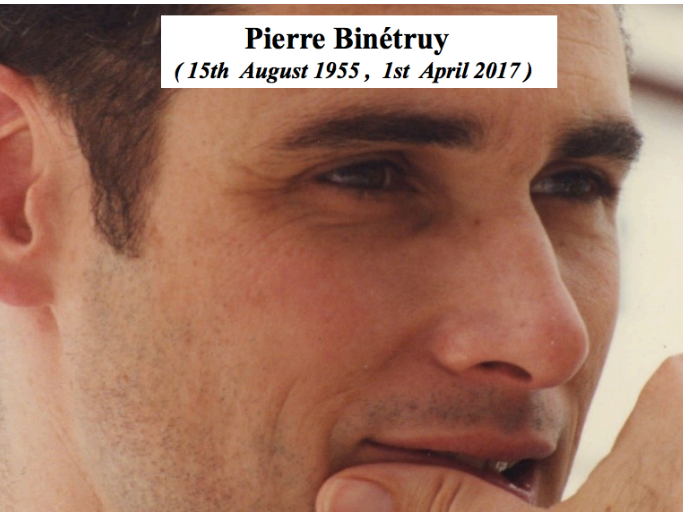
EW Theory Summary

J. Hewett
Moriond EW 2018

SLAC NATIONAL ACCELERATOR LABORATORY

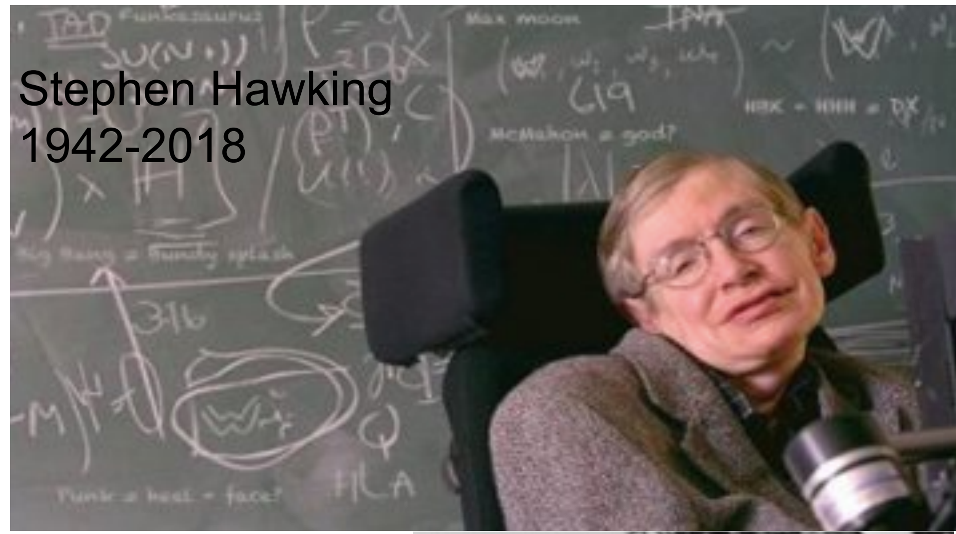
A year punctuated by remembrances

Colleagues who left us too young



Marge Cocoran
1950-2017

Recent losses



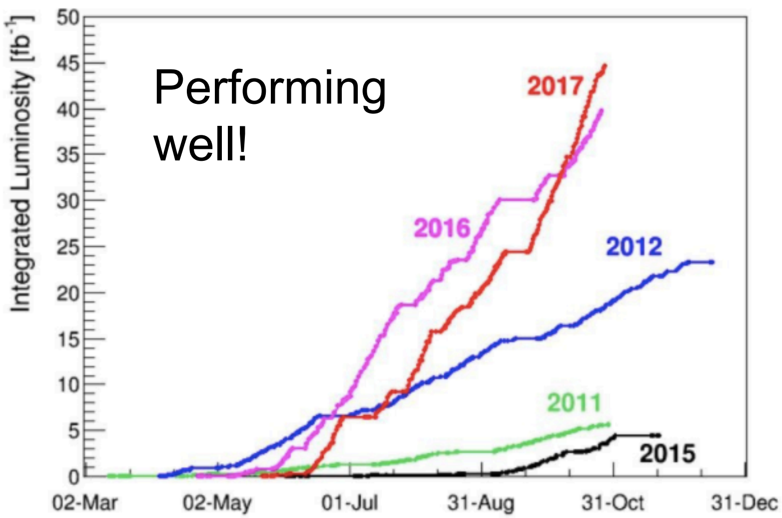
Stephen Hawking
1942-2018

Dick Taylor
1929-2018

What we have learned from the LHC

1. A Higgs boson exists
2. If new particles or interactions exist in this kinematic range, they have complex signatures
3. There are exactly 3 generations of fermions in the Standard Model
4. Flavor Physics & Precision EW can serve as a guide to new physics scale

The world is following our adventure!



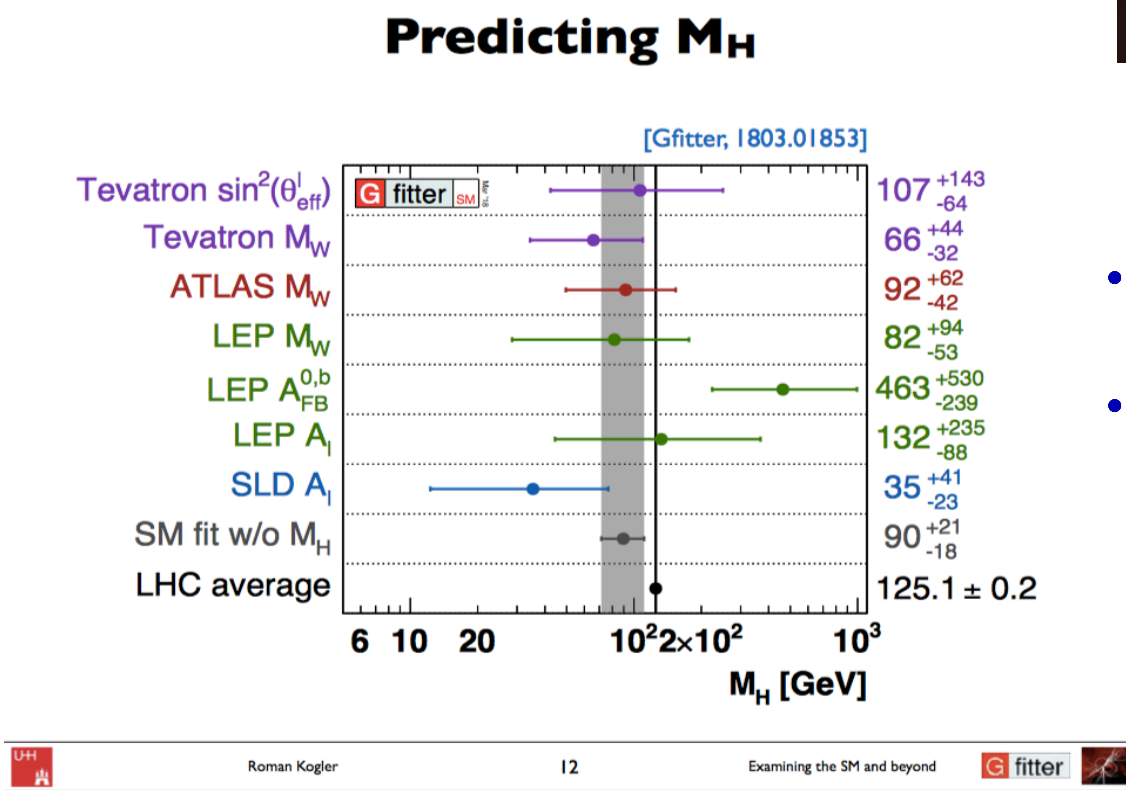
What we have learned from the LHC guides the future

1. A Higgs boson exists
   - The Higgs opens new windows for discovery
2. If new particles or interactions exist in this kinematic range, they have complex signatures
   - Room for discovery with sophisticated analyses
   - Room for discovery at future upgrades/colliders
3. There are exactly 3 generations of fermions in the Standard Model
   - Explanation demands theorist's attention
4. Flavor Physics & Precision EW can serve as a guide to new physics scale
   - Not really new, but deserves more of our attention

A Higgs Boson Exists

We should not lose sight of this accomplishment!

- Marching towards precision measurements of Higgs properties

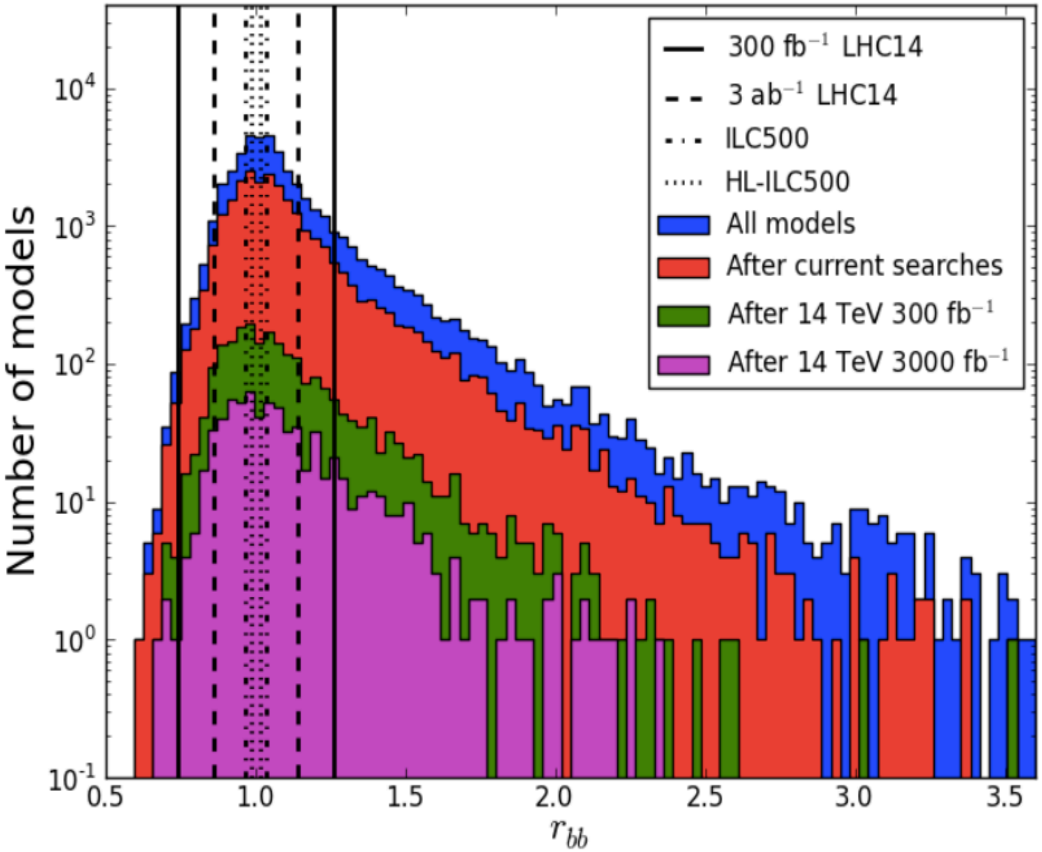


- Higgs mass measured to order 0.16%
- Reasonable agreement with EW fit

Precision measurement of Higgs couplings

Window to indirect effects of new physics

Discovery possible even in absence of LHC signal



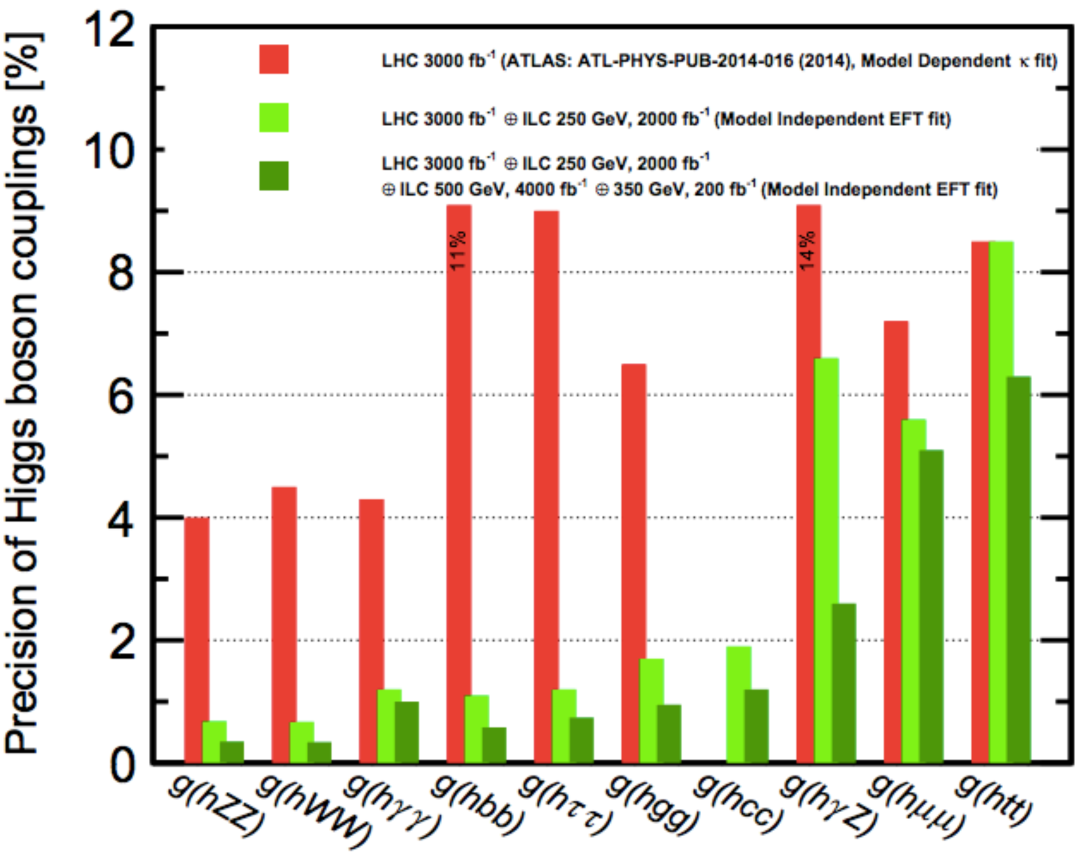
Predictions for Γ(h→bb) in pMSSM as ratio to SM prediction

Cahill-Rowley etal, 1407.7021

Precision measurement of Higgs couplings

Driving force for physics at HL-LHC and motivation for

e^+e^- Higgs Factory



Latest forecast for future coupling measurements

HL-LHC + ILC

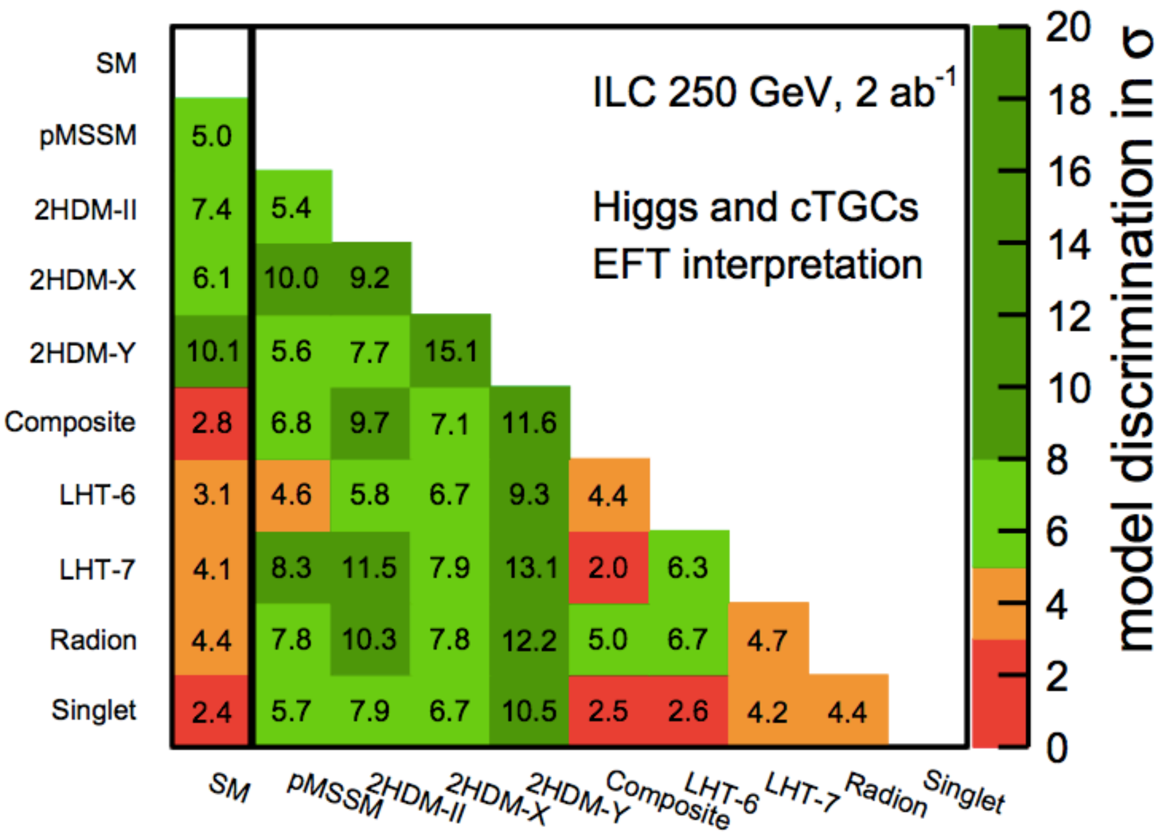
at or below 1% level

Self-coupling remains difficult

Fujii etal, 1710.07621

Precision measurement of Higgs couplings

Precision coupling measurements discriminate between new physics models



Latest forecast for future coupling measurements

HL-LHC + ILC

Fujii etal, 1710.07621

Higgs as a window for discovery

Fundamental questions to be addressed

- Is there more than one Higgs?
    - Active playground for theorists!
    - Active enterprise for BSM experimenters!
- Is the Higgs fundamental?
    - Not yet excluded
- Does the Higgs violate CP?
- What principle determines the Yukawa couplings?
- How does the Higgs relate to neutrino masses?
- Does the Higgs couple to Dark Matter?

Precision versus energy: Effective Field Theory

Strong bounds on New Physics from Flavor Physics

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

ΔF=2 Operators

$$\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2}(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$$

Trade-off between scale vs coefficient bounds

Isidori etal 1002.0900

Strong bounds on New Physics from Precision EW

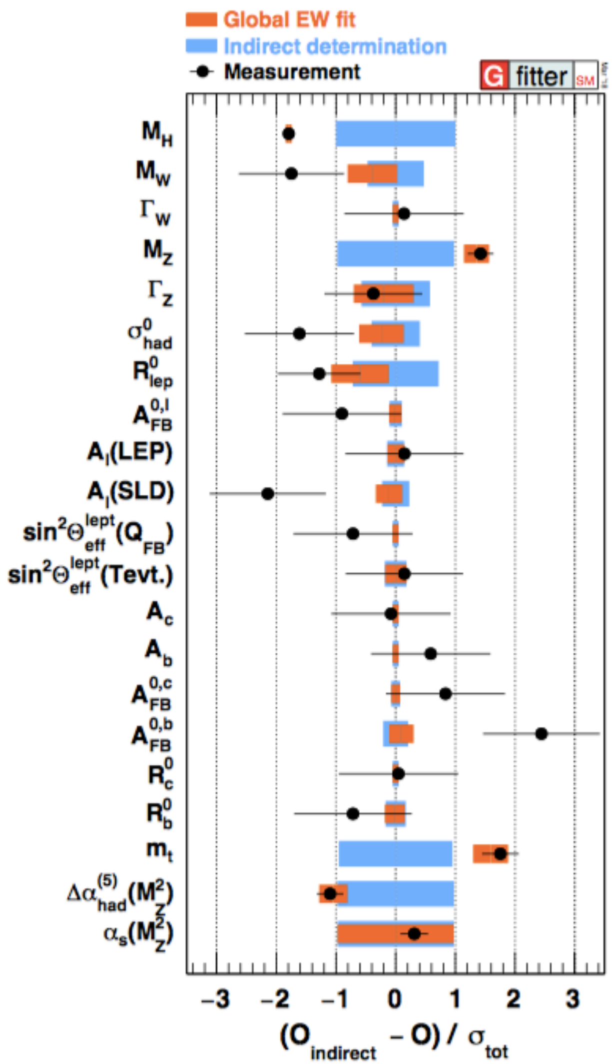
$(ee)(qq)$

(units of 10^{-3})

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
Low-energy	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
$\mathrm{LHC}_{1.5}$	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
$\mathrm{LHC}_{1.0}$	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
$\mathrm{LHC}_{0.7}$	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

Falkowski etal 1706.03783

Precision EW measurements

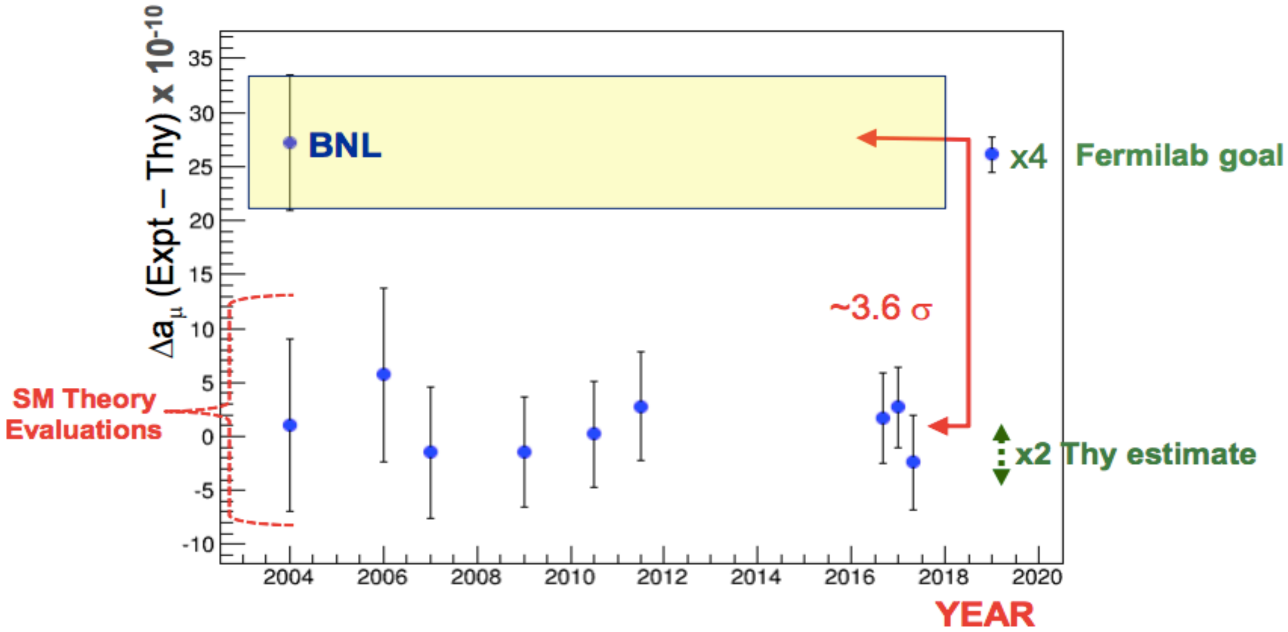


- Latest global EW fit
- Agreement with SM continues as measurements improve
- Tension between A^l_{FB}, A_l(LEP & SLD), A_b(SLD) & A^b_{FB} remains…

Gfitter 1803.01853

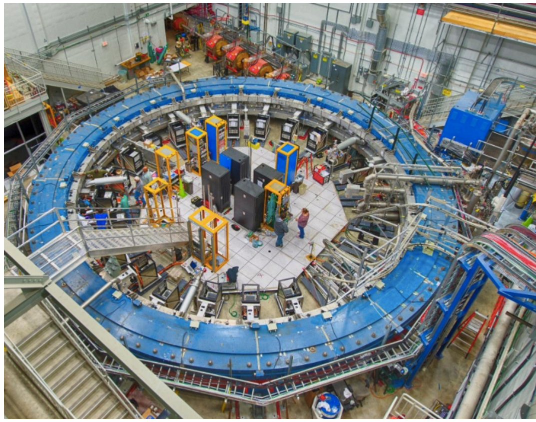
Anomalous magnetic moment of the muon

Long-standing discrepancy with the SM



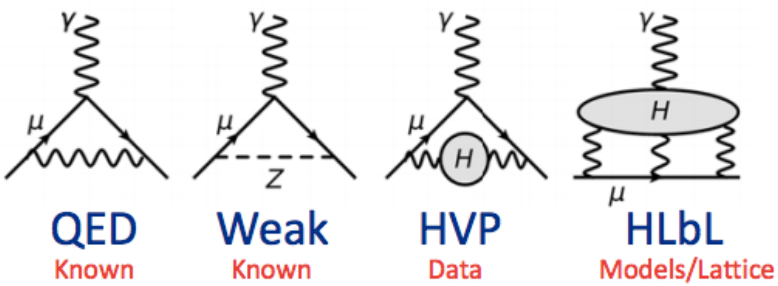
a_μ is now measured to 540 ppb; Goal is 140 ppb

FNAL exp't in commissioning phase



Anomalous magnetic moment of the muon

Arduous computation of ever more precise SM prediction



Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED	11 658 471.895	0.008
Electroweak Corrections	15.4	0.1
HVP (LO) [7]	692.3	4.2
HVP (LO) [8]	694.9	4.3
HVP (NLO)	-9.84	0.06
HVP (NNLO)	1.24	0.01
HLbL	10.5	2.6
Total SM prediction [7]	11 659 181.5	4.9
Total SM prediction [8]	11 659 184.1	5.0
BNL E821 result	11 659 209.1	6.3
Fermilab E989 target		≈ 1.6

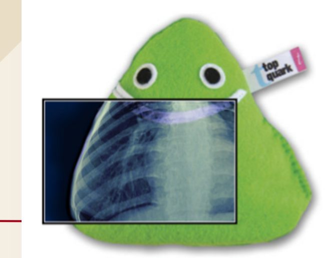
New lattice computation for HLBL term

- physical pion mass and large lattice
- Statistical precision x2 improvement
- Systematics in progress

Blum etal, 1705.01067, 1610.04603

$$a_\mu^{\rm HLbL} = 5.35(1.35) \times 10^{-10}$$

Top-Quark Physics



Top provides special window to new physics

- only quark with natural Yukawa couplings

Determination of properties has entered the high precision era

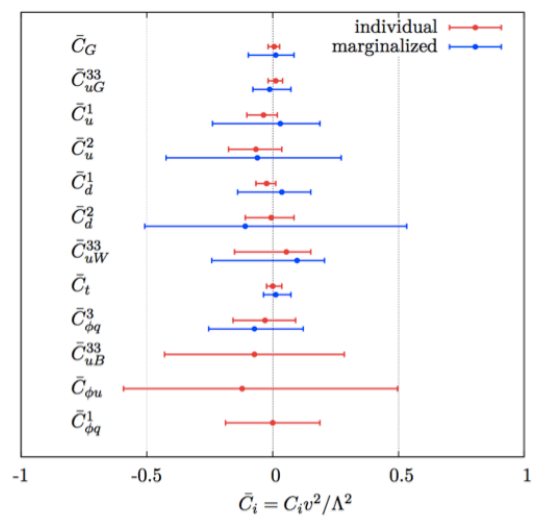
- Calculations approaching level of NNLO, NNLL QCD, NLO EW, differential distributions, being implemented in event generators

Search for BSM effects through effective operator approach

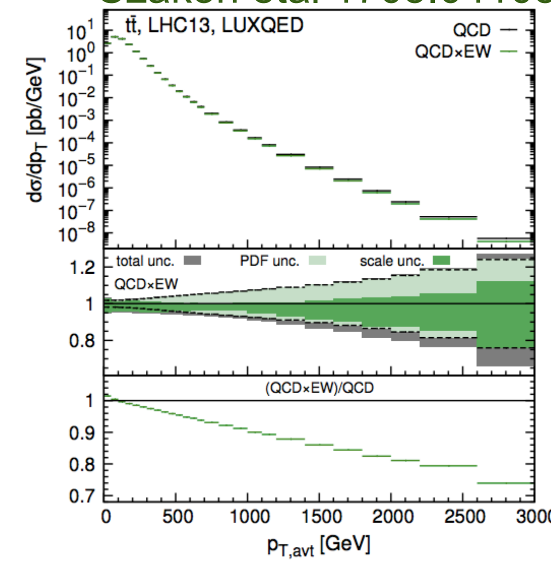
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

Towards a global fit, see Aguilar-Saavedra 1802.07237

Fit to EFT coefficients
Buckley etal 1512.03360



p_T pair production @
NNLO QCD, NLO EW
Czakon etal 1705.04105



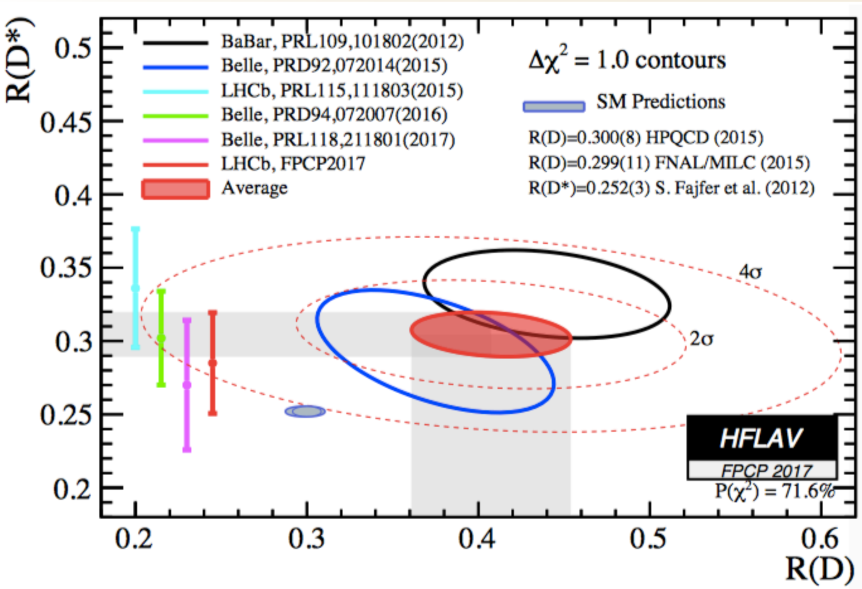
Lepton Flavor Universality in B decays

Deviations observed at ~ 4σ in b-quark semi-leptonic decays

- tau/mu and tau/e universality in b → clv charged currents
- mu/e universality in b → sl^+l^- neutral currents
- Angular distribution of B → $K^*l^+l^-$
- size of NP required is ~10% of SM amplitudes
- New physics must be mainly coupled to 3rd generation

We should all keep an eye on this as data accumulates!

B-Physics anomalies SM explanation?



Persistent signal for flavor universality violation in $B \rightarrow D^* l \nu$

- Tantalizing 4σ hint for new physics

Harrison etal, 1711.11013
Belle, 1702.01521
Bigi etal, 1707.09509

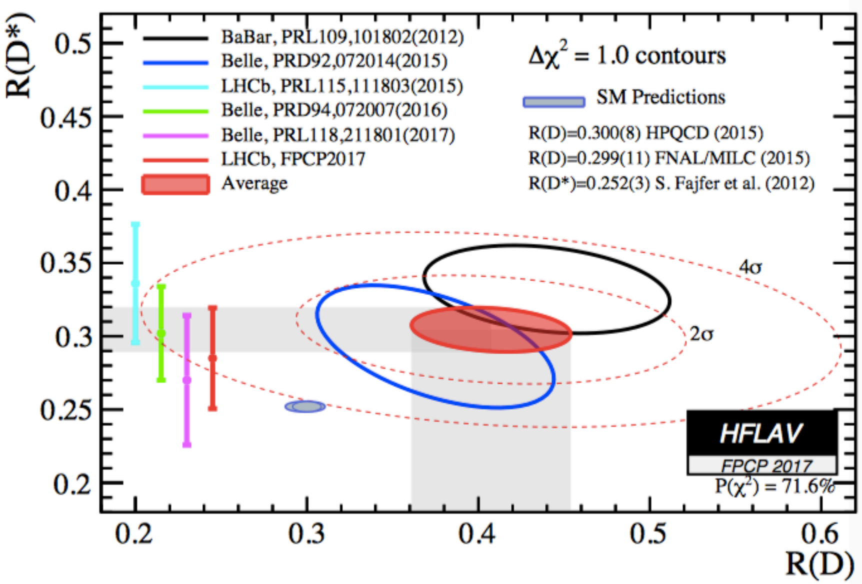
Re-analysis of V_{cb}

- New lattice result @ zero recoil
- New Belle result
- Employ HQS relations

Exclusive V_{cb} nudged closer to inclusive value
R(D*) anomaly slightly reduced

Ref.	$R(D^*)$	Deviation
Experiment [HFLAV update]	0.304(13)(7)	—
2017 theory results, using new lattice and exp. data:		
[Bernlochner Ligeti Papucci Robinson 1703.05330]	0.257(3)	3.1σ
Our result [Bigi Gambino Schacht 1707.09509]	0.260(8)	2.6σ
[Jaiswal Nandi Patra 1707.09977]	0.257(5)	3.0σ
2012 theory results:		
[Fajfer Kamenik Nisandzic 1203.2654]	0.252(3)	3.5σ
[Celis Jung Li Pich 1210.8443]	0.252(2)(3)	3.4σ
[Tanaka Watanabe 1212.1878]	0.252(4)	3.4σ

B-Physics anomalies: New physics?



Persistent signal for flavor universality violation in B → D*lν

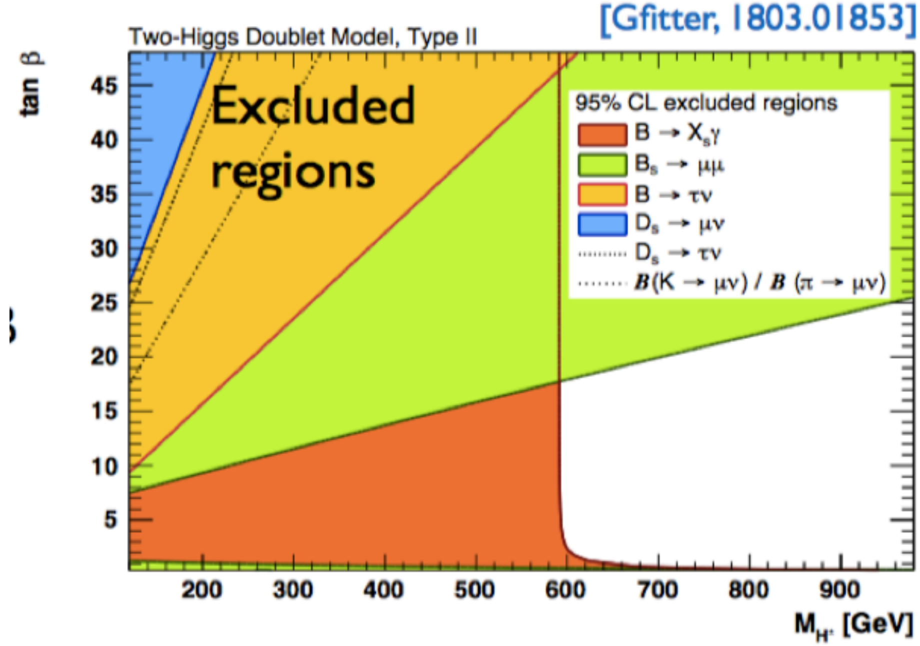
- New NP MC being developed for more detailed analysis of NP effects

Bernlocher etal, 180x.yyyyy

BSM Explanation: Two-Higgs-Doublet Model Type II

- R(D) & R(D*) explained with large tanβ and small m_{H+}
- Region excluded by other flavor data!

[Gfitter, 1803.01853]



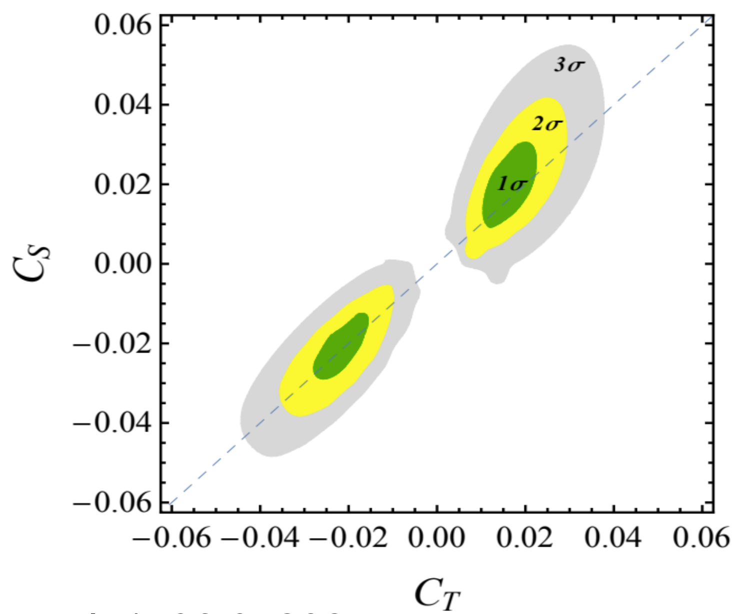
B-Physics Anomalies

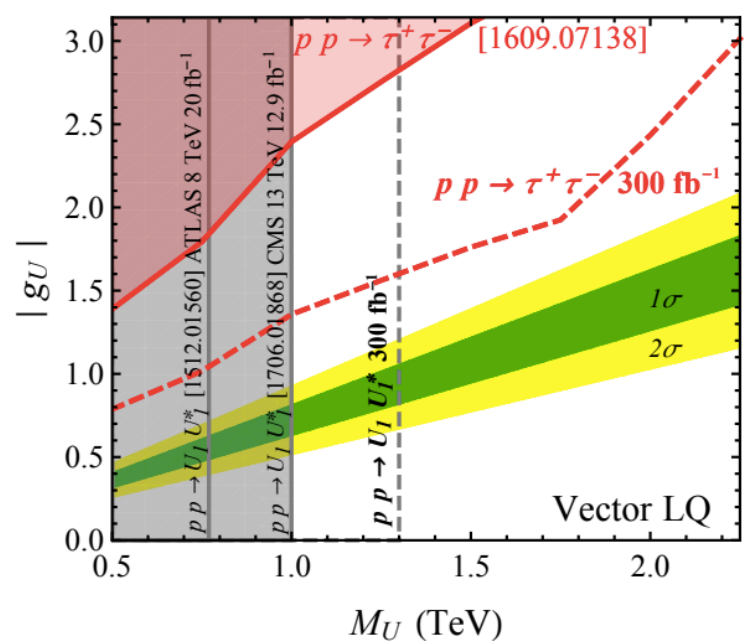
Global numerical study of new physics explanations

Expand Lagrangian into general new physics operators with $U(2)_q \times U(2)_l$ Flavor symmetry

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

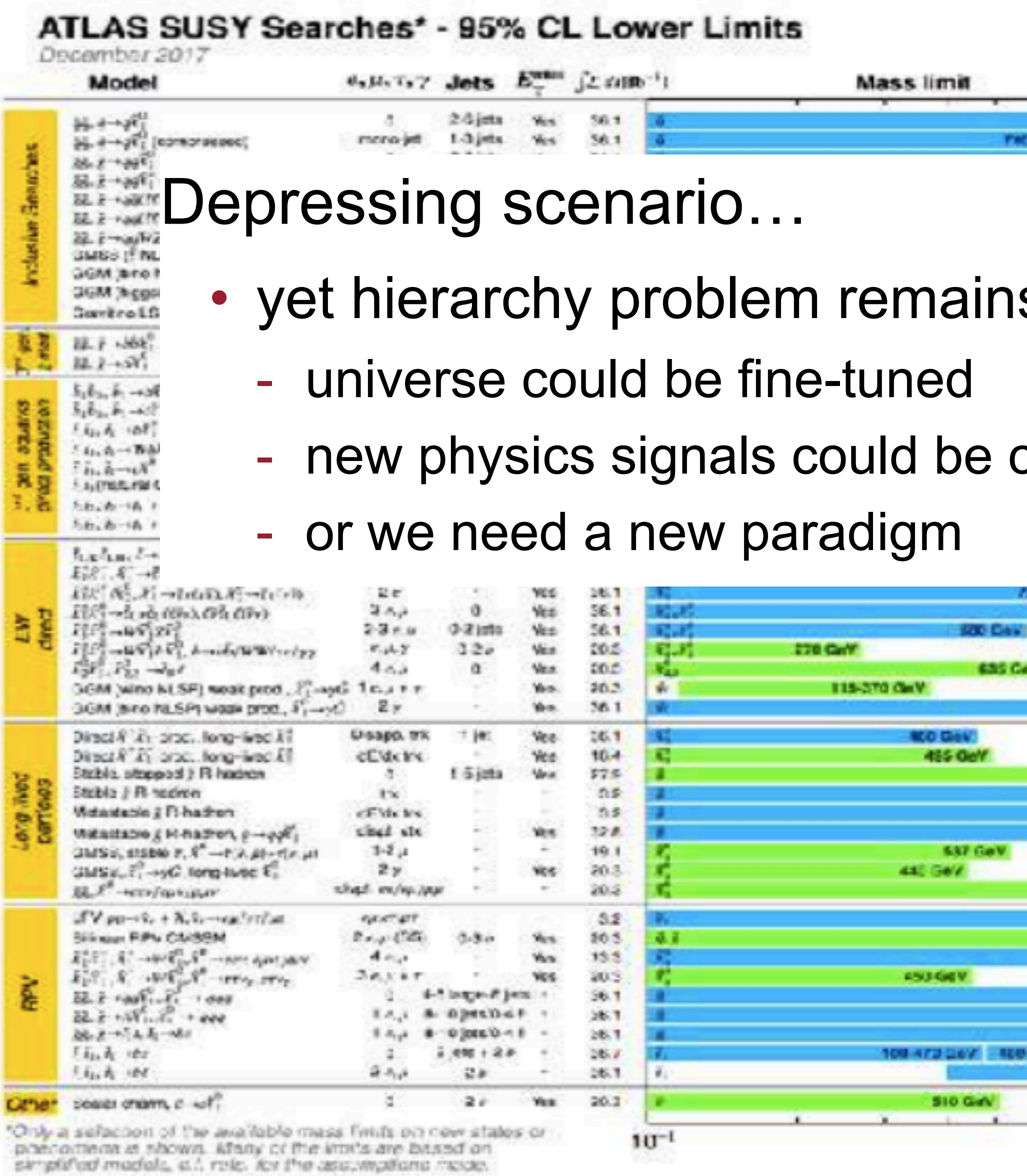
Fit to data!





Buttazzo etal, 1706.07808

New particles & interactions: direct production



Depressing scenario…

- yet hierarchy problem remains
  - universe could be fine-tuned
  - new physics signals could be complex & hiding (HL-LHC)
  - or we need a new paradigm

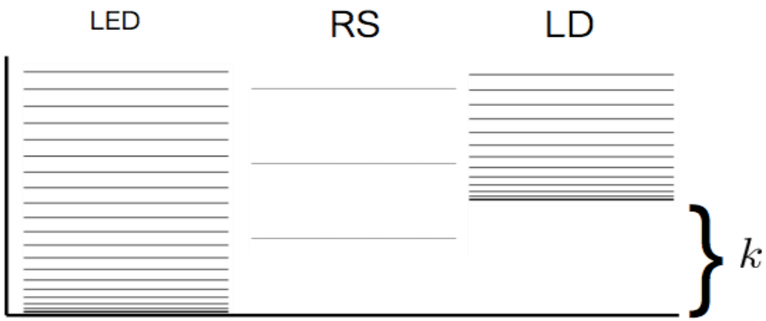
Example: new models - clockwork theories

Linear Dilaton: extra dimension lies between ADD and RS

novel LHC phenomenology that provides an interesting benchmark!

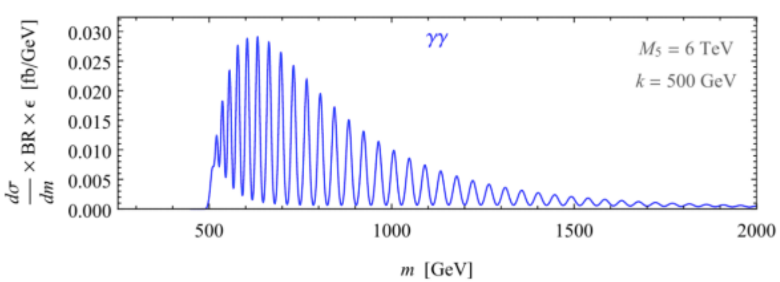
Giudice etal, 1711.08437

KK gravitons have cascade and displaced decays

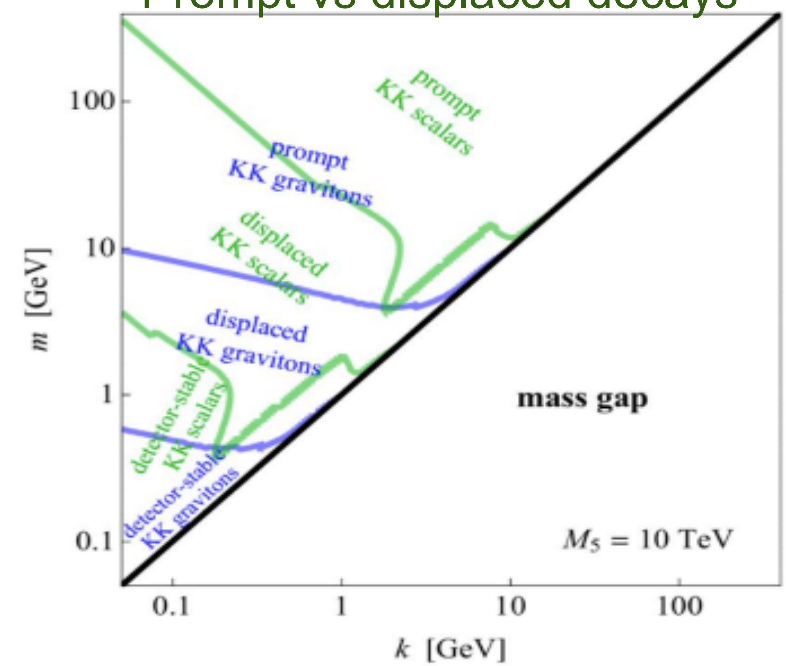


a forest of resonances

Resonances



Prompt vs displaced decays



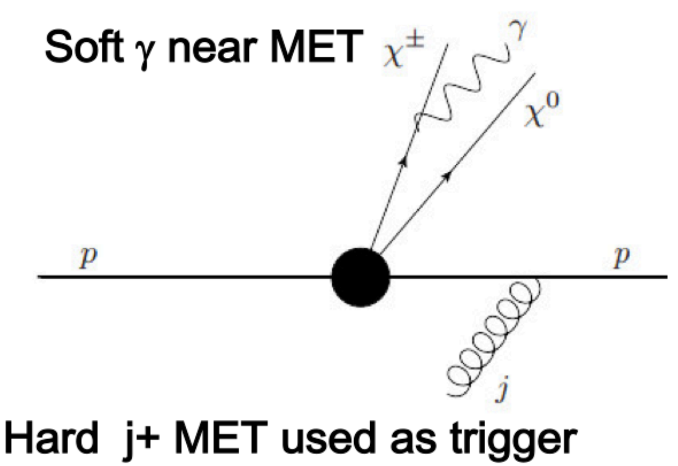
Example: New search techniques for light states

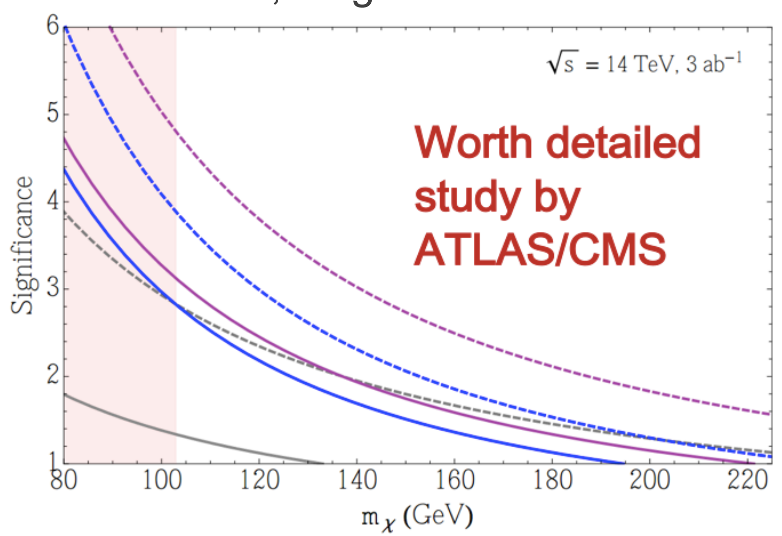
Light EWK multiplets, eg, Higgsinos, have small production σ's with large SM backgrounds. Constraints only from colored state cascades.

- Mass splittings in multiplets (Δm) define phenomenology
  - Δm <~200 MeV there is a long-lived charged state (=disappearing track)
  - Δm > ~a few GeV, soft decays visible.
  - In between?

Idea: boost system with QCD ISR similar to monojet searches. Look for a soft γ from EWK radiation in charged state decay ~ aligned with 'MET' /soft decay products due to boost.

Ismail, Izaguirre & Shuve : 1605.00658





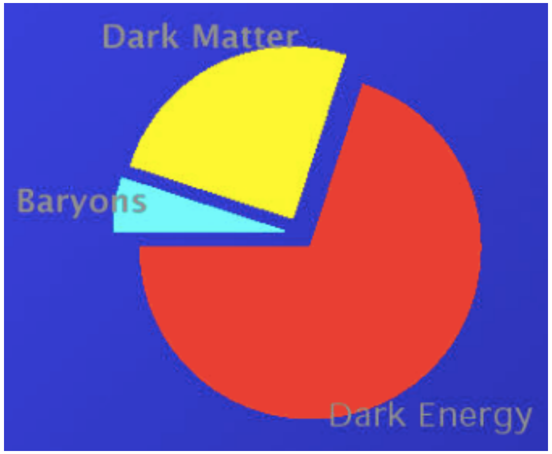
Identification of Dark Matter is a pressing issue

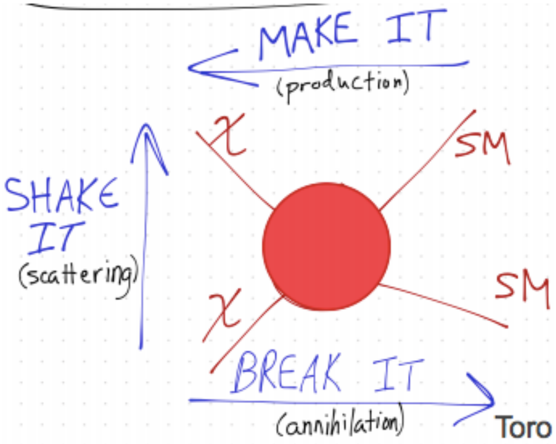
Dark Matter is ~85% of the matter in the universe

New physics that we know exists!

Has sparked our collective imagination

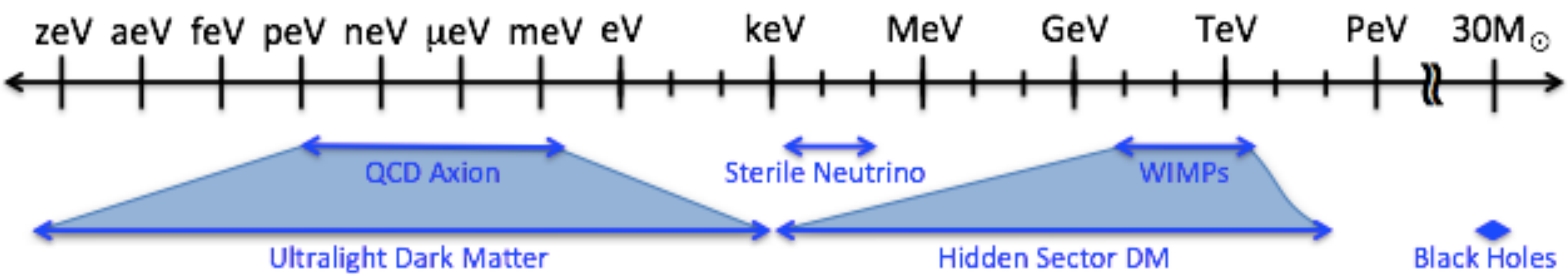
- Novel DM models and potential signals appear on the arXiv everyday
- Novel ideas for DM detection techniques/experiments are flourishing
- Present and planned DM experiments are pushing to the limit





Toro

Large mass range for DM candidates



- bosonic DM produced during inflation or high temp phase transition
- DM acts as oscillating classical field

- WIMPs: act through SM forces
- Hidden Sector: act through new force, very weakly coupled to SM
- Thermal contact in early universe

Beyond WIMPS: novel, low-cost, search techniques

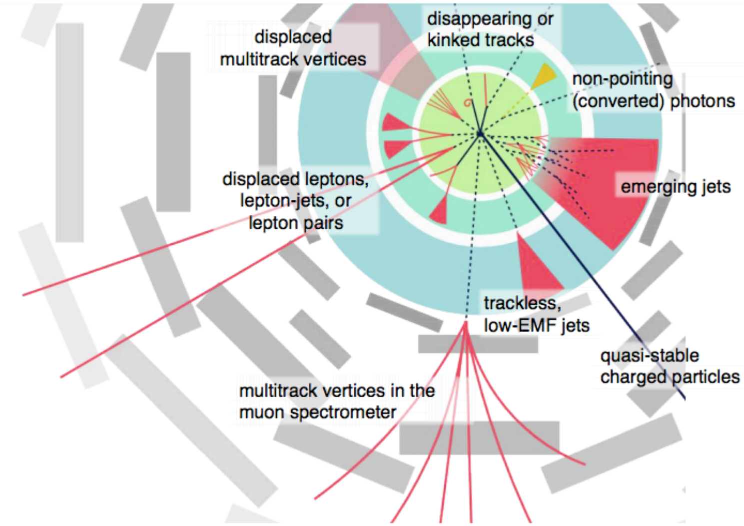
US Cosmic Visions Report, 1707.04591

New dark matter modeling @ Moriond

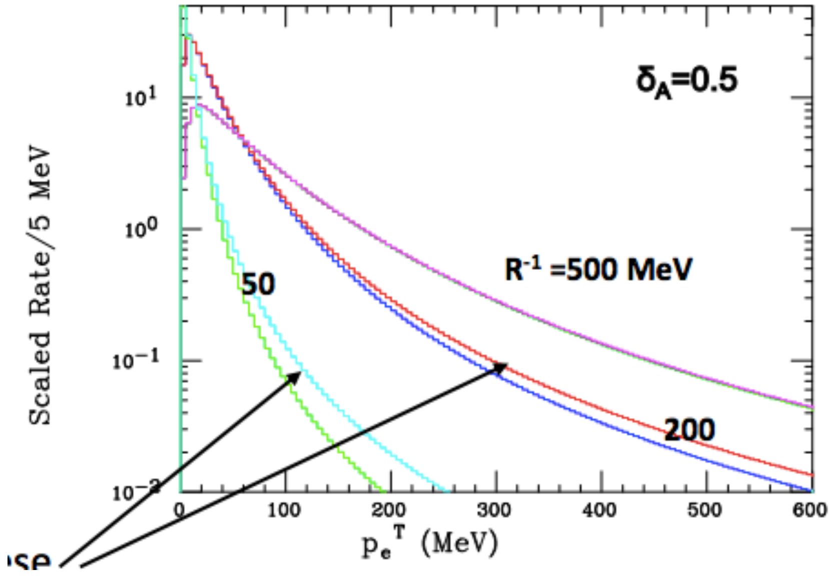
Many new dark matter models!

- Colored DM: Bound colored octets ~ 9.5 TeV
- Extra Dimensions are Dark ~ MeV DM
- Higgs portals for fermionic DM
- Low-mass DM with neutrino portals
- Long-lived particles

Zurek, Honorez, Heisig, Stadnik, Rizzo, Hryczuk, Mitridate



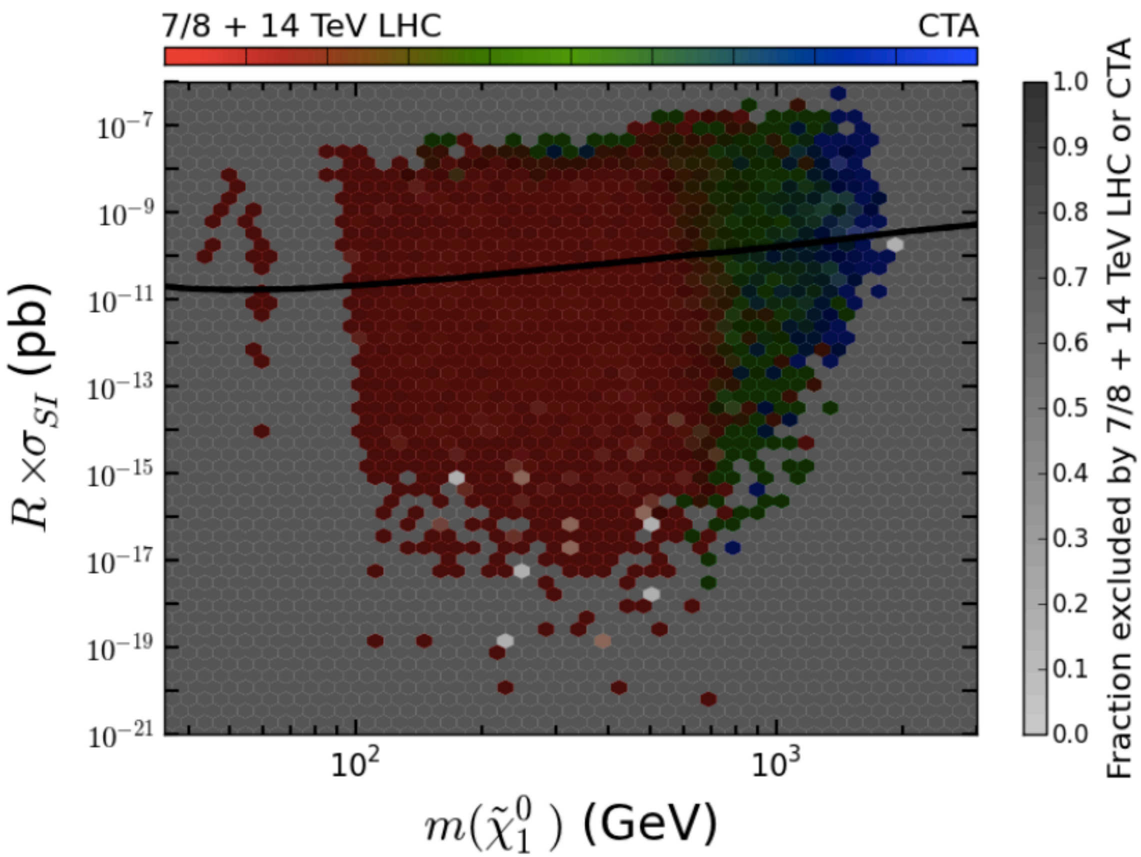
[Figure from Heather Russell]



WIMP Dark Matter

WIMP searches have dominated DM search program to date

Complementarity of WIMP searches in the pMSSM



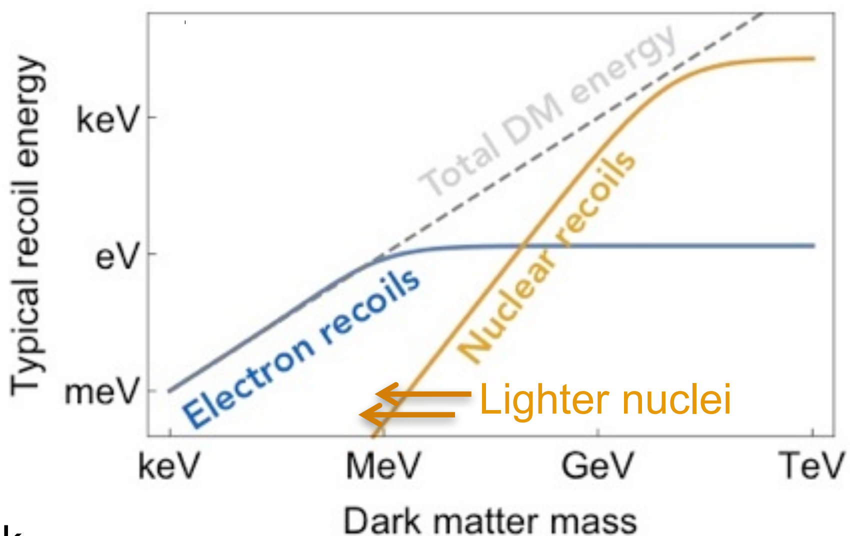
LHC searches important!

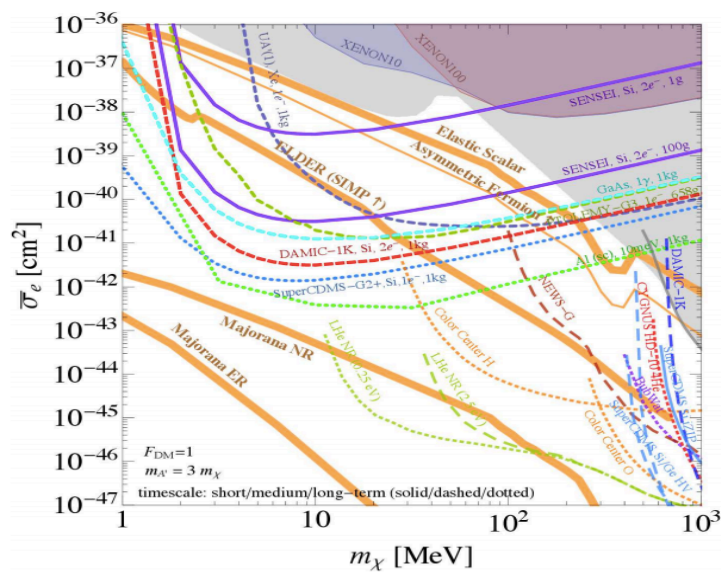
- Mono-whatever
- Cascade decays
- Long-lived particles
- portal (Z', Higgs, neutrino) dark matter interactions

Cahill-Rowley etal, 1405.6716

Sub-GeV Hidden Sector Dark Matter

- dark photon mediator and dark matter
- $m_{med} > m_{DM}$; abundance set by mediator mass, couplings to DM and SM. Highly predictive!
- Secluded, Assymetric DM, loop-level weak couplings
- new regime for direct detection: low threshold, collective modes





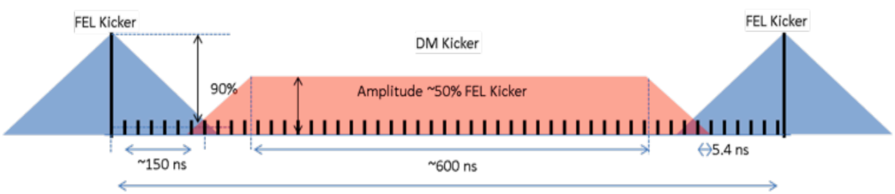
Zurek

Sub-GeV Hidden Sector Dark Matter

Accelerator experiments ideal to fully cover thermal targets due to relativistic mechanics

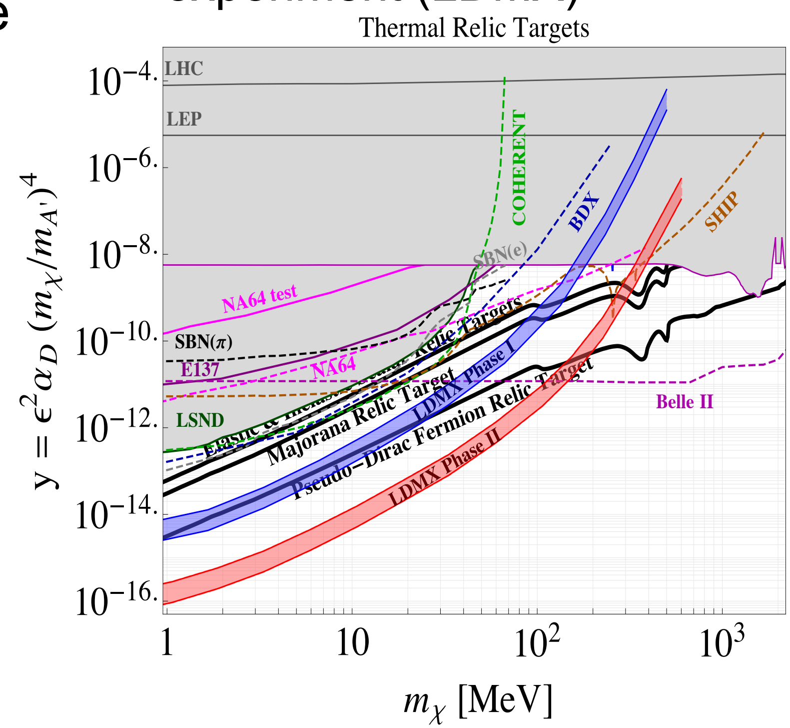
DArk Sector Experiments at LCLS-II: DASEL

- High repetition MHz e^- beam is ideal tool
- In between FEL bunches, linac accelerates
- ~200 gun dark current bunches for free



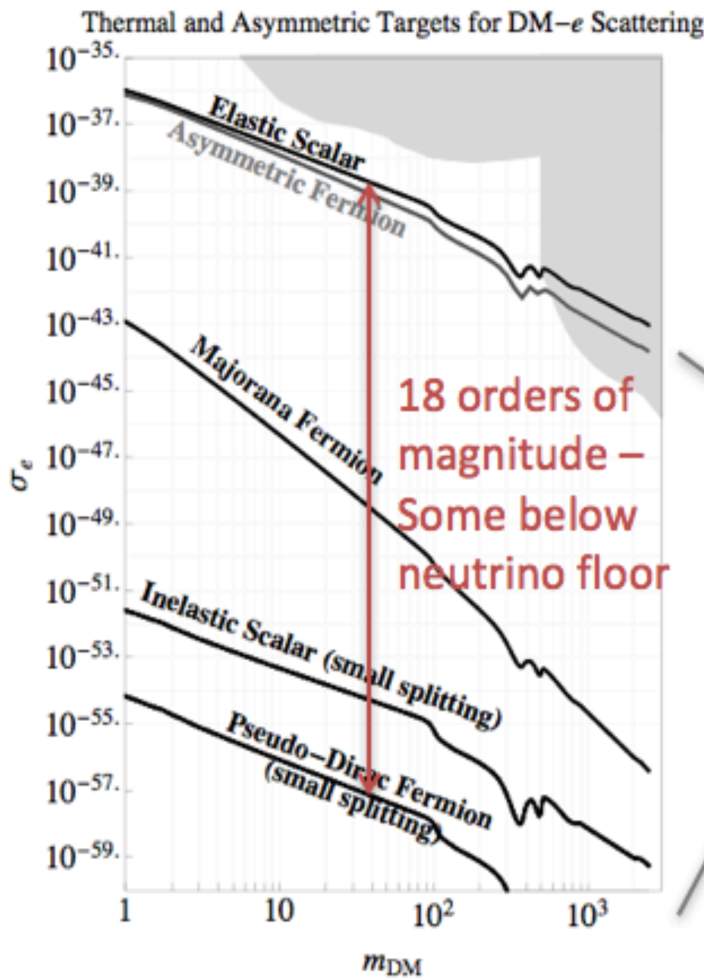
- Study underway to determine what it takes to use this beam without impact to LCLS-II
- Studies also underway at CERN accelerator complex

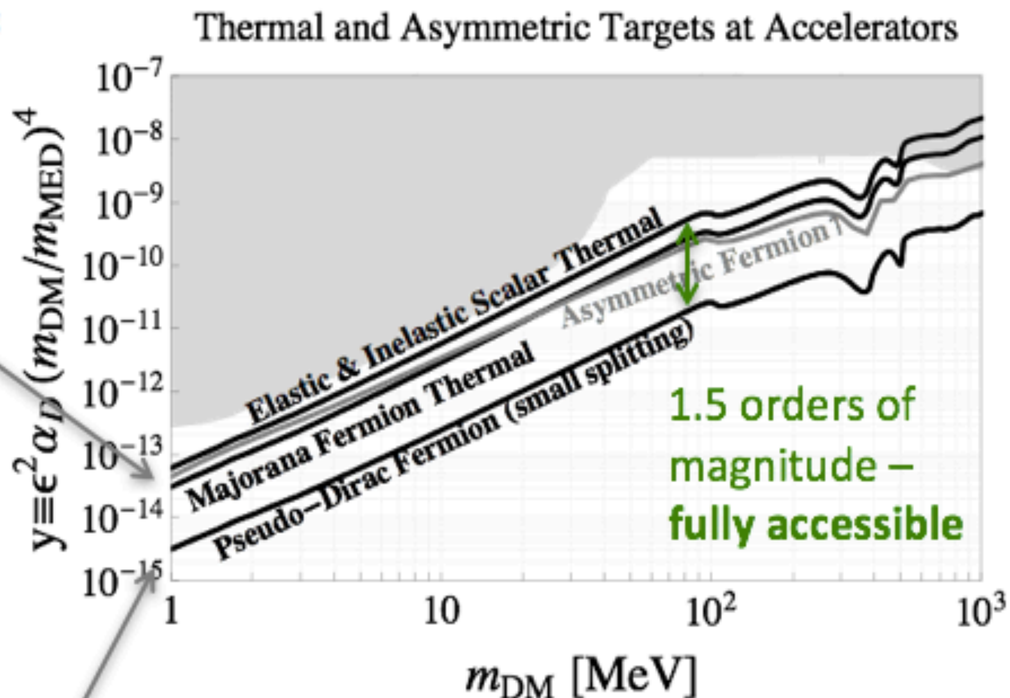
Proposed missing momentum experiment (LDMX)



Sub-GeV Hidden Sector Dark Matter

High-value targets accessible at accelerators (*v~c*) but invisible to direct detection (*v~10^{-3} c*)





Accelerators are robust to details of DM mass structure

Ultralight Dark Matter

Sharp goal: Explore full range for QCD axion-like dark matter

DM mass: 10^{-22} eV, 10^{-18} eV, 10^{-14} eV, 10^{-10} eV, 10^{-6} eV, 10^{-2} eV

10^{-8} Hz, 10^{-4} Hz, 1 Hz, 10^{4} Hz, 10^{8} Hz, 10^{12} Hz

Technique:

← torsion balances →

← E&M →

← atom interferometry →

← NMR →

← x-ray →

← NMR →

Experiment:

Eot-Wash (spin)

Eot-Wash (scalar)

CASPEr-Electric

CASPEr-Wind

ADMX

HAYSTAC

LC Circuit

DM Radio

ABRACADABRA

Atom Interferometry (spin)

Atom Interferometry (scalar)

IAXO

ARIADNE

<u>Couplings</u>

E&M

QCD

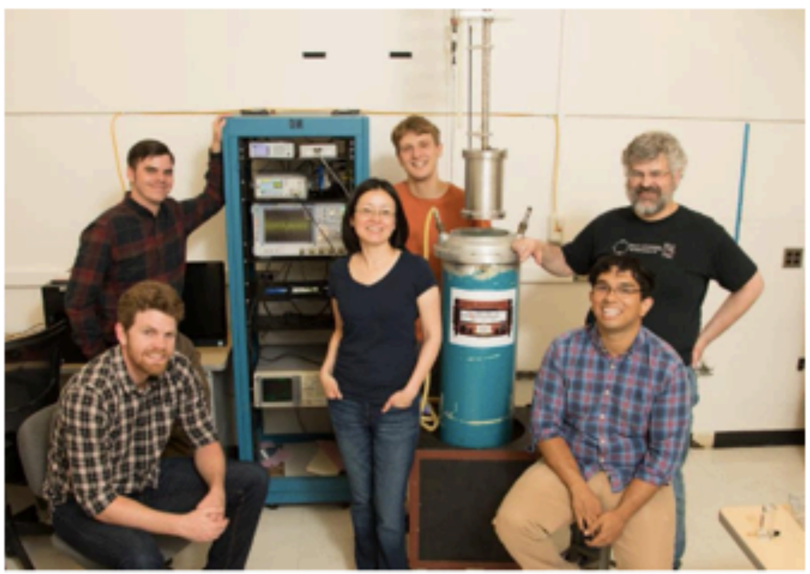
Spin

Scalar

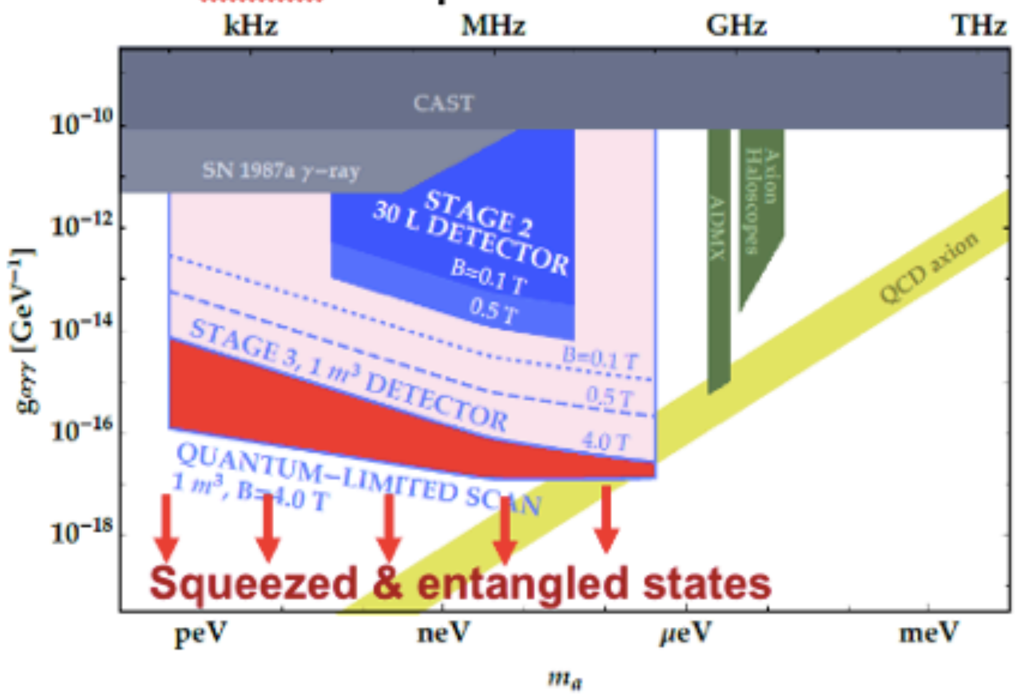
Ultralight Dark Matter

Quantum sensor technology enables novel Dark Matter searches: can "tune" precisely to axion-like-particle oscillation frequency

Prototype up and running
Funded by LDRD + Heising-Simons



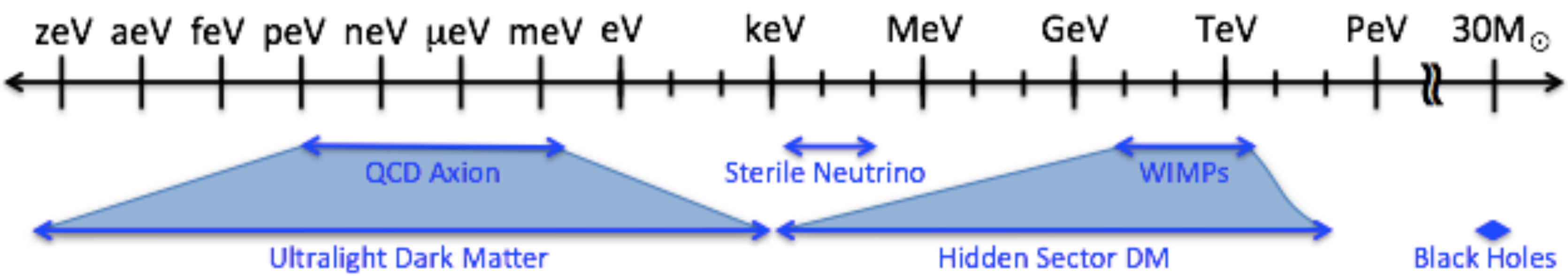
Phenomenal sensitivity to axion-like-particles



Primordial BHs as dark matter

- PBHs may constitute a fraction of the DM
  - Several bounds must be better understood
  - Future observations (Gaia) must see the PBH effects in astrophysics
- Single field double inflation may produce light PBHs
  - Unusual potentials, slow roll approximation is usually violated, precise computations are needed
- Stochastic GW bkg. offers most sensitive tests of PBHs
  - Fits suggest: just a small fraction of DM in PBHs
  - PBH DM can be excluded by non-observation of the GW background by LIGO and LISA
- However, all the DM can be in the form of light ECOs, requiring gravity theories beyond GR

Leading search techniques



<peV
CASPER

μeV
ADMX

peV-μeV
DM Radio

keV-MeV
e⁻ recoil DD

MeV-GeV
Accelerator
Searches

GeV-100 TeV
Direct Detection
LHC
Fermi, CTA

LIGO

All of these are needed to cover the parameter space!

Neutrino Physics

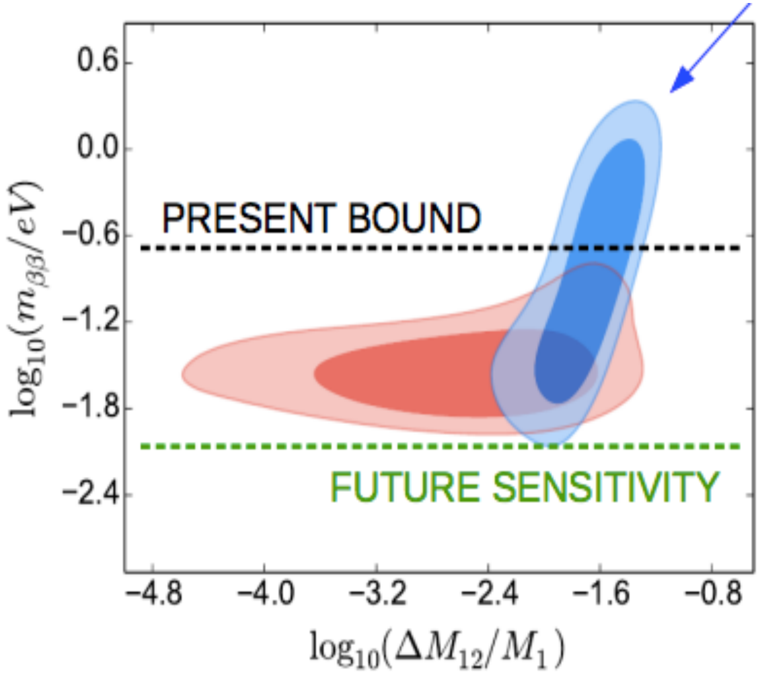
Fundamental Questions addressed by Diverse Neutrino Program

- What is the origin of neutrino mass?
- How are the neutrino masses ordered?
  - *Oscillation experiments*
- What is the absolute neutrino mass scale?
  - *Beta-decay spectrum*
  - *Cosmic surveys*
- Do neutrinos and anti-neutrinos oscillate differently?
  - *Oscillation experiments*
- Are there additional neutrino types and interactions?
  - *Oscillation experiments*
  - *Cosmic surveys*
- Are neutrinos their own anti-particles?
  - *Neutrinoless double-beta decay*

Neutrinoless double-beta decay

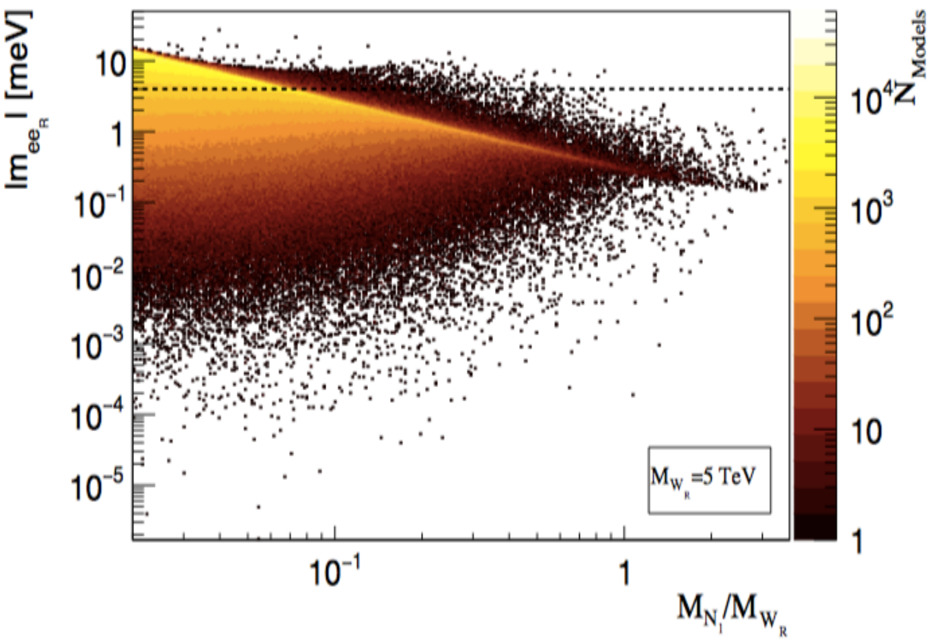
Next generation of experiments testing BSM physics

GeV scale Leptogenesis with N_R=2



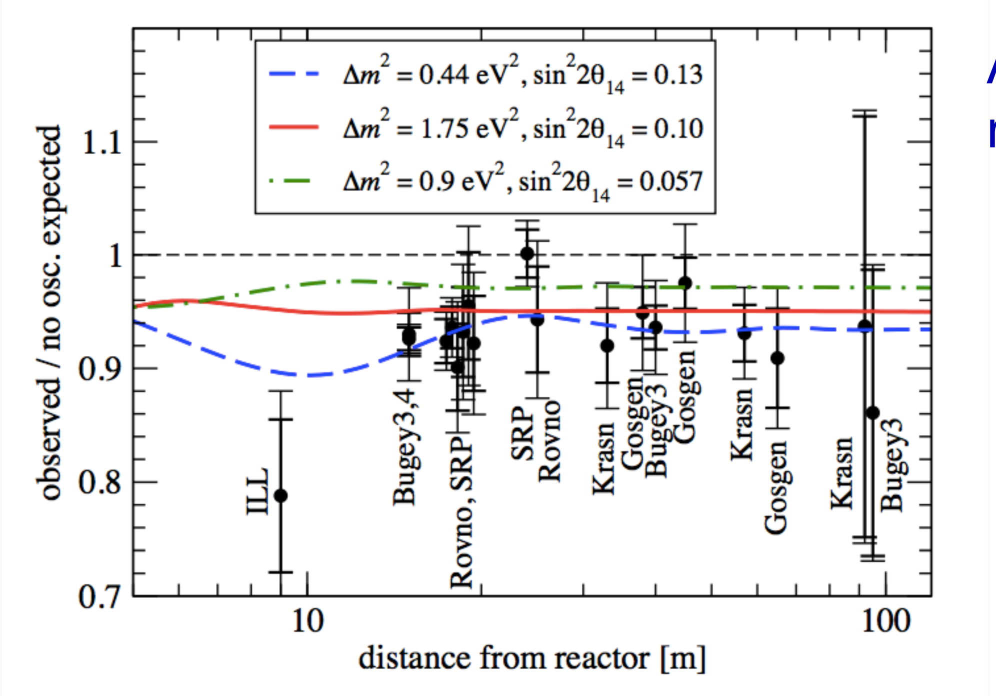
Hernandez etal, 1606.06719

Left-Right Symmetric Model parameter scan



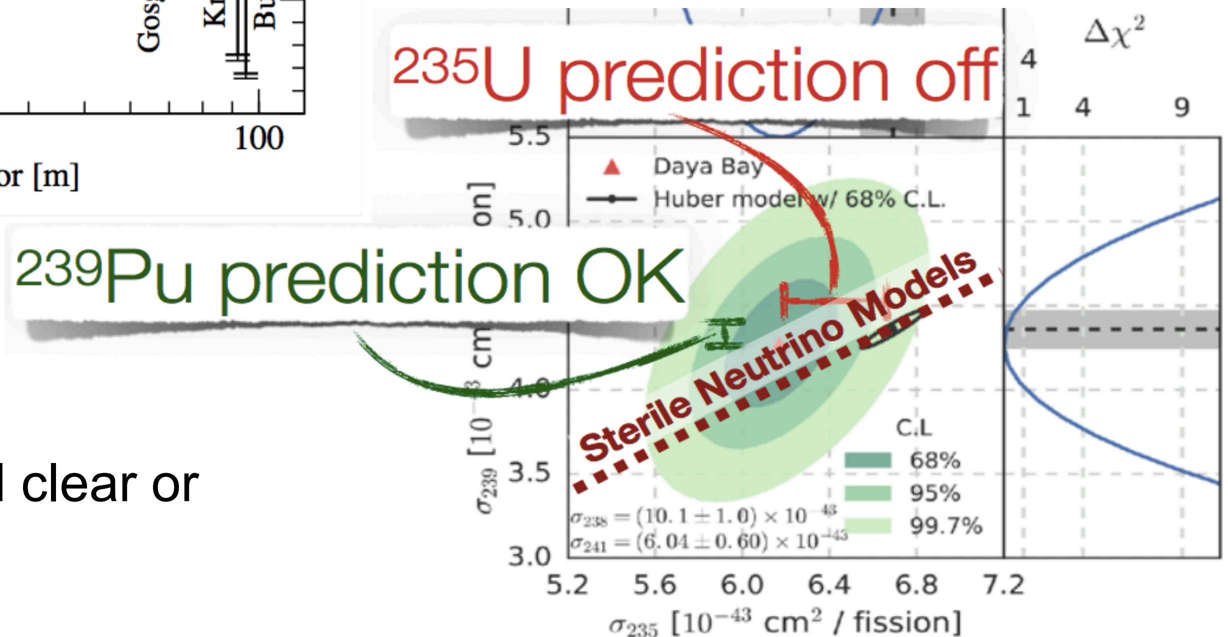
de Blas etal, 180x.0ASAP

Whither sterile neutrinos?



Anomaly hints from reactor experiments

Some consistency with both sterile neutrinos & new nuclear models!



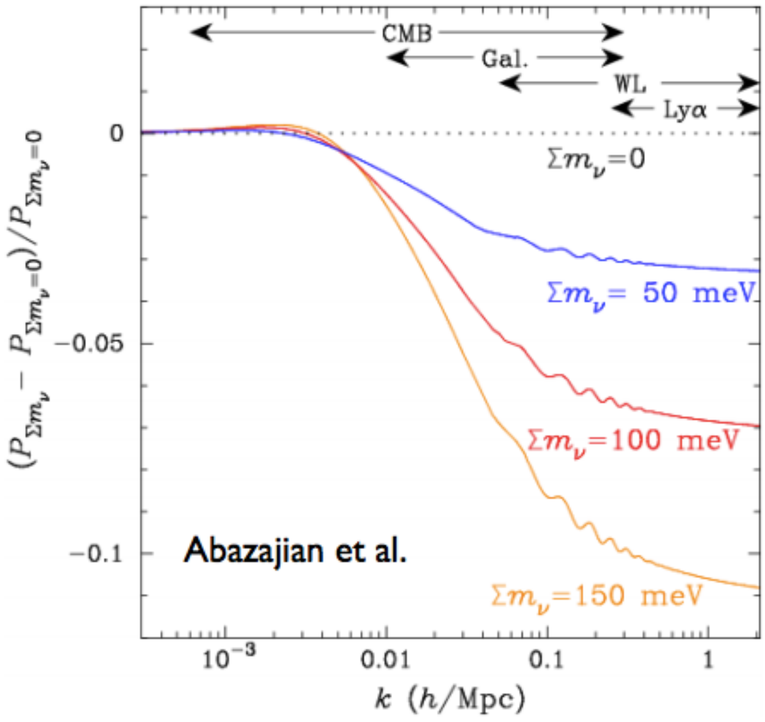
New data (SBN) could clear or muddy these waters

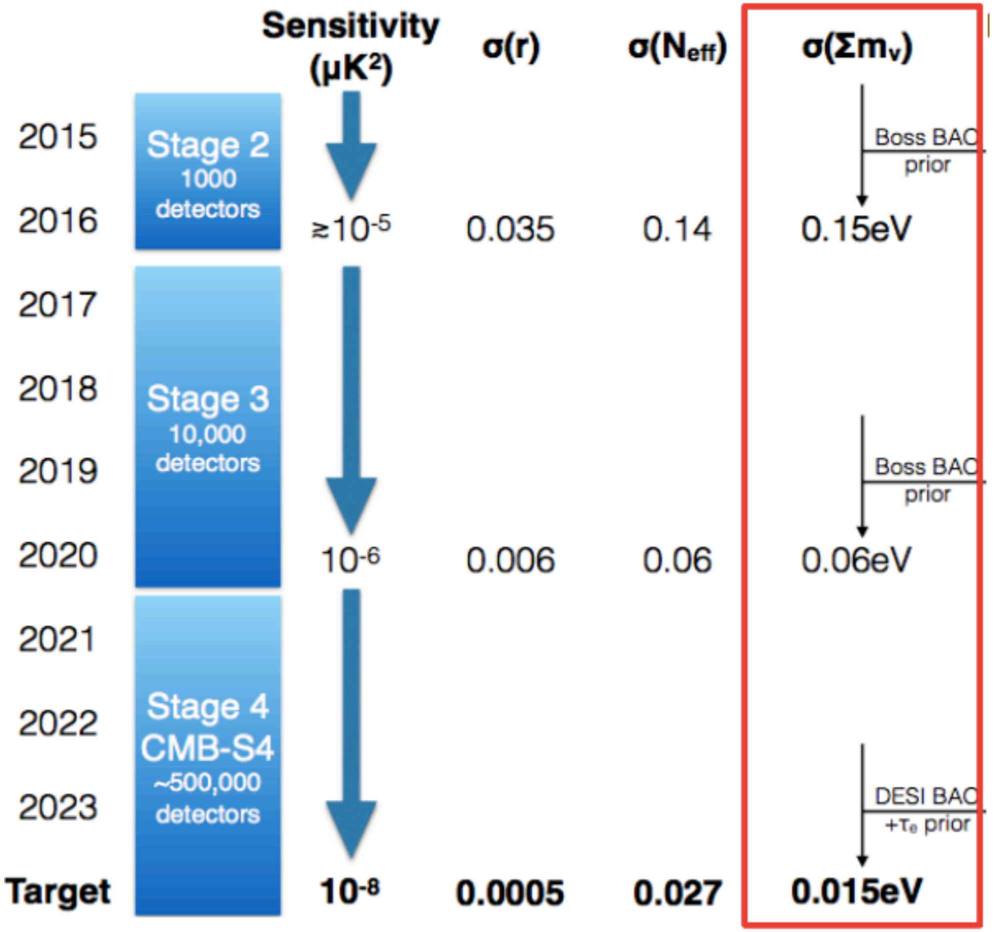
See Hernandez, 1709.04294, in prep for more details

Kopp

Neutrino masses from Cosmology

Neutrinos effect the CMB power spectrum

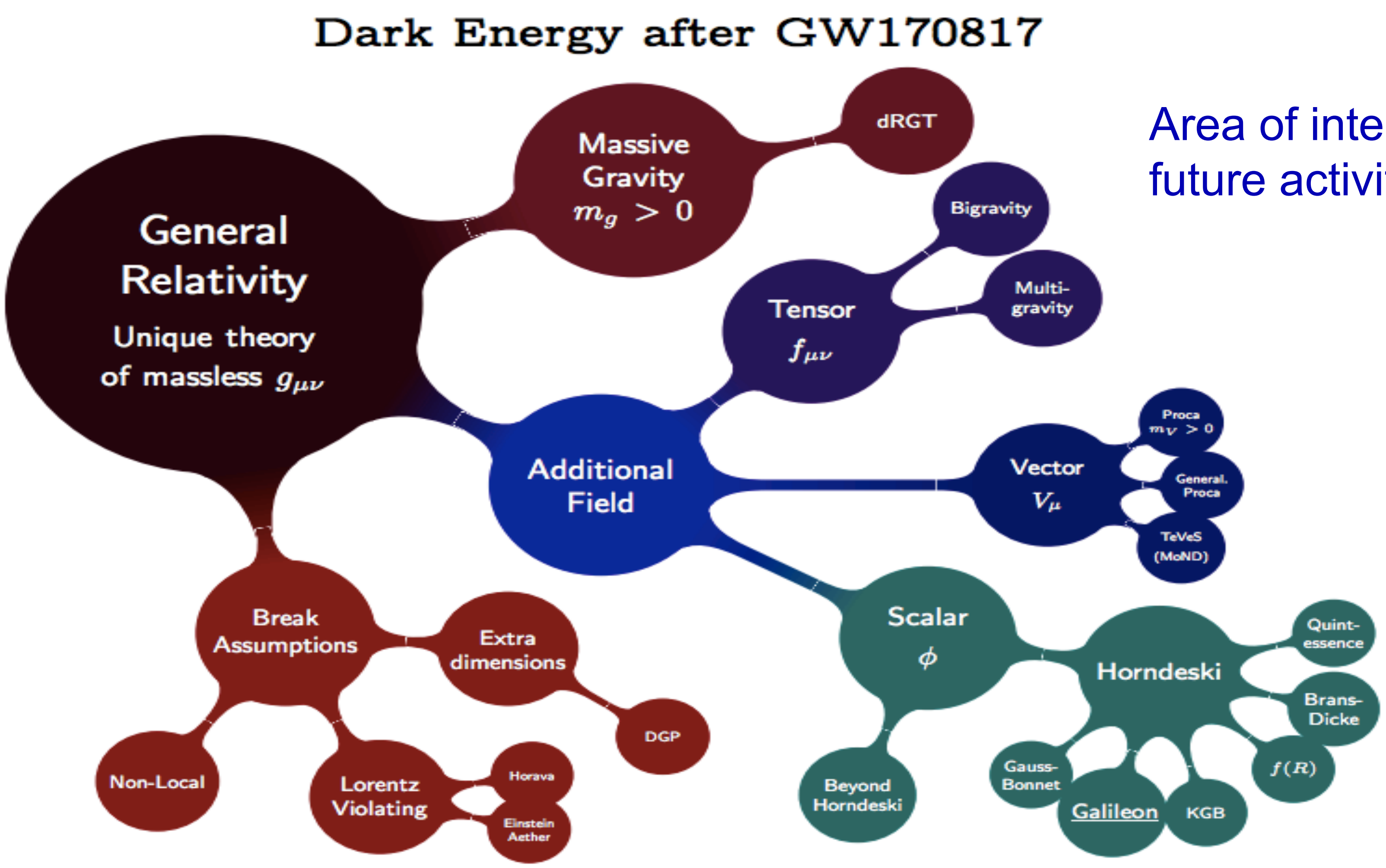




Implications for 0νββ

Latanzzi

Multi-messenger astronomy & LIGO



Area of intense future activity!

[modified from original diagram by M. Zumalacárregui]

Theory Summary: Moriond 2018

New ideas yield new experiments

Precise calculation of signal and background quantifies discovery

Much new data and many novel ideas in 2018/17

- Yet more needed

Look for emerging new areas of activity

- Neutrinos
- Light dark matter
- multi-messenger astronomy
- Dark energy
- ramp-up to HL-LHC

Look forward to Moriond 2019 for the next breakthrough!