Particle Physics Parallel Session Summary

TRIUMF Science Week 2020

Patrick de Perio & David McKeen

Talks by Daniel Stolarski, Joseph Formaggio, & Masha Baryakhtar

Particle Physics: A Roadmap for Discoveries

Tim M.P. Tait

Daniel Stolarski
Discovery Opportunities at Future Colliders

Masha Baryakhtar
Discoveries at the Precision Frontier: Axions and New Ultralight Particles

Joseph Formaggio
Trying to weigh the lightest particles in the universe without losing your patience

The Future Gets Brighter?

- With the discovery of the Higgs boson, the Standard Model of Particle Physics has been established as a complete theory that could in principle describe physics up to very high energies.
- Still, many questions remain:
  - The nature of dark matter and dark energy
  - The origin of the baryon asymmetry of the Universe.
  - Flavor and neutrino masses.
- Future experiments, including the high luminosity Large Hadron Collider, future observatories, and searches for dark matter offer the opportunity to shed light on these mysteries.
- The next few years offer the opportunity for great discoveries!

Discovery Opportunities at Future Colliders

Daniel Stolarski

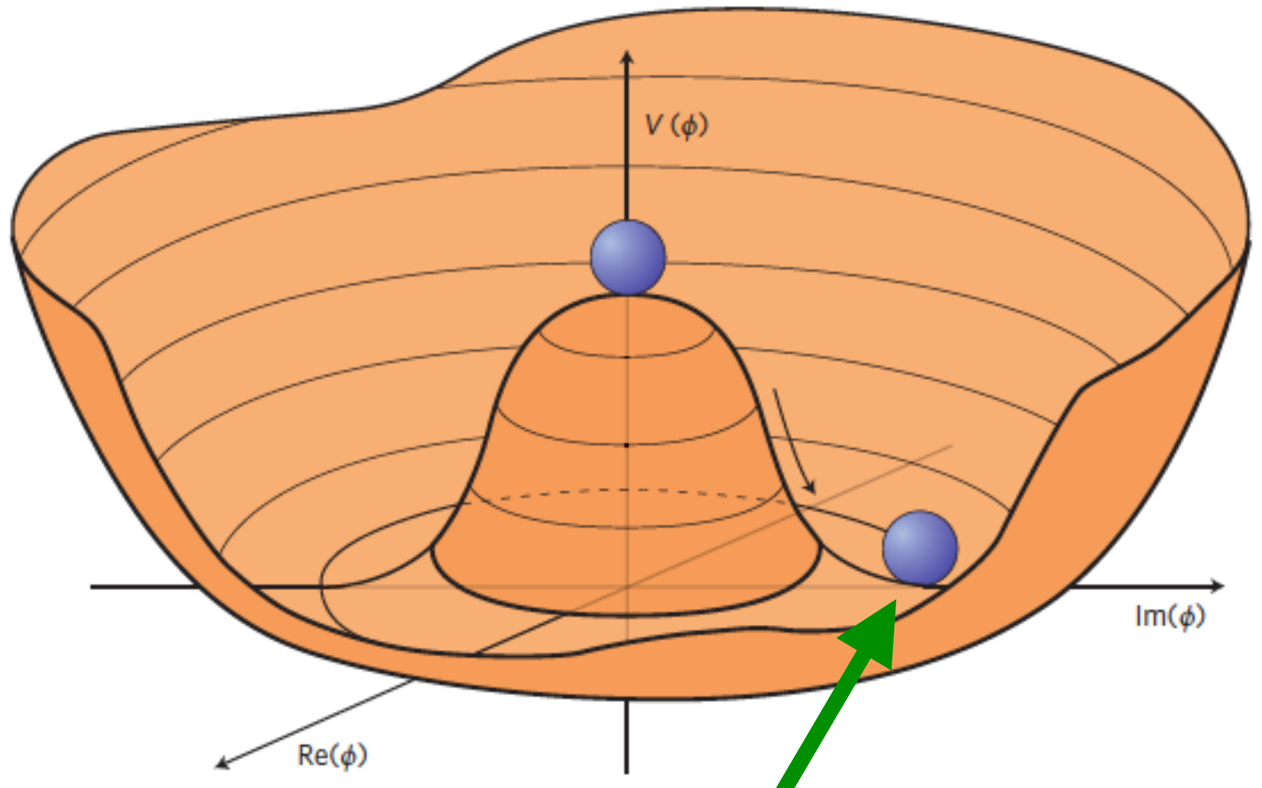
We've discovered the Higgs boson but we **do not know** much about its potential

HIGGS POTENTIAL

SM says Higgs breaks electroweak symmetry with this potential.

No direct experimental evidence of this.

Can measure derivatives of potential.



Taylor series:

$$V(h) \sim \frac{1}{2} m_h^2 h^2 + \frac{1}{3!} \lambda_3 h^3 + \frac{1}{4!} \lambda_4 h^4 + \dots$$

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Discovery Opportunities at Future Colliders

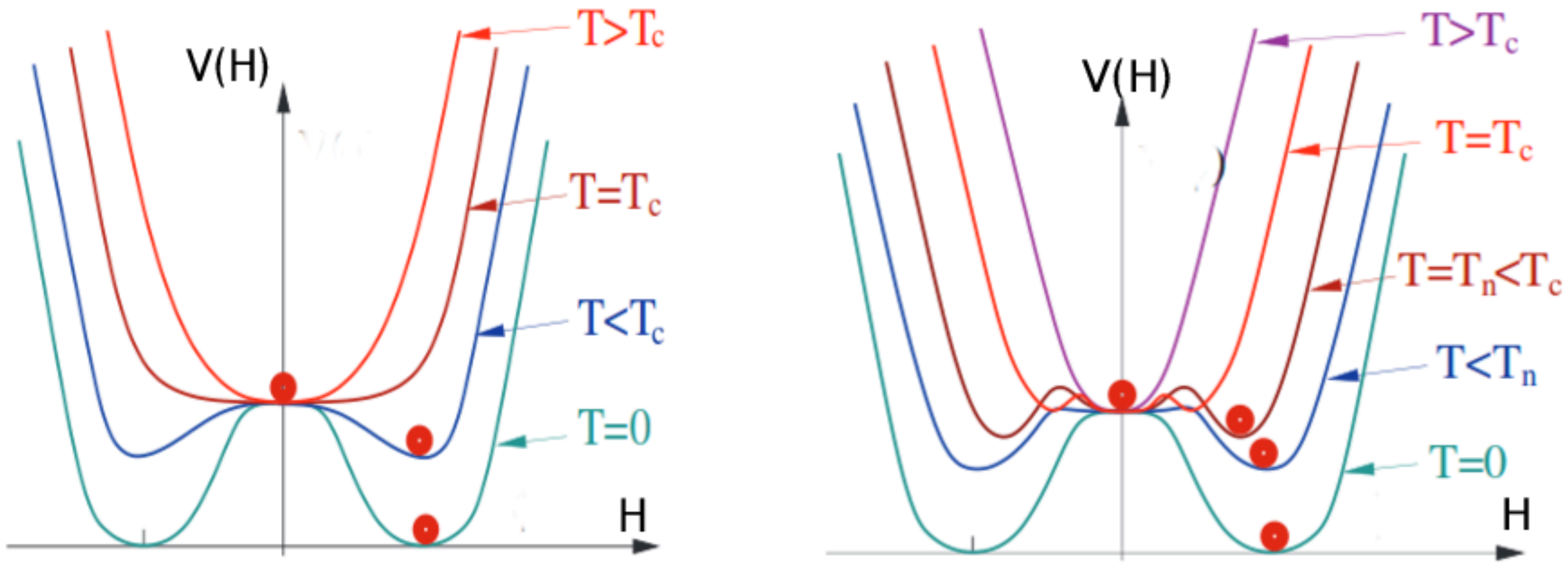
Daniel Stolarski

We’ve discovered the Higgs boson but we **do not know** much about its potential

Shape of the Higgs potential can tell us about why we are here

ELECTROWEAK PHASE TRANSITION (hh)

In the early universe, electroweak symmetry is restored.



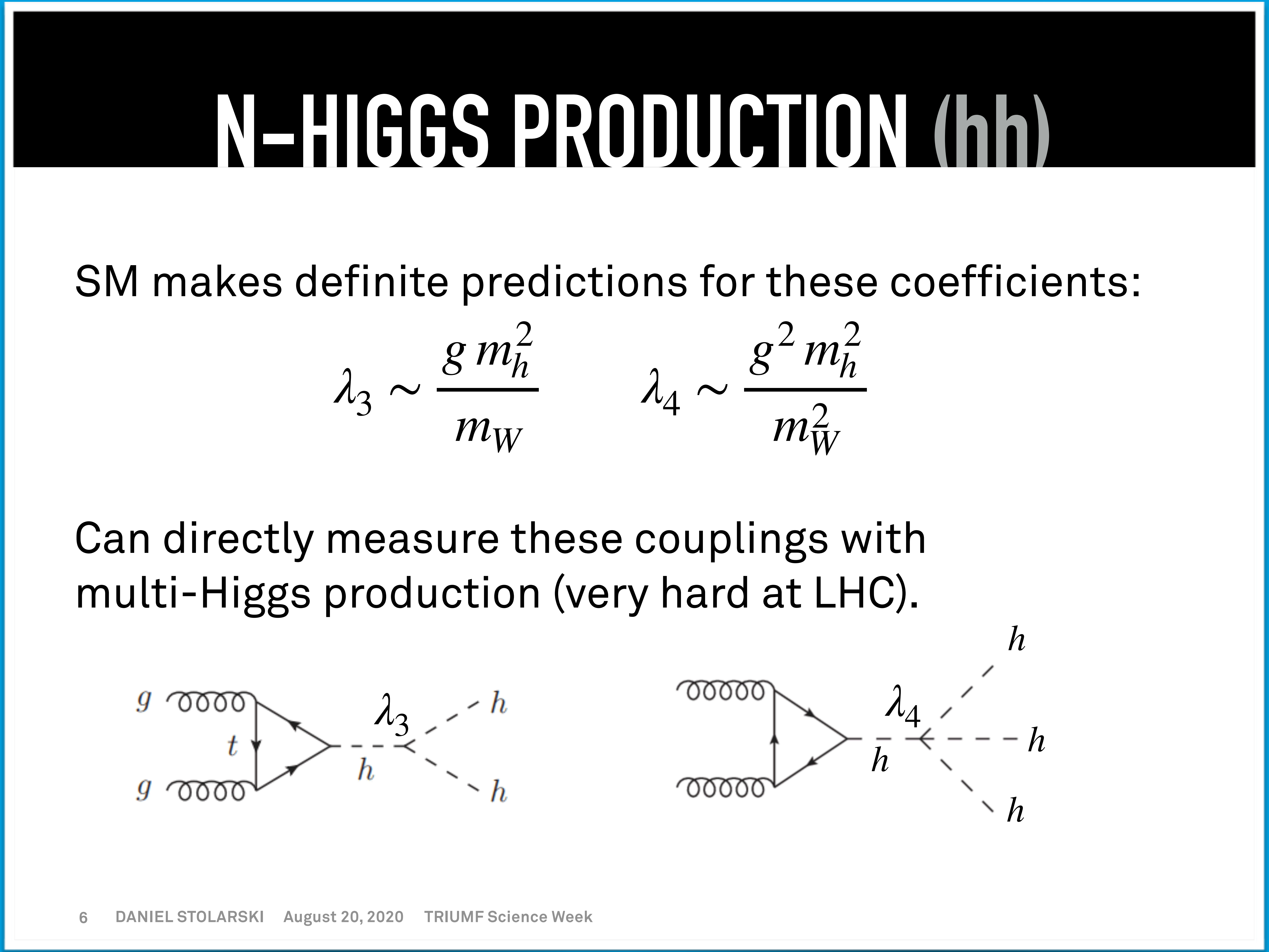
BSM theories (with new states) could have violent transition, possible baryogengesis mechanism.

Curtin, Meade, Yu, arXiv:1409.0005. See also talk by T. Tait on Wednesday.

Discovery Opportunities at Future Colliders

Daniel Stolarski

To map out the Higgs potential we need new colliders



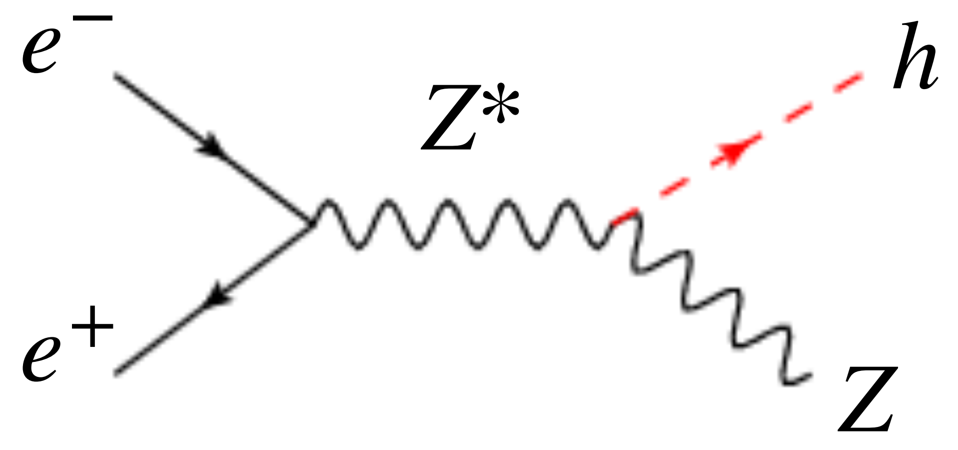
Discovery Opportunities at Future Colliders

Daniel Stolarski

Future colliders can also tell us about new states (e.g. DM) that are impossible to see at the LHC

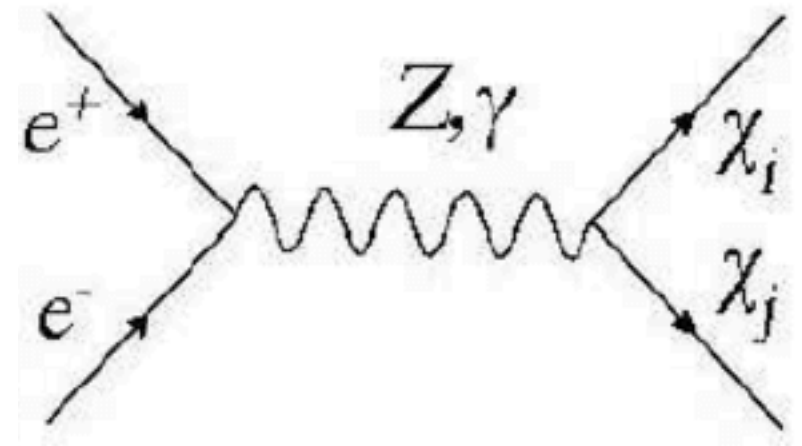
NEW LIGHT PARTICLES (ee/he?)

In lepton collider, can use knowledge of initial state to detect that a Higgs was created without seeing it.



Search for Higgs decays to new particles.

Can also look for new electroweakly charged particles with difficult decays.



Could be connected to dark matter or SUSY.

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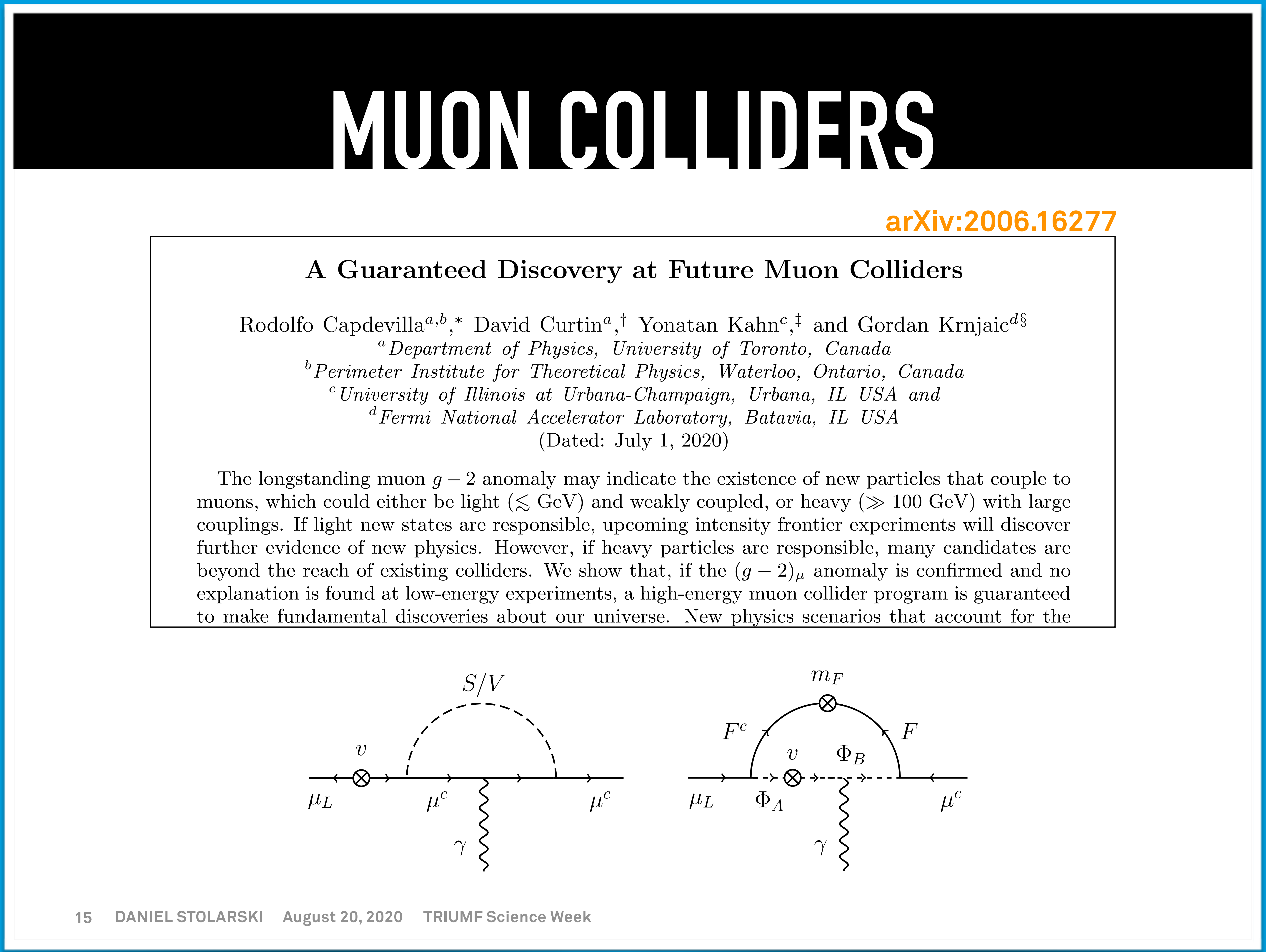
Discovery Opportunities at Future Colliders

Daniel Stolarski

If muon g-2 remains discrepant from SM value, future muon collider has a "no lose theorem"



MUON COLLIDERS

arXiv:2006.16277

A Guaranteed Discovery at Future Muon Colliders

Rodolfo Capdevilla[a,b,*] David Curtin[a,†] Yonatan Kahn[c,‡] and Gordan Krnjaic[d§]
[a] Department of Physics, University of Toronto, Canada
[b] Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
[c] University of Illinois at Urbana-Champaign, Urbana, IL USA and
[d] Fermi National Accelerator Laboratory, Batavia, IL USA
(Dated: July 1, 2020)

The longstanding muon $g-2$ anomaly may indicate the existence of new particles that couple to muons, which could either be light ($\lesssim$ GeV) and weakly coupled, or heavy ($\gg$ 100 GeV) with large couplings. If light new states are responsible, upcoming intensity frontier experiments will discover further evidence of new physics. However, if heavy particles are responsible, many candidates are beyond the reach of existing colliders. We show that, if the $(g-2)_\mu$ anomaly is confirmed and no explanation is found at low-energy experiments, a high-energy muon collider program is guaranteed to make fundamental discoveries about our universe. New physics scenarios that account for the

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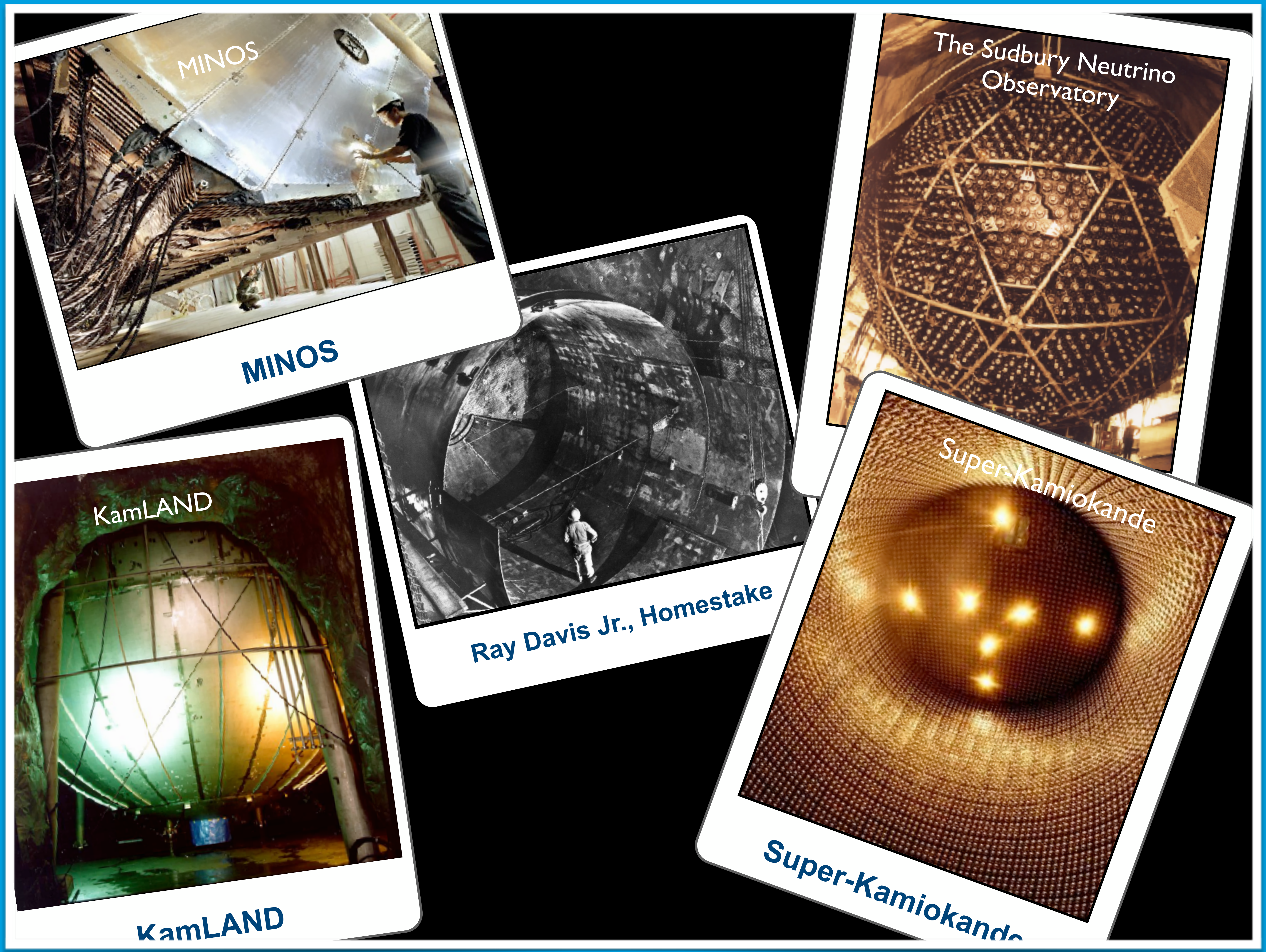
Weighing the Lightest Particles

Joseph Formaggio

A myriad of experiments demonstrated that neutrinos transmute flavor (oscillate).

Proof that neutrinos must have mass.

There are predictions that stem from alteration of the Standard Model.

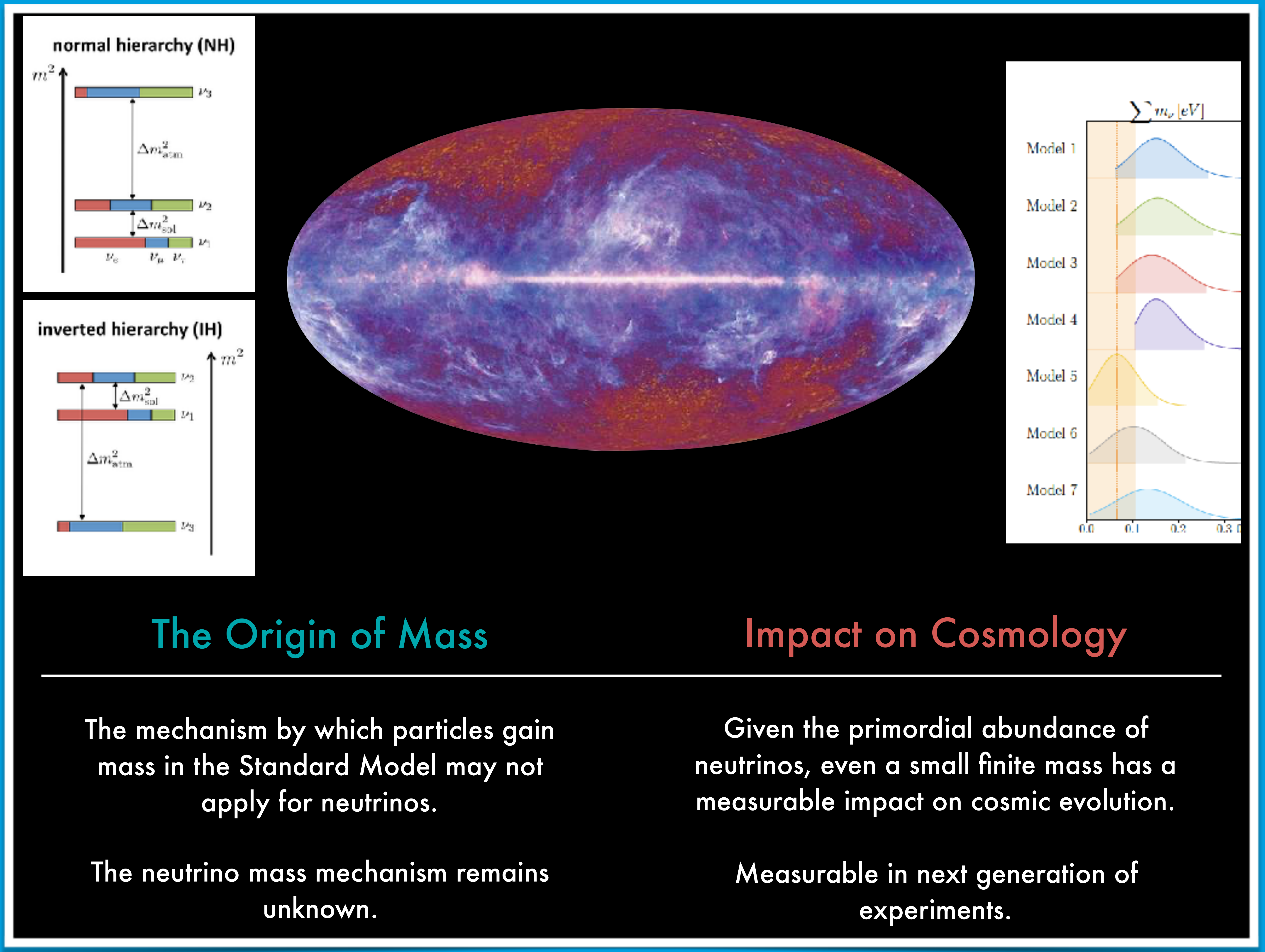


Weighing the Lightest Particles

Cosmology (@ 50 meV) and 0νββ (@ 15 meV) has the potential to probe the deepest into the oscillation prediction for the mass scale over the next decade.

However, the method with the most strongly tested assumptions is direct kinematic searches through beta decay.

Joseph Formaggio

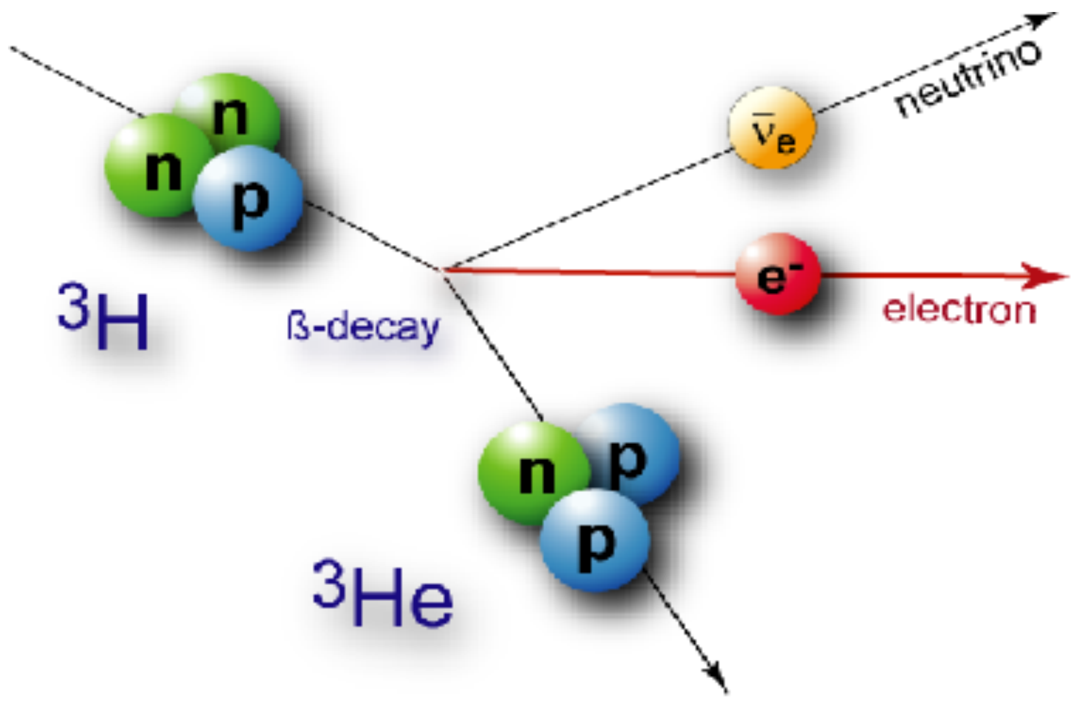


Weighing the Lightest Particles

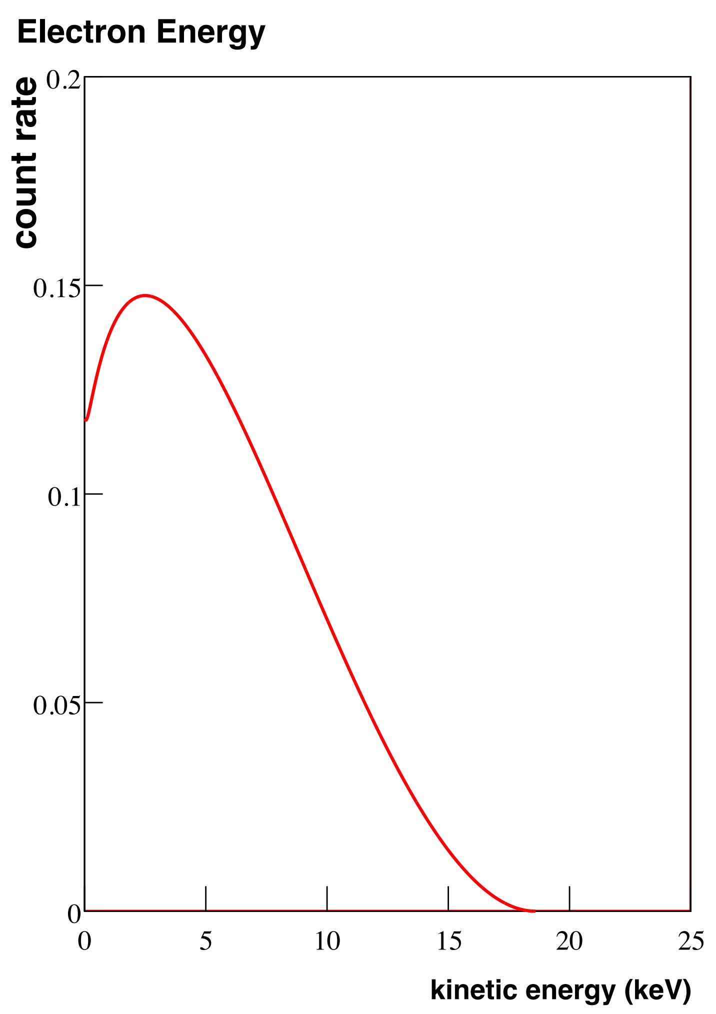
Joseph Formaggio

Necessary
[Experimental] Conditions:
High Flux and High Precision

Tritium beta decay



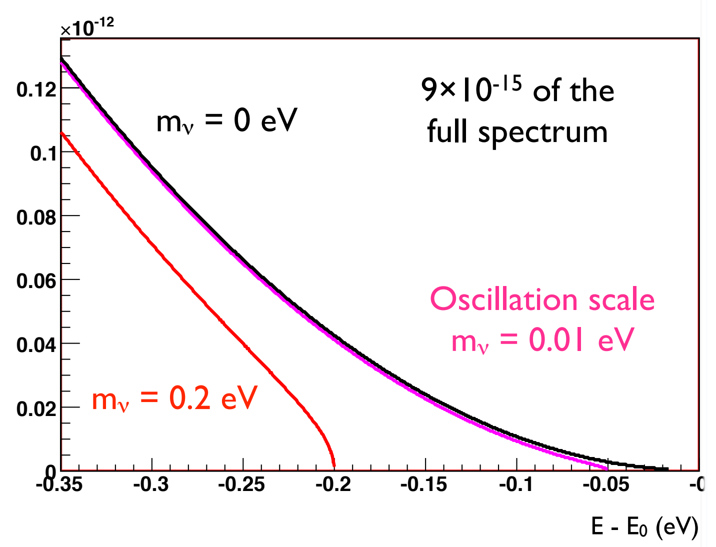
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$



$$\dot{N} \propto p_\nu E_\nu$$

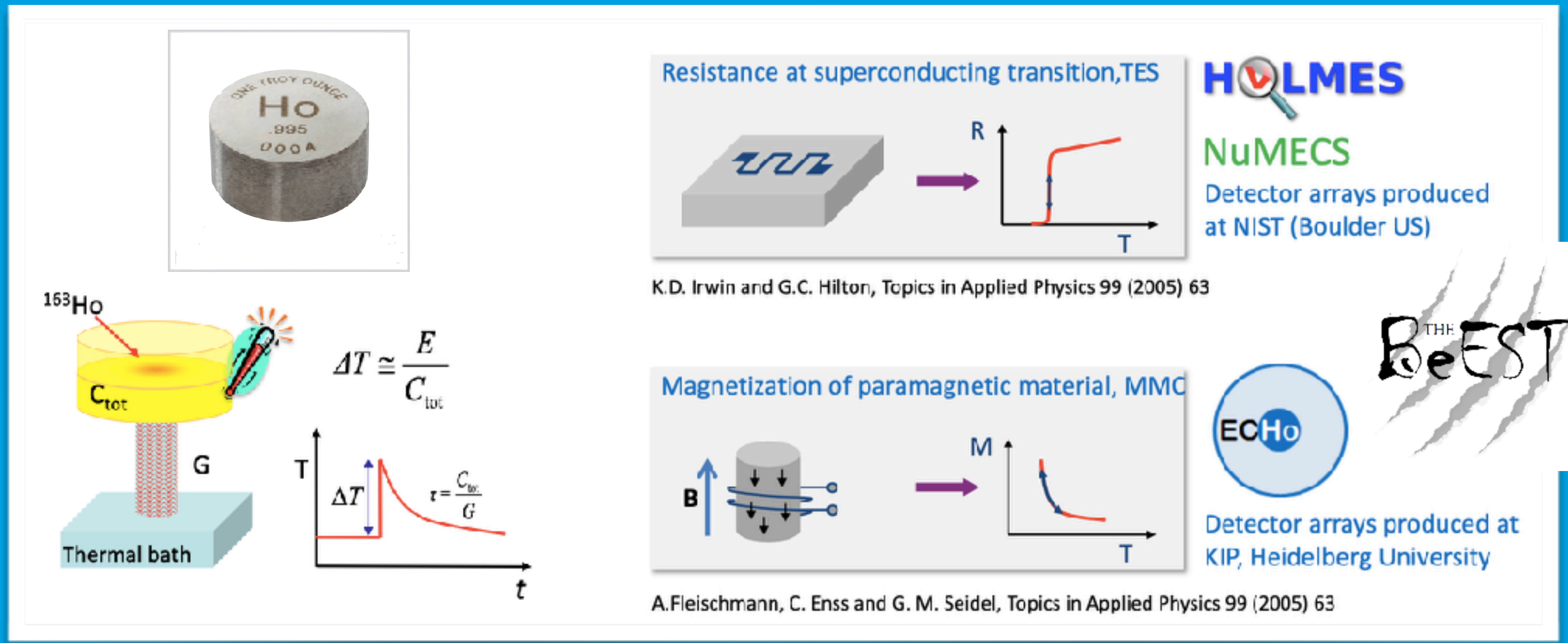
differential spectrum depends on the neutrino momentum.

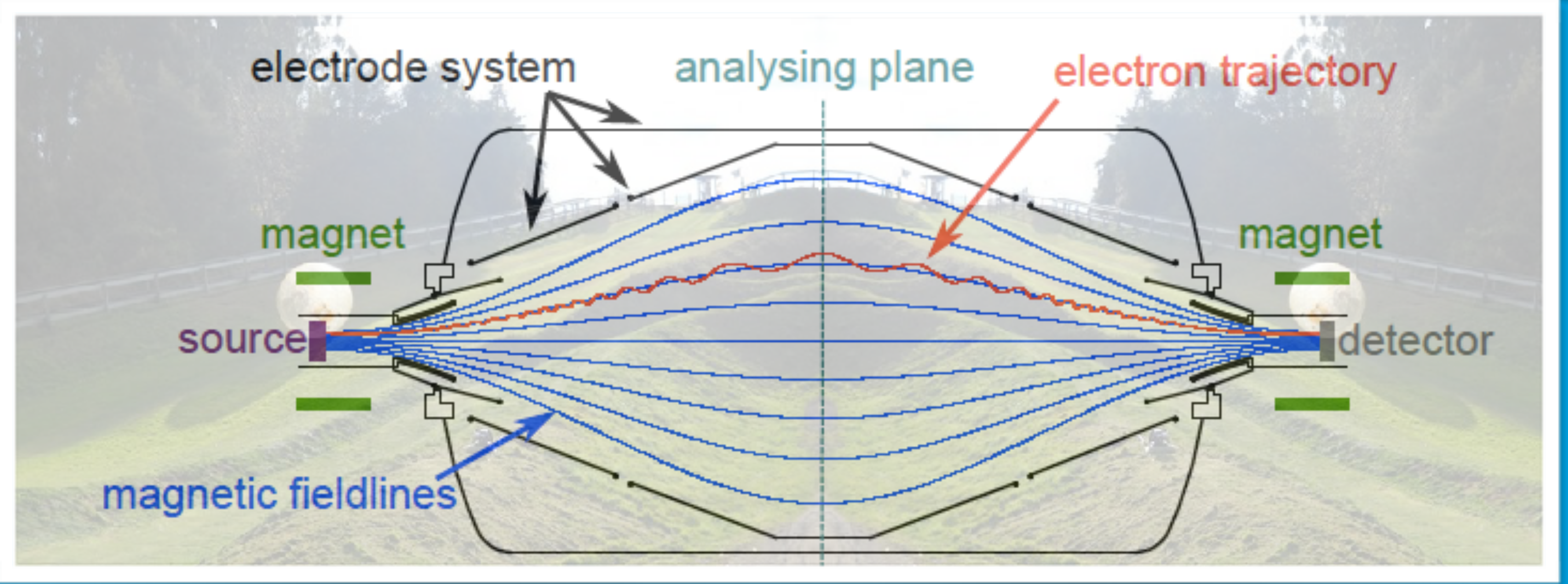
Endpoint of the Tritium β-decay Spectrum



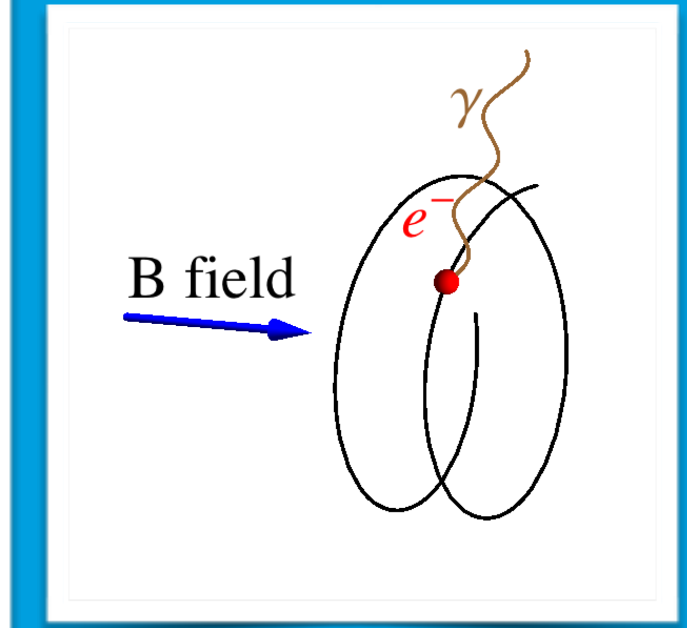
Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.

Weighing the Lightest Particles





Mainz ⇒ Troitsk ⇒ Katrin



[Joseph Formaggio]

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

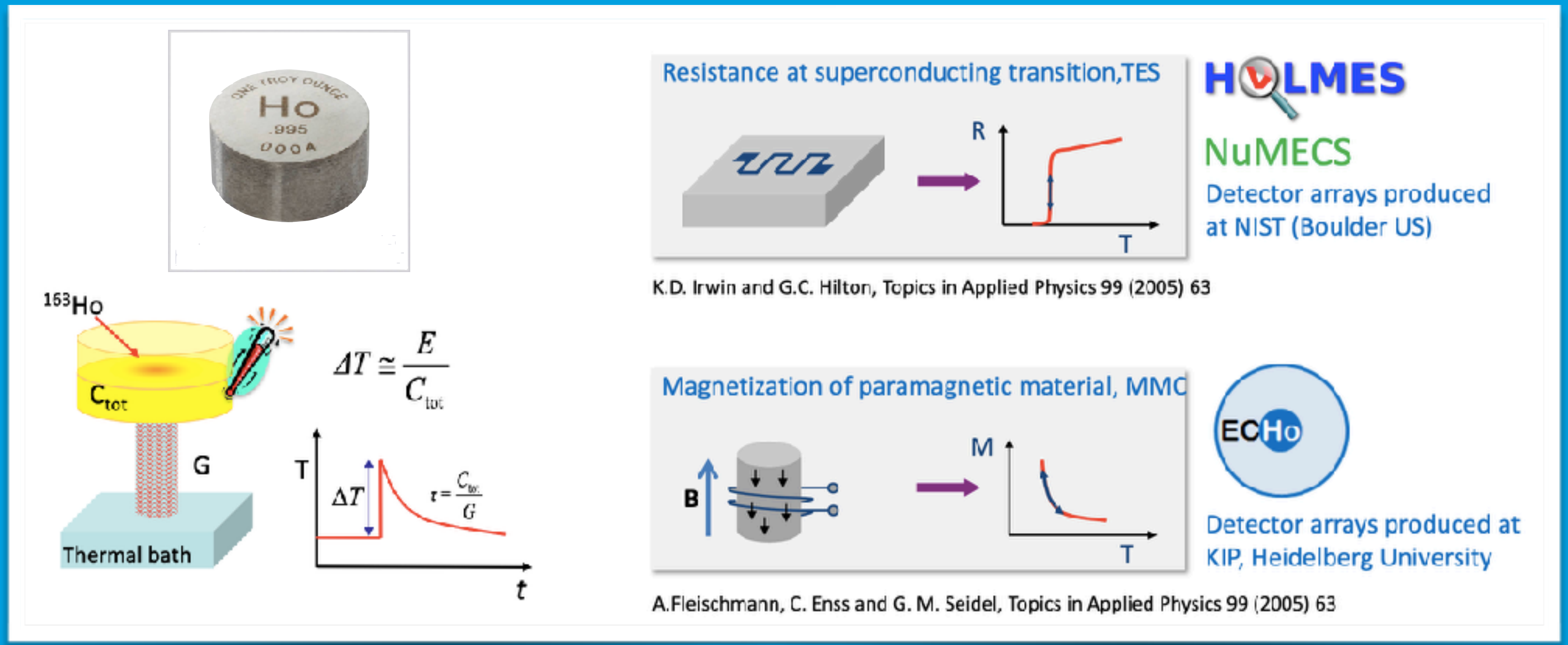
Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

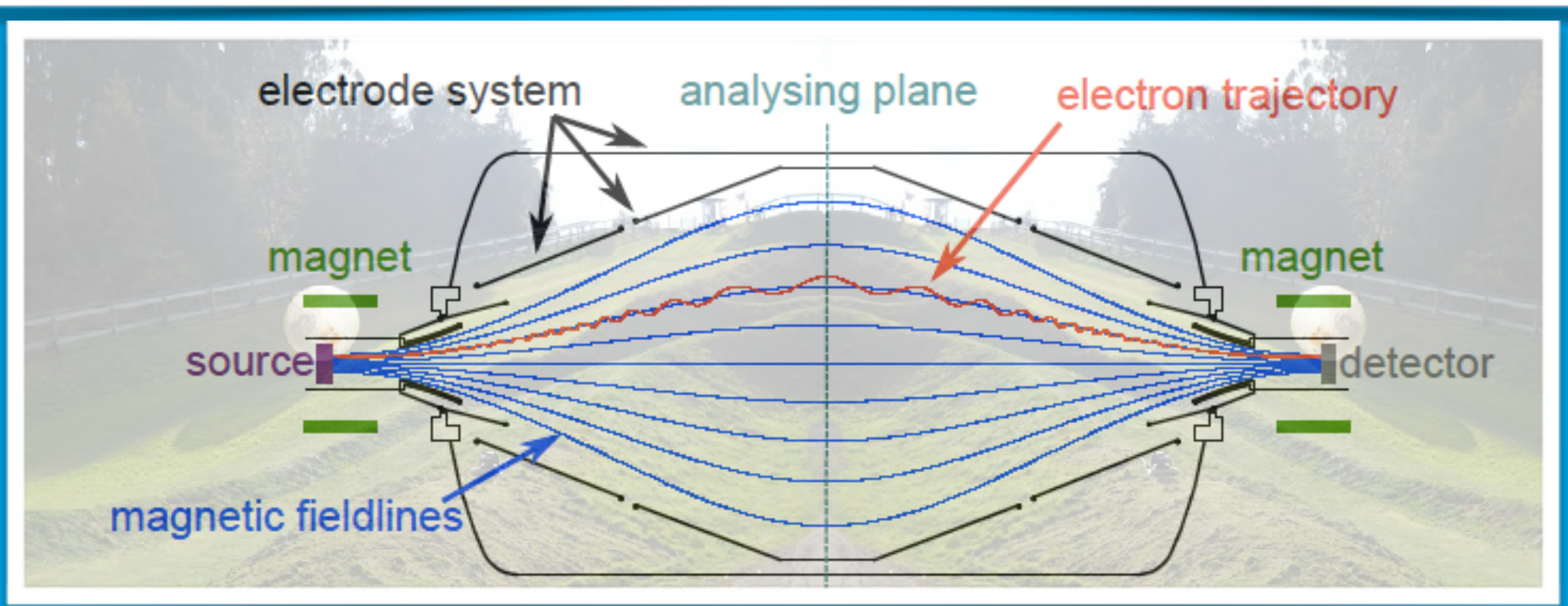
Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

Weighing the Lightest Particles



Calorimetric experiments such as ECHO and HOLMES are progressing well toward the eV scale.



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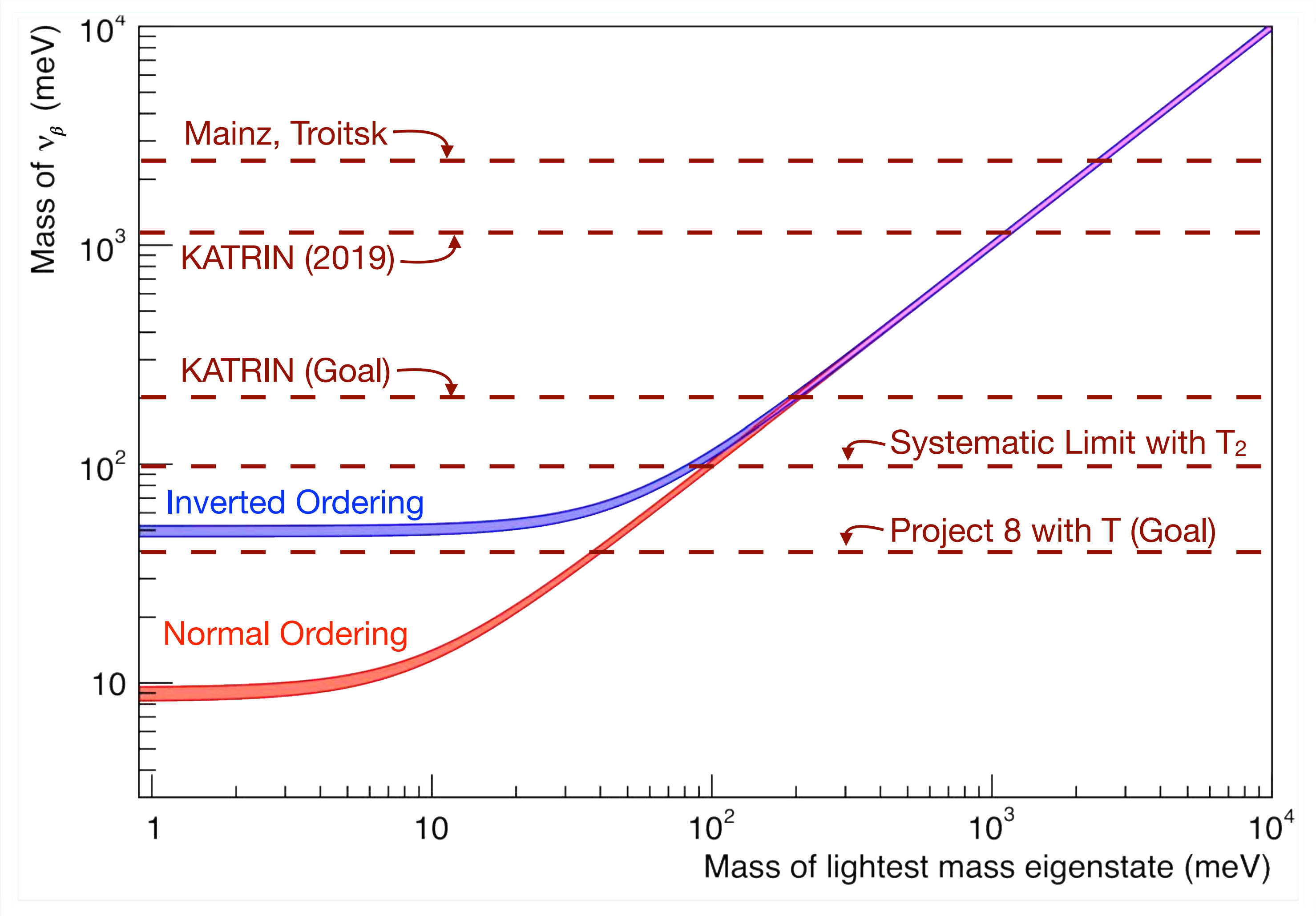
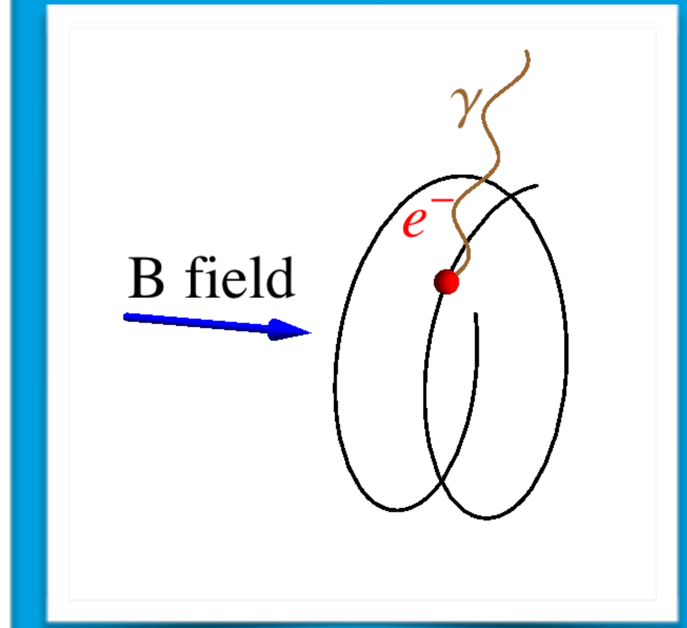


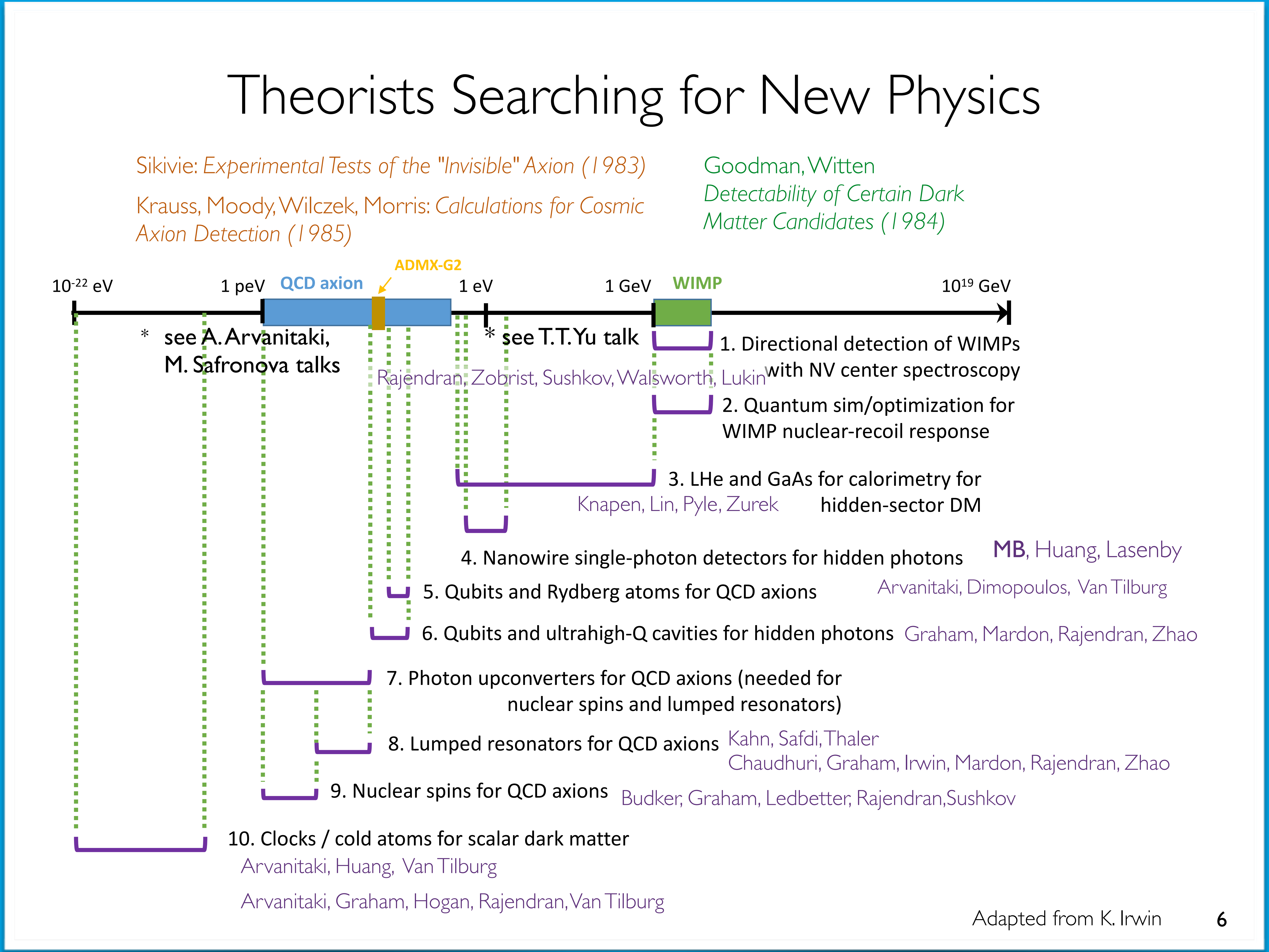
KATRIN is now taking data, finally pushing the mass scale limit below the eV scale for the first time.



The CRES technique through Project 8 is pusing forward, with the eventual target of using an atomic tritium source.

Discoveries at the Precision Frontier

Masha Baryakhtar



DM candidates can span many orders of magnitude in mass—lots of work moving beyond WIMP (10 GeV-TeV) regime

See also talks by A. Arvanitaki, M. Safranova, T. T. Yu

Discoveries at the Precision Frontier

Masha Baryakhtar

Excellent light (<eV) dark matter candidates include axion(-like particles) and dark photons

Axions and New Ultralight Particles

- Axions are
  - Solutions to a theoretical puzzle of small numbers: the strong-CP problem: approximately massless particle with mass and couplings fixed by a high scale f_a,

$$m_a = 5.70(6)(4)\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

Dark photons and axion like particles

  - Low-energy remnants of complex physics at high scales
    Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell
  - Automatically produced as dark matter in the early universe

Nelson, Scholtz
Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald
Graham, Mardon, Rajendran

Preskill, Wise, Wilczek

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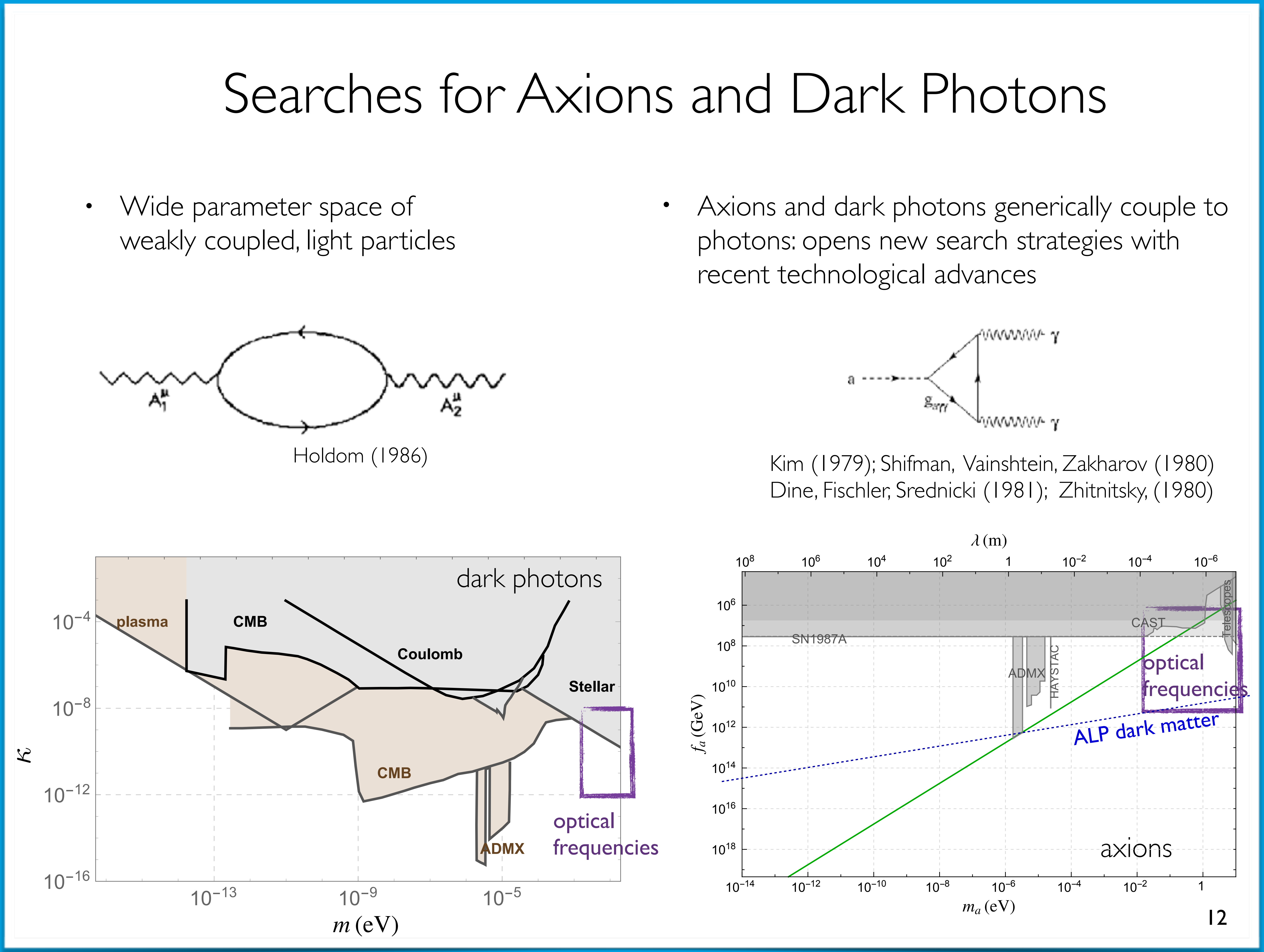
Discoveries at the Precision Frontier

Masha Baryakhtar

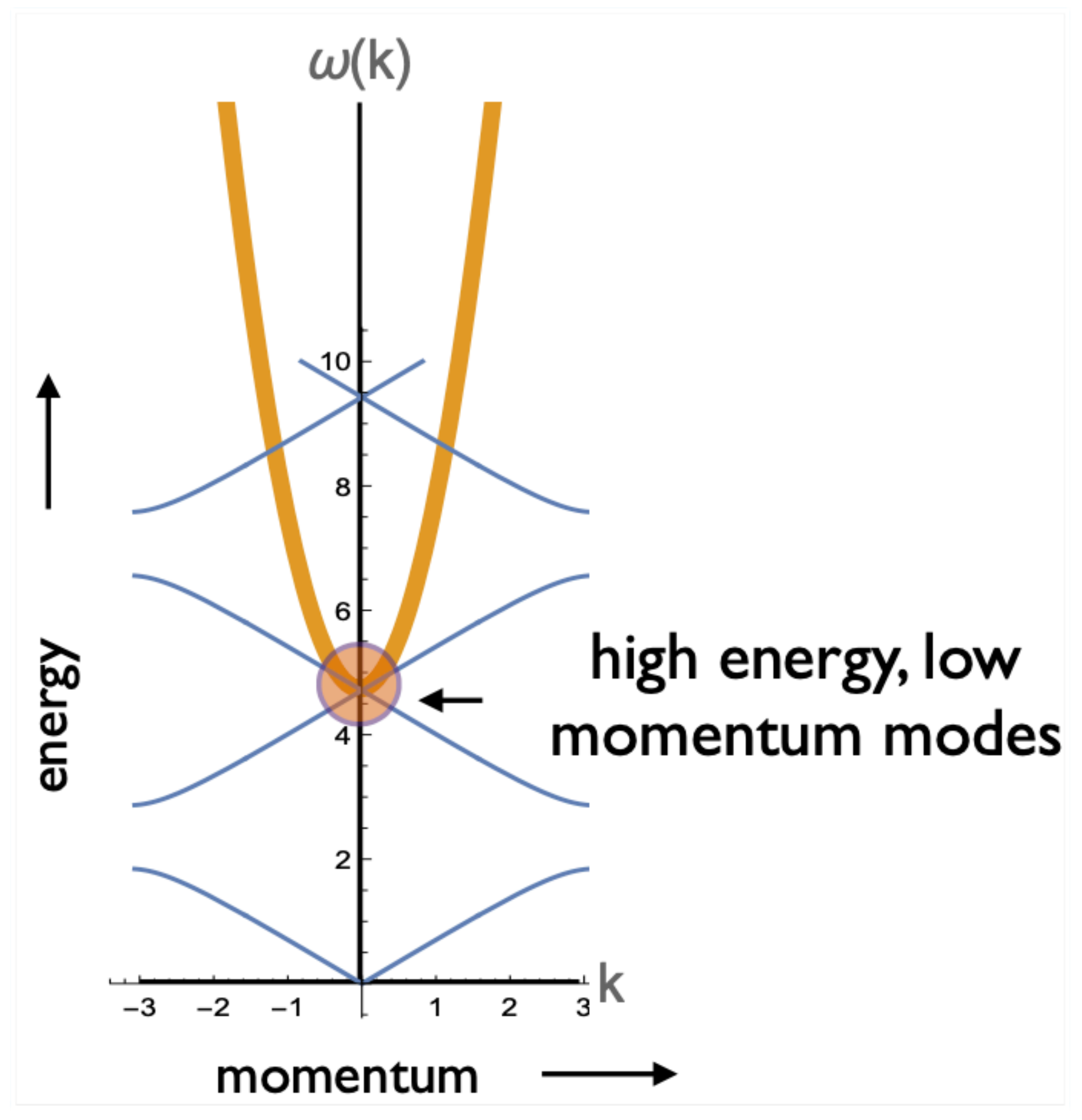
These bosons naturally interact with photons—a handle to detect them with!



Discoveries at the Precision Frontier

Masha Baryakhtar

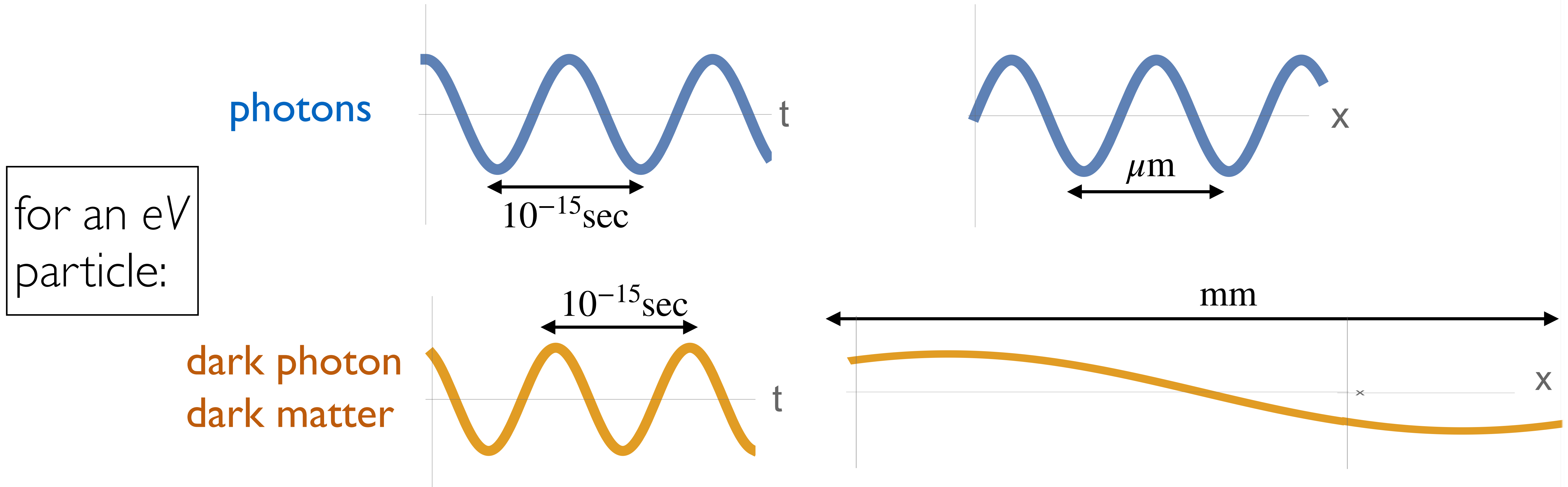
Kinematics of converting light (but not massless) boson DM to photons means we need to change photon dispersion relation



Seeing Dark Matter

- For a given energy, photons have much more momentum than dark matter
- Even when ***interactions*** in the dark matter model allow one-to-one conversion to photons, ***kinematics*** do not

$$\omega_A = \omega_\gamma \Rightarrow k_\gamma \sim 0$$



- Need systems which can efficiently absorb the momentum mismatch

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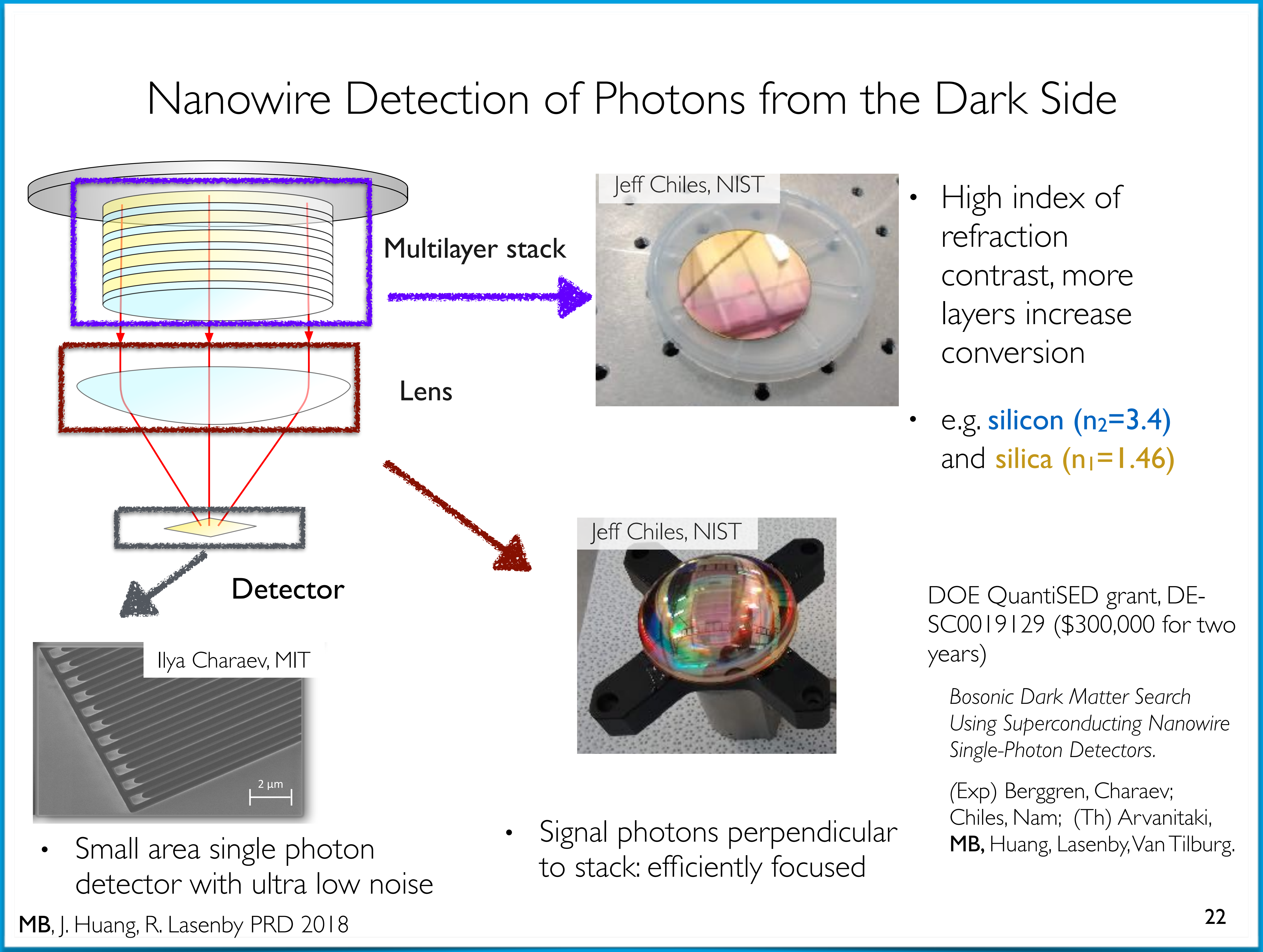
Discoveries at the Precision Frontier

Masha Baryakhtar

New idea: stack of different dielectrics . DM axions or dark photons convert to photons that are focused onto detector

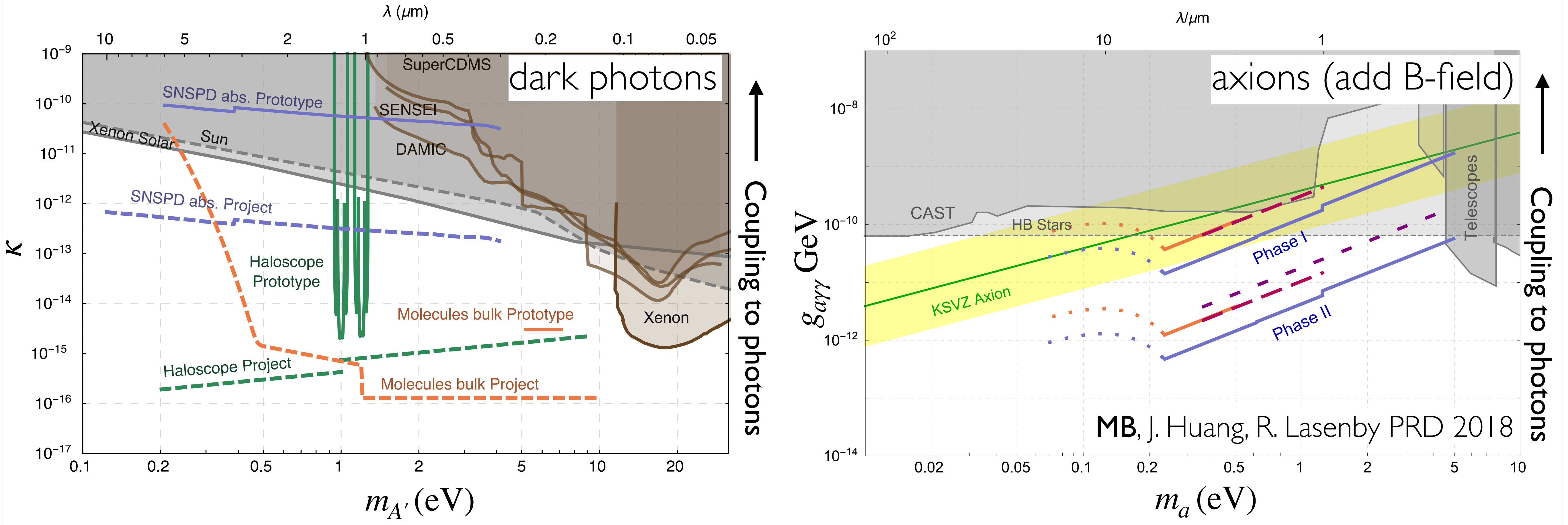


Discoveries at the Precision Frontier

[Masha Baryakhtar](#)

New idea: stack of different dielectrics . DM axions or dark photons convert to photons that are focused onto detector

Searches for dark matter with light



- Dielectric materials /crystal structures/ molecules can correct the dispersion mismatch in waves between a massless and massive particle of the same energy
- First steps underway, use well-established optics and detector technology; possible to reach very small couplings with larger setups
- Improve on parameter space by orders of magnitude, and perhaps see dark matter

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Summary^2

Particle physics has made incredible progress

Questions remain! Neutrino masses, DM, matter-antimatter asymmetry of the Universe…

Many avenues for progress across wide range of energy scales (<eV to 100 TeV)

Discussed just a few possibilities—next 20+ years will be exciting