Astrophysical constraints on FIPs and Dark Matter

Felix Kahlhoefer

FIPs in the Alps – Les Houches School of Physics

19 May 2023

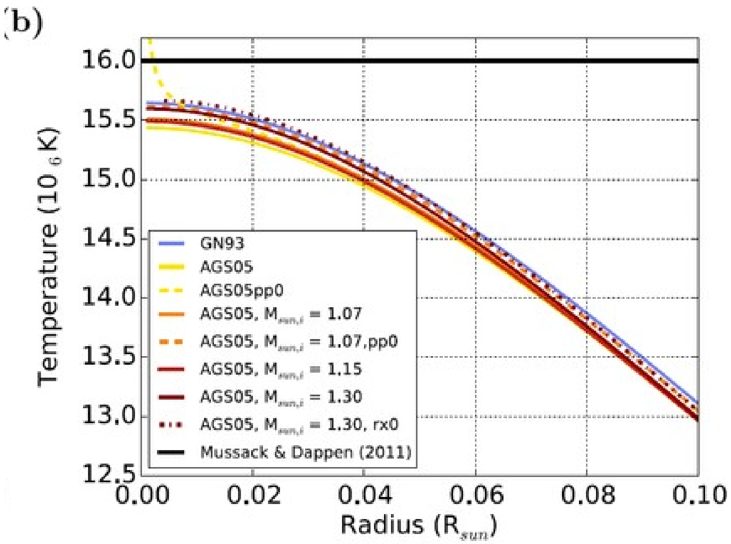
Outline

- Lecture 1: Constraints on FIPs from stellar cooling
  - Solar lifetime
  - Horizontal branch stars
  - Supernova explosions

- Lecture 2: Constraints on light dark matter from structure formation
  - Warm dark matter
  - Self-interacting dark matter
  - Small-scale hints

The sun exists!

- Typical core temperatures: 10^7 K ~ 1 keV
- Approximate age: 5 billion years
  → Half-way through hydrogen burning cycle
- Luminosity: $L_\odot = 4 * 10^{26}$ W
- If another type of particle could be produced in the sun with a luminosity $L > L_\odot$, the sun would have already burnt all its hydrogen



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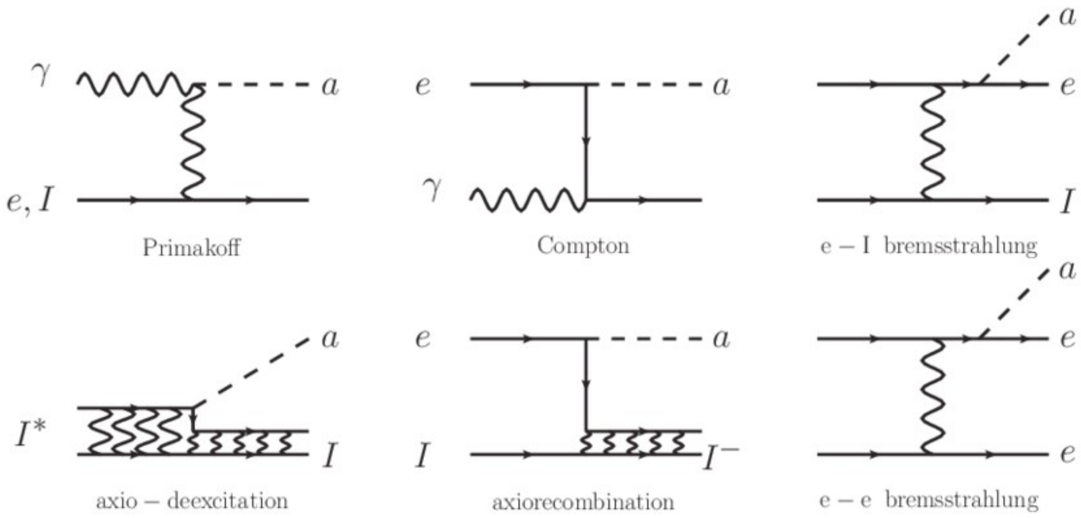
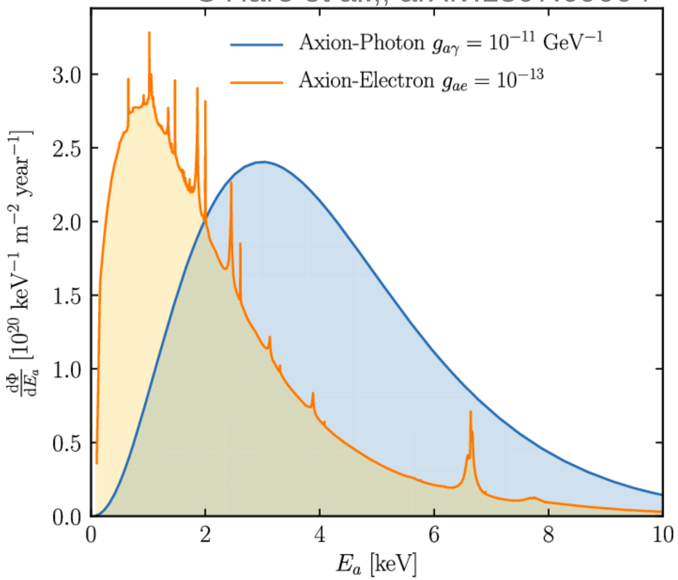
Example: Solar production of axions



O'Hare et al.,, arXiv:1807.09004



- The existence of the sun implies $g_{a\gamma} < 10^{-9}$ GeV^{-1} and $g_{ae} < 10^{-11}$
- Agreement between neutrino fluxes and solar models gives slightly stronger bound

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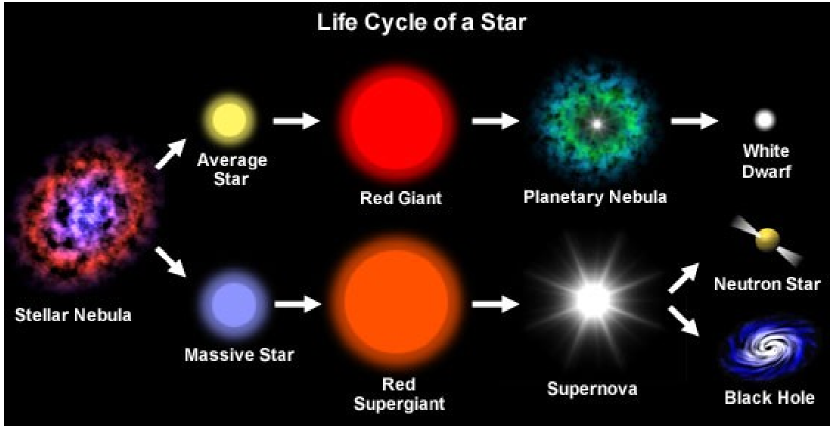
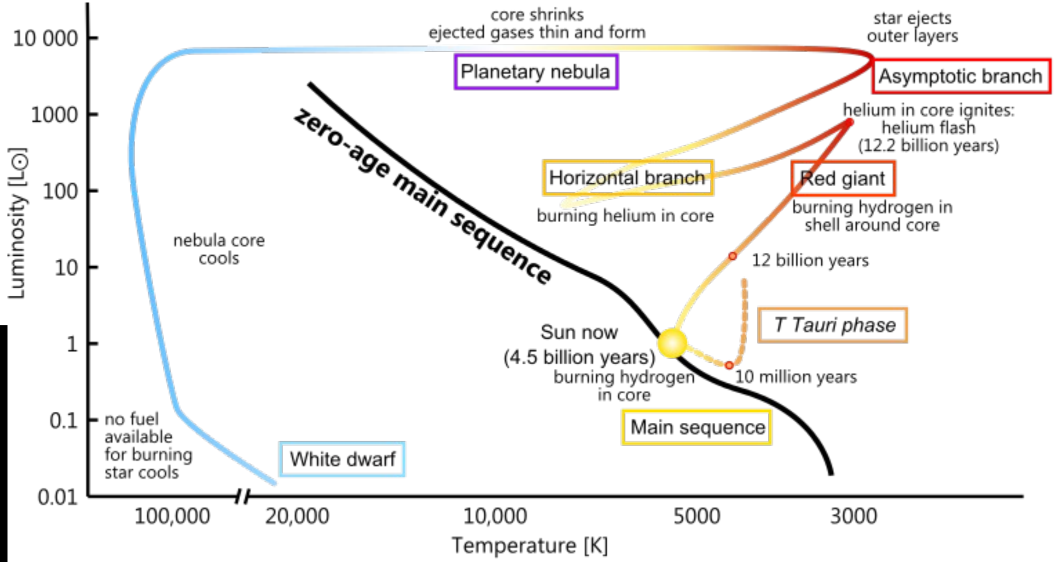
The life-cycle of a solar-mass star

- When the hydrogen in the core is depleted the sun will become a red giant

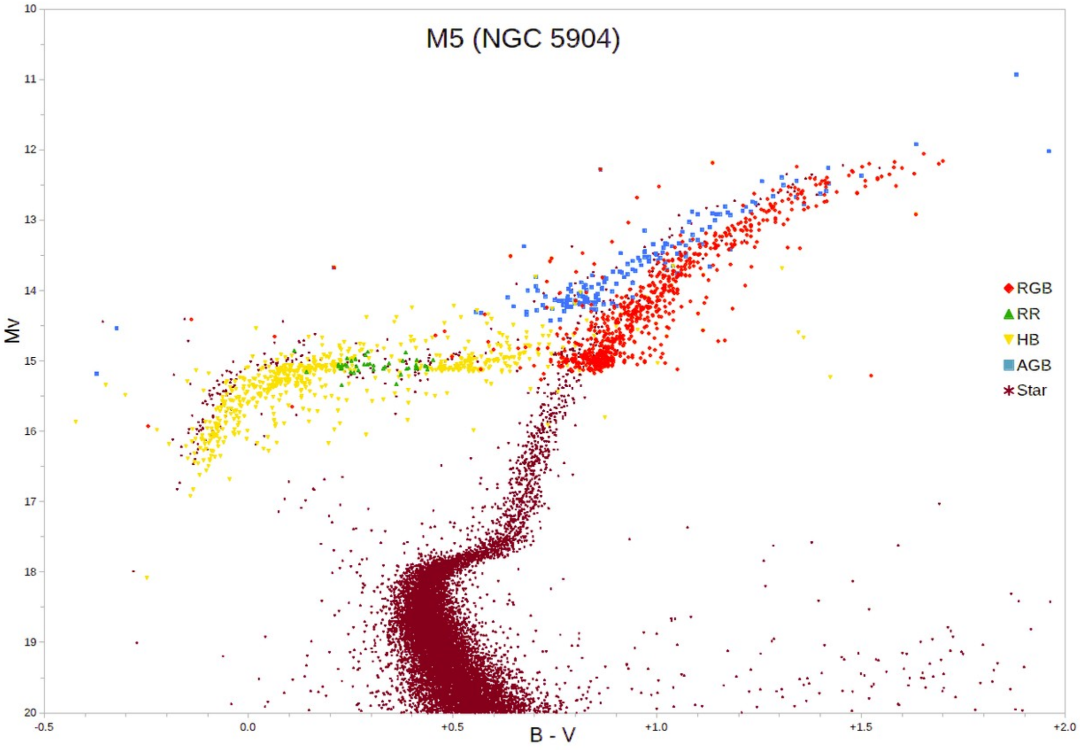




- Temperature and brightness grow and helium burning begins

Horizontal branch stars

- We can witness stars at any stage of that evolution (for example in globular clusters)
- Interesting observable 1: Tip of the red giant branch (RGB)
- FIP production delays helium ignition and thereby leads to larger and brighter red giants



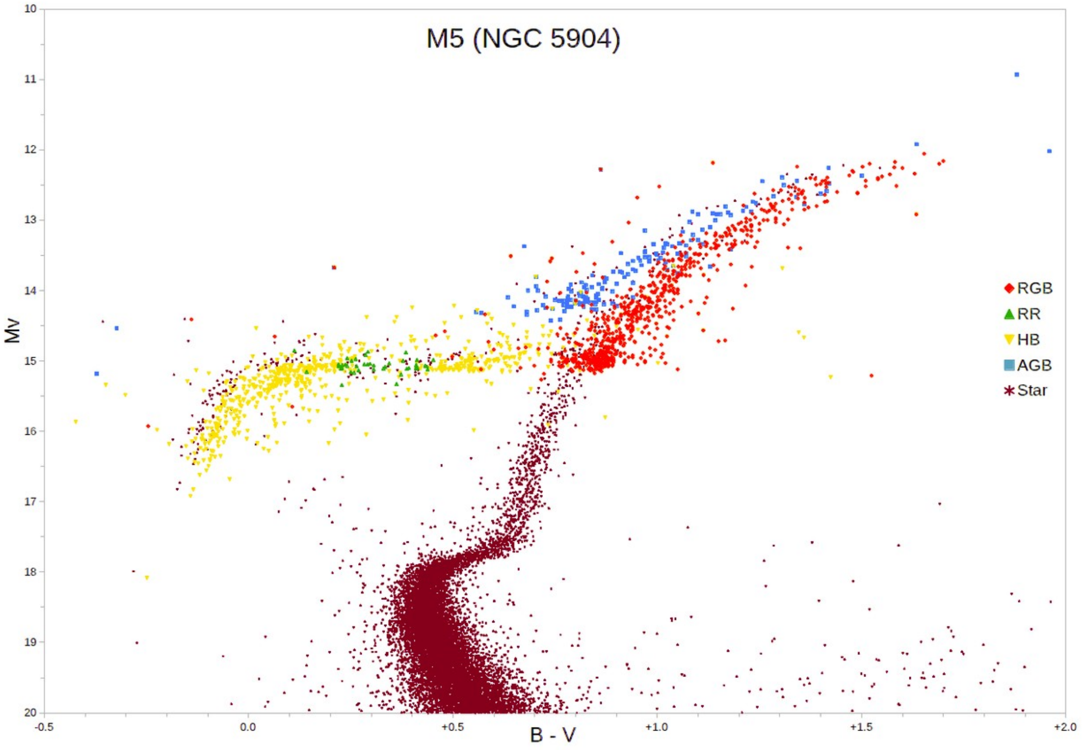
Horizontal branch stars

- We can witness stars at any stage of that evolution (for example in globular clusters)

- Interesting observable 2: Ratio of the number of stars in the horizontal branch (HB) and red giant branch (RGB)

  Data: R ~ 1.39 ± 0.03

  Theory: R ~ 1.42 – 1.45



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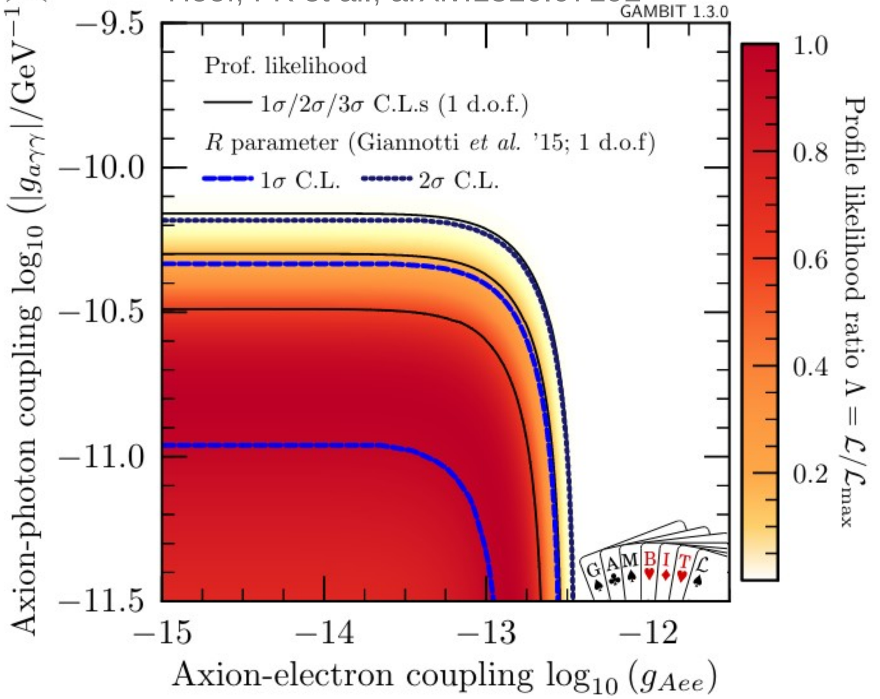
FIPs production in helium burning stars

- Higher core temperature than for hydrogen burning (~10 keV)
  - → "Heavier" FIPs can be produced
- For $g_{a\gamma} \sim 10^{-10}$ GeV^{-1} R parameter would be reduced by ~0.4
  - → Much more sensitive to FIPs than solar environment
- Generally considered to give the strongest and most robust bound on keV-scale FIPs

Hoof, FK et al., arXiv:1810.07192



Stellar production of dark photon

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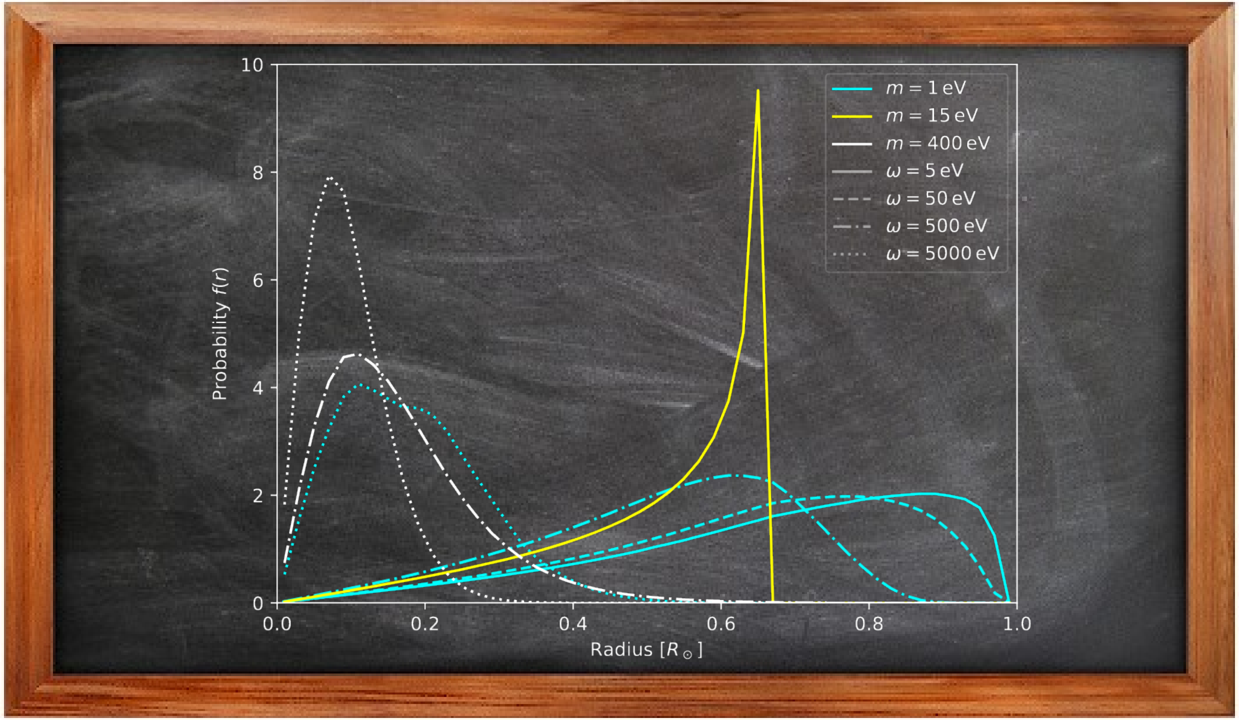
Stellar production of dark photon



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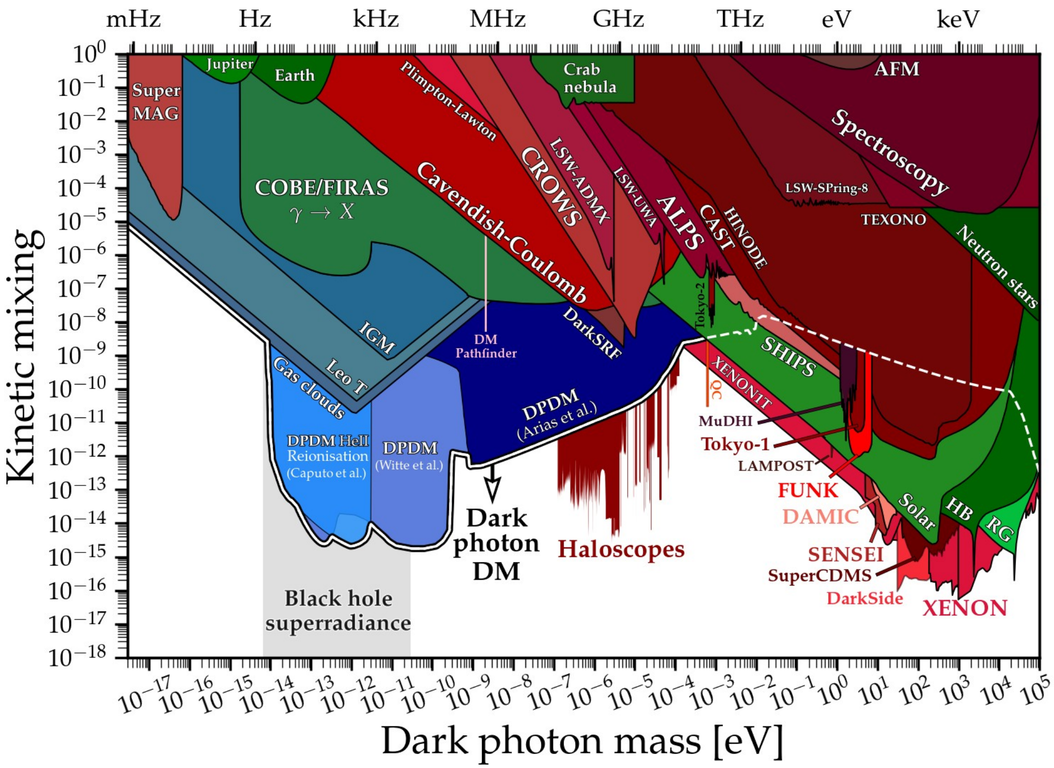
Summary

- Sensitivity of the sun, HB stars and RGB stars peak at different dark photon masses corresponding to the plasma mass in the core
- Even stronger bounds from laboratory experiments , assuming dark photons are dark matter (dark photoelectric effect)



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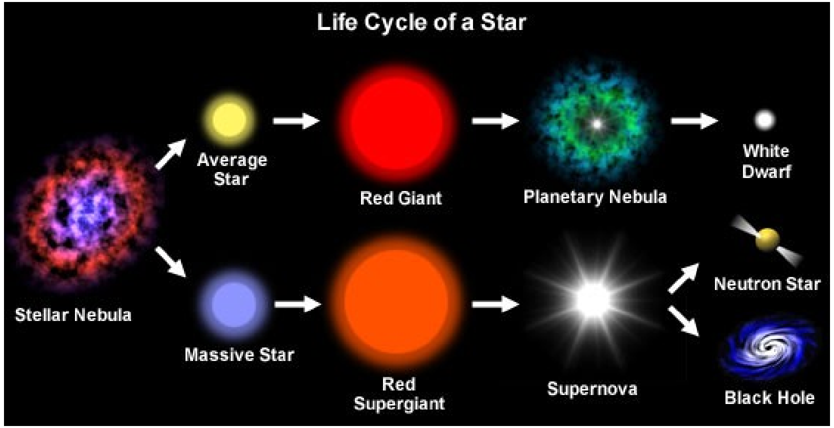
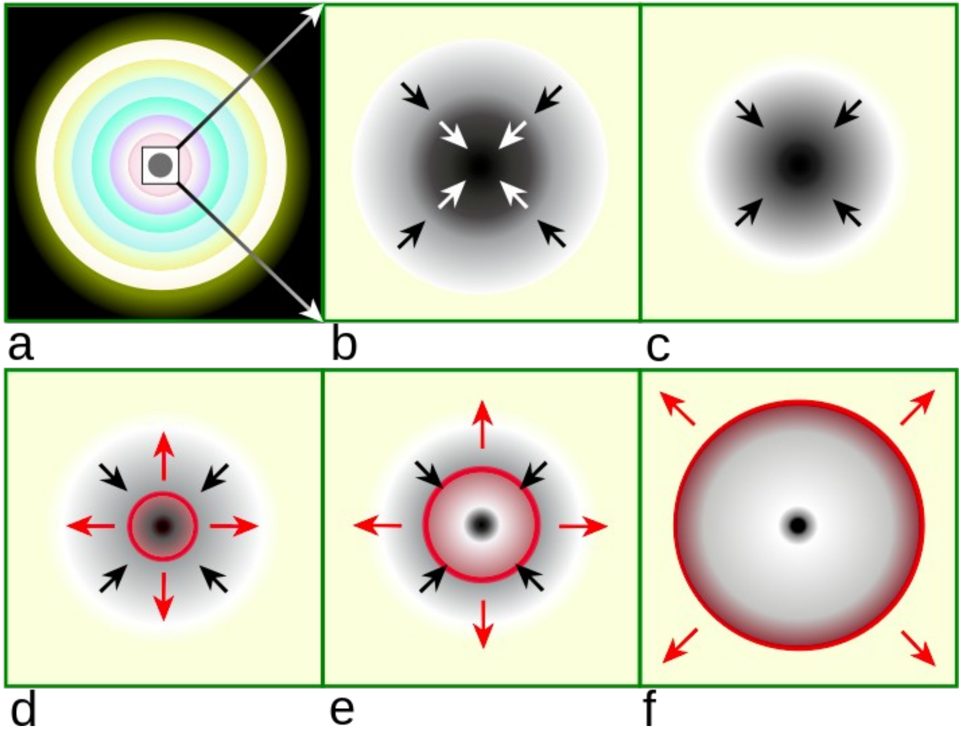
What about more massive stars?

- Stars much more massive than the sun end their life-cycle in a supernova explosion





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What about more massive stars?

a) A nickel-iron core forms, which cannot undergo further fusion

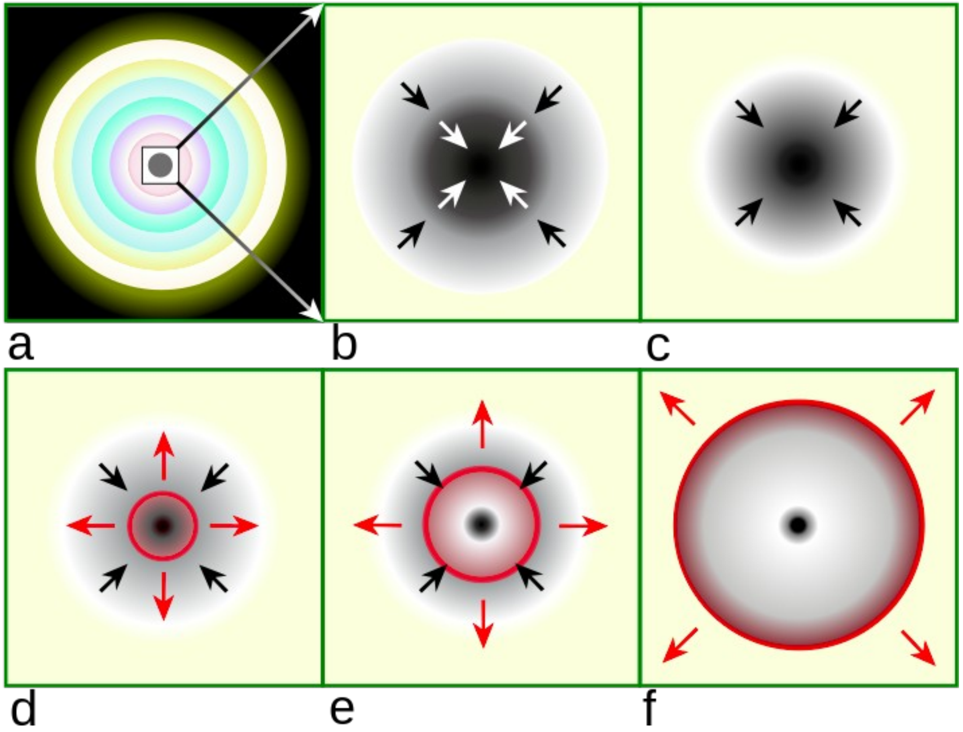
b) (Electron) degeneracy pressure can no longer support the core

c) Core heats up, nuclei are disintegrated/converted into neutrons

d) Collapse halted by neutron interactions and degeneracy

e) Infalling material bounces and creates a shock wave

f) Neutrinos accelerate the shock wave and create a supernova explosion



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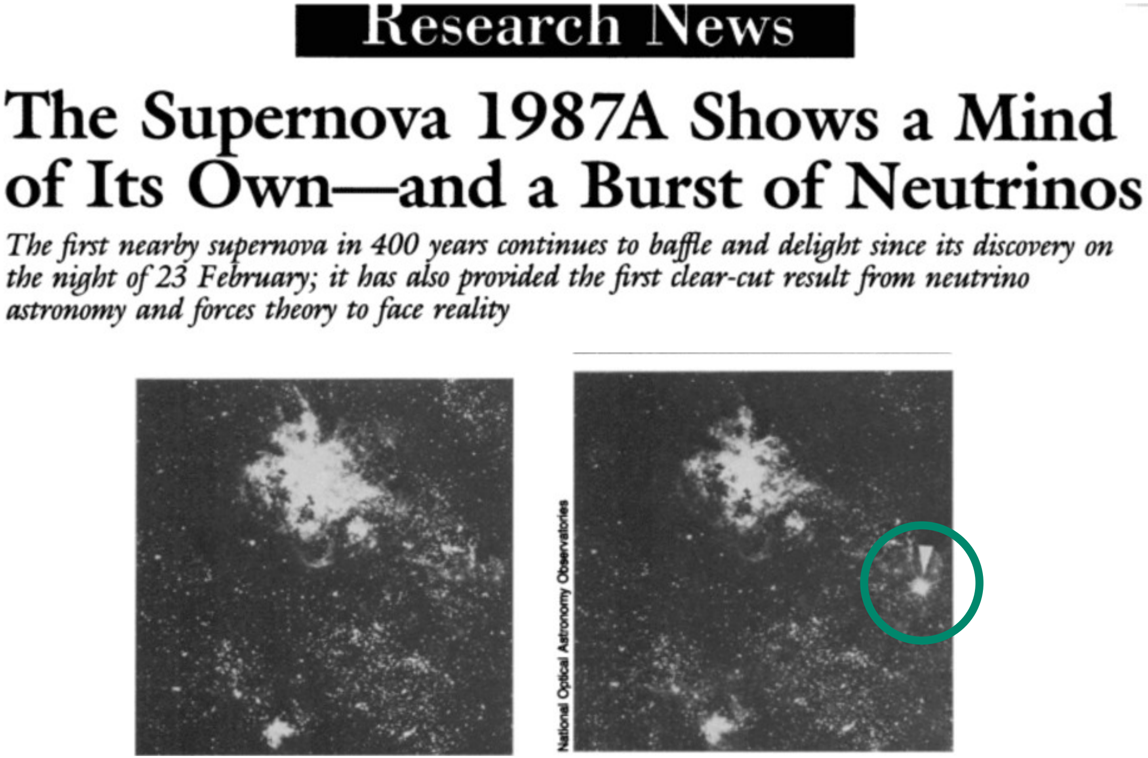
SN1987a

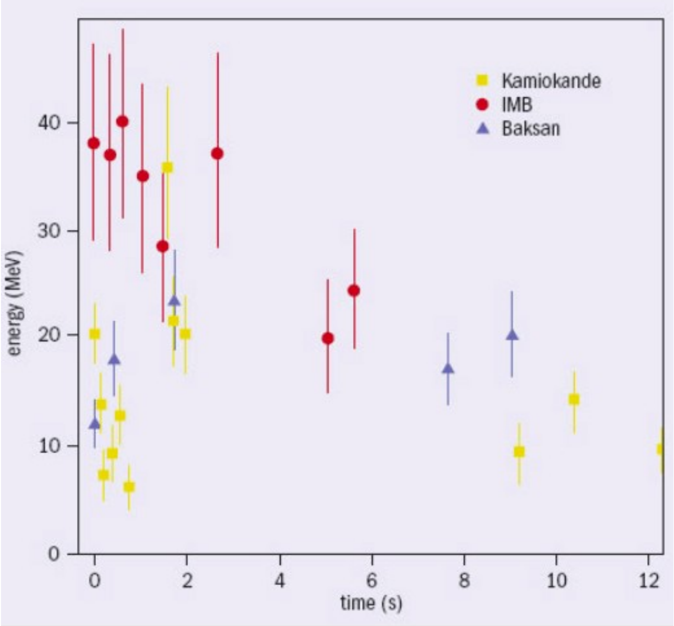


Research News

The Supernova 1987A Shows a Mind of Its Own—and a Burst of Neutrinos

The first nearby supernova in 400 years continues to baffle and delight since its discovery on the night of 23 February; it has also provided the first clear-cut result from neutrino astronomy and forces theory to face reality

National Optical Astronomy Observatories



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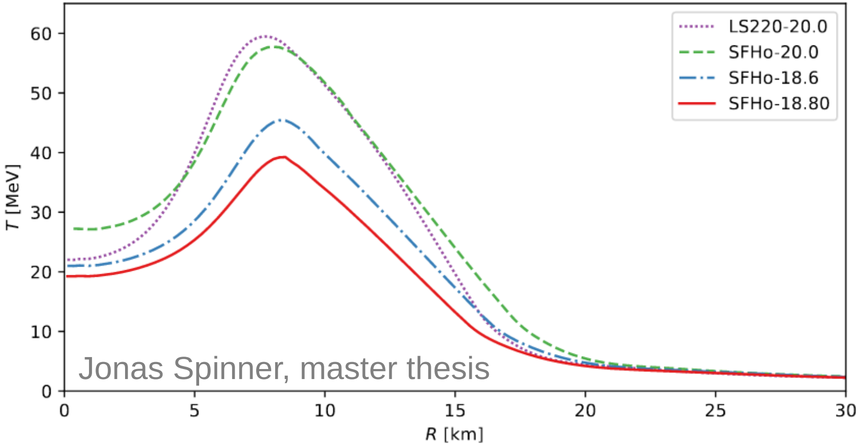
Neutrino burst

- The neutrino burst was observed to last approximately 10 seconds

  → Time it takes for the SN core to cool sufficiently for neutrinos to escape

- FIPs production accelerates SN cooling and shortens the neutrino burst
- Core temperature ~ 30 MeV
- Neutrino luminosity ~ 10^{45} W (almost 20 orders of magnitude larger than the sun)
- Require FIP luminosity < neutrino luminosity (Raffelt criterion)



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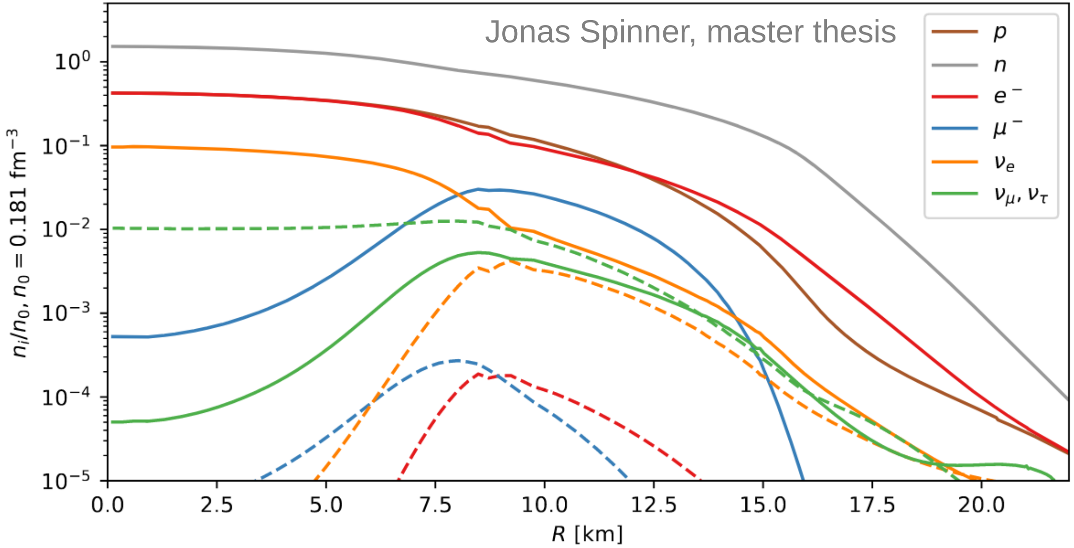
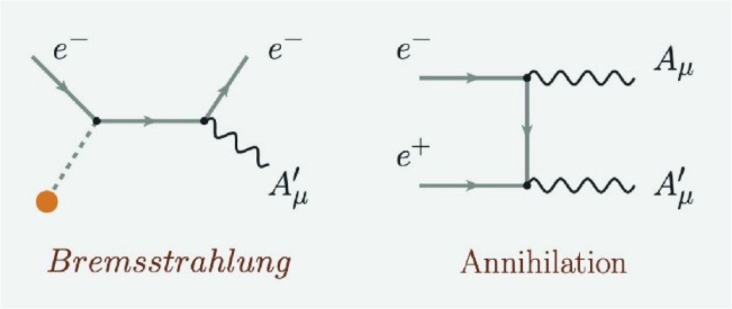
Dark photon production in SN1987a





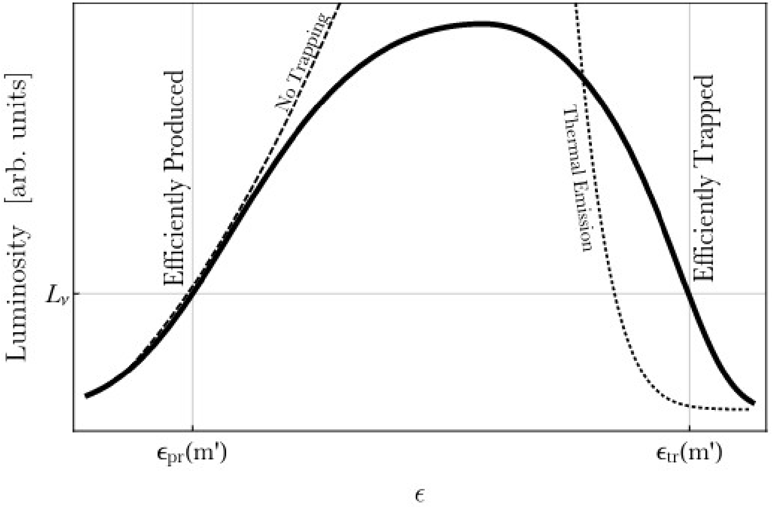
- Temperature large enough to produce positrons (and even muons)

- Possibility to produce dark photons in Bremsstrahlung, Compton scattering or pair annihilations

Supernova trapping

- If dark photons are too "strongly" coupled, they are absorbed again before they leave the supernova
- Efficient trapping suppresses energy loss
- Rigorous treatment:
  - Calculate optical depth $\tau(r, E)$ for dark photons
  - Escape probability given by $\exp(-\tau(r, E))$
- Useful simplification: Calculate trapping radius r_{tr} for which $\tau(r_{tr}, E) = 2/3$
  - Dark photons produced at $r < r_{tr}$ never escape
  - Dark photons produced at $r > r_{tr}$ always escape

Chang et al., arXiv:1611.03864



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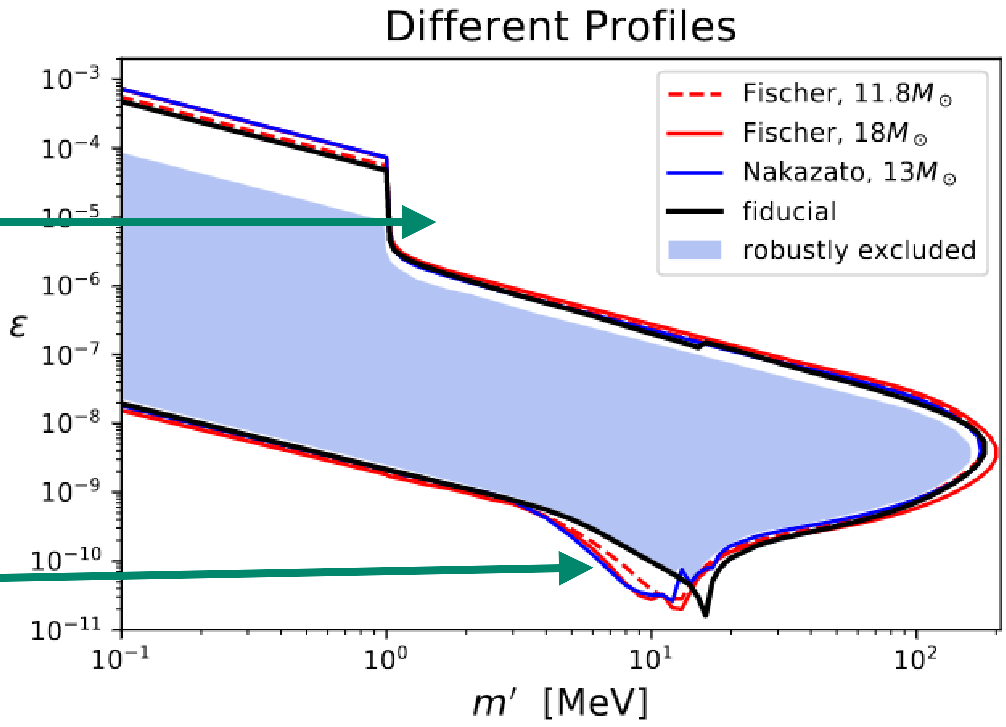
Results

Efficient trapping

Resonant production

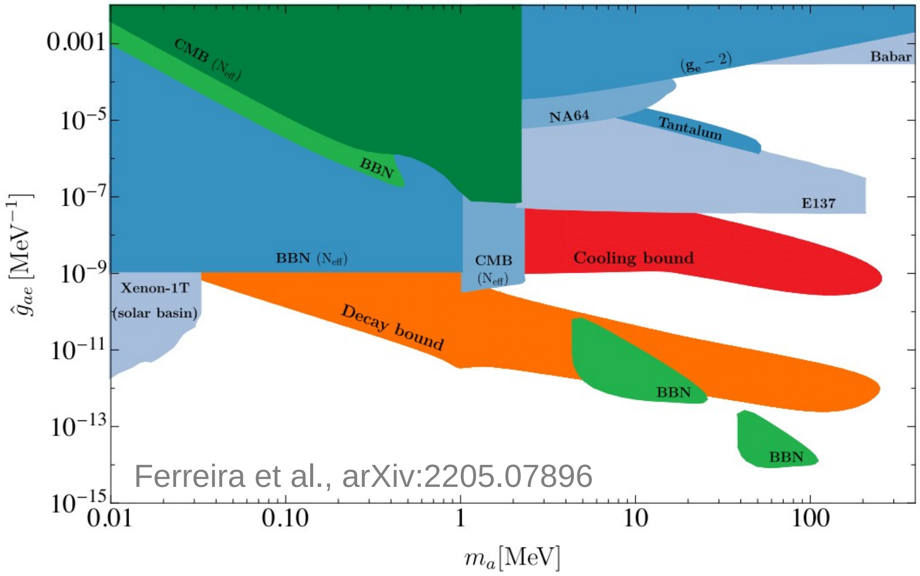


Chang et al., arXiv:1611.03864

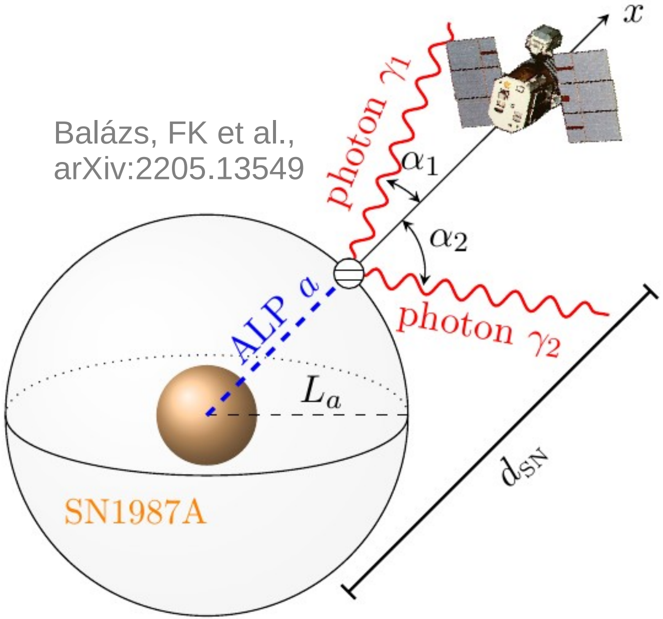
Boltzmann suppression

Additional constraints from SN1987a

- If the FIPs produced in the SN can decay (or be converted) into photons on their way to Earth, even stronger bounds can be obtained



Balázs, FK et al.,
arXiv:2205.13549



Open questions: Trapping

- Huge experimental efforts to investigate models in the trapping regime
- How sure are we that SN constraints are absent?
- Could imagine modifications to heat transport inside supernova
- Problem: No detailed understanding of SN explosion mechanism
- Data & simulations not good enough to constrain BSM processes within SN core
- We need another supernova (ideally not too close)!

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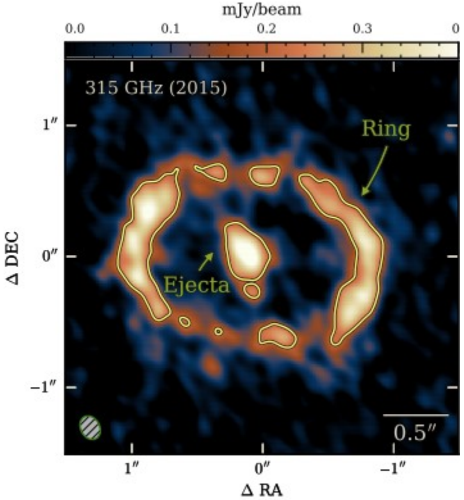
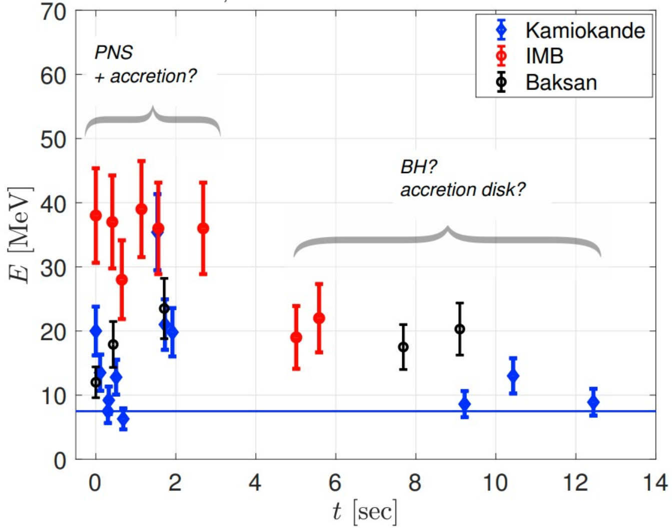
Open question: Accretion disk

- Conceivable that some of the observed neutrinos are emitted from an accretion disk
- If true, would invalidate the SN cooling bound



- Can be tested if we can identify the SN remnant
  - Neutron star would favour core collapse
  - Black hole would favour accretion disk

Bar et al., arXiv:1907.05020



Page et al., arXiv:2004.06078

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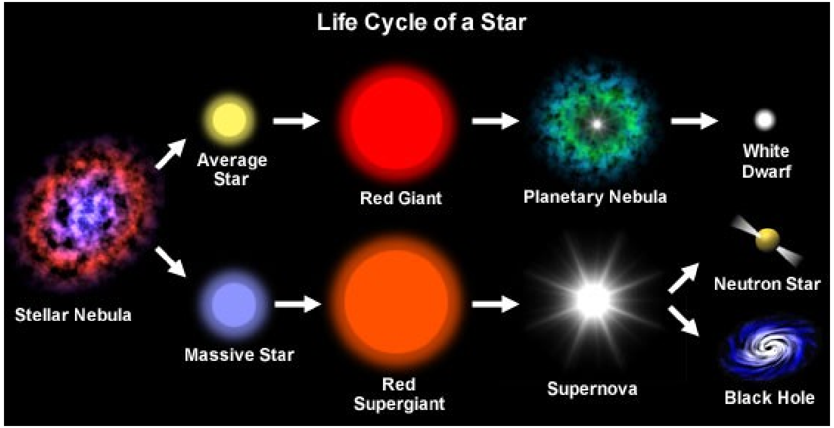
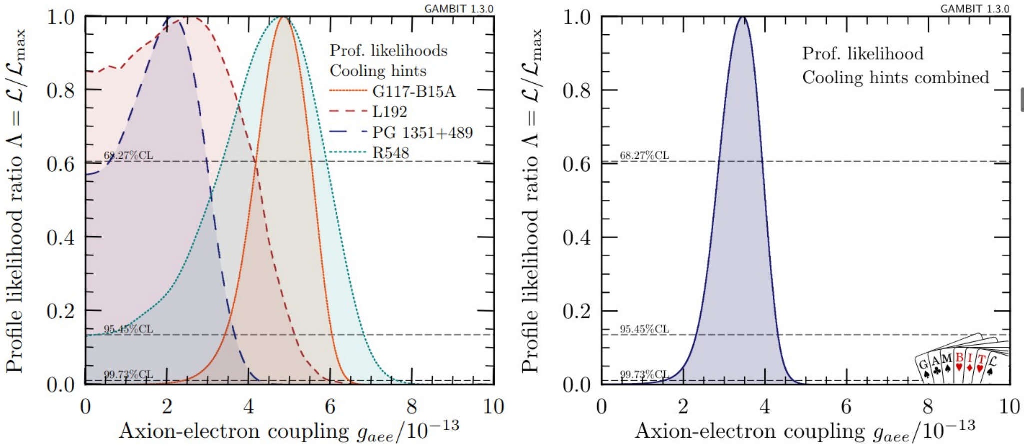
The end (of the lifetime of a star)

- White dwarfs are electron-degenerate stellar remnants
- Certain white dwarfs pulsate, i.e. their brightness oscillates with time
- Exotic cooling via FIP production would increase the pulsation period
- Observations reveal preference for ALPs with non-zero coupling to electrons

Giannotti et al., arXiv:1512.08108

Hoof, FK et al., arXiv:1810.07192





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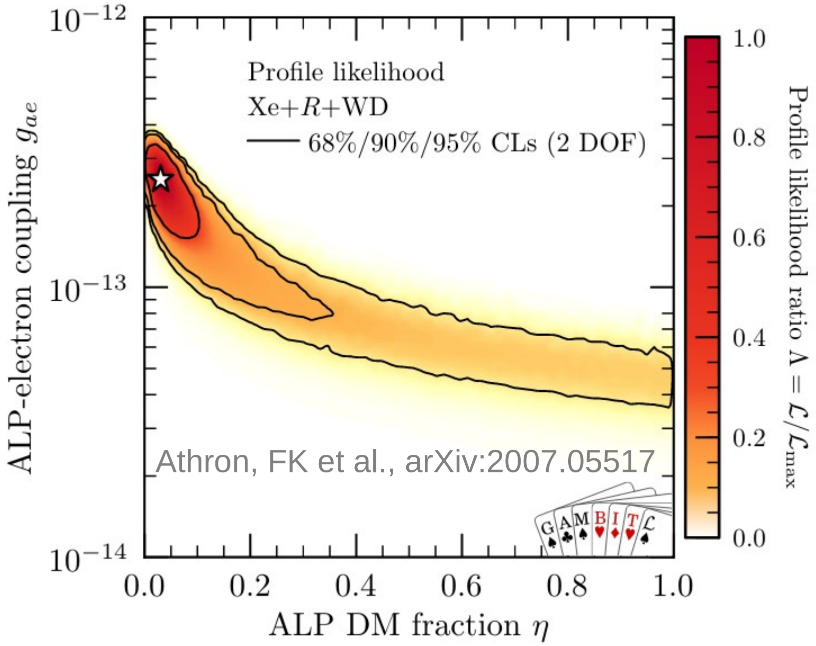
Global fits

- Want to test your model against astrophysical constraints?
- All of the constraints discussed before have been implemented as likelihood functions in the GAMBIT global fitting framework
  - Automated construction of composite likelihoods for a given model
  - Efficient scans of multi-dimensional parameter space
  - Consistent treatment of uncertainties and nuisance parameters
  - Easy comparison of astrophysical bounds and laboratory experiments



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Conclusions (lecture 1)

- FIPs can contribute to stellar cooling and accelerate stellar evolution
  - Lifetime of sun, RGB stars, HB stars
  - Duration of SN1987a neutrino pulse
  - Period increase of WD pulsation

- Strong constraints on axions, dark photons, light dark matter, …
  - Up to ~10 keV for stars
  - Up to ~100 MeV for SN1987a
  - Large couplings allowed due to trapping

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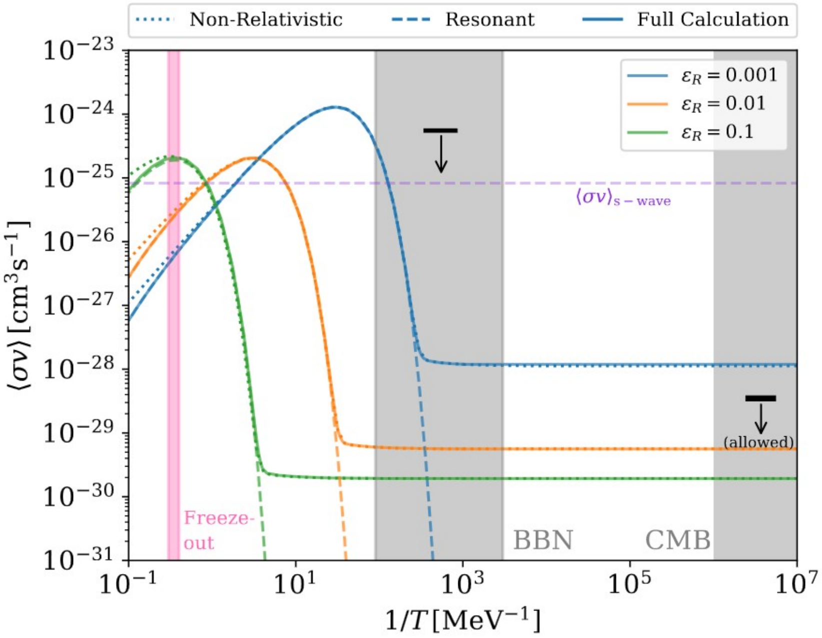
Sub-GeV dark matter

- Cosmology places strong constraints on thermally produced dark matter
- BBN bound on N_{eff} implies m_{DM} > 10 MeV
- CMB bound on exotic energy injection implies m_{DM} > 10 GeV for s-wave annihilation
- Even larger masses may be excluded for resonant annihilations / Sommerfeld enhancement
- Interesting to consider non-thermal DM!

Bernreuther, FK et al., arXiv:2010.14522



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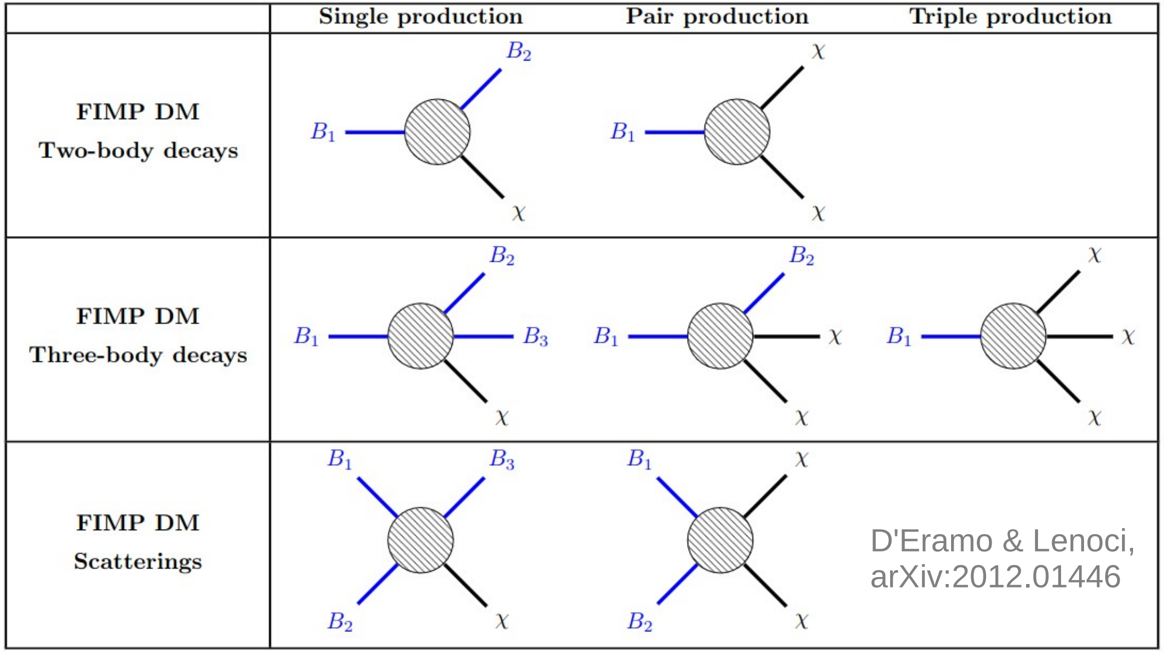
Freeze-in production of DM

- DM may also be produced via out-of-equilibrium processes
- Freeze-in mechanism: “energy leakage” from the visible sector
- Well-known example: Production of keV-scale sterile neutrinos



D'Eramo & Lenoci, arXiv:2012.01446

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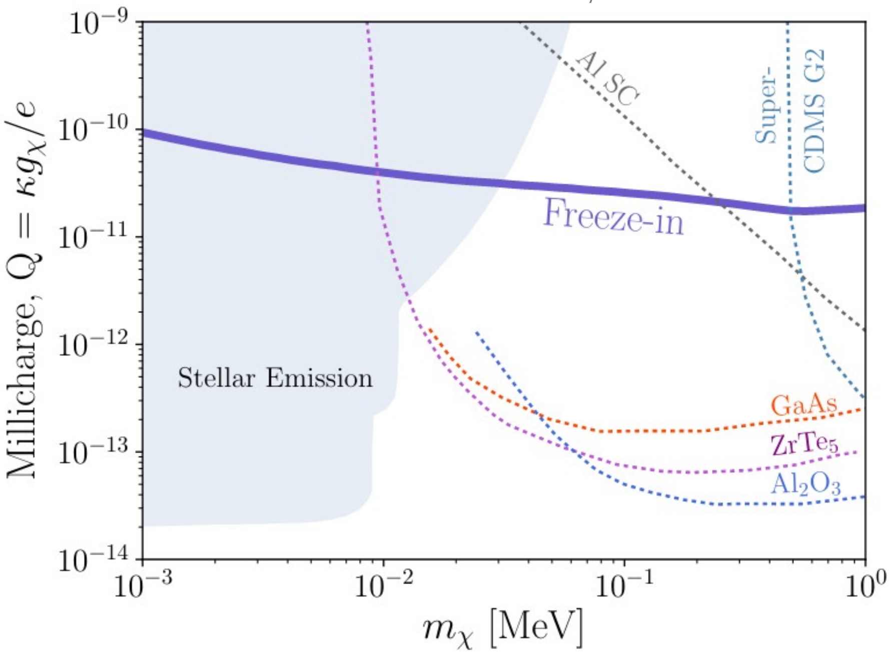
Testing freeze-in

- For DM produced via the freeze-in mechanism, typical couplings are much smaller than for thermal DM
- Laboratory searches mostly hopeless (with some notable exceptions)
- Need to rely on astrophysical constraints to make progress!

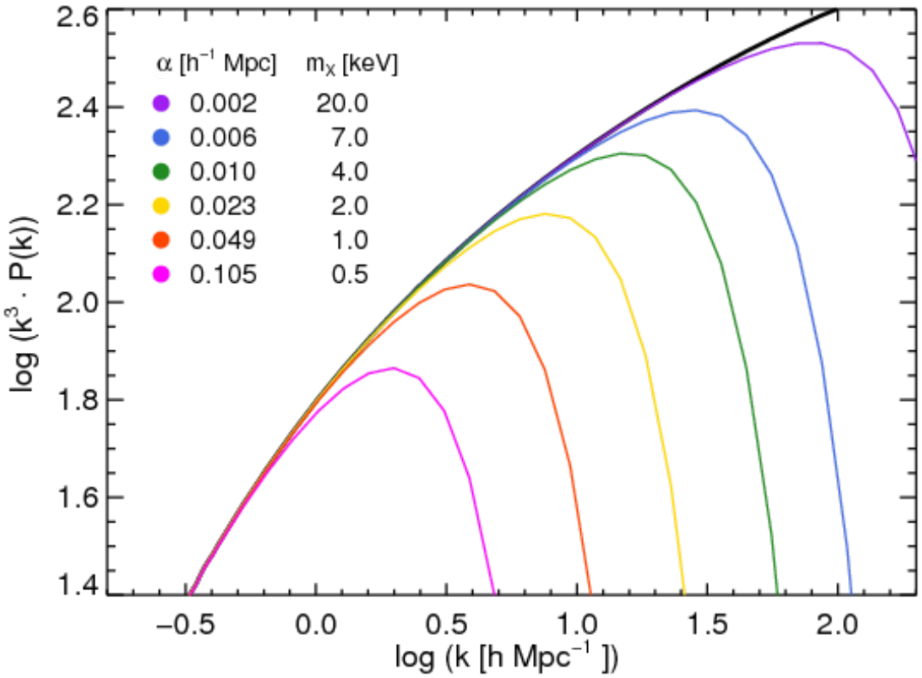
Dvorkin et al., arXiv:1902.08623

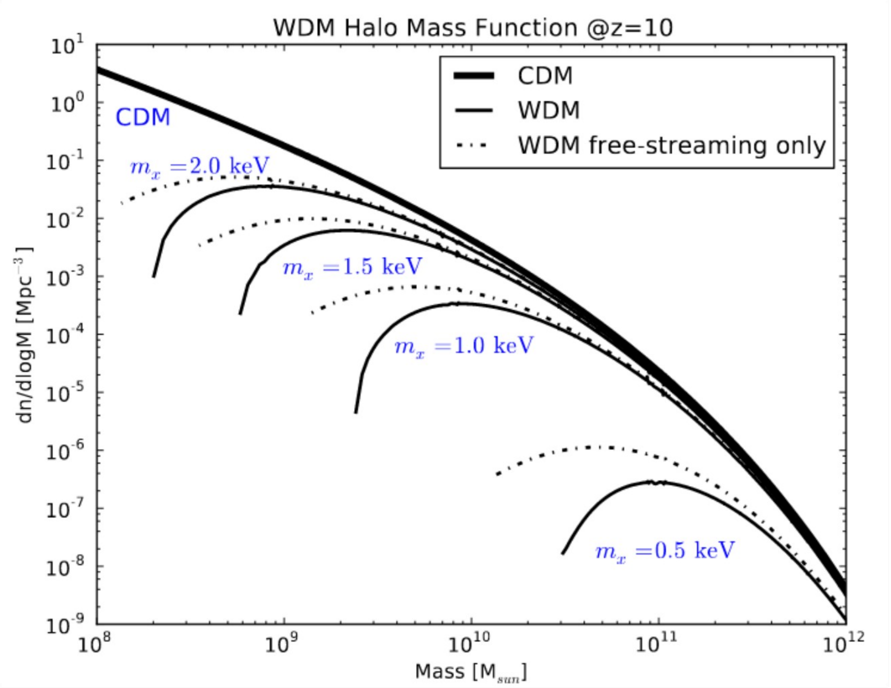


Lower bound on DM mass

- The freeze-in mechanism in principle works down to very small DM masses
- For fermionic DM, we have to satisfy the Tremaine-Gunn bound
  - Pauli exclusion prevents the formation of very dense DM halos
  - Observations of such systems imply $m_{DM} > 500$ eV
- Moreover, for keV-scale DM the kinetic energy is not completely negligible
  - Free-streaming prevents the formation of small-scale structures
  - Cut-off in the matter power spectrum

Suppression of small-scale structure





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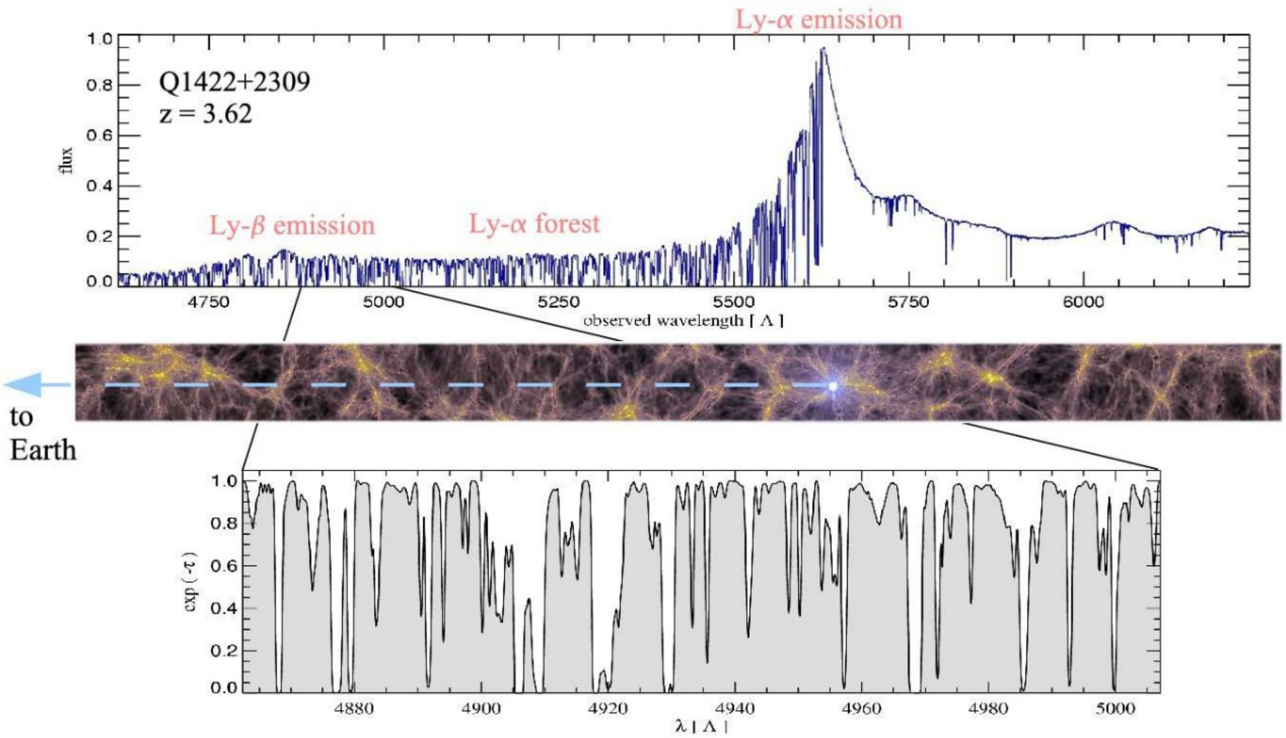
Lyman-alpha forest



- Bound on mass of thermal DM:

  m_{DM} > 3.5 – 5.3 keV

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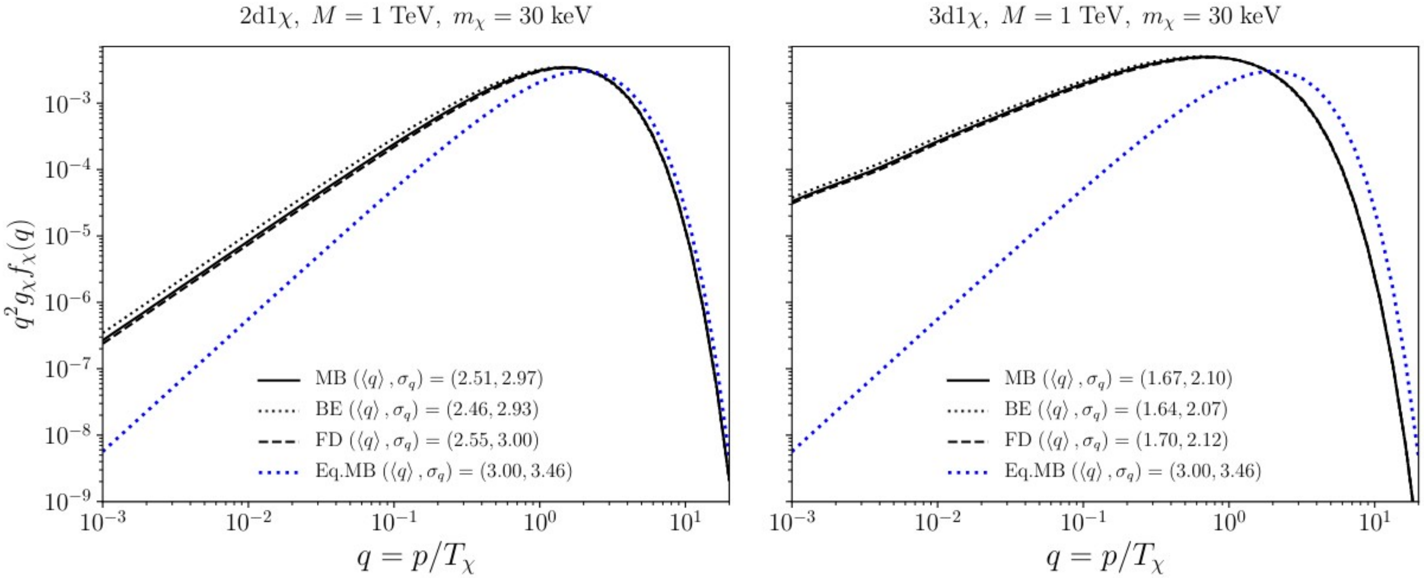
Non-thermal dark matter

- Subtlety: Non-thermal DM has non-thermal phase space distribution

- Precise bound on DM mass becomes model-dependent

- Can be as strong as m_{DM} > 20 keV



D'Eramo & Lenoci, arXiv:2012.01446

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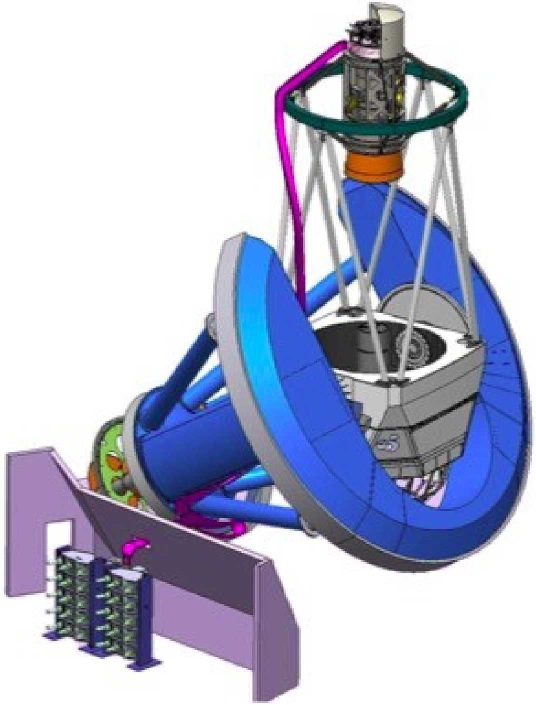
DESI: The future of Lyman-alpha data

- Dark Energy Spectroscopic Instrument
- Measure of Lyman-alpha forest absorptions auto-correlation and cross-correlations with quasars
- 3d map of the distribution of matter at redshift z = 2–5
- Infer BAO scale and constrain dark energy models
- Sensitive probe of suppression of small-scale structure
- Can expect much stronger (and more robust) bounds on warm DM



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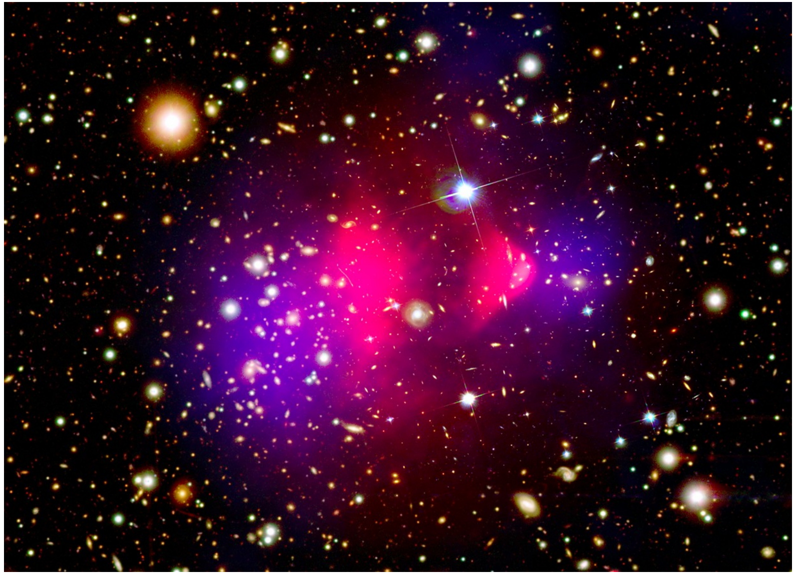
DM self-interactions

- We (roughly) know the mass density ρ and velocity v of DM in astro systems
- Typical numbers: $\rho \sim 0.1 – 1\ \text{GeV cm}^{-3}$ $v \sim 100 – 1000$ km/s
- Corresponding number density $n = \rho/m_{DM}$ increases with decreasing DM mass
- Scattering rate given by $n\, v\, \sigma = \rho\, v\, \sigma/m_{DM}$
- Astrophysical observations place upper bound on σ/m_{DM}
- Naive dimensional analysis: $\sigma \sim m_{DM}^{-2}$

  → Lower bound on m_{DM}

Bullet Cluster

- Bullet Cluster shows that DM behaves more like (collisionless) galaxies than like (collisional) gas
- Can make this statement more precise by measuring mass-to-light ratio and separation between DM and galaxies in each cluster
- Result: $\sigma/m_{DM} < 1\ \text{cm}^2\ \text{g}^{-1} \sim 2\ \text{barn} / \text{GeV}$
- Comparable to nucleon-nucleon scattering cross section



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Example 1: SIMPs

- Consider DM particles similar to SM pions (but stable!)
- Self-scattering cross section:

$$\frac{\sigma_{\text{self}}}{m_\pi} = \frac{m_\pi}{4\pi\, f_\pi^4} \sim 10^{-3}\,\text{cm}^2/\text{g} \left(\frac{m_\pi}{1\,\text{GeV}}\right)^{-3} \left(\frac{g}{\sqrt{4\pi}}\right)^4$$

- Assuming coupling close to perturbativity limit ($g \sim \sqrt{4\pi}$), Bullet Cluster implies $m_\pi > 100$ MeV
- Very difficult to realize strongly-interacting dark sector below this scale!

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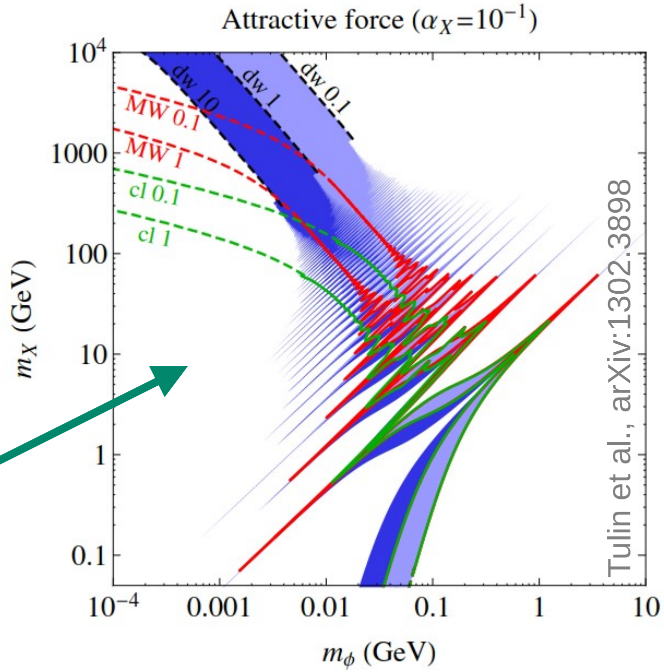
Example 2: Dark photon models

- Consider self-scattering of DM particles via exchange of a light dark photon
- Perturbative result:

$$\sigma \approx 5 \times 10^{-23}\,\mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_\phi}\right)^4$$

- Huge non-perturbative corrections

Excluded by Bullet Cluster



Tulin et al., arXiv:1302.3898

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Example 3: Long-range interactions

- If the dark photon mass is negligible, the cross section correspond to Rutherford scattering

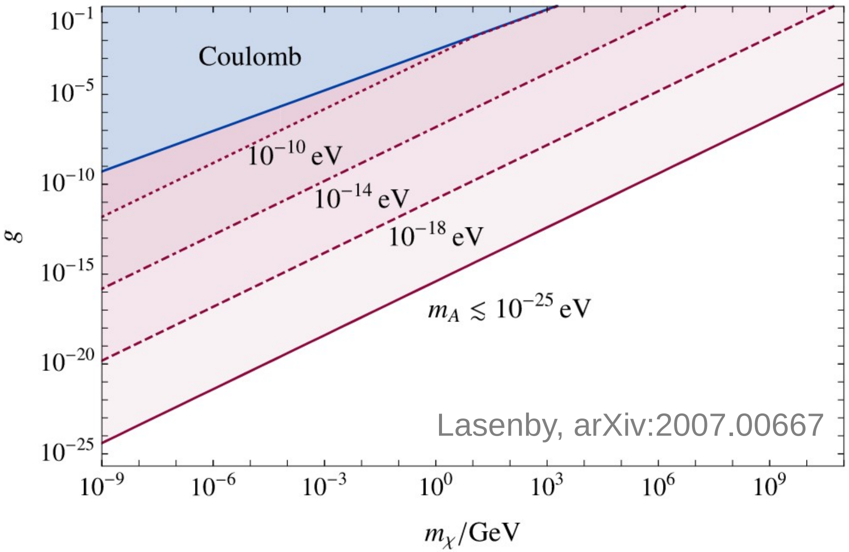
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ruth}} \sim \frac{1}{16E^2 \sin^4 \frac{\theta}{2}}$$

with $E = m_{DM}\, v^2 / 2$

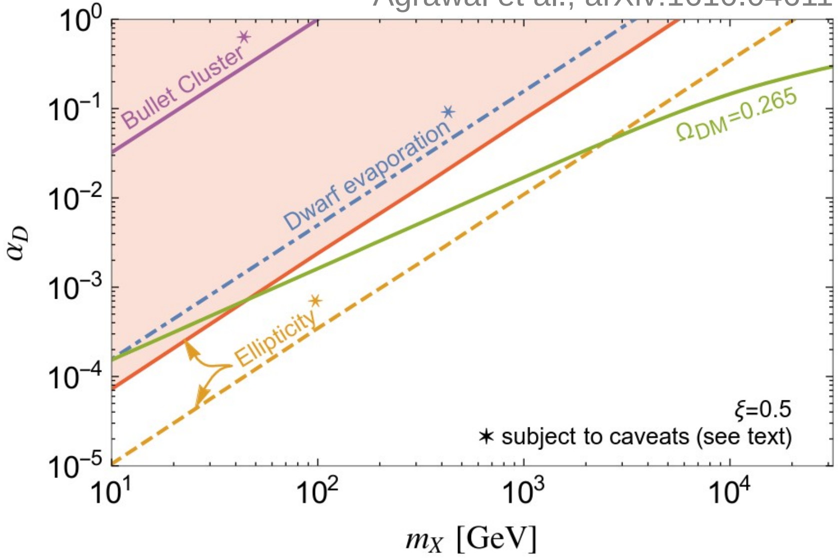
- Scattering dominated by small velocities and scattering angles
- Effect of self-interactions in galaxy clusters (large v) strongly suppressed
- Averaging over large number of scatters leads to effective drag force $F \sim v^{-2}$ (like dynamical friction)

Bounds on long-range interactions

- Leading constraint comes from the observation of elliptical DM haloes, which would be isotropised by self-interactions



Agrawal et al., arXiv:1610.04611

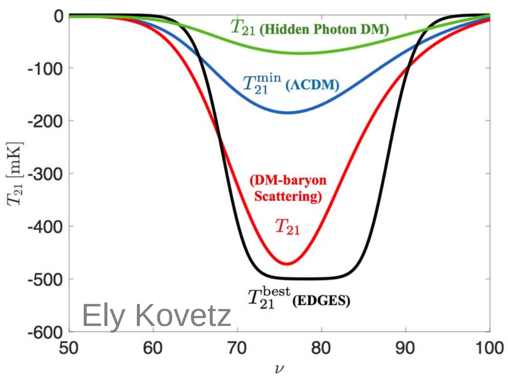


- However, constraints from Bullet Cluster become stronger for ultra-light dark photons due to plasma instabilities

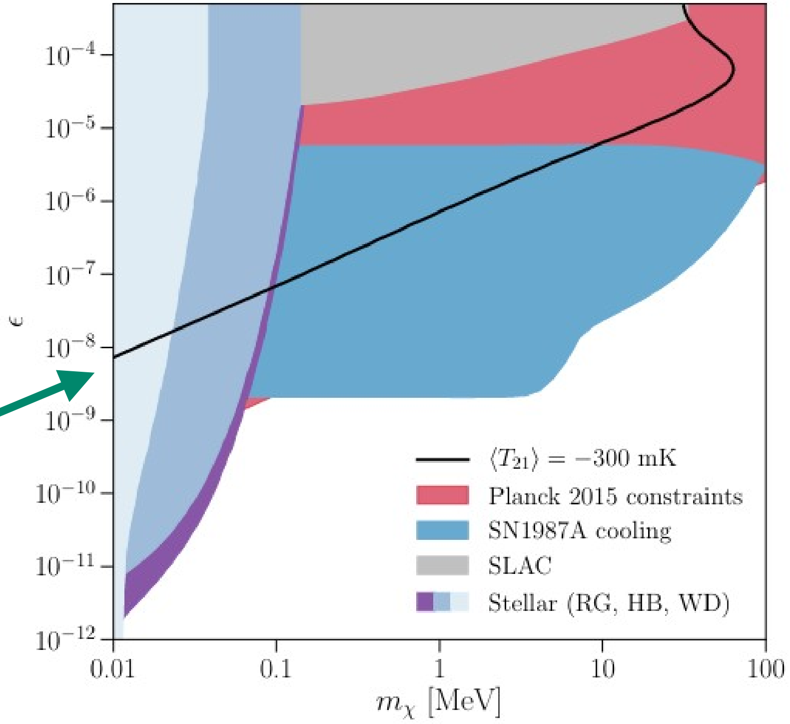
Bounds on millicharged dark matter

Kovetz et al., arXiv:1807.11482

- Long-range self-interaction from exchange of SM photons
- Leading constraints from stellar cooling and cosmology (N_{eff}, CMB)



Interesting parameter range for 21cm brightness temperature



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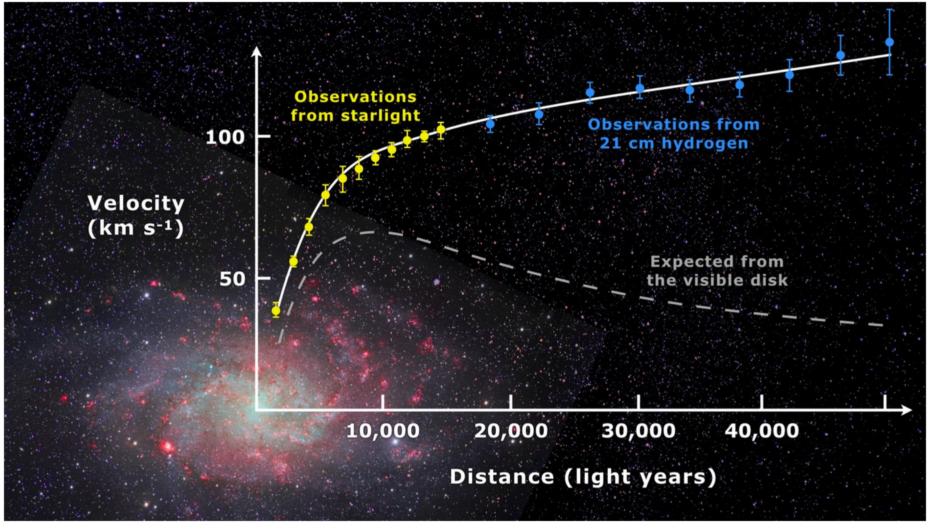
Stronger bounds on DM self-interactions

- Numerical simulations of structure formation predict the radial distribution of DM particles in DM halos:

  NFW profile: $\rho(r) \sim r^{-1} (r + r_s)^{-2}$

- Prediction broadly confirmed by measurements of galactic rotation curves: $v_{rot}(r)^2 = G\, M(r)\, r^{-1}$



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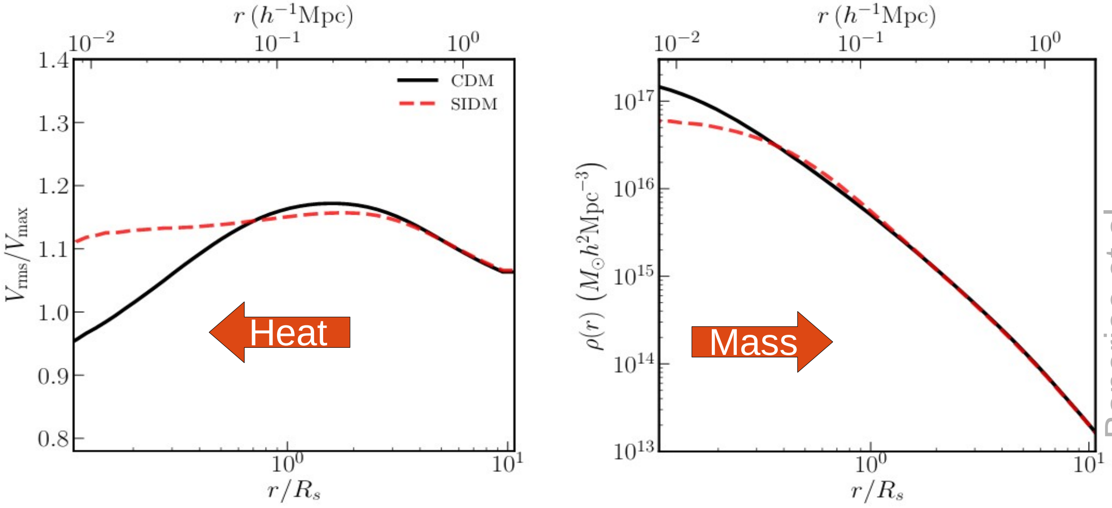
Core formation

- Dark matter (DM) self-interactions can transfer energy from hot regions of a DM halo (shallow gravitational potential) to cold regions (deep gravitational potential)
- As a result, they transform halos with cuspy profiles into halos with central cores



Banerjee et al., arXiv:1906.12026

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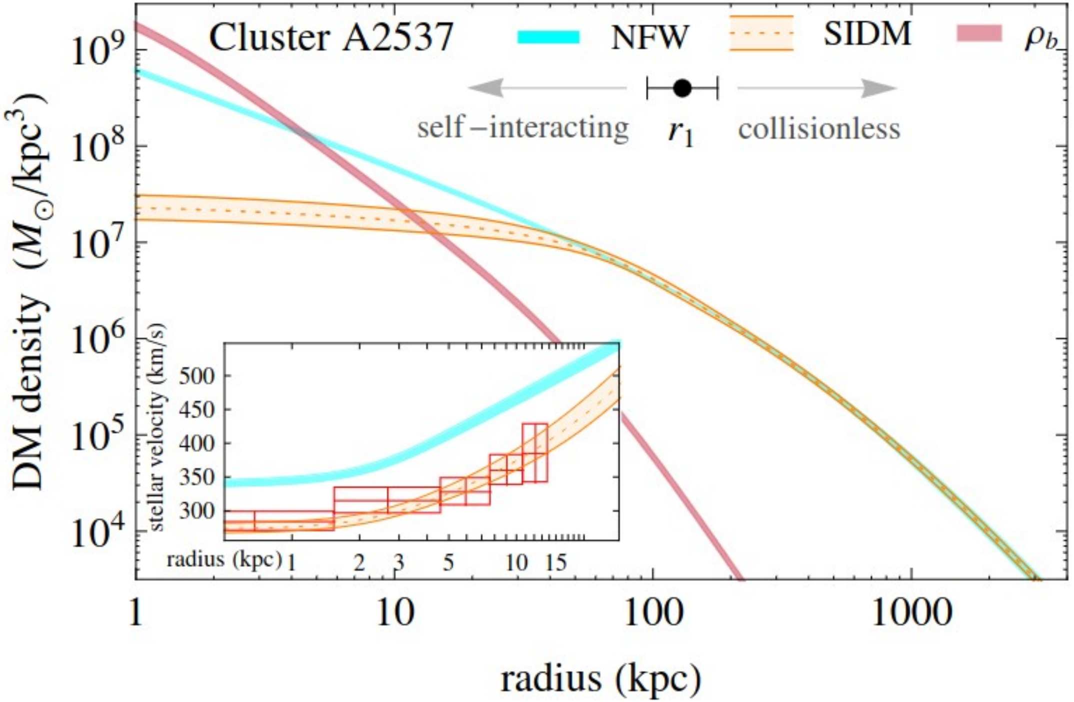
Empirical Jeans formalism

Kaplinghat et al., arXiv:1508.03339

- Rule of thumb: Core radius r_1 given implicitly by $\rho(r_1)\ \sigma/m_{DM}\ v\ t_{age} \sim 1$
- Observational upper bound on r_1 implies upper bound on σ/m_{DM}



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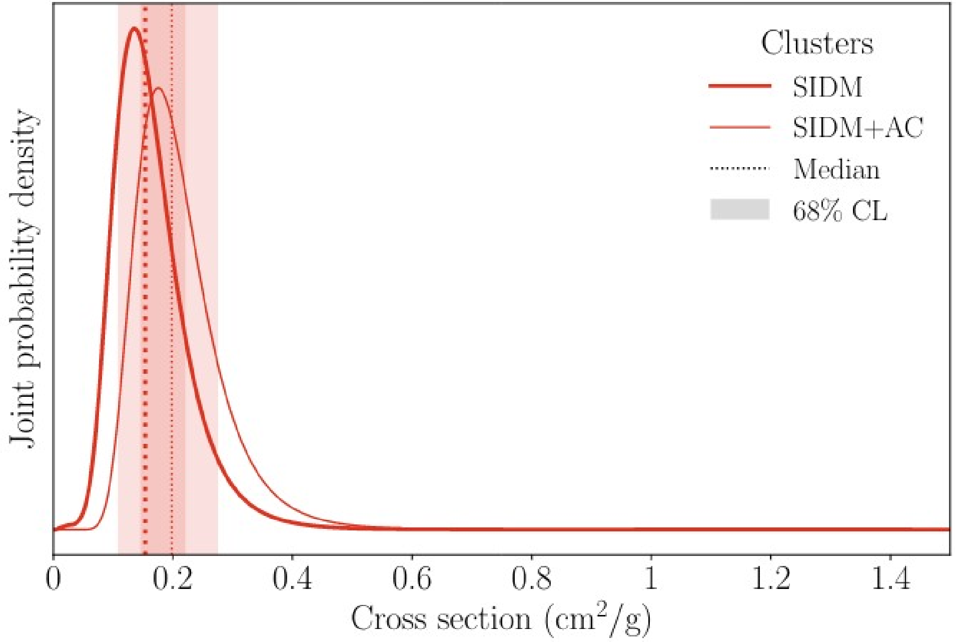
SIDM bounds from core sizes

Sagunski et al., arXiv:2006.12515

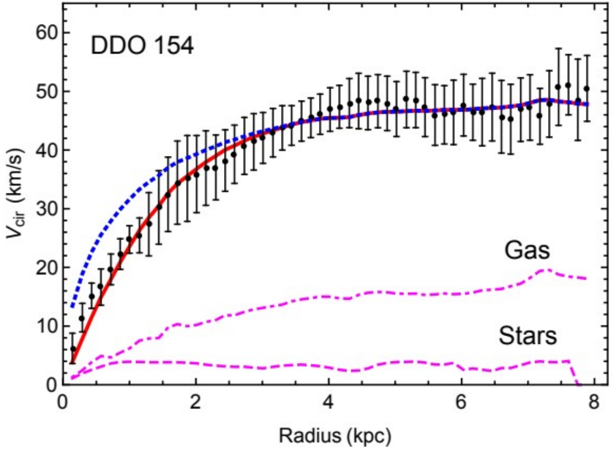


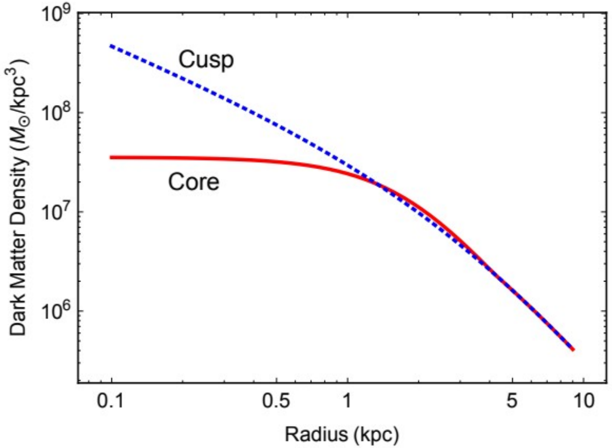
- A recent analysis of galaxy clusters gives $\sigma/m_{DM} < 0.3\ cm^2\ g^{-1}$
- Main challenge: Account for baryonic effects (e.g. adiabatic contraction) that could counteract core formation
- Note: Vanishing cross section strongly disfavoured!

The cusp-core problem

- Various systems exhibit discrepancy between predicted and observed $v_{rot}(r)$ in central region
- Deficit in mass points to constant-density cores rather than cuspy density profiles

Tulin & Yu, arXiv:1705.02358





- Note: Important caveat: Neither the observational situation nor the predictions from numerical simulations are fully robust, so there may be no cusp-core problem

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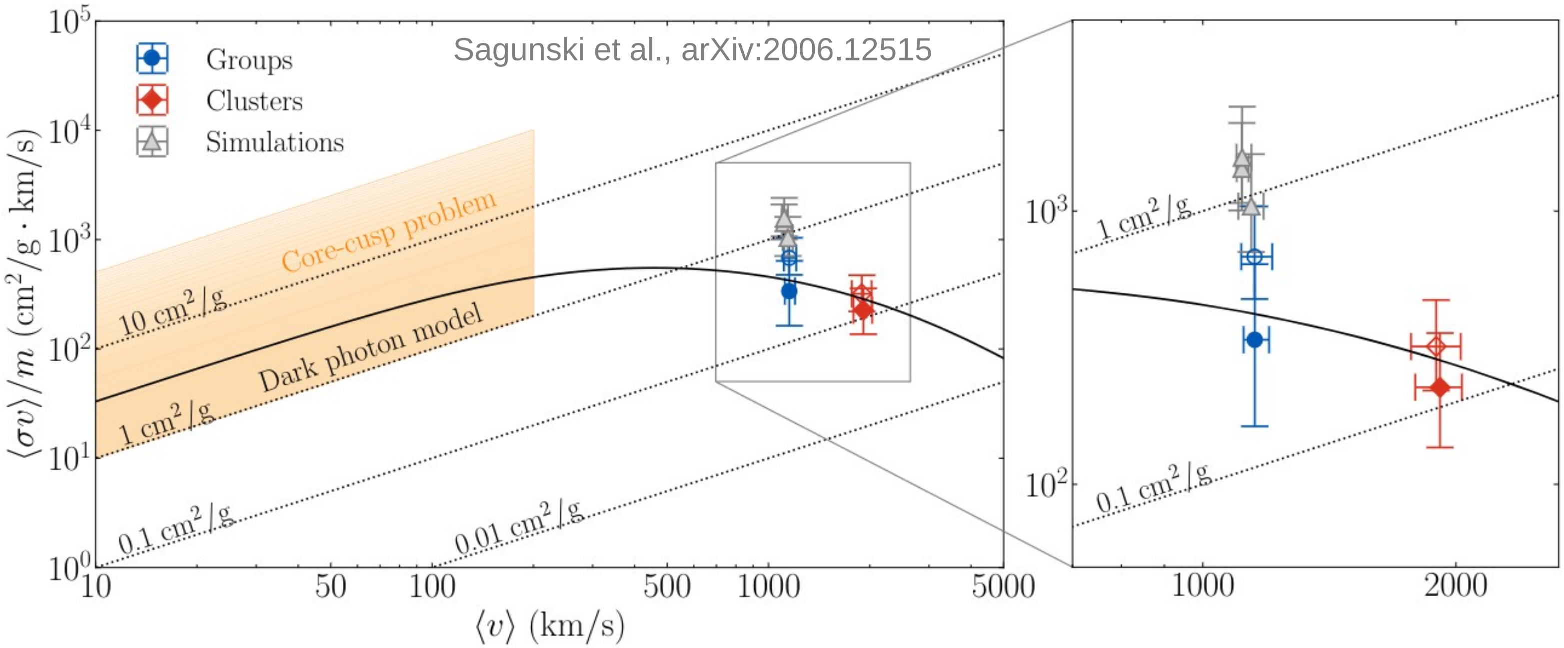
Solving the cusp-core problem

- Velocity-dependent DM self-interactions can resolve the cusp-core problem



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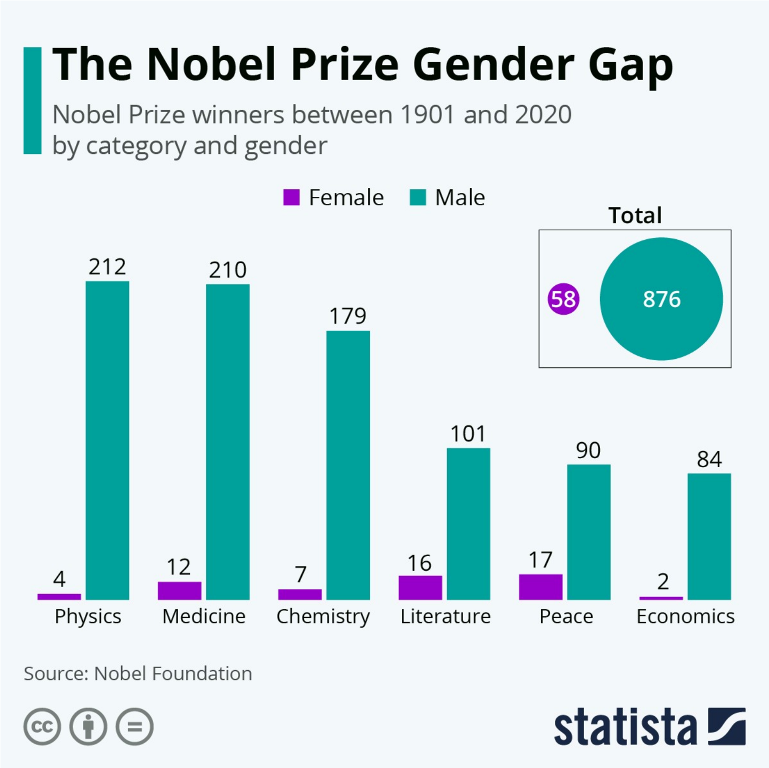
The diversity problem



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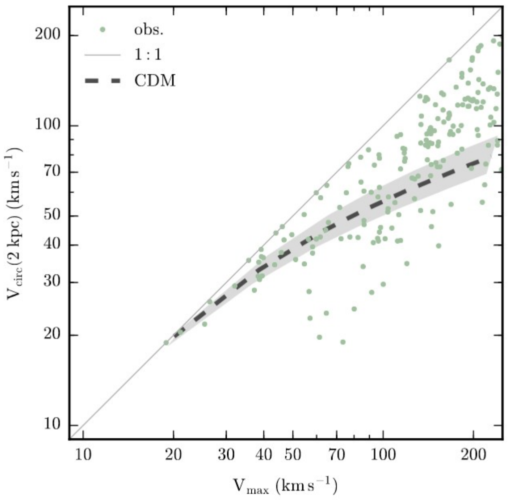
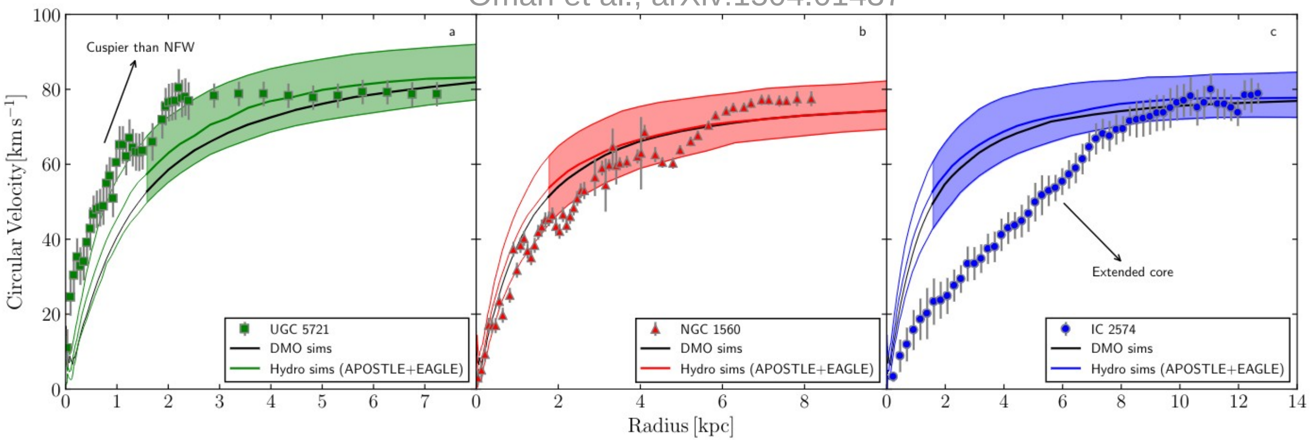
The other diversity problem

- Dwarf galaxy rotation curves exhibit much more diversity than expected

Creasey et al., arXiv:1612.03903



Oman et al., arXiv:1504.01437



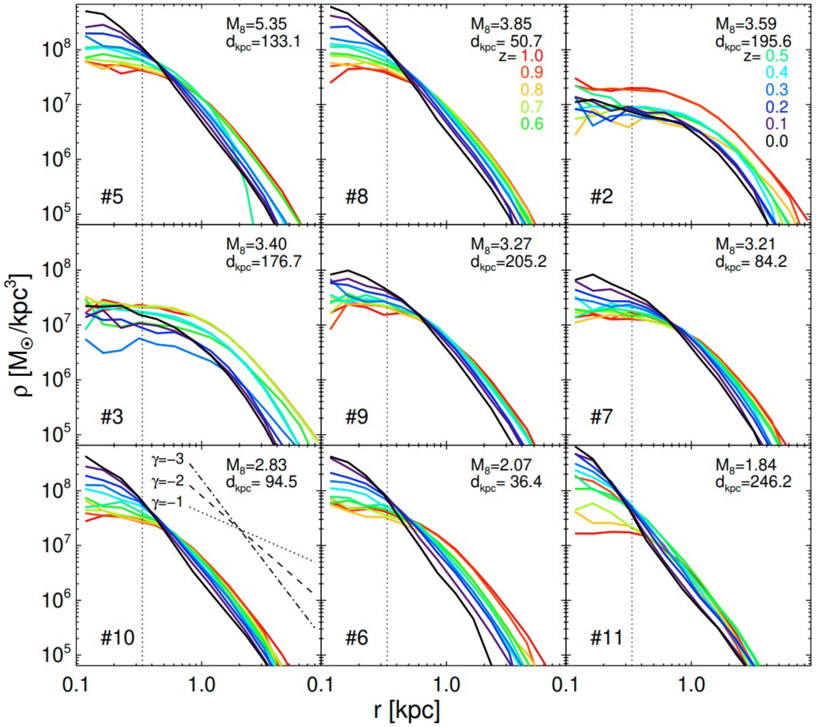
- In fact, some dwarf galaxies are even cuspier than in ΛCDM!
- Speculated to be a projection effect due to non-circular motion
- No conclusive demonstration that enough diversity is achieved
- Possibly greatest challenge for ΛCDM on small scales

Gravothermal collapse

Turner et al., arXiv:2010.02924

- Cores created by DM self-interactions are not stable
- Once the inner region is fully thermalised, the direction of the heat flow reverses and the central region starts cooling down
- After sufficiently long times (or for very large cross sections) cores experience gravitational collapse and cusps reappear

  → gravothermal catastrophe



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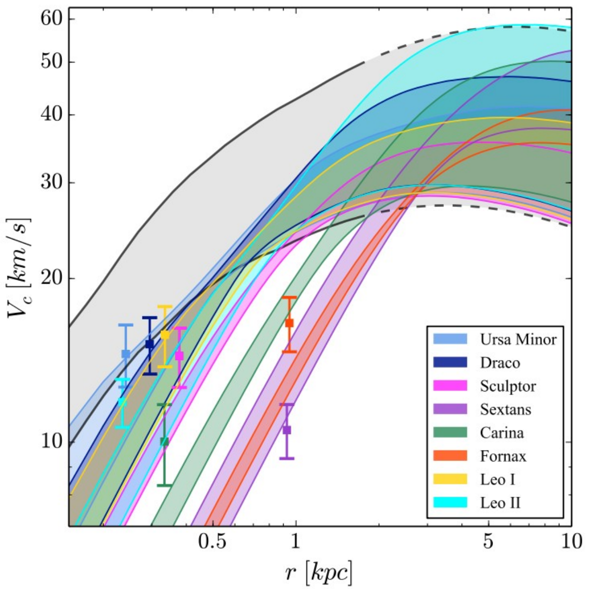
The impact of tidal forces

- If the outer parts of a DM halo are stripped by tidal forces (e.g. from a nearby galaxy), the heat loss increases and core collapse accelerates



- High concentration halos become even denser while low concentration halos are disrupted

Sameie et al., arXiv:1904.07872; FK et al., arXiv: 1904.10539

- Moreover, central density of a Milky Way satellite depends on its precise orbit (i.e. the pericenter distance)

- Possible explanation of the observed diversity of MW satellites

Valli & Yu, arXiv:1711.03502

Conclusions (part 2)

- Non-thermal DM particles can have masses below the MeV scale
- Below the keV scale there are strong bounds from small-scale structure
- Need to account for non-thermal phase space distribution

- Astrophysical bounds on self-interactions constrain the ratio σ/m
- Bullet Cluster gives lower bound on the mass of many DM candidates

- Measurements of core sizes give even stronger bounds, but also hints
- Self-interactions may solve the cusp-core and diversity problem

Hooked?

https://indico.scc.kit.edu/event/3490/

Light Dark World 2023

19-21 September 2023
KIT
Europe/Berlin timezone

- Overview
- Call for Abstracts
- Participant List
- Equity, diversity and inclusion
- Venue
  - Accommodation
  - Travel

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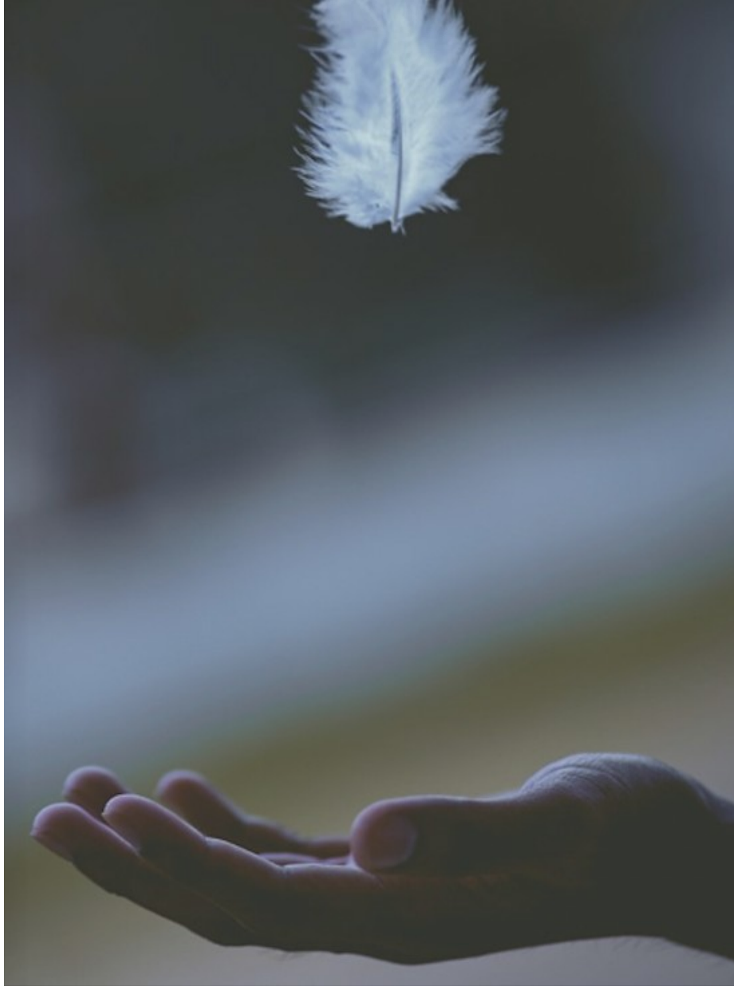
Confirmed speakers:

- Sebastian Baum
- Kim Berghaus
- Elisabetta Bossio
- Jamie Boyd
- Torsten Bringmann
- Pilar Coloma
- Pratika Dayal
- Miguel Escudero
- Angelo Esposito
- Elina Fuchs
- Saniya Heeba
- Kyle Leach
- Seung Joon Lee
- Laura Molina Bueno
- Diego Redigolo
- Giovanni Villadoro
- Susanne Westhoff
- Sam Witte

Thank you...

- … to all the lecturers for giving an excellent overview of the FIPs landscape
- … to all participants for making FIPs in the ALPs such an exciting, entertaining and inspirational event
- …, Gaia, for all your time and hard work, which made this school possible



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