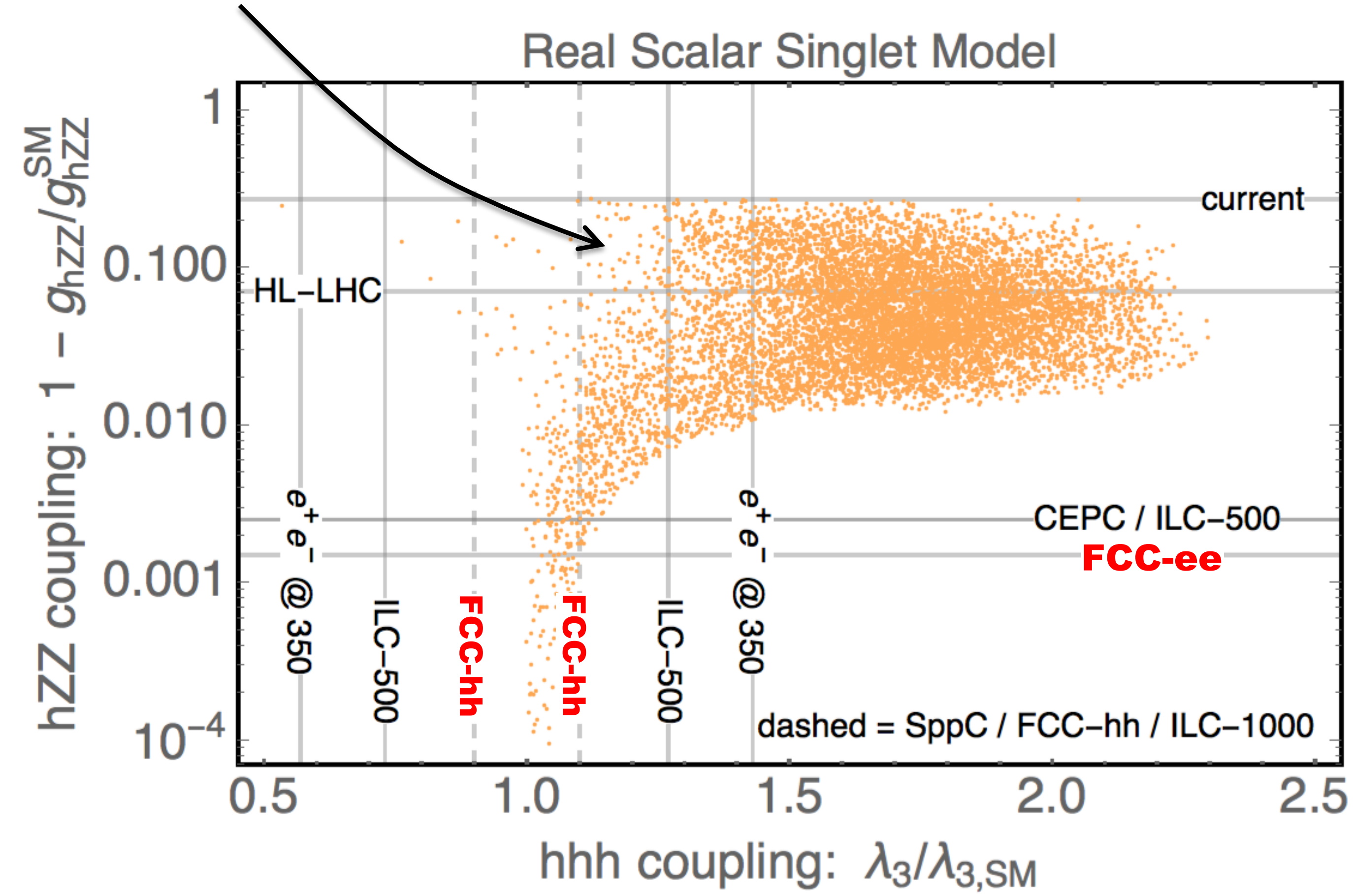
The GW spectrum from a 1st order electroweak PT
is peaked around the milliHertz frequency

Complementary GW - Colliders

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



Grojean, Servant, Wells '04

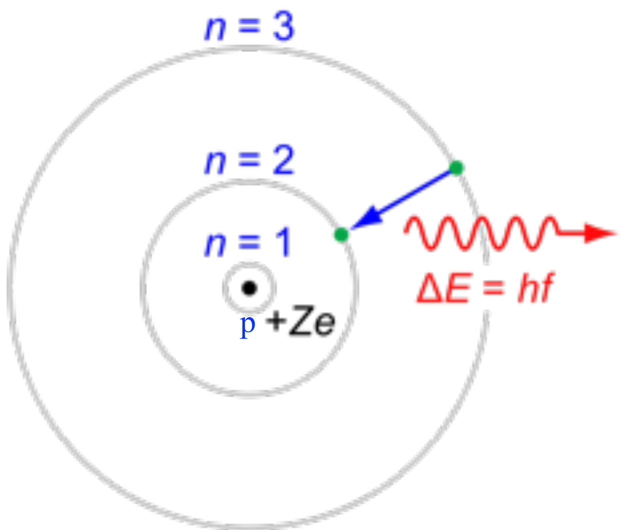


Huang, Long, Wang '16

"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.

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

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

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

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

mass shift — field shift — BSM or NLO SM/QED

K_i and F_i are difficult to compute to the accuracy needed 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

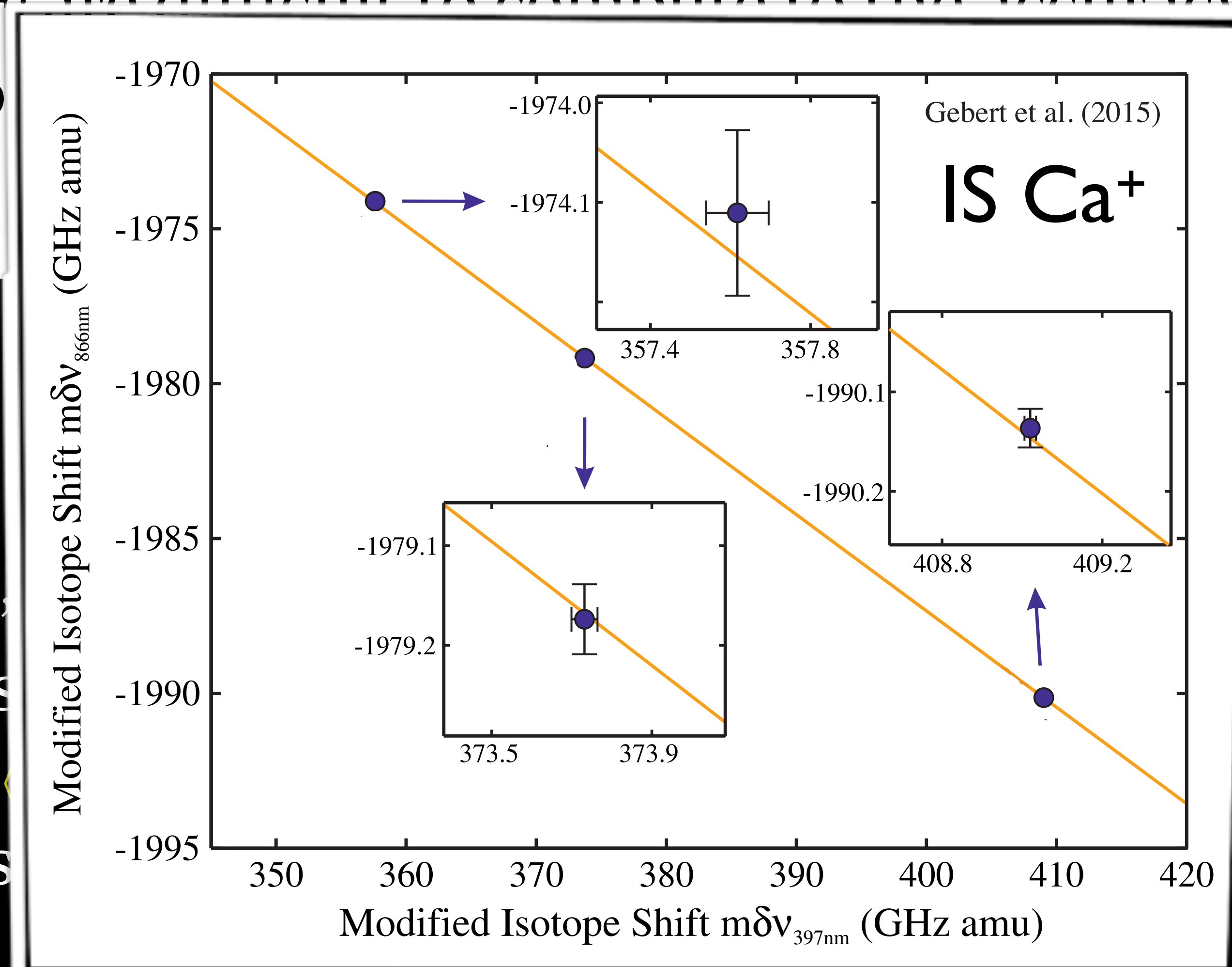
K_i and F_i are difficult to compute to the accuracy needed

b ... es

The ... . H. King, ... 538 (1963)

- First, ... $_{AA'}$
- Meas... 1 to set δ... trans...

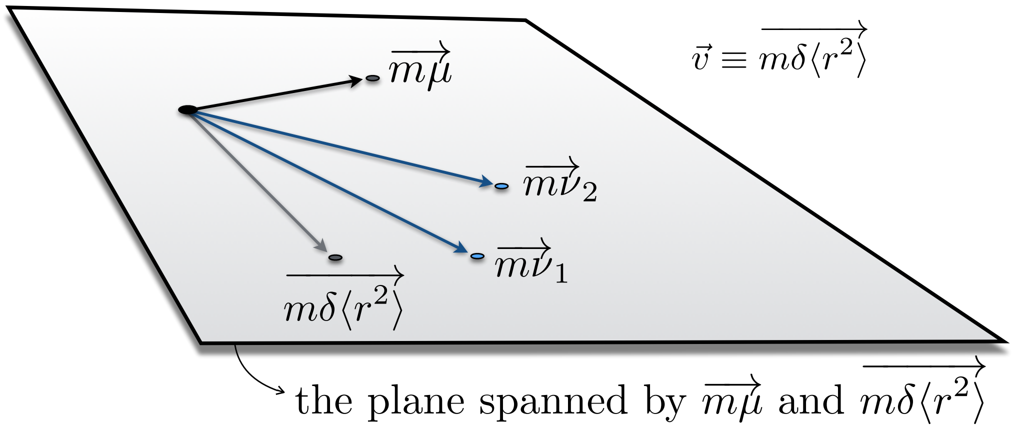
$\equiv F_2/F_1$
$\equiv K_2 - F_{21}K_1$
$\equiv H_2 - F_{21}H_1$

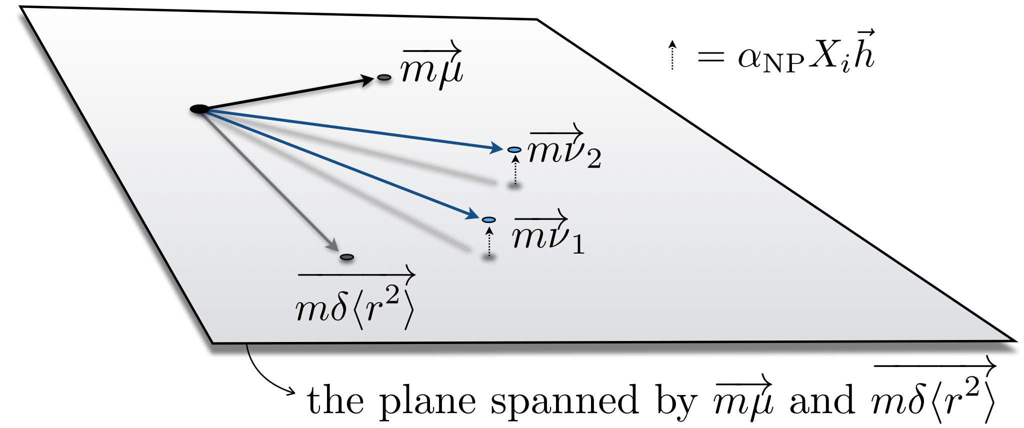


$$m\delta\nu^2_{AA'} = K_{21} + F_{21}m\delta\nu^1_{AA'} - AA'H_{21}$$

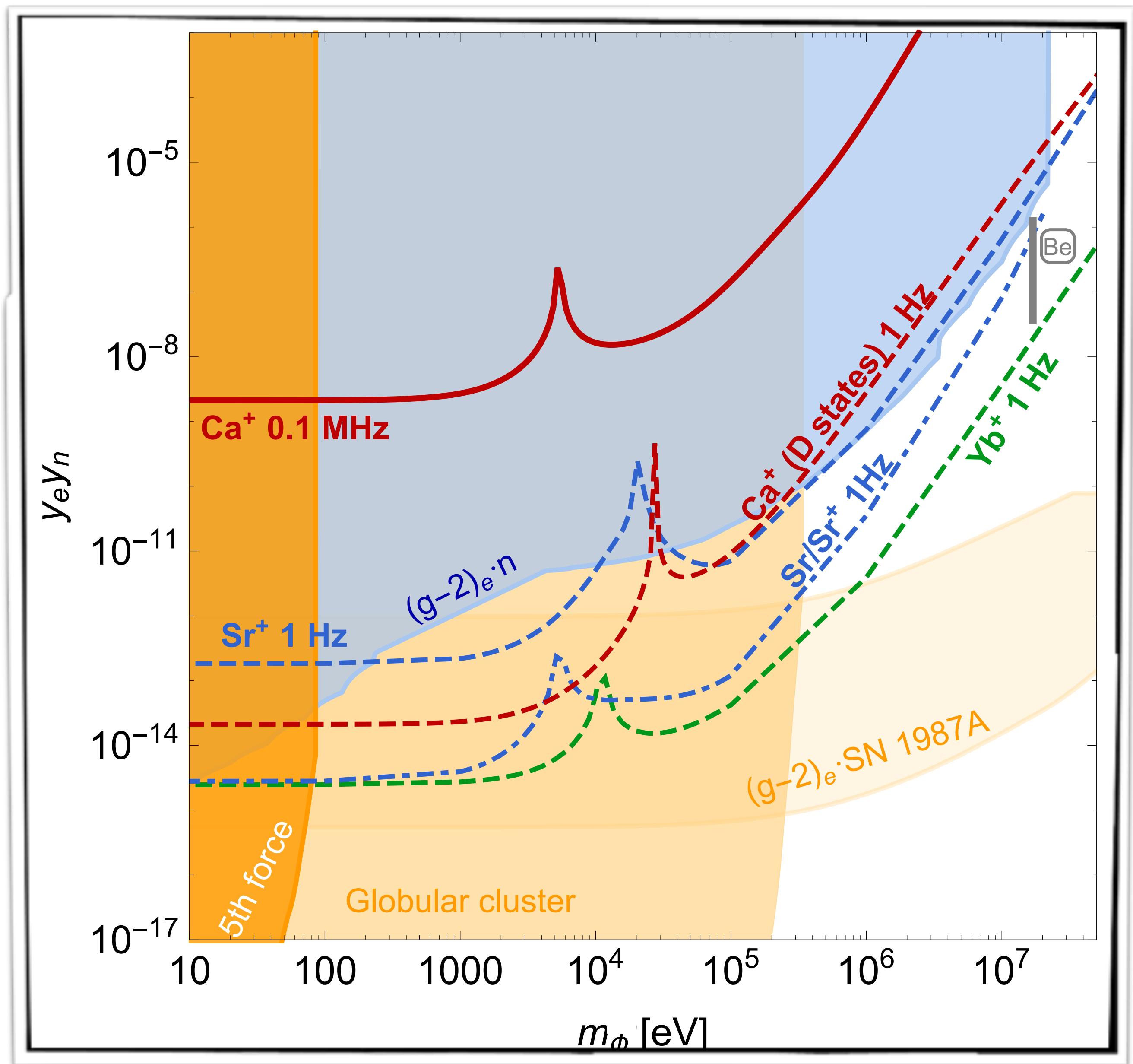
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain

Constraining light NP





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

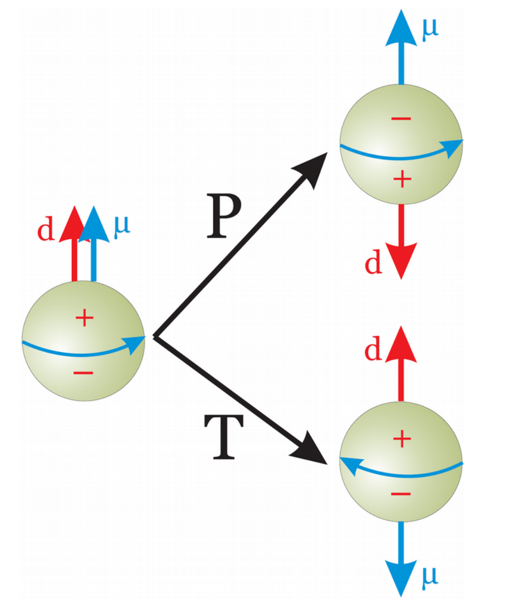
Electric Dipole Moment

(M. Riembau, PhD defense '18)

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

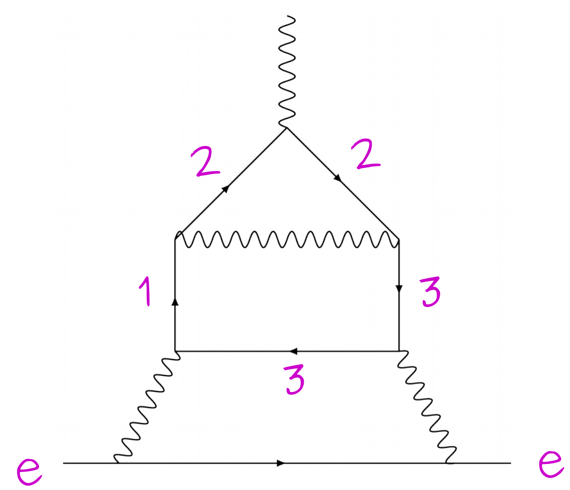
Non-relativistic limit

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



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

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

$$d_e \sim \delta_{\rm CPV}\left(\frac{\lambda}{16\pi^2}\right)^k \frac{m_e}{M^2}$$

Then dimensional analysis tells us that the experiment probes masses **Preliminary: experimental result not yet known**

0-loop	1-loop	2-loop
800 TeV	40 TeV	2 TeV

(M. Reece, SUSY '18)

EDM - experimental status

Science 343, p. 269-272 (2014)

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

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

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

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

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

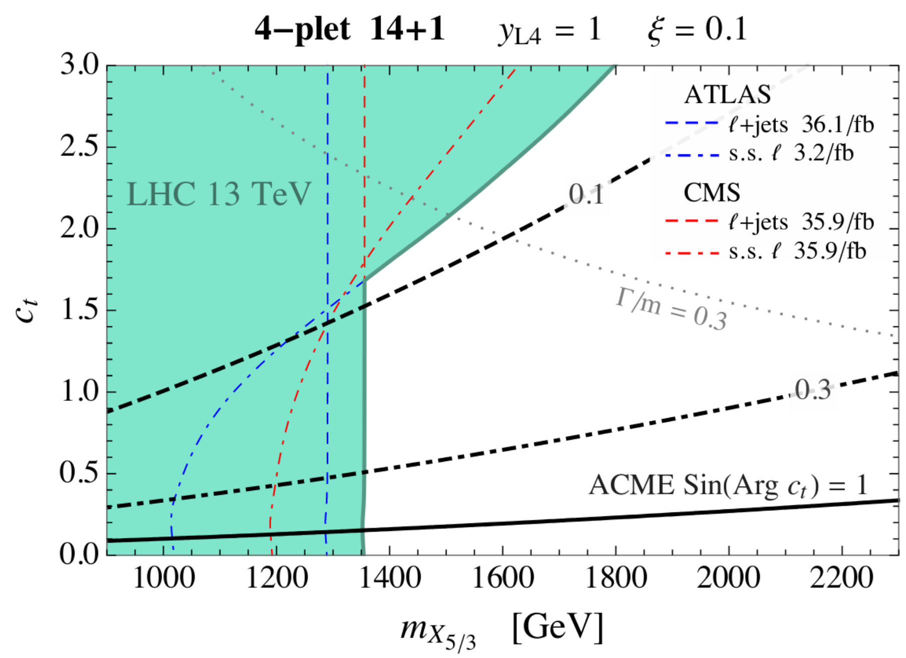
$$|d_e| \lesssim 10^{-35}\, e\, cm$$ arXiv:1710.08785

EDM as a BSM probe

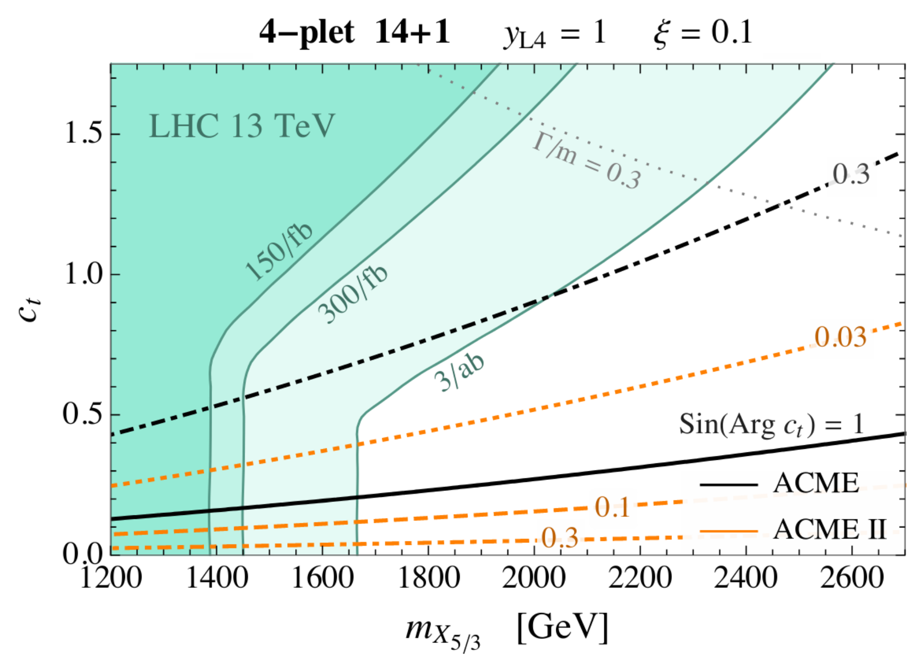
Panico, Riembau, Vantalon '17

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

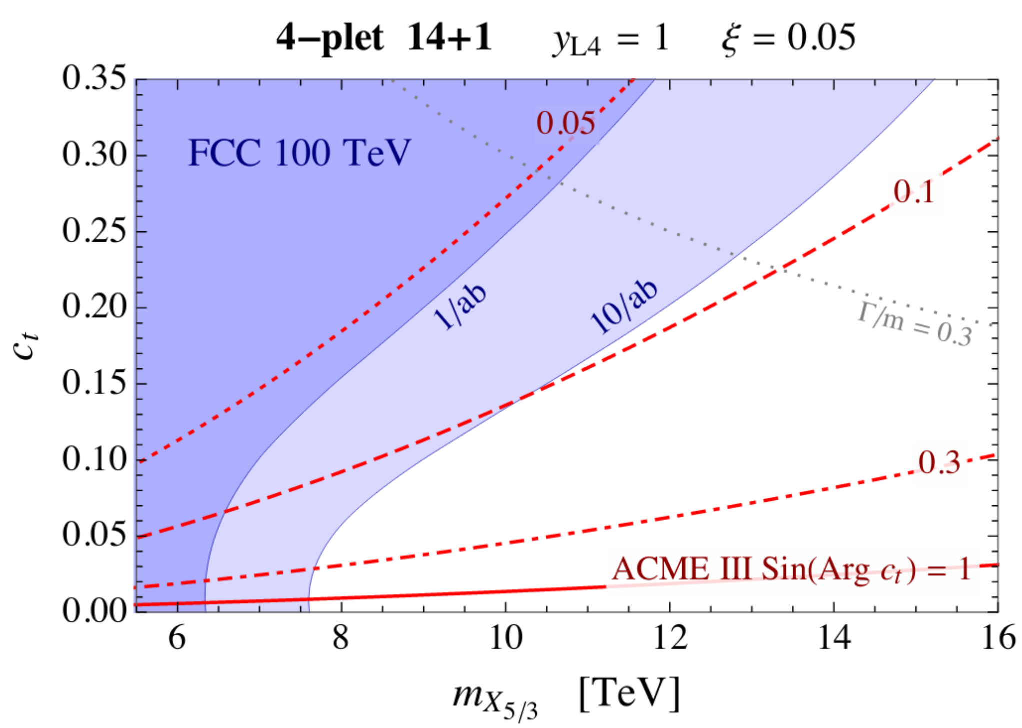
LHC



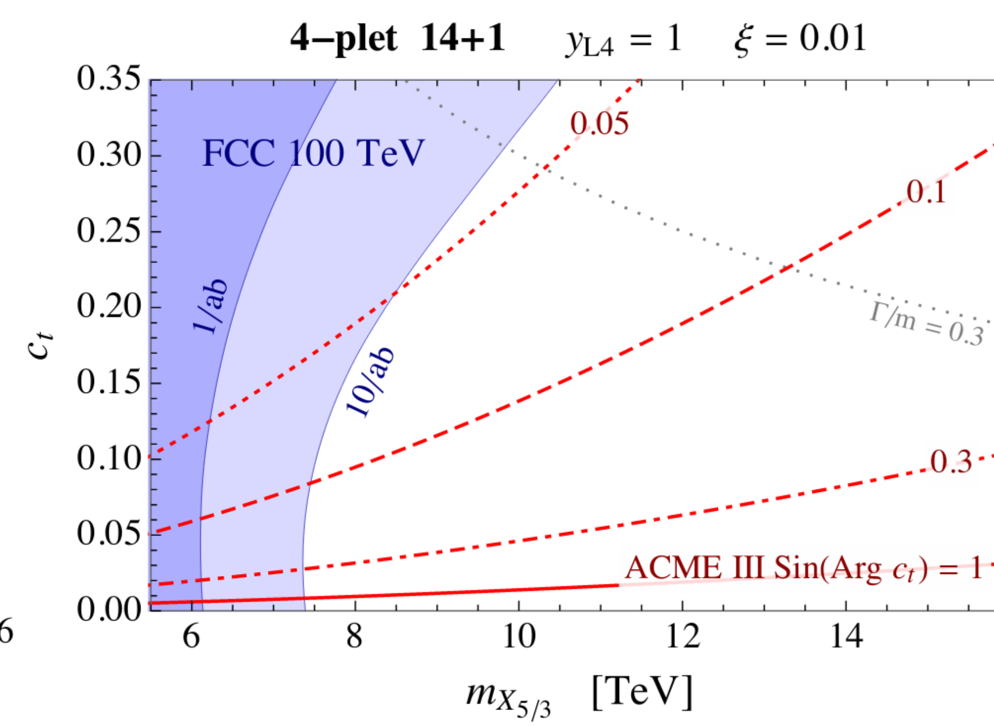
HL-LHC



FCC-hh



FCC-hh

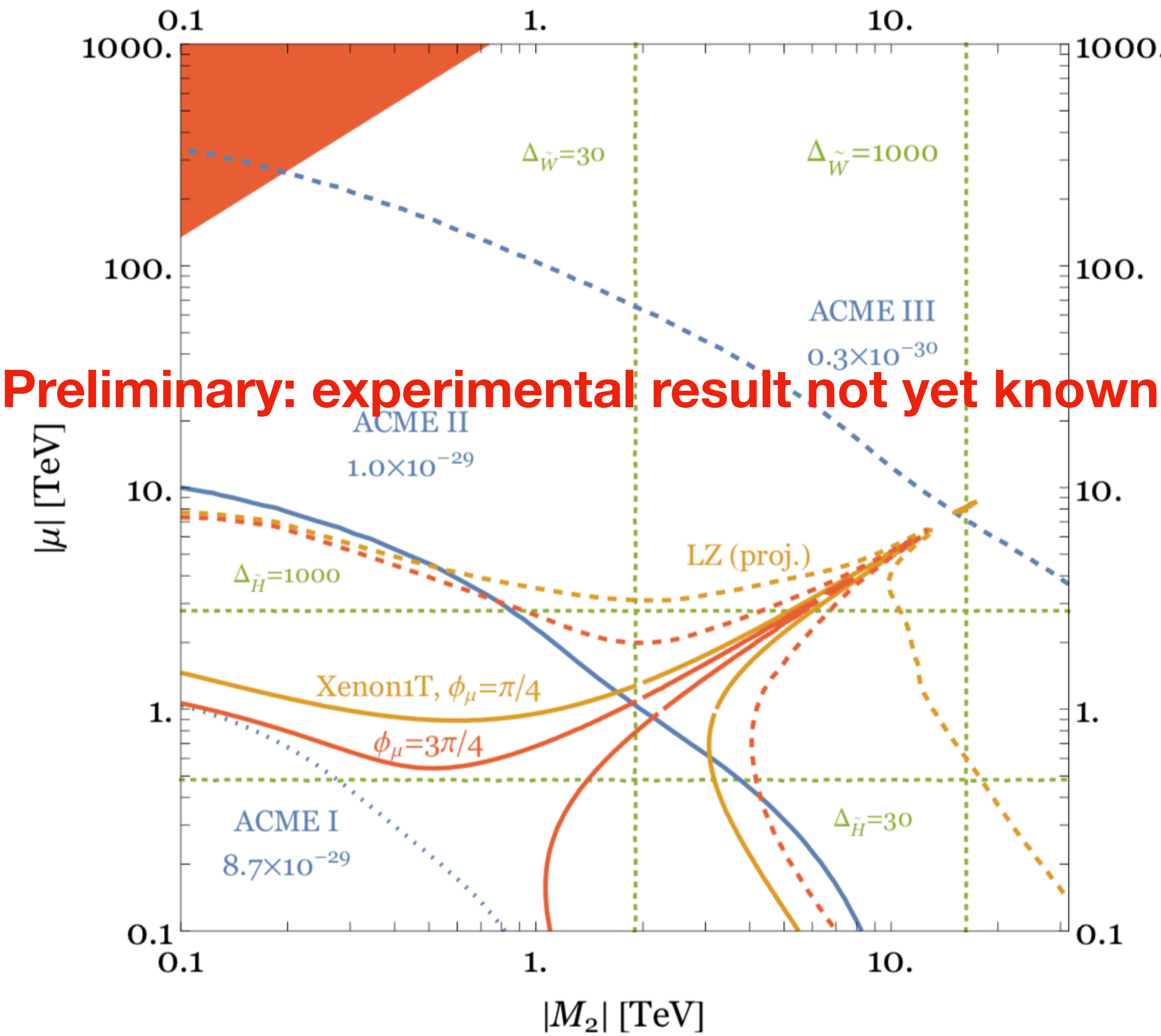


EDM as a BSM probe

(M. Reece, SUSY '18)

Powerful split SUSY constraints (forecast) from ACME 2!

d_e/e [cm], $\sin(\phi_\mu) = \frac{1}{\sqrt{2}}$, $\tan\beta = 10$



Preliminary: experimental result not yet known

Neutron-antineutron oscillations

Baryon number violation(s)

Why are we expecting B violation(s)?

1) Neutral meson oscillations, neutral lepton oscillations (very likely), why not neutral baryon oscillations?

2) Global symmetry are not consistent with quantum gravity

3) Need to generate matter-antimatter imbalance

Selection rule

conservation of angular momentum ⇒ spin of nucleon should be transferred to another fermion

1) $\Delta B = \Delta L$ (nucleon → antilepton)
2) $\Delta B = -\Delta L$ (nucleon → lepton)
3) $\Delta L = \pm 2$ ($0\nu\beta\beta$)
4) $\Delta B = \pm 2$ ($n\bar{n}$ oscillations, dinucleon decays)

Proton stability doesn't exclude baryogenesis!

If h3 coupling is SM-like, unlikely that baryogenesis occurs at weak scale
Large scale baryogenesis requires B-L violation
otherwise any B asymmetry created above EWSB scale is wiped out by active EW sphalerons

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*

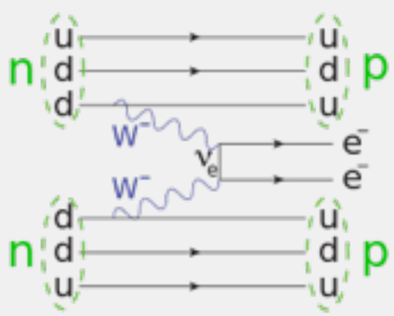
*For flavour universal models, nn gives the strongest constraints. For other flavour setups (e.g. MFV-RPV susy), dinucleon decays might be win

Pattern of B violation in SM(EFT)

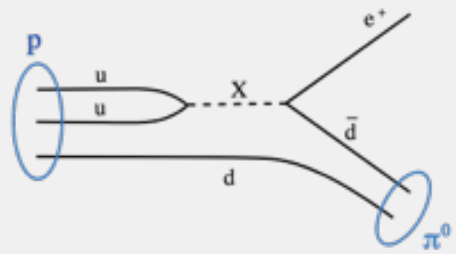
$\mathcal{L}$ =	$\mathcal{L}_{SM}$	+ dim-5	+ dim-6	+ dim-7	+ dim-8	+ dim-9 + …
allowed $(\Delta B, \Delta L)$	(0, 0)	**(0, 2)**	(0, 0), **(1, 1)**	(0, 2), (1, -1)	(0, 0), (1, 1)	**(2, 0)**, (1, -1), (0, 2), (1, 3)

A. Kobach '16

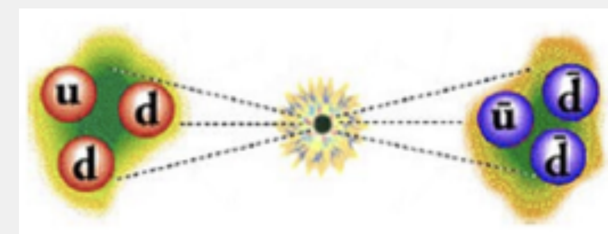
$0\nu\beta\beta$ decay



proton decays



neutron-antineutron oscillation

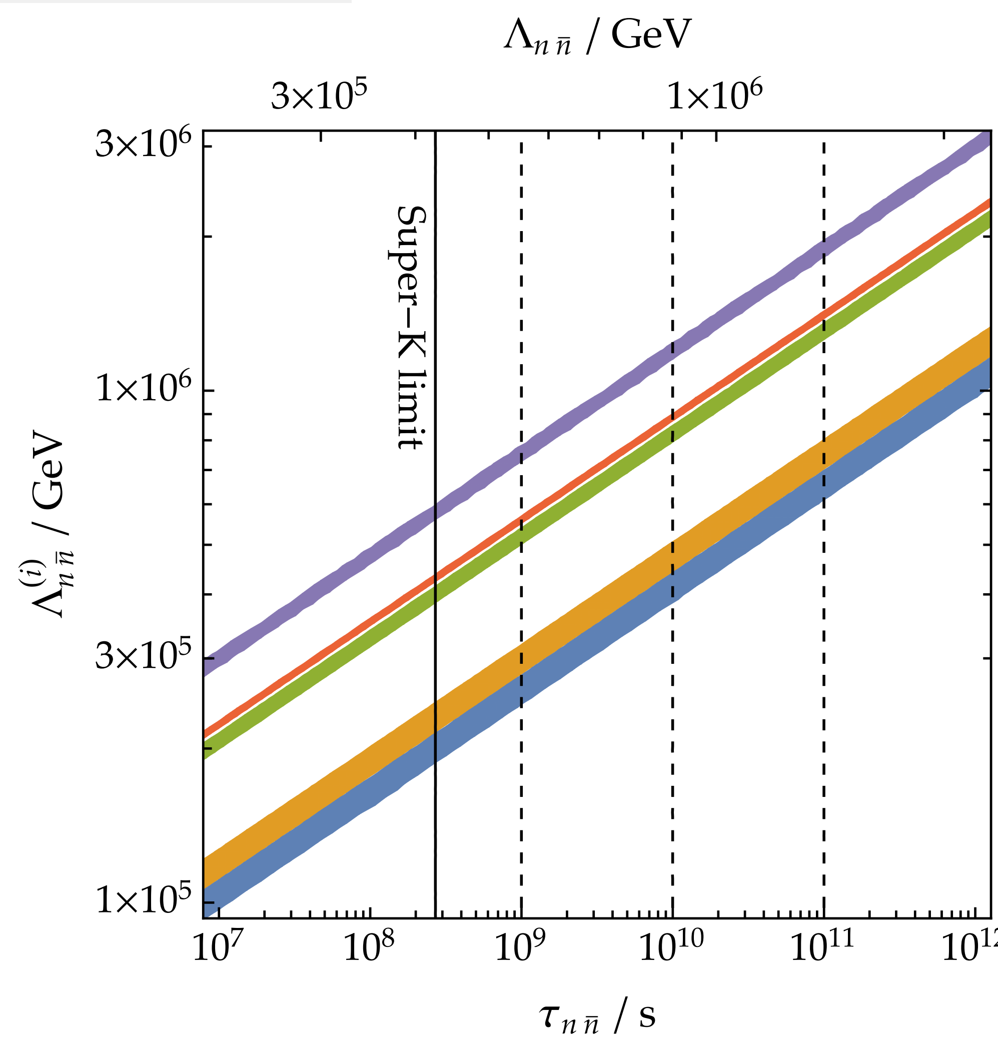


Slide stolen to Z. Zhang @ Pascos'18

12 operators (of the type 'uudddd')

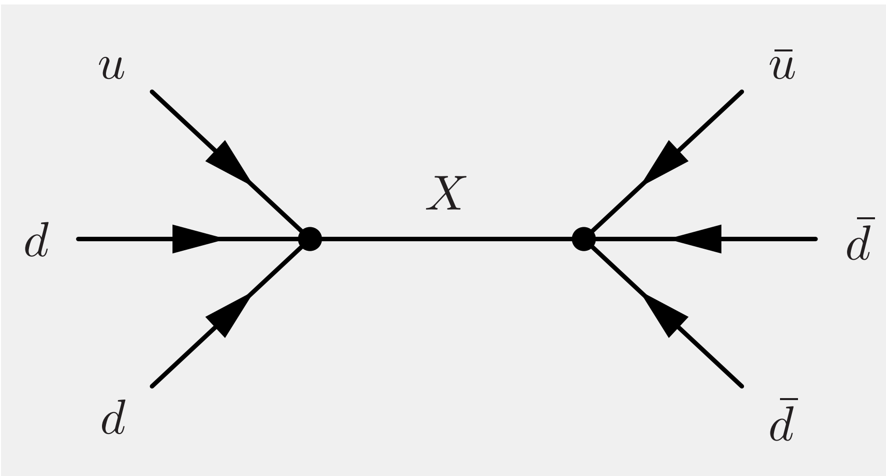
$$\tau_{n\bar{n}}^{-1} = \left|\langle \bar{n} | \mathcal{H}_{\rm eff} | n \rangle\right|$$

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

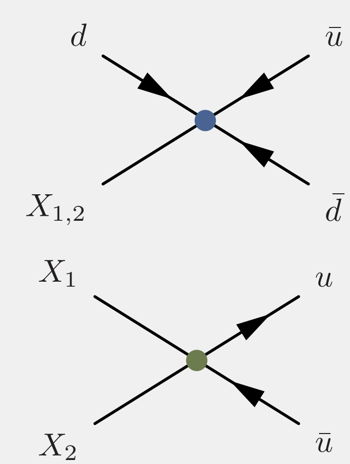
Single mediator X decays cannot generate a baryon asymmetry at leading order in the B violating coupling (Nanopoulos-Weinberg theorem '1979)

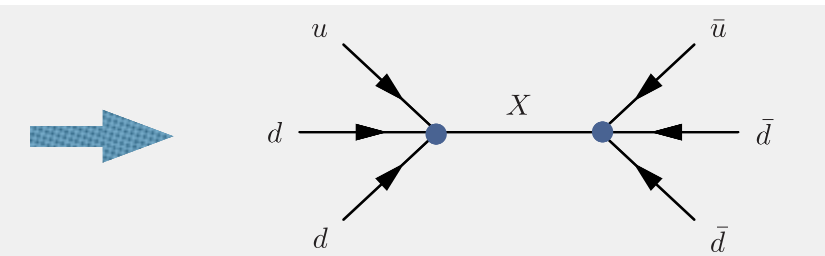
Two mediators X_1, X_2 ($M_{X1}<M_{X2}$)

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

$$|\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}, \; |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}, \; |\eta_c| \equiv \Lambda_c^{-2}.$$

- 2 *B-violating* operators
- 1 *B-conserving* operator





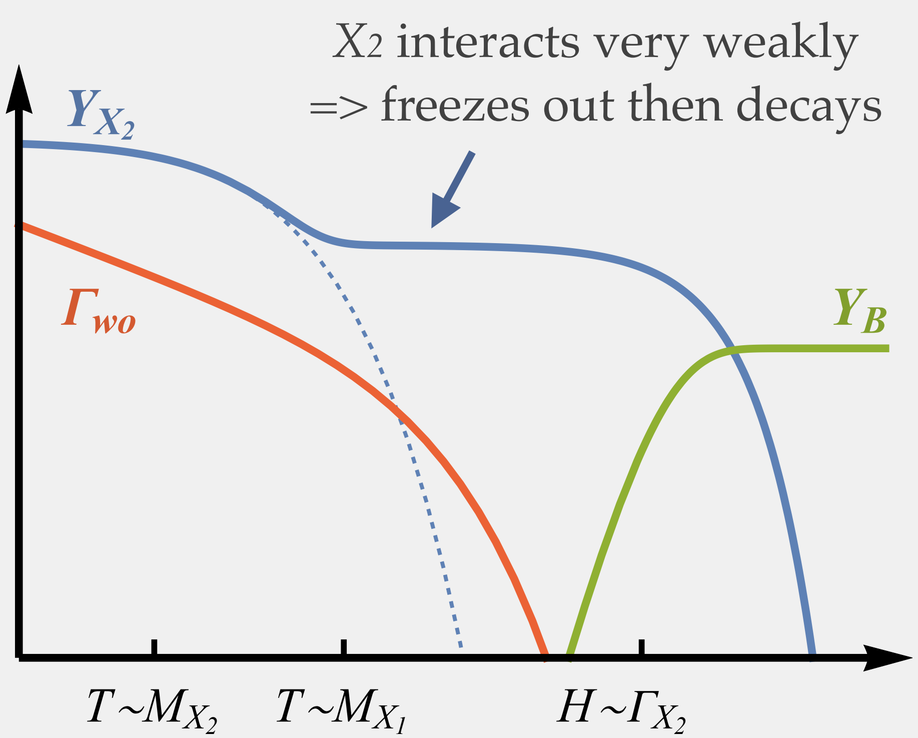
$$c_1 = \frac{1}{(\Lambda_{n\bar{n}}^{(1)})^5} = \frac{1}{M_{X_1}\Lambda_{X_1}^4} + \frac{1}{M_{X_2}\Lambda_{X_2}^4}$$

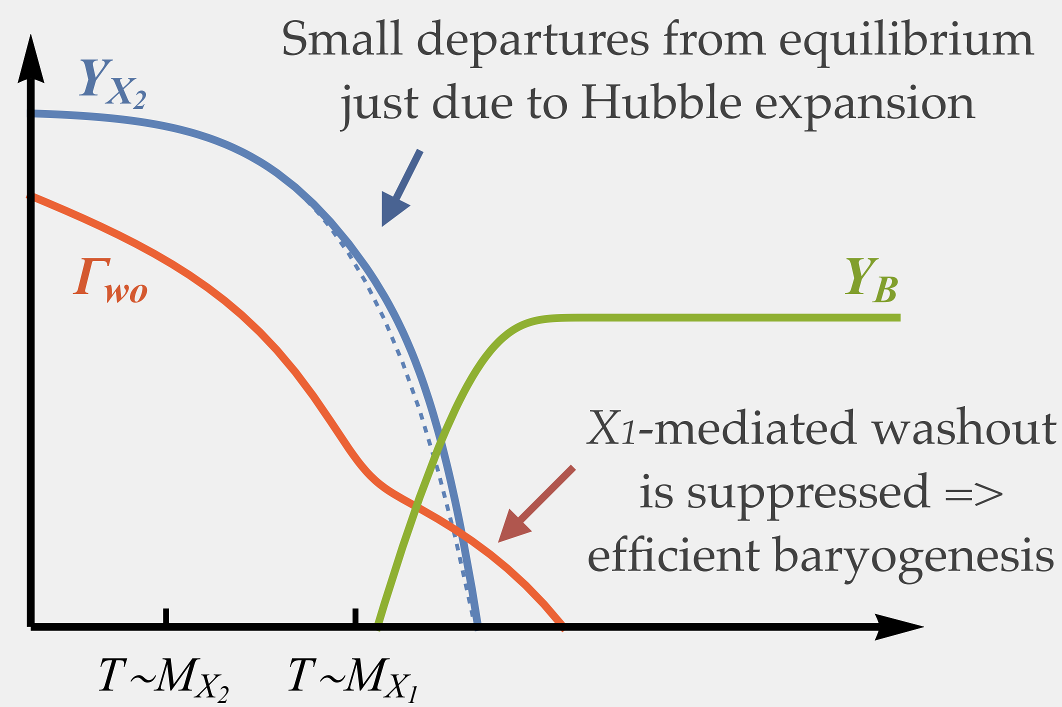
Two mediators with both B and $\not{B}$ couplings are enough to evade Nanopoulos-Weinberg

Baryogenesis

Grojean, Shakya, Wells, Zhang '18

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

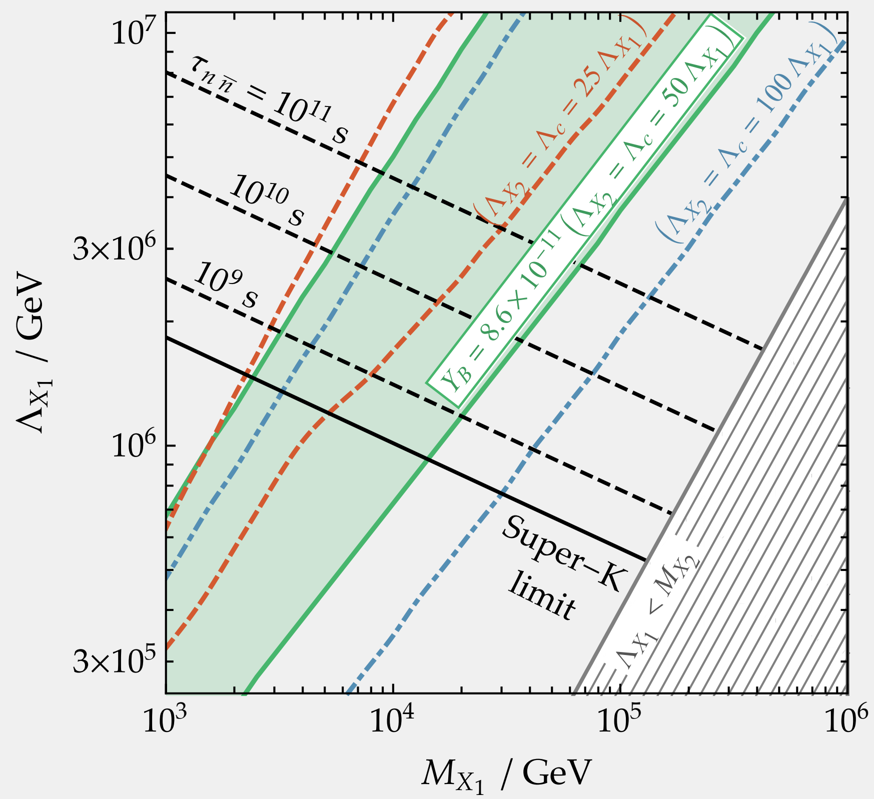


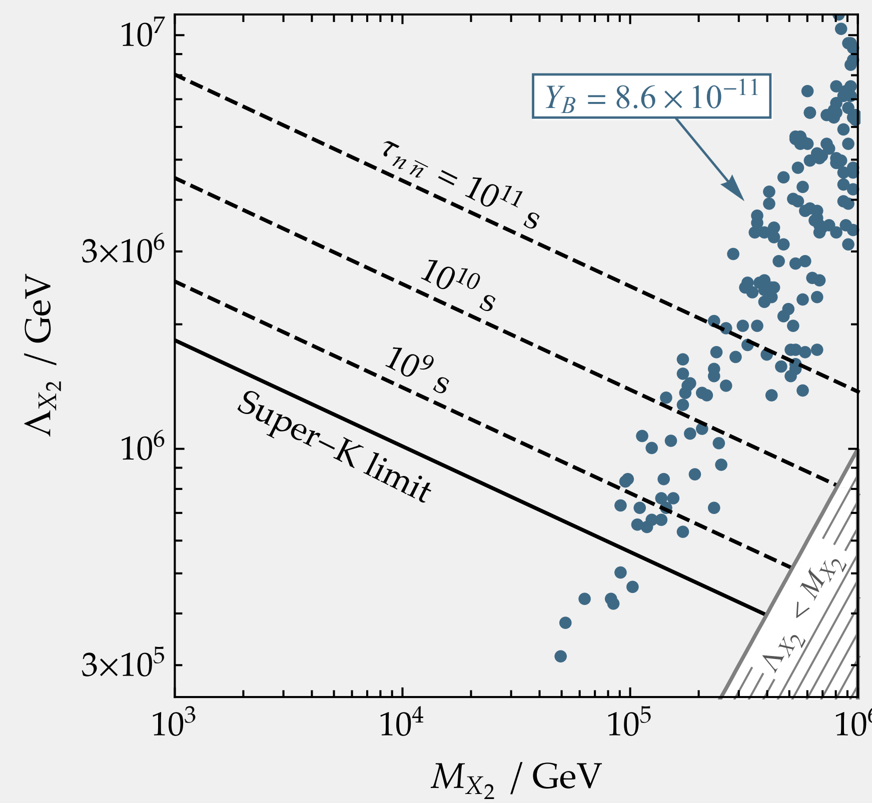


Baryogenesis

Grojean, Shakya, Wells, Zhang '18

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



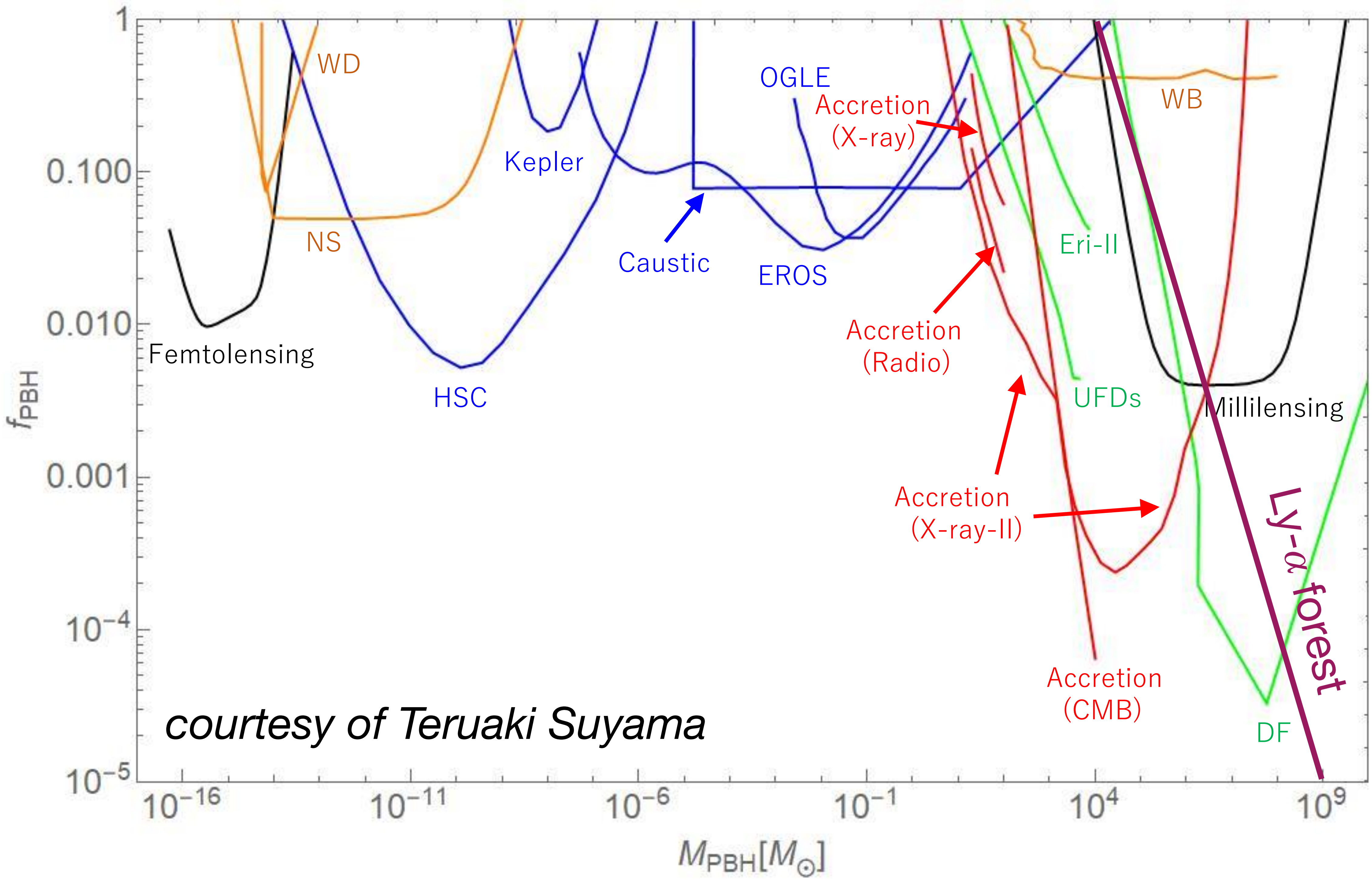


Explicit realisation of late decay scenario:
RPV SUSY with late decays of the bino in presence of a wino/gluino
[F.Rompineve, 1310.0840] [Y.Cui, 1309.2952] [G.Arcadi, L.Covi, M.Nardecchia, 1507.05584]

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

Searching for a black moon

PBHs as DM



1
0.100
0.010
0.001
10^{-4}
10^{-5}
f_{PBH}
10^{-16}
10^{-11}
10^{-6}
10^{-1}
10^{4}
10^{9}
$M_{PBH}[M_\odot]$
WD
NS
Femtolensing
HSC
Kepler
Caustic
OGLE
EROS
Accretion (X-ray)
Accretion (Radio)
Accretion (X-ray-II)
Accretion (CMB)
Eri-II
UFDs
WB
Millilensing
DF
Ly-α forest
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

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

(~ a few in our solar system)

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

How can we detect PBHs in the Solar system?

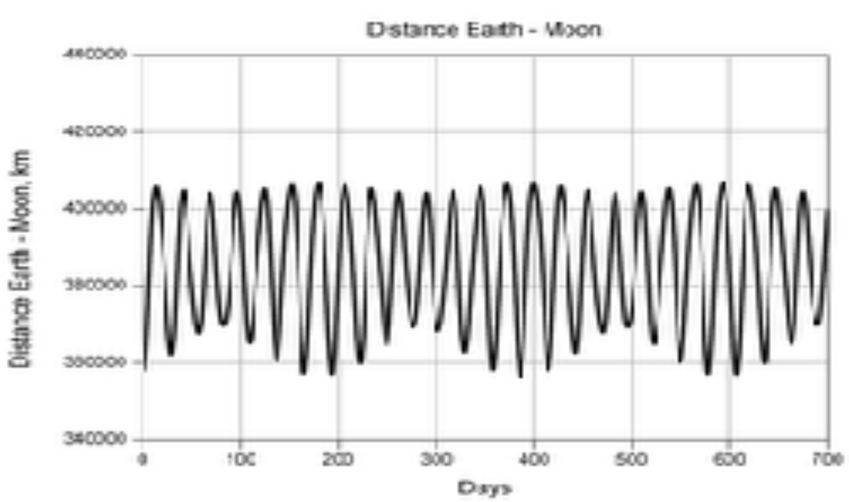
JR Espinosa @ Benasque 2018

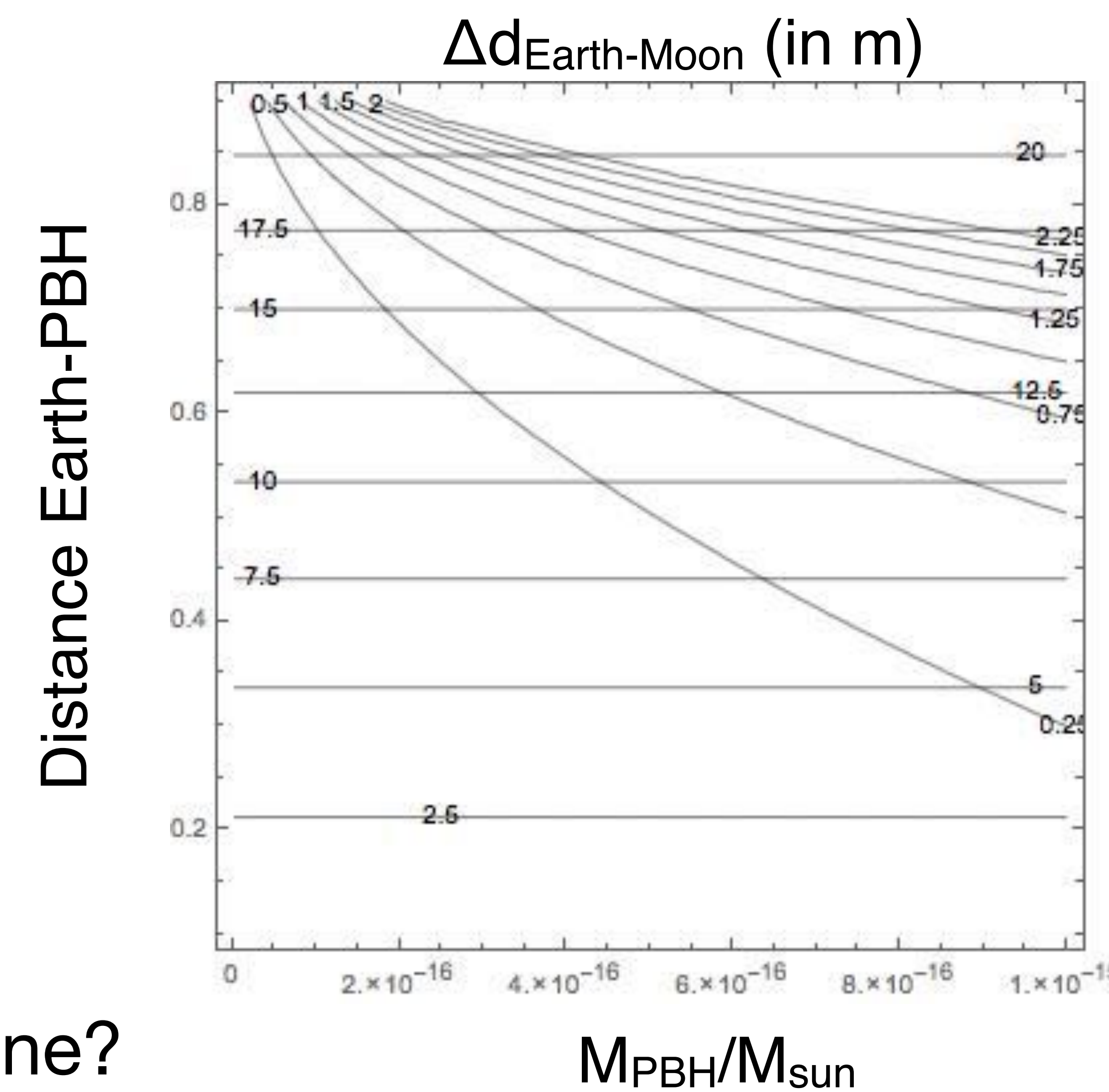
A PBH orbiting around Earth

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)

Sailing to India with the right tool...

Once upon a time...

Columbus had a great proposal: "reaching India by sailing towards the West"

He had a theoretical model

- the Earth is round,
- Eratosthenes of Cyrene first estimated its circumference to be 250'000 stadia
- other measurements later found smaller values ☞Toscanelli's map
- lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70'000 stadia, so he believed he could reach India in 4 weeks

He had the right technology

- Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée. Actually, the Vikings had the right technology too but the knowledge was lost

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His proposal was scientifically rejected twice (by Portuguese's & Salamanca U.)
by the decision was overruled by Isabel ... and America became great (already)

Moral(s)

"if your proposal is rejected, submit it again"

"you need the right technology to beat your competitors"

"theorists don't need to be right!
but progress needs theoretical models to motivate exploration"

Knowledge is power

B. Clinton, Davos 2011

ippog.web.cern.ch/resources/2011/bill-clinton-davos-2011

What is the current US president would say about HEP?

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