Dark Matter in the Cosmic Context

Rencontres du Vietnam on Cosmology 2017

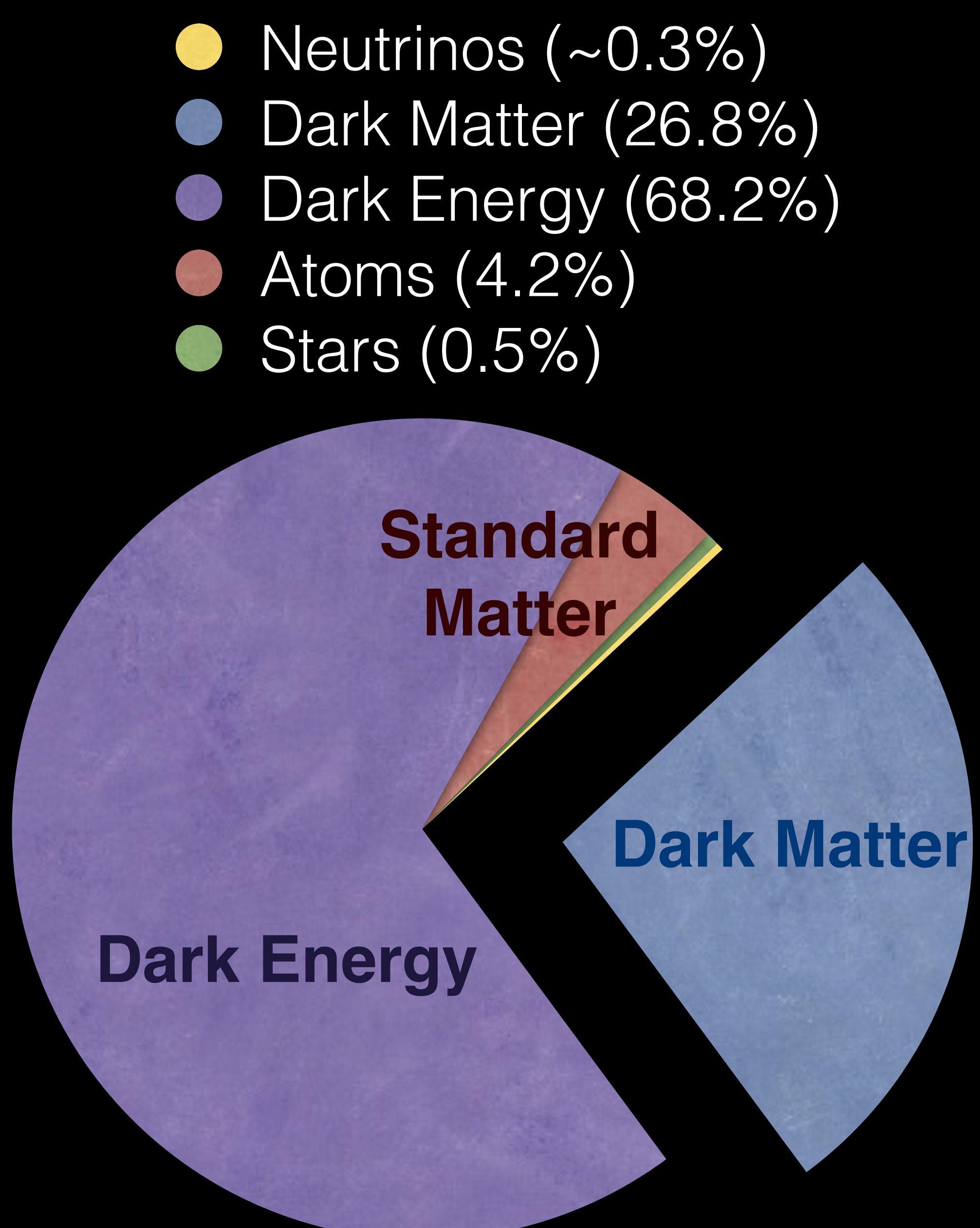
Sarah Schön
University of Melbourne

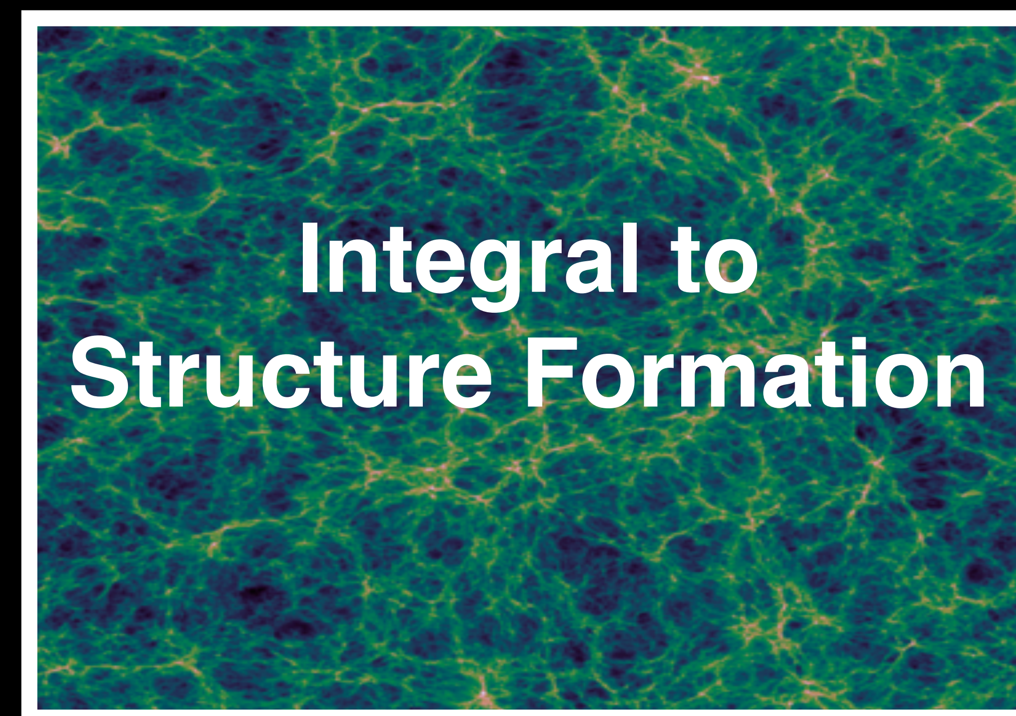
THE UNIVERSITY OF
MELBOURNE

Overview

- **Dark Matter Review** -key pieces of evidence and the empirical picture of dark matter that emerges from these
- **Dark Matter Now** - cosmological simulations, open questions and challenges for the current dark matter paradigm
- **Current DM Searches** - looking to uncover the fundamental nature of dark matter

Dark Matter at a Glance





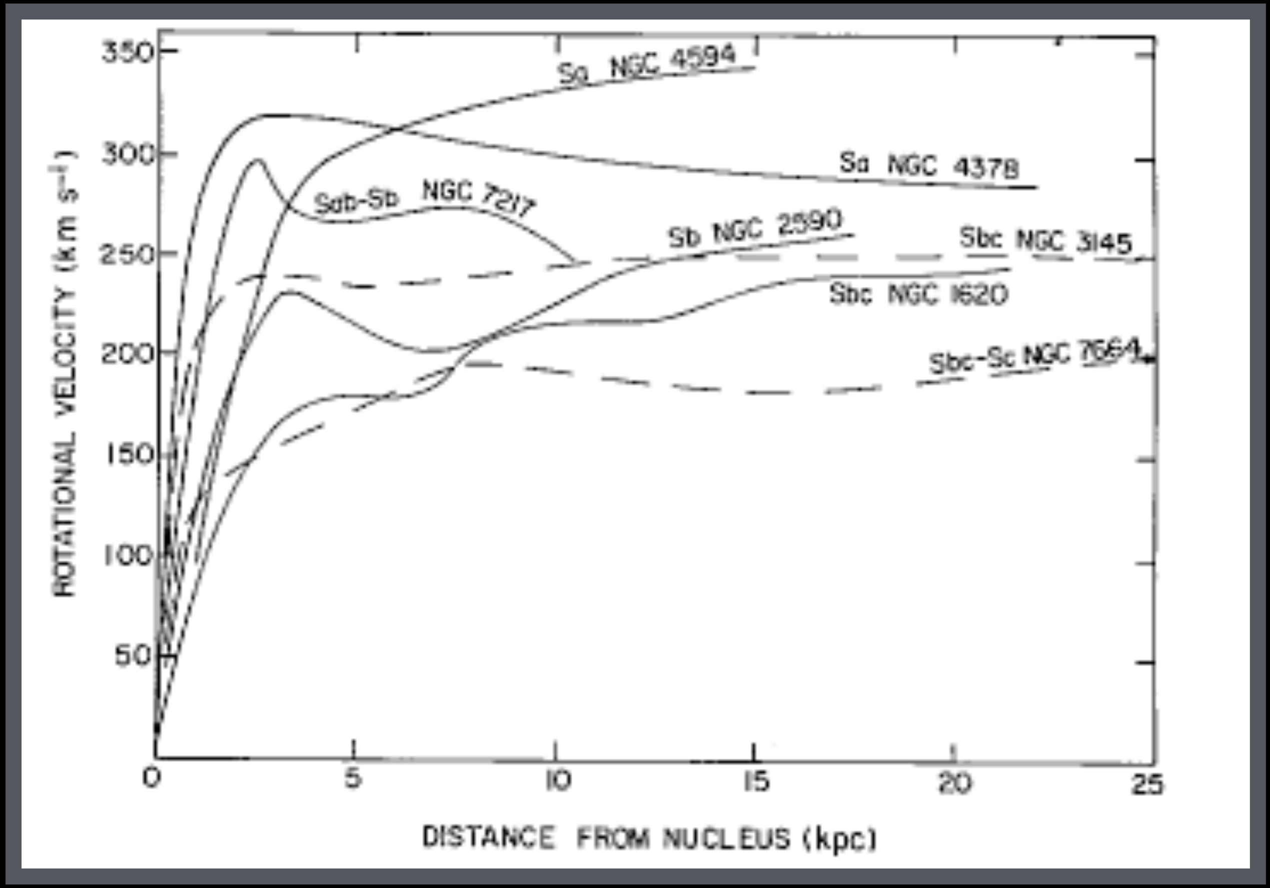
- massive, collisionless, at most weakly interacting
- unclear on fundamental nature

Key Dark Matter Evidence

Earliest Observations

Cluster Dynamics & Galaxy Rotation Curves

image credit: O. Lopez-Cruz (INAOEP)

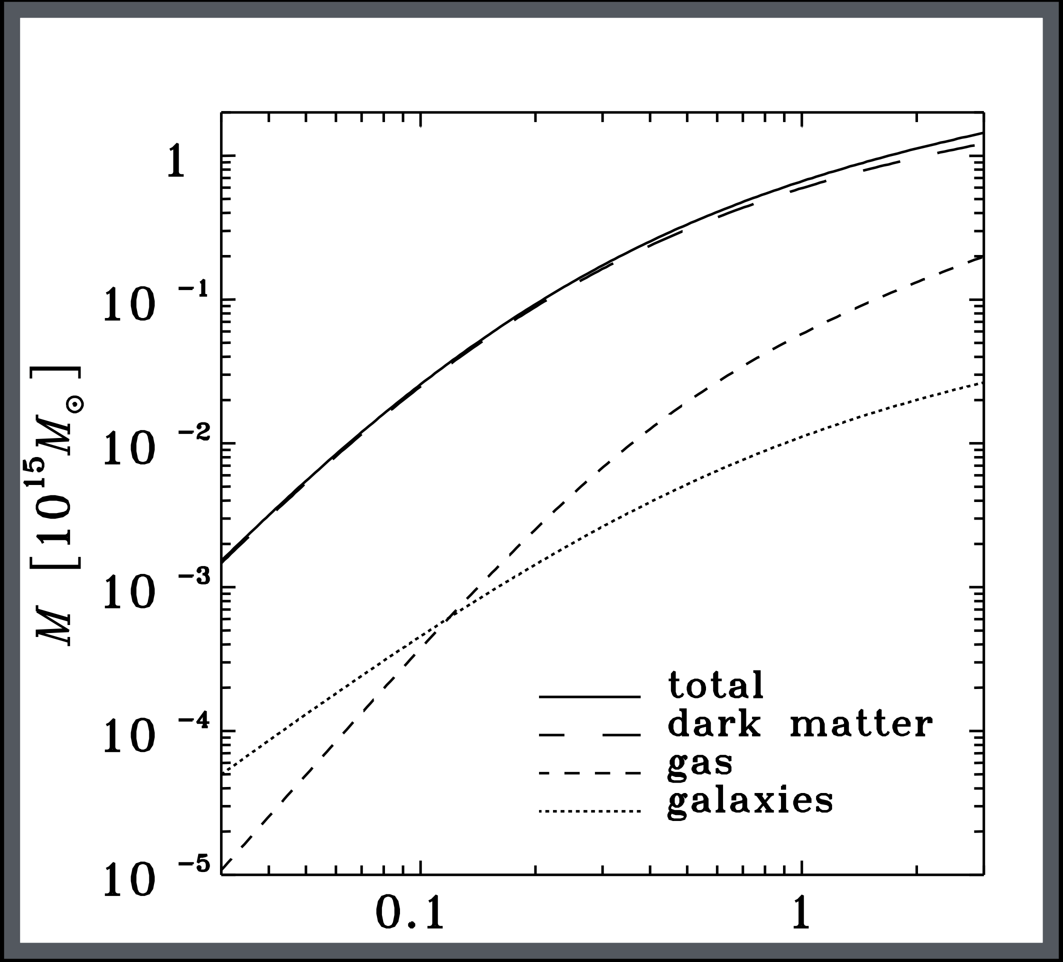


Rubin, Ford and Thonnard, Ap. J. Lett. 1978

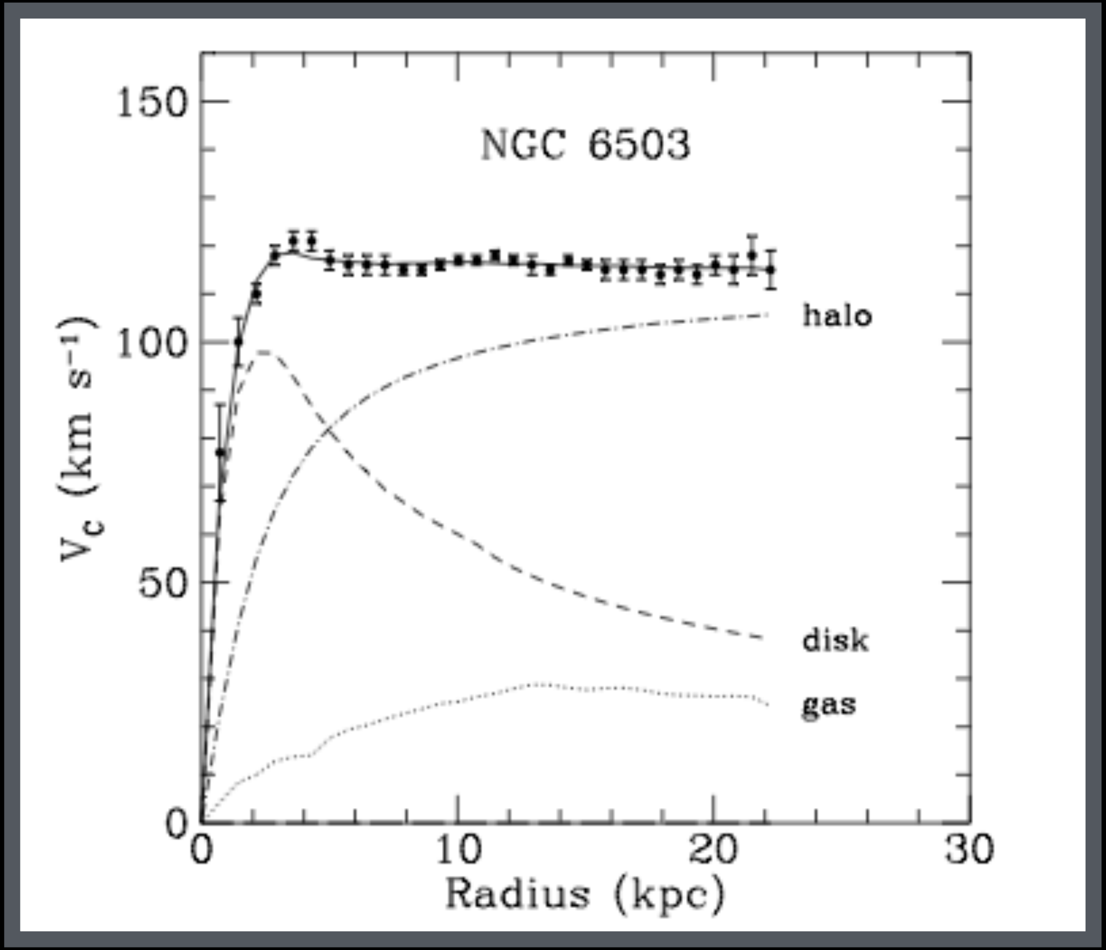
Key Dark Matter Evidence

Earliest Observations (in hindsight)

Cluster Dynamics & Galaxy Rotation Curves



Lokas & Mamon, MNRAS 2003



Begeman et al., 1991

Key Dark Matter Evidence

Observational Tools

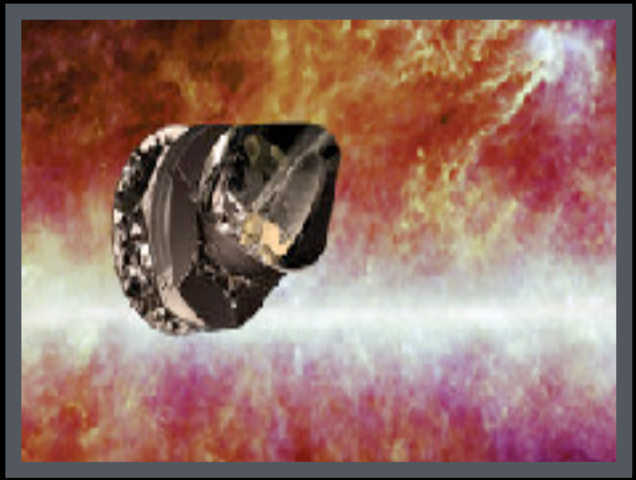
Optical

Hubble Space Telescope (NASA)

Cosmic Rays

AMS - 02 (AMS collaboration)

CMB



Planck satellite (ESA)

X-Rays

Chandra X-Ray Observatory (NASA)

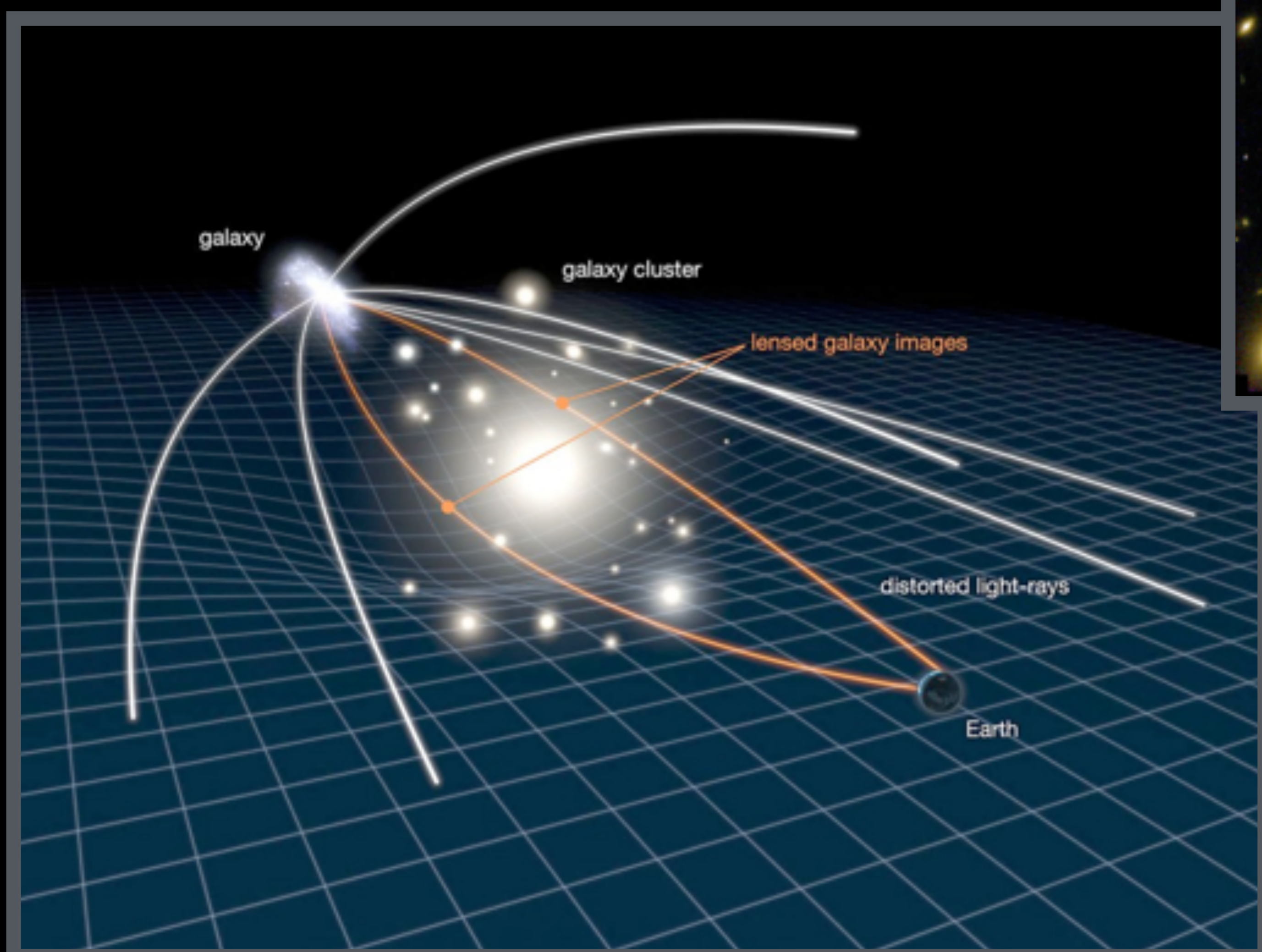
Future Radio Telescope Arrays

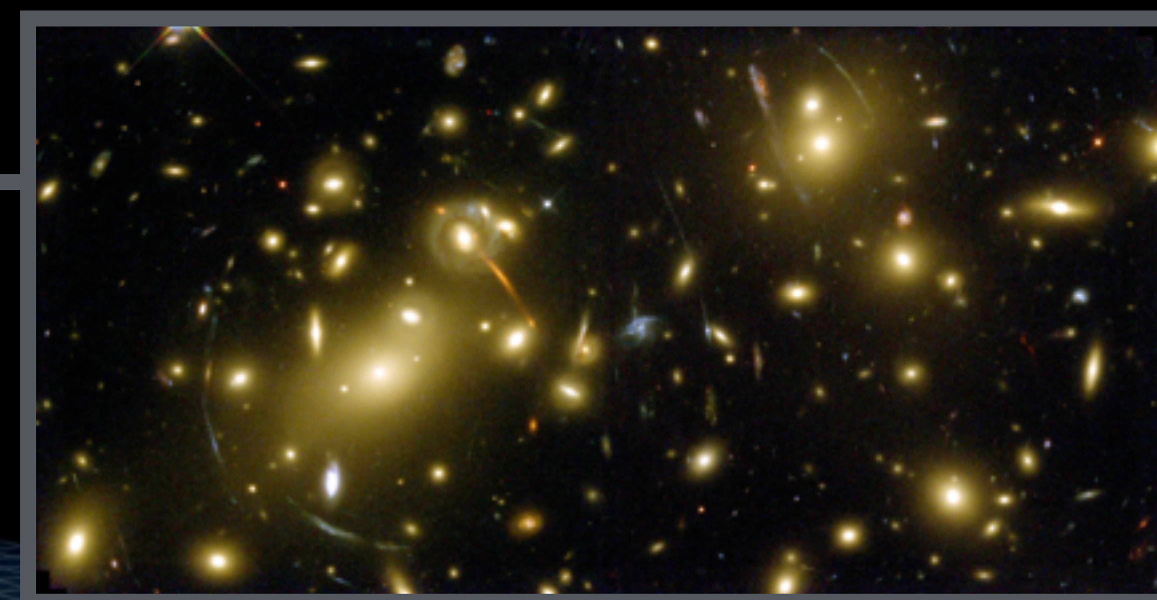
Square Kilometer Array (SKA)

Key Dark Matter Evidence

Observational Tools

Gravitational Lensing





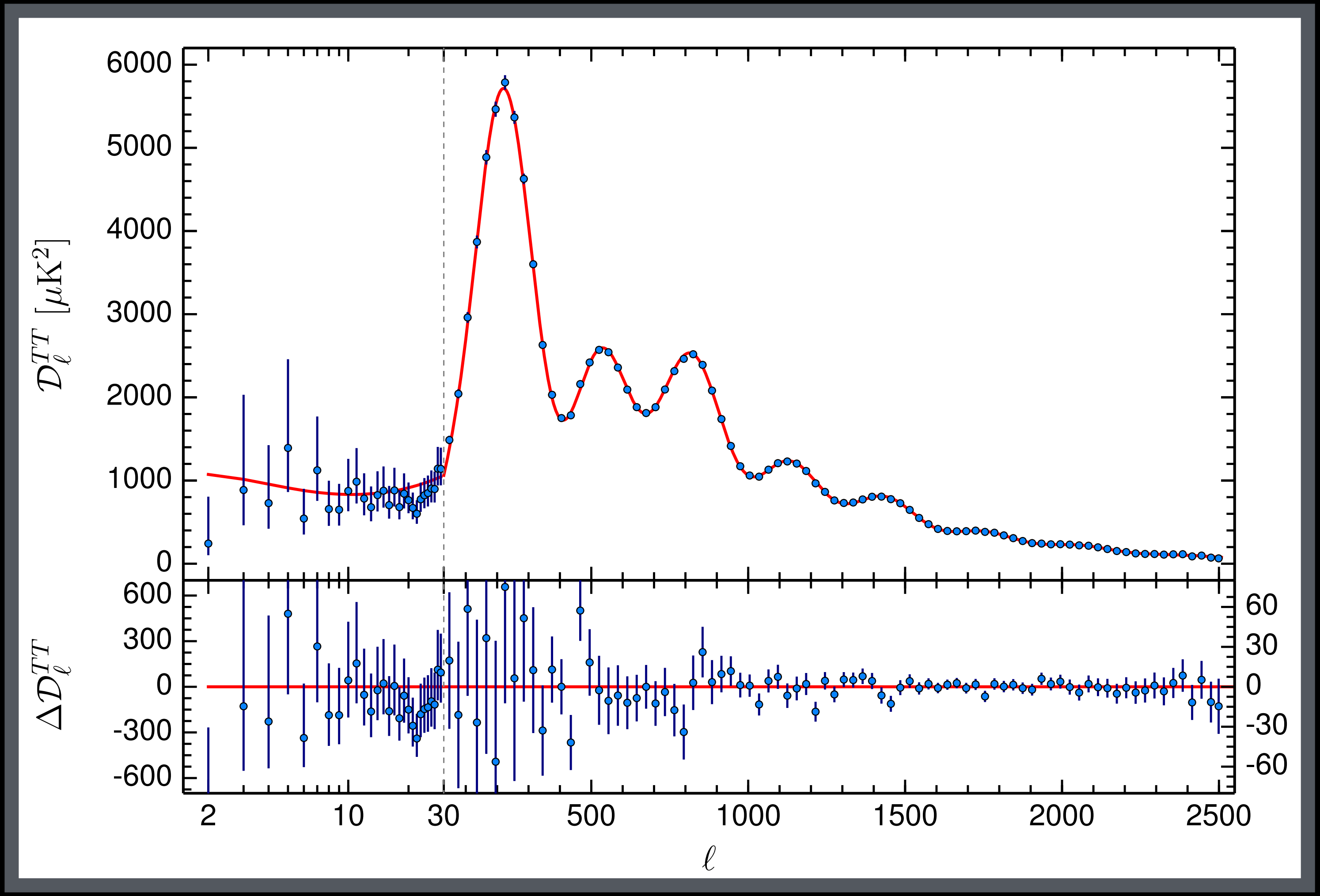
- used to determine mass distribution
- useful for DM, especially in conjunction with X-ray and (visible) optical observations

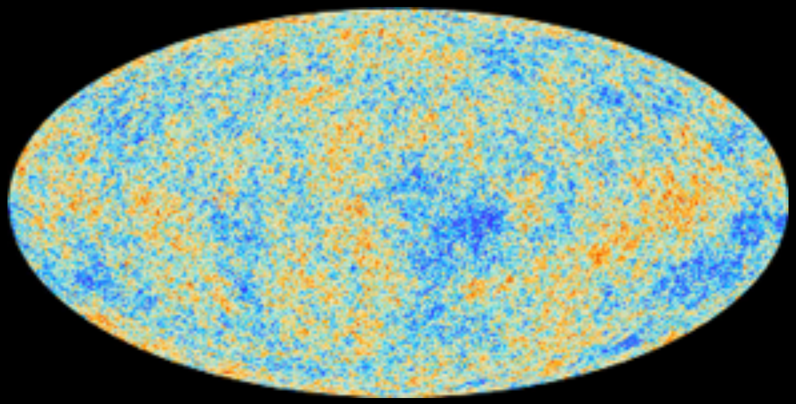
image credits: NASA/ESA

Key Dark Matter Evidence

Determining Cosmic Parameters

CMB and Baryon Acoustic Oscillations





ESA and Planck collaboration

Planck collaboration 2015

Key Dark Matter Evidence

Cluster Dynamics II - The Bullet Cluster

Chandra

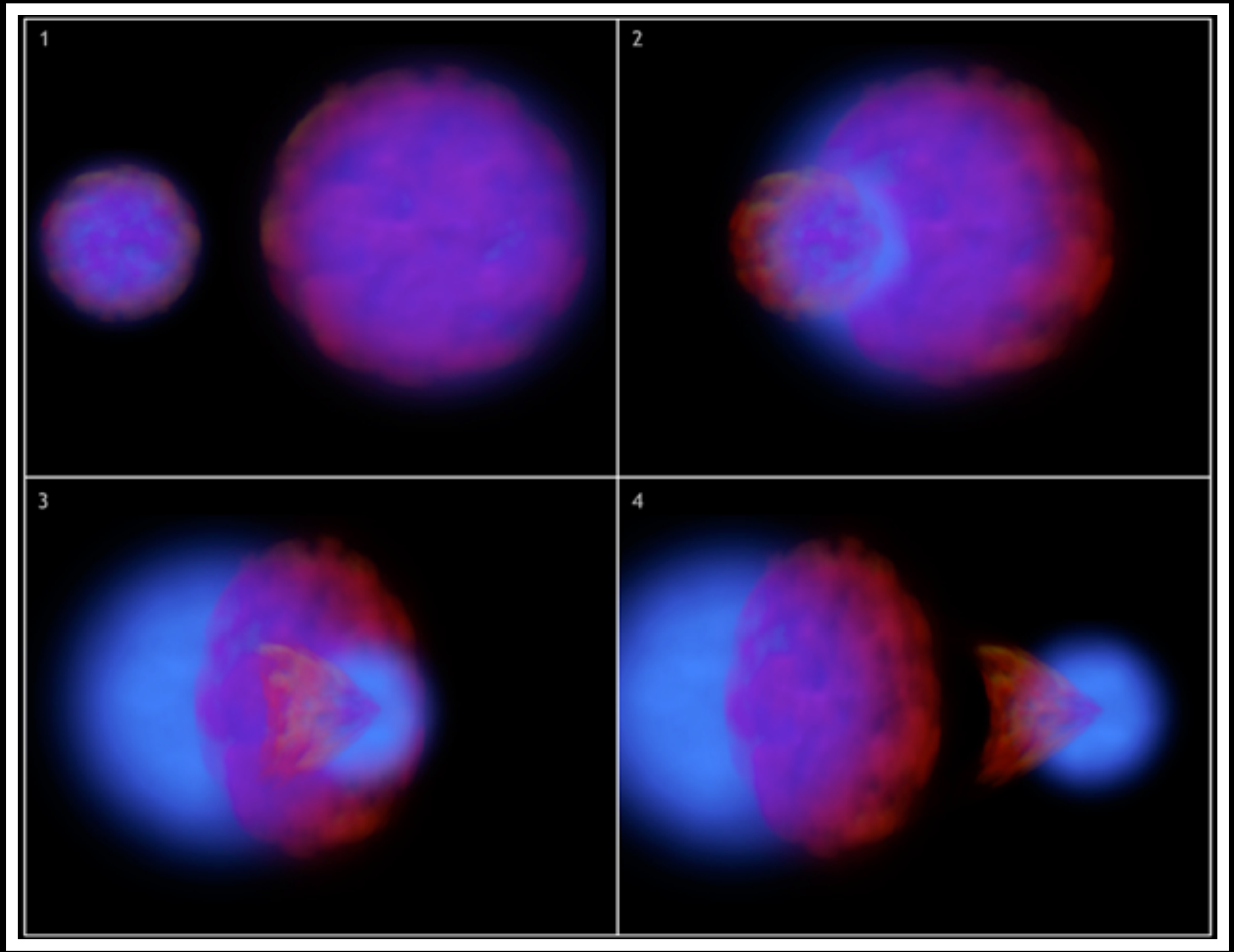
Key Dark Matter Evidence

Cluster Dynamics II

Chandra

Key Dark Matter Evidence

Cluster Dynamics II



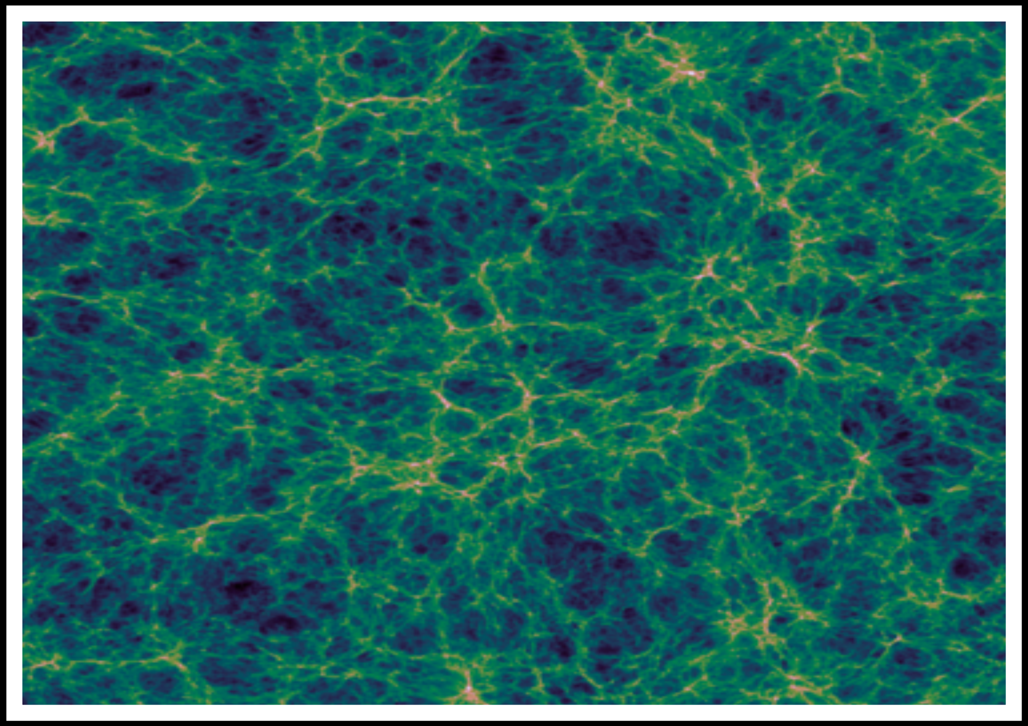
Chandra

Key Dark Matter Evidence

Cluster Dynamics II

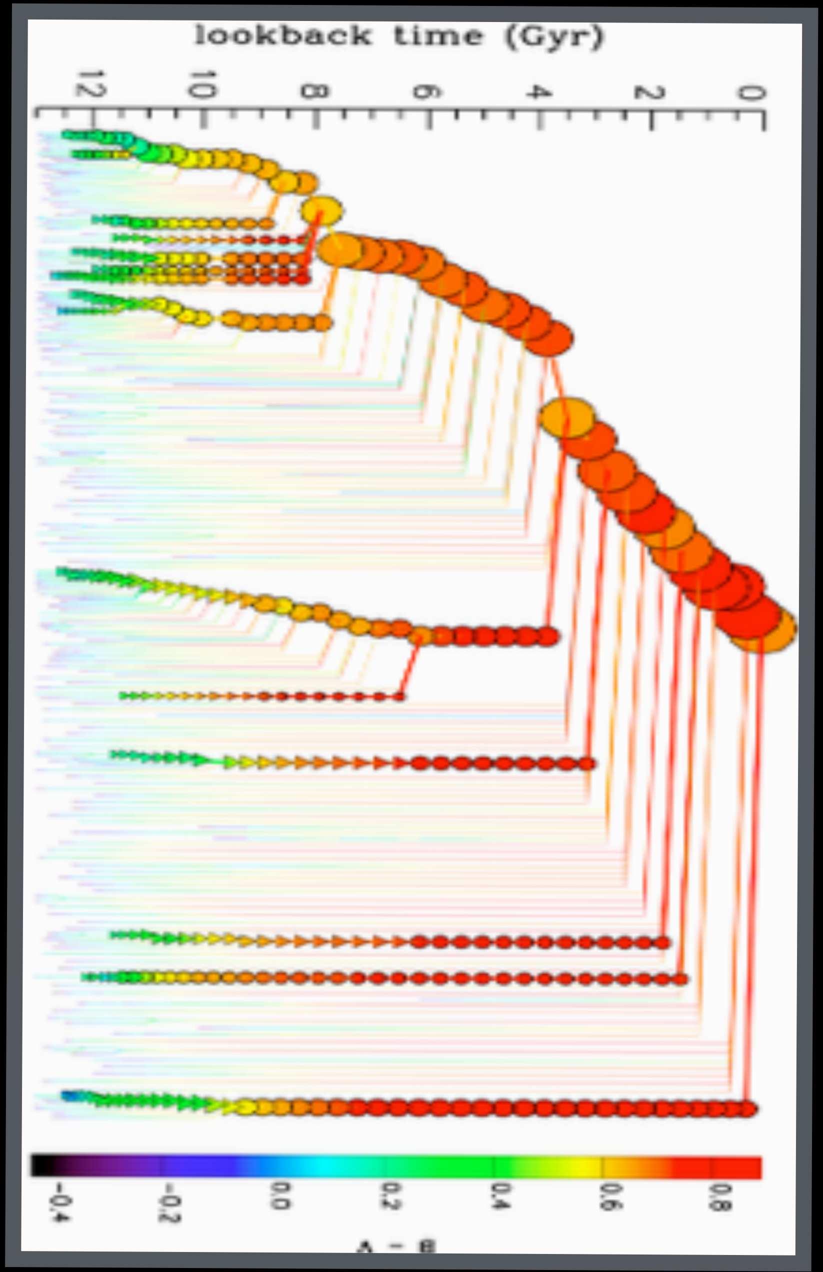
Chandra

Structure Formation



DRAGONS

hierarchical growth of structure



universal halo profiles

$$\rho_{NFW} = \frac{\rho_0}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

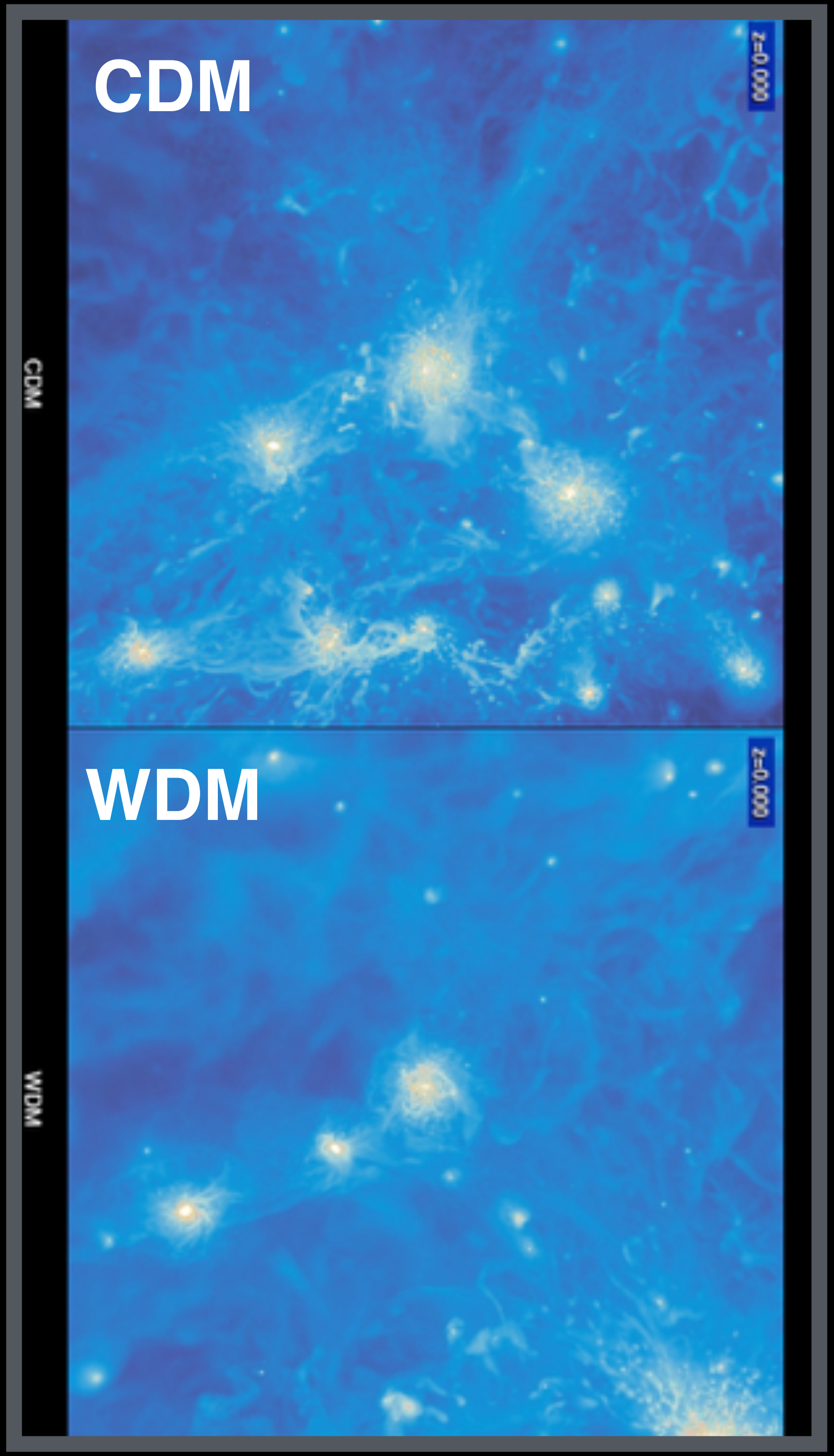
Structure Formation

- Useful to test some aspects of models such as hot vs warm vs cold DM

- Compare DM vs baryon only structure formation

- Could also test non-gravitational DM interactions

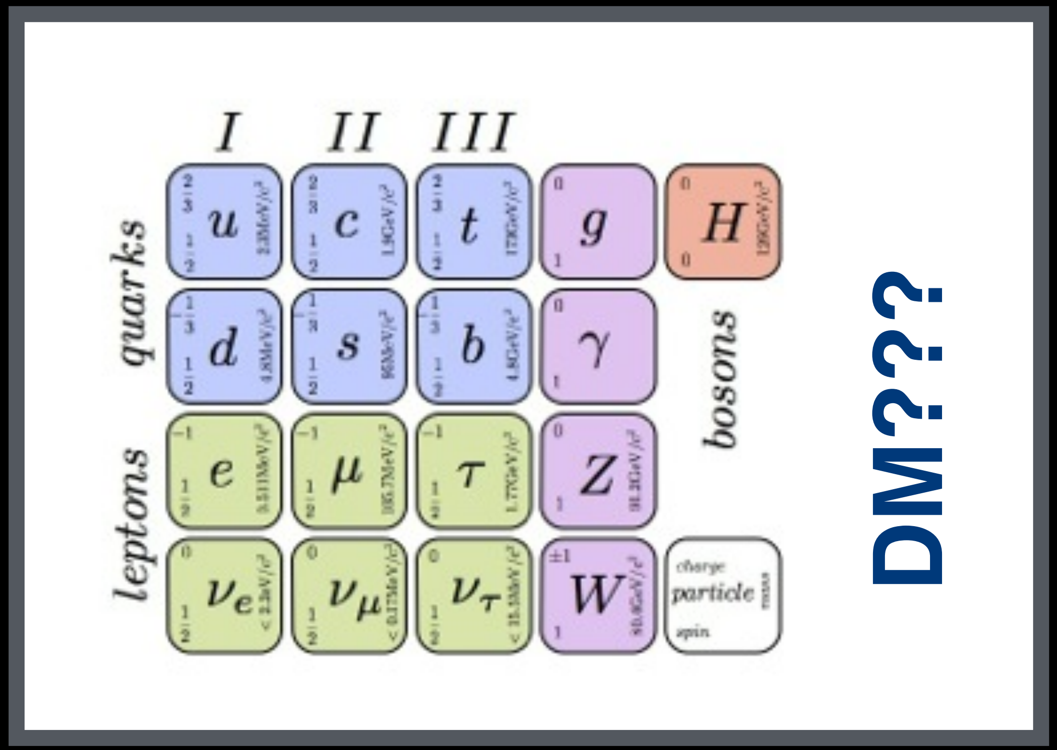
- limited by understanding of baryonic processes, resolution



CLUES-Project

What is the Fundamental Nature of Dark Matter ???

- Particle phenomenology ie: production and non-gravitational interactions?
- Structure formation - cups/core problem, missing satellites
- Impact DM interaction could have on structure?



Dark Matter Candidates

Past and Present, Rejected and Realisable

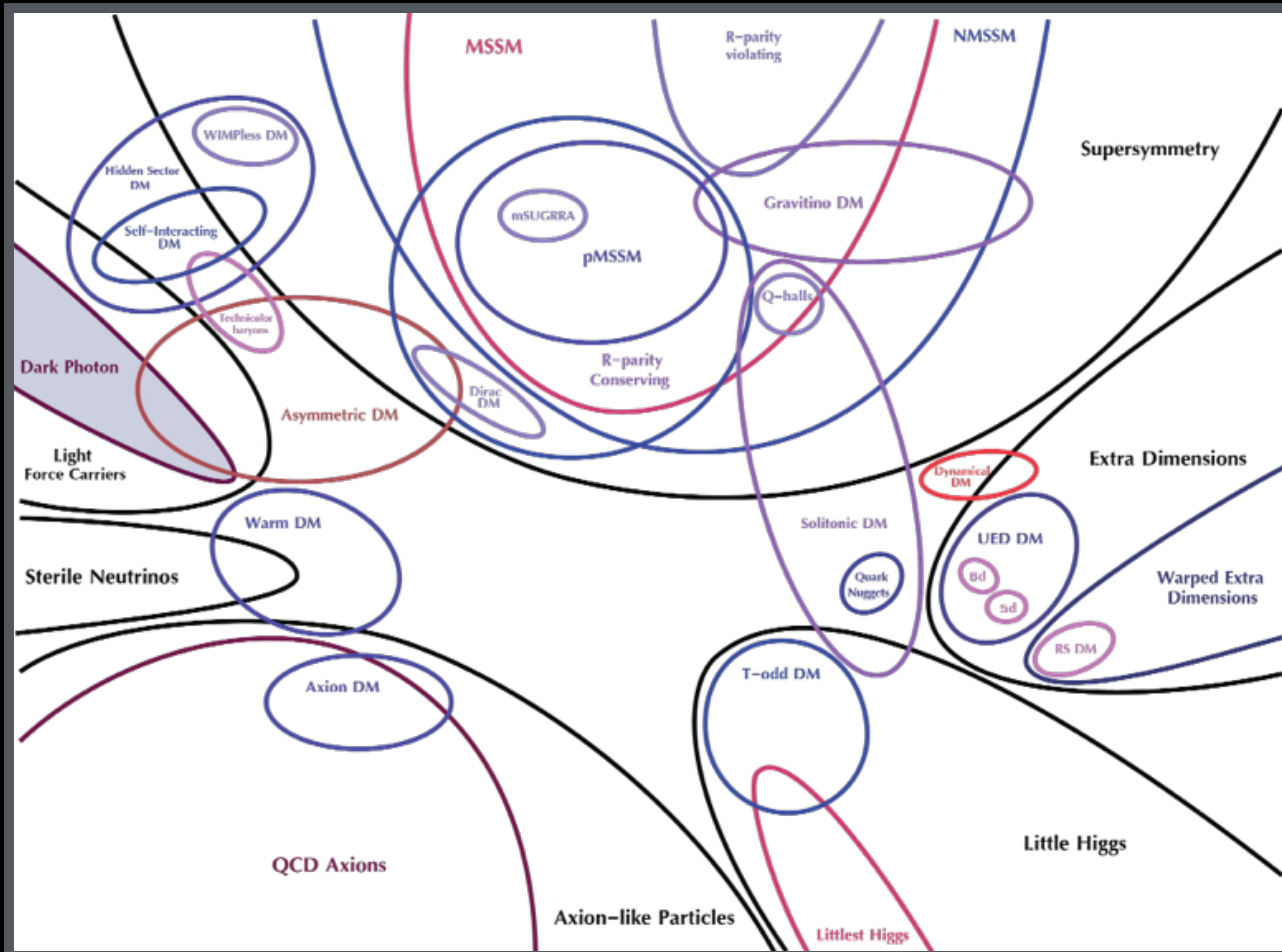
- Cold gas, dim stars
- MACHOS

not sufficient to account for complete DM phenomenology

- Neutrinos (useful template)
- Primordial Black Holes ???
- MOND ???
- Non-Standard Model Matter →

Dark Matter Candidates

DM in the Particle Context



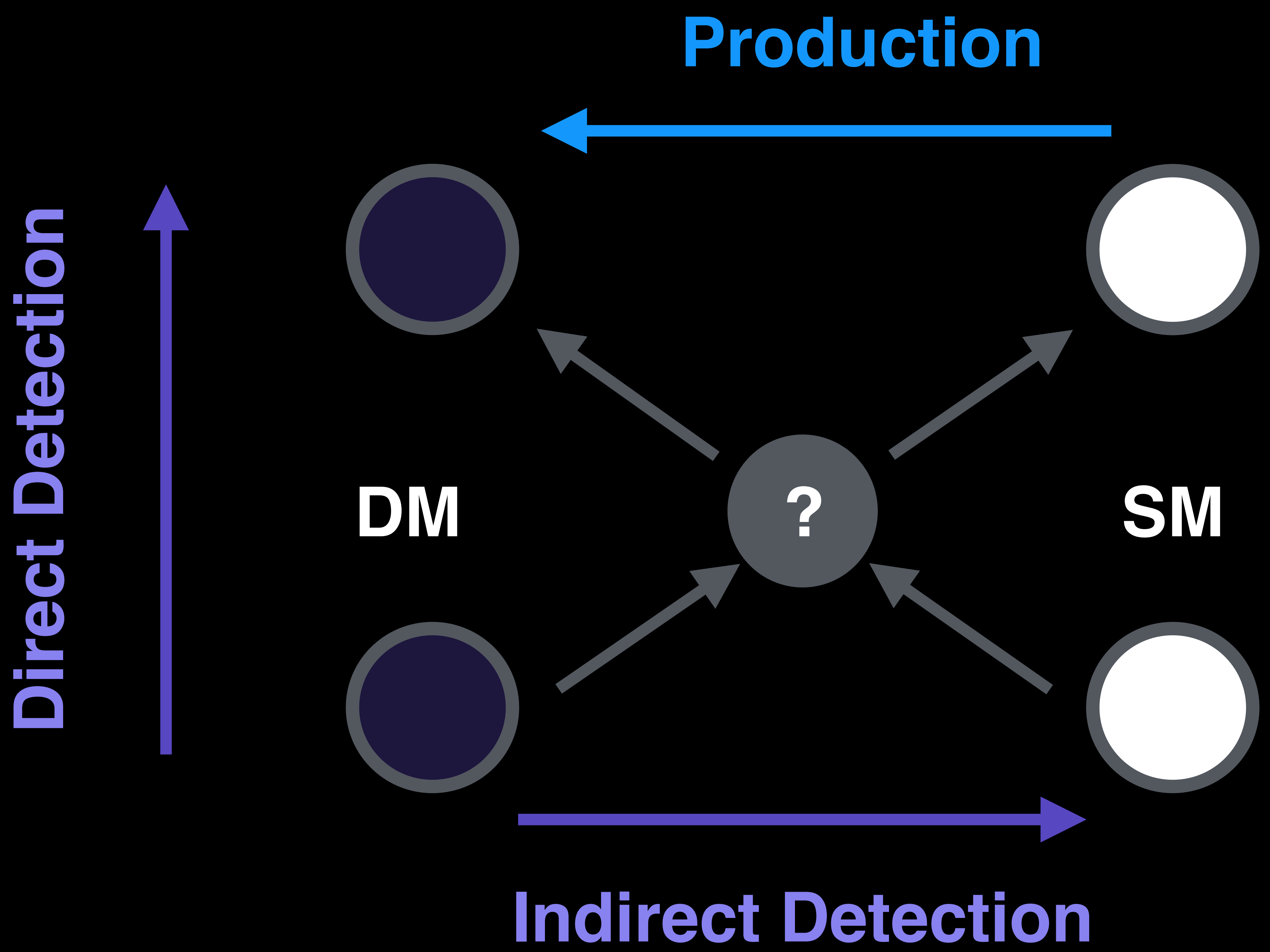
credit T. Tait from Feng et al 2014

Dark Matter Candidates
from beyond the Standard Model

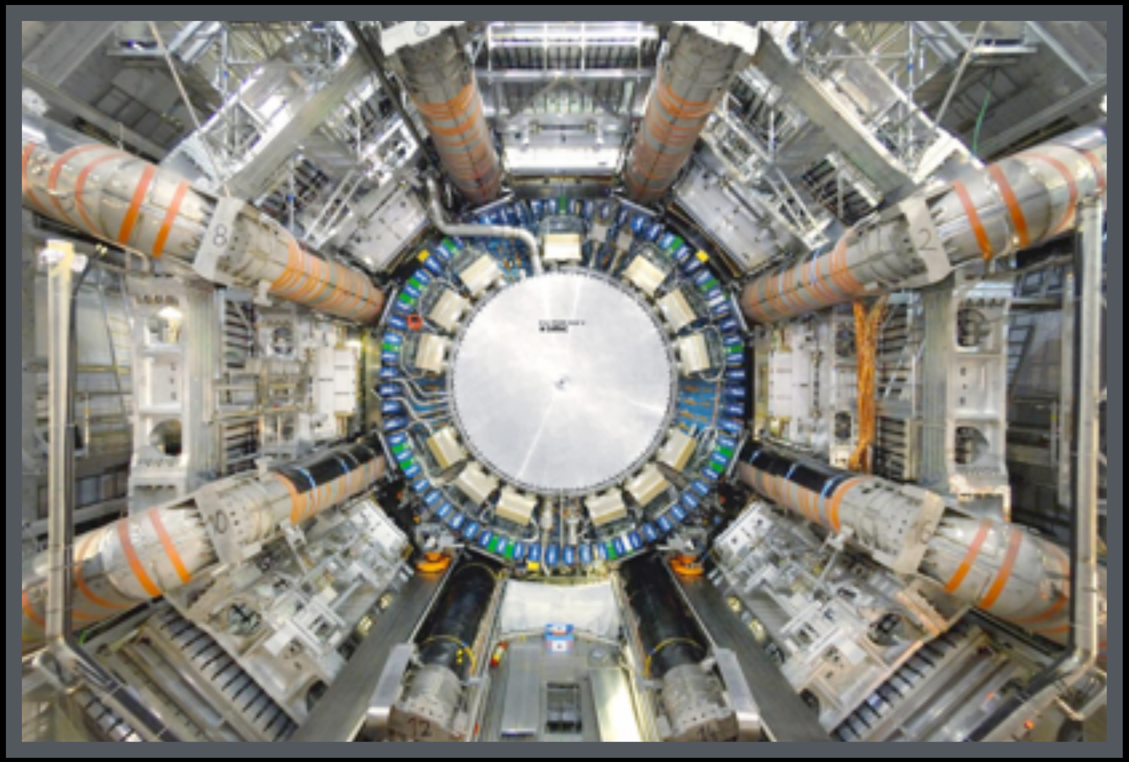
- **WIMPS (weakly interacting massive particles)**
- **SUSY particles -** solves SM issues such as Hierarchy Problem and gauge coupling unification, so far no detection
- **Axions -** arise as part of Peccei-Quinn Theory to solve the Strong CP Problem
- **Kaluza-Klein -** from extra dimensions, aim to unify electromagnetism with gravity
- **Sterile Neutrino** - motivated by chirality arguments

Ongoing Dark Matter Searches

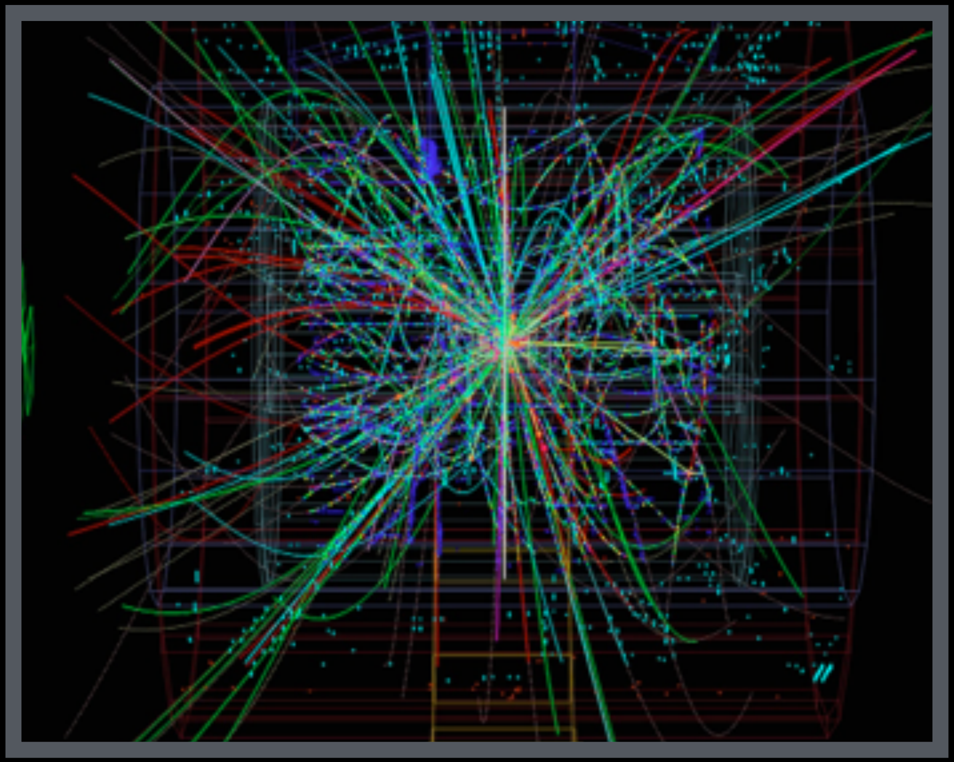
On A Collision Course with Particle Physics



DM Collider Searches



CERN

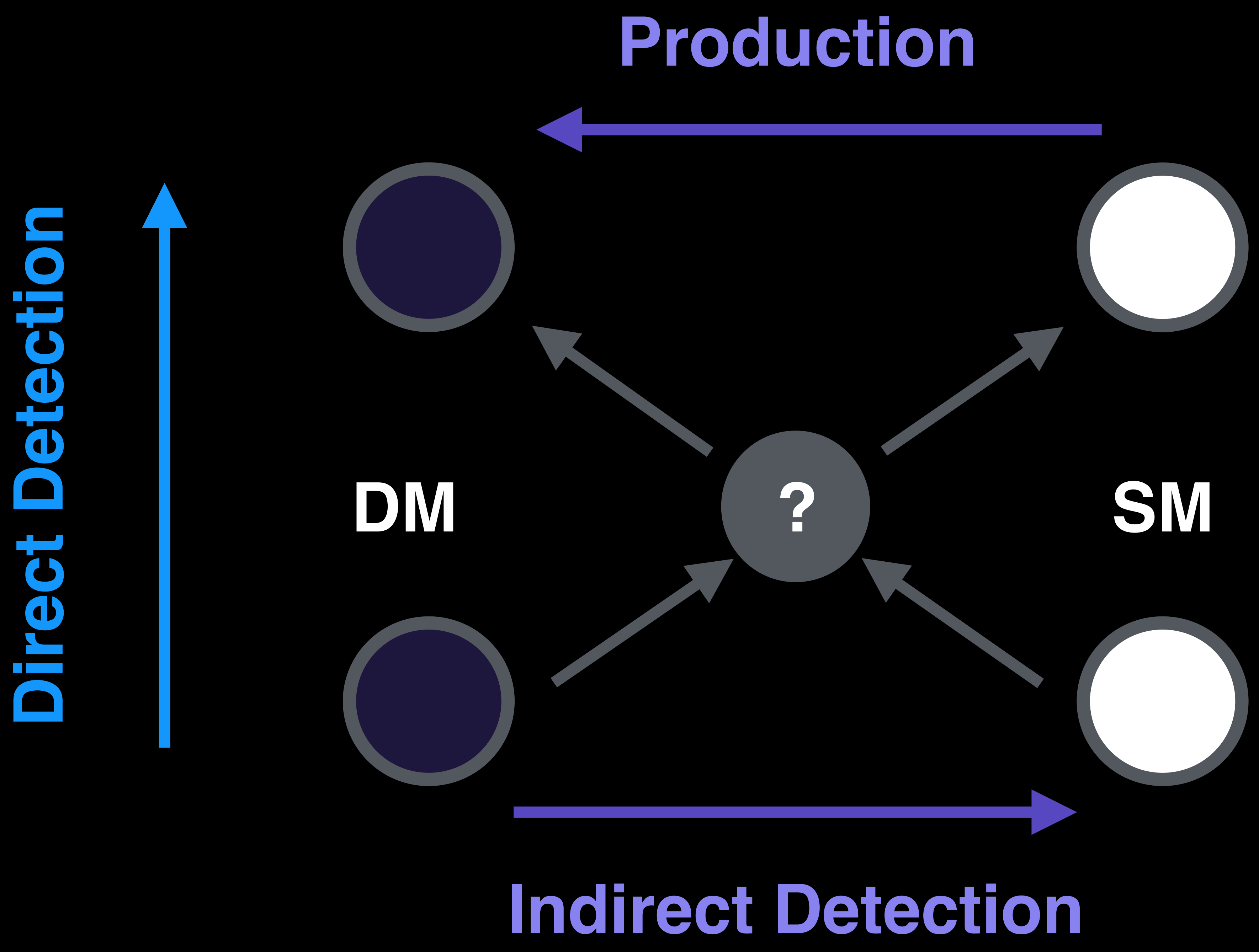


Event at LHC (CERN)

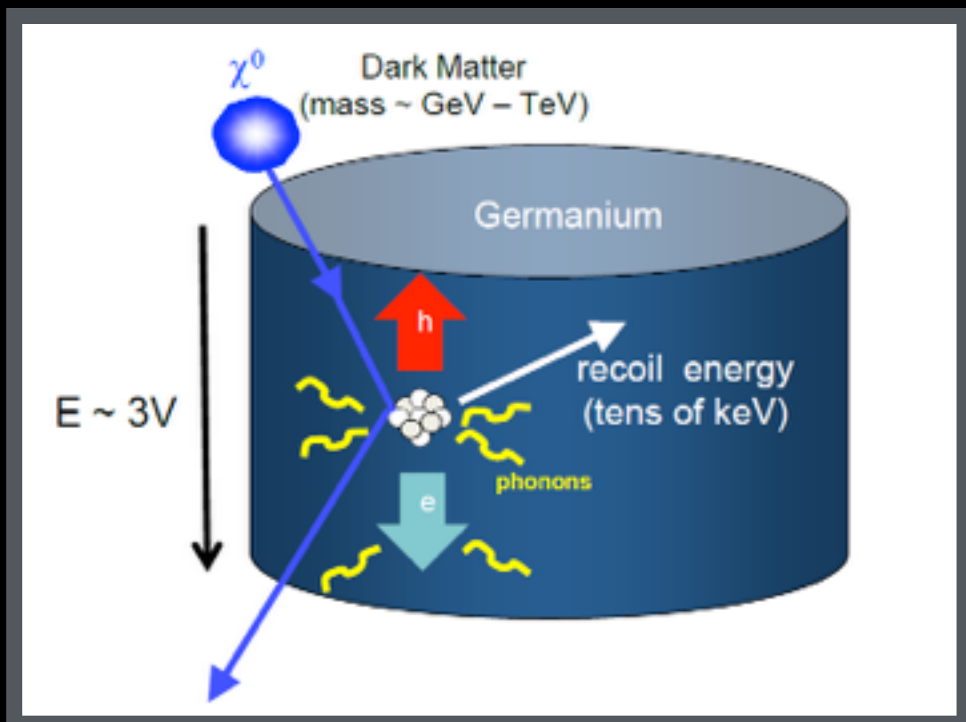
Searches at colliders look for missing energy to try and identify potential DM candidates

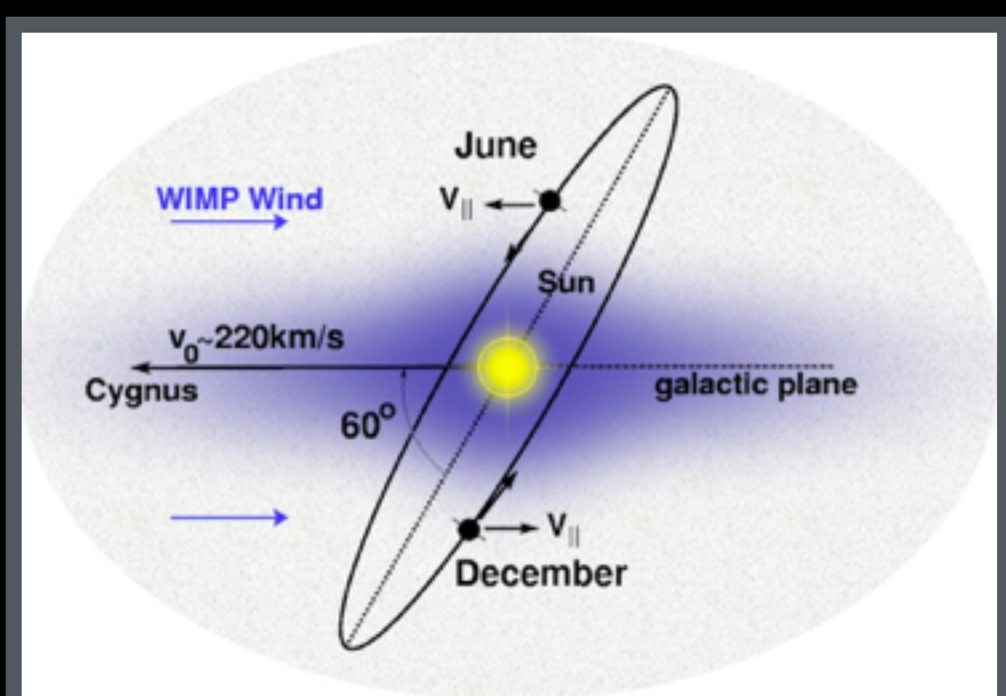
Ongoing Dark Matter Searches

On A Collision Course with Particle Physics



Direct DM Searches

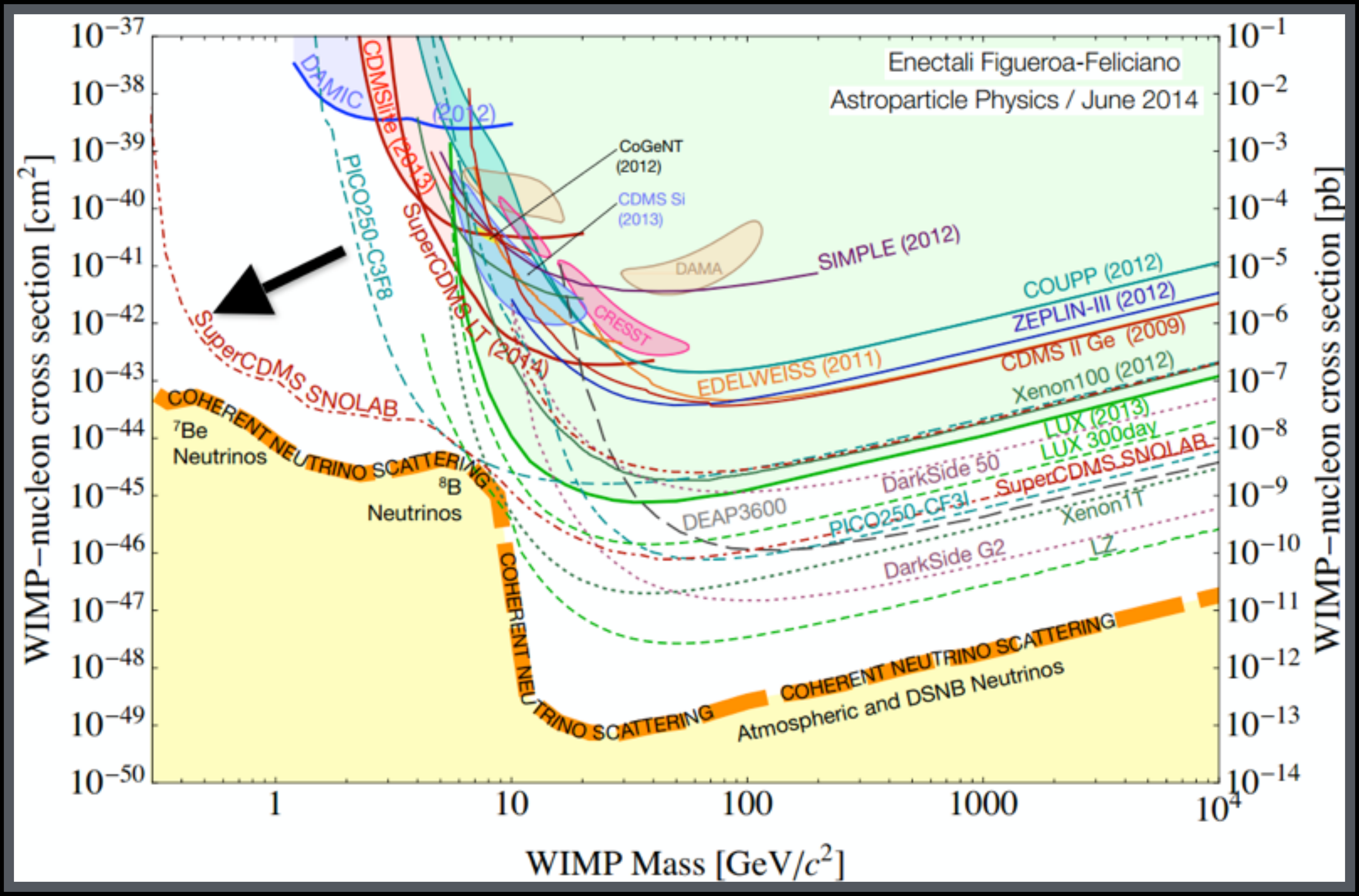




SLAC Stanford

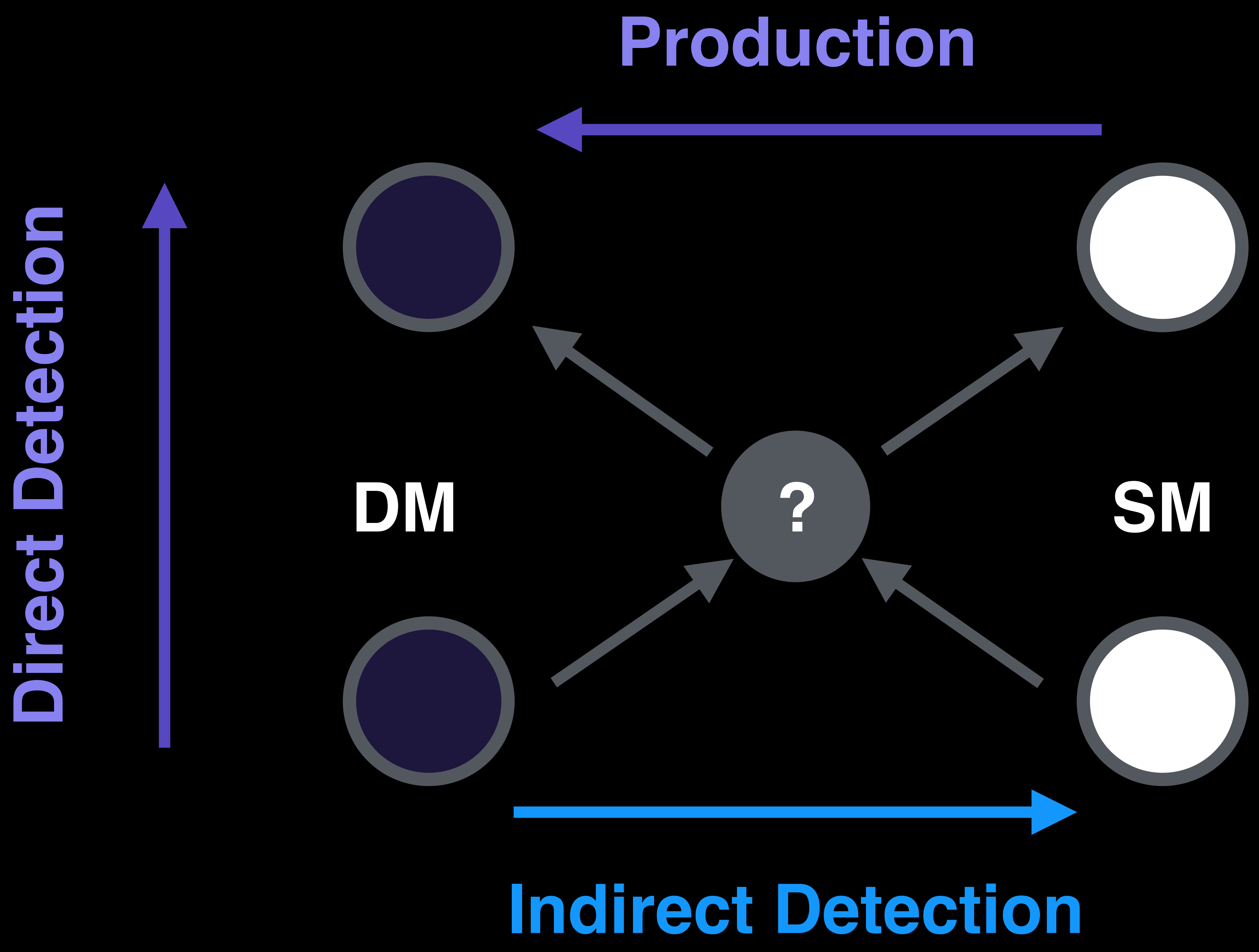
- **Search for photon signature from nuclear recoil**
- **Look for oscillations in detection results as earth orbits sun**

Direct DM Searches

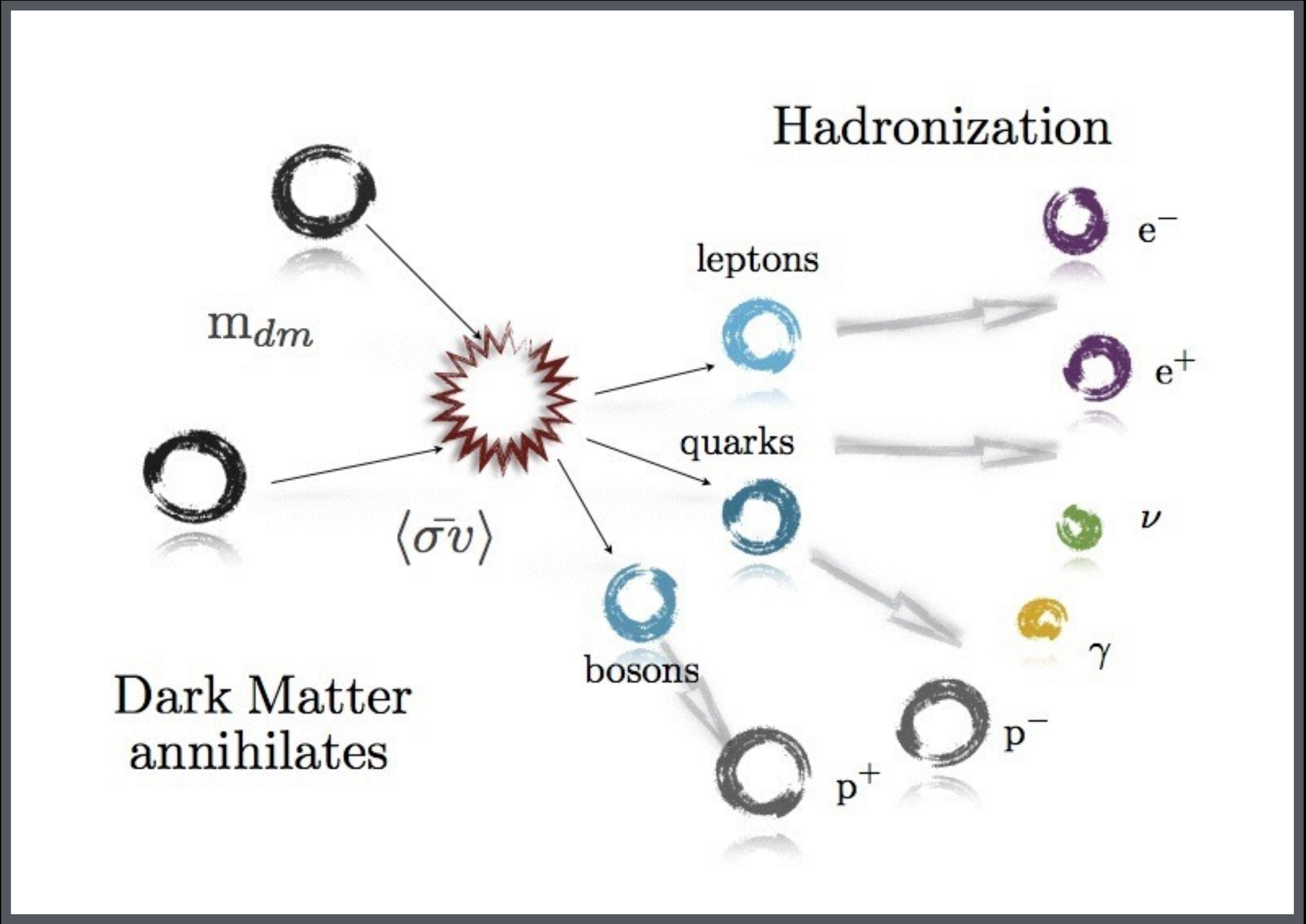


Ongoing Dark Matter Searches

On A Collision Course with Particle Physics



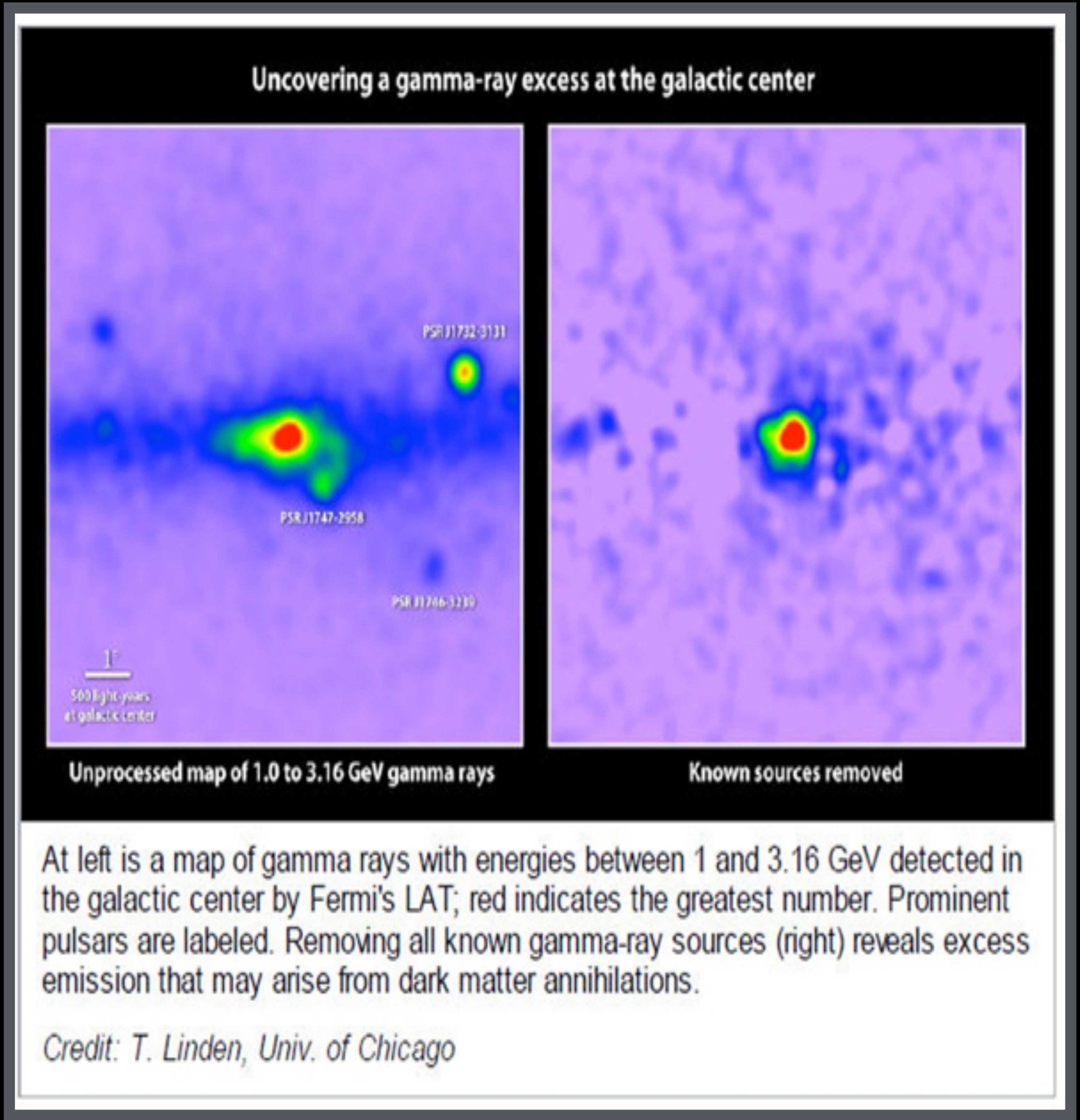
Indirect DM Searches



Astrophysical DM Signals

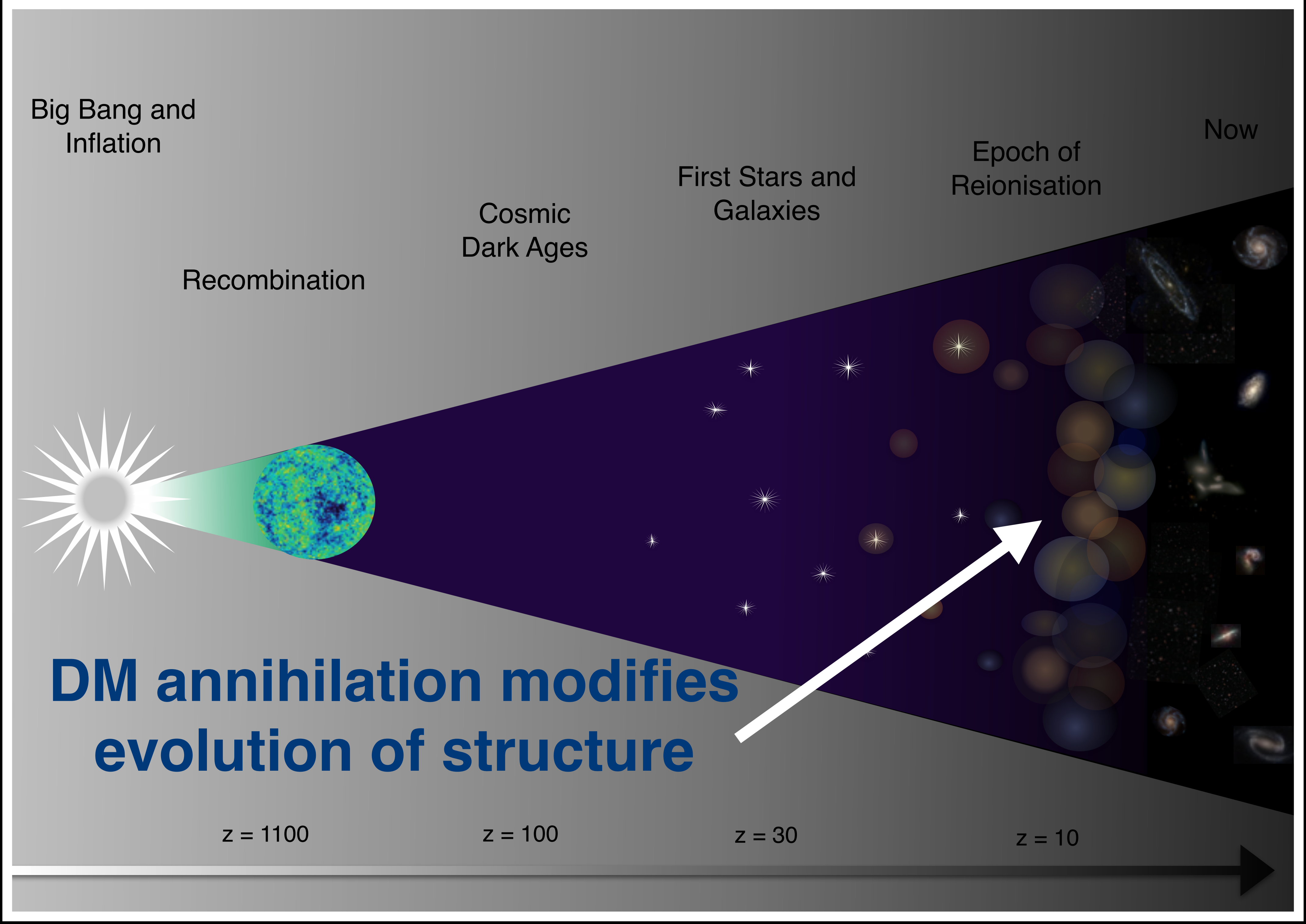
- **Look for DM annihilation products**
- **Cosmic Rays -** positron excess as seen by AMS/PAMELA
- **Gamma Rays -** excess in Galactic Centre
- **Cosmological Signature -** 21cm signal
- **Overlay of other astrophysical structure and processes complicates analysis of these**

Astrophysical DM Signals

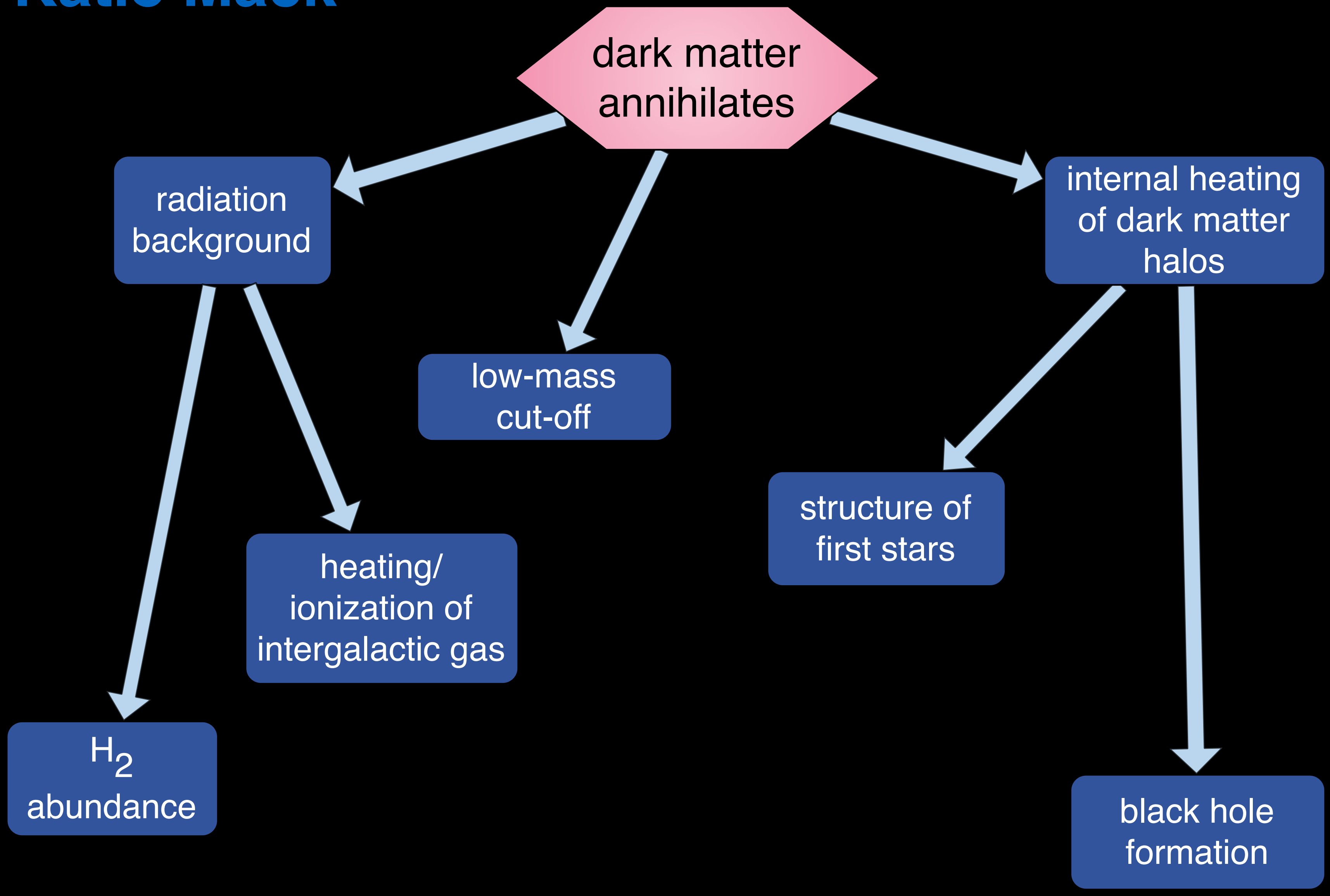


- Both gamma ray and positron excess could be due to DM annihilation
- Could also be pulsars

Epoch of Reionization



courtesy of Katie Mack



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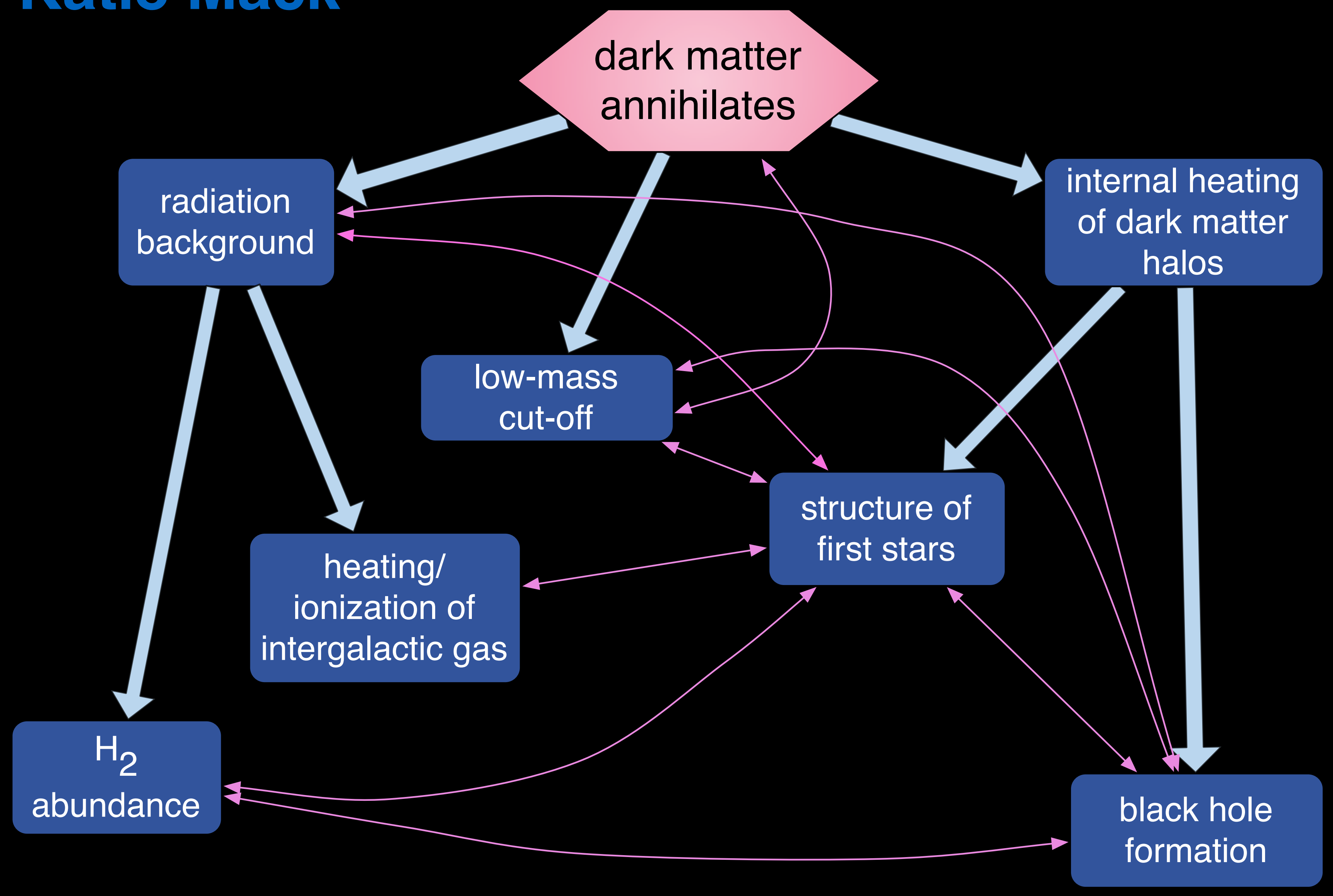
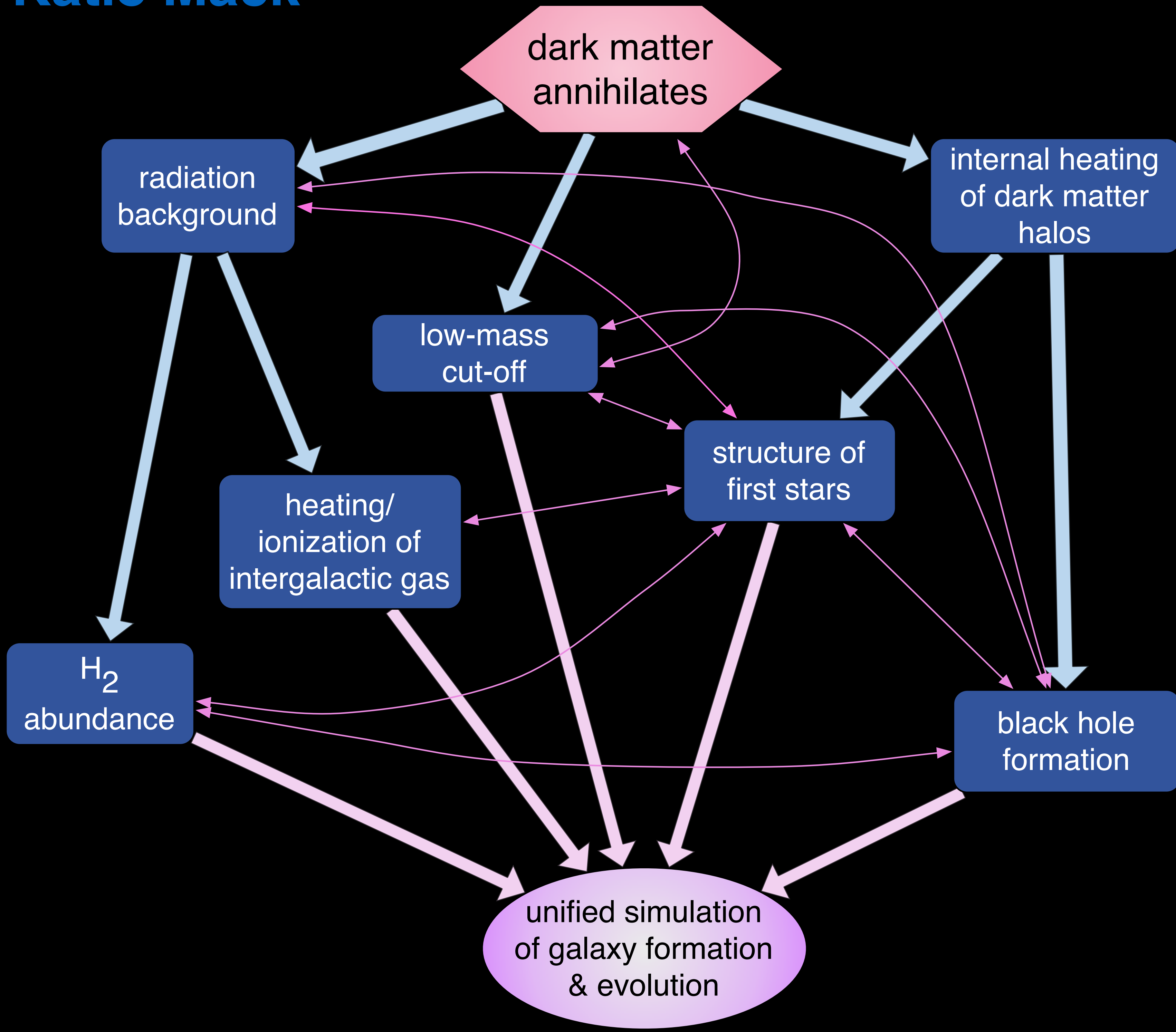


courtesy of Katie Mack



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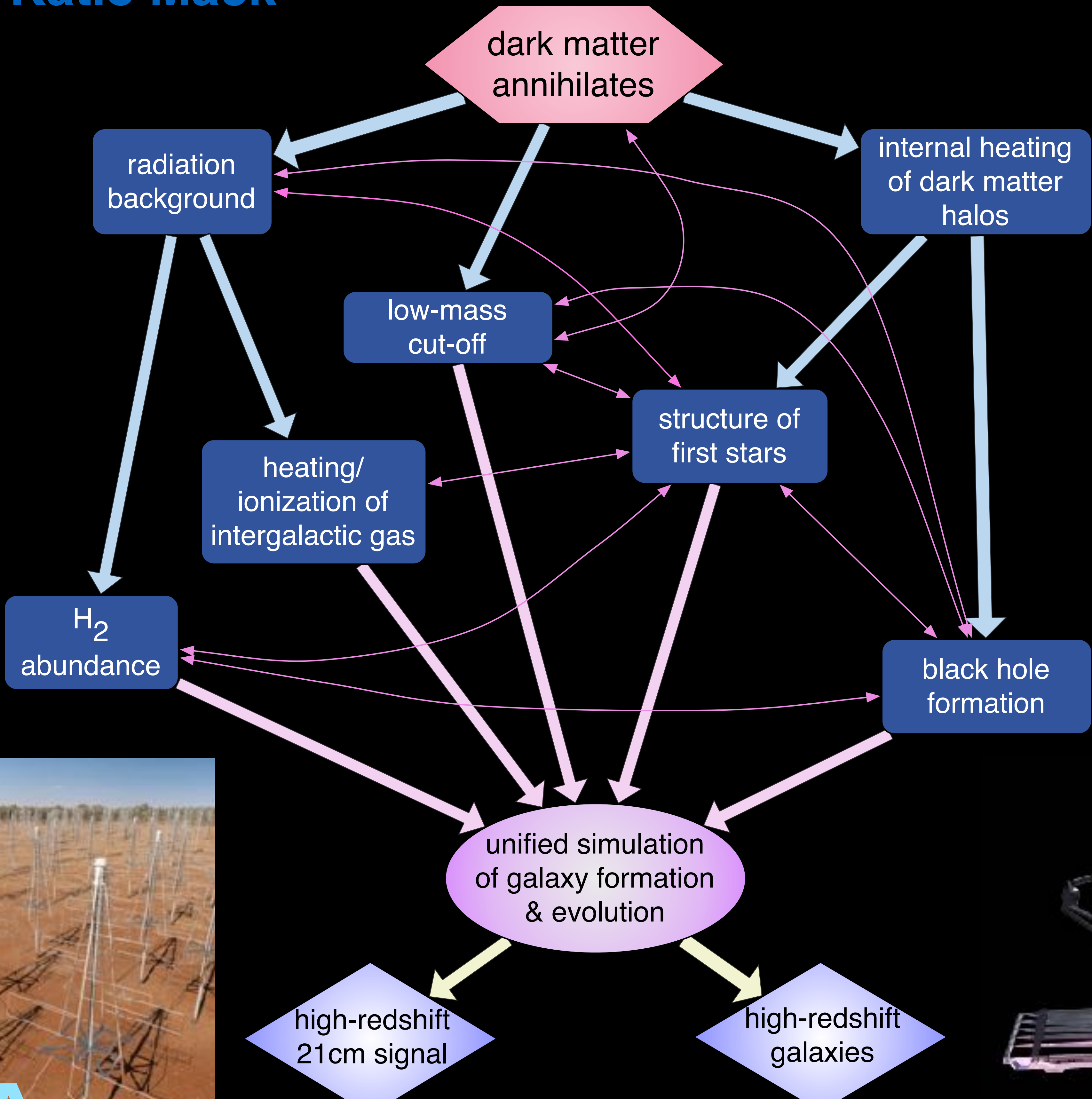


Image credit: Swinburne/ ICRAR/Cambridge/ASTRON

JWST

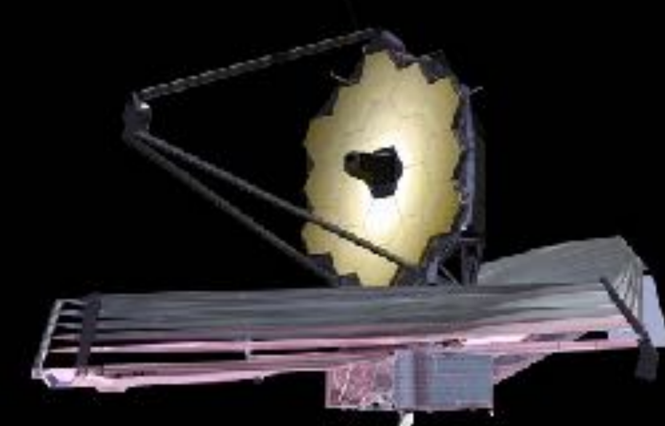


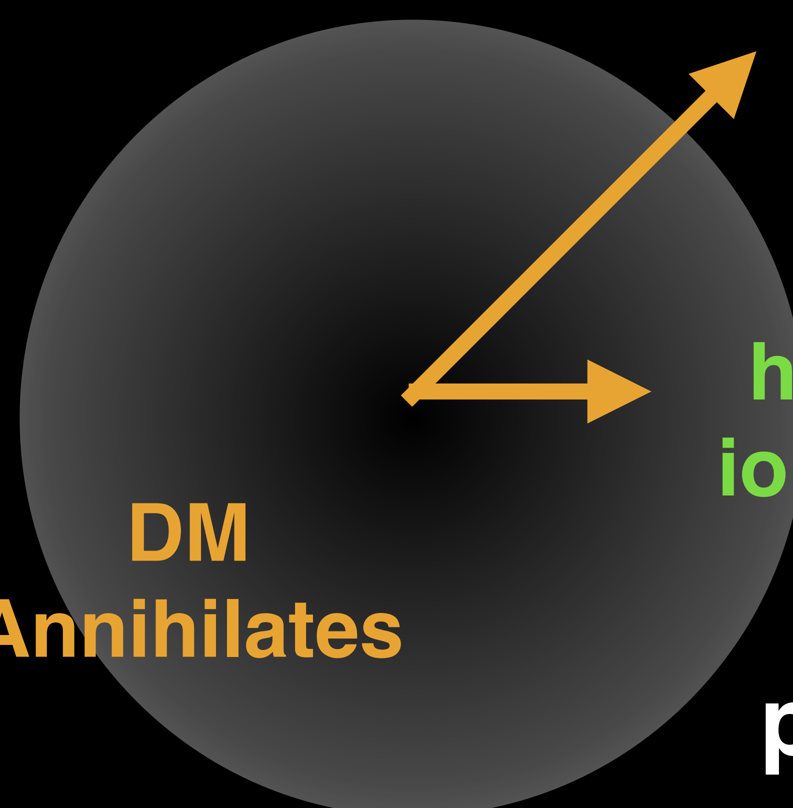
Image credit: NASA

DM Annihilation and Structure Formation

DM Annihilation Model

DM Halo Model

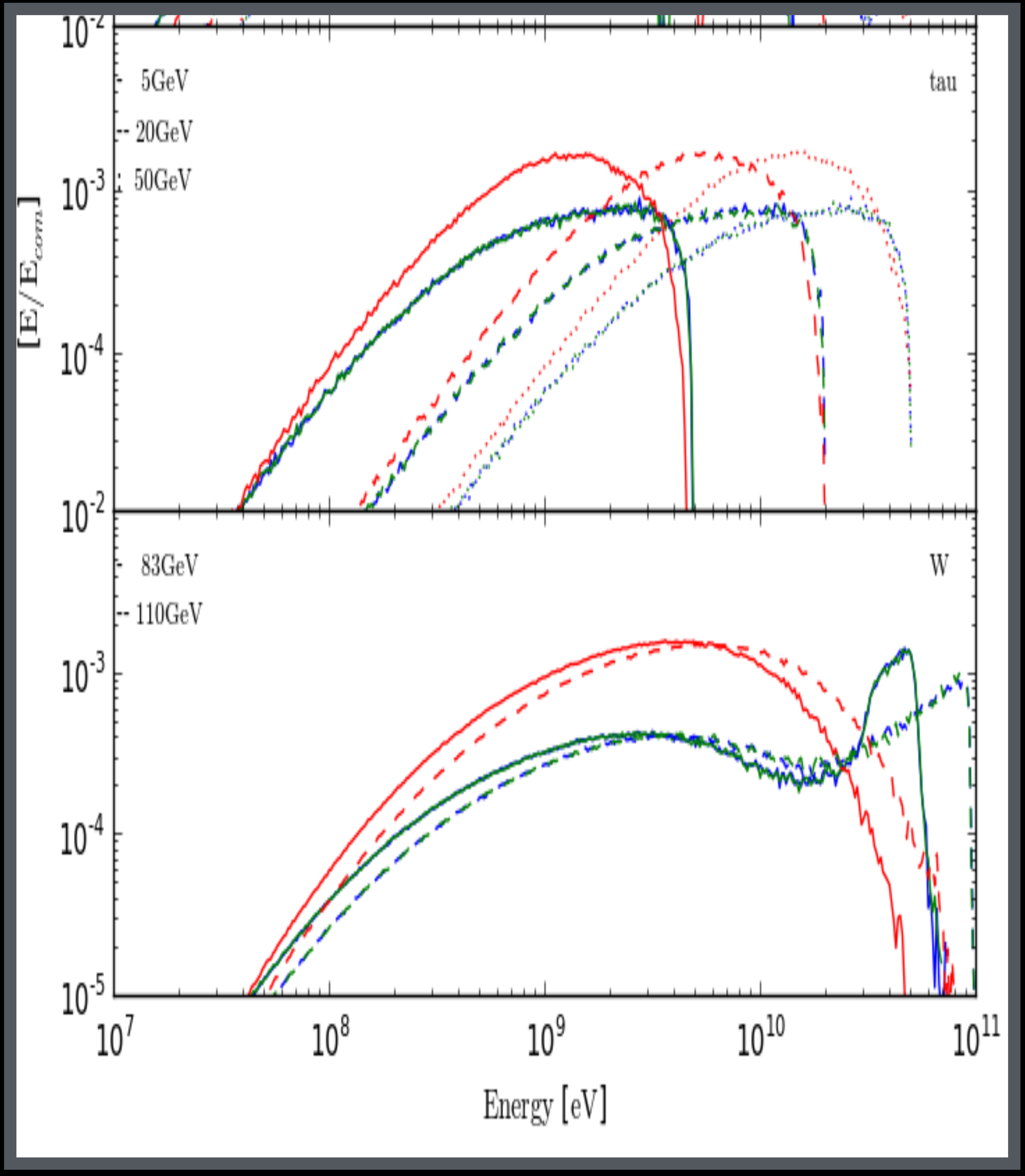
Energy Transfer



DM Annihilation Model

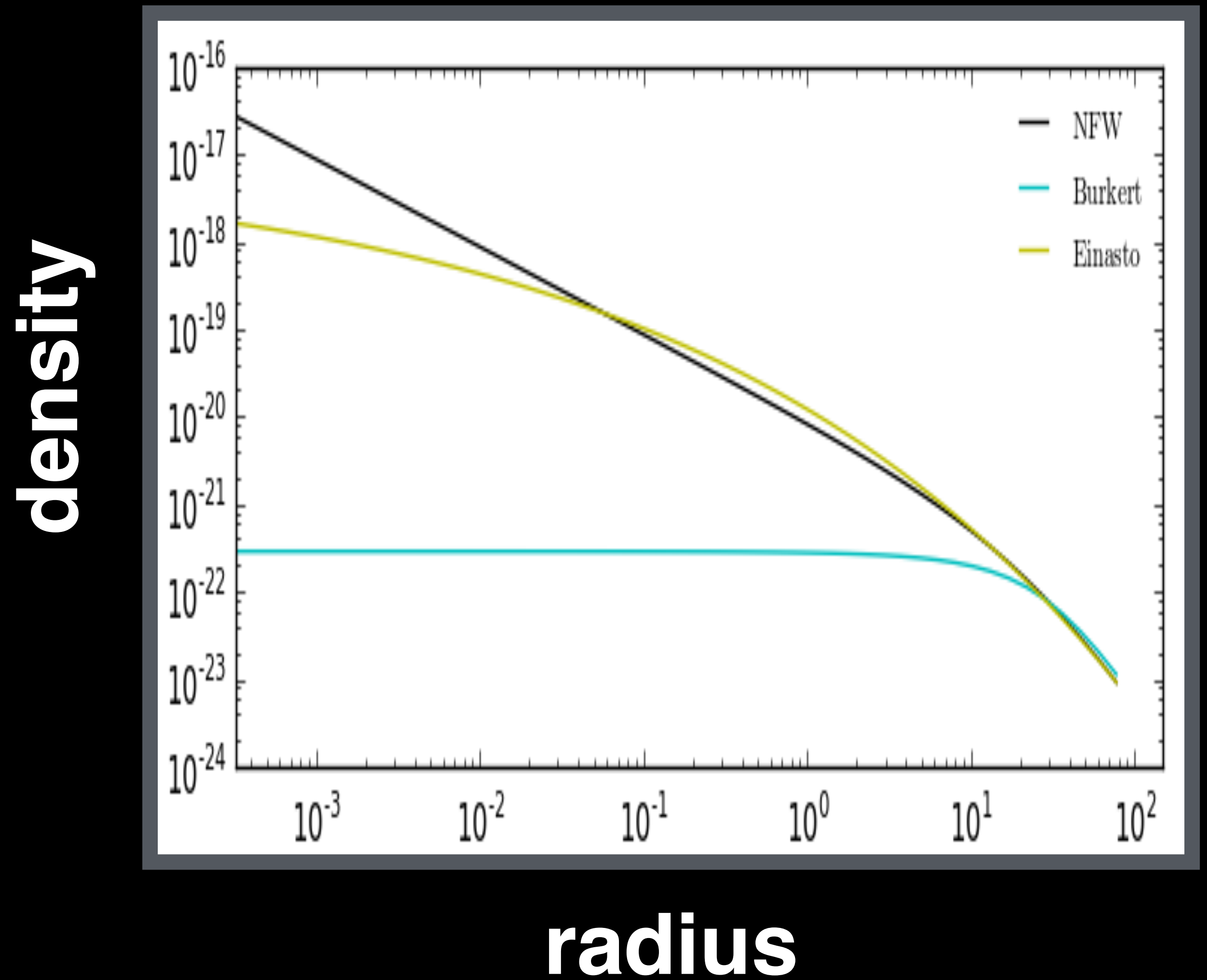
$$P_{dm} = \frac{c^2}{m_{dm}} < \bar{v\sigma} > \rho_{dm}^2$$

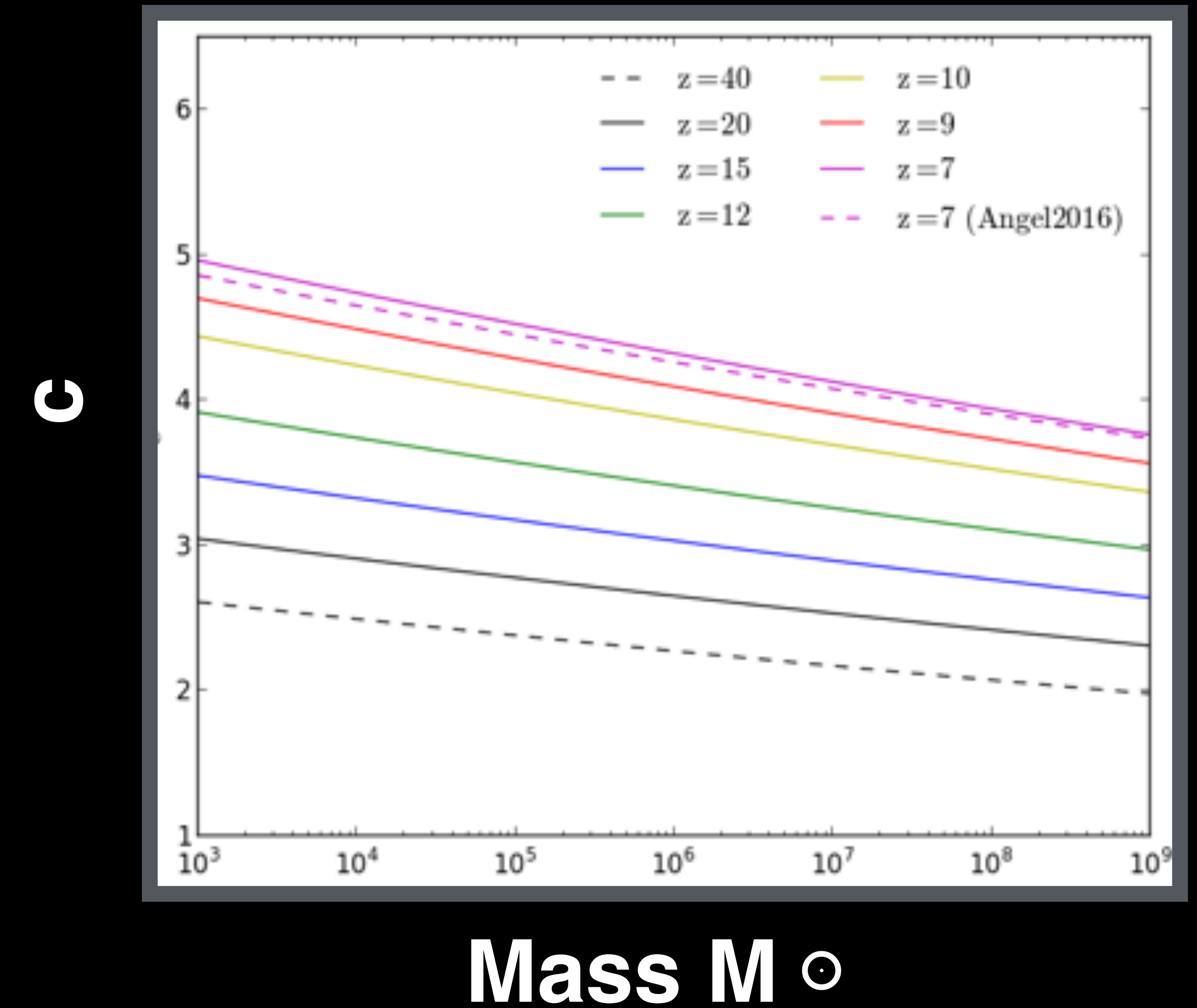
- annihilation cross-section and mass to match annihilation power limits from Planck
- consider different annihilation channels
- generate realistic end product spectra using PYTHIA



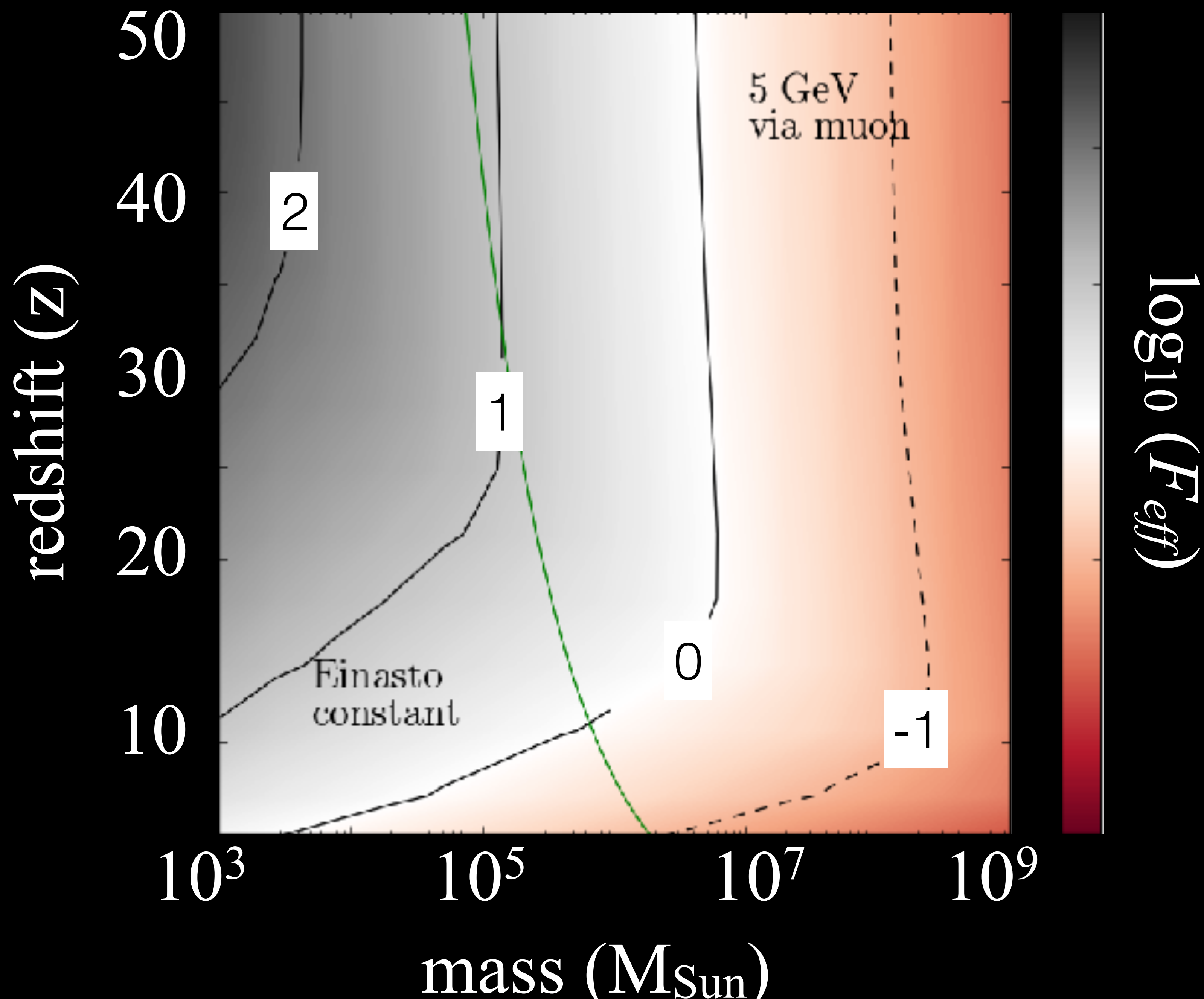
DM Halo Model

DM density profile + Mass-concentration relation





First Look



Compare gravitational binding energy to heating over the Hubble time

Schon et al MNRAS 2015, arxiv: 1411.3783

Energy Transfer

Electrons

- Ionisation
- Excitation
- Coulomb Interactions
- Inverse Compton
- Recombination

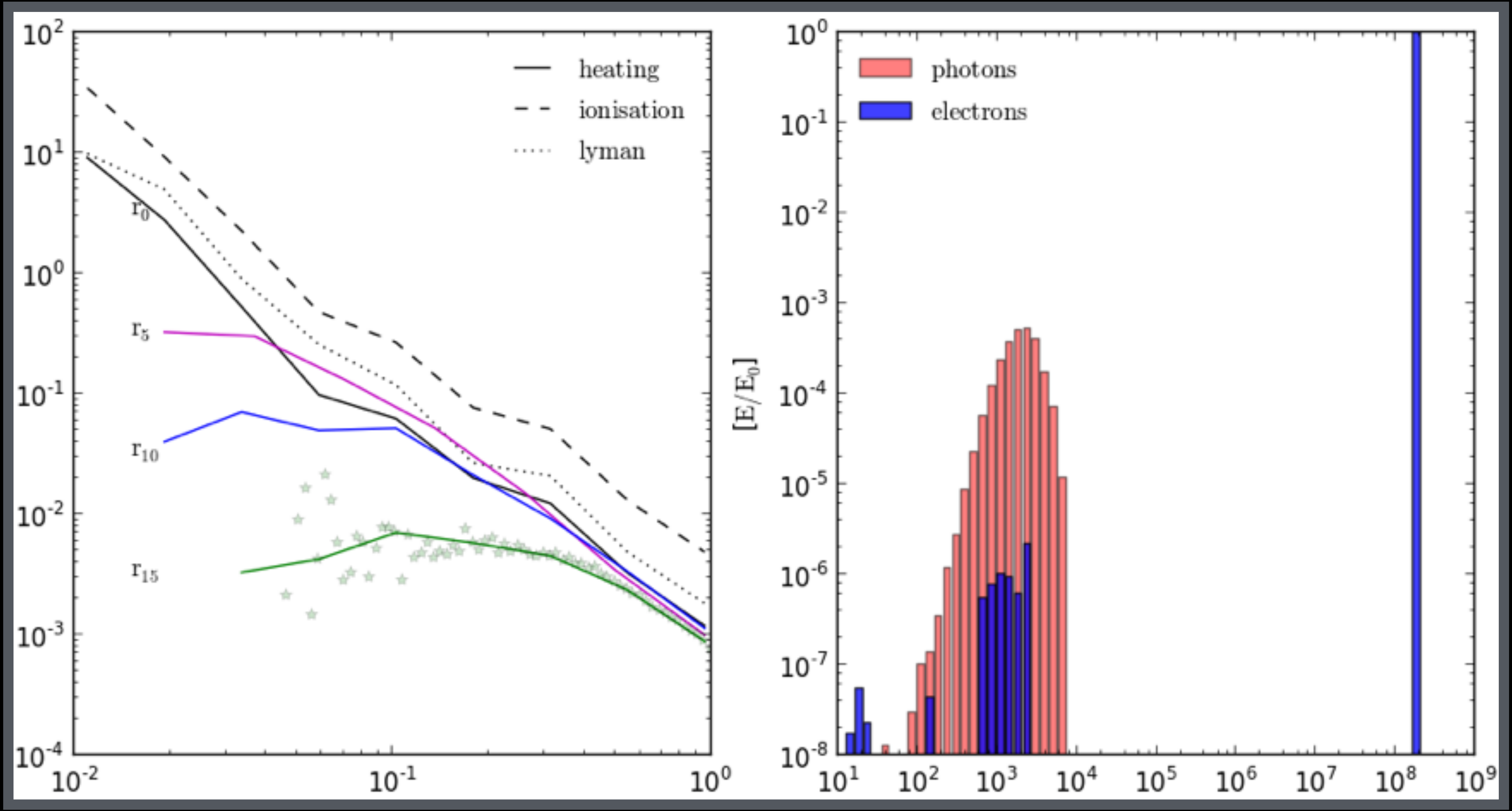
Positrons

- Electron interactions +
- Annihilation

Photons

- Ionisation
- Compton scattering
- Pair-creation (gas + CMB photons)

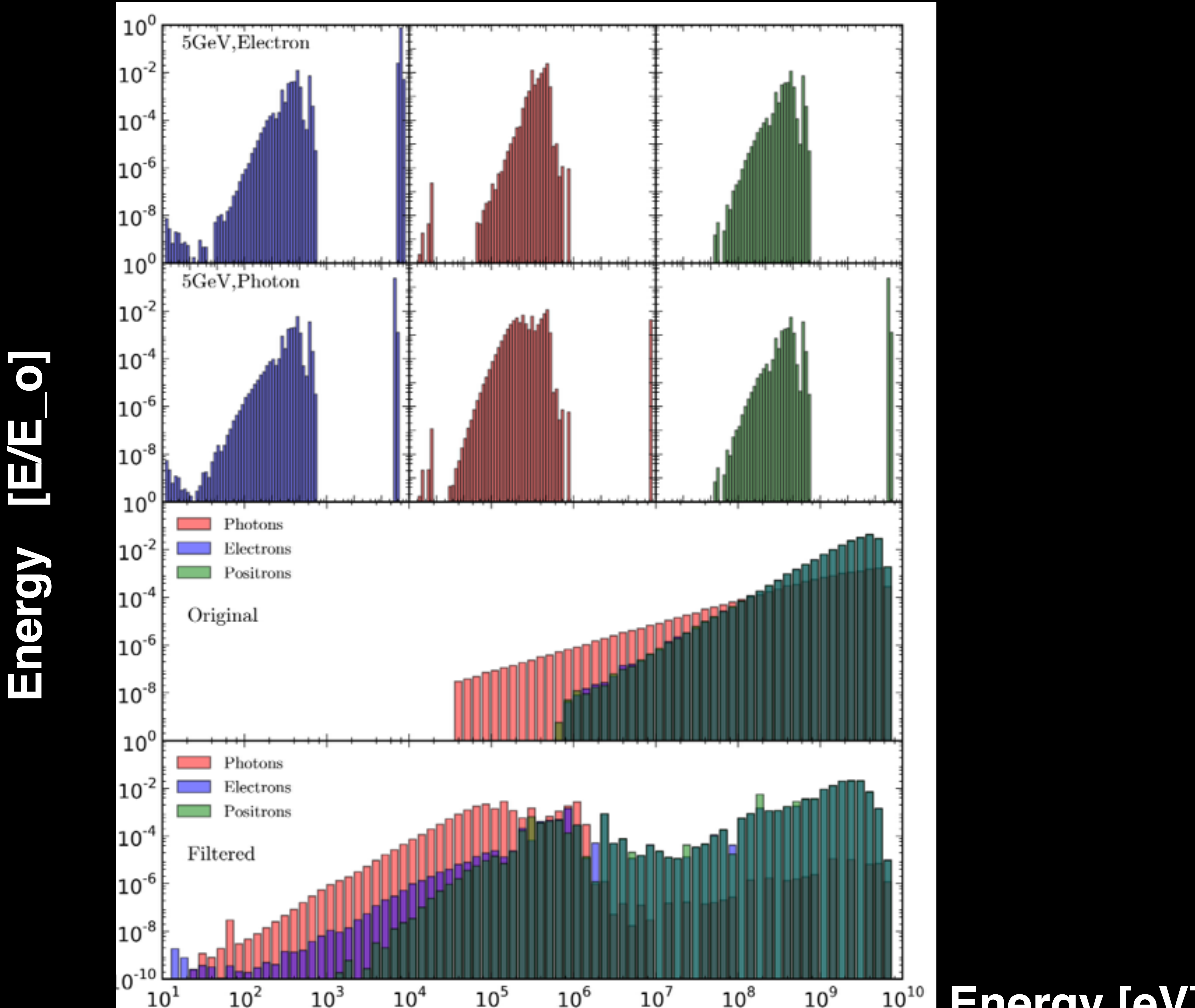
Energy Transfer



eV/pc^3

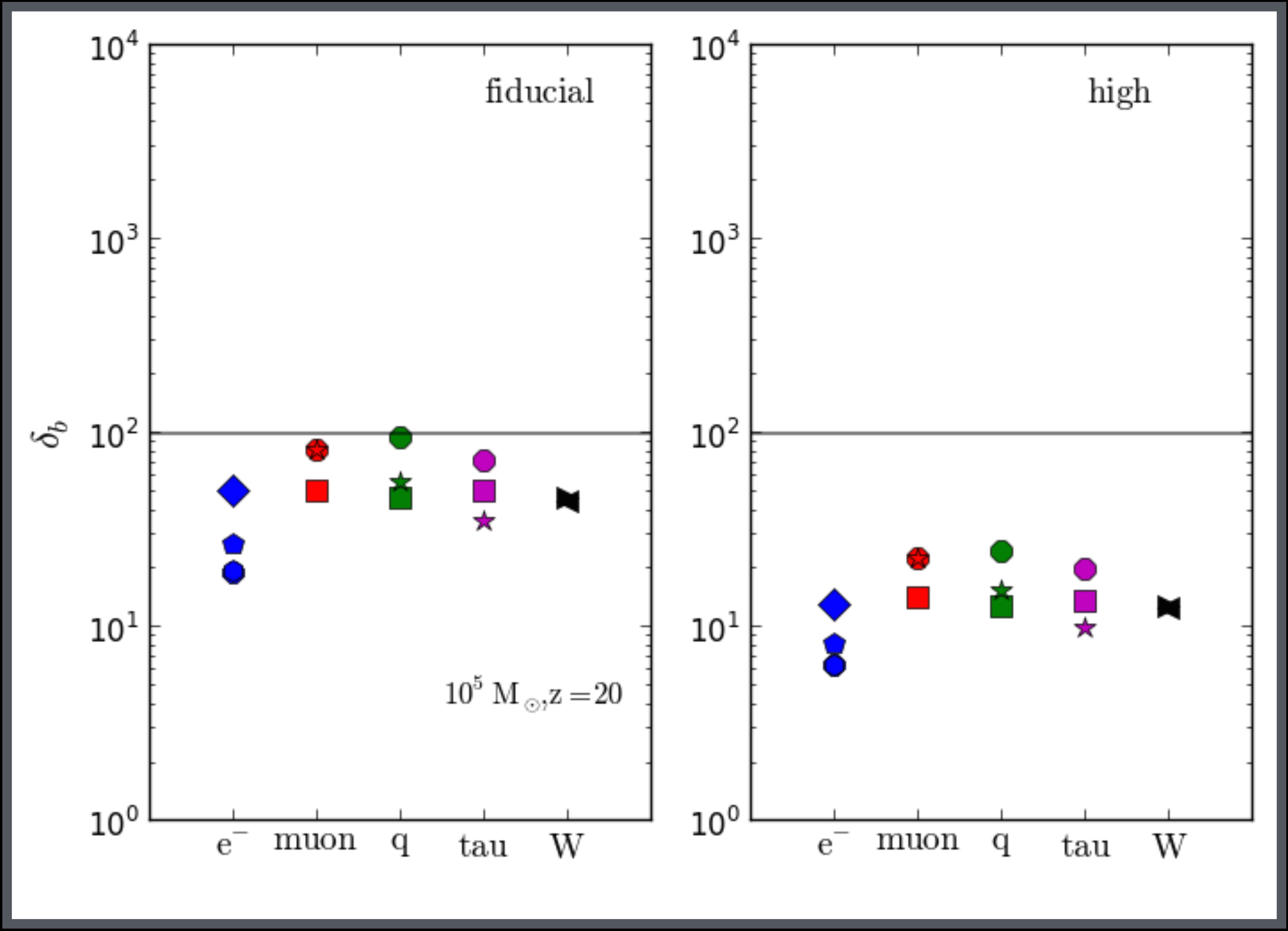
radius

energy



5GeV,Electron
5GeV,Photon
Photons
Electrons
Positrons
Original
Filtered
Energy [E/E_o]
Energy [eV]

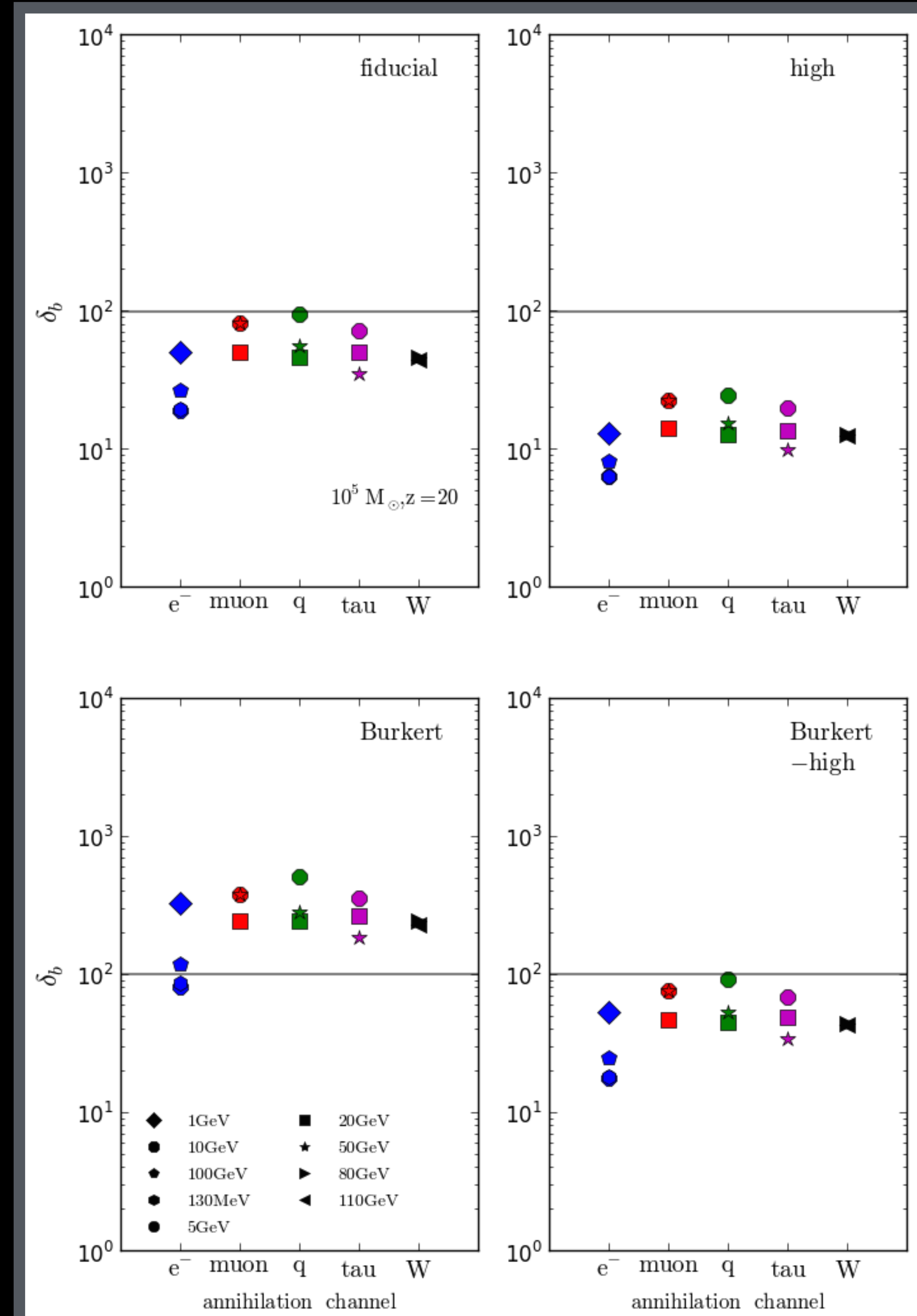
Detailed Halo Calculation



Schon et al submitted to MNRAS (arxiv:)

Detailed Halo Calculation

- **Examine DM annihilation impact on first stars**
- **Sufficient heating to suppress gas infall for some models**
- **Results can vary significantly with DM halo and annihilation models**



Summary

- We have a functional understanding of Dark Matter but not yet a full picture
- Particle physics can guide future searches, in particular when looking for non-gravitational signatures
- DM searches in astrophysical settings need careful treatment of baryonic physics
- Future DM exploration will contribute fundamentally to both cosmology and particle physics