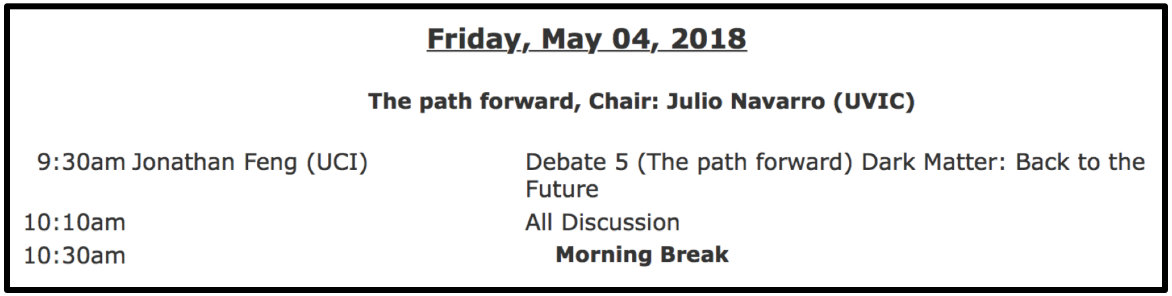
THE PATH FORWARD

Dark Matter Detection and Detectability:
Paradigm Confirmation or Shift?

KITP, Santa Barbara

Jonathan Feng, University of California, Irvine
4 May 2018

OUTLINE



Friday, May 04, 2018

The path forward, Chair: Julio Navarro (UVIC)

9:30am Jonathan Feng (UCI)	Debate 5 (The path forward) Dark Matter: Back to the Future
10:10am	All Discussion
10:30am	**Morning Break**

A rather one-sided debate! Of course, the real goal of a “debate” is to encourage people to get to the heart of the matter and give their frank opinions. In that spirit, I’ll provide my perspective about various topics that have come up at this conference:

- Is dark matter particles?
- Are there small scale structure problems?
- Are WIMPs dead?
- What are promising directions?
- Is our field healthy?

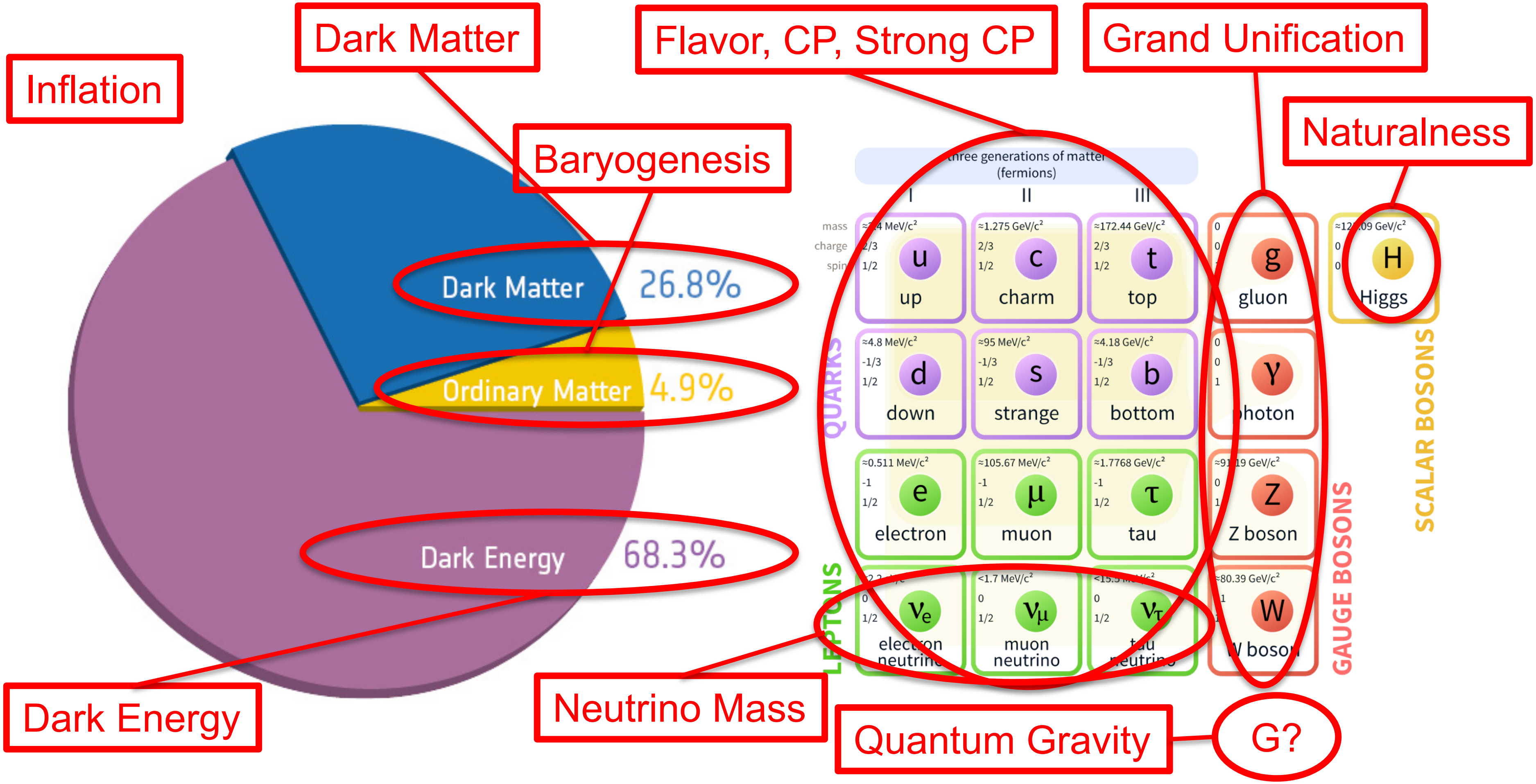
IS DARK MATTER PARTICLES?

IS DARK MATTER PARTICLES?

- Solving the dark matter problem is often posed as a choice: do you want to add new particles or do you want to find a new theory of gravity?

- But this is a false dichotomy -- we need both! The dark matter problem does not exist in isolation.

OUTSTANDING PROBLEMS



Inflation

Dark Matter

Baryogenesis

Flavor, CP, Strong CP

Grand Unification

Naturalness

Dark Energy

Neutrino Mass

Quantum Gravity

G?

IS DARK MATTER PARTICLES?

- The lesson: our standard models are not crystalline gems of perfection; they are works in progress. There are many problems: some demand new particles, some demand new gravity. New theories of gravity do not save us from needing new particles.

- Given that we need new particles, could some be dark matter? In fact, the new particle paradigm solves the dark matter problem with extraordinary efficiency: *one particle* explains a wonderfully broad range of phenomena, a unifying achievement to rival Maxwell's. (Cf. baryogenesis.)

- Of course, we need to find non-gravitational evidence for particle dark matter. But absent that, the case for particle dark matter could not be more compelling.

ARE THERE SMALL SCALE STRUCTURE PROBLEMS?

SMALL SCALE STRUCTURE PROBLEMS?

- Number of subhalos, too big to fail, cusp vs. core: are these problems? Lots of interesting discussion at this meeting; some say Yes, some say No.

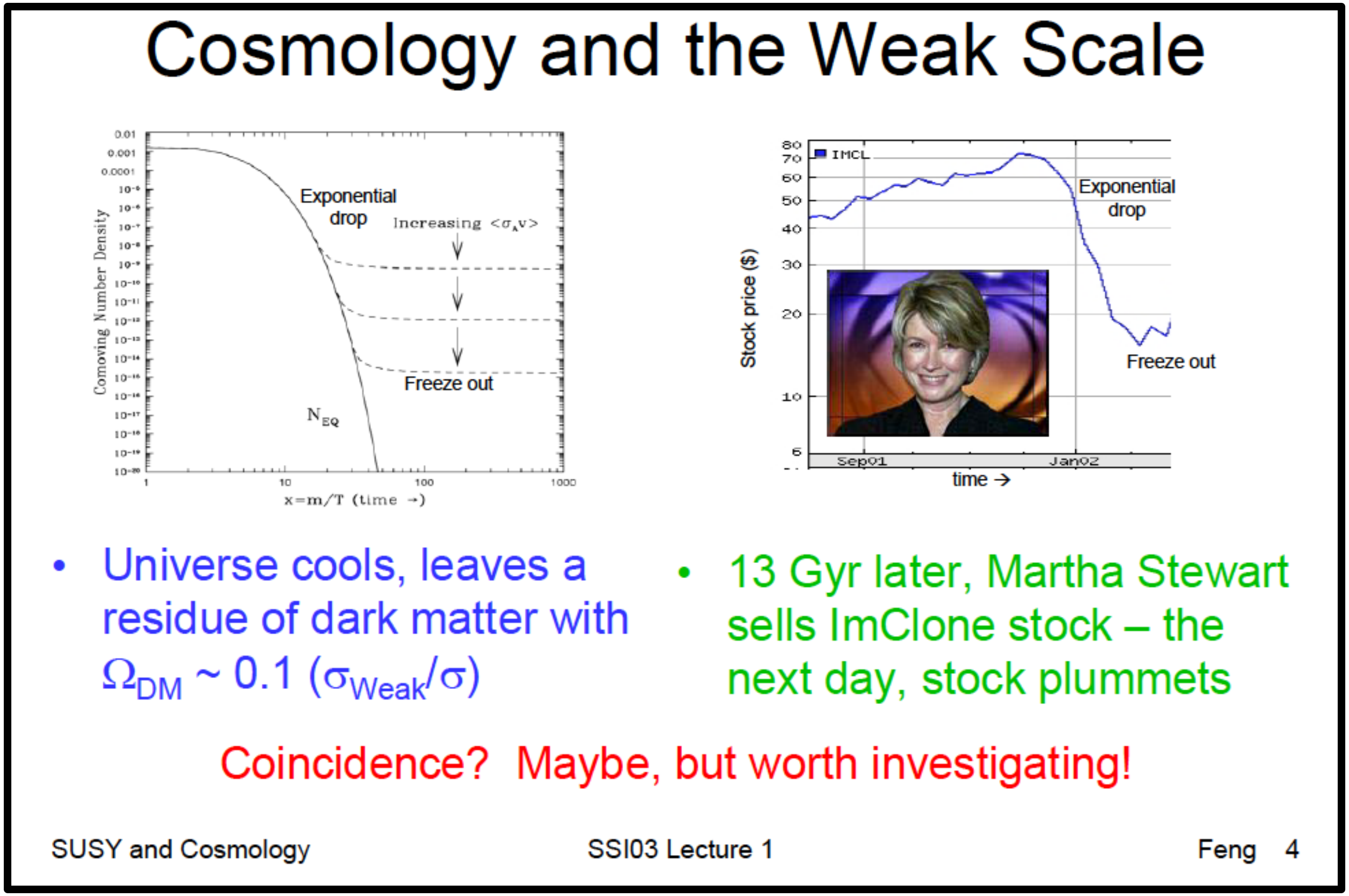
- But this is not a Yes/No question. The real question is: can astrophysics tell us more about the particle properties of dark matter? Given null particle results, this is an essential part of the path forward.

- Some seem enthusiastic when they confirm collisionless, cold DM. This seems odd to me. This means that we have failed to follow in the glorious footsteps of our predecessors by looking to the heavens and learning something significantly new about what makes up the universe. Of course, we want to find the truth, but a twinge of remorse would be more appropriate. (Cf. LHC experimentalists who gleefully confirm the SM.)

ARE WIMPS DEAD?

ARE WIMPS DEAD?

- The WIMP miracle has been a driving force for a long time



Cosmology and the Weak Scale

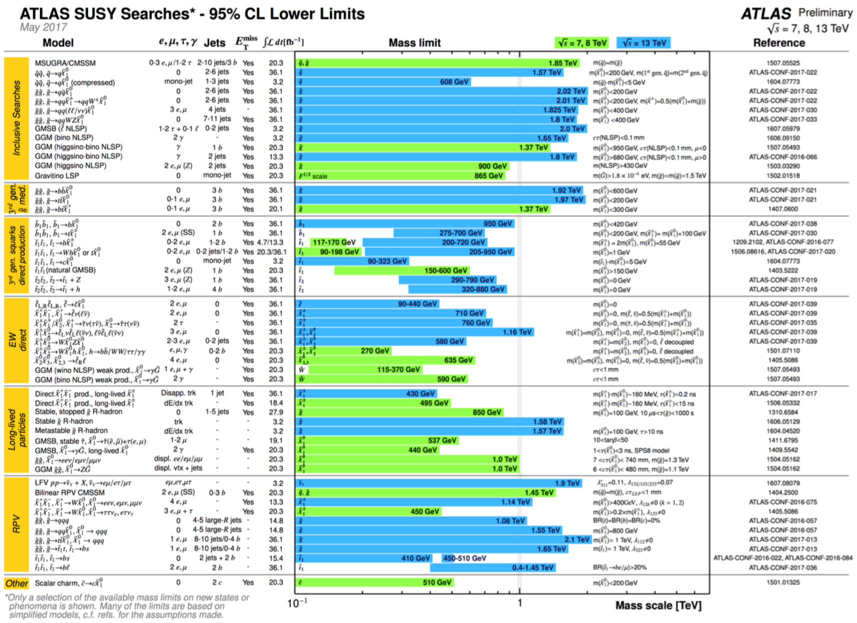
- Universe cools, leaves a residue of dark matter with $\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$
- 13 Gyr later, Martha Stewart sells ImClone stock – the next day, stock plummets

Coincidence? Maybe, but worth investigating!

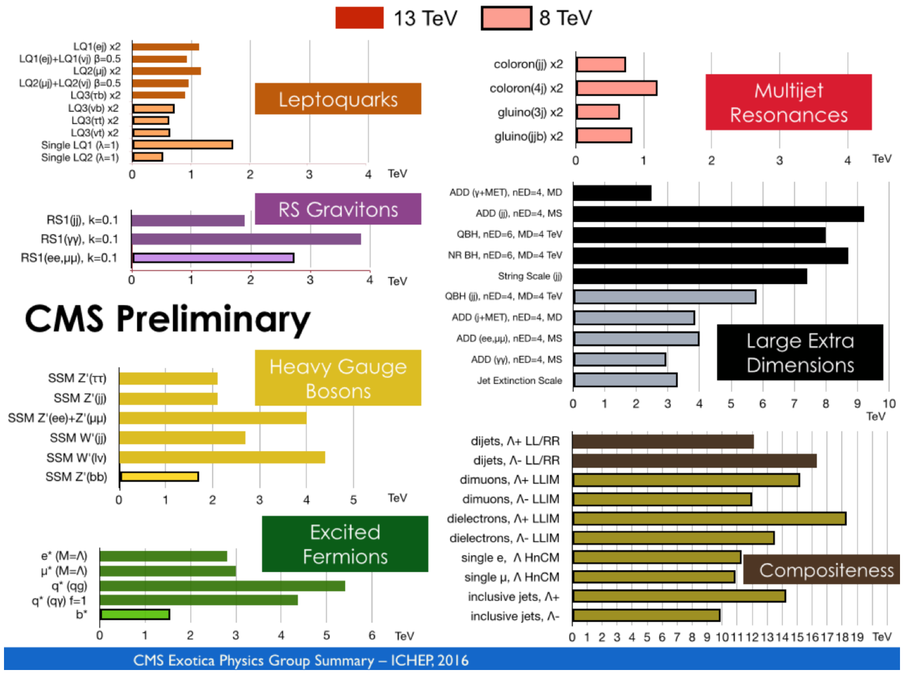
SUSY and Cosmology SSI03 Lecture 1 Feng 4

ARE WIMPS DEAD?

- Of course, WIMPs aren’t dead. But a more interesting question is, how about the leading frameworks that include WIMPs along with other beautiful motivations (e.g., naturalness)? For example: weak-scale supersymmetry.
- There are many constraints on SUSY from the LHC.



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



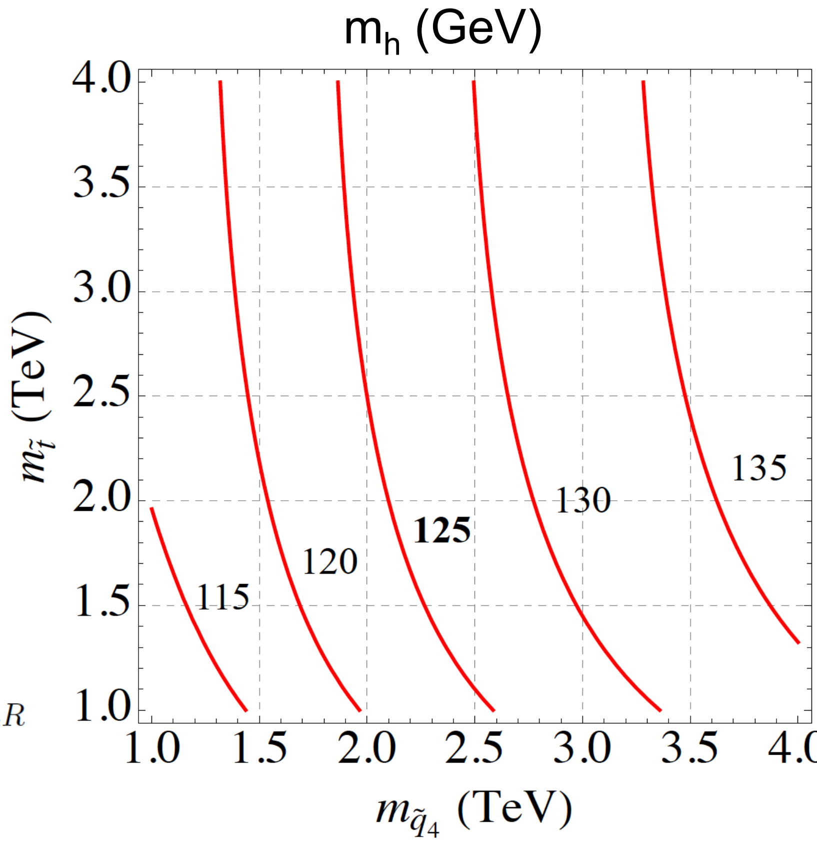
MSSM4G

- But there remain viable models that preserve all of the central motivations for SUSY: e.g., MSSM4G.
- Naturalness suggests light stops and sbottoms; $m_h = 125$ GeV suggests heavy stops and sbottoms.
- A resolution: introduce a vector-like 4th generation of particles to raise the Higgs mass.
- For example, add a 10 of SU(5) consistent with gauge coupling unification:

Dirac fermions: T_4, B_4, t_4, τ_4

Complex scalars: $\tilde{T}_{4L}, \tilde{T}_{4R}, \tilde{B}_{4L}, \tilde{B}_{4R}, \tilde{t}_{4L}, \tilde{t}_{4R}, \tilde{\tau}_{4L}, \tilde{\tau}_{4R}$

Moroi, Okada (1992); Martin (2010)



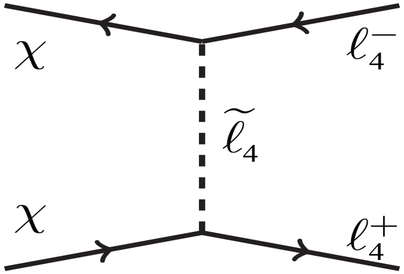
Abdullah, Feng (2015)

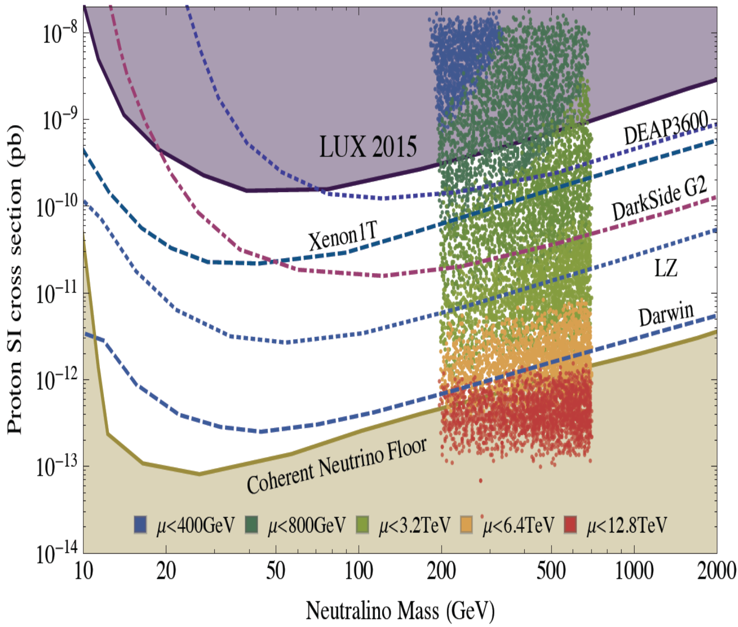
MSSM4G DARK MATTER

- MSSM4G predicts heavy Bino-like dark matter that freezes out with the right thermal relic density through $\chi\chi \rightarrow \tau_4\tau_4$.

- Direct detection cross sections naturally fall between current bounds and the neutrino floor.

- Also interesting signals for LHC, indirect detection (CTA).



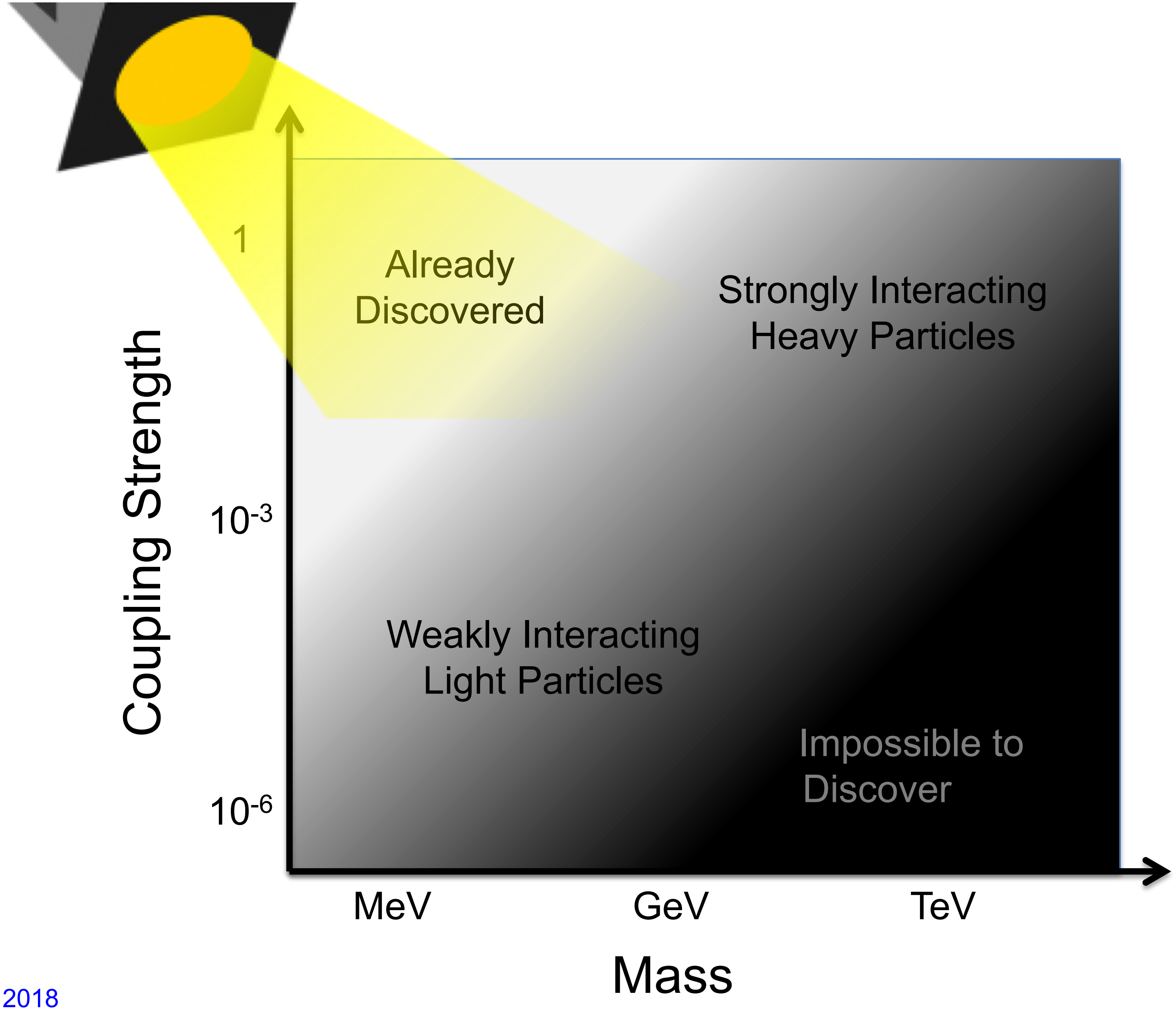


Abdullah, Feng, Iwamoto, Lillard (2016)

Models like these preserve all the fundamental motivations of SUSY and promise an exciting program of discovery for DM and collider searches. The WIMP paradigm is doing fine.

WHAT ARE PROMISING DIRECTIONS?

LAMPPOST LANDSCAPE



WEAKLY INTERACTING, LIGHT PARTICLES

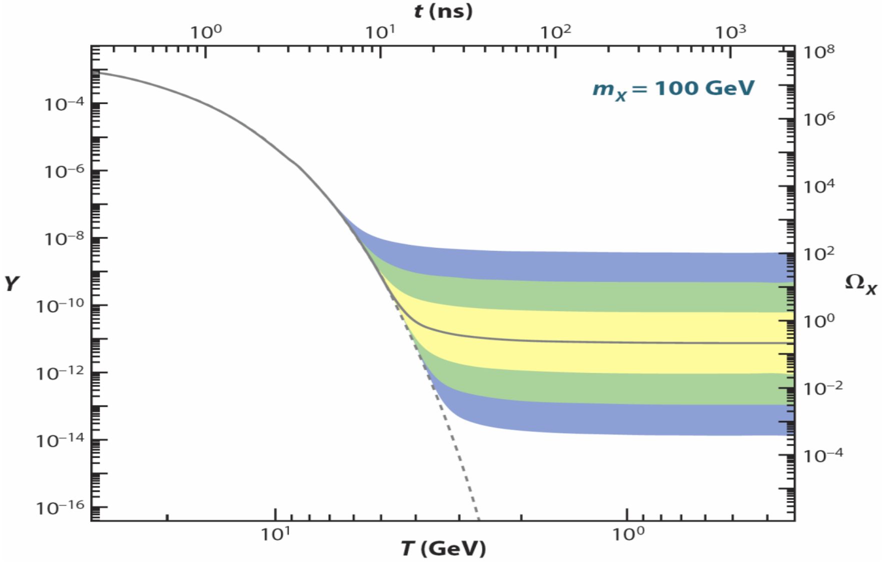
- A new target for new physics searches, but with similarly strong motivations

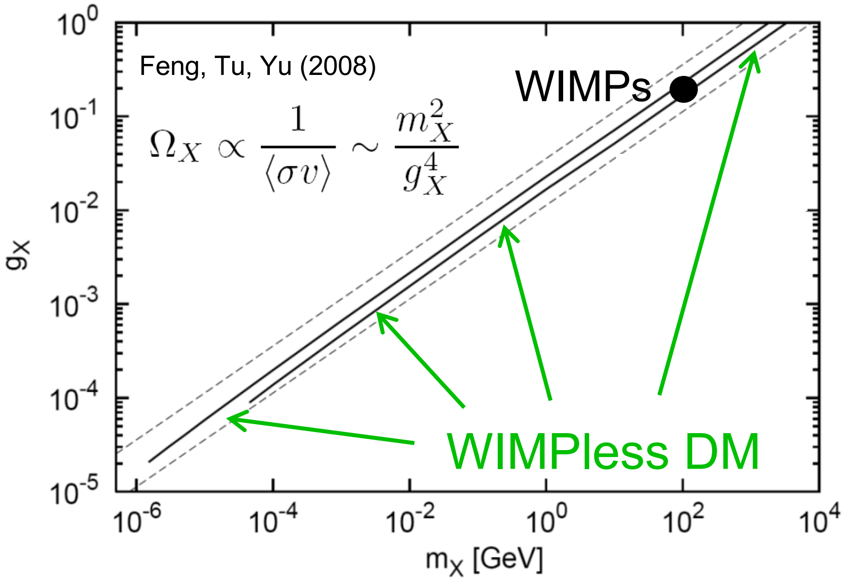
- Weakly interacting, light particles can be thermal relic dark matter.

Boehm, Fayet (2003)

- WIMPless Miracle: in fact, in analogy with the WIMP miracle, the structure of theories motivated by particle physics alone (SUSY with GMSB, AMSB) produces particles with exactly the required properties.

Feng, Kumar (2008)



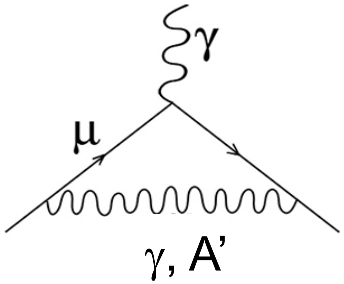


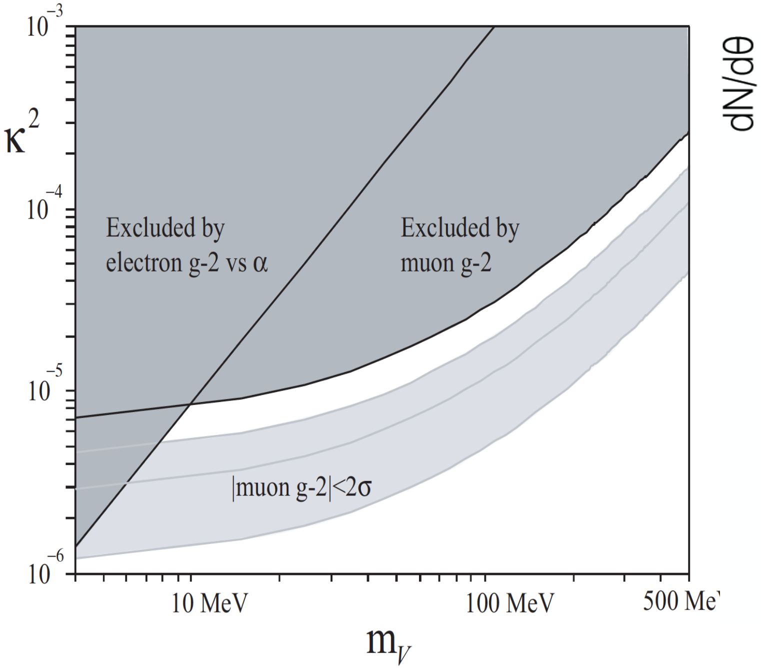
- Weakly-interacting, light particles can naturally have the right thermal relic density, be probed by the intensity frontier, nuclear, AMO, and CM physics.

WEAKLY INTERACTING, LIGHT PARTICLES

- Anomalies

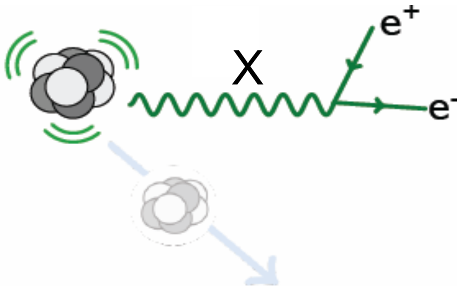
Muon g-2



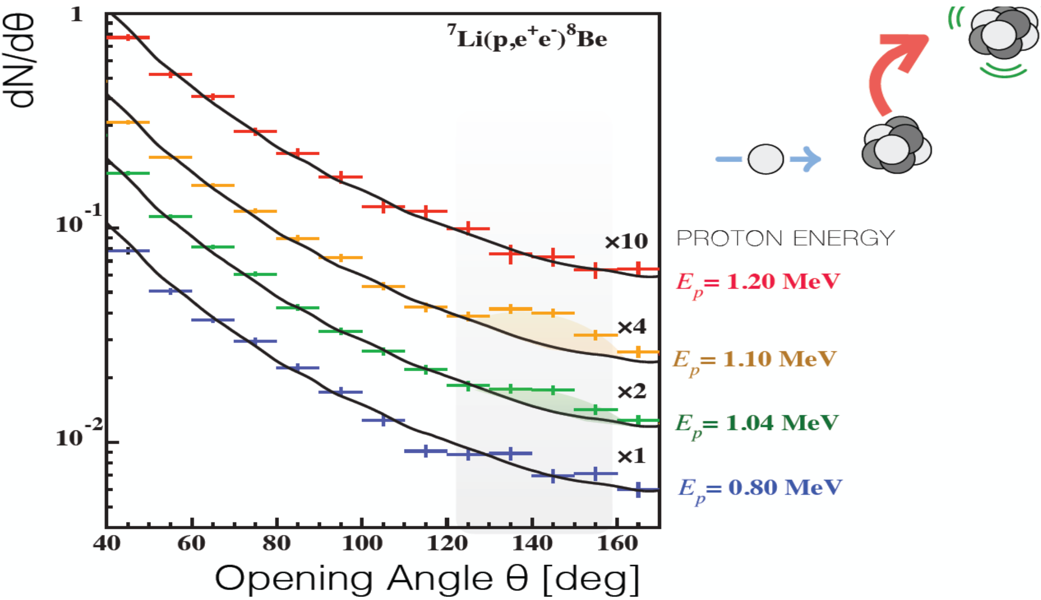


Boehm, Fayet (2003); Pospelov (2008)

^{8}Be

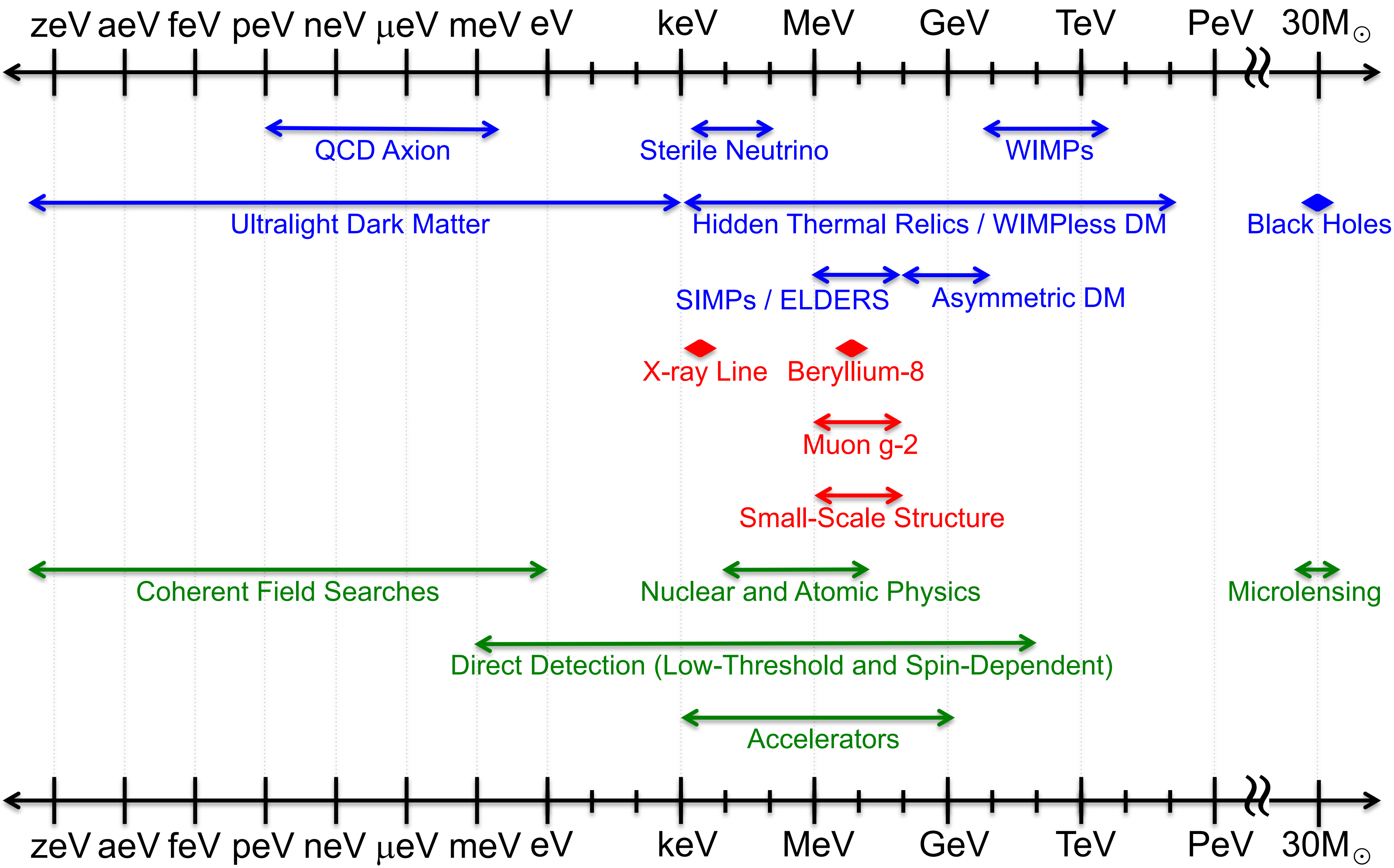


6.8σ anomaly seen in decays → milli-charged, 17 MeV boson



Krasznahorkay et al. (2015)
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)

Dark Sector Candidates, Anomalies, and Search Techniques



QCD Axion

Sterile Neutrino

WIMPs

Ultralight Dark Matter

Hidden Thermal Relics / WIMPless DM

Black Holes

SIMPs / ELDERS

Asymmetric DM

X-ray Line

Beryllium-8

Muon g-2

Small-Scale Structure

Coherent Field Searches

Nuclear and Atomic Physics

Microlensing

Direct Detection (Low-Threshold and Spin-Dependent)

Accelerators

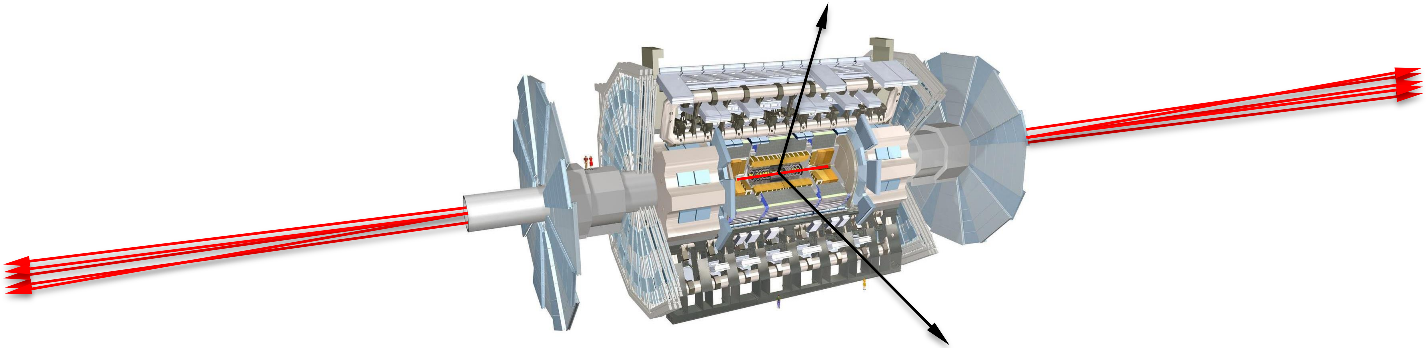
Cosmic Visions Report (2017)

THE LIFETIME FRONTIER

- Light, weakly-interacting particles motivate new connections to other fields of physics: nuclear physics, condensed matter physics, AMO, etc.
- They also typically live a long time, and so motivate new particle physics analyses and experiments, including LHCb, HPS, Belle-II, NA62, SHiP, SeaQuest, MilliQan, MATHUSLA, Codex-b, and many others.
- One example: FASER: ForwArd Search ExpeRiment. "The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds."

FASER: THE IDEA

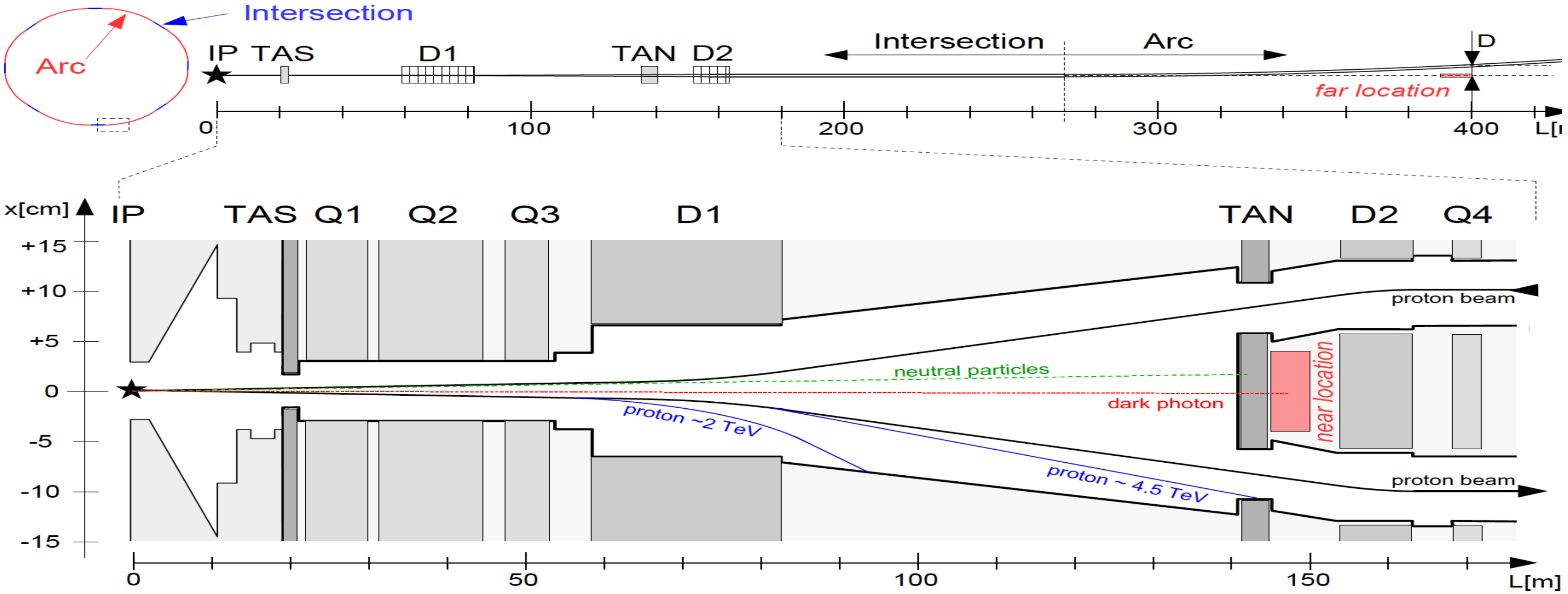
- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly interacting particles
  - $\sigma \sim$ fb to pb → $N \sim 10^3 - 10^6$, produced ~isotropically
- However, if new particles are light and weakly interacting, this may be completely misguided. Instead should exploit
  - $\sigma_{inel} \sim 100$ mb → $N \sim 10^{17}$, $\theta \sim \Lambda_{QCD} / E \sim 250$ MeV / TeV ~ mrad



- FASER is a small (~1 m^3), inexpensive experiment, designed to catch these particles in the very forward region of ATLAS/CMS, a few 100m downstream of the IP.

FASER LOCATION

- We want to place FASER along the beam *collision* axis
  - Far location: ~400 m from IP, after beams curve, ~3 m from the beams
  - Near location: 150 m, after TAN, between the beams



Feng, Galon, Kling, Trojanowski (2017)

- Here, focus on far location, assume FASER is exactly on-axis

- If ATLAS/CMS beams cross at 285 (590) μrad in vertical/horizontal plane, far location shifts by 6 (12) cm

DARK PHOTONS

- Dark matter is our most solid evidence for new particles. In recent years, the idea of dark matter has been generalized to dark sectors.

- A prominent example: vector portal, leading to dark photons

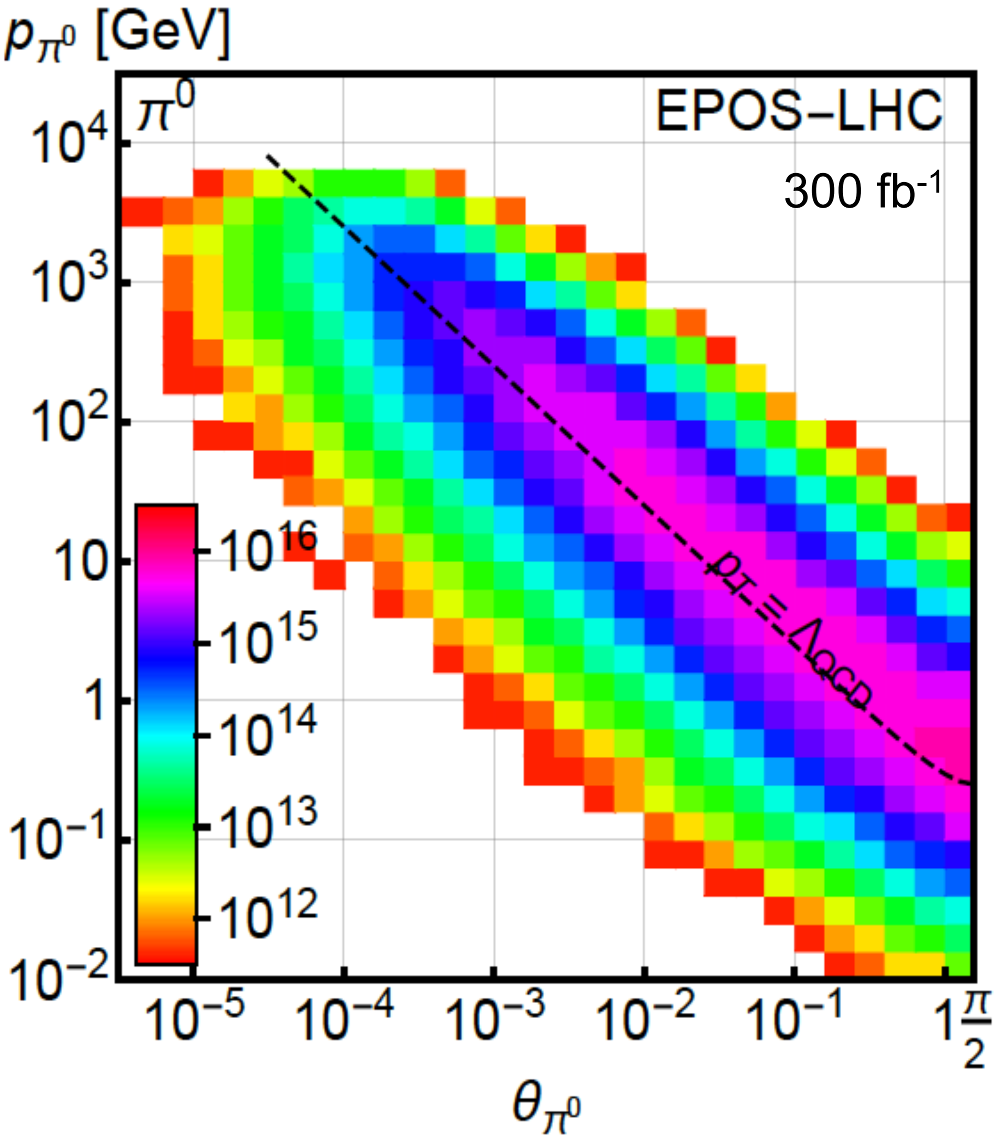
SM - - - $\epsilon F_{\mu\nu} F^{\mu\nu}_{\text{hidden}}$ - - - Hidden U(1)

- The resulting theory contains a new gauge boson A' with mass $m_{A'}$ and εQ_f couplings to SM fermions f.

- Dark photons are produced in $\pi^0 \rightarrow A' \gamma$, decay after ~100 m.

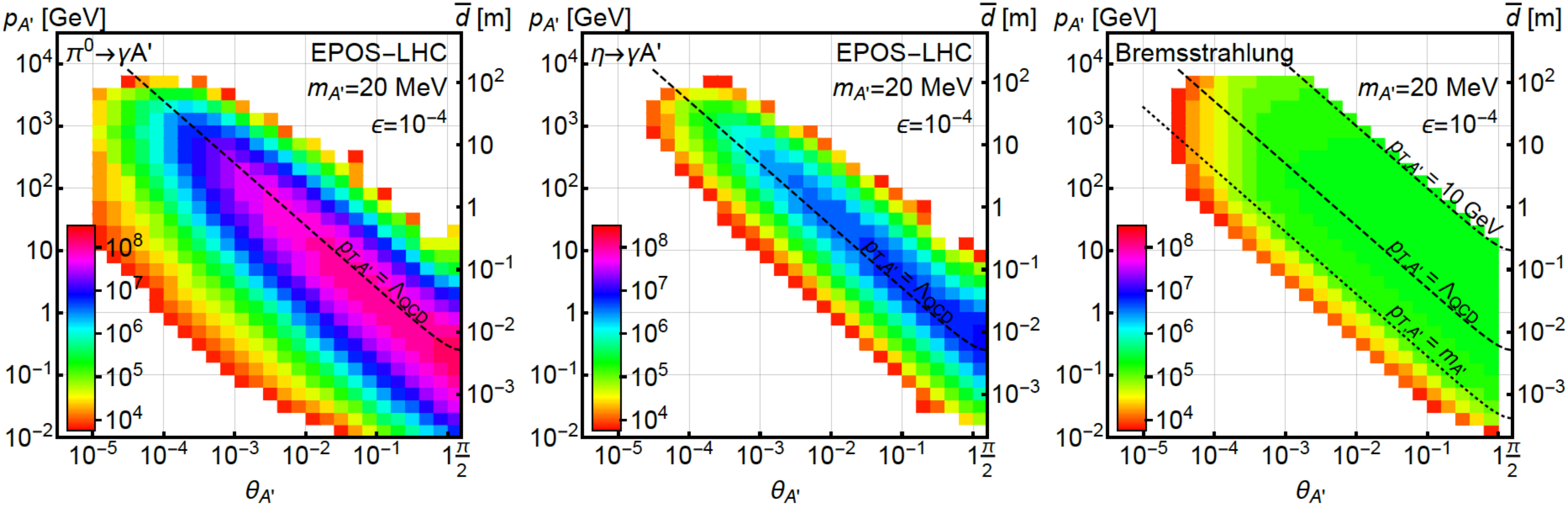
PION PRODUCTION AT THE LHC

- Forward particle production simulations and models have been greatly constrained by LHC data
- EPOS-LHC, SIBYLL 2.3, QGSJETII-04 agree very well
- Enormous event rates (σ_{inel}~70 mb, N_{inel}~10^{17}), production is peaked at $p_T \sim \Lambda_{QCD}$



DARK PHOTON PRODUCTION

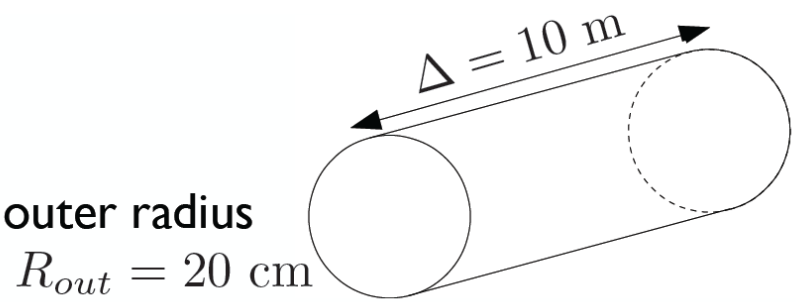
- Consider π^0 decay, η decay, dark bremsstrahlung
- Results for 1st model point: $(m_{A'}, \varepsilon) = (20\ \text{MeV}, 10^{-4})$

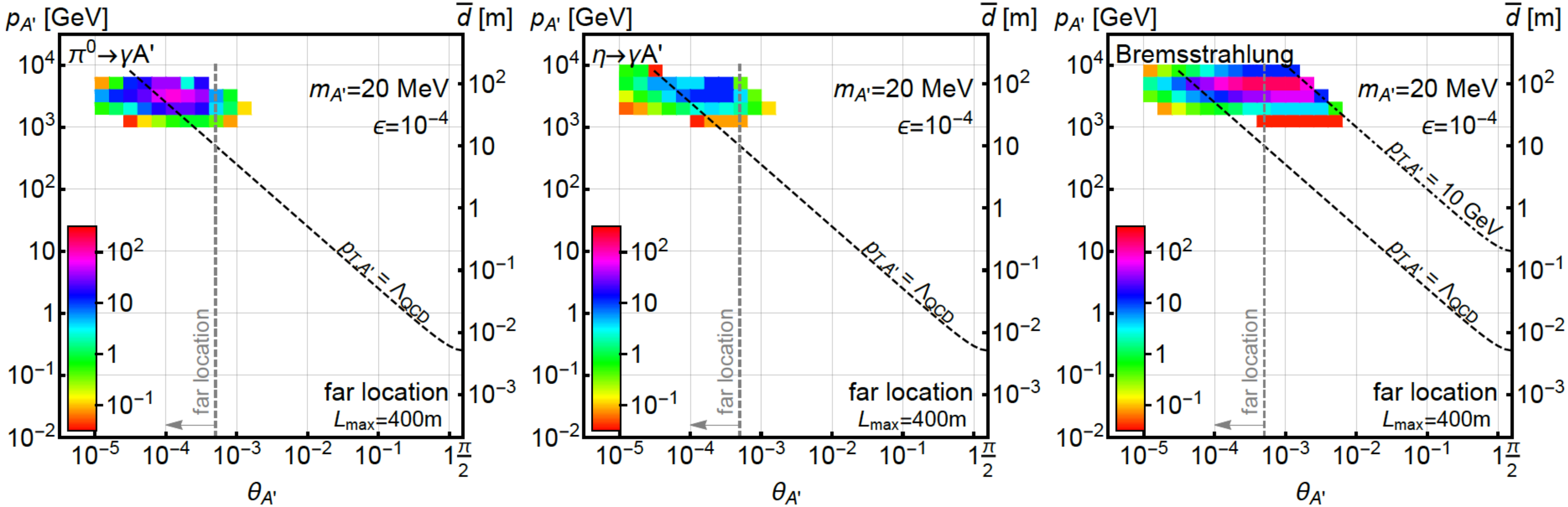


- From $\pi^0 \to \gamma A'$, $E_{A'} \sim E_\pi / 2$ (no surprise)
- But note rates: even after ε^2 suppression, $N_{A'} \sim 10^8$; LHC may be a dark photon factory!

DARK PHOTONS IN FASER

- Now require dark photons to decay in FASER: consider cylindrical detector with volume ~1 m^2

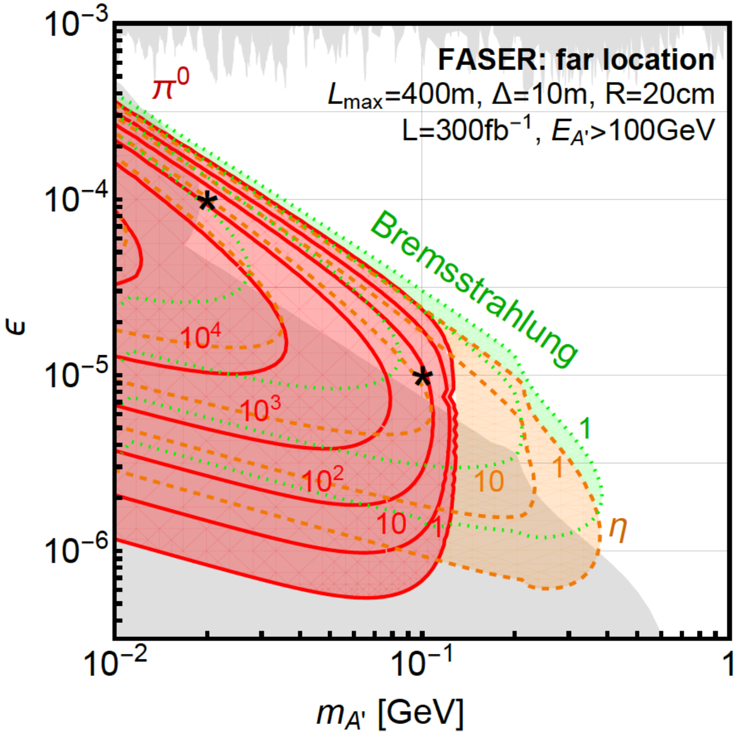


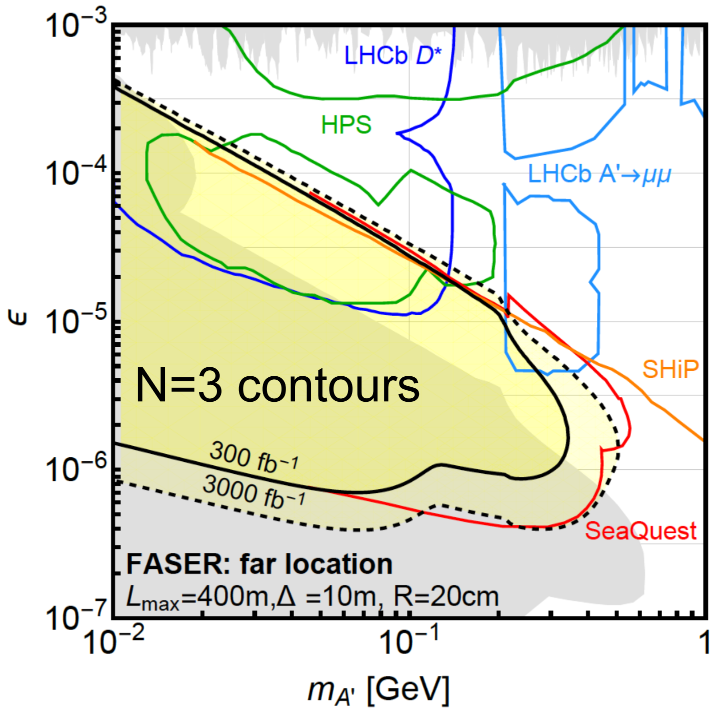


- Only the highest energy A's survive, but there are still many of them, and they are highly collimated

DARK PHOTON EVENT RATES AND REACH

- Up to 10^5 dark photons decay in FASER in 300 fb^{-1} in parameter regions with $m_{A'} \sim 10 - 500$ MeV, $\varepsilon \sim 10^{-6} - 10^{-3}$

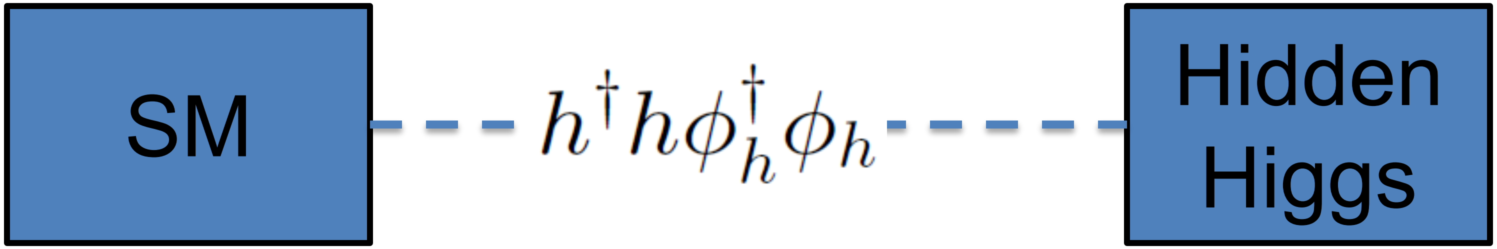




- Note that at upper ε boundary, rates are extremely sensitive to ε and the reach is quite insensitive to background, provided it is known

DARK HIGGS BOSONS

- Another renormalizable coupling: Higgs portal



SM

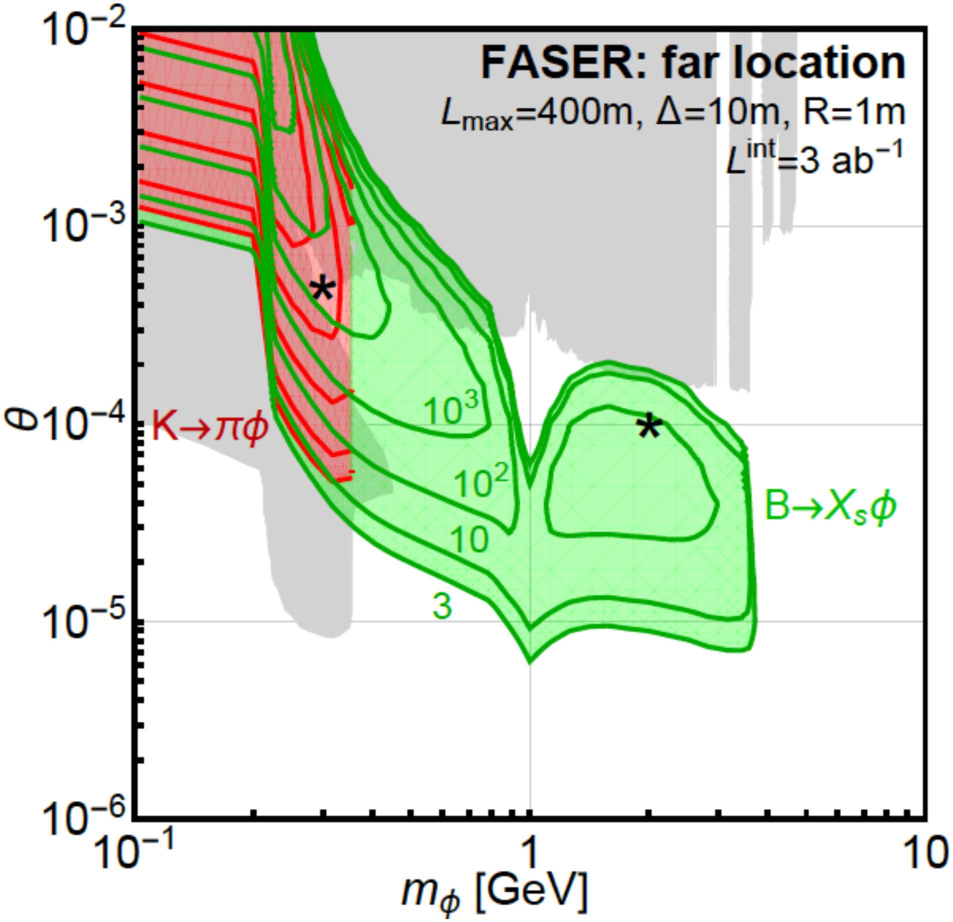
$h^\dagger h \phi_h^\dagger \phi_h$

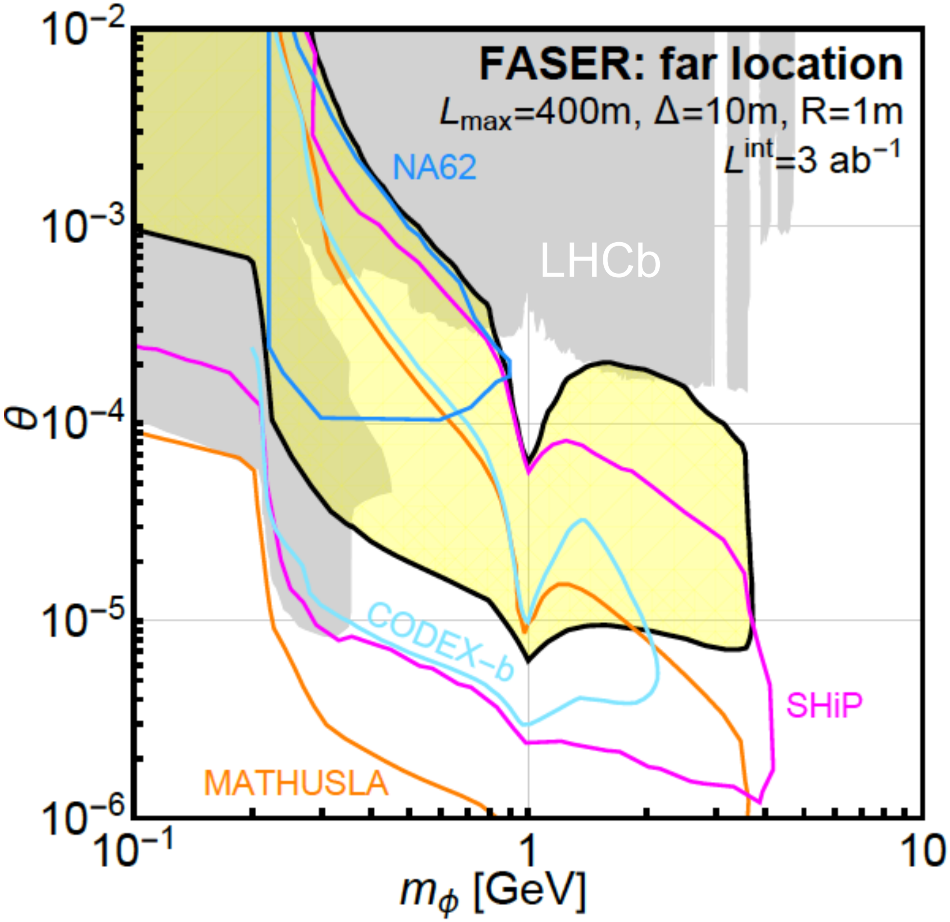
Hidden Higgs

- The resulting theory contains a new scalar boson ϕ with mass m_ϕ , Higgs-like couplings suppressed by sin θ, and a trilinear coupling λ

$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \, \frac{m_f}{v} \, \phi \bar{f} f - \lambda v h \phi \phi + \ldots$$

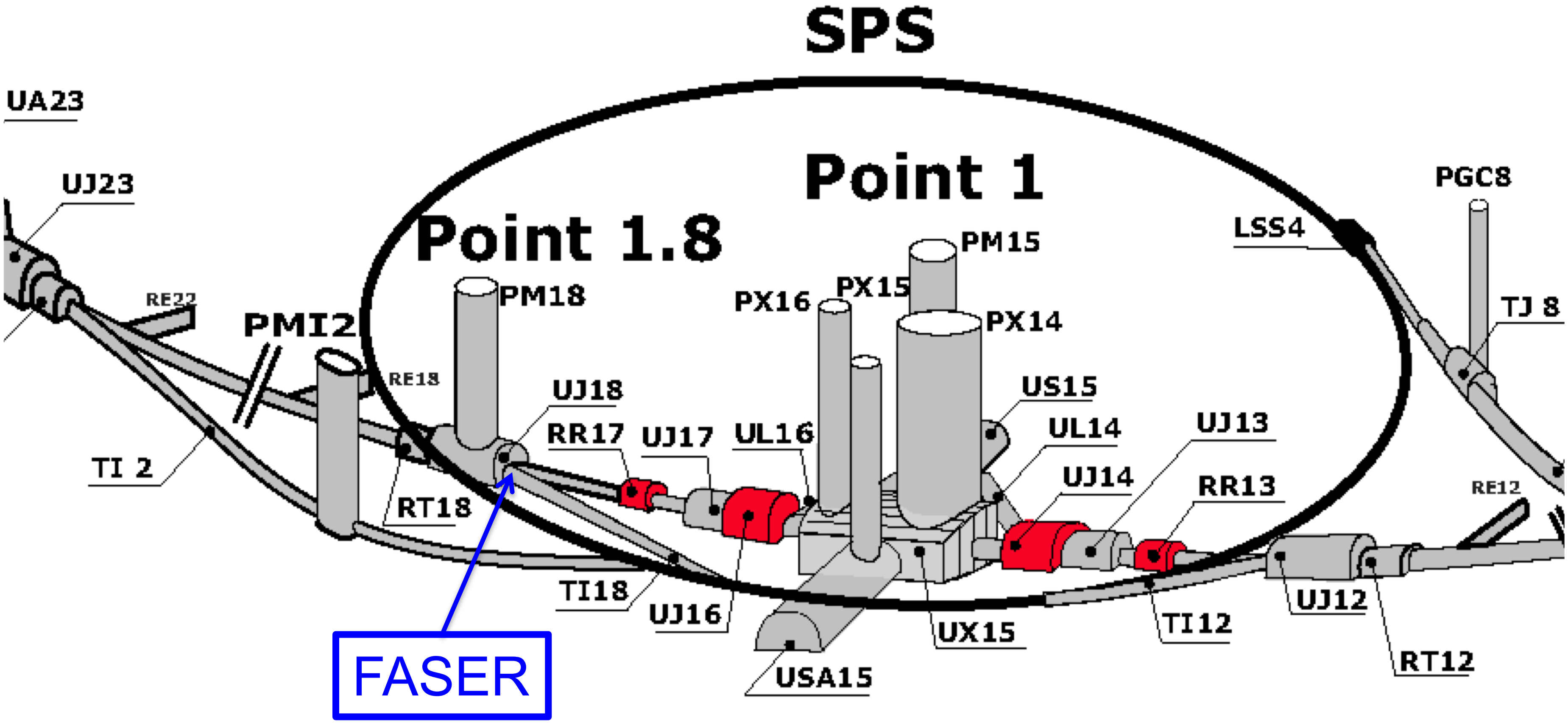
DARK HIGGS EVENT RATES AND REACH





- FASER probes a large swath of new parameter space and is complementary to other current and proposed experiments

FASER: LOCATION



FASER

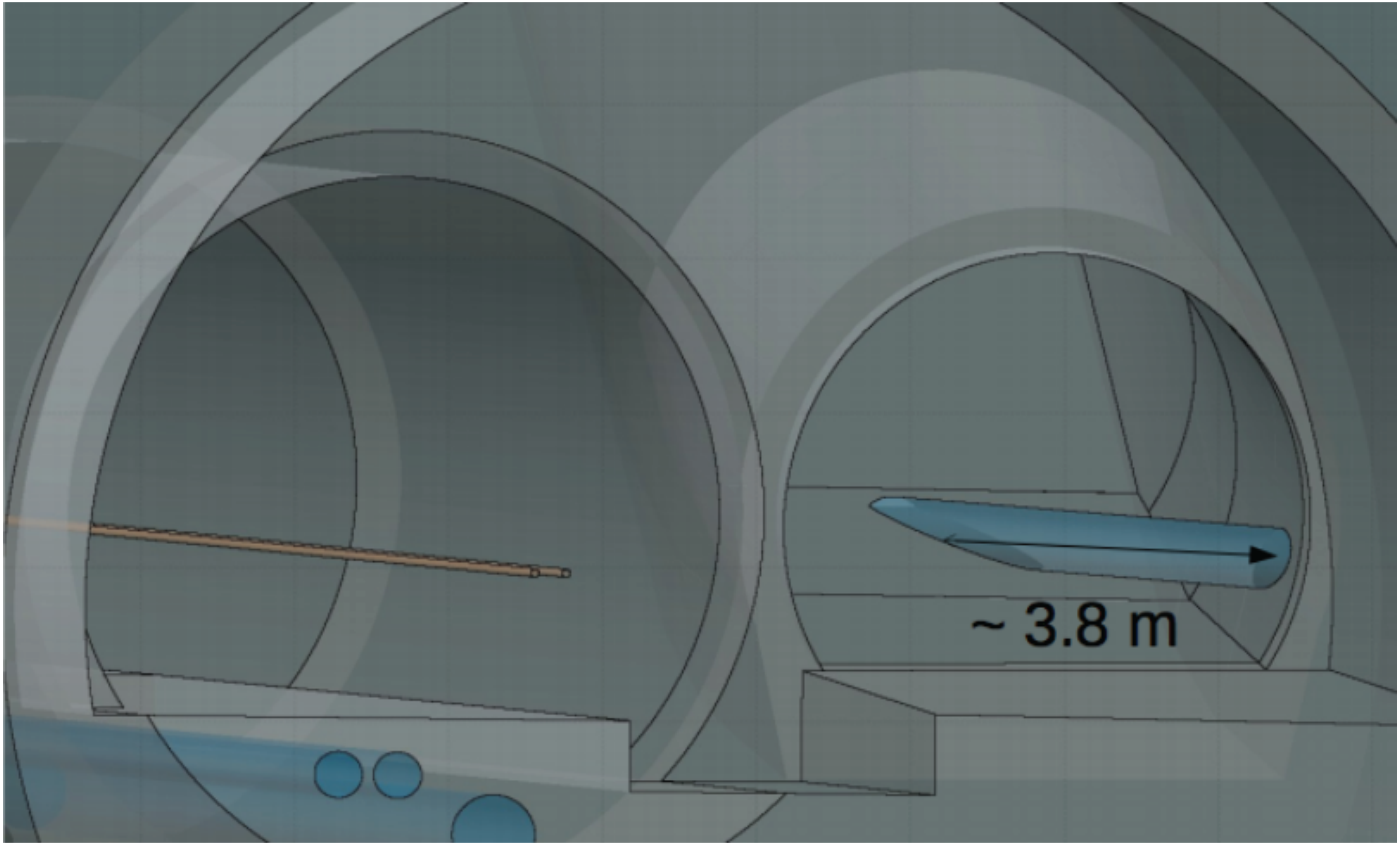
ATLAS

FASER: LOCATION

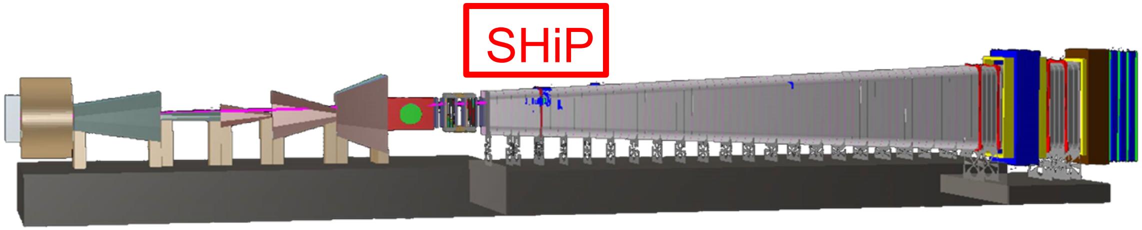
FASER: LOCATION

FASER: LOCATION

FASER: LOCATION

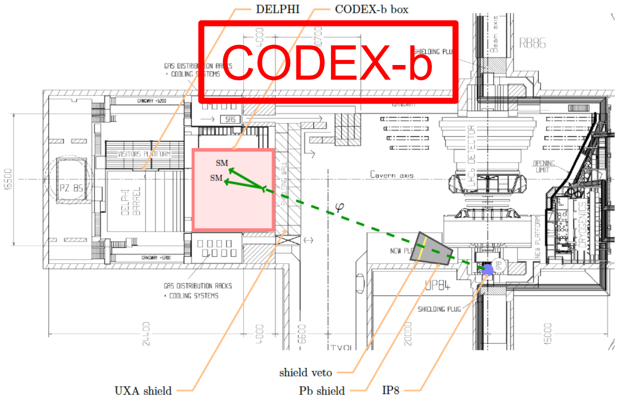


COMPLEMENTARY PROPOSED EXPERIMENTS



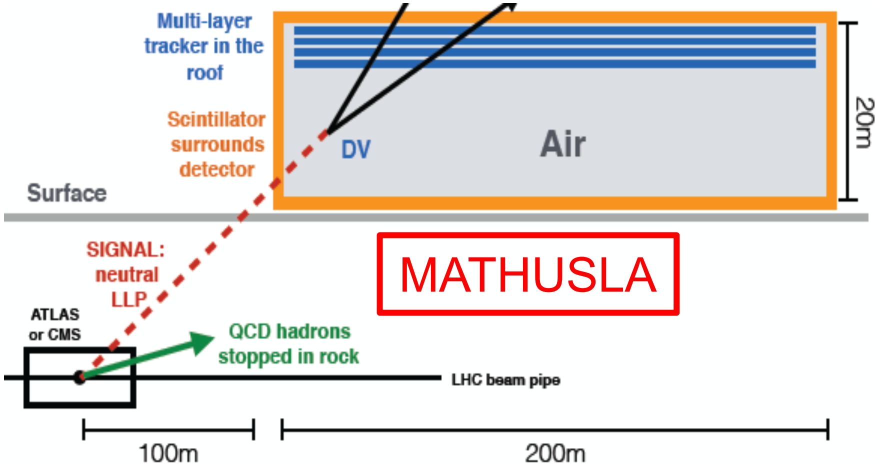
~1000 m^3, ~100M CHF + beam

Alekhin et al. (2015)



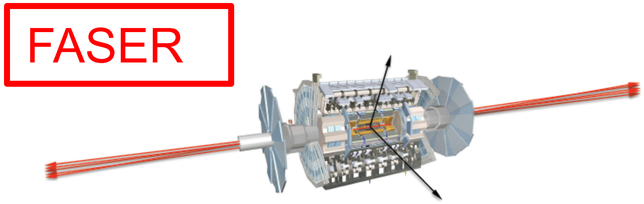
~1000 m^3

Gligorov, Knapen, Papucci, Robinson (2017)



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

Chou, Curtin, Lubatti (2016)



~1 m^3 ~ 1 μIKEA

Feng, Galon, Kling, Trojanowski (2017)

IS OUR FIELD HEALTHY?

NEWTON AND NATURALNESS

- In 1687, Isaac Newton published the *Principia*. 6 years later, a clergyman, Robert Bentley, asked him how the law of universal gravitation could be consistent with a static universe.

- Newton's rueful reply: "That there should be a central particle, so accurately placed in the middle, as to be always equally attracted on all sides, and thereby continue without motion, seems to me a supposition fully as hard as to make the sharpest needle stand upright on its point upon a looking-glass."

IS OUR FIELD HEALTHY?

- It would be hundreds of years before the answer was clear: the universe is not actually static.
- We are in a similar situation: we are 6 years past a triumphant discovery, the completion of the standad model, and it seems to have a small naturalness problem.
- It would be great to discover dark matter tomorrow, and it could very well happen, but there is no guarantee of fast answers.

IS OUR FIELD HEALTHY?

- There are many good signs, though.
- Huge influx of new ideas, cross pollination between particle physics and astrophysics, of course, but also now nuclear physics, condensed matter physics, AMO.
- Experiments: ~10 collaborators, ~$1M, ~few years.
- The barrier between experiment and theory (on the particle side) has never been lower in my scientific lifetime. (Overheard conversation among theory graduate students: “The only way to get a job now is to propose and build an experiment.”)
- Lots of interested, talented young people. (Compare DMSAG and Cosmic Visions.)

CONCLUSIONS

- Is dark matter particles?

SURE LOOKS LIKE IT

- Small scale structure problems?

LET'S HOPE SO

- Are WIMPs dead?

NO

- What are promising directions?

LIGHT DM

- Is our field healthy?

YES!