Journal Club 2015.07.09@IoA

Stellar and Quasar feedback in concert (Hopkins et al. 2015)

Reported by T.Izumi

Phil. Hopkins et al.

- http://www.tapir.caltech.edu/~phopkins/Site/

- Hydro-dynamic simulations of *"concert of SMBH, stars, and ISM".*
  - ~2010; GADGET-3 code (SPH simulation; Springel 2005)
  - 2014~: GIZMO (modified ver. of GADGET-3; Hopkins 2013, 2014)
  - 2015~: mesh-less finite mass/volume code for MHD (Hopkins&Raives 2015)

- So many papers per year…

- I think you CAN NOT avoid reading their piles of papers if you want to study SMBH-evolution.

This seminar

- **Stellar and Quasar Feedback in Concert: Effects on AGN Accretion, Obscuration, and Outflows** (Hopkins et al. 2015: http://jp.arxiv.org/abs/1504.05209)
  - I mainly introduce this paper because it is new, but the basic is almost the same as in HQ10.

- **Dynamical delays between starburst and AGN activity in galaxy nuclei** (Hopkins 2012, MNRAS, 420, 8: http://ads.nao.ac.jp/abs/2012MNRAS.420L...8H)

- **How do massive black holes get their gas?** (Hopkins & Quataert 2010, MNRAS, 407, 1529: http://ads.nao.ac.jp/abs/2010MNRAS.407.1529H)

- **Some more references** are introduced in each relevant part.

Stellar and Quasar Feedback in Concert: Effects on AGN Accretion, Obscuration, and Outflows

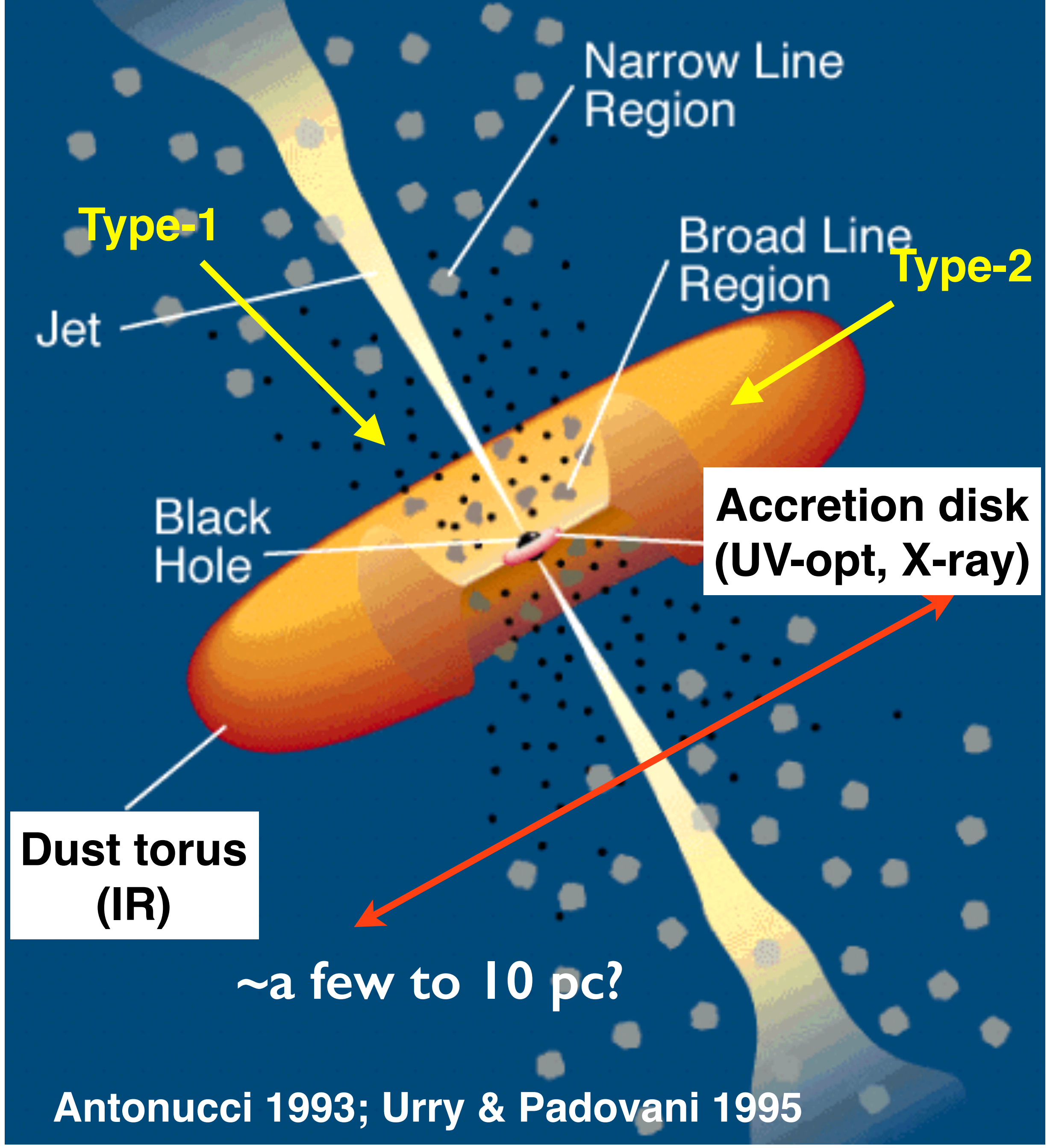
Philip F. Hopkins∗[1], Paul Torrey[2], Claude-André Faucher-Giguère[3], Eliot Quataert[4], & Norman Murray[5,6]

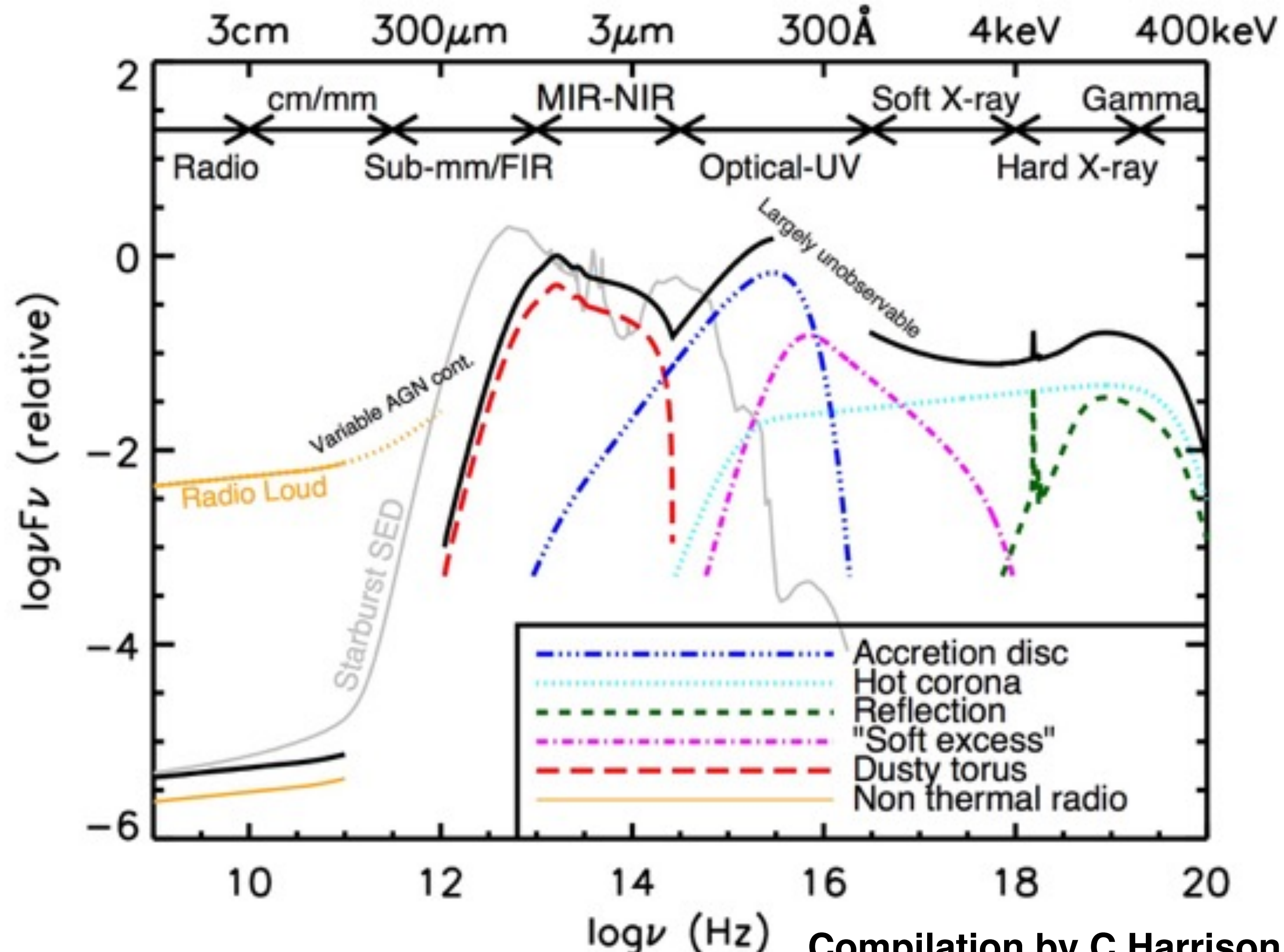
[1] *TAPIR & The Walter Burke Institute for Theoretical Physics, Mailcode 350-17, California Institute of Technology, Pasadena, CA 91125, USA*
[2] *Department of Physics, MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*
[3] *Department of Physics and Astronomy and CIERA, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA*
[4] *Department of Astronomy and Theoretical Astrophysics Center, University of California Berkeley, Berkeley, CA 94720*
[5] *Canadian Institute for Theoretical Astrophysics, 60 St. George Street, University of Toronto, ON M5S 3H8, Canada*
[6] *Canada Research Chair in Astrophysics*

ABSTRACT

We use hydrodynamic simulations to study the interaction of realistic active galactic nucleus (AGN) feedback mechanisms (accretion-disk winds & Compton heating) with a multi-phase interstellar medium (ISM). Our ISM model includes radiative cooling and explicit stellar feedback from multiple processes. We simulate radii $\sim 0.1-100$ pc around an isolated (non-merging) black hole. These are the scales where the accretion rate onto the black hole is determined and where AGN-powered winds and radiation couple to the ISM. Our primary results include: (1) The black hole accretion rate on these scales is determined by exchange of angular momentum between gas and stars in gravitational instabilities. This produces accretion rates of $\sim 0.03-1\,M_\odot$ yr^{-1}, sufficient to power a luminous AGN. (2) The gas disk in the galactic nucleus undergoes an initial burst of star formation followed by several Myrs where stellar feedback suppresses the star formation rate per dynamical time. (3) AGN winds injected at small radii with momentum fluxes $\sim L_{\rm AGN}/c$ couple efficiently to the ISM and have a dramatic effect on the ISM properties in the central ~ 100 pc. AGN winds suppress the nuclear star formation rate by a factor of $\sim 10-30$ and the black hole accretion rate by a factor of $\sim 3-30$. They increase the total outflow rate from the galactic nucleus by a factor of ~ 10. The latter is broadly consistent with observational evidence for galaxy-scale atomic and molecular outflows driven by AGN rather than star formation. (4) In simulations that include AGN feedback, the predicted column density distribution towards the black hole is reasonably consistent with observations, whereas absent AGN feedback, the black hole is isotropically obscured and there are not enough optically-thin sight lines to explain observed Type I AGN. A 'torus-like' geometry arises self-consistently because AGN feedback evacuates the gas in the polar regions.

Active Galactic Nuclei = AGNs

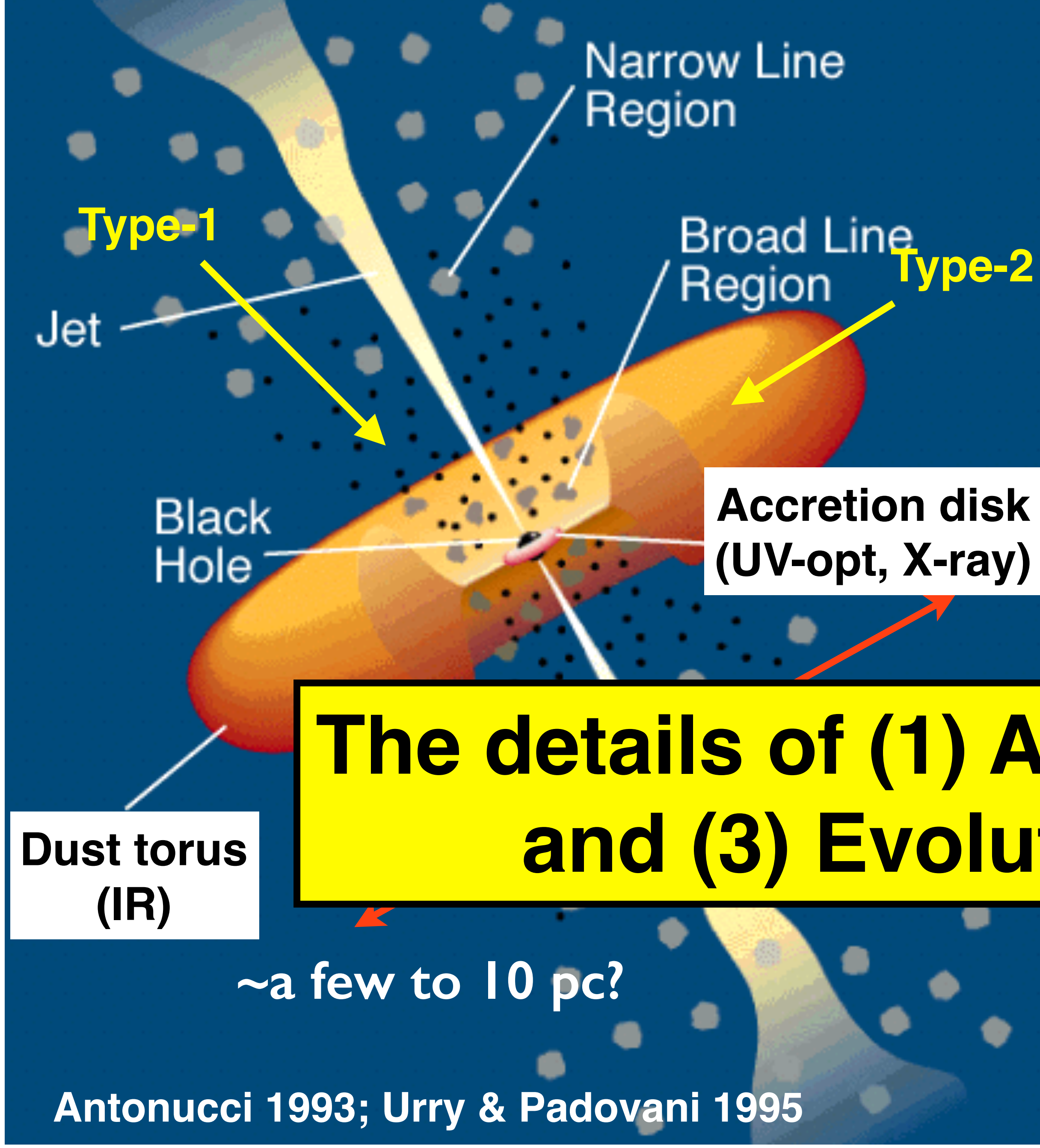


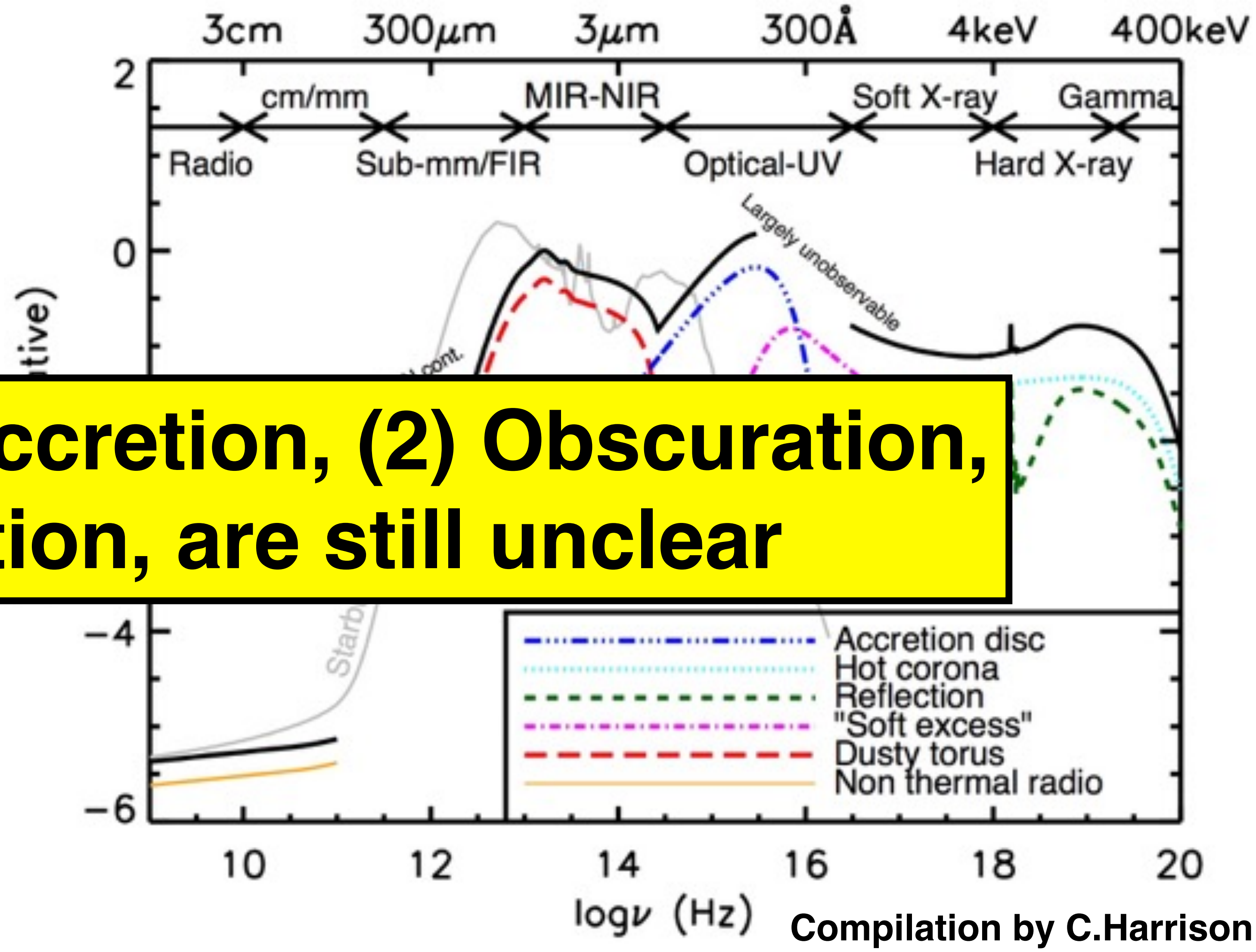


Compilation by C.Harrison (see also Elvis et al. 1994)

- @centers of galaxies
- Bright at wide wavelengths from radio to X-ray ($L_{Bol} > 10^{10}\ L_{sun}$)
- Dust torus + central engine (SMBH + accretion disk); SMBH = $M_{BH} > 10^{6}\ M_{sun}$
- Time variability in flux

Active Galactic Nuclei = AGNs





Compilation by C.Harrison (see also Elvis et al. 1994)

The details of (1) Accretion, (2) Obscuration, and (3) Evolution, are still unclear

- @centers of galaxies
- Bright at wide wavelengths from radio to X-ray ($L_{Bol} > 10^{10}$ L_{sun})
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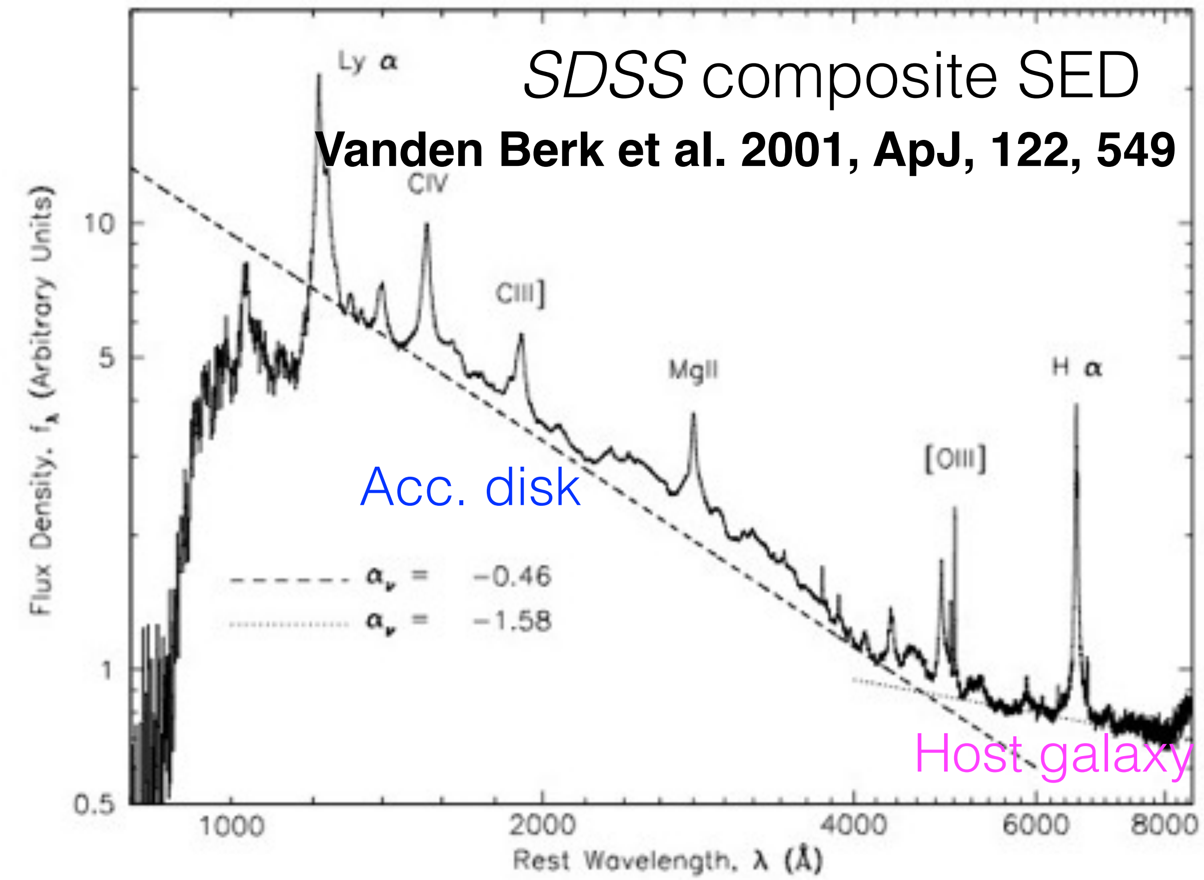
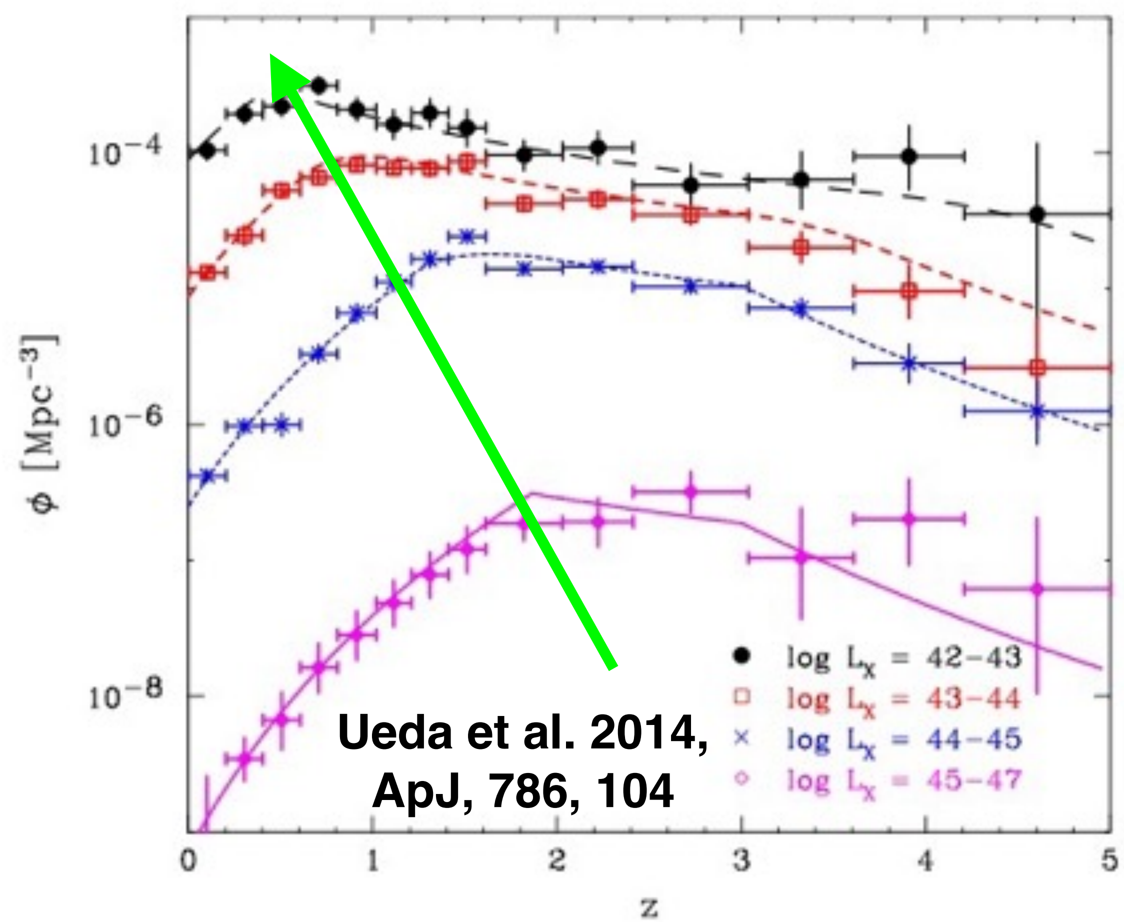
- Time variability in flux

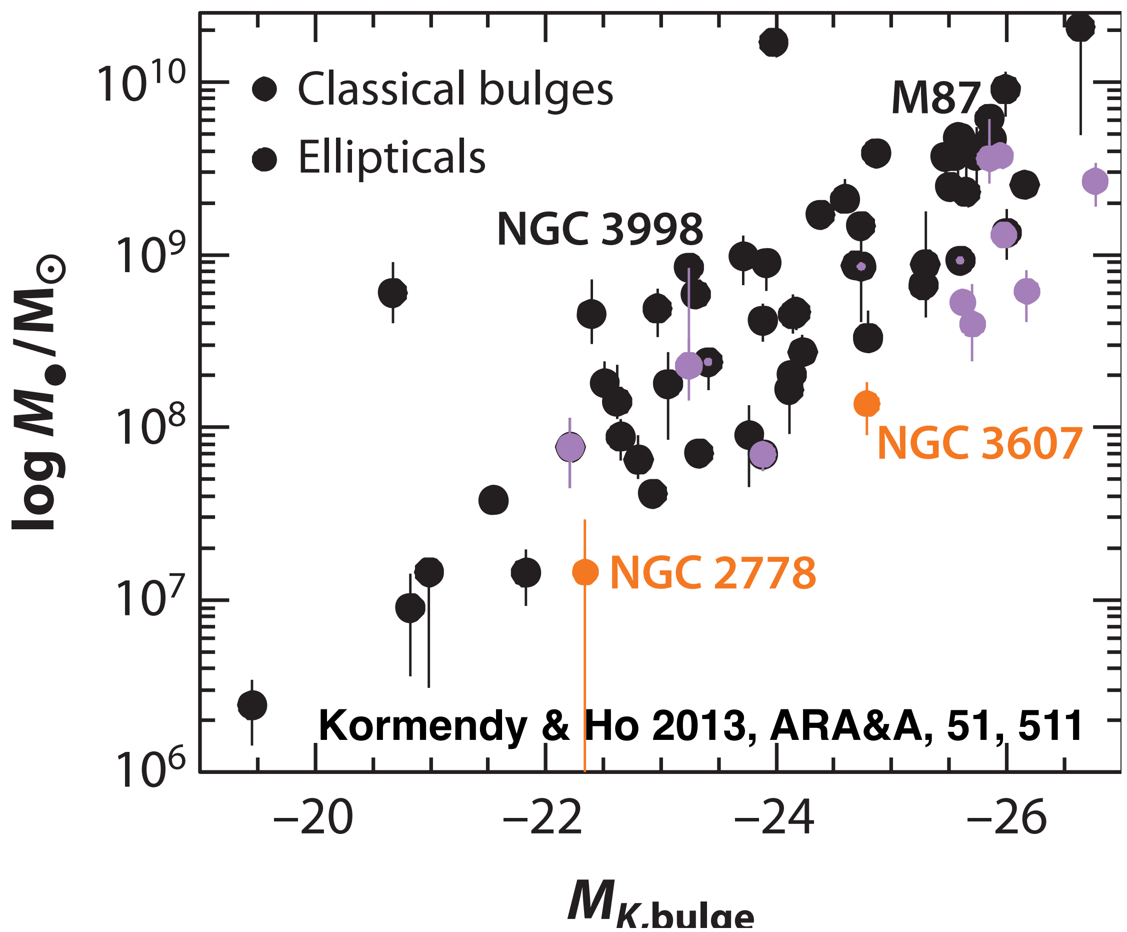
Quasars (QSOs)

- Extremely bright type-1, high-z AGNs; > 100,000 QSOs are discovered @0<z<5 (SDSS)
- $M_{BH} \sim 10^{7\text{-}10}\ M_{sun}$
- Eddington ratio ~ 0.01-1 (some show super-Edd. accretion!?) → "standard accretion disk" (Shakura & Sunyaev 1973)?
- Known to show "down-sizing" evolution (e.g., Ueda et al. 2014, ApJ, 786, 104) → Anti-hierarchical evolution in the hierarchical universe? (Enoki et al. 2014, ApJ, 794, 69)
- Tend to live in starburs galaxies? - merger-induced origin??





Introduction



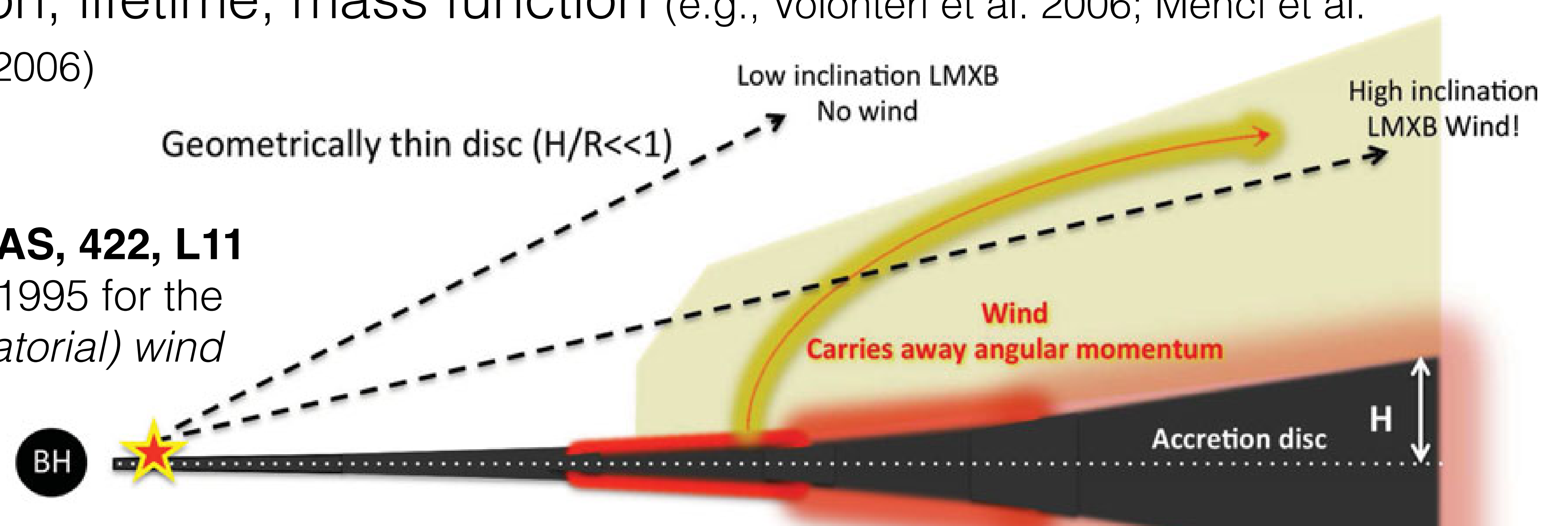
- M_{BH} and properties of the bulge component of the host galaxy (bulge mass, luminosity, stellar velocity dispersion) are well correlated = **co-evolution** (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Tremaine et al. 2002; Marconi & Hunt 2003; Gultekin et al. 2009; Normandy & Ho 2013 for a review).
  - see also Ho & Kim (2014) for an application of Kormendy's treatment.

- Some kind of feedback from a rapidly mass accreting SMBH would be the key to establish the relation → AGN feedback (e.g., Silk & Rees 1998; King 2003; Di Matteo et al. 2005).

- Understanding the gas fuelling process onto a SMBH is thus critically important (see reviews of possible mechanisms in, e.g., Jogee 2006; Alexander & Hickox 2012).

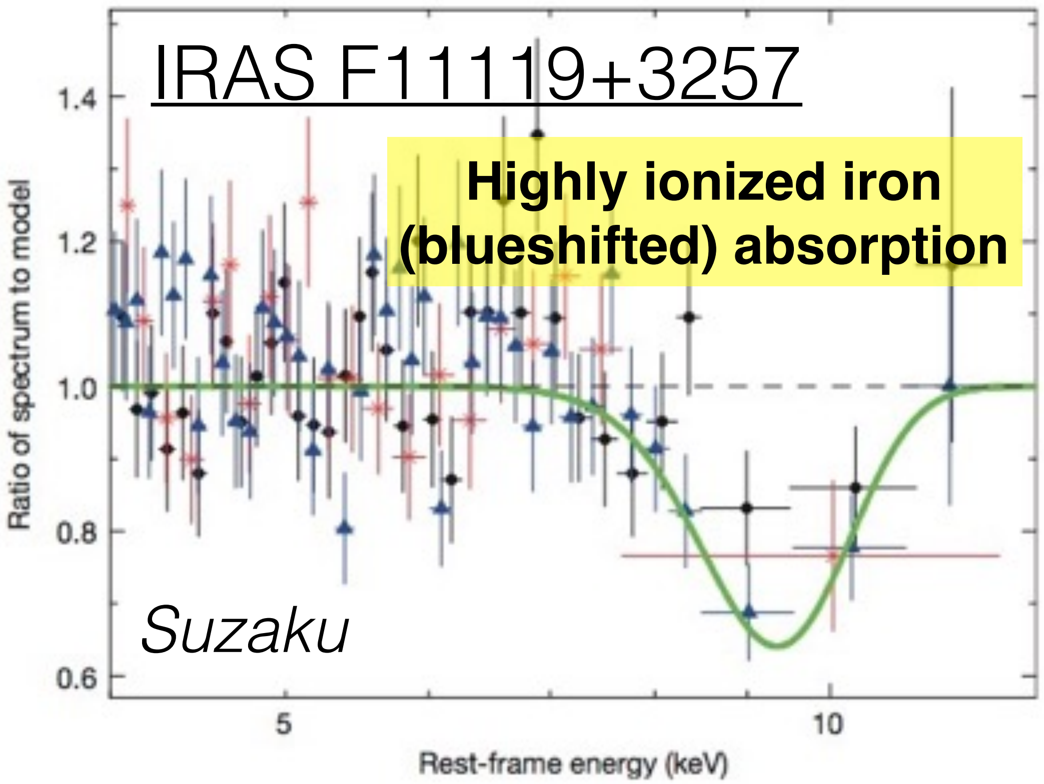
Feedback mechanism in AGNs

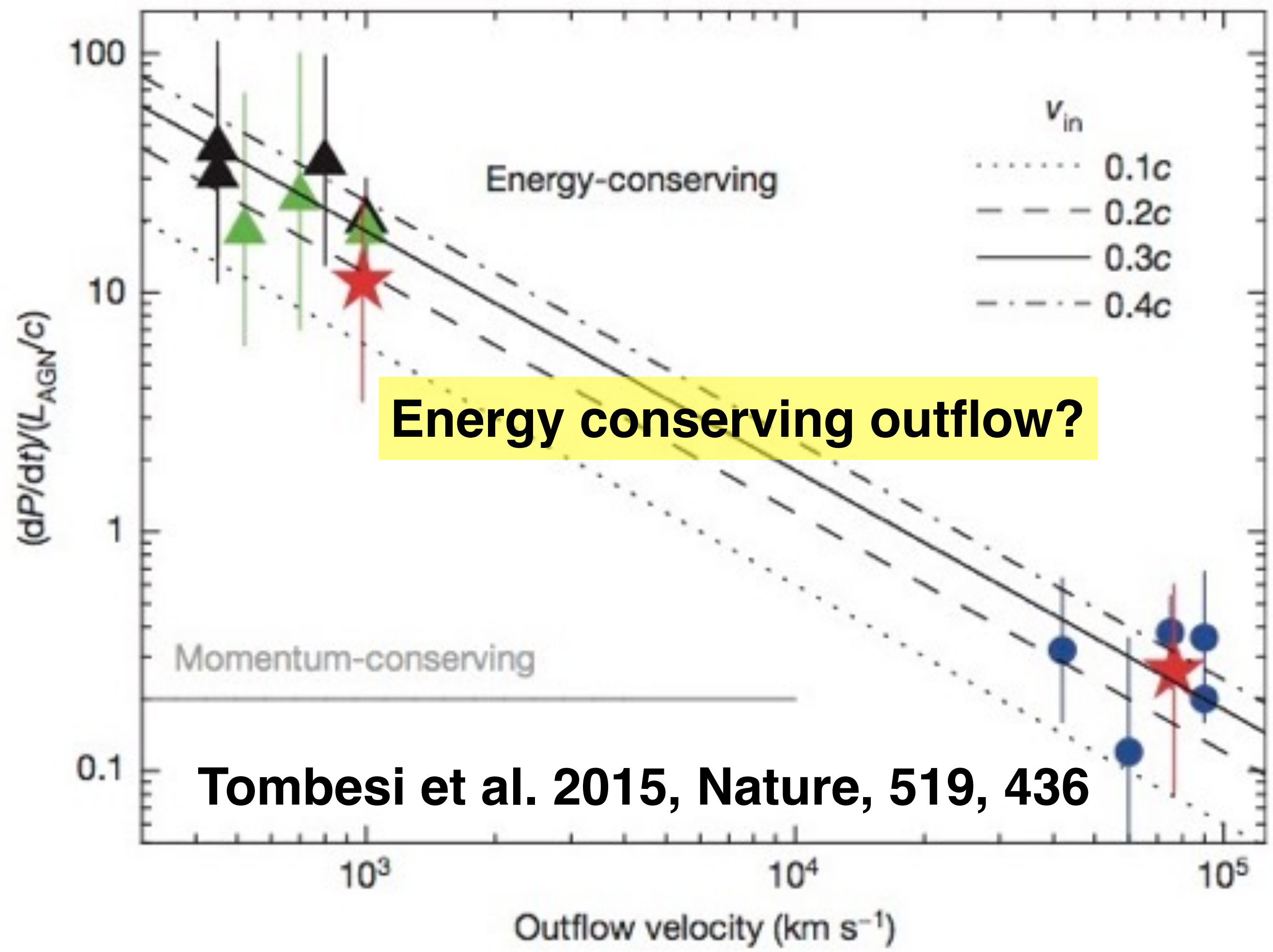
- Gas inflows from the host galaxy triggers rapid SMBH growth = AGN
- AGN will expel or heat nearby gas, which will quench star formation in the galaxy (e.g., Granato et al. 2004; Croton et al. 2006; Hopkins et al. 2008a);
  stars should be formed in cold, dense molecular cloud.
  → high velocity wind (outflow), harsh radiation
- But the expelled material is also the fuel for the AGN (*suicide*)
  → short-lived, bright quasar phase
- Above mechanism can roughly reproduce many quasar observables; luminosity function, lifetime, mass function (e.g., Volonteri et al. 2006; Menci et al. 2003, 2014; Lapi et al. 2006)

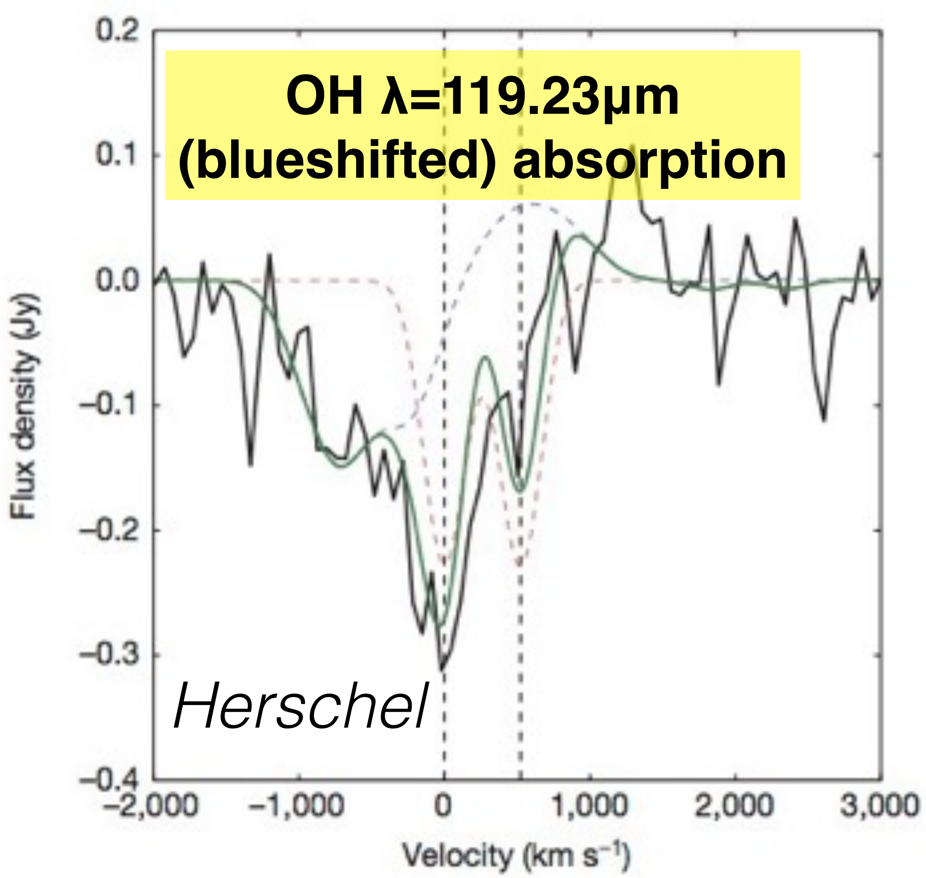


Ponti et al. 2012, MNRAS, 422, L11
see also Murray et al. 1995 for the validity of *planar (equatorial) wind*

High velocity wind (outflow)







- Indeed, powerful molecular/atomic/ionized outflow have been observed in many AGNs :)
- See, e.g., King & Pounds (2015) for a review of outflow models (http://ads.nao.ac.jp/abs/2015arXiv150305206K)

This paper

- The detailed launching mechanism of the outflow and its influence on the surrounding ISM (i.e., AGN feedback) is still unclear.
- So, anyhow simulate them and take a look at the results.
- "*We believe that to model this interaction with some fidelity, it is critical to include both a realistic description of the physics of the ISM, star formation, and stellar feedback, as well as a plausible description of AGN feedback mechanisms*"
- Include: *stellar radiation pressure,*
  HII photo-ionization, photoelectric heating,
  supernovae feedback, stellar winds,
  + stellar evolution model.

- ***AGN heating*** (Compton w/ $T_{comp} = 2\times10^7$ K, AGN wind)

Models

Table 1. Simulations

Model	η_p	η_E	β	$v_{\rm BAL}$	Notes	
no_BAL	0	0	0	0	no AGN FB	w/o feedback
v5000	1	0.008	6.0	5,000	"default"	w/ feedback
v5000_hiP	10	0.08	60	5,000	high-momentum	
v5000_loP	0.1	0.0008	0.6	5,000	low-momentum	
v30000	1	0.05	1.0	30,000	high-energy	
v500	1	0.0008	60	500	low-energy	
v5000_C	1	0.008	6.0	5,000	+Compton heating	
v5000_iso	1	0.008	6.0	5,000	isotropic winds	

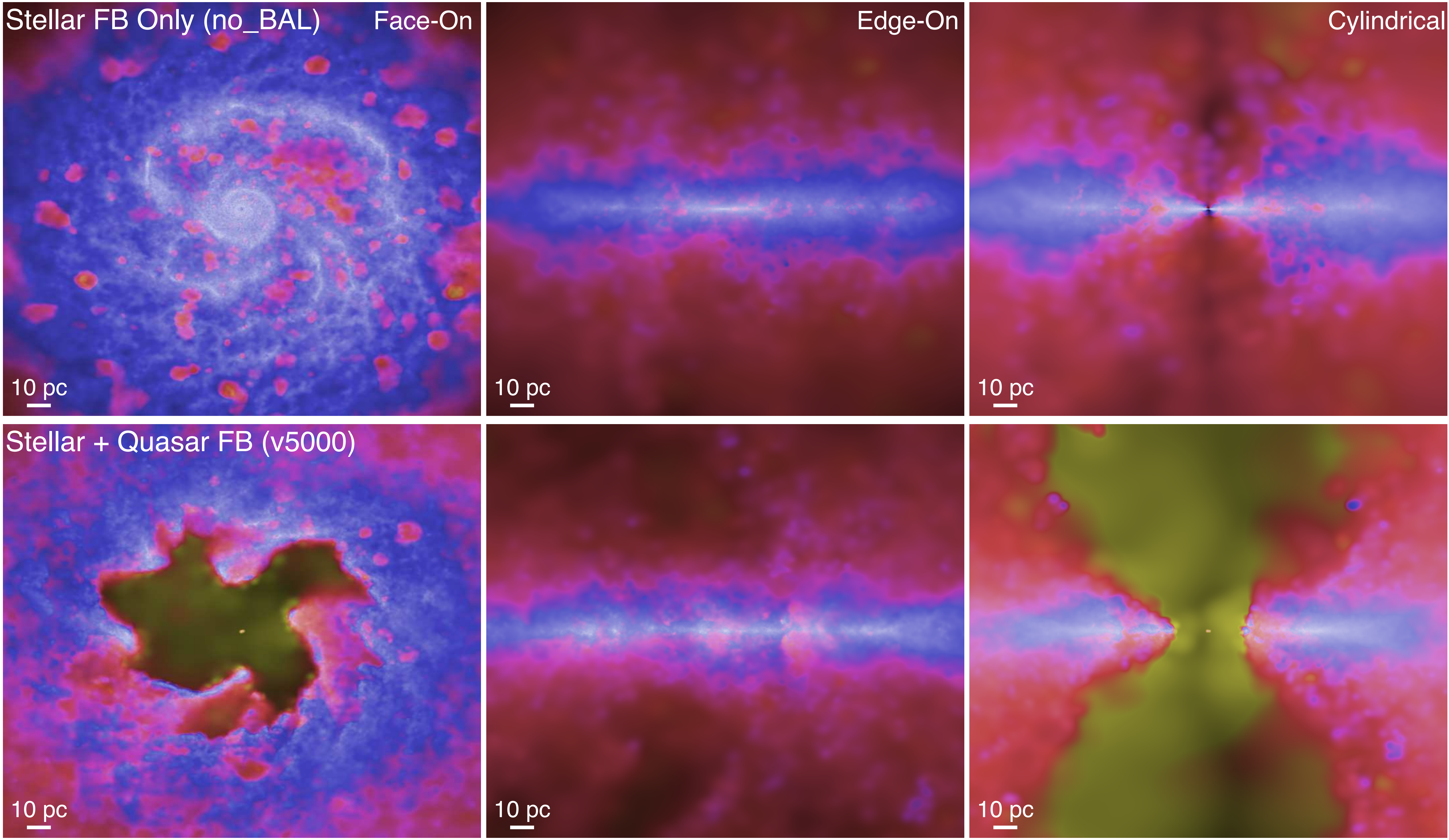
Parameters describing the simulations in the text: Each employs a gas particle mass of $13.5\,h^{-1}\,M_\odot$ and minimum SPH smoothing length of $0.014\,h^{-1}$ pc. Additional simulations for numerical tests are in Appendix C.
(1) Model name
(2) η_p: Momentum-loading of BAL wind feedback ($\dot{p} = \eta_p\,L/c$)
(3) η_E: Energy-loading of BAL wind feedback ($\dot{E} = \eta_E\,L$)
(4) β: Mass-loading $\beta \equiv \dot{M}_{\rm BAL}/\dot{M}_{\rm BH}$ (determined by η_p & η_E)
(5) $v_{\rm BAL}$: AGN wind launching velocity at the simulation resolution (in km s^{-1}; determined by η_p & η_E)

Initial conditions	
M_{BH}	3E+07 M_{sun}
M_{bulge}	1E+10 M_{sun}
M_{halo}	2E+12 M_{sun}
M_{gas}	8E+07 M_{sun}
M_*	2.6E+07 M_{sun}
Toomre-Q	1
Σ_{disk}	1E+05 M_{sun}/pc^2
Particle mass	20 M_{sun}

- Molecular fraction; Krumholz & Gnedin (2011)
  → depends on the local column density and metallicity

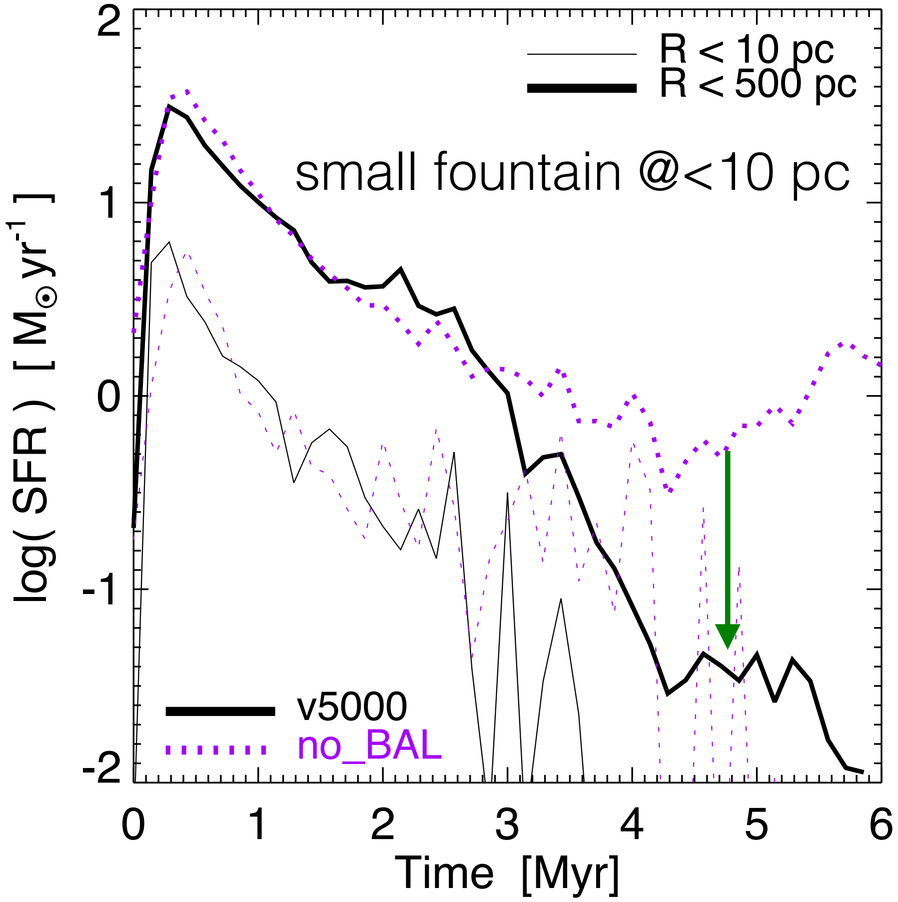
- Stars are formed in dense (n_{H2} > 1E4 cm^{-3}) cloud, at a 100% efficiency per free-fall time.

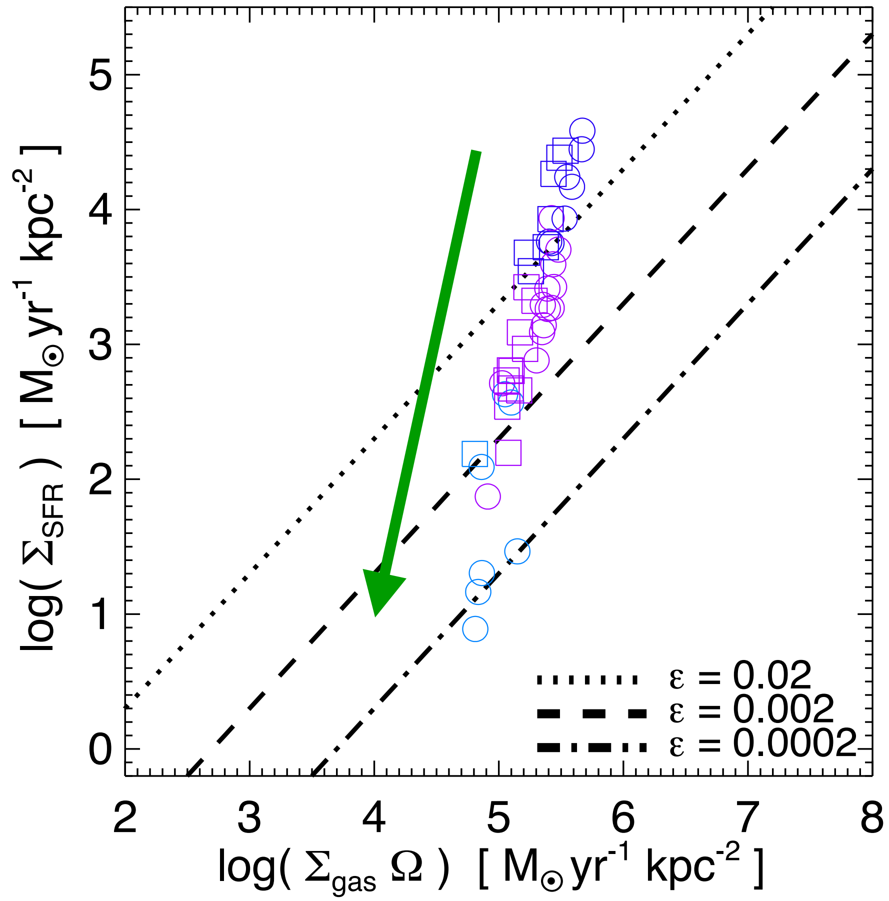
Results

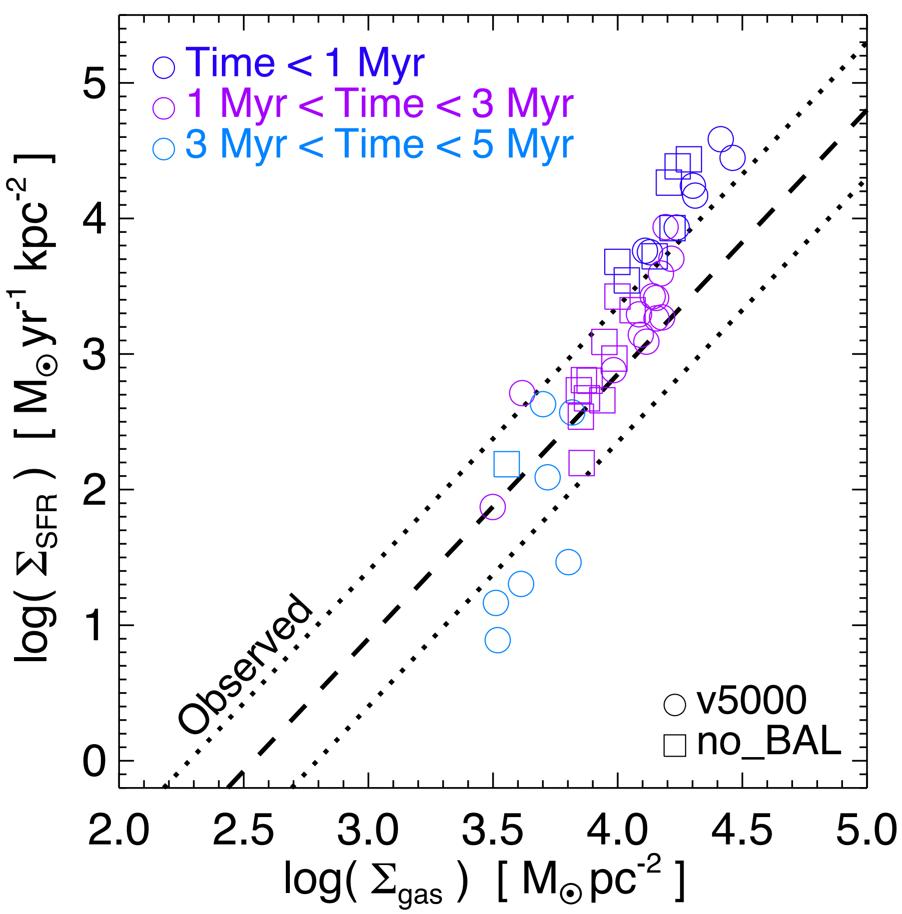


- Brightness = density; Blue < 10^3 K; Red ~ $10^{4\text{-}5}$ K; Yellow > 10^6 K

Results

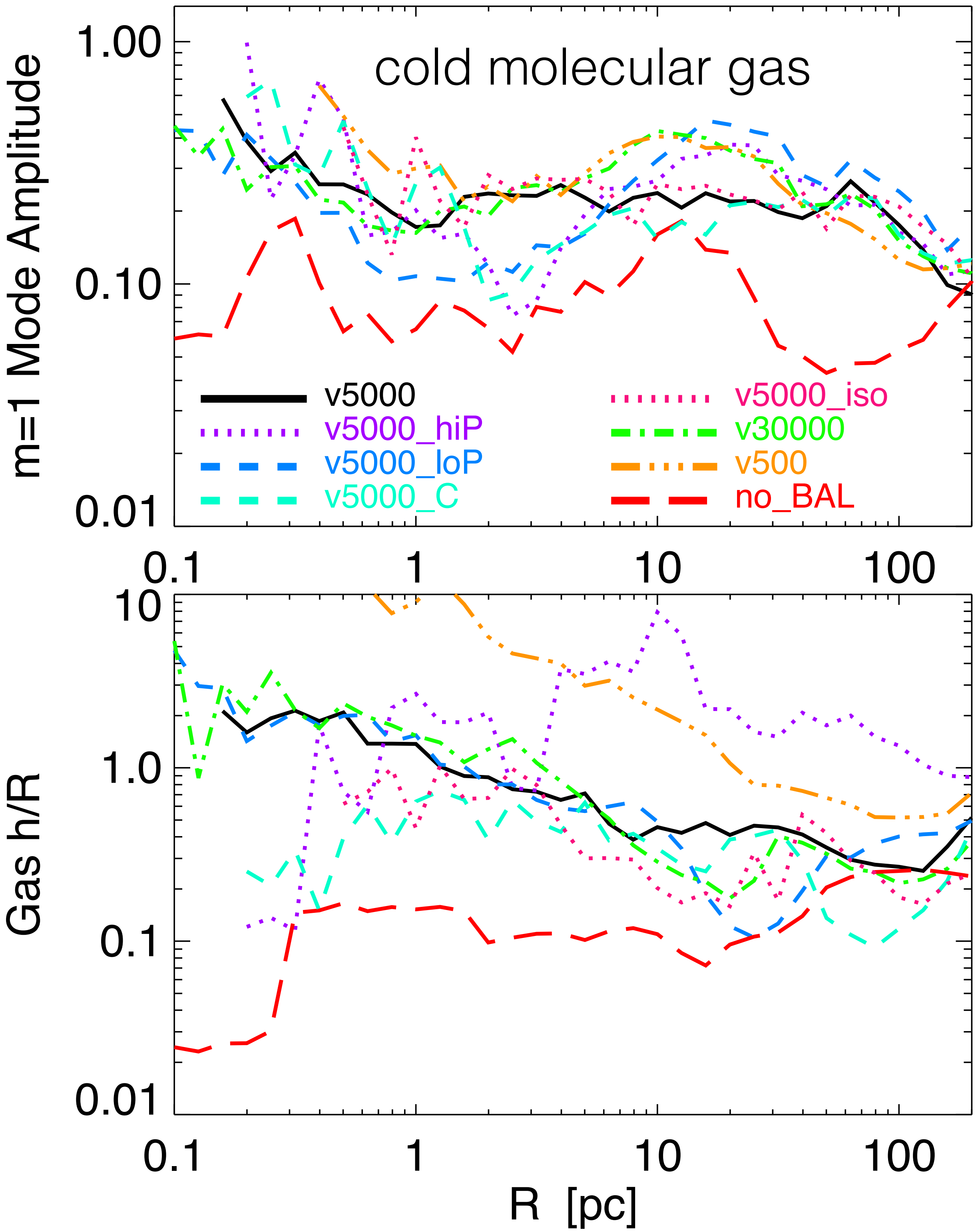


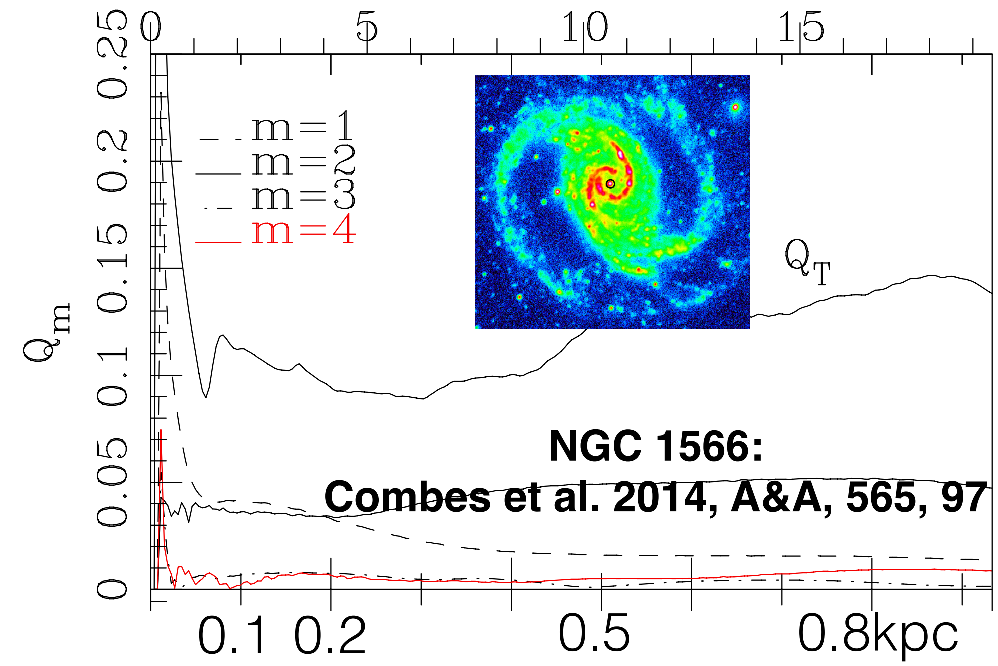




- $dM_*/dt \sim 1\ M_{sun}/yr$ in a steady state, without AGN feedback (r < 500 pc).
- AGN influences star formation kpc scale significantly.
- At r < 10pc, stellar feedback alone can clear most of the gas after a few Myr.
- ***Star formation efficiency per τ_{dyn}*** evolves significantly with time.

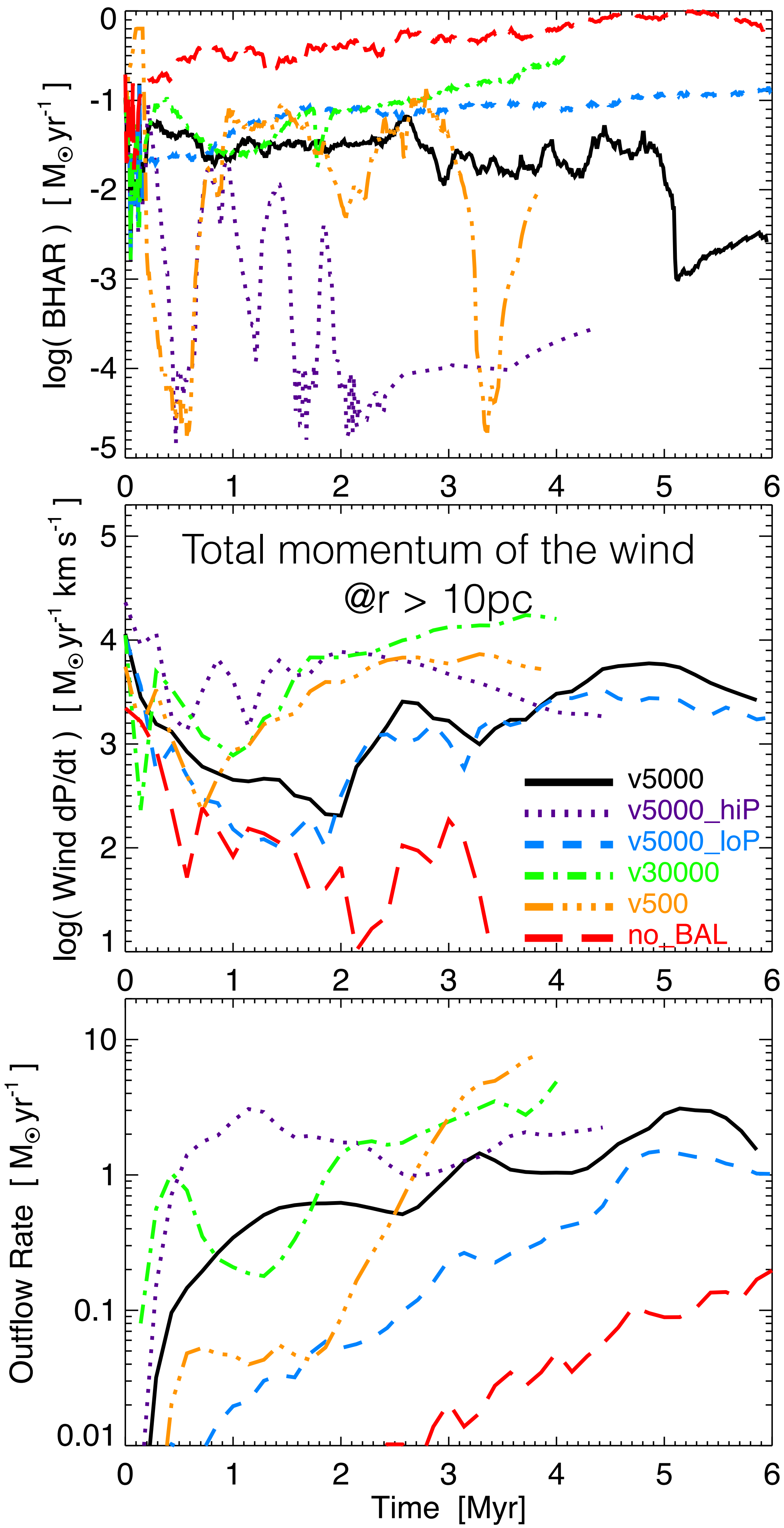
Geometry and Black hole accretion: mass inflow at r<2.8ε (min. Keplerian distance)





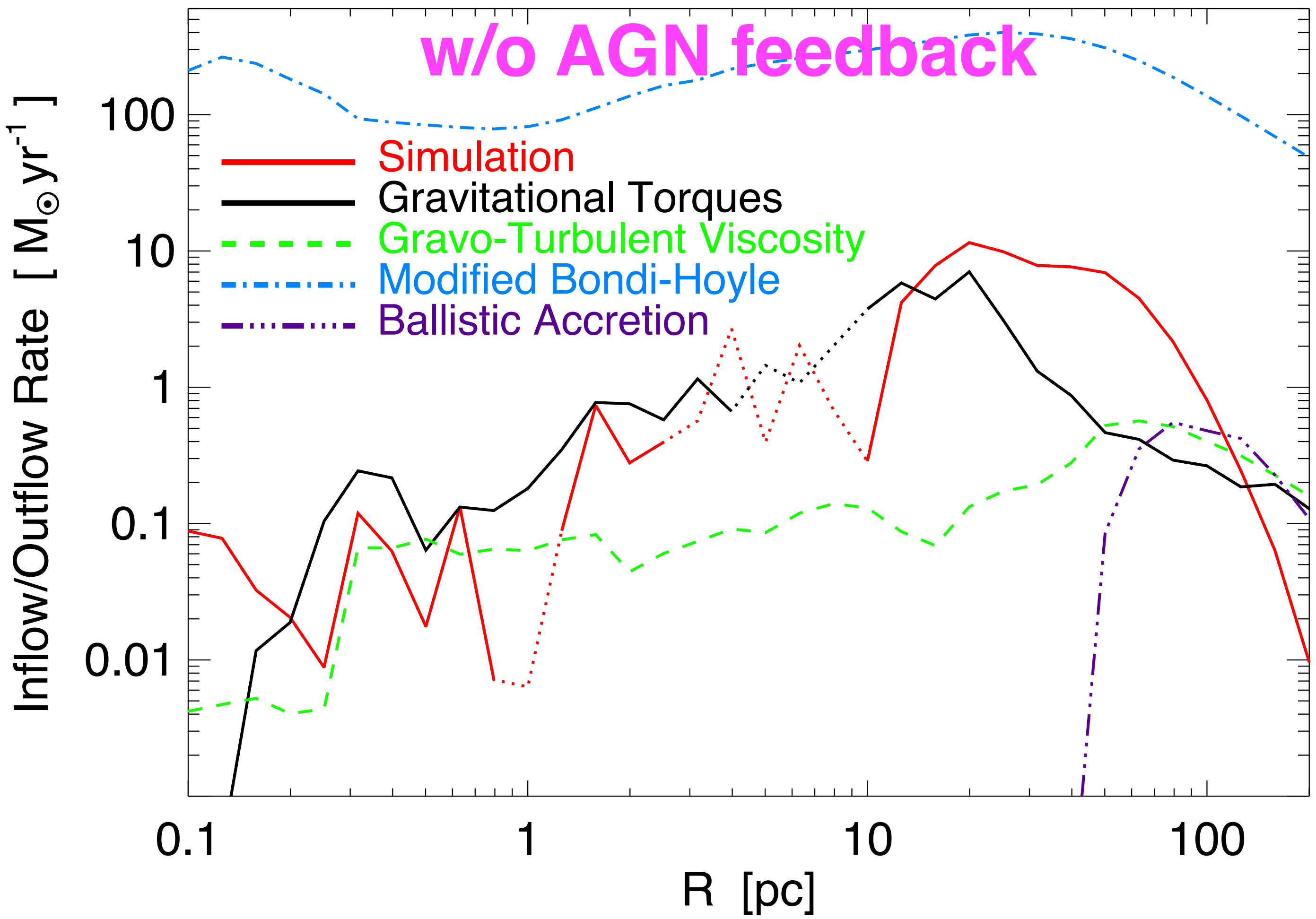
- **m=1** mode (not m=2) develops, which is the dominant mechanism to remove angular momentum at r < 10 pc (same as in HQ10)
- Warm gas disk becomes thick when AGN feedback is switched-on, in concordant with thick molecular disk (e.g., Hicks et al. 2009, ApJ, 696, 448).
- But the h/R of cold molecular gas keeps ~const. value, which is very low (e.g., Fathi&TI et al. 2013, ApJ, 770, 27).

Accretion/outflow rate (1)



- Rather large accretion rate when no AGN feedback
  → decreased by a factor ~ 10, when feedback is imposed (i.e., suicide)
- Lower dM_{BH}/dt when η_p is higher.
- Time variation reflects that of star formation and dynamics.
- Models with AGN feedback all equilibrate at similar outflow momentum flux; high-η_p models adjust to have low dM_{BH}/dt.

Accretion/outflow rate (2)



- Comparison between the simulated (~observed) in/out-flow rate with various analytic models.

- Mass inflow rate due to grab. torques induced by trailing spiral waves is (see basics in Lynden-Bell & Kalnajs 1972),

$$\dot{M} = \Sigma_{\rm gas} R^2 \Omega \left| \frac{\Phi_a}{V_c^2} \right| \left[\frac{m S(\omega, \Phi_a) F(\zeta)}{1 + \partial \ln V_c / \partial \ln R} \right]$$

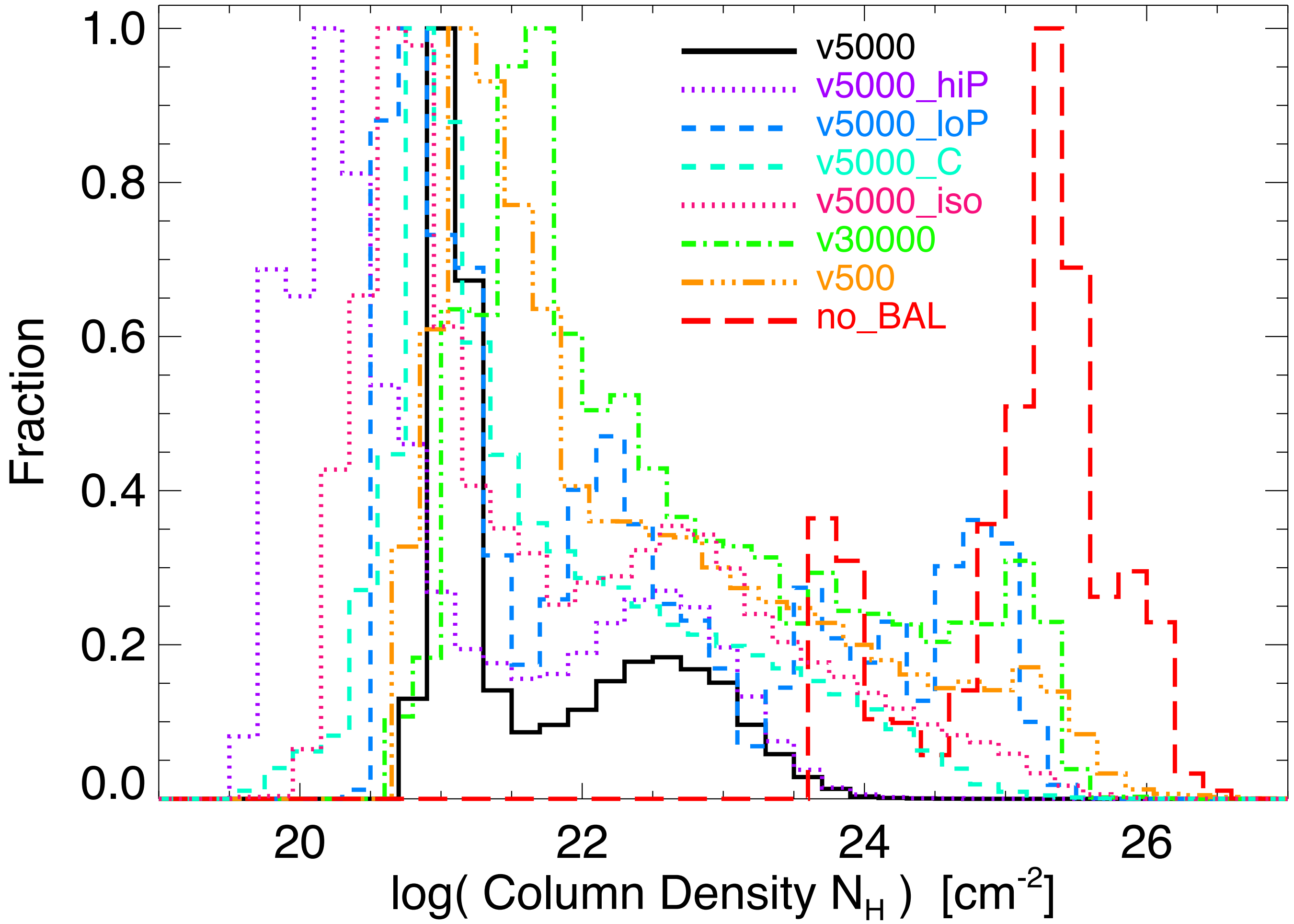
~amp. of the mode in a quasi-Keplerian potential, which is rather **constant**!

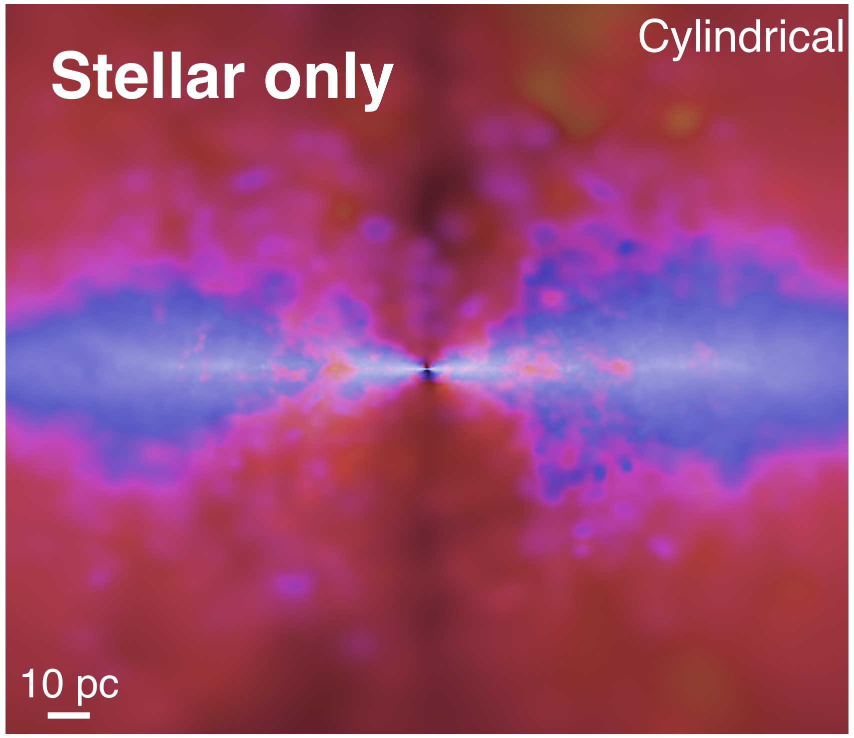
- Bondi accretion & modified-Bondi accretion: clearly bad, because now gas is supported not by pressure but by angular momentum at these scales.

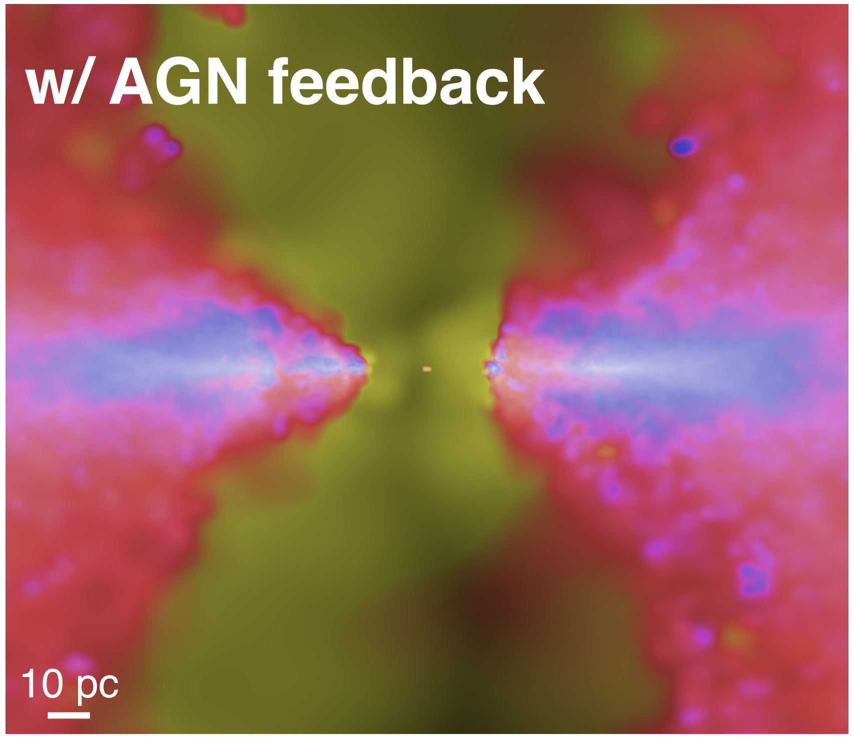
- Ballistic accretion: random accretion of gas in the lower-tail of angular momentum distribution. This strongly depends on the geometry (h/R) is rejected in these simulations.

- Gravito-turbulent viscosity: maybe OK at outer radii, but predicts lower value at r < 1pc, due to the dependence of the geometry (h/R).

AGN Obscuration







- Stellar feedback can make a geometrically thick disk.
- But it can not make a low-column sight-line, which is necessary to explain type-1 AGNs.
- AGN wind is necessary in this model.
  → see other wind-driven (fountain) obscuration models (e.g., Wada 2012 ApJ, 758, 66; Schartmann et al. 2014, MNRAS, 445, 3878)

Summary: the role of AGN feedback

- Evacuate gas from the circum-BH disk
- Enhance outflow (consistent to observations?)
  → significant influence on the ISM at least to r ~ 100 pc
- Suppress the nuclear star formation by a factor of 10-30
- Suppress the dM_{BH}/dt by a factor of 3-30
  → Throttle the nuclear activity (negative feedback)
- Necessary to make a sight-line with $N_H < 10^{24}$ cm^{-2}, i.e., to reproduce type-1 AGNs

TI's Question: can they really explain "evolution" of SMBHs?