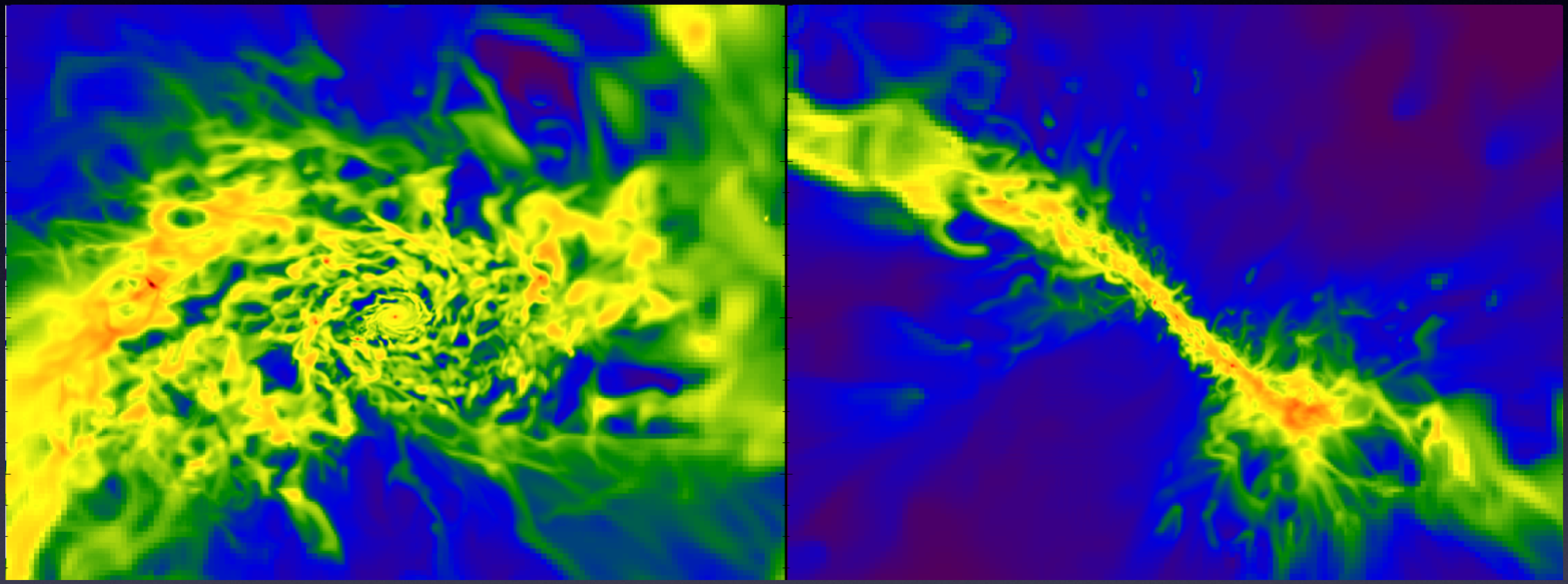
Gas Inflows and Outflows: Cosmic flow penetration and gas recycling



IGM@50
June 8, 2015

Colin DeGraf
Hebrew University of Jerusalem

With Avishai Dekel

Outline

- Motivation
- Flow evolution with redshift
- Flow evolution with radius
- Inflow/Outflow direction
- Gas recycling

Motivation

- Matter flow onto halos:

$$\frac{\dot{M}_h}{M_h} \propto M_{12}^{0.14} (1+z)^{5/2}$$

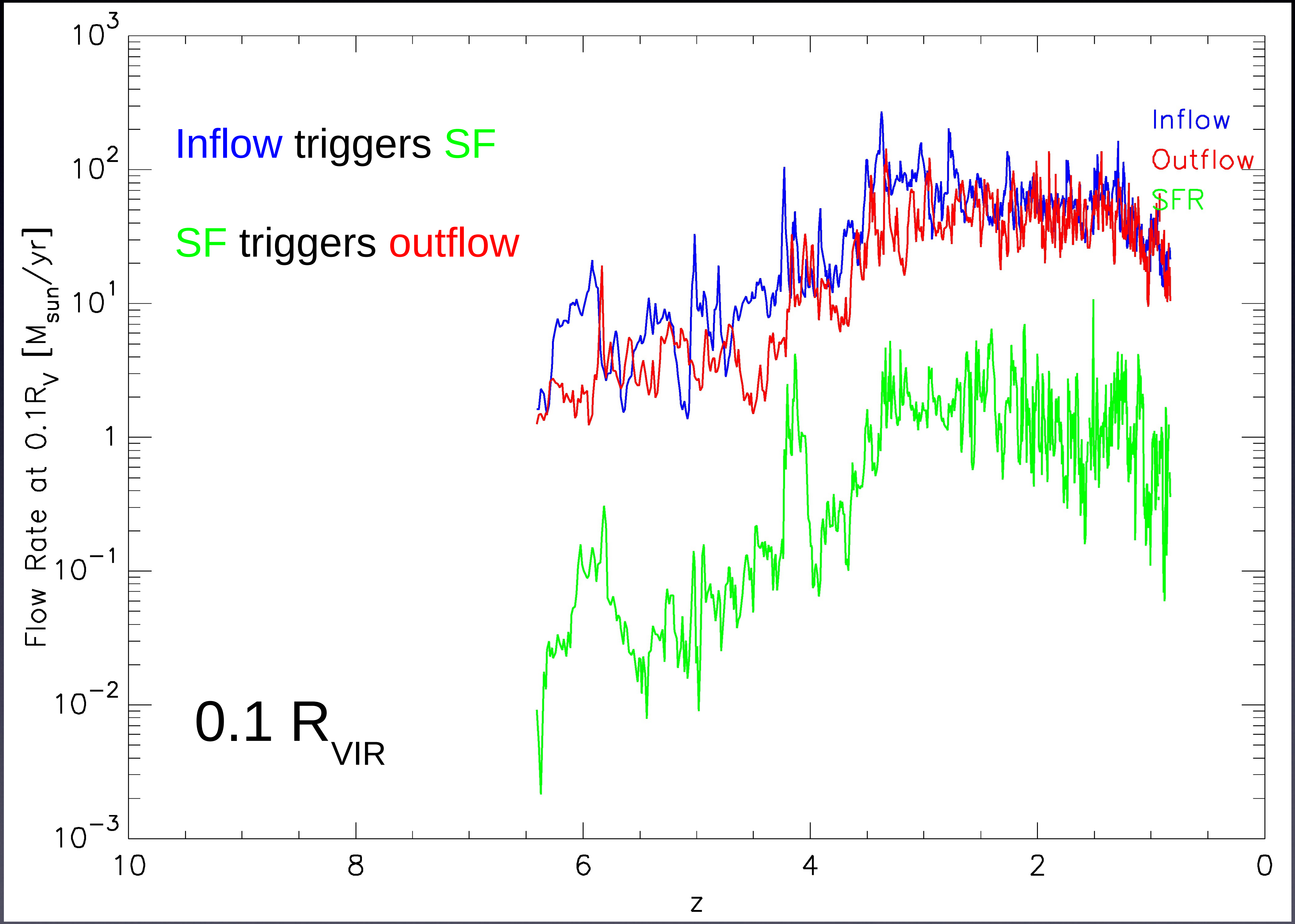
(Dekel et al. 2013)

- How efficiently does this gas reach the central galaxy?
- What about outflowing gas?

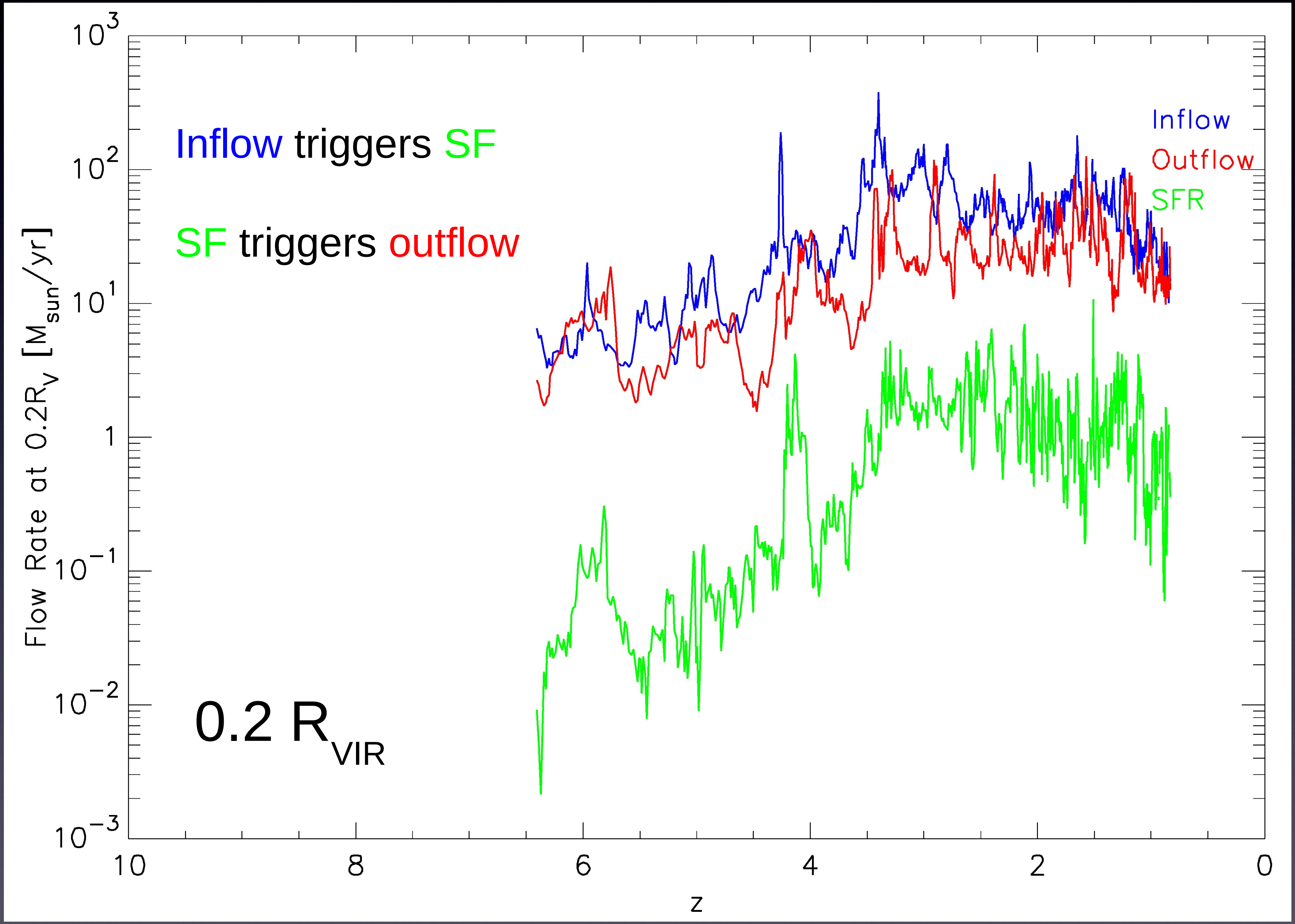
Simulations

- AMR (grid) code HYDRO-ART (Kravtsov+ 1997, Kravtsov 2003)
- Gas Cooling, Star Formation, Stellar Feedback
  (Ceverino & Klypin 2009, Ceverino, Dekel & Bournaud 2010)
  - Atomic H and He, metal and molecular line cooling (T_{min} ~ 300K)
  - SF in <10^4 K , > 1 cm^{-3} gas
  - Thermal feedback from stellar winds and SNII
  - Radiation pressure in cells neighboring young stars
- Maximum resolution ~35-70 pc
- 34 galaxies for z>~1
  - Focus on 8 galaxies, 500-1200 snapshots each

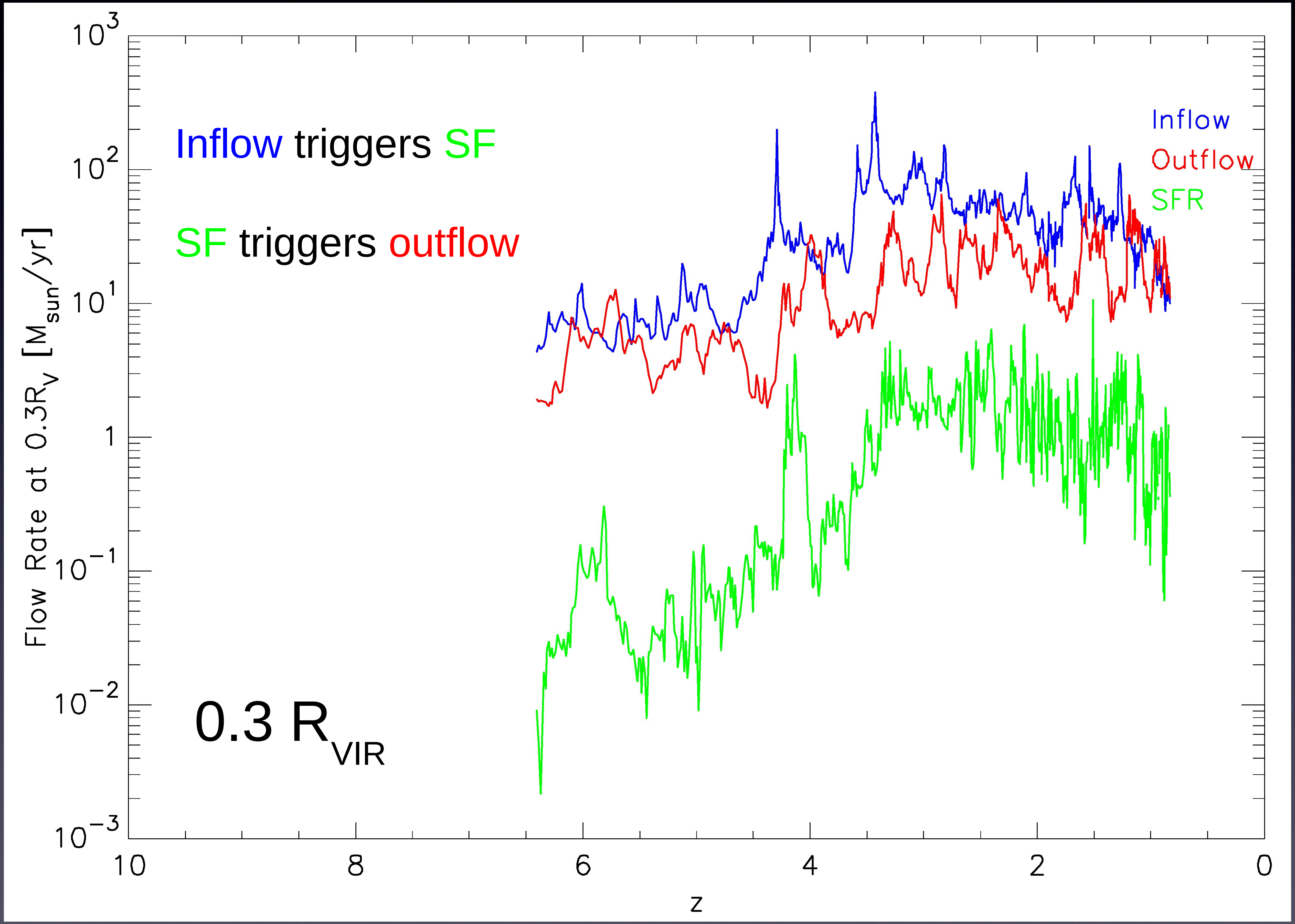
Typical Flow vs. Time



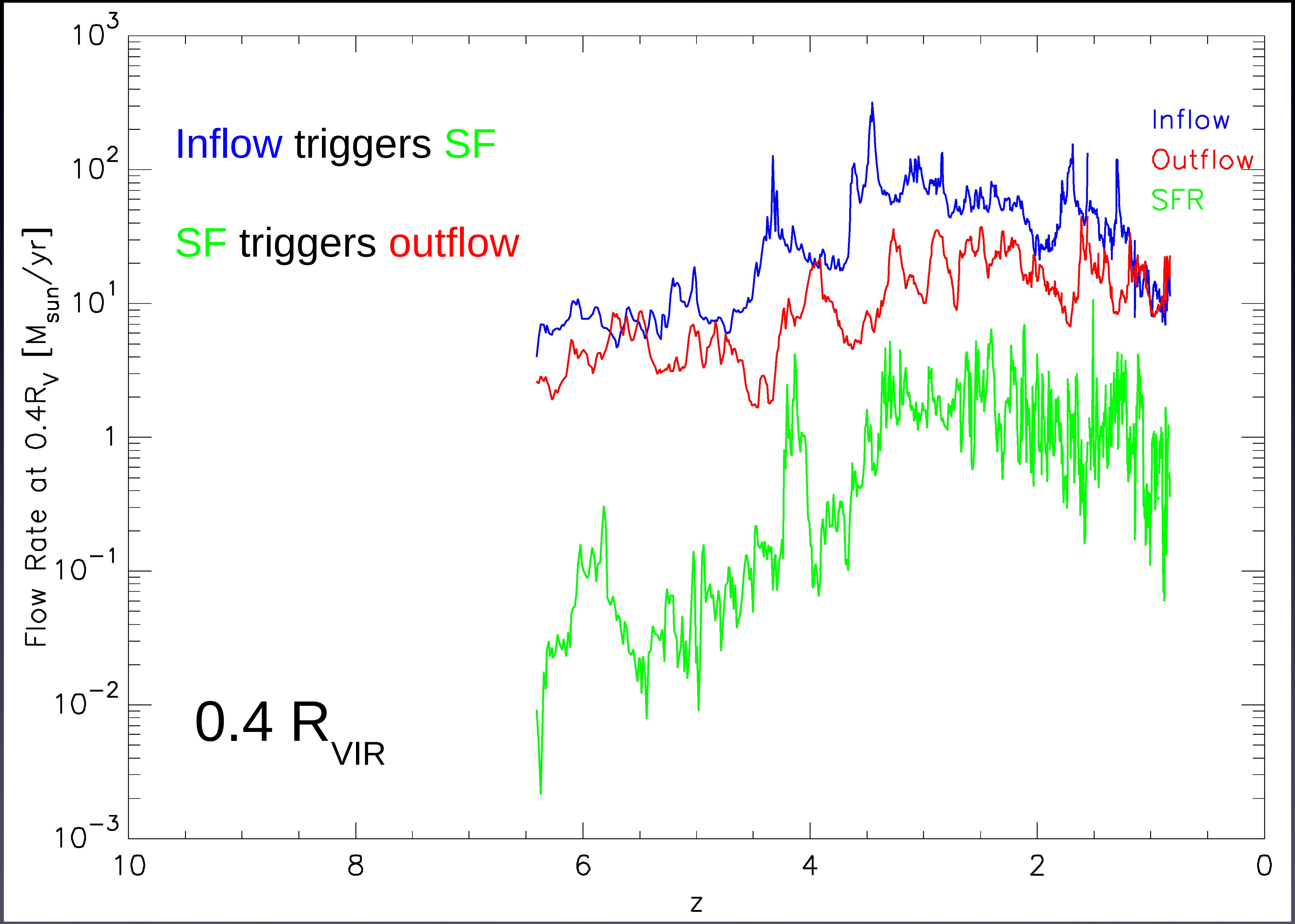
Typical Flow vs. Time



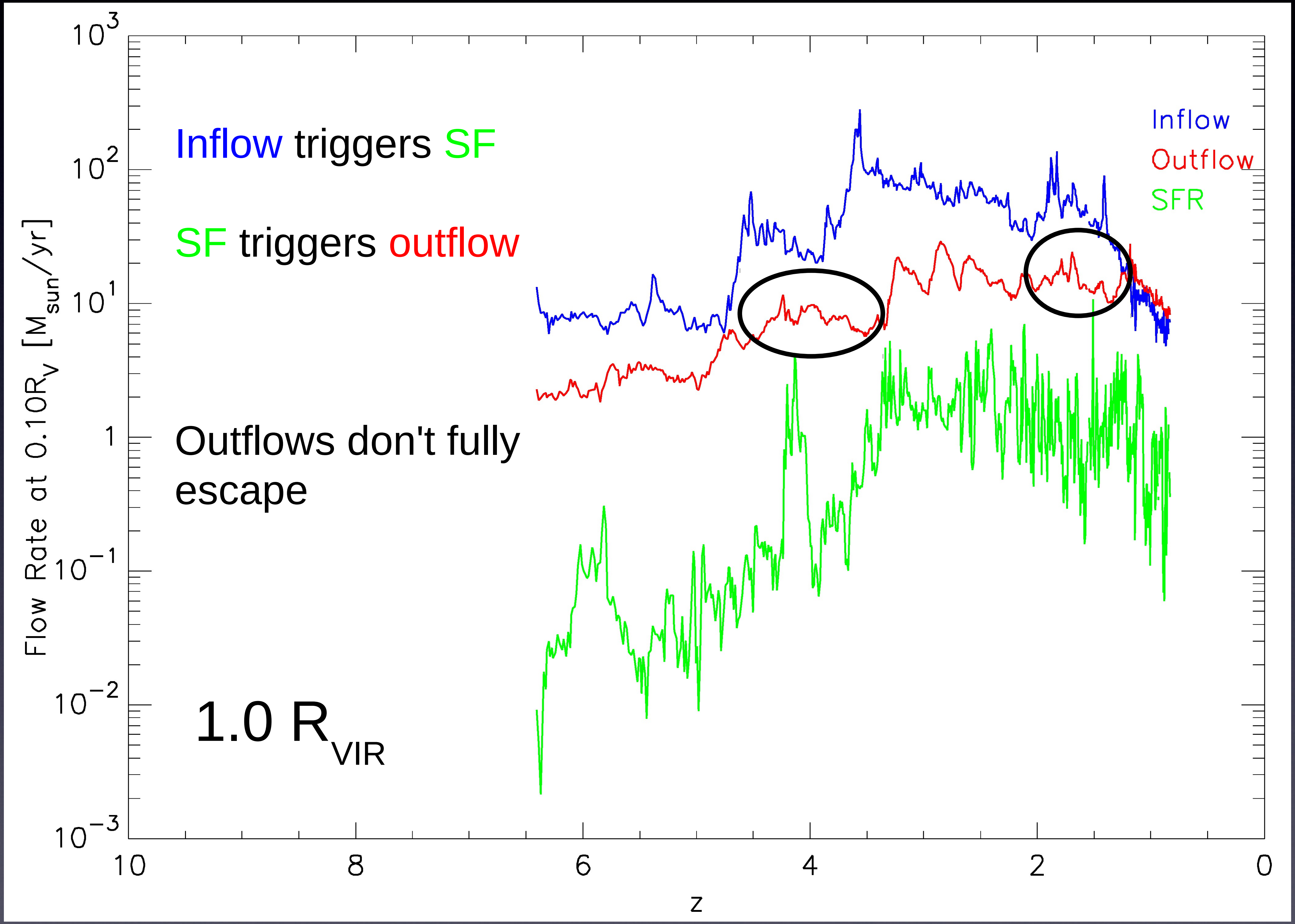
Typical Flow vs. Time



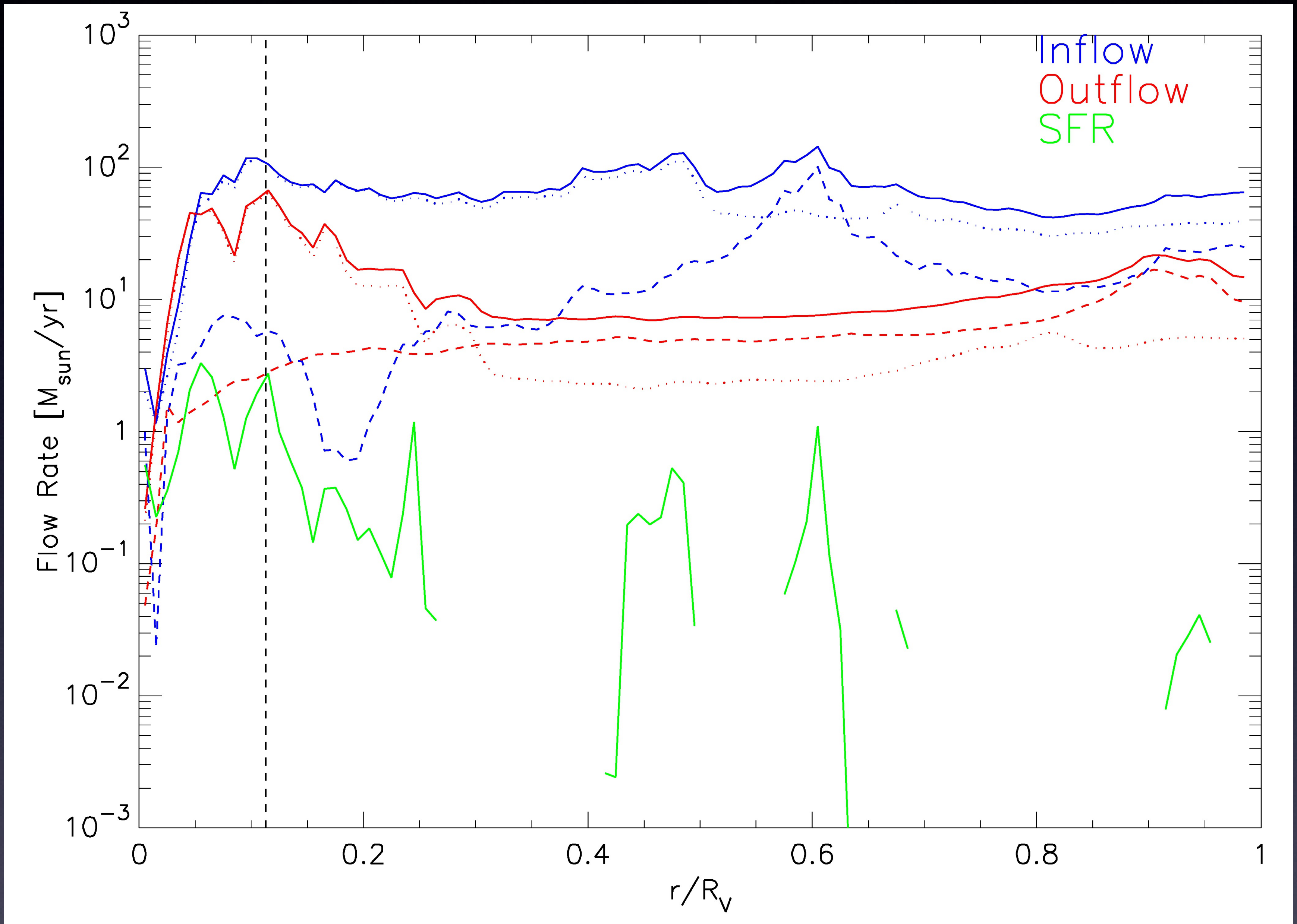
Typical Flow vs. Time



Typical Flow vs. Time



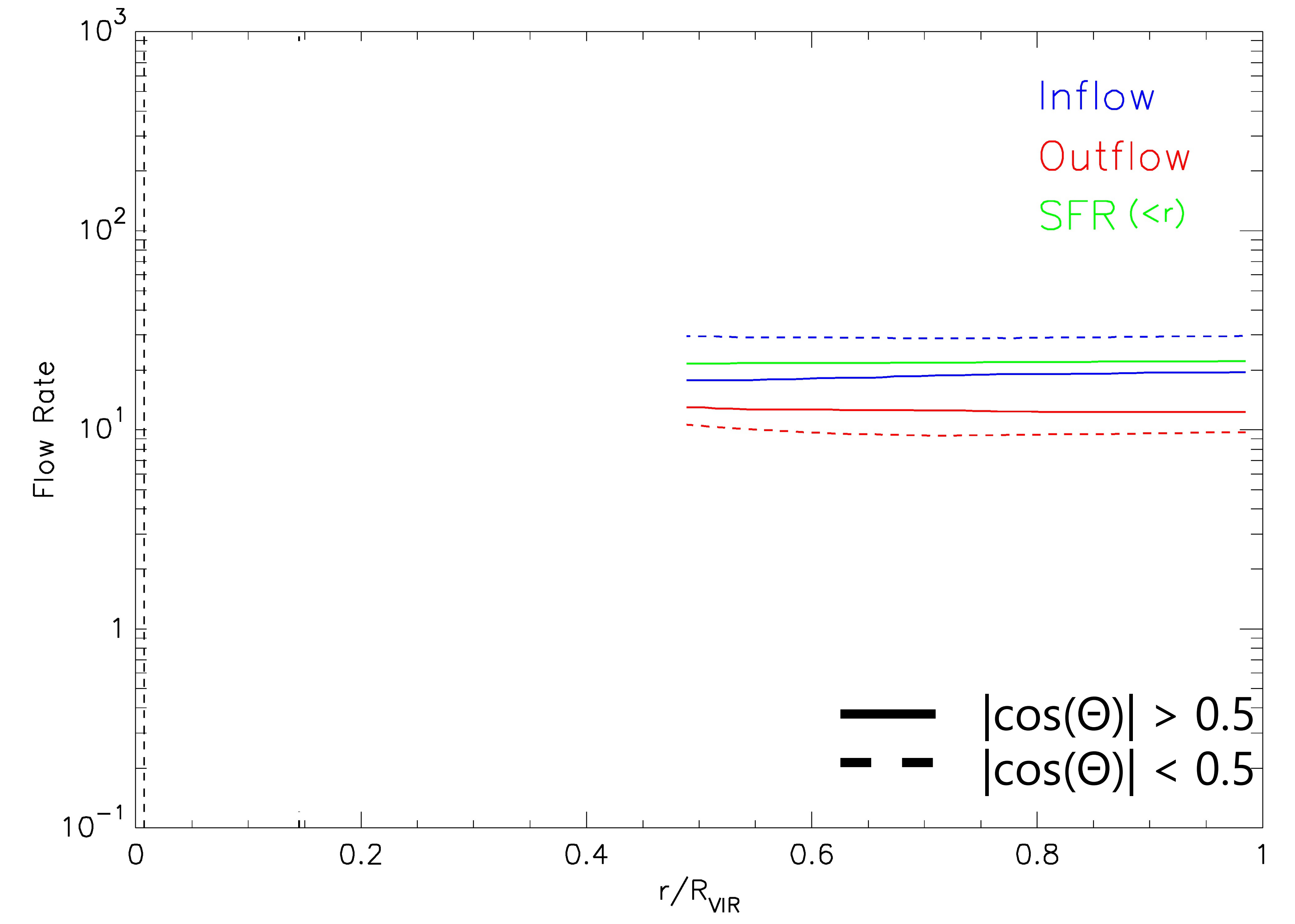
Typical Flow vs. r



- Inflow – Planar
- Outflow:
  small r - Planar
  large r - Polar
- Planar outflow is stopped at ~0.2 R_{vir}

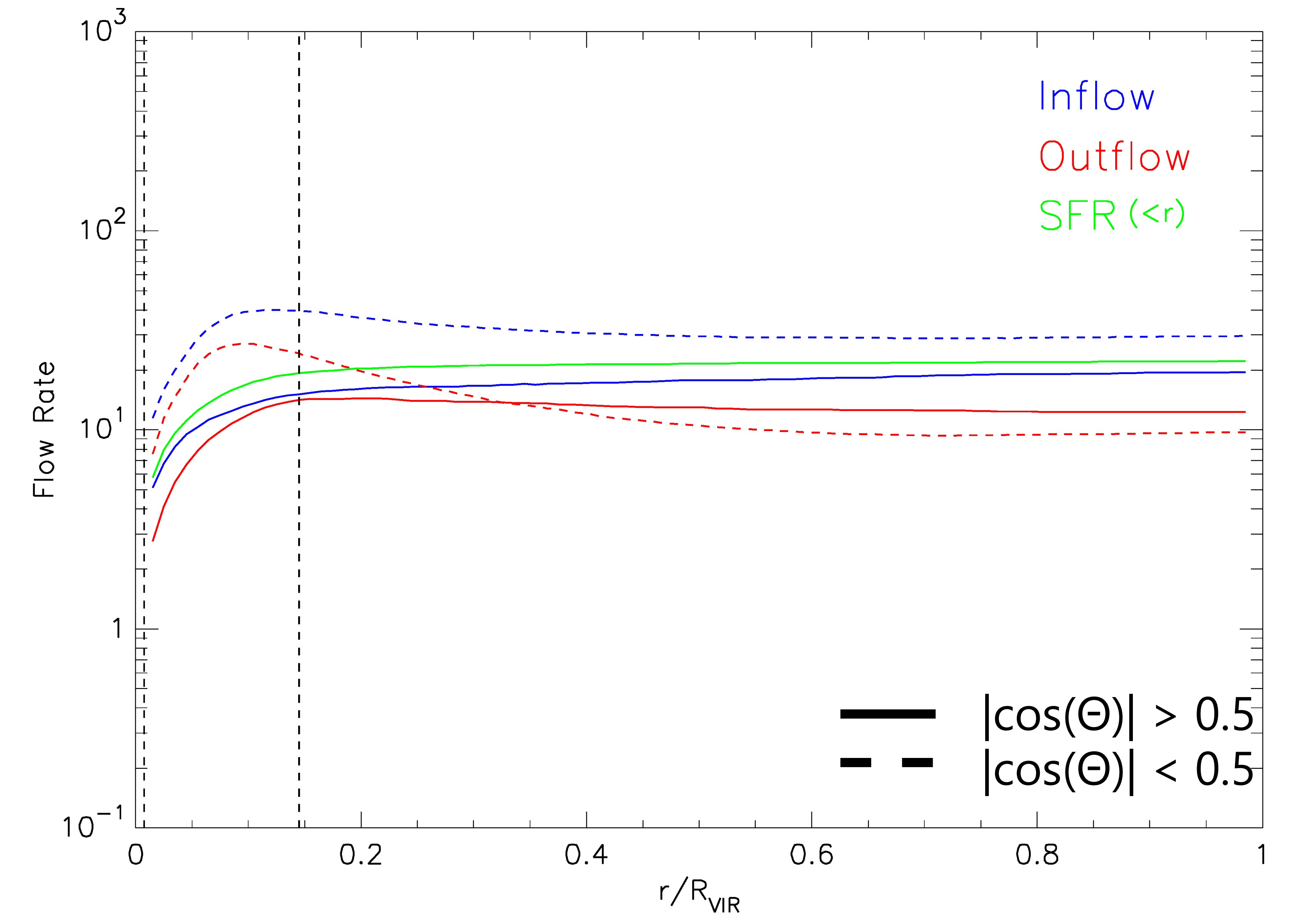
Stacked Flow Behavior

- Outer regions:
  Planar infow
  Polar outflow

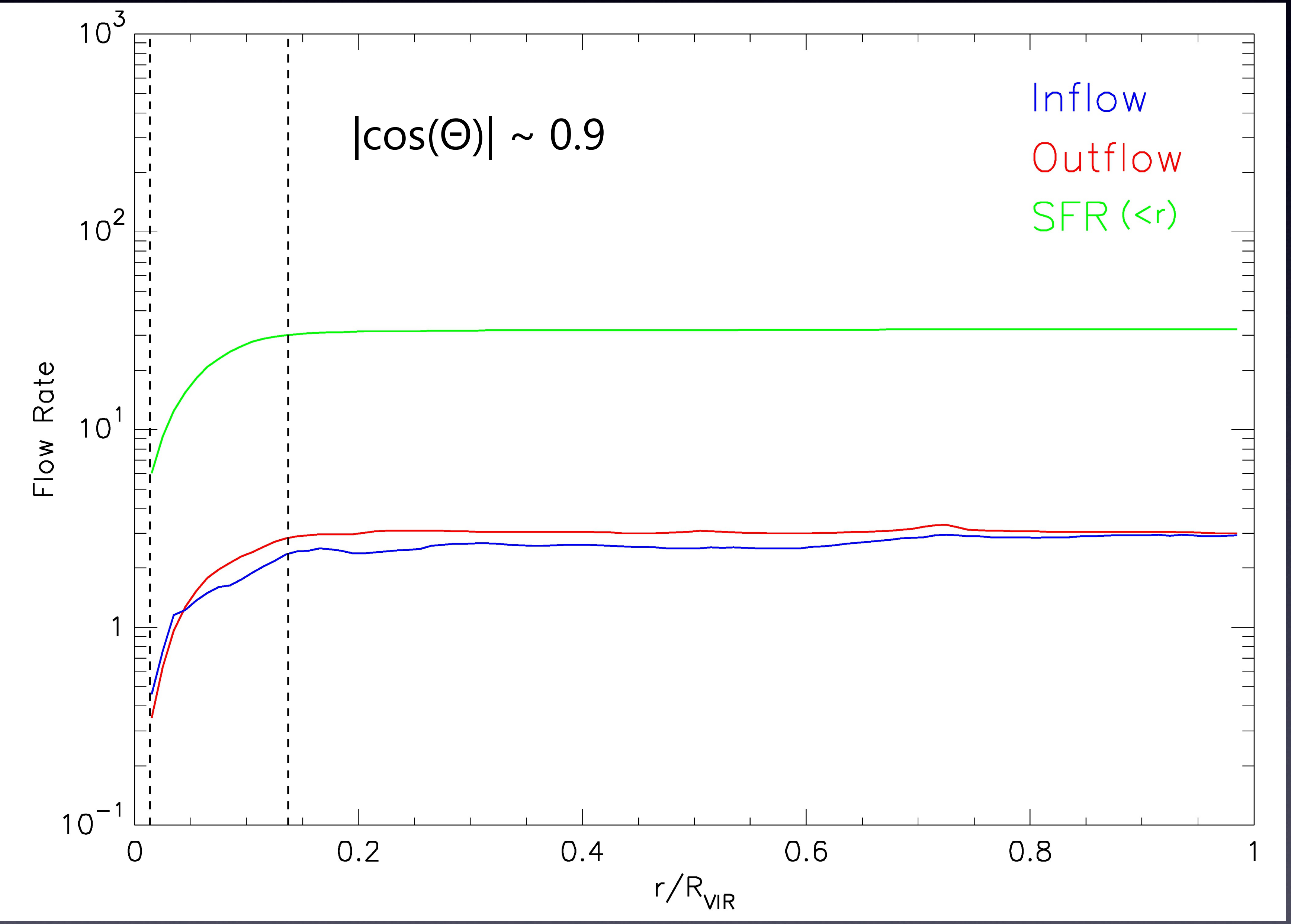


Stacked Flow Behavior

- Outer regions:
  Planar infow
  Polar outflow
- Inner regions:
  Strong planar outfow

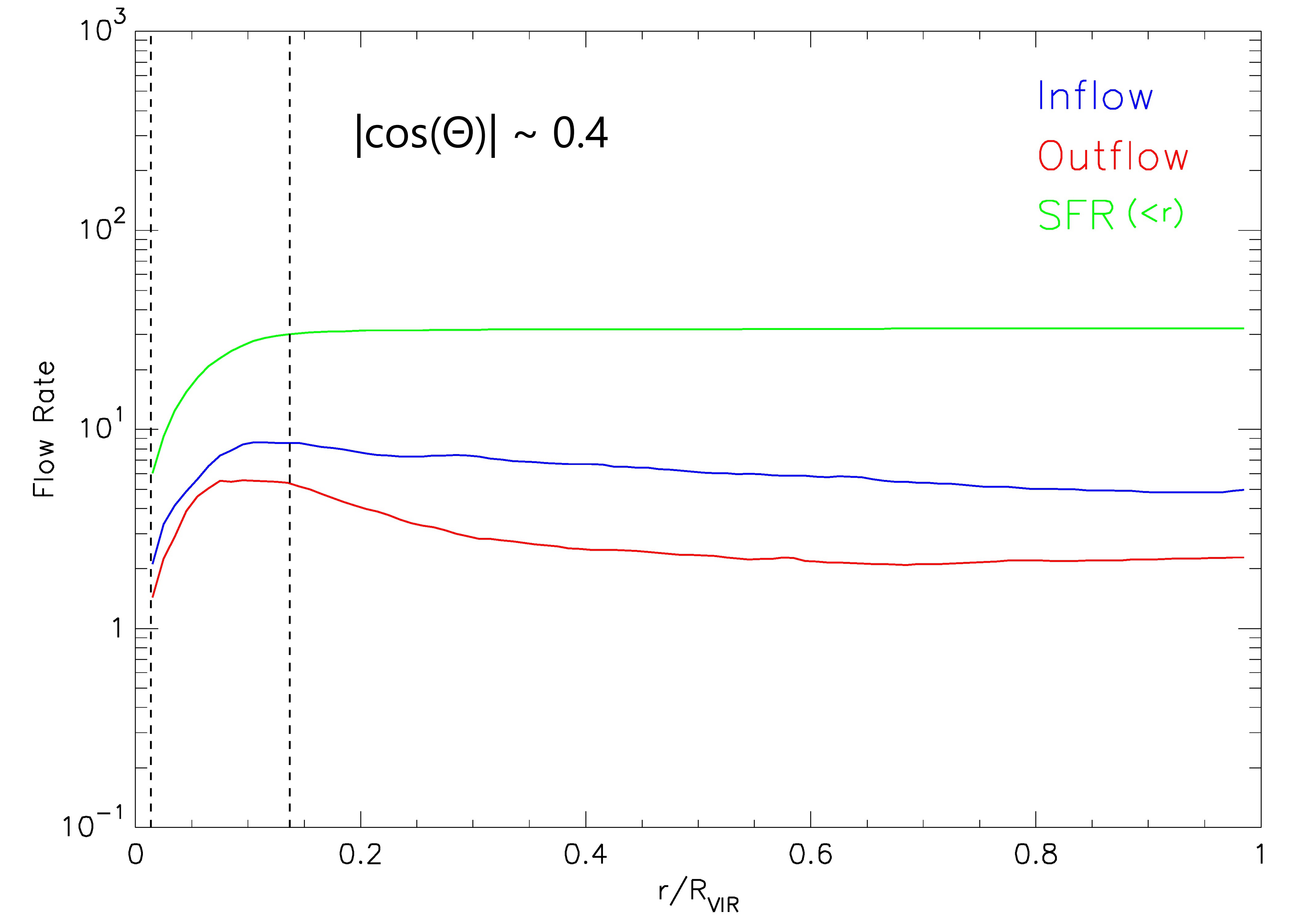


Planar Flow



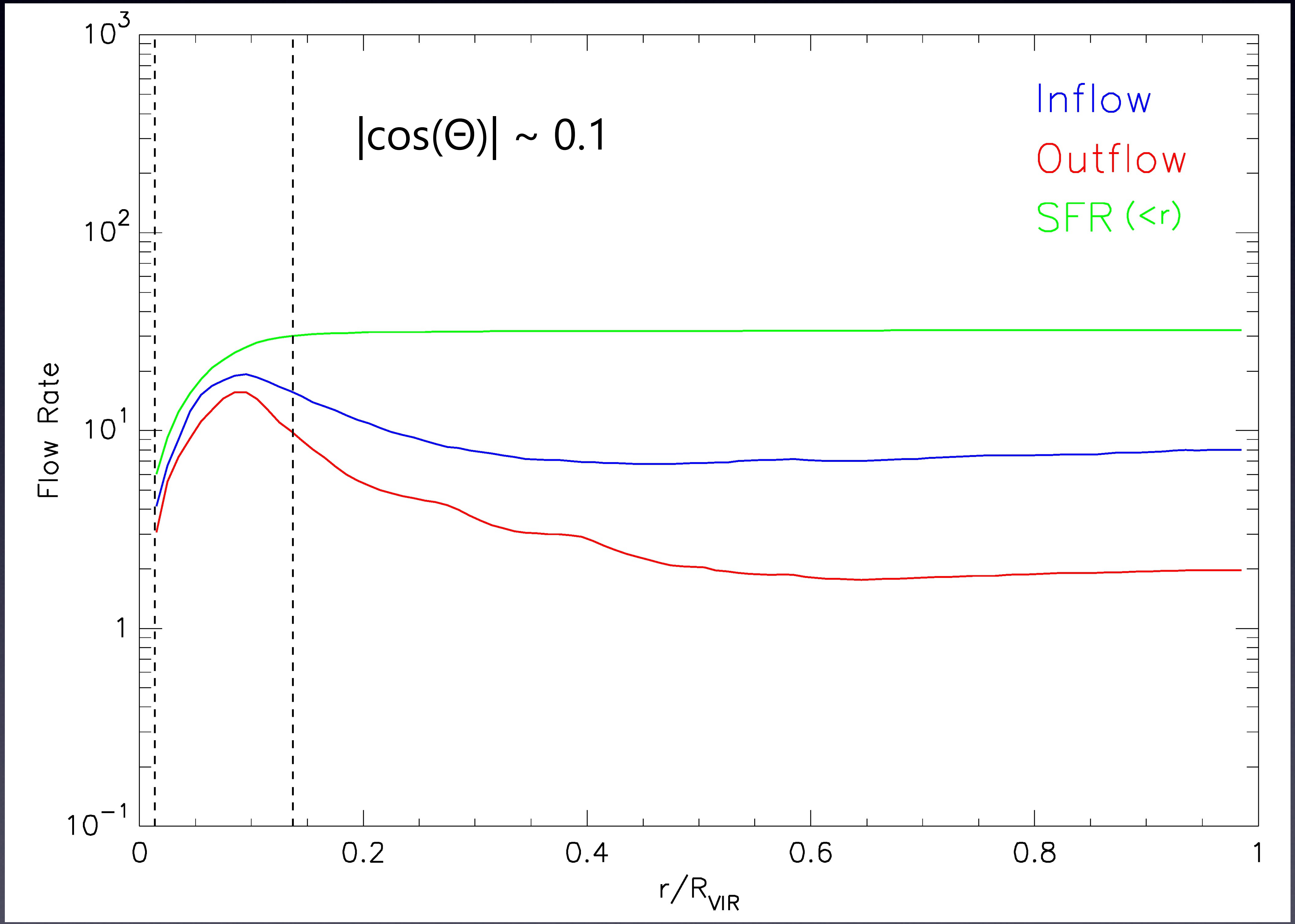
- Smooth flow at all r

Planar Flow



- Outflow decreases out to ~0.3 R_{vir}

Planar Flow



- In- and Out-flows decrease out to ~0.3-0.4 R_{VIR}

Edge on Flow

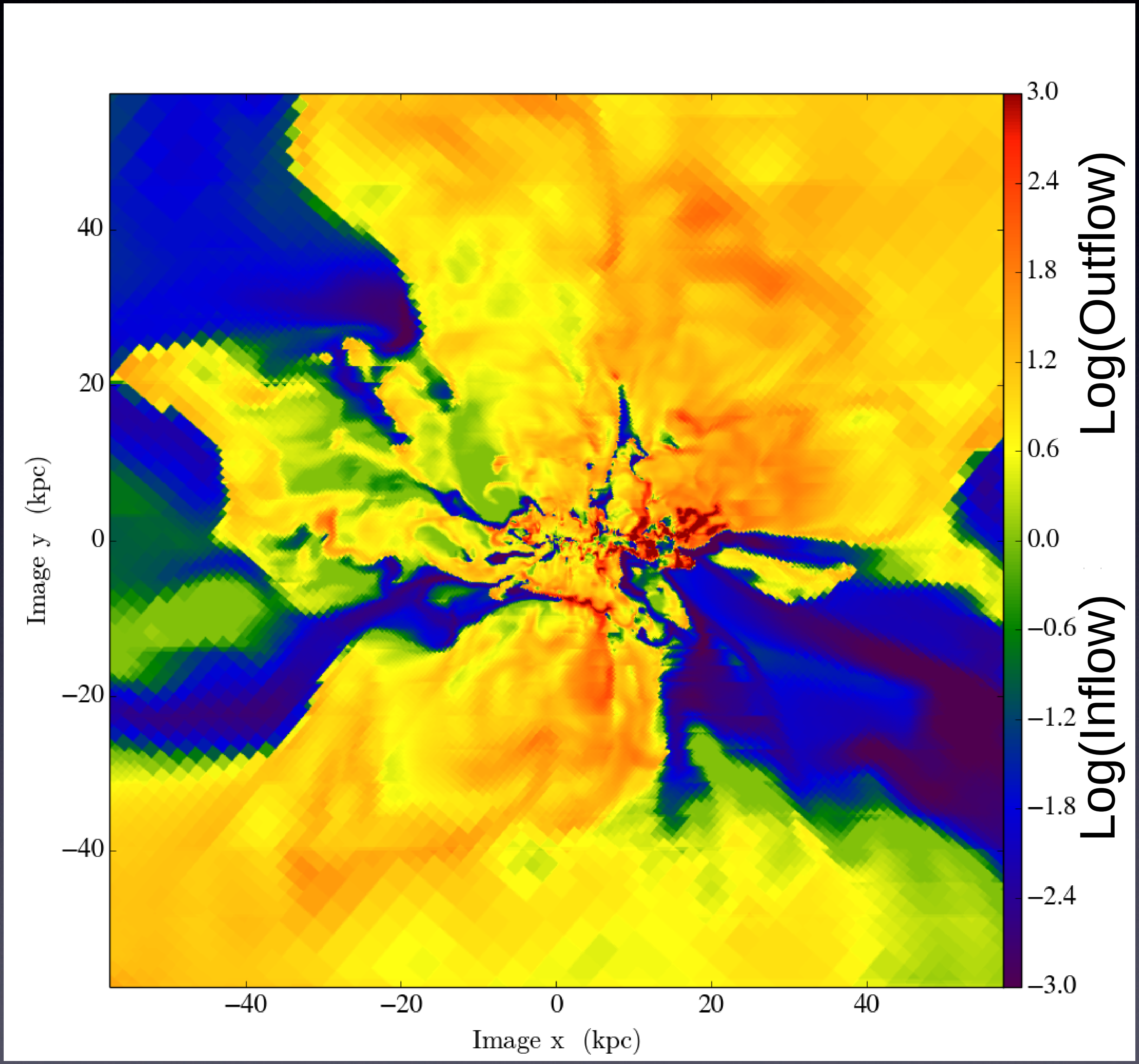


Image x (kpc)
Image y (kpc)
−40
−20
0
20
40
3.0
2.4
1.8
1.2
0.6
0.0
−0.6
−1.2
−1.8
−2.4
−3.0
Log(Outflow)
Log(Inflow)

Face on Flow

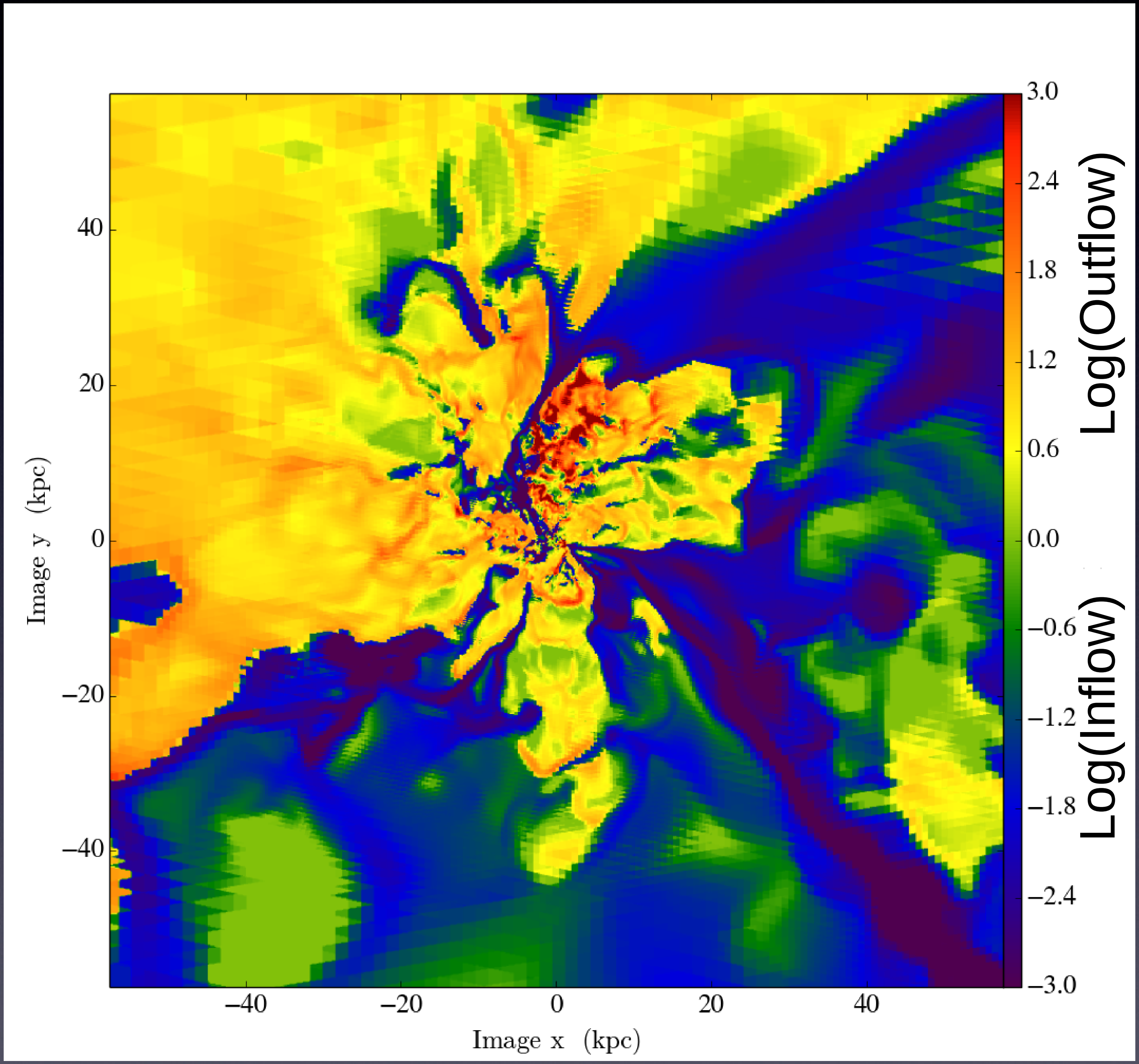
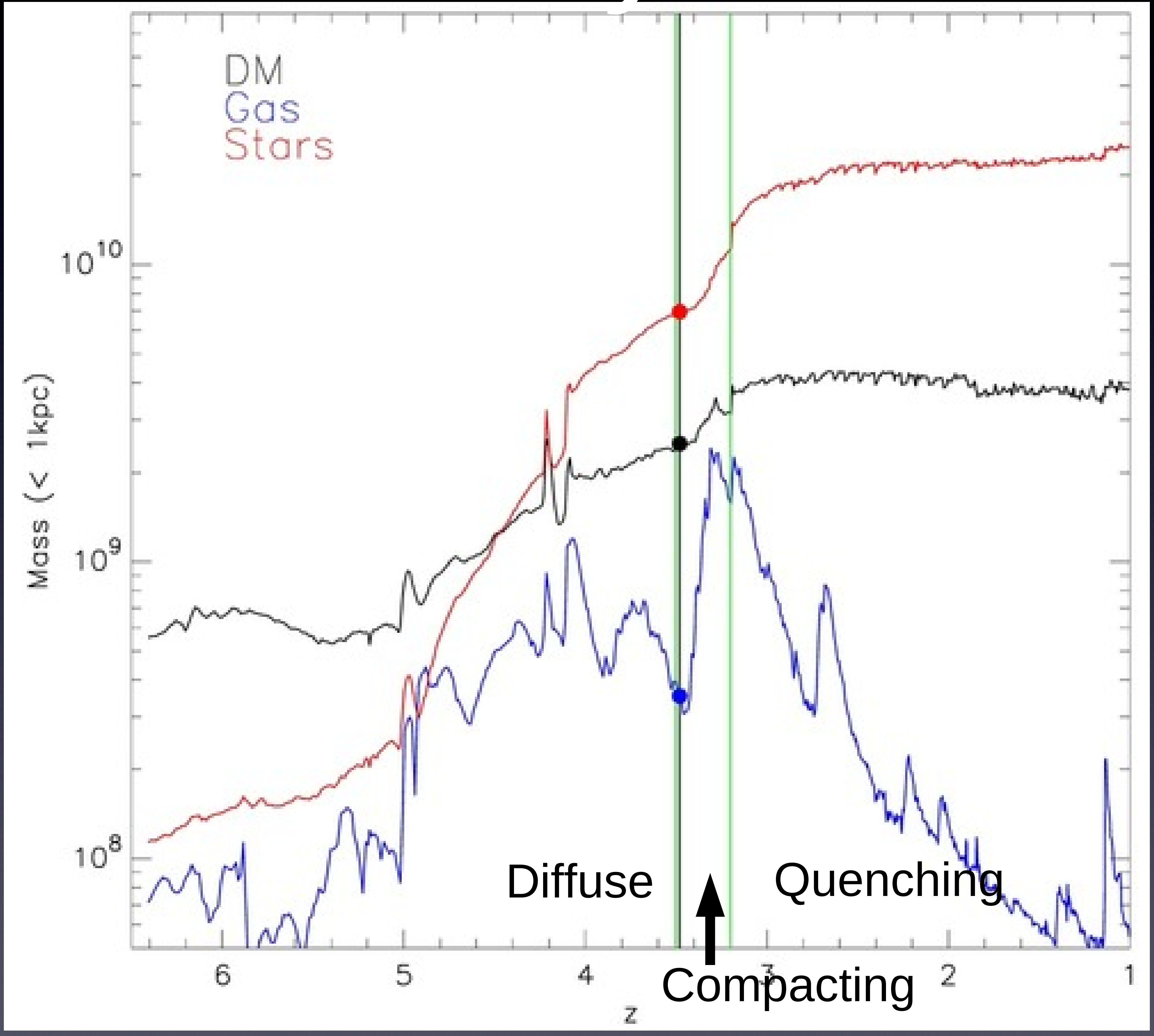
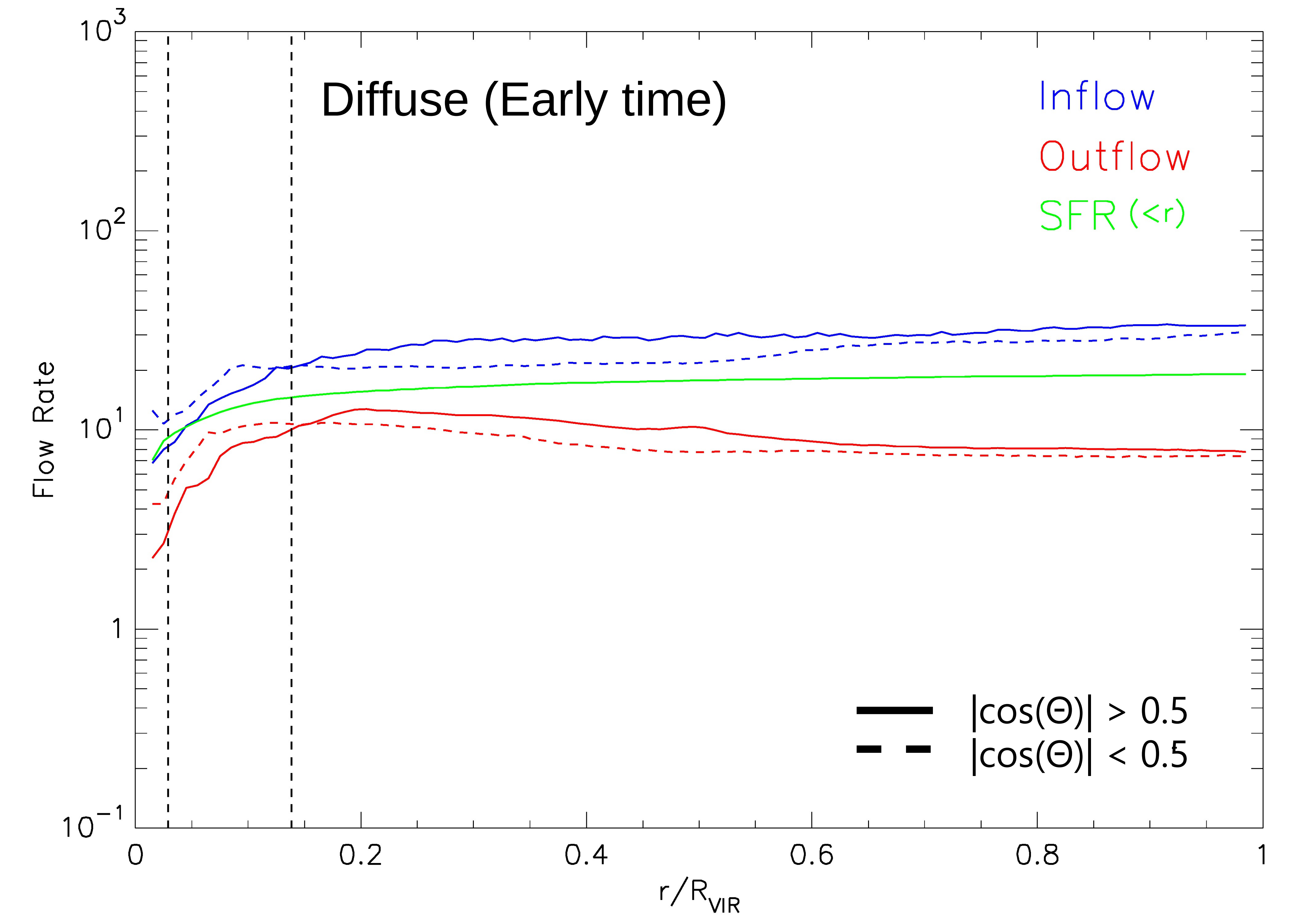


Image y (kpc)
40
20
0
−20
−40
Image x (kpc)
−40
−20
0
20
40
3.0
2.4
1.8
1.2
0.6
0.0
−0.6
−1.2
−1.8
−2.4
−3.0
Log(Outflow)
Log(Inflow)

Evolutionary Phases



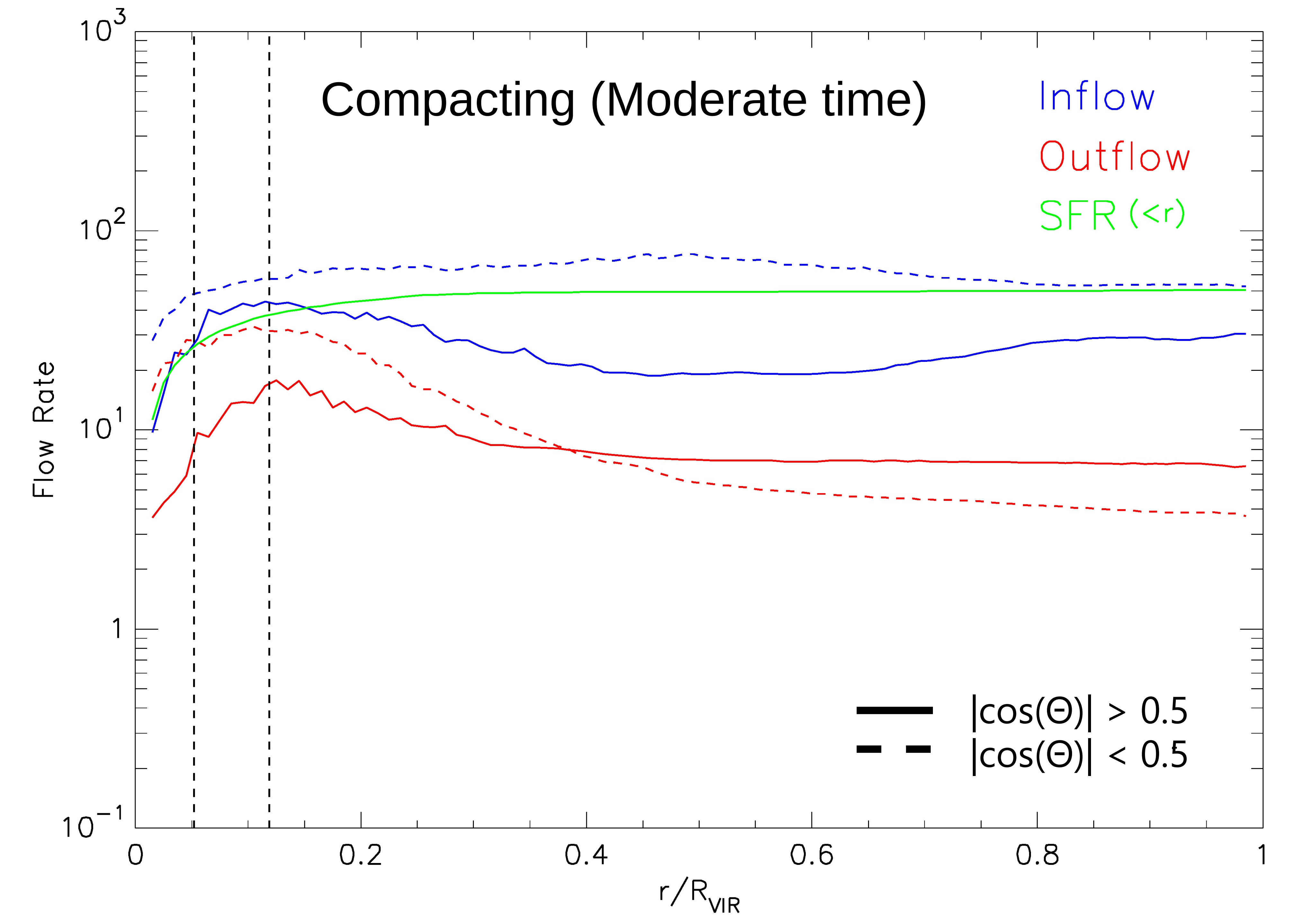
Evolutionary Phases



Diffuse

- In > Out
- Flow constant with r
- No planar dependence

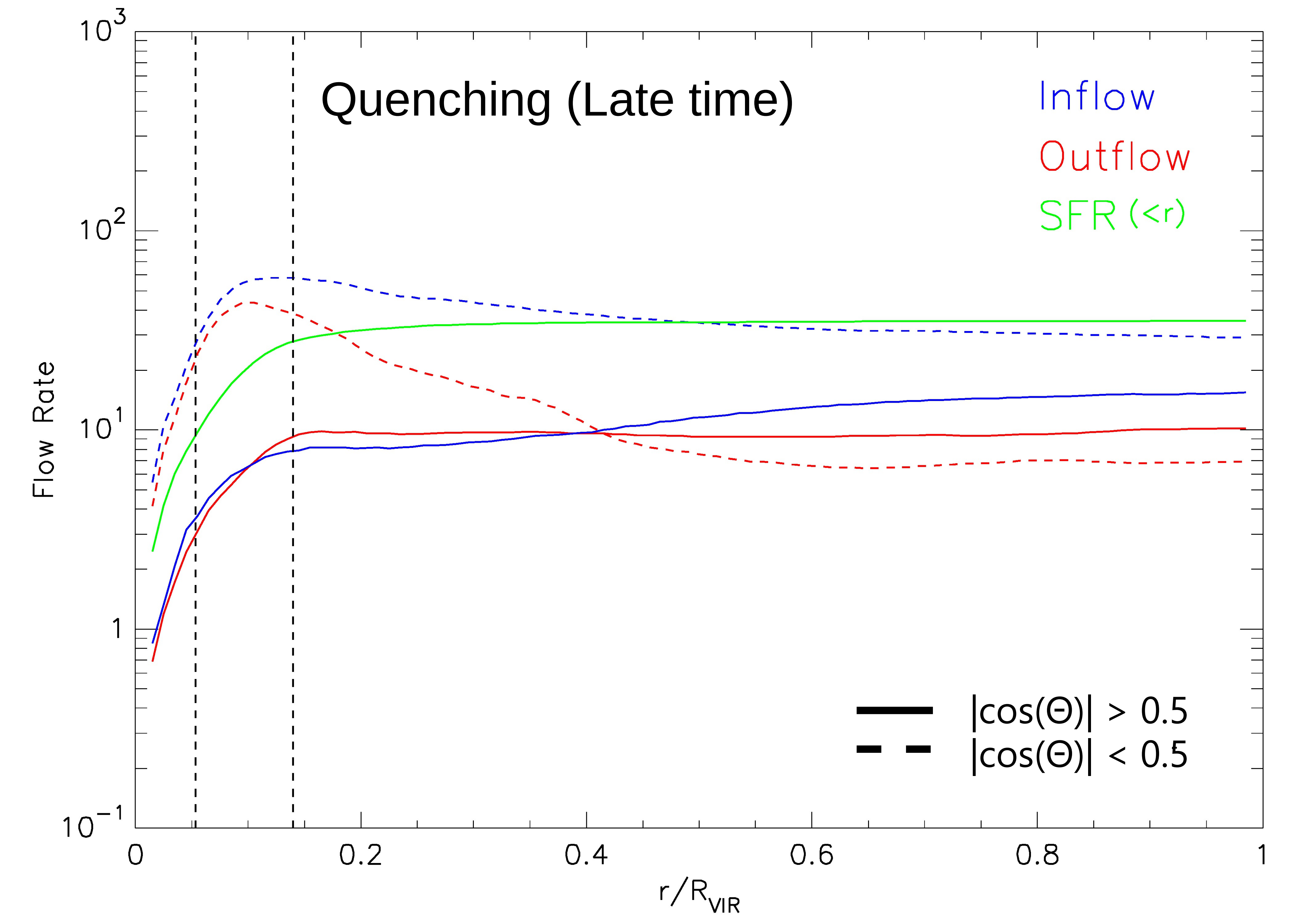
Evolutionary Phases



Compacting

- In > Out
- Stronger flow at small r
- Significant planar dependence

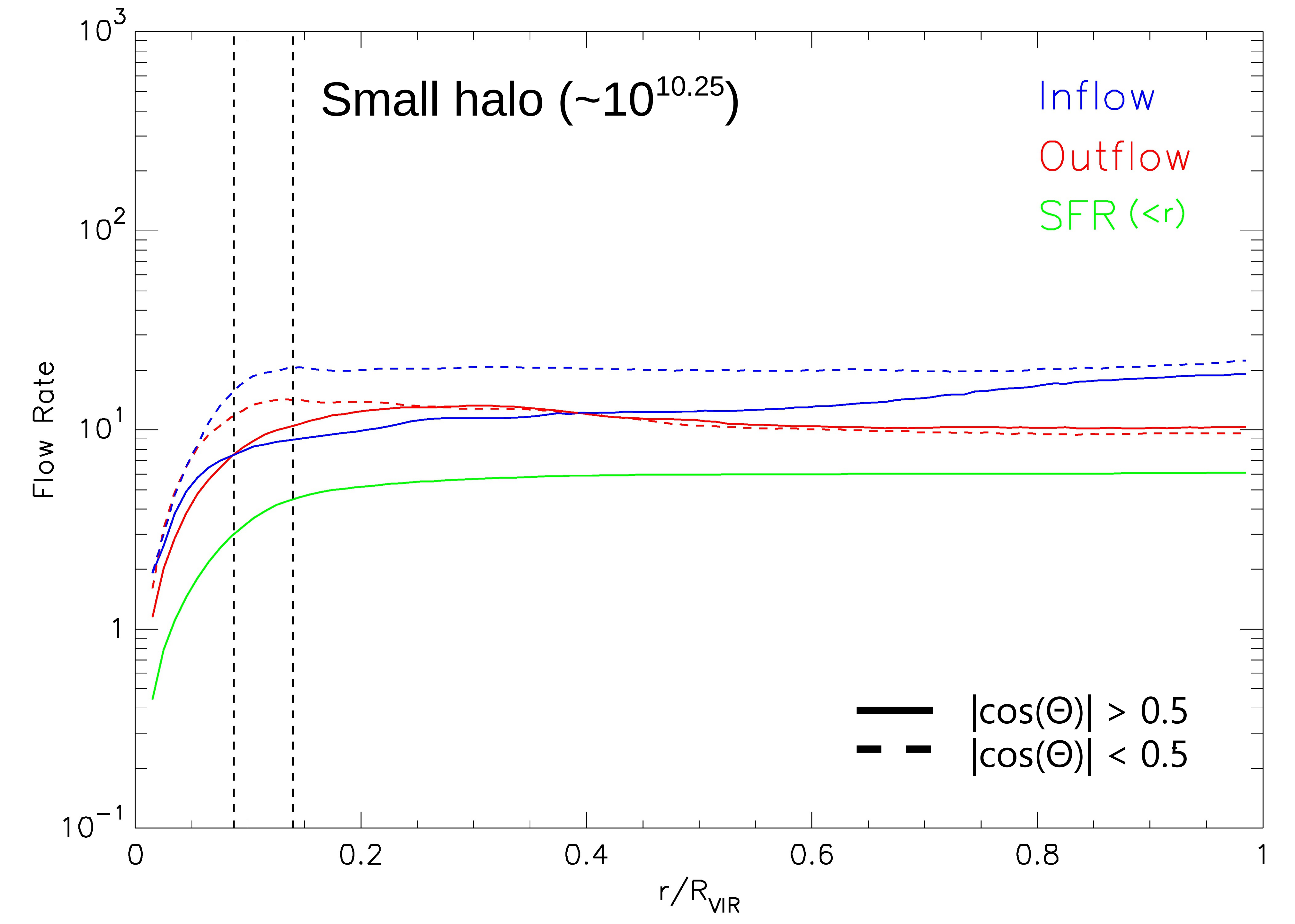
Evolutionary Phases



Quenching

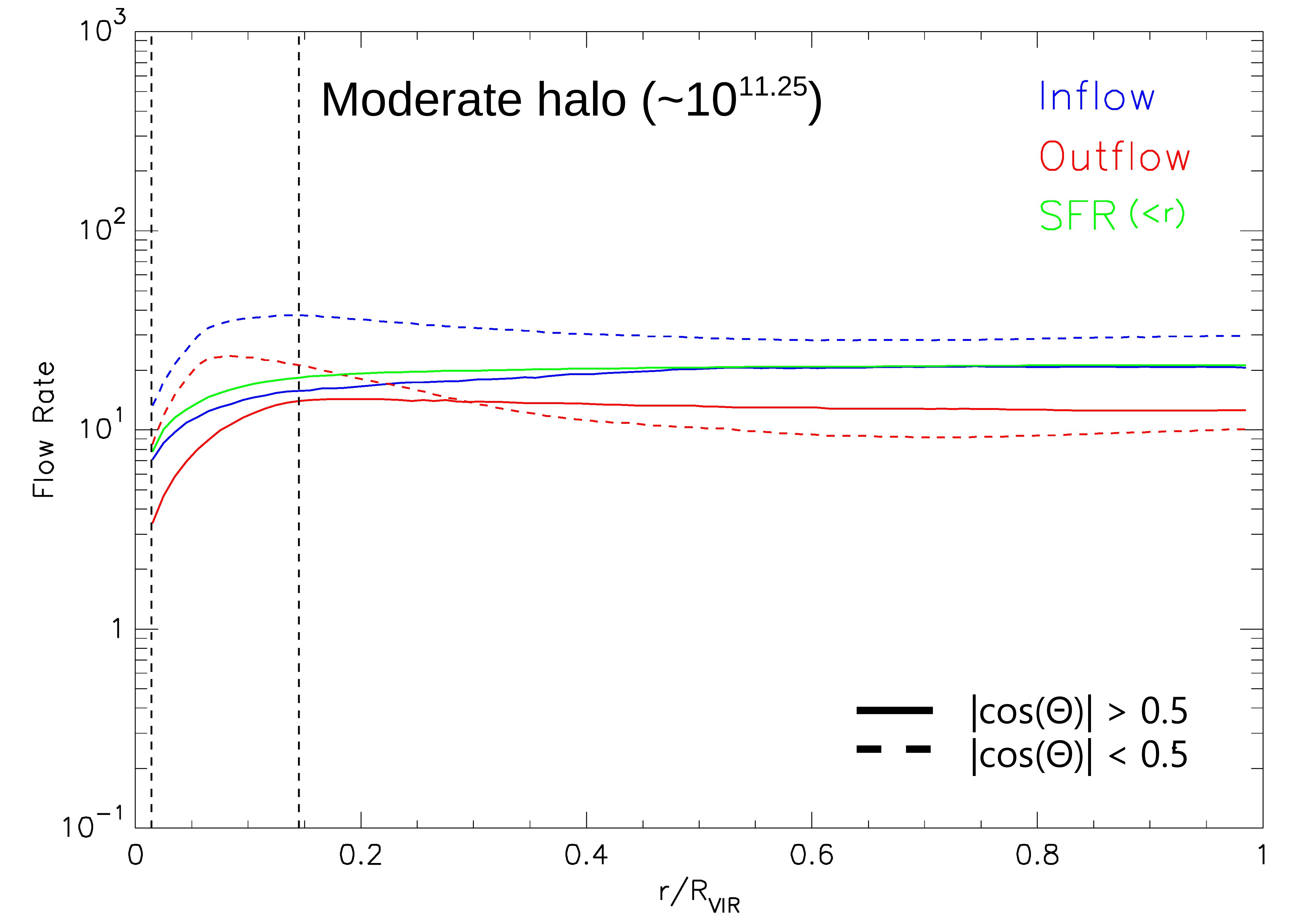
- Stronger flow at small r
- Strong outflow decrease with r
  - Entirely planar

M_{Halo} dependency



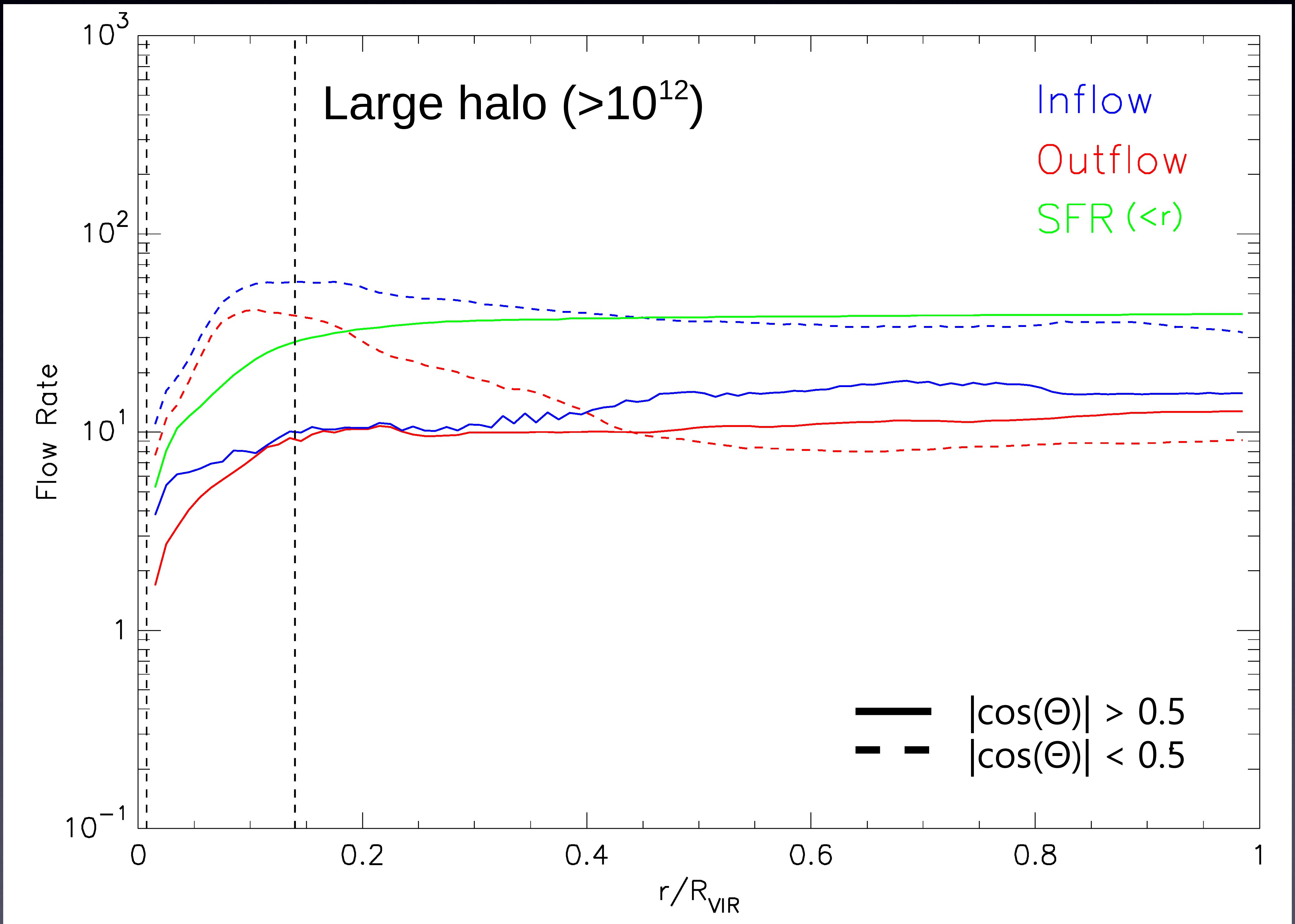
- In > Out
- Flow constant with r
- Small angular dependence

M_{Halo} dependency



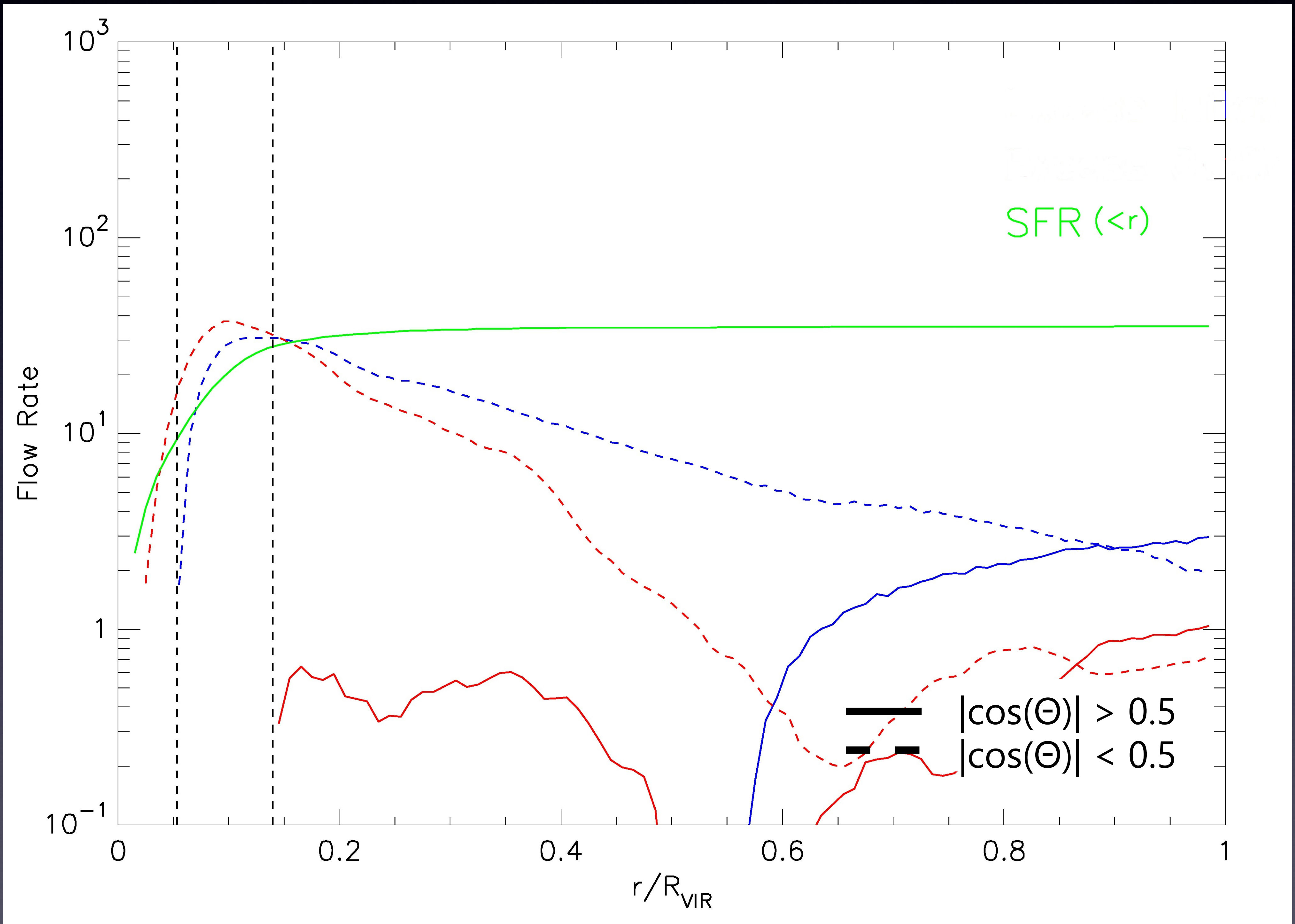
- In > Out
- Stronger flow at small r
- Stronger angular dependence

M_{Halo} dependency



- Stronger flow at small r
- Strong outflow decrease with r
  - Entirely planar

Small scale excess



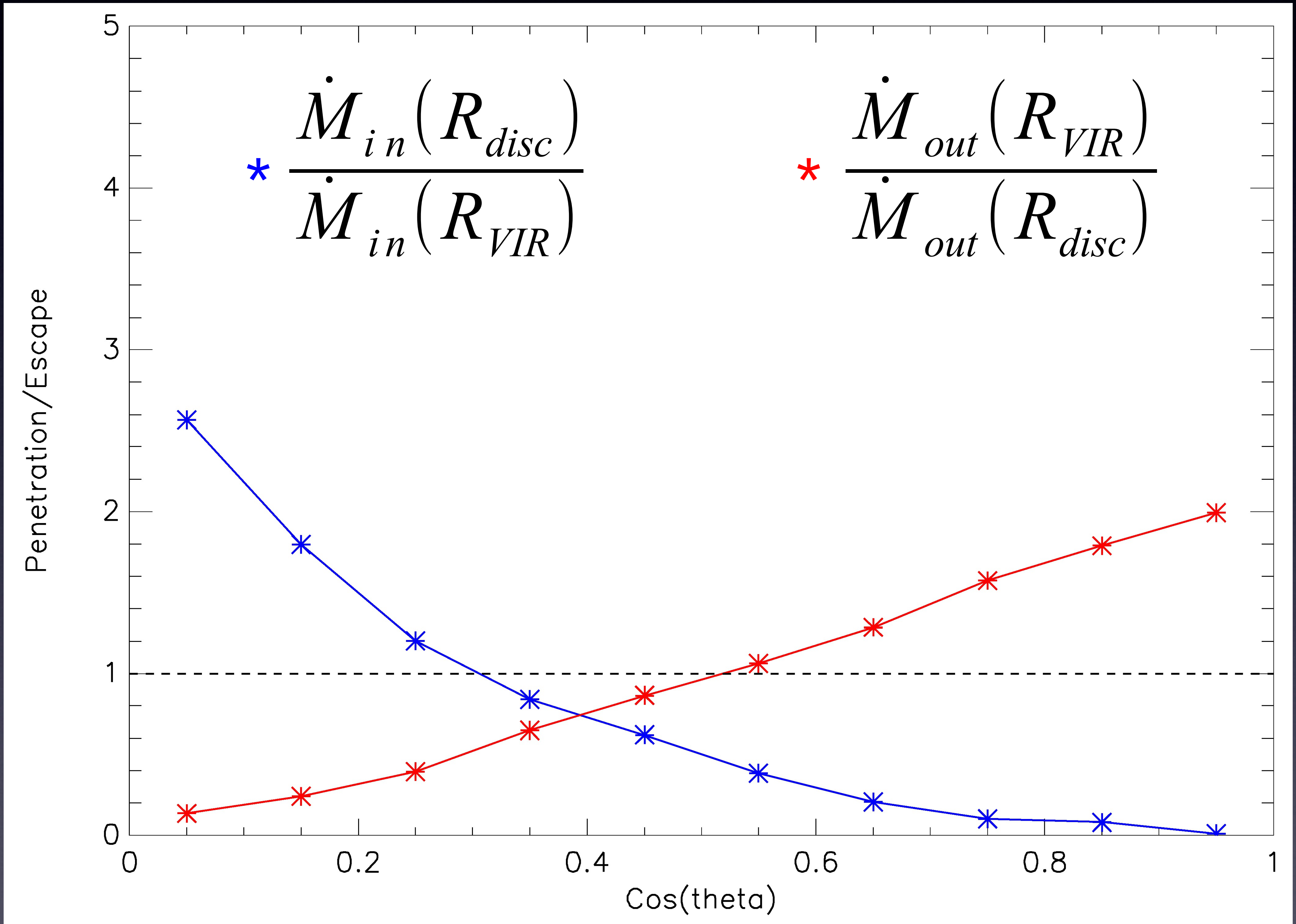
Excess flow relative to median in [0.5, 1] R_{vir}

Gas Penetration

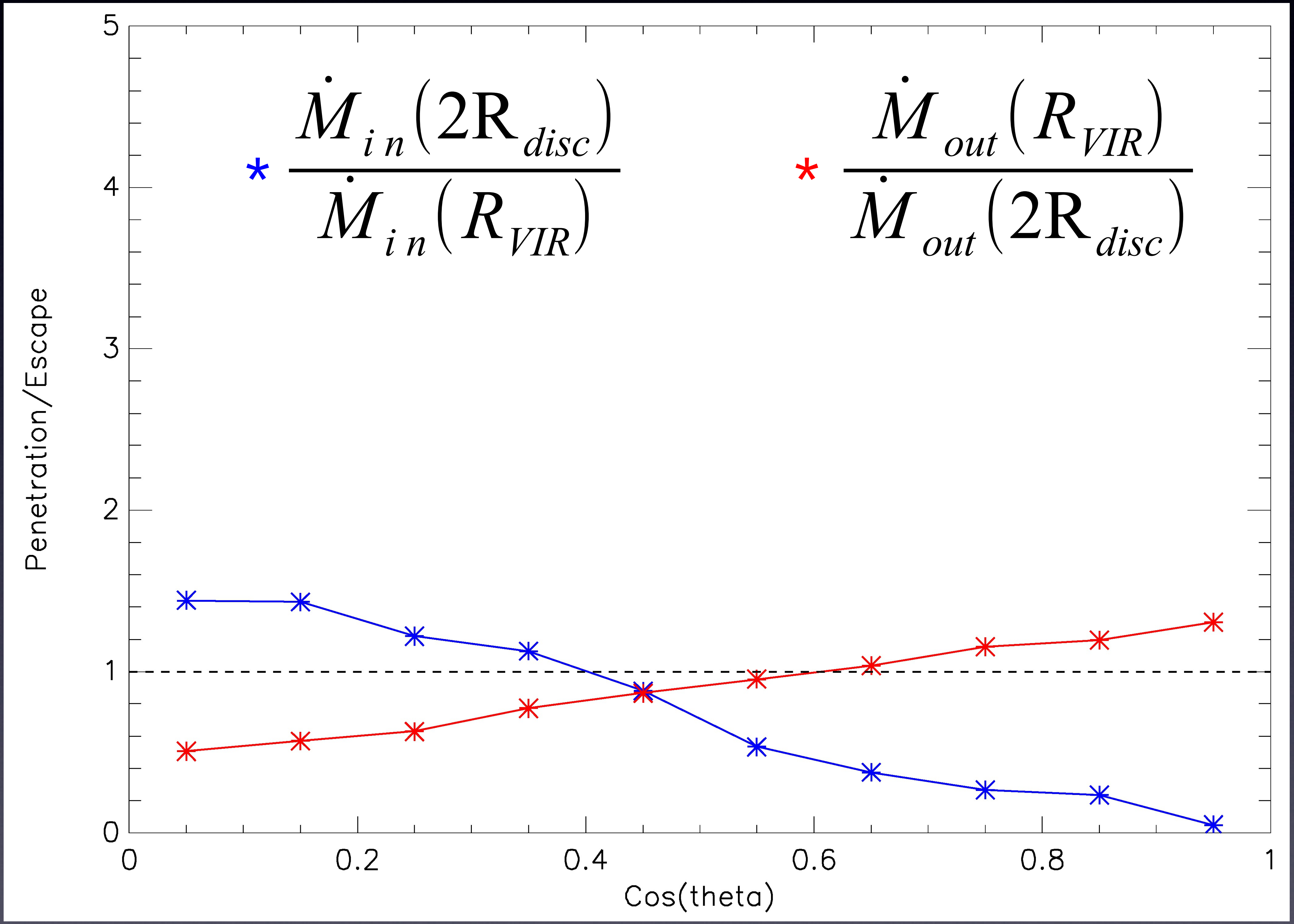
Penetration: $$P_{\alpha}=\frac{\dot{M}_{in}(\alpha R_{disc})}{\dot{M}_{in}(R_{VIR})}$$

Escape: $$E_{\alpha}=\frac{\dot{M}_{out}(R_{VIR})}{\dot{M}_{out}(\alpha R_{disc})}$$

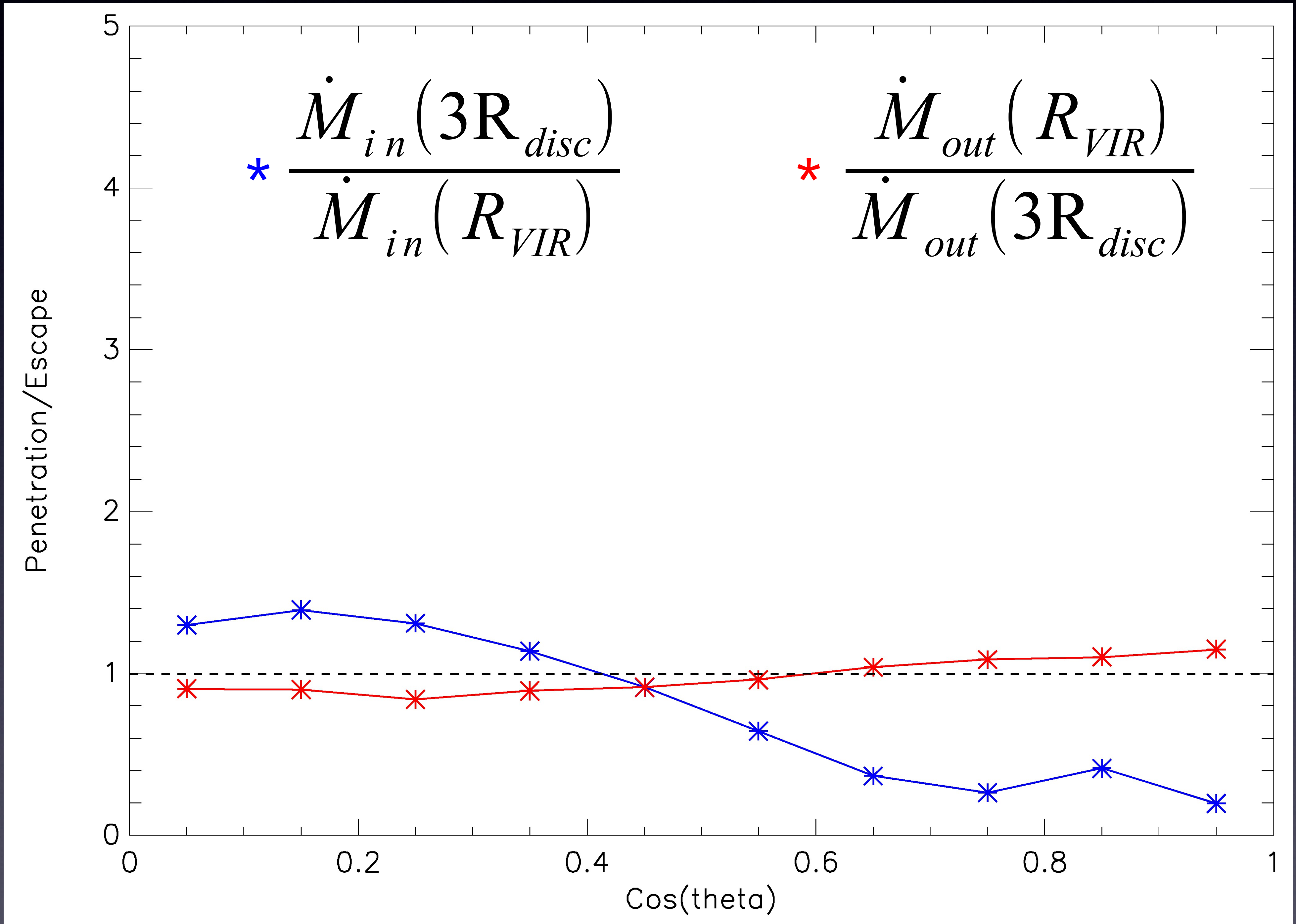
Gas Penetration



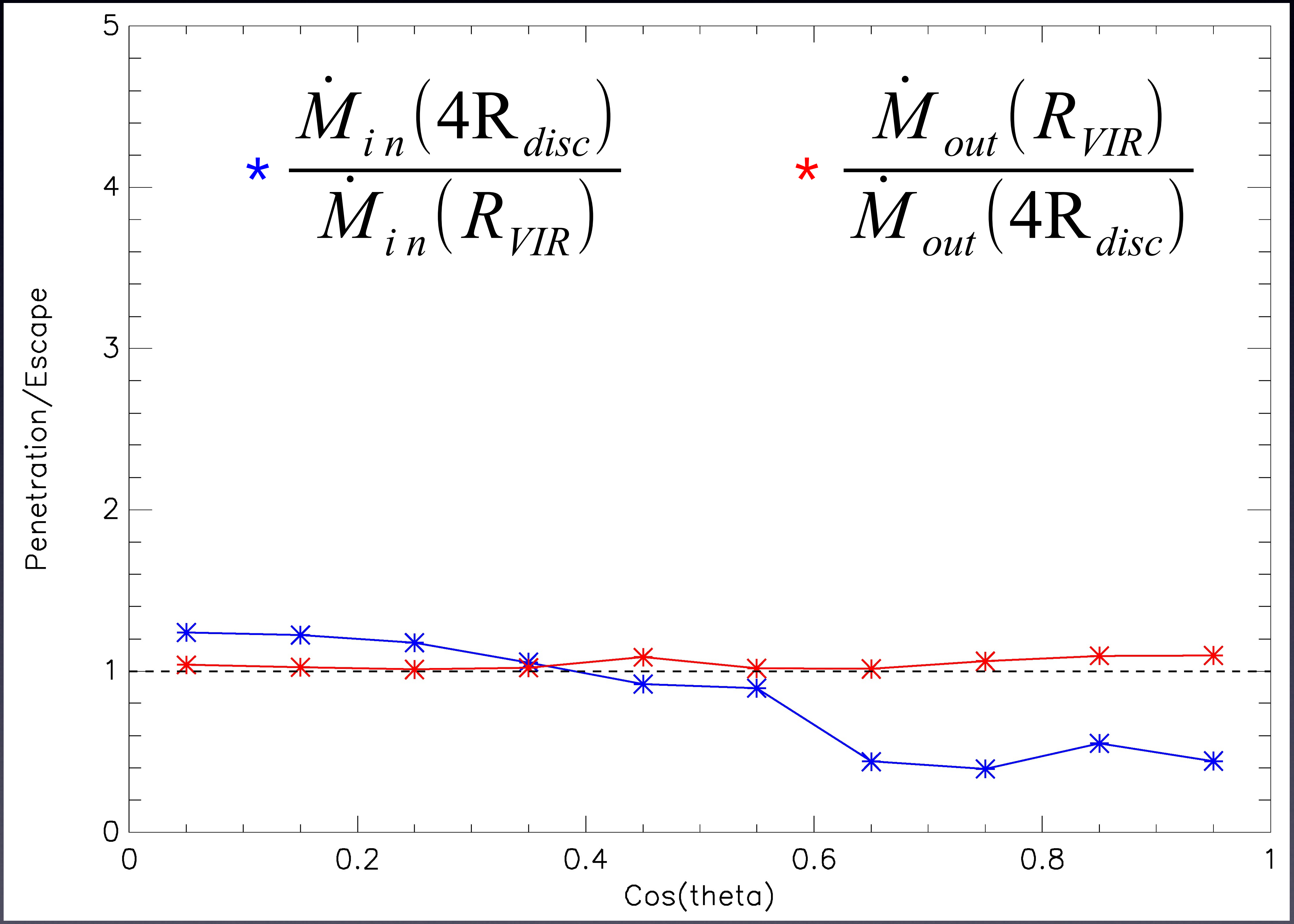
Gas Penetration



Gas Penetration



Gas Penetration



Edge on Flow Movie

- Dominant inflow in-plane
- Out of plane outflows escape effectively
  - Stops inflows from penetrating

Face on Flow Movie

- Still significant outflows
  - Some escapes, but most get stopped and return to galaxy
- Most outflows stopped by interactions with inflow
- Some outflows fall back to galaxy due to insufficient energy to escape

Summary

- Gas inflow penetrates efficiently to ~0.2 R_{vir} ~ 2 R_{disc}
  - → Stronger penetration in-plane
- Outflow escapes only out-of-plane
- Strong in-plane outflow near galaxy (< 0.3 R_{vir})
  - → Strong recycling below ~0.2 R_{vir}
- Continual inflow/outflow in-plane interaction causes recycling

Simulations

- AMR (grid) code HYDRO-ART (Kravtsov+ 1997, Kravtsov 2003)
- Gas Cooling, Star Formation, Stellar Feedback (Ceverino & Klypin 2009, Ceverino, Dekel & Bournaud 2010)
  - Atomic H and He, metal and molecular line cooling (T_{min} ~ 300K)
  - SF in $<10^4$ K , > 1 cm^{-3} gas
  - Thermal feedback from stellar winds and SNII
  - Radiation pressure in cells neighboring young stars
- Maximum resolution ~35-70 pc
- 34 galaxies for z>~1
  - Focus on 8 galaxies, 500-1200 snapshots each