Filament gas shock and splash back dynamics

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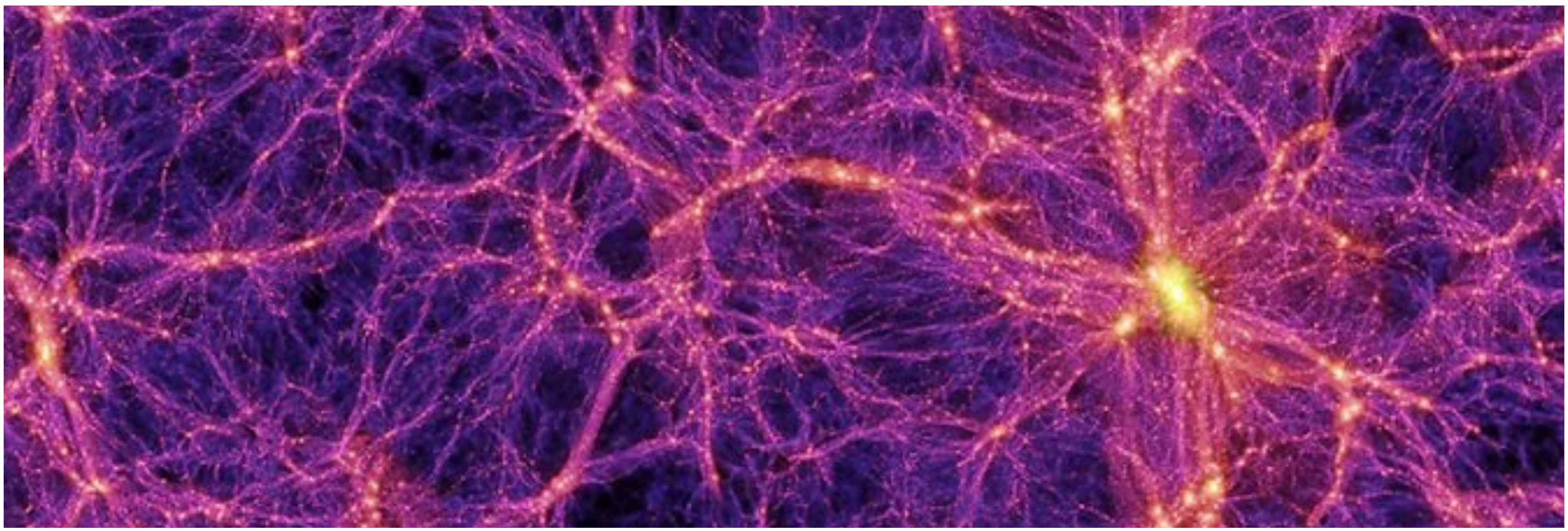
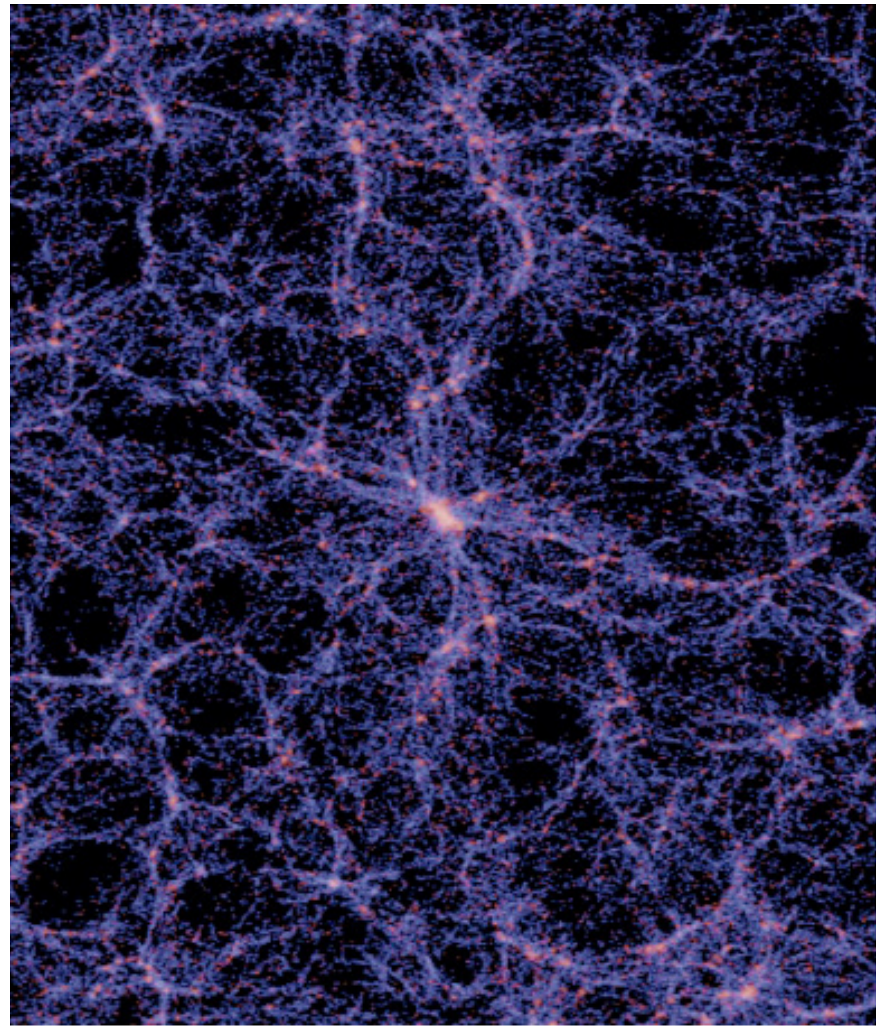
with Han Aung and Prof. Daisuke Nagai at *Yale University*



Yale Physics

Background: filaments

- What are filaments?
- Largest known structures in the universe; most of the cosmic web by area.
- Massive thread-like formations on the scale of 200-500 million ly.
- Consist of gravitationally bound galaxies
- Studying secondary mass accretion onto existing densities



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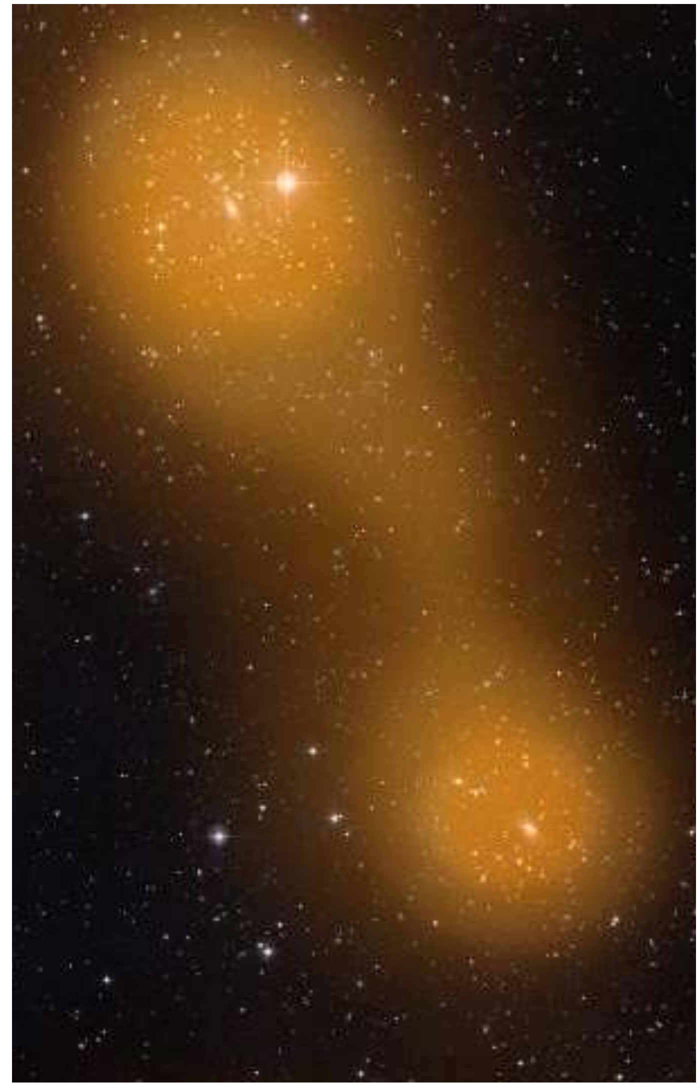
Motivations & research questions

- Gas and collisionless DM profiles for 3d spherical halos have been well studied. Collisionless self-similar solutions for 2d filaments have also been found. (Bertschinger 1985, Fillmore & Goldreich 1984).

- Gas behavior around 2d cylindrical filaments has not been modeled. With **better technology**, more data will be collected in future surveys on less dense filaments. Analytical prediction is essential (Umehata et al., Tanimura et al. 2019).

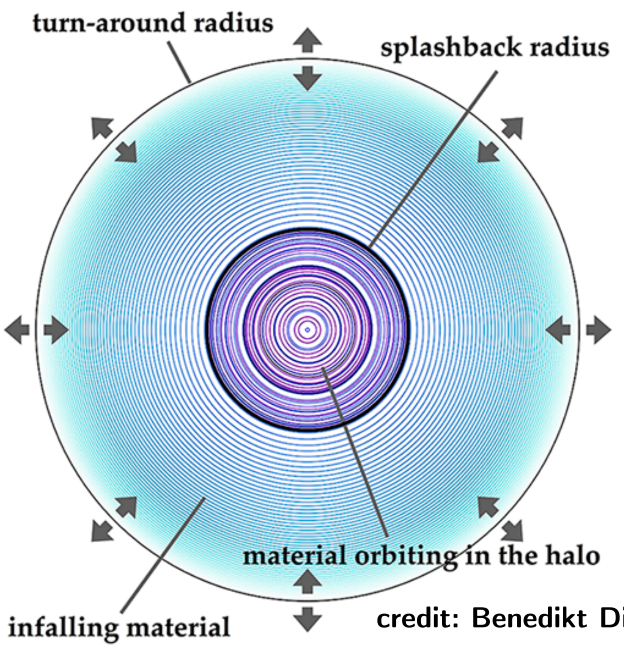
- ***Questions:***

- How does collisional gas accreting onto a filament behave?
- At what radius does shock occur?
- Do the shock radius align with the DM splashback radius?
- When is self-similarity valid, and what are the dependences on heat capacity ratio and mass accretion rate?



credit: ESA/PLANCK

The classic solutions: *3d gas and DM*



credit: Benedikt Diemer

- Physical picture: Co-moving mass shells infall on spherical mass. DM shells are stopped at a a fraction of their largest radius of expansion ("turnaround radius") and continue on. Gas accretes under a potential, shocks, and settles. Studied using "self-similarity" paradigm.

Gas accretion with normal jump shock

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{\rho}{r^2}\frac{\partial}{\partial r}(r^2 v)$$
$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{Gm}{r^2} - \frac{1}{\rho}\frac{\partial p}{\partial r}$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(p\rho^{-\gamma}\right) = 0$$
$$\frac{\partial m_{\mathrm{gas}}}{\partial r} = 4\pi r^2 \rho$$

$$V_2 = \frac{\gamma-1}{\gamma+1}\left[V_1 - \lambda_{\mathrm{sh}}\delta\right] + \lambda_{\mathrm{sh}}\delta$$
$$D_2 = \frac{\gamma+1}{\gamma-1} D_1$$
$$P2 = \frac{2}{\gamma+1} D_1 \left[V_1 - \lambda_{\mathrm{sh}}\delta\right]^2$$
$$M_2 = M_1$$

(*V*, *D*, *P*, *M* nondimensionalized by self-similar scaling)

3d cold accretion model (P=0)

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{Gm}{r^2}$$

Linearized (Newtonian) limit

Assumptions

$m_i \propto a^s = t^{2s/3}$	$\Omega_b = 1$	$\gamma = 5/3$
Init. mass excess power law	Einstein-de Sitter	if not specified

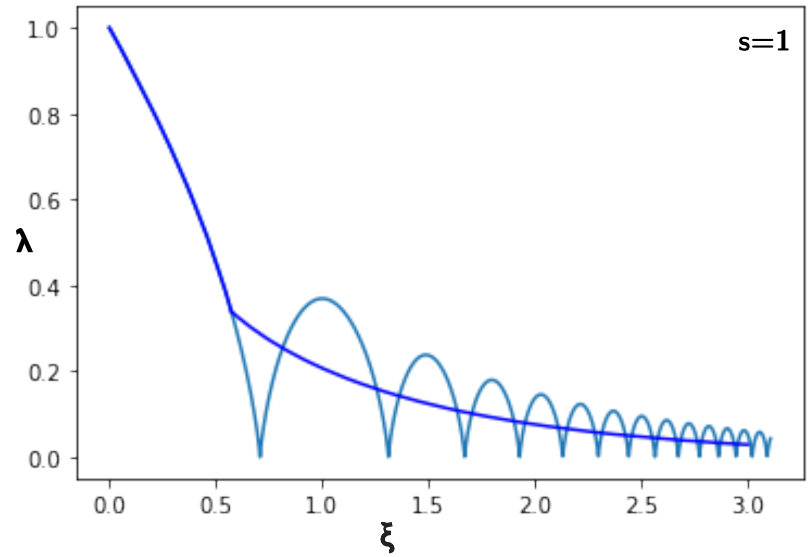
(Hubble flow unperturbed)

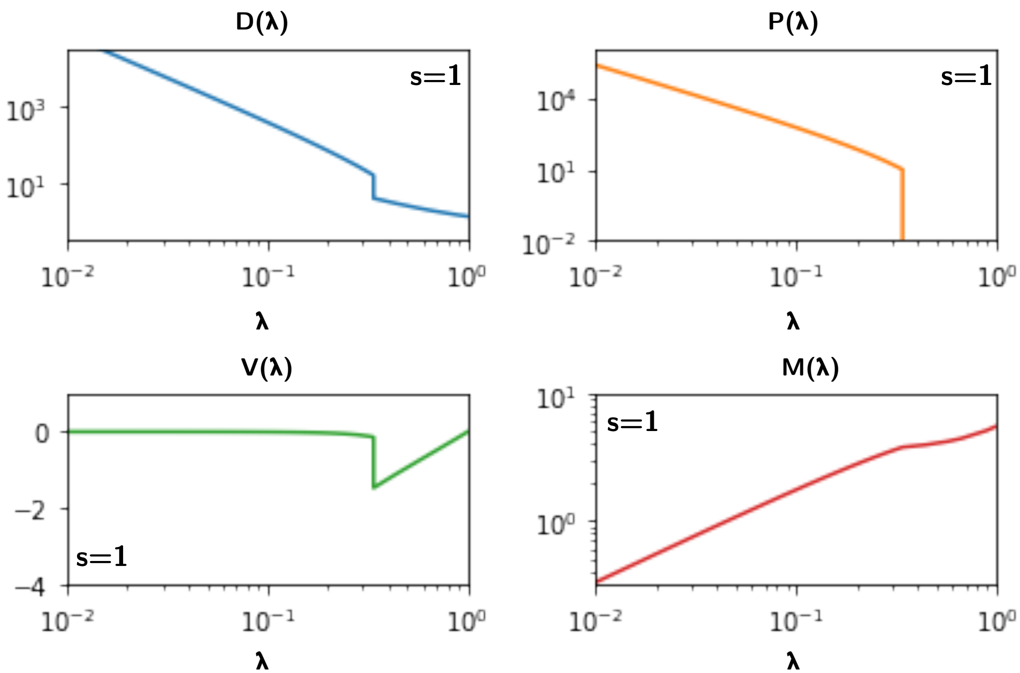
Self-similar solutions: *3d gas and DM*

Non-dimensional point trajectory (gas or DM):

$$\frac{\mathrm{d}^2\lambda}{\mathrm{d}\xi^2} + (2\delta - 1)\frac{\mathrm{d}\lambda}{\mathrm{d}\xi} + \delta(\delta - 1)\lambda = -\frac{2}{9}\frac{M(\lambda)}{\lambda^2} - \frac{P'}{D}$$

we have $\delta = 2(1+s/n)/3$, where n is the dimension and *s* the mass accretion rate. The dimensionless profiles *M*, *P*, *D* must be known or found by successive approximations. $\lambda(0) = 1$ and $\mathrm{d}\lambda/\mathrm{d}\xi = 0$.





Non-dimensional gas equations

$$[V - \lambda\delta]D' + DV' = 2D - \frac{2DV}{\lambda}$$

$$[V - \lambda\delta]V' + \frac{P'}{D} = -\frac{2}{9}\frac{M}{\lambda^2} - (\delta - 1)V$$

$$[V - \lambda\delta]\left(\frac{P'}{P} - \gamma\frac{D'}{D}\right) = -2(\gamma - 1) - 2(\delta - 1)$$

$$M'_{\mathrm{gas}} = 3\lambda^2 D$$

Our contribution: 2d gas and DM

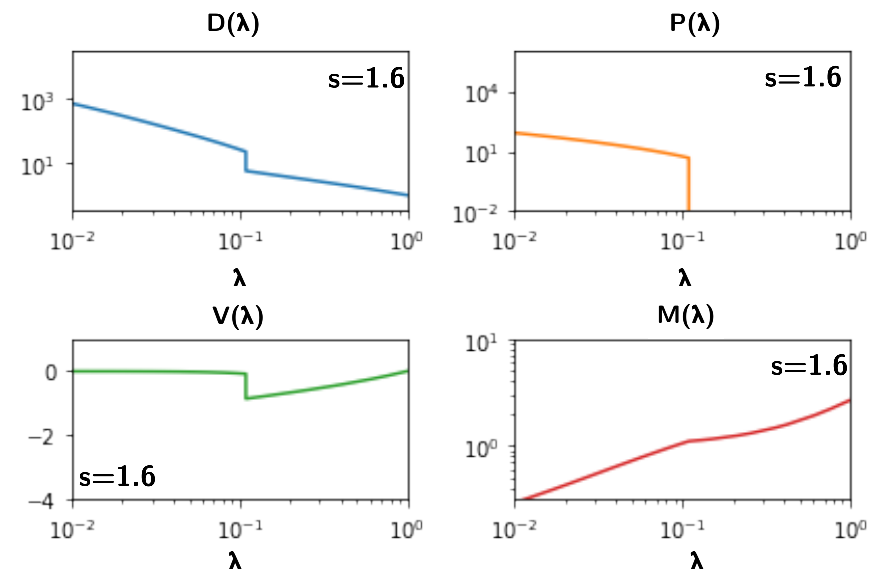
- Extend to 2d cylindrical filaments. Same physics involved. Geometry has changed: Different potentials in the equations.

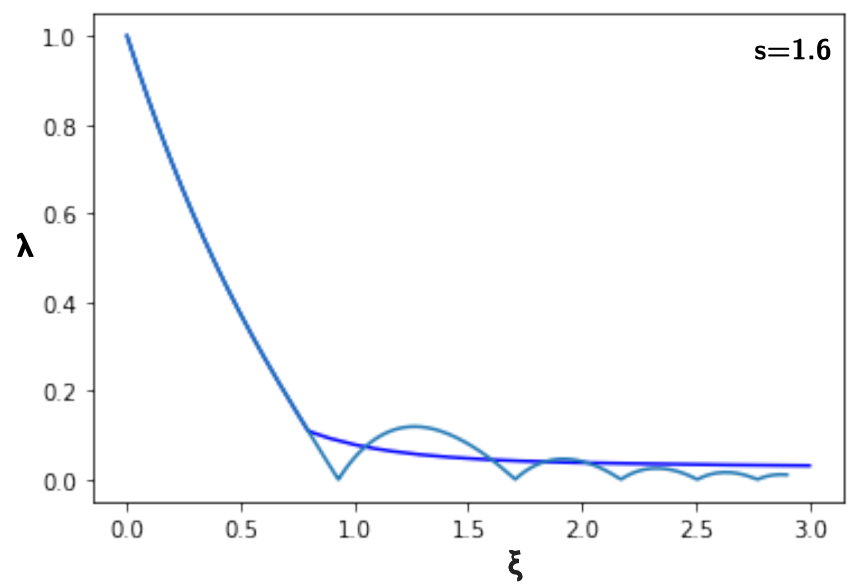
- The **trajectory for a point particle obeys:**

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{2G\lambda}{r}$$

- For **gas profiles**, we have:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{\rho}{r}\frac{\partial}{\partial r}(rv)$$
$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - \frac{2G\lambda}{r}$$
$$\frac{\mathrm{d}}{\mathrm{d}t}(p\rho^{-\gamma}) = 0$$
$$\frac{\partial \lambda}{\partial r} = 2\pi r\rho$$





Our contribution: 2d gas and DM

- Extend to 2d cylindrical filaments. Same physics involved. Geometry has changed: Different potentials in the equations.

- The **trajectory for a point particle becomes:**

$$\frac{\mathrm{d}^2\lambda}{\mathrm{d}\xi^2} + (2\delta - 1)\frac{\mathrm{d}\lambda}{\mathrm{d}\xi} + \delta(\delta - 1)\lambda = -\frac{M}{3\lambda} - \frac{P'}{D}$$

- For **gas profiles**, we have:

$$\left[V - \delta\lambda\right] D' + DV' + \frac{DV}{\lambda} - 2D = 0$$

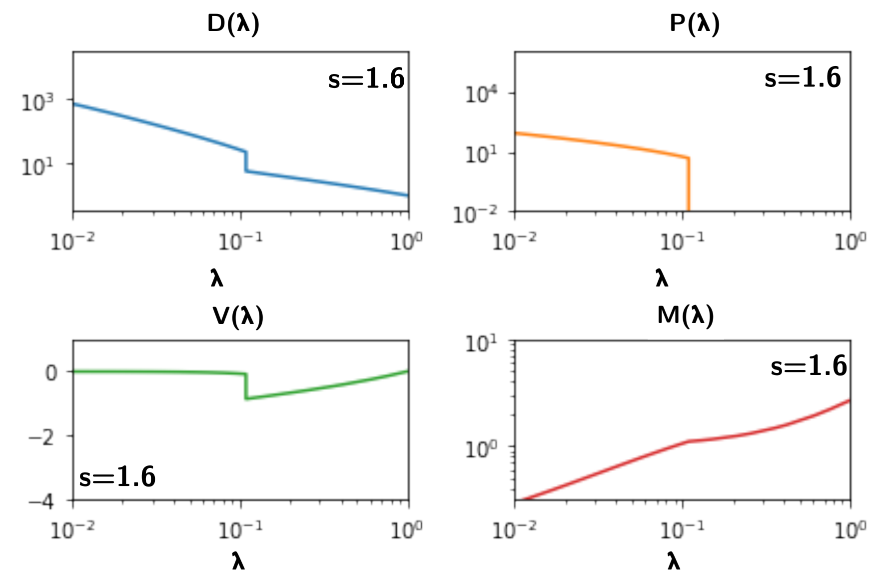
$$(V - \delta\lambda)\, V' - (\delta - 1)V(\lambda) = -\frac{P'}{D} - \frac{1}{3\lambda}M$$

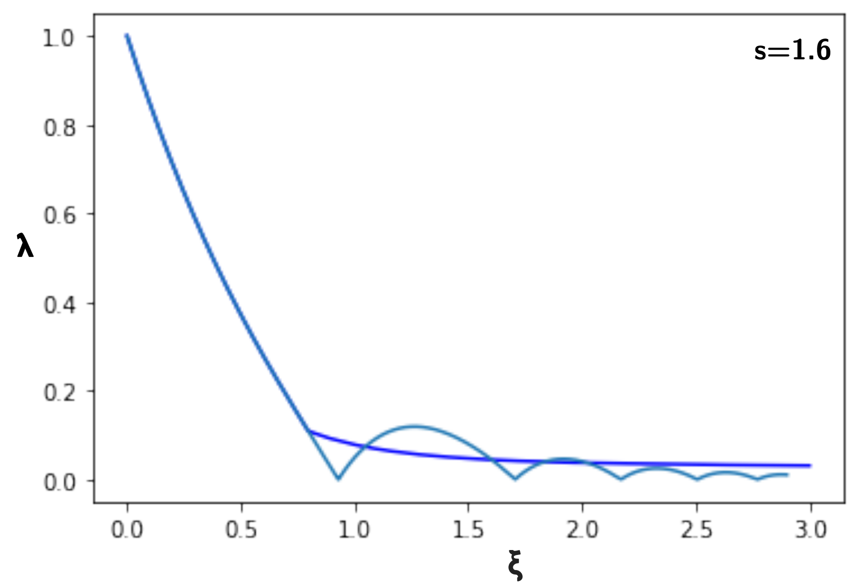
$$(V - \delta\lambda)\left(\frac{P'}{P} - \gamma\frac{D'}{D}\right) = -2(\gamma - 1) - 2(\delta - 1)$$

$$M' = 2\lambda D$$

- These self-similar equations (along with jump conditions) define the 2d filament case. In the cold case, there is an analytical mass-dependent integral:

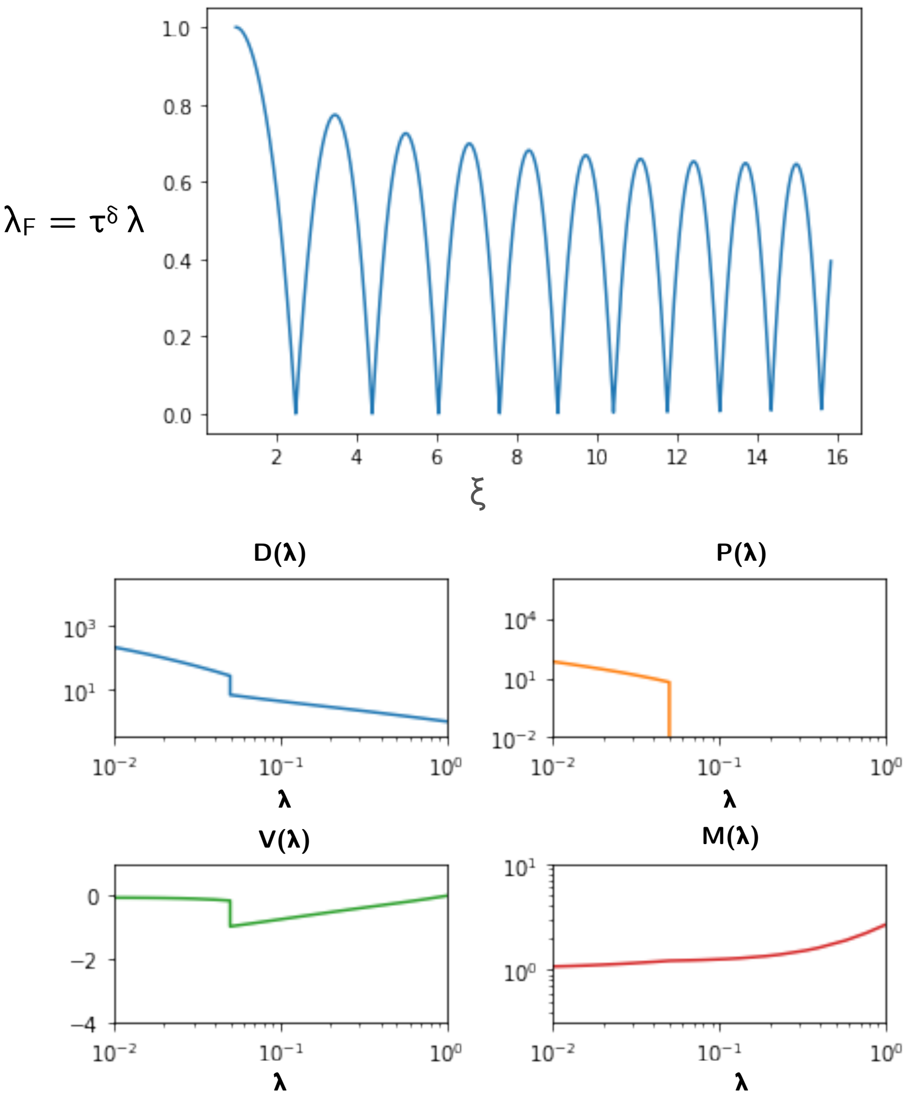
$$V = -\sqrt{\tfrac{2}{3}M\ln(1/\lambda)}$$



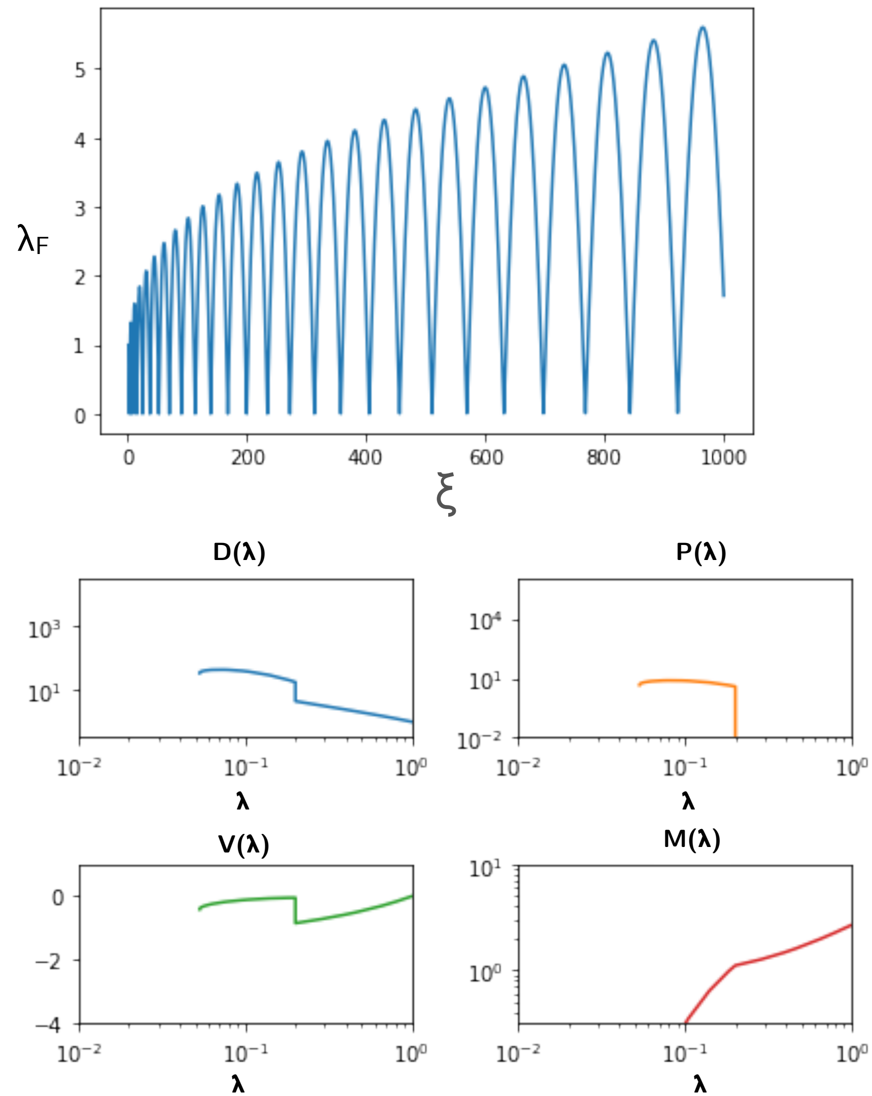


Self-similar solutions: 2d gas and DM

s = 5



s=13/12

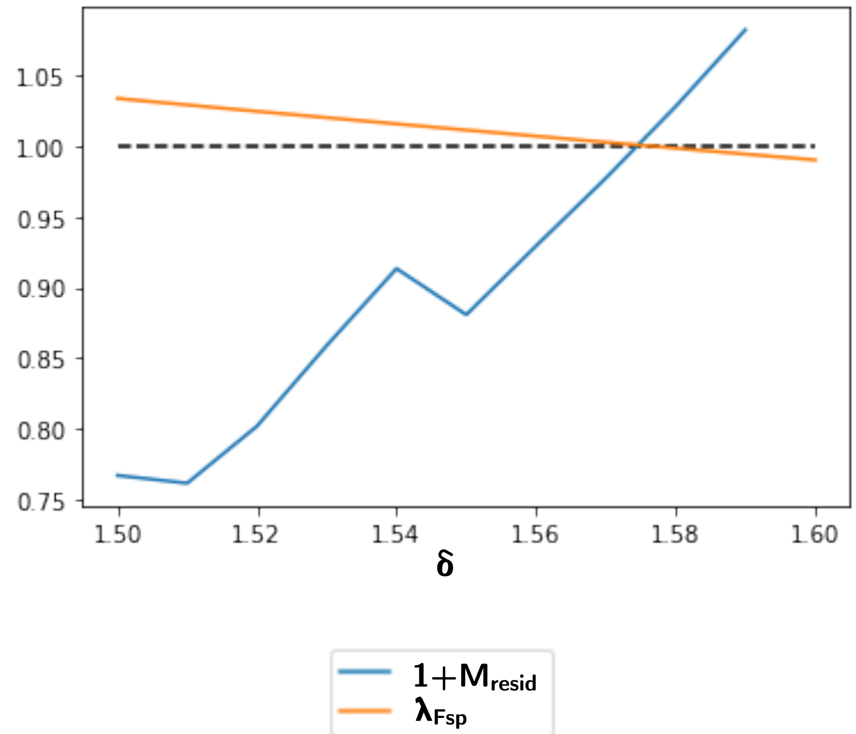


Preliminary results: 2d stability critical point

- What gives? There is 2d critical point at $\delta \approx 1.57$ (or $s \approx 2.71$) This provides a fundamental lower limit to stable filaments accreting in this way.

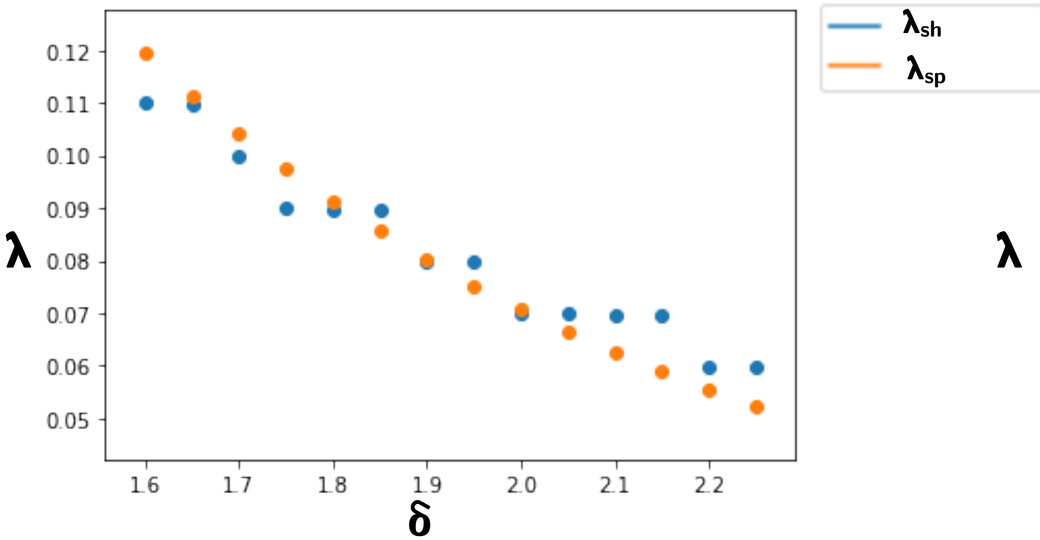
- Why does this happen? Why does self-similarity fail for filaments when δ drops below this threshold?

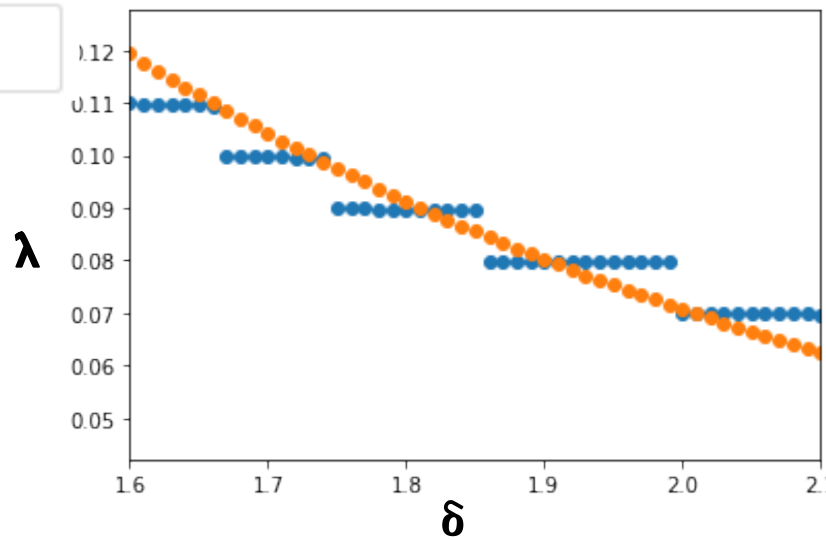
- Some reasons: Hubble flow; gravitational instability; insufficient mass accretion to constrain higher energy particles

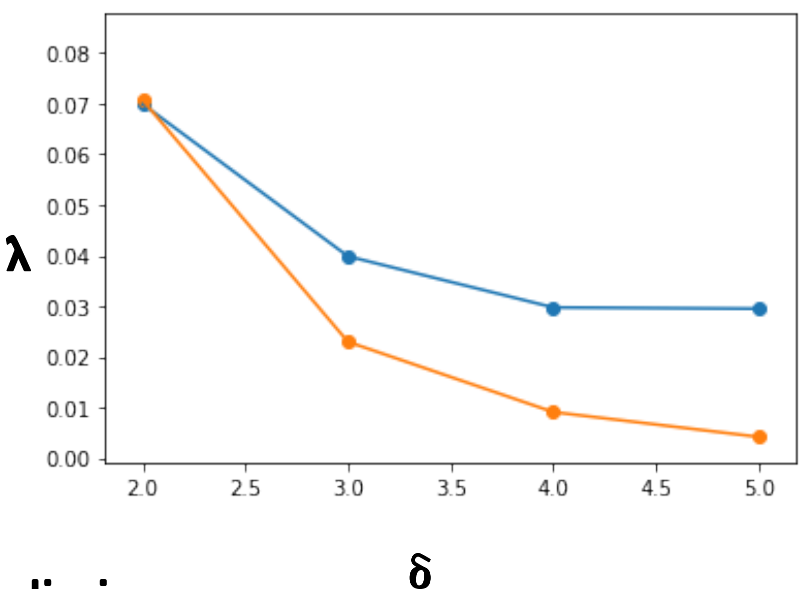


Note: **Orange curve reflects residual mass at the origin. Nonnegative residual mass necessary for stability, or i.e. $1 + M_{resid} \geq 1$. Blue curve is first maxima of the DM trajectory. When this is greater than 1, the solution is unbound.**

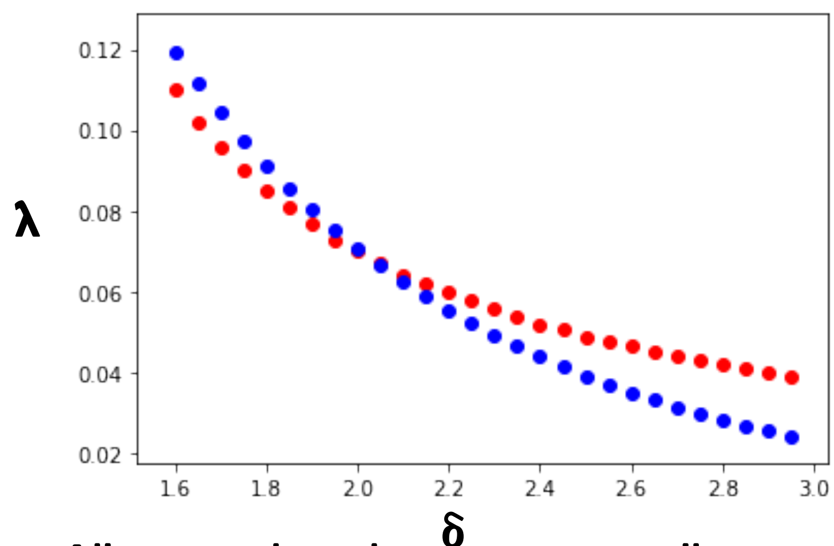
DM splash back and gas shock align?







Preliminary



Alignment less than error up until around δ ≈ 3 at least. (Contrast against the 3d cutoff 5).

Next steps

- Implications for (comparisons with) cosmological N-body simulations.
- How can filament search algorithms be improved with this understanding?
- Incorporating the effect of thermodynamic cooling (cf. Birnboim 2016)
- Explore qualitatively the dependence on the heat capacity ratio (already explicit in our models)
- Effect of a given filament feeding halos or absorbing small halos over time.

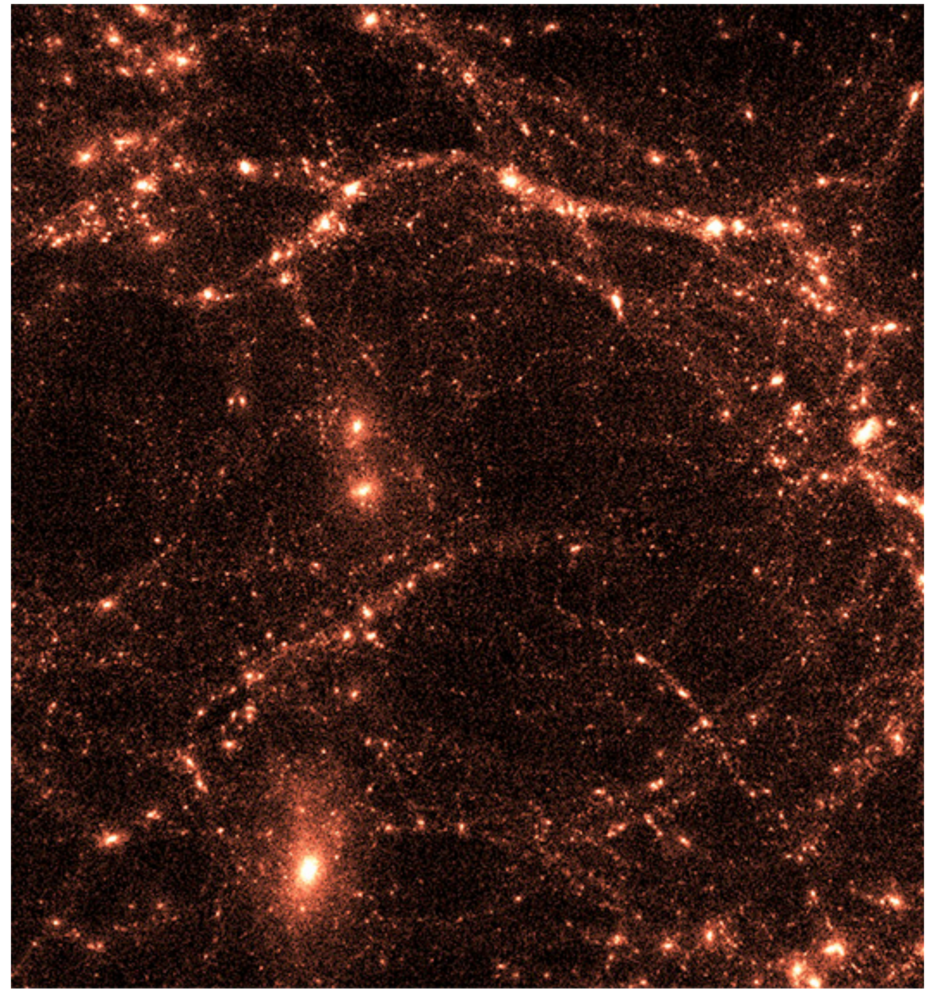


photo credit: Argonne National Laboratory
Cosmological Simulations for Large-Scale Sky Surveys.

Thank you!

- Many thanks to Han Aung and Prof. Daisuke Nagai for their immense help and guidance with this project.

- Numerical integrations were performed in Python 3.0 on a Google Compute Engine, using packages from the `scipy`, `numpy`, and `pandas` libraries. Plots were generated using `matplotlib`. This presentation was arranged in Keynote, with equations typeset in $\LaTeX$.

- Thank you to Yale University and the NASA Connecticut Space Grant Consortium for supporting the presenter.

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