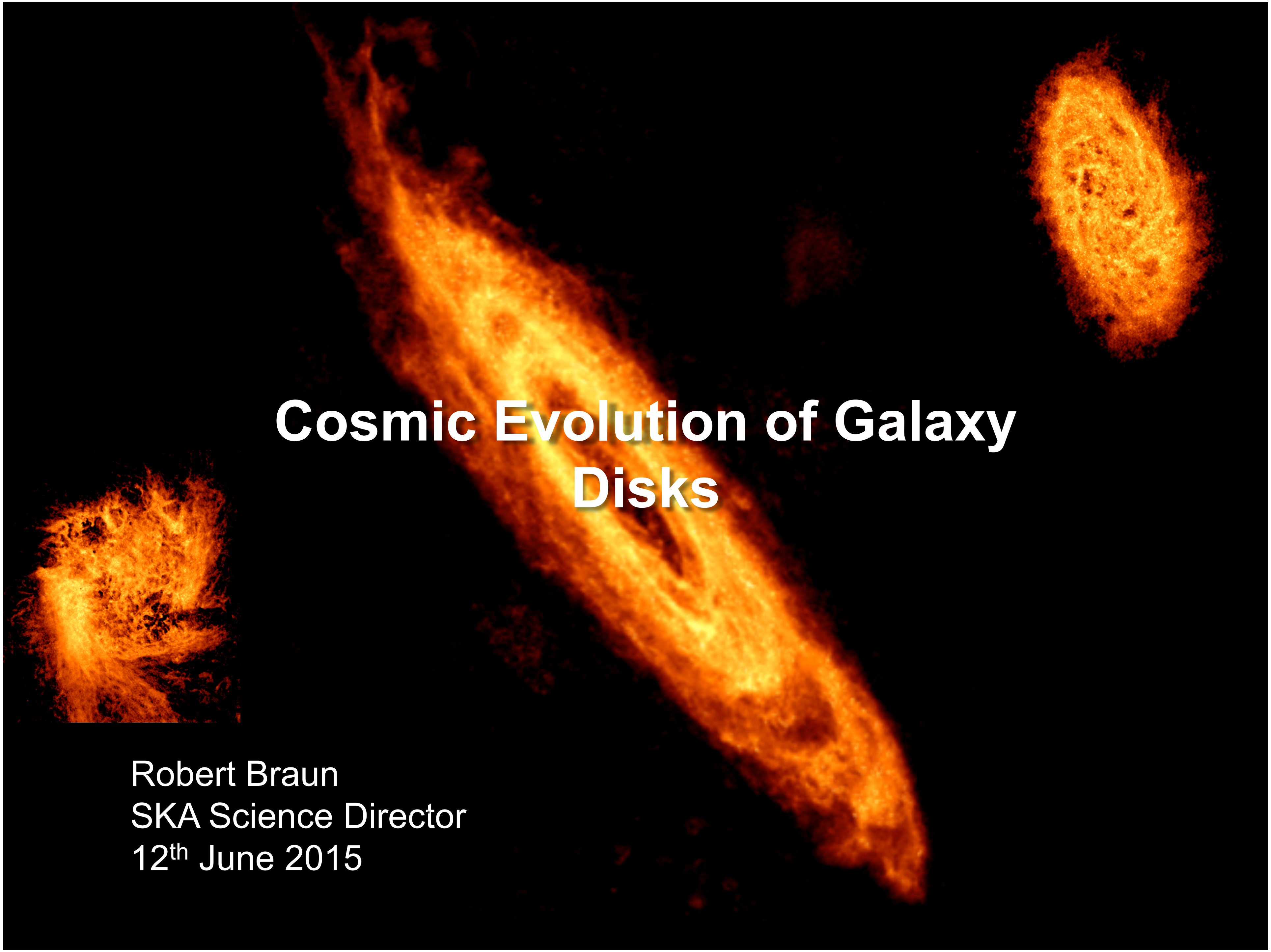


Cosmic Evolution of Galaxy Disks

Robert Braun
SKA Science Director
12th June 2015

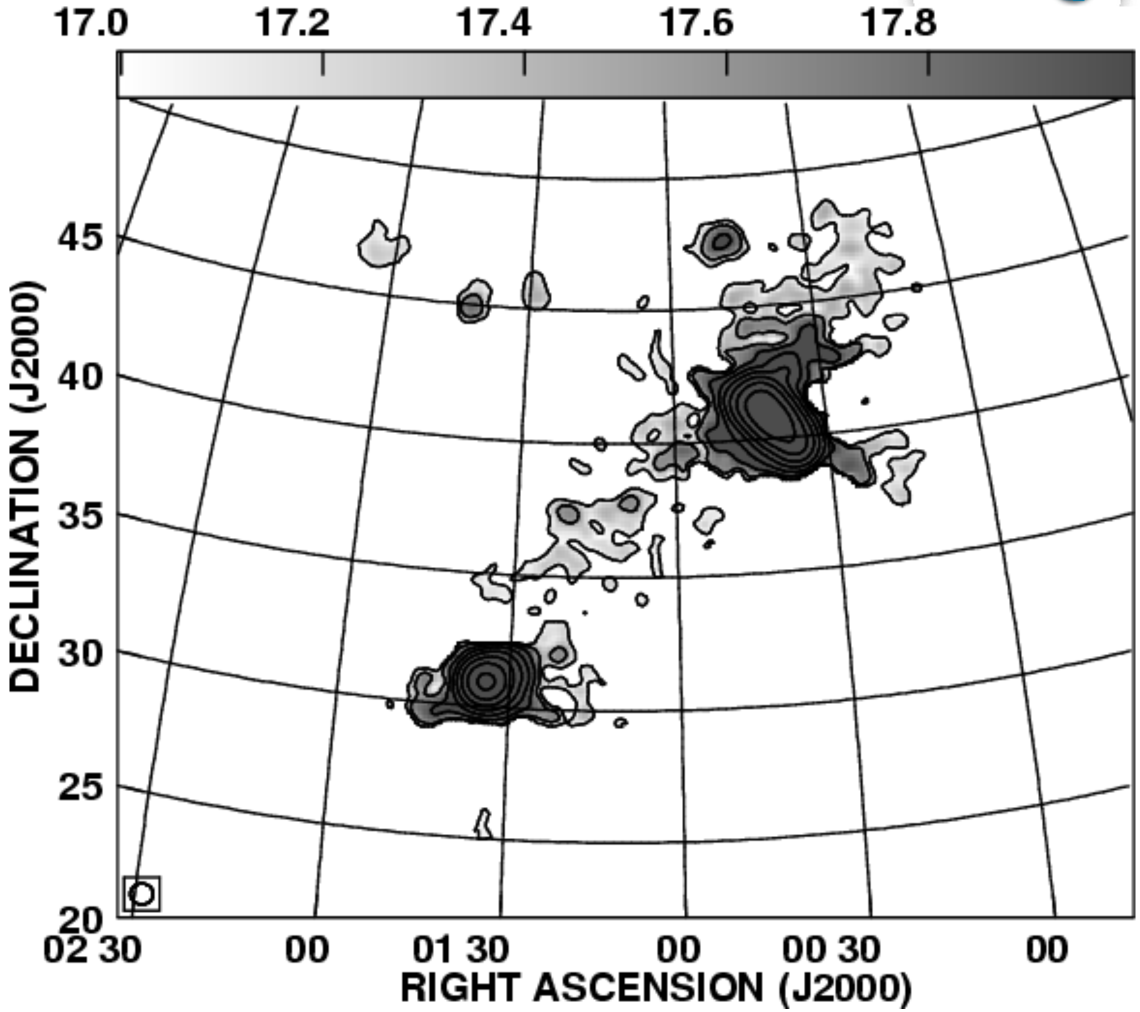
Outline

1. Direct imaging of the low z cosmic web
   (Braun & Thilker 2004, A&A **417**, 421)
   - Ultra-sensitive HI emission observations
2. Direct imaging of low z DLAs:
   Cosmic evolution of the HI Distribution Function
   (Braun 2012, ApJ **749**, 87)
   - The HI column density and mass distribution functions at z = 0 contrasted to those at z = 1 and 3
3. Ram pressure interactions
   (Haan & Braun, 2014a/b, MNRAS **440**, L21, **443**, 186, 2015 in prep.)
   - Kinematic and morphological indicators of space velocity and IGM density

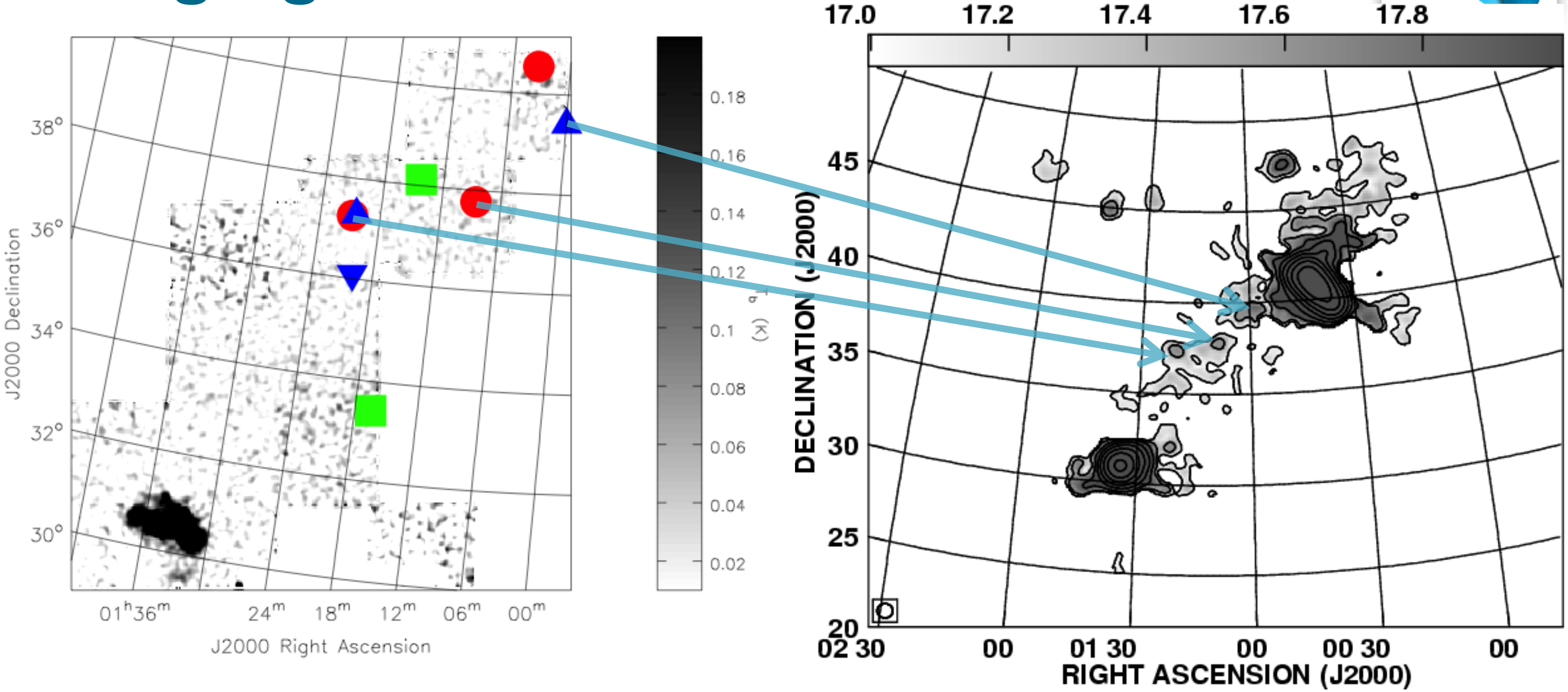
Imaging the HI cosmic web

Braun & Thilker 2004, A&A

- Sensitive(!) HI total power image reveals M31 – M33 bridge (14 single dishes)
- Connects the two V_{SYS}-es
- HI column equivalent to Lyman Limit systems in QSO absorption studies
- N_{HI} in 99% ionized regime
- Tidal or primordial origin? Need modeling to determine scenario.
- Cold accretion feeds both galaxy disks



Imaging the HI cosmic web

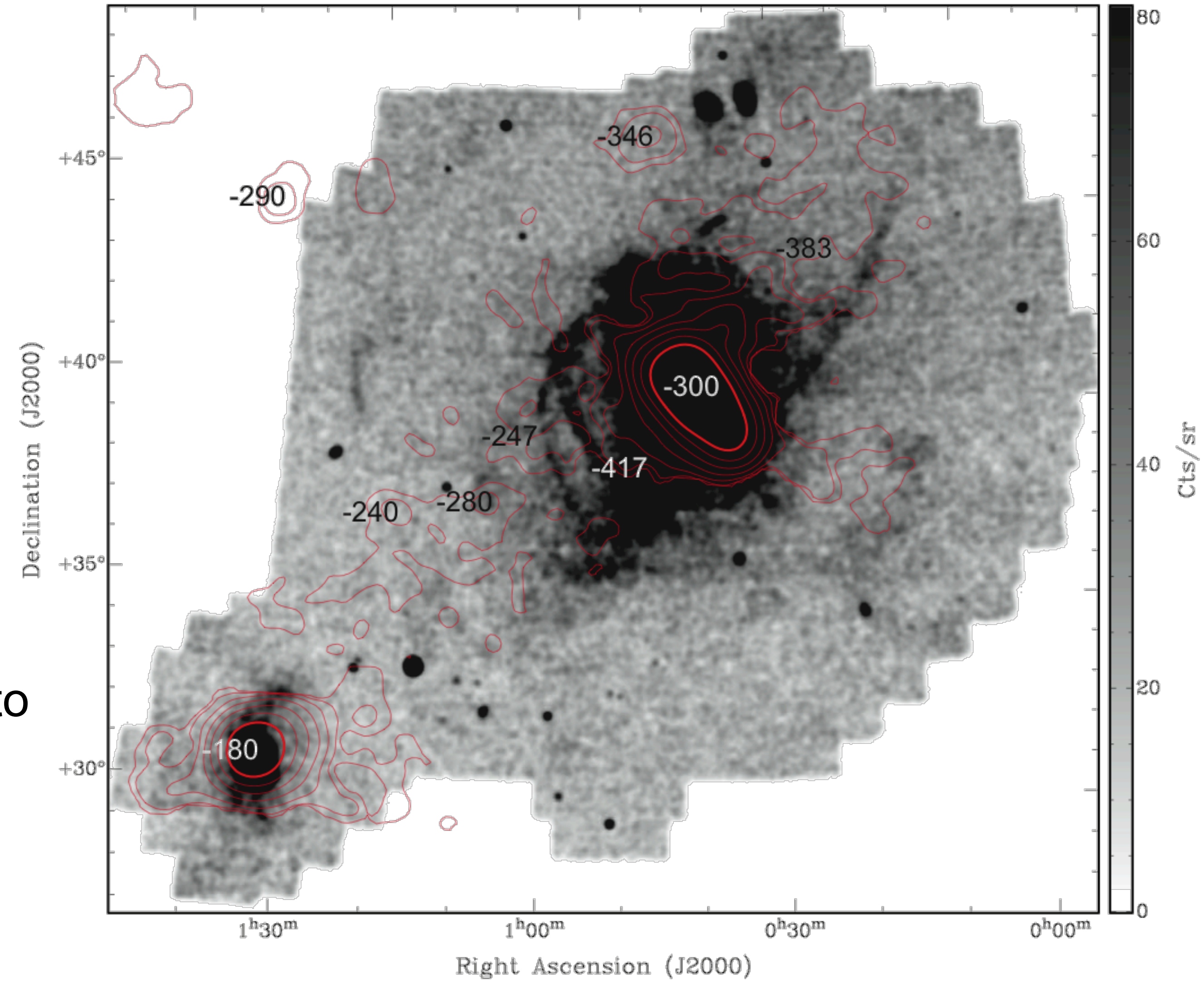


- Confirmation of bridge by Lockman et al 2012, AJ, with the Green Bank Telescope
- Some brighter sub-structure, but intrinsic N_{HI} really only few 10^{17} cm^{-2} in places, $M_{BAR} > 100\ M_{HI} \sim 10^9\ M_{Sun}$!

Imaging the HI cosmic web

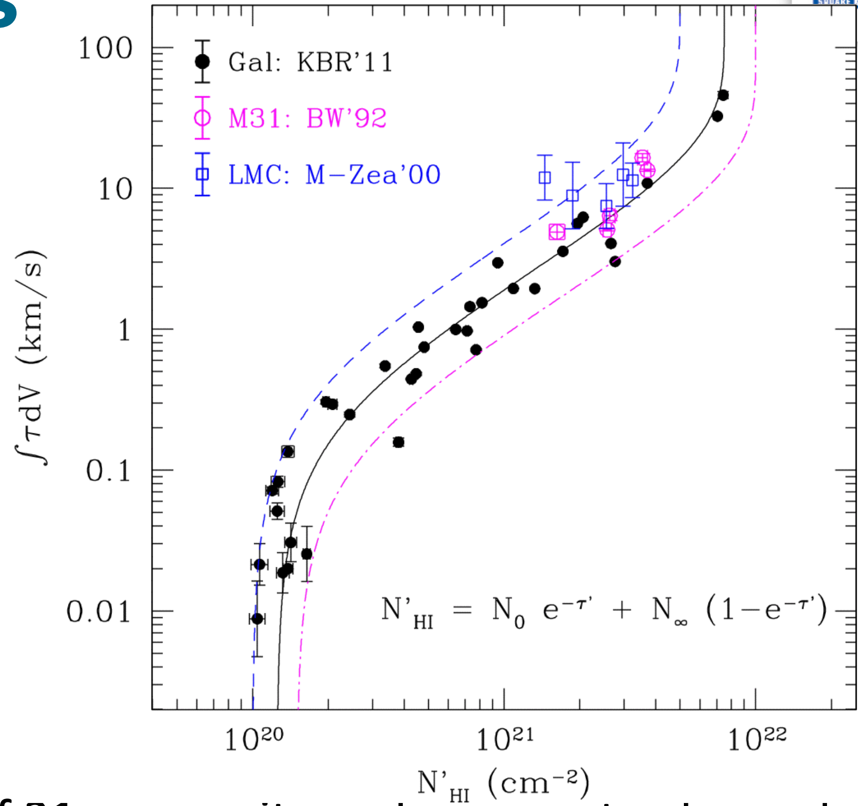
Lewis, Braun et al 2012

- "PAndAS in the Mist" shows **very loose correspondence** of stars and gas
- Gas is dissipative, stars are not.
- Need simulations to reconstruct interactions



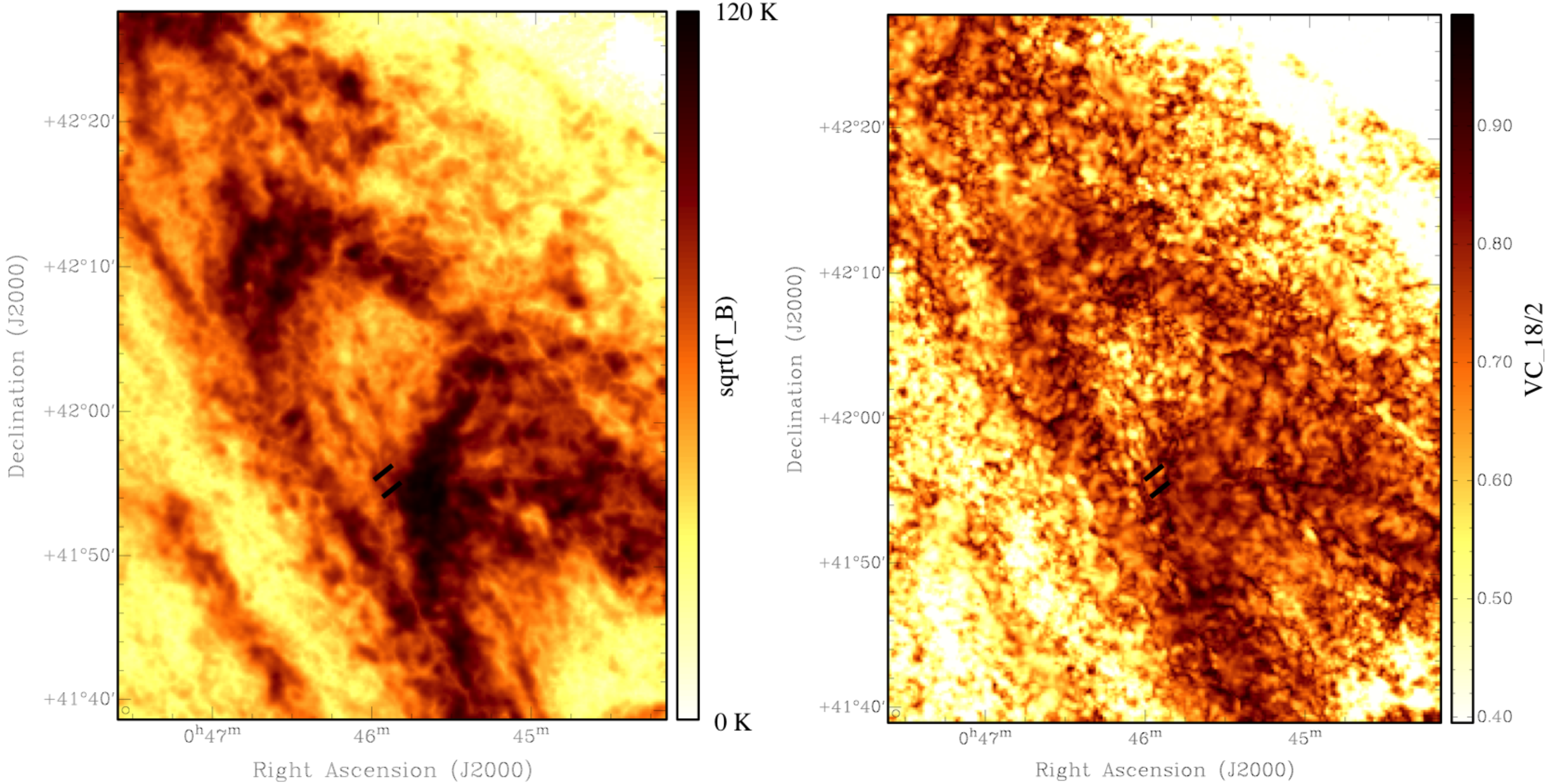
Imaging low z DLAs

Relation between HI apparent column and 21cm opacity



- Non-linear correspondence of 21cm opacity and apparent column density (Kanekar, Braun & Roy 2011, ApJL)
  - Well-fit with warm / cool / warm "sandwich" model
  - Cloud shielding column gives threshold log $N_{HI} \approx 20.1$
  - Self-opacity gives saturation at apparent log $N_{HI} \approx 21.8$

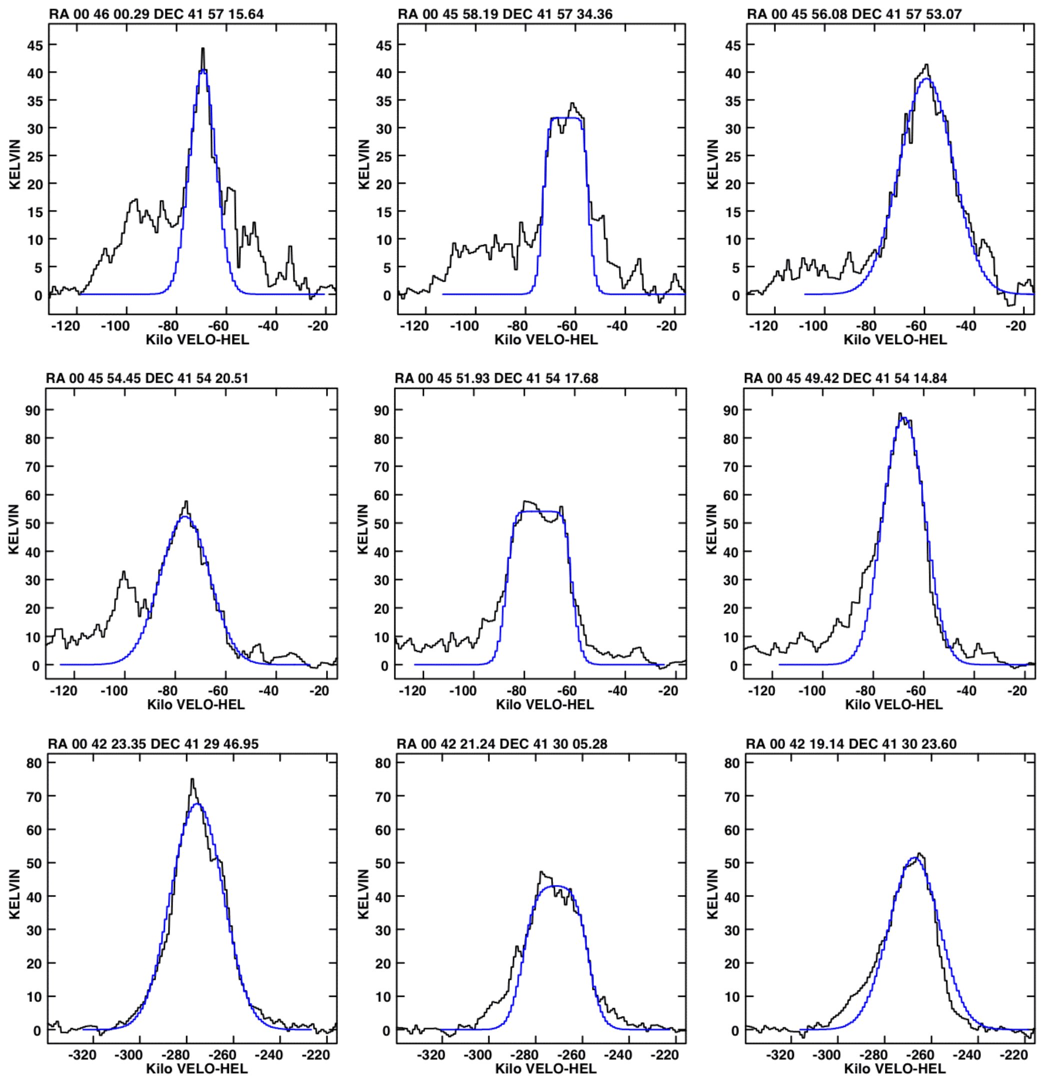
Opaque HI Filaments in M31



- Filamentary local minima in T_B are correlated with broad, flat-topped profiles
- Association with leading edge of spiral arms, > 1 kpc length

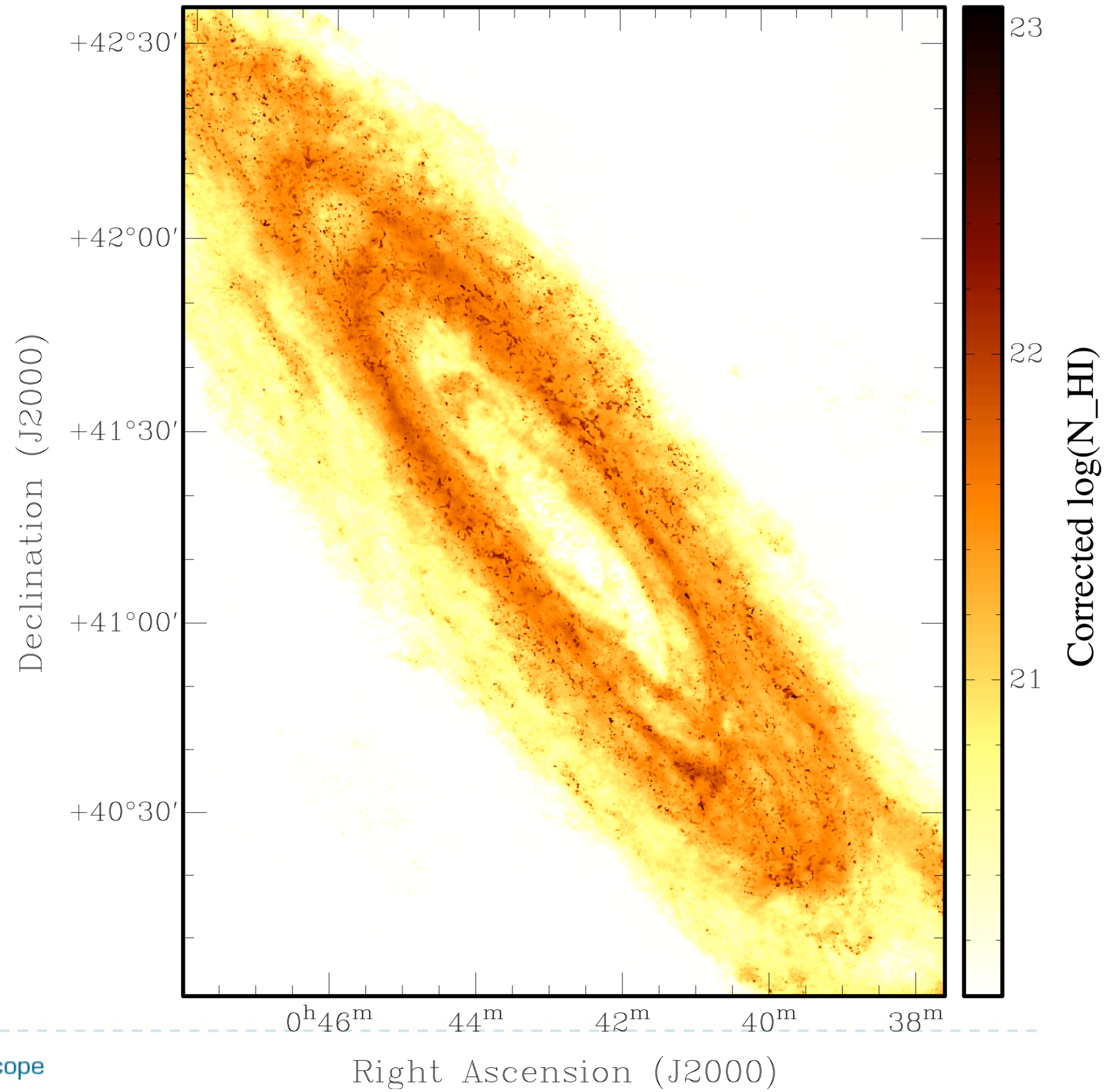
Opaque HI Filaments in M31

- Examples of HI spectra separated by 100 pc
- Each sequence centered on a “dark” filament
- “Dark” features have boxy line profiles and small physical size in at least one dimension



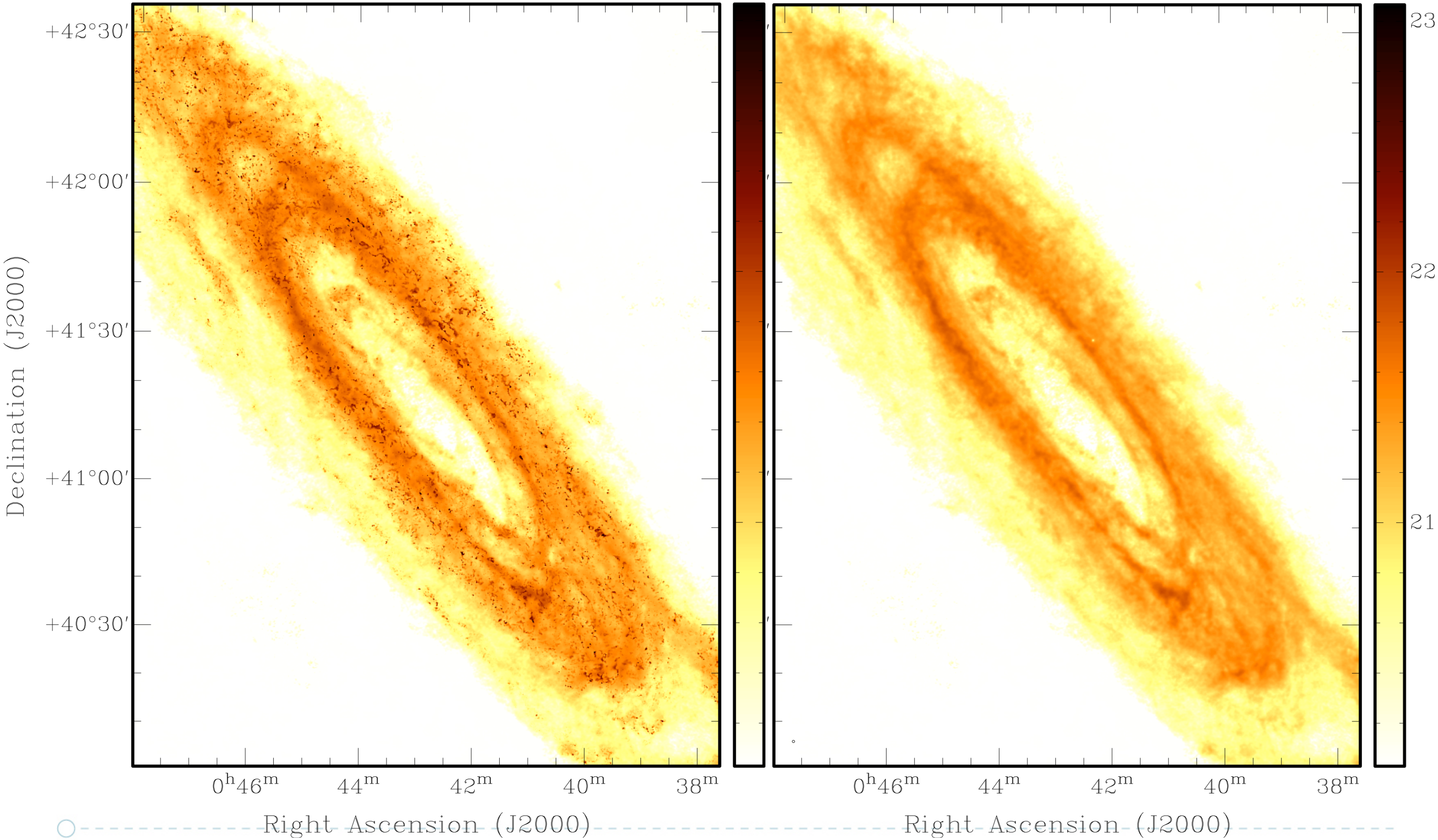
Opaque HI Filaments in M31

- Population of opaque filaments and clumps
- Some gaps (<2%) where velocity field becomes multi-valued (poor fits)
- Local correction to N_{HI} up to 10+ times
- Global correction to M_{HI}: 1.3 times

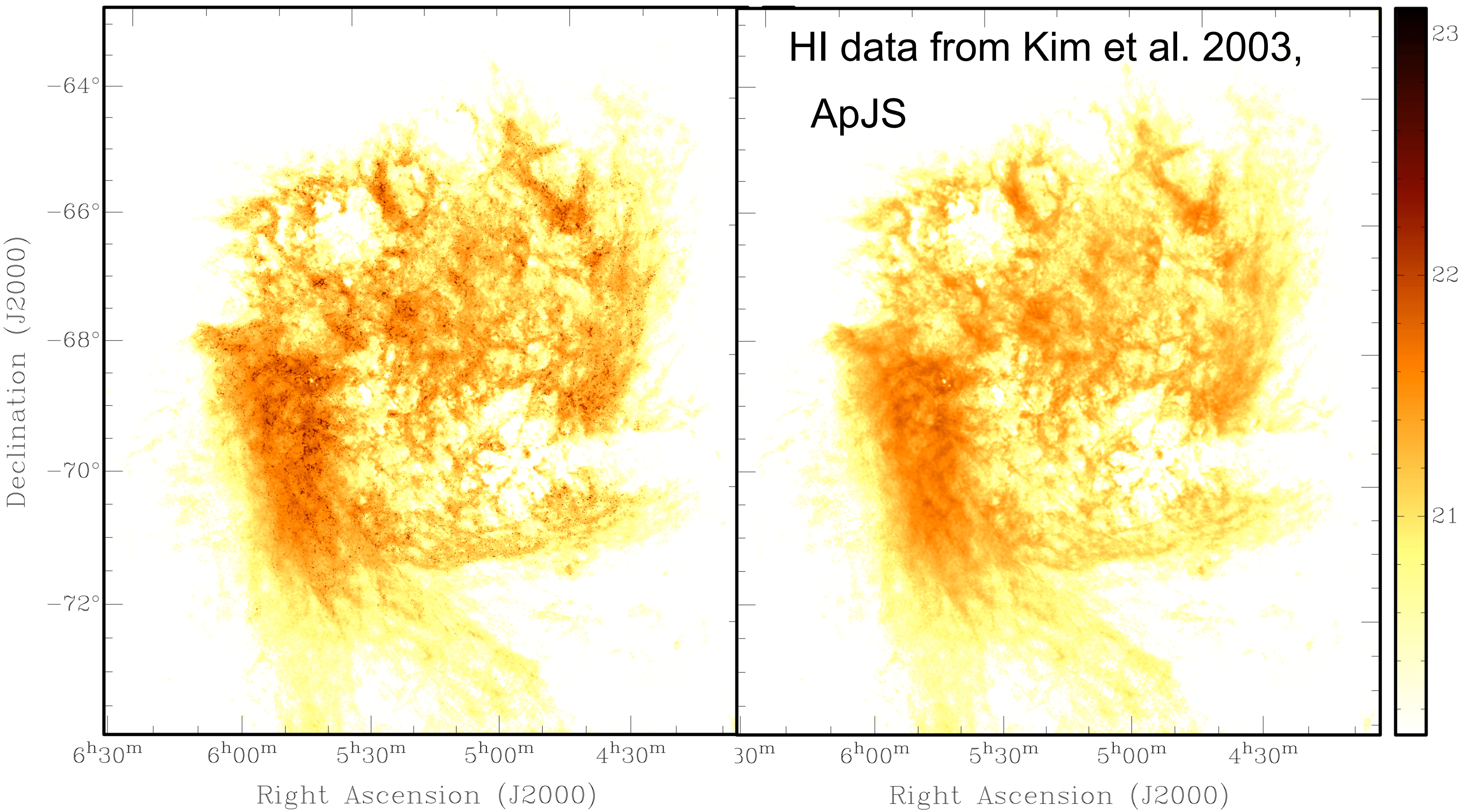


Braun et al 2009, ApJ

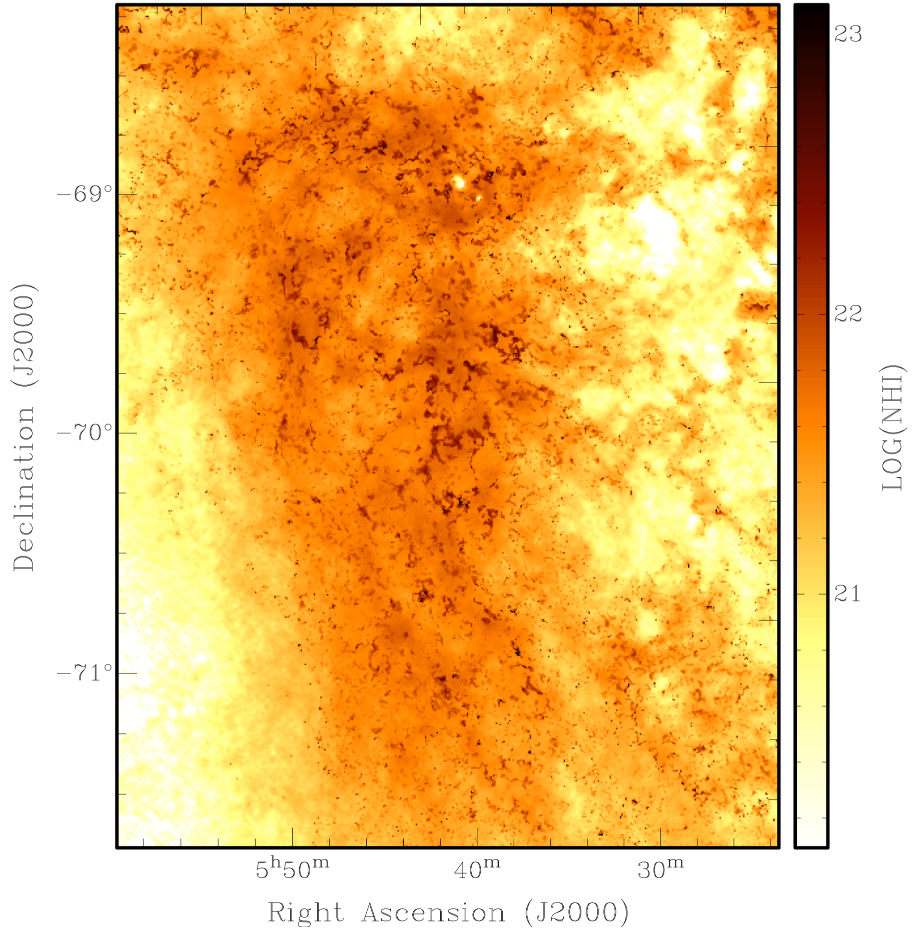
Opaque HI Filaments in M31

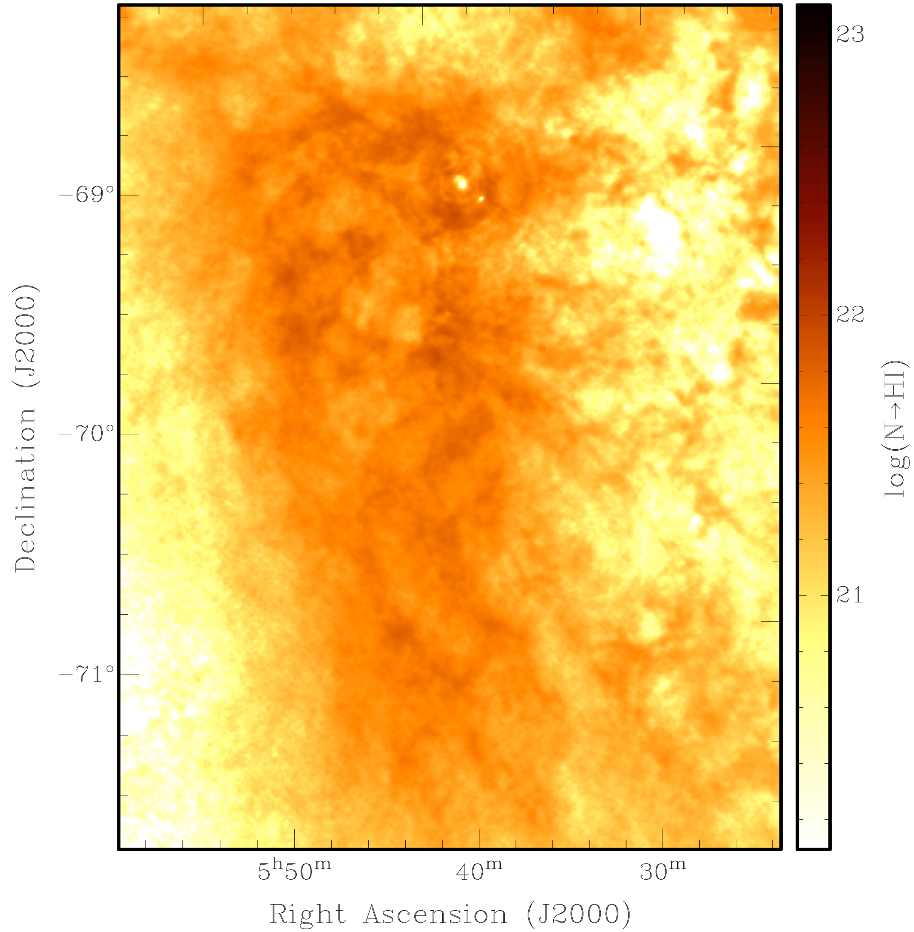


Opaque HI Filaments in the LMC



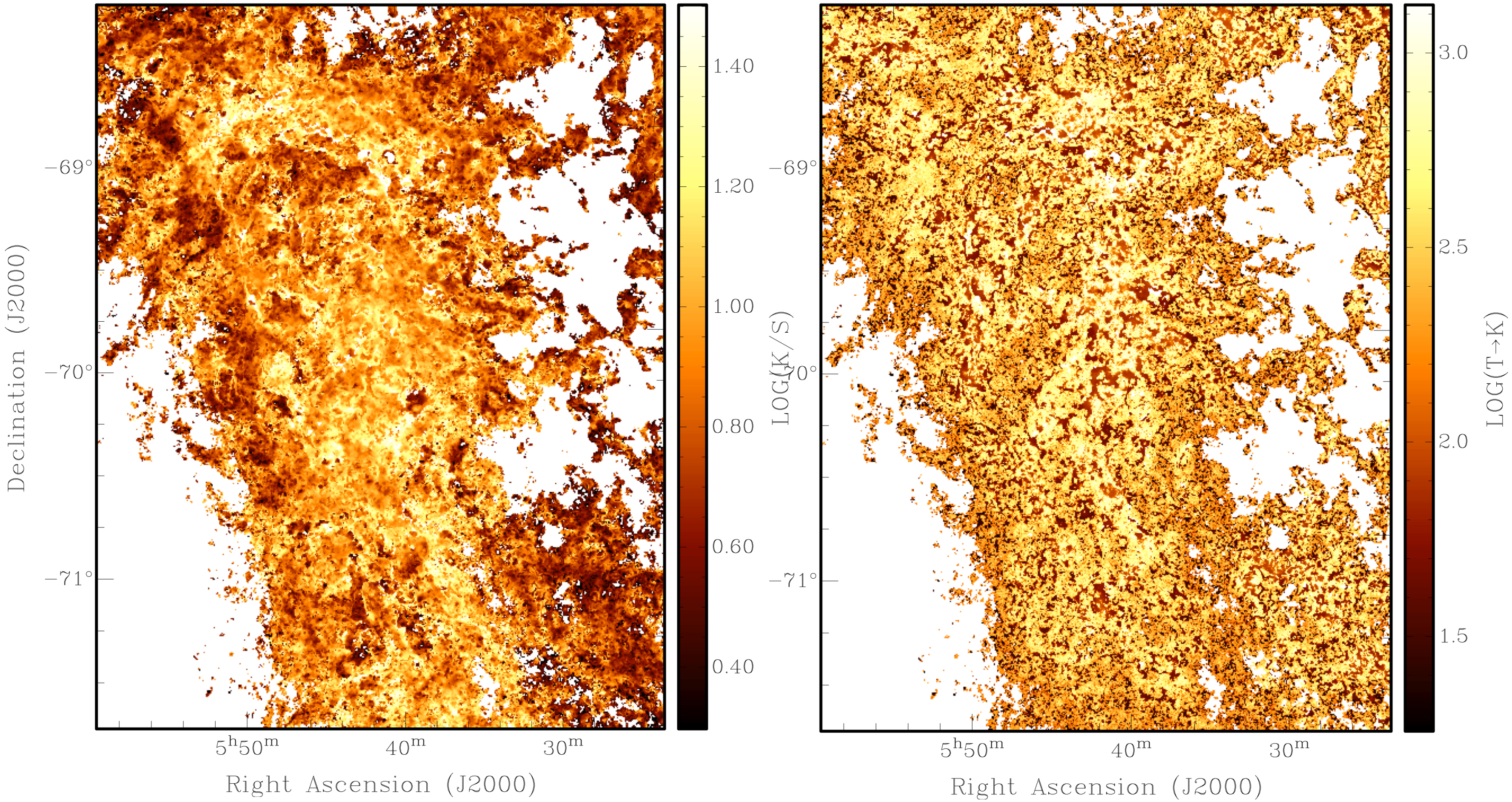
Opaque HI Filaments in the LMC





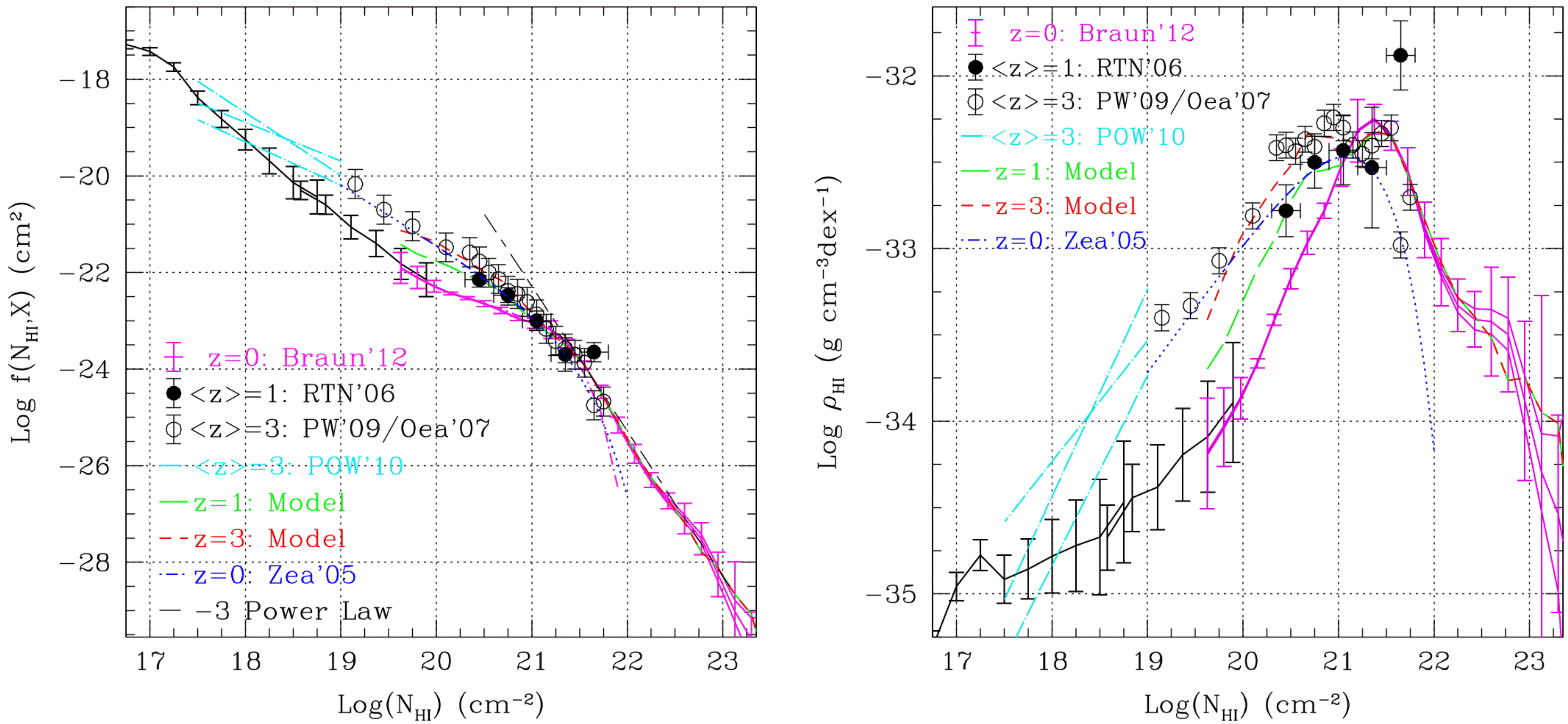
- Opaque filaments on flocculent arms, + more uniformly distributed clumps
- Locally 10+ times N_{HI}, globally 1.32 times M_{HI}

Opaque HI Filaments in the LMC



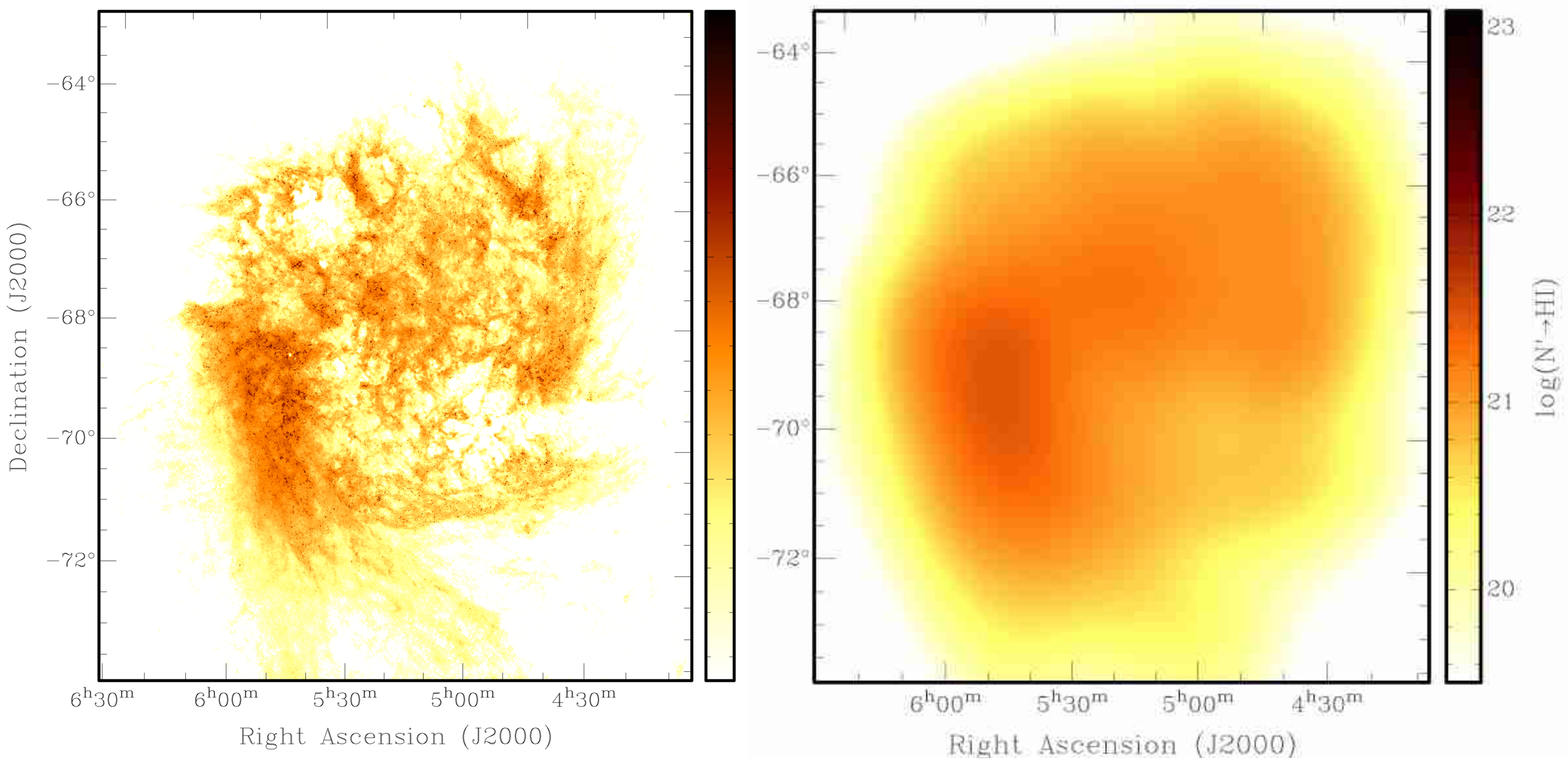
- Cold filaments and clumps in warmer matrix, beautifully "resolved" with 15 pc
- High σ_{NT} on the flocculent arms, also organized into "filaments"

HI column density and mass distribution functions



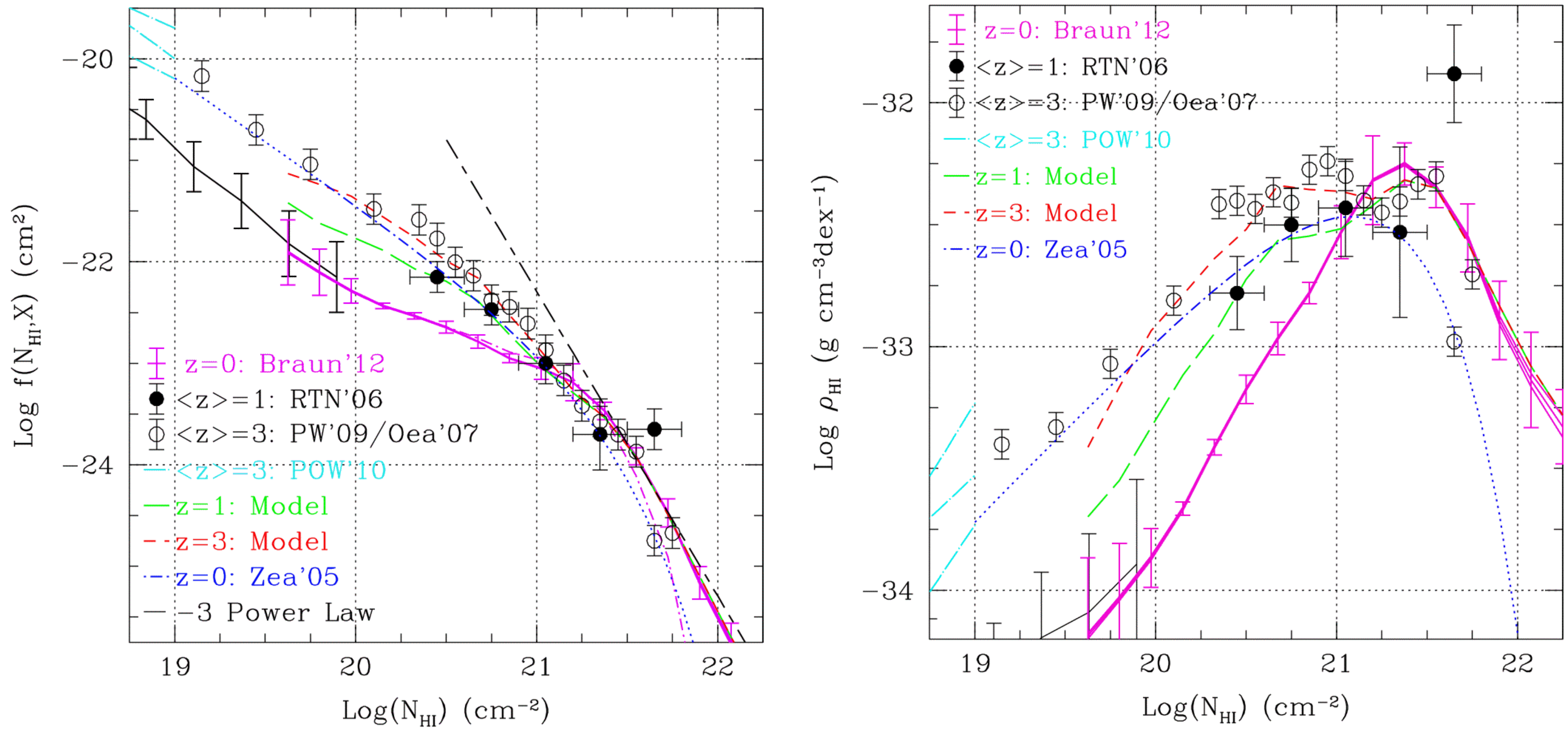
- Use opacity-corrected M31, M33 & LMC images, plus ultra-deep Local Group HI to calculate HI column density and mass distribution functions
  - Normalised using space density of galaxies from HIPASS HIMF
  - Compare with <z> = 1 & 3 QSO absorption lines

HI column density and mass distribution functions



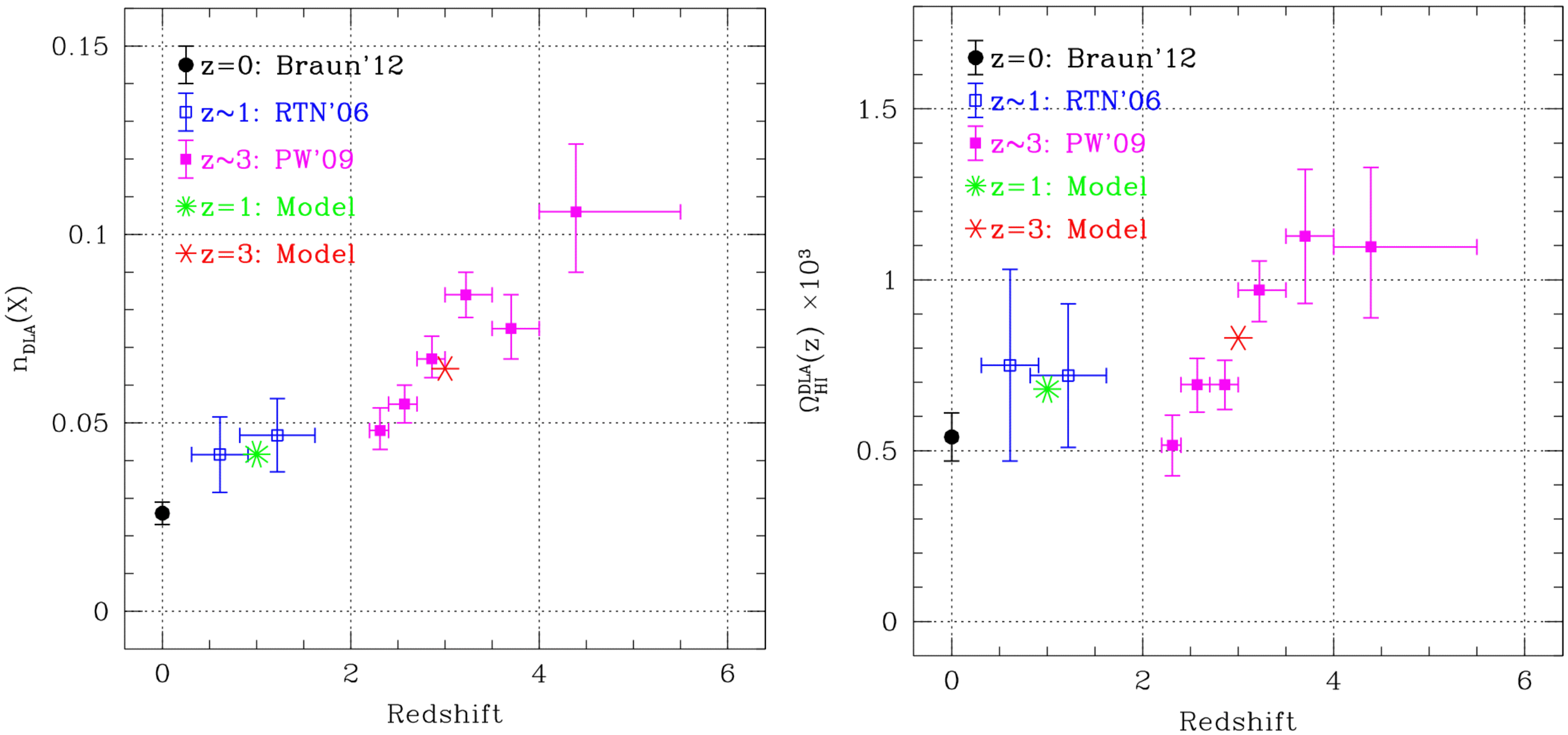
- Previously published z = 0 HI column density distribution functions
  - Based on large galaxy samples, but **low** resolution of 1.4 kpc (like above)
  - Intrinsic HI peaks completely lost, no ability to determine opacity corrections
  - Reached conclusion that distribution function unchanged with z

HI column density and mass distribution functions



- Rough agreement at and above mass peak (log $N_{HI} > 21$) for all z
  - Dense atomic phase very similar over past 12 Gyr
  - Dense HI phase is a short-lived transition from diffuse to molecular
- Systematic decline in diffuse HI (log $N_{HI} < 21$) by factor 5 since z = 3
  - HI halos (refueling of the dense phase) are on their way out

HI path-length function and DLA evolution



- Damped Lyman Alpha (log N_{HI} > 20.3) evolution of number and mass is systematic but modest
- Decline in Ω_{HI} since z = 3 only factor of two

Ram Pressure Interactions?

"Common wisdom":

1. Most galaxies are essentially at rest with respect to their CGM environment
2. The CGM density is typically so low that it can be neglected (except in dense cluster environments)

But are these assumptions true?

Ram Pressure Interactions?

Recent "facts":

1. The majority of galaxies occur in intermediate mass groups
   – First in Eke et al. 2005, now Nurmi et al. 2013 using SDSS

   The median group properties are:

   – Mass, $M_{Dyn} = 10^{13}\ h^{-1}\ M_{\odot}$
   – 3D Galaxy separation, $\langle R \rangle = 0.16\ h^{-1}$ Mpc
   – 3D Velocity dispersion, **$\langle \sigma \rangle = 260$ km/s**

2. The CGM has a "universal" baryonic density profile at intermediate radii within bound potentials:
   – Dave et al. 2010

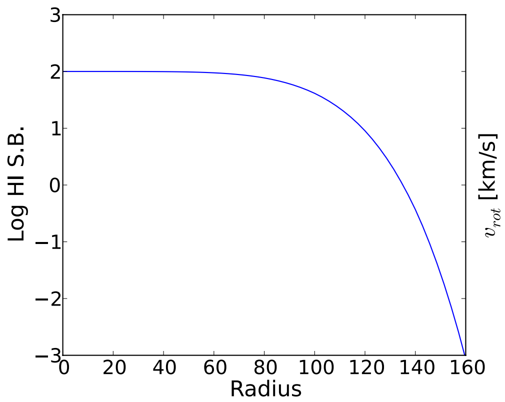
$$n_H(r) = \frac{\rho(r)}{\mu m_H} = \frac{\rho_c}{\bar{\rho}} \left(\frac{r}{r_{200}} \right)^{-2} \frac{\Omega_b 3 H_0^2}{\mu m_H 8 \pi G}.$$

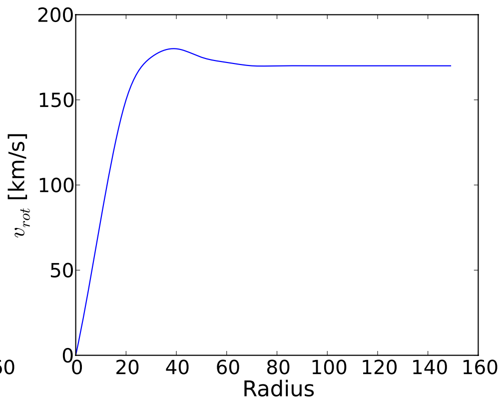
   – **$n_H(\langle R \rangle) = 1.0 \times 10^{-4}\ \mathrm{cm}^{-3}$**

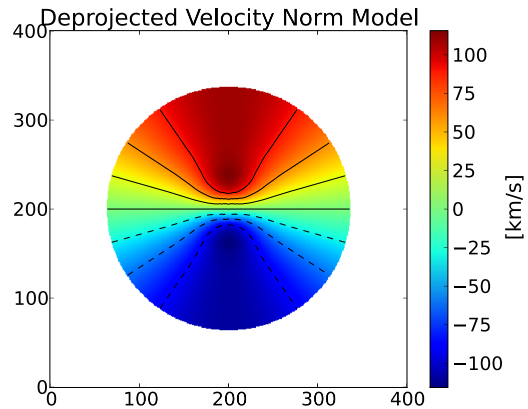
Ram Pressure Interactions?

But is that really true?

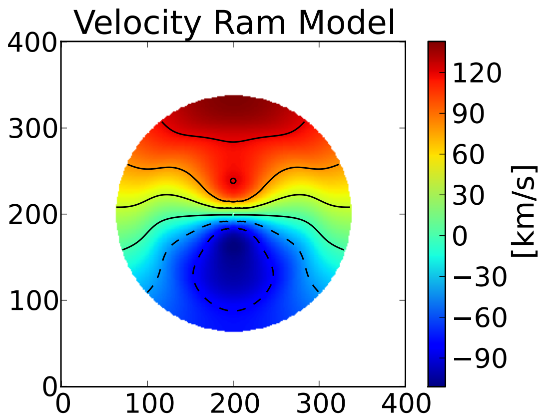
Galaxy Model

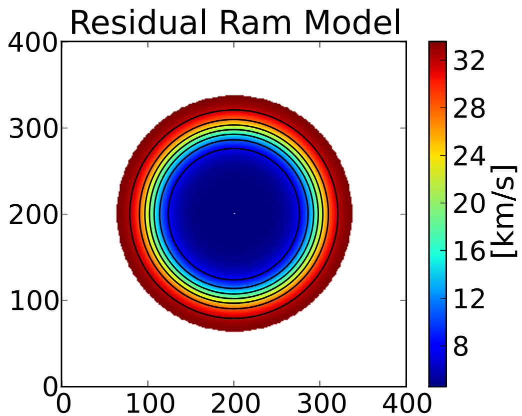






- Ram wind **perpendicular** to disk:



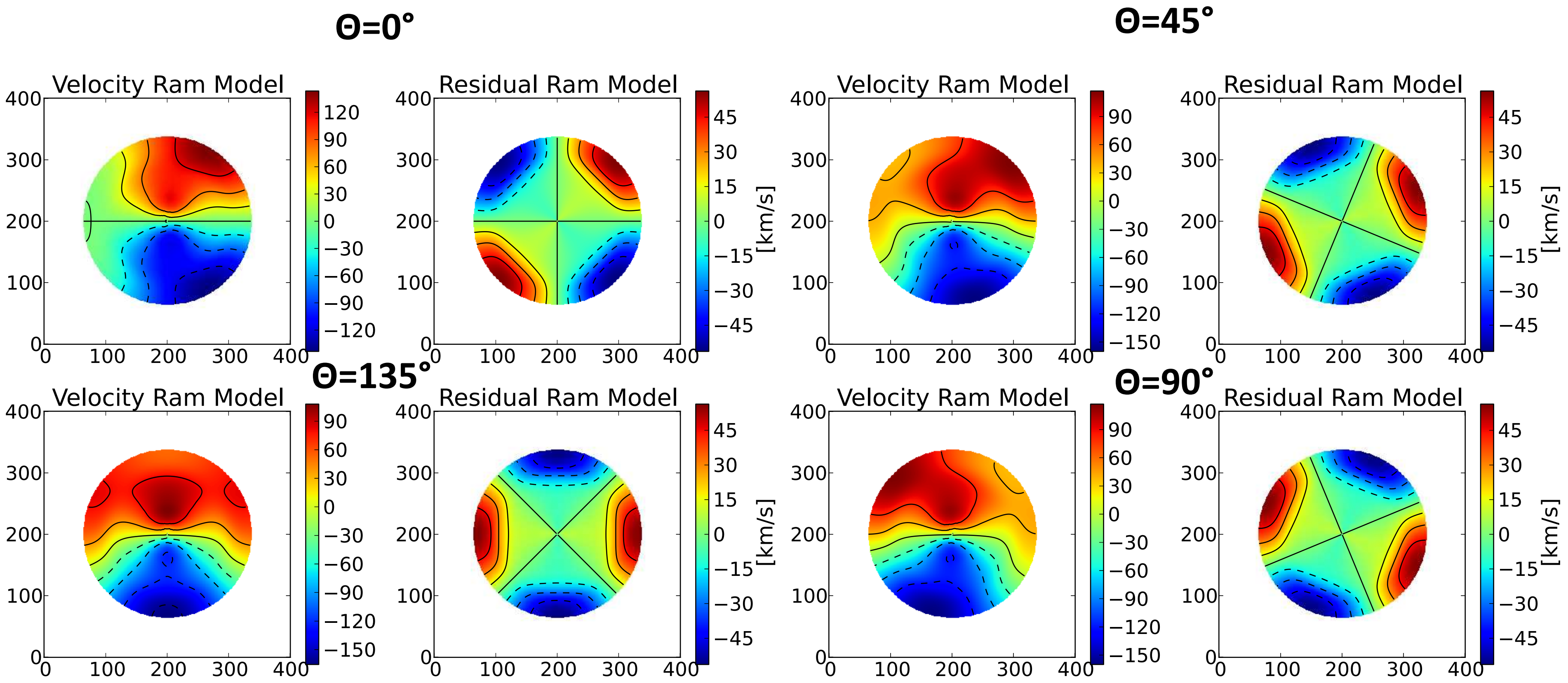


Induced velocity component:

m=0 mode

Galaxy Model

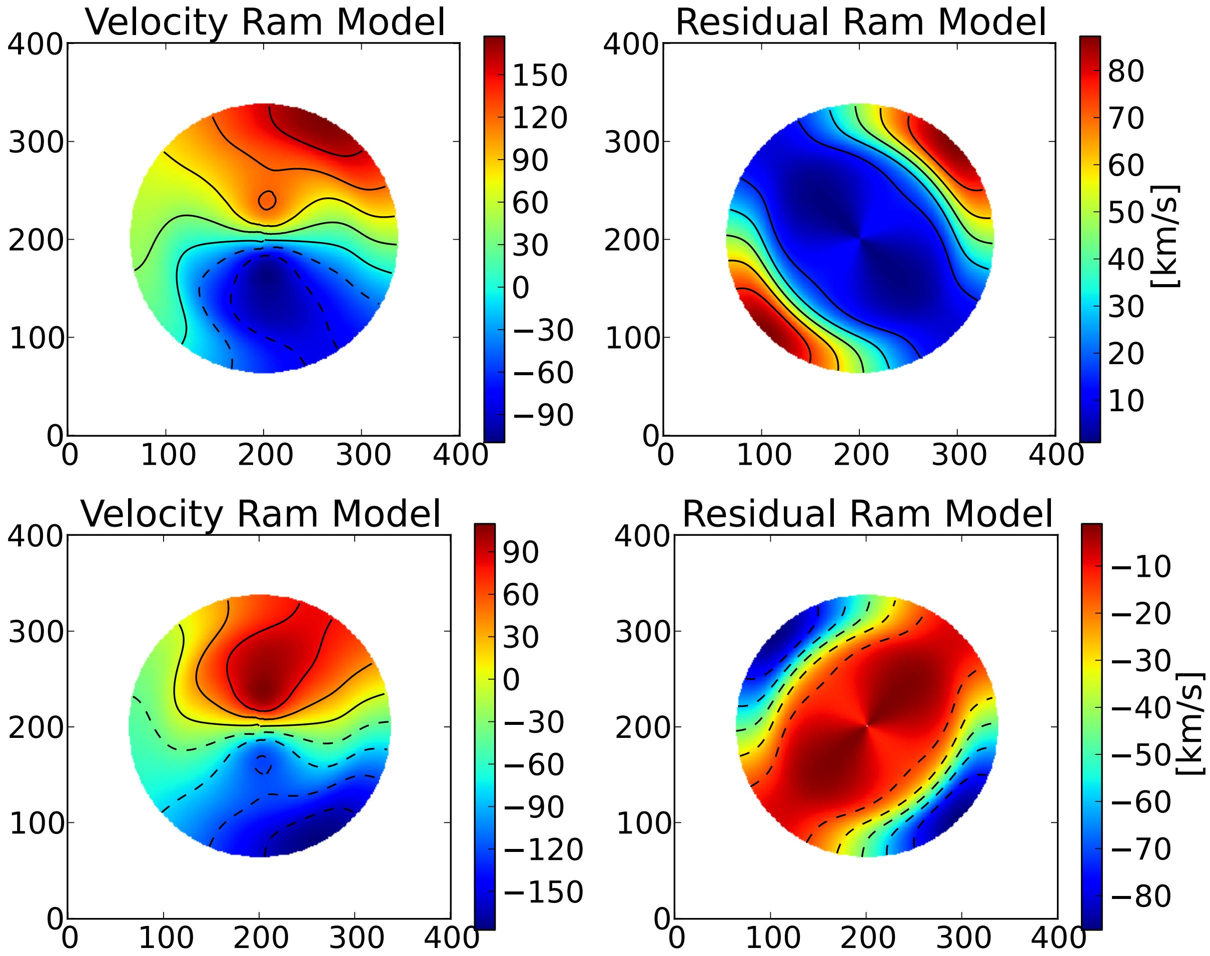
- Ram wind **parallel** to disk:



Induced velocity component: **m=2 mode**

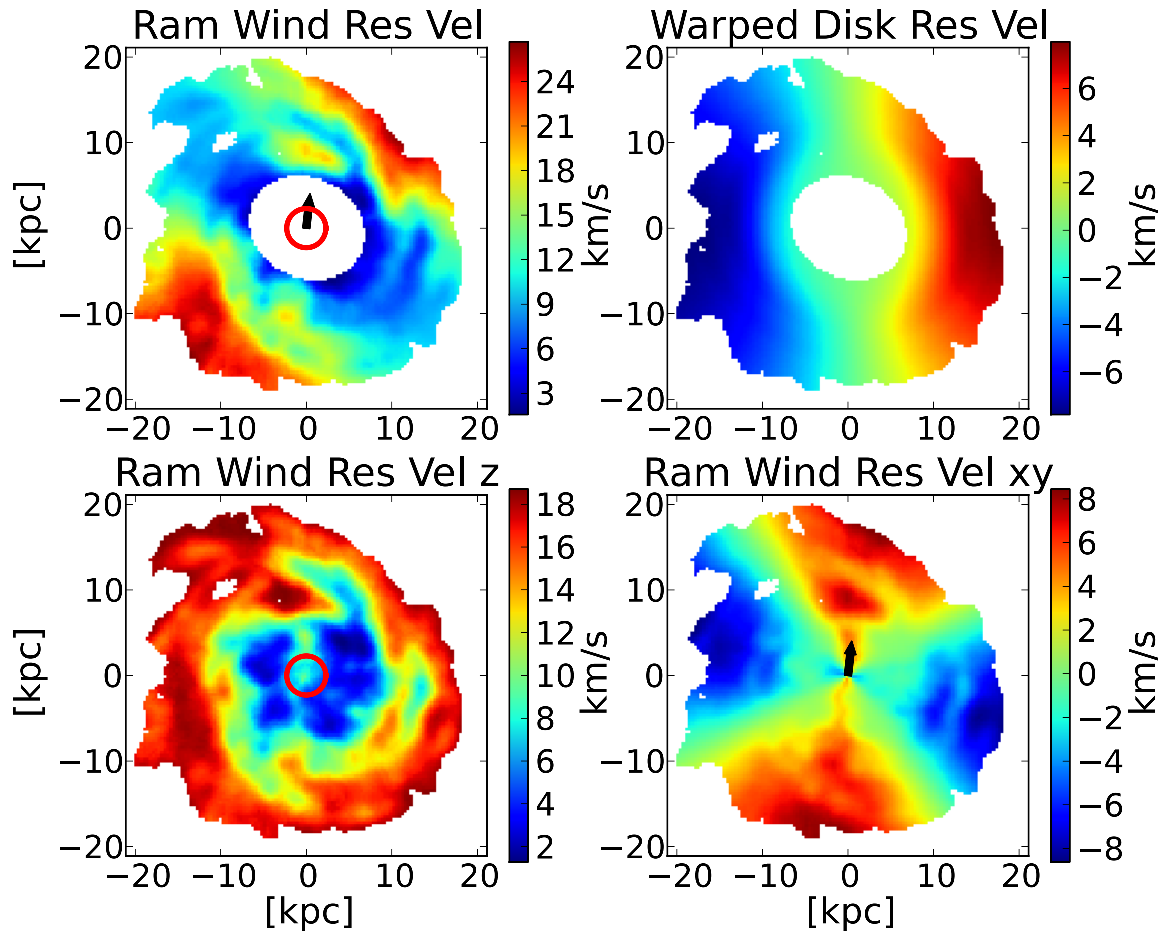
Galaxy Model

- Ram wind inclined by +45° and -45° to disk:



Example: NGC 6946

Decomposition of non-circular velocity field:



Applications:

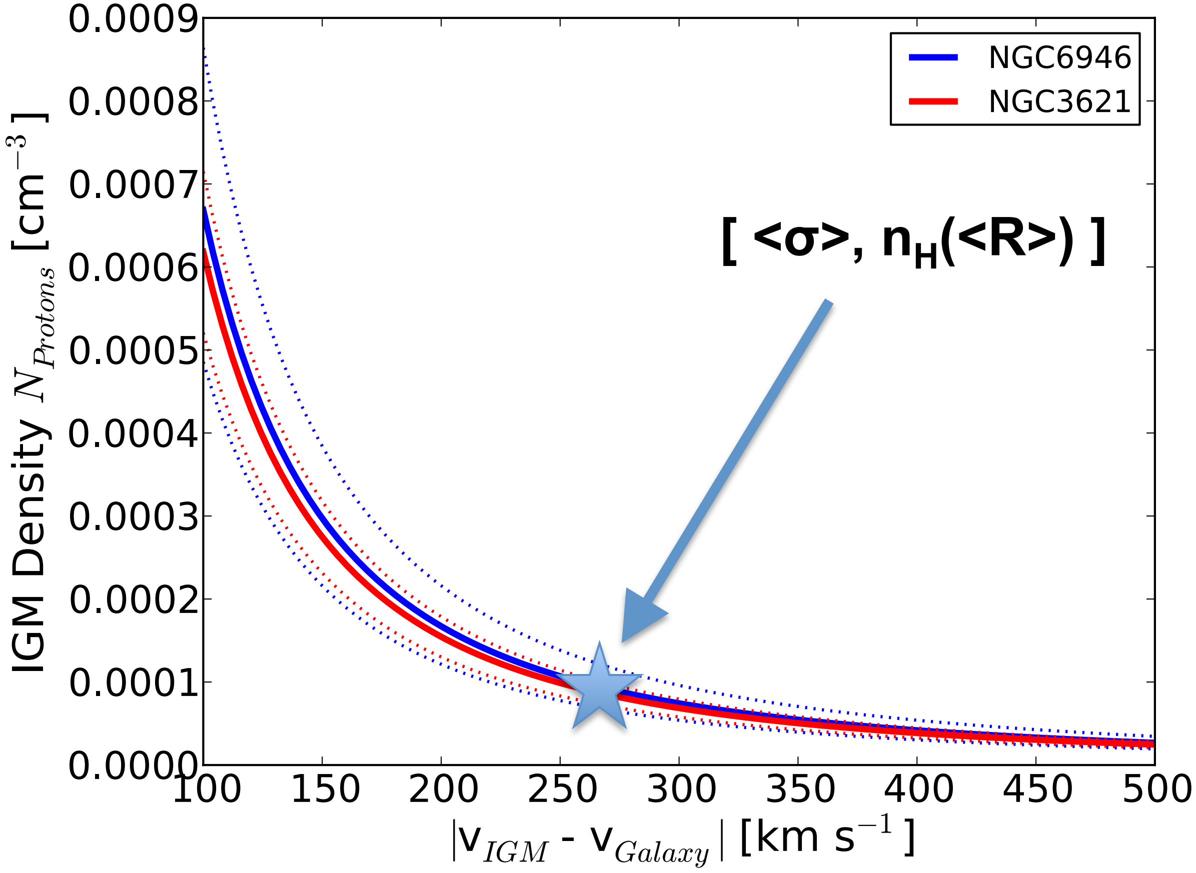
Single Object:

- Measurement of 3D vector of the galaxies' movement through IGM
- Constrain product: (relative velocity × IGM density)

Multi-object:

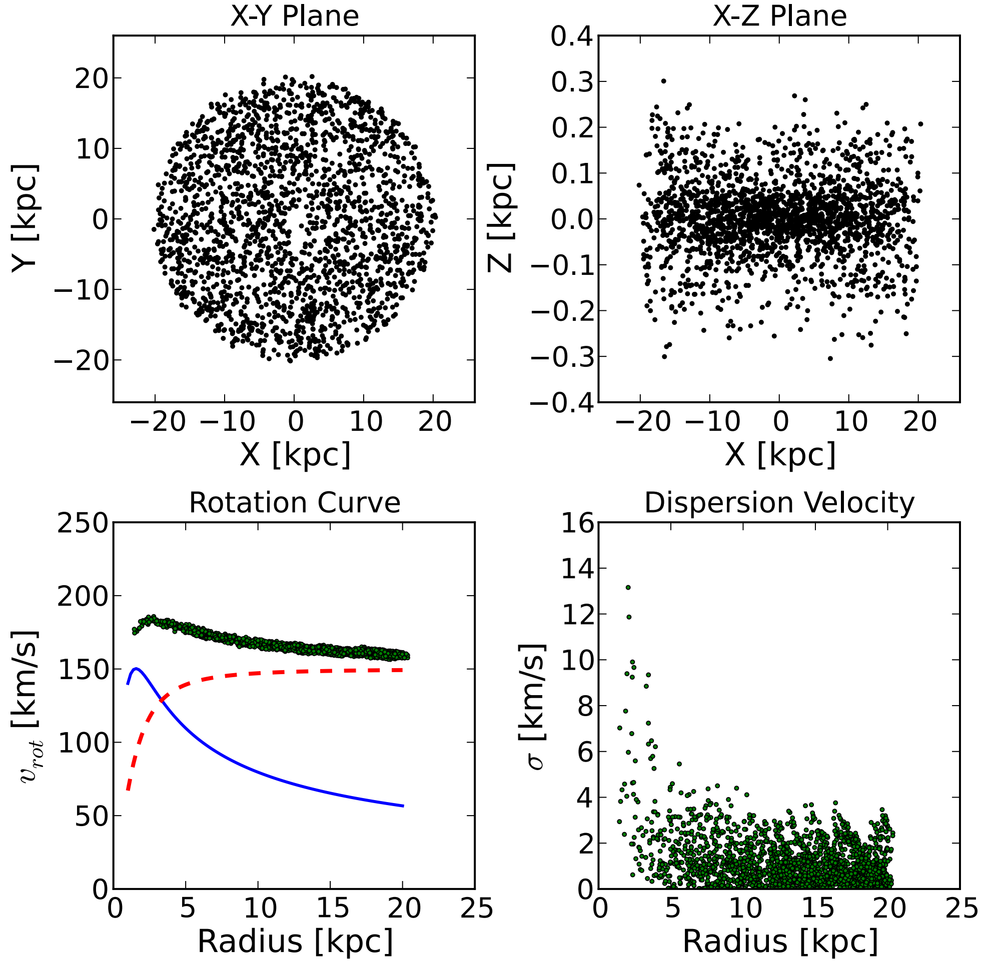
- Determine galaxy orbits and IGM density profile

Current measurements already confirm IGM properties fully consistent with median group conditions

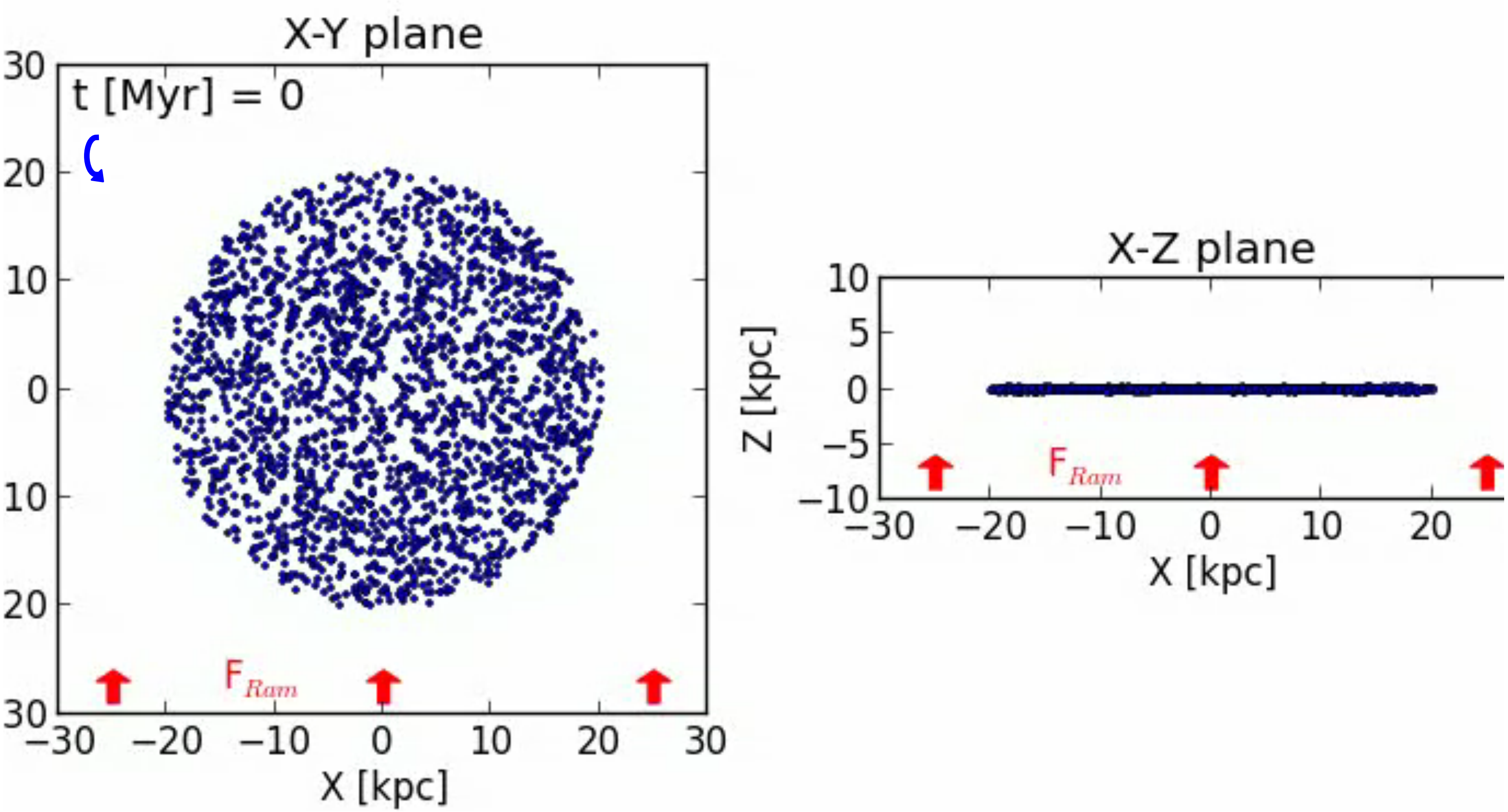


Long-Term Consequences of Ram Pressure

How about setting up a whole population of clouds in a realistic galaxy potential ?



Long-Term Consequences of Ram Pressure



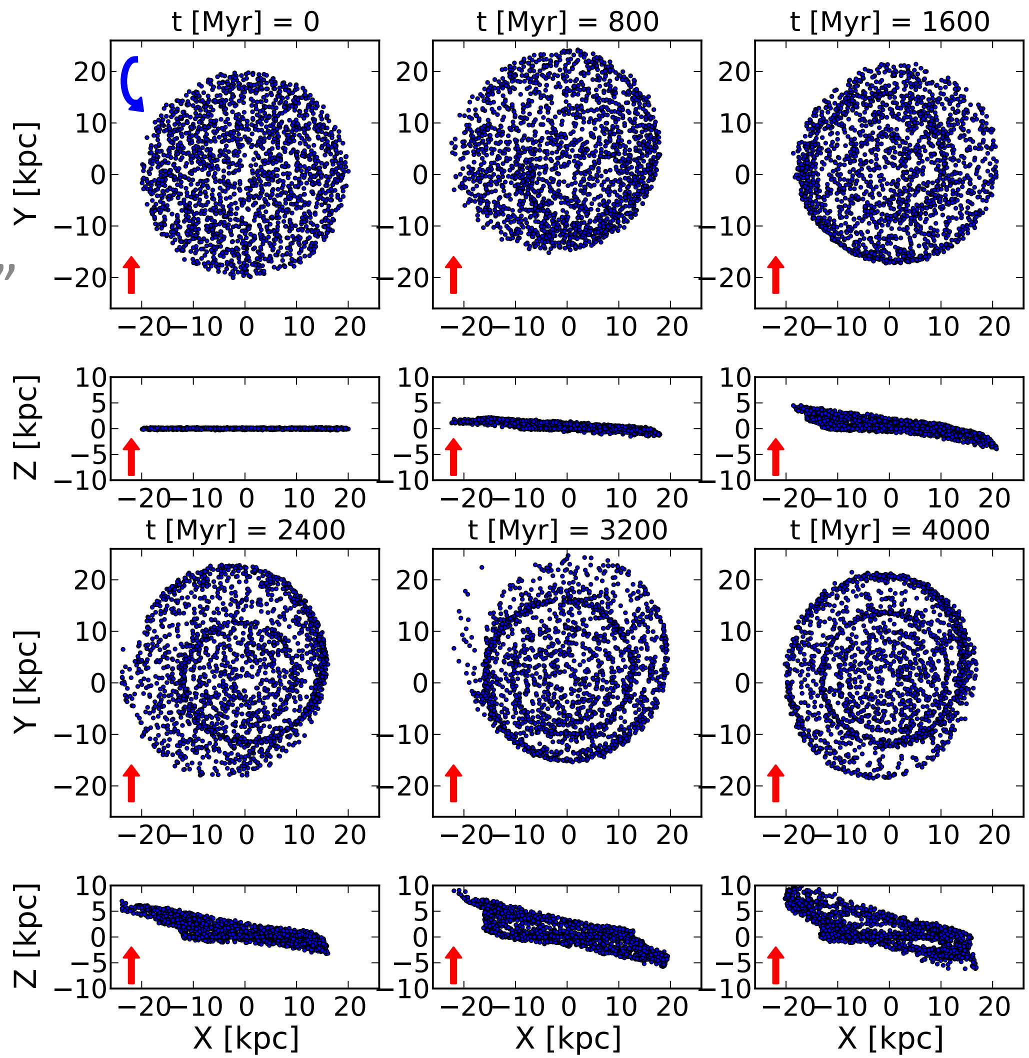
Now what happens ?

Long-Term Consequences of Ram Pressure

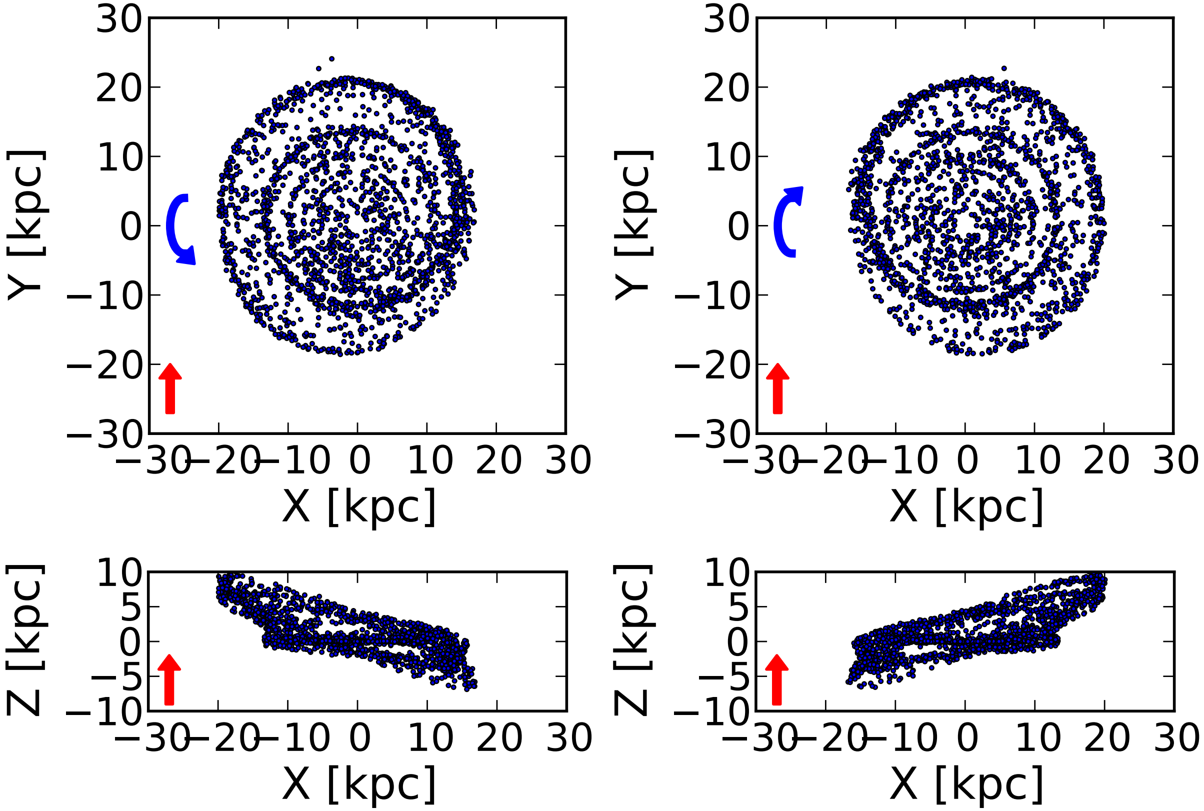
Continuous exposure to a ram wind induces a "classical" S-shaped warp of outer disk

- warp sets in within $2P_{Rot}$
- warp is stable for $>10P_{Rot}$

Also induces one arm retrograde spiral density wave pattern in disk



Long-Term Consequences of Ram Pressure



How does outcome depend on relative galaxy spin?

- Mirror Z-X symmetry of induced warp signatures for CW vs CCW

1. Summary

Ultra-sensitive HI emission studies can reach the densest parts of the cosmic web ($\log(N_{HI}) \sim 17$, $\log(N_H) \sim 19$)

- Direct imaging of ongoing cold ($T \sim 10^4$ K) accretion

2. Summary

Opaque HI accounts for 30 – 40 % more HI in galaxies than is apparent in standard imaging (local correction often > factor 10)

- Decline in Ω_{HI} by only a factor of two from z = 3 to z = 0
- Contrast with ULIRG M_{H2} which has declined by factor 10 since z = 0.5

Similar dense atomic phase (log N_{HI} > 21) for all z

- Dense atomic phase is a short-lived transition from diffuse to molecular gas

Strong evolution of diffuse atomic phase (log N_{HI} < 21) for all z

- Decline by factor of 5 since z = 3
- Accretion for continued star formation has all but disappeared

3. Summary

- Median Galaxy – CGM ram pressure interaction produces a significant kinematic and morphological signature in the diffuse HI disk: **CGM n_H is significant** and galaxy **not at rest w.r.t. CGM**
- "Short-term" effects are m=0 and m=2 **kinematic modes** in the residual velocity field and have a strong dependence on ISM density
- "Long-term" effect is the formation of a classical, m = 1, S-shaped warp **(addresses long-standing puzzle of why so many "isolated" galaxies are warped)** as well as m = 0 **morphological** distortion
- Applications:
  - Reveal 3D vector of single galaxies' movement through the CGM
  - Reconstruct CGM density profile and individual member orbits within galaxy groups

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