Cosmological Gas Accretion @ z=2
(with: Hernquist, Kereš, Nelson, Sijacki, Springel, Vogelsberger)

&

Accretion-driven Turbulence in Disks
(with: Cacciato, Dekel)

Shy Genel (ITC-Harvard)
Outline

• Following gas flow in Arepo with tracer particles

• Gas accretion onto galaxies at z=2

• Accretion as a turbulence-driver and implications
Tracer particles in Arepo

**Velocity field tracers:**
- Tracer particle
- Mesh point
- Search circle
- Velocity field

**Monte Carlo tracers:**
- Tracer
- Mass fluxes

Genel et al. in prep.
Vogelsberger et al. in prep.
Tracer particles in Arepo – uniform flow

Velocity field tracers

Monte Carlo tracers

Fixed mesh:

Moving mesh:
Tracer particles in Arepo – turbulence

Driven isothermal turbulence (Bauer & Springel 2012), 128^3 cells

- Density PDF
- Density power spectrum

- green: gas
- blue dashed: 10 MC tracer/cell
- blue dotted: 1 MC tracer/cell
- red: velocity field tracers

- green: gas
- blue: 100 MC tracers/cell
- blue dotted: 1 MC tracer/cell
- red dotted: 1 velocity field tracer/cell
- red dashed: 10 velocity field tracers/cell
- black: Kolmogorov
Tracer particles in Arepo – halo centers

Velocity field tracers

Monte Carlo tracers
Accretion bimodality?

Dekel et al. 2009

Kereš et al. 2005

Ocvirk et al. 2008

Kereš et al. 2009
Do cold streams reach the galaxy?

Agertz et al. 2009

Ceverino et al. 2009
Maximum past temperature of galaxy gas

- Agreement at $M < 10^{10.5}M_{\text{sun}}$: $T_{\text{max}} \approx T_{\text{vir}}$

- At $M > 10^{10.5}M_{\text{sun}}$:
  - Both codes show bimodality
  - With Gadget, ‘cold mode’ dominates
  - With Arepo, ‘hot mode’ dominates

Nelson, Vogelsberger, SG et al. in prep.
Cold mode fraction of galaxy gas

• For a hot/cold cut at $T_{\text{vir}}$: gradual transition from cold-dominated to hot-dominated at $10^{10} < M [M_{\odot}] < 10^{12}$

• For a fixed $T_c = 10^{5.5} K$ cut: ‘transition mass’ where $T_{\text{vir}}(M) \approx T_c$ – no ‘cold accretion’ where $T_{\text{vir}} \gg T_c$

Nelson, Vogelsberger, SG et al. in prep.
Possible origins of differences

- With Arepo, some streams heat up
- SPH ‘cold blobs/drizzle’
- Spurious heating by dissipation of turbulence in SPH

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• With Arepo, some streams heat up

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• Spurious heating by dissipation of turbulence in SPH (Bauer & Springel 2012)

Vogelsberger et al. 2012
Possible origins of differences

by dissipation of turbulence in SPH

(Bauer & Springel 2012)
Does temperature even matter?

- Accretion rate remains high(er)

- Issues possibly more important than temperature are:
  - Shocked / non-shocked?
  - Collimated / spherical?
  - Clumpy / smooth?
  - How much angular momentum?
http://www.cfa.harvard.edu/itc/research/movingmeshcosmology/

Moving Mesh Cosmology

This website presents online material related to the first cosmological simulations of galaxy formation with the new moving mesh code AREPO.

Contact: Mark Vogelsberger

Moving mesh cosmology: numerical techniques and global statistics
Mark Vogelsberger, Debora Sijacki, Dusan Keres, Volker Springel, Lars Hernquist

Abstract | arXiv | Images | Movies

Moving mesh cosmology: tracing cosmological gas accretion
Dylan Nelson, Mark Vogelsberger, Shy Genel, Debora Sijacki, Volker Springel, Lars Hernquist

Gadget/Arepo Halo Comparison Project

Gadget | Arepo

Gadget | Arepo

Gadget | Arepo
The Illustris Project

- $(75\,\text{Mpc}/h)^3$ box with $2 \times 1820^3$ resolution elements
- $M > 10^{14} M_{\odot}$ halos @ $z = 0$, resolving down to $M \approx 10^8 M_{\odot}$
- WMAP-7 cosmology
- ✓ DM-only run: done

Genel et al. in prep.
Sijacki et al. in prep.
Vogelsberger et al. in prep.
Illustris galaxy formation physics

- Star formation and evolution: mass loss, SN rates
- Chemical enrichment following 9 elements
- Primordial + metal line cooling
- UV/X-ray cosmic background + AGN proximity effects
- Galactic winds
- BH growth, quasar & radio-mode feedback

Genel et al. in prep.
Sijacki et al. in prep.
Vogelsberger et al. in prep.

AREPO: large scale wind implementation
Quasi-steady state disks

Self-regulation to a mass quasi-steady state driven by cosmological accretion:

\[ \dot{M}_g = \dot{M}_{\text{cosmo}} - \dot{M}_{\text{sink}} \]

\[ \dot{M}_{\text{sink}} = M_g \tau^{-1} \]

\[ \dot{M}_{\text{SFR}} = M_g t_{\text{SF}}^{-1} \]

\[ \dot{M}_g \approx 0 \]

\[ M_g \approx \dot{M}_{\text{cosmo}} \tau \]

\[ M_g = \dot{M}_{\text{cosmo}} t_{\text{SF}} \]

and:

\[ \dot{M}_{\text{SFR}} = \dot{M}_{\text{cosmo}} \]

See also Bouché+ 2010; Elmegreen & Burkert 2010; Davé+ 2011
Quasi-steady state disks

Self-regulation to a **turbulent energy** quasi-steady state driven by cosmological accretion:

\[
\begin{align*}
\dot{E}_\sigma &= \dot{E}_{\text{cosmo}} - \dot{E}_{\text{sink}} \\
\dot{E}_{\text{sink}} &= E_\sigma \tau^{-1} \\
\dot{E}_{\text{dis}} &= E_\sigma t_{\text{dis}}^{-1}
\end{align*}
\]

\[
\begin{align*}
\dot{E}_\sigma &= \approx 0 \\
E_\sigma &\approx \dot{E}_{\text{cosmo}} \tau \\
E_\sigma &= \dot{E}_{\text{cosmo}} t_{\text{dis}} \\
\dot{E}_{\text{dis}} &= \dot{E}_{\text{cosmo}}
\end{align*}
\]

and:

\[
\dot{E}_{\text{dis}} = \dot{E}_{\text{cosmo}}
\]
Gravitationally-driven turbulence

• Writing $E_\sigma \approx M_g \sigma^2$ and $\dot{E}_{\text{cosmo}} \approx \dot{M}_{\text{cosmo}} V_{\text{rot}}^2$, and combining the steady state results:

$$\frac{\sigma}{V_{\text{rot}}} = \sqrt{\frac{t_{\text{dis}}}{t_{\text{SF}}}}$$

• Taking $t_{\text{dis}} \equiv \gamma_{\text{dis}} t_{\text{dyn}} \approx (1 - 3) t_{\text{dyn}}$ ; $t_{\text{SF}} \equiv \frac{t_{\text{dyn}}}{\epsilon_{\text{SF}}} \approx \frac{t_{\text{dyn}}}{0.02}$, we obtain a fiducial value:

$$\frac{\sigma}{V_{\text{rot}}} = \sqrt{\epsilon_{\text{SF}} \gamma_{\text{dis}}} \approx 0.2 \quad \Rightarrow \quad Q \approx \sqrt{2 \delta^{-1}} \frac{\sigma}{V_{\text{rot}}} \approx 0.3 \delta^{-1}$$

Gravitationally-driven turbulence

\[
\frac{\sigma}{V_{\text{rot}}} = \sqrt{\epsilon_{\text{SF}} \gamma_{\text{dis}}} \approx 0.2 \quad \Rightarrow \quad Q \approx \sqrt{2\delta^{-1}} \frac{\sigma}{V_{\text{rot}}} \approx 0.3\delta^{-1}
\]

In the local Universe:

• Gas velocity dispersions of \(\sigma \approx 10\text{km/s}\), and

\[
\frac{\sigma}{V_{\text{rot}}} \approx 0.05 \quad \times 5
\]

• Gas fraction \(\delta \sim 0.03 \times 10\)

At high redshift (\(z \sim 2\)):

• Gas velocity dispersions of \(\sigma \approx 40 - 80\text{km/s}\), and

\[
\frac{\sigma}{V_{\text{rot}}} \approx 0.25
\]

• Gas fraction \(\delta \sim 0.3\)

\[
Q \approx \sqrt{2\delta^{-1}} \frac{\sigma}{V_{\text{rot}}} \sim 2 - 3 \quad \div 2 \quad Q \approx \sqrt{2\delta^{-1}} \frac{\sigma}{V_{\text{rot}}} \sim 1
\]