Title: Session 2 - Simon May

Speakers: Simon May

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ALL ABOUT DARK MATTER (FUZZY OR OTHERWISE)

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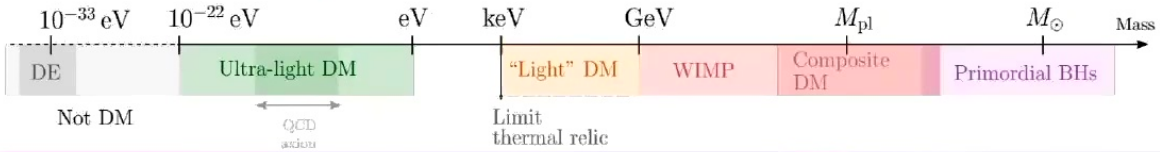
About me

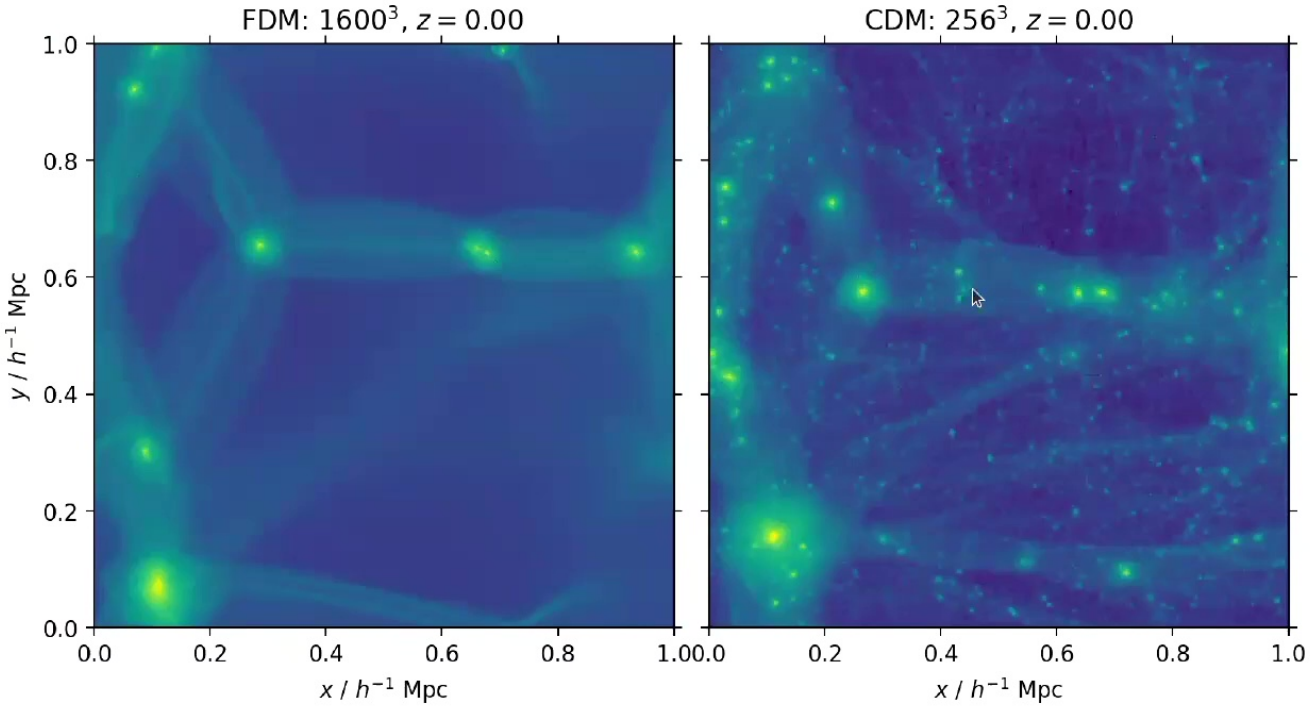
- **Master's** on WIMP DM models with radiative neutrino masses & particle phenomenology
- **PhD:** Numerical simulations of cosmic structure formation with fuzzy DM
  - With Volker Springel at Max Planck Institute for Astrophysics (MPA)
- Just arrived in Canada 2 weeks ago
- "In private": interested in cool stuff that can be done with computers (programming, free software, video games, cryptography...)

What is “fuzzy dark matter”?



- F(C)DM, BECDM, ULDM, ELBDM, ψDM, quantum-wave DM, (ultra-light) axion(-like) DM (ULA, ALP)...
- DM as an **extremely light scalar** particle ($m \approx 10^{-22}\,\mathrm{eV}/c^2$!)
- Aggregations of bosons can form a **Bose–Einstein condensate**
- Tiny mass $\Rightarrow$ large de Broglie wavelength ($\lambda \sim 1/m$)
  - $\Rightarrow$ **macroscopic quantum (wave) effects** on kpc scales
  - Structures resist collapse below quantum wavelength (**Heisenberg uncertainty principle**/“quantum pressure”)
- **Large scales: equivalent to CDM**
- *Particle physics motivation:* axion(-like) particles, “axiverse”
- *Astrophysics motivation:* Small-scale challenges (cusp vs. core, missing satellites, ...)
- **No sign of WIMP CDM**

Fuzzy vs. cold dark matter



- Small-scale (sub-)structure suppressed compared to CDM
- Smooth (like WDM) instead of clumpy (like CDM)
- Wave fluctuations and interference patterns

Fuzzy vs. cold dark matter: filaments

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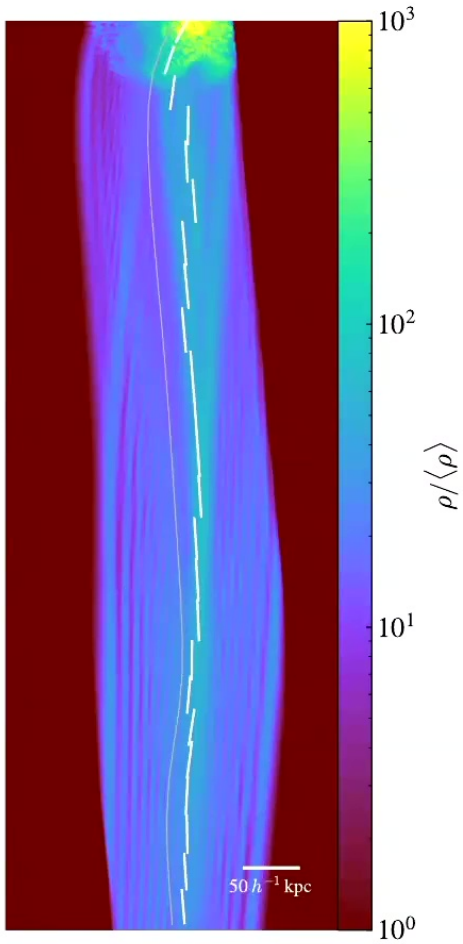
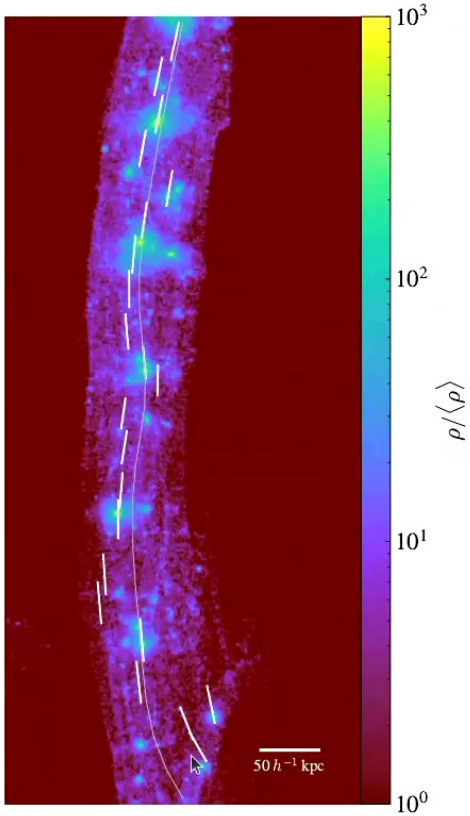
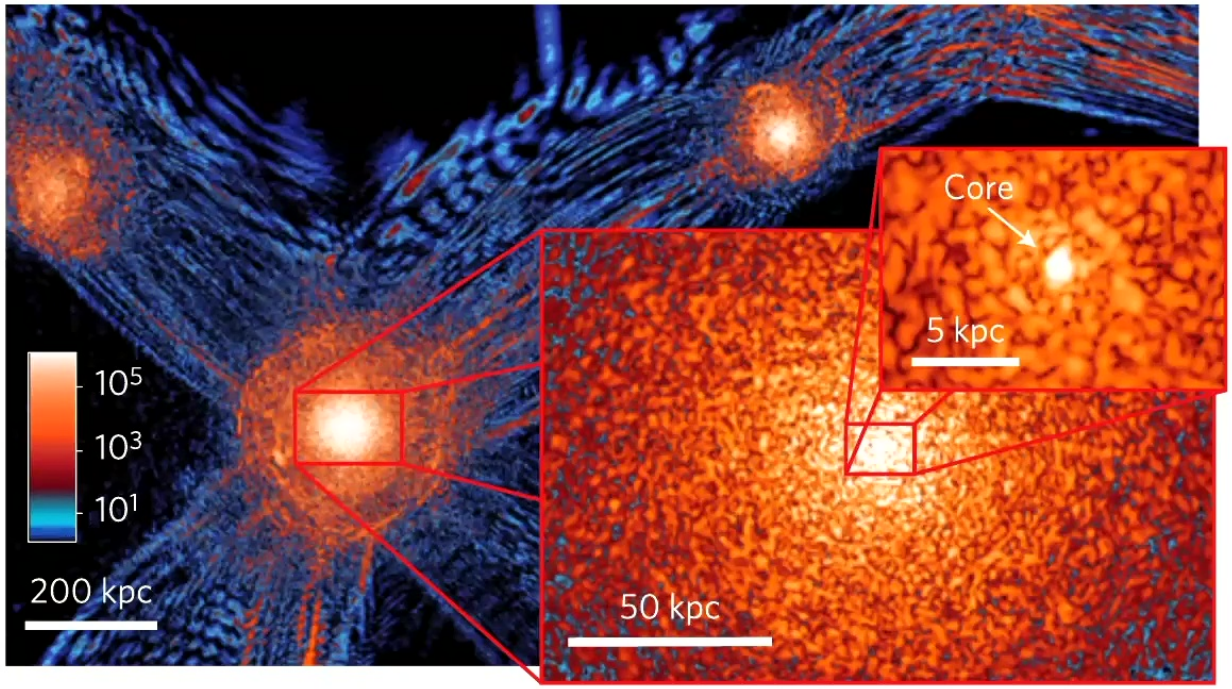




Fuzzy dark matter cores & wave fluctuations



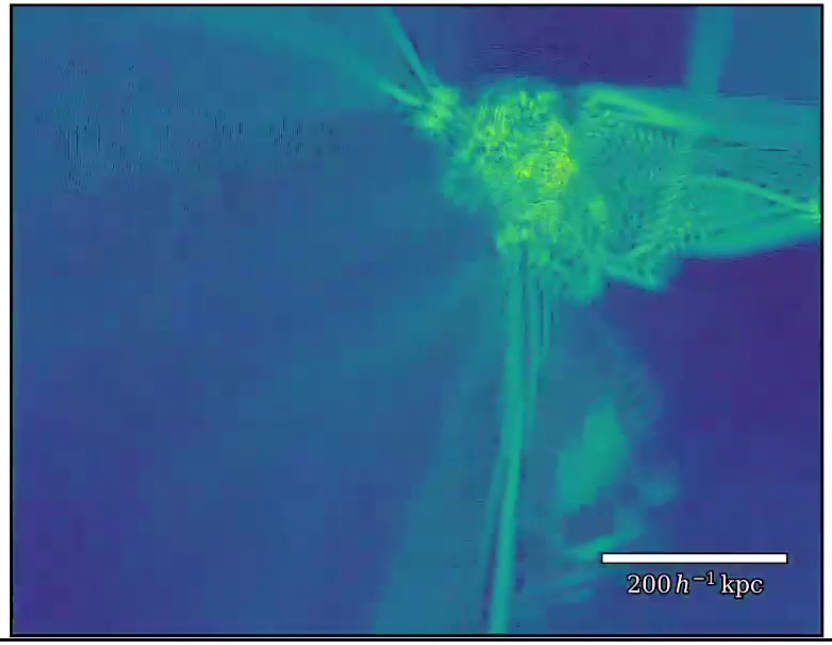
Schive, Chiueh, and Broadhurst (2014)

- Ground state of FDM equations: **soliton** (spherical "**core**")
- Soliton(-like) cores form at the center of all virialized halos
- Fluctuations around & within soliton cores ⇒ **dynamical heating** (e. g. of stars), potential **disruption** (e. g. of globular clusters)

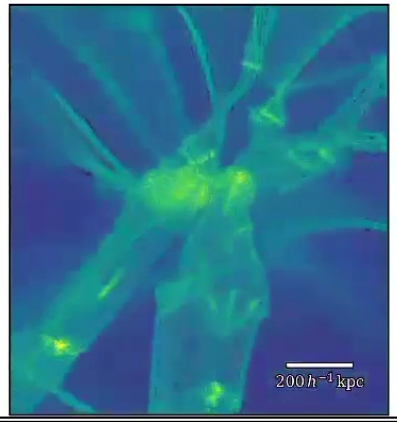
Largest cosmological full FDM wave simulations to date

10 $^{\mathrm{Mpc}}/_{h}$ box (slices through simulation volume)

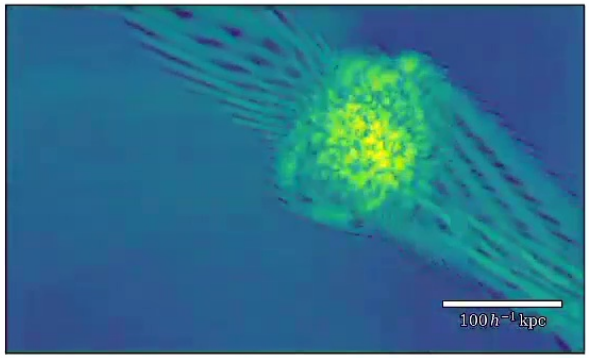
$N^3 = 8640^3$, $mc^2 = 7 \times 10^{-23}$ eV, $z = 2.56$



$N^3 = 8640^3$, $mc^2 = 7 \times 10^{-23}$ eV, $z = 2.59$



$N^3 = 8640^3$, $mc^2 = 7 \times 10^{-23}$ eV, $z = 2.54$

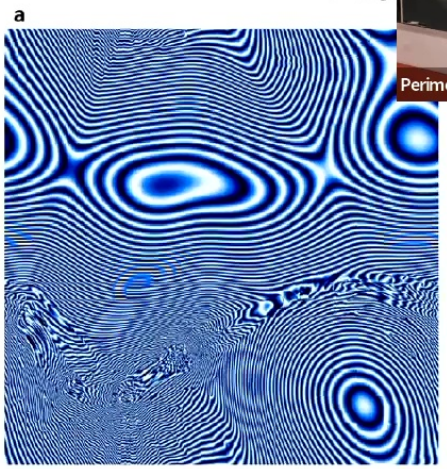


May and Springel (2021)

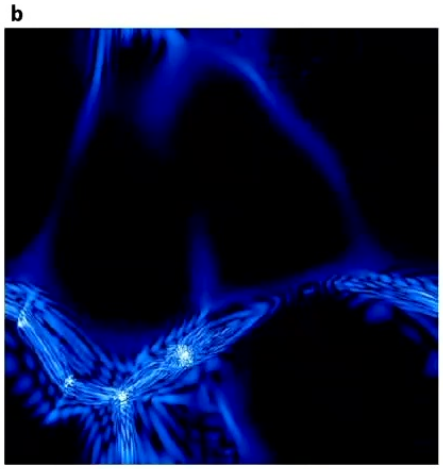
Scale of these simulations & why they're so difficult/costly

- 8640^3 grid: $>$ 10 TiB memory/data per snapshot, $> 5 \times 10^6$ CPU h per simulation
- **Large dynamic range**: **Both** large scales and small (kpc-scale) de Broglie wavelength (**everywhere!**) must be resolved for correct evolution
- High velocities require **high resolution** even in **low-density** regions ($\rightarrow$ rapid oscillations)
  Velocity criterion: $\Delta x \propto \frac{1}{v}$
- **Time step criterion:** $\Delta t \propto \Delta x^2$

Pha



Density:



Schive, Chiueh, and Broadhurst (2014)


Thanks – that's it for now!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