What tools are critical for making progress in cosmology in the coming decades?

Ask a theorist!

Jonathan Feng

Rashid Sunyaev

Roger Blandford

What tools are critical for making progress in cosmology in the coming decades?

Cosmic Controversies Panel

University of Chicago

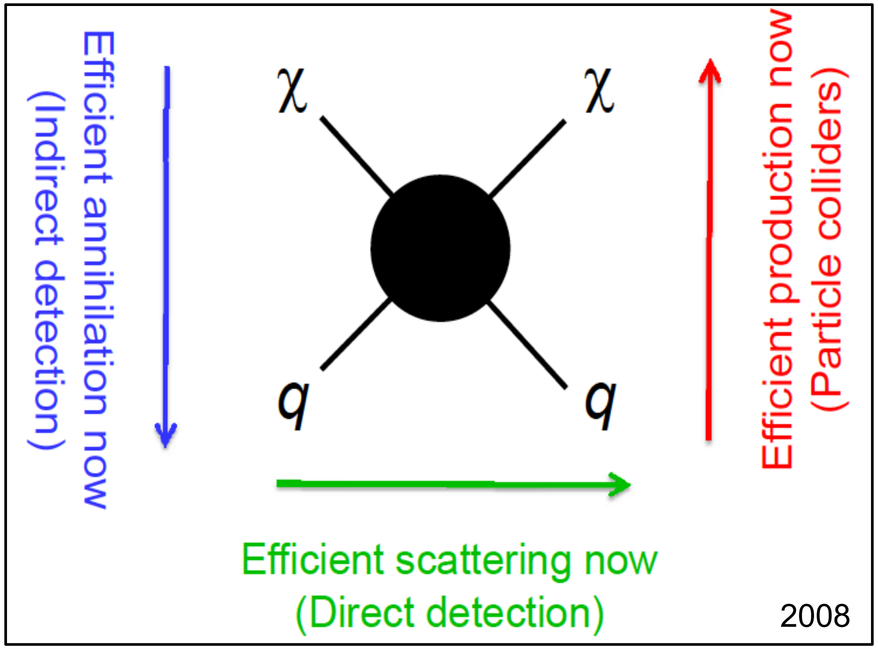
Jonathan Feng, UC Irvine, 7 October 2019

DARK MATTER

- For dark matter, the question is very timely
- New community exercises underway in both astrophysics and particle physics
  - Astro 2020
  - European Strategy for Particle Physics Update 2020
  - Snowmass 2021
- Many new developments in dark matter
  - WIMPs and other classic candidates not discovered, but remain interesting
  - Other DM candidates are rising in prominence
  - Both facts have implications for what tools and experiments will be needed for progress

WIMP PARADIGM

- For decades, the WIMP paradigm has been dominant, bolstered by the WIMP miracle and its many implications



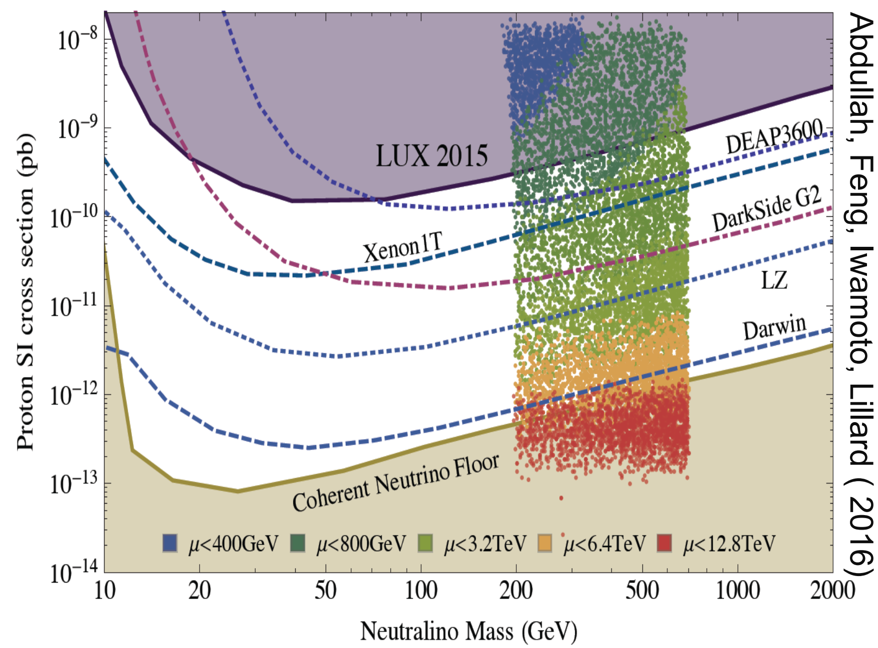
- Indirect detection: interesting signals in ν, γ, e^+, pbar, …
- Direct detection: mass matched to scattering off all nuclei
- Colliders: almost all BSM signals, mono-X

WIMP STATUS

- Many constraints, but still viable. E.g., there are viable SUSY models with thermal relic neutralinos, and all squarks/sleptons below a few TeV.

- For example: MSSM4G, MSSM + vector-like 4th generation.

- DM is 200-700 GeV and Bino-like, so scatters very weakly, but freezes out correctly through $\chi\chi \to \tau_4\tau_4$.



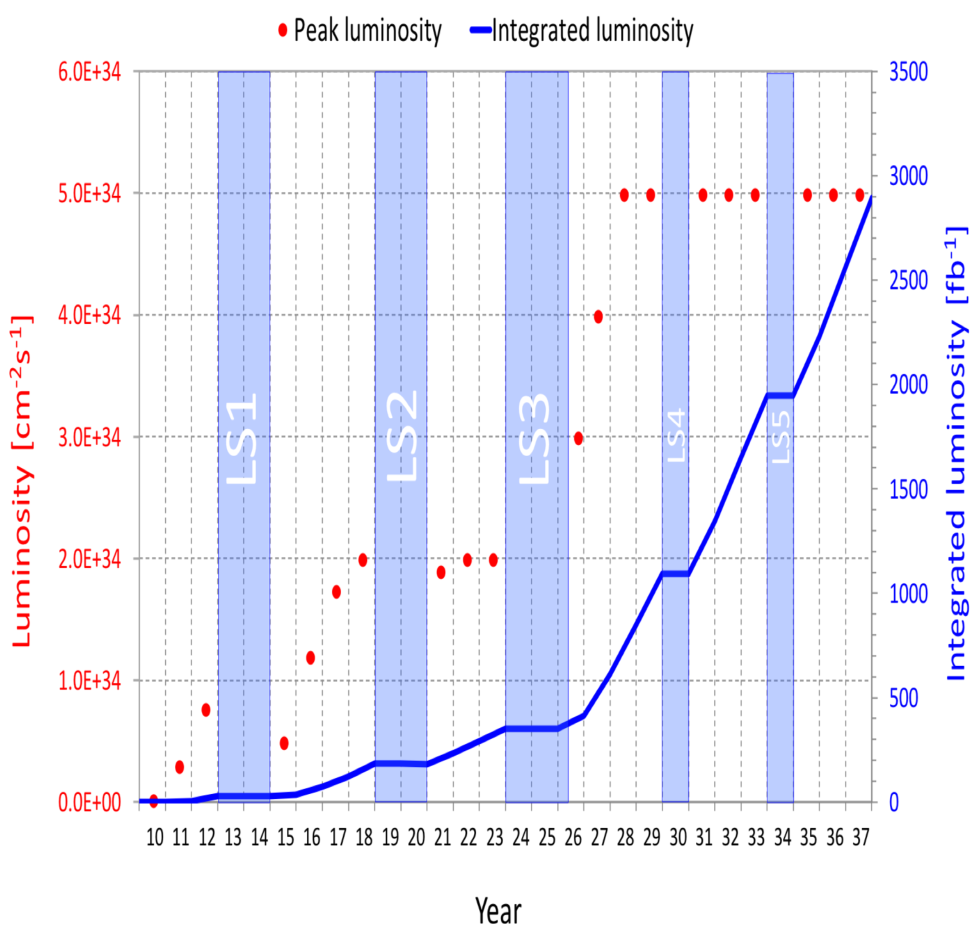
- There remain strong motivations to pursue direct detection down to the neutrino floor, both in xenon (XENON-nT, LZ, Panda-X, Darwin) and argon (Darkside-20K, ARGO).

COLLIDER SEARCHES

- For the next many years, the energy frontier will continue to be dominated by the LHC and HL-LHC.

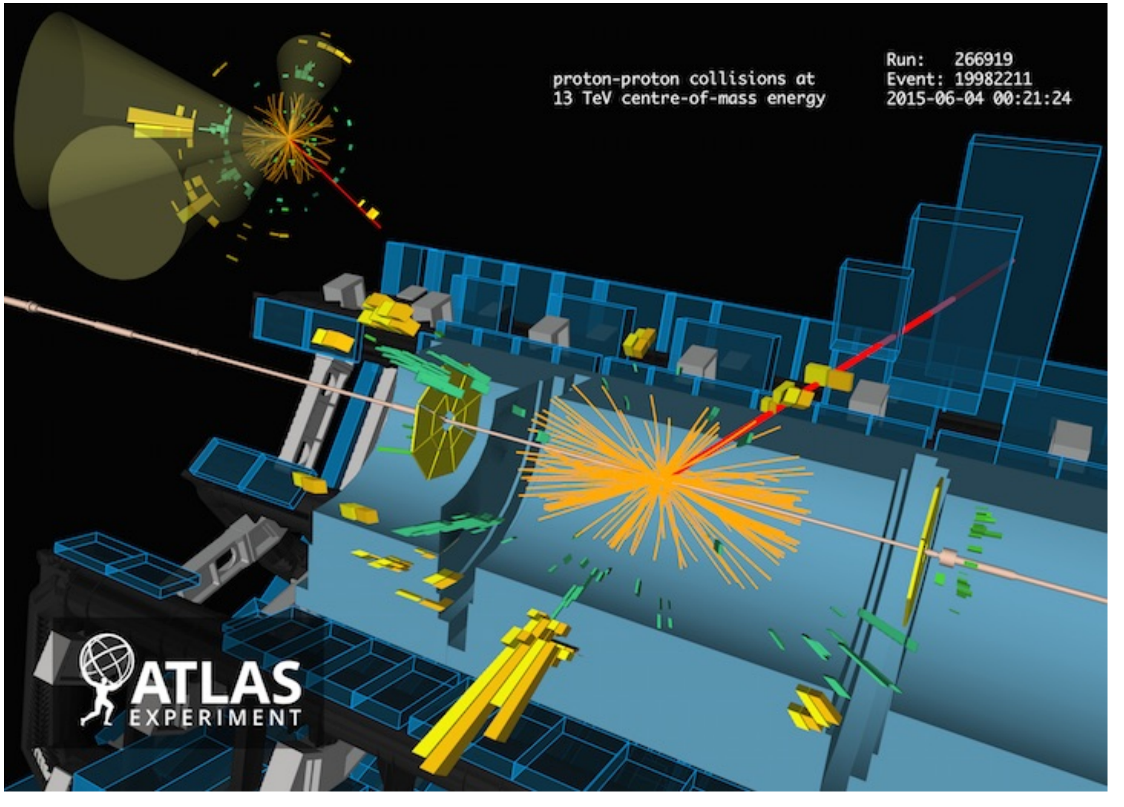
- The LHC is currently in Long Shutdown 2, but will start up again in 2021 and run till ~2037. Will we find new particles through conventional searches?

- What other approaches can enhance the prospects for discovering DM and other new particles?



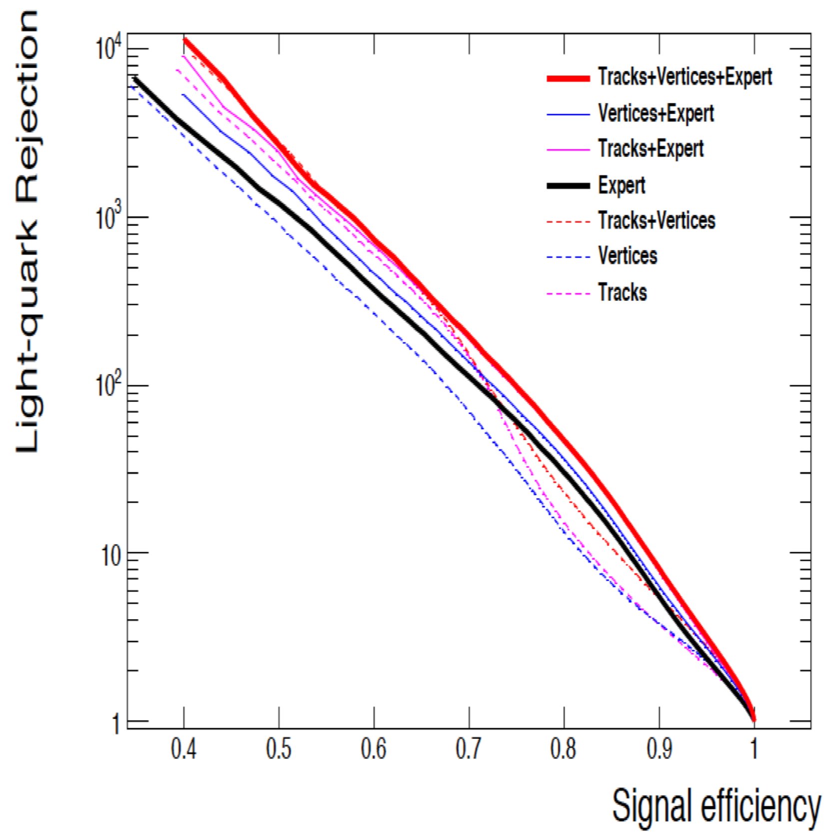
MACHINE LEARNING

- Machine learning is now able to optimize searches over conventional methods.
- For example: identifying the originating quark / gloun from a hadronic shower.

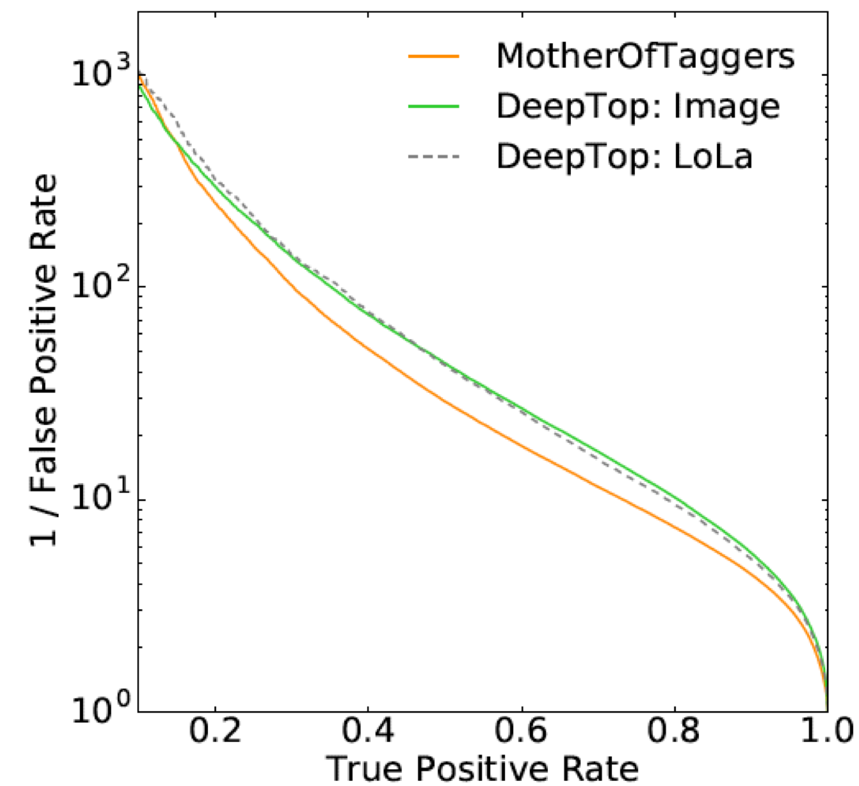


MACHINE LEARNING

- Examples: b-quark tagging (left) and top-quark tagging (right). Top curves are from neural network, bottom curves are using expert-curated variables (note log scale).



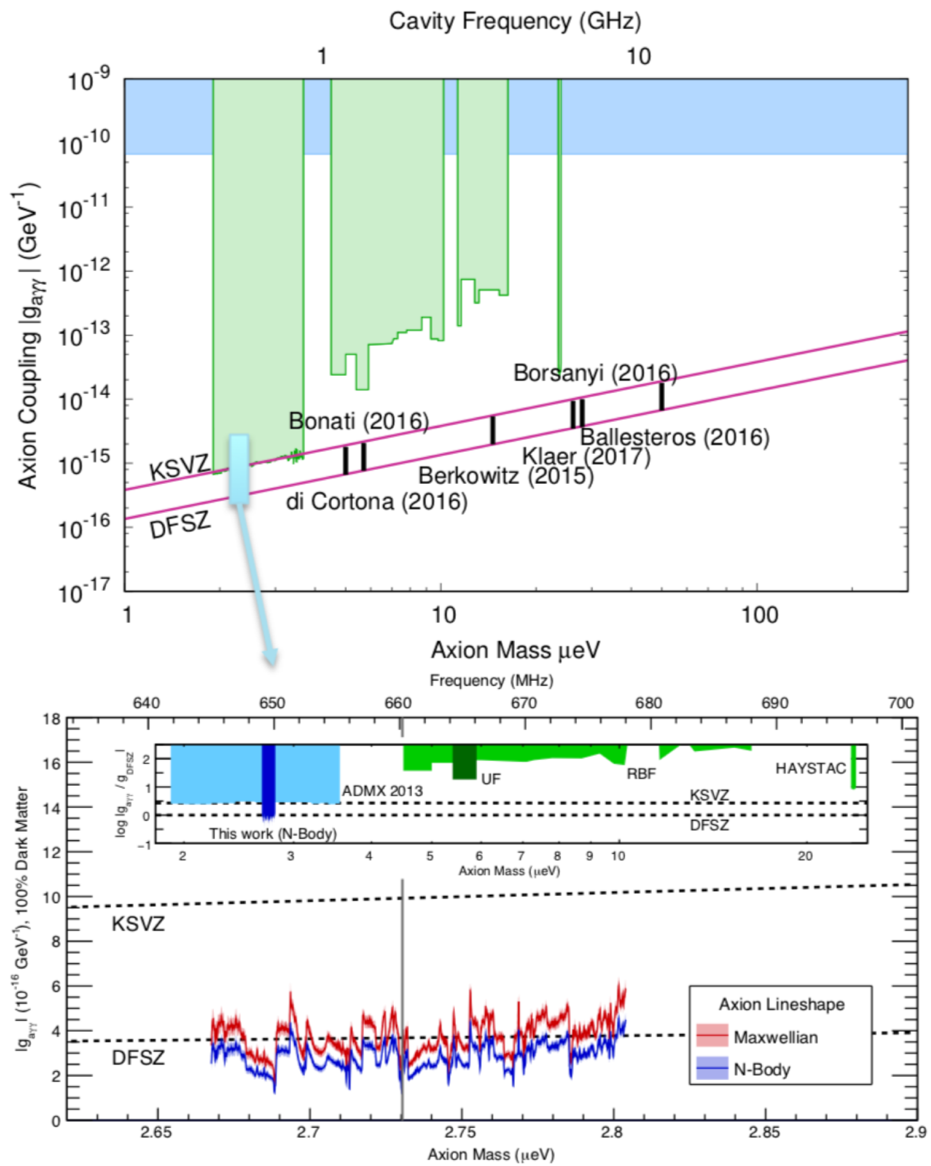
Guest, Collado, Baldi, Hsu, Urban, Whiteson (2016)



Butter, Kasieczka, Plehn, Russell (2018)

AXIONS

- The QCD axion remains a highly motivated DM candidate.
- ADMX-G2 has finally probed down to the canonical sensitivity and mass range.
- Strong motivation to continue to higher (and lower) masses.

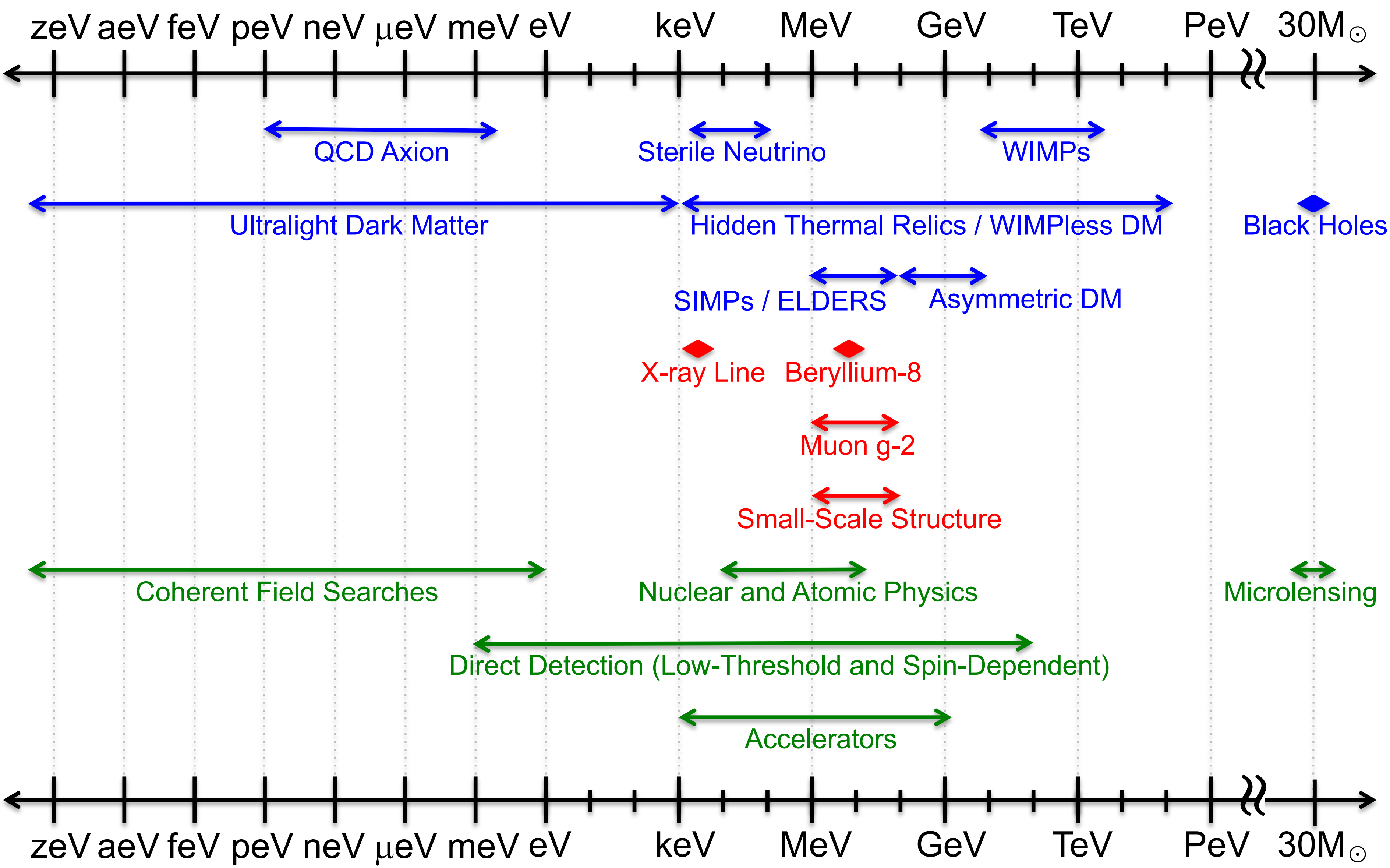


ADMX-G2 (2018)

NEW CANDIDATES

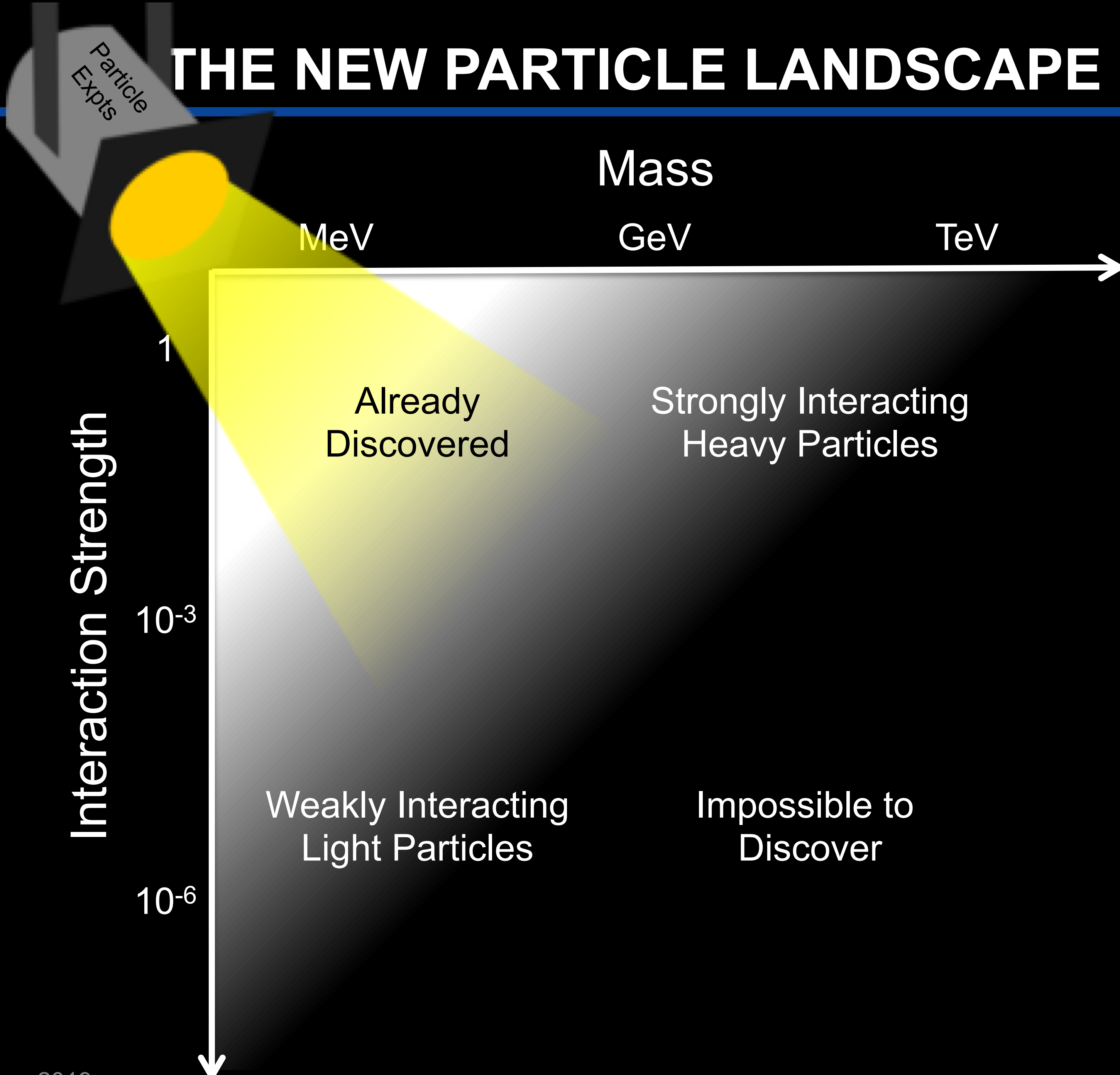
- Of course, the absence of a compelling DM signal (and, in fact, a compelling BSM signal of any kind) motivates the study of other possibilities.
- In recent years, there has been a huge growth in the number of DM candidates under investigation.
- Most exciting, many of these motivate relatively small, cheap, and fast experiments.

Dark Matter Candidates, Anomalies, and Search Techniques



Cosmic Visions Report (2017)

THE NEW PARTICLE LANDSCAPE



LIGHT, WEAKLY-INTERACTING PARTICLES

- The possibility that new particles are light and very weakly-interacting also has a cosmological motivation.

- The thermal relic density is

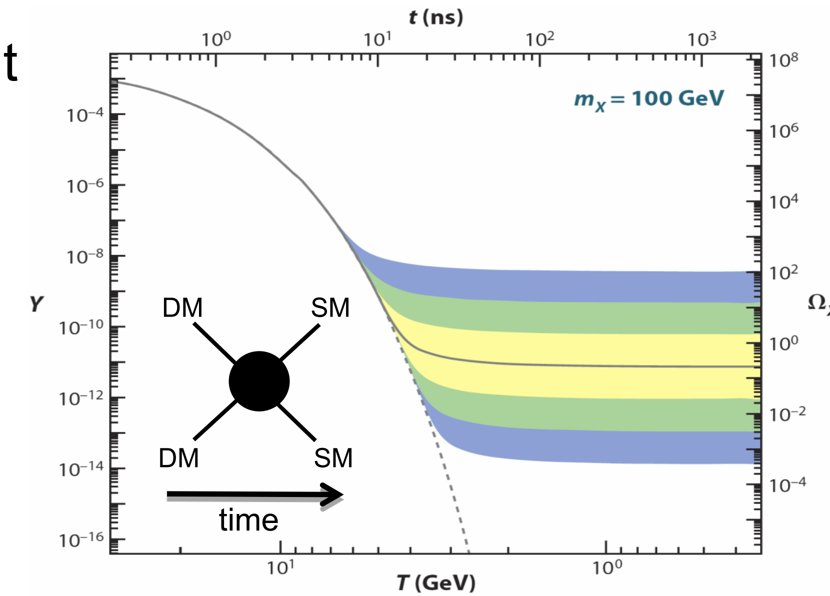
$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

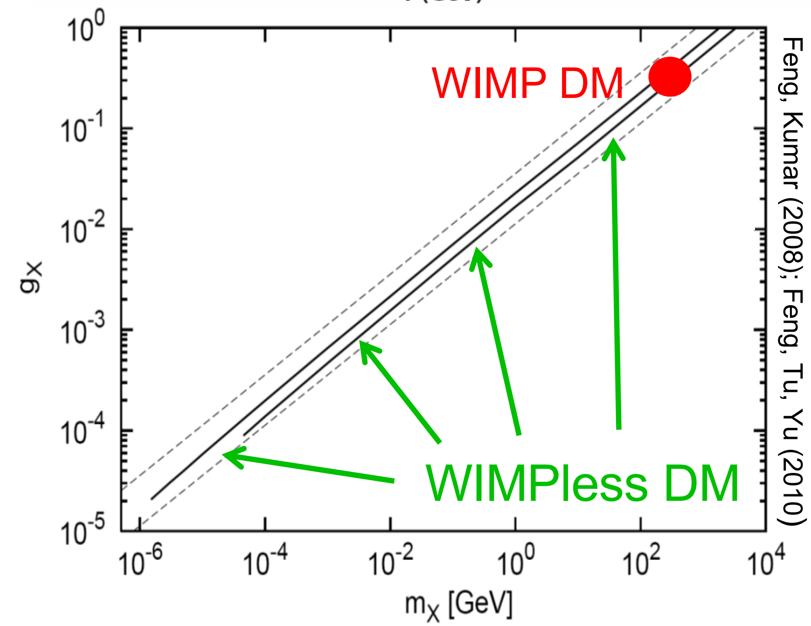
- WIMP Miracle: ~100 GeV to 1 TeV masses, strong couplings → right abundance

- WIMPless Miracle: lighter particles, weaker interactions → right abundance

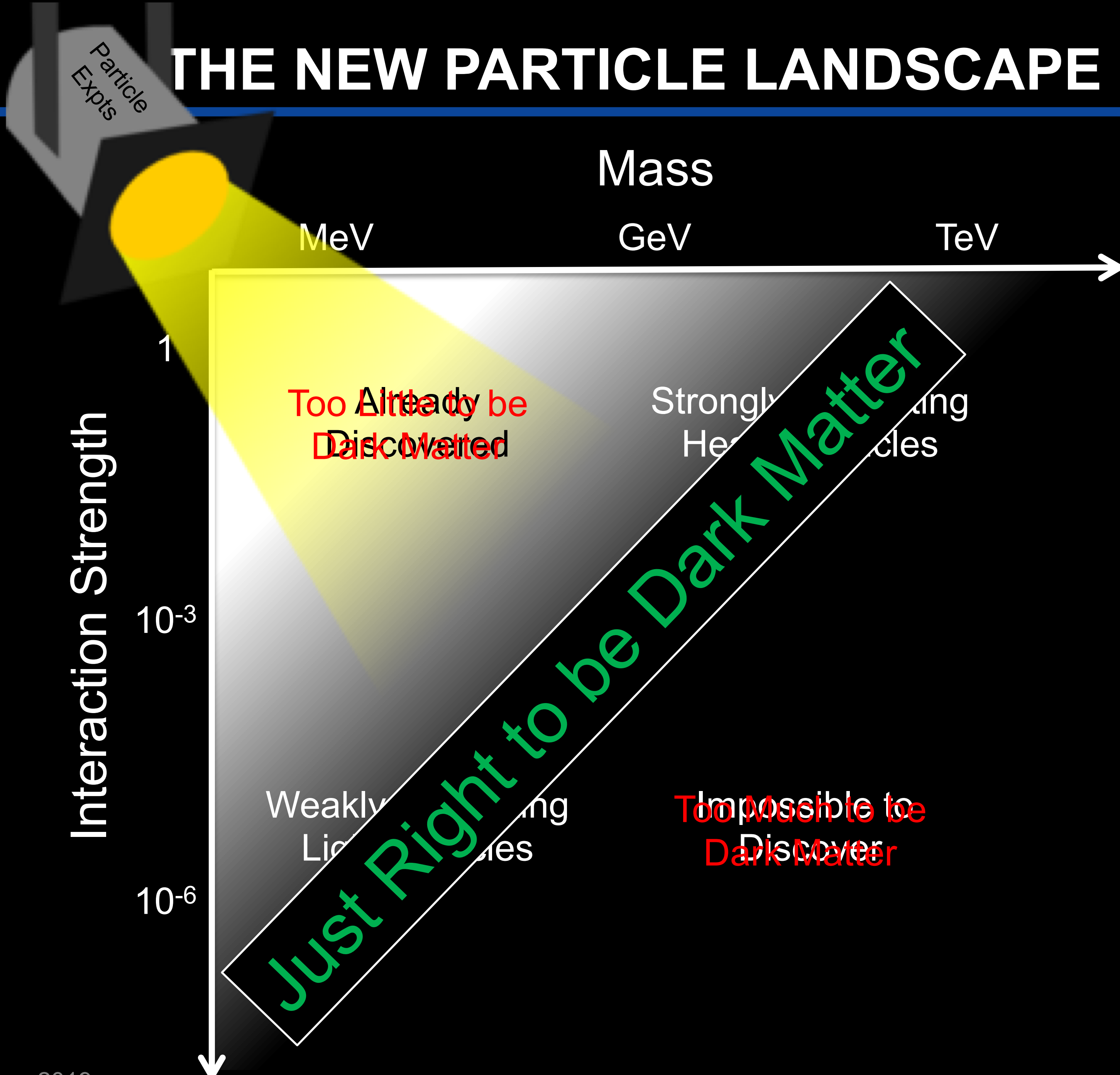
Boehm, Fayet (2003);

Pospelov, Ritz, Voloshin (2007); Hooper, Zurek (2008)



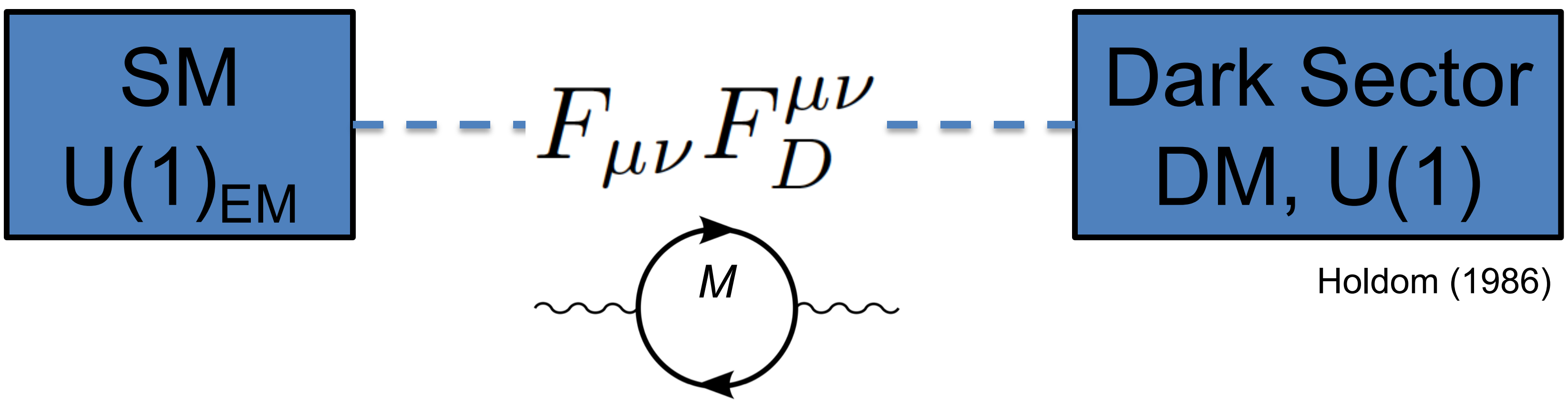


THE NEW PARTICLE LANDSCAPE



DARK SECTORS

- Light, weakly interacting particles naturally emerge from generalizing dark matter → dark sectors.
- E.g: suppose there's a dark sector with DM and its own EM force. It can interact with the SM through a dim 4 operator:

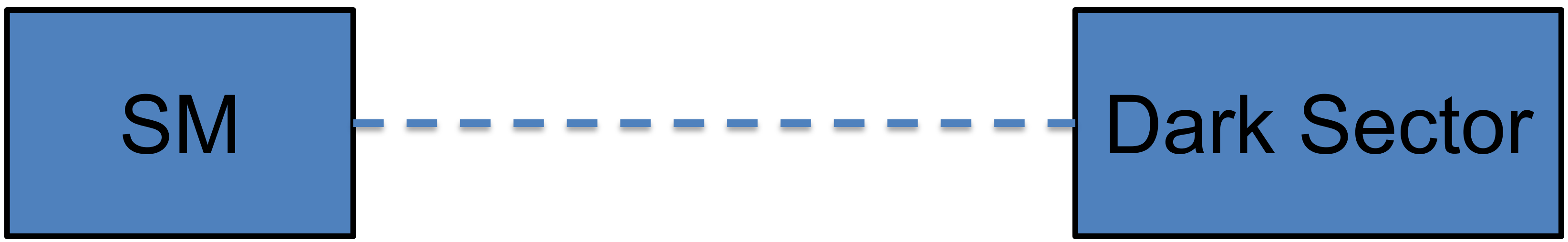


Holdom (1986)

- The result is a weakly interacting (since interactions are induced by a loop) particle ("mediator"): the dark photon.
- Other mediator possibilities: dark scalar, dark fermion.

STRUCTURE FORMATION WITH SIDM

- The possibility of a dark sector naturally allows DM to be strongly self-interacting. It is even more motivated by the idea of a light thermal relic with mass around MeV – GeV, which naturally generates σ/m ~ barn/GeV ~ cm^2/g.



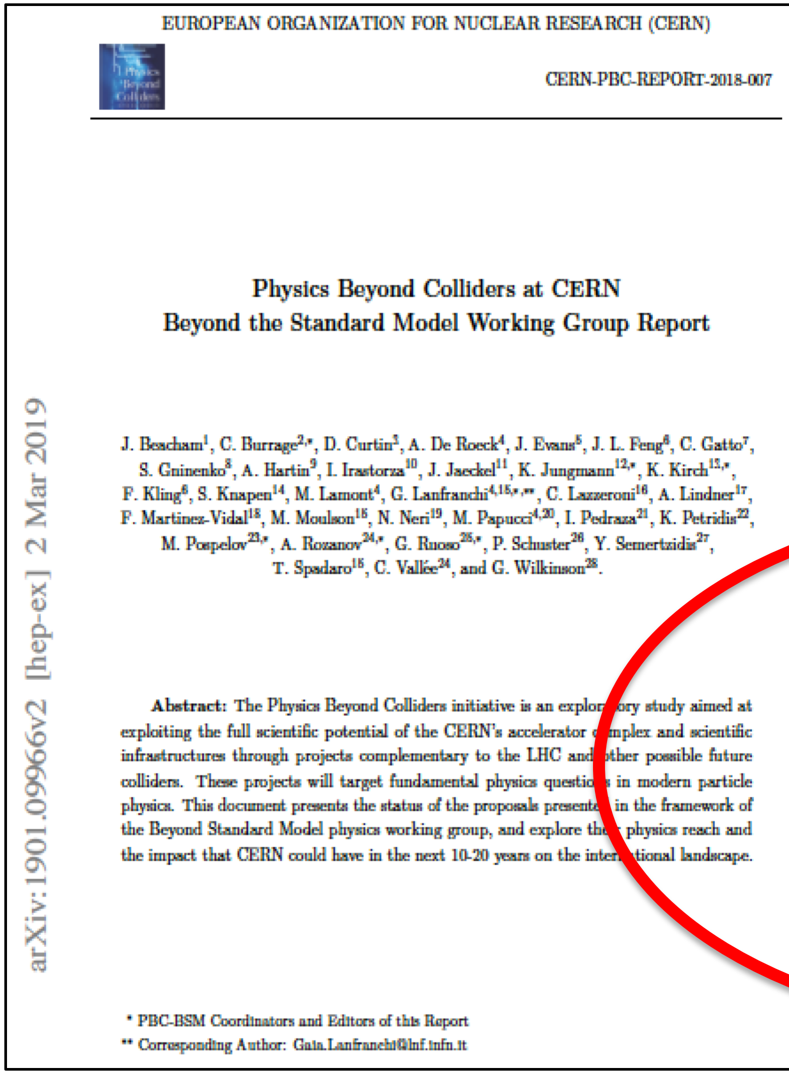
- From this viewpoint, perhaps "Is a theory beyond Cold Dark Matter needed to describe structure formation?" should be "What can structure formation tell us about dark matter's self-interactions and other properties?"

- Strong motivation for N-body simulations with SIDM and DM with other properties.

LIGHT, WEAKLY INTERACTING PARTICLES

- The possibility of light, weakly interacting particles can be explored without enormous investments.
- It puts a premium on new ideas, new techniques, new collaborations between theorists and experimentalists.
- Many new ideas in indirect detection and direct detection, both for existing DM detectors and in proposed experiments (see earlier talks).
- Also many new ideas for collider and accelerator experiments probing light, weakly interacting particles and/or long-lived particles

NEW COLLIDER/ACCELERATOR EXPERIMENTS



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

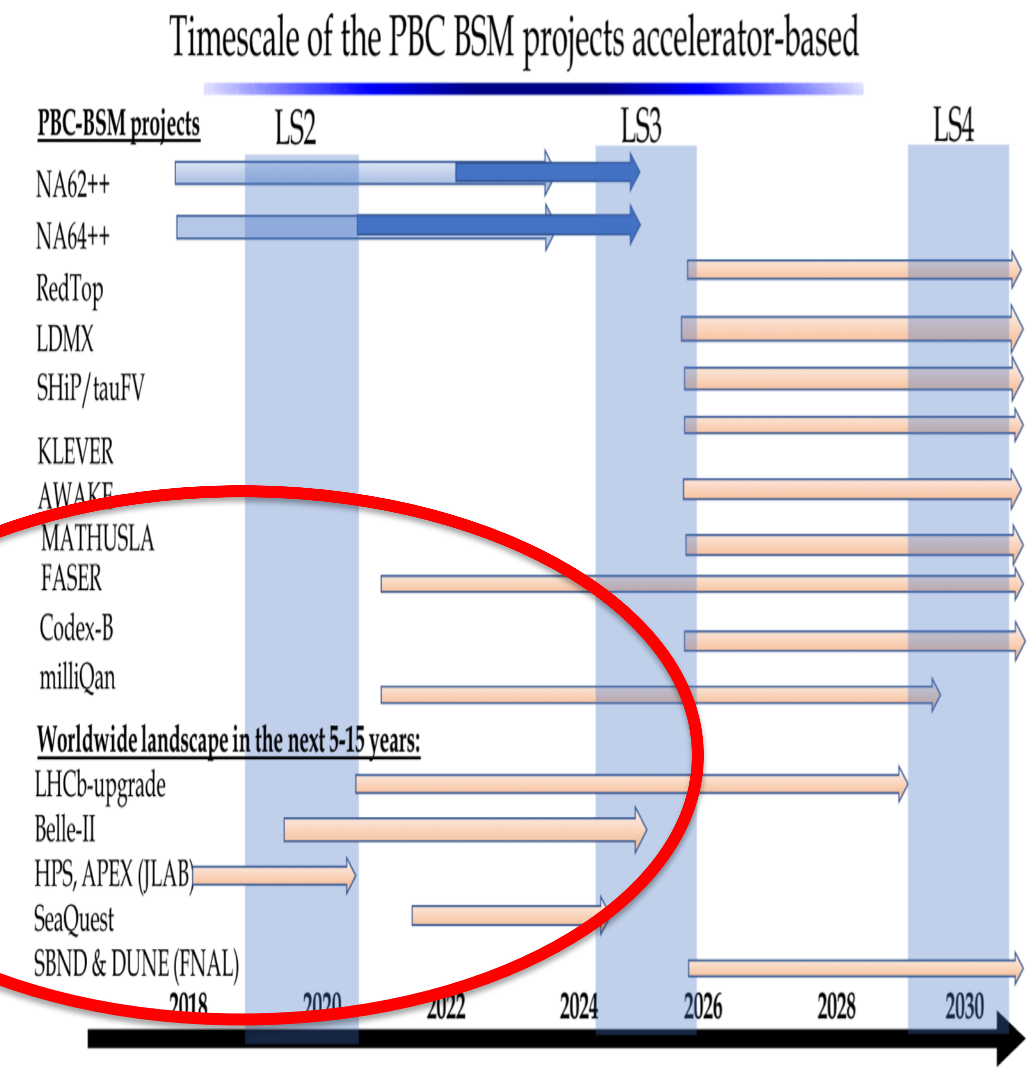
CERN-PBC-REPORT-2018-007

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

Abstract: The Physics Beyond Colliders initiative is an exploratory study aimed at exploiting the full scientific potential of the CERN's accelerator complex and scientific infrastructures through projects complementary to the LHC and other possible future colliders. These projects will target fundamental physics questions in modern particle physics. This document presents the status of the proposals presented in the framework of the Beyond Standard Model physics working group, and explore their physics reach and the impact that CERN could have in the next 10-20 years on the international landscape.

* PBC-BSM Coordinators and Editors of this Report
** Corresponding Author: Gaia.Lanfranchi@lnf.infn.it



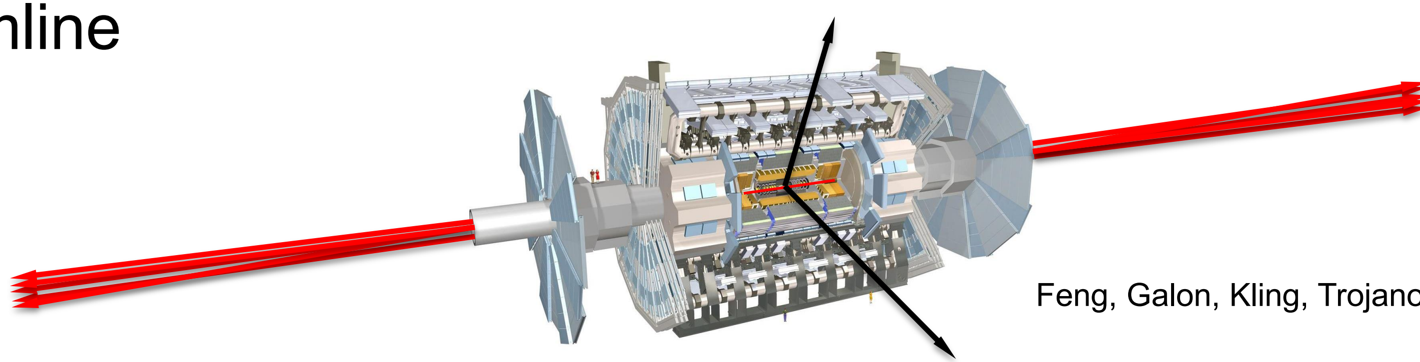
- A wealth of new experiments, some on very short timescales

FASER: FORWARD SEARCH EXPERIMENT

- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly interacting particles, like TeV-scale superpartners

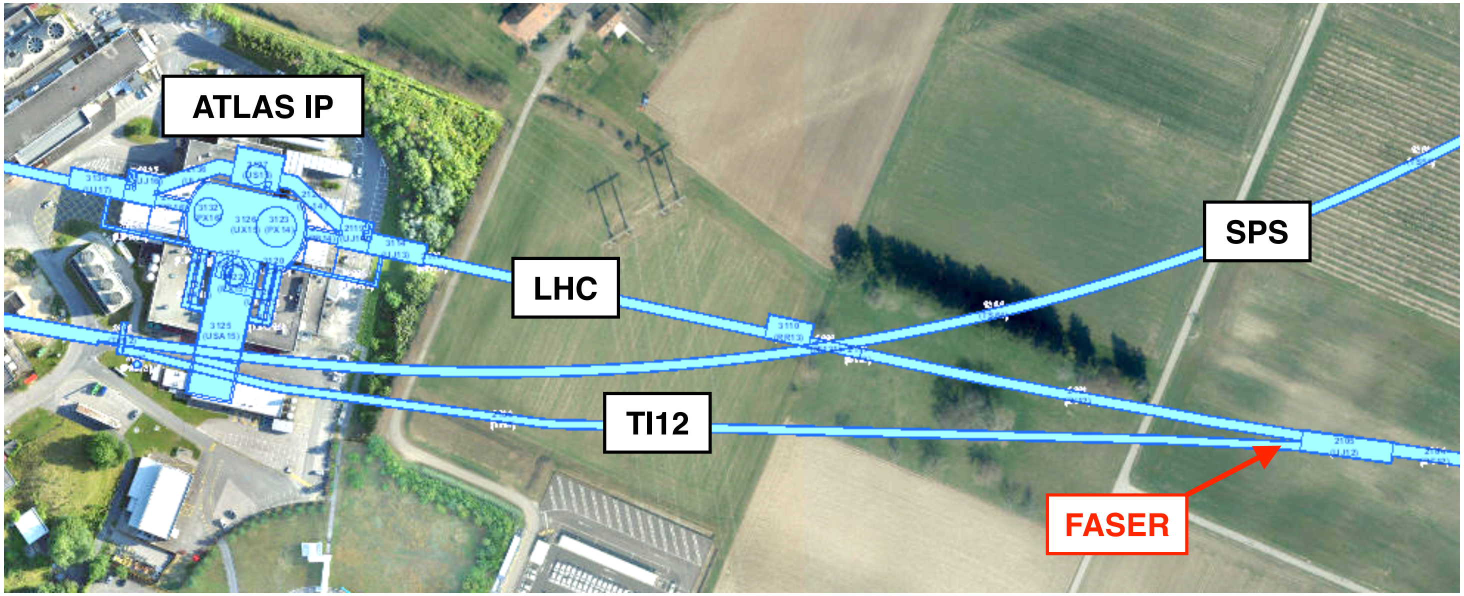
- However, if new particles are light and weakly interacting, this may be completely misguided
  – Light and weakly-interacting → we can be produced in π, *K*, *D*, *B* decays, but they are typically produced along the beamline, where the detectors have a blind spot

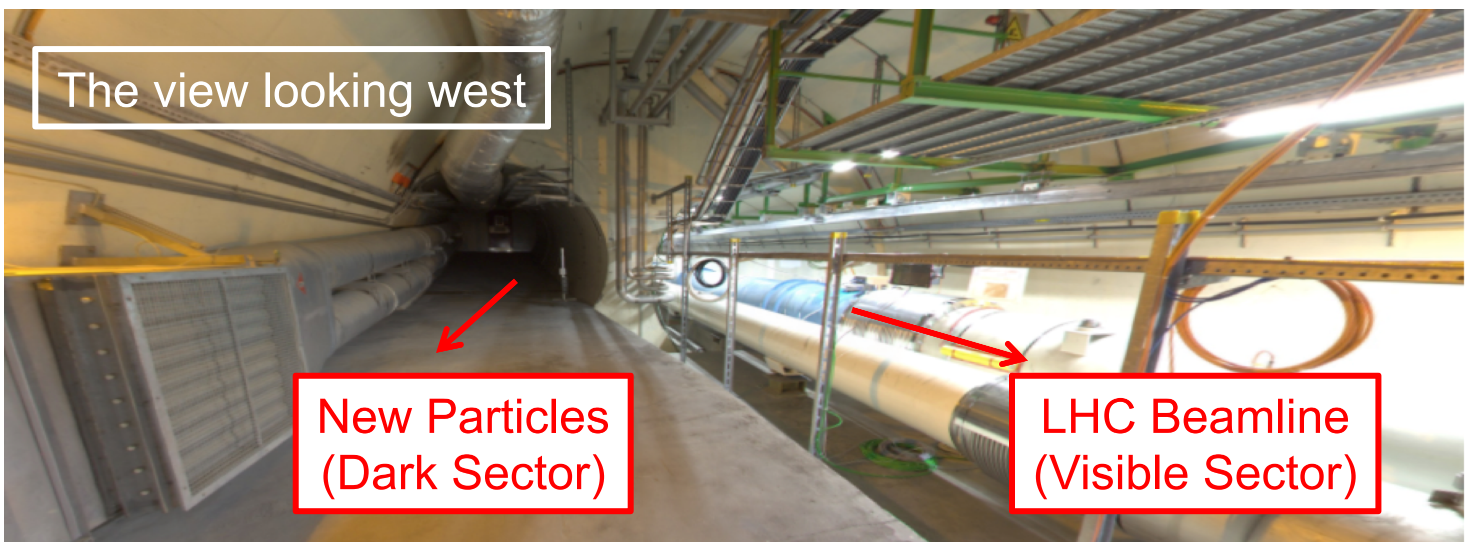
- Conclusion: we can enhance the LHC's discovery reach by putting a detector where the pions are: at low p_T along the beamline



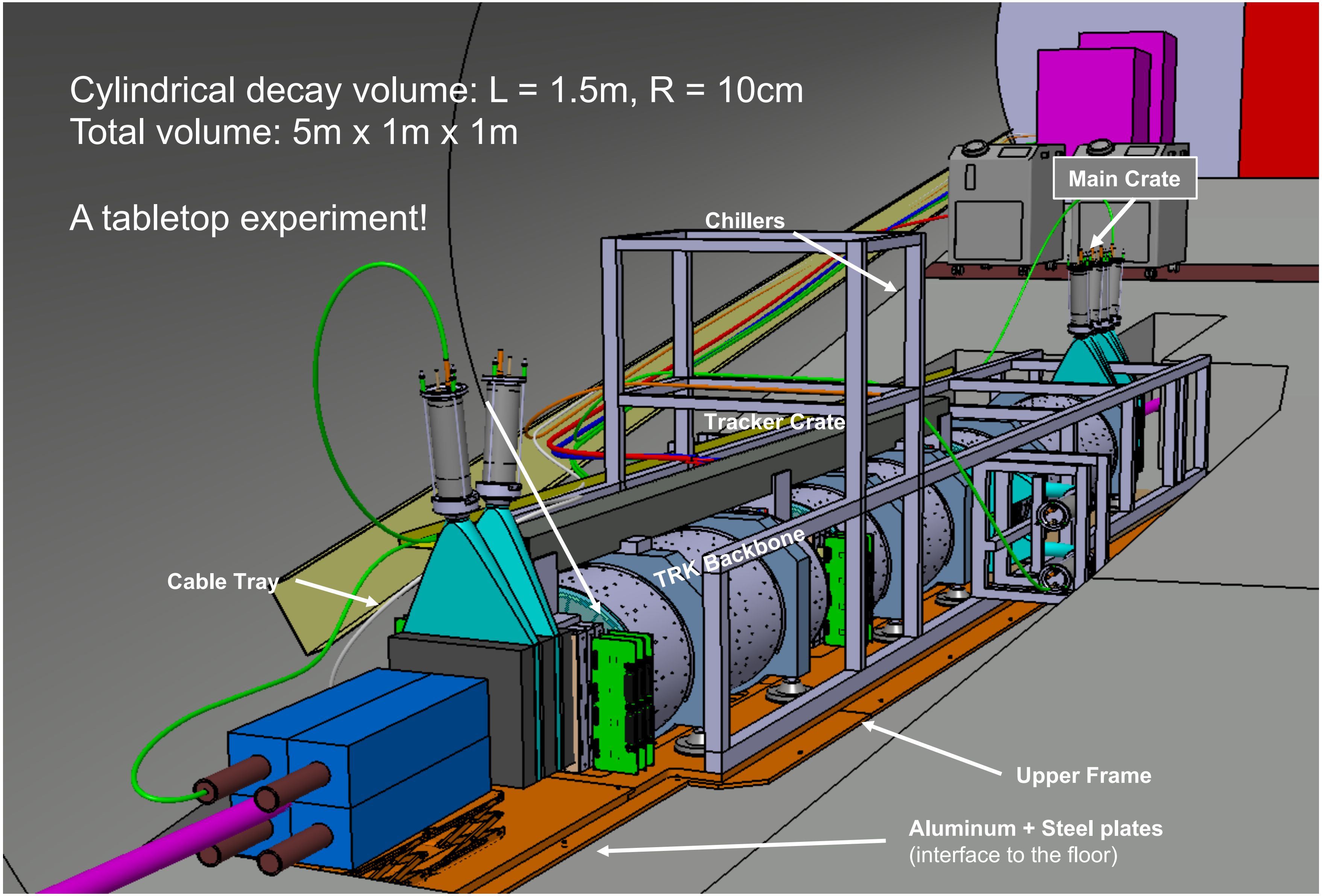
Feng, Galon, Kling, Trojanowski (2017)

FASER LOCATION



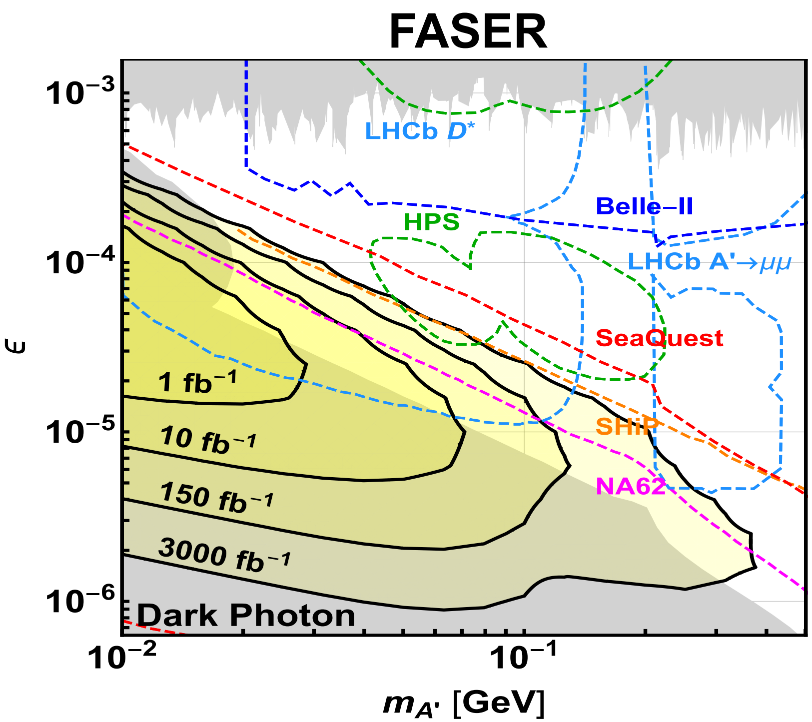


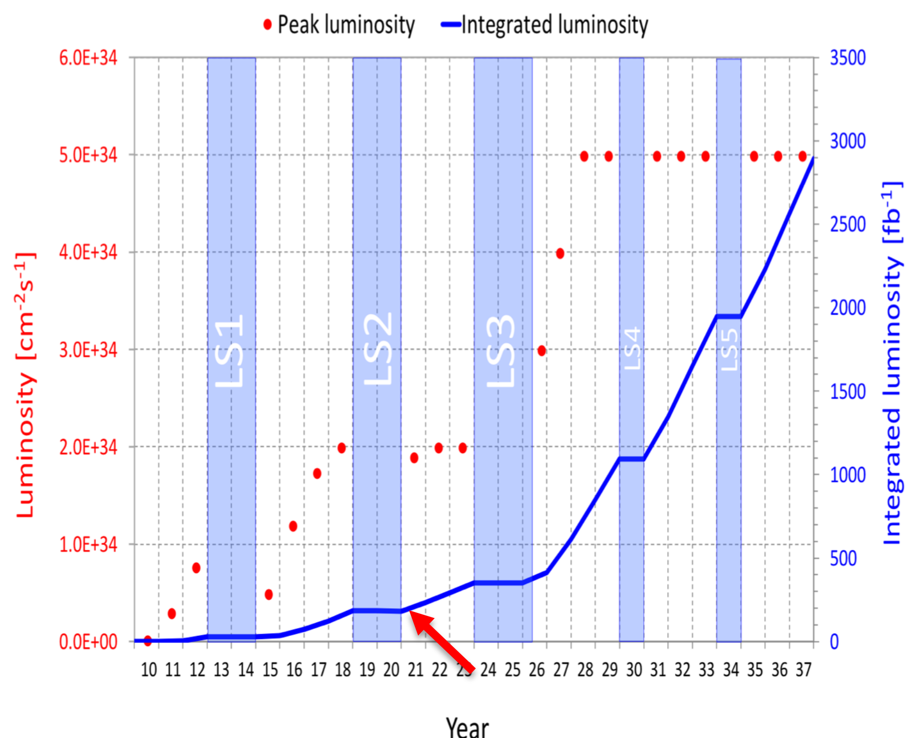
FASER DETECTOR



DARK PHOTON SENSITIVITY REACH

- FASER was approved and funded in early 2019 by CERN and the Heising-Simons and Simons Foundations.
- Now under construction with very helpful contributions from LHCb and ATLAS SCT Collaborations.





- FASER probes new parameter space with just 1 fb^{-1} starting in 2021
- Possible upgrade to FASER 2 for HL-LHC will increase (Lum*Vol) by ~10^6.

FASER COLLABORATION

- 46 collaborators, 18 institutions, 8 countries

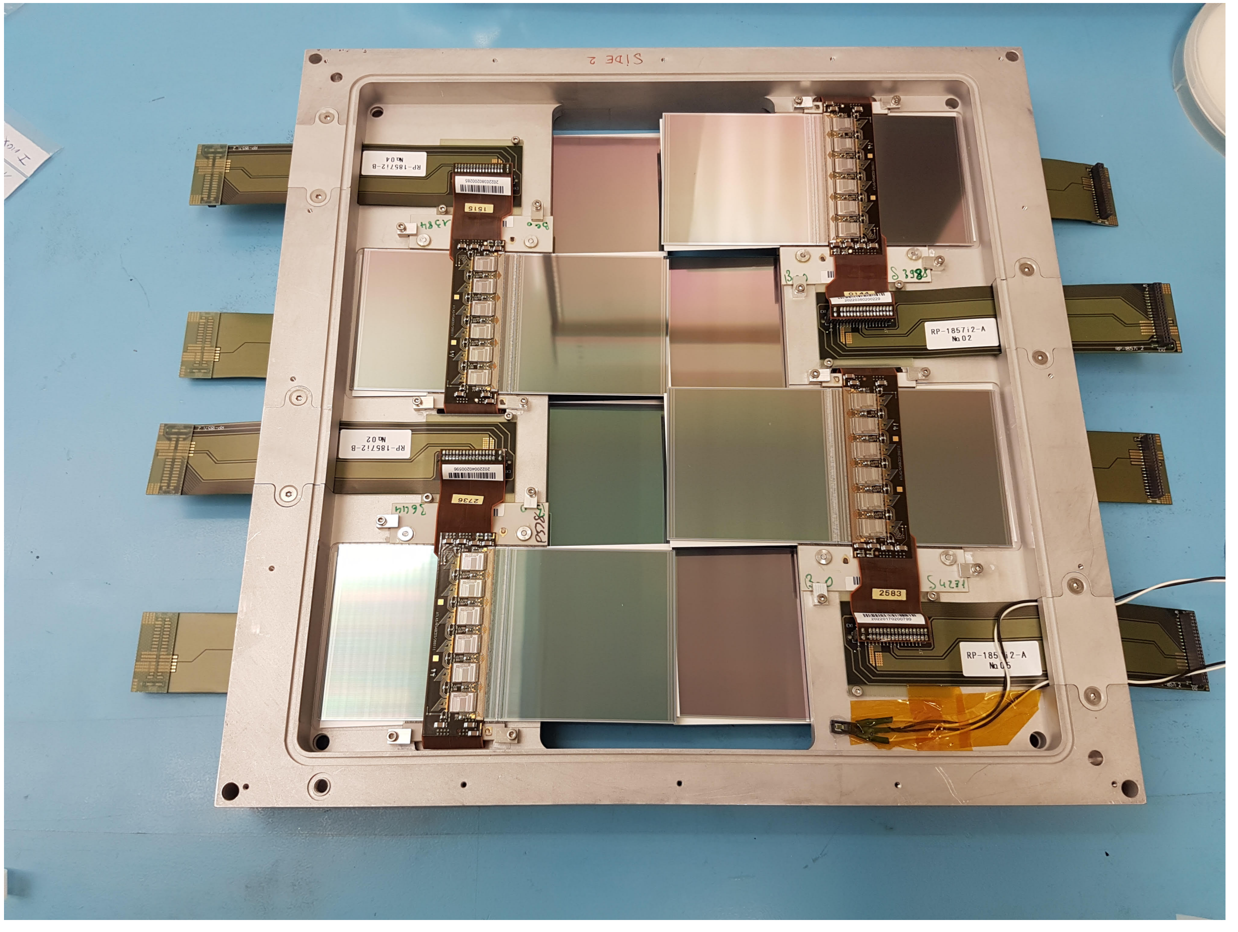
Henso Abreu (Technion), Claire Antel (Geneva), Akitaka Ariga (Bern), Tomoko Ariga (Kyushu/Bern), Jamie Boyd (CERN), Dave Casper (UC Irvine), Franck Cadoux (Geneva), Xin Chen (Tsinghua), Andrea Coccaro (INFN), Candan Dozen (Tsinghua), Yannick Favre (Geneva), Jonathan Feng (UC Irvine), Didier Ferrere (Geneva), Iftah Galon (Rutgers), Stephen Gibson (Royal Holloway), Sergio Gonzalez-Sevilla (Geneva), Shih-Chieh Hsu (Washington), Zhen Hu (Tsinghua), Peppe Iacobucci (Geneva), Sune Jakobsen (CERN), Roland Jansky (Geneva), Enrique Kajomovitz (Technion), Felix Kling (SLAC), Susanne Kuehn (CERN), Lorne Levinson (Weizmann), Congqiao Li (Washington), Josh McFayden (CERN), Sam Meehan (CERN), Friedemann Neuhaus (Mainz), Hidetoshi Otono (Kyushu), Brian Petersen (CERN), Helena Pikhartova (Royal Holloway), Michaela Queitsch-Maitland (CERN), Jakob Salfeld-Nebgen (CERN), Osamu Sato (Nagoya), Kristof Schmieden (CERN), Matthias Schott (Mainz), Anna Sfyrla (Geneva), Savannah Shively (UC Irvine), Jordan Smolinsky (UC Irvine), Aaron Soffa (UC Irvine), Yosuke Takubo (KEK), Eric Torrence (Oregon), Sebastian Trojanowski (Sheffield), Dengfeng Zhang (Tsinghua), Gang Zhang (Tsinghua)

FASER LOCATION NOW

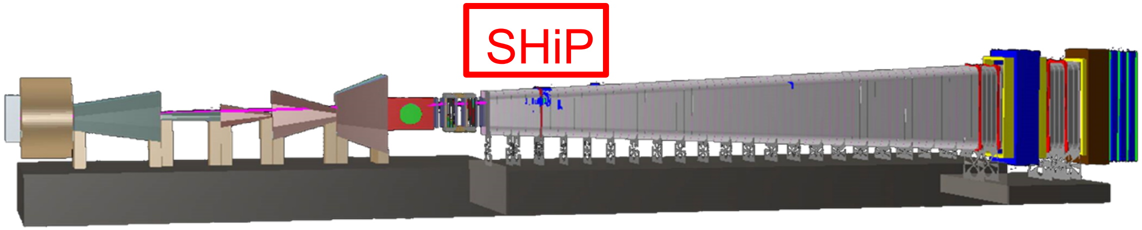
- In TI12, unused ventilation ducts, cables, etc. have been removed to prepare for FASER trench excavation and installation.

FASER CONSTRUCTION NOW

- The main component of FASER is the tracker, composed of spare SCT modules from ATLAS. 8 SCT modules make up a 24cm x 24cm tracking layer, 3 layers make up a tracking station, and FASER has 3 tracking stations. Tests of prototype tracking layers have started.

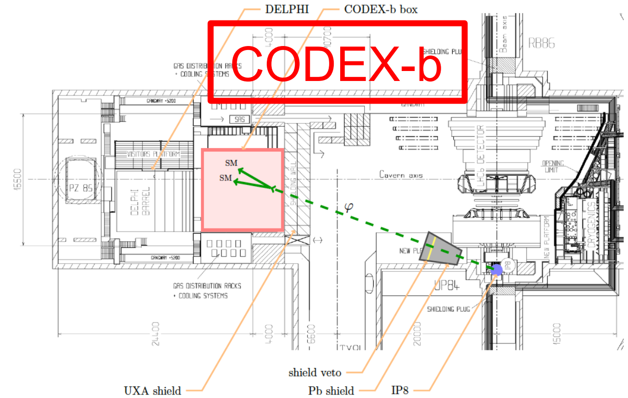


COMPLEMENTARY EXPERIMENTS AT THE LHC



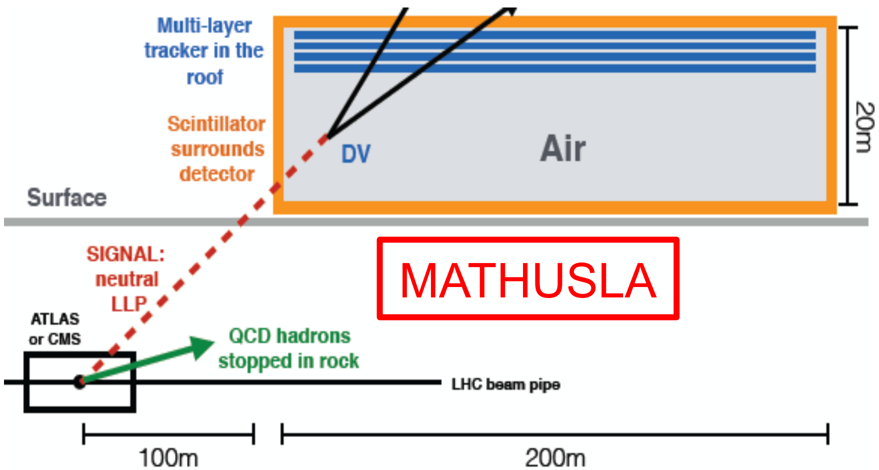
~1000 m^3, ~100M CHF + beam

Alekhin et al. (2015)



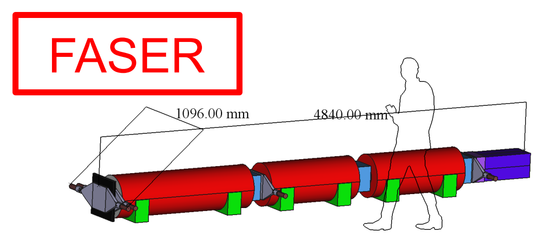
~1000 m^3 ~ 1 mIKEAs

Gligorov, Knapen, Papucci, Robinson (2017)



~800,000 m^3 ~ 1 IKEA, ~$50M

Chou, Curtin, Lubatti (2016)



~1 m^3 ~ 1 μIKEAs

Feng, Galon, Kling, Trojanowski (2017)