HI Filaments towards the Virgo Cluster

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Introduction

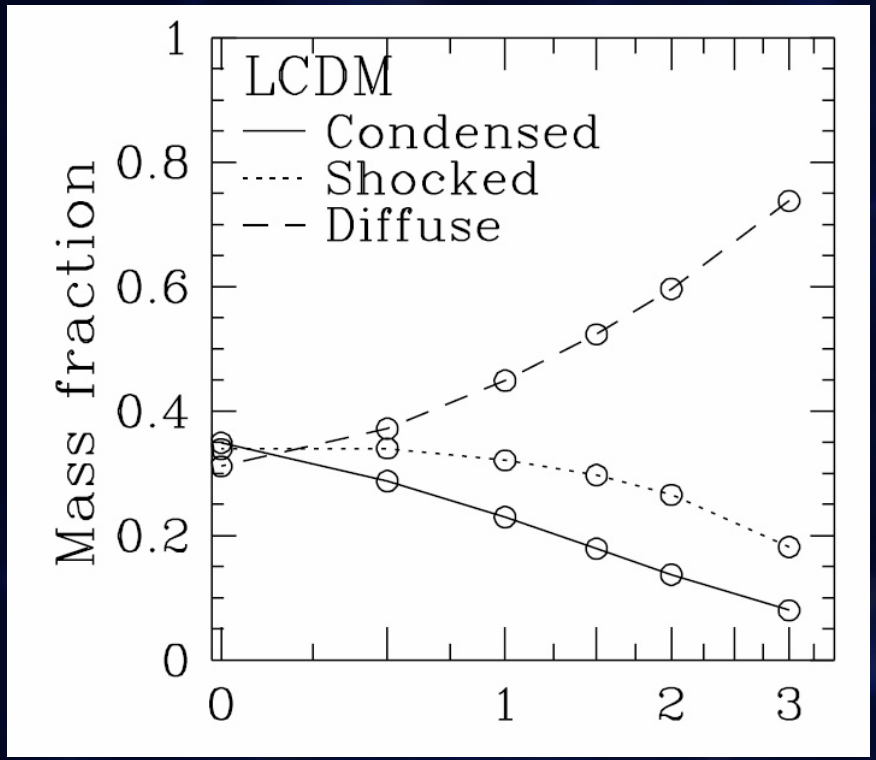
- DLA's observed in HI emission
- Lyman alpha forest detected with QSO absorption lines.
- Lyman Limit System unexplored region

- WMAP 3: 4% universe composed of atoms
- less than half is directly probed at z=0 (e.g. Fukugita et al. ApJ 503, 1998)

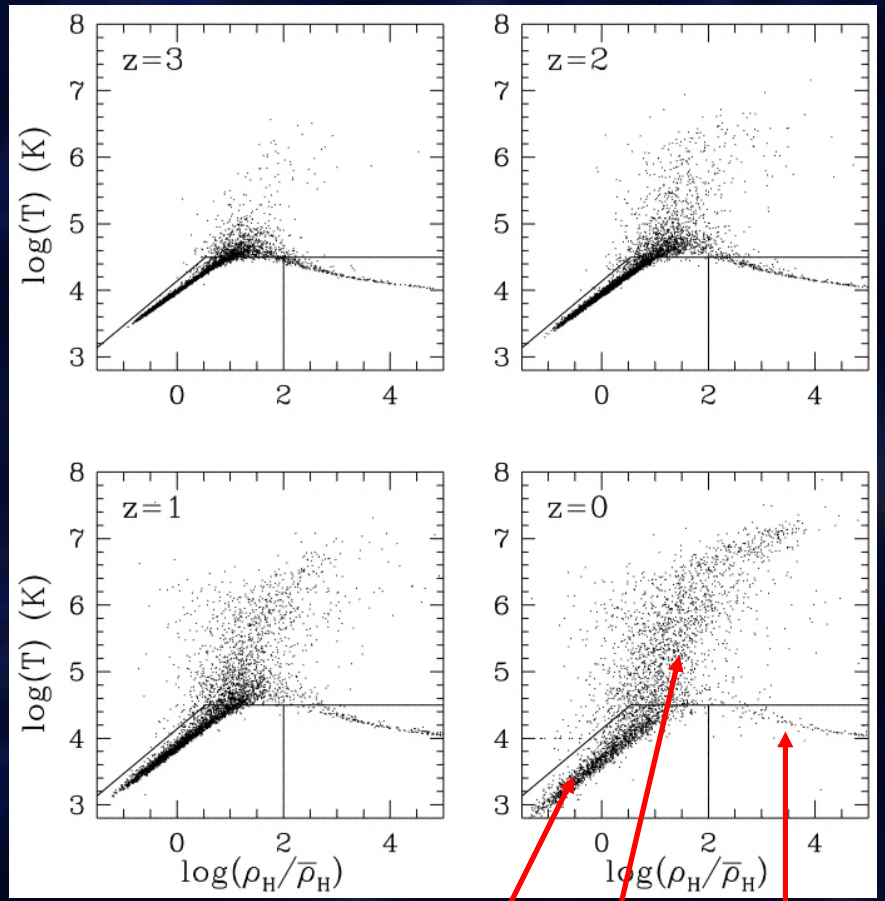
- Diffuse filamentary gas structures are predicted by simulations.
  - Expected Hα EM=5×10^{-4} cm^{-6} pc and T~10^5-10^7 K

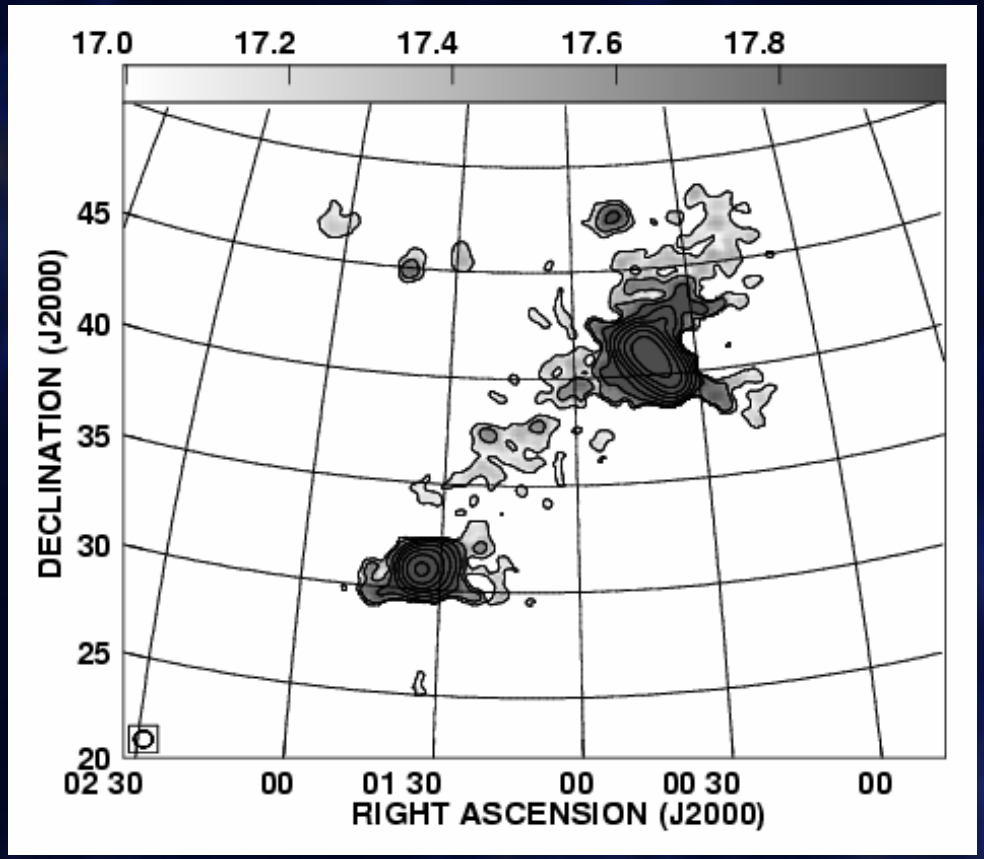
- One has to reach column density of NHI ~10^{17} cm^{-2}

Evolution of Gas Phases



Dave et al. 1999, ApJ 511,521

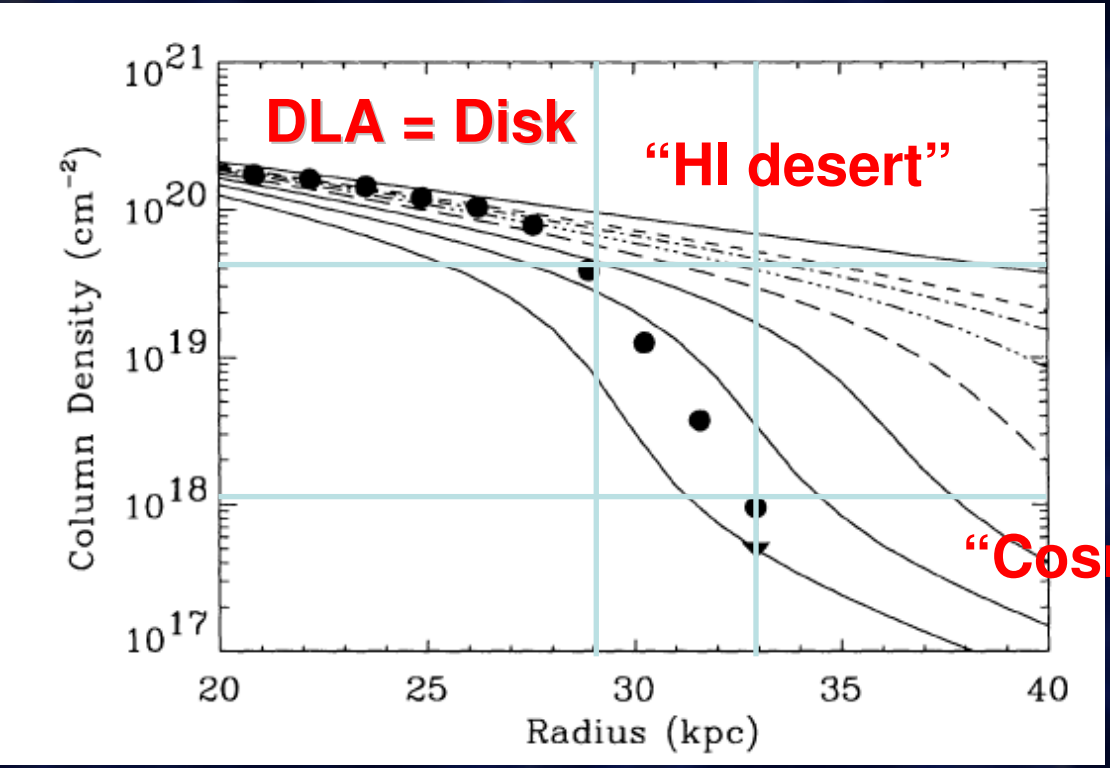




Braun & Thilker 2004, A&A, 417, 421

- First image probing Lyman limit column densities (10^{17} - 10^{18} cm^{-2})
  - Shows filaments between galaxies (M31 & M33).

Imaging the low-z Cosmic Web

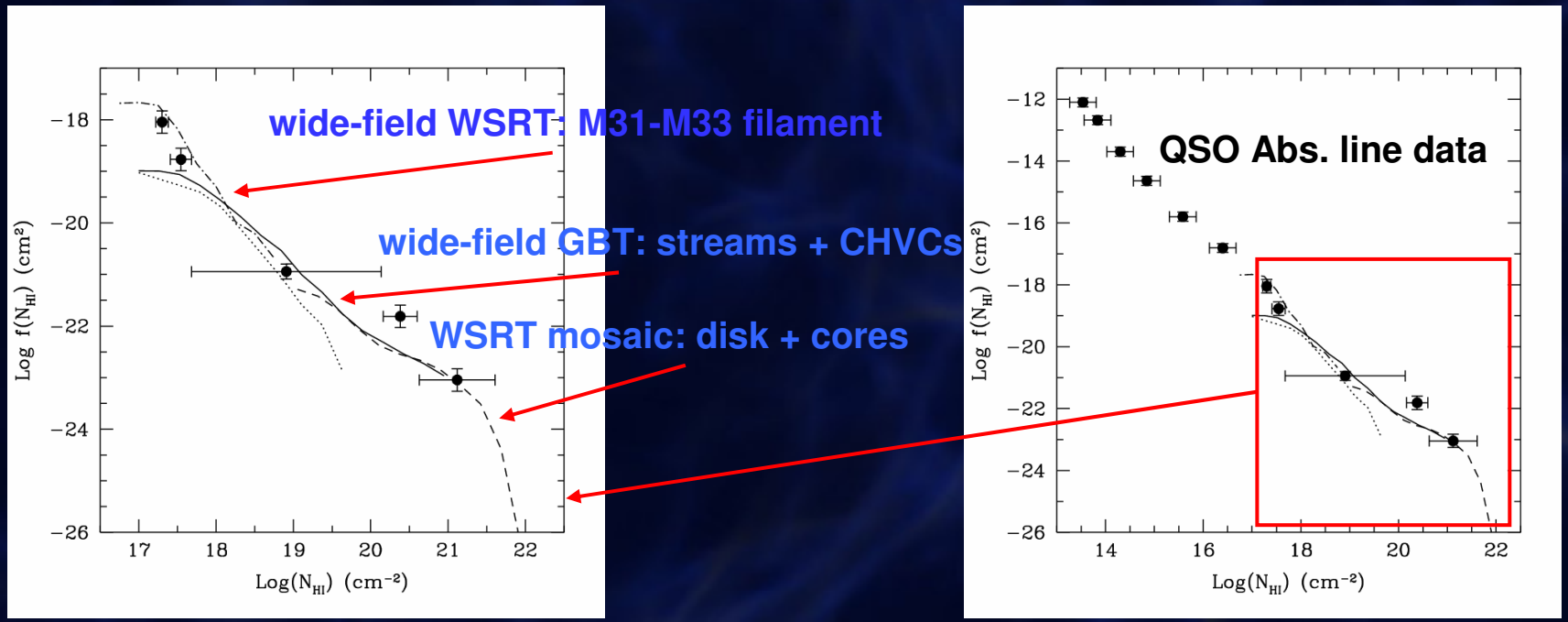


eg. Dove & Shull 1994, ApJ 423, 196

- ionization by intergalactic UV leads to exponential decline in neutral fraction: ~100 % to ~3 % from log(N_{HI}) ~ 19.5 to ~ 18
- "HI desert" is major observational challenge !!
- slow decline of neutral fraction below log(N_{HI}) ~ 18 !!

M31 filament and QSO absorption lines

Braun & Thilker 2004, A&A, 417, 421

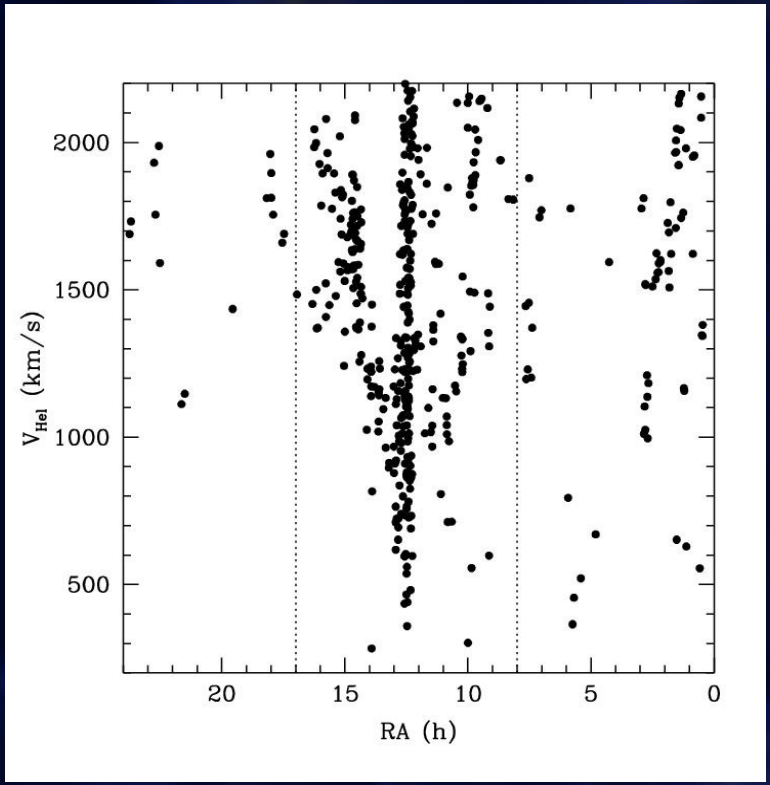


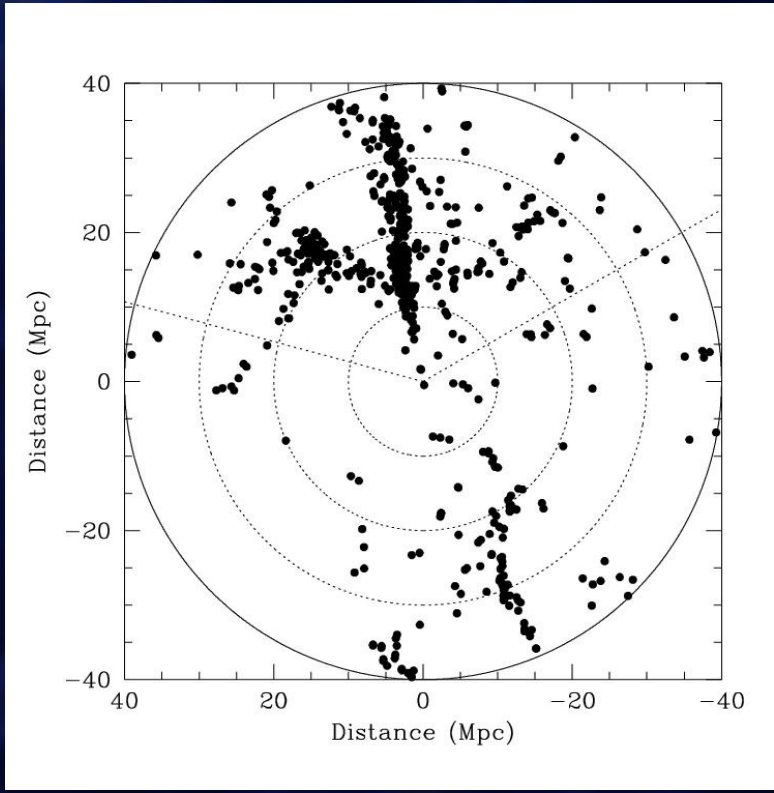
- composite N_{HI} distribution from WSRT mosaic, GBT, wide-field WSRT
- normalization from HIPASS BGC (Zwaan et al. 2003, AJ, 125, 2842)

➢ good agreement with QSO absorption line data

➢ the first image of a Lyman Limit absorption System

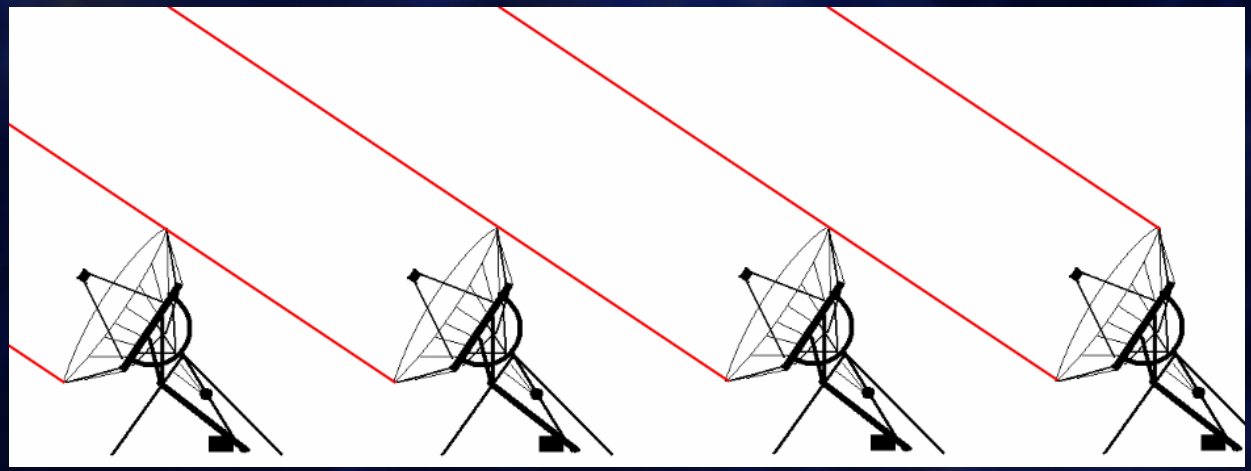
Observations



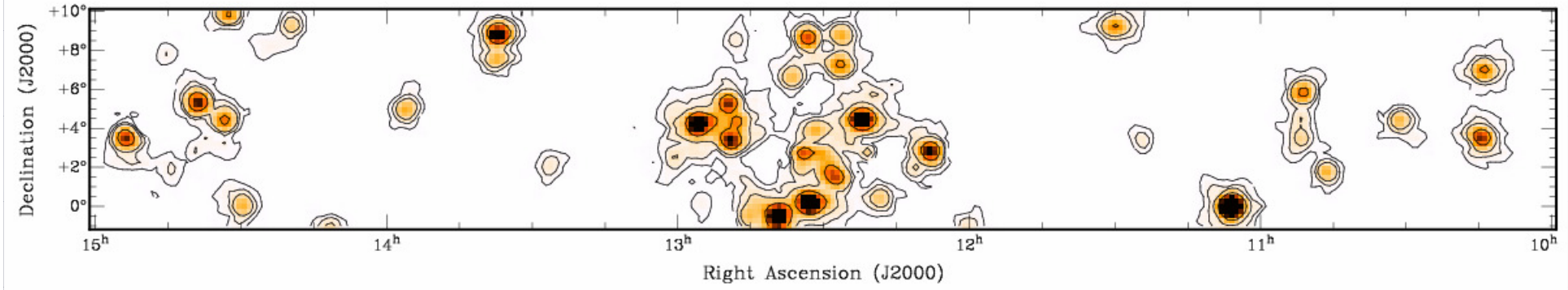


- Survey the filament joining the Local Group to the Virgo Cluster
- Observe from 8 to 17 hours in RA and from -1 to +10° in DEC in HI with WSRT.
- Probe extended environments of > 340 galaxies within 40 Mpc with a 23760 pointing mosaic, $\Delta N_{HI} \sim 2 \times 10^{17}$ cm^{-2} over ΔV=20 km/s

Observations



- **simulated filled aperture**
  - simulate filled aperture by observing at extreme HA's where projected telescope separation = aperture size
  - grating array (12x144 m) becomes ~ filled aperture (25x300 m)
  - brightness sensitivity of single dish telescope
  - spectral baseline quality of interferometer (>10^4:1)
  - well-defined PSF of interferometer (>10^4:1)
  - FOV of 25m dish with beam of 25x300m dish



Contour levels: 1e17, 3e17, 7e17, 3e18 cm^{-2}

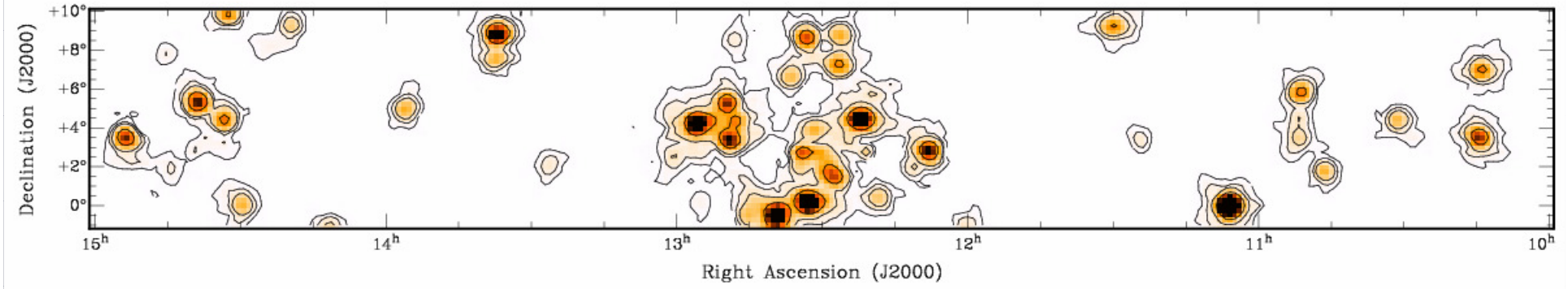
Total Power Data:

rms = 13 mJy/Beam 20 km/s

3.4×10^{16} cm^{-2}

Intrinsic Beam = 35`

Smoothed Beam = 49’



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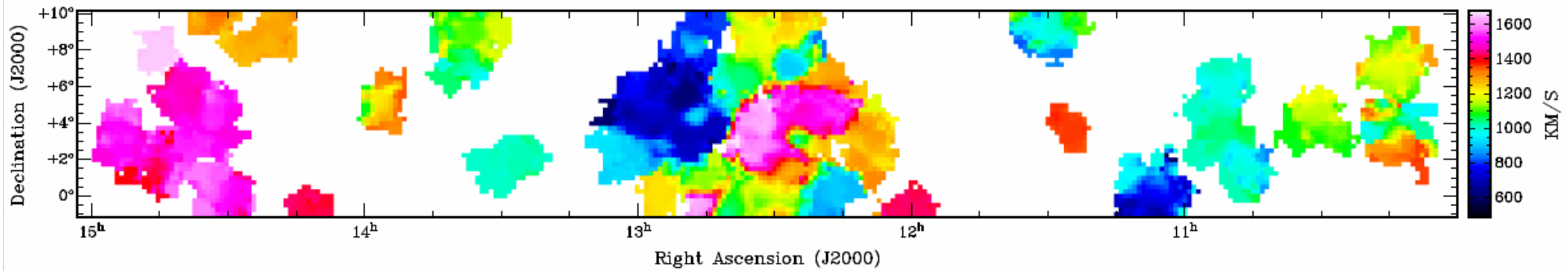
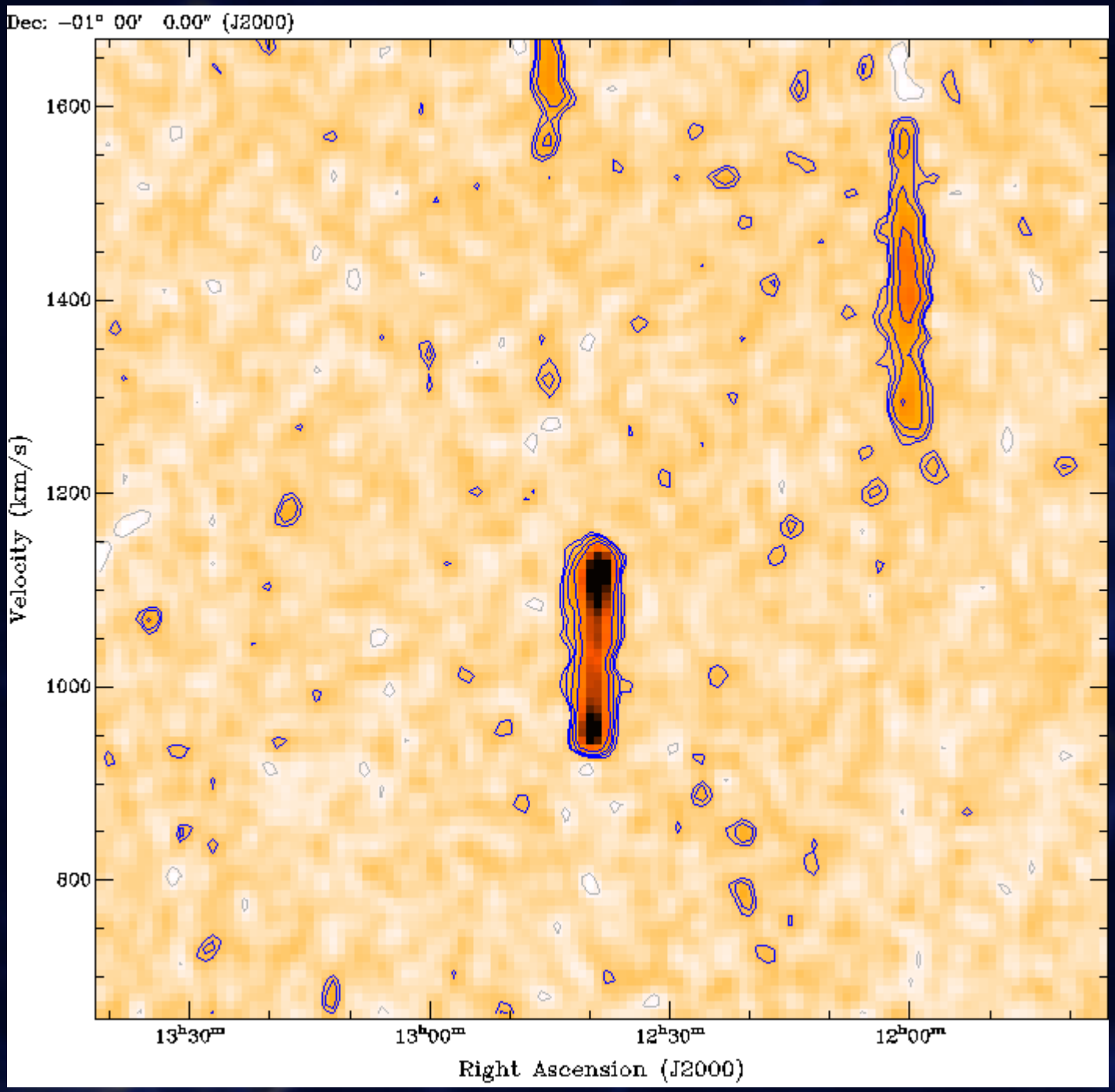
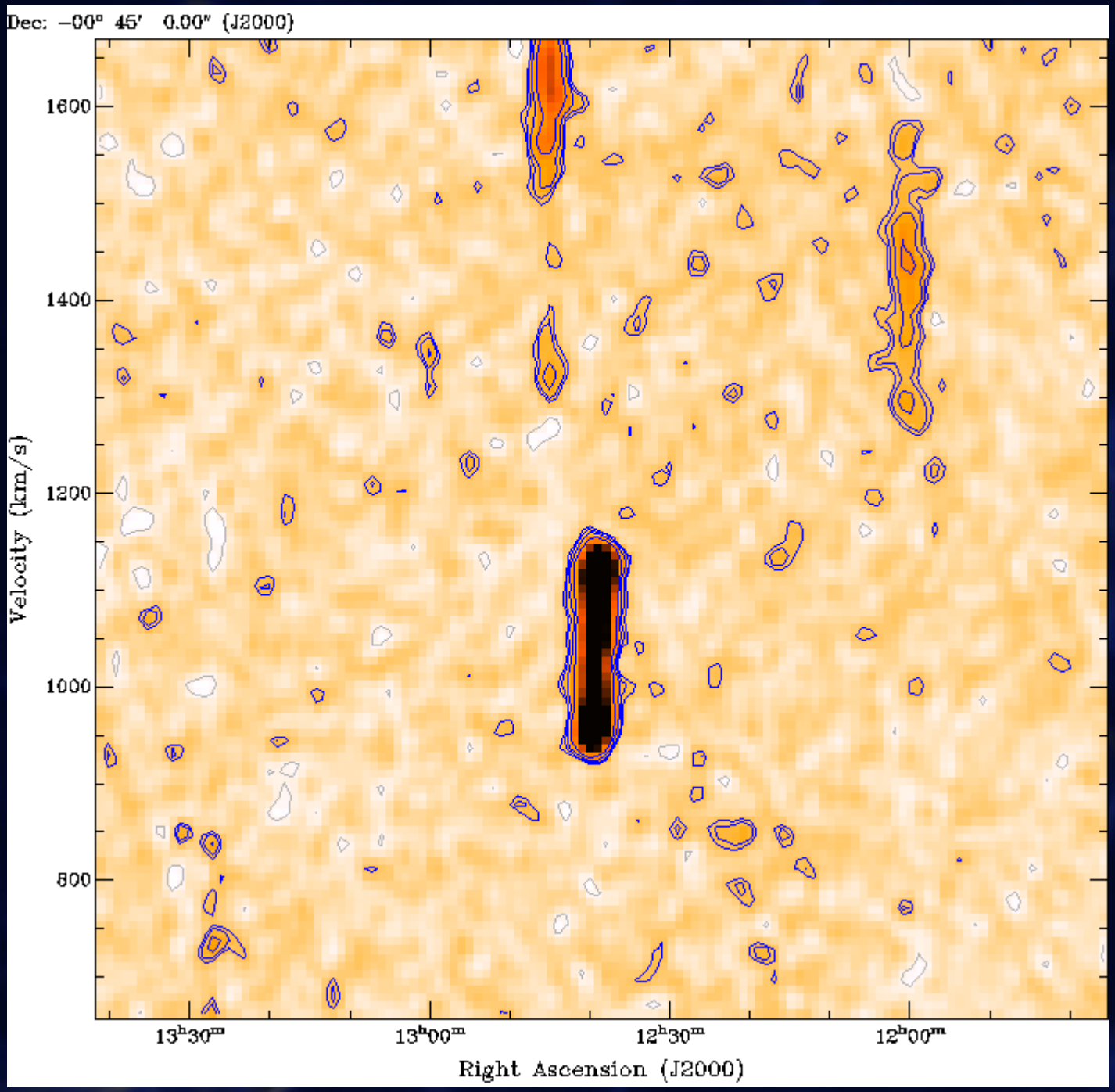


Regions with same radial velocity



Contours at
-1.5σ, 1.5σ,
2σ, 3σ
and 5σ !



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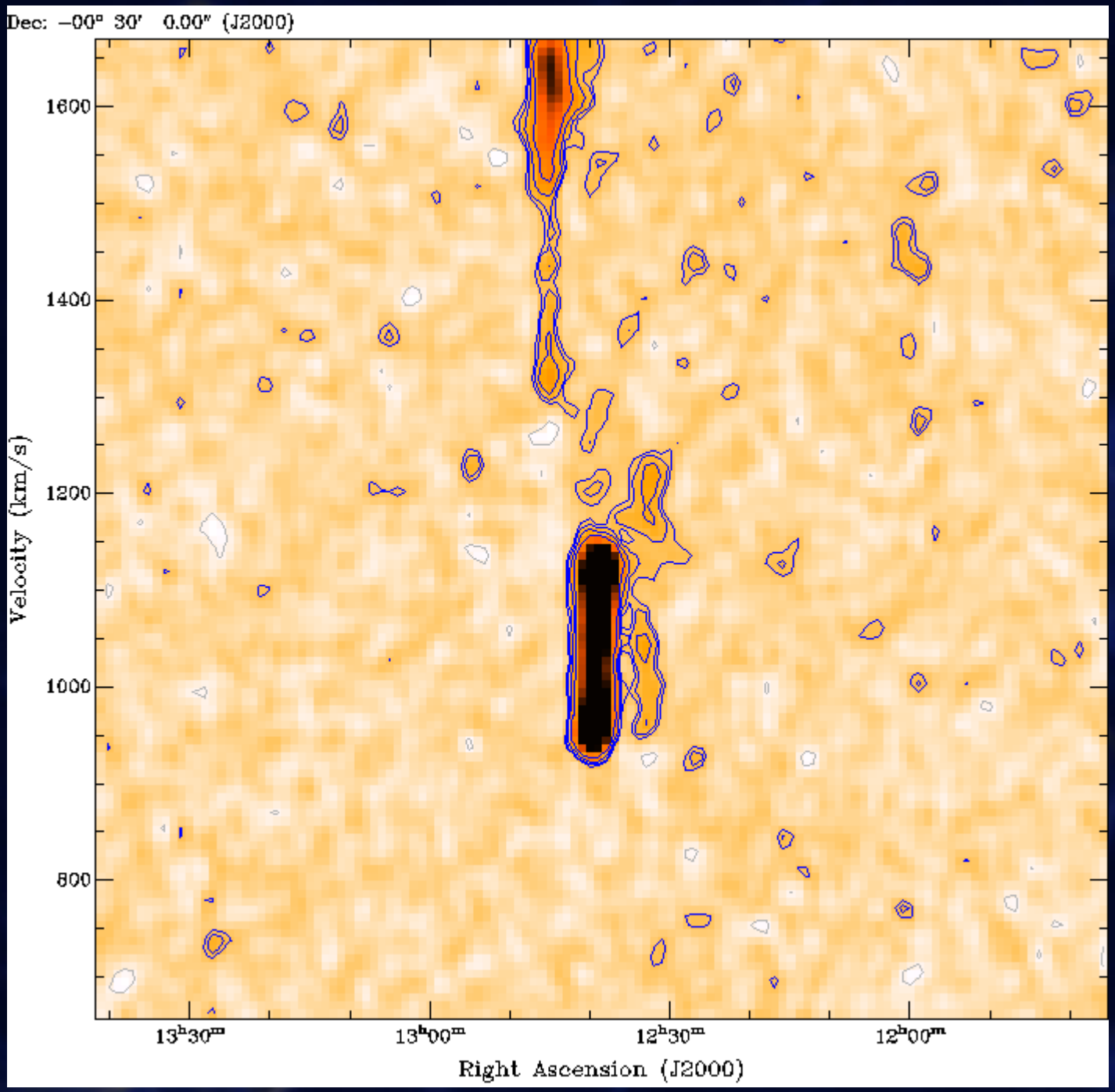

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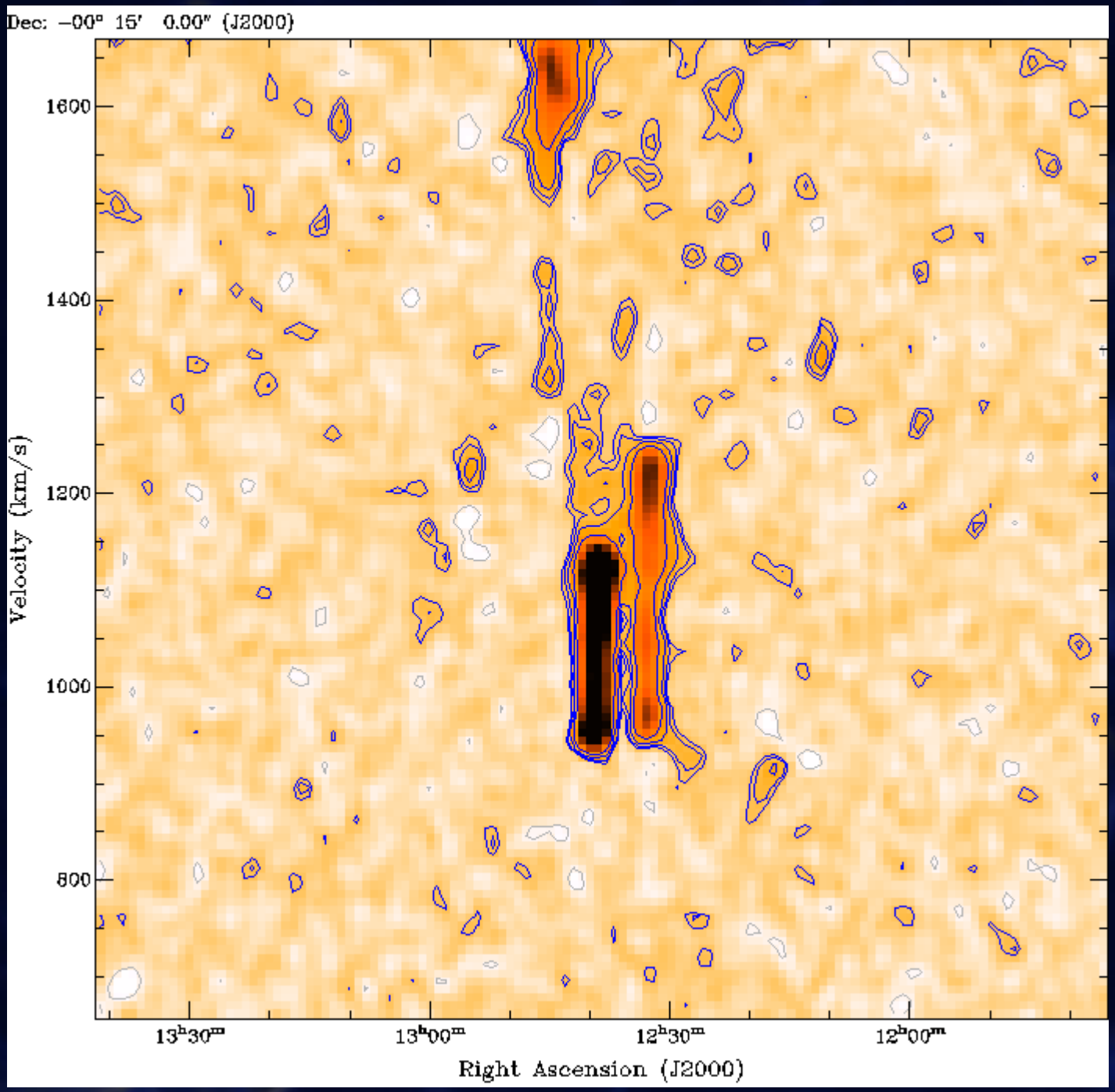

Contours at
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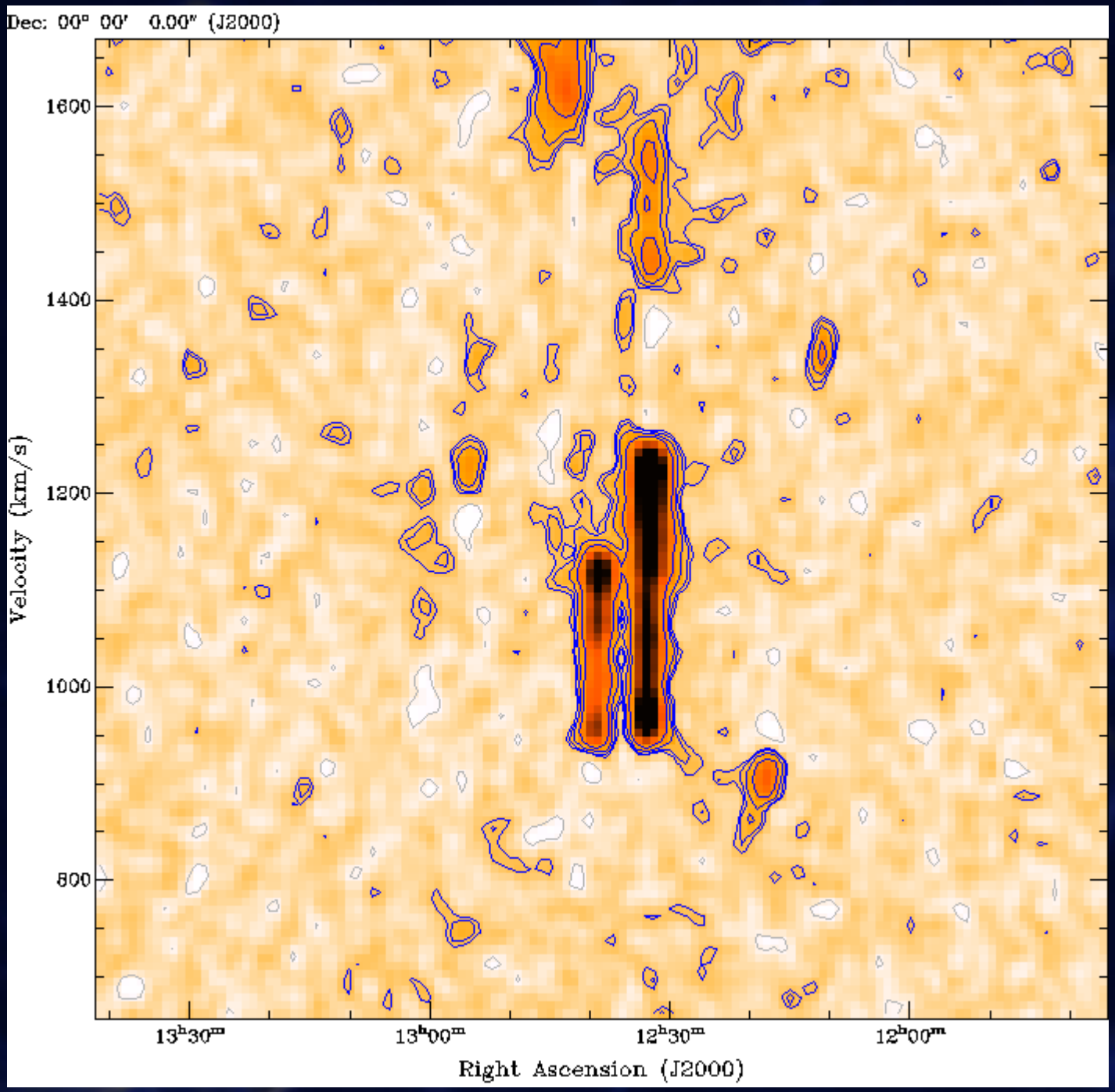
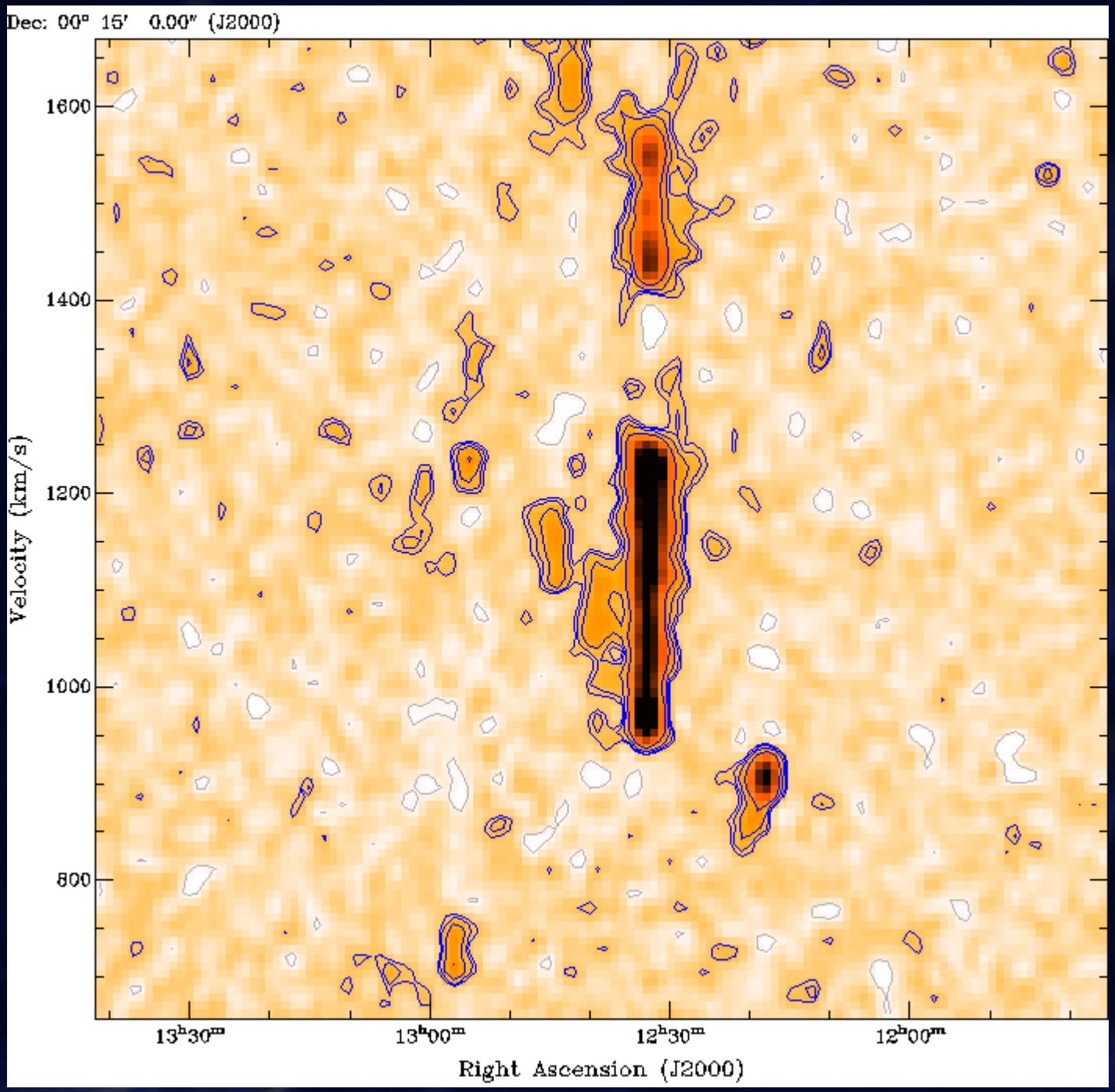
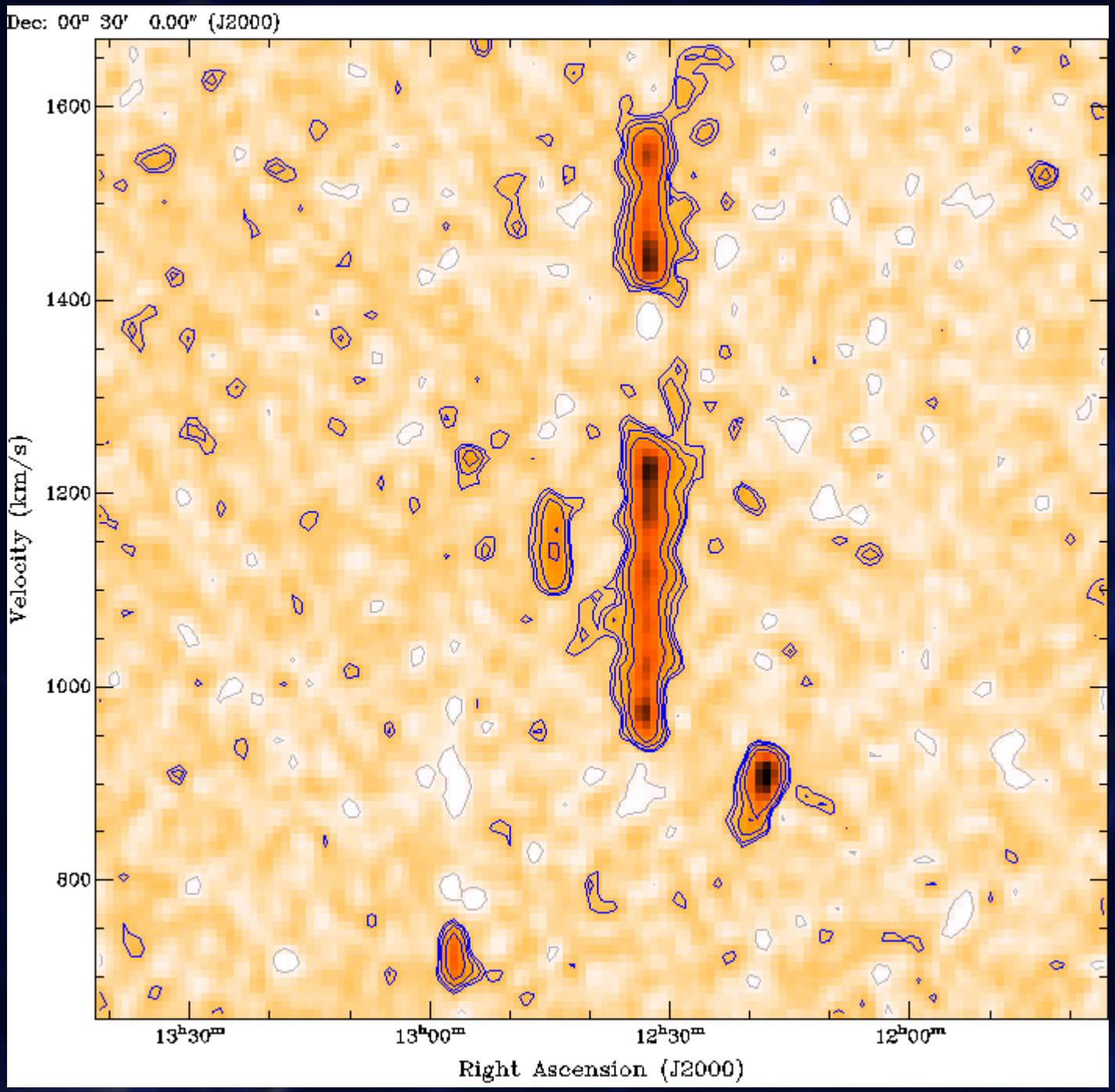


Contours at
-1.5σ, 1.5σ,
2σ, 3σ
and 5σ !



Contours at
-1.5σ, 1.5σ,
2σ, 3σ
and 5σ !

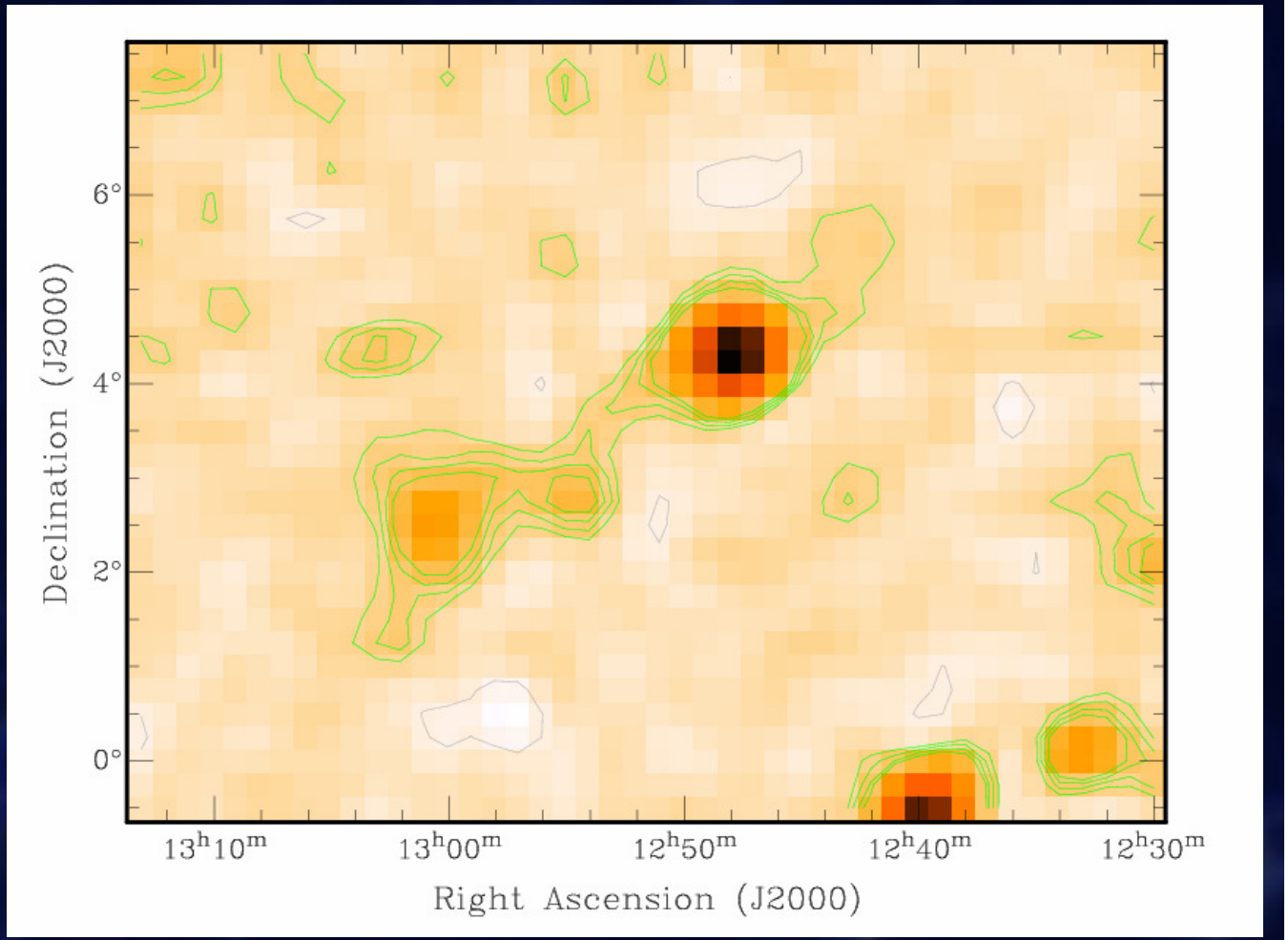


Contours at
-1.5σ, 1.5σ,
2σ, 3σ
and 5σ !

WVFS Filament

- NGC 4900
- NGC 4688

- Contours at -0.8 0.8 1.2 1.6 2 Jy/Beam



WVFS Filament

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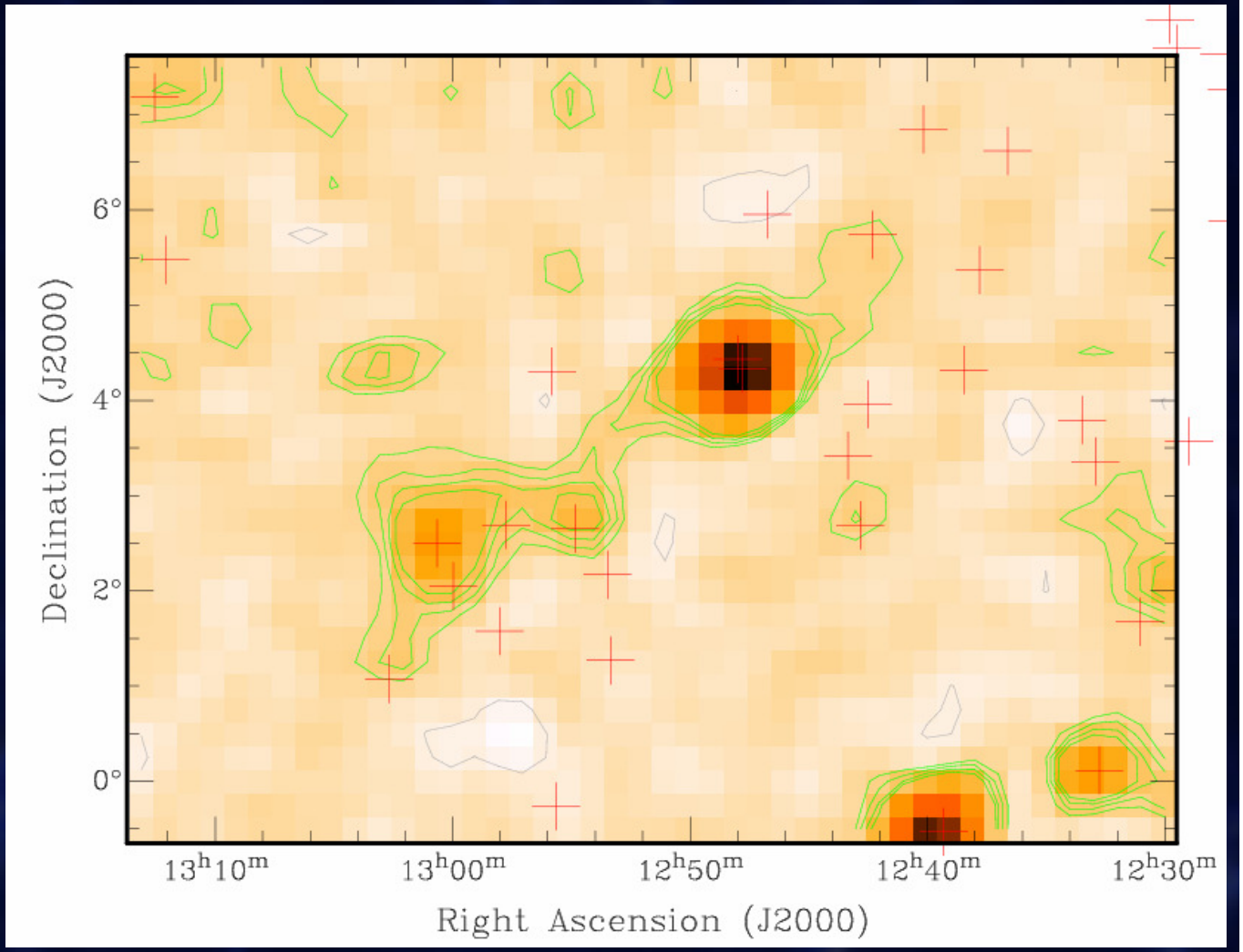
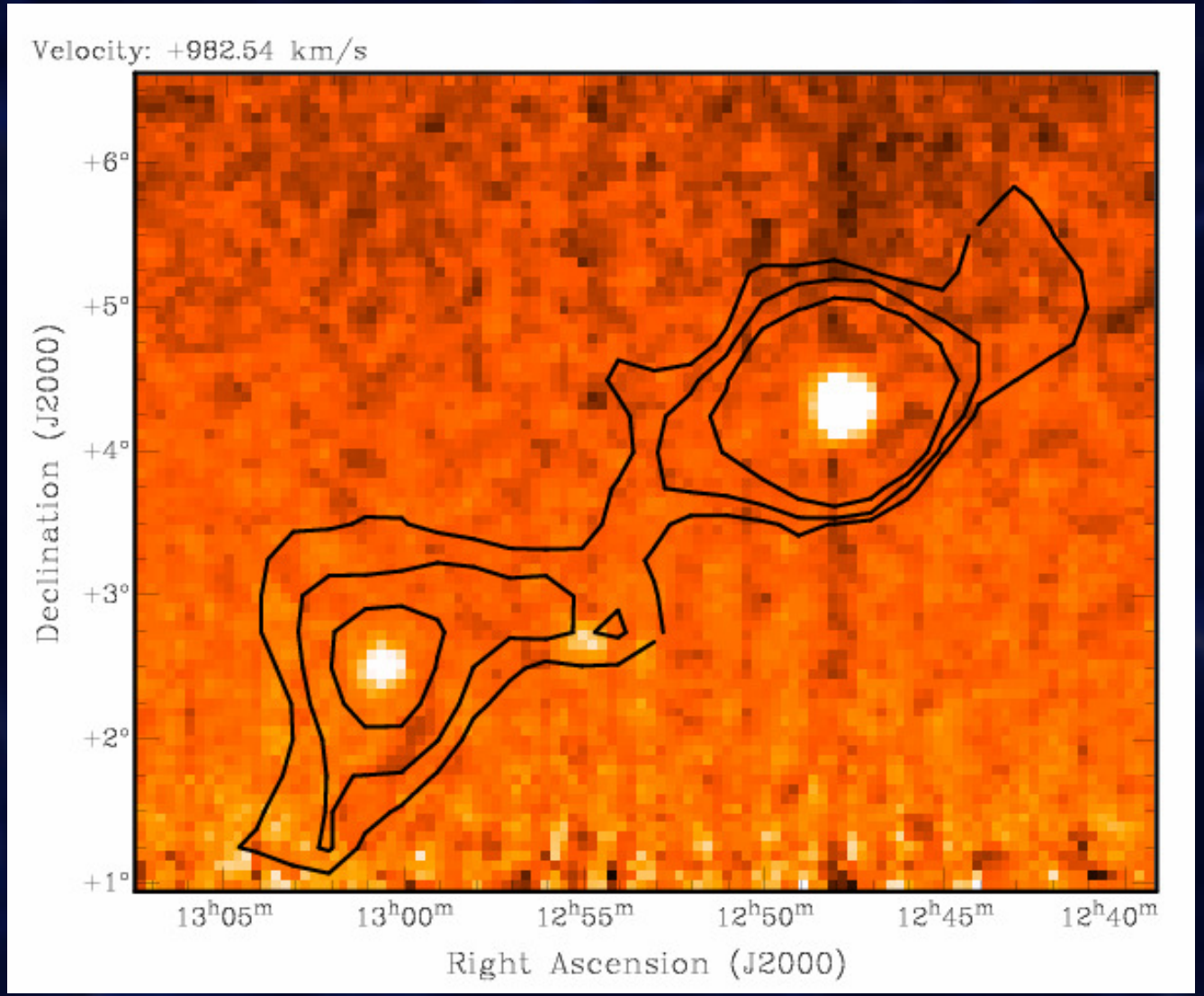




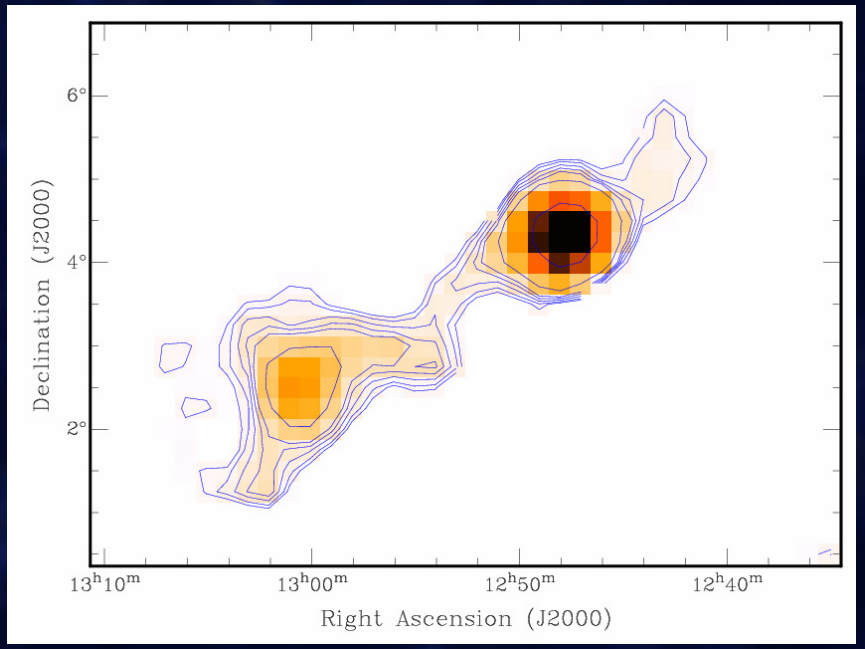
Re-reduced HIPASS image

WSRT contours at 1e17, 2e17, 4e17 cm^{-2}

WVFS filament

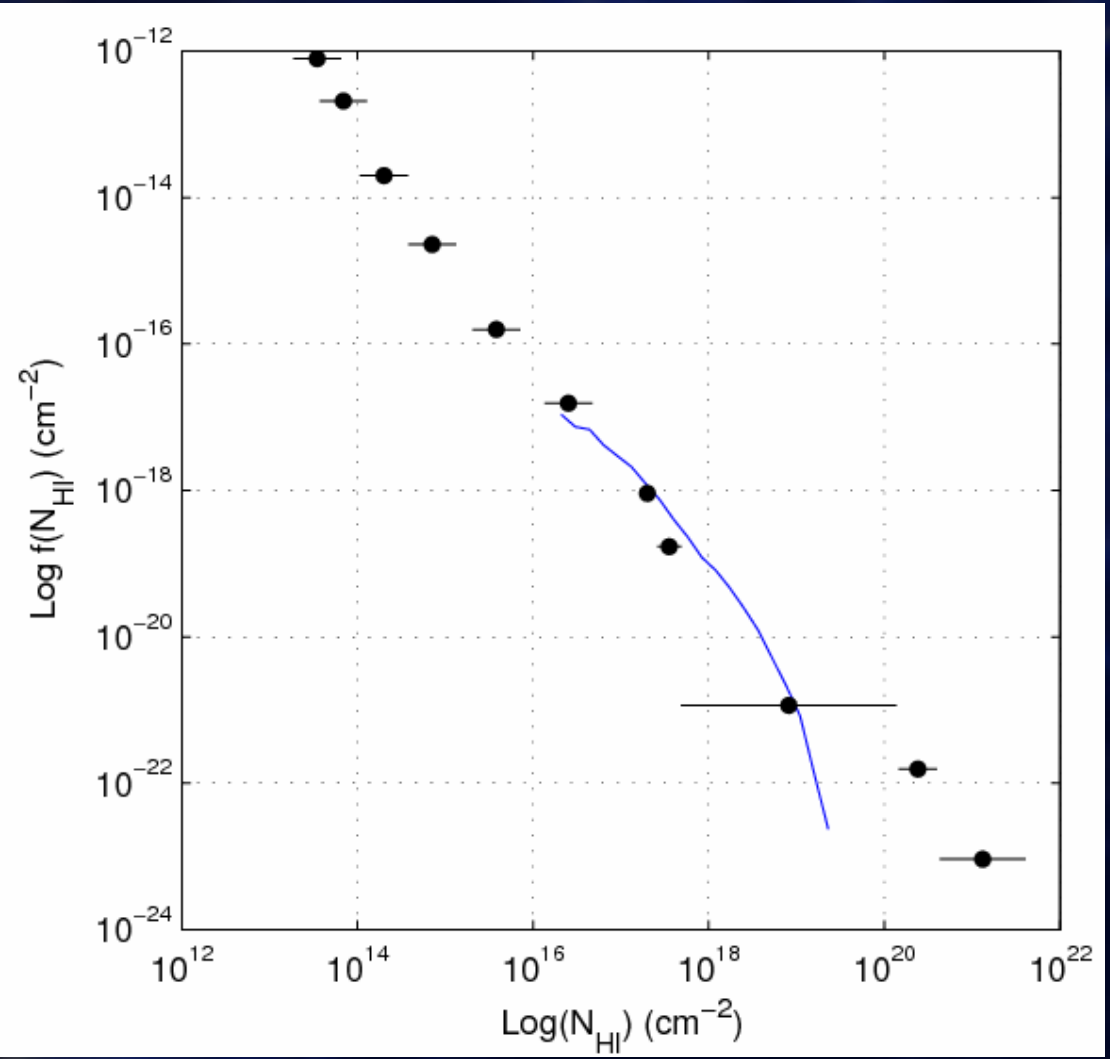
- Connecting NGC 4900 and NGC 4688

- NHI ~ 8×10^{16} cm^{-2}
- Velocity width ~60 km/s
- Distance ~ 12 Mpc
- Mass ~ 5×10^{7} M_{sun}
- Size ~ 300 kpc
- Full size ~1.5 Mpc



Contours at 0.8e17, 1e17, 1.3e17, 1.6e17, 1.9e17, 3e17 and 1e18

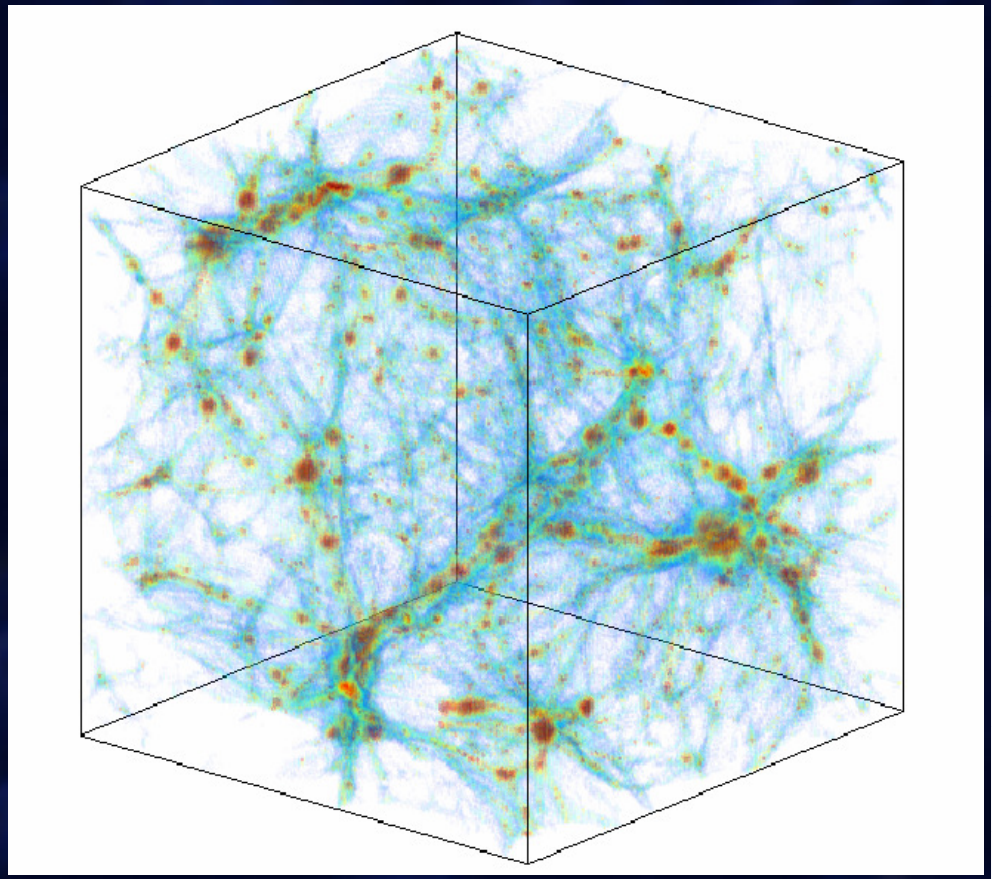
WVFS Distribution Function



QSO data tabulated by Corbelli & Bandiera 2001

Simulations

- SPH simulation kindly provided by R. Davé.



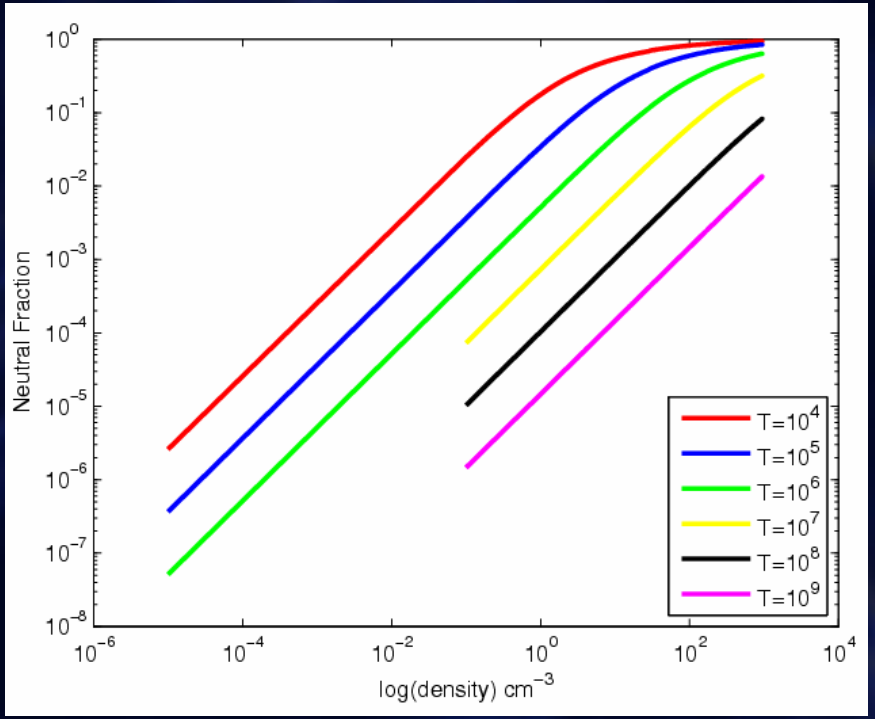
- 32 h^{-1}Mpc cube
- 1.6e7 sph particles
- Ω=0.3, Λ=0.7, z=0, σ_8= 0.9, H_0=70 km s^{-1} Mpc^{-1}
- Galactic feedback included
- Cooling Included

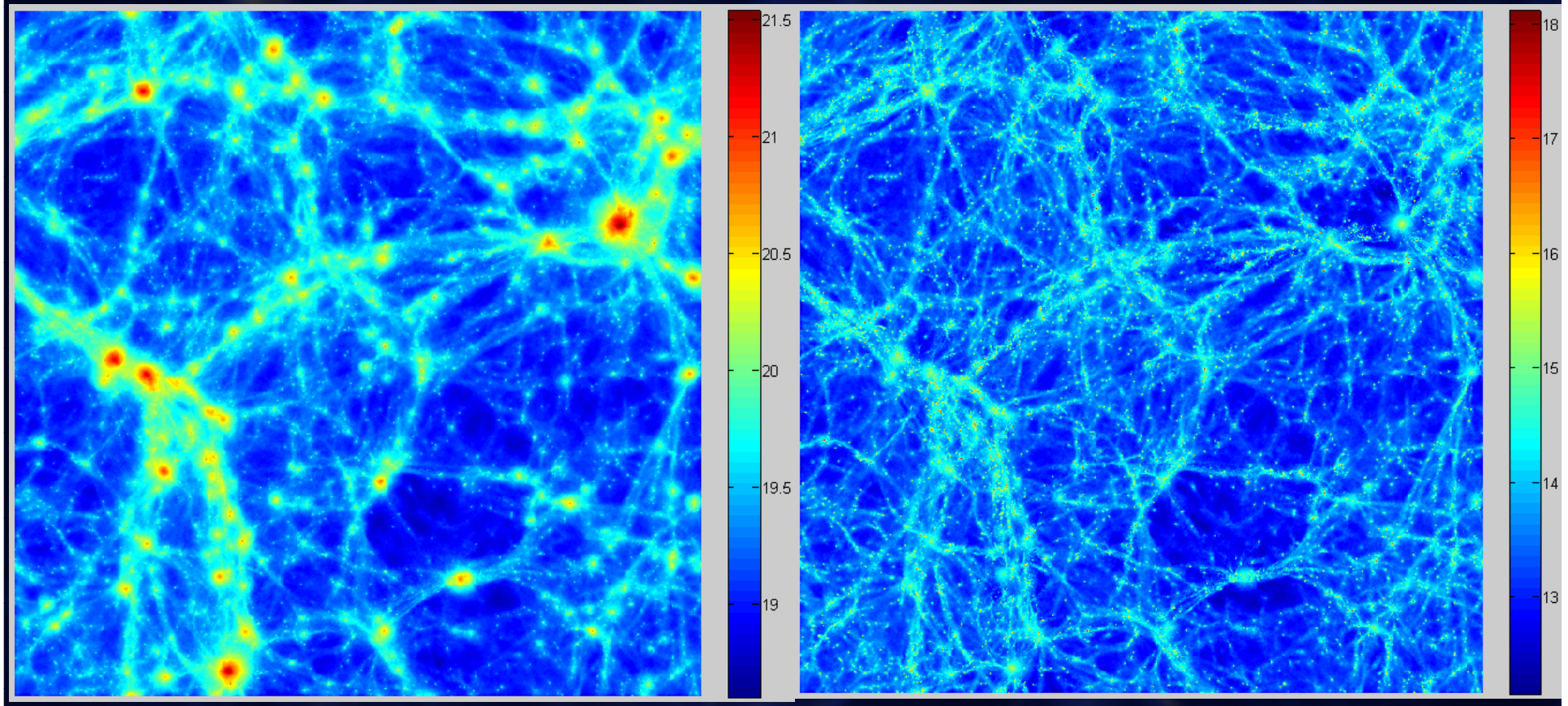
Theory

The balance between photo ionization and radiative recombination determines the degree of ionization

$$\xi n \Gamma_{HI} = (1-\xi)^2 n^2 \beta(T)$$

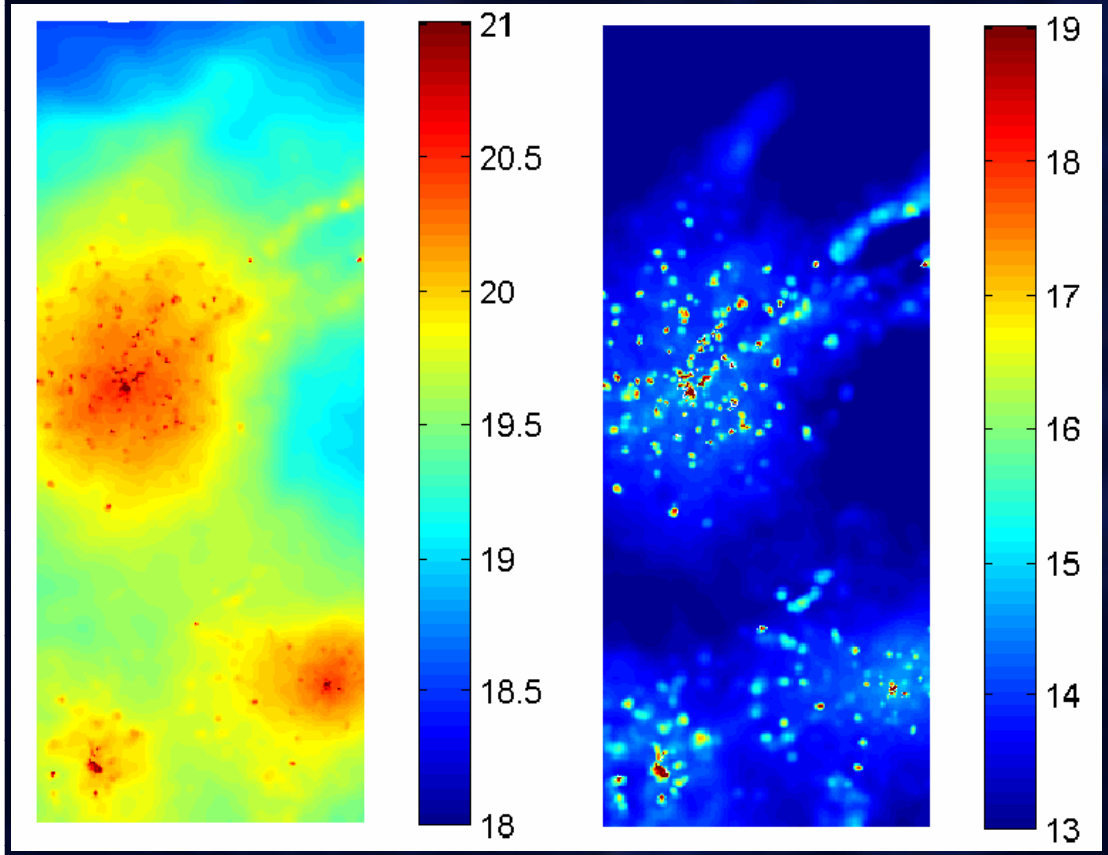
- n = total density
- ξ = neutral fraction
- $\beta(T)$ = recombination rate, given between 3 and 10^{10} K by Vermes and Ferland 1996
- Γ = Photo Ionization rate (1×10^{-13} s^{-1}) (Haardt & Madau 2001)

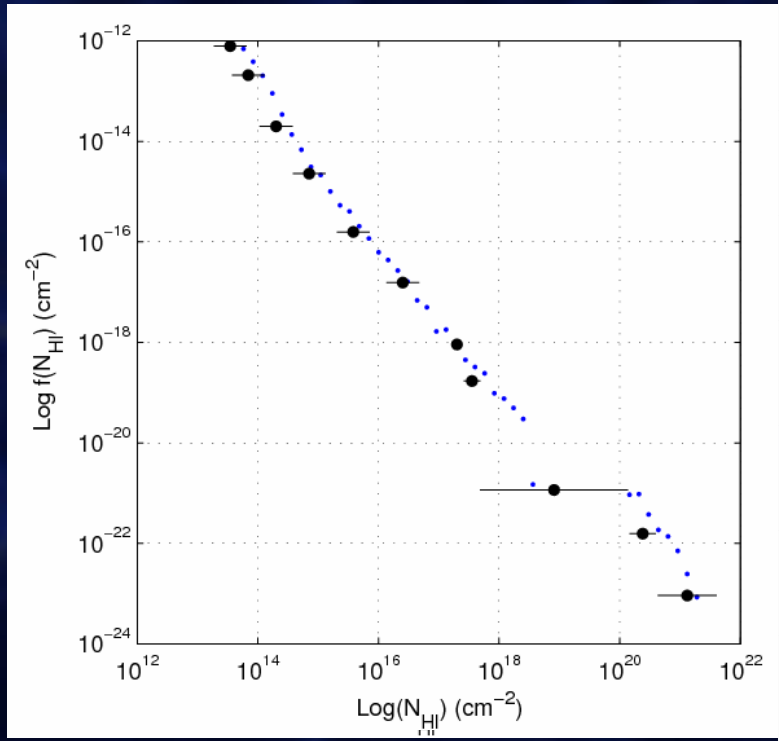




- Self Shielding Correction has to be applied
- Critical Density of e.g. n = 0.01 cm^{-3} (Haehnelt et al. 1998)
- Gridding to high resolution is needed

Simulated Distr. Function





QSO data tabulated by Corbelli & Bandiera 2001

Self shielding correction applied at critical density of n=0.01 cm^{-3}
This under estimates the effect of shielding (Haehnelt et al. 1998)

Summary

- We are able to detect the Lyman Limit System in emission
- We can observe HI filaments at $N_{HI}<10^{17}$ cm^{-2}
- Column densities are consistent with QSO absorption lines.

- Follow up study at same sensitivity with higher resolution needed.
- Follow up study towards background AGN/QSO required to yield neutral fraction (and so mass) and metallicity (and so enrichment history).