A Novel Scheme for Dark Matter Annihilation Feedback in Cosmological Simulations

Florian List

TeV Particle Astrophysics 2019

Supervisor: Geraint F. Lewis (USyd)
Collaborators: Nikolas Iwanus (USyd),
Pascal Elahi (ICRAR),
Ishaan Bhat (Utrecht)

Sydney Institute for Astronomy
School of Physics

References:

- N. Iwanus, P. J. Elahi, G. F. Lewis, MNRAS 472, 1214, 2017
- N. Iwanus, P. J. Elahi, **F. L.**, G. F. Lewis, MNRAS 485, 1420, 2019
- **F. L.**, N. Iwanus, P. J. Elahi, G. F. Lewis, MNRAS 489, 4217, 2019
- **F. L.**, I. Bhat, G. F. Lewis, MNRAS 490, 3134, 2019

DM annihilation in cosmological simulations

- In the early Universe, **WIMPs** (weakly interactive massive particles) were in a **thermal equilibrium** with the cosmic plasma.
- *After DM freeze-out:* **DM mass loss** due to DM annihilation becomes **negligible**:

  Present day:
  - for mean cosmic density: ~ one in $\mathbf{10^{15}}$ particles annihilates per Hubble time
  - in bound structures: ~ one in $\mathbf{10^{10}}$ particles annihilates per Hubble time

However:
Energy created by DM annihilation feedback (**DMAF**) throughout the cosmic history may have an impact on structure formation ($E = mc^2$)!

→ *Investigate impact of* ***DMAF*** *using* ***numerical simulations****:* (**see also Geraint's talk on Tuesday!**)

- Imprint of DMAF on **large-scale structure** can be analysed (e.g. delayed formation of galaxies due to heating from high-energy particles produced by DMAF).
- Impact of DMAF on **individual haloes and galaxies** can be probed.
- Numerical simulations are an excellent tool for **distinguishing astrophysical sources from DMAF.**

DM annihilation in cosmological simulations

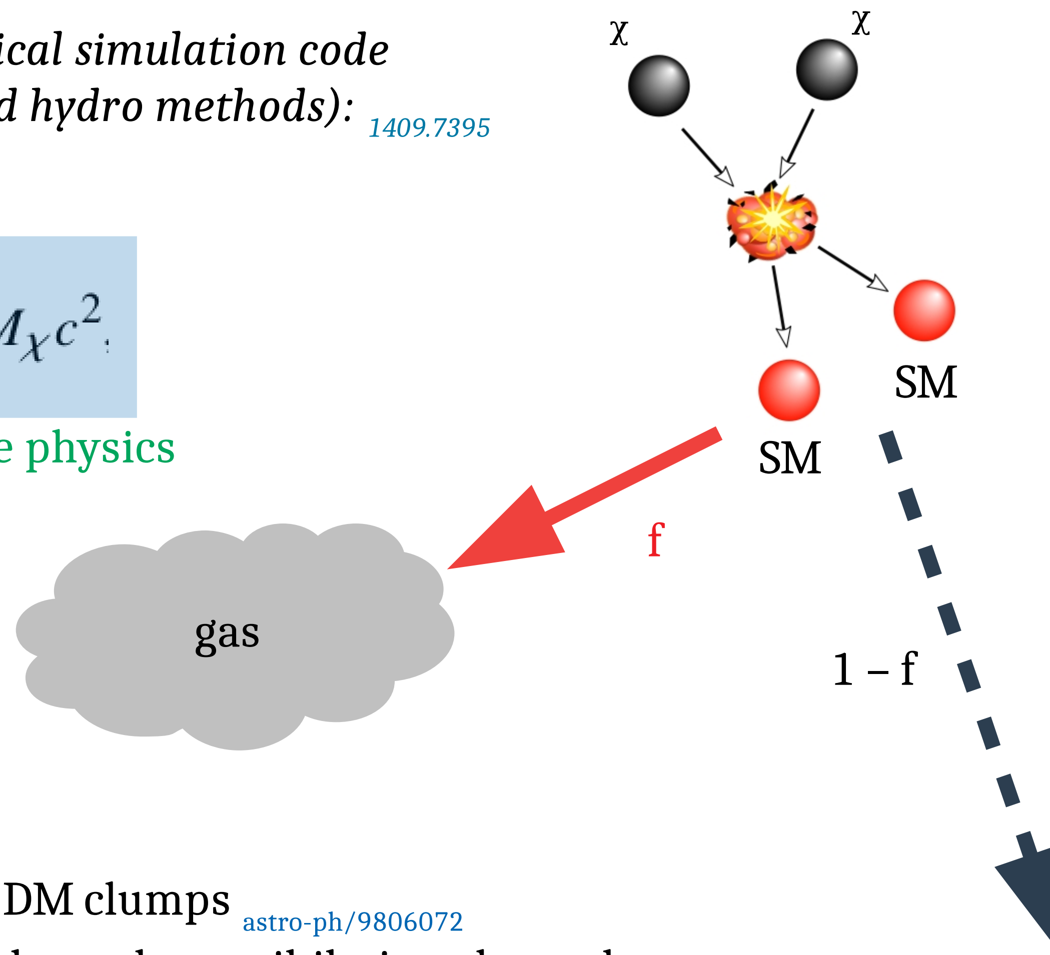
Implementation of DMAF into the cosmological simulation code ***GIZMO*** *(highly parallel, multi-physics, hybrid hydro methods):* 1409.7395

Generated power from DMAF:

$$\frac{dE}{dt} = B\, f\, \frac{\langle \sigma v \rangle}{m_\chi} \rho_\chi M_\chi c^2,$$

→ particle physics

in a comoving volume of DM mass M_χ

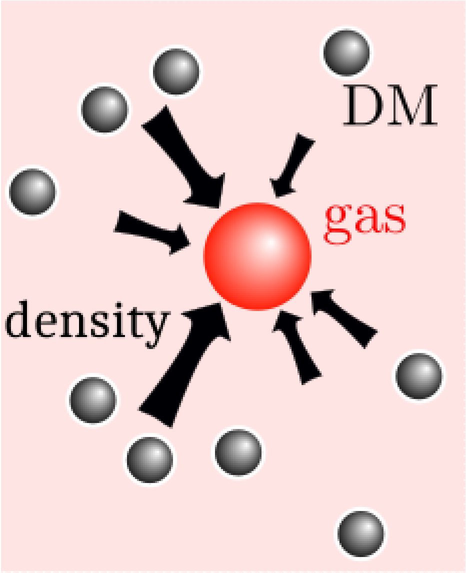


- B: **boost factor** (~1 – 10), or unresolved DM clumps astro-ph/9806072
- f: **absorption fraction** (0.01 – 1), depends on the annihilation channels 1310.3815

DM annihilation in cosmological simulations

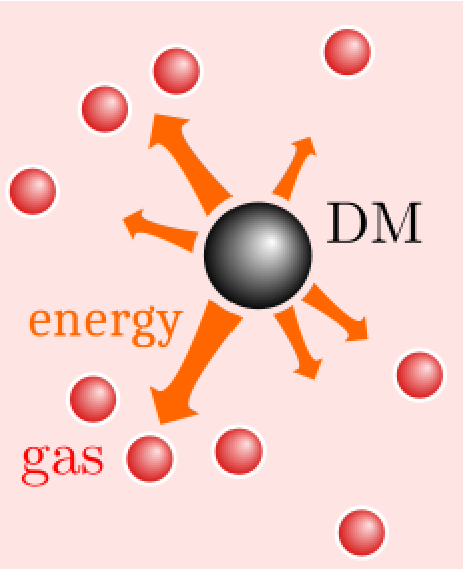
- *We implemented two methods:*

Receiver-based: MNRAS 472, 1214 (2017) MNRAS 485, 1420 (2019)



- DMAF evaluated at **gas** N-body particles
- Assumes a **well-defined DM density field** of which DM N-body particles are tracers

Donor-based: MNRAS 489, 4217 (2019)

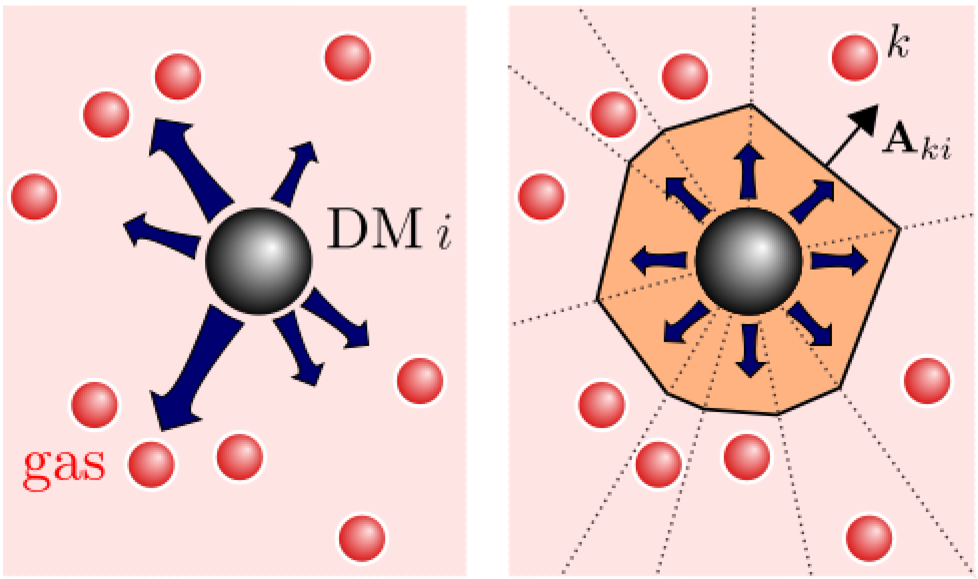


- DMAF evaluated at **DM** N-body particles
- The **generated energy** is **distributed** to the surrounding gas particles

- For both methods, the DMAF energy is calculated and deposited **self-consistently** from the DM distribution evolving in the simulation, **without** the need for **analytic halo models** or **post-processing**.

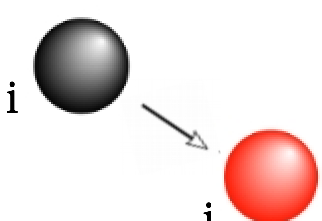
DM annihilation in cosmological simulations

Choice of weights for the **donor-based** method:



a) **b)**

- For case **a)**, the direction of energy injection depends on the local gas distribution and is **biased towards high gas density** regions.
- For case **b)**, the weights are given by the solid angle subtended by each gas particle as seen from the injecting DM particle.
  This leads to an (almost) **isotropic energy injection**, independent of the gas distribution.



$$\frac{dE_{i\to j}}{dt} = \frac{\langle \sigma v \rangle}{m_\chi} \rho_{\chi,i} M_i c^2 \frac{w_j}{\sum_{k \in N_{\mathrm{gas}}(i)} w_k}$$

a) mass weighted injection:

$$w_k = M_k W(r_{ki}, h_i),$$

b) solid angle weighted injection:

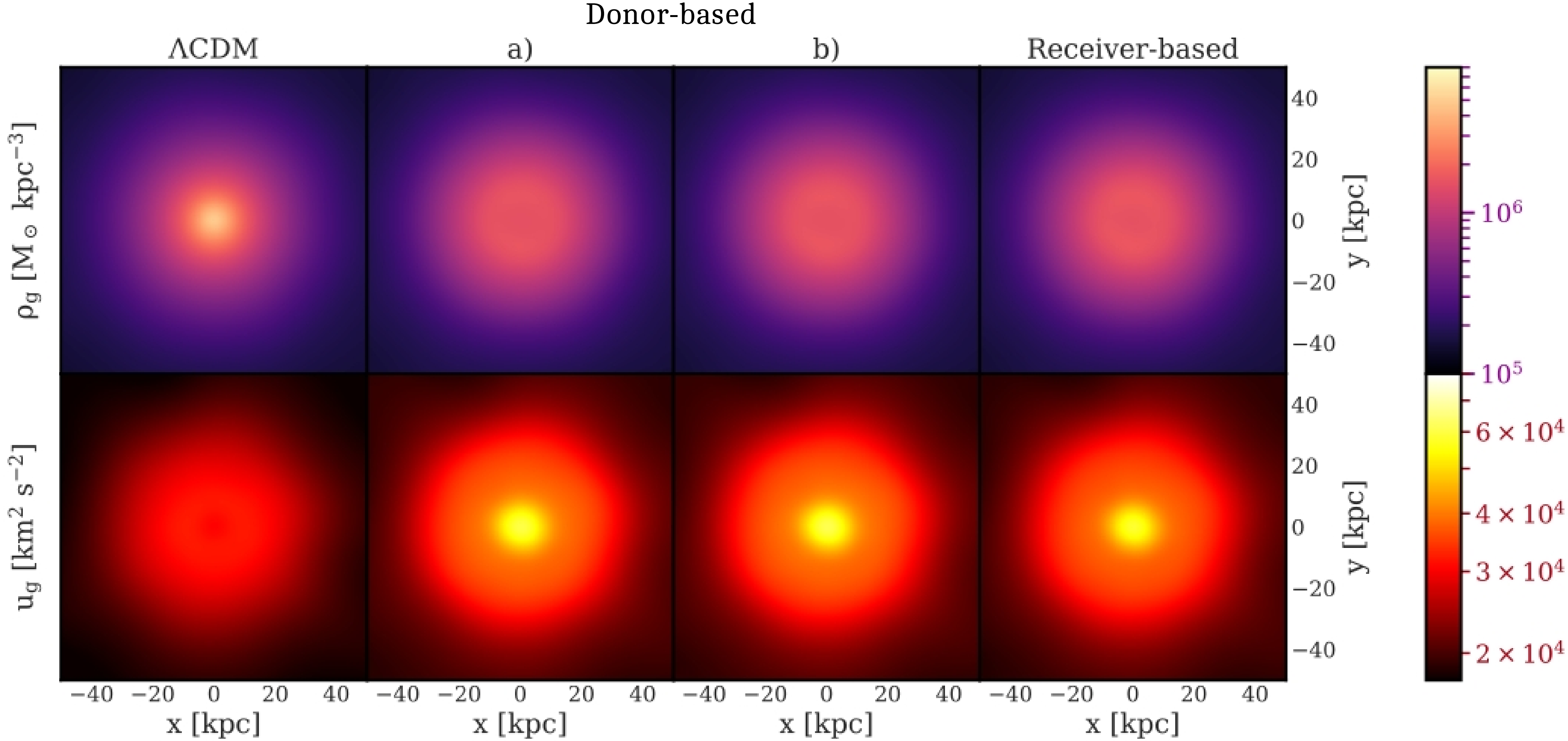
$$w_k = \frac{1}{2}\left(1 - \left(1 + (\mathbf{A}_{ki} \cdot \hat{\mathbf{r}}_{ki}) \,/\left(\pi \,|\mathbf{r}_{ki}|^2\right)\right)^{-1/2}\right).$$

Results

Implementation of DMAF into GIZMO:

Comparison of the **donor-based** and **receiver-based** method:

- Individual halo (MW-sized, NFW profile, m_χ = 100 keV) after ~100 Myr:

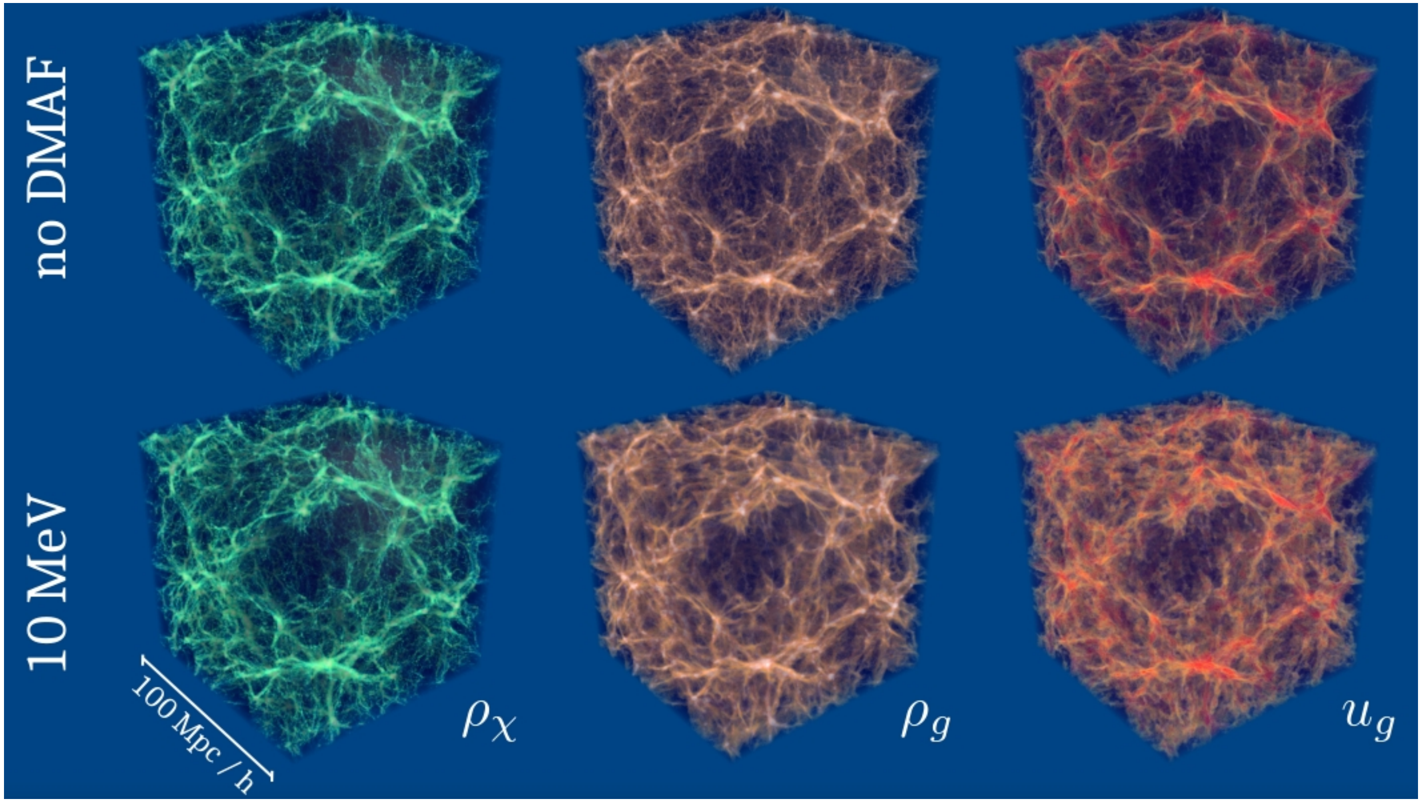


Results

Implementation of DMAF into GIZMO:

Cosmological simulation (100 h^{-1} Mpc box, 10 MeV WIMP, 2 x 512^3 particles):

z = 0:



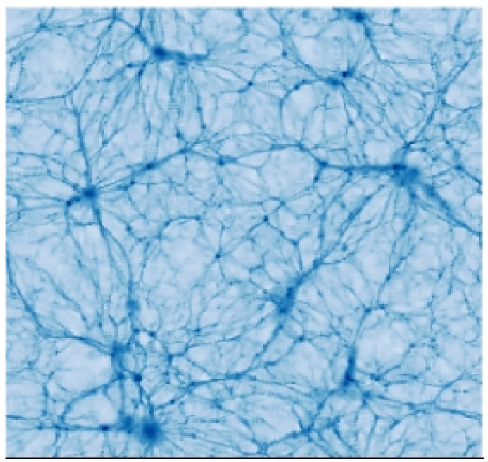
- DMAF **washes out** the **substructure** of the gas
- DMAF **heats** clusters, sheets and filaments
- DM density is not significantly affected by DMAF on a large scale

Predicting DMAF with cGANs

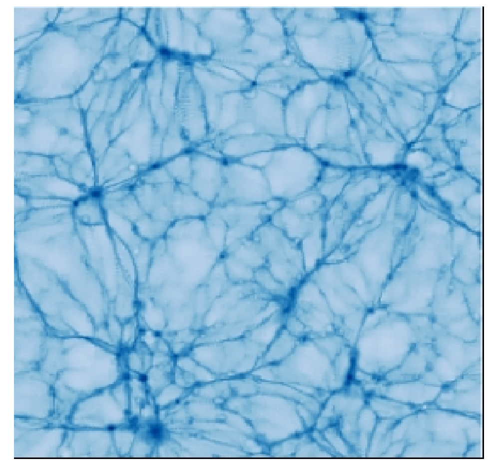
Running numerical simulations for many different DM candidates is expensive!

Can we use neural networks to predict the change in the gas distribution caused by DMAF?

Gas density slices **without DMAF**



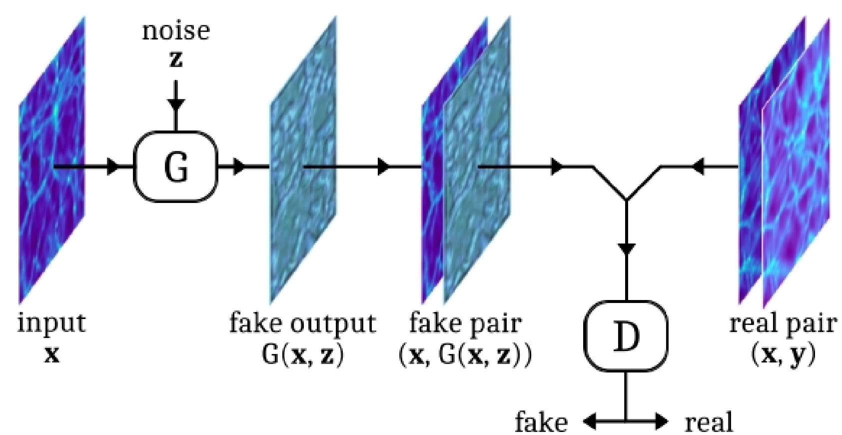
NN



Gas density slices **with DMAF** ?

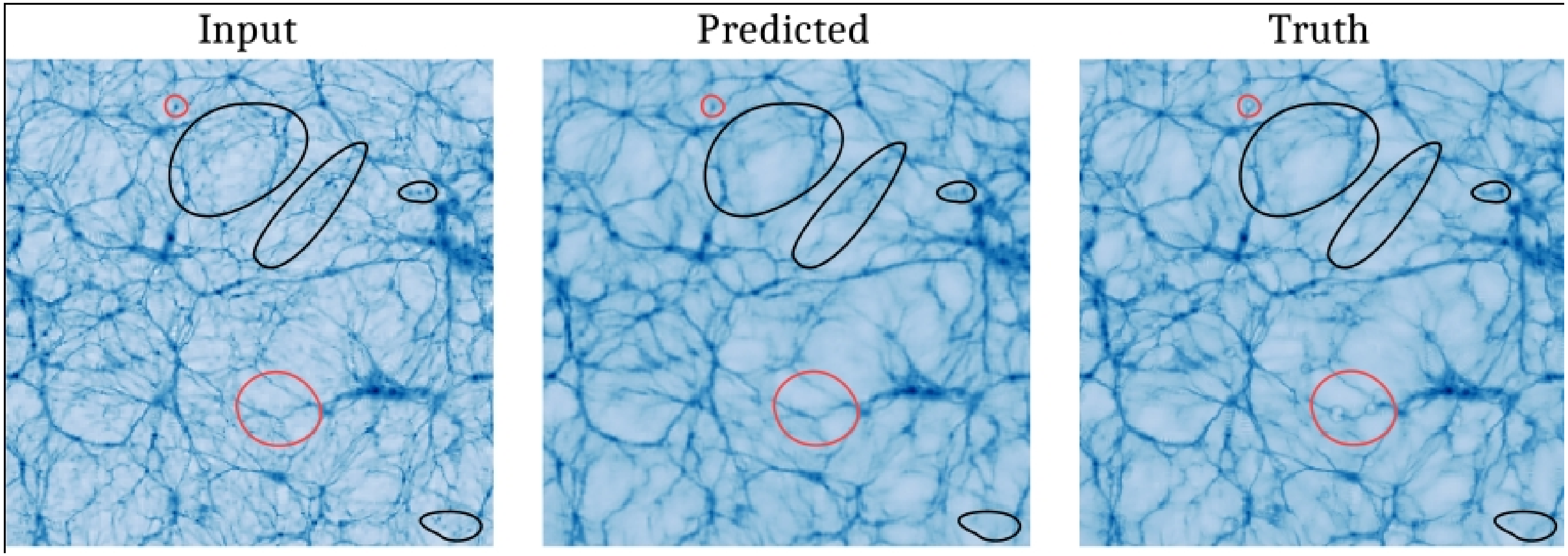
Idea: use conditional Generative Adversarial Networks (**cGANs**) to model the impact of DMAF on the gas distribution: 1411.1784 1611.07004

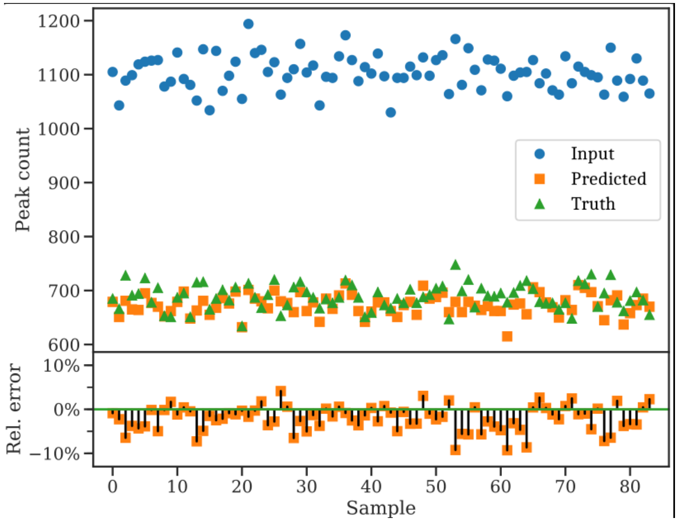
- *Generator network* G: tries to **generate** realistic samples with DMAF
- *Discriminator network* D: tries to **distinguish** DMAF samples produced by G from real DMAF samples



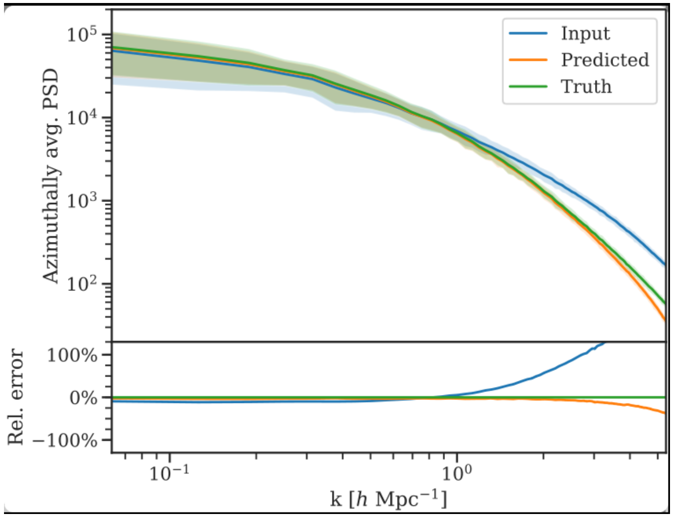
Predicting DMAF with cGANs

- **Results:** MNRAS 490, 3134 (2019)
- cGAN reproduces the smoothing of the gas distribution.
- DMAF struggles with the prediction of bubbles caused by high DMAF injection.





Reduction of peak counts is well replicated.



Power spectrum reduction agrees down to k = 2 – 3 h Mpc^{-1}.

Conclusions and future work

- Cosmological simulations can reveal the impact of DMAF on individual haloes and on the formation of structure.
- The main effect of DMAF is to heat gas and drive it out of their host haloes, thus **reducing** the **halo masses** and leading to **delayed galaxy formation**
- **Dwarf galaxies** are particularly **sensitive** to DMAF and are an ideal test ground for probing DM models.

- **Trained neural networks** are able to **augment** cosmological simulation results *a posteriori* with **additional physics** such as DMAF.

- We will investigate the **interplay** between **DMAF** and **baryonic cooling physics** (bremsstrahlung, inverse Compton scattering, …)
- We will consider extensions such as ionisation due to DMAF, velocity-dependent annihilation cross sections (p-wave annihilation), Sommerfeld enhancement, …

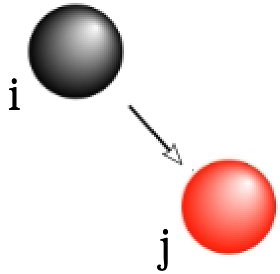
→ *versatile dark matter toolbox for cosmological simulations*

Thank you for your attention!

Extra slides

DM annihilation in cosmological simulations

Implementation of DMAF into GIZMO:

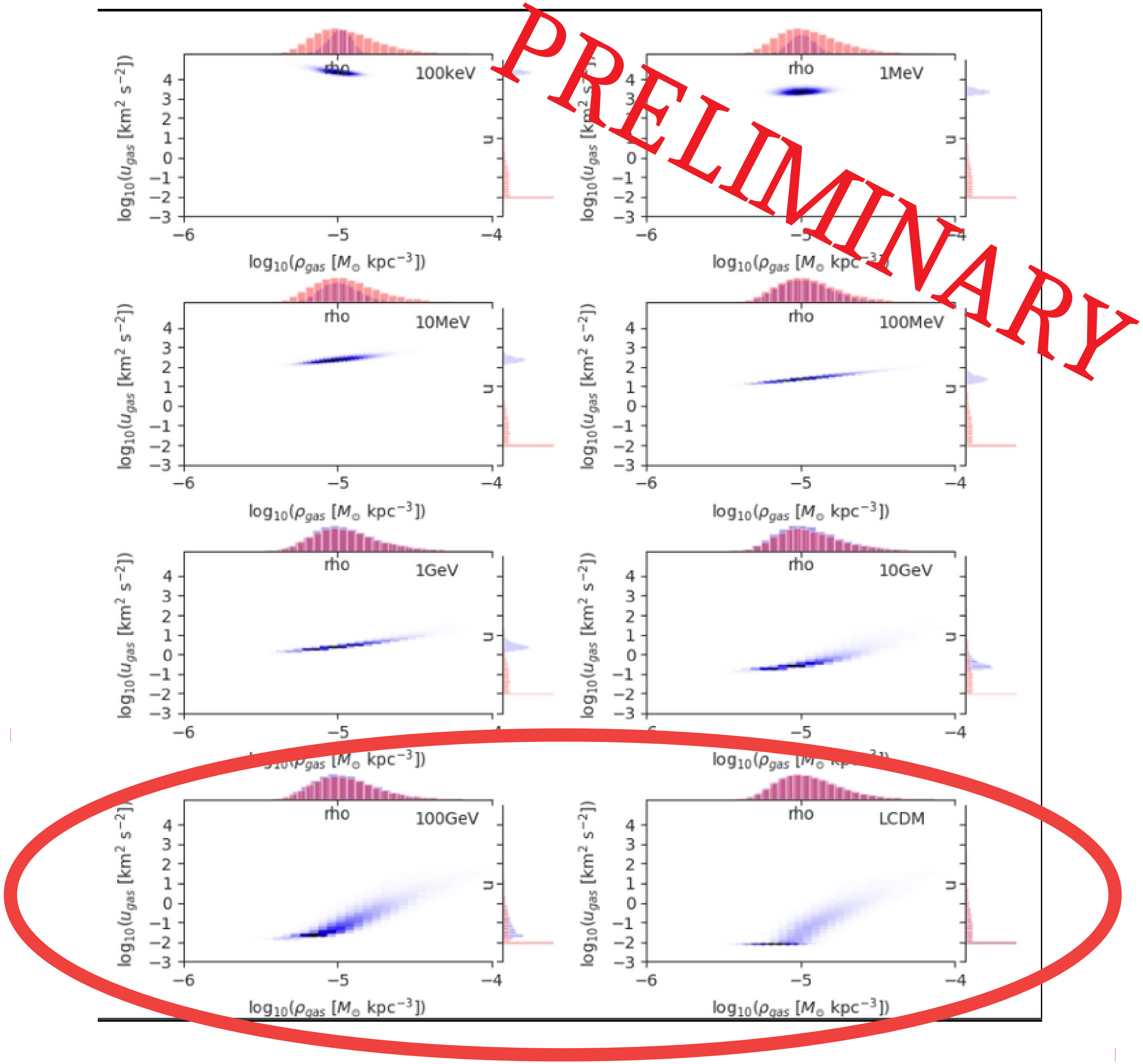


	Receiver-based	**Donor-based**
Evaluation of DMAF	at receiving **gas** particles	at annihilating **DM** particles
Injected power (assuming B=f=1)	$\frac{1}{M_j}\frac{dE_{j\leftarrow\chi}}{dt} = \frac{\langle\sigma v\rangle}{m_\chi}\frac{\rho^2_{\chi,j}}{\rho_{g,j}}c^2$	$\frac{dE_{i\rightarrow j}}{dt} = \frac{\langle\sigma v\rangle}{m_\chi}\rho_{\chi,i}M_i c^2 \frac{w_j}{\sum_{k\in\mathcal{N}_{\mathrm{gas}}(i)} w_k}$
Locality of energy injection	local injection inherently built in	injection flexible, dependent on weights w_k
DMAF power generation coupled to DM mass loss?	no	yes

- The results of the two methods differ for very steep DM density gradients
- For **realistic situations** (individual halo, cosmological simulation) the two methods give **similar results** (if the weights w_k in the donor-based method model local deposition)

DMAF implementation

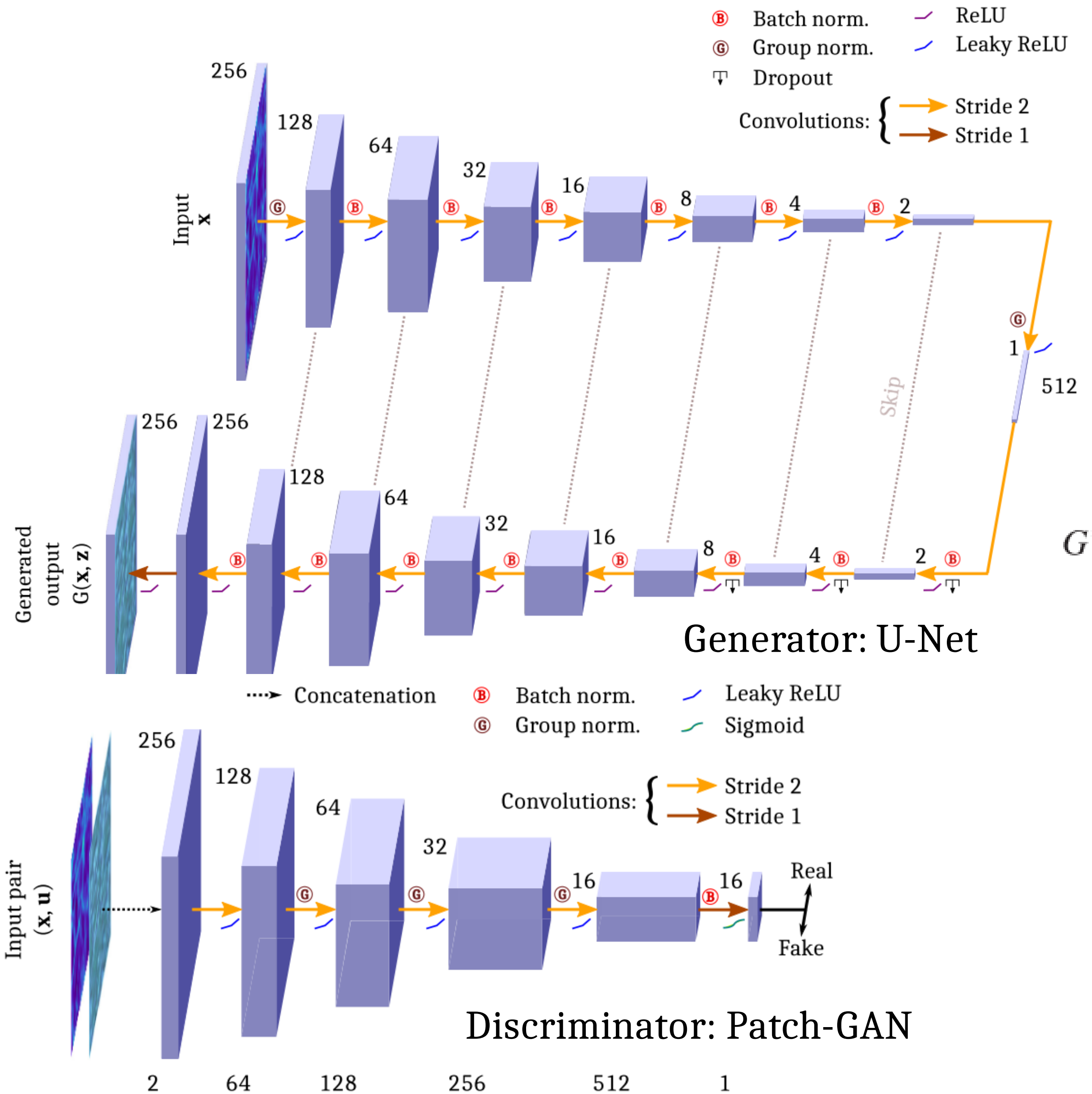
Heating of the gas at high redshift (z = 10.7):



Boost factor 1
Absorption rate 1

z = 10.7 is just before the UV background turns on in the GIZMO standard cooling libraries.

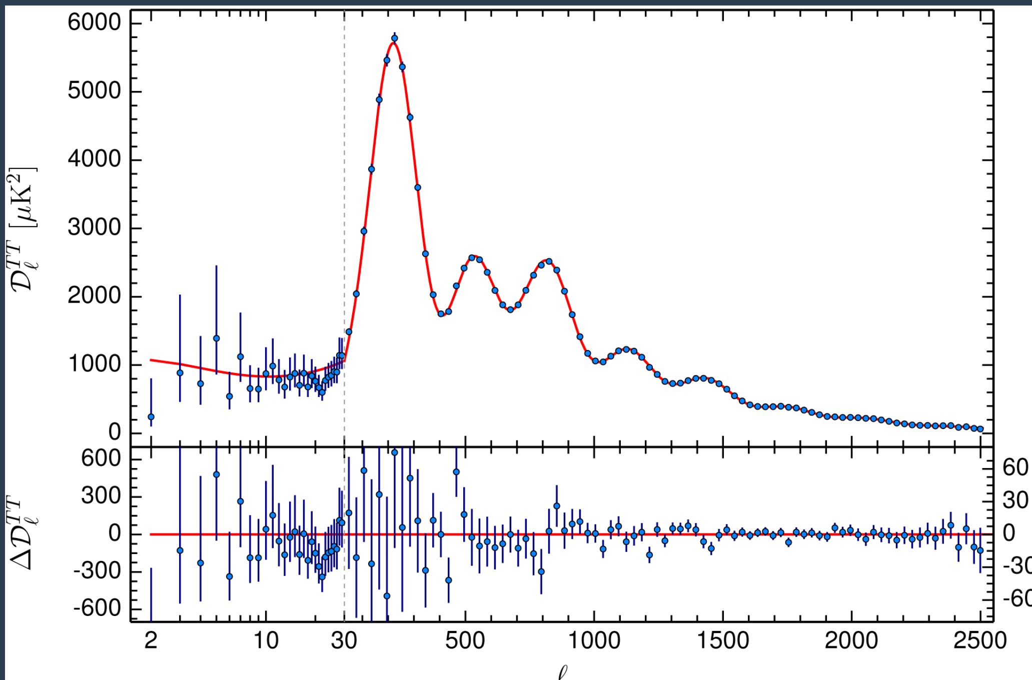
cGAN architecture

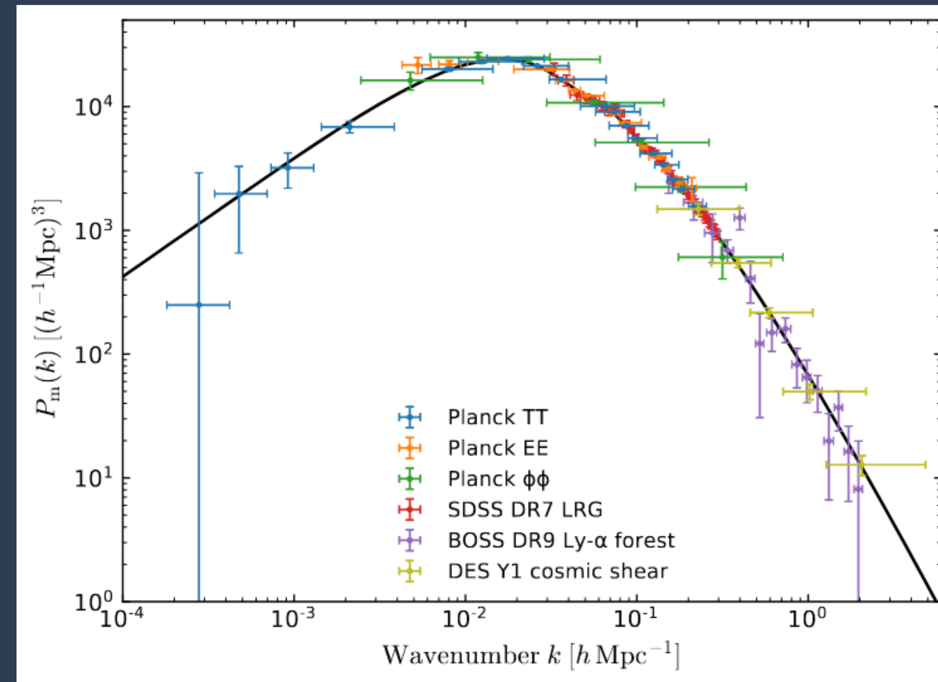


Training:
* GAN loss
* 600 epochs on 300 training images (+ data augmentation by mirroring)
* Adam optimiser (LR = 2 x 10^{-4})

Min-max problem:

$$G^* = \arg\min_G \max_D (\mathbb{E}_{x\sim p(x), y\sim p(y)}[\log(D(x, y))]$$
$$+ \mathbb{E}_{x\sim p(x), z\sim p(z)}[\log(1 - D(x, G(x, z)))]$$
$$+ \lambda \mathbb{E}_{x\sim p(x), y\sim p(y), z\sim p(z)}[\|G(x, z) - y\|_1])$$



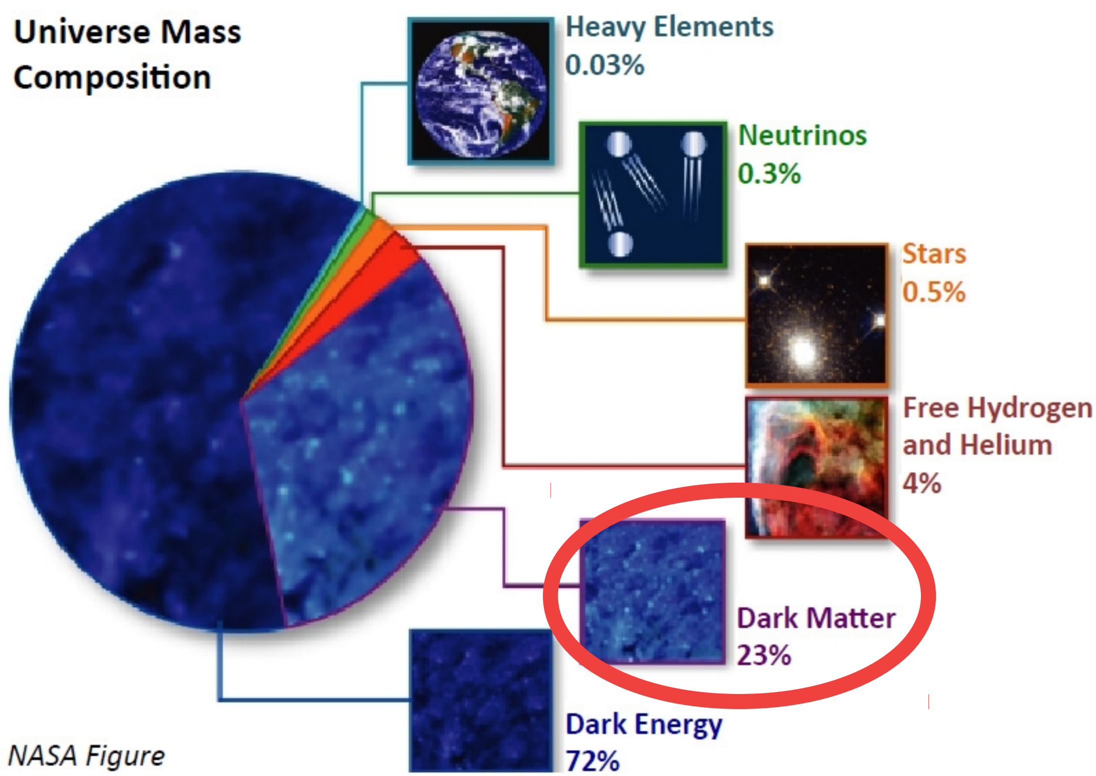


Planck Collaboration

Cosmological probes (in particular Planck data) agree remarkably well with the predictions from ΛCDM

Dark matter

BUT:

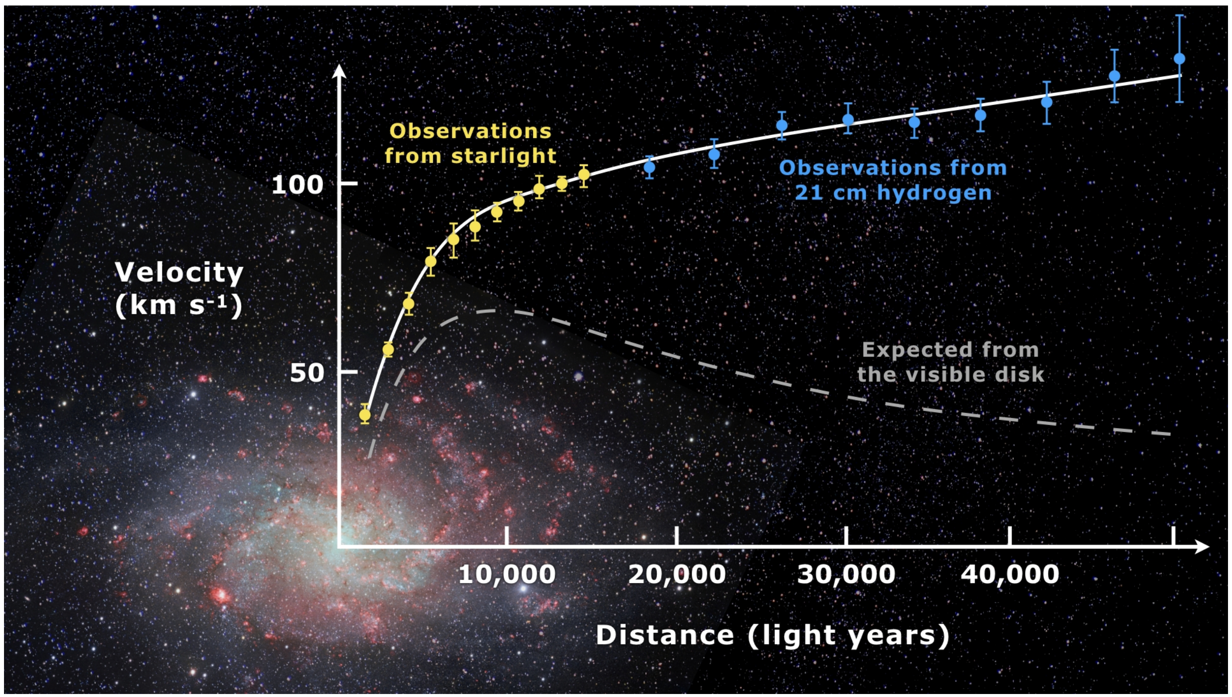


- ~ **95%** of the energy density in the Universe are made up of components that are **poorly understood** to date, DM and dark energy
- There is approximately 5 times as much DM in the universe as baryonic ("visible") matter
- At location of the sun: DM density is ~0.35 GeV / cm^3 (~ 1/100 $M_\odot$ / pc^3)

Dark matter

Why is a species needed that only interacts via gravity (and possibly via the weak force)?

Evidence from **rotation curves of galaxies** (here M33, spiral galaxy in the Local Group):



By Mario De Leo, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74398525

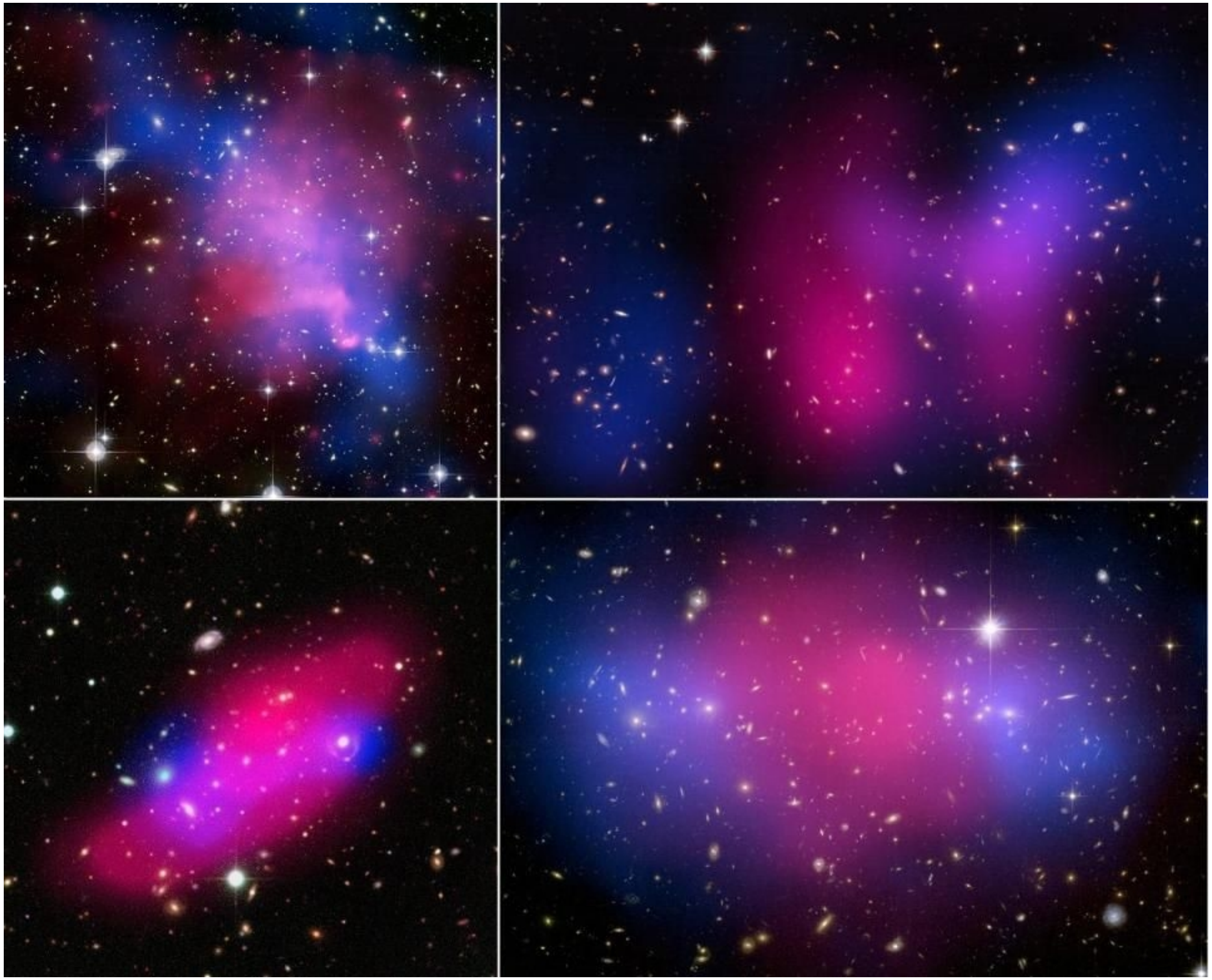
- Observed rotation velocities of stars are higher than can be inferred from the visible mass
- *Possible explanation*: there is more matter than what we can see! → **DM**
- Influence of DM increases at the outer region of the galaxy
- *Possible alternative explanation*: the law of gravity needs to be modified on large scales
  → MOND-type models
- BUT: many modified gravity models ruled out by GW170817 neutron star merger *

* Boran, Sibel, et al. "GW170817 falsifies dark matter emulators." Physical Review D 97.4 (2018): 041501.

Dark matter

Why is a species needed that only interacts via gravity (and possibly via the weak force)?

Colliding galaxy clusters (e.g. Bullet cluster):



Blue: gravitational mass, inferred from lensing
Purple: X-ray emission

- Gravitational mass center does *not* coincide with X-ray emission from baryons
- DM components pass through each other unhindered
- Baryonic matter collides and subsequently drags behind DM
- Observations of galaxies at rest disfavour non-local theories of gravity as an alternative explanation
  → Challenge for MOND-like models!

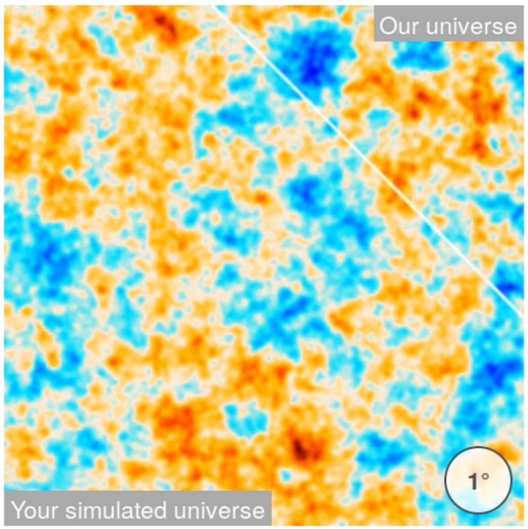
X-ray: NASA/CXC/UVic./A.Mahdavi et al. Optical/Lensing: CFHT/UVic./A. Mahdavi et al. (top left); X-ray: NASA/CXC/UCDavis/W.Dawson et al.; Optical: NASA/ STScI/UCDavis/ W.Dawson et al. (top right); ESA/XMM-Newton/F. Gastaldello (INAF/ IASF, Milano, Italy)/CFHTLS (bottom left); X-ray: NASA, ESA, CXC, M. Bradac (University of California, Santa Barbara), and S. Allen (Stanford University) (bottom right)

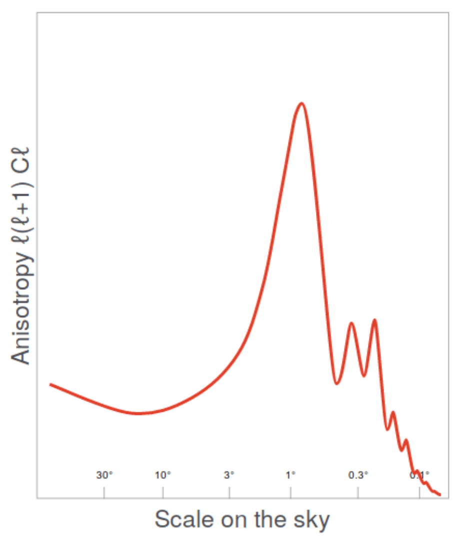
Dark matter

Why is a species needed that only interacts via gravity (and possibly via the weak force)?

CMB:

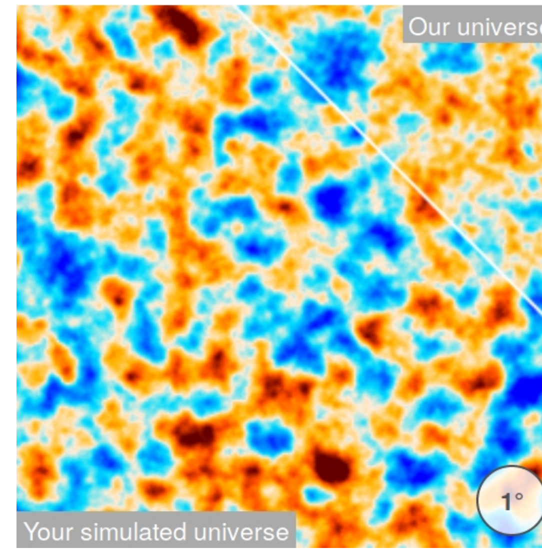
ΛCDM:

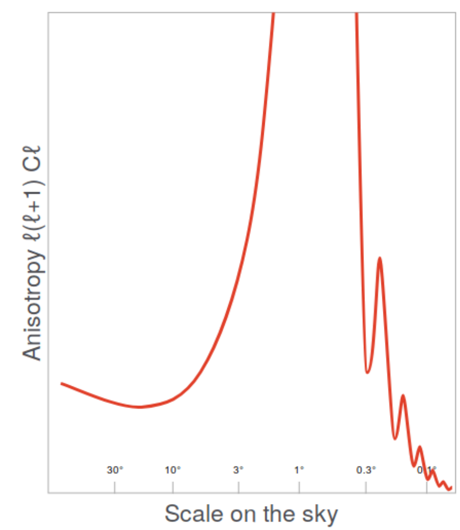




Flat universe with
$\Omega_b = 0.325$
$\Omega_\Lambda = 0.675$

- Before recombination: baryonic ion / photon fluid has pressure and supports soundwaves ↔ DM is pressureless!
- First peak in the CMB power spectrum is set by the largest sound wave with half an oscillation between the Big Bang and the time of recombination





https://chrisnorth.github.io/planckapps/Simulator/

Dark matter

Why is a species needed that only interacts via gravity (and possibly via the weak force)?

More evidence for ΛCDM:

- Weak lensing observation
- Type Ia Supernovae measurements
- Lyman-alpha forest
- Velocity dispersion in elliptical galaxies
- Baryonic acoustic oscillation (BAO) measurements from Large Scale surveys (Sloan, 2dF)
- Redshift-space distortions (Finger of God effect, Kaiser effect)
- ...

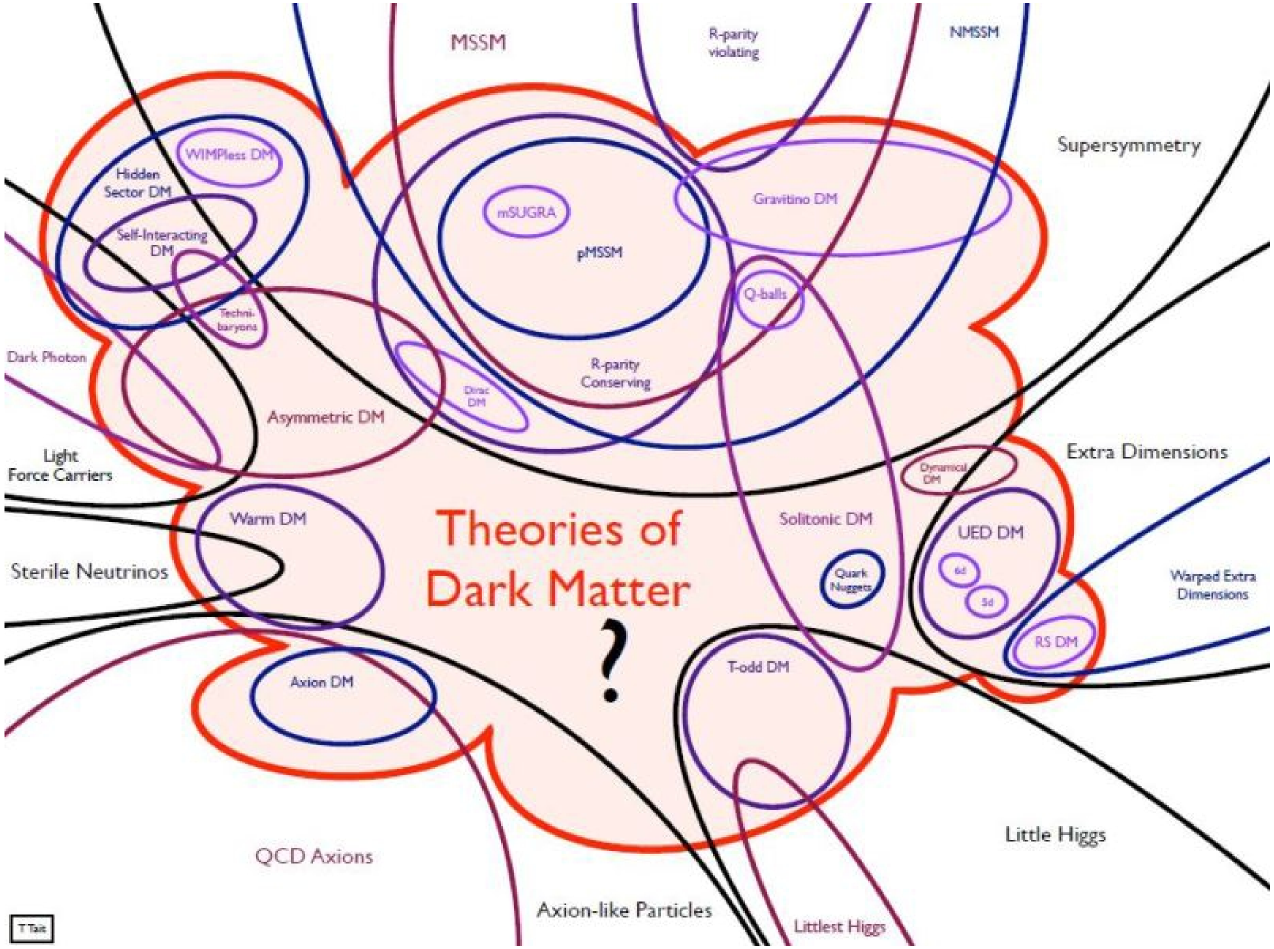
Dark matter

What properties does DM need to have?

- Massive / inert (interacts gravitationally)
- Stable (must not decay within some billion years since we still observe it)
- Slow enough (“cold” or possibly “warm” - this rules out the neutrino)
- Electrically neutral (otherwise not “dark”)
- must reproduce the observed DM density of $\Omega\chi \sim 0.22$
- self-interaction is tightly constrained

But what exactly *is* DM?

Dark matter candidates



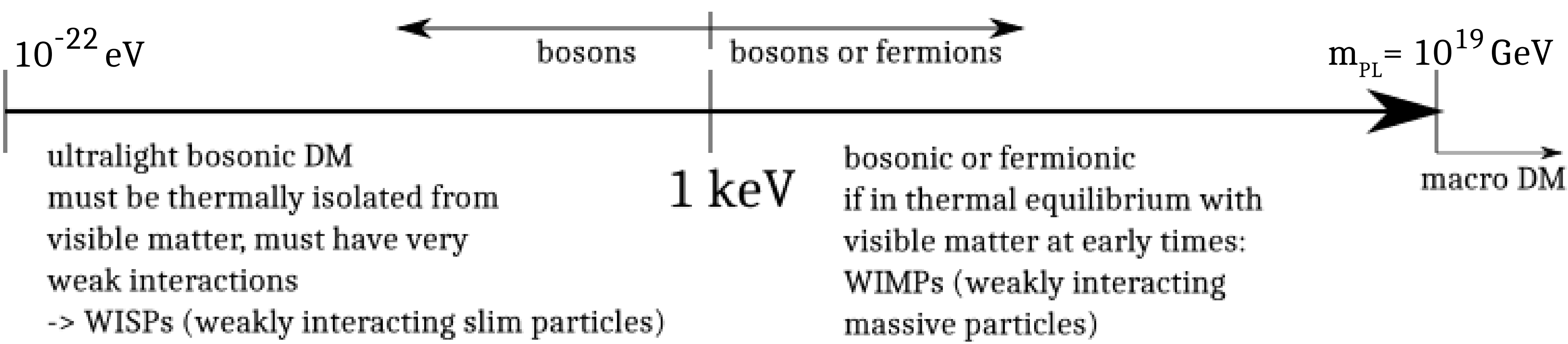
Tim Tait, University of California

- DM candidates span a huge mass range from 10^{-22} eV for fuzzy DM over 10^{28} eV for Planckian interacting DM, to several solar masses for primordial black holes (PBHs)
- Many candidates are motivated from other physical problems such as the strong CP problem in QCD (axion DM) or the hierarchy problem of the Standard Model (lightest SUSY particle)

Dark matter candidates

Can we say more about the mass range for the DM particle?

- DM wavelength can't be larger than the smallest observed DM structures
- → wavelength < 1 kpc => $m_\chi > 2 - 3 \times 10^{-21}$ eV
- *For fermions*: a lower bound comes from the Tremaine-Gunn bound (based on Pauli exclusion principle): $m_\chi > O$(a few hundred eV)
- Upper limit: ??? (e.g. if DM is made up of primordial black holes)



Dark matter candidates

- During the past decades, the search for DM has been dominated by the following classes of candidates:

WIMPs
(weakly interacting massive particles)

vs. **MACHOs**
(massive compact halo objects)

vs. **axions**

- To date, no convincing detection of DM has been made

Dark matter candidates

MACHOs:

- DM could consist of macroscopic objects such as black holes or ultra-compact minihaloes: electrically neutral, dark, no radiation pressure
- *But*: they would need to form very early in the Universe (since the CMB indicates that DM already existed at time of recombination)
- Possible production during inflation
- MACHO candidates also include white dwarfs, faint red dwarfs, brown dwarfs, neutron stars
- Tight limits on stellar DM candidates come from microlensing probes, and Big Bang Nucleosynthesis, CMB, and BAOs constrain baryonic content of the Universe

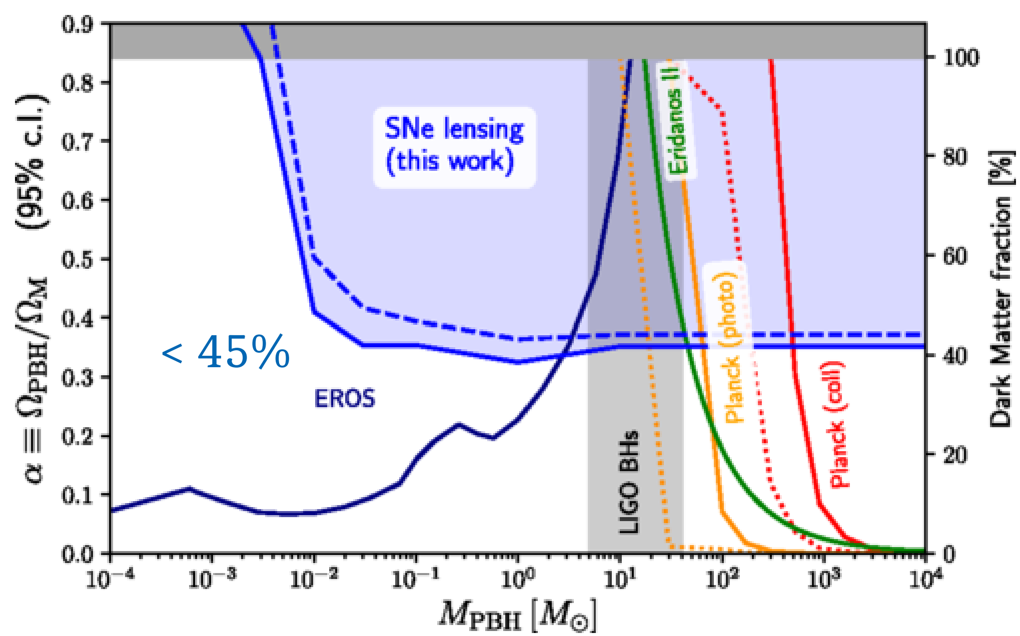
LIMITS ON STELLAR OBJECTS AS THE DARK MATTER OF OUR HALO: NONBARYONIC DARK MATTER SEEMS TO BE REQUIRED

Katherine Freese[1], Brian Fields[2], and David Graff[3]

1)*University of Michigan*
The Harrison M. Randall Laboratory of Physics
Ann Arbor, MI 48109-1120 USA
2) *University of Illinois*
Dept. of Astronomy
Champagne-Urbana, IL USA
3) *Ohio State University*
Dept. of Astronomy
Columbus, OH USA
1) ktfreese@umich.edu, 2)bdfields@astro.uiuc.edu, 3)graff.25@osu.edu

1999

Abstract. The nature of the dark matter in the Halo of our Galaxy remains a mystery. Arguments are presented that the dark matter does not consist of ordinary stellar or substellar objects, i.e., the dark matter is not made of faint stars, brown dwarfs, white dwarfs, or neutron stars. In fact, faint stars and brown dwarfs constitute no more than a few percent of the mass of our Galaxy, and stellar remnants must satisfy $\Omega_{WD} \leq 3 \times 10^{-3} h^{-1}$, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. On theoretical grounds one is then pushed to more exotic explanations. Indeed a nonbaryonic component in the Halo seems to be required.



Miguel Zumalacárregui and Uroš Seljak, Phys. Rev. Lett. 121, 141101, 2018

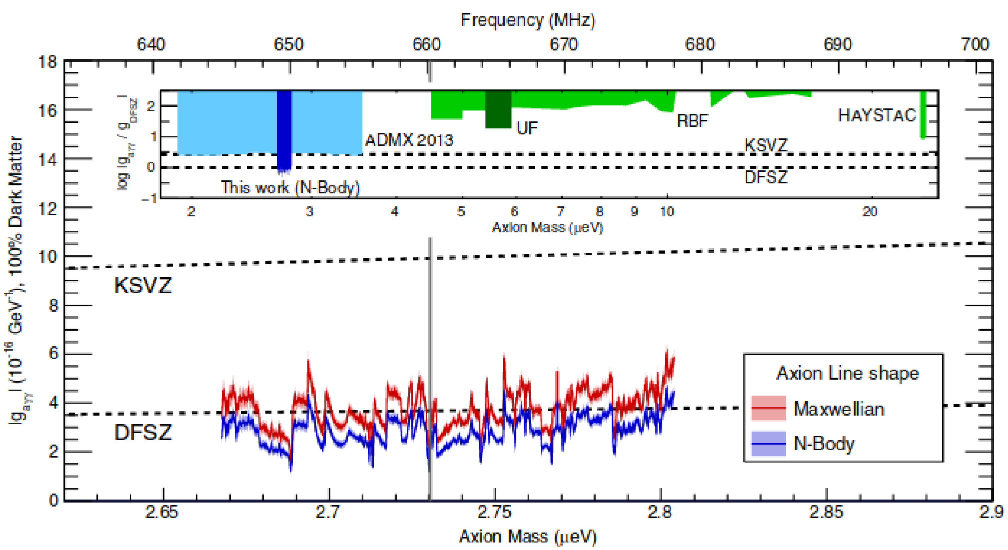
Dark matter candidates

Axions

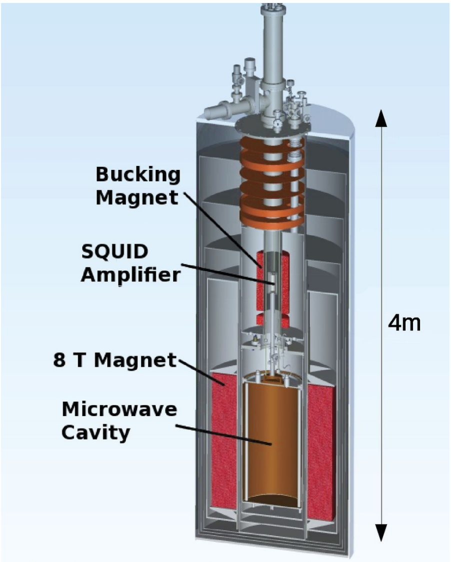
- Postulated in 1977 by the Peccei-Quinn theory as a possible solution of the Strong CP Problem ("Why do experiments show that the strong force does *not* violate CP-symmetry although it could, based on theory?"
→ fine-tuning problem)
- Very light (< 1 eV) → high number density → very weak interactions
- Bosonic
- Were never in a thermal equilibrium with baryonic matter
- *Idea for detection:* in a strong magnet field, axions should be converted to photons

axion field

$$\mathcal{L} = \left(\bar{\Theta} - \frac{\phi_A}{f_A}\right)\frac{\alpha_s}{8\pi}G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$



N. Du et al (ADMX Collaboration), Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment, 2018, Phys. Rev. Lett. 120, 151301



L. J. Rosenberg, Dark-matter QCD-axion searches, 2015, PNAS 112 (40), 12278

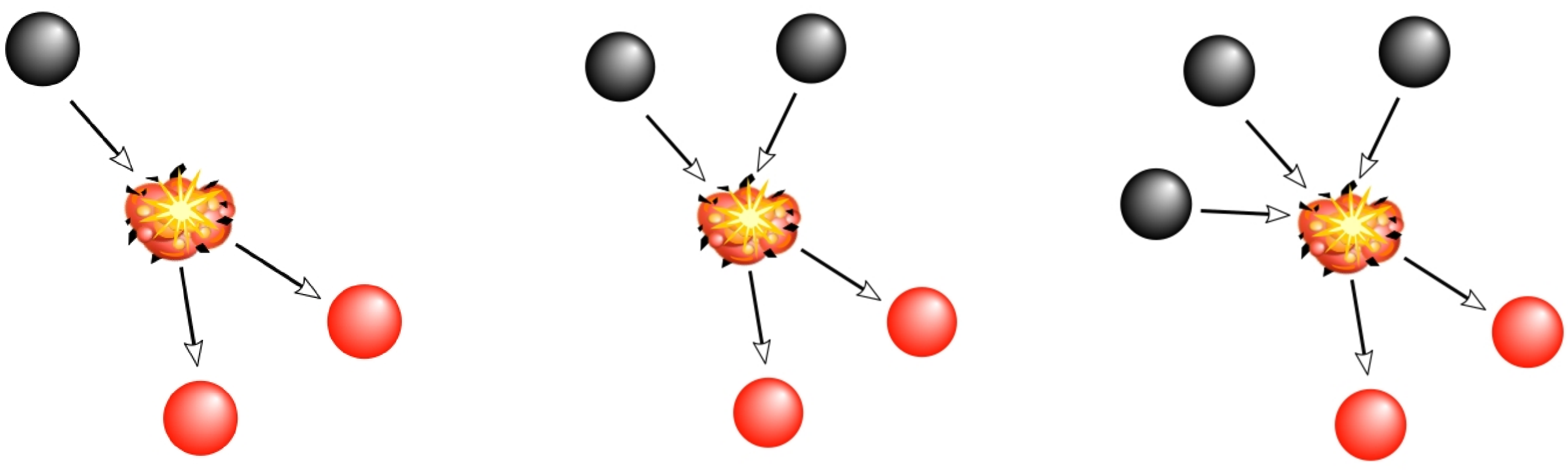
Dark matter candidates

WIMPs

- Assume DM particles were in thermal equilibrium with baryonic matter in the early Universe
- Without (number-changing) interaction processes, one has:

$$\frac{d}{dt}\left(na^3\right) = 0 \Rightarrow \frac{dn}{dt} + 3Hn = 0$$

- *But*: interactions with baryonic matter are needed in order to maintain thermal equilibrium
- **Options:**

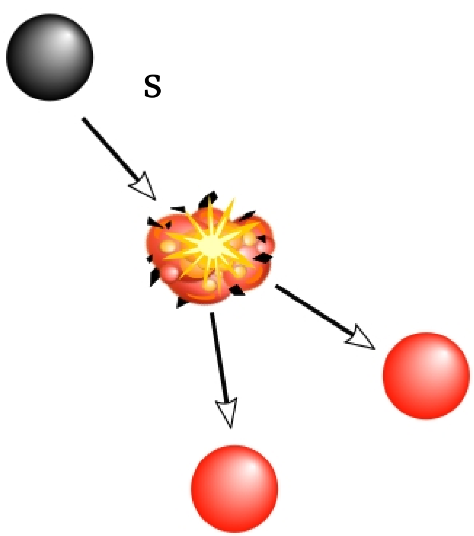


Dark matter candidates

WIMPs

- *Option 1*: decay (into one or several SM particles)
  but: DM is stable over billions of years, decay should not be dominant
- *Option 2*: pair annihilation (into one or several SM particles)
  This is somehow analogous to the annihilation of a particle with its anti-particle in the standard model
- *Option 3*: N-particle annihilation (into one or several SM particles)
- These processes scale with higher powers of the particle density and are thus expected to be less relevant than pair annihilation
  (but note that pair-annihilation might be suppressed)

1



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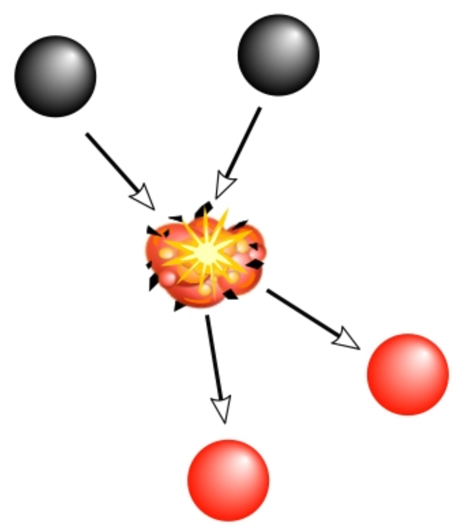

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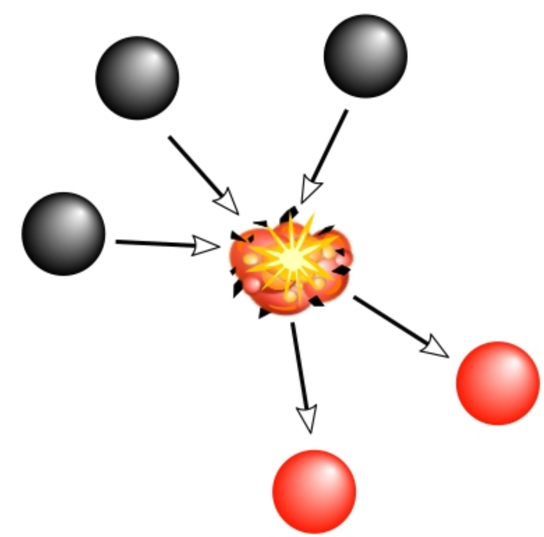


Dark matter annihilation

WIMPs

- Consider DM pair annihilation into SM particles:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - b(T)\right)$$

- Annihilation rate is $\frac{1}{2}\langle \sigma v \rangle n^2$ whereby each annihilation destroys 2 particles
- The term $b(T)$ comes from the reverse mechanism: production of DM particles from SM particles
- The interaction term on the right hand side drives the DM number density towards an equilibrium state

$$b(T) = n_{eq}(T)^2.$$

- For non-relativistic temperatures, the equilibrium state can approximately be described as Boltzmann distribution:

$$n_{\text{eq}} \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$$

whereas for relativistic temperatures:

$$n_{\text{eq}} \sim T^3$$

Dark matter annihilation

WIMPs

- Consider DM pair annihilation into SM particles:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - n_{\rm eq}^2\right)$$

- If $\langle \sigma v \rangle$ is small, the cosmic expansion dominates over the annihilation and the DM density scales as $n \sim a^{-3}$

- If $\langle \sigma v \rangle$ is large, the DM density is quickly driven towards an equilibrium state,

  $n \to n_{\rm eq}$

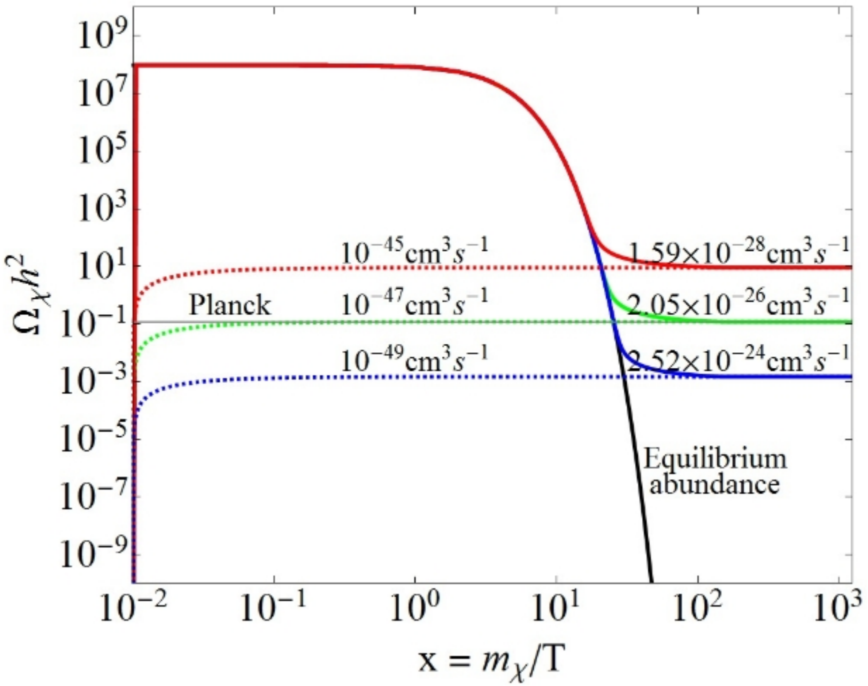
- As the expansion rate of the Universe becomes so large that the annihilations become too rare to keep the DM particles in a thermal equilibrium with baryonic matter, the WIMPs "*freeze out*".

- This happens when $n\langle \sigma v \rangle \sim H$

Dark matter annihilation

WIMPs

- Evolution of the DM density over cosmic time:



freeze-out approximately at

$$T_F \simeq m_\chi/20$$

P. S. Bhupal Dev, Anupam Mazumdar, and Saleh Qutub, Frontiers in Physics, 2014

The velocity-cross section required to explained the observed DM relic density today is in the range of 2 – 3 x 10^{-26} $cm^3\,s^{-1}$, which corresponds to the **weak scale**, where many well-motivated candidates from particle physics reside
→ “WIMP miracle”

Dark matter annihilation

WIMPs

- *But:* WIMPs have not shown up yet in detectors or LHC experiments...

49,852 views | Feb 22, 2019, 02:00am

The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group
Science
The Universe is out there, waiting for you to discover it.

- LUX and XENON experiments rule out most of the parameter space of "natural" SUSY candidates

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

Rebecca K. Leane,[1,*] Tracy R. Slatyer,[1,†] John F. Beacom,[2,3,4,‡] and Kenny C. Y. Ng[5,§]
[1]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2]*Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210, USA*
[3]*Department of Physics, Ohio State University, Columbus, OH 43210, USA*
[4]*Department of Astronomy, Ohio State University, Columbus, OH 43210, USA*
[5]*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*
(Dated: July 13, 2018)

Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates. The observed dark matter abundance can be naturally obtained by freeze-out of weak-scale dark matter annihilations in the early universe. This "thermal WIMP" scenario makes direct predictions for the total annihilation cross section that can be tested in present-day experiments. While the dark matter mass constraint can be as high as $m_\chi \gtrsim 100$ GeV for particular annihilation channels, the constraint on the *total* cross section has not been determined. We construct the first model-independent limit on the WIMP total annihilation cross section, showing that allowed combinations of the annihilation-channel branching ratios considerably weaken the sensitivity. For thermal WIMPs with *s*-wave $2 \to 2$ annihilation to visible final states, we find the dark matter mass is only known to be $m_\chi \gtrsim 20$ GeV. This is the strongest largely model-independent lower limit on the mass of thermal-relic WIMPs; together with the upper limit on the mass from the unitarity bound ($m_\chi \lesssim 100$ TeV), it defines what we call the "WIMP window". To probe the remaining mass range, we outline ways forward.

11 Jul 2018

A new era in the search for dark matter

Gianfranco Bertone[1]* & Tim M. P. Tait[1,2]*

Oct 2018

There is a growing sense of 'crisis' in the dark-matter particle community, which arises from the absence of evidence for the most popular candidates for dark-matter particles—such as weakly interacting massive particles, axions and sterile neutrinos—despite the enormous effort that has gone into searching for these particles. Here we discuss what we have learned about the nature of dark matter from past experiments and the implications for planned dark-matter searches in the next decade. We argue that diversifying the experimental effort and incorporating astronomical surveys and gravitational-wave observations is our best hope of making progress on the dark-matter problem.

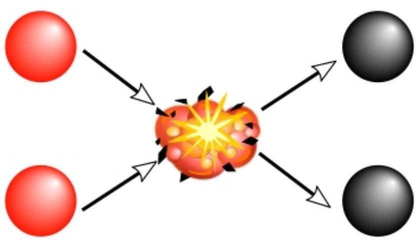
Giudice, G. F. The dawn of the post-naturalness era. Preprint at https://arxiv.org/abs/1710.07663 (2017).

"... the new guiding principle should be 'no stone left unturned'"

Dark matter annihilation

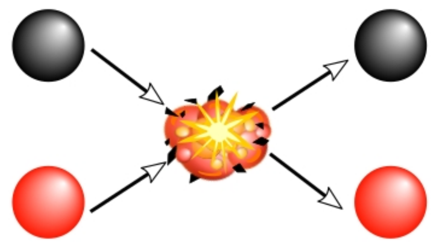
WIMPs

Collider production:



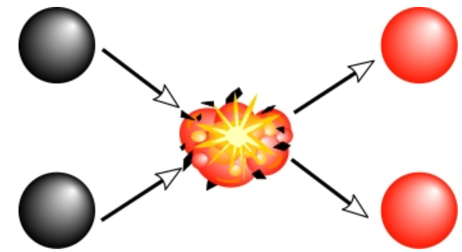
e.g. LHC
→ DM detectable as missing energy

Direct detection:

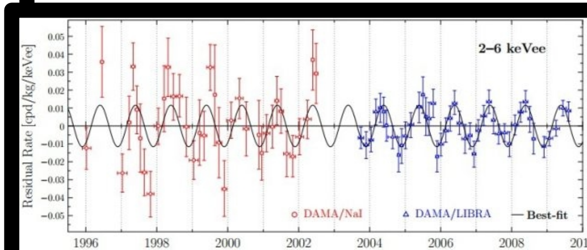


e.g. LUX, ZEPLIN, EDELWEISS, DAMA, ...

Indirect detection:



e.g. AMS-02, HAWC, Chandra, HESS, Fermi, IceCube, ...



- **Model-*dependent***:
  - collider production
  - direct detection experiments require a DM – SM interaction cross-section
  - DM – DM annihilation to specific SM particles

→ only specific interactions can be probed

- **Model-*independent***:
  - total DM – DM annihilation rate

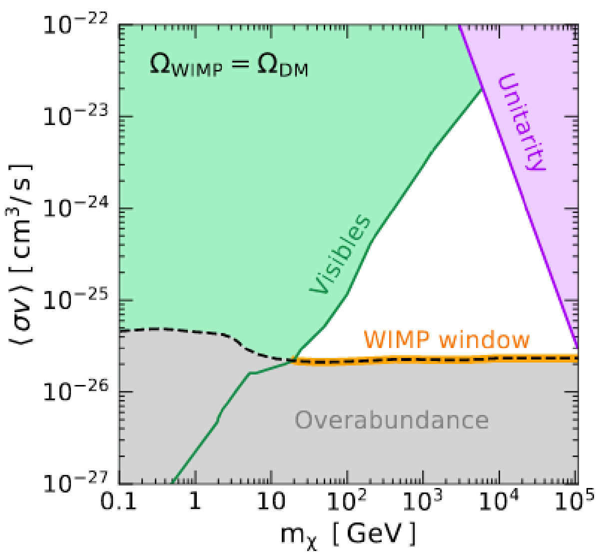
Dark matter annihilation

WIMPs

Constraints from indirect detection:

- *For* $m_\chi \sim 10$ GeV: strongest constraints come from CMB (sensitive to total ionising energy)
  - Early-time constraint, independent of current DM annihilation rate
  - Robust estimates due to the precision measurements from *Planck*
- *For* $m_\chi > 10$ GeV: tightest constraints come from gamma-ray data from *Fermi* and cosmic ray observations from *AMS-02*
- *For* $m_\chi < 100$ keV: WIMPs no longer behave as CDM
- *For* $m_\chi < 10$ MeV: WIMPs are ruled out by BBN (independent of s-wave or p-wave annihilation)

WIMP window for s-wave 2→2 annihilation assuming 100% WIMP DM (May 2018)



R. K. Leane, T. R. Slatyer, J. F. Beacom, K. C. Y. Ng, GeV-scale thermal WIMPs: Not even slightly ruled out, 2018, Phys. Rev. D 98, 23016

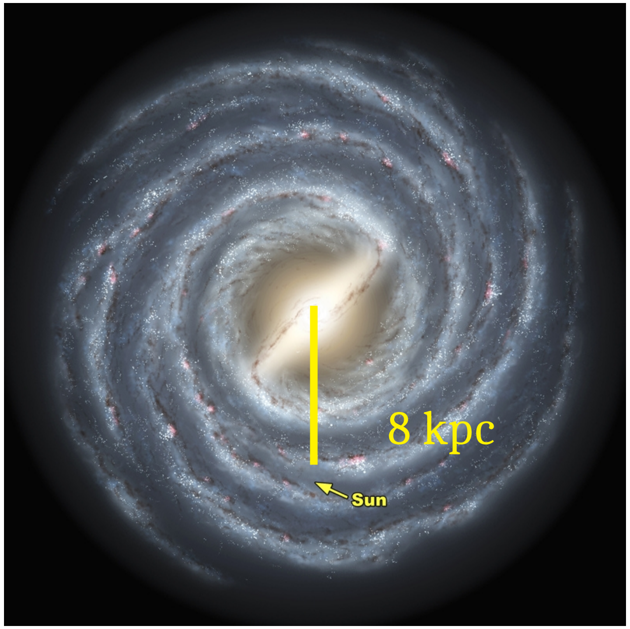
- Strongest constraint on general 2 → 2 s-wave annihilation to visible states is $\mathbf{m_\chi > 20}$ **GeV**
- Upper limit: unitarity bound $m_\chi < 100$ TeV.
- Constraints for 2 → 3 annihilation, annihilation to dark products, or assuming late-time suppression of $\langle \sigma v \rangle$ are much weaker

Dark matter annihilation

In addition to constraints from *non-detection* of DM annihilation, can we say something about *positive* detection results that possibly come from DM annihilation?

Galactic centre excess (GCE)

- High DM density in the Galactic centre implies high DM annihilation rates (scales with DM density squared!)
  → good place to look for DM annihilation signals
- *Caveat:* Galactic centre is crowded with astrophysical sources and there are many sources between the Galactic centre and the earth



Dark matter annihilation

In addition to constraints from *non-detection* of DM annihilation, can we say something about *positive* detection results that possibly come from DM annihilation?

Galactic centre excess (GCE)

- Excess of O(a few GeV) gamma-rays from within a ~1.5 kpc region around the Galactic Centre in *Fermi* data
- **Explanation I**: population of faint unresolved millisecond pulsars
- **Explanation II**: signal from DM annihilation
- Hundreds of papers published on GCE

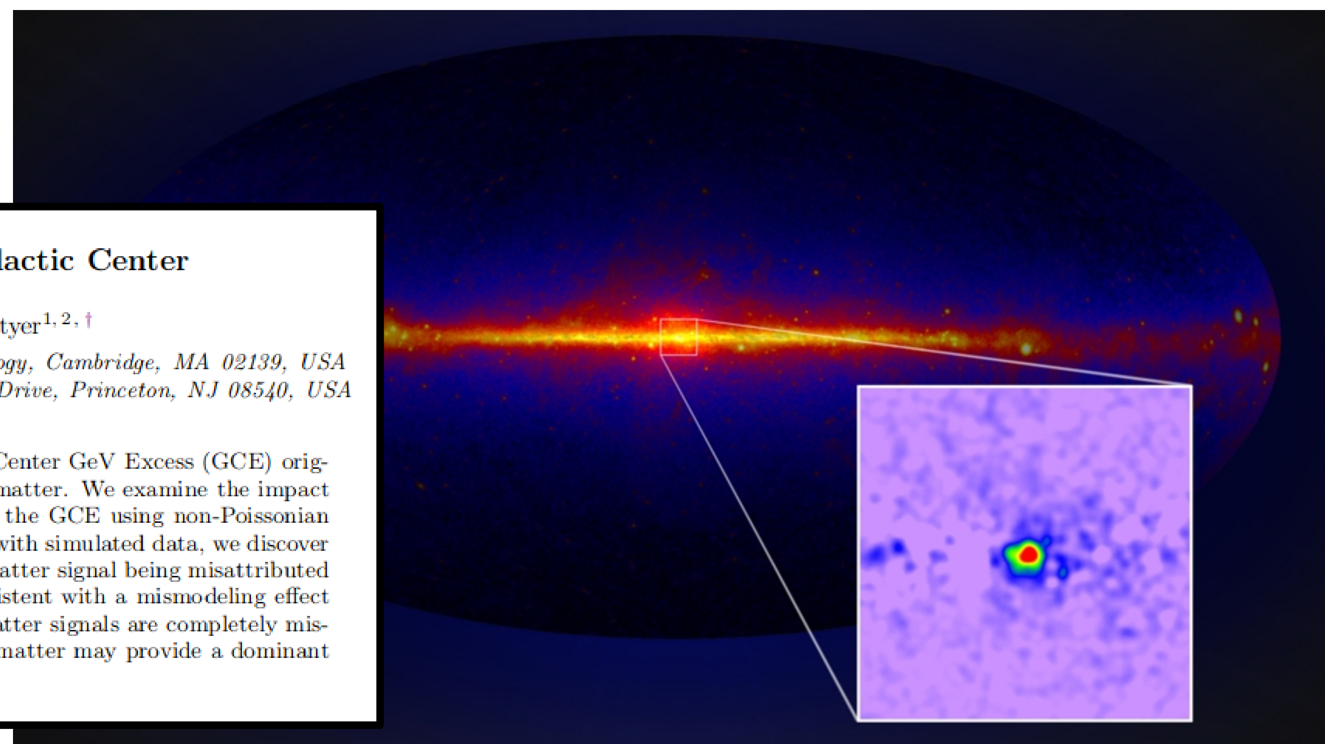
- Recently (April 2019):

Dark Matter Strikes Back at the Galactic Center

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*
(Dated: April 19, 2019)

Statistical evidence has previously suggested that the Galactic Center GeV Excess (GCE) originates largely from point sources, and not from annihilating dark matter. We examine the impact of unmodeled source populations on identifying the true origin of the GCE using non-Poissonian template fitting (NPTF) methods. In a proof-of-principle example with simulated data, we discover that unmodeled sources in the *Fermi* Bubbles can lead to a dark matter signal being misattributed to point sources by the NPTF. We discover striking behavior consistent with a mismodeling effect in the real *Fermi* data, finding that large artificial injected dark matter signals are completely misattributed to point sources. Consequently, we conclude that dark matter may provide a dominant contribution to the GCE after all.



Dark matter annihilation

In addition to constraints from *non-detection* of DM annihilation, can we say something about *positive* detection results that possibly come from DM annihilation?

Excess in cosmic ray p^- spectrum:

- ~10–20 GeV excess of cosmic ray antiprotons in *AMS-02* data (*AMS-02* is an antimatter detector mounted on the ISS)
- Would be consistent with a DM particle of mass m_χ ~ 64 – 88 GeV with a cross-section of ~(0.8 – 5.2) x 10^{-26} cm^3 s^{-1}, annihilating to bottom + antibottom quark

A Robust Excess in the Cosmic-Ray Antiproton Spectrum: Implications for Annihilating Dark Matter

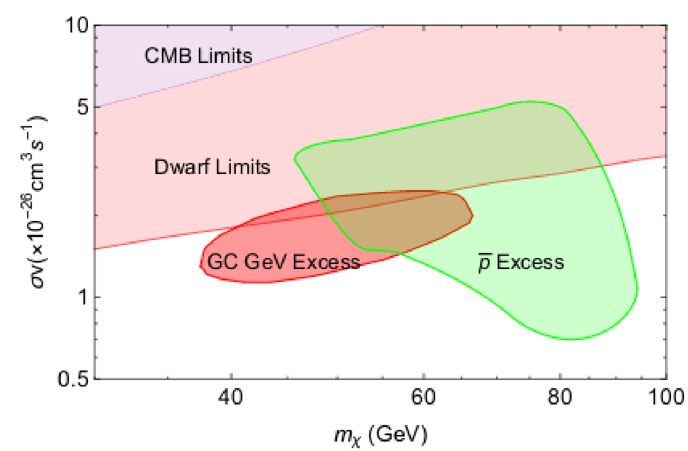
Mar 2019

Ilias Cholis,[1,*] Tim Linden,[2,†] and Dan Hooper[3,4,‡]

[1]Department of Physics, Oakland University, Rochester, Michigan, 48309, USA
[2]Center for Cosmology and AstroParticle Physics (CCAPP) and Department of Physics, The Ohio State University Columbus, Ohio, 43210 USA
[3]Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, Illinois, 60510, USA
[4]University of Chicago, Department of Astronomy and Astrophysics, Chicago, Illinois, 60637, USA

(Dated: March 7, 2019)

An excess of ~10-20 GeV cosmic-ray antiprotons has been identified in the spectrum reported by the *AMS-02* Collaboration. The systematic uncertainties associated with this signal, however, have made it difficult to interpret these results. In this paper, we revisit the uncertainties associated with the time, charge and energy-dependent effects of solar modulation, the antiproton production cross section, and interstellar cosmic-ray propagation. After accounting for these uncertainties, we confirm the presence of a 4.7σ antiproton excess, consistent with that arising from a $m_\chi \approx 64-88$ GeV dark matter particle annihilating to $b\bar{b}$ with a cross section of $\sigma v \simeq (0.8-5.2)\times 10^{-26}$ cm^3/s. If we allow for the stochastic acceleration of secondary antiprotons in supernova remnants, the data continues to favor a similar range of dark matter models ($m_\chi \approx 46-94$ GeV, $\sigma v \approx (0.7-3.8)\times 10^{-26}$ cm^3/s) with a significance of 3.3σ. The same range of dark matter models that are favored to explain the antiproton excess can also accommodate the excess of GeV-scale gamma rays observed from the Galactic Center.



Scrutinizing the evidence for dark matter in cosmic-ray antiprotons

Mar 2019

Alessandro Cuoco,[1,2,*] Jan Heisig,[3,†] Lukas Klamt,[2,‡] Michael Korsmeier,[2,4,5,§] and Michael Krämer[2,¶]

[1]Université Grenoble Alpes, USMB, CNRS, LAPTh, F-74940 Annecy, France
[2]Institute for Theoretical Particle Physics and Cosmology, RWTH Aachen University, Sommerfeldstr. 16, 52056 Aachen, Germany
[3]Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium
[4]Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy
[5]Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

DM annihilation in N-body simulations

Why investigate DM annihilation feedback (DMAF) in numerical simulations?

- Imprint of DMAF on large-scale structure can be analysed (e.g. delayed formation of galaxies due to heating from high-energy particles produced by DMAF)

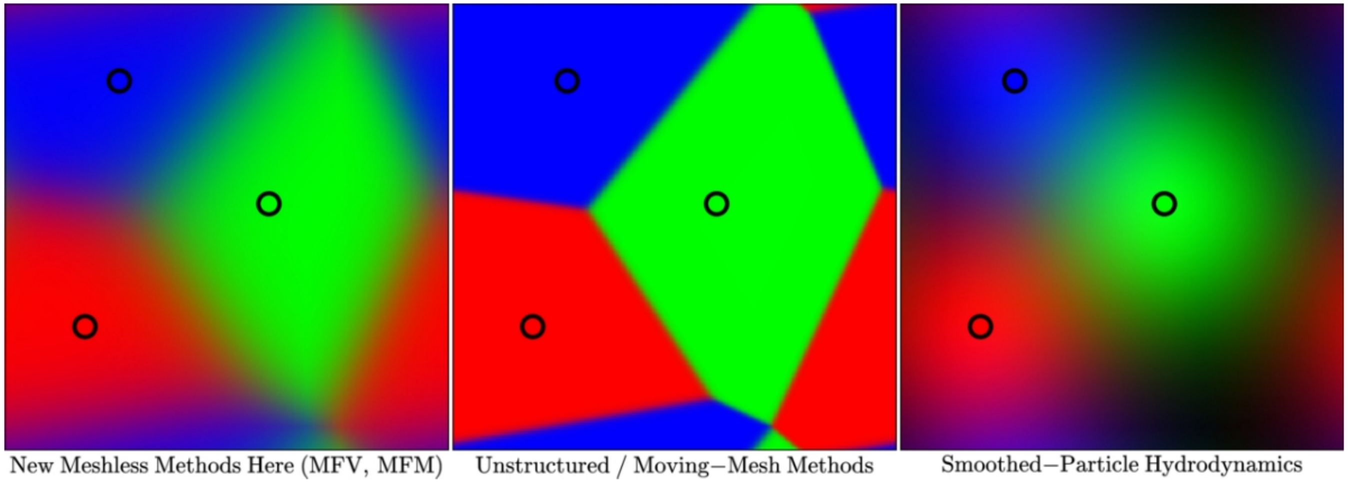
- Impact of DMAF on individual haloes and galaxies can be probed

- Numerical simulations are an excellent tool for distinguishing astrophysical sources from DMAF

DM annihilation in N-body simulations

Implementation of DMAF into a cosmological simulation code:

- We use GIZMO (offspring of the Gadget series of simulation codes (*Springel et al. 2001*), *Hopkins 2015*)
- In addition to "traditional" SPH:
  modern meshless methods that combine the advantages of AMR codes and SPH code:
  Meshless Finite Volume Method and Meshless Finite Mass Method
- Many modules for baryonic physics such as cooling, star formation, supernovae, magnetic fields, turbulence, sub-grid feedback models, supermassive black holes, ...
- Highly parallelisable
- Code is public



P. Hopkins, A new class of accurate, mesh-free hydrodynamic simulation methods, 2015, MNRAS 450, 53

DM annihilation in N-body simulations

Implementation of DMAF into a cosmological simulation code:

- Recall that DM annihilates as

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle n_\chi^2$$

(omitting the converse reaction after freeze-out which occurs fractions of a second after BB)

- In a co-moving volume containing DM of mass M_χ, this leads to a total mass loss of

$$\frac{dM_\chi}{dt} = -\frac{\langle\sigma v\rangle}{m_\chi}\rho_\chi M_\chi$$

- Consequently, the power from DMAF deposited into the gas is given by

$$\frac{dE}{dt} = Bf\frac{\langle\sigma v\rangle}{m_\chi}\rho_\chi M_\chi c^2$$

B: boost factor, accounts for unresolved DM clumps, can be as high as ~10 for large haloes
f: absorption fraction of the gas, highly dependent on annihilation products, ~ 0.01 – 1

DM annihilation in N-body simulations

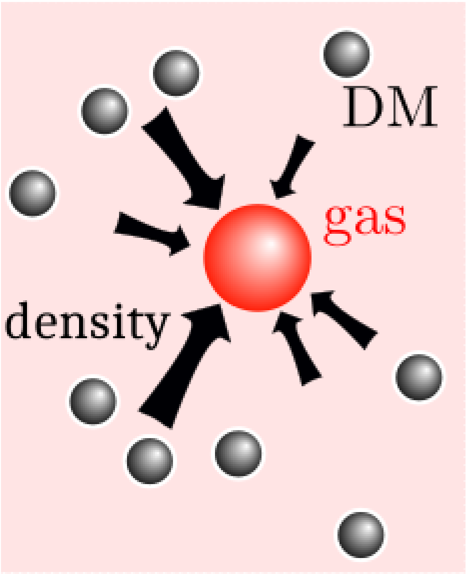
Implementation of DMAF into a cosmological simulation code:

Generated power from DMAF:

$$\frac{dE}{dt} = Bf\frac{\langle\sigma v\rangle}{m_\chi}\rho_\chi M_\chi c^2,$$

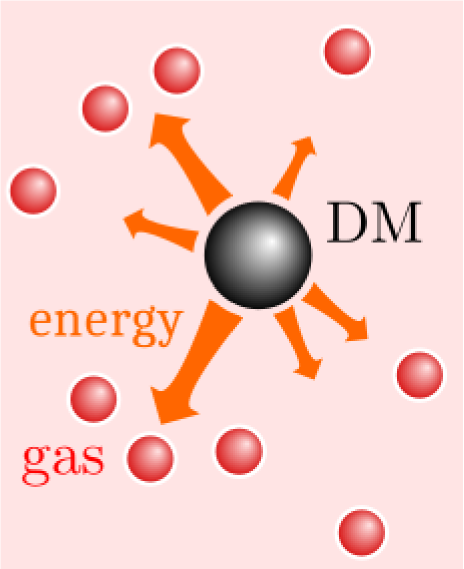
We implemented two methods:

Receiver-based:



- Each **gas** N-body particle evaluates the local DM density and calculates the resulting DMAF power
- Assumes a well-defined DM density field of which DM N-body particles are tracers

Donor-based:



- Each **DM** N-body particle evaluates the local DM density and calculates the resulting DMAF power
- The generated energy is distributed to the surrounding gas particles

- For both methods, the DMAF energy is calculated and deposited self-consistently from the DM distribution evolving in the simulation, without the need for analytic halo models.

DM annihilation in N-body simulations

Implementation of DMAF into a cosmological simulation code:

Generated power from DMAF:

$$\frac{dE}{dt} = B f \frac{\langle \sigma v \rangle}{m_\chi} \rho_\chi M_\chi c^2,$$

We implemented two methods:

	Receiver-based	Donor-based
Evaluation of DMAF	At receiving gas particles	At annihilating DM particles
Injected power (assuming B = f = 1)	$\frac{1}{M_j}\frac{dE_{j\leftarrow\chi}}{dt} = \frac{\langle \sigma v \rangle}{m_\chi}\frac{\rho_{\chi,j}^2}{\rho_{g,j}}c^2$	$\frac{dE_{i\to j}}{dt} = \frac{\langle \sigma v \rangle}{m_\chi}\rho_{\chi,i} M_i c^2 \frac{w_j}{\sum_{k\in\mathcal{N}_{\mathrm{gas}}(i)} w_k}$
Locality of energy injection	Local injection inherently built in	Injection flexible, dependent on weights w_k
DMAF power generation coupled to DM mass loss	No	Yes

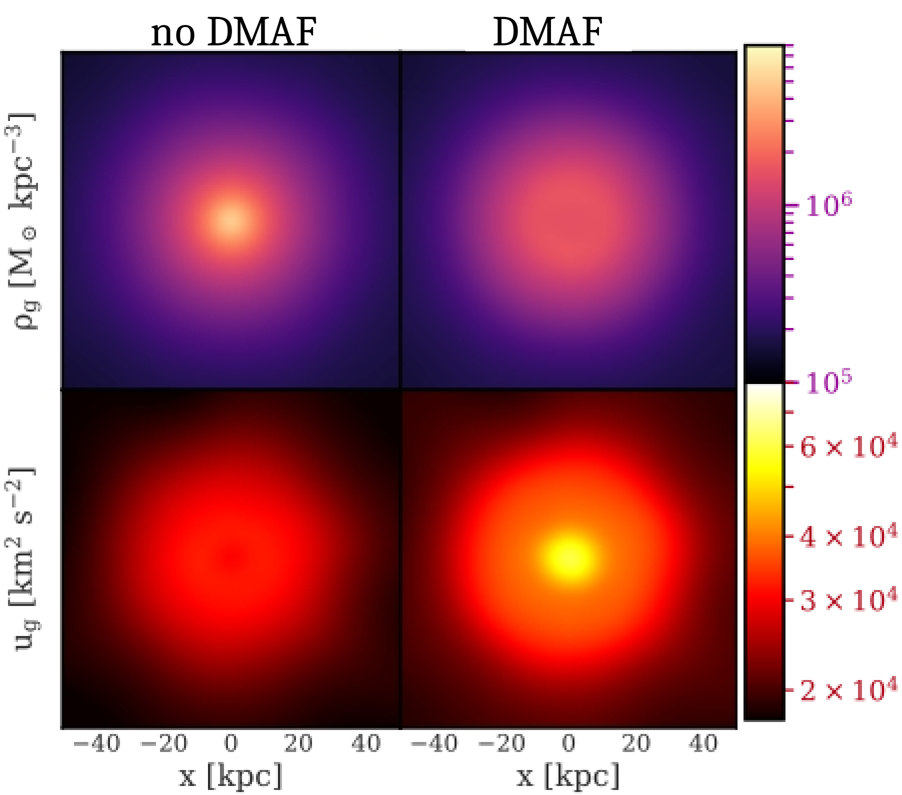
- The results of the two methods differ for very steep DM density gradients
- For realistic situations (individual halo, cosmological simulation) the two methods give similar results (if the weights w_k in the donor-based method model local deposition)

Results

Individual halo (MW-sized, NFW profile):

- Very light DM particle of mass m_χ = 100 keV, thermal relic-cross section
- Assuming absorption fraction 1, no boost factor

After ~100 Myr:

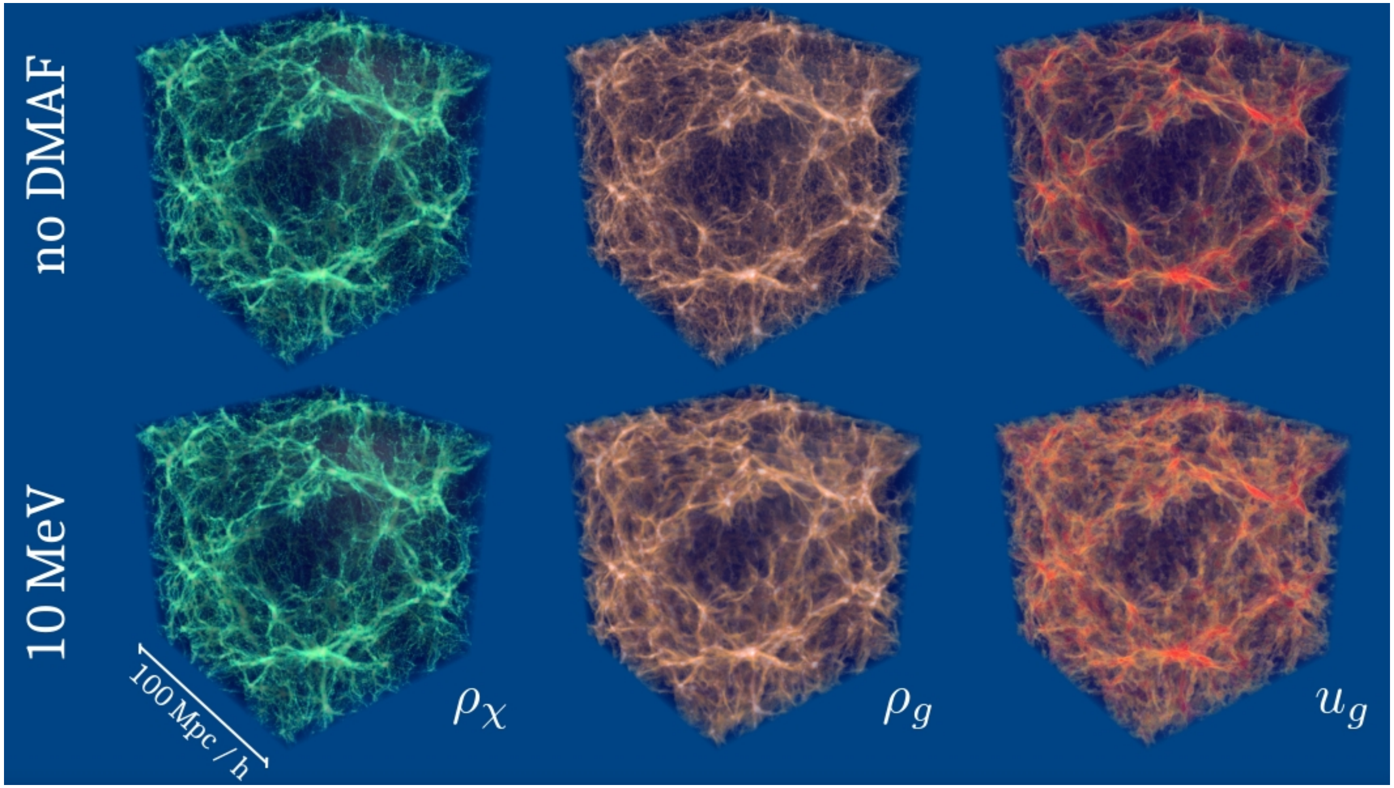


- DMAF leads to a temperature increase in a central region of the halo
- Hot gas has left the halo centre → gas density is depleted by an order of magnitude
- Cuspy gas density profile has been flattened due to DMAF
- Central DM density is also reduced, although not as drastically as for the gas
- *possibly:* DMAF alleviates small-scale tensions between ΛCDM and observations (cusp-core problem, missing satellite problem…) ?

Results

Cosmological simulation:

z = 0:



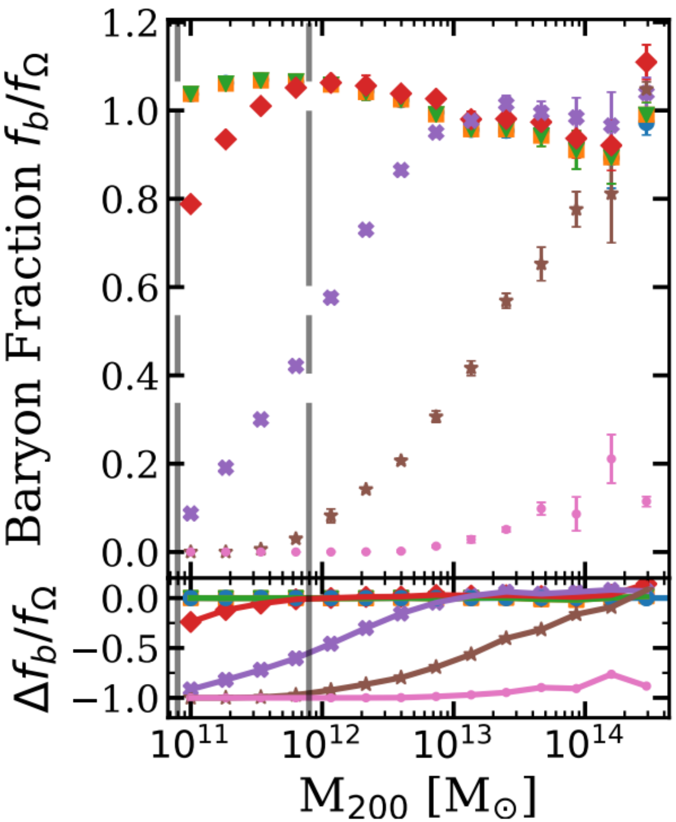
- DMAF washes out the cosmic web substructure of the gas
- DMAF heats up sheets and filaments
- DM density is not significantly affected by DMAF on a large scale

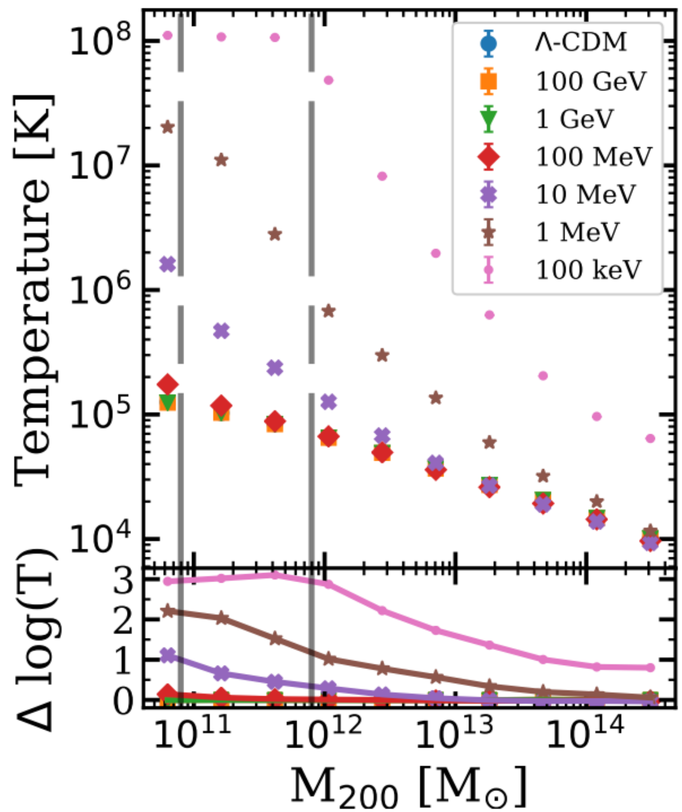
Movie

Results

Cosmological simulation:

Halo properties:





- DMAF heats up the haloes
- Heating is strongest in small haloes
- While the mass fraction of baryons is approximately Ω_b / Ω_m without DMAF, small haloes are left completely without gas for high annihilation rates

Conclusions and future work

- Cosmological simulations can reveal the impact of DMAF on individual haloes and on the formation of structure
- The main effect of DMAF is to heat up gas and drive it out of their host haloes, thus reducing the halo masses and leading to delayed galaxy formation
- Dwarf galaxies are particularly sensitive to DMAF and are an ideal test ground for probing DM models

- We will investigate the interplay between DMAF and baryonic cooling physics (bremsstrahlung, inverse Compton scattering, ...)
- We will consider generalisations such as velocity-dependent annihilation cross sections (p-wave annihilation), Sommerfeld enhancement, ...

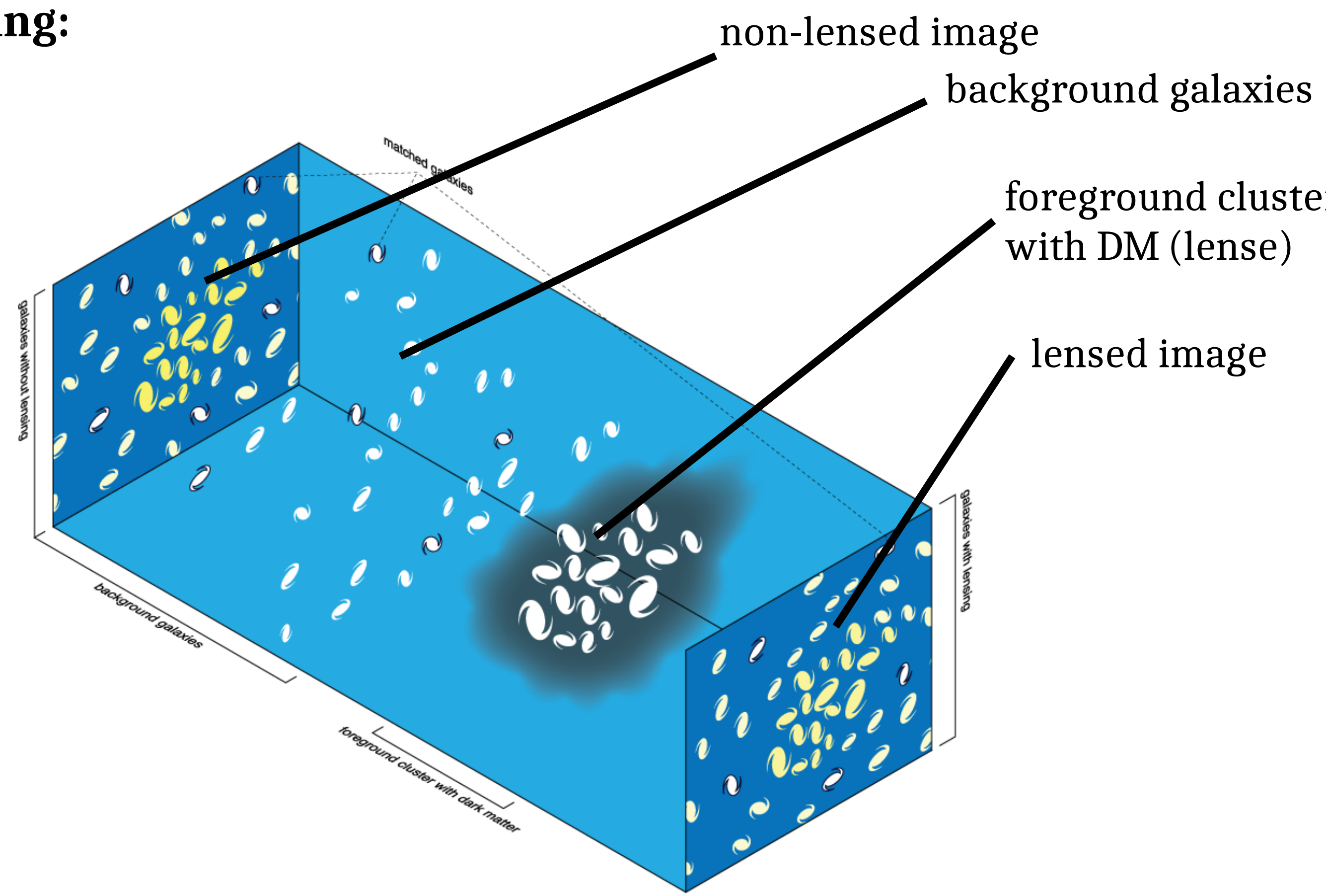
- More information can be found here:
  - *N. Iwanus, P. J. Elahi, G. F. Lewis, 2017, MNRAS 472, 1214*
  - *N. Iwanus, P. J. Elahi,* ***F. L.****, G. F. Lewis, 2019, MNRAS 485, 1420*
  - ***F. L.****, N. Iwanus, P. J. Elahi, G. F. Lewis, 2019, MNRAS 489, 4217*

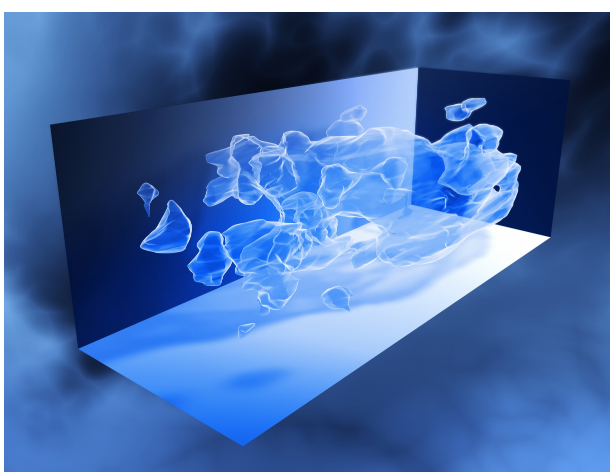
Dark matter

Why is a species needed that only interacts via gravity and possibly via the weak force?

Weak gravitational lensing:

- From distorted geometry, mass of the foreground cluster can be obtained
- Mass-to-light ratio from lensing is in good agreement with dynamic DM measurements in clusters





DM map from Hubble Space Telescope using weak gravitational lensing

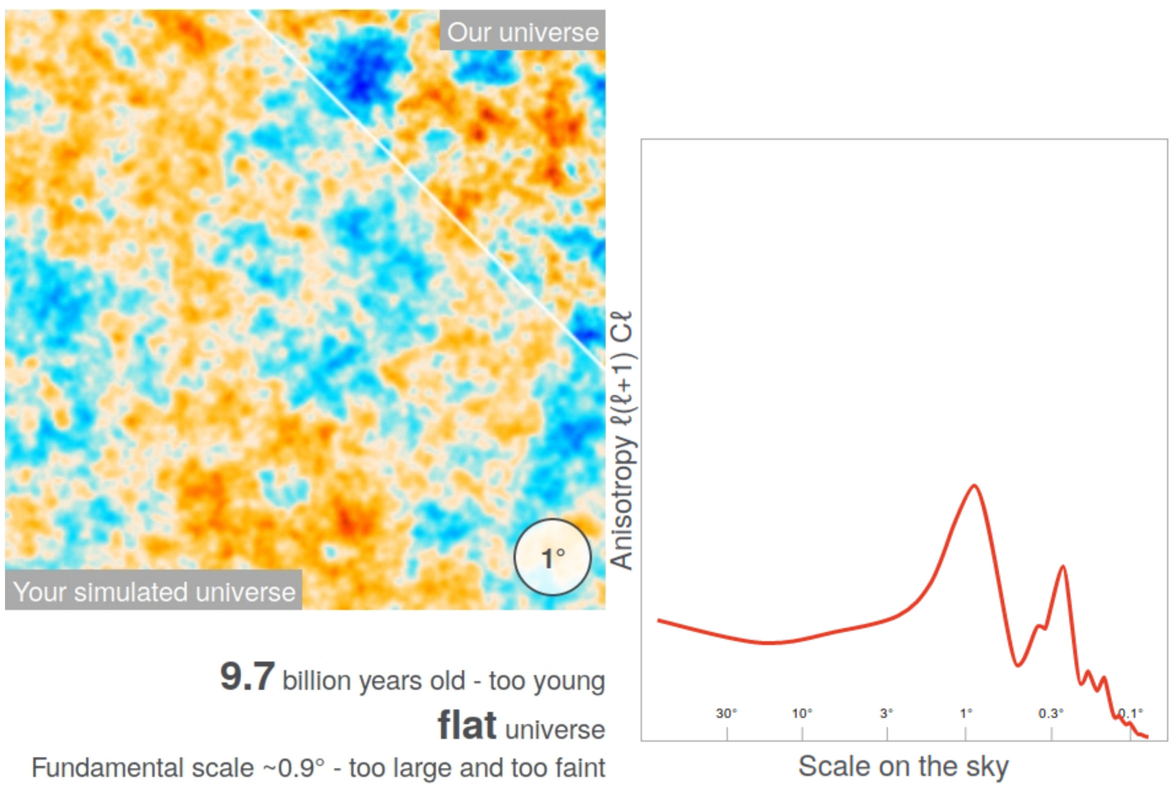
By NASA/ESA/Richard Massey (California Institute of Technology) - http://spacetelescope.org/images/heic0701b/Isosuface

Dark matter

Why is a species needed that only interacts via gravity (and possibly via the weak force)?

CMB:

Flat, matter-dominated universe
with $\Omega_b = 0.05$, $\Omega_m = 1$, and $\Omega_\Lambda = 0$:



https://chrisnorth.github.io/planckapps/Simulator/

Dark matter annihilation

WIMPs

- Consider DM pair annihilation into SM particles:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - b(T) \right)$$

- Annihilation numbers at freeze out compared to present day:
  - at freeze out: by definition, an $O(1)$ fraction of DM particles annihilates
  - present day:
    - for mean cosmic density: ~ one in 10^{15} particles annihilates
    - in bound structures: ~ one in 10^{10} particles annihilates

Dark matter annihilation

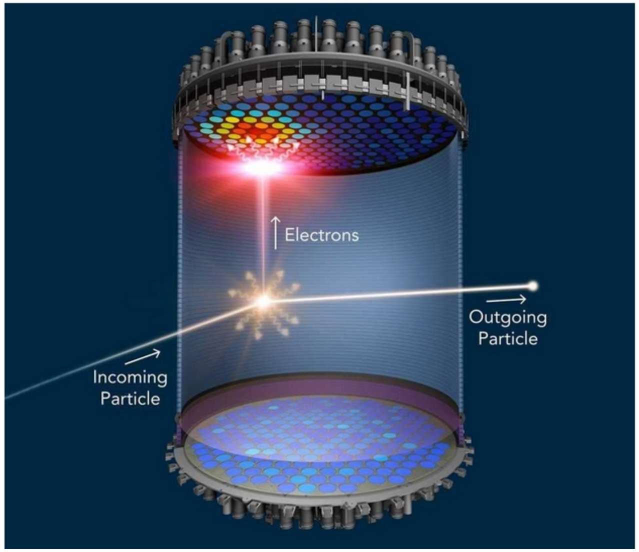
WIMPs
Planned detectors in the near future:

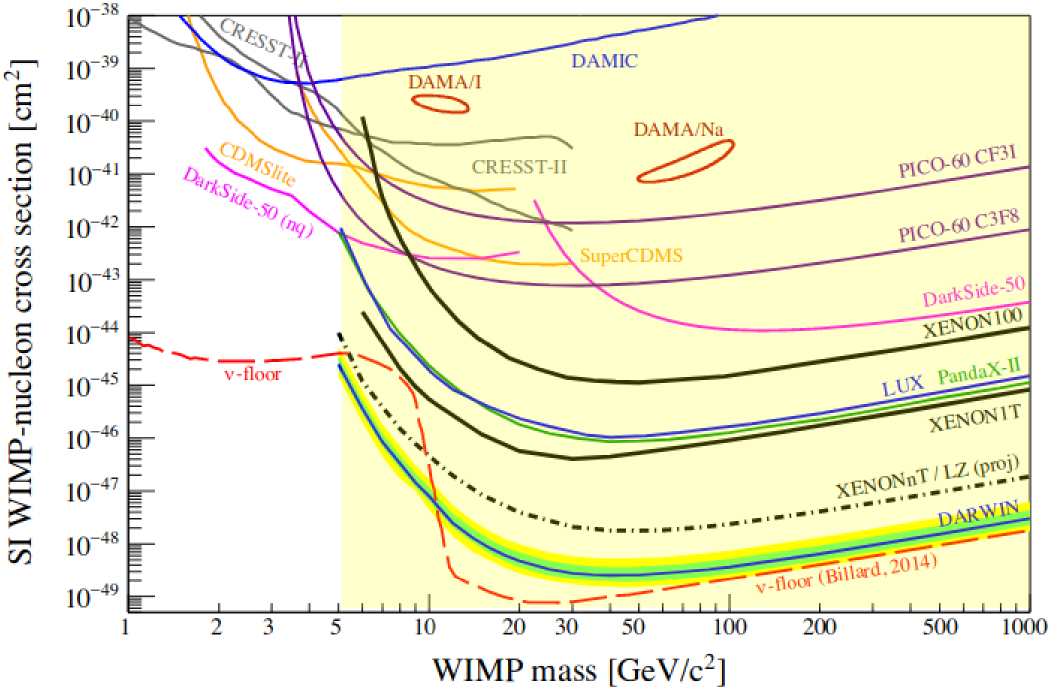
- *LUX-Zeplin experiment in South Dakota*
  - Installation is expected to be completed this year
  - Data collection will start in 2020 and will run for 3 years

- *DARWIN experiment*
  - Liquid xenon detector
  - also sensitive for axions and neutrinos

“The DARWIN observatory is the ultimate WIMP detector.
It will uncover any trace of medium to heavy mass WIMPs above the neutrino floor.”

https://indico.cern.ch/event/699961/contributions/3043321/attachments/1692547/2723495/2018_07_DARWIN_IDM.pdf





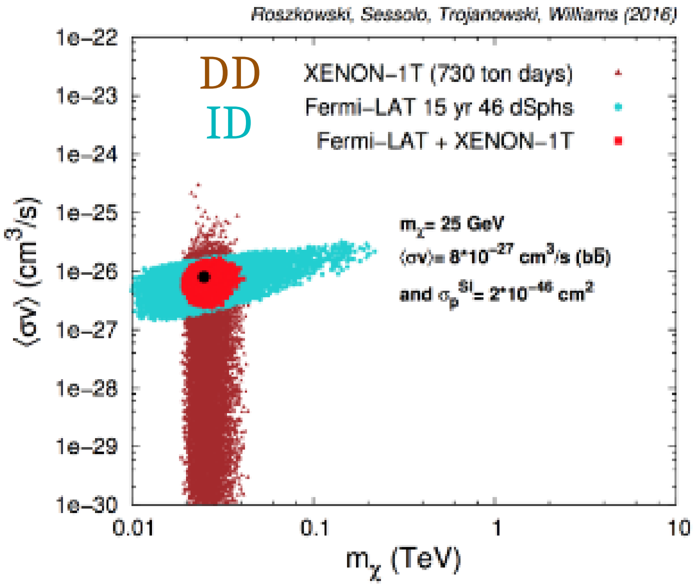
Dark matter annihilation

WIMPs

How can direct detection and indirect detection measurements be combined?

- **Direct detection**:
  - Recoil rate: $$\frac{dR}{dE_r}(E_r) = \left(\frac{\sigma_0}{2\mu^2\, m_\chi}\right) \times F^2(E_r) \times \left(\rho_\chi \int_{v \geq v_{\min}}^{v \leq v_{\rm esc}} d^3v\, \frac{f(\mathbf{v},t)}{v}\right)$$
  - For DM masses > 100 GeV: recoil rate is degenerate w.r.t. σ^0/m_χ
  - not sensitive to $\langle \sigma v \rangle$

- *But*: the DM particle mass can be reconstructed using direct detection
  → combined analysis using direct & indirect detection gives improved estimate for $\langle \sigma v \rangle$



L. Roszkowski, E. M. Sessolo, S. Trojanowski, and A. J. Williams,Reconstructing WIMPproperties through an interplay of signal measurements in direct detection, Fermi-LAT, and CTA searches for dark matter, 2016, JCAP 1608

Dark matter annihilation

WIMPs

Constraints from Planck:

Planck Collaboration: Cosmological parameters

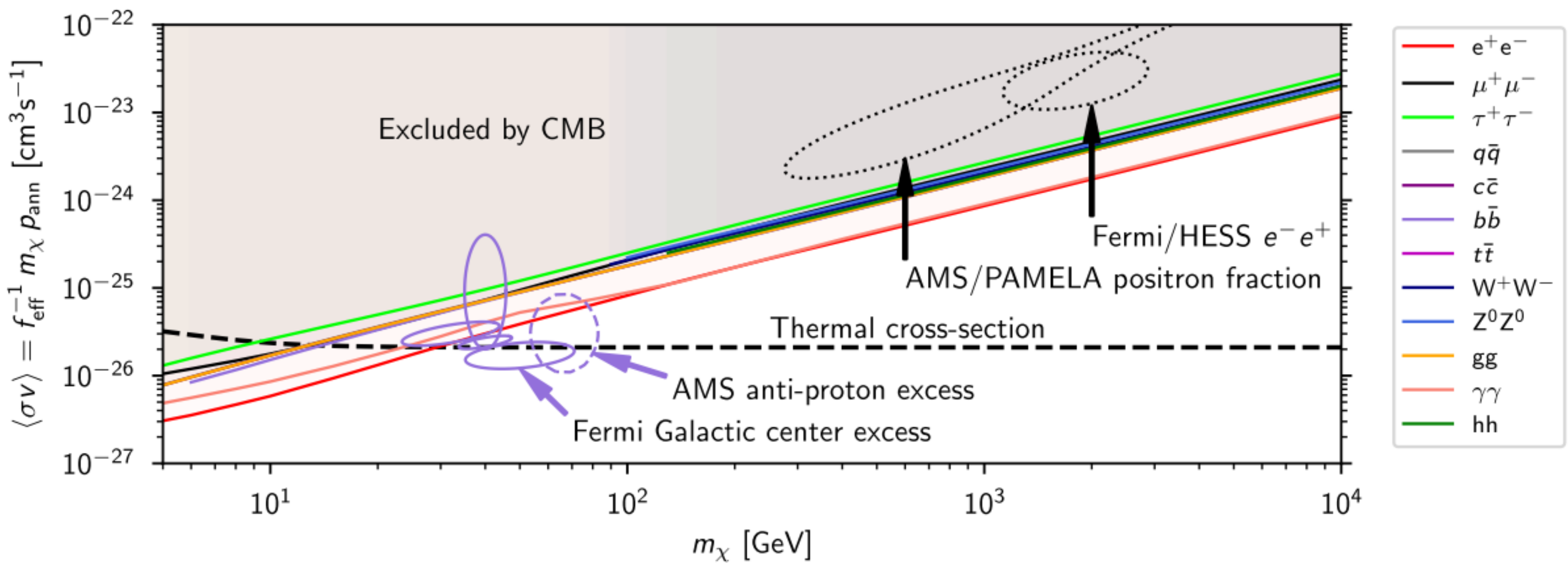


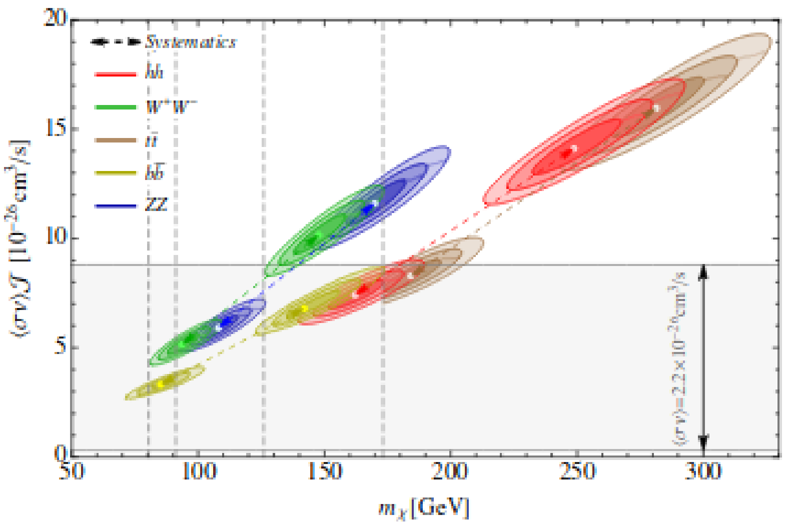
Fig. 46. *Planck* 2018 constraints on DM mass and annihilation cross-section. Solid straight lines show joint CMB constraints on several annihilation channels (plotted using different colours), based on $p_{\rm ann} < 3.2 \times 10^{-28}\,\mathrm{cm^3\,s^{-1}\,GeV^{-1}}$. We also show the $2\,\sigma$ preferred region suggested by the AMS proton excess (dashed ellipse) and the *Fermi* Galactic centre excess according to four possible models with references given in the text (solid ellipses), all of them computed under the assumption of annihilation into $b\bar{b}$ (for other channels the ellipses would move almost tangentially to the CMB bounds). We additionally show the $2\,\sigma$ preferred region suggested by the AMS/PAMELA positron fraction and *Fermi*/H.E.S.S. electron and positron fluxes for the leptophilic $\mu^+\mu^-$ channel (dotted contours). Assuming a standard WIMP-decoupling scenario, the correct value of the relic DM abundance is obtained for a "thermal cross-section" given as a function of the mass by the black dashed line.

Dark matter annihilation

In addition to constraints from *non-detection* of DM annihilation, can we say something about *positive* detection results that possibly come from DM annihilation?

Galactic centre excess (GCE)

Possible annihilation channels:



P. Agrawal, B. Batell, P. J. Fox, and R. Harnik,WIMPs at the Galactic Center, 2015, JCAP1505, 011

Dark matter annihilation

In addition to constraints from *non-detection* of DM annihilation, can we say something about *positive* detection results that possibly come from DM annihilation?

More possible DM annihilation signals:

- 3.5 keV in *XMM-Newton* observations of galaxy clusters, discovered in 2014
  (possible decaying sterile neutrino or signal from axion-like candidate)
- Excess in cosmic ray positrons (measured by *PAMELA* and subsequently confirmed by *AMS-02* and *Fermi*)
  if caused by DMAF: heavy particle *O*(few hundred GeV), annihilation cross-section well above thermic relic value
  But: candidate in conflict with indirect detection limits
- *Fermi/HESS* electron- positron flux, excluded by CMB

Dark matter annihilation

In addition to constraints from *non-detection* of DM annihilation, can we say something about *positive* detection results that possibly come from DM annihilation?

WIMP constraints from BBN:

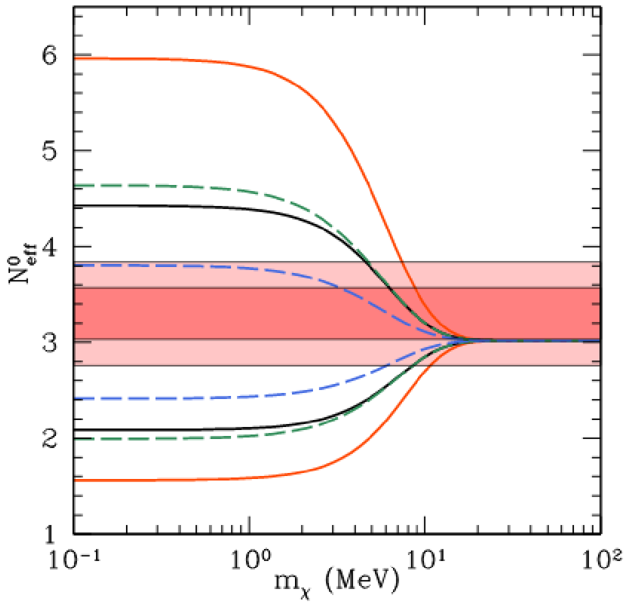


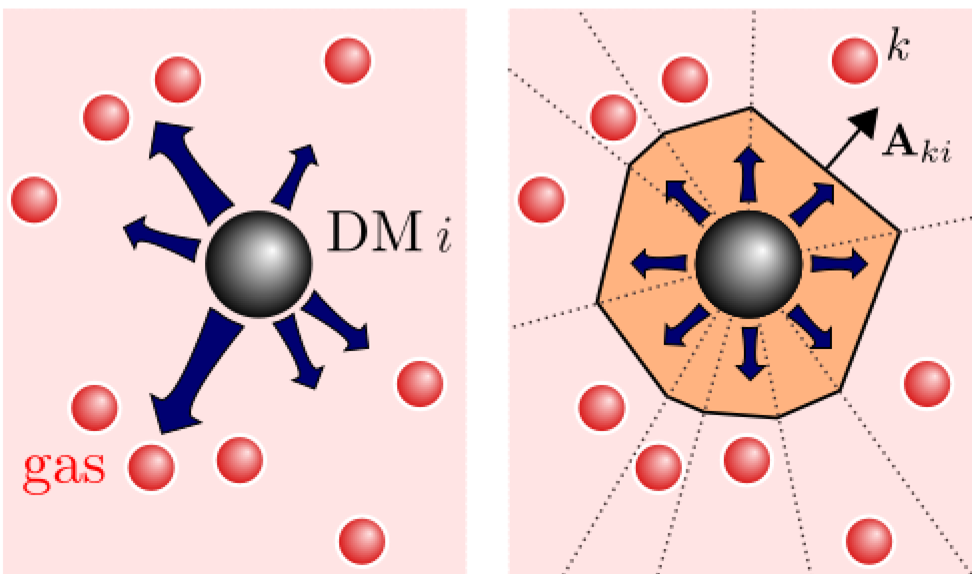
FIG. 1. (Color online) N^0_{eff}, the value of N_{eff} for $\Delta N_\nu = 0$, as a function of the WIMP mass for WIMPs that annihilate to $e^\pm$ pairs and photons (lower set of curves) and those that annihilate to the SM neutrinos (upper set of curves). For the top set of curves (neutrino coupled), from top to bottom, the solid (red) curve is for a Dirac WIMP, the dashed (green) curve is for a complex scalar, the solid (black) curve is for a Majorana WIMP, and the dashed (blue) curve is for a real scalar. The order of the curves is reversed for the lower set (EM coupled). The horizontal (red/pink) bands are the Planck CMB 68.3% and 95.5% ranges for N_{eff}.

Nollett, K. M., & Steigman, G. (2015). BBN and the CMB constrain neutrino coupled light WIMPs. Physical Review D, 91(8), 083505.

DM annihilation in N-body simulations

Implementation of DMAF into a cosmological simulation code:

Choice of weights for the donor-based method:



a) b)

- For case a), the direction of energy injection depends on the local distribution of the gas and is biased towards high gas density regions
- For case b), the weights are given by the solid angle subtended by each gas particle as seen from the injecting DM particle
- This leads to an (almost) isotropic energy injection, independent of the gas distribution

a) mass weighted injection:

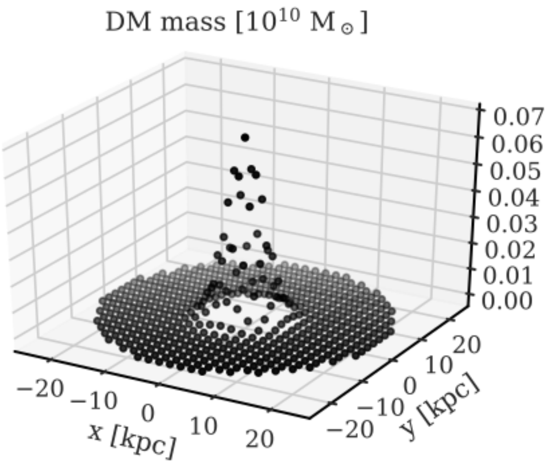
$$w_k = M_k W(r_{ki}, h_i),$$

b) solid angle weighted injection:

$$w_k = \frac{1}{2}\left(1 - \left(1 + (\mathbf{A}_{ki} \cdot \hat{\mathbf{r}}_{ki}) / \left(\pi \, |\mathbf{r}_{ki}|^2\right)\right)^{-1/2}\right).$$

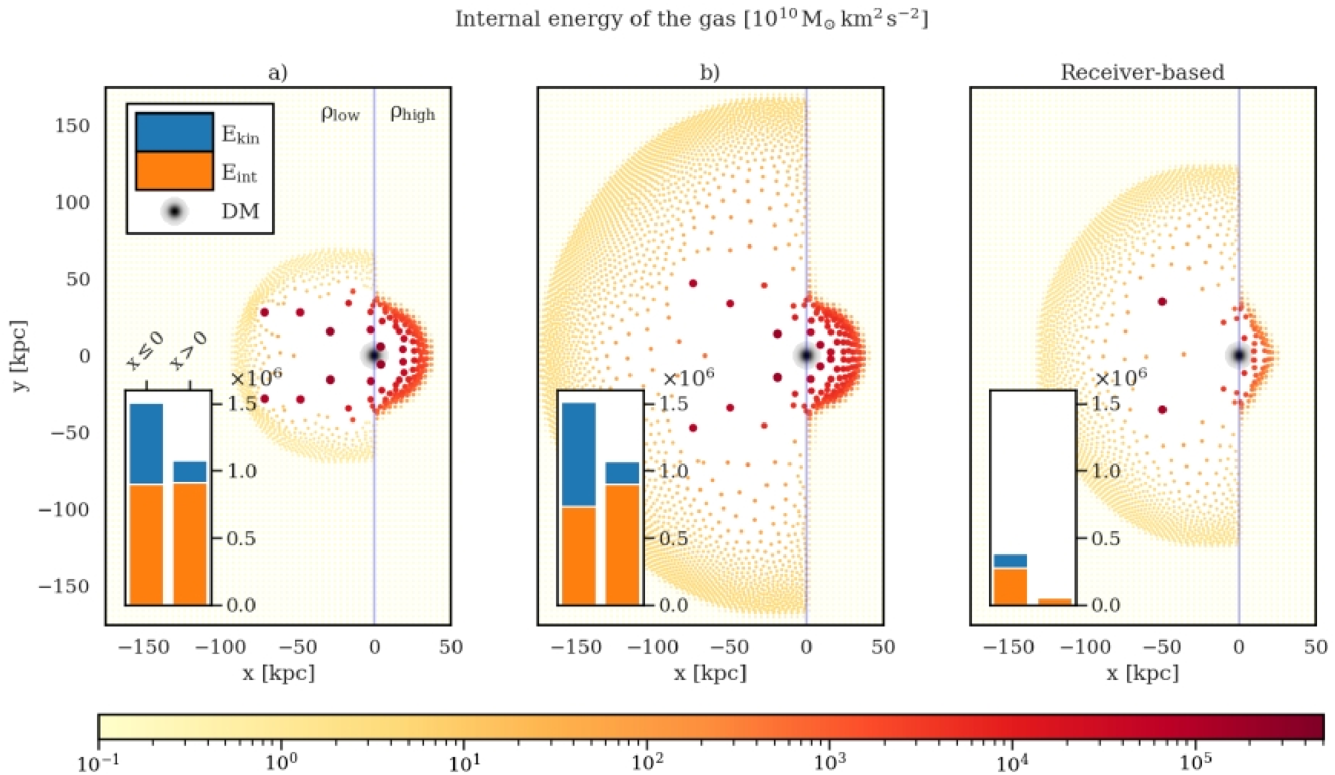
DM annihilation in N-body simulations

Implementation of DMAF into a cosmological simulation code:



Comparison of the donor-based an receiver-based method:

- “Academic” example: no gravitation, static DM particles
- gas density has a jump of magnitude 10^4 at x =0, m_χ = 100 keV



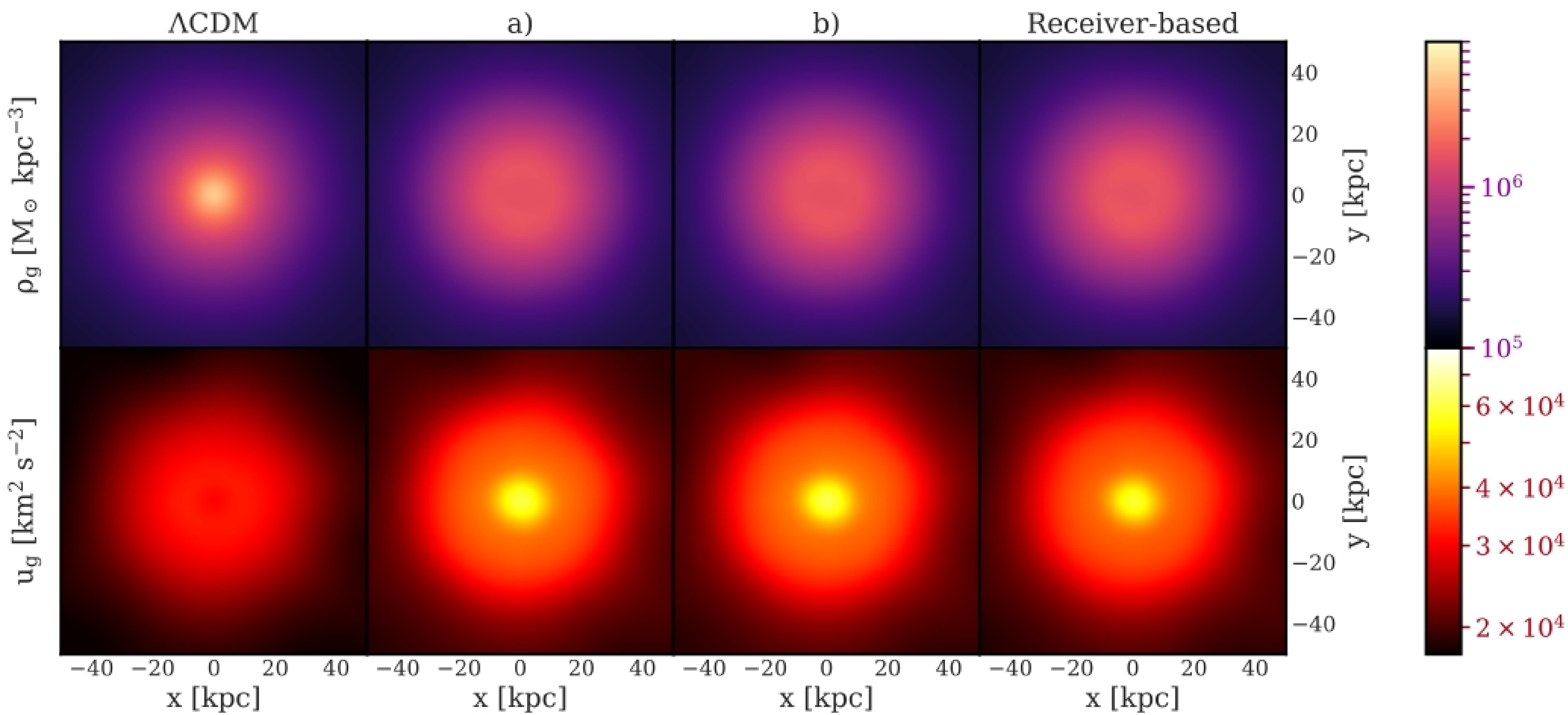
- Total energy with receiver-based method is only 1/6 as compared to donor-based method
- Total energy with donor-based method is almost identical for both choices of weights (as it should be)
- Impact of weights clearly visible

DM annihilation in N-body simulations

Implementation of DMAF into a cosmological simulation code:

Comparison of the donor-based and receiver-based method:

- Individual halo (MW-sized, NFW profile, m_χ = 100 keV) after ~100 Myr:

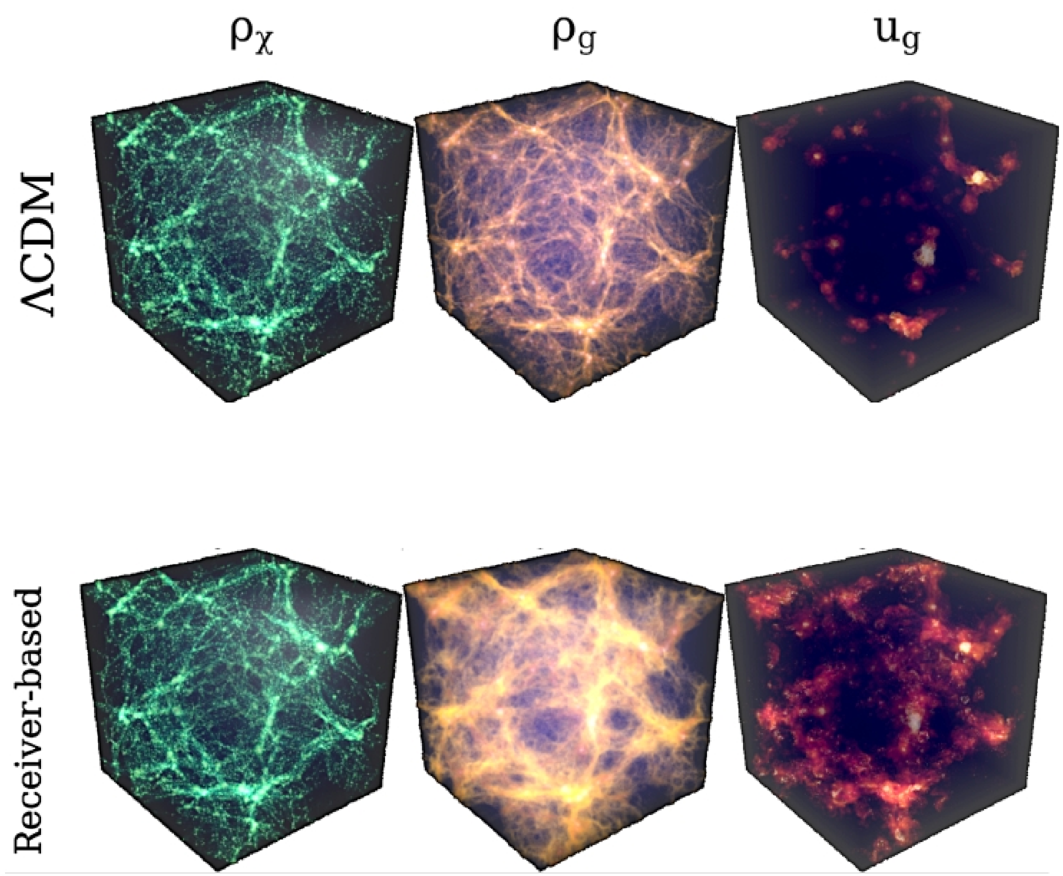


DM annihilation in N-body simulations

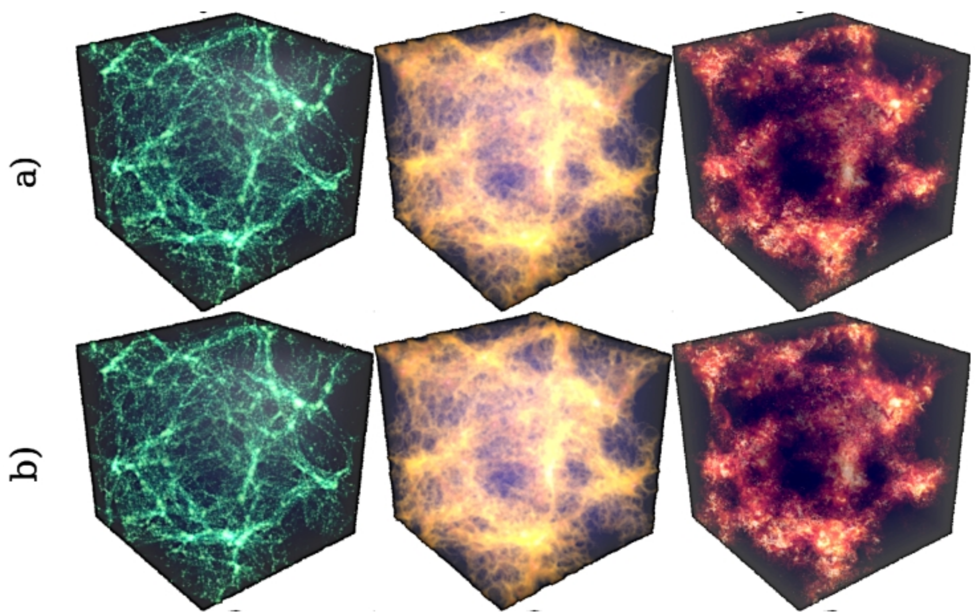
Implementation of DMAF into a cosmological simulation code:

Comparison of the donor-based an receiver-based method:

- Cosmological simulation, mχ = 1 MeV, at z = 0, box size = (50 Mpc / h)^3



donor-based

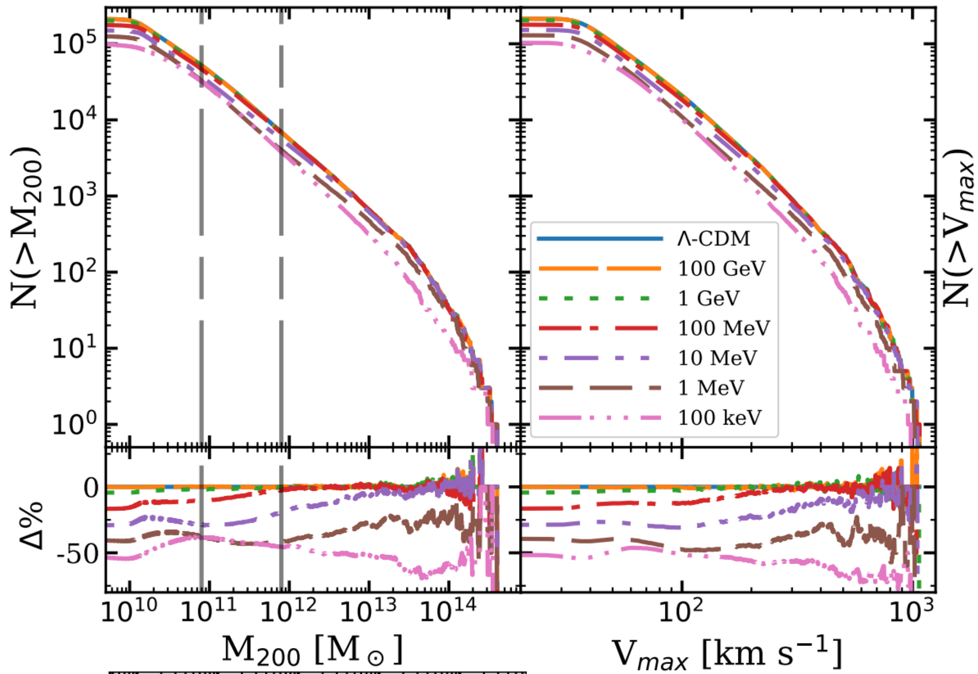


Results

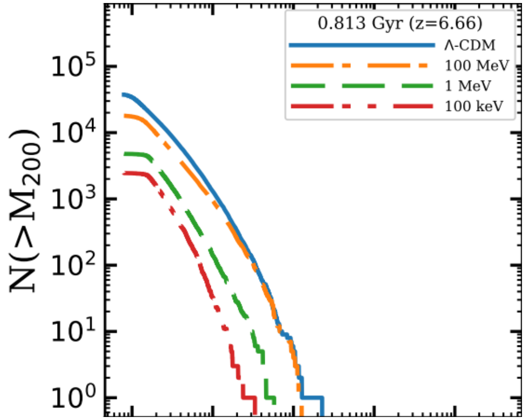
Cosmological simulation:

Halo mass function   Halo velocity function

z = 0:



z = 6.66:



- DMAF suppresses abundance of haloes as it drives the gas out of the haloes
- Small haloes are most sensitive to DMAF due to low gravitational binding energy
  → dwarf galaxies are ideal test ground for DMAF
- At early times, suppression of haloes is more pronounced, then, haloes “catch up”
- For DM masses of ⩾ 100 GeV, higher resolution is needed

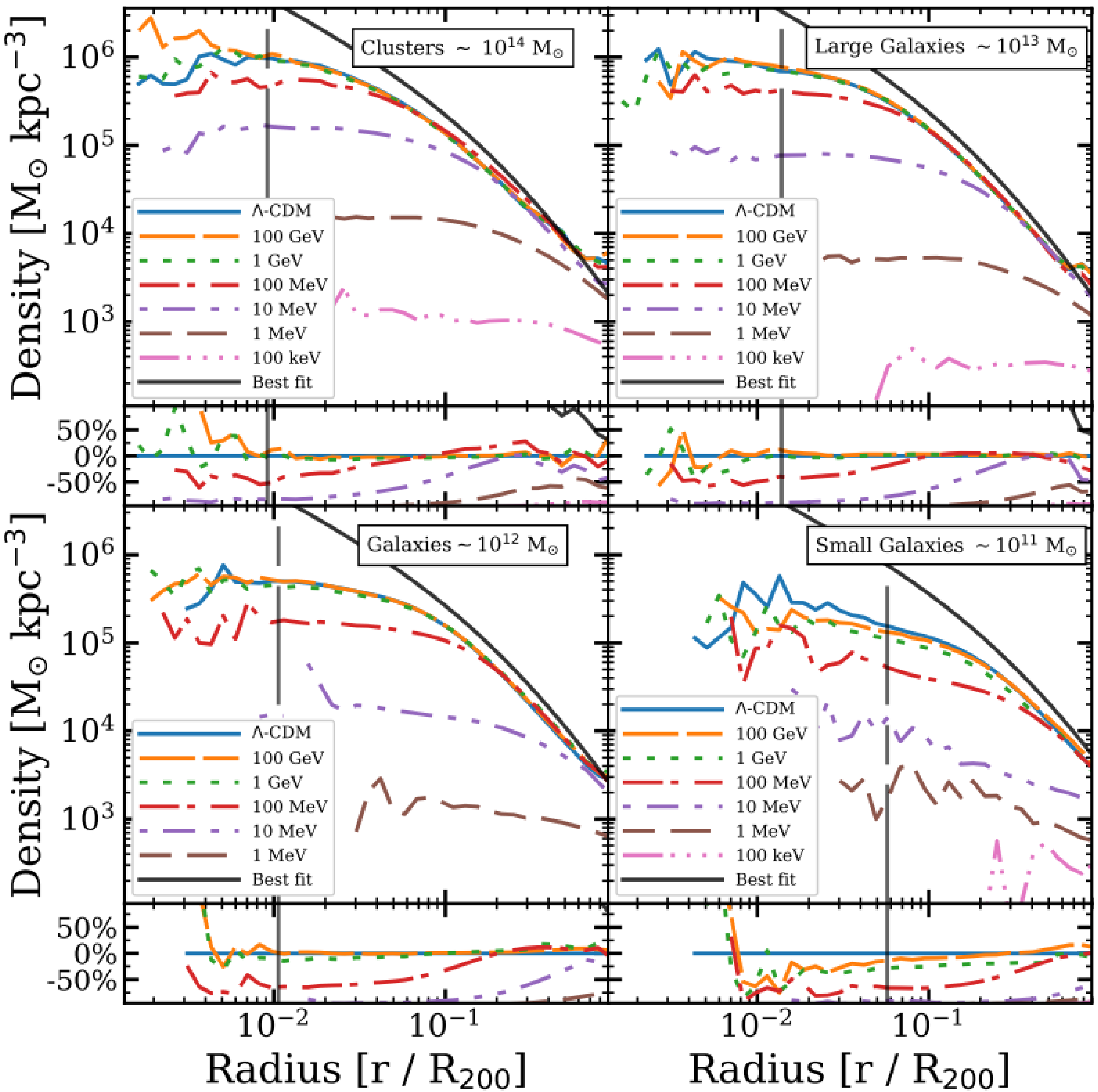
Results

Cosmological simulation:

Halo properties:

- DMAF flattens the gas density profiles of galaxies
- In small galaxies, a slight depletion of gas density in the halo centre can even be observed for DM masses of 100 GeV (recall that the preferred mass range for explaining the antiproton excess and GCE is $m_\chi \sim 30 - 100$ GeV)

Gas density profiles



Results

Cosmological simulation:

Particle properties:

- DMAF leads to slightly more particles at very high temperature ($T > 10^8$ K)
- Main effect: *less particles* with temperatures $10^6 - 10^8$ K
- *Reason:* gas particles leave hot haloes; only a few particles remain