Lake Louise and Aspen Winter Conferences 2018

PPD seminar

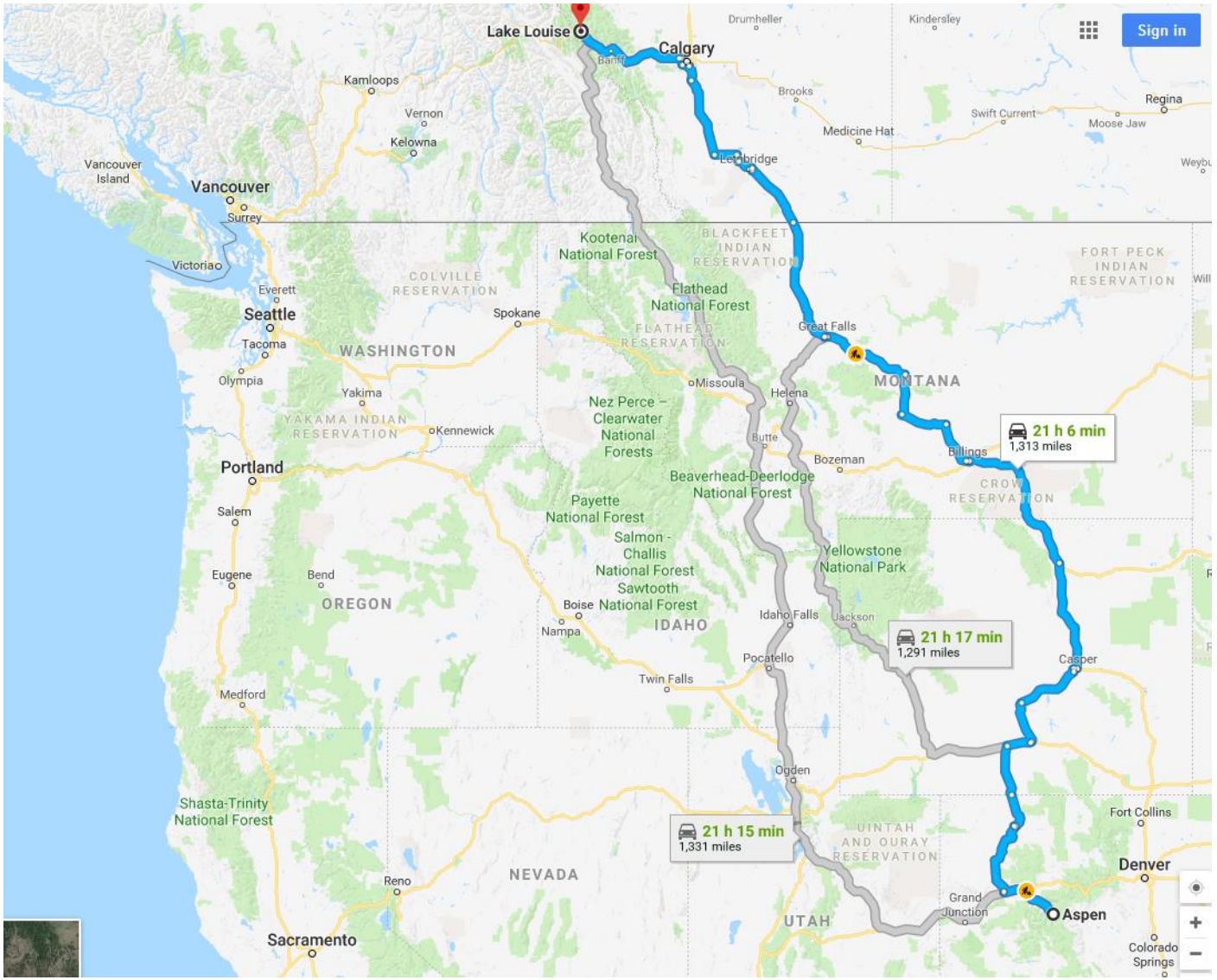
23rd May 2018

Fergus Wilson

Outline

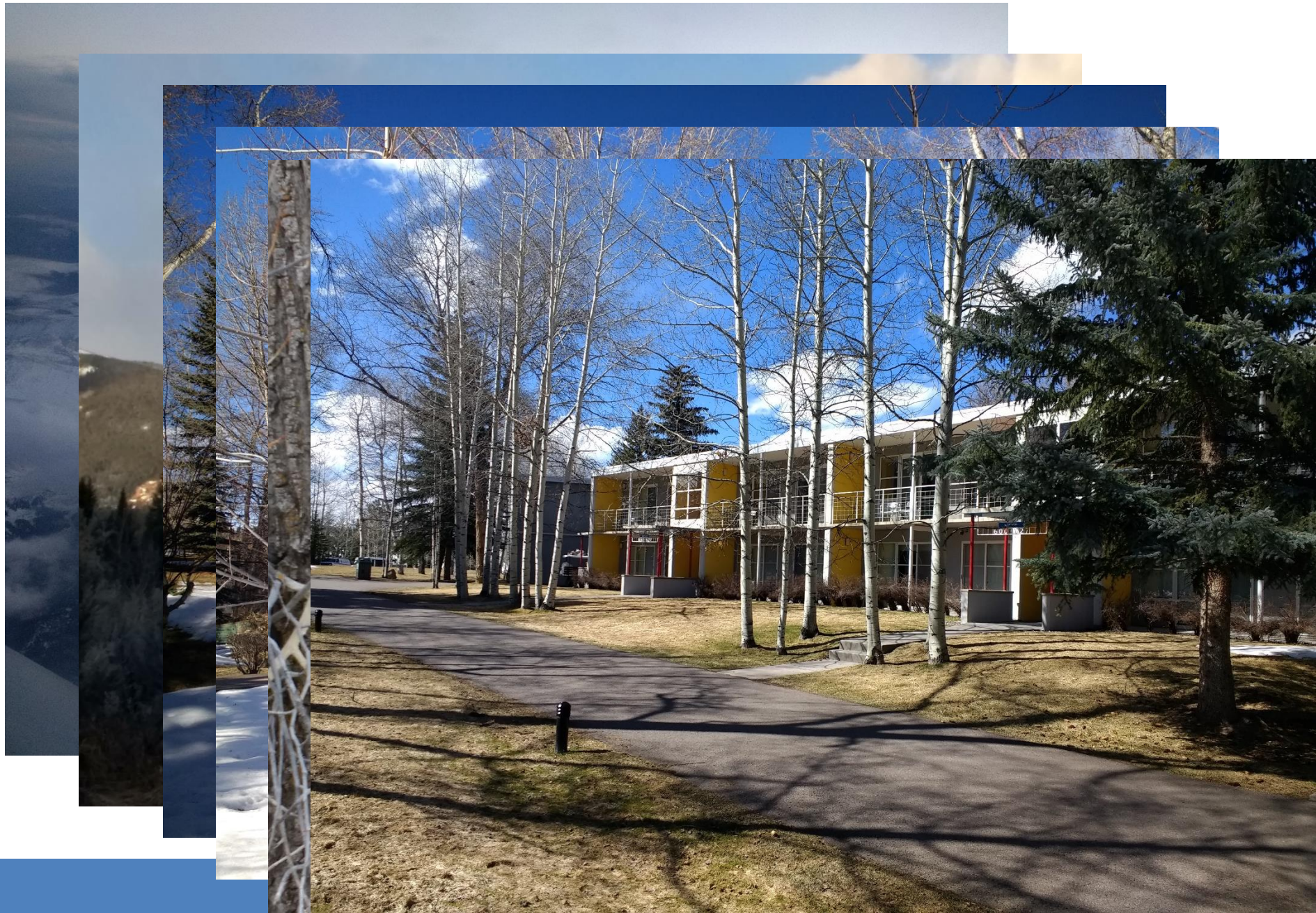
- Holiday snaps
- SUSY (ATLAS/CMS)
- Long Lived Particles
- Dark Photons
- g-2
- Dark Matter
- Flavour - Neutrinos
- Flavour – Leptons and quarks
- Gravitational Waves

Lake Louise (Canada) and Aspen (USA)



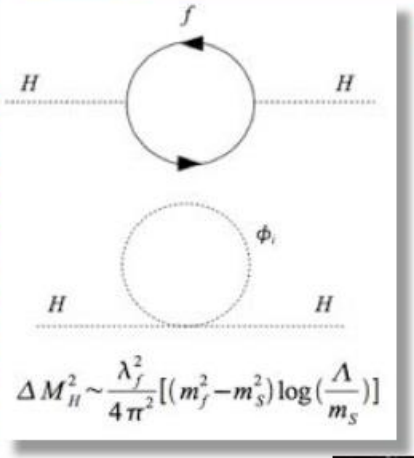
Lake Louise, Alberta

Aspen, Colorado



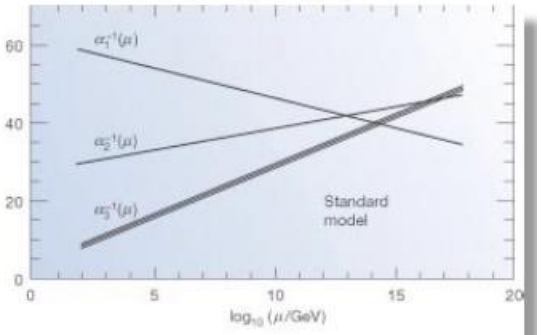
SUSY

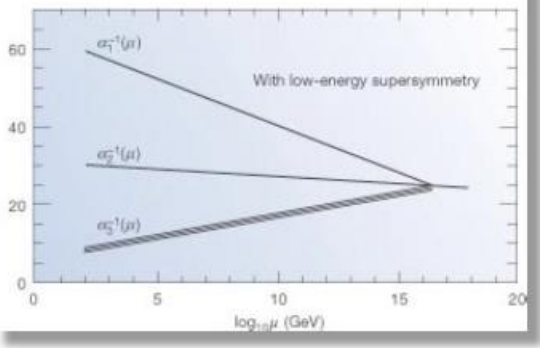
Three Miracles of SUSY



- Elegant solution to the hierarchy problem (i.e., why the Higgs boson mass is not found at the Planck scale)

- Gauge unification

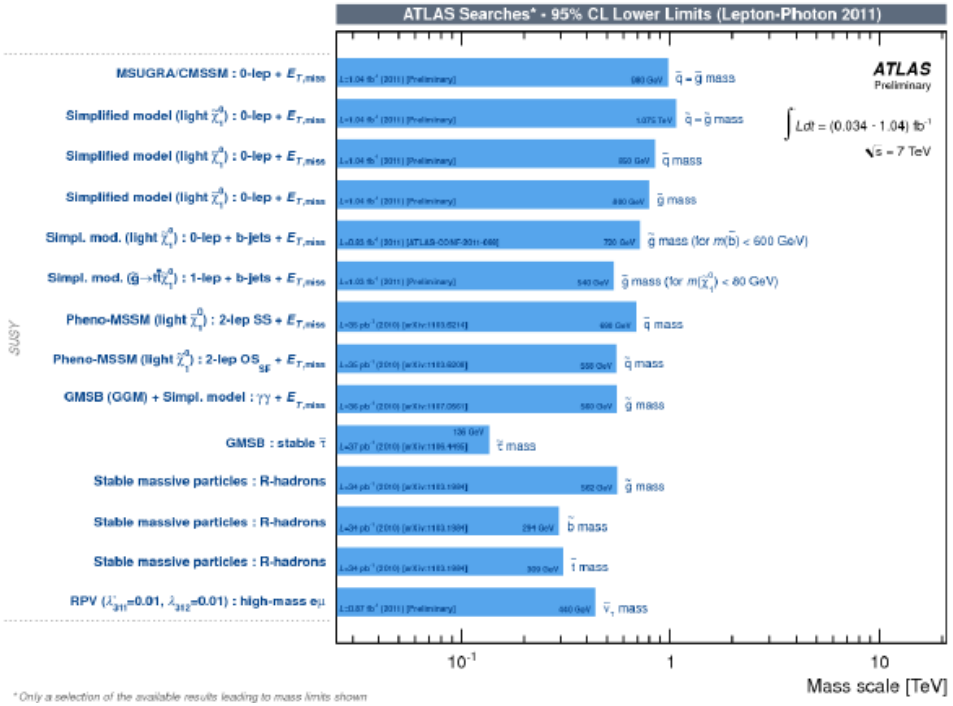




- Dark matter candidate with the right abundance

ATLAS searches pre-Higgs (2011)

- The majority of searches were inclusive. They targeted strongly-produced SUSY particles that cascade decay to WIMPS (DM candidates) and generic models like MSUGRA/MSSM/GMSB.
- Searches for the 3rd generation were emerging (e.g. arXiv:1101.1963)



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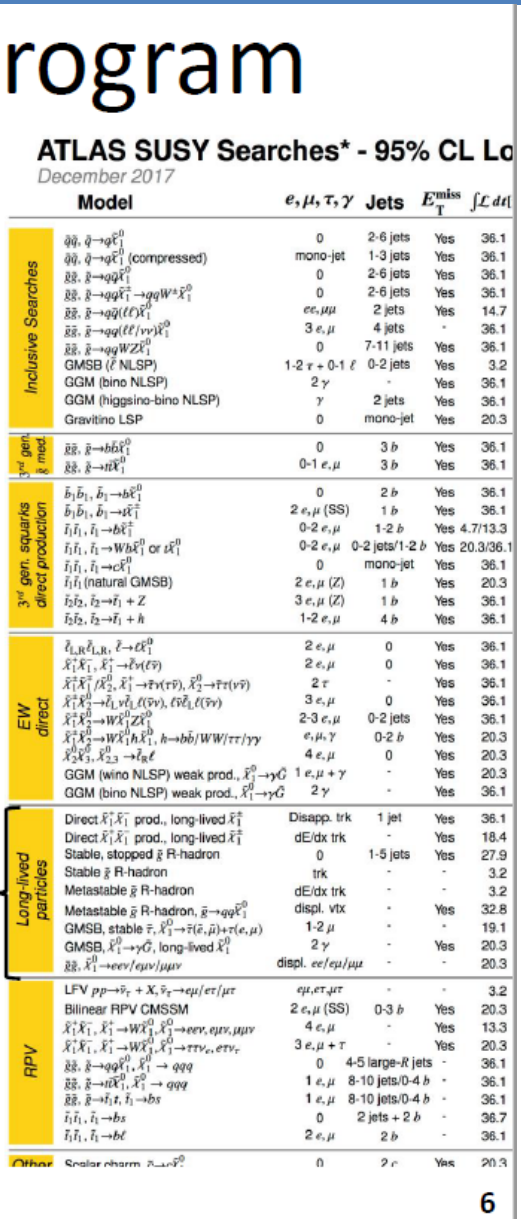
Contemporary search program

- The 125 GeV Higgs is considered as "SUSY model killer" (tension with high-scale theories). However, the discovery of Higgs inspired a number of searches for m~O(1 TeV) 3rd generation squarks.
- Overall, the search program is more exciting than ever before.
- Goes even beyond the R-parity conserving models and in the corners of phase space where the mass differences are small (compressed and long-lived).
- Caveat: The data are often interpreted for simplified models so the limits need to be translated carefully for your model of choice.
  - The simplified models may give overly high or low exclusion.

Hidetoshi will discuss this later on.



ATLAS SUSY Searches* - 95% CL Lo

December 2017

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm \to qqW^*\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2
	GGM (bino NLSP)	2 γ	-	Yes	36.1
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1
	Gravitino LSP	0	mono-jet	Yes	20.3
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	1 b	Yes	36.1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1
EW direct	$\tilde{\ell}_{LR}\tilde{\ell}_{LR}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\tilde{\ell}\nu)$	2 e, μ	0	Yes	36.1
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0/\tilde{\chi}_1^+\tilde{\chi}_1^-\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\ell}\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3
	$\tilde{\chi}_2^0\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 e, μ + γ	-	Yes	20.3
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to eev/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to eev, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	-	Yes	20.3
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qq\ell$	0	4-5 large-R jets	-	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qq\ell$	1 e, μ	8-10 jets/0-4 b	-	36.1
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3

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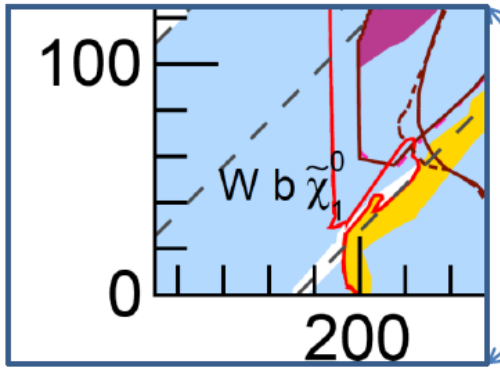
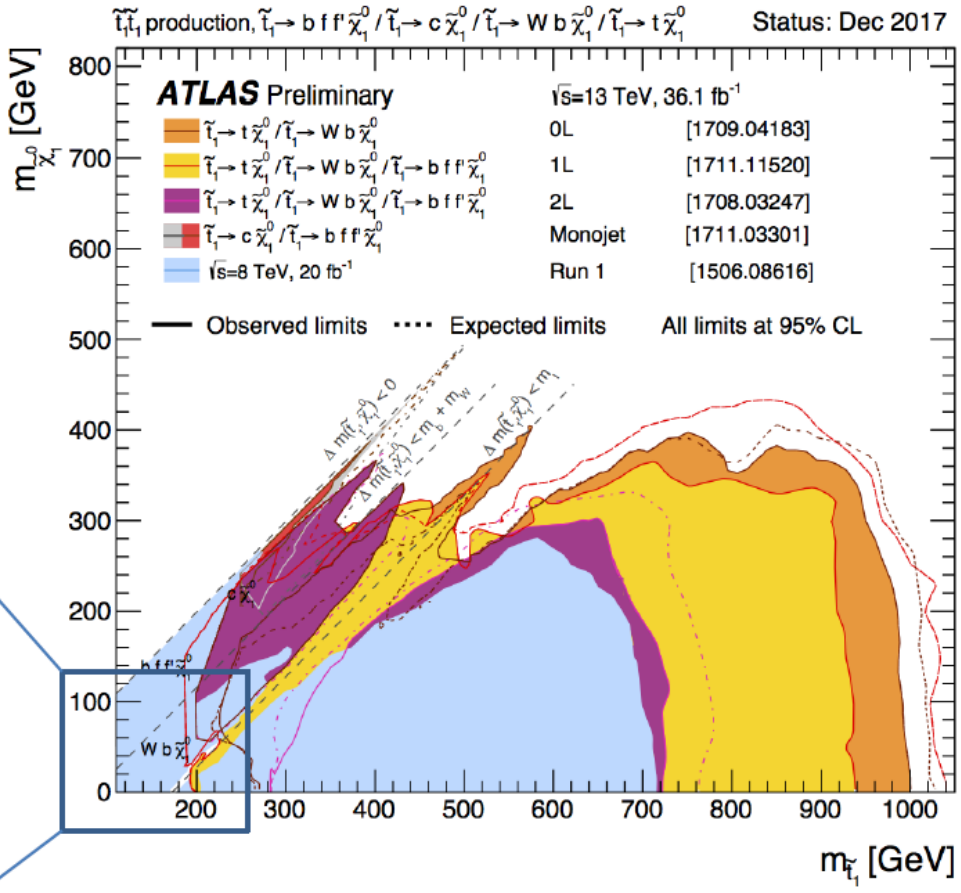
Direct stop pair-production: Overview

- Huge improvement in sensitivity in comparison to Run 1
- Decays with neutralinos heavier than 300-400 GeV are difficult to probe.
- What is happening with m(stop)~220 GeV and m(LSP)~50 GeV?





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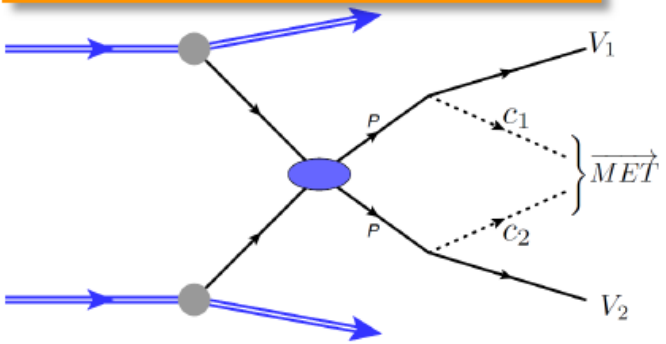
The M_{T2} Variable

- M_{T2}: ***"stransverse mass"*** - a generalization of the transverse mass in case of a pair of invisible particles
- For a simplified case of no extra jets and zero masses for visible and invisible systems:

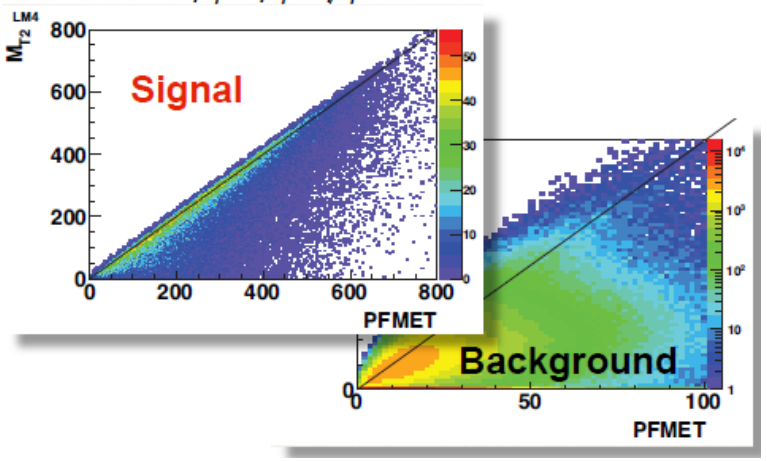
$$(M_{T2})^2 \simeq 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

  - M_{T2} ~ ME_T for symmetric SUSY-like topologies
- M_{T2} kills QCD background very efficiently:
  - M_{T2} ~ 0 for dijets
  - M_{T2} < ME_T in case of mismeasured dijets

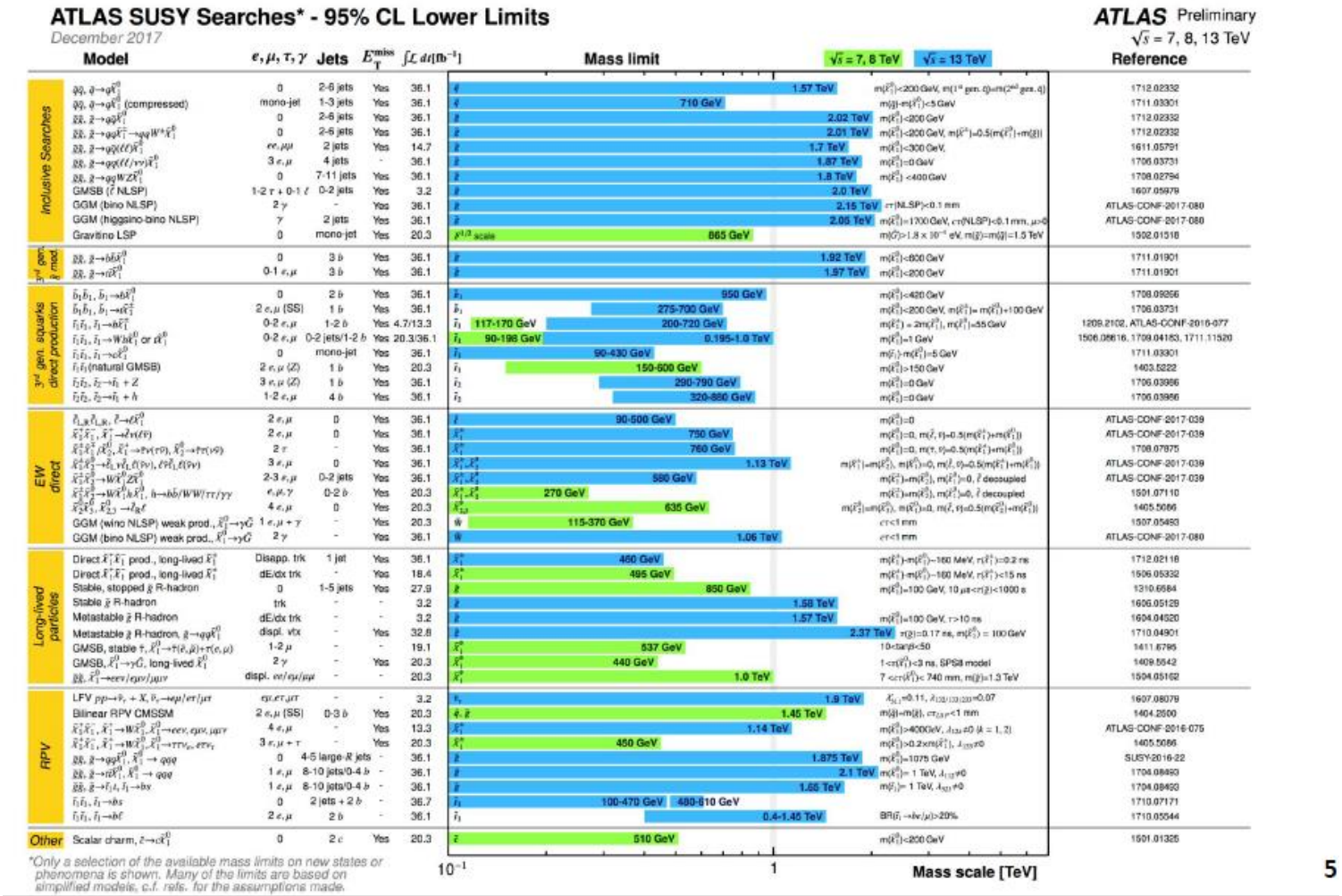
Lesters & Summers, hep-ph/9906349



$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not{p}_T} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$$

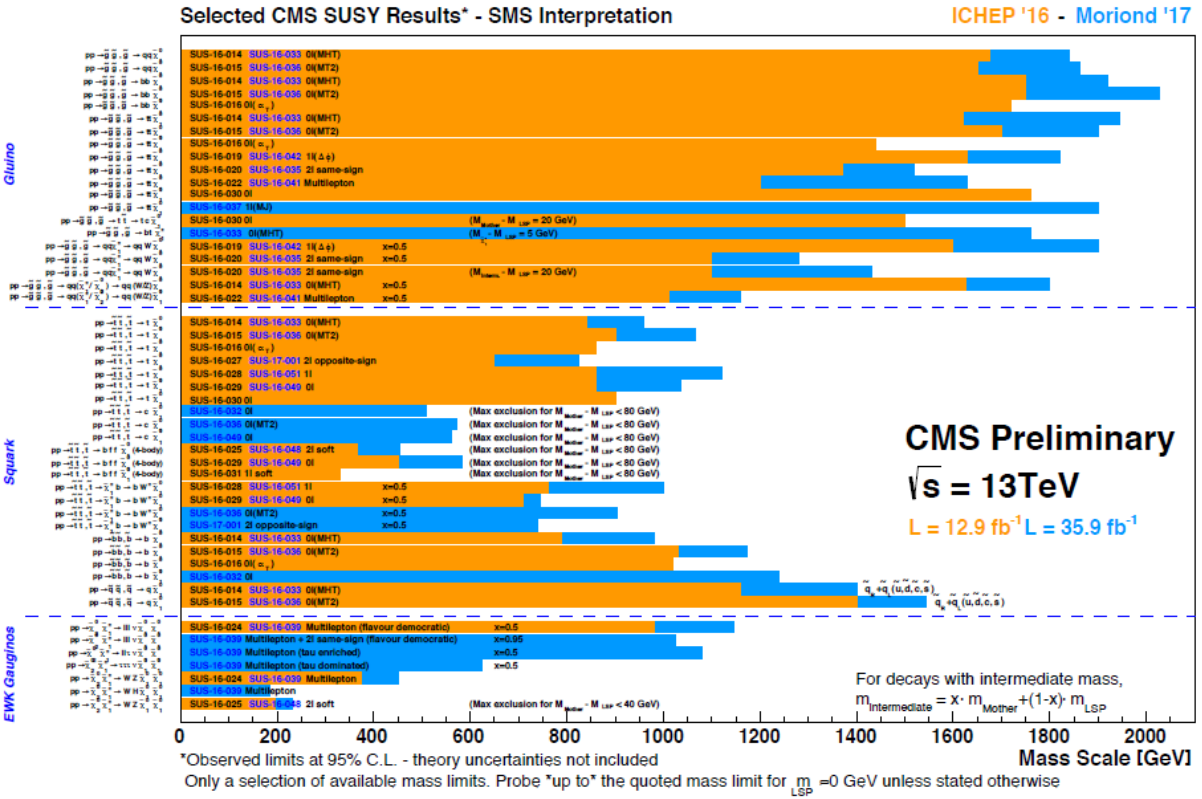


Contemporary search program



Supersymmetry or Supercemetry?

- Summary of all recent results:



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Summer_Conferences_2017_36_fb_1

Greg Landsberg - SUSY Searches at CMS - Corfu 2017

Slide 48

LONG LIVED PARTICLES

Physics behind long-lived particles

Caveat : These are just examples.

SUSY

- Long-lived $\tilde{g}$: Heavy squark, $\tilde{g}$-Bino co-annihilation
- Long-lived $\tilde{\chi}^{\pm}$: Wino/Higgsino Lightest Stable Particle (LSP)
- Long-lived $\tilde{\chi}^{0}$: Gravitino LSP, R-parity violation, Wino-Bino co-annihilation

Hidden/dark sector scenario

- Long-lived dark photon : Higgs portal model
- Long-lived neutral scalar : Heavy neutral boson portal model

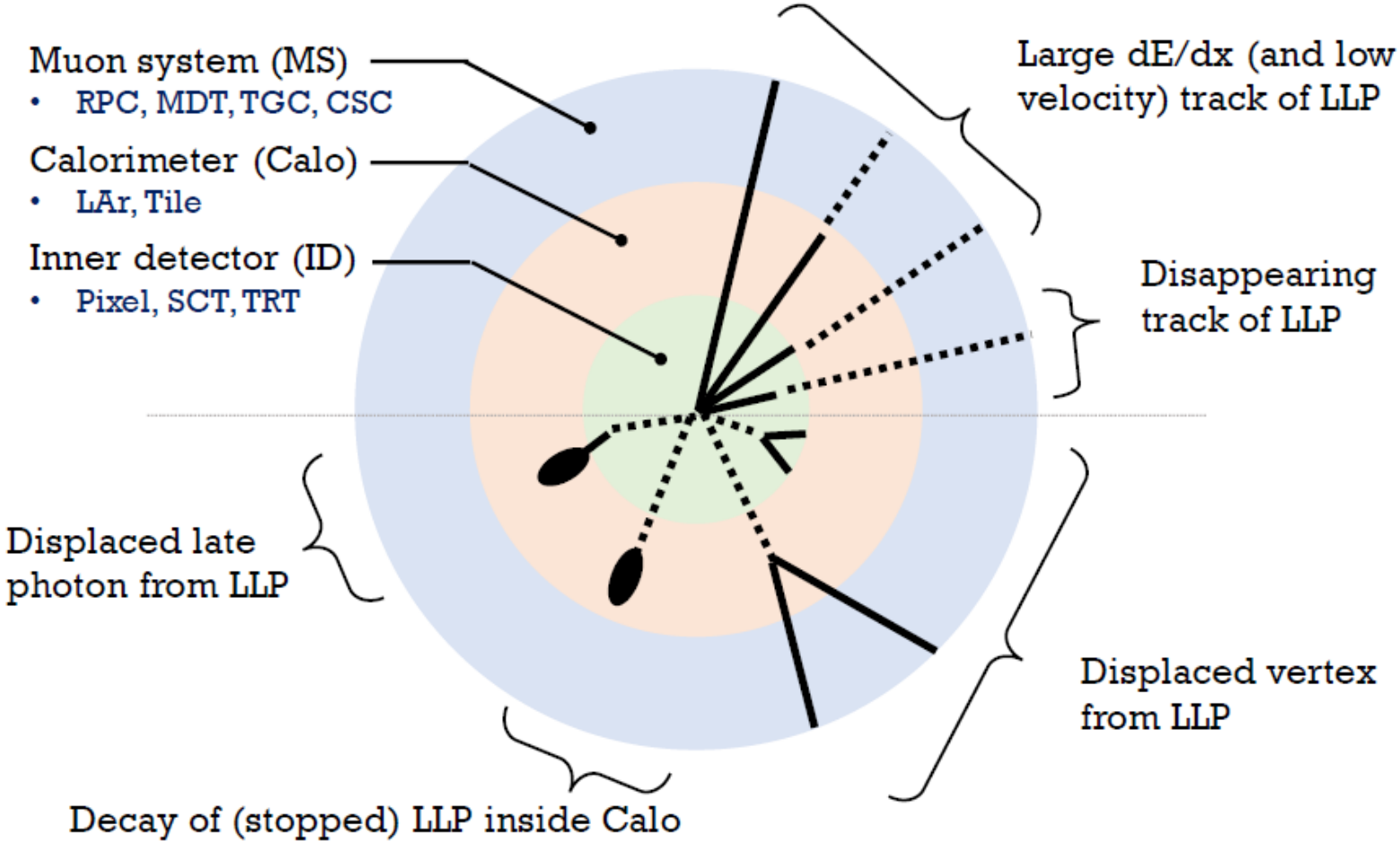
Others

- Long-lived right-handed neutrino : Left-right symmetry extension of SM
- Long-lived multi-charged particle : Monopole, Micro black hole, Q-ball

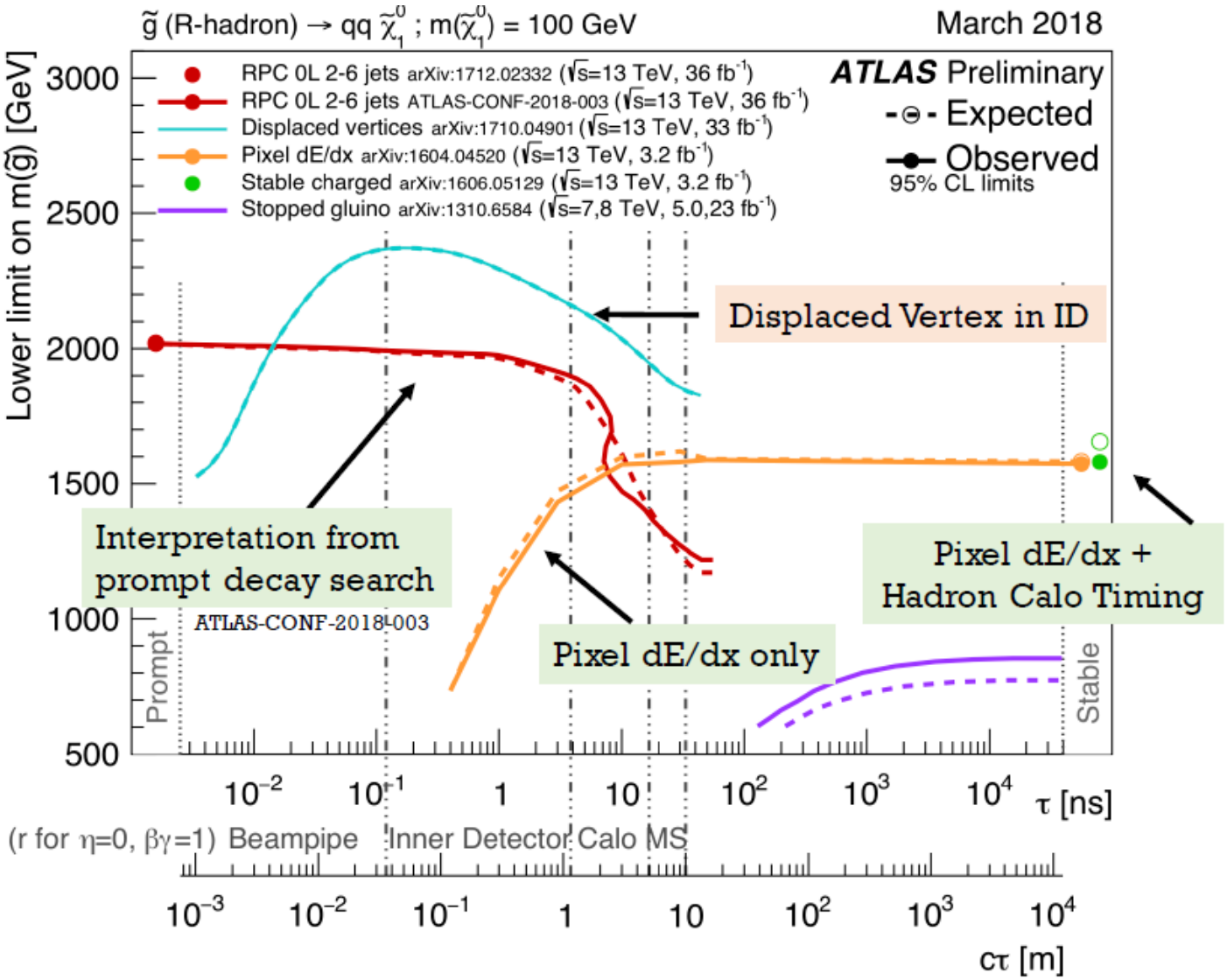
And many more !!

Long Lived Particles

Signatures of long-lived particles

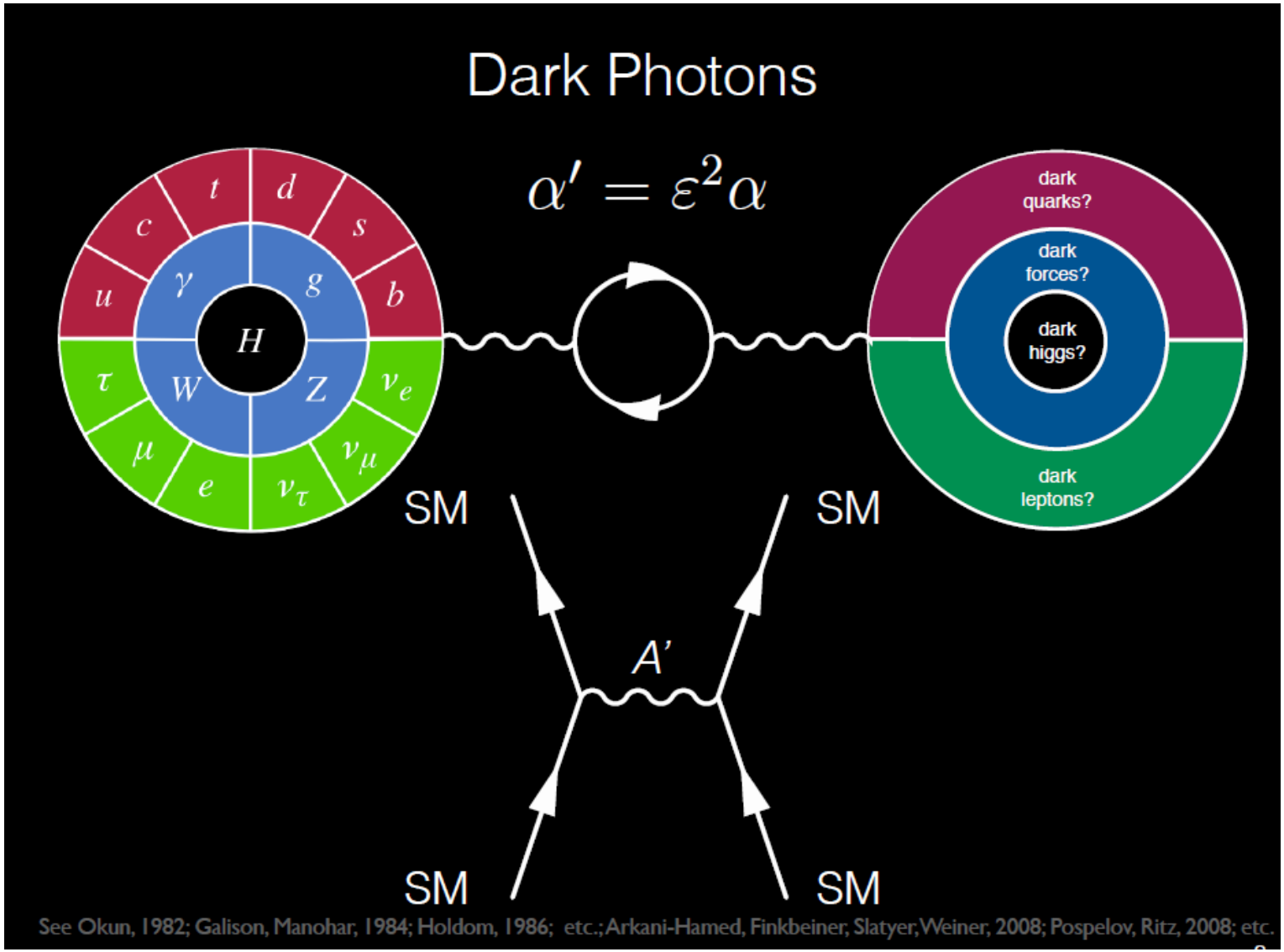


Long Lived Particles



DARK/HIDDEN SECTOR

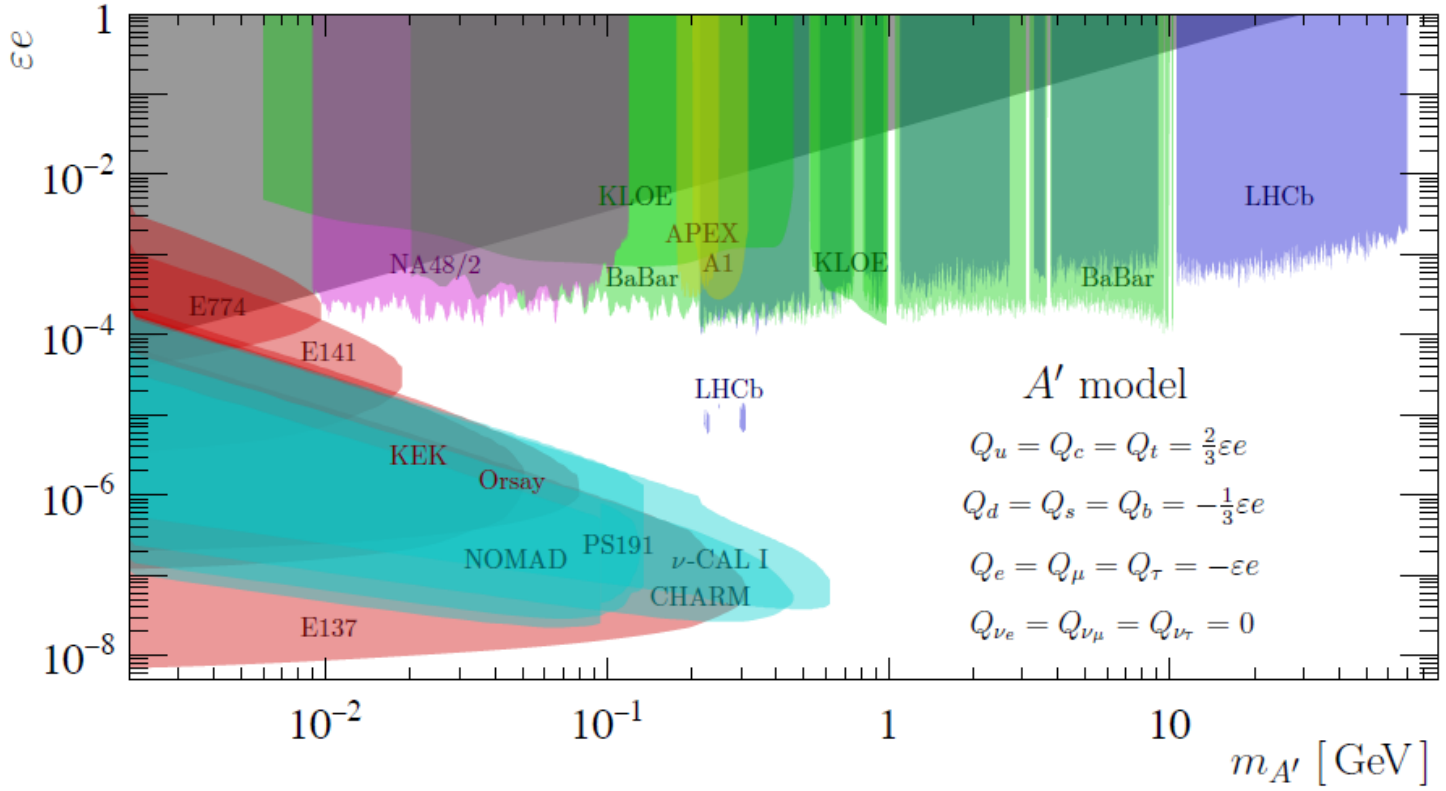
Dark Sector


Dark Photons
$\alpha' = \varepsilon^2 \alpha$
t
d
c
s
u
b
γ
g
H
τ
W
Z
ν_e
μ
ν_μ
e
ν_τ
dark quarks?
dark forces?
dark higgs?
dark leptons?
SM
SM
A'
SM
SM
See Okun, 1982; Galison, Manohar, 1984; Holdom, 1986; etc.; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008; Pospelov, Ritz, 2008; etc.

Recasting for other Models

Dark photon searches provide sensitivity to (many) other models.

Ilten, Soreq, MW, Xue [1801.04847]



We developed a data-driven way to easily recast any dark photon search to obtain limits on any other vector model (auto-calculates hadronic decay rates for all masses).

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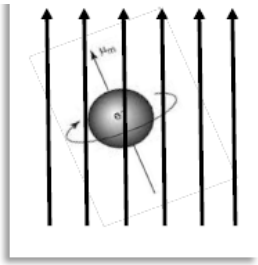
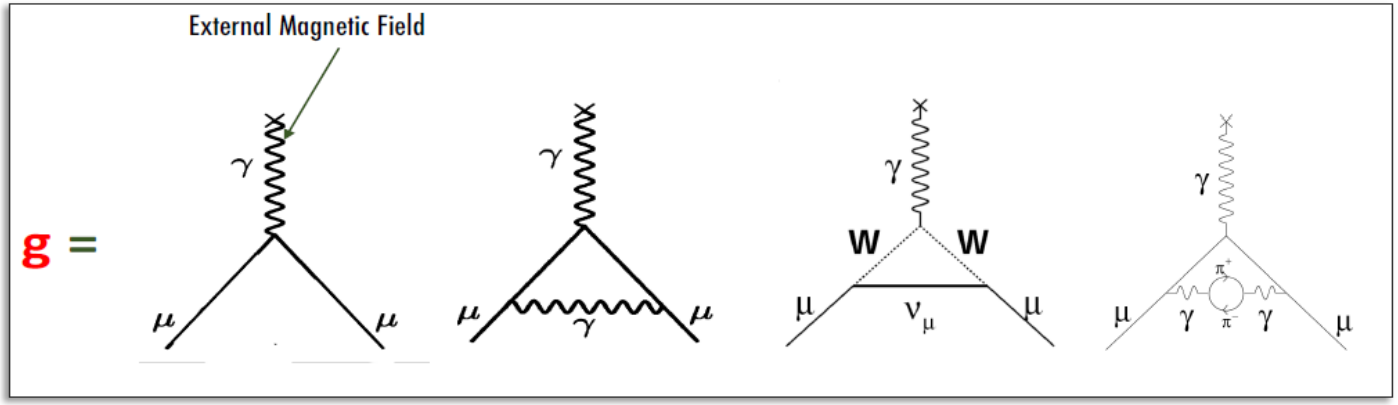
G-2

$\vec{\mu}$ = magnetic moment
$\vec{S}$ = spin
g = g-factor
q = charge
m = mass

$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$





$$g = 2(1 + a)$$

$$a_\mu^{SM} = {}^{(g-2)}/_{2} = a^{QED} + a^{EW} + a^{QCD}$$

muon anomalous magnetic moment

Fermilab

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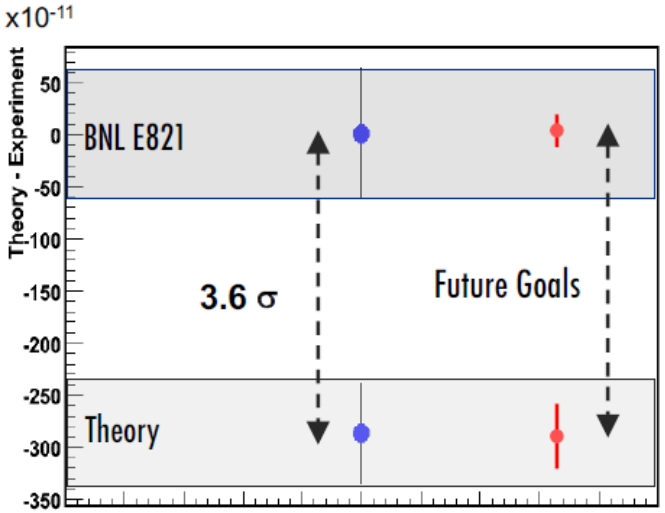
g-2

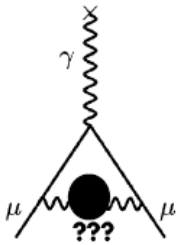


$> 7\ \sigma$ for unchanged central values

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after FNAL [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	140

Theory uncertainty remains the same, both the theoretical and experimental central values are unchanged, but the experimental uncertainty is reduced.

New Physics!



$5\ \sigma$ discrepancy

Outline

- Muon g-2 Physics
- Muon g-2 Experiment
- Muon g-2 Status
- Conclusions

Brookhaven Muon g-2 Experiment

BNL experiment was statistically limited.

Need more muons!

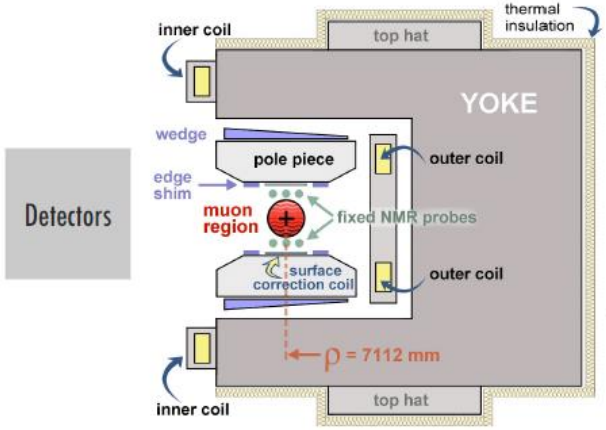
Lets move to Fermilab!

Reduce the 480 ppb statistical uncertainty to 100 ppb! → 10 x BNL data

Fermilab

Magnetic Field = 1.4513 T
Current = 5176 A
3 x 15 m
700 tons
12 Yokes: C shaped flux

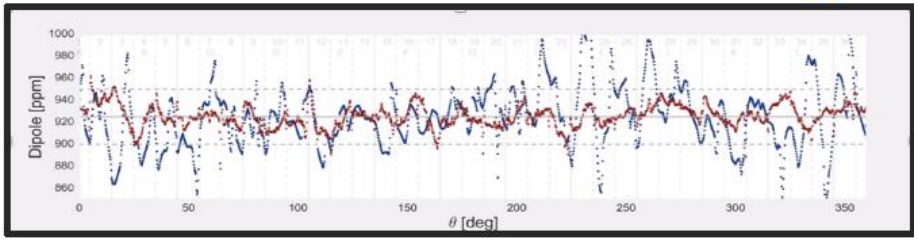
$$a_\mu(\text{Expt}) = \frac{g_e\,\omega_a\,m_\mu\,\mu_p}{2\,\tilde{\omega}_p\,m_e\,\mu_e}$$

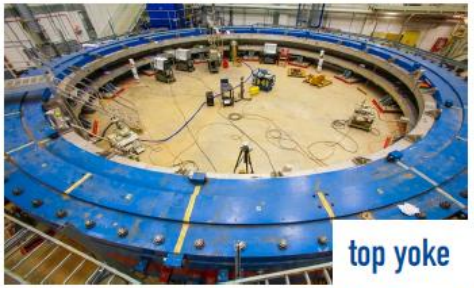


g-2 Magnet in Cross Section

Results of Shimming the Magnet

FNAL
BNL





Fermilab

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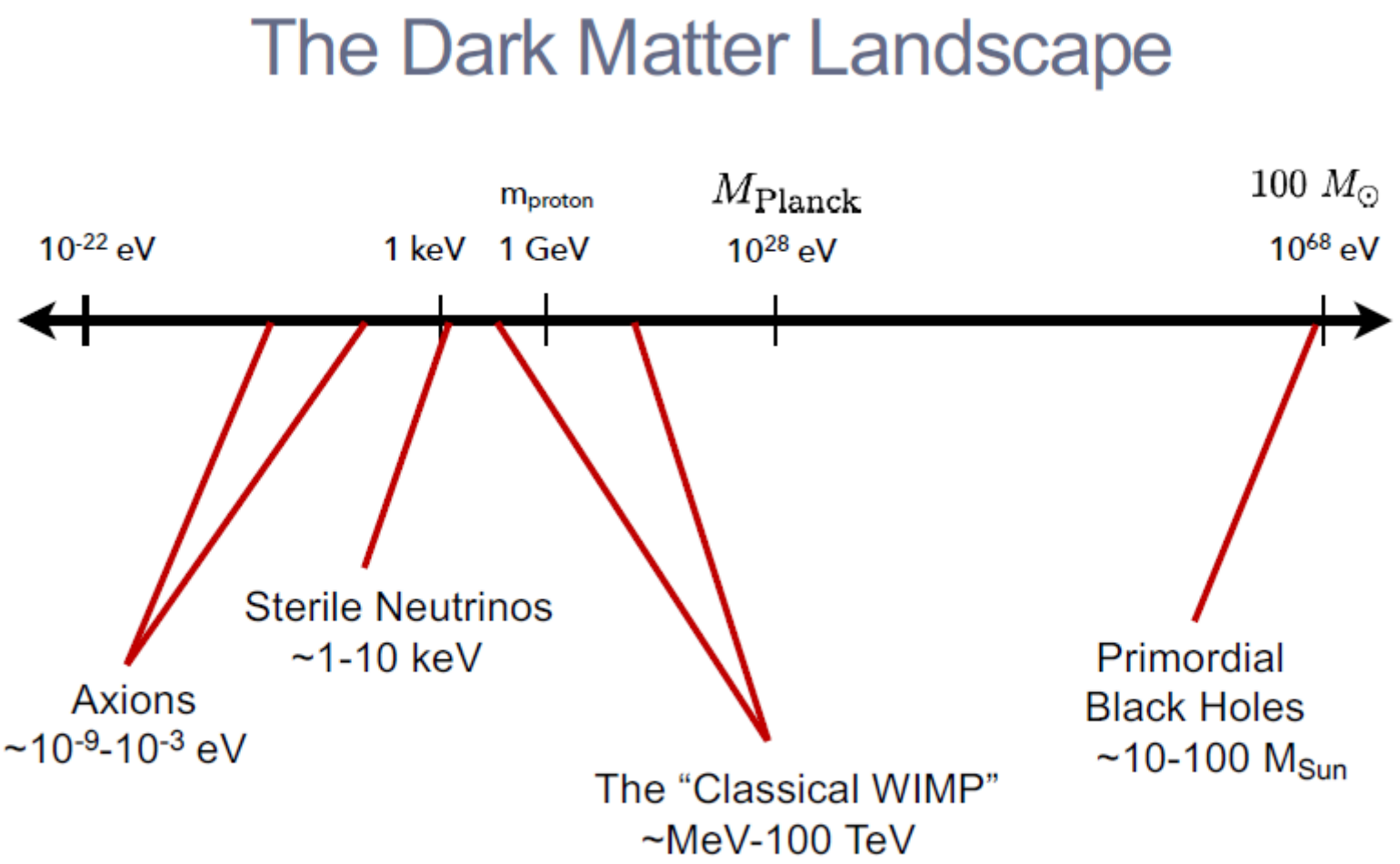
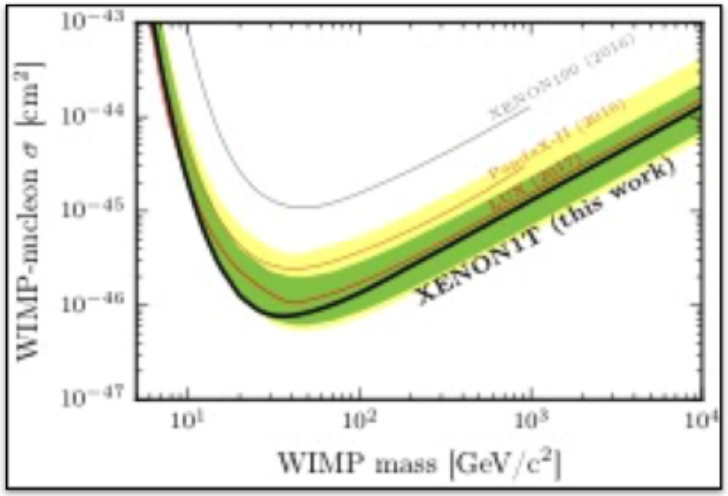
DARK MATTER

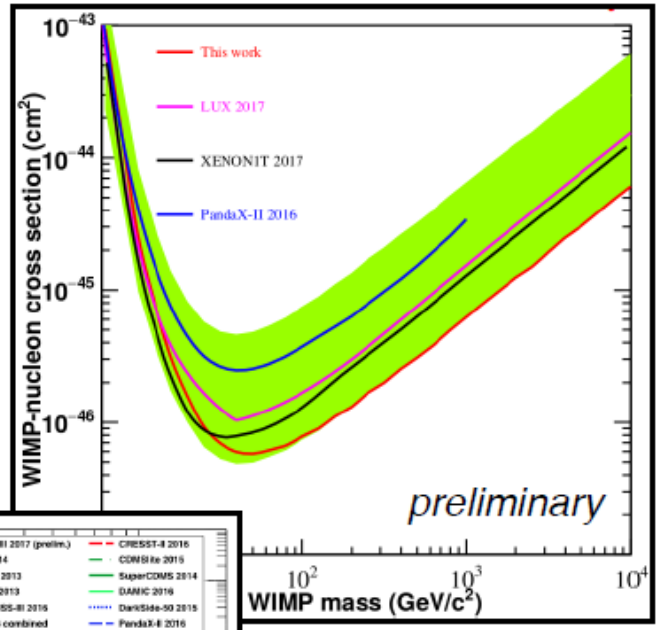
Dark Matter

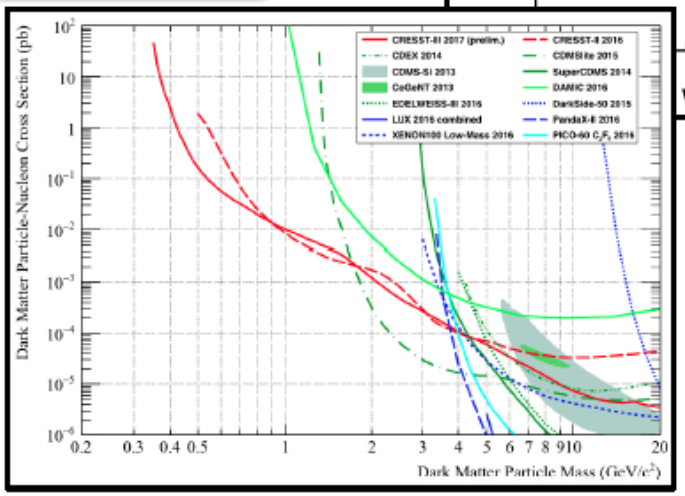

The Dark Matter Landscape
10^{-22} eV
1 keV
m_{proton}
1 GeV
M_{Planck}
10^{28} eV
100 $M_\odot$
10^{68} eV
Axions
~10^{-9}-10^{-3} eV
Sterile Neutrinos
~1-10 keV
The "Classical WIMP"
~MeV-100 TeV
Primordial
Black Holes
~10-100 M_{Sun}

Dark Matter

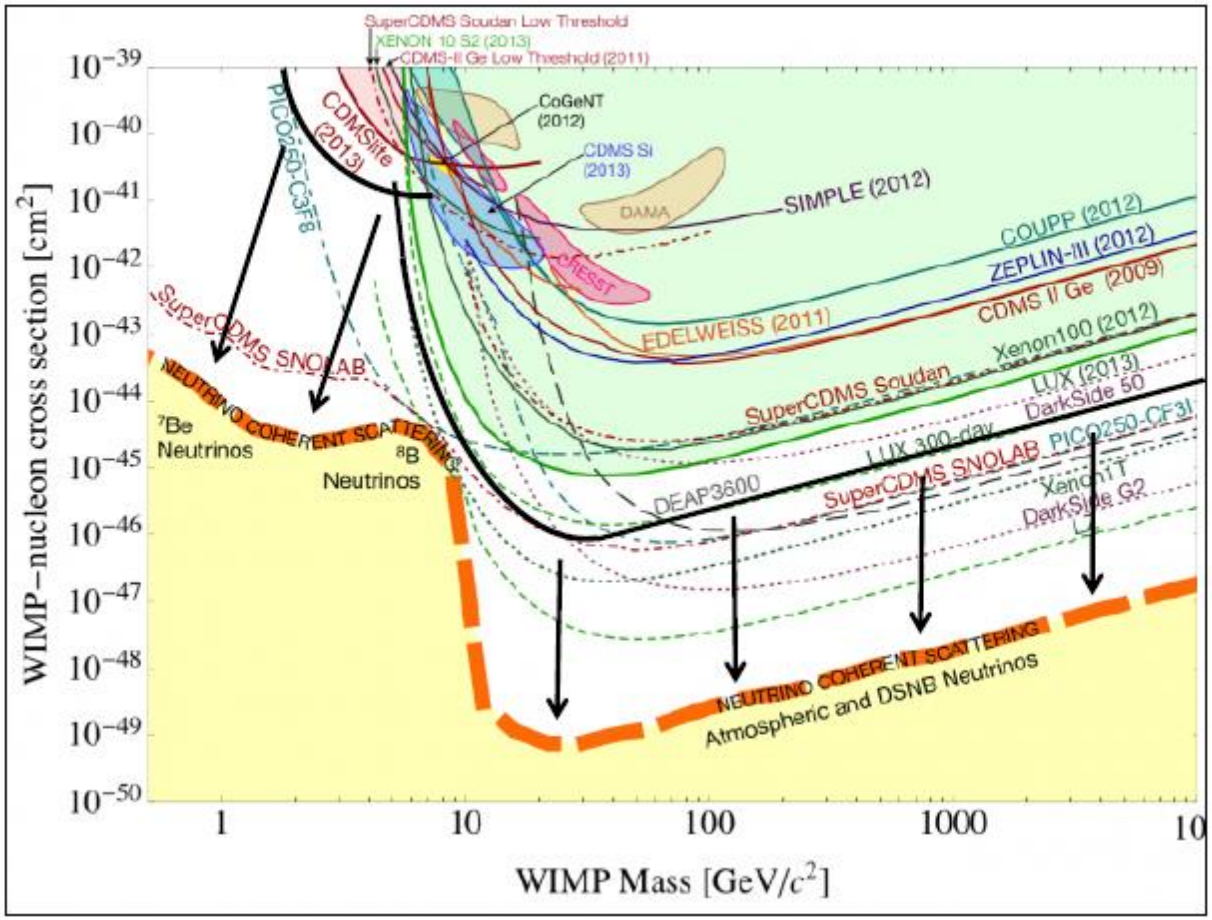
Recent Results From XENON1T, PandaX-II, CRESST-III







The Future of Direct Detection



Dark Matter

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams

3) Interaction which suppress elastic scattering with nuclei by powers of velocity or momentum

4) Dark matter that is lighter than a few GeV (evading direct constraints)

5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

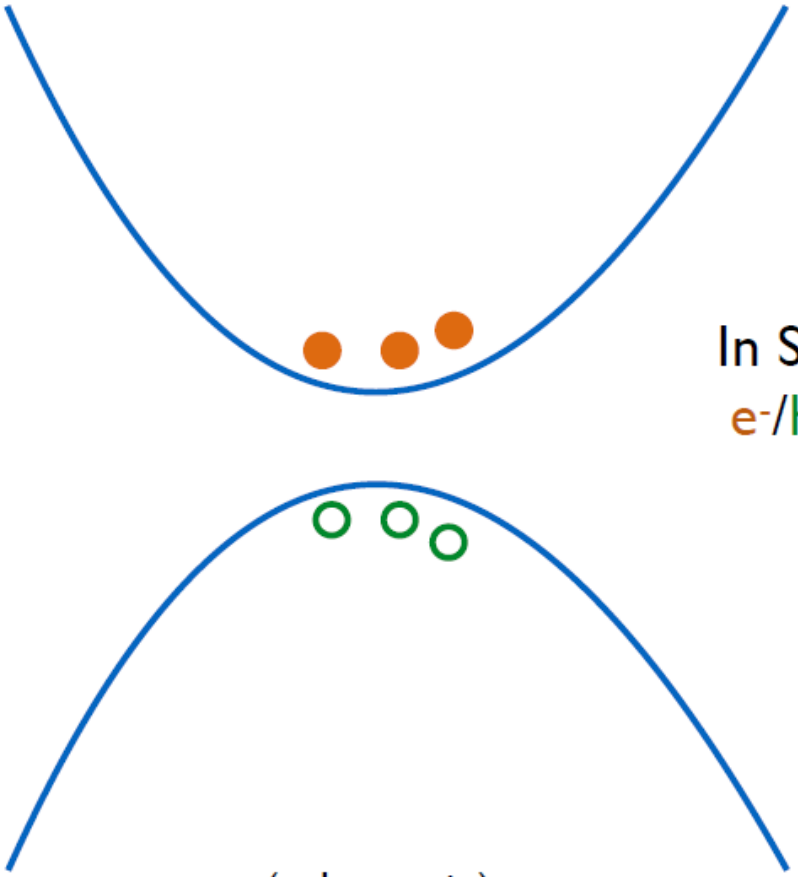
6) The dark matter annihilates to unstable non-Standard Model states (*ie*. hidden sector models)

Although potentially invisible to both underground detectors and colliders, many of these scenarios are testable with indirect searches

In this sense, the lack of such signals has strengthened the motivation for gamma ray, cosmic ray and neutrino searches for dark matter

SENSEI detector

A dark matter event in silicon



(schematic)

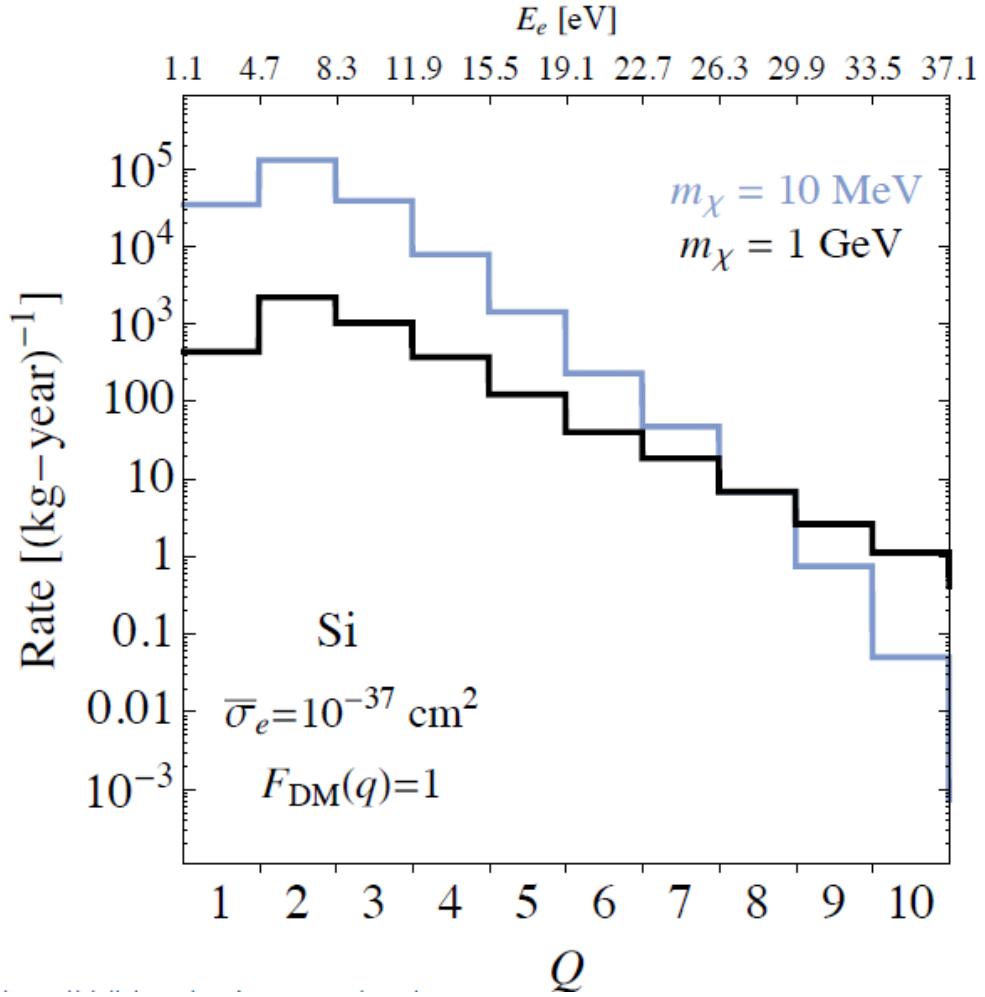
In Si, create one additional e^-/h^+ pair for each 3.6 eV of recoil energy

here Q = 3

D

SENSEI detector

Rates increase dramatically for lower Q



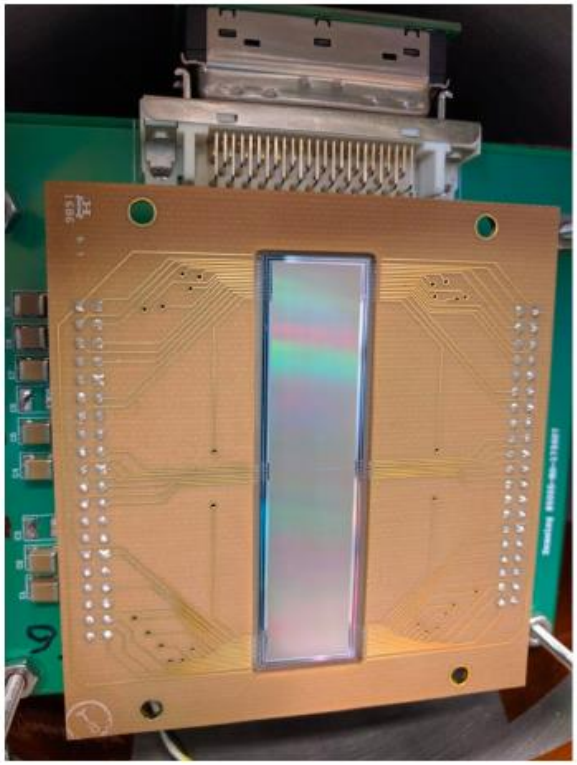
RE, Fernandez-Serra, Mardon, Soto, Volansky, Y

Best threshold for a Si detector before June 2017: ~ 11e^- (40 eV)

A recent technological breakthrough enables much lower thresholds: SENSEI

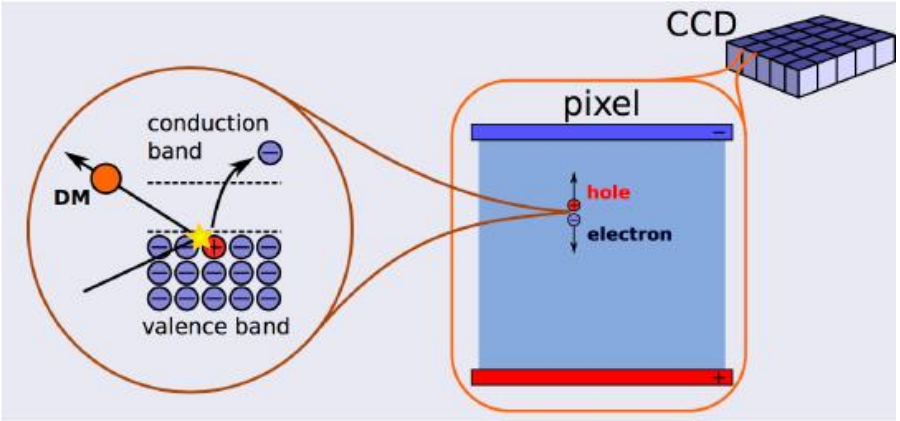
SENSEI detector

SENSEI's target material are special silicon CCDs



~million pixels

"Skipper CCDs"



SENSEI detector

Skipper CCD

- has a modified readout stage that allows multiple sampling of the same pixel without corrupting the charge packet:

$$\text{pixel value} = \frac{1}{N}\sum_{i}^{N}(\text{pixel sample})_i$$

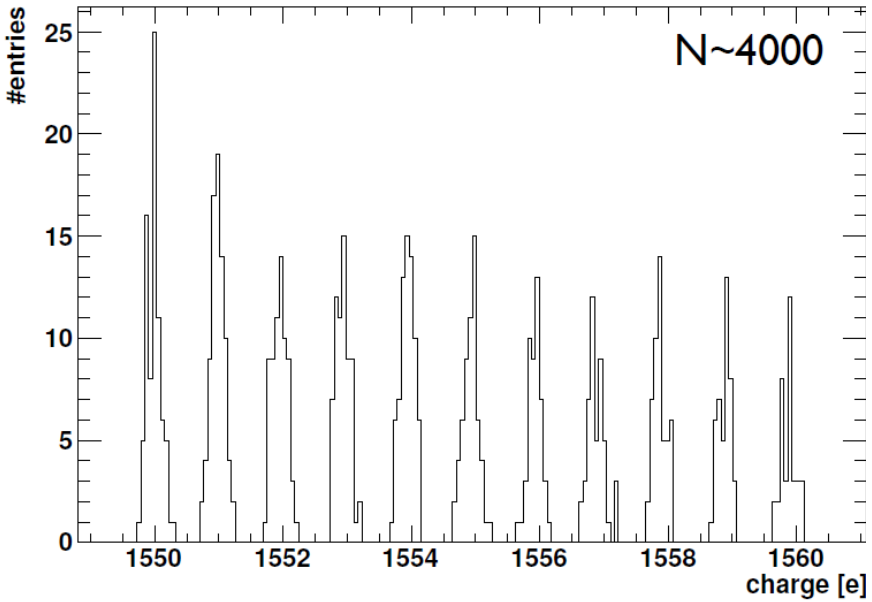
- developed in collaboration with LBNL MicroSystems Lab
- successfully demonstrated in a Fermilab LDRD project (2016)

Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

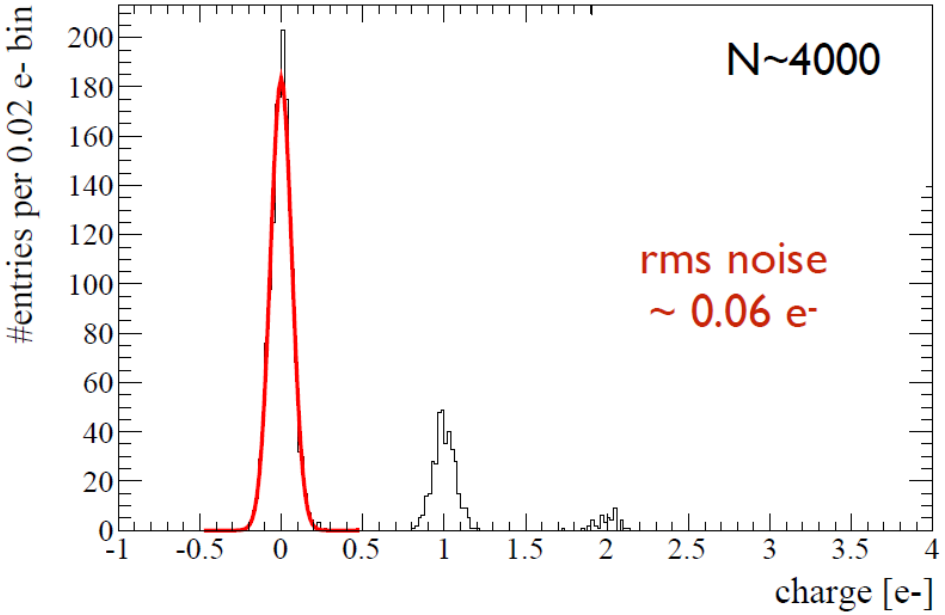
Achieved rms noise ~ 0.06 e^- $\Longrightarrow$ Dramatic reduction in threshold!

SENSEI detector

Counting Electrons

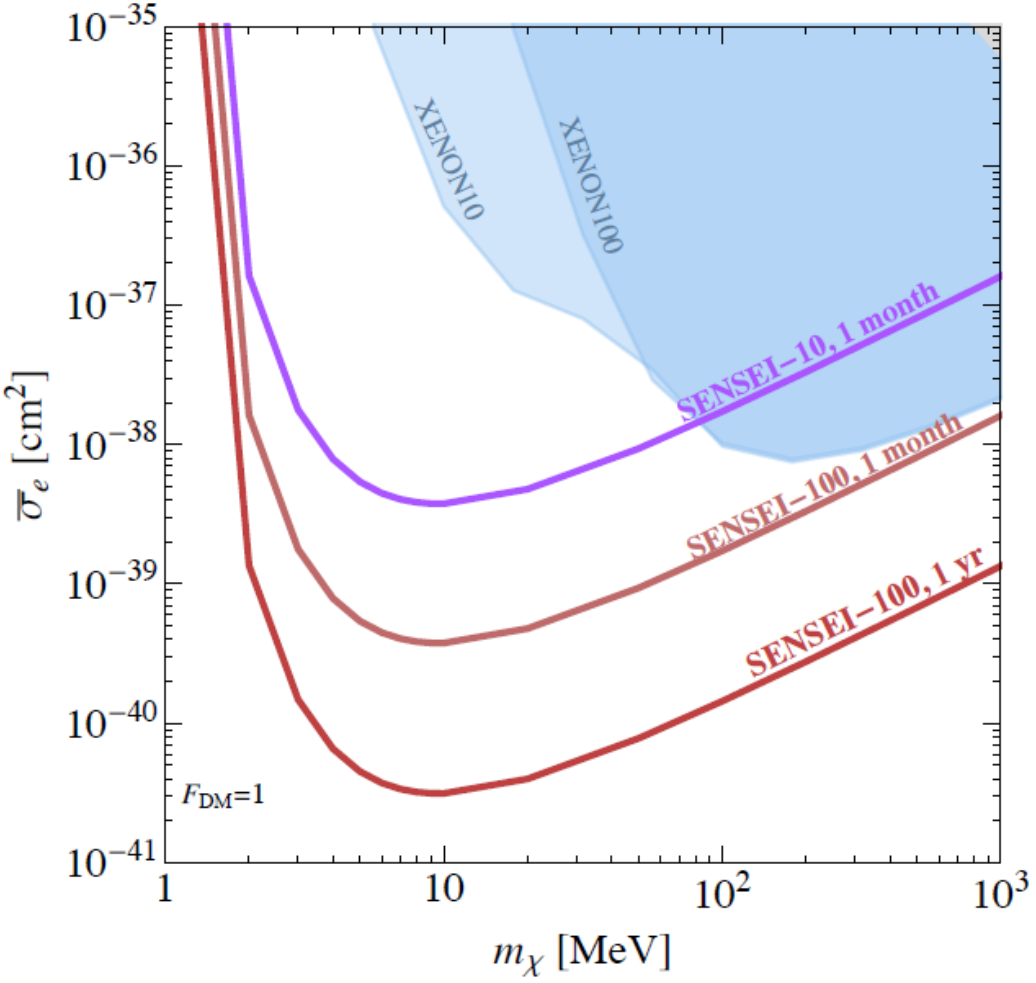


Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, I



SENSEI detector

SENSEI projections

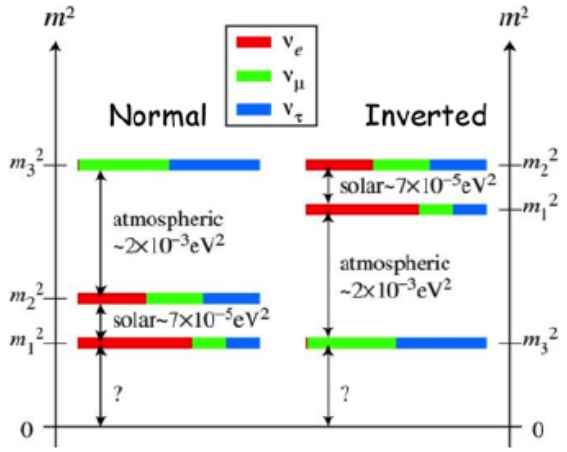


heavy mediator

NEUTRINOS

Still many profound unknowns

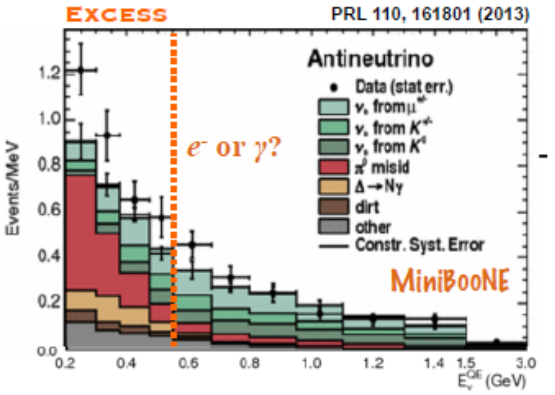
- Are there more than 3 neutrino flavors?
  — do light sterile neutrinos exist?
- Is CP violated in the leptonic sector?
  — understanding matter - anti-matter asymmetry?
- What is the Neutrino mass hierarchy?
  — which neutrino is the lightest?



Several anomalies that don't fit in the 3 oscillation scenario:
A New Neutrino?

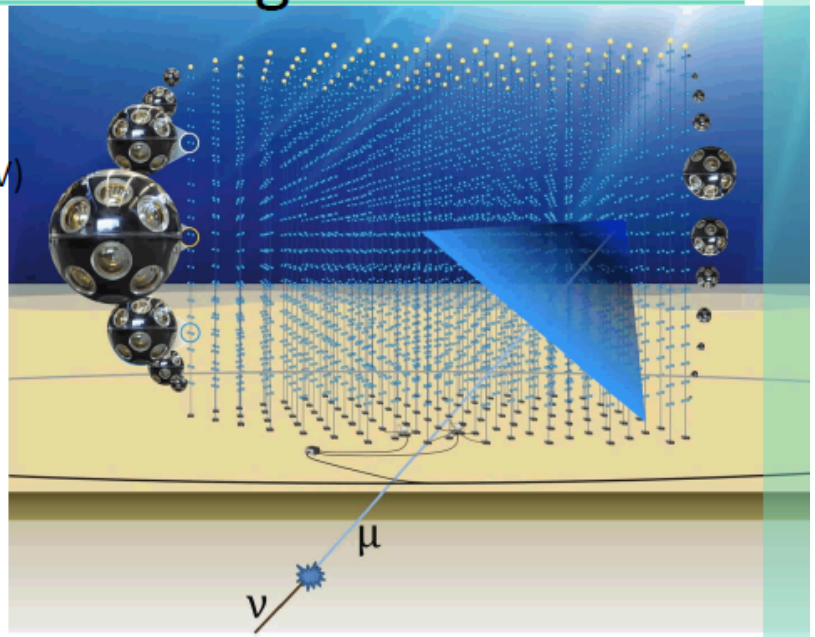
Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ

arXiv:1204.5379 (2012)



KM3NeT detector design

- Detection principle Optical Cherenkov radiation
- 6 orders of magnitude in energy (GeV-PeV)
- All flavour detection
- A 3D array built with a modular design
- **Optical sensor: multi-PMT (DOM)**
- **Detection units (DU): vertical slender strings host 18 DOMs**
- **Building blocks of 115 DUs each**
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Sea network of submarine cables and Junction Boxes connected to shore via a main e/o cable
- All data to shore



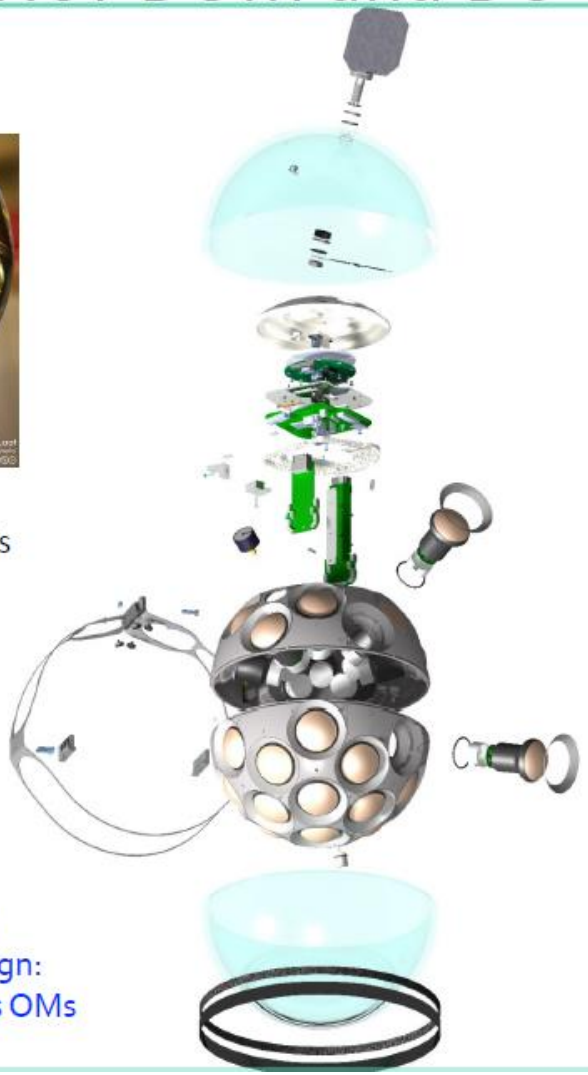
	ARCA	ORCA
Location	Italy	France
DU distance	90m	20m
DOM spacing	36m	9m
Instrumented mass	2*500Mton	5.7 Mton

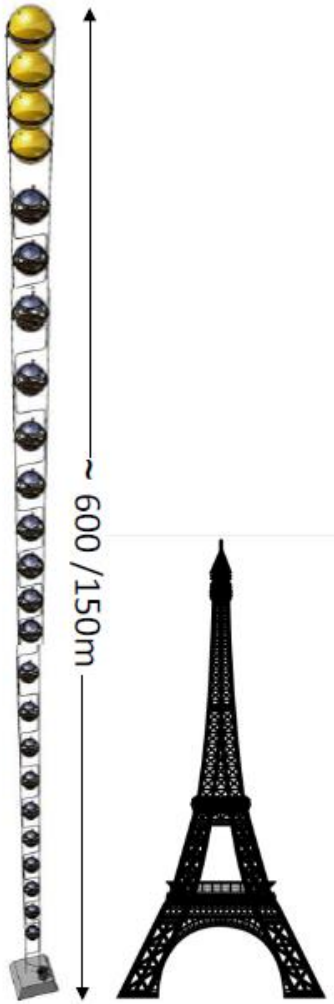
KM3NeT DOM and DU

Optical module

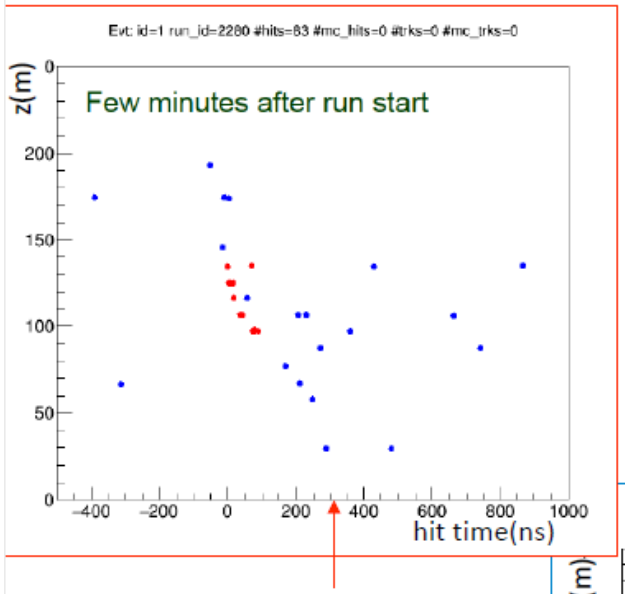
- 31 x 3" PMTs
- Light reflector rings around PMTs
- LED & acoustic piezo inside
- Tiltmeter/compass
- Gbit/s fibre DWDM
- Hybrid White Rabbit

- Digital photon counting
- Directional information
- Wide angle of view
- Improved background rejection
- Compact and cost effective design:
  1 DOM equivalent to 3 Antares OMs

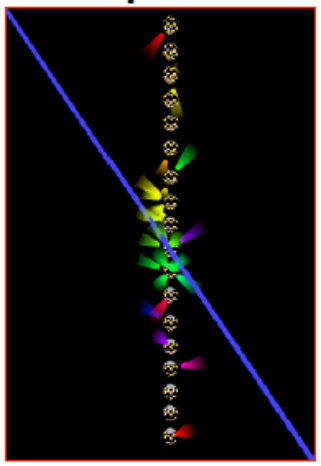


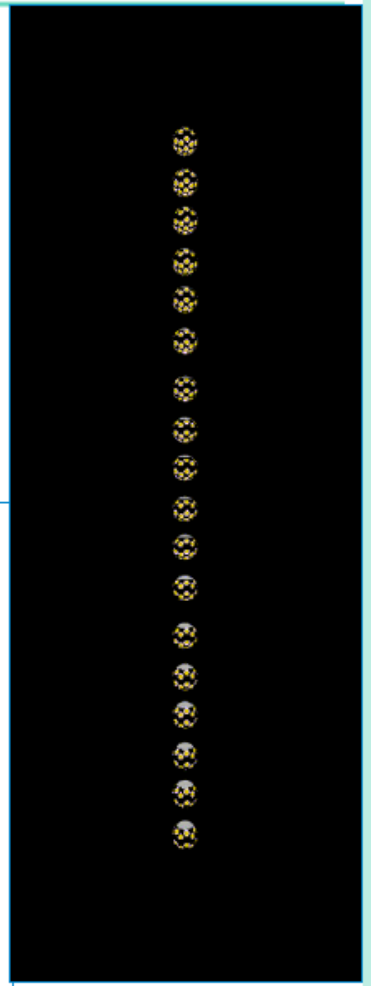


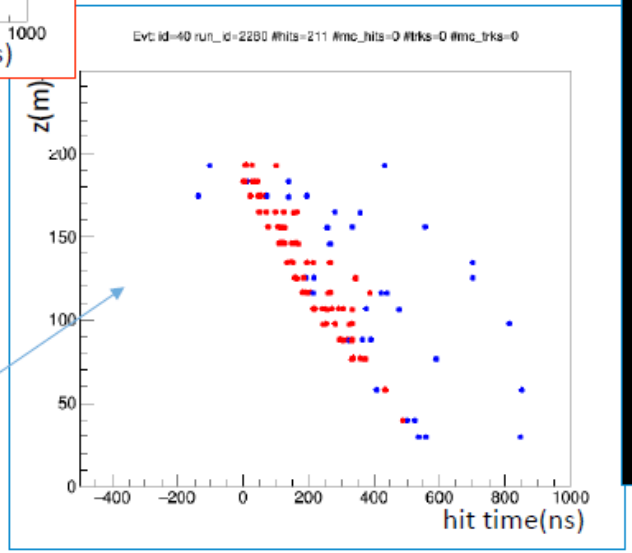
First ORCA DU preliminary results



First event with recorded track reconstructed by ORCA (down-going muon)

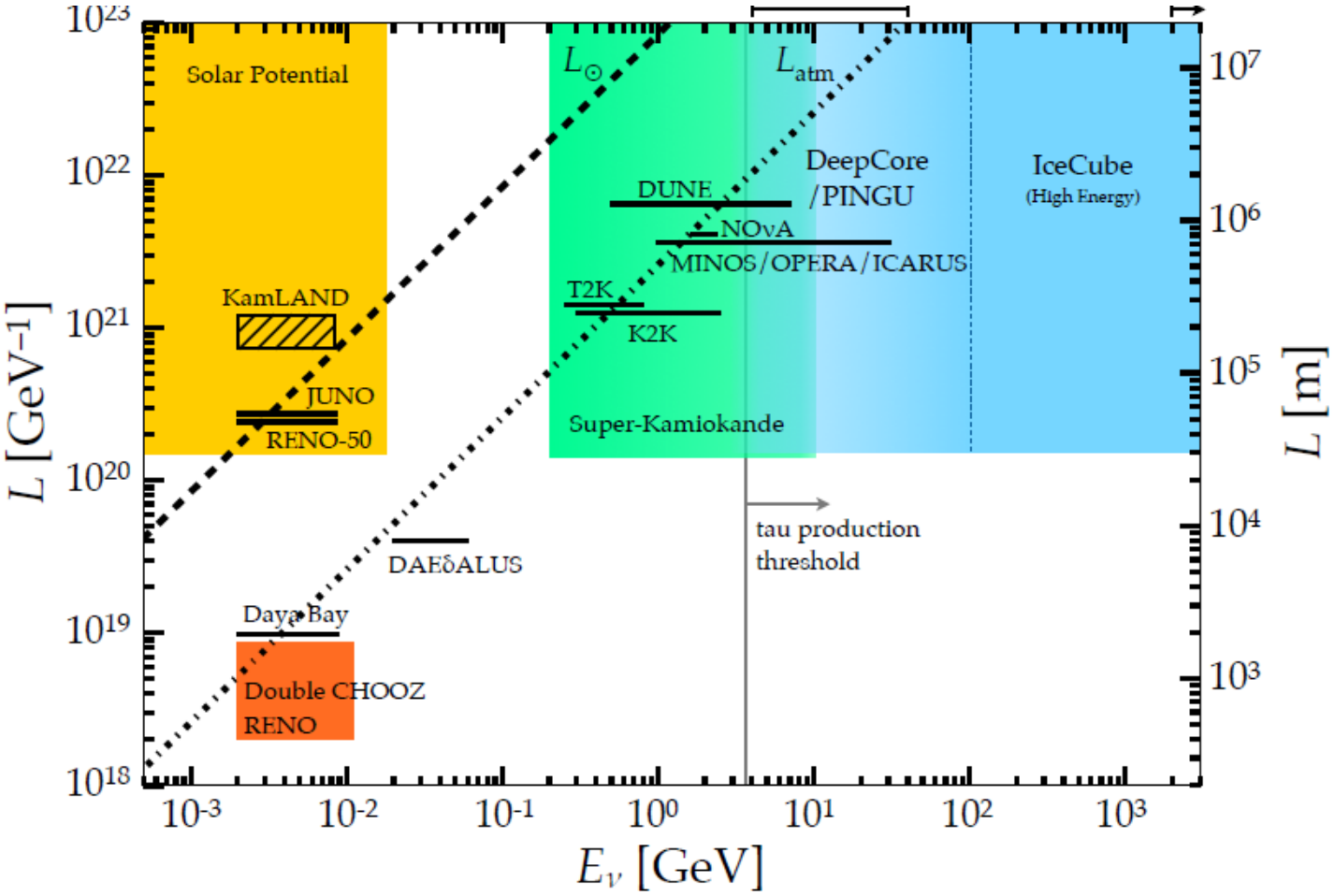






A bright muon bundle

IceCube

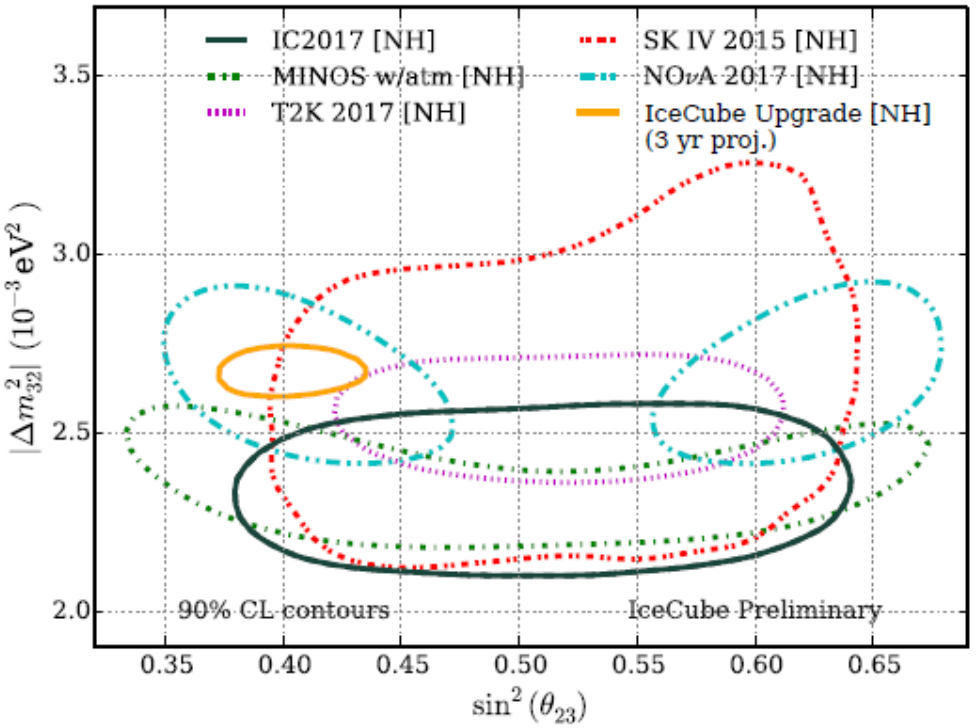


IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments – essential for constraining new physics

Atmospheric Oscillation Parameters

arXiv:1707.07081, *Phys. Rev. Lett.* 120, 071801 (2018)

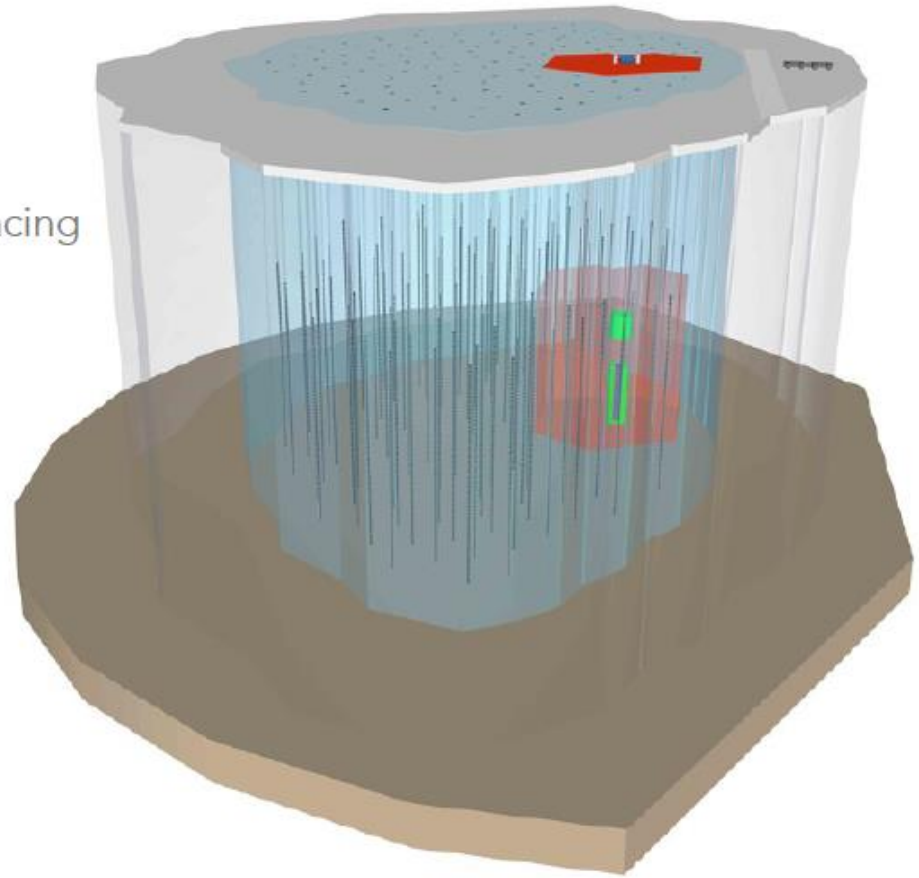
- Currently unclear whether $\sin^2\theta_{23}$ is maximal
  - 3rd mass state made up of equal parts ν_μ, ν_τ
  - Evidence of new symmetry?
- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at 2.6σ*



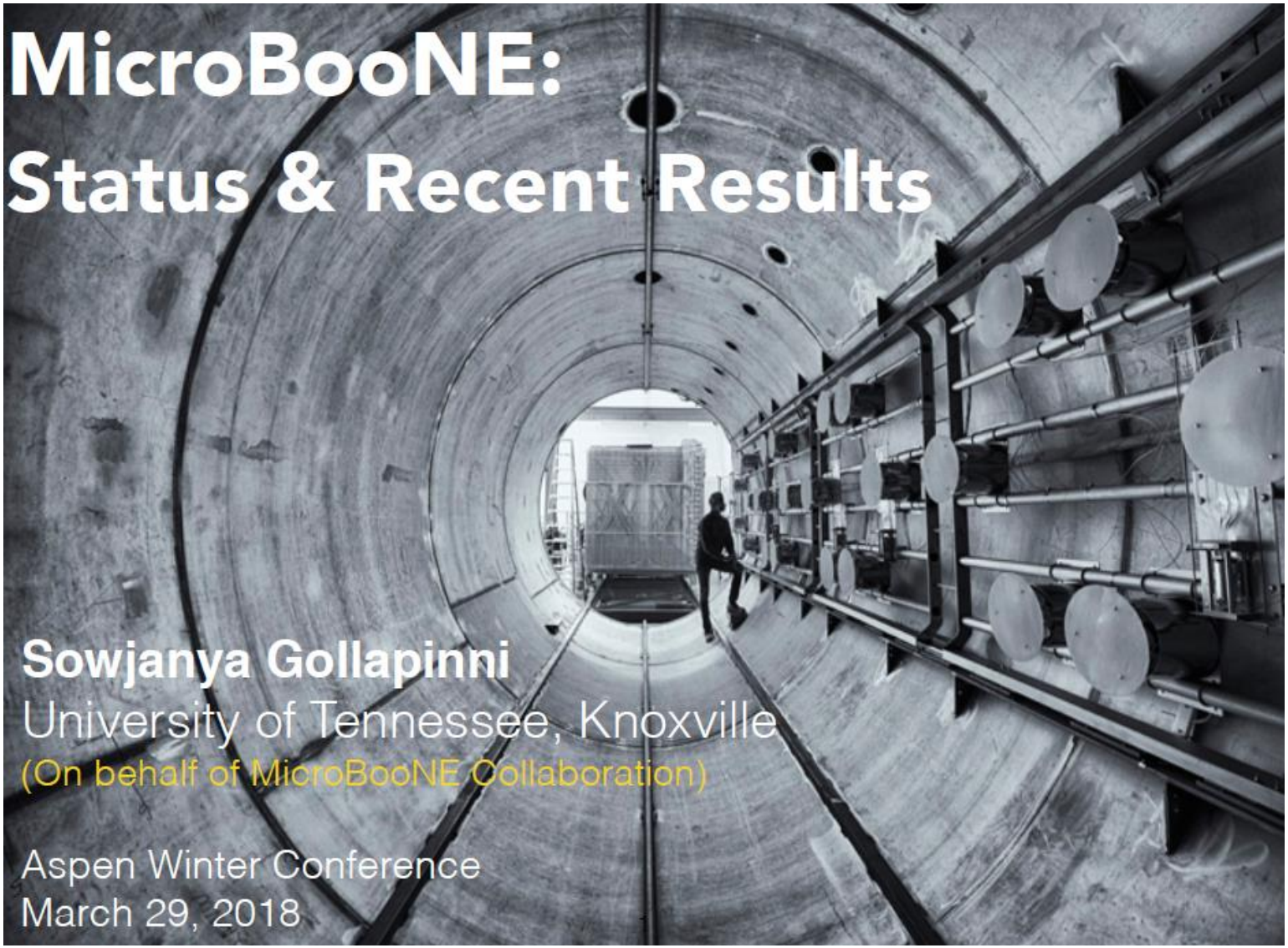
- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)

The Future: IceCube-Gen2

- High Energy Array
  - 120 strings x 80 sensors/string
  - ~8 km^3 volume, wider string spacing
- PINGU
  - Low energy infill
  - 26 strings (incl. IC Upgrade)
- Also investigating surface arrays, UHE radio detection
- Cost scale similar to IceCube

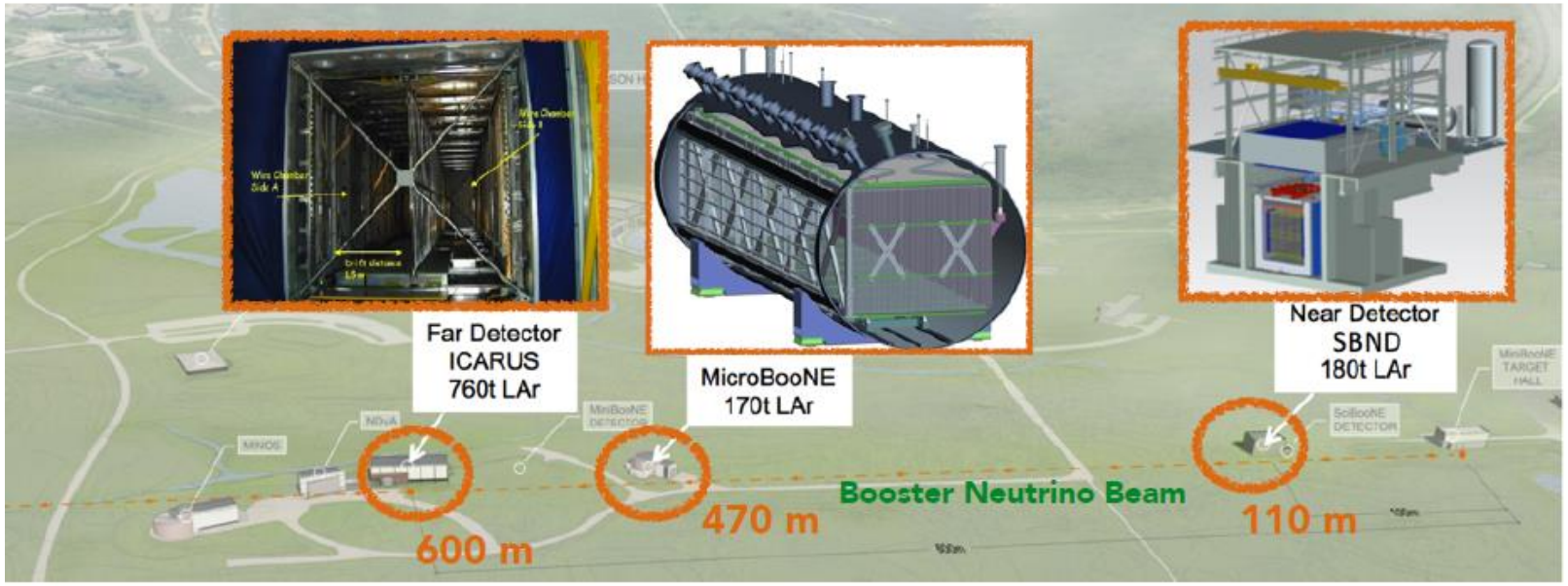


MicroBoone

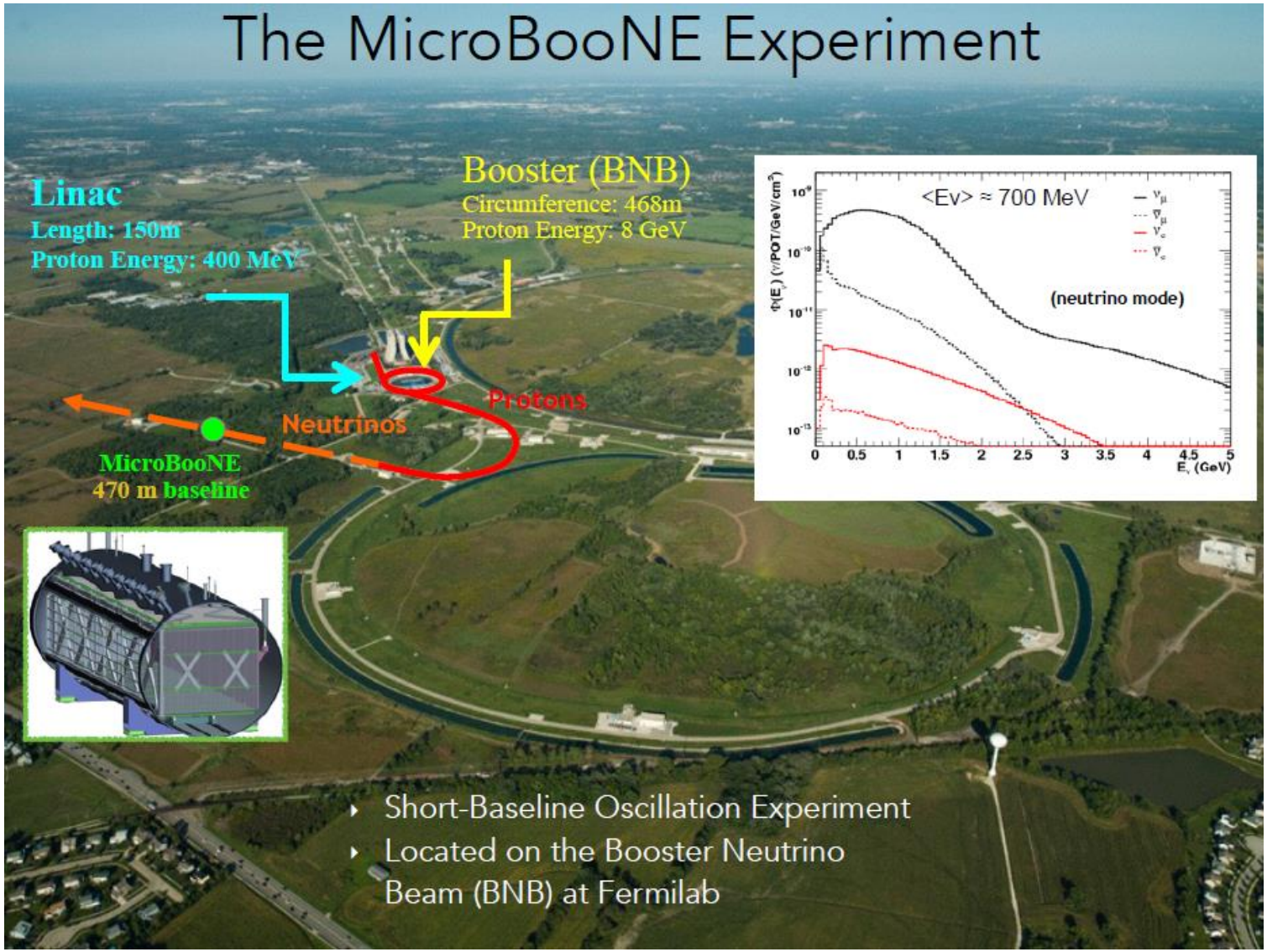

MicroBooNE:
Status & Recent Results
Sowjanya Gollapinni
University of Tennessee, Knoxville
(On behalf of MicroBooNE Collaboration)
Aspen Winter Conference
March 29, 2018

The Short-Baseline Neutrino Program

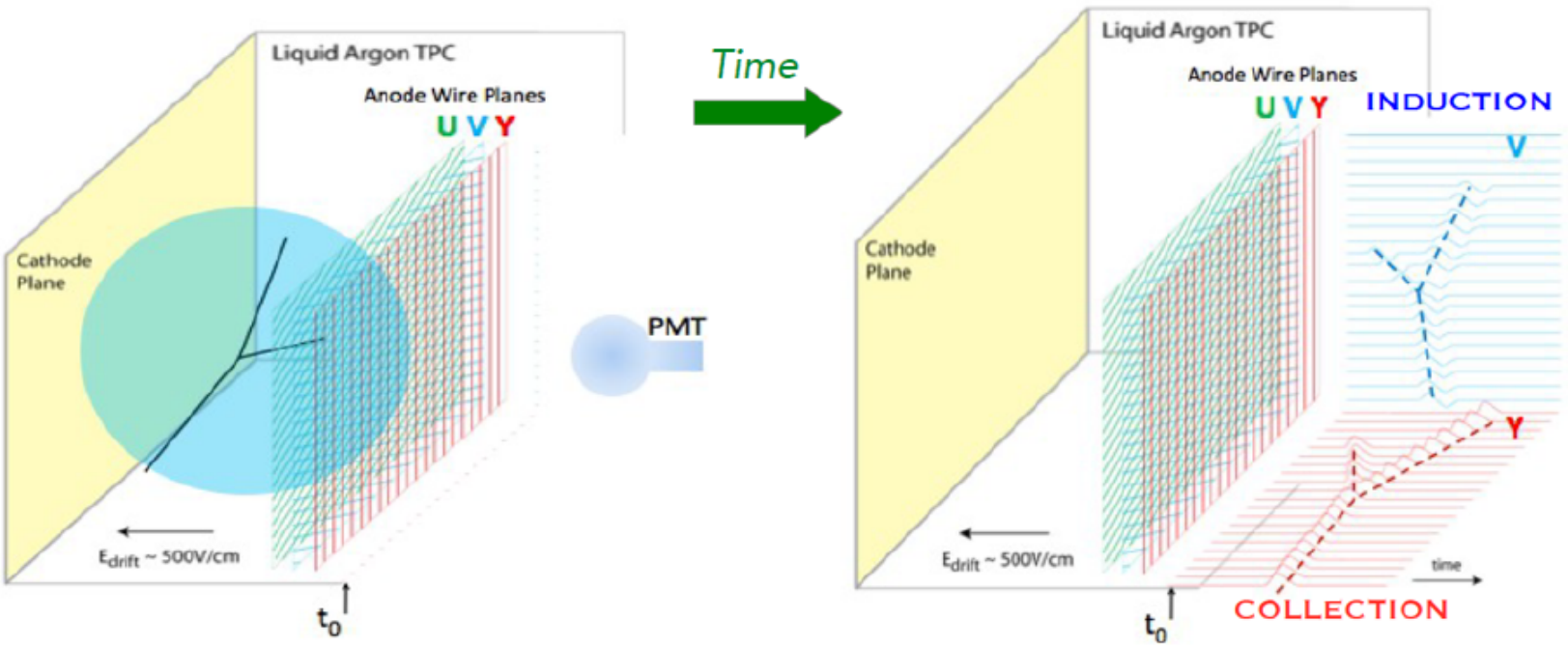
- MicroBooNE is paving way for the three-detector SBN program to more definitively address the sterile neutrino question where we have existing hints
  - Well understood BNB beam
  - Same detector technologies, same beam = reduced systematics!



MicroBoone


The MicroBooNE Experiment
Linac
Length: 150m
Proton Energy: 400 MeV
Booster (BNB)
Circumference: 468m
Proton Energy: 8 GeV
Protons
Neutrinos
MicroBooNE
470 m baseline
<Ev> ≈ 700 MeV
(neutrino mode)
E, (GeV)
Short-Baseline Oscillation Experiment
Located on the Booster Neutrino Beam (BNB) at Fermilab

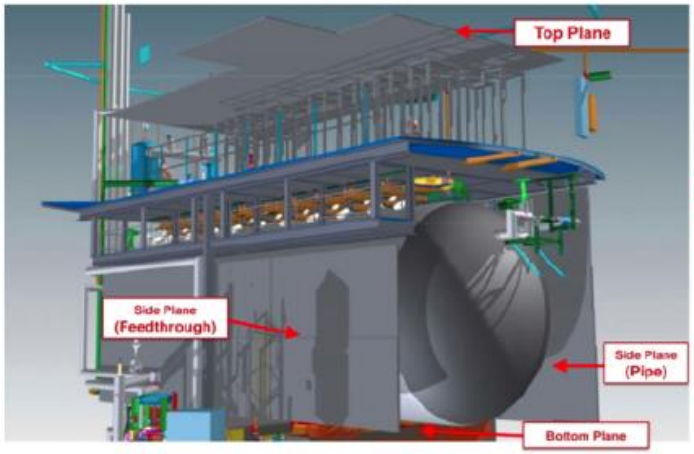
The LArTPC Principle

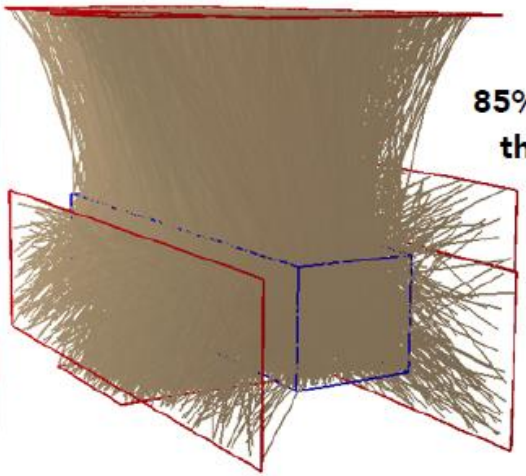


- Argon makes a desirable target (dense, abundant,…)
- Two signals: Ionization signal & Scintillation light
- Finely (mm-scale) segmented anode wires — excellent resolution!
- Bubble chamber quality images in HD!
- Technology allows for scalability — can build massive detectors

Wire Planes + Signal Arrival Time = 3D Image

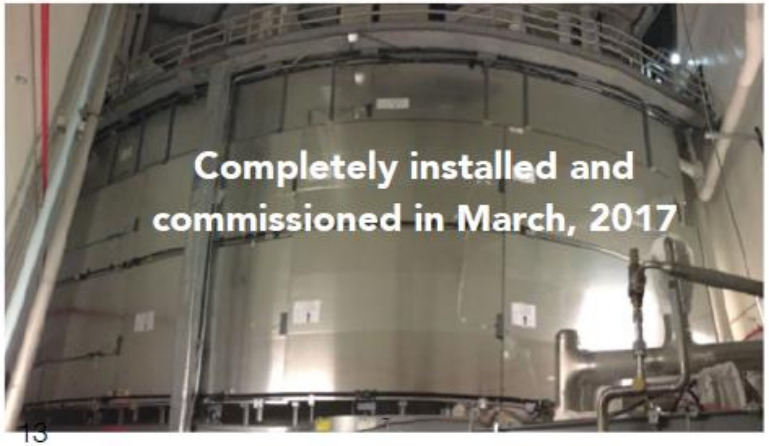
Upgrades: Cosmic Ray Tagger System





85% coverage for through-going muons

- Plastic Scintillator Modules & SiPM readout
- Design & Construction paper under preparation for JINST
- Currently developing matching techniques between TPC and CRT



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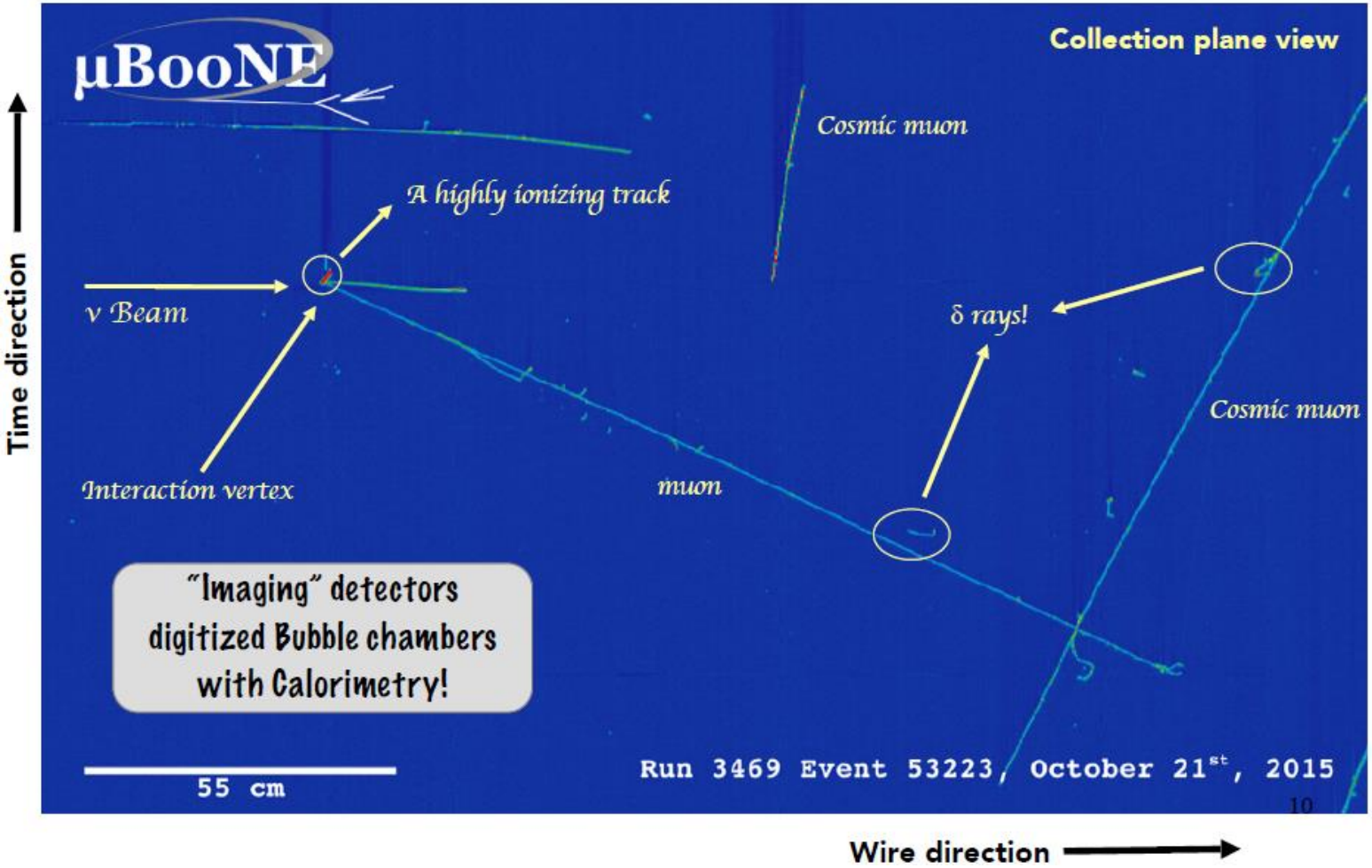
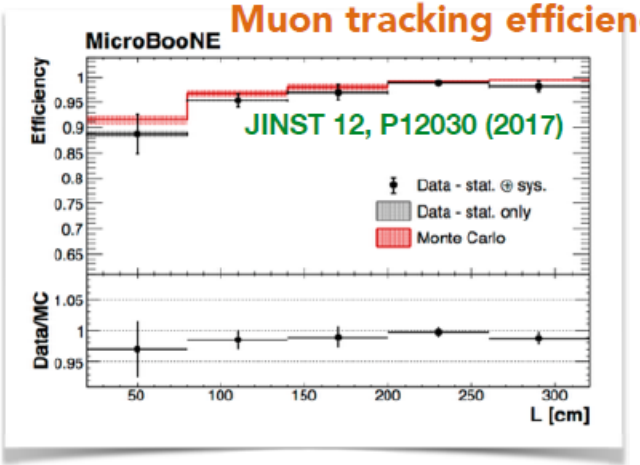
MicroBoone

A neutrino event in MicroBooNE LArTPC

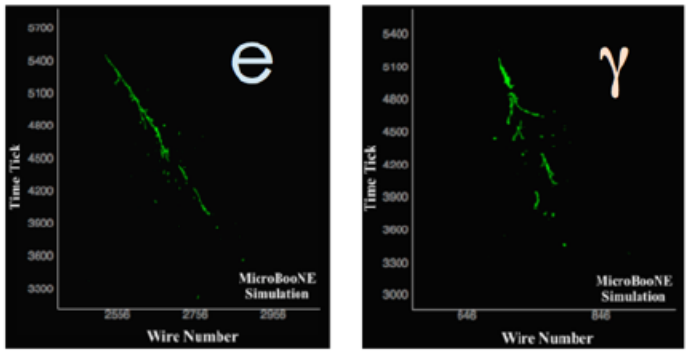


Reconstruction & Particle ID

Muon tracking efficiency

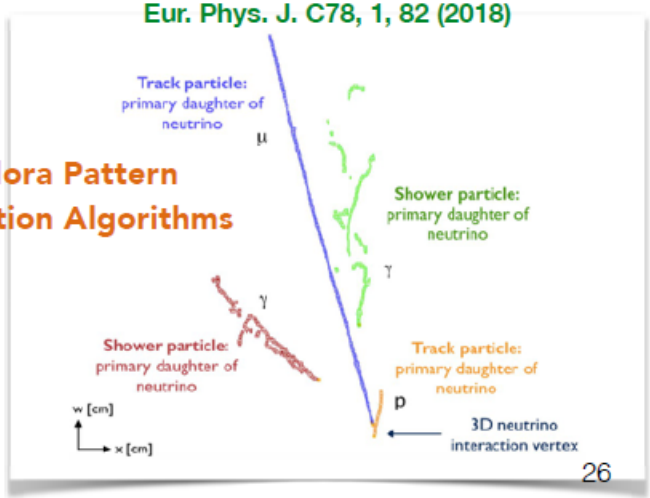


Deep Learning techniques

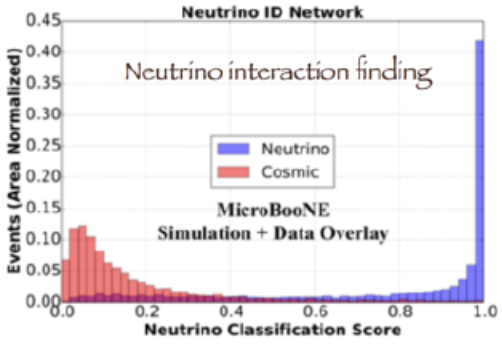


Pandora Pattern Recognition Algorithms

Eur. Phys. J. C78, 1, 82 (2018)



JINST 12, P03011(2017)



Developing multiple approaches for the flagship oscillation analysis

FLAVOUR

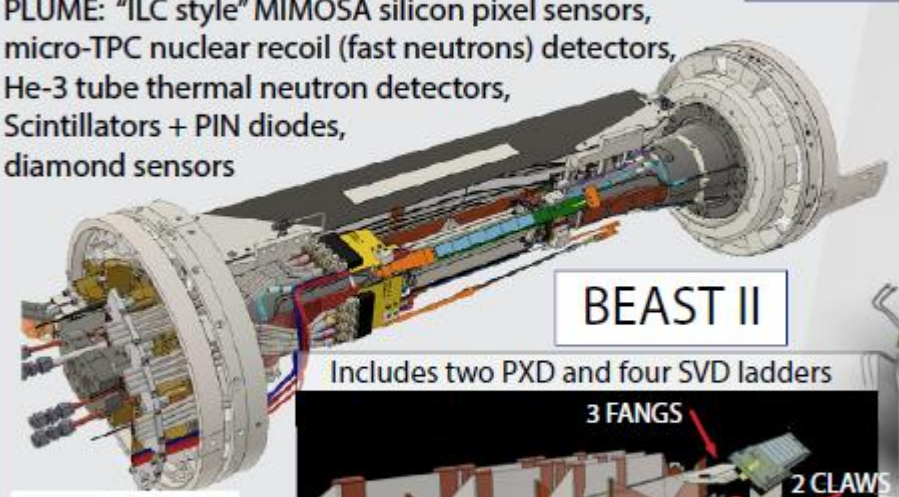
Belle II

BEAST II (Phase 2 Commissioning Detector inside Belle II)

A system of radiation detectors: beam background monitors, first responders

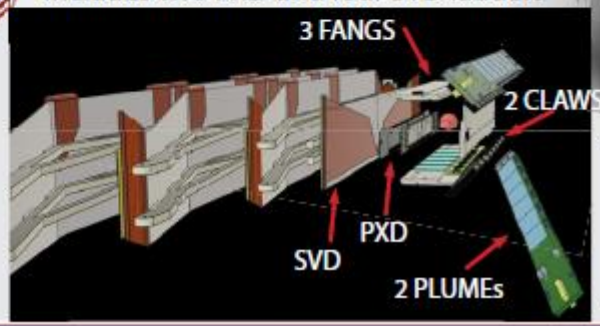
FANGS: "LHC/ATLAS style" silicon pixel sensors,
CLAWS: scintillator tiles read-out by silicon PMTs,
PLUME: "ILC style" MIMOSA silicon pixel sensors,
micro-TPC nuclear recoil (fast neutrons) detectors,
He-3 tube thermal neutron detectors,
Scintillators + PIN diodes,
diamond sensors

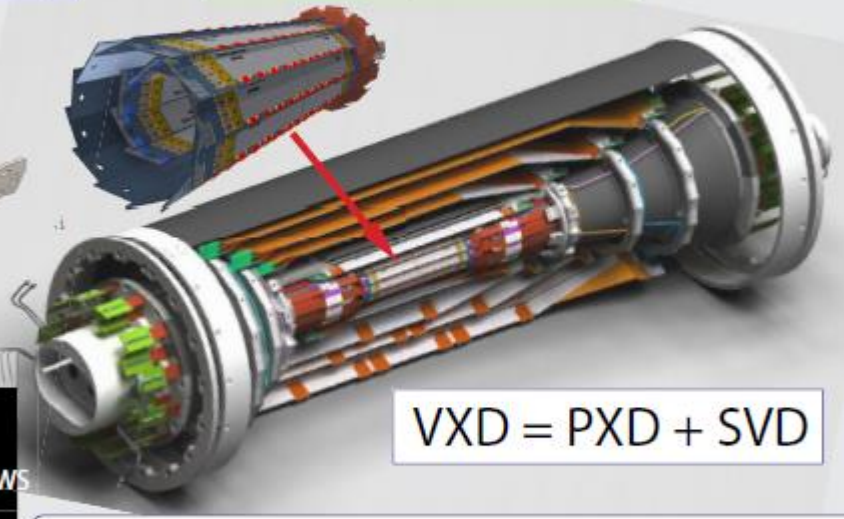
Now → End of 2018



BEAST II

Includes two PXD and four SVD ladders





VXD = PXD + SVD

Understanding beam-related backgrounds (and physics backgrounds!) is of great importance
There is only that much of radiation hardness...

Aspen 2018 - The Particle Frontier - March 25-31

Vladimir Savinov (University of Pittsburgh) on behalf of the Belle II Collaboration

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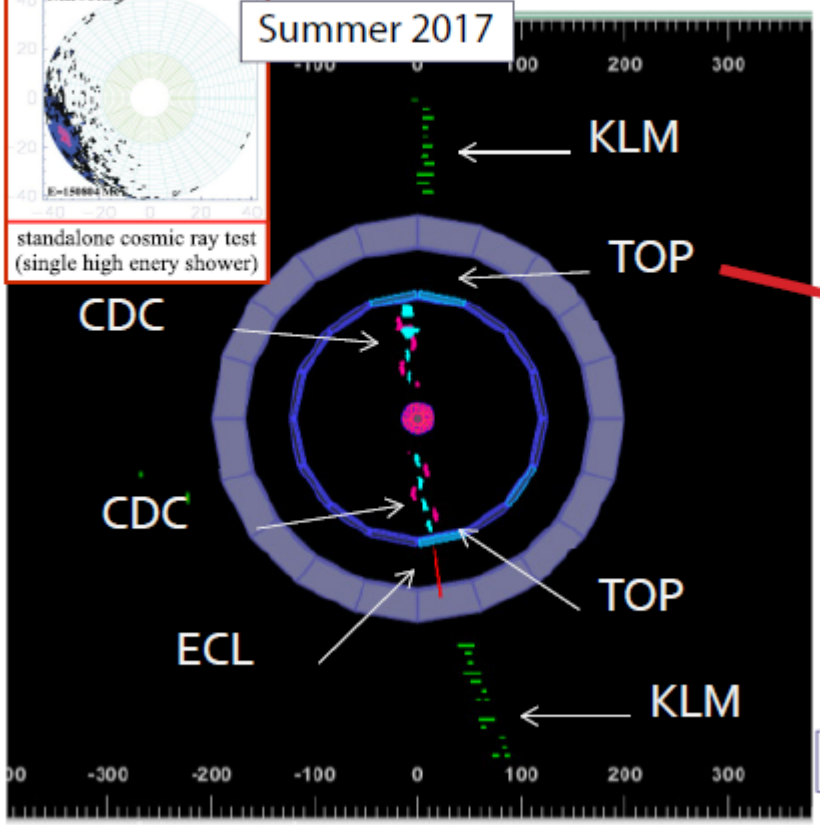
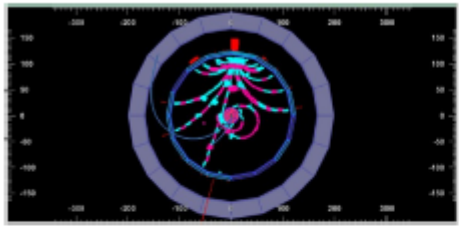
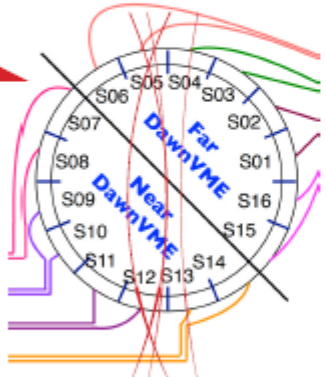
Belle II Had Been Recording Cosmic Events Until Recently

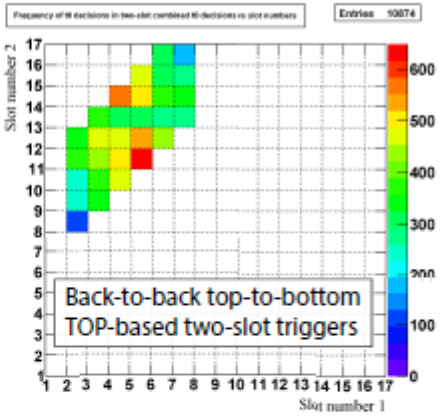
standalone cosmic ray test
(single high enery shower)



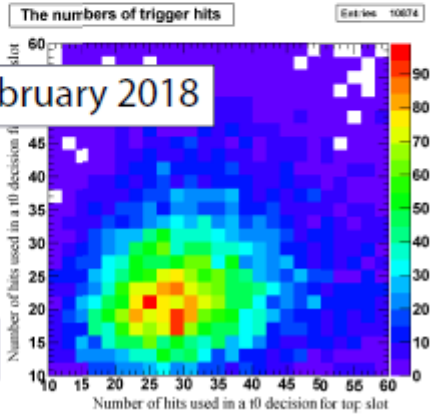




Beam view layout
of 16 TOP slots

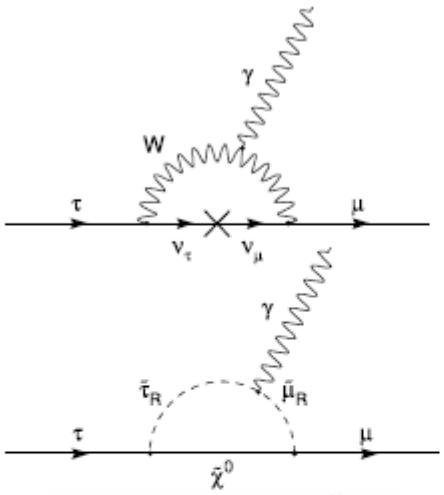


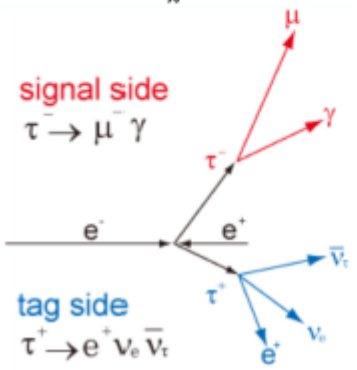
February 2018



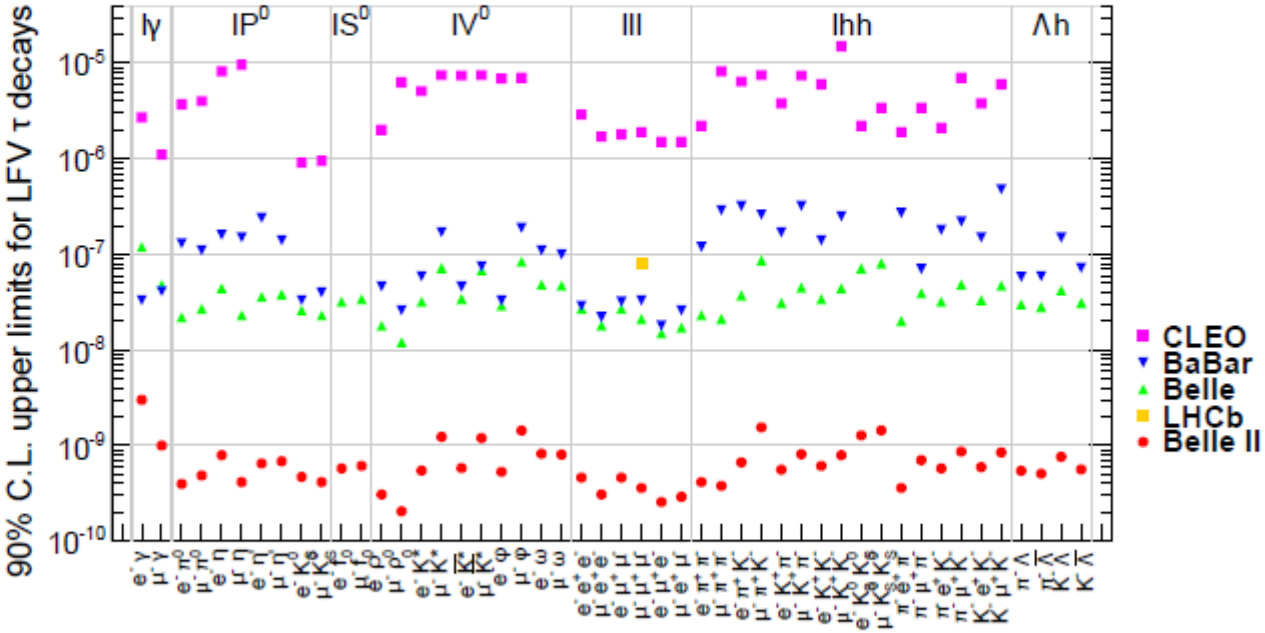
Clean standalone TOP triggering on cosmic muons

τ Leptons Provide a Unique Laboratory to Search for LFV





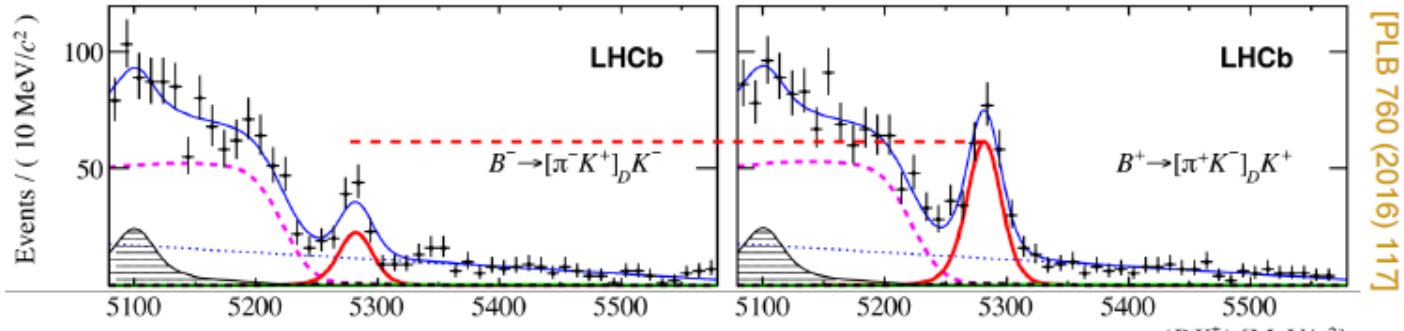
Upper limits for LFV τ decays with the full 50 ab^{-1} data sample at Belle II



B2TiP report / to be submitted to PTEP (2018)

CP violation - γ

Almost all the best channels for the determination of the CKM angle γ have now been analysed for run 1. For example, suppressed 'ADS' mode, $B^- \to (\pi^- K^+)_D K^-$ (+CC)



[PLB 760 (2016) 117]

Combination of LHCb B→DK results obtained so far

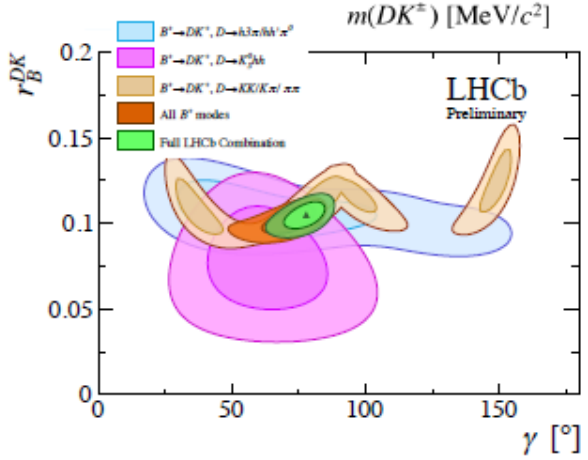
LHCb-CONF-2017-004

$$\gamma = (76.8\,^{+5.1}_{-5.7})^\circ$$

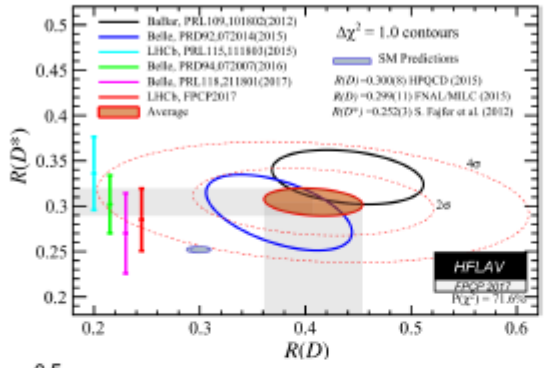
Uncertainty significantly better than that obtained with combined B-factory results.

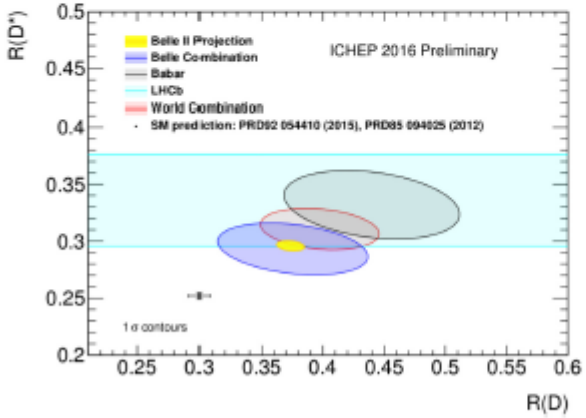
Agrees with prediction from rest of triangle

$$\gamma^{\text{indirect}} = (65.3\,^{+1.0}_{-2.5})^\circ$$



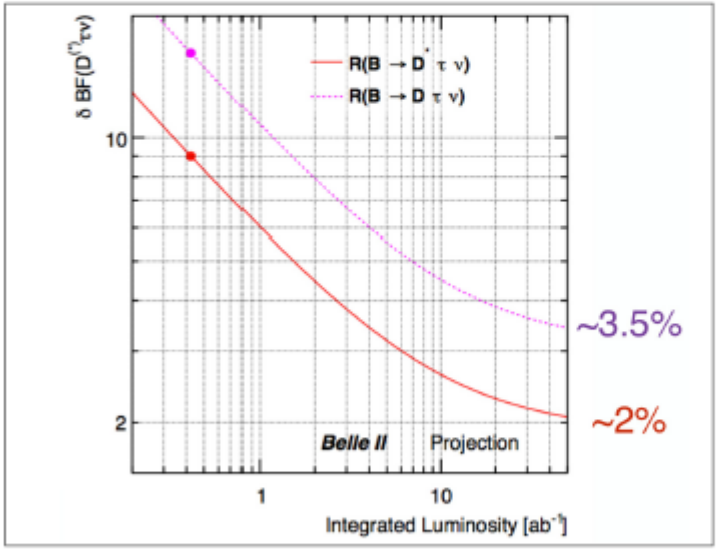
Flavor Anomaly in R(D) and R(D*)





$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

[τ helicity provides a handle to investigate the new (virtual) particle (if confirmed)]



If the current 4.1σ deviation is real, Belle II should be able to make a discovery with 5/ab (i.e. around 2021)

Aspen 2018 - The Particle Frontier - March 26-31

Vladimir Savinov (University of Pittsburgh) on behalf of the Belle II Collaboration

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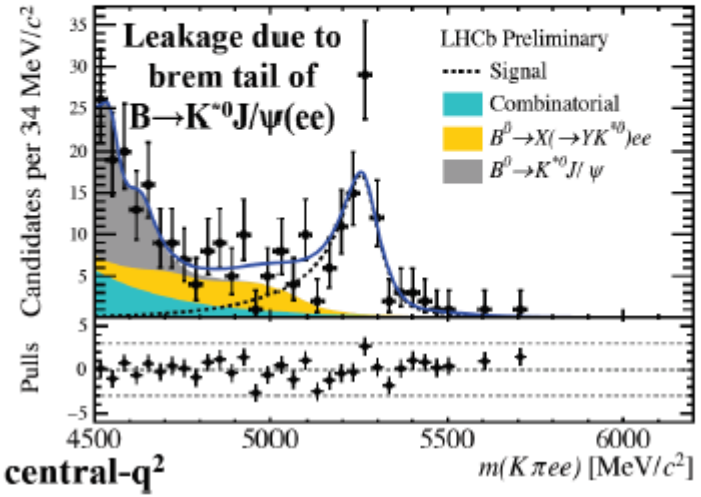
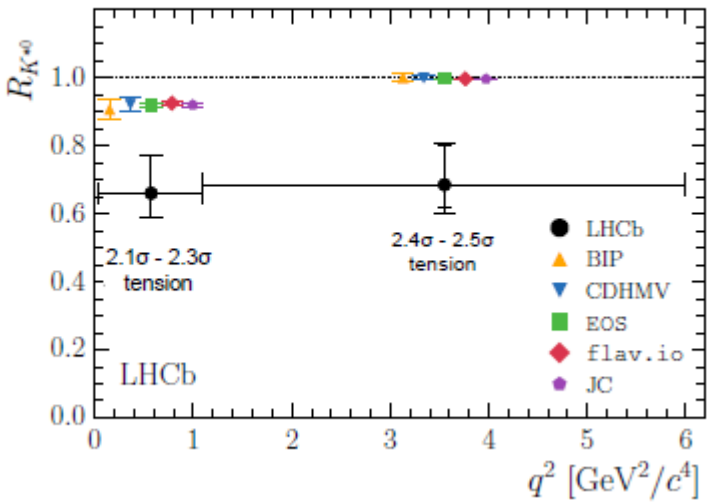
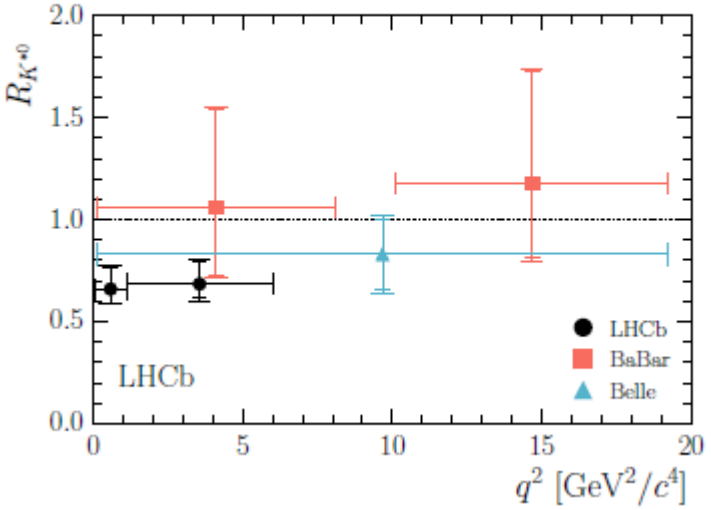
R(K*)

JHEP 08 (2017) 055



	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]





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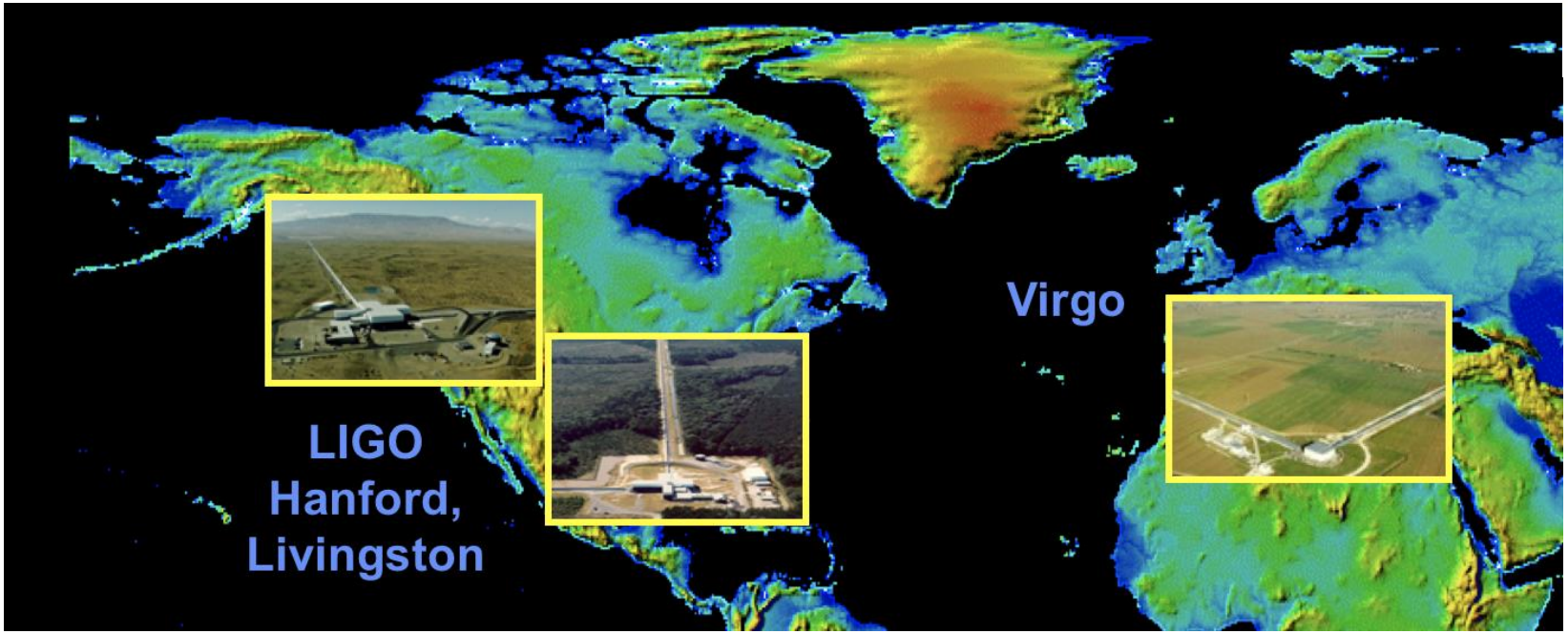
GRAVITATIONAL WAVES

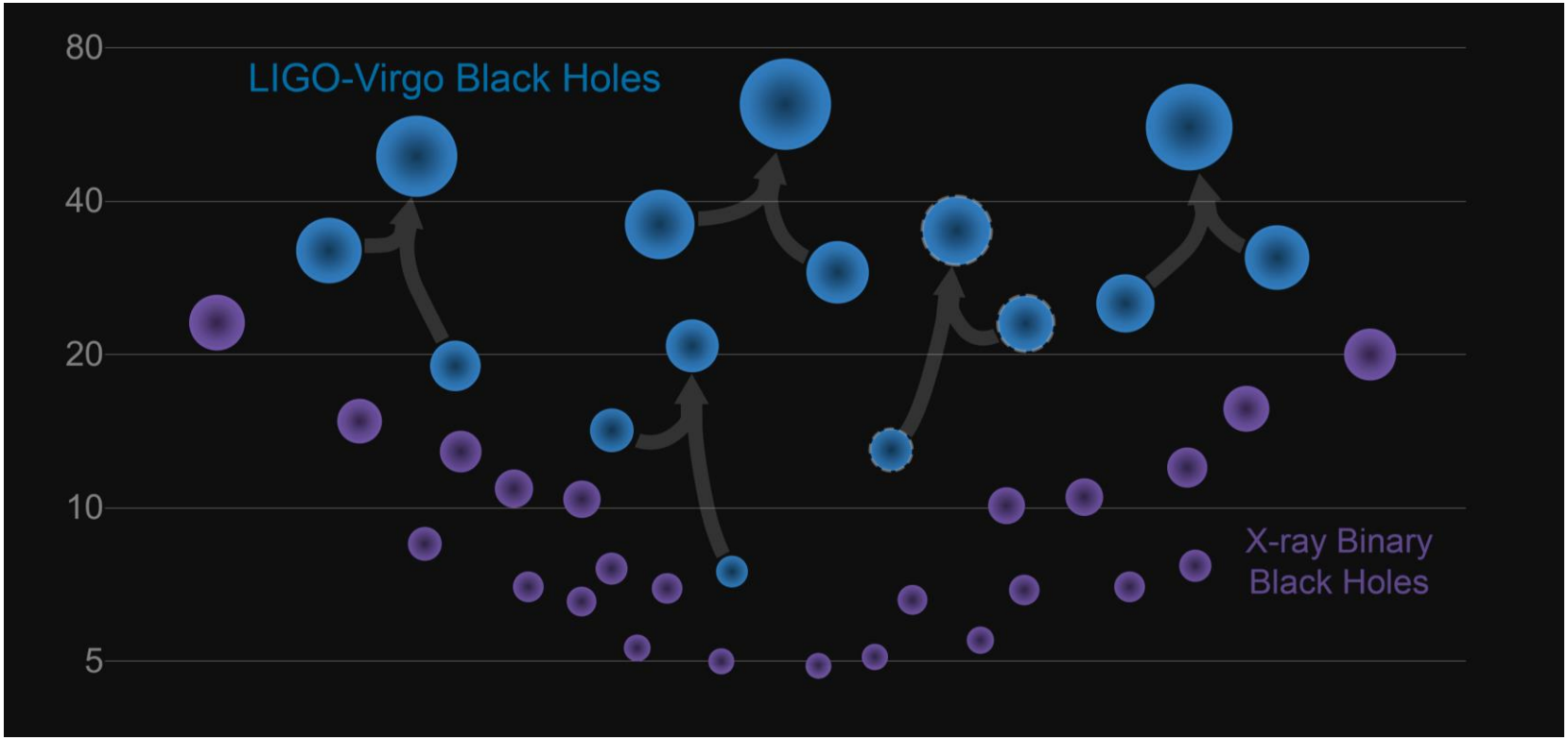
Ground based detectors



- Initial observatories, and instruments, constructed starting in mid-90's
  - **NSF Physics** for LIGO; Virgo's support from CNRS and INFN
- Observed, setting upper limits until 2011
- Both Virgo and LIGO undertook a complete rework of the instruments
- Advanced LIGO came on line in 2015 – First discovery 15 Sept 2015
- Advanced Virgo came on line in 2017 – First signal 14 August 2017

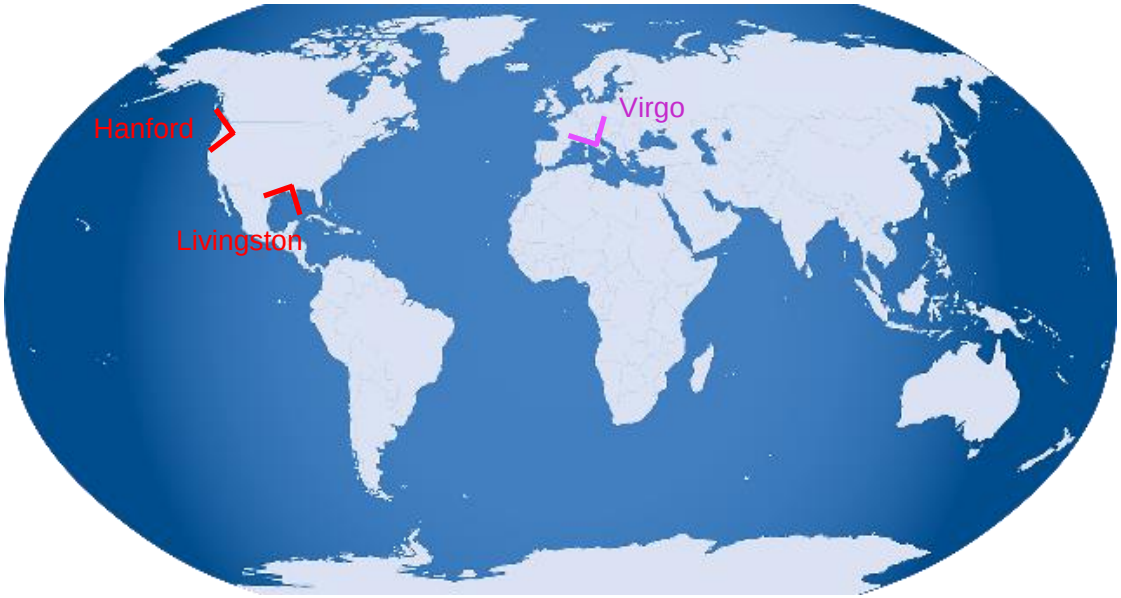
Stellar-mass Binary Black Holes

- 5 events published to date; 1 with both LIGO and Virgo detectors
- Consistency with GR in extremes of compactness and *v/c* ~0.6
- Revealed an unexpected class of heavier Stellar-mass BH



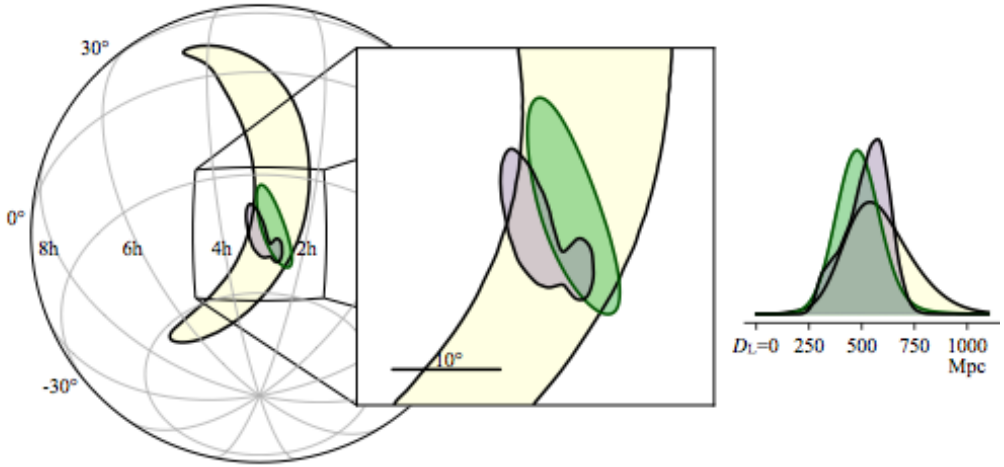
LIGO + VIRGO

GW170814: Virgo **and** LIGO detectors, enabling triangulation, polarization sensing



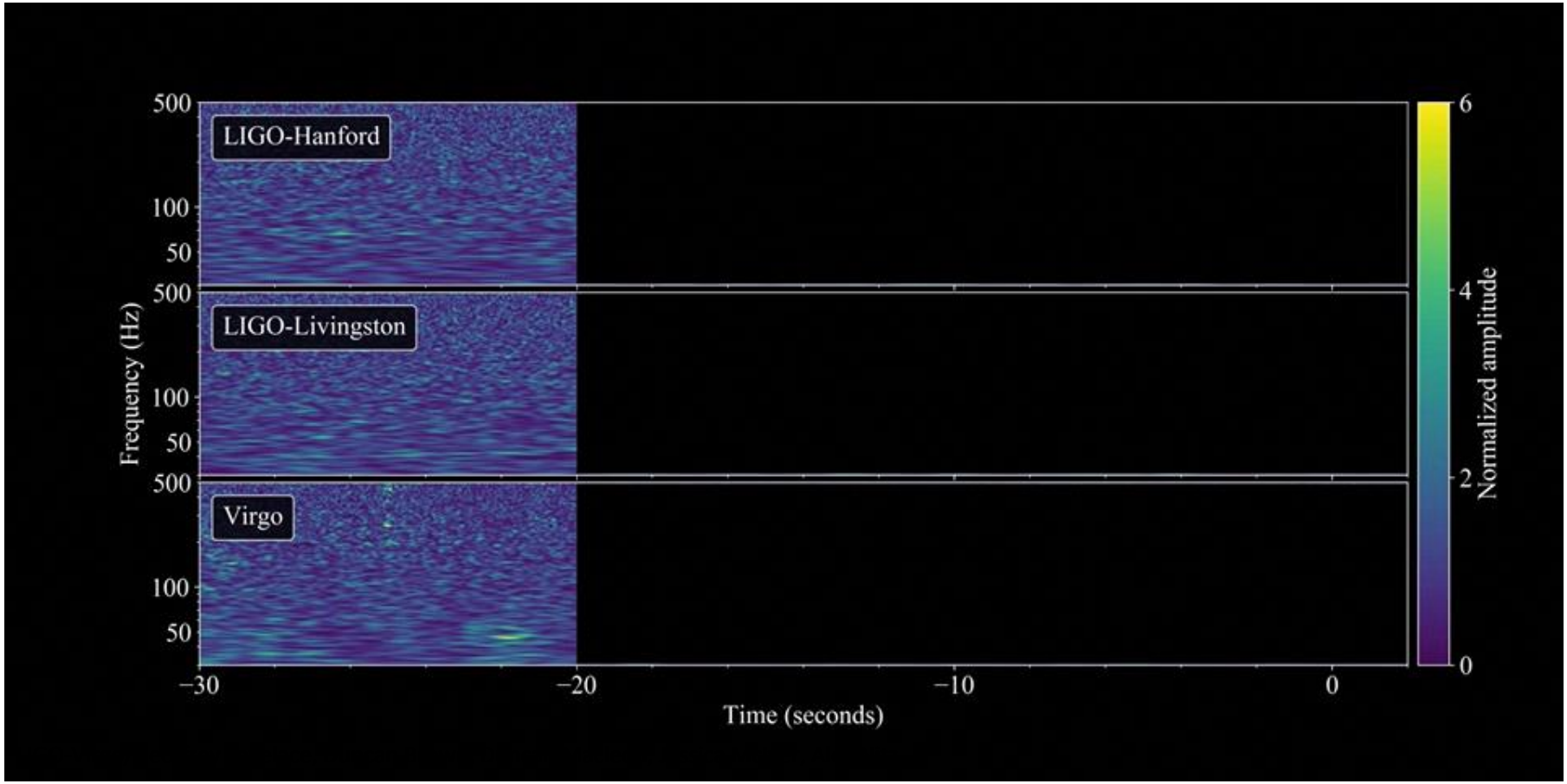
LIGO-Hanford and Livingston have similar orientations -> little information about GW polarizations

Virgo is not aligned with LIGO – giving polarization information



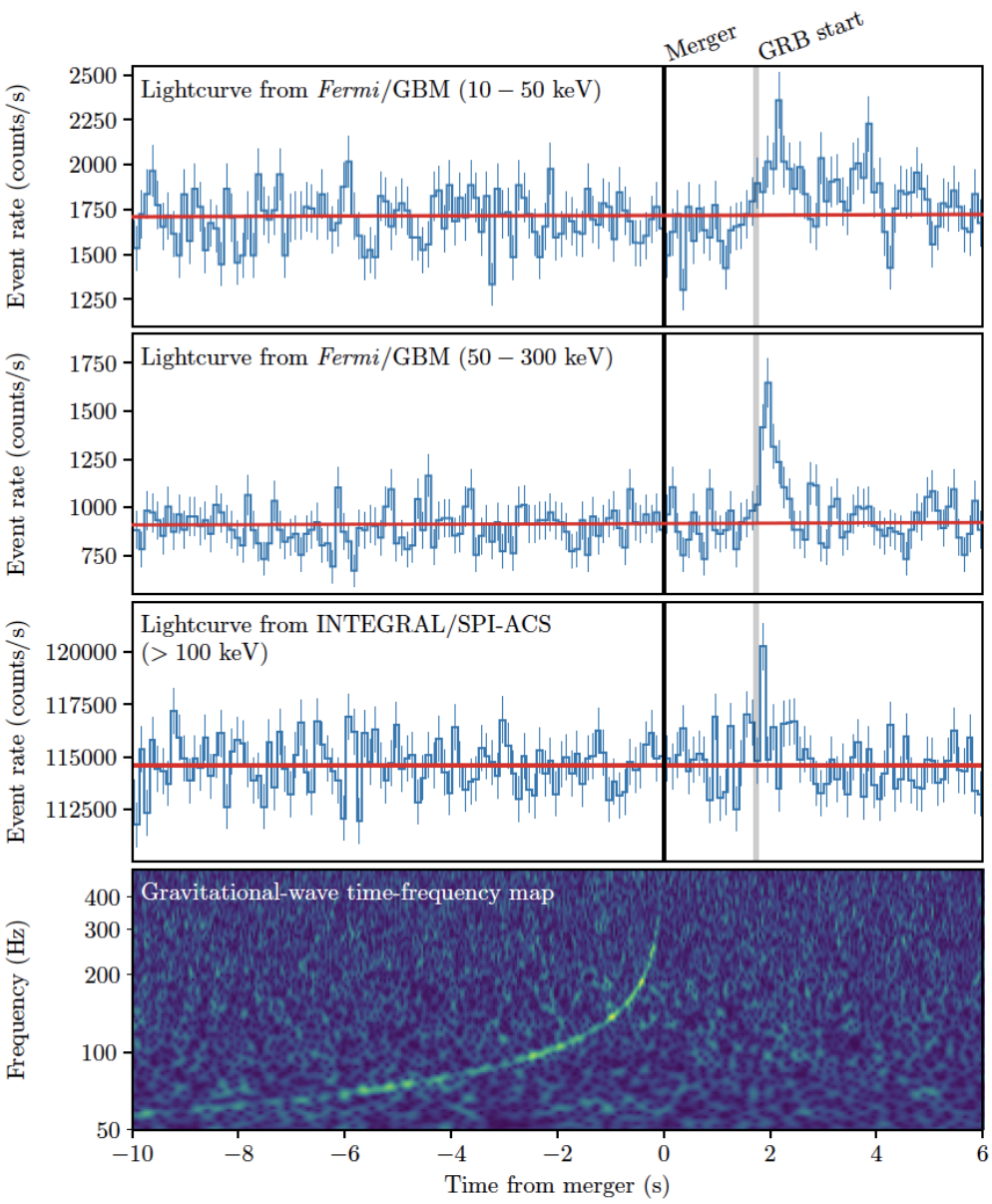
Sky localization improves ~20x; Uncertainty in volume reduced ~34x

GW170817: Binary Neutron Star Coalescence



https://doi.org/10.1103/PhysRevLett.119.161101

GRB 170817A



GRB 170817A occurs (1.74 ± 0.05) seconds after GW170817

It was autonomously detected in-orbit by Fermi-GBM (GCN was issued 14s after GRB) and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB 170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)

-> BNS mergers are progenitors of (at least some) SGRBs

B. P. Abbott et al., *Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A,* 2017, ApJL

Multimessenger Observations

Approximate timeline:

GW170817 - August 17, 2017 12:41:04 UTC = t_0

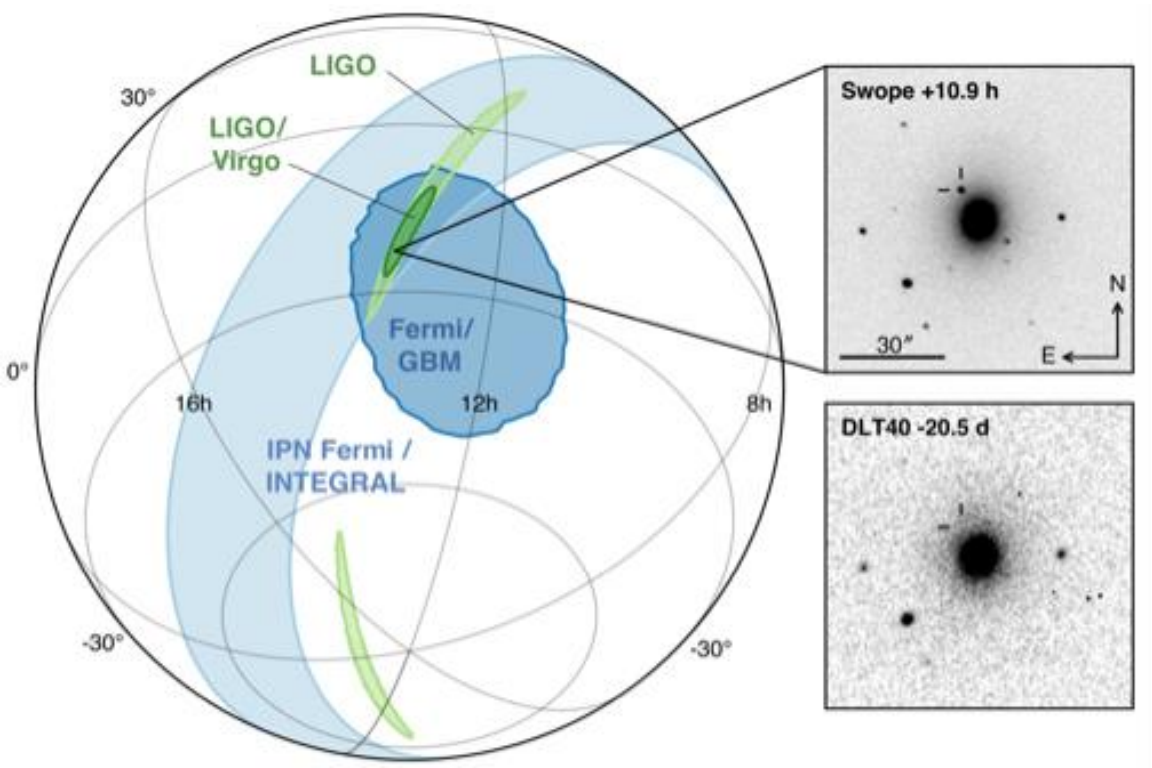
GRB 170817A
t_0 + 2 sec

LIGO signal found
t_0 +6 minutes

LIGO-Virgo GCN reporting BNS signal associated with the time of the GRB
t_0 +41 minutes

SkyMap from LIGO-Virgo
t_0 + 4 hours

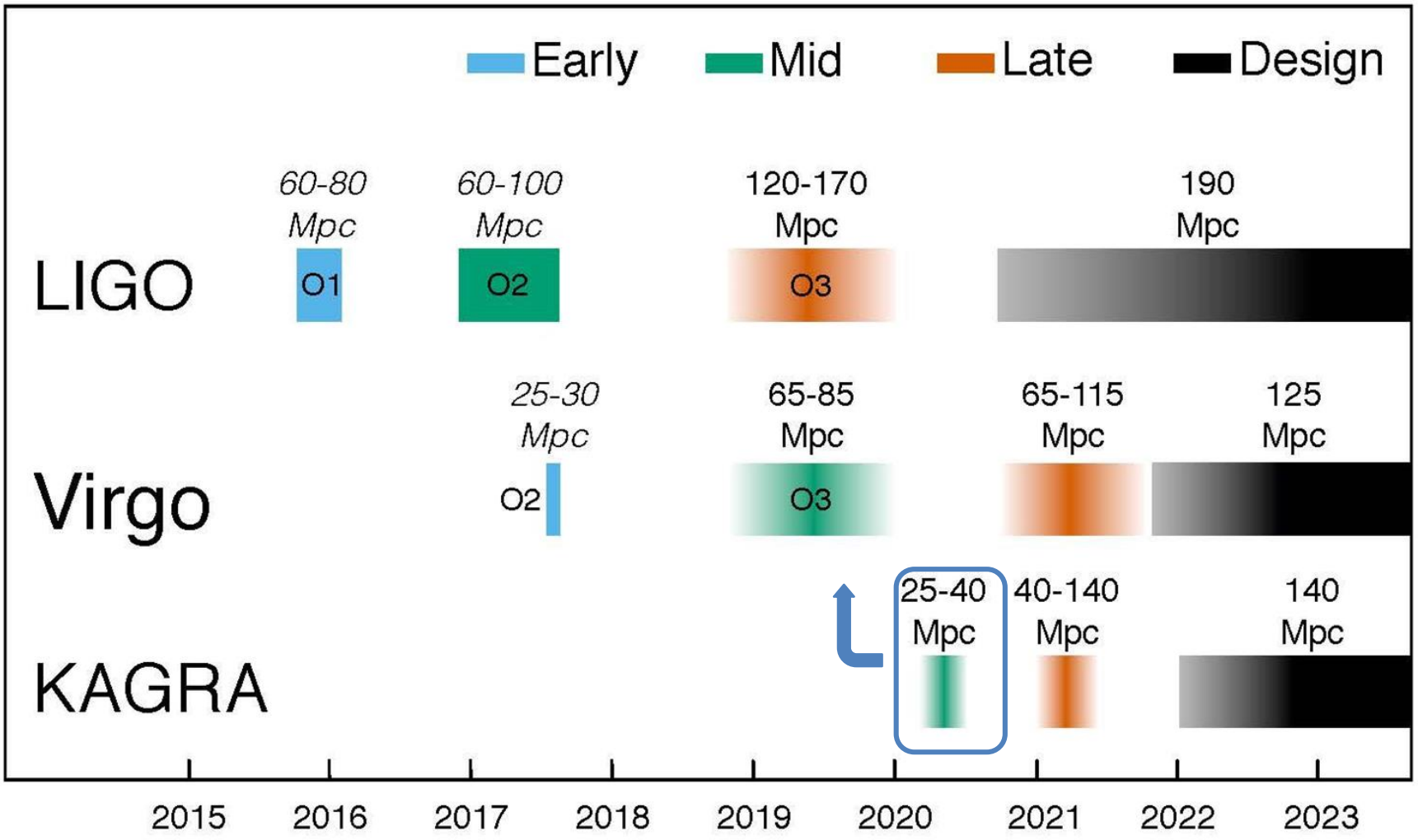
Optical counterpart found
t_0 + 11 hours



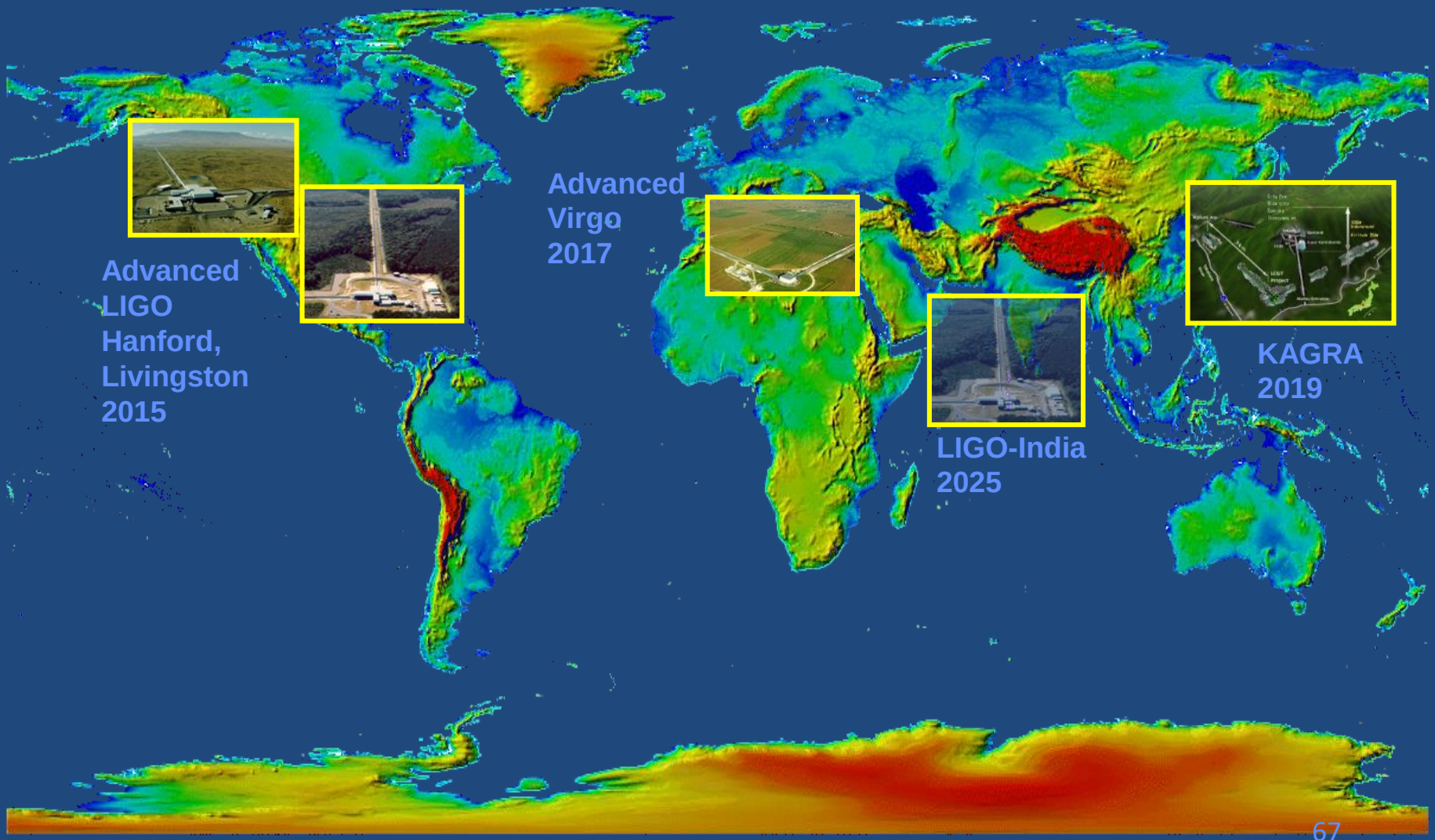
- The localisation region became observable to telescopes in Chile 10 hours after the event time (wait for nightfall!)
- Approximately 70 ground- and space- based observatories followed-up on this event
- **And…: transmutation of common elements (pure neutron matter) into gold!**

B. P. Abbott, *Multi-messenger Observations of a Binary Neutron Star Merger*, 2017, ApJL in press. doi:10.3847/2041-8213/aa91c9

5-year plan


Early
Mid
Late
Design
LIGO
60-80 Mpc
O1
60-100 Mpc
O2
120-170 Mpc
O3
190 Mpc
Virgo
25-30 Mpc
O2
65-85 Mpc
O3
65-115 Mpc
125 Mpc
KAGRA
25-40 Mpc
40-140 Mpc
140 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023

The advanced GW detector network



THE END