Probing Self-Interacting Warm Dark Matter via Matter Power Spectrum

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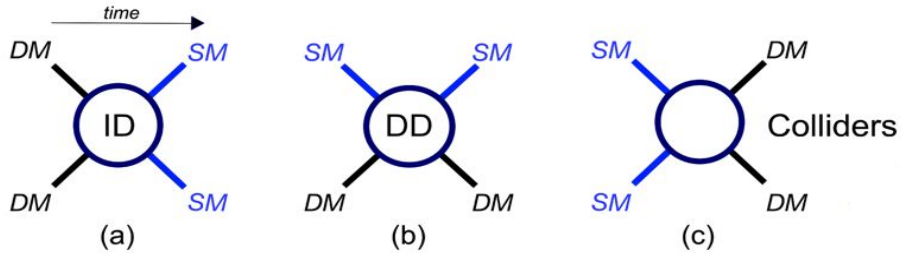
Dark Matter: “Nightmare Scenario”

- Lots of efforts to measure: directly, indirectly, collider

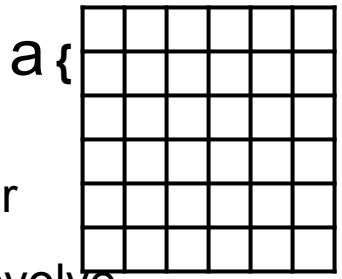


- If it doesn’t interact with the Standard Model: How and what can we learn about Dark Matter (DM)?
- **Dynamics of dark sector can be probed by measurements of structure formation**

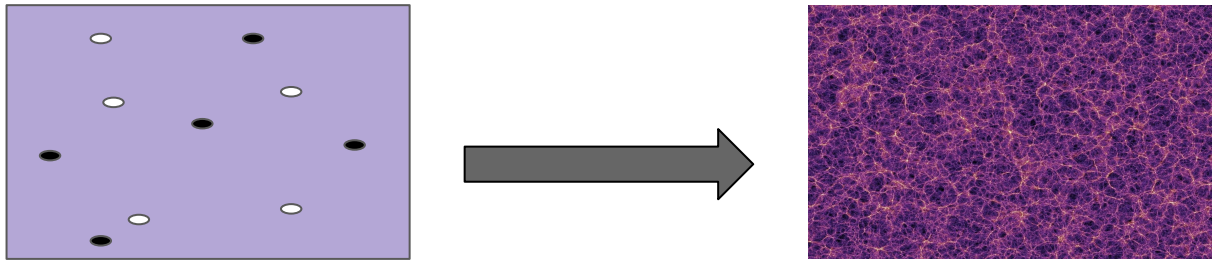
Structure in the Universe

- Universe expands, size is measured by scale factor a; $a = \frac{1}{1+z}$

$$H = \frac{da/dt}{a}$$



- Energy density dominated initially by radiation, later by matter
- Primordial fluctuations in otherwise homogeneous universe evolve
  - Overdensities draw in more matter, interactions, etc.



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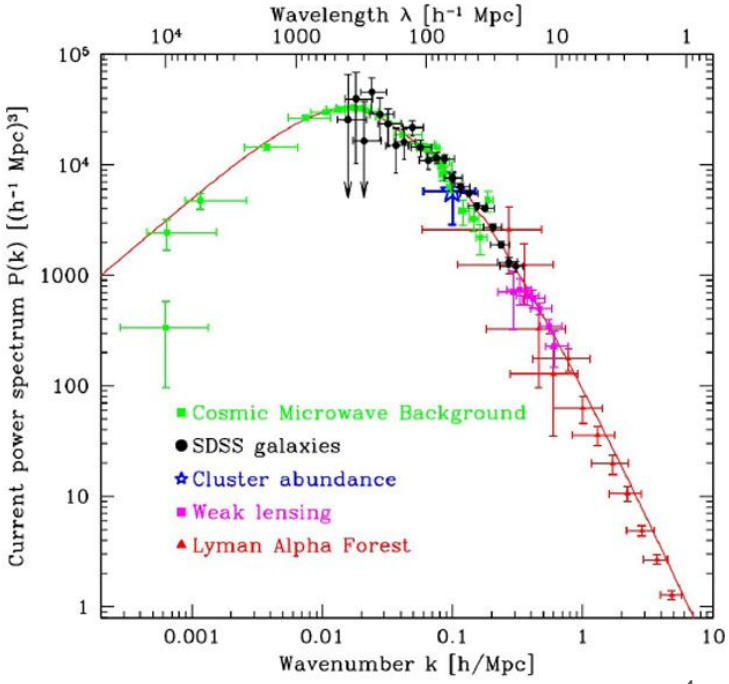
Matter Power Spectrum

- How big are the perturbations of various sizes today?
- Smallest sizes → biggest k values
- Shape tells us something about DM dynamics

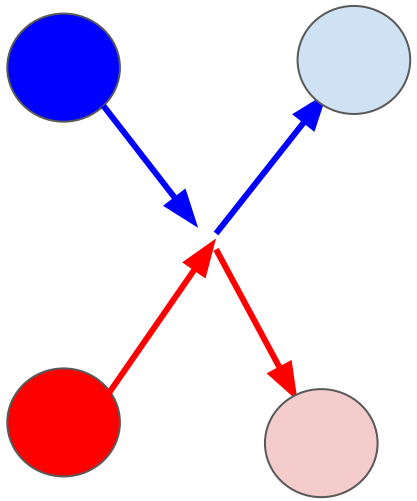


Self-interacting Dark Matter

- Free streaming: any particle with a velocity will travel unless interrupted
- Self-scattering interrupts free-streaming
- Decouples when interaction rate ($\Gamma_{2\to2}$) drops below Hubble expansion rate:

$$\Gamma_{2\to2} < nH$$

Happens at scale factor $a = a_{dec}$



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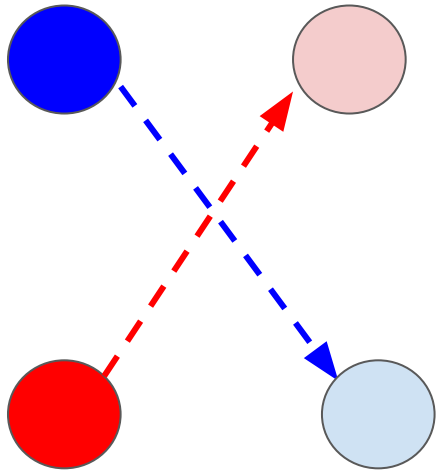

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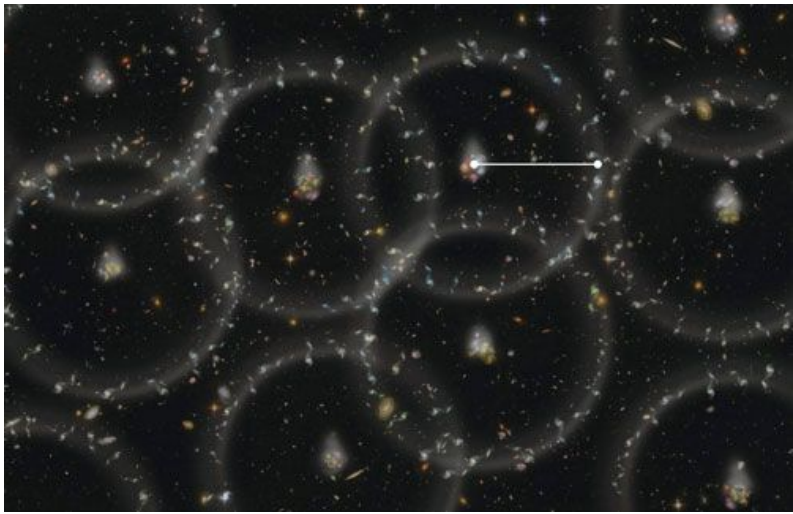
Self-interactions and Acoustic Oscillations

- Self interactions → pressure
- Pressure waves drive out matter from overdensity at speed of sound
- Distance travelled by pressure wave = sound horizon (r_s)
  - Perturbations suppressed at scales < r_s



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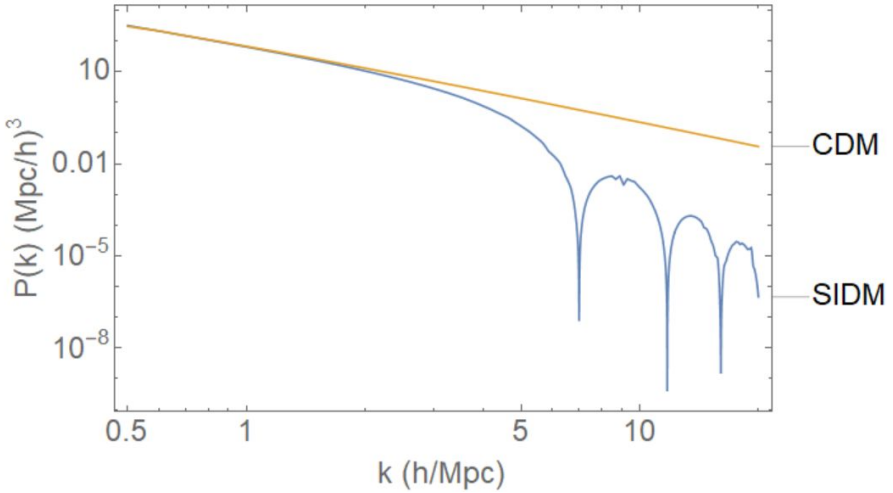
Suppression scales

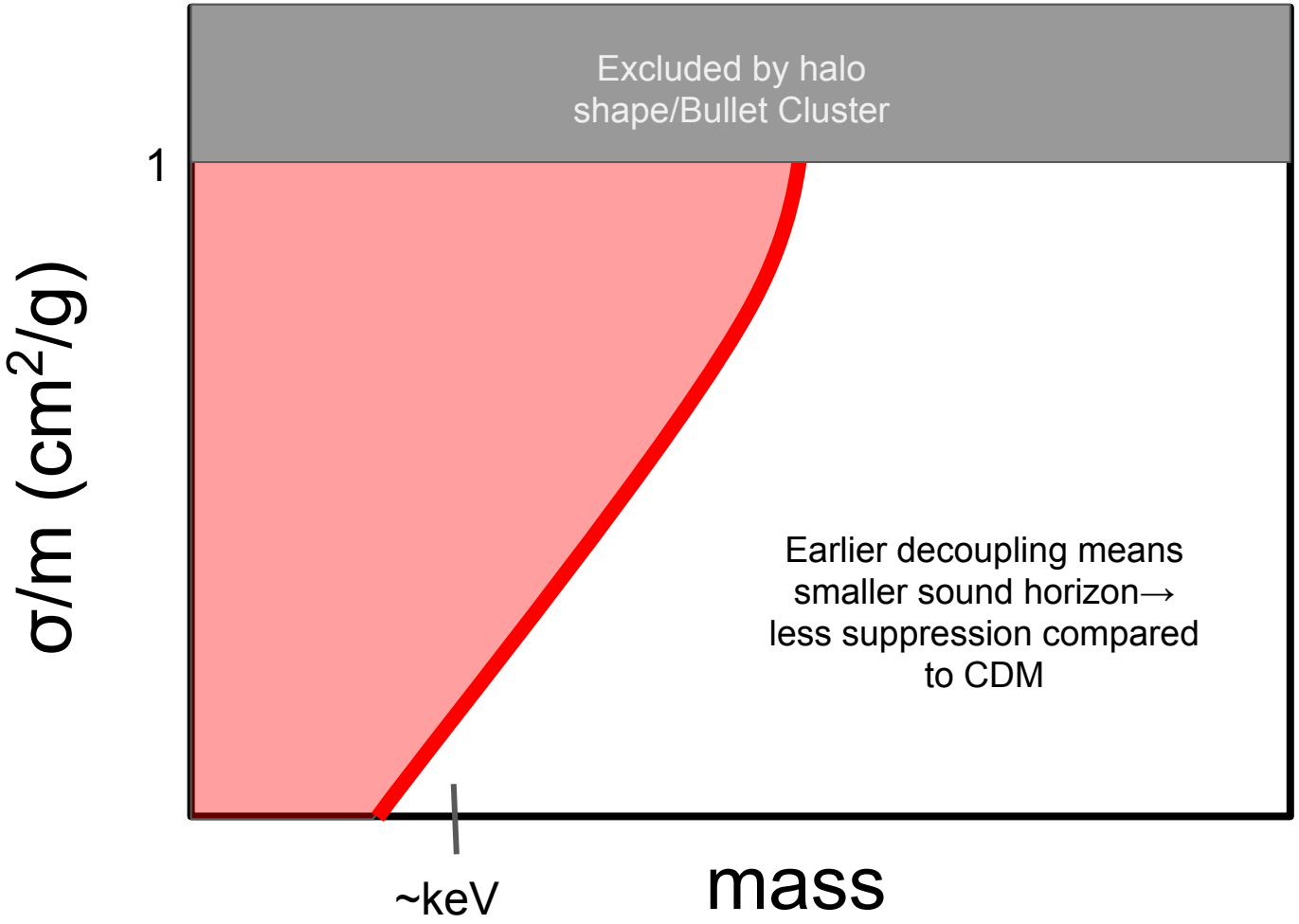
- **a_{NR}**: Scale factor when DM becomes non-relativistic

$$a_{NR} \sim \sqrt{\frac{T_{0,DM}}{m}}$$

- Sound horizon depends mostly on a_{NR}, but also partly on interaction strength (through a_{dec})

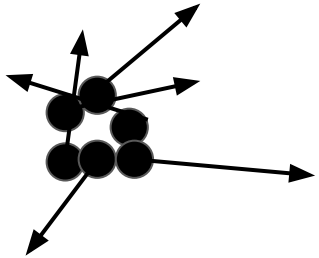
$$r_s \sim \frac{a_{NR}}{\sqrt{3}H_0}[1 + \ln(a_{dec}/a_{NR})], \quad a_{dec} > a_{NR}$$

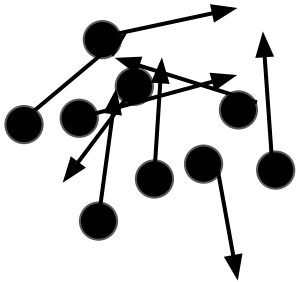



Excluded by halo
shape/Bullet Cluster
1
σ/m (cm²/g)
Earlier decoupling means
smaller sound horizon→
less suppression compared
to CDM
~keV
mass

KeV-scale Warm Dark Matter (WDM)

- All particles with velocity will **free-stream**
  - Travel furthest when relativistic





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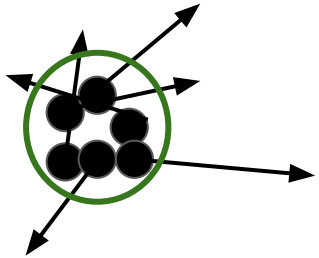
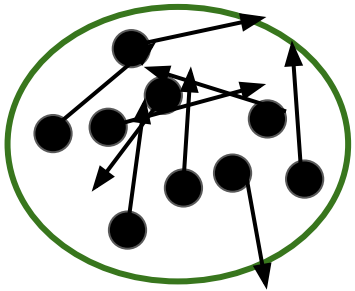


- All particles with velocity will **free-stream**
  - Travel furthest when relativistic
- Small overdensities smooth out



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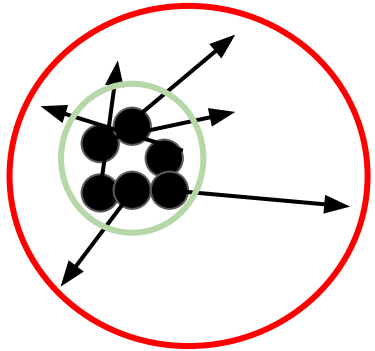

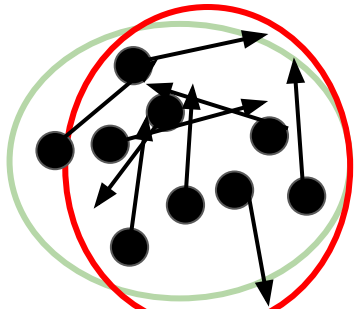

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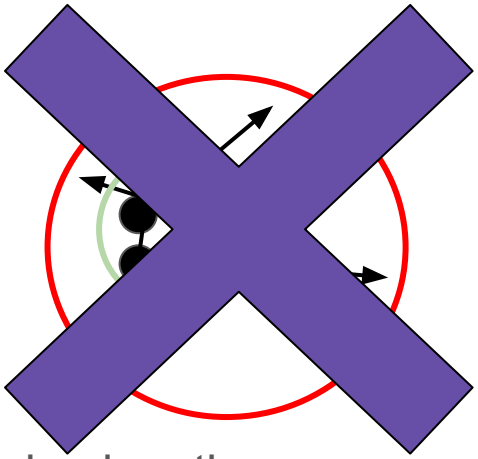
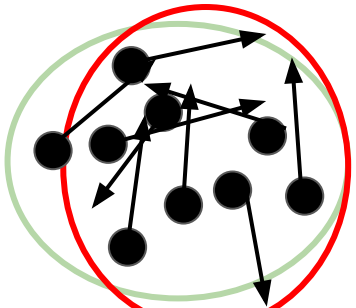
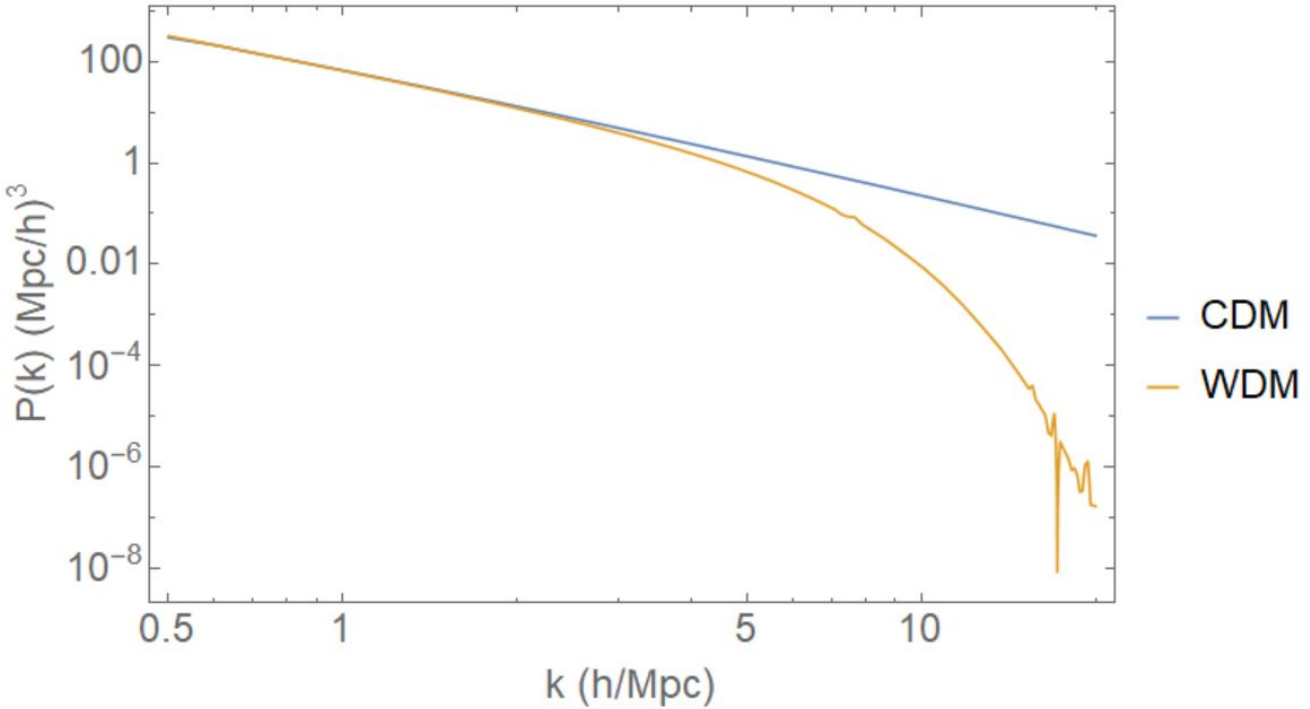


- All particles with velocity will **free-stream**
  - Travel furthest when relativistic
- Small overdensities smooth out
- DM won't have overdensities on scales below free streaming length

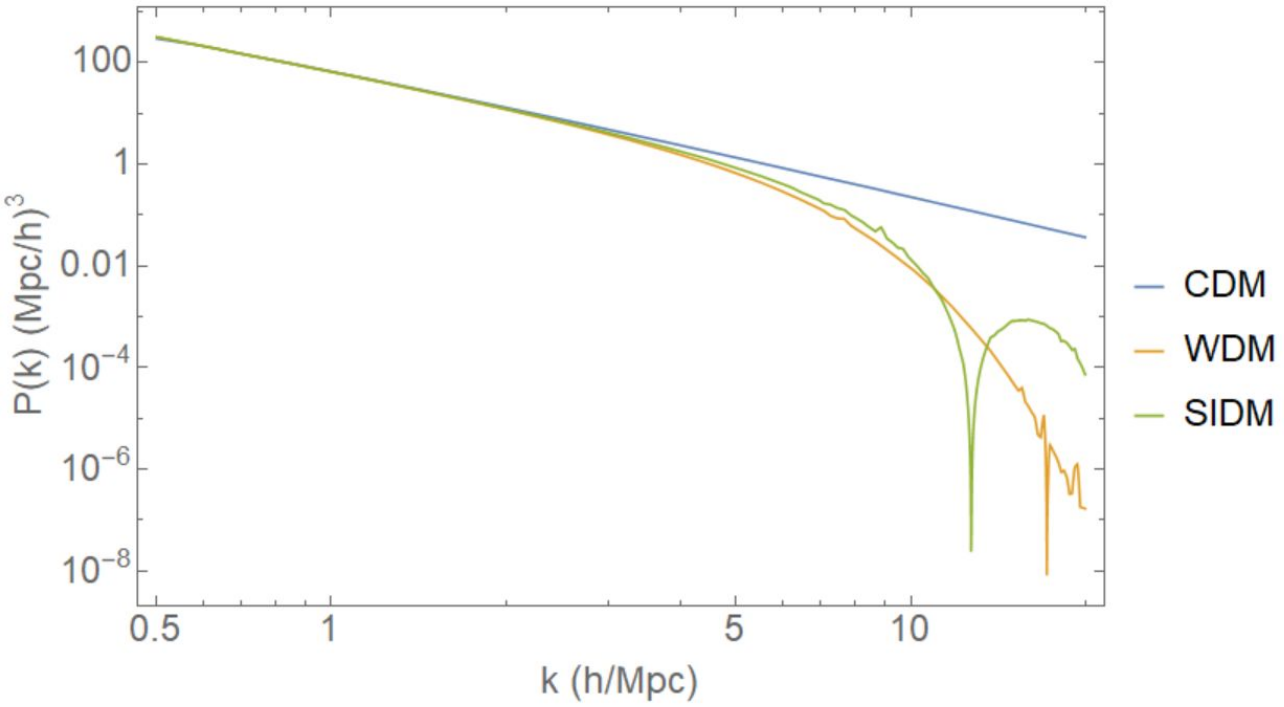
$$\lambda_{fs} \sim \frac{a_{NR}}{H_0} \ln\left(\frac{a_{eq}}{a_{dec}}\right), \qquad a_{dec} > a_{NR}$$



Free Streaming Suppression



High-k Power Spectrum



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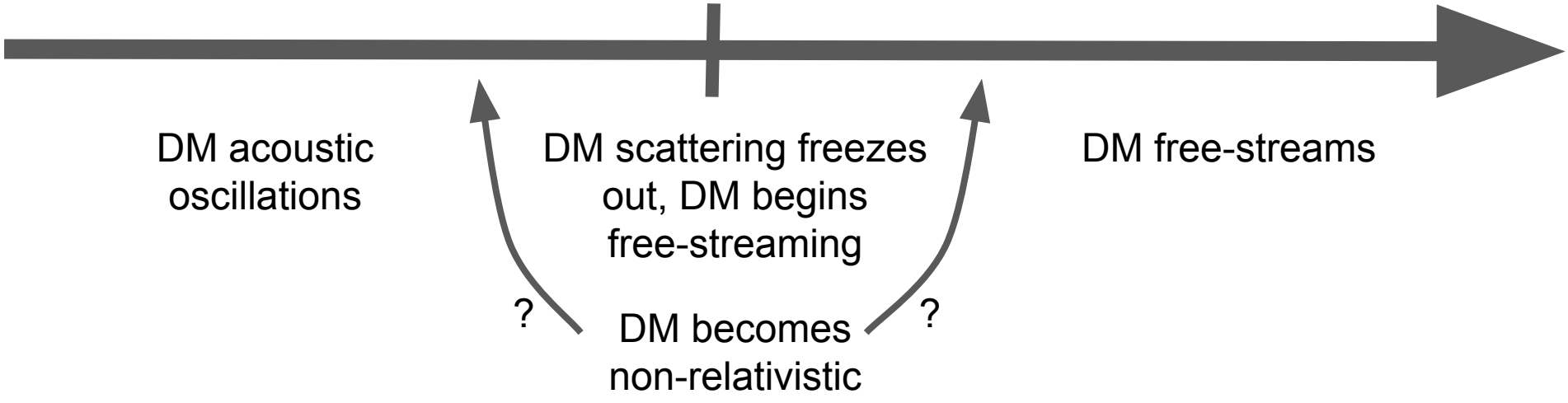
Big Picture

$$\Gamma_{2\to 2} \sim nH$$



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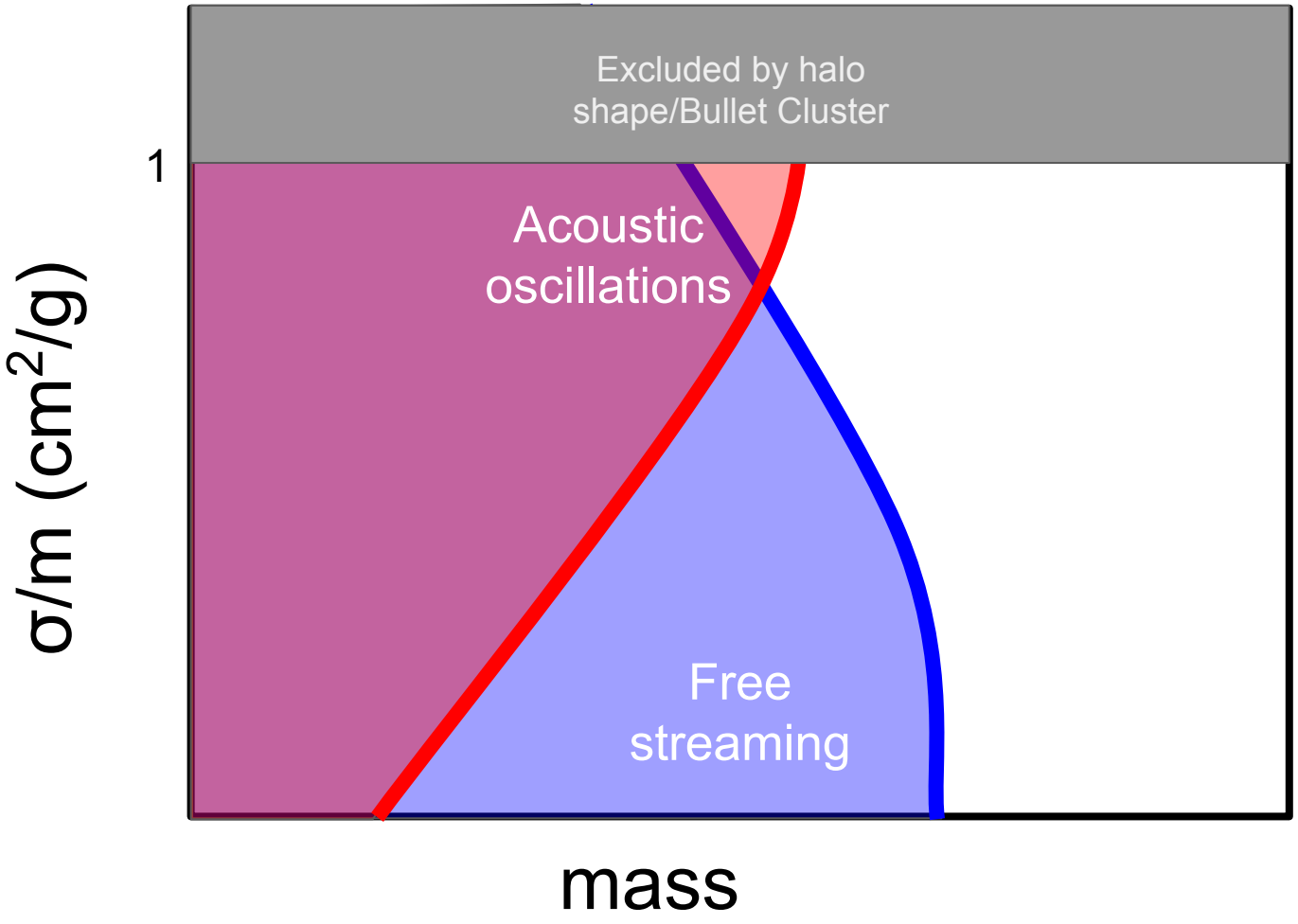
Excluded by halo
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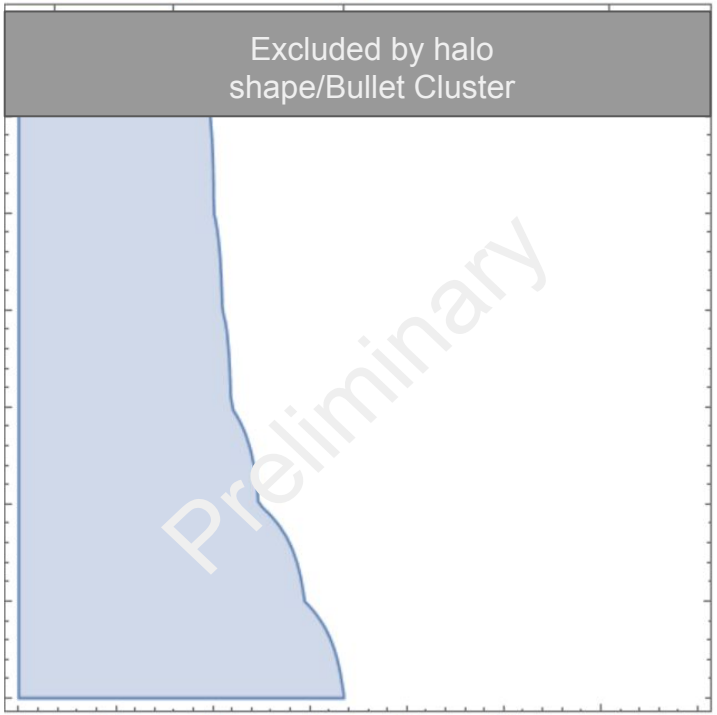
Acoustic
oscillations
Free
streaming
σ/m (cm²/g)
mass

Preliminary Results



Conclusions

- Self-Interactions affect WDM bounds
- Acoustic Oscillations and Free Streaming suppress structure formation
- Understanding the interplay of the two will help set more robust bounds
- Current work is making more precise the bounds given by Boltzmann evolver code

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Thank You!

Backups

a_{NR}

- Redshift at which DM becomes non-relativistic: $T_{DM} = m$
- Relationship between a_{NR} and m depends on specific model

$$a_{NR} \sim \frac{T_{0,SM}}{\xi m}$$

- $\xi = T_{SM}/T_{DM}$ at $T_{DM} > m$

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Evolution of Perturbations

- During radiation domination: $\frac{\delta\rho_{DM}}{\rho_{DM}} \propto \ln(a)$
- During matter domination: $\frac{\delta\rho_{DM}}{\rho_{DM}} \propto a$
- If perturbations suppressed during matter domination, will affect what we see today

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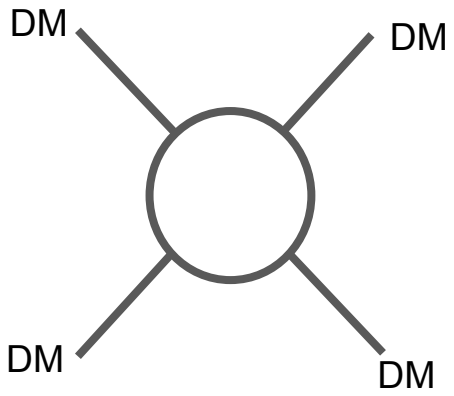
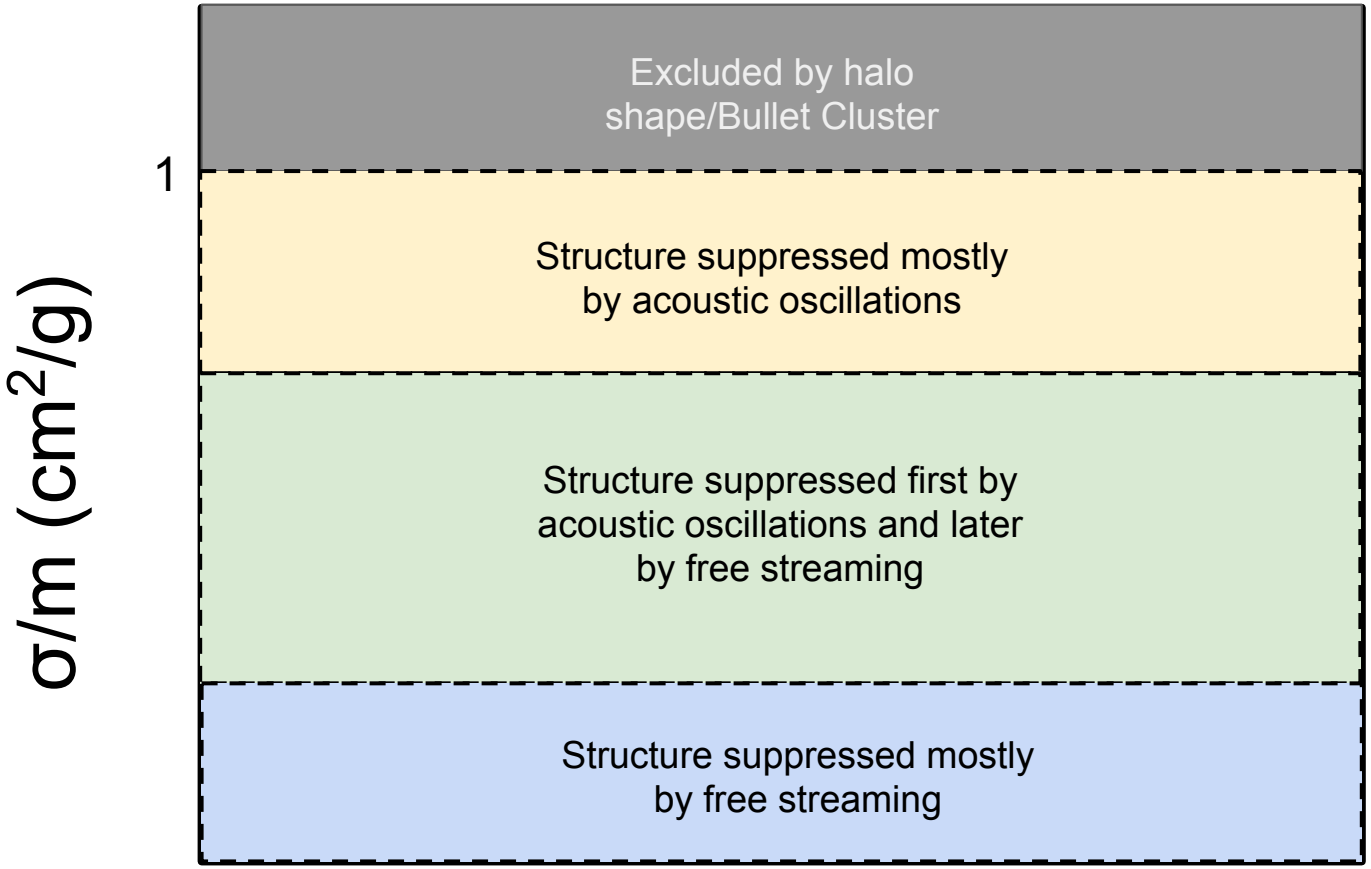
Sample model

- Scalar: $\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{m^2}{2}\phi^2 - \frac{\lambda}{4!}\phi^4$





$$a_{NR} \sim \sqrt{\frac{T_{0,DM}}{m}}$$

Preliminary Results