Massachusetts
Institute of
Technology

FROM THEORY TO DISCOVERY IN THE SKY

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For TF09: Astrophysics and Cosmology

SEATTLE SNOWMASS SUMMER MEETING 2022

MAJOR POINTS OF THE TF09 REPORT: WHAT ARE WE DOING

Broadly, the impact of theoretical effort in cosmology and astrophysics over the past decade can be viewed through the lenses of (i) advancing our understanding of fundamental physics by forcing us to ponder extreme scenarios where e.g. quantum effects and gravity must be considered simultaneously, (ii) developing new microscopic models that can potentially explain the outstanding problems facing our understanding of nature, and (iii) inventing new approaches to test our best-motivated theories, in addition to developing the theoretical tools needed to properly interpret the resulting data.

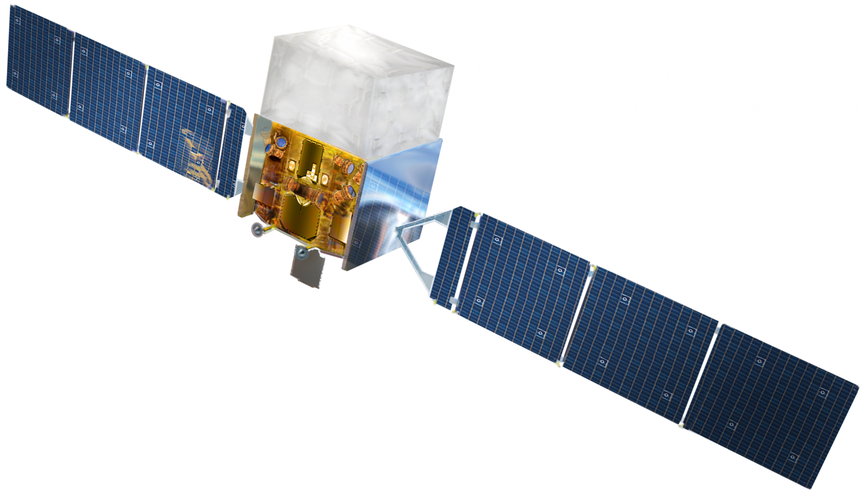
MAJOR POINTS OF THE TF09 REPORT: WE ARE DOING A GOOD JOB

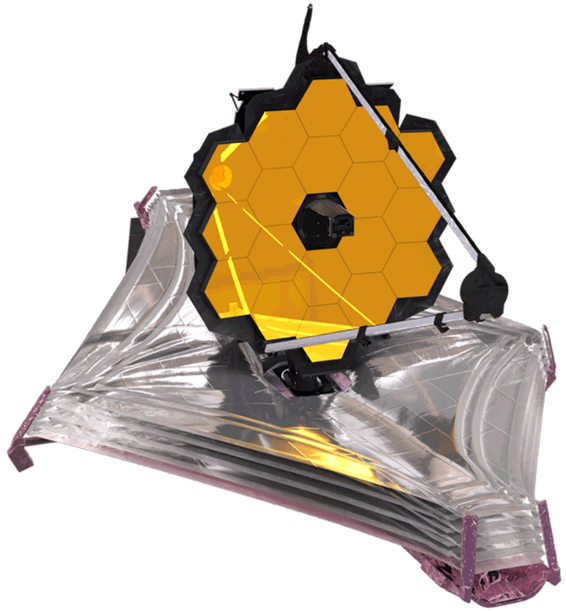
Novel analyses of astrophysical data in searches for DM have unveiled anomalies and helped resolve outstanding observations of the cosmos. At the same time, a whole host of new astrophysical and cosmological signatures of new physics in the early Universe have emerged with the expanded development of theories of non-minimal dark particle physics.

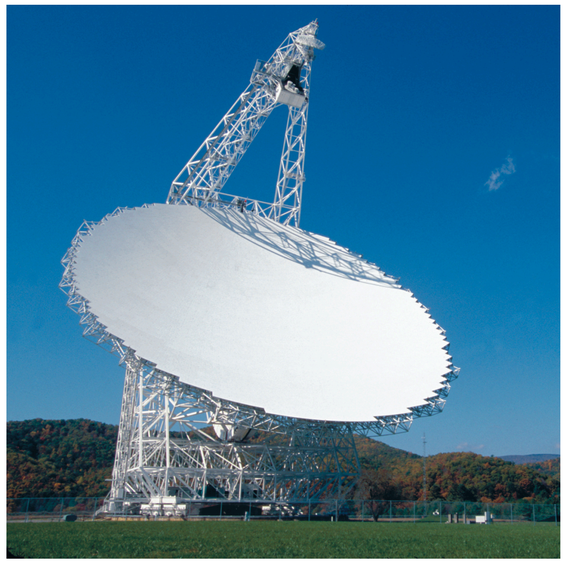
OUTLINE FOR TALK

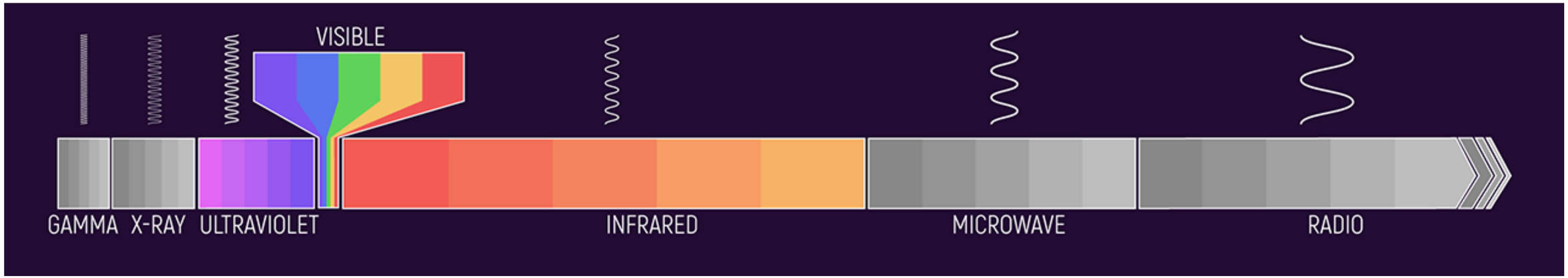
- **Particle dark matter**
  - WIMPs, sterile neutrinos, and beyond
  - Prospects and targets for future telescopes
- **Theory and indirect detection of wave-like matter**
  - Theory and phenomenology of axions & ALPs
  - Indirect searches for DM and dark sectors
- **Theory and prospects for new/other physics paradigms**

ASTROPHYSICS AS A BROAD SPECTRUM PROBE OF NEW PHYSICS



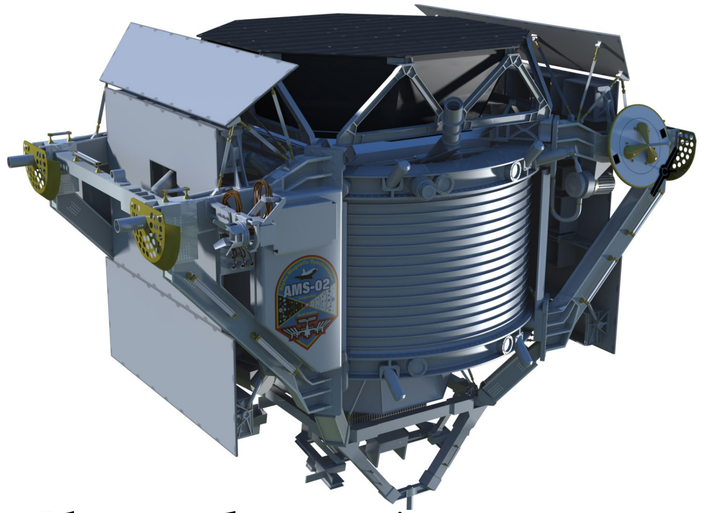






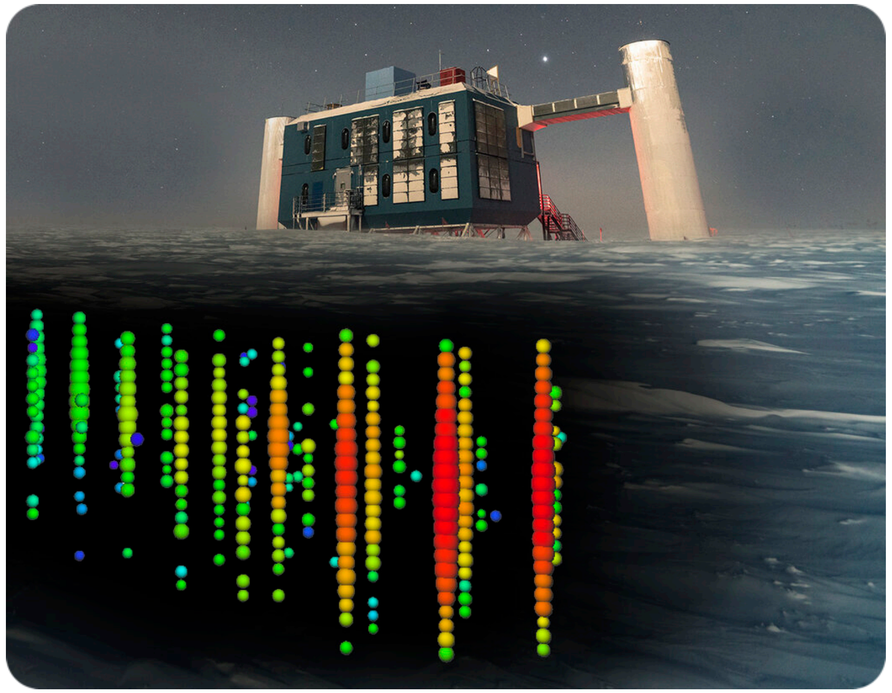
NASA and J. Olmsted (STScI)

ASTROPHYSICS AS A BROAD SPECTRUM PROBE OF NEW PHYSICS



Charged cosmic rays

Gravitational Waves



Neutrinos

- Physics from sky ≠ photons from the sky
  - Charged cosmic rays
  - Gravitational waves
  - Astrophysical neutrinos
- Beyond “event-level” measurements: astrometry, 21cm cosmology, LSS, CMB + more

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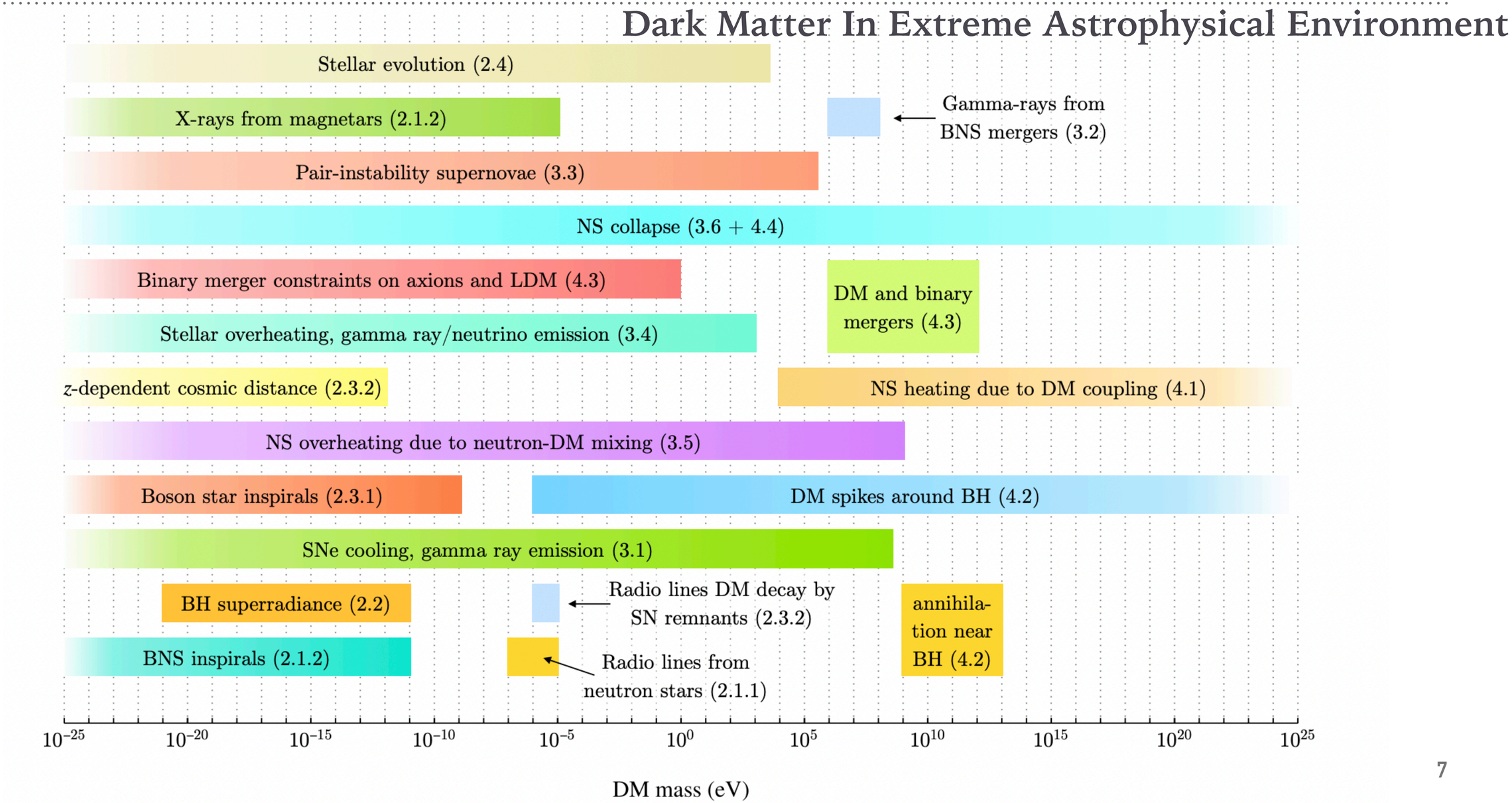
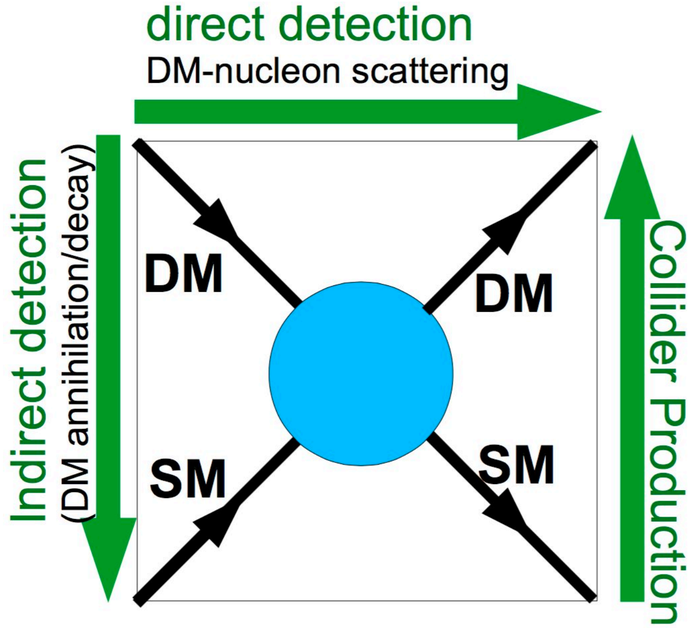


PARTICLE DARK MATTER

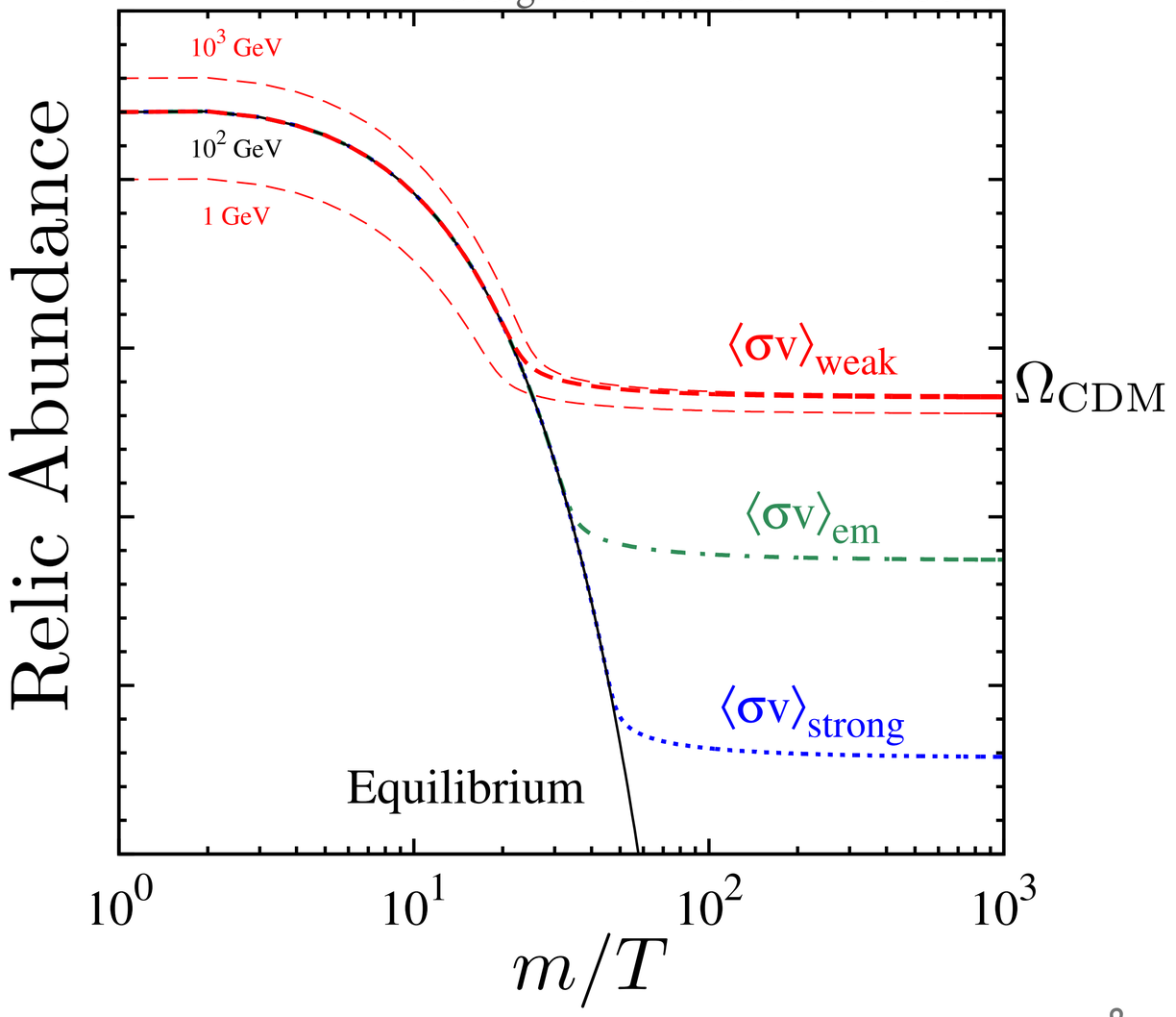
Symmetry Magazine, Illustration by Sandbox Studio, Chicago

WIMP DARK MATTER: FROM PRODUCTION TO DETECTION

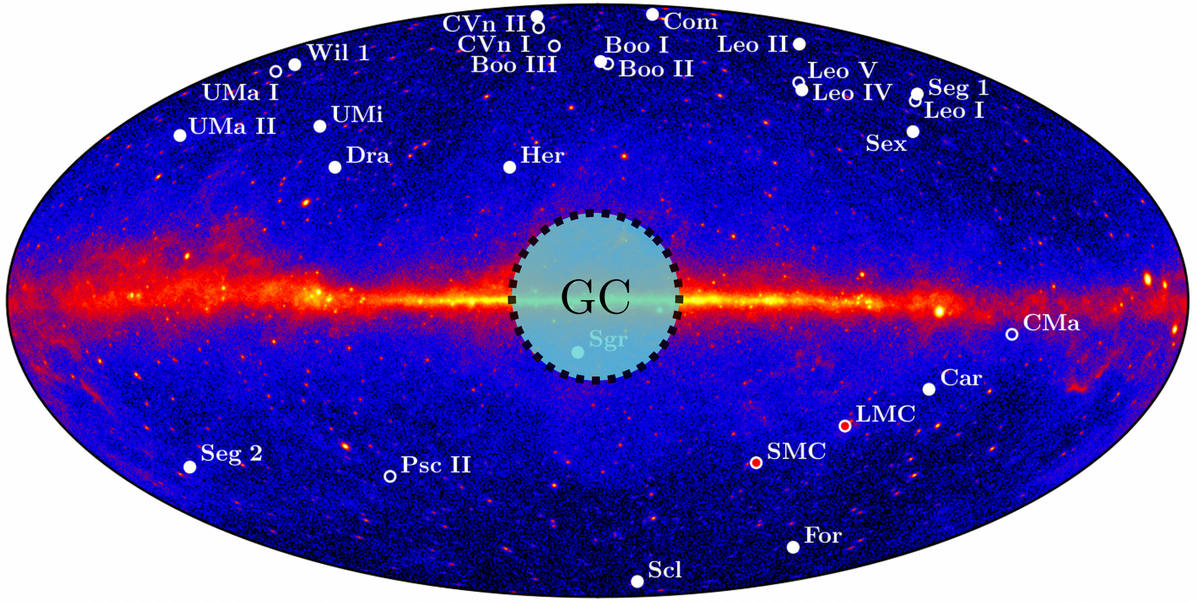


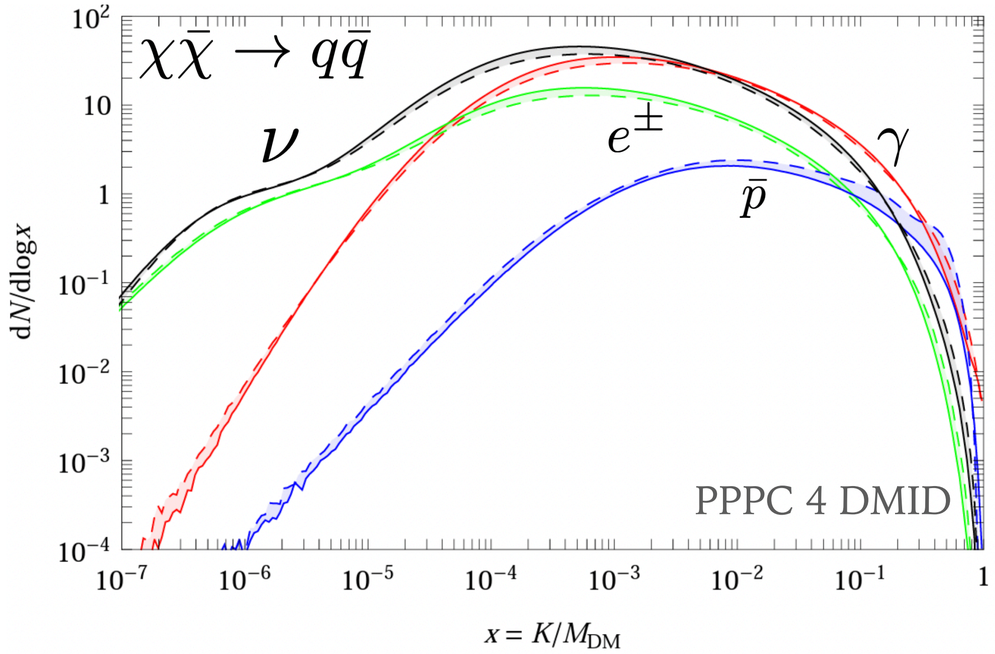
- WIMP miracle:
  - Particle with weak-scale mass and cross-section can produce DM abundance
  - Motivated by supersymmetry, hierarchy problem
  - More to the story: asymmetric DM, co-annihilation, …, N-to-2 processes

Steigman et al. arXiv:1204.3622



THE SPATIAL AND SPECTRAL MORPHOLOGY OF ANNIHILATION SIGNALS



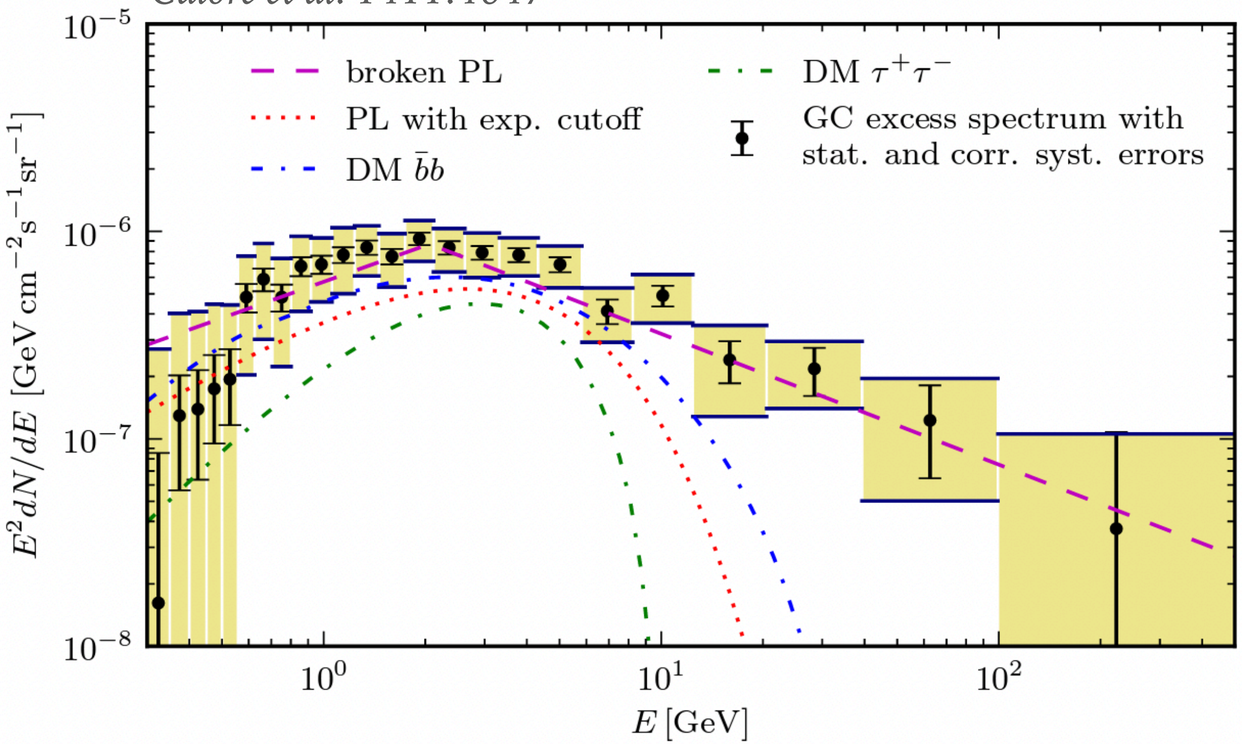


- **Spatial morphology**
  - Data-driven reconstruction of dwarf galaxy density profiles
  - Large scale simulation of galaxy formation with baryonic effects + astrometry
- **Background modeling:**
  - Improved diffuse emission modeling
  - New analyses for point source detection

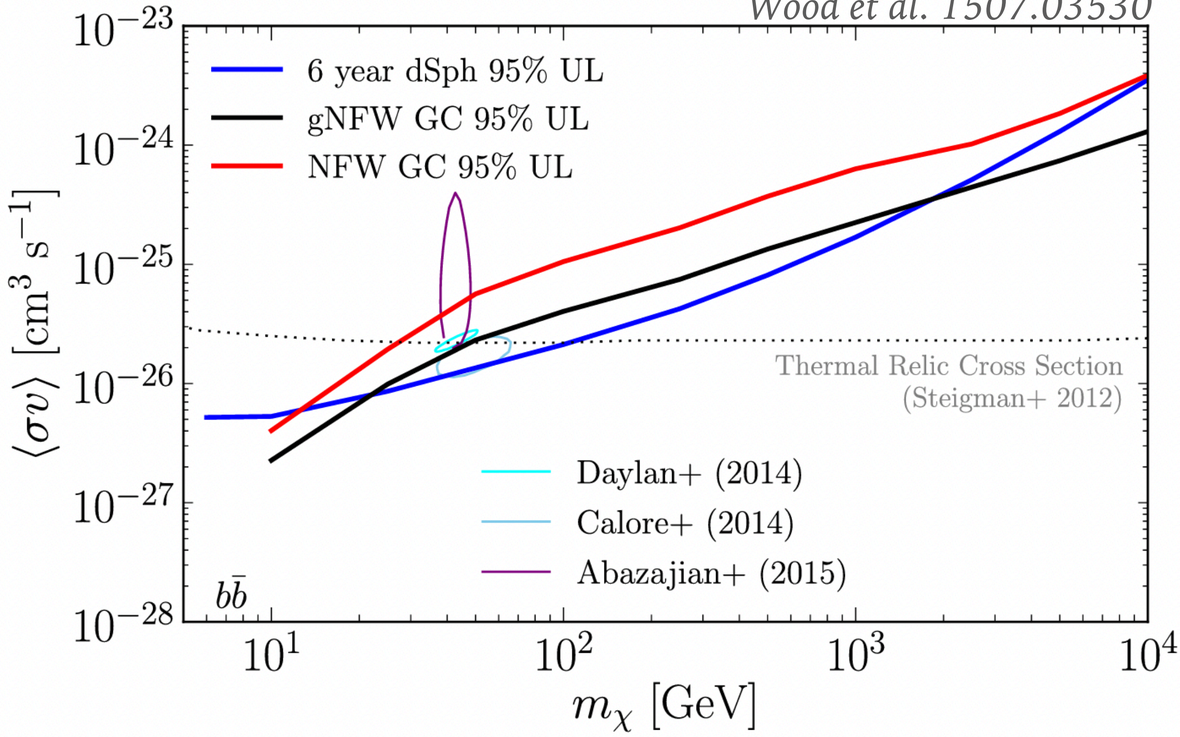
- **Spectral Morphology**
  - Calculation of annihilation spectrum given branching ratios
  - Ongoing work to characterize annihilation spectra, relic abundance of best-motivated WIMP candidates
  - For TeV mass DM: Sommerfeld enhancement, resummation of Sudakov double logarithms, end-point continuum photons all critical

STATUS AND PROSPECTS FOR THE GALACTIC CENTER EXCESS

Calore et al. 1411.4647



Wood et al. 1507.03530

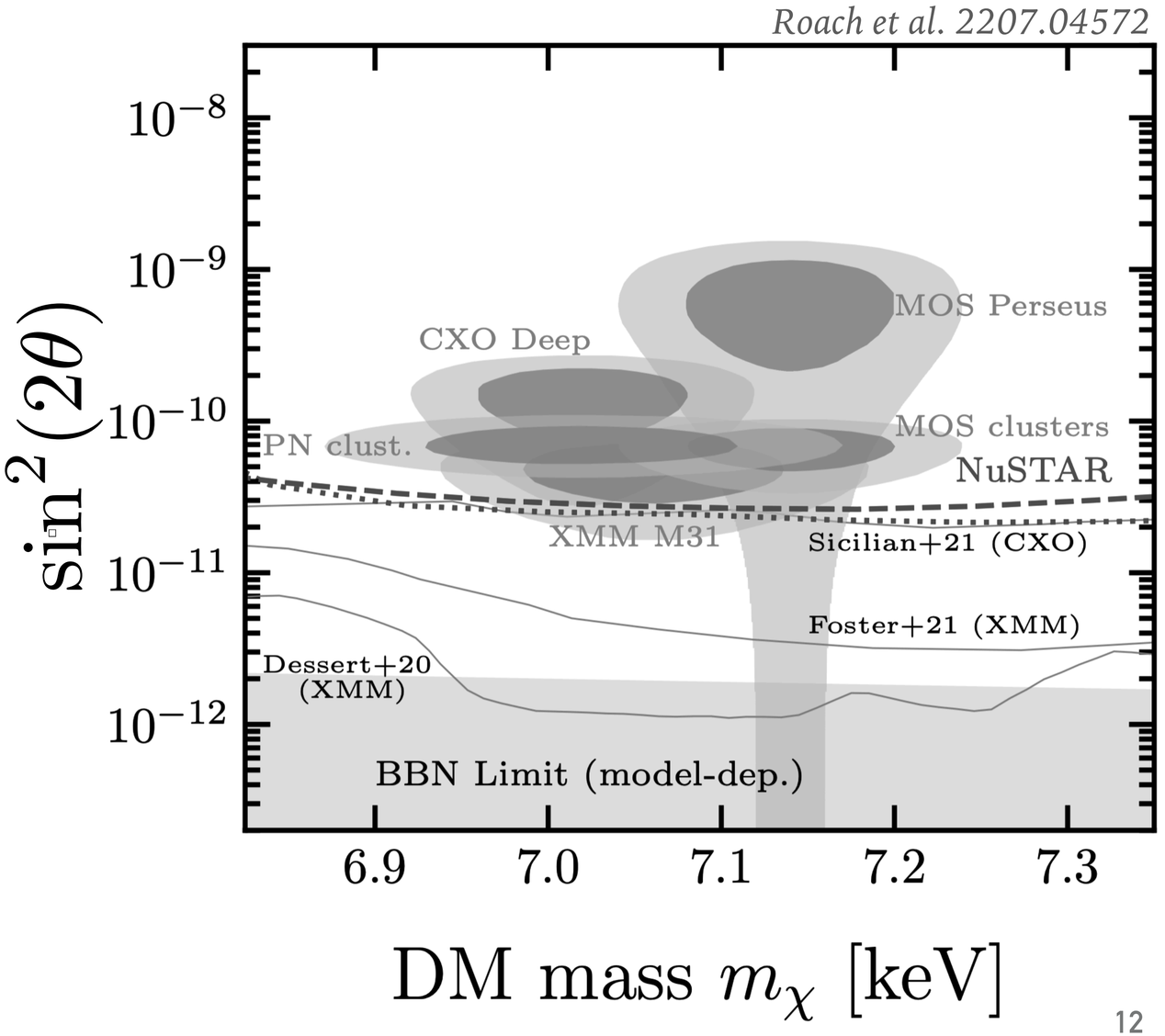


- **Advancements in analysis methodologies:**
  - Non-poissonian template fitting, Wavelet analyses, ML-based approaches
- Coming opportunities for new detection targets, cross-correlation analyses + more

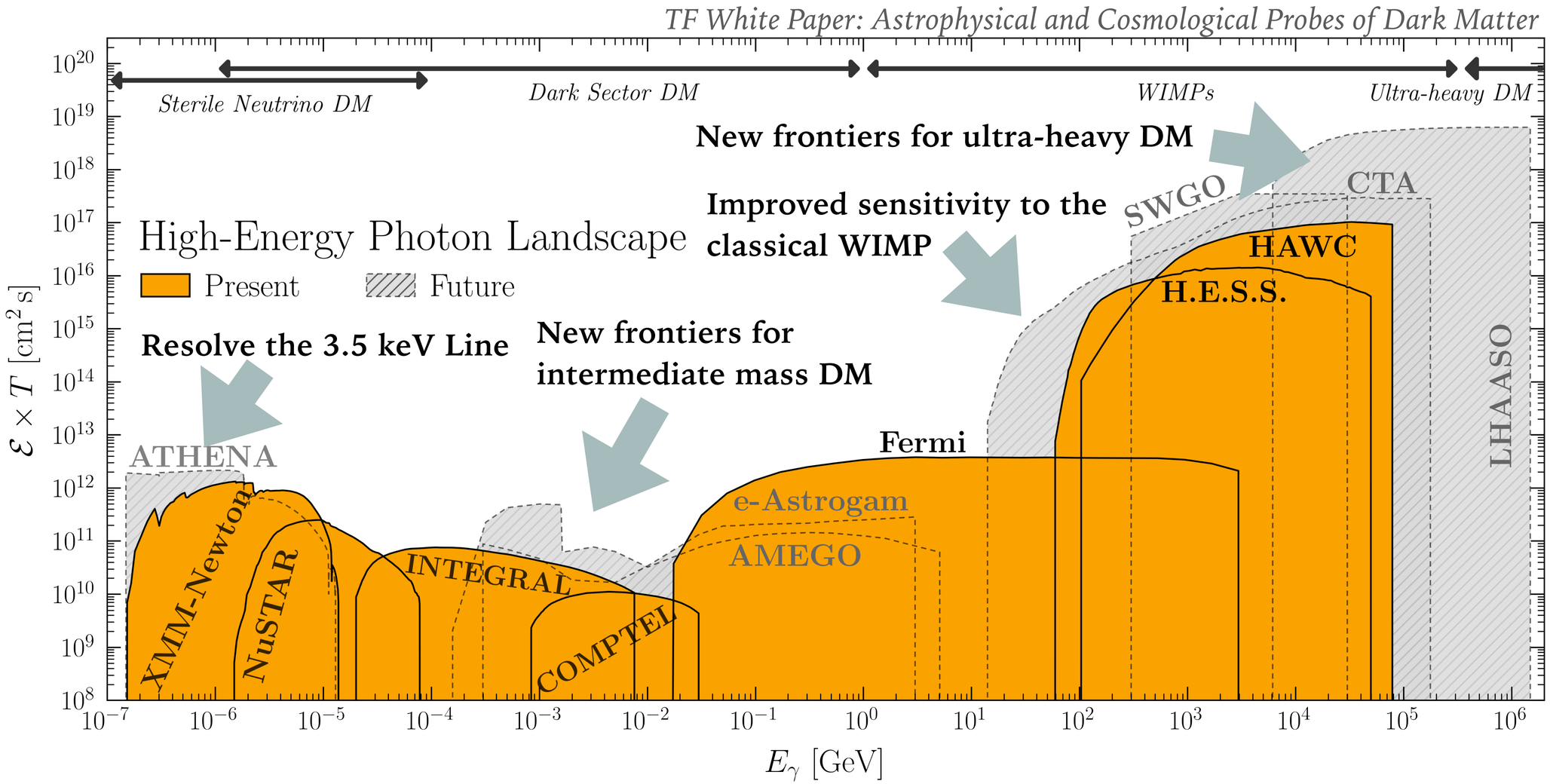
See also Puzzling Excesses in Dark Matter Searches and How to Resolve Them

STERILE NEUTRINOS: A KEV-SCALE DECAYING DM CANDIDATE

- keV-scale neutrino can be the DM
  - Dodelson-Widrow, Shi-Fuller
- Radiative decay of sterile can produce detectable *X*-ray lines
  - General motivation for *X*-ray observables
- Outstanding anomaly:
  - Claimed high significance detection
  - Constraining limits from blank sky searches with archival data
- Continued search efforts with existing data + future telescopes
- **See also neutrino frontier!**



FUTURE PROSPECTS FOR INDIRECT DETECTION

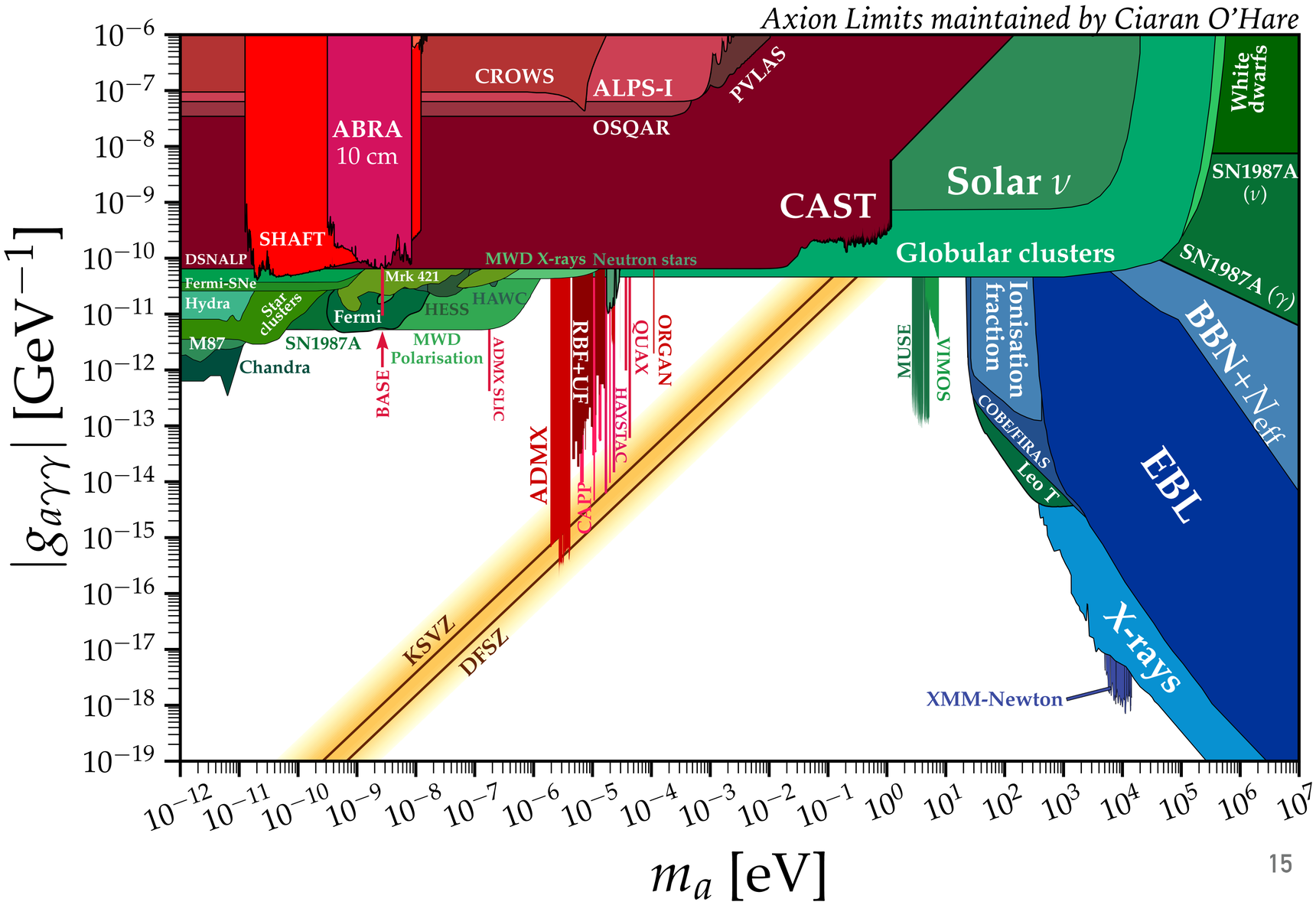


AXION AND ALPS

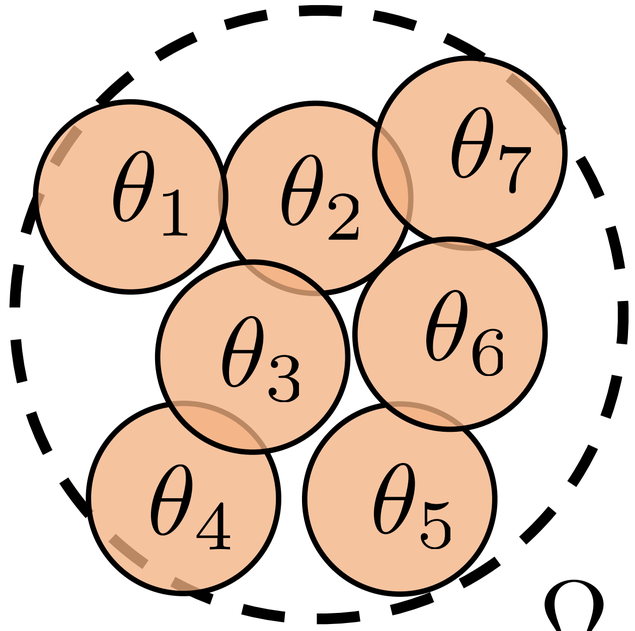
Symmetry Magazine, Illustration by Sandbox Studio, Chicago

PROBING AXION DARK MATTER WITH ASTROPHYSICS

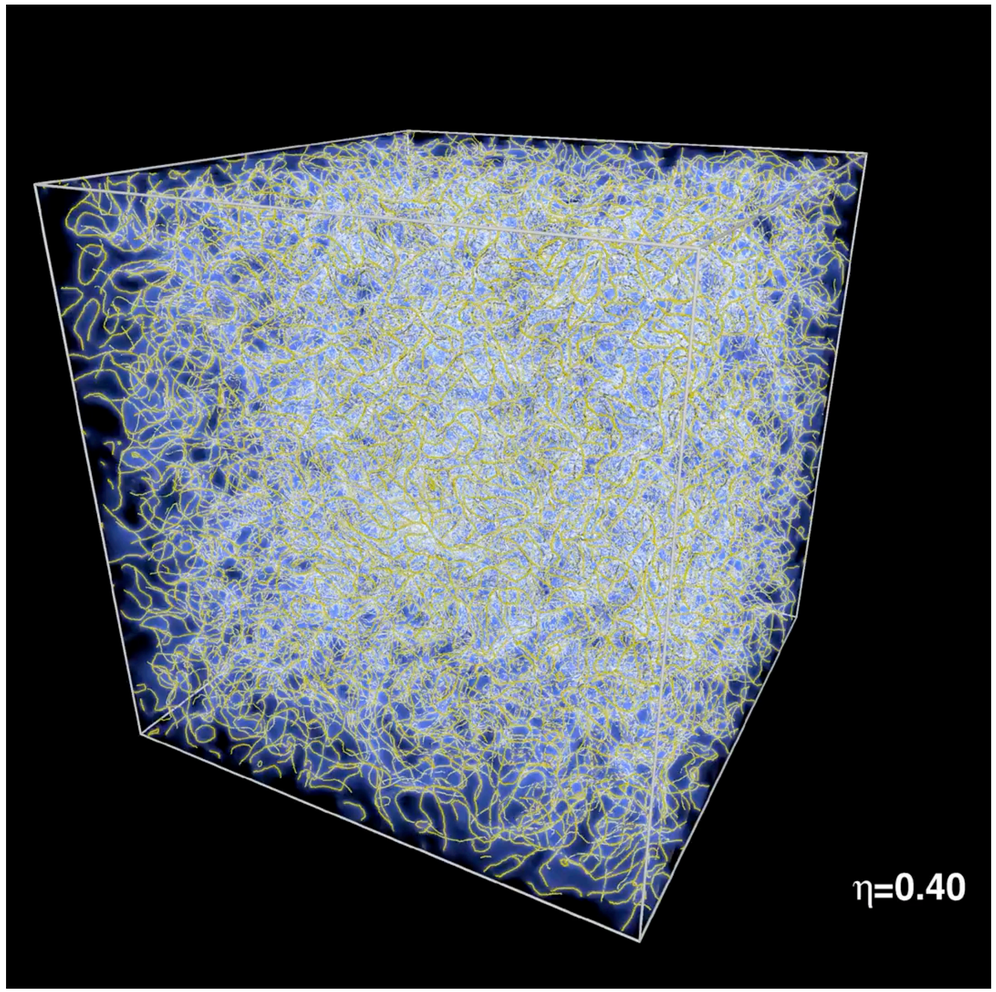
Many of the leading probes on axion DM come from astrophysics



AXION THEORY AND PRODUCTION IN THE EARLY UNIVERSE



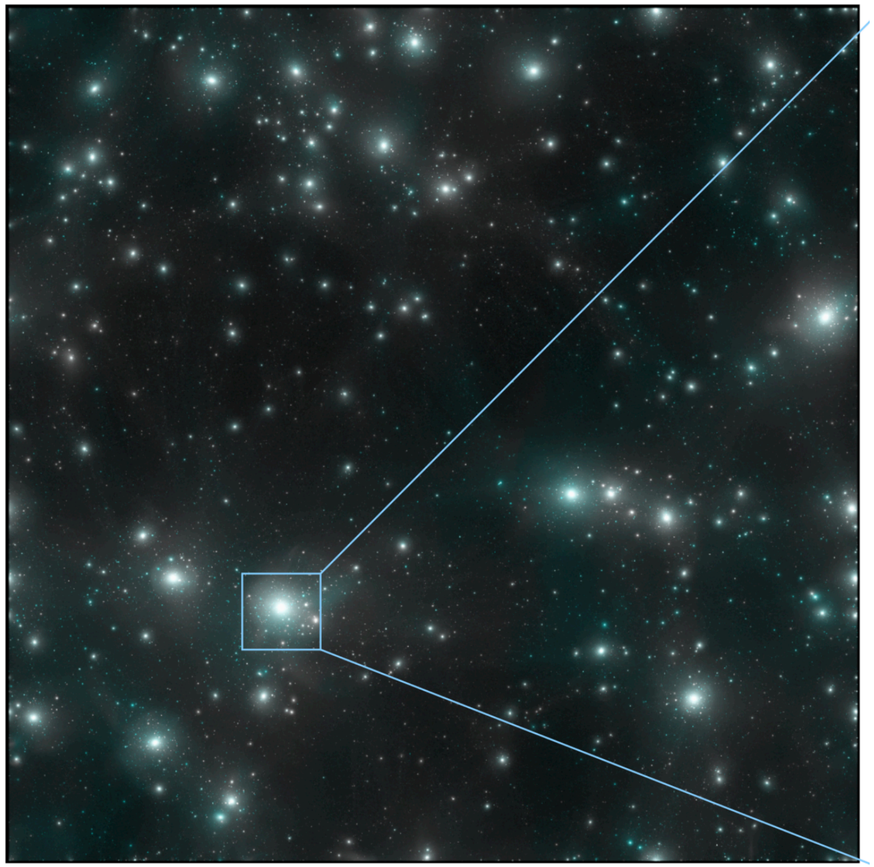
$$\Omega_a \sim m_a^2 \langle \theta^2 \rangle$$



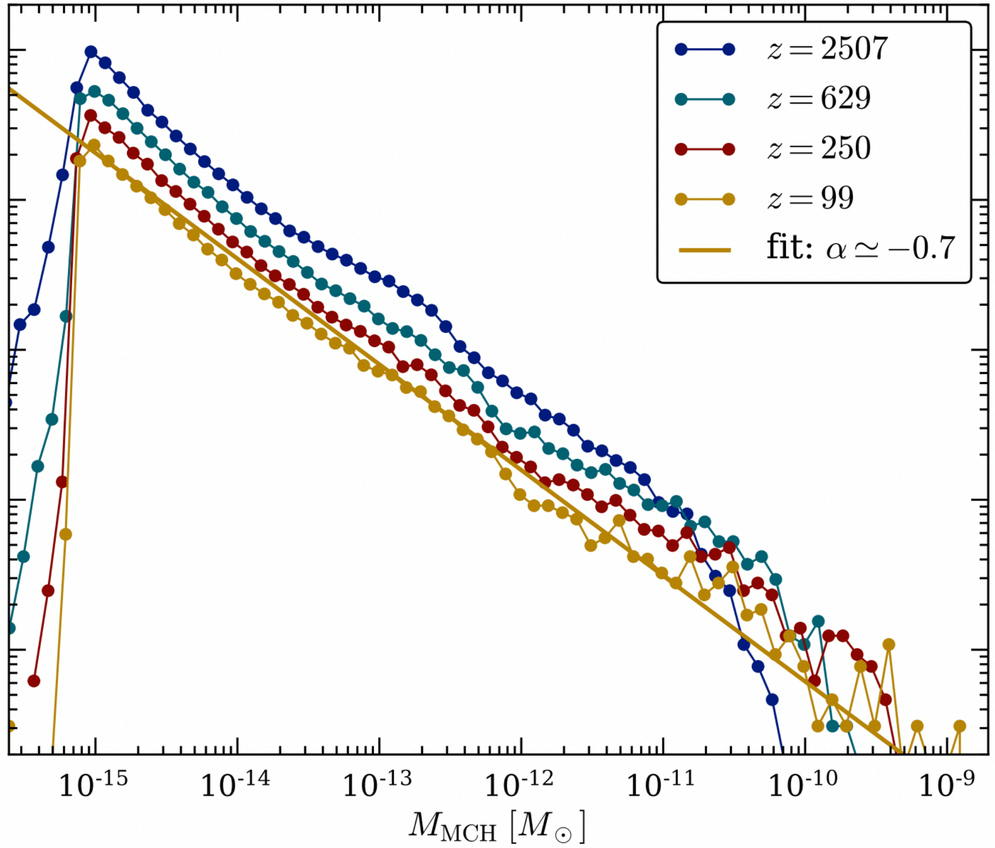
- **Ongoing simulation work**: Moore+ 1708.07521, Vaquero +1809.09241, Gorghetto+ 1806.04677, 2007.04990, Buschmann+1906.00967, 2108.05368
- **Towards theory understanding:** Hindmarsh+ 2102.07723, Dine+ 2012.13065

Other production channels possible: see **Early-Universe Model Building** white paper!

COSMOLOGICAL PROBES OF AXIONS AND AXION DARK MATTER

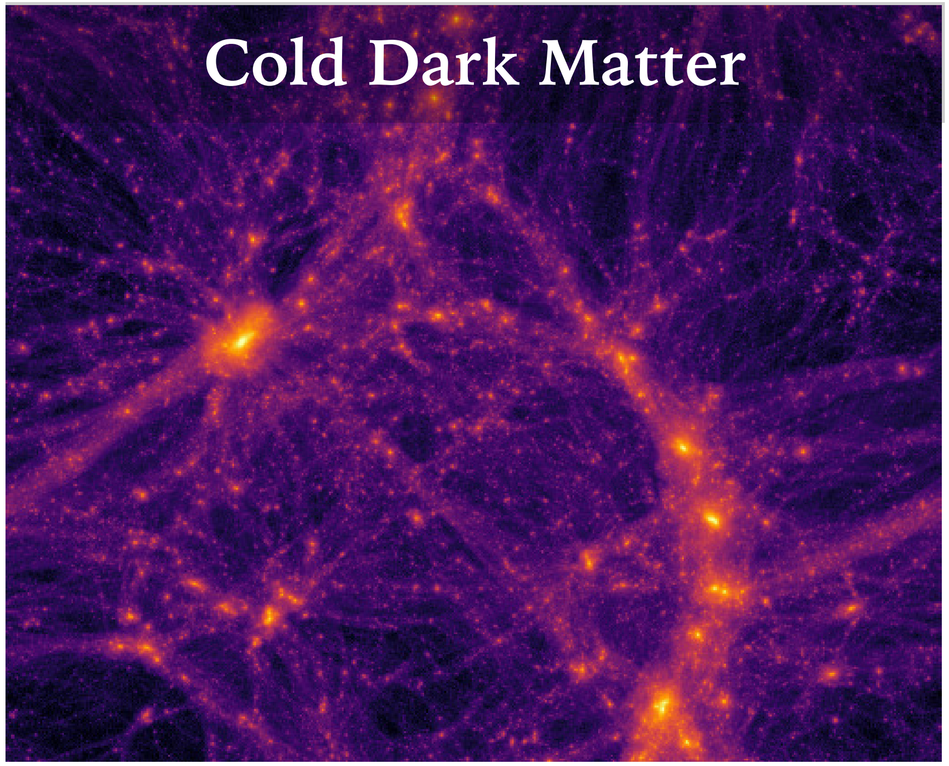


Eggemeier et al. 1911.09417



- **Simulation**: Eggemeier+ 1911.09417, Xiao+ 2101.04177
- **(Semi)Analytic**: Ellis+ 2006.08637, 2204.13187, Kavanagh+ 2011.05377
- **Anharmonic effects**: Arvintaki+1909.11665
- Theory for small-scale structure formation, observational probes (see cosmo talks)

COSMOLOGICAL PROBES OF AXIONS AND AXION DARK MATTER

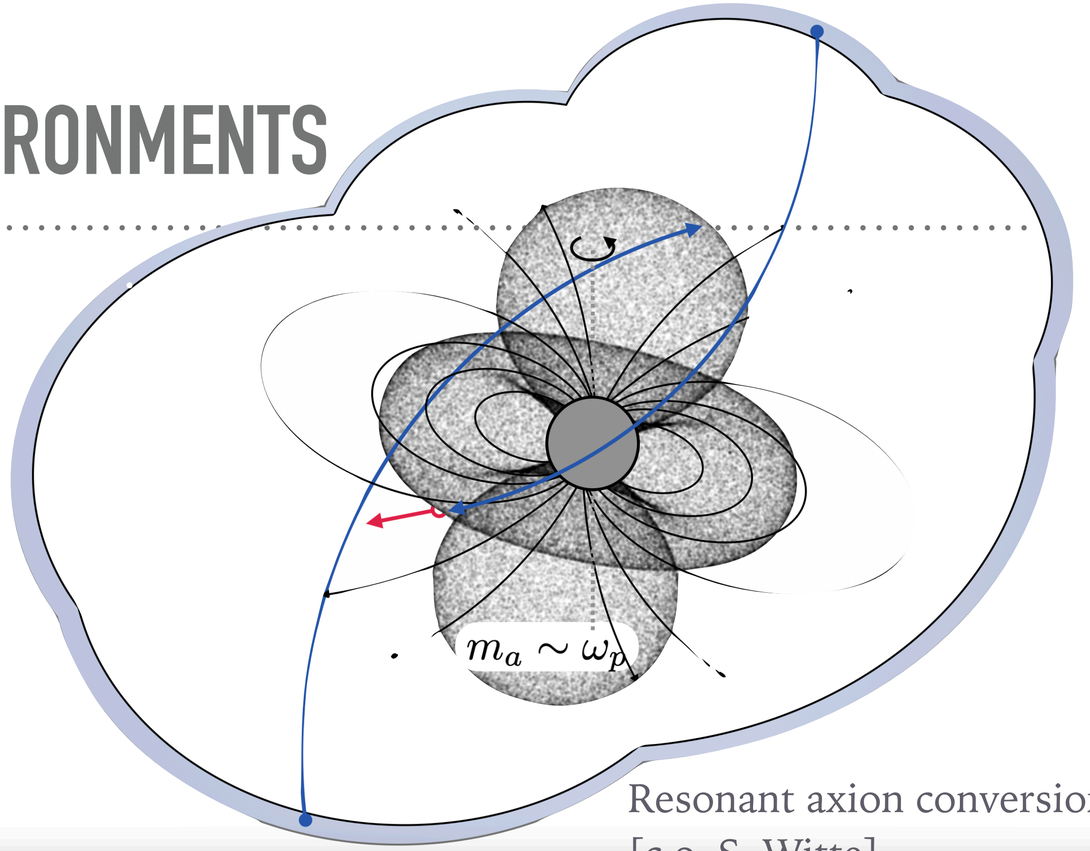


- For ultralight dark matter, modified structure formation, can be probed at dwarf scales and above
- Similar efforts for self-interacting, dissipative, or warm DM
- **See Cosmological Simulations for Dark Matter Physics**

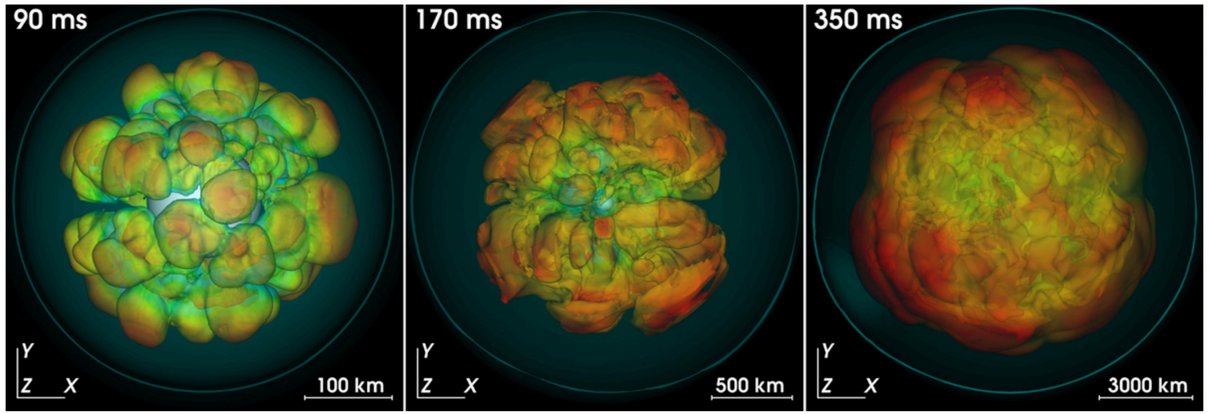
AXION INDIRECT DETECTION IN STELLAR ENVIRONMENTS

- Resonant conversion of axions at neutron stars
  - **Theory calculations**: Huang+ 1803.08230; Hook+ 1804.03145; Leroy+1912.08815 Battye+ 1910.11907, 2104.08290; Witte+ 2104.07670; Millar+ 2107.07399,
  - **Searches in data:** Foster+ 2004.00011, 2202.08274; Darling 2008.01877, 2008.11188; Battye+ 2107.0122

- Stellar cooling/evolution and supernova constraints
- X-ray signatures from stellar production



Resonant axion conversion [c.o. S. Witte]

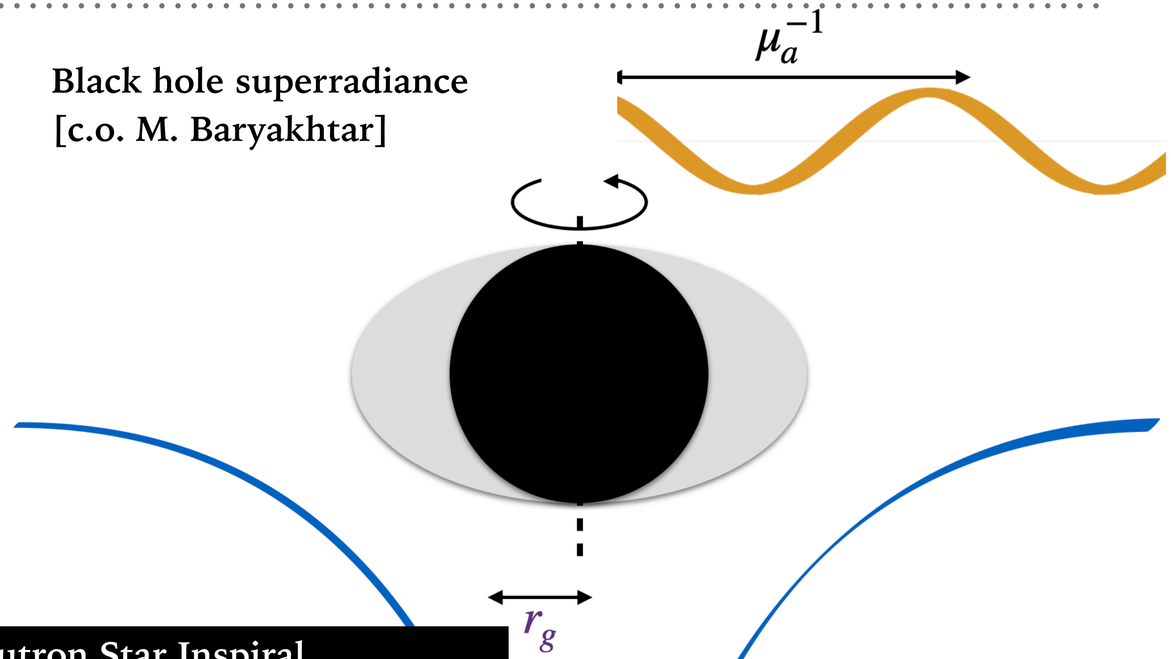


SN simulation. Melson+ 1501.01961

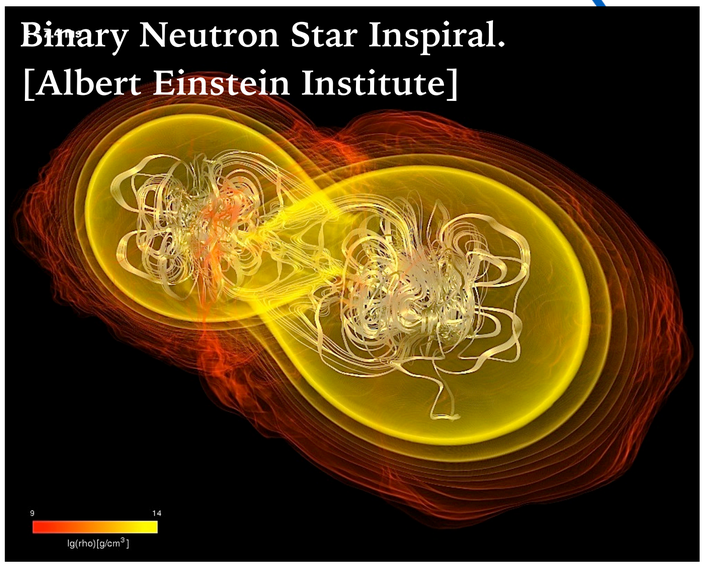
AXION INDIRECT DETECTION WITH COMPACT OBJECTS

- **Black hole superradiance:** axion cloud production, angular momentum, spindown BH
  - Gravitational wave production from spin-down process
  - Detection of high-spin BHs can rule out axion parameter space
  - Ongoing work to characterize theory predictions in context of self-interactions
- Axions mediating long-range force between neutron stars, modifying inspiral process
- Theory insights driving LIGO efforts

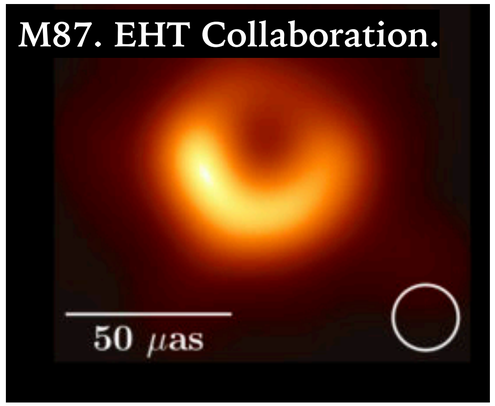
Black hole superradiance
[c.o. M. Baryakhtar]



Binary Neutron Star Inspiral.
[Albert Einstein Institute]



M87. EHT Collaboration.



ADDITIONAL PARADIGMS AND OPPORTUNITIES

QUESTIONS/DISCUSSION