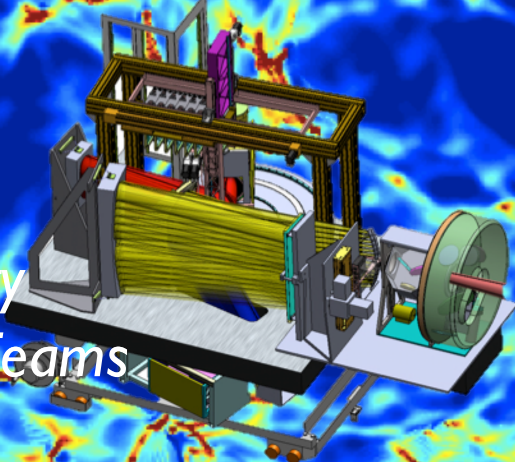
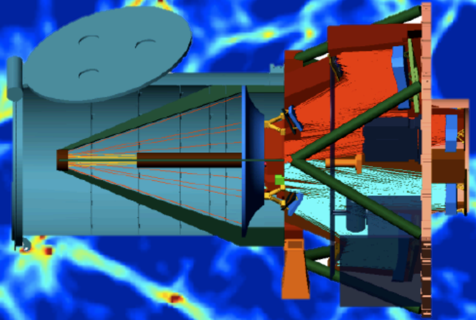
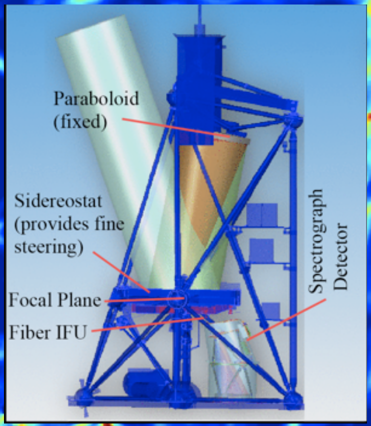
Prospects for Imaging the IGM/CGM with TMT

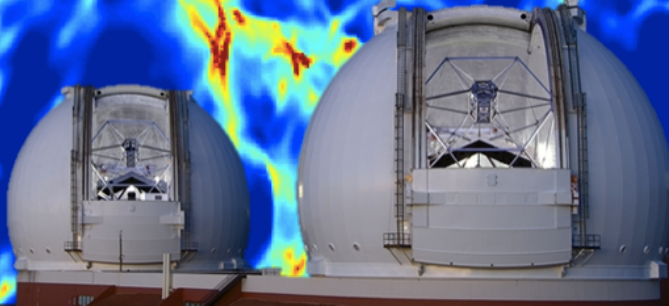


Christopher Martin
California Institute of Technology
For CWI, KCWI, FIREBALL, ISTOS Teams

1. Why/How to Image CGM/IGM?
2. Cosmic Web Imager: PCWI/KCWI
3. Data from PCWI and Science from KCWI
4. A TMT CWI?





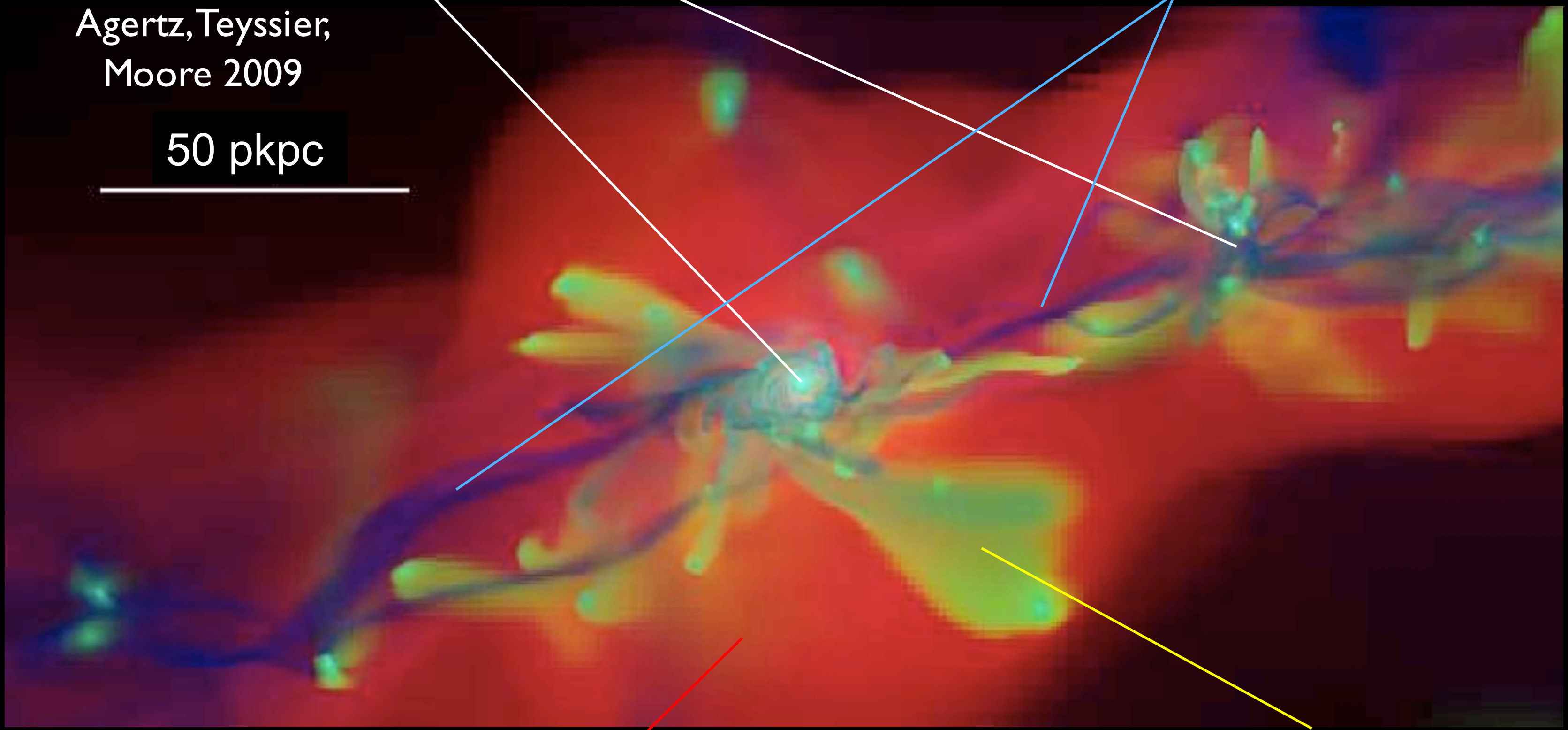


1. Why Map IGM/CGM Emission?

1. IGM tracing structure interconnecting galaxies

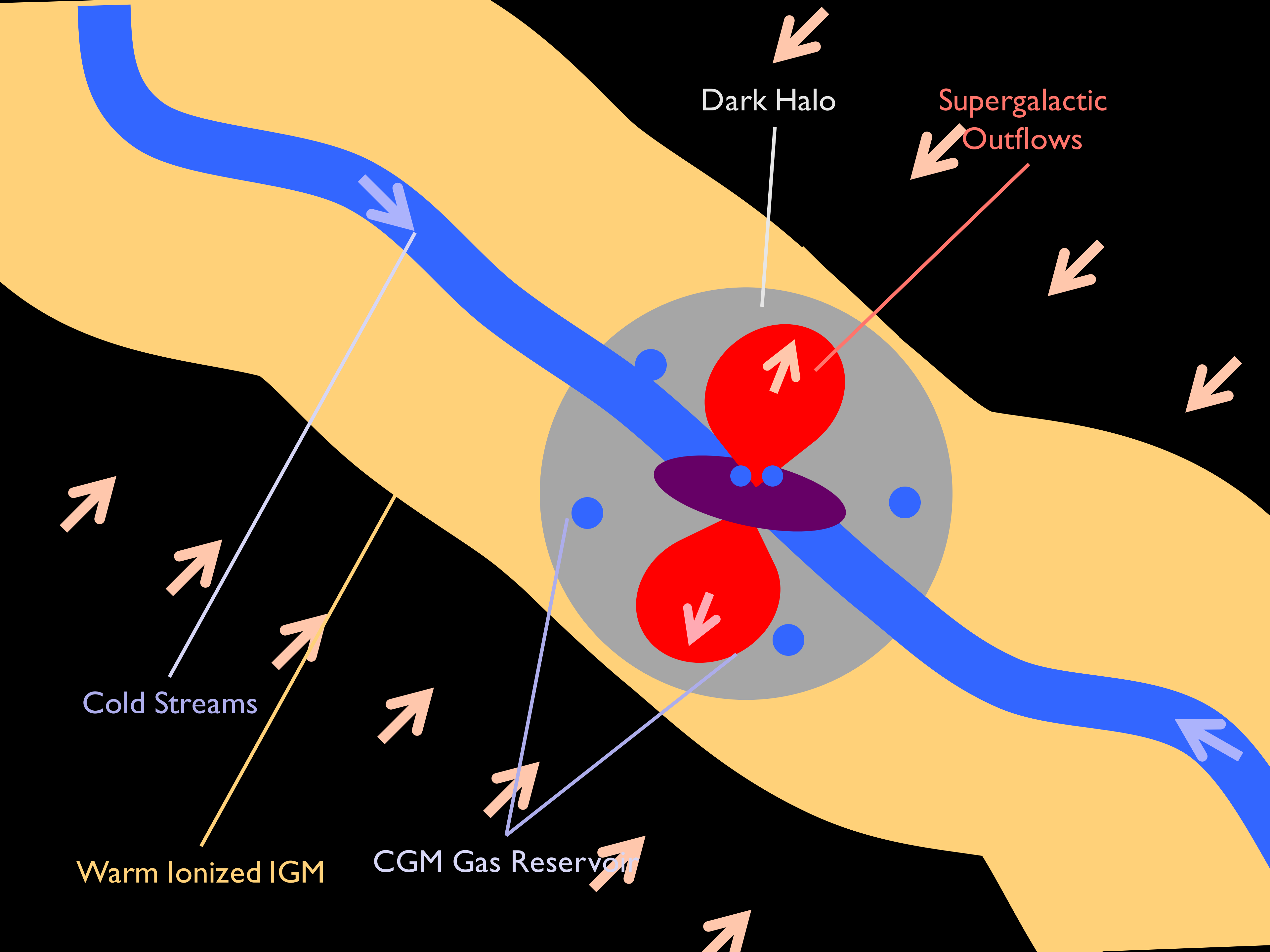
3. Galaxy properties depend on recent gas flow (in/out)

4. Star forming galaxies fed by cold streams from Cosmic Web



2. Most baryons in IGM, Some in warm IGM

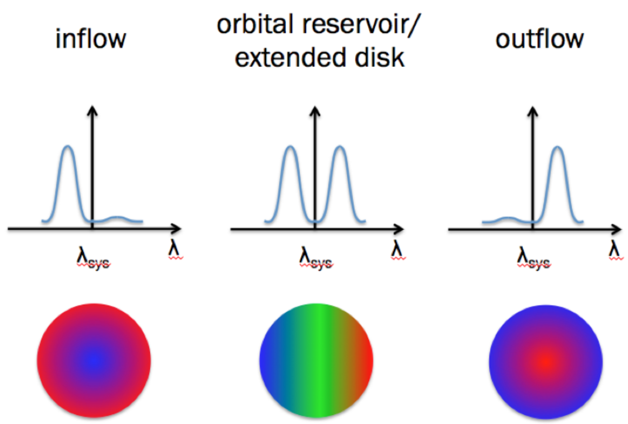
5. Star forming galaxies are ejecting gas & chemicals into Cosmic Web


Dark Halo
Supergalactic
Outflows
Cold Streams
Warm Ionized IGM
CGM Gas Reservoir

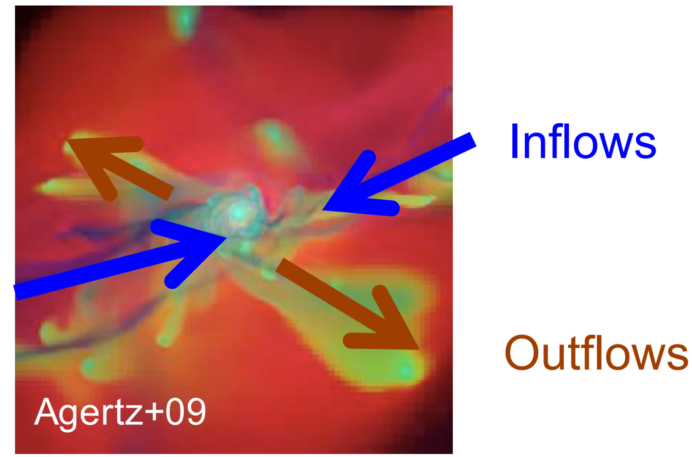
IGM Project: 1. Goals

Imaging & Mapping the Hidden Cosmic Web of Baryons

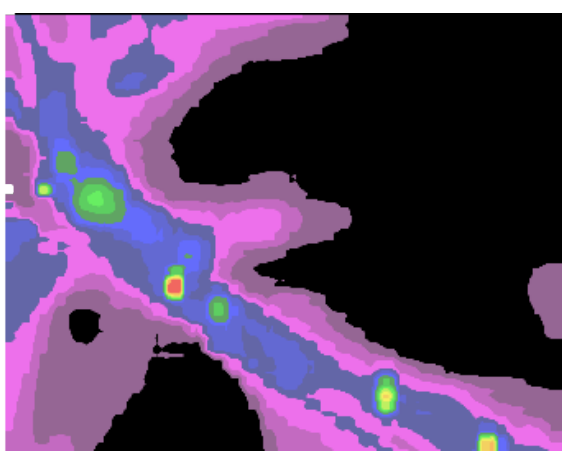
A. Decode Lyα Emission & UV Line Diagnostics



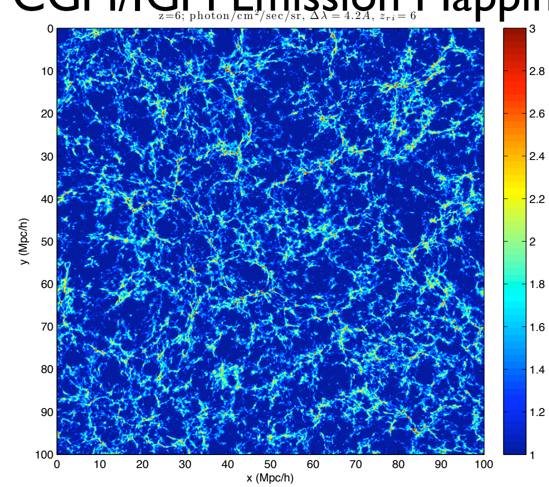
B. Discover/Map CGM Baryons, Co-evolution with Galaxies



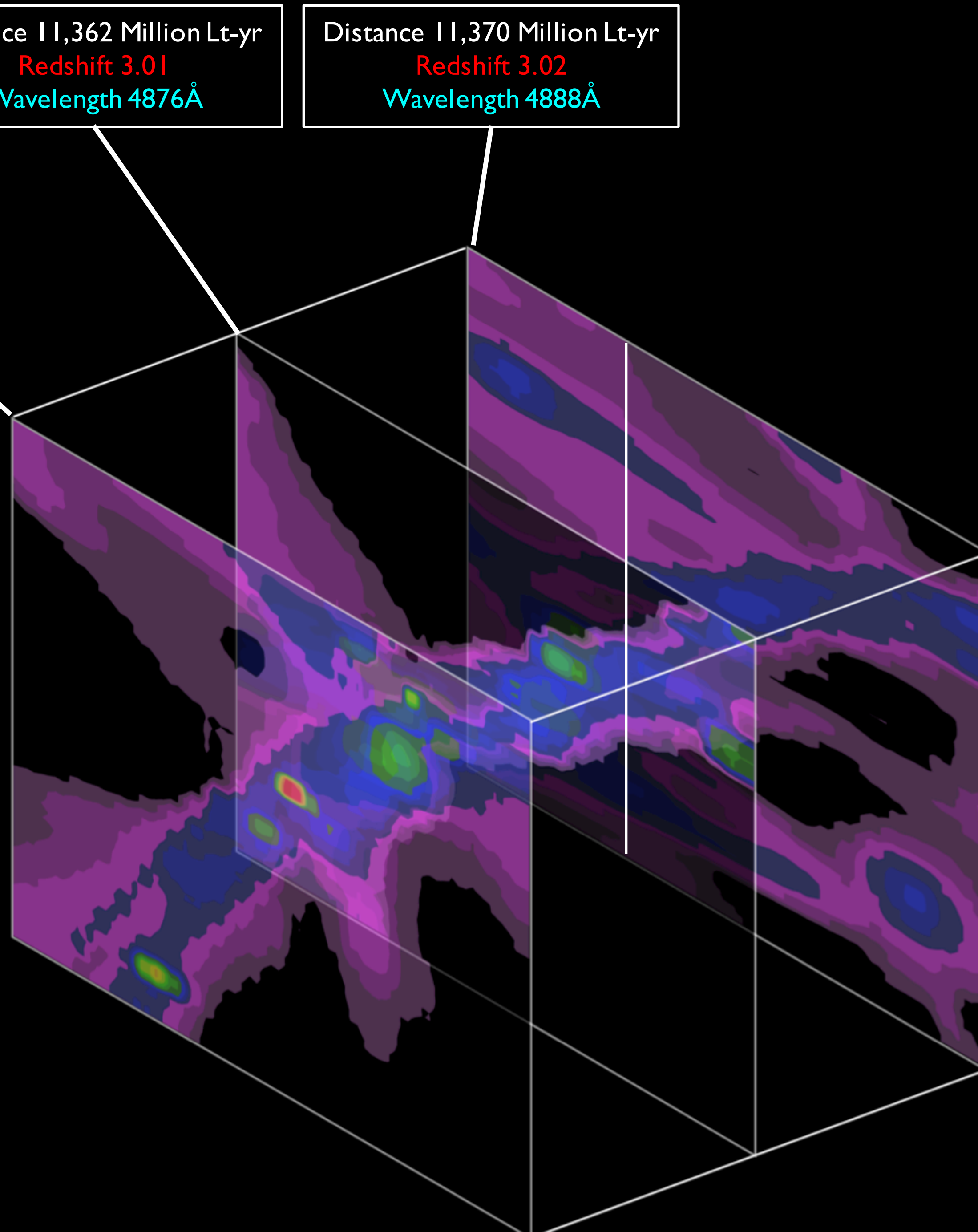
C. Discover & Map IGM Baryons, Correlate with Cosmic Web & Galaxies



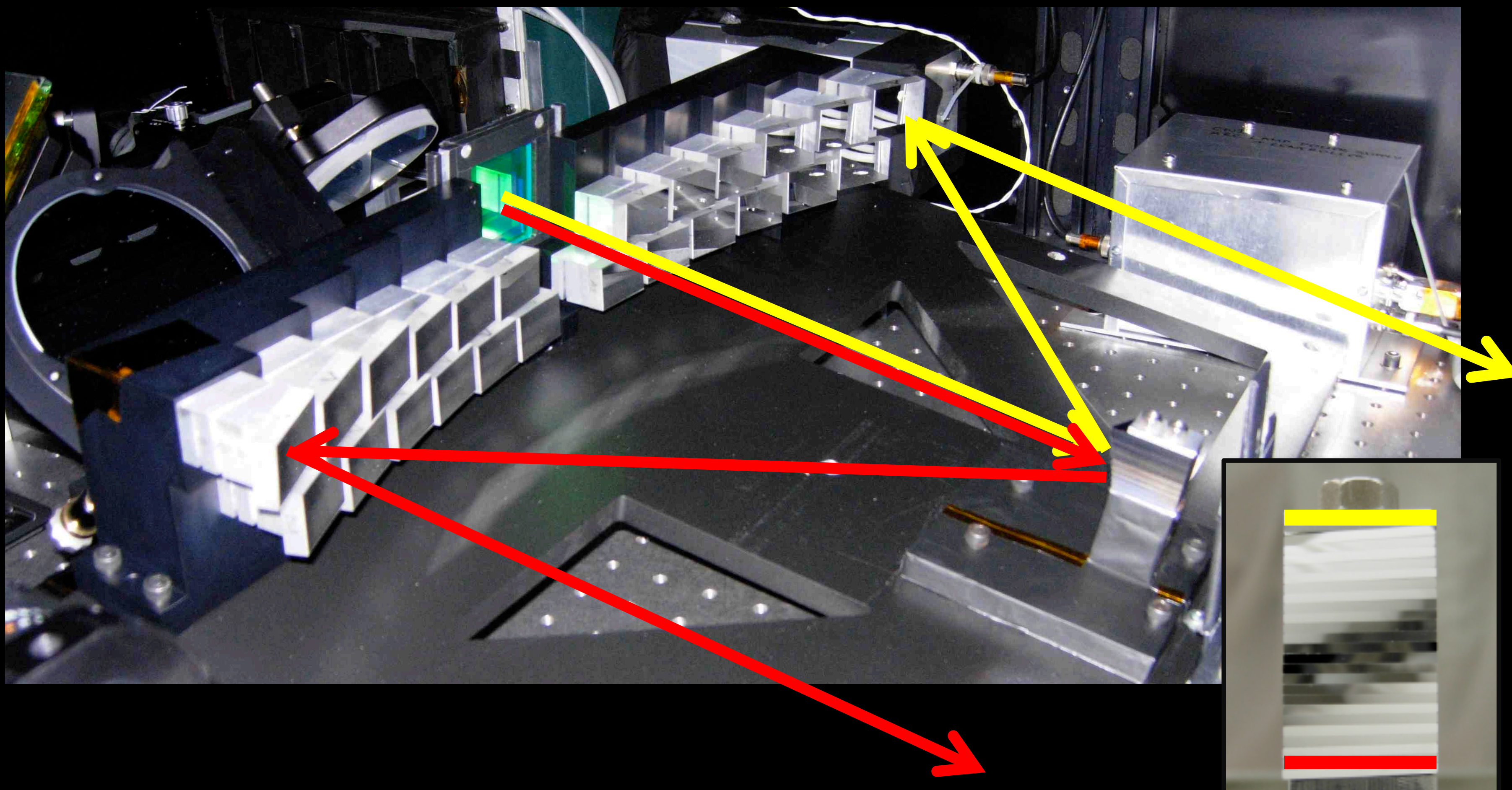
D. Cosmological Applications of CGM/IGM Emission Mapping



Map IGM/CGM using 2D Imaging Spectroscopy of Rest UV Lines: Lyα, CIV, OVI



PCWI : Image Slicer



Observational Strategies Enabled by 2D Imaging Spectroscopy of Rest UV IGM/CGM Emission

1) Direct Detection
→Maximize deep exposure volume
→Optimal smoothing on extended scales

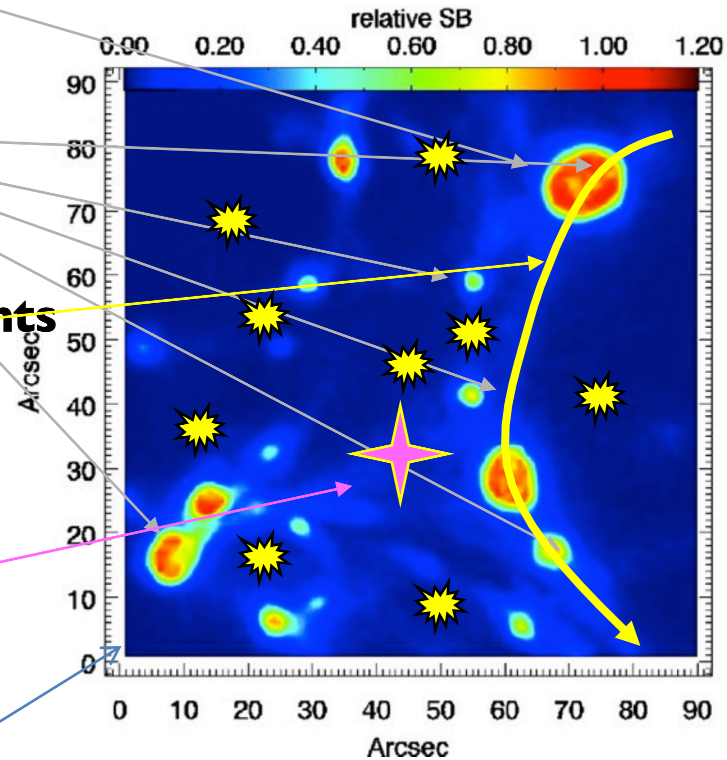
2) Stacking on known galaxies
→redshift survey regions
→large survey volume

3) Stacking on galaxy-traced filaments
→redshift survey regions
→low luminosity galaxies

4) Cross-correlate QSO abs/IGM em
→redshift survey regions
→low luminosity galaxies

5) Cross-correlate Gal abs/IGM em
→redshift survey regions

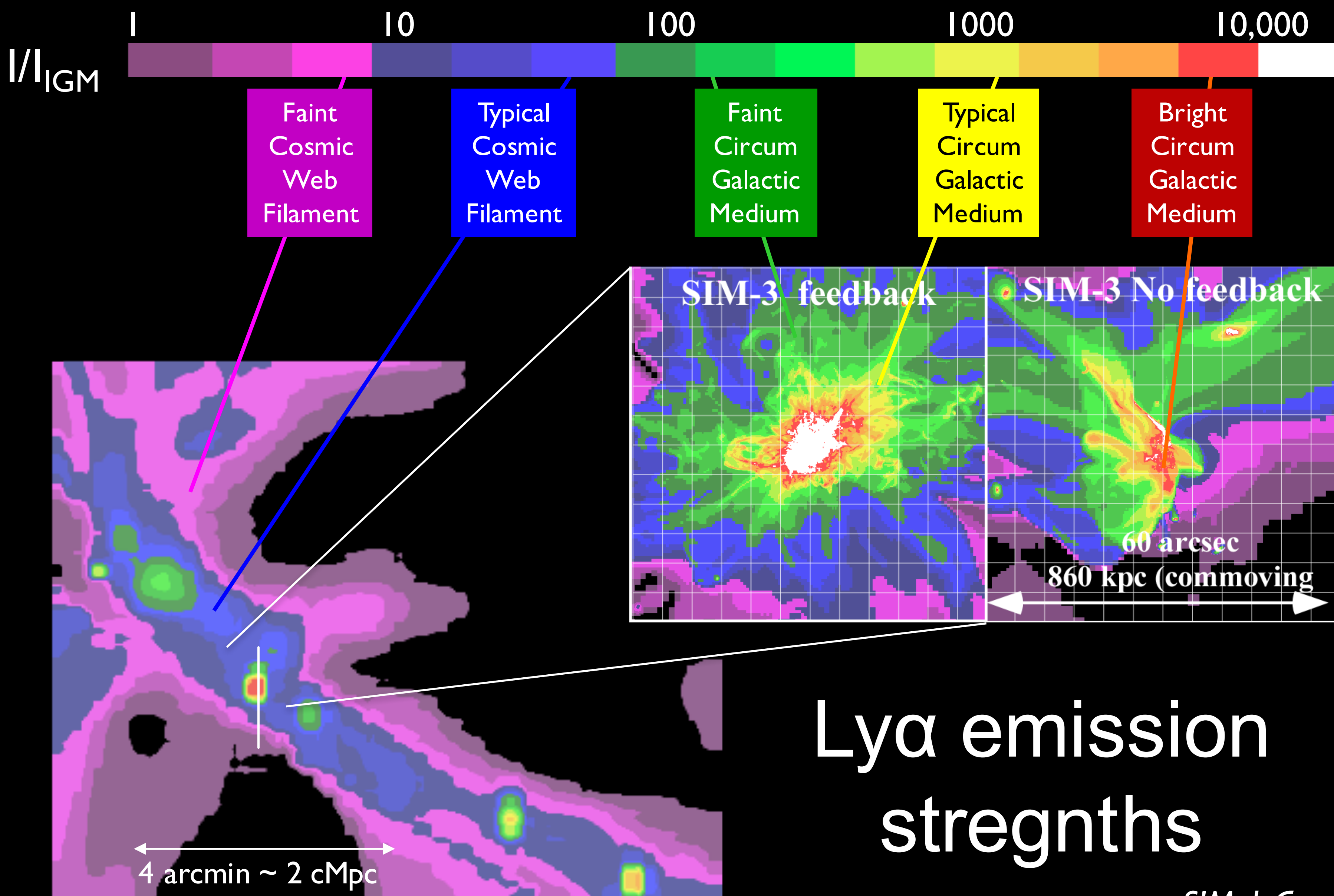
6) Light bucket mode – Smooth large features



Lyman alpha Fluorescence
(Cantalupo et al 2005)

UV IGM Emission → Baryon Census (Where?)

1 LU = 1 ph cm^{-2} s^{-1} sr^{-1} = 10^{-22} erg cm^{-2} s^{-1} arcsec^{-2} (at 5000Å)



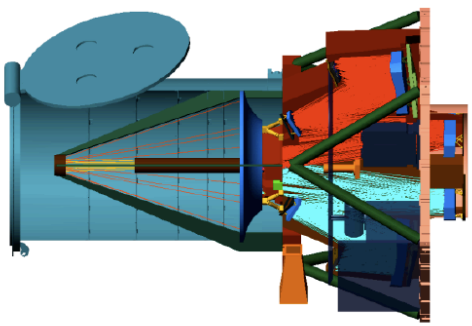
Lyα emission stregnths

SIM-1 Cen

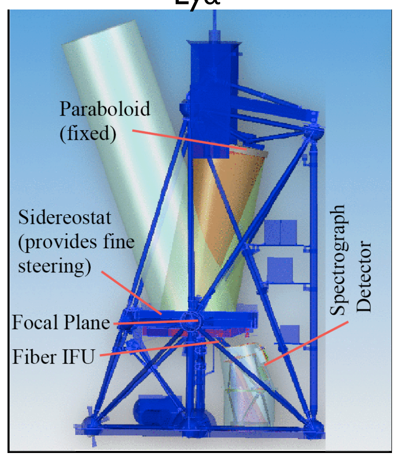
IGM Project

Imaging & Mapping the Hidden Cosmic Web of Baryons

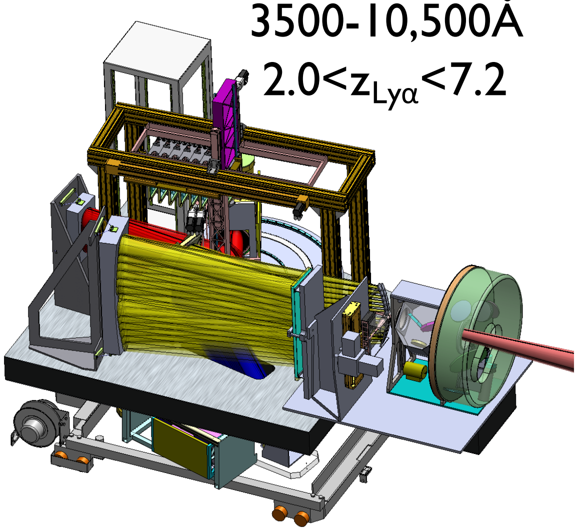
ISTOS
Explorer
1250-2800Å
$0.05 < z_{Ly\alpha} < 1.2$



FIREBALL
Balloon
2050-2250Å
$0.7 < z_{Ly\alpha} < 0.85$



KCWI
Keck
3500-10,500Å
$2.0 < z_{Ly\alpha} < 7.2$



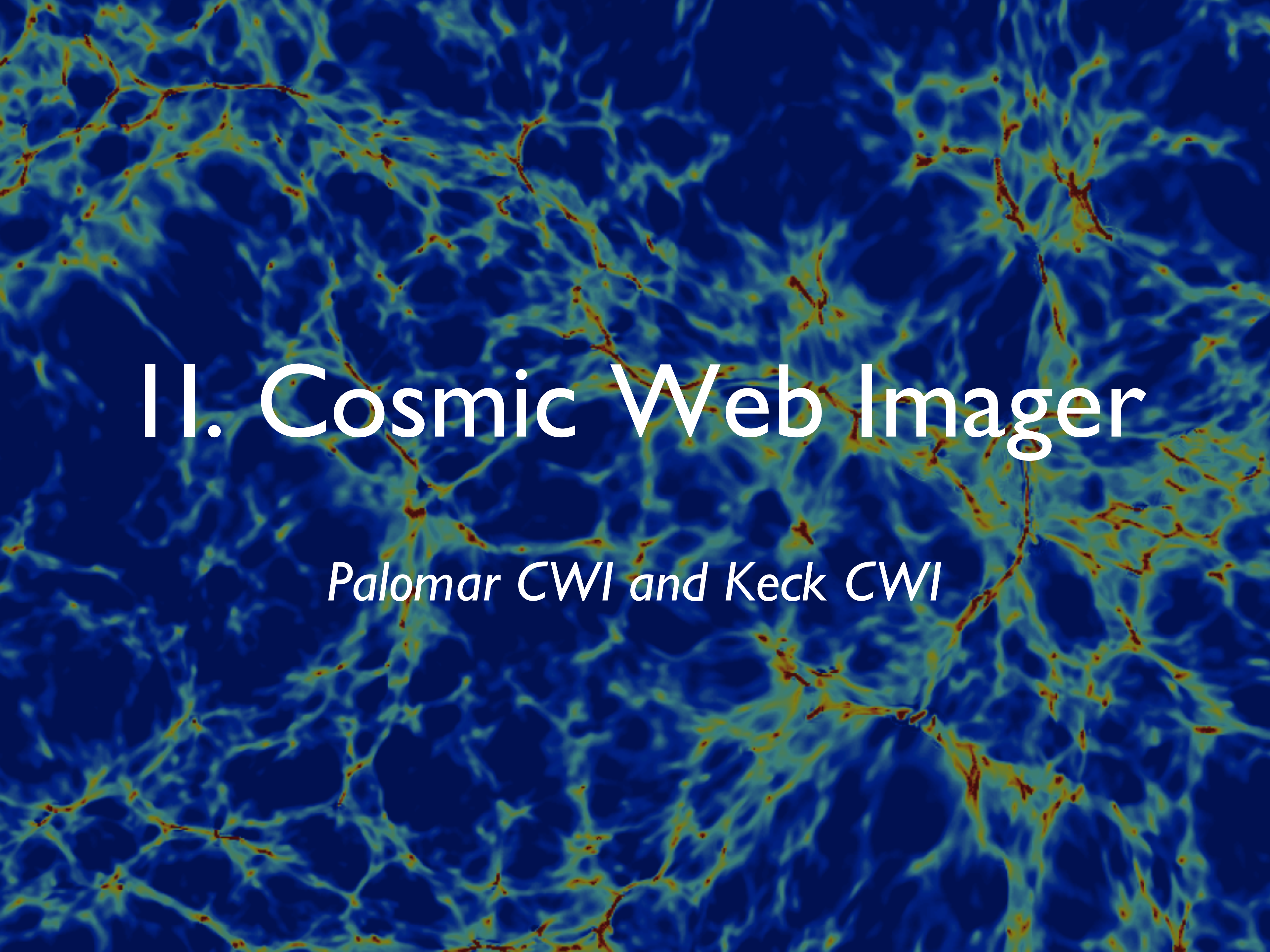
Goals (rough chronological order)

(1) Discover & map Circum-Galactic Medium (CGM) & IGM-galaxy co-evolution

(2) Discover & map IGM emission from the hidden baryons (WHIM, cosmic web)

(3) Use IGM emission to trace large scale structure & cosmology

(4) Detect & map emission from growing reionization HII regions



II. Cosmic Web Imager

Palomar CWI and Keck CWI

PCWI Palomar Cosmic Web Imager

Chris Martin, Anna Moore, Matt Matteuzski, Patrick Morrissey, Daphne Chang, Shahin Rahman

3D, Low Surface Brightness Spectroscopy at Palomar

Science Applications (examples)

① Map circum-galactic medium 2<z<7

② Map circum-QSO medium

③ Composition & age of stellar remnants (halos, intracluster light)

④ Low mass/surface brightn. universe

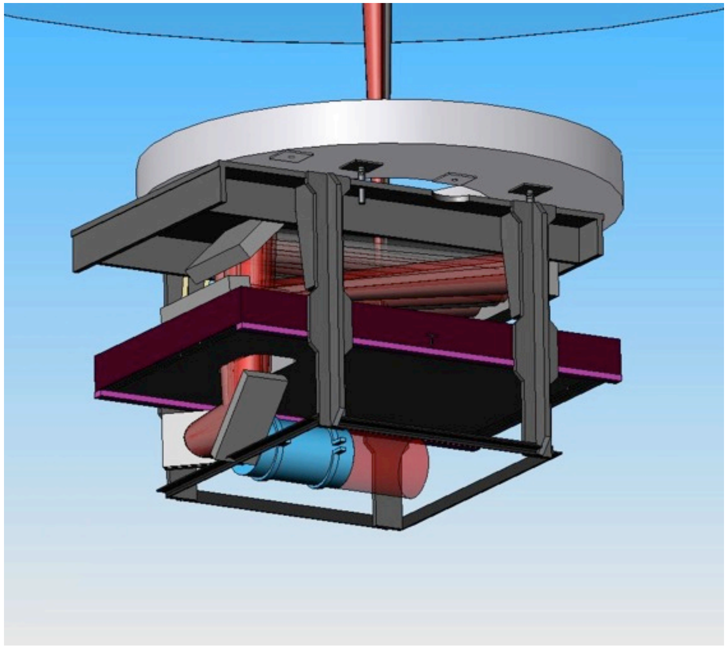
⑤ Galaxy kinematics & stellar pops

⑥ GRB/SNe host properties

⑦ Galactic superwinds/feedback

Design

- ✓ Integral Field Spectrograph: 60 x 40 $arcsec^2$
- ✓ R~5000 spectrograph
- ✓ 1 channel, 0.38-0.95 μm coverage w/ multiple gratings
- ✓ Designed for low surface brightness emission
- ✓ Designed for precision sky subtraction
- ✓ First light 2009



KCWI Keck Cosmic Web Imager

3D, Low Surface Brightness Spectroscopy at Keck

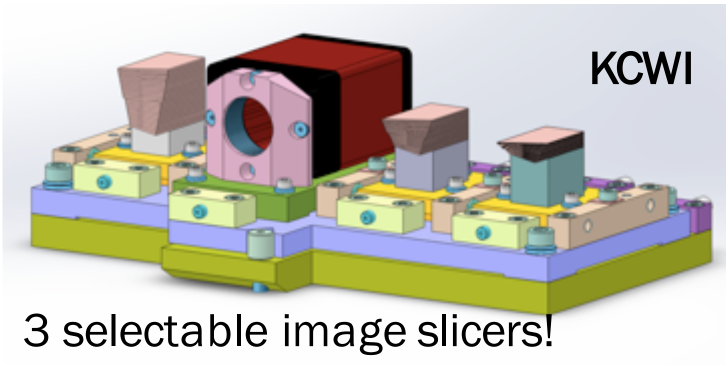
Key Features

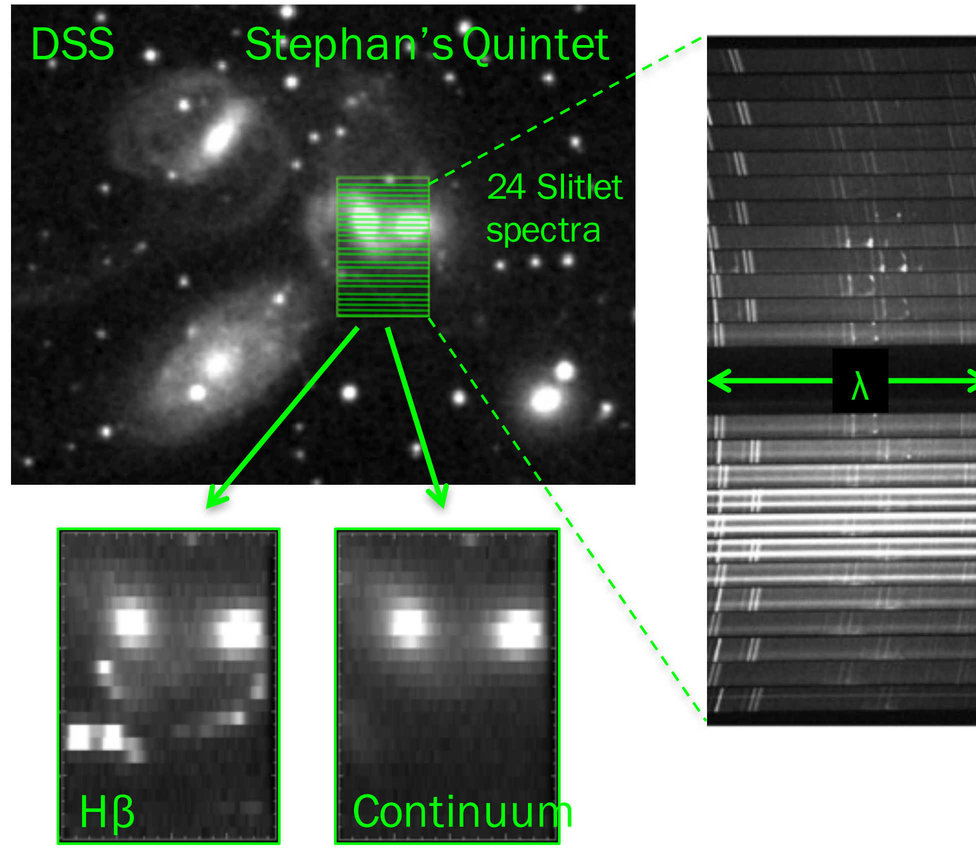
- Wide spectral range (3500-10500Å)
- Flexible field of view, image resolution
- Flexible spectral resolution, coverage
- Superb sky subtraction
- Excellent imaging & Dark Sky on Mauna Kea
- 1st Light Feb 2015 (KCWI-Blue)

Science Applications (examples)

- Map circum-galactic medium 2<z<7
- Map circum-QSO medium
- Map z~6 reionization bubbles
- Composition & age of stellar remnants
- Unusual stellar nebulae
- Low mass galaxies
- Galaxy outskirts
- Galaxy kinematics & stellar age, composition
- Galaxy gas halos, fountains
- Stong lens systems
- Transient sky -- Explosions
- Galactic superwinds/feedback
- Exoplanet transit spectroscopy

KCWI Flexible & Powerful 2D Spectroscopy

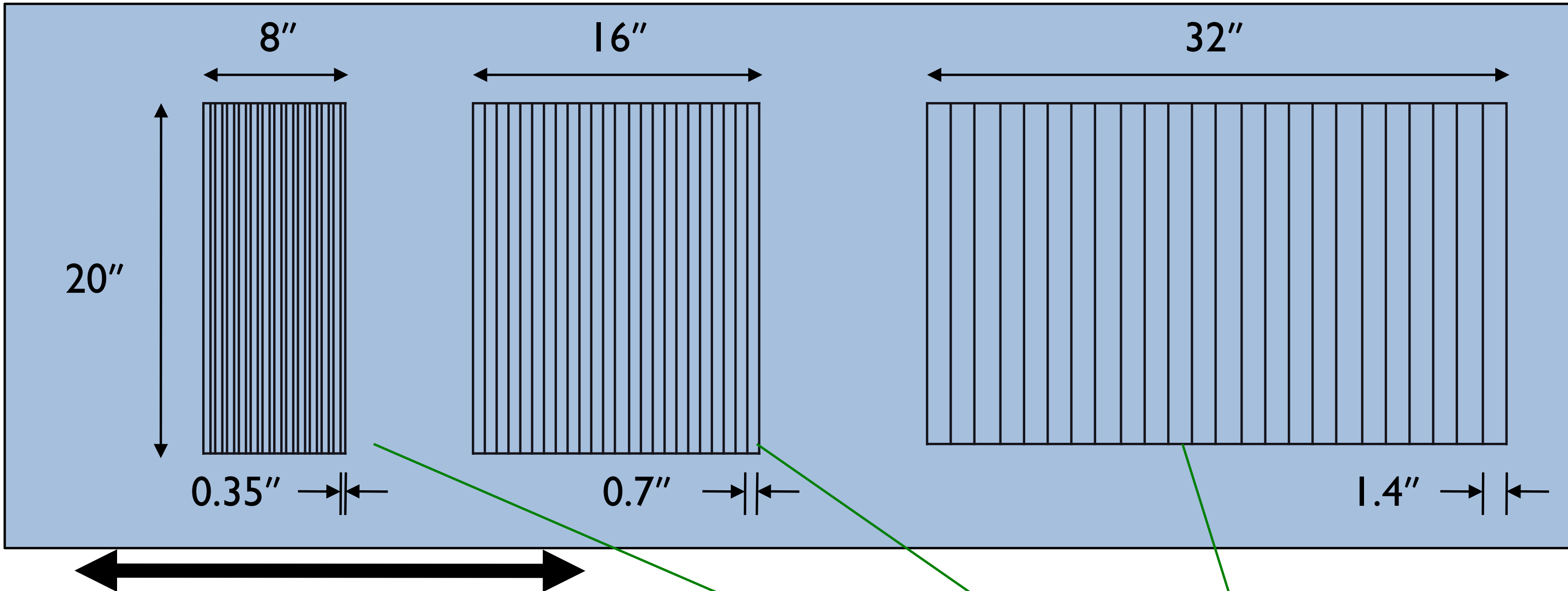




Strengths
- Blue coverage (3500-6000Å)
- Red coverage (5600-10500Å)
- Precision Sky Subtraction
- Flexible observing modes
- High Resolution (R~20,000)

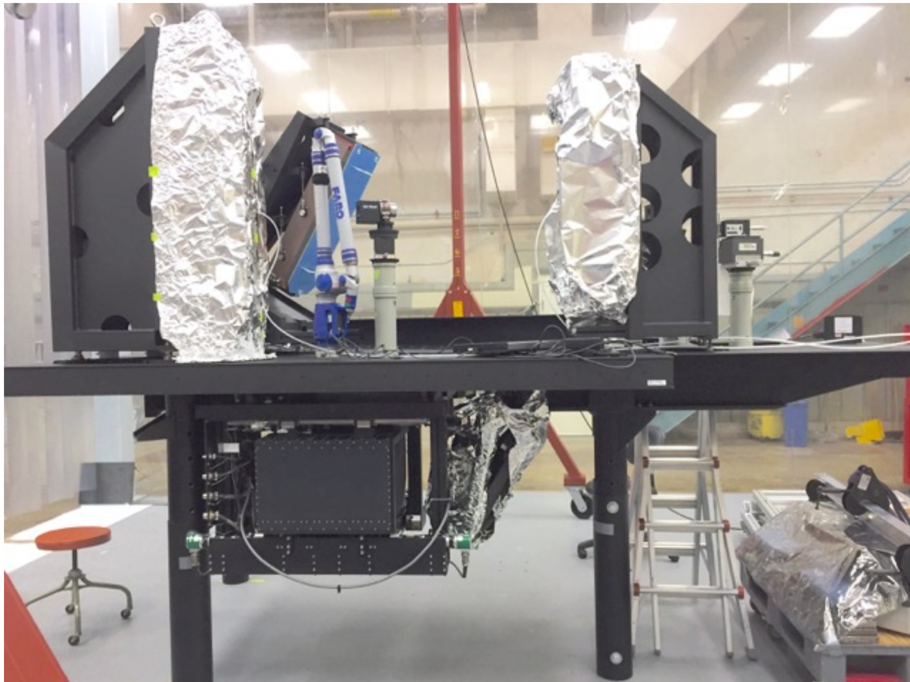
Slicer	Field of View	Spatial Resolution	Spectral Resolution
Small	20" x 8"	0.6" x 0.35"	0.23 Å (R 20,000)
Medium	20" x 16"	0.6" x 0.7"	0.45 Å (R 10,000)
Large	20" x 32"	0.6" x 1.4"	0.90 Å (R 5,000)

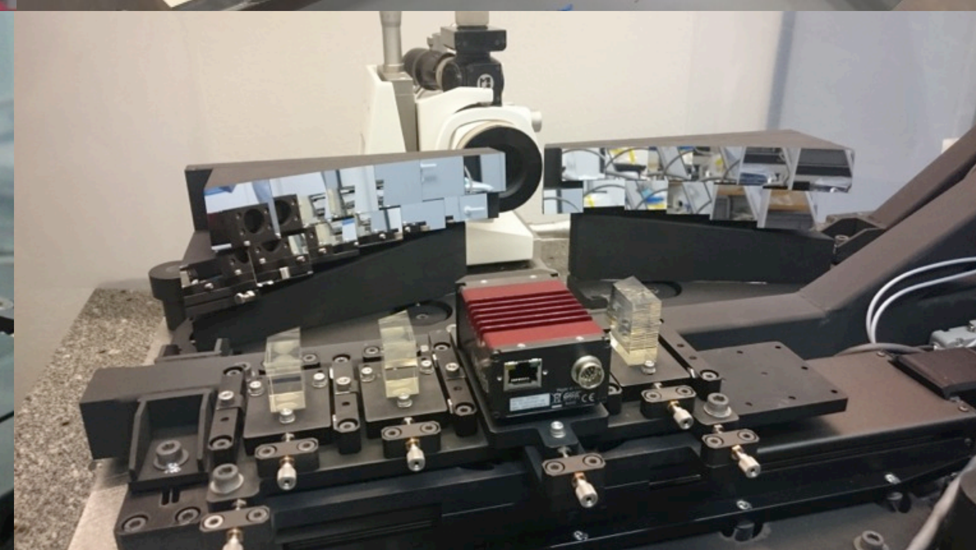
KCWI IFU Formats



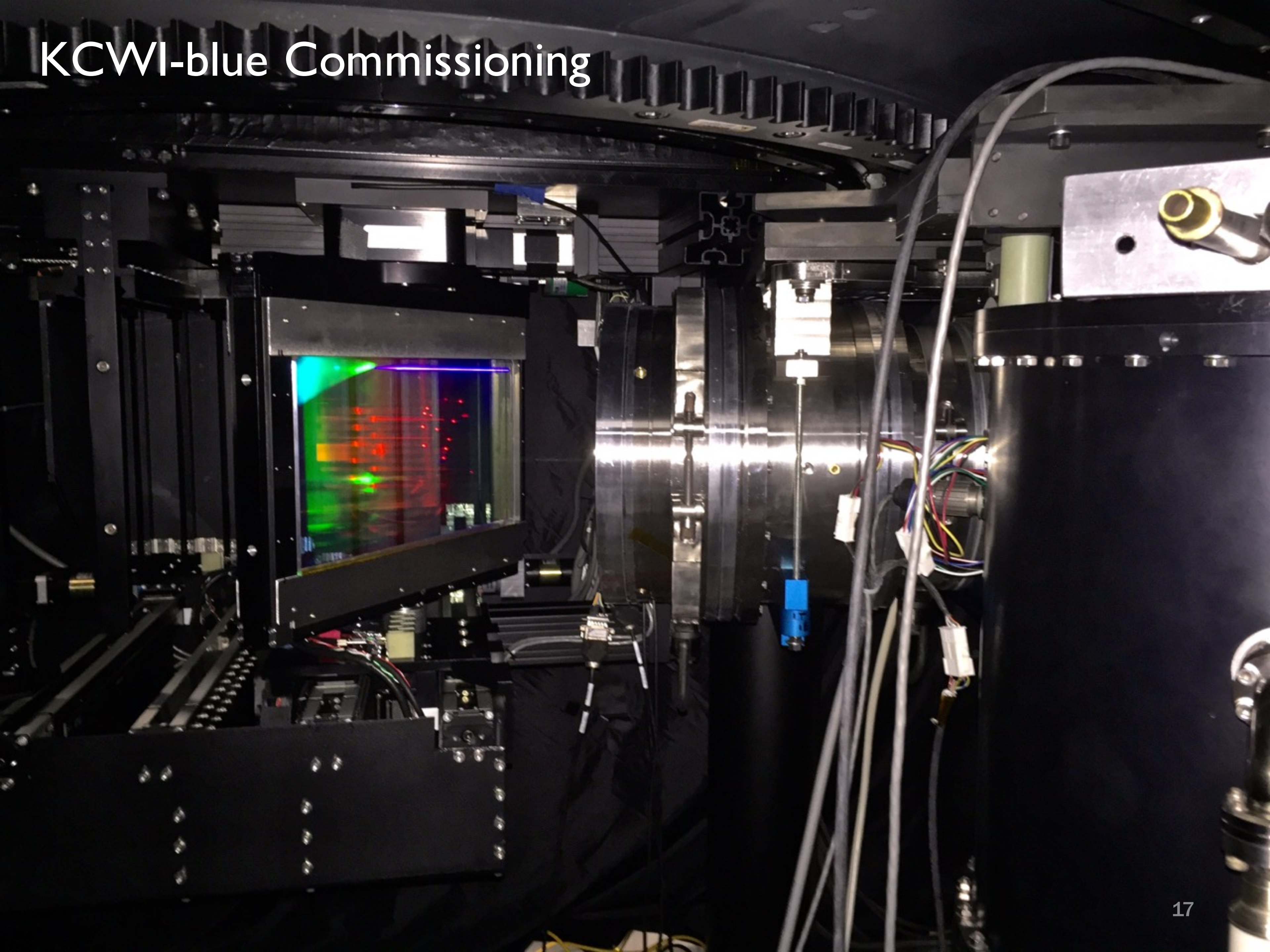
		Spatial Resolution			
		⊥ Dispersion	∥ Dispersion (Slicer-width) Direction		
			Fine	Medium	Course
		0.3″	0.35″	0.7″	1.4″
		FOV 20″x	8.4″	16.8″	34″
Spectral Resolution					
High	Instant. Δλ/λ	300Å /4000Å	R~20,000	R~10,000	R~5000
	Avail. Δλ	1200Å			
	Full optical band coverage requires 3 gratings (blue channel), 3 (red channel)				
Medium	Instant. Δλ/λ	1000Å /4500Å	R~8400	R~4200	R~2100
	Avail. Δλ	2000Å			
	Full optical band coverage requires 1-2 gratings (blue channel), 1-2 (red channel)				
Low	Instant. Δλ/λ	2500Å /5000Å	R~3600	R~1800	R~900
	Avail. Δλ	3000Å			
	Full optical band coverage obtained instantaneously				

KCWI-blue Commissioning

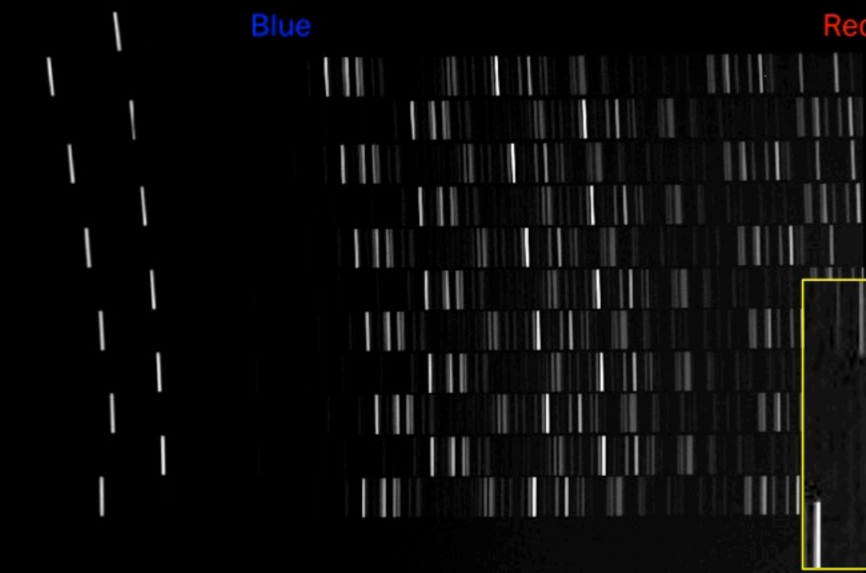


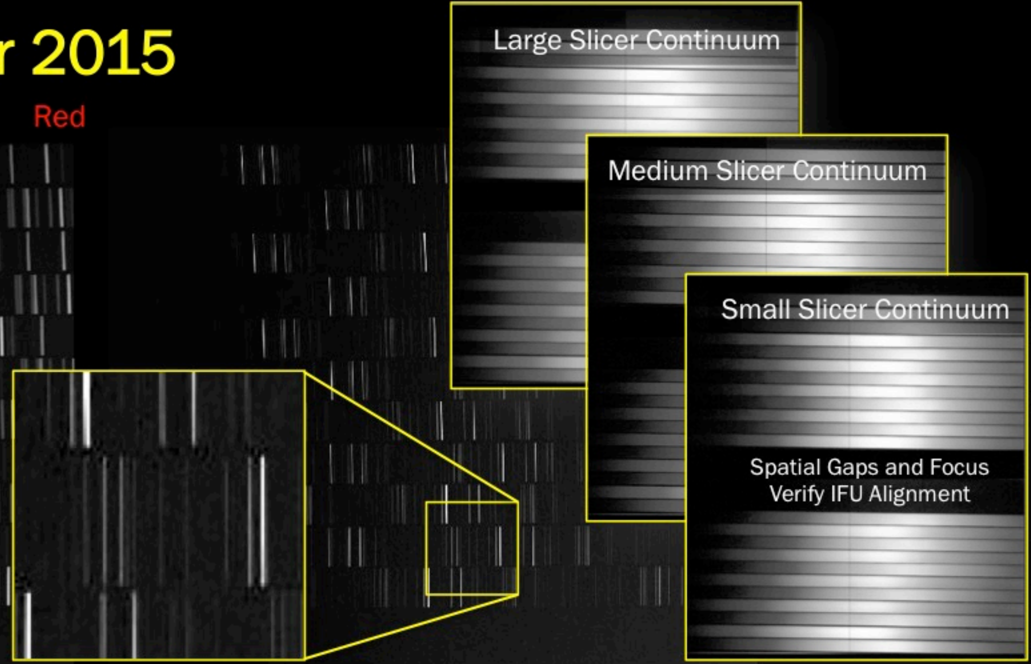


KCWI-blue Commissioning

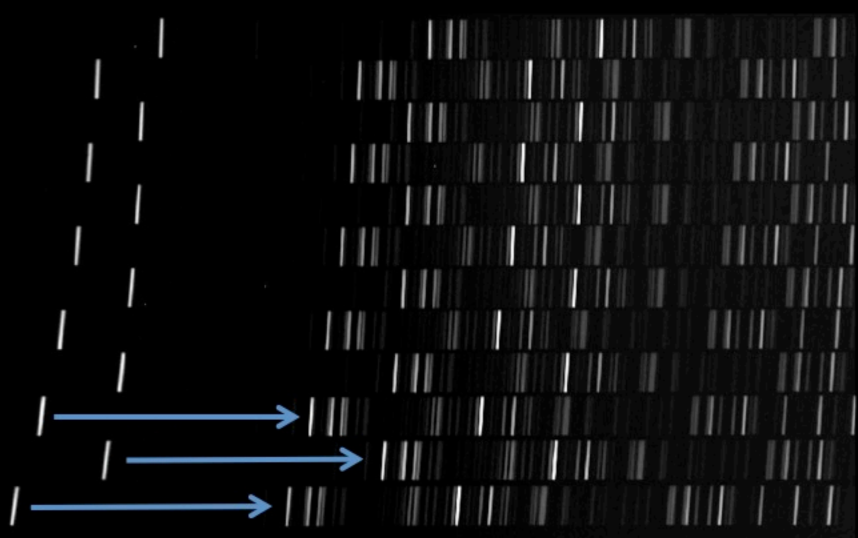


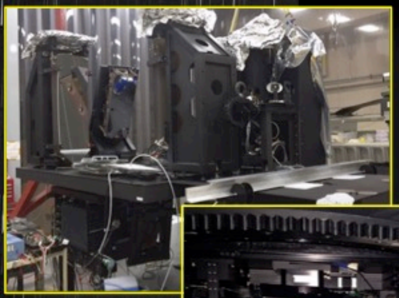
KCWI First Light Spectra October 2015

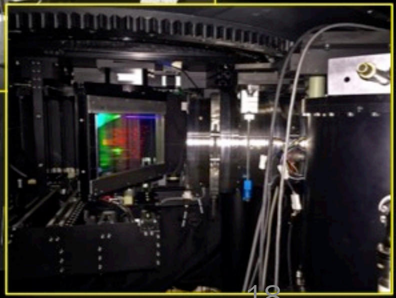




Zero Order | Large Slicer, BM Grating, 370 nm FeAr | Small Slicer, BM Grating, 370 nm FeAr



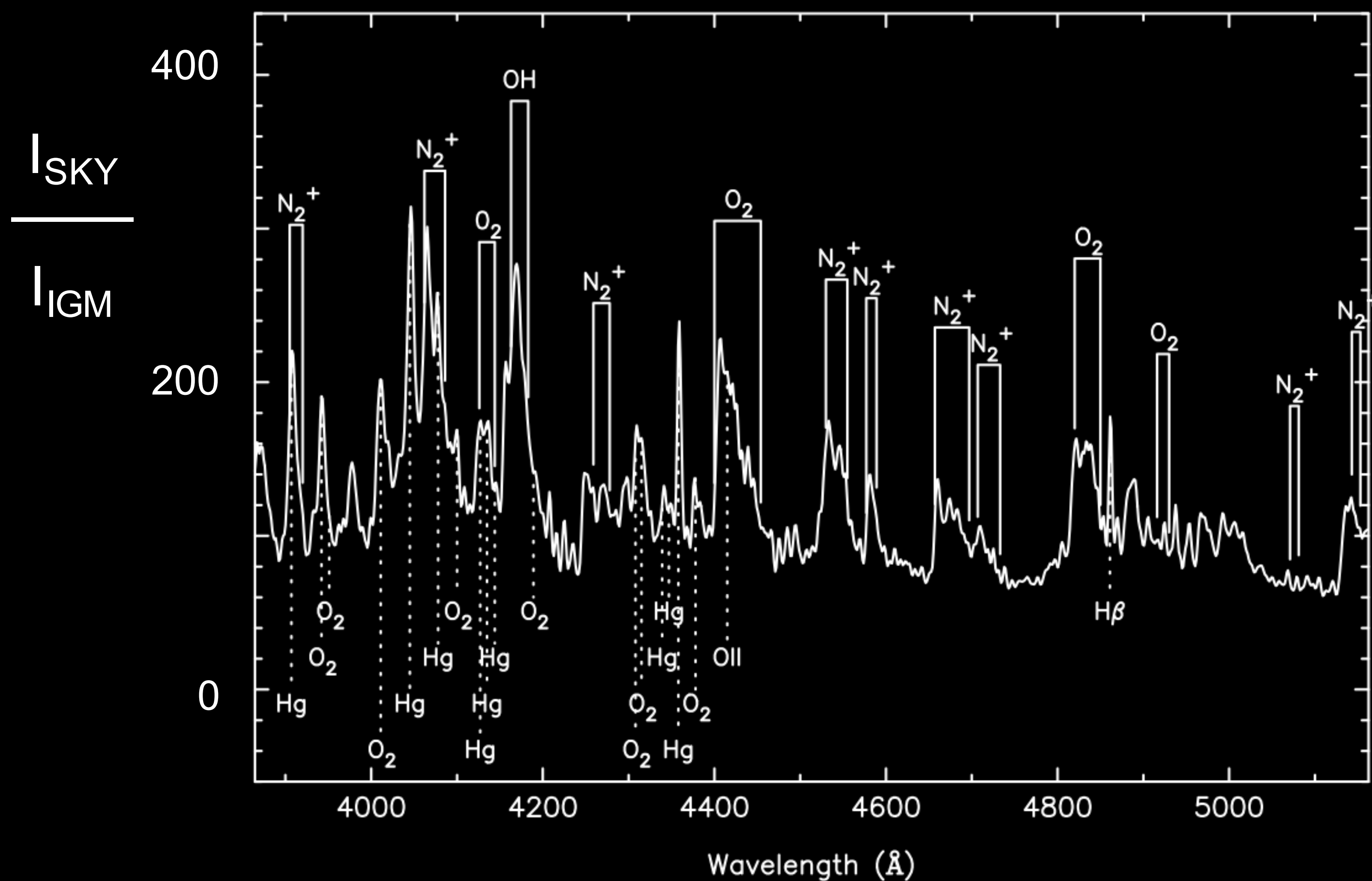




End-to-end, with UCSC camera and KCWI CCD

Spatial shift of spectra is due to a residual grating misalignment

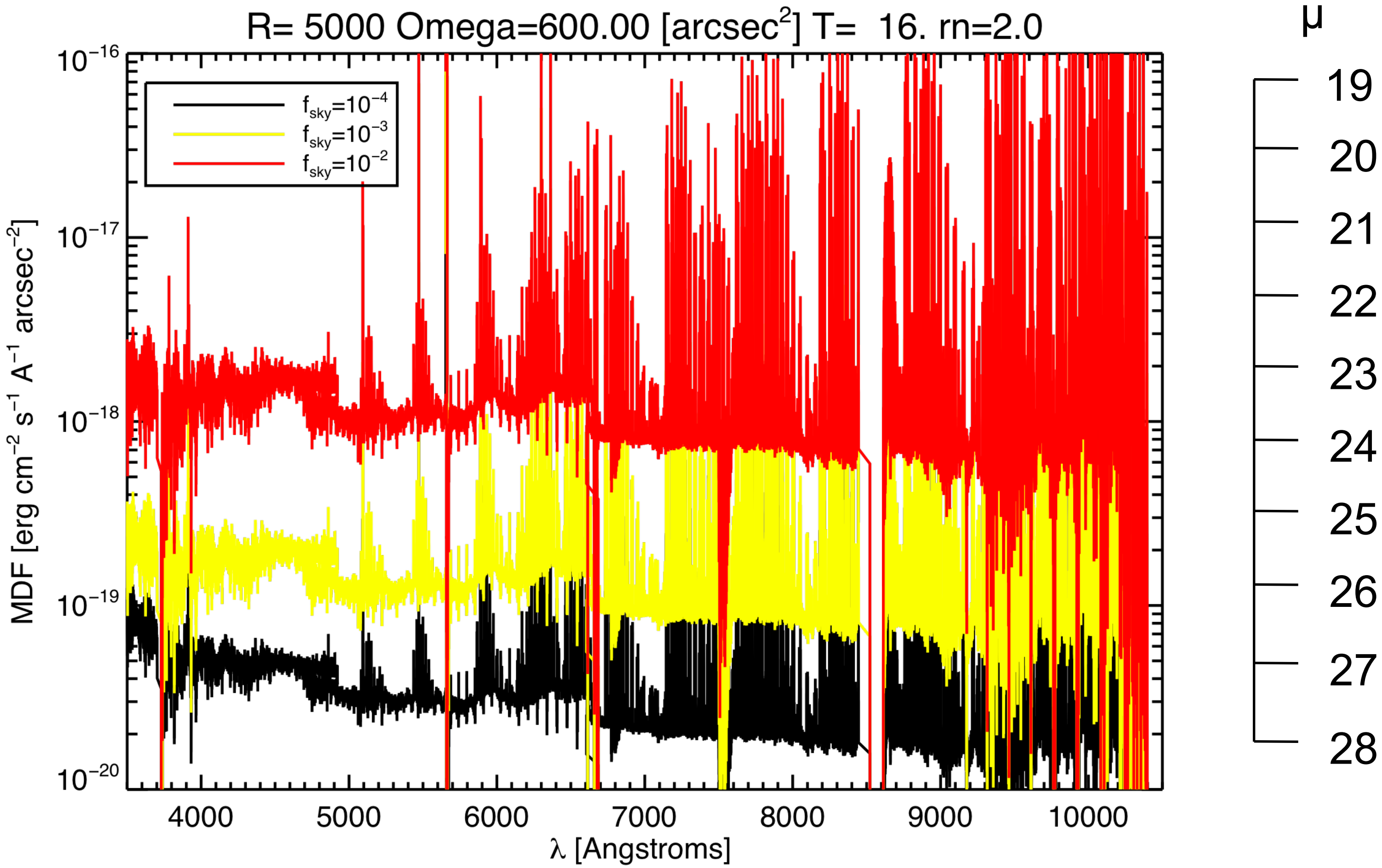
Airglow



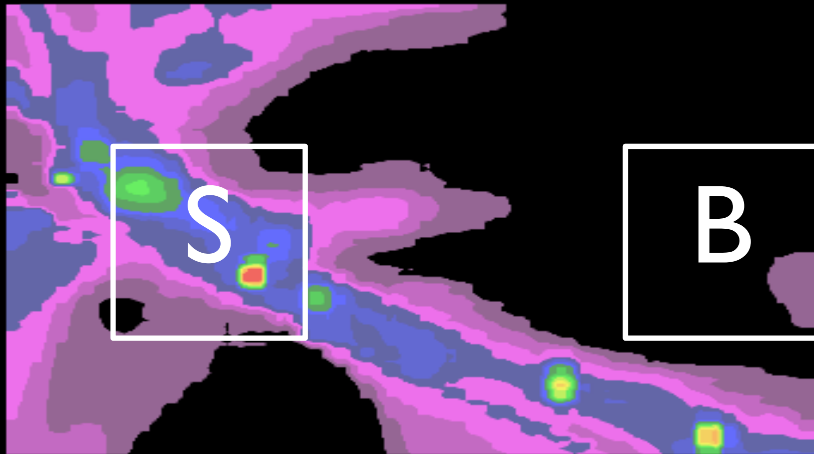
Bernstein, Freedman, Madore 2002

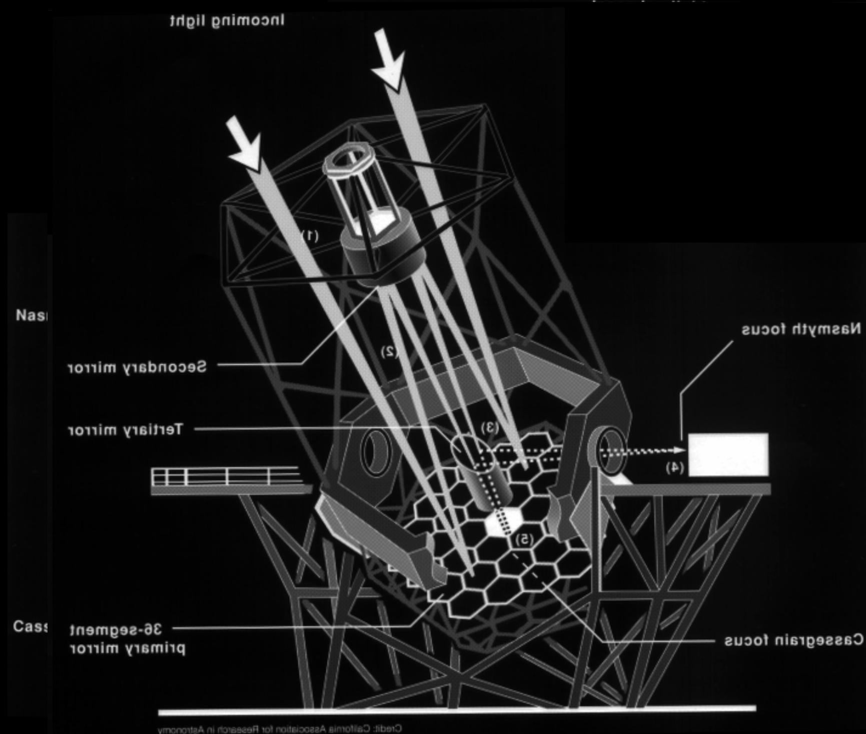
Sensitivity

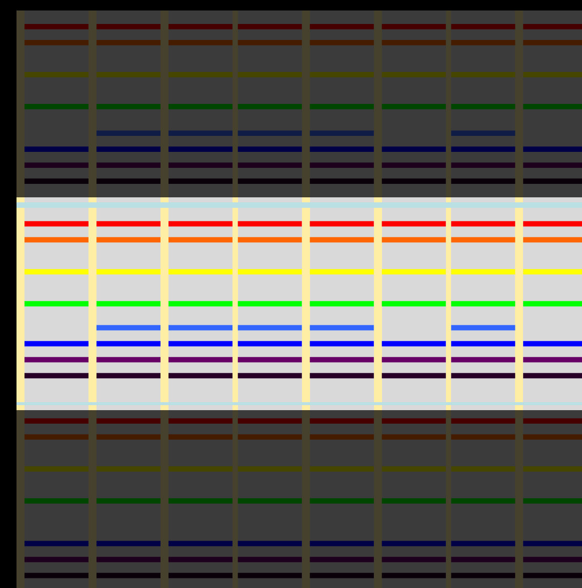
Effect of Sky Subtraction Accuracy



Nod & Shuffle

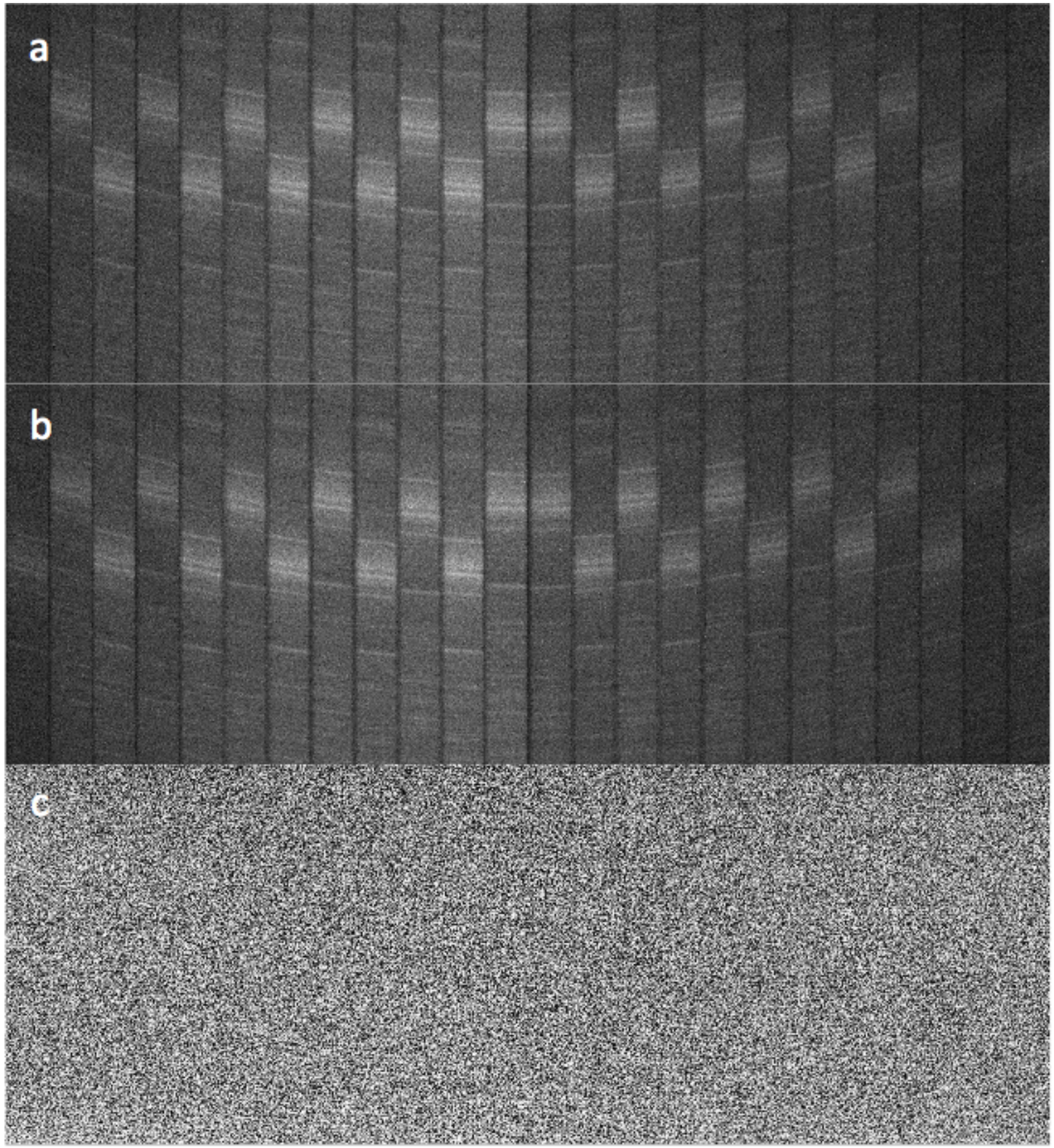


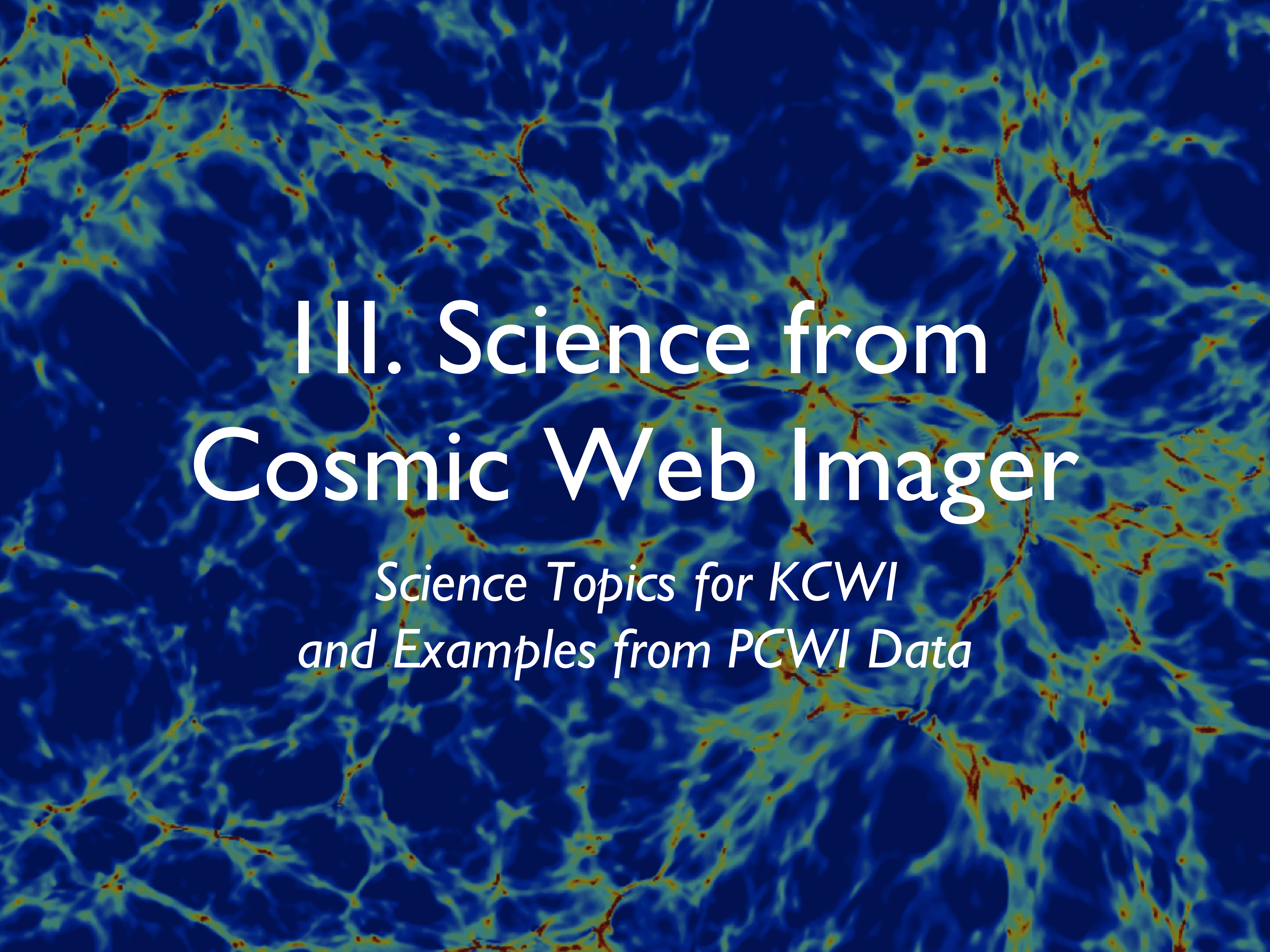




see Sembach and Tonry 1996

Nod-and-Shuffle Sky Subtraction

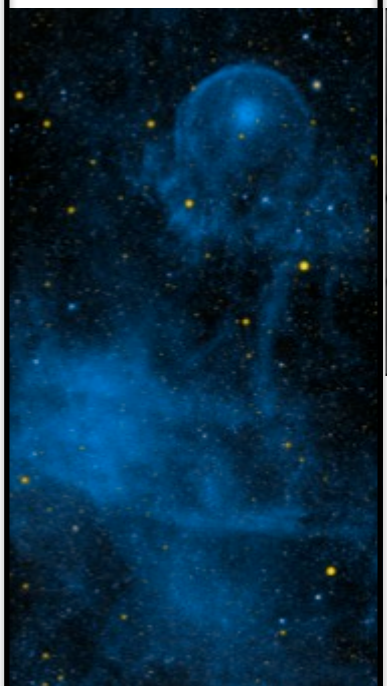
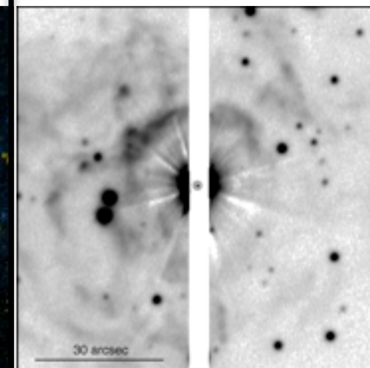
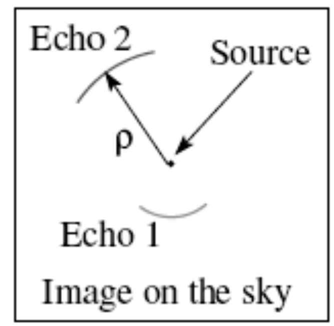
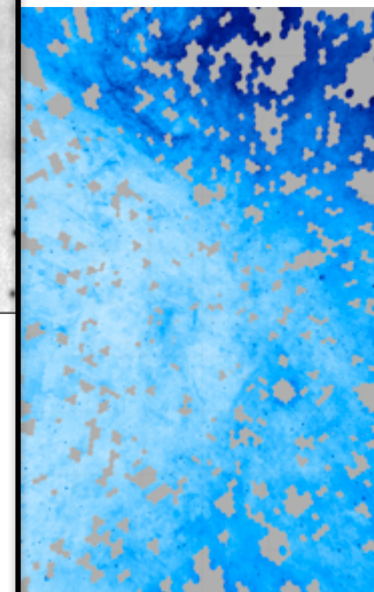




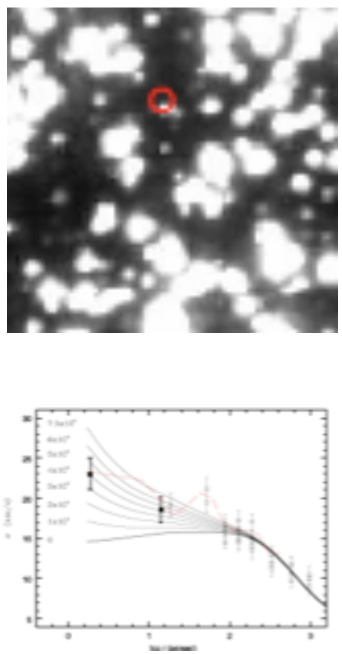
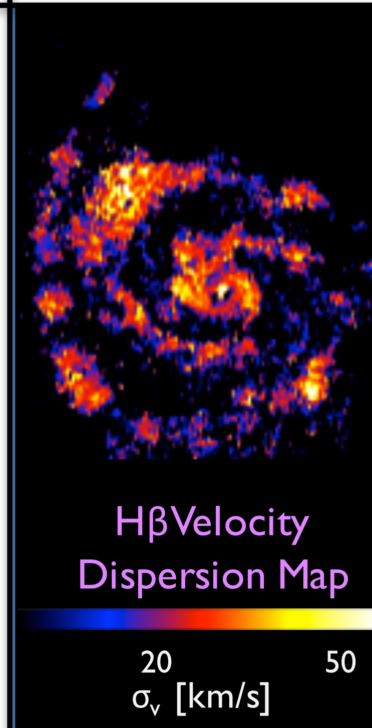
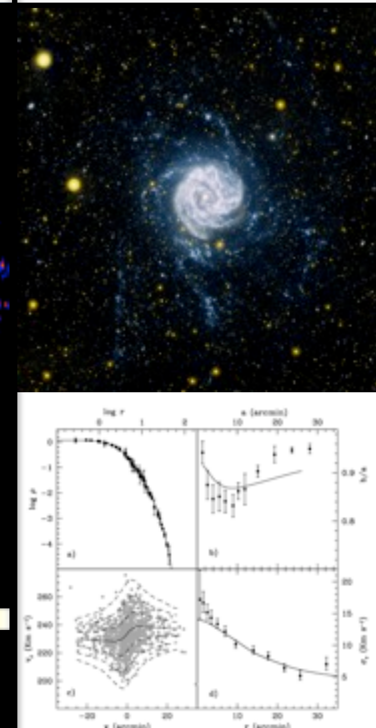
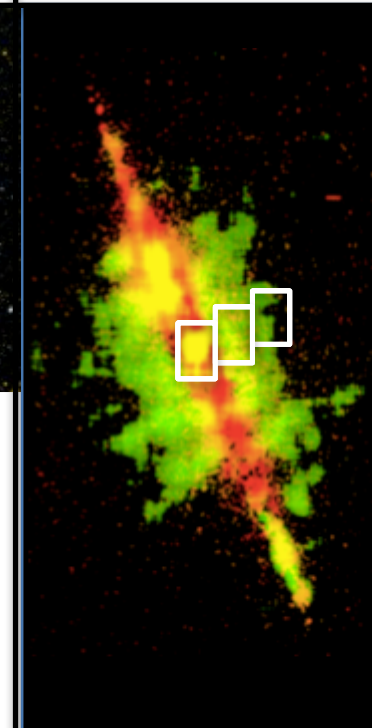
III. Science from Cosmic Web Imager

Science Topics for KCWI
and Examples from PCWI Data

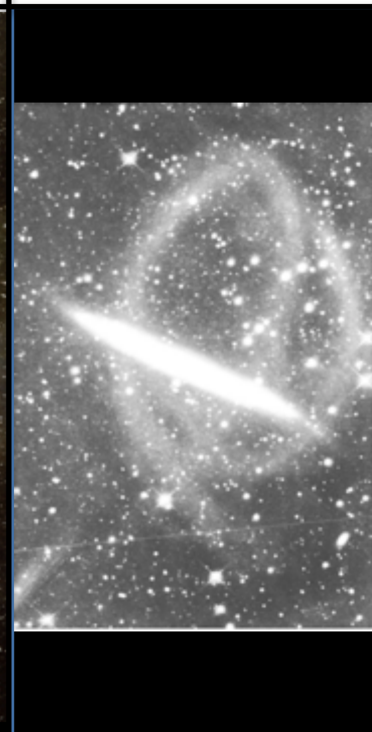
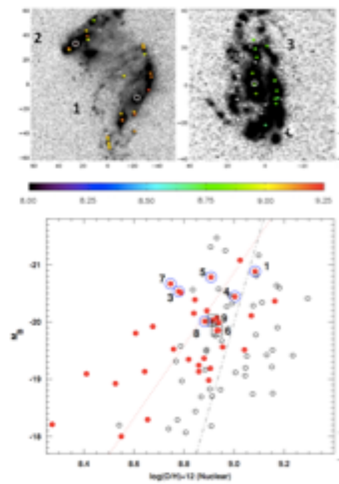
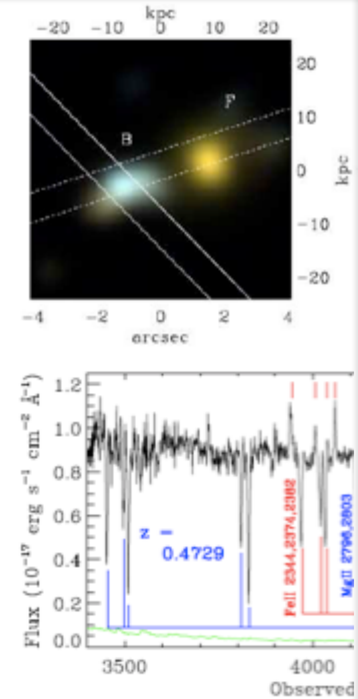
KCWI Science

	(1) Young Stars	(2) Nebulae	(3) Light Echos	(4) ISM
				
Slicer	SMALL	LARGE	LARGE	LARGE
Resolution	HIGH	MEDIUM	LOW	HIGH
Sky Subtraction	NO	YES	YES	YES
Polarization	YES	YES	YES	YES

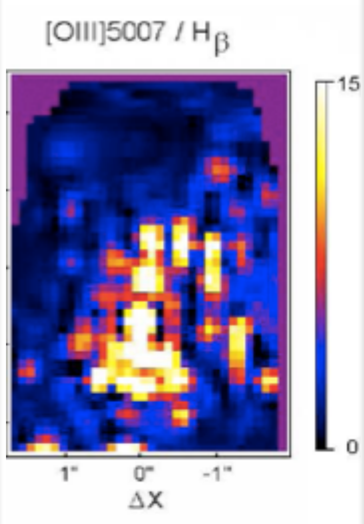
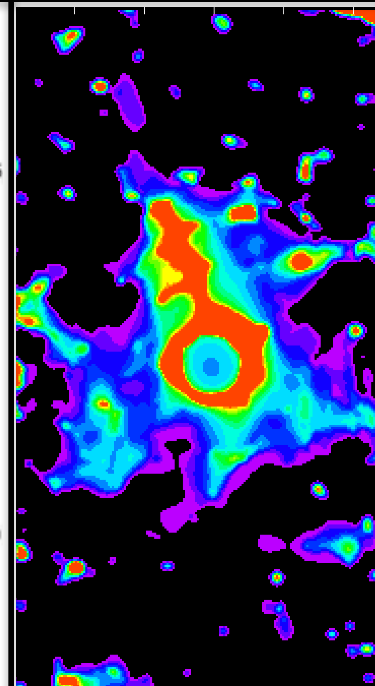
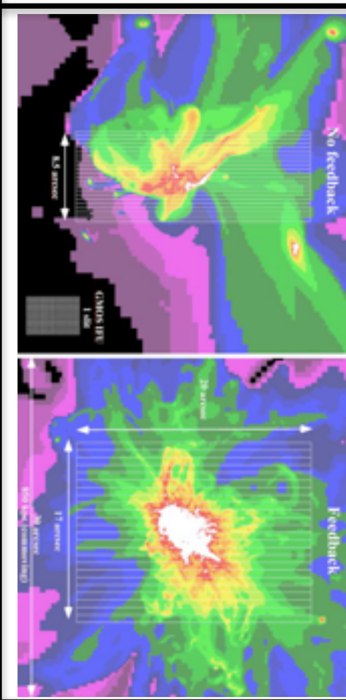
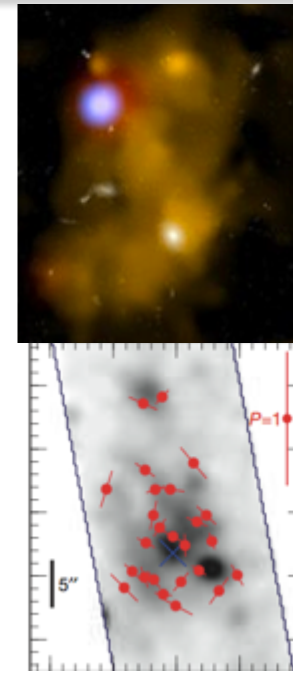
KCWI Science

	(5) * Clusters	(6) Galaxy Gas	(7) LSB Galaxies	(8) Gas Halos
				
Slicer	SMALL	LARGE	SMALL	LARGE
Resolution	HIGH	MEDIUM	HIGH	MEDIUM
Sky Subtraction	NO	YES	YES	YES
Polarization	NO	NO	NO	NO

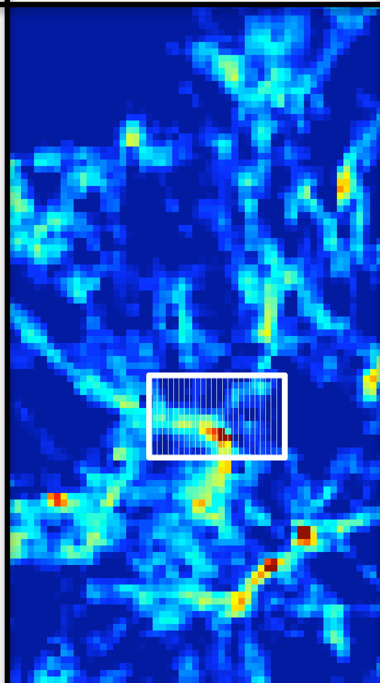
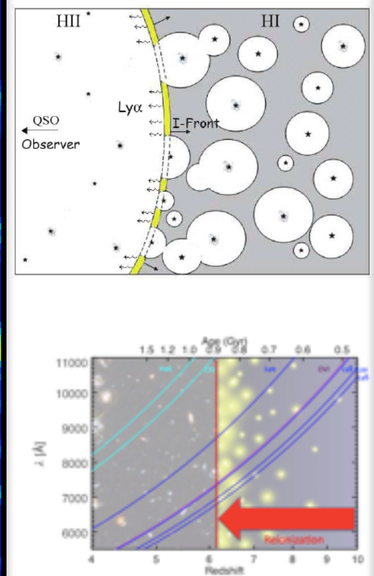
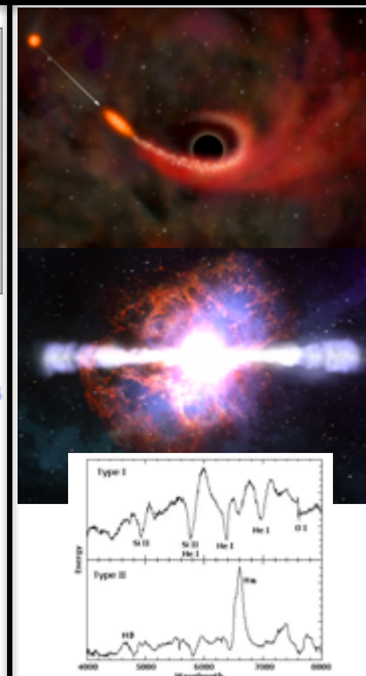
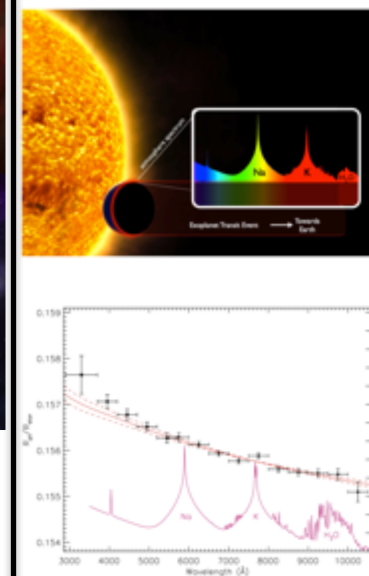
KCWI Science

	(9) Ellipticals	(10) Stellar Halos	(11) dZ/dr	(12) Galaxy Assy
				
Slicer	SMALL	MEDIUM	MEDIUM	LARGE
Resolution	HIGH	MEDIUM	LOW	MEDIUM
Sky Subtraction	NO	YES	YES	YES
Polarization	NO	NO	YES	NO

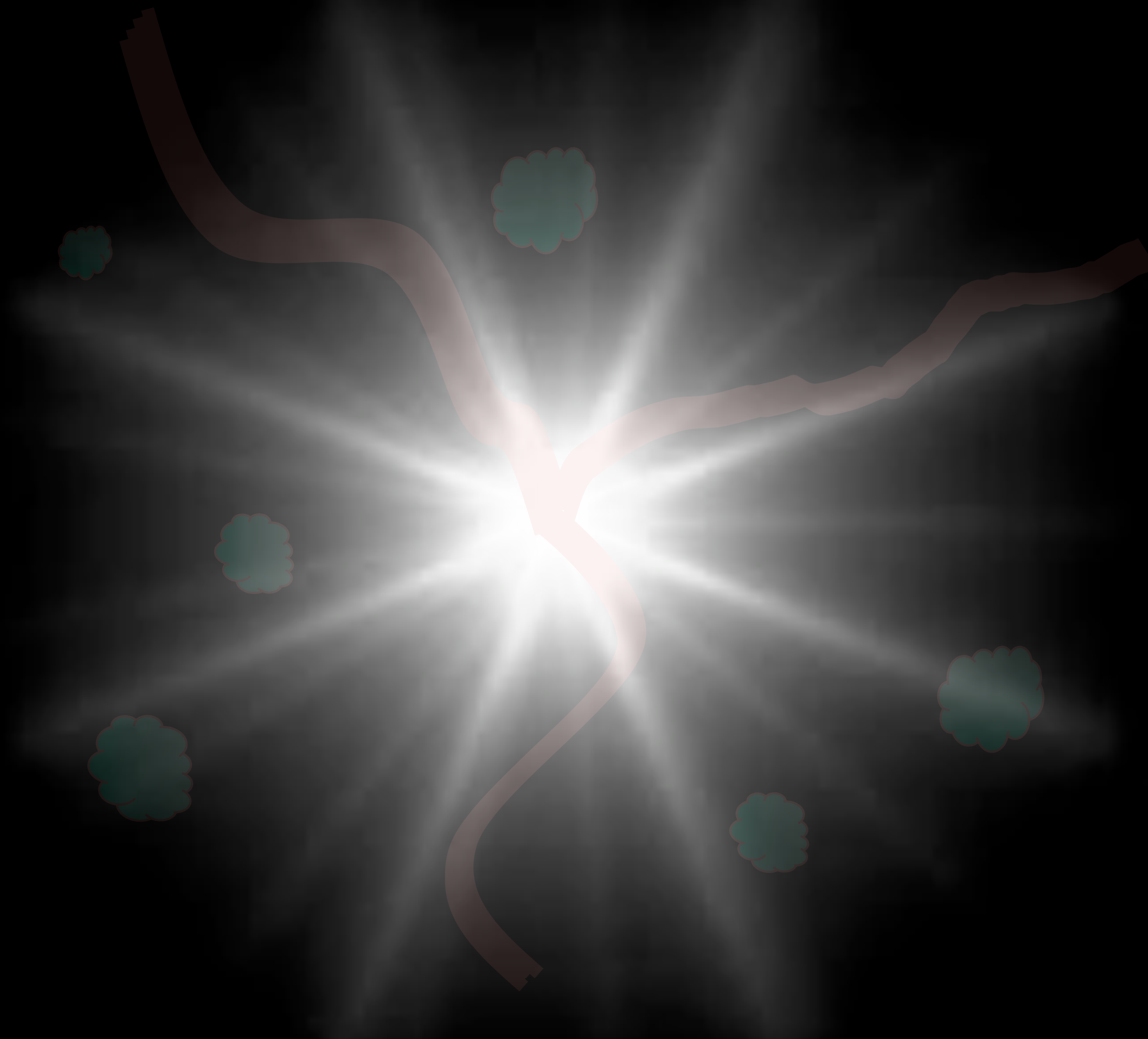
KCWI Science

	(13) AGN/Galaxy Coevolution	(14) Circum QSO Medium	(15) Circum Galactic Medium	(16) Lyα blobs
				
Slicer	SMALL	MEDIUM	MEDIUM	SMALL
Resolution	MEDIUM	MEDIUM	MEDIUM	MEDIUM
Sky Subtraction	NO	YES	YES	YES
Polarization	NO	YES	YES	YES

KCWI Science

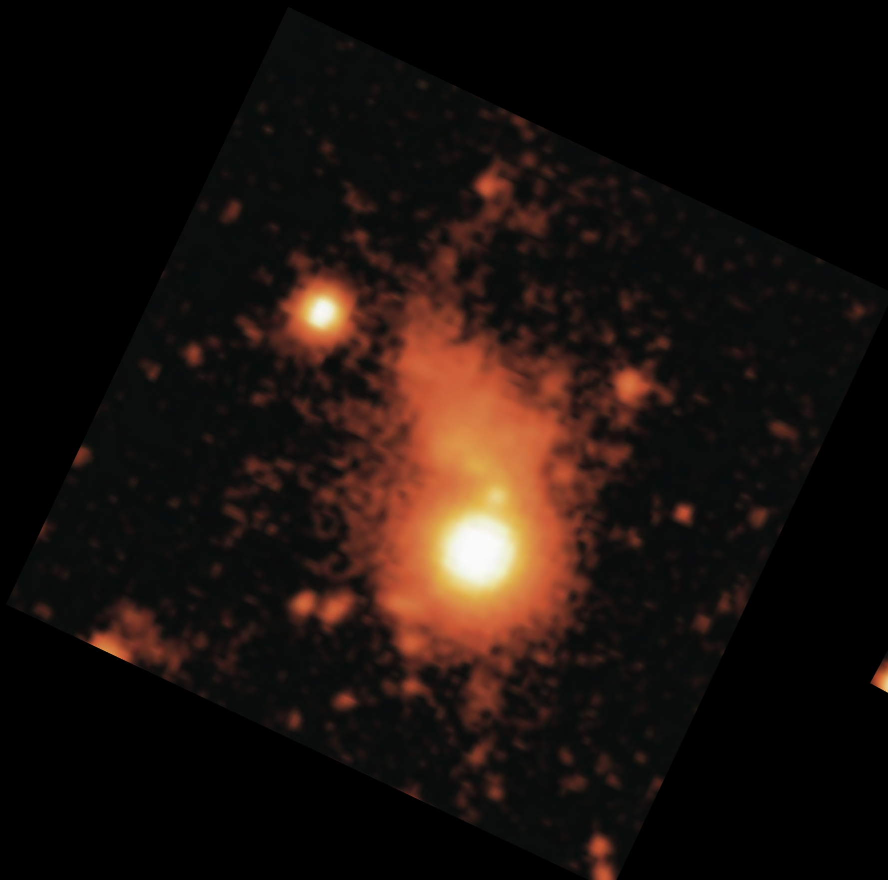
	(17) Cosmic Web	(18) Reionization	(19) Transient Universe	(20) Exoplanet Transit Spectra
				
Slicer	MEDIUM	MEDIUM	MEDIUM	LARGE
Resolution	MEDIUM	MEDIUM	LOW	HIGH
Sky Subtraction	YES	YES	NO	NO
Polarization	YES	NO	NO	NO

(14) Circum-QSO Medium

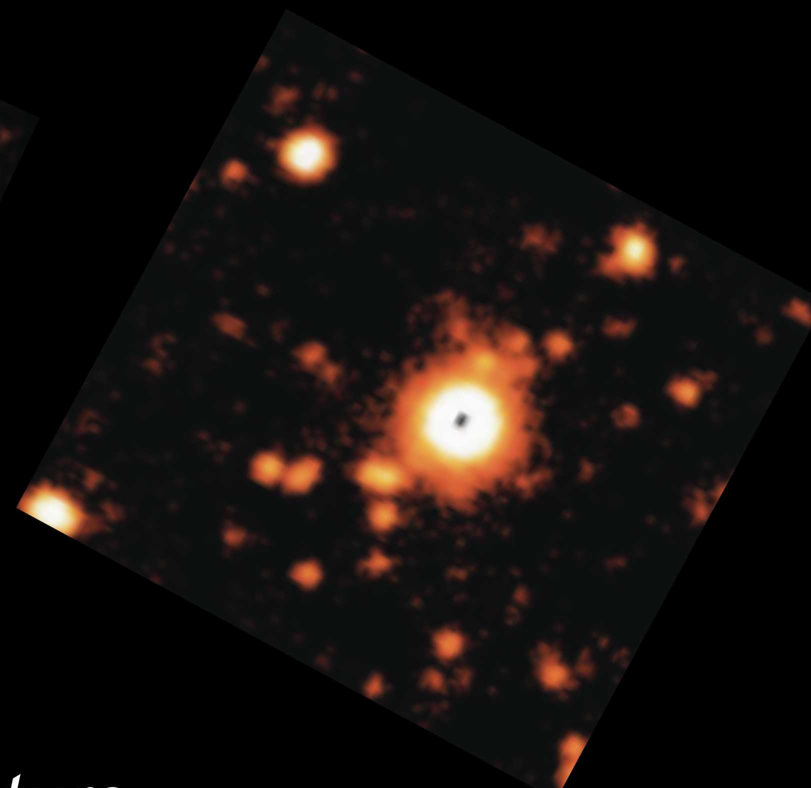


UM287: Cosmic Web Filament?

Lya Narrow Band (z=2.28)

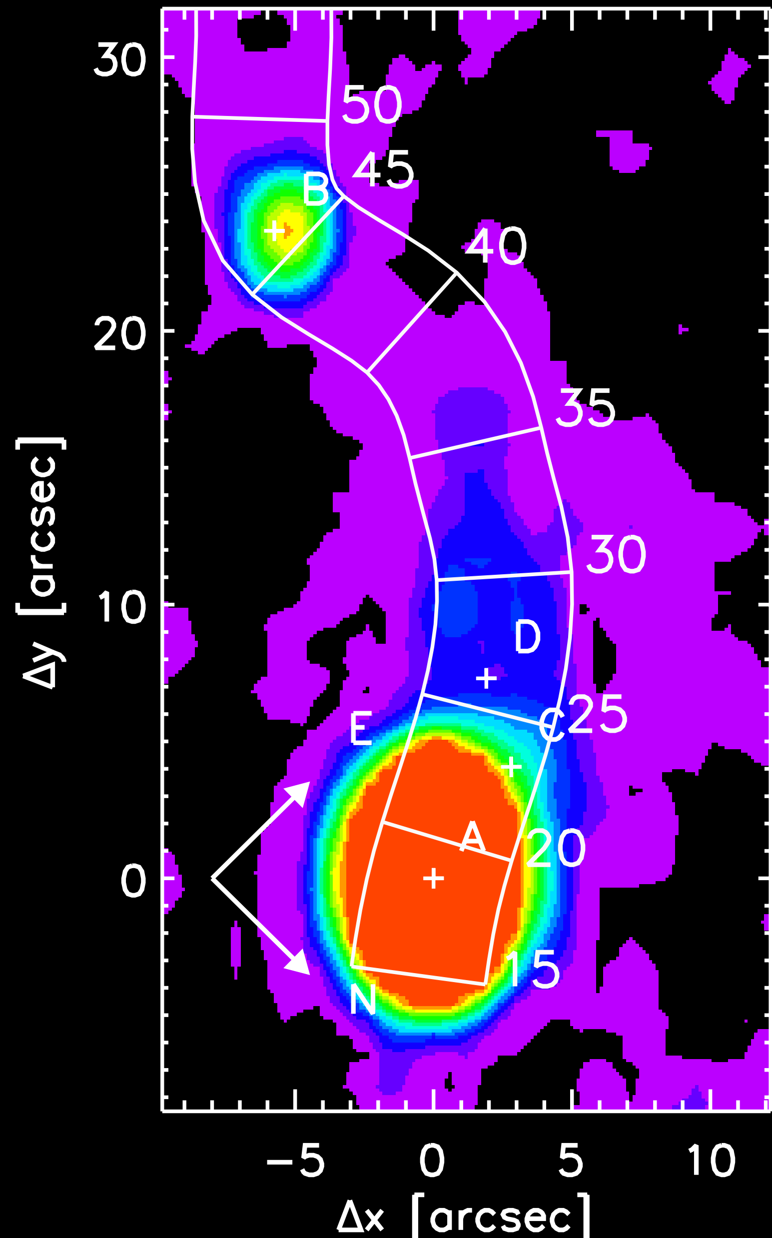


Continuum



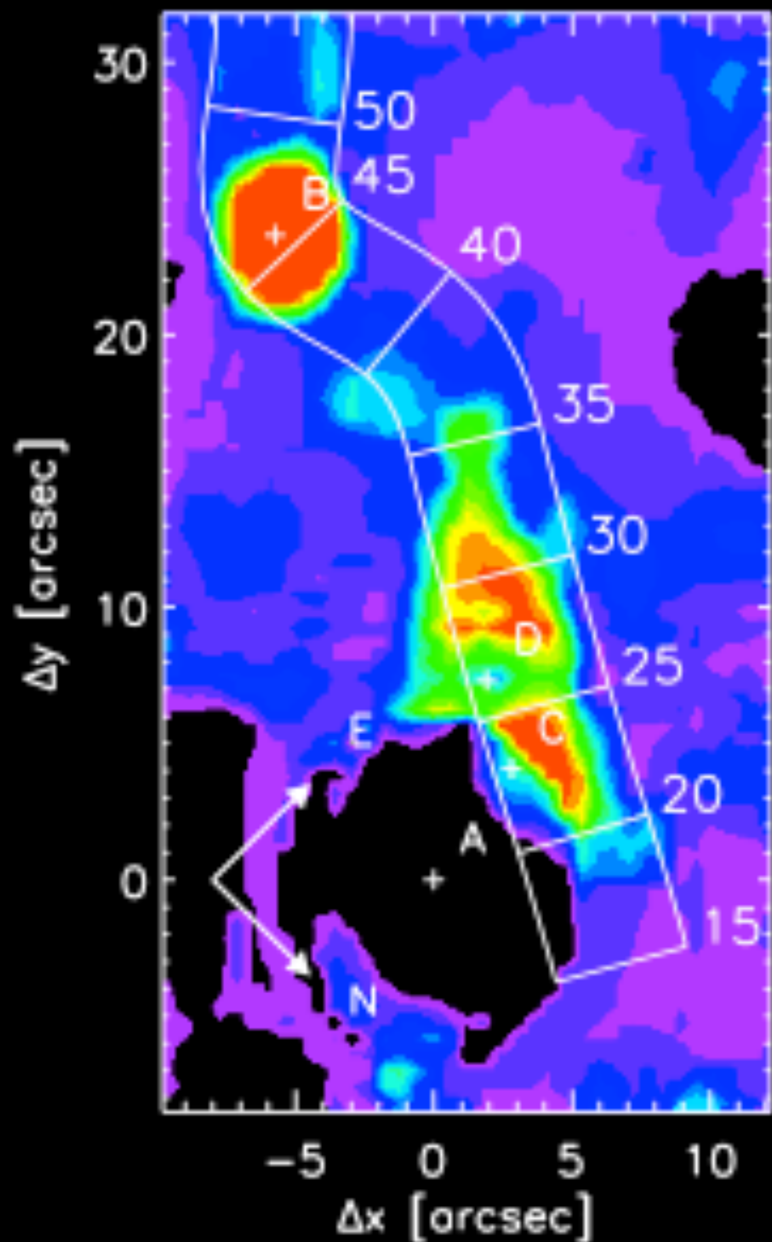
Cantalupo et al. 2014 Nature

UM287



40Å around systemic velocity

UM287



Special spatially variable narrow-band filter of data cube

Martin+2015, Nature, 524, 192

¥

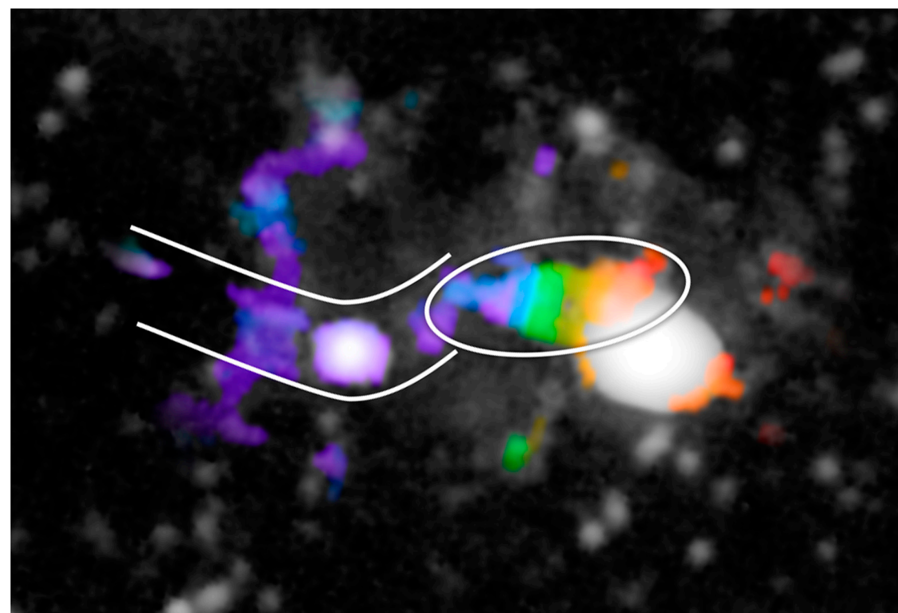
LETTER

doi:10.1038/nature14616

A giant protogalactic disk linked to the cosmic web

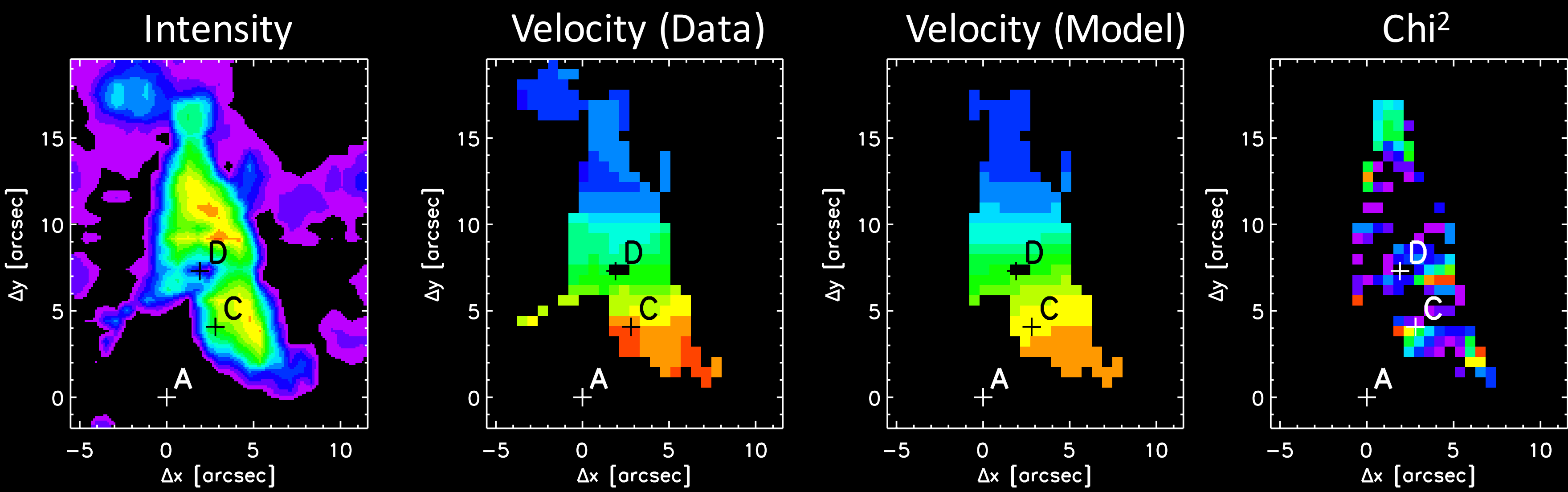
D. Christopher Martin[1], Mateusz Matuszewski[1], Patrick Morrissey[1], James D. Neill[1], Anna Moore[2], Sebastiano Cantalupo[3], J. Xavier Prochaska[4,5] & Daphne Chang‡

The specifics of how galaxies form from, and are fuelled by, gas from the intergalactic medium remain uncertain. Hydrodynamic simulations suggest that 'cold accretion flows'—relatively cool (temperatures of the order of 10^4 kelvin), unshocked gas streaming along filaments of the cosmic web into dark-matter halos[1–3]—are important. These flows are thought to deposit gas and angular momentum into the circumgalactic medium, creating disk- or ring-like structures that eventually coalesce into galaxies that form at filamentary intersections[4,5]. Recently, a large and luminous filament, consistent with such a cold accretion flow, was discovered near the quasi-stellar object QSO UM287 at redshift 2.279 using narrow-band imaging[6]. Unfortunately, imaging is not sufficient to constrain the physical characteristics of the filament, to determine its kinematics, to explain how it is linked to nearby sources, or to account for its unusual brightness, more than a factor of ten above what is expected for a filament. Here we report a two-dimensional spectroscopic investigation of the emitting structure. We find that



Martin+15

#1: UM287 PGD

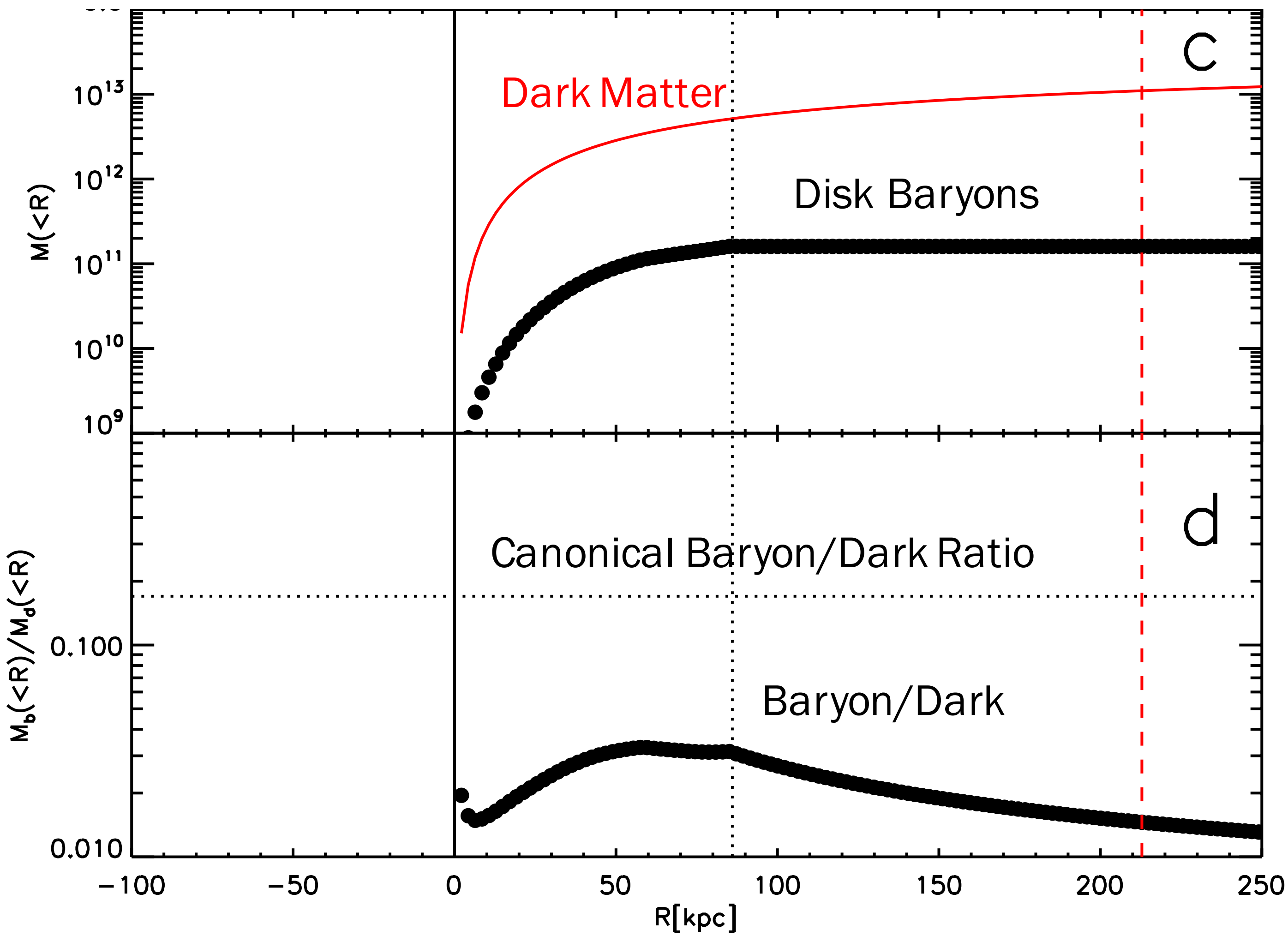


- M_h= 11 x 10^{12} $M_\odot$
- M_d = 1.6 x 10^{11} $M_\odot$
- M_d/M_h = 0.015
- c = 3.2
- D(max) = 130 kpc
- R(vir) = 216 kpc

- z=2.28
- t(orb) = 0.9 Gyr
- t(vir) = 2.8 Gyr
- t(age) = 2.8 Gyr
- λ_b=0.14

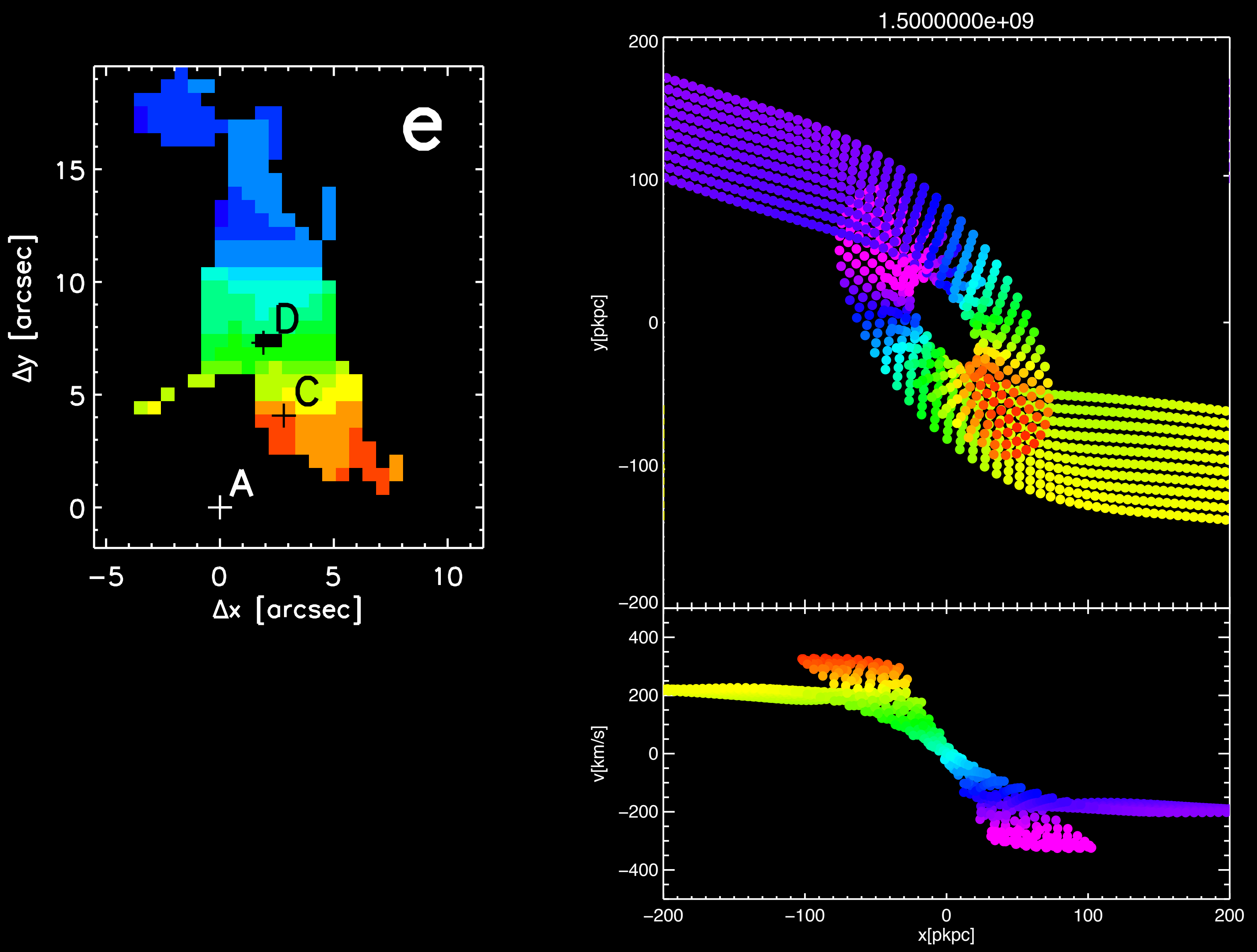
Martin+2015, Nature, 524, 192

Protogalactic Disk: Baryon / Dark Matter Profile

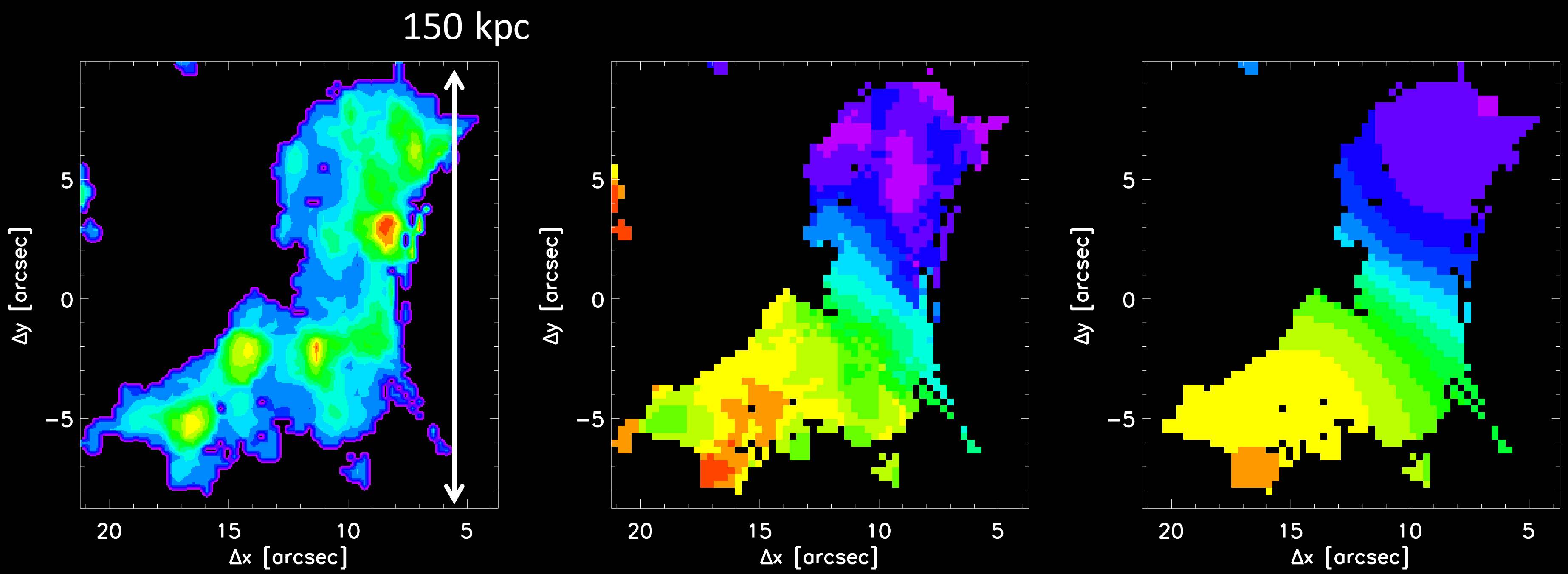


Martin+2015, Nature, 524, 192

Filament Model



#2: HS1549+19 PGD



- M_h= 4 x $10^{12} M_\odot$
- M_d = 9 x $10^{10} M_\odot$
- M_d/M_h = 0.024
- c = 3.1
- D(max) = 200 kpc
- R(vir) = 125 kpc

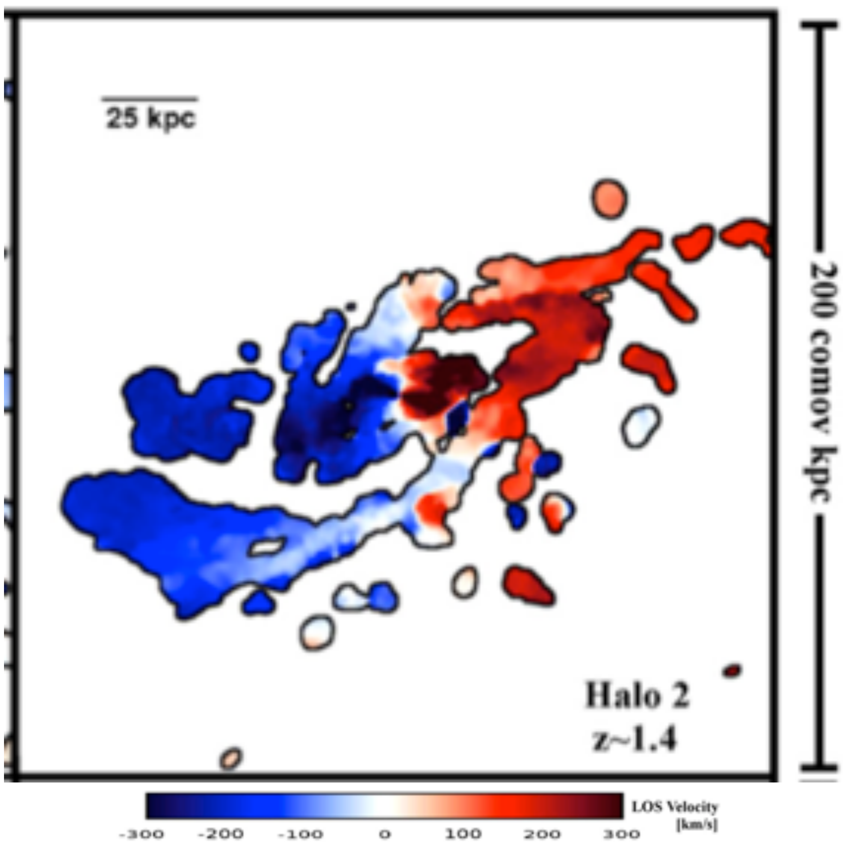
- z=2.84
- t(orb) = 2.0 Gyr
- t(vir) = 1.6 Gyr
- t(age) = 2.2 Gyr
- λ_b=0.34

Martin et al. 2016 ApJLett (in press)

CGM Emission → How does gas get into galaxies?

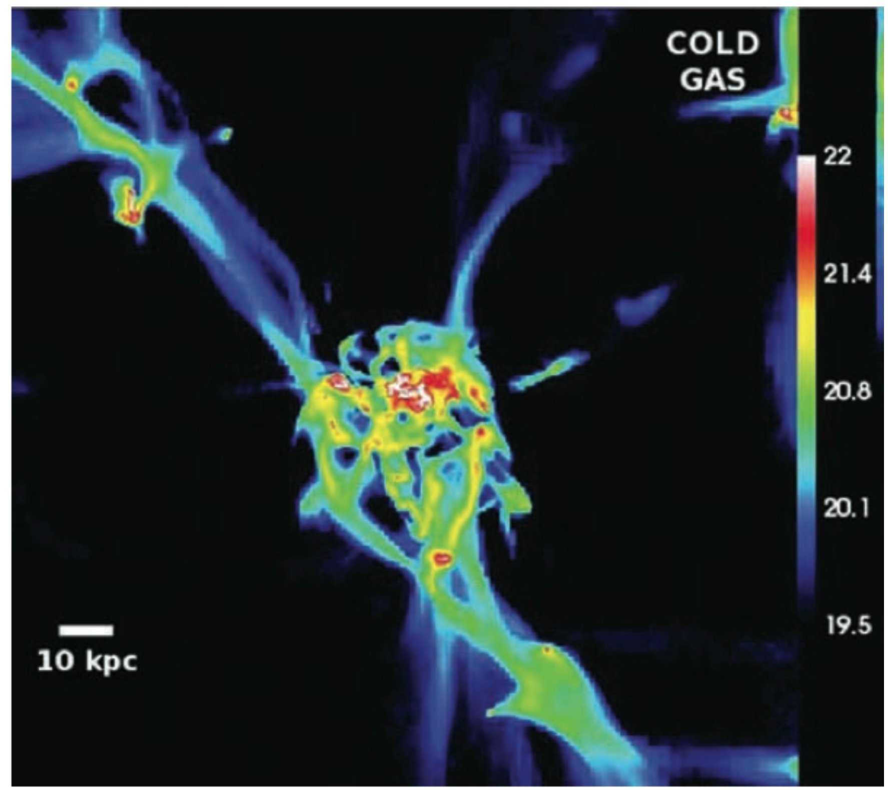
Cold Filament Accretion → Large Angular Momentum → Giant Rotating Disks/Rings of Gas

Velocity Profile



Stewart+2013

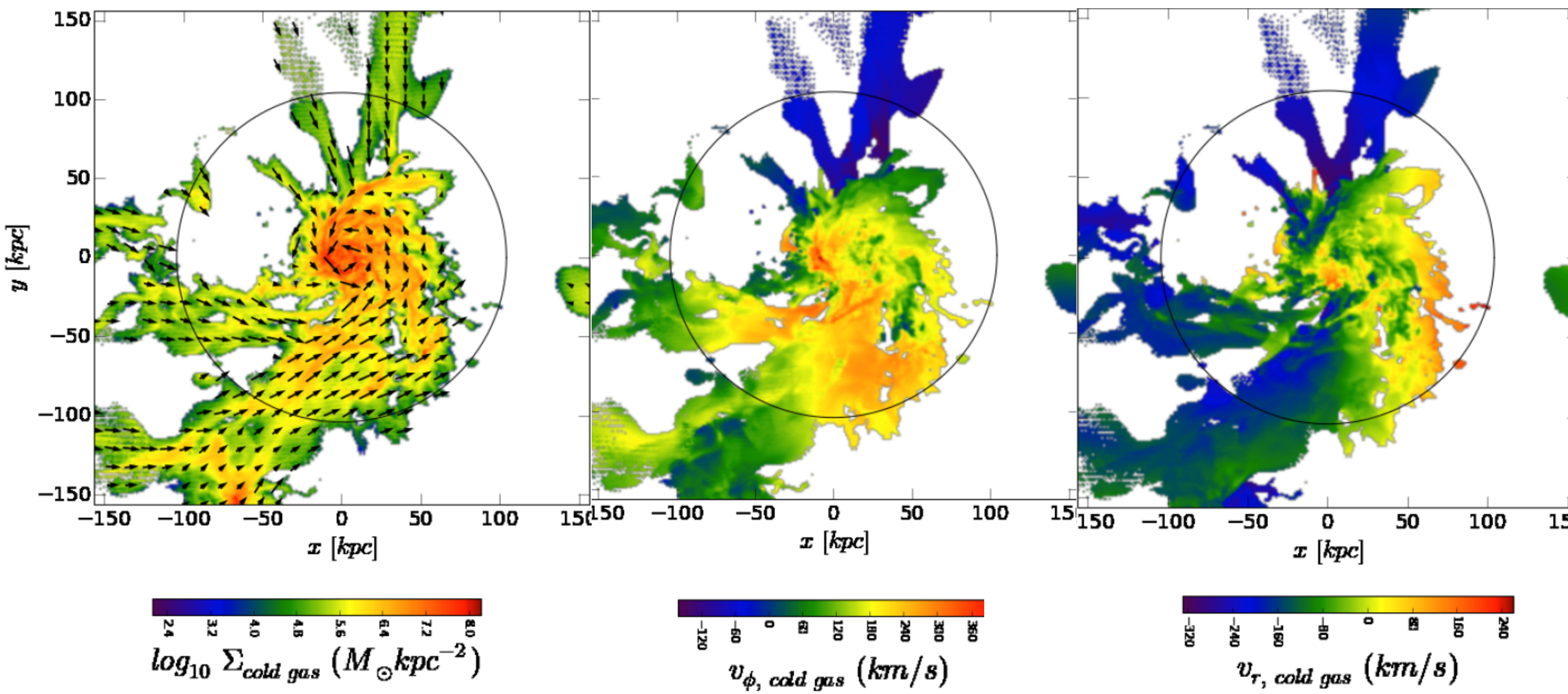
Cold Gas Profile



Pichon+11; Ceverino+10, Danovich+12,14

Cold Flow Inspiral

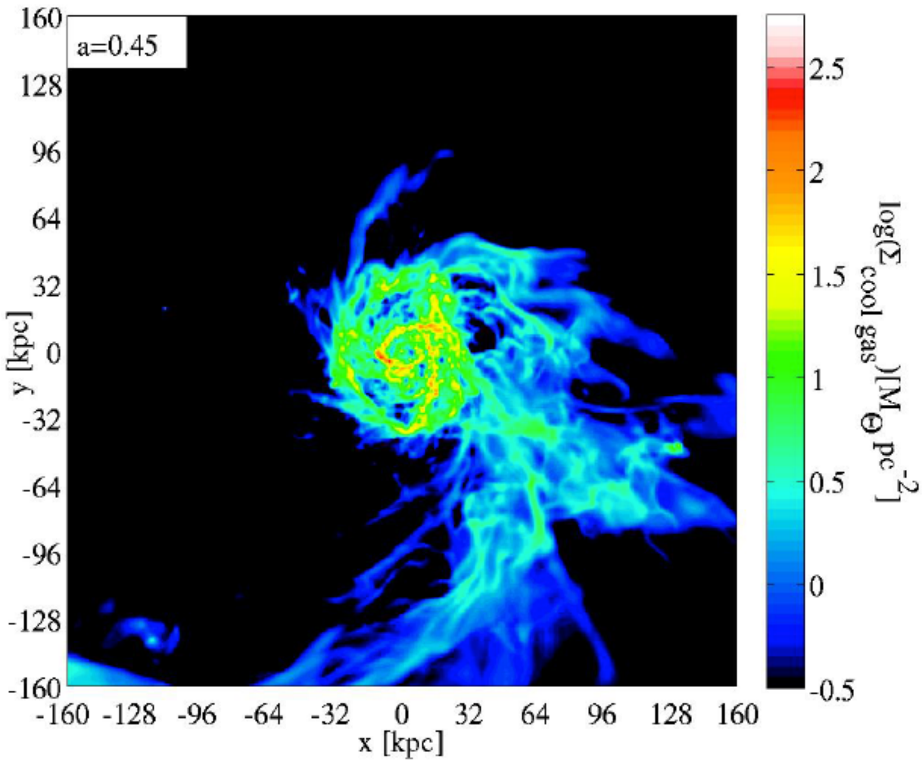
Surface Density/Flow | Azimuthal Velocity | Radial Velocity



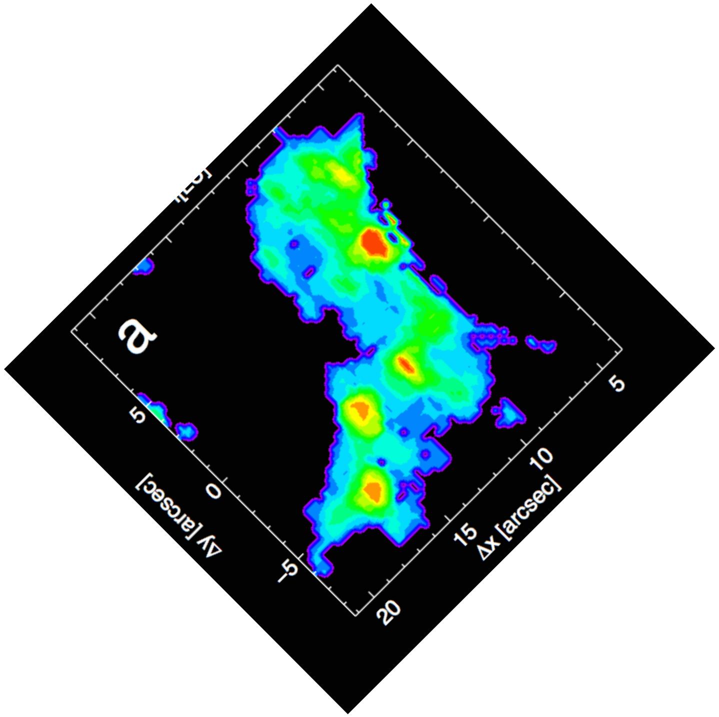
Dekel 2016

Cold Flow Inspiral

Simulation

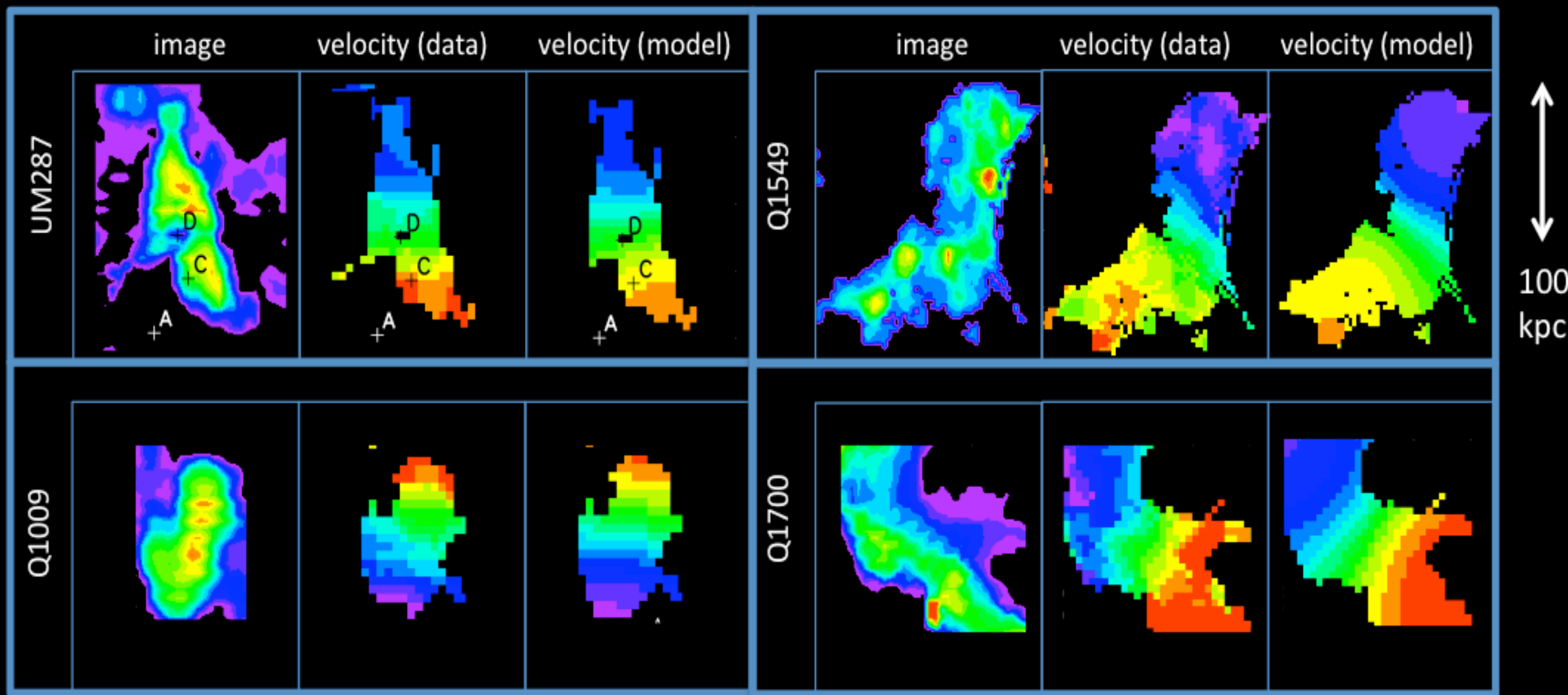


QSO 1549+19



Dekel 2016

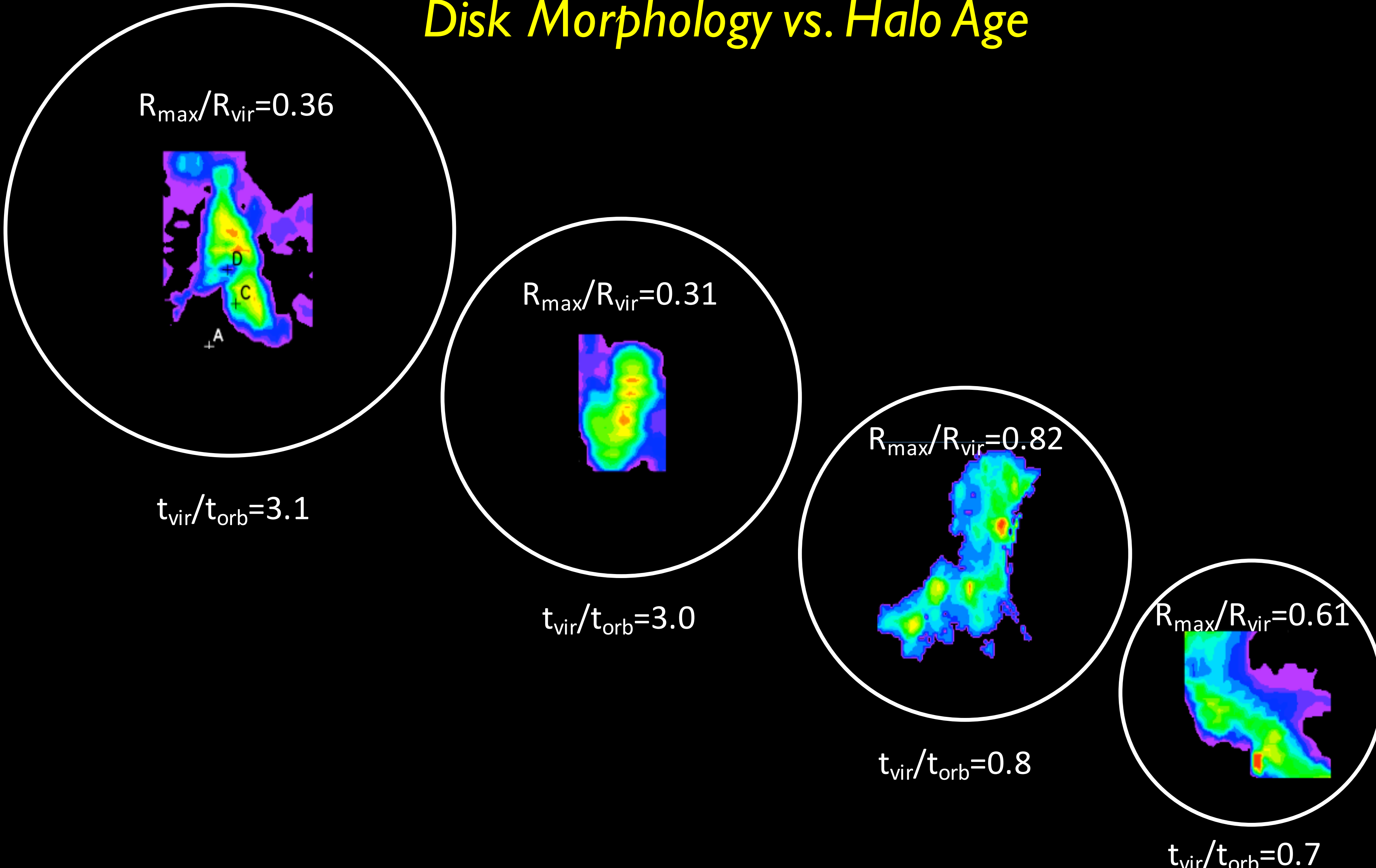
Lyα Proto-Galactic Disks (PGDs)



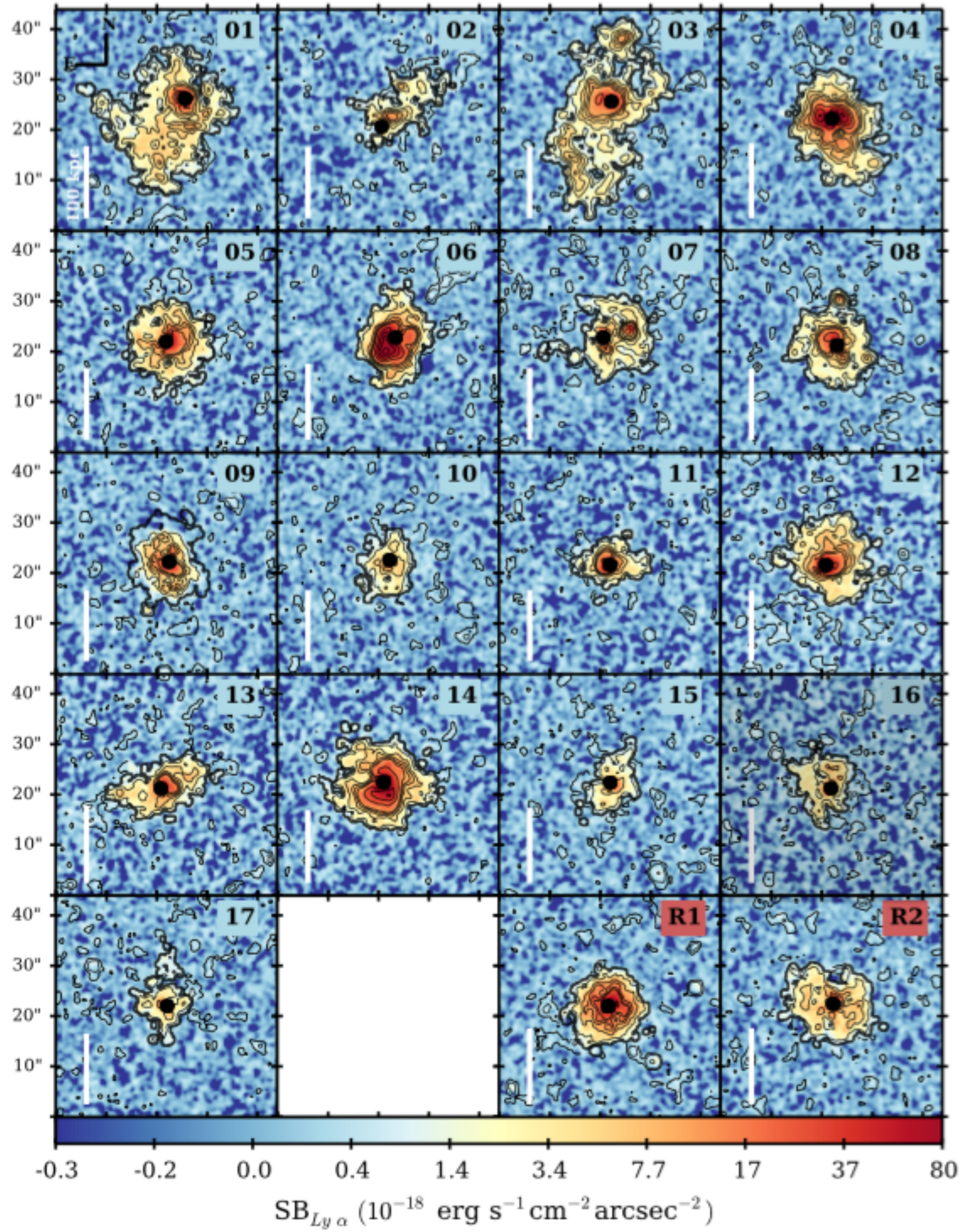
Disk	z	R_{max} [kpc]	Log M_h	c	λ_b	T_{orb} [Gyr]	T_{vir} [Gyr]	σ_v [km/s]	#Fila-ments
UM287	2.28	65	13.0	3.2	0.14	0.9	2.8	53	1+
Q1549	2.84	110	12.6	3.1	0.30	2.0	1.6	44	2+
Q1009	2.65	45	12.7	1.7	0.24	0.8	2.4	54	1
Q1700	2.74	65	12.3	1.1	0.39	2.1	1.5	52	2?

Lyα Proto-Galactic Disks (PGDs)

Disk Morphology vs. Halo Age

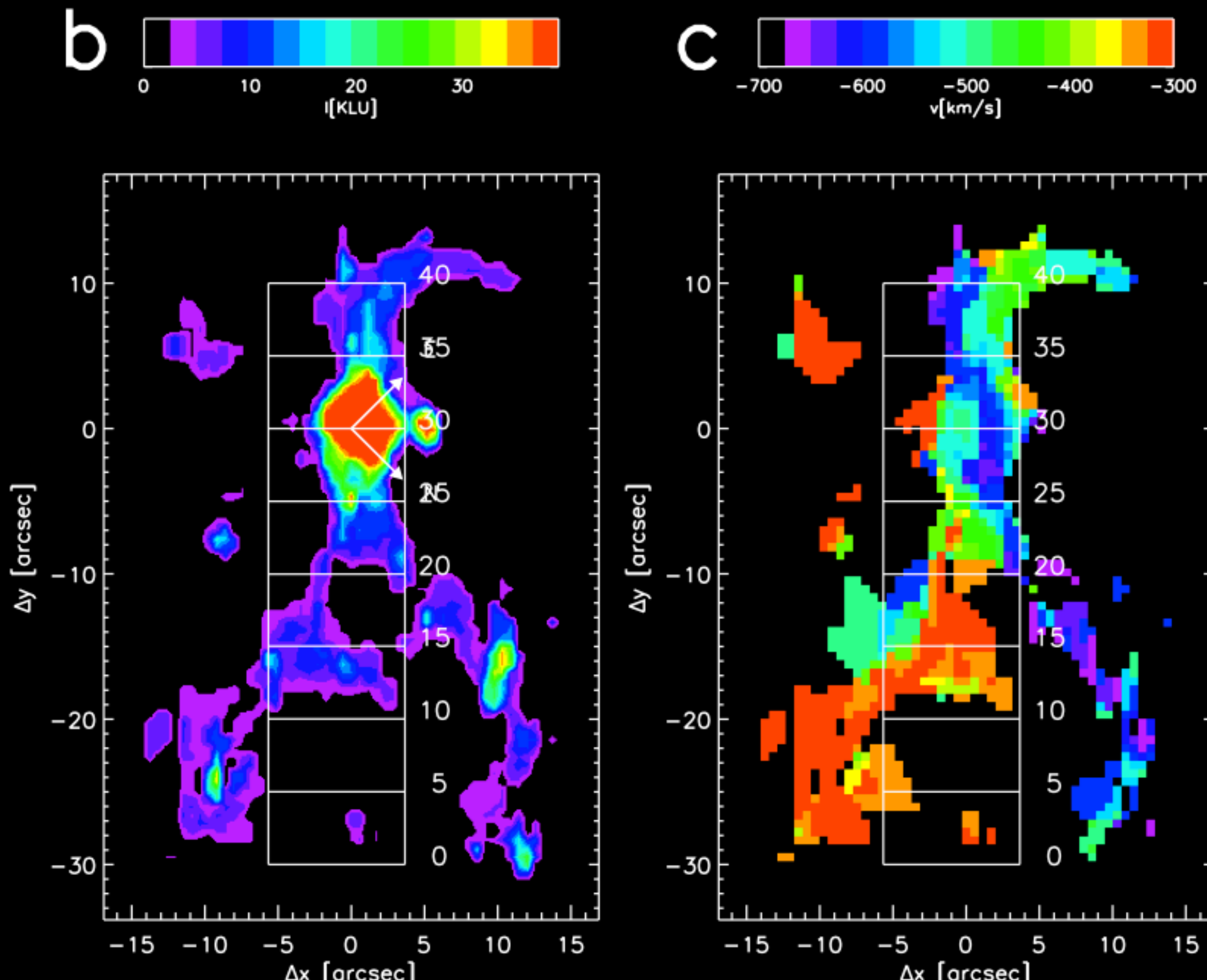


QSO Giant Lyα Nebulae



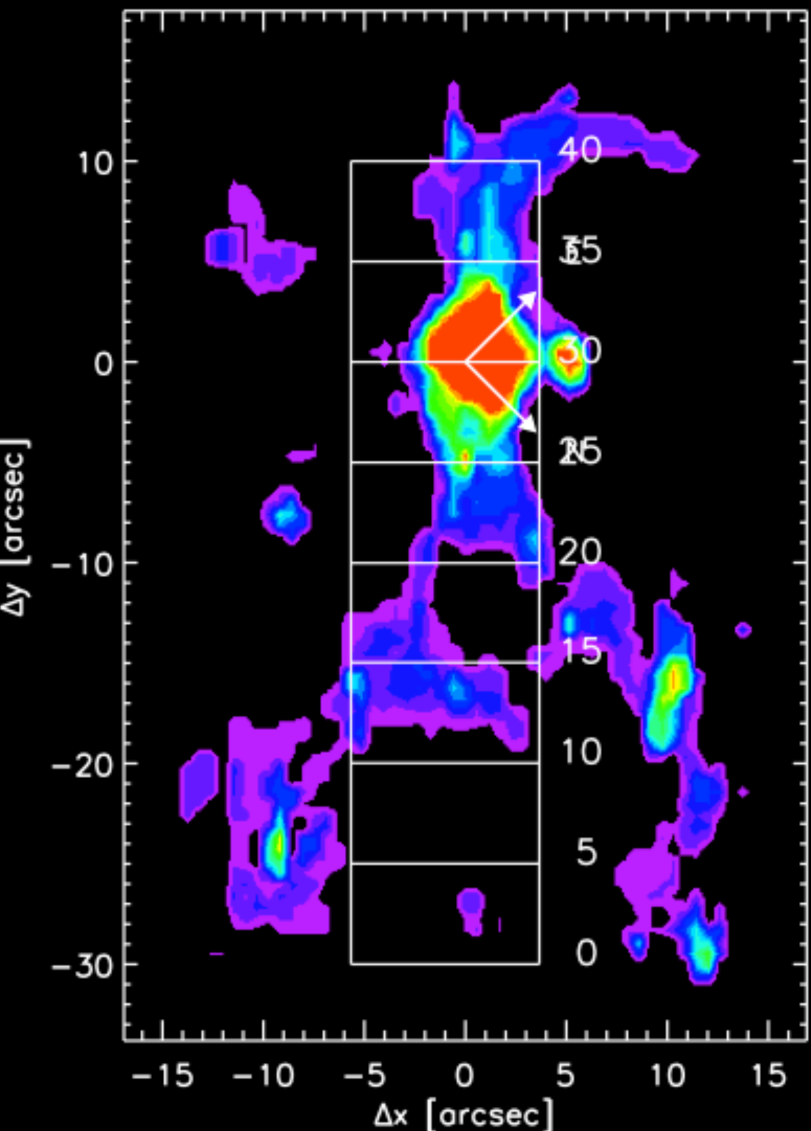
Borosova+2016

Lyα Emission Near QSO Q

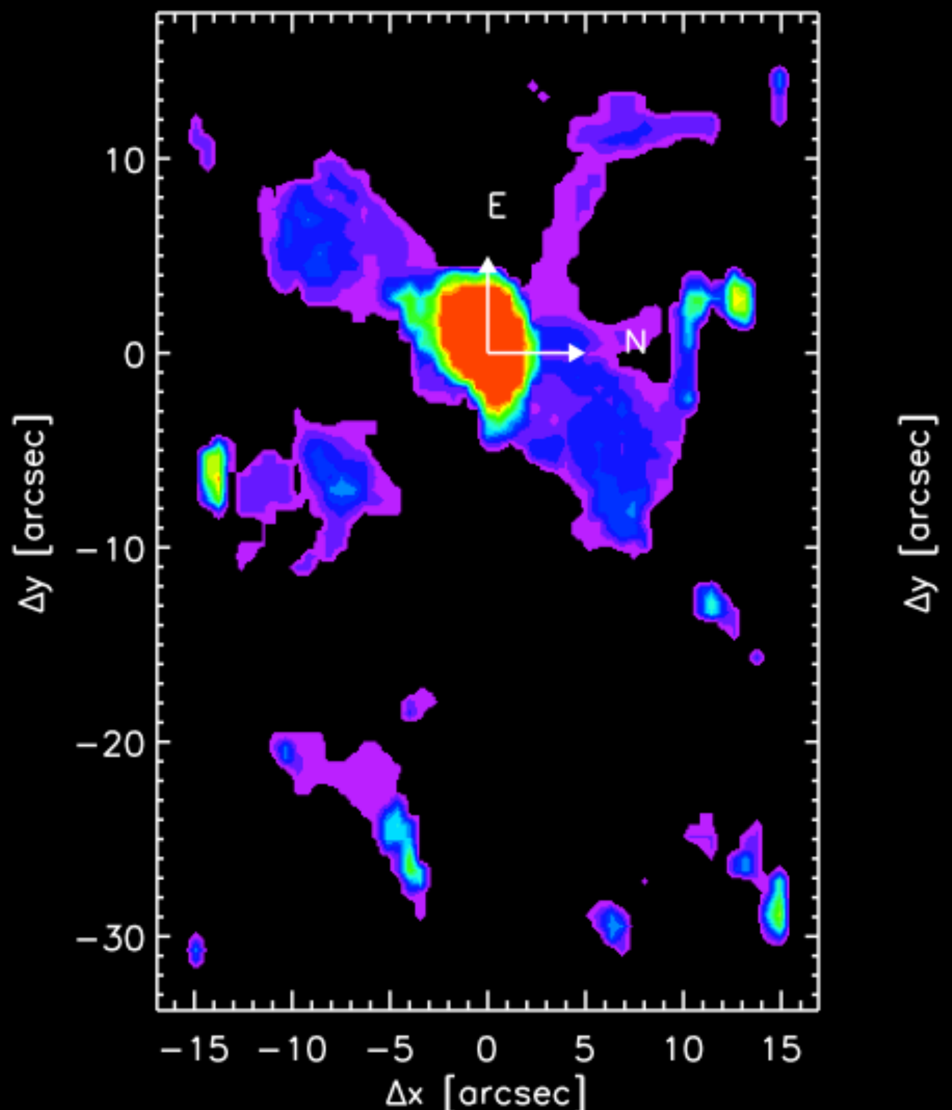


Lyα Emission Near QSO Q

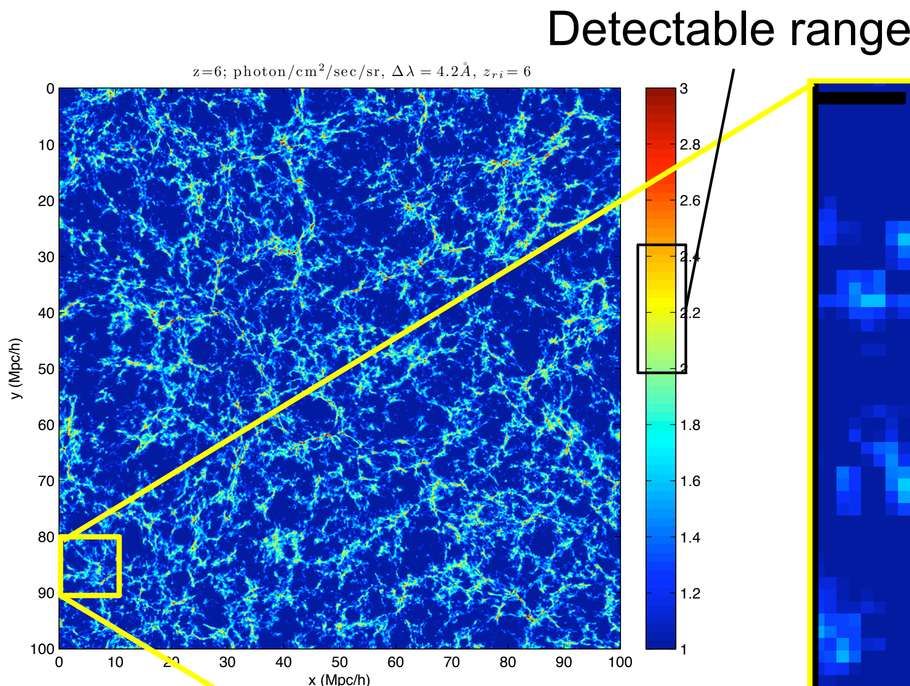
INFLOW?

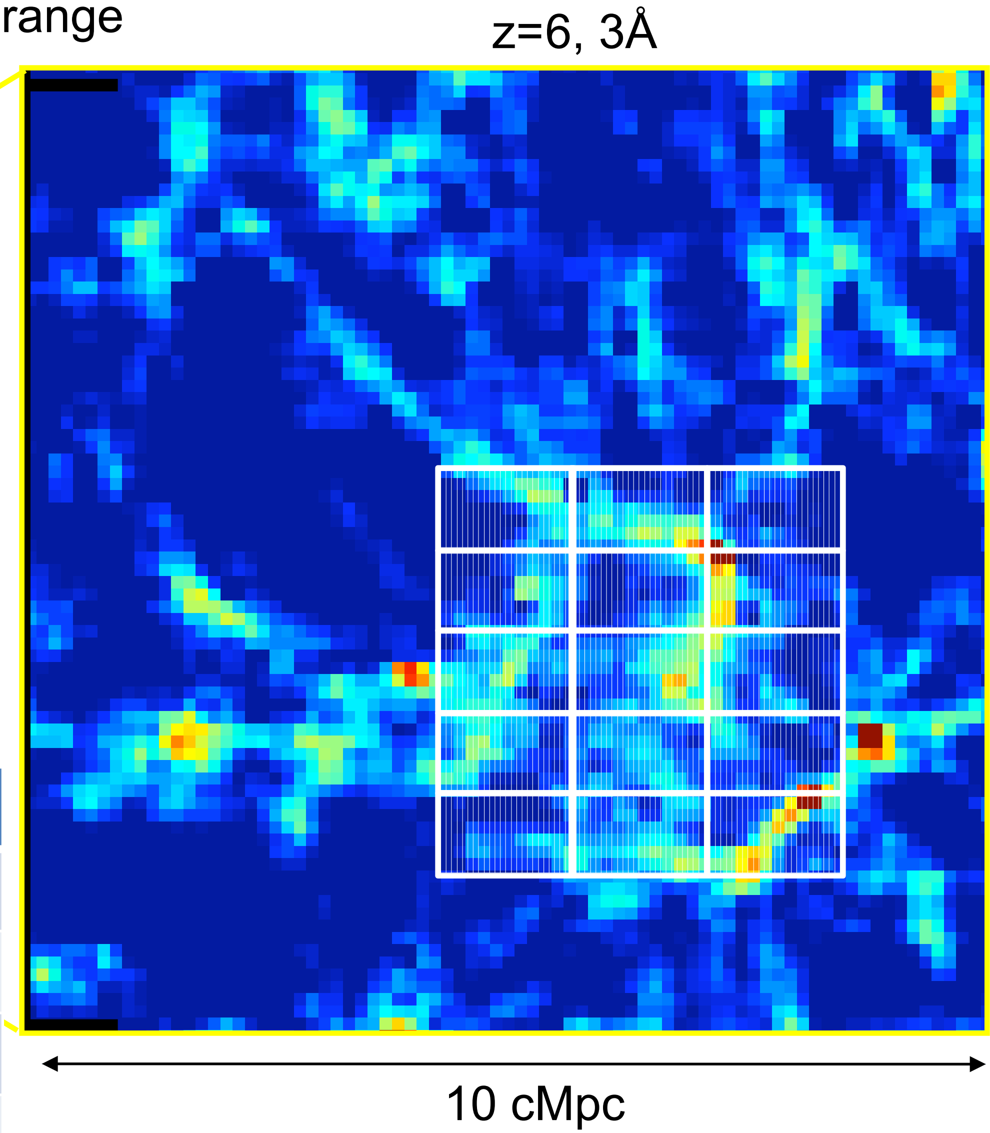


OUTFLOW?



(17) Lyα emission from IGM Cosmic Web

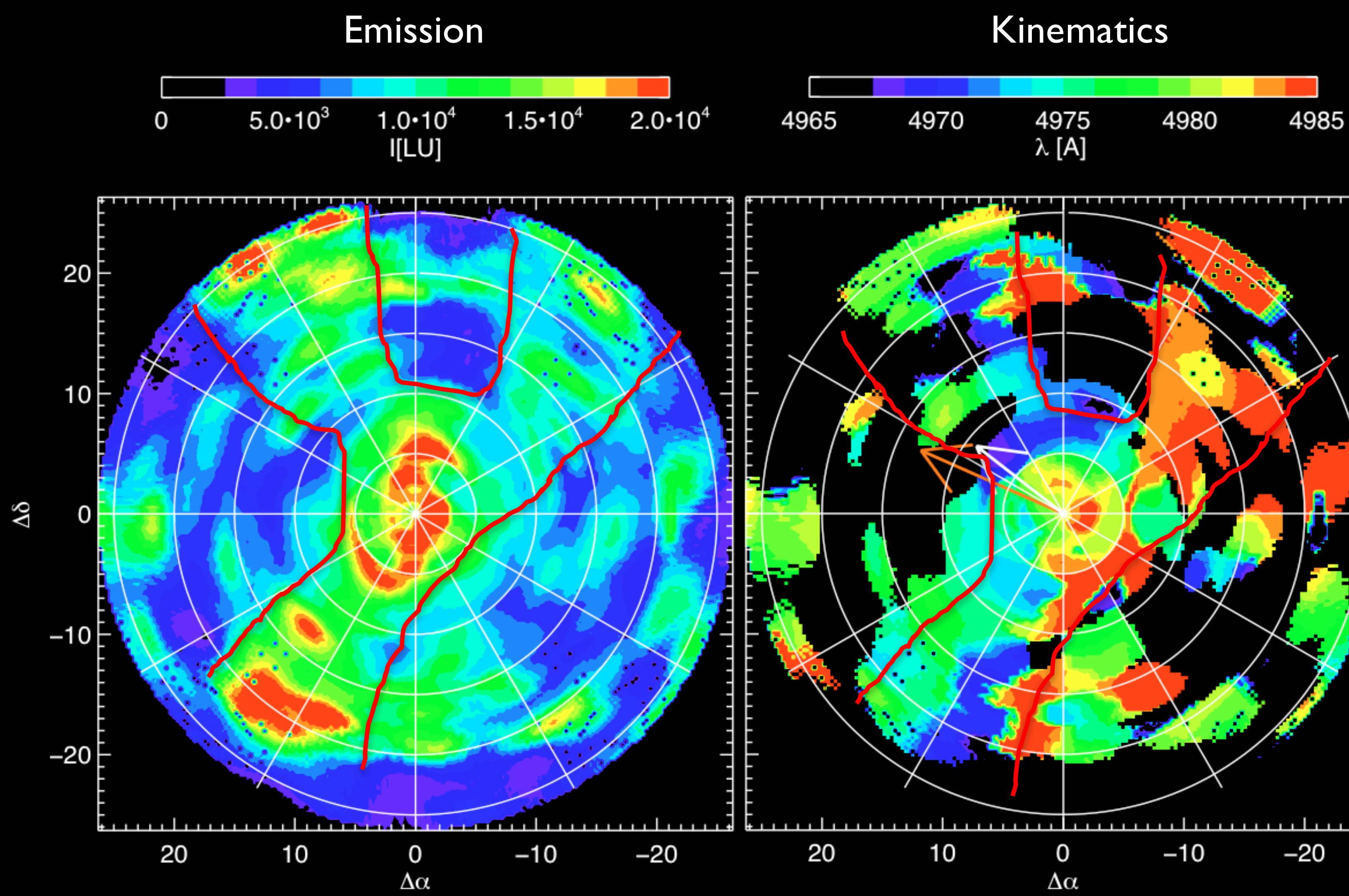




	Grating Dispersion (R)		
Slicer	Low	Medium	High
Large		2000	
Medium		4000	
Small			

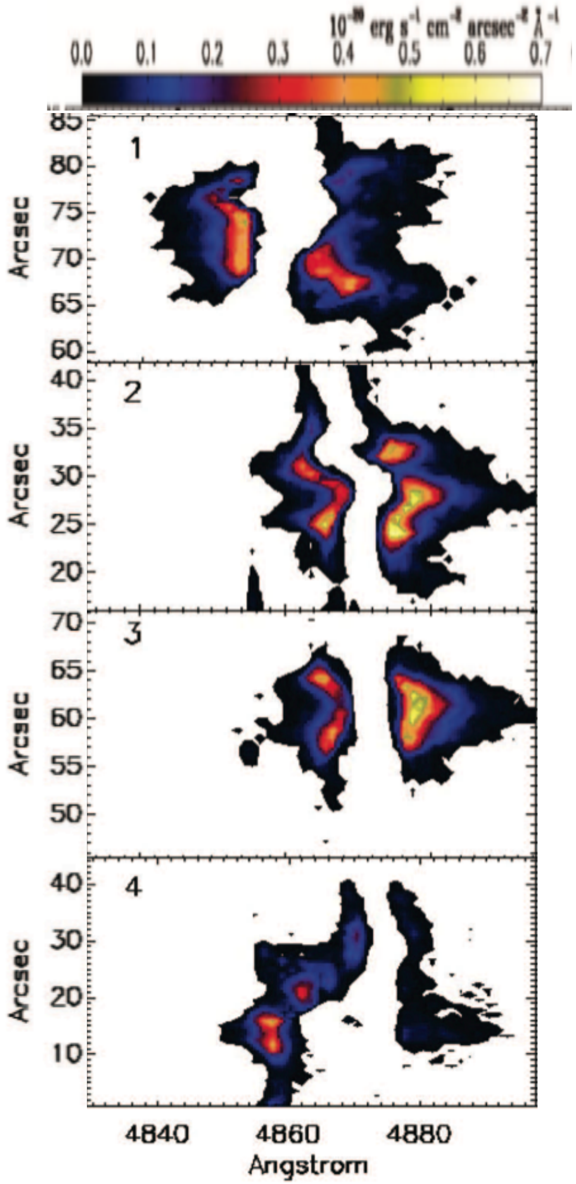
Cen 2008

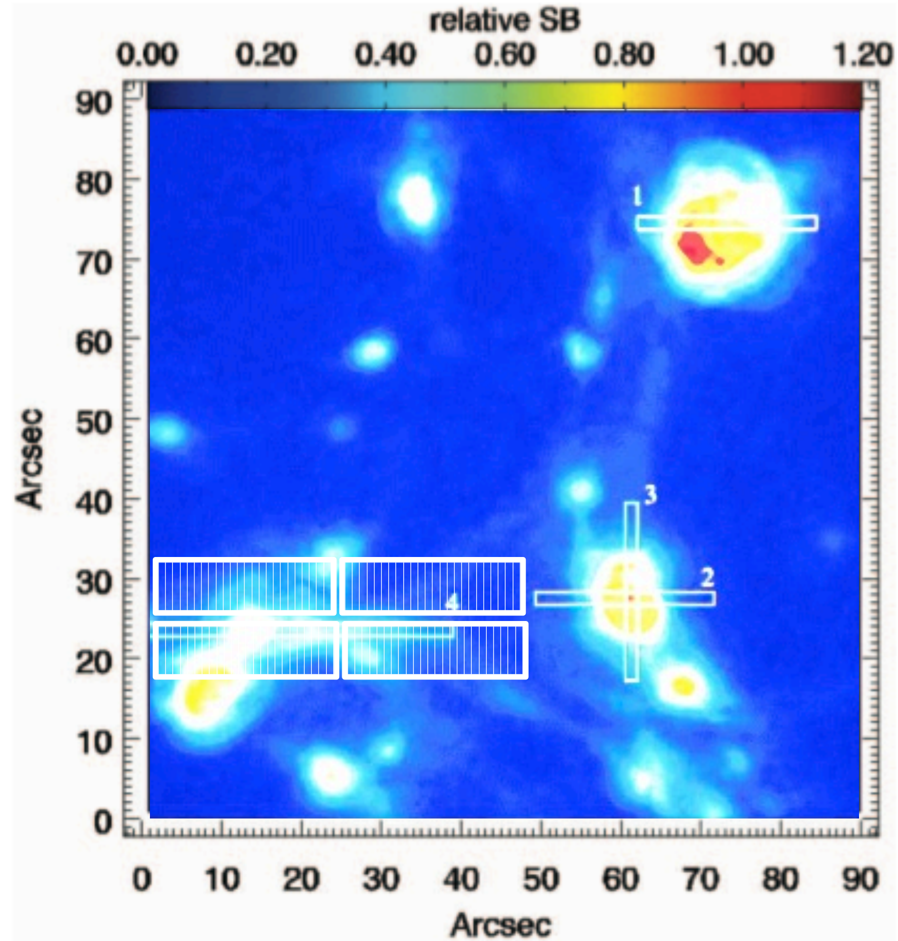
(17) IGM/CGM Emission & Kinematics
z~3 Lyman α blob



IGM/CGM Emission Models

Spectral Image Plots



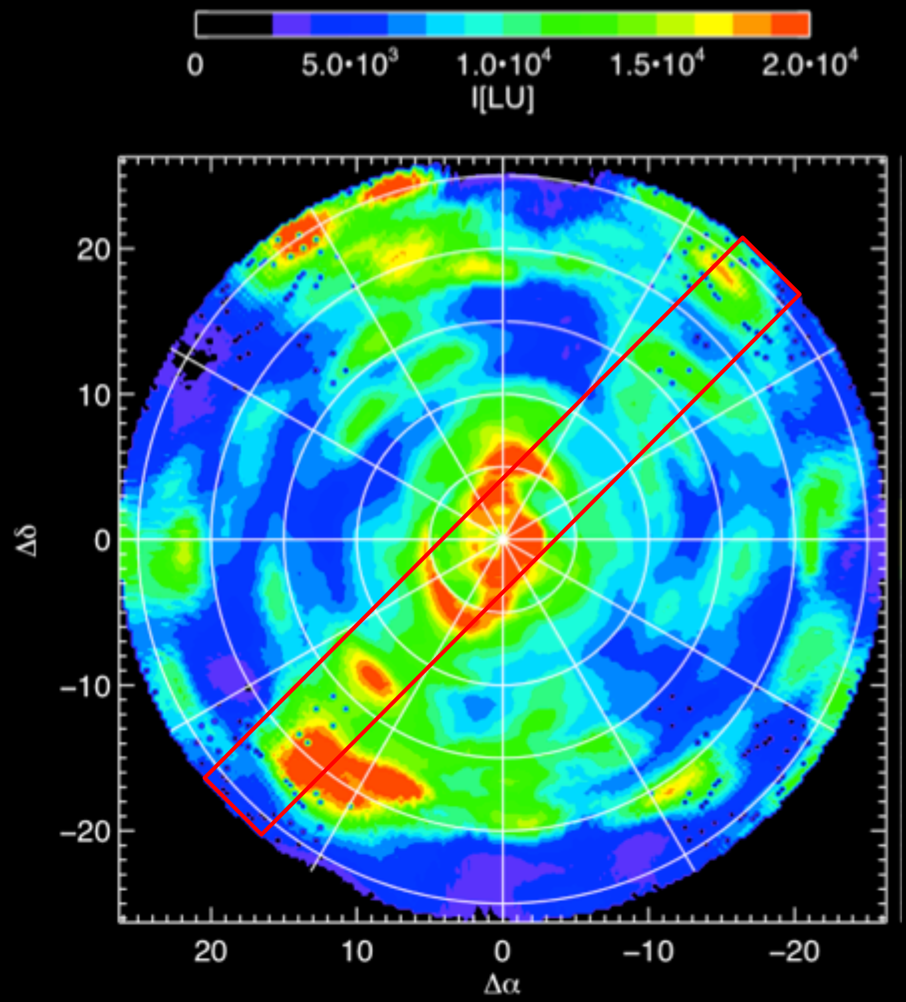


500 pKpc

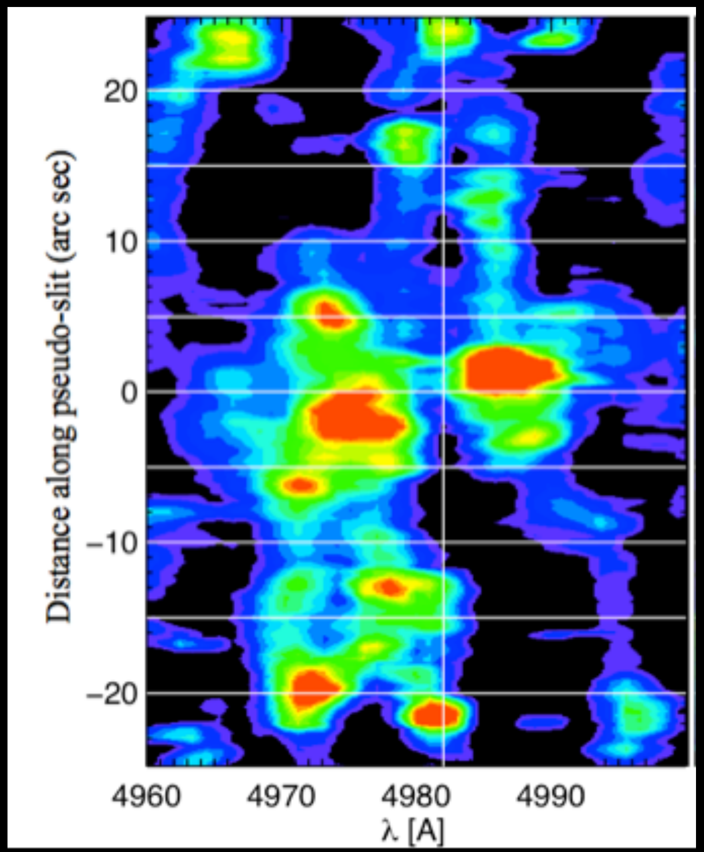
Cantalupo+06

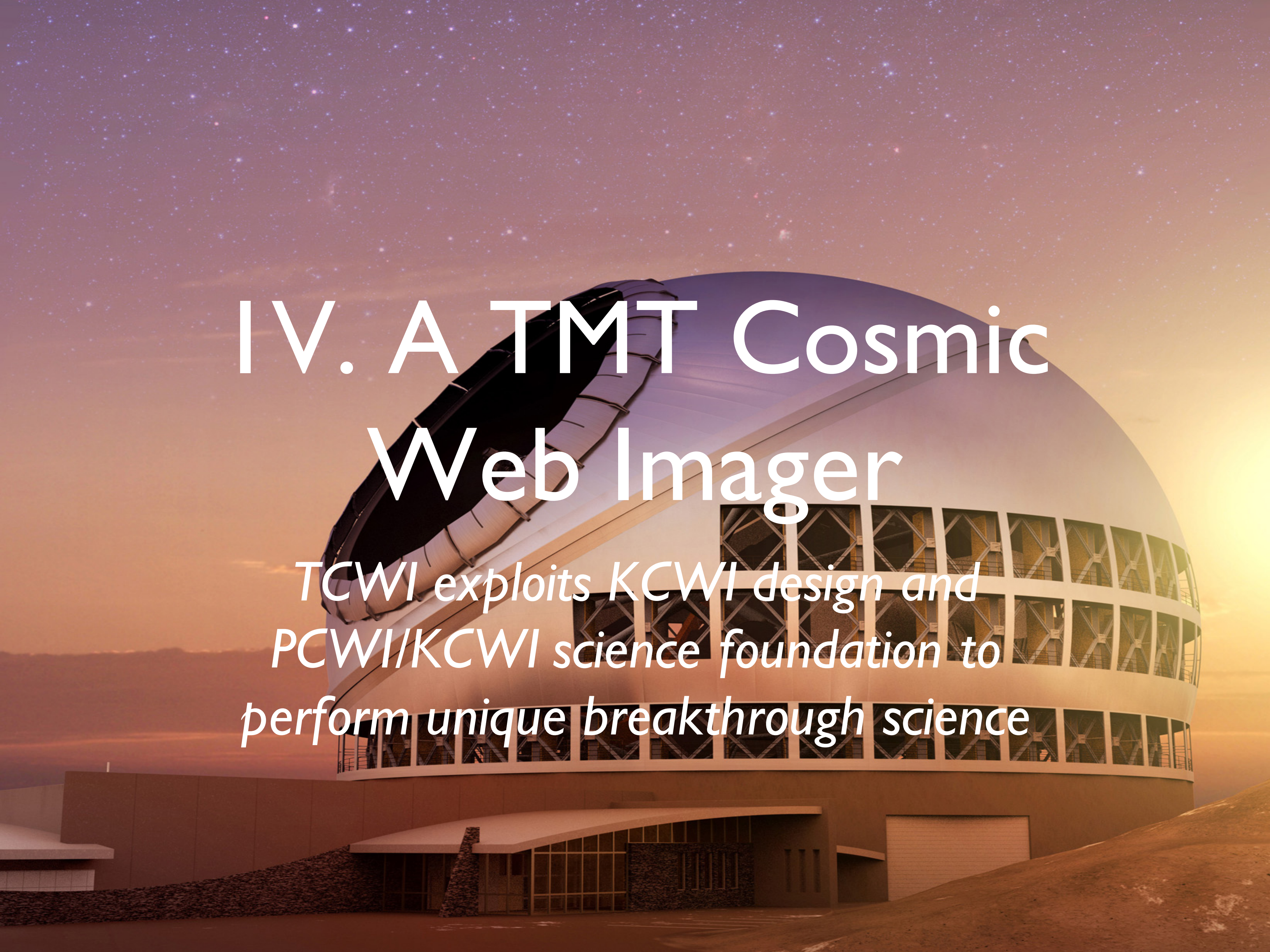
(17) CGM Emission & Kinematics
z~3 Lyman α blob

Emission

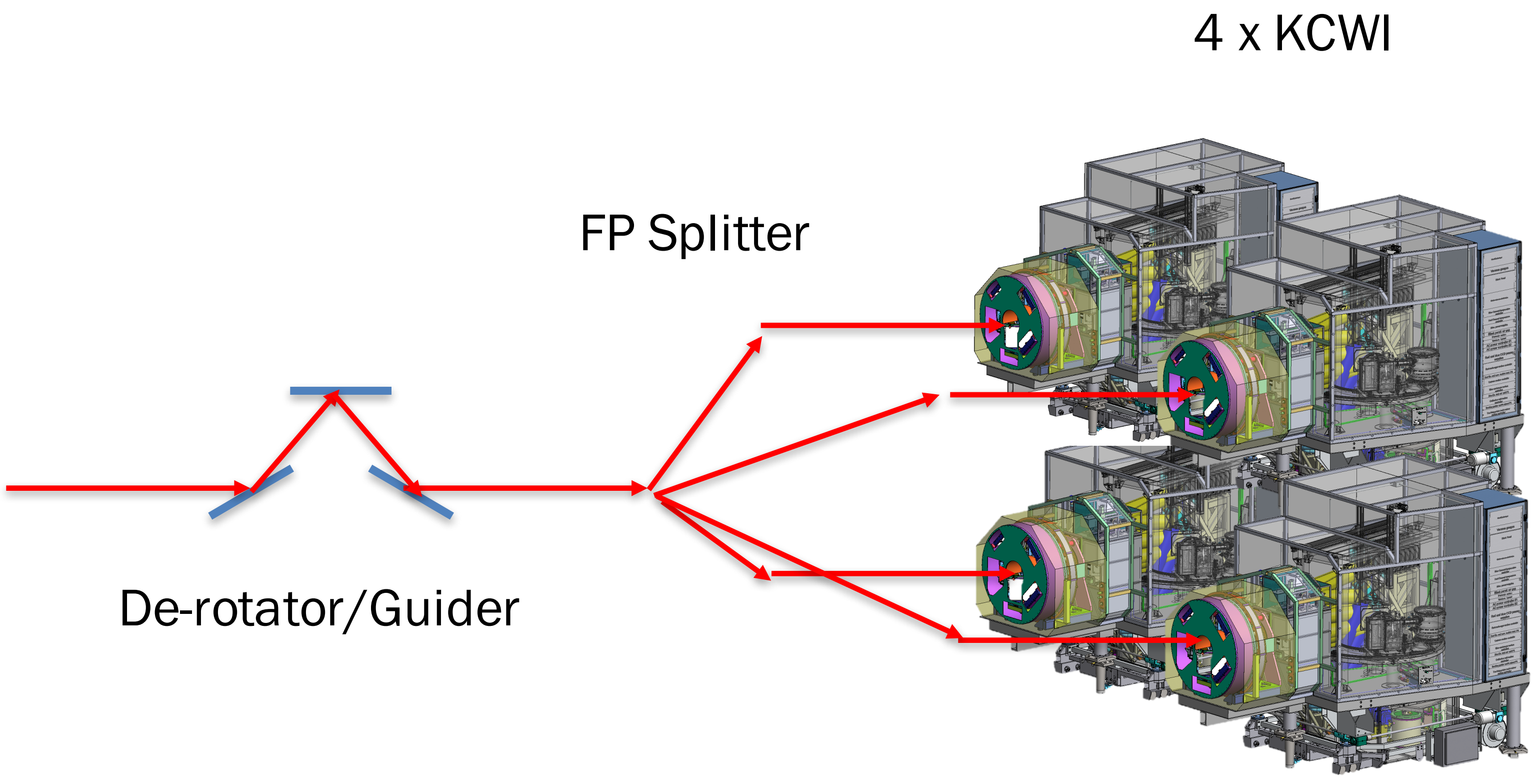


Spectral Image




IV. A TMT Cosmic Web Imager
TCWI exploits KCWI design and PCWI/KCWI science foundation to perform unique breakthrough science

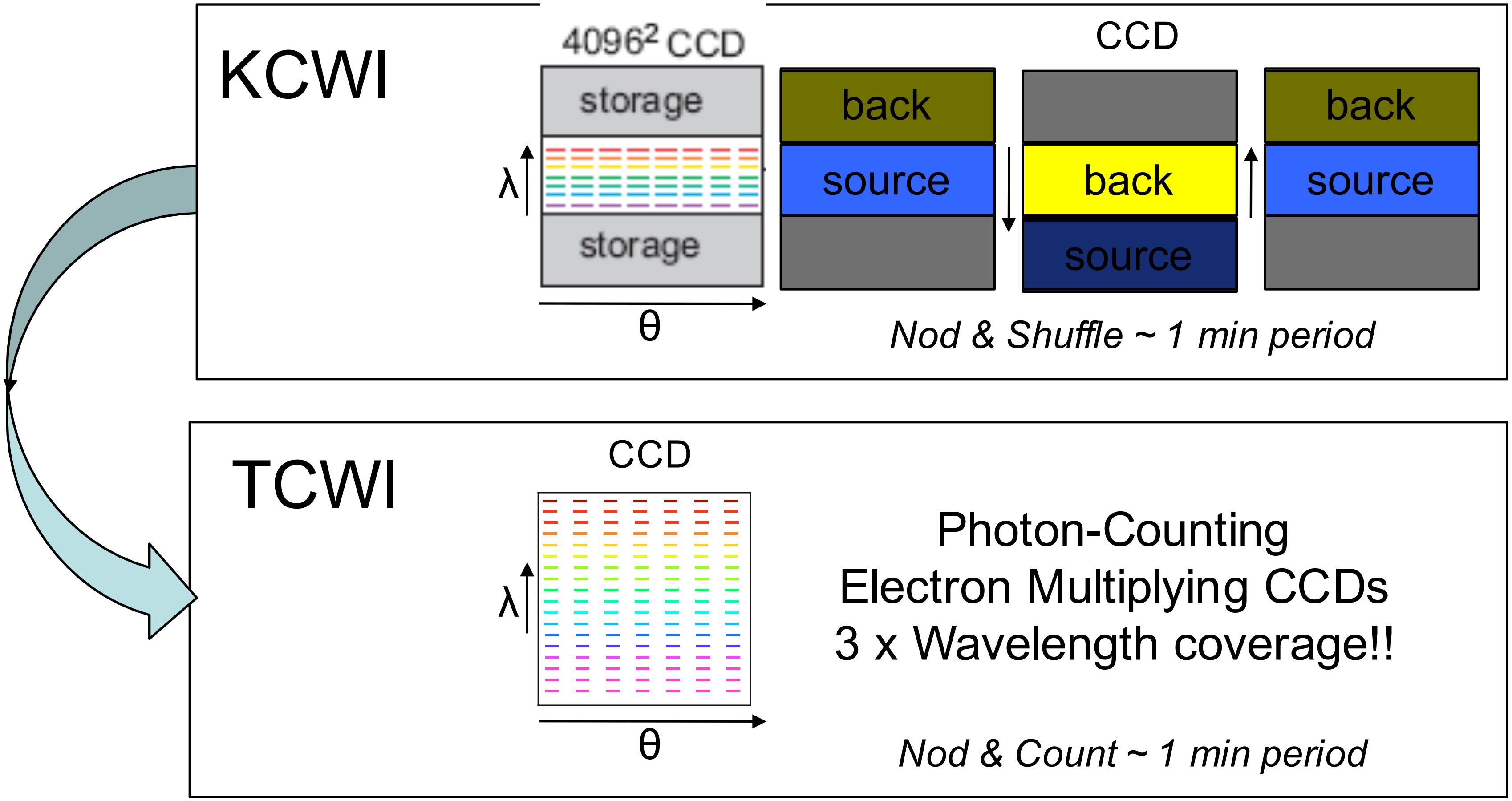
A TCWI Concept



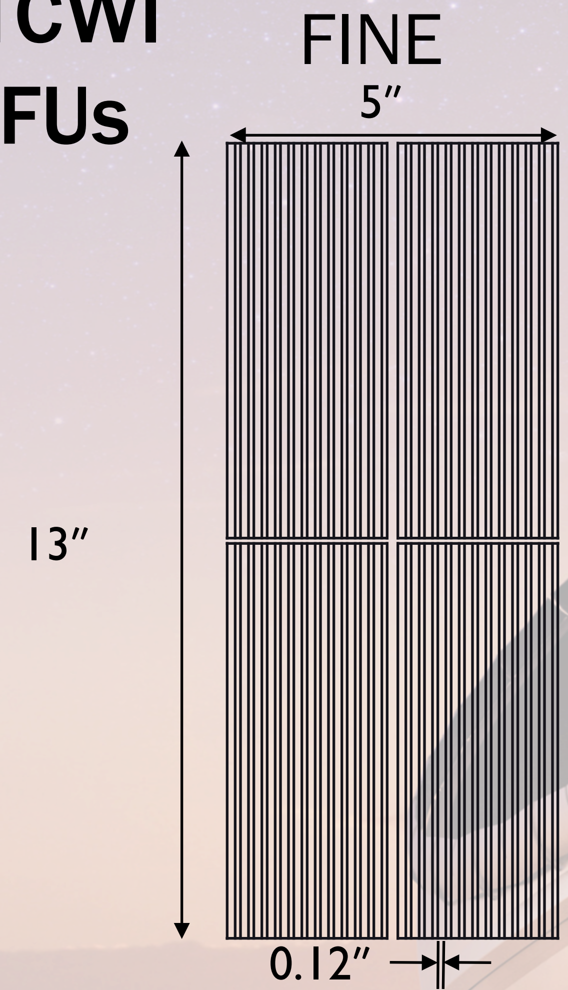
ROM COST: $10M NRE + 4 x $10M = $50M
Like IRMOS, major design heritage from KCWI-B/R

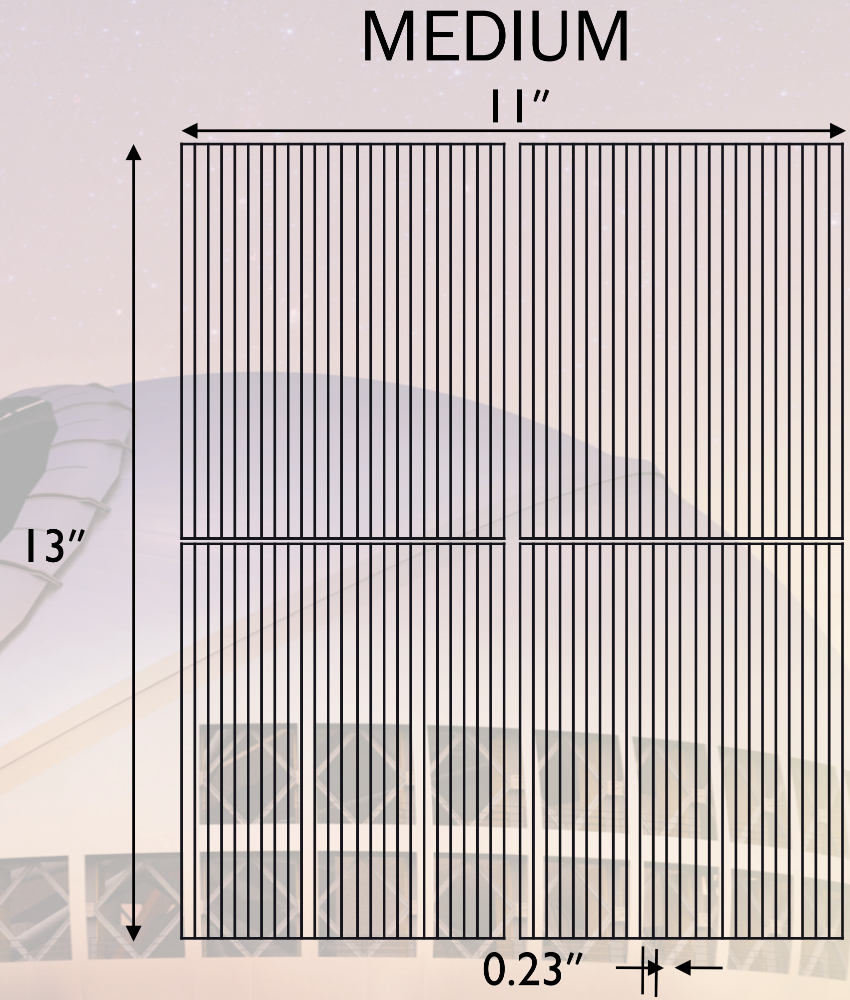
KCWI → TCWI

Nod & Shuffle → Photon-counting CCDs



TCWI IFUs

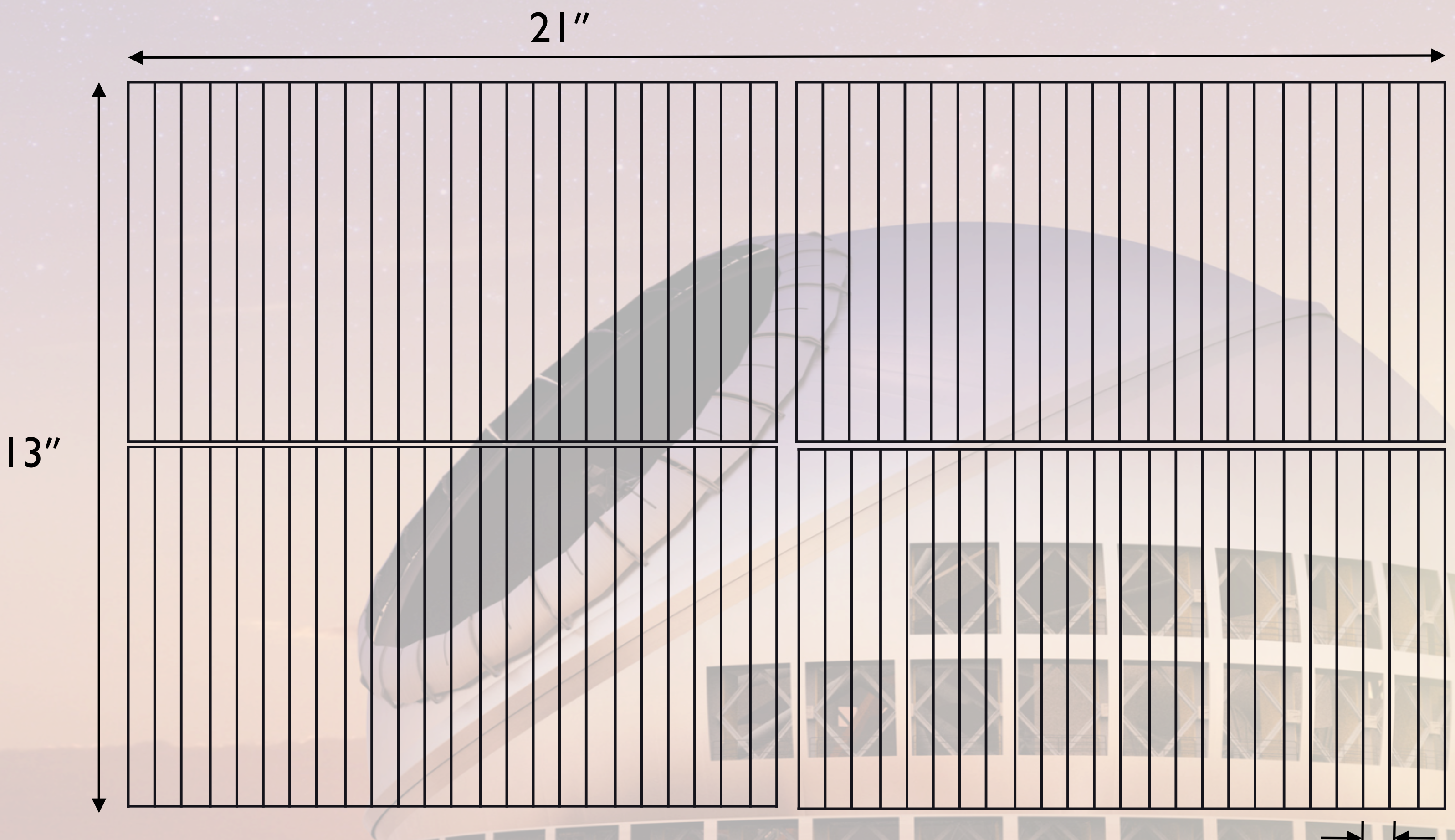




	Grating Dispersion		
	High	Medium	Low
R	20,000	8400	3600
Band Δλ	400Å	1000Å	2500Å

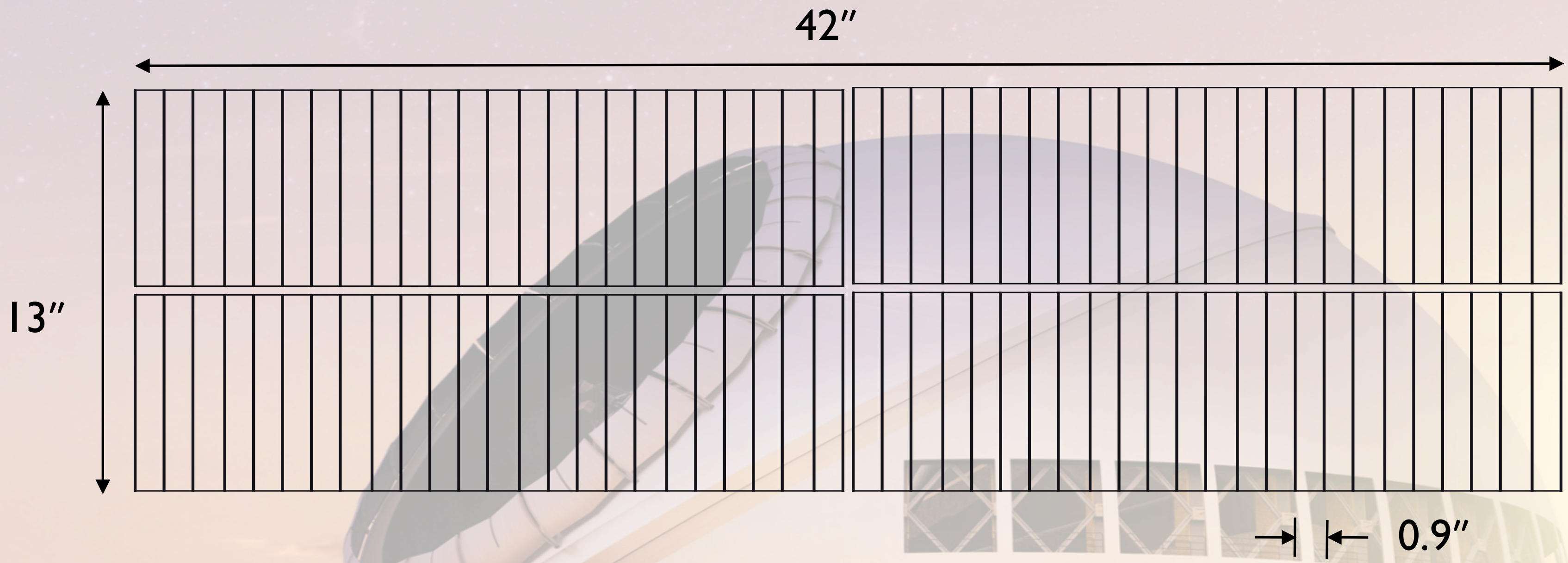
	Grating Dispersion		
	High	Medium	Low
R	10,000	4200	1800
Band Δλ	400Å	1000Å	2500Å

TCWI IFU Formats: WIDE



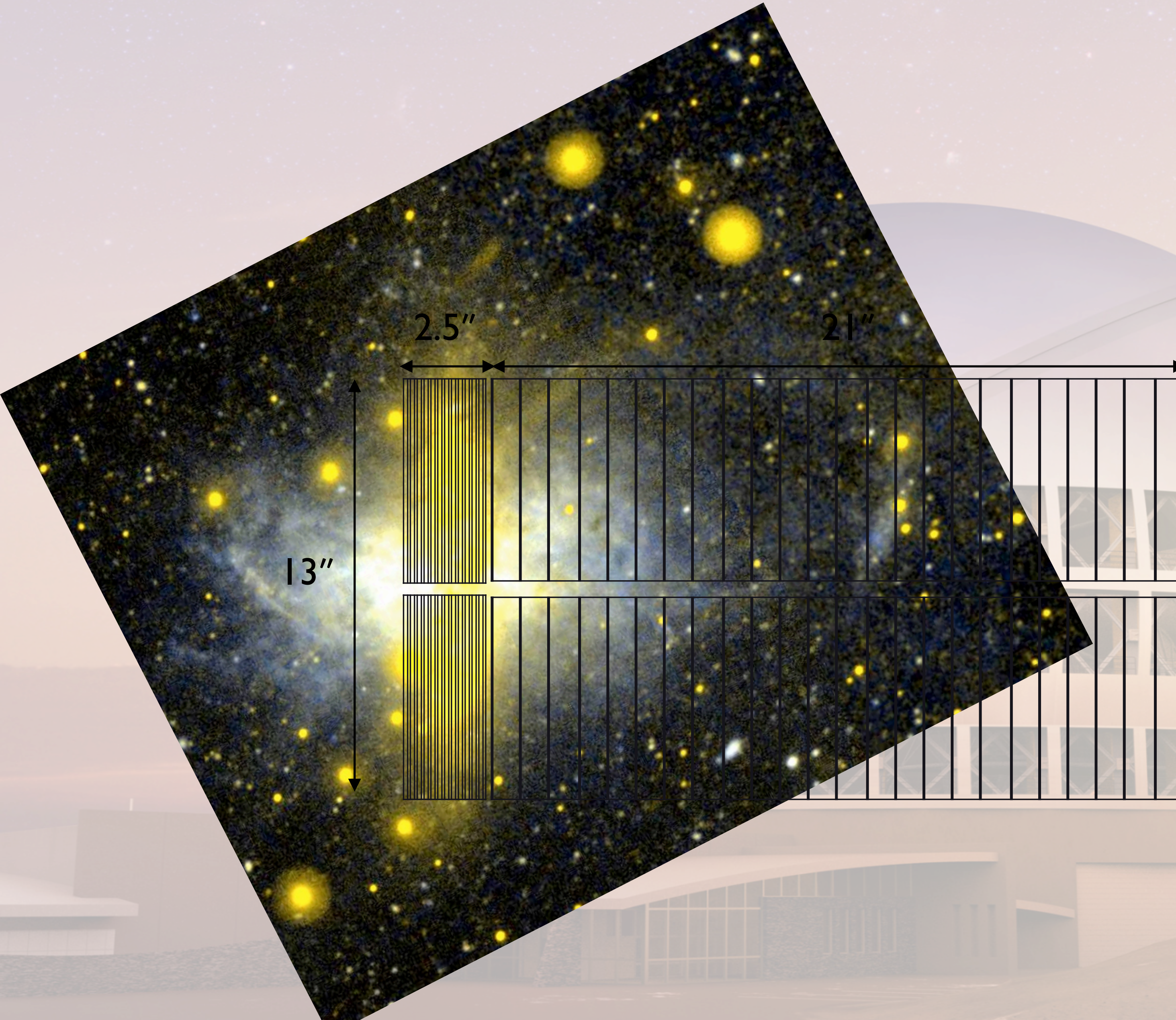
	Grating Dispersion		
	High	Medium	Low
R	5,000	2400	900
Band Δλ	300Å	1000Å	2500Å

TCWI IFU Formats: SUPER WIDE



	Grating Dispersion		
	High	Medium	Low
R	2500	1200	450
Band Δλ	300Å	1000Å	2500Å

TCWI IFU Formats: MIXED



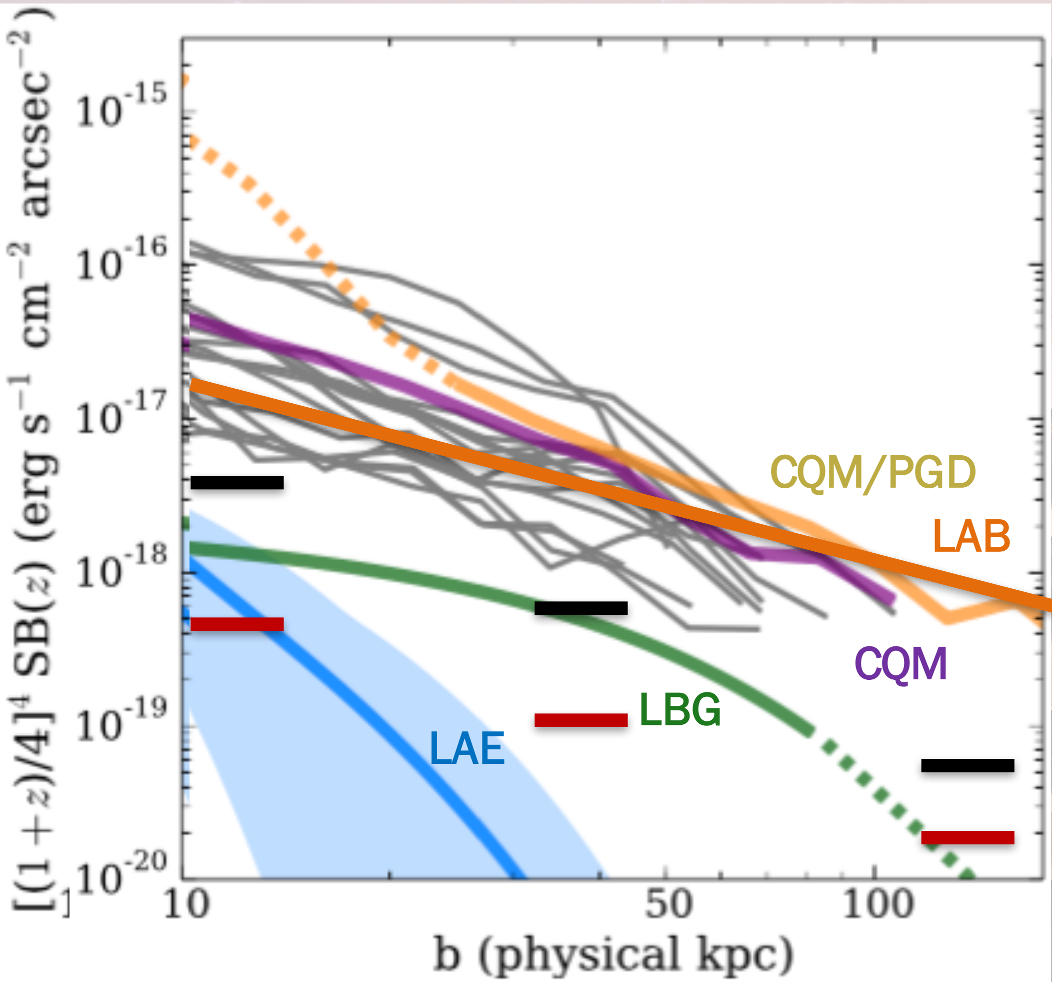
PCWI, KCWI, TCWI Comparison

	PCWI	KCWI	TCWI
# pixels	24 x 33 = 800	24 x 33 = 800	48 x 22 = 1100
R	1000-5000	900-20,000	500-20,000
IFU formats	WIDE	FINE, MED, WIDE	FINE, MED, WIDE, SUPER WIDE
Band Δλ	4000-9500Å	3500-10500Å	3000-10500 [-18000Å]
Precision Sky Subtraction	Nod & Shuffle 1/3 bandwidth	Nod & Shuffle 1/3 bandwidth	Nod and Count 3/3 bandwidth Ph counting
Photon-counting spectroscopy	NO	NO	YES
SUPER WIDE IFU	NO	NO	YES
Sky	BRIGHT	DARK	DARK

PCWI, KCWI, TCWI Comparison

	PCWI	KCWI	TCWI
GRASP = FOV * Area * Δz (arcsec^{-2} cm^2)	400	1000	40,000
MDF (point) [1 hr]	21.2	23.6	25.3
MDF (bucket) [1 hr]	1500 LU/Å	550 LU/Å	160 LU/Å
MDF (point) [8 hrs]	22.4	24.6	26.8
MDF (bucket) [8 hrs]	600 LU/Å	200 LU/Å	60 LU/Å
MDF (point) [40 hrs]	23.6	26.6	27.7
MDF (bucket) [40 hrs]	200 LU/Å	80 LU/Å	30 LU/Å
Structure	CGM/CQM Elliptical galaxy central	IGM bright ETG outer zones	IGM faint Stellar streams

CGM Sensitivity

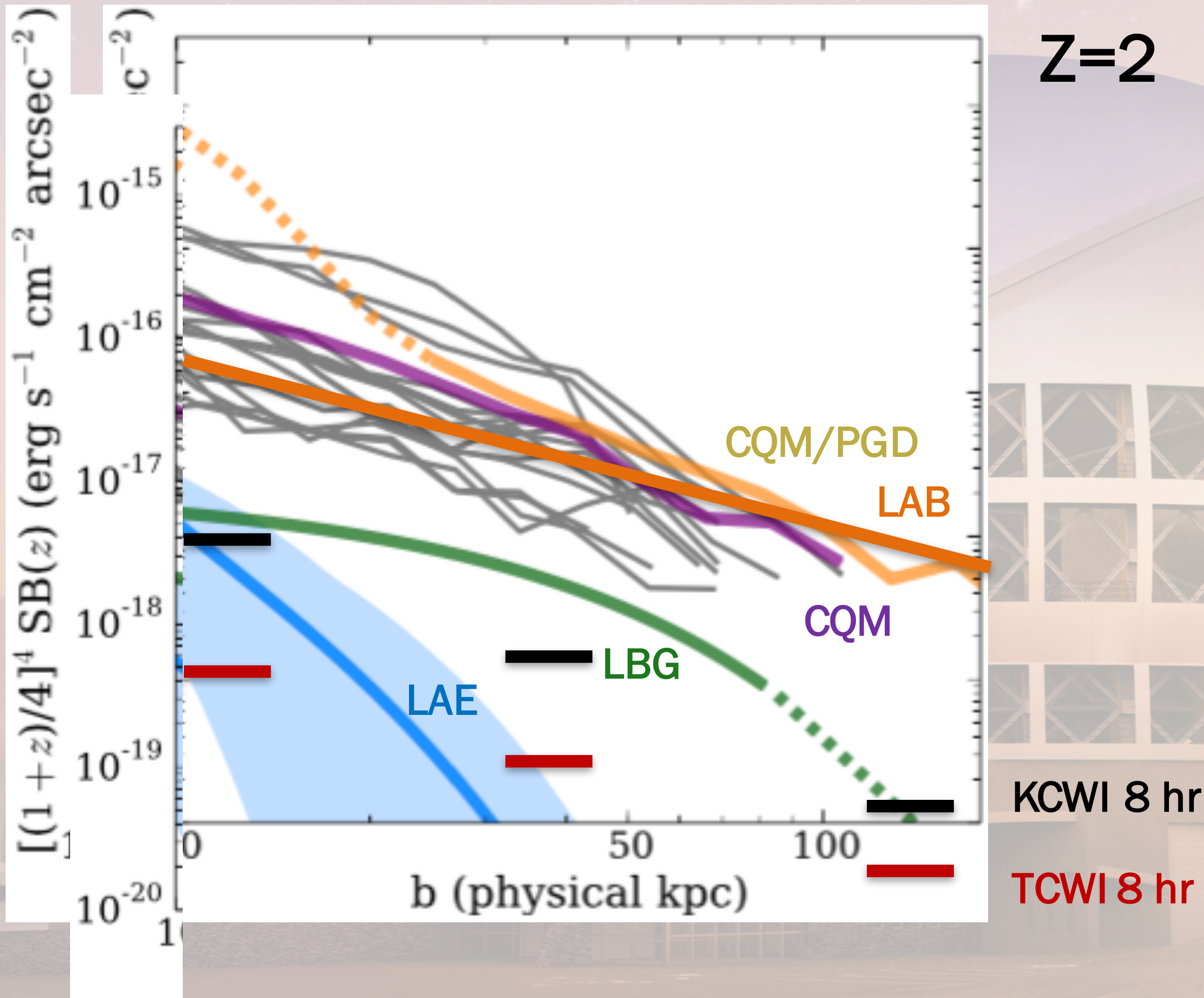


z=3

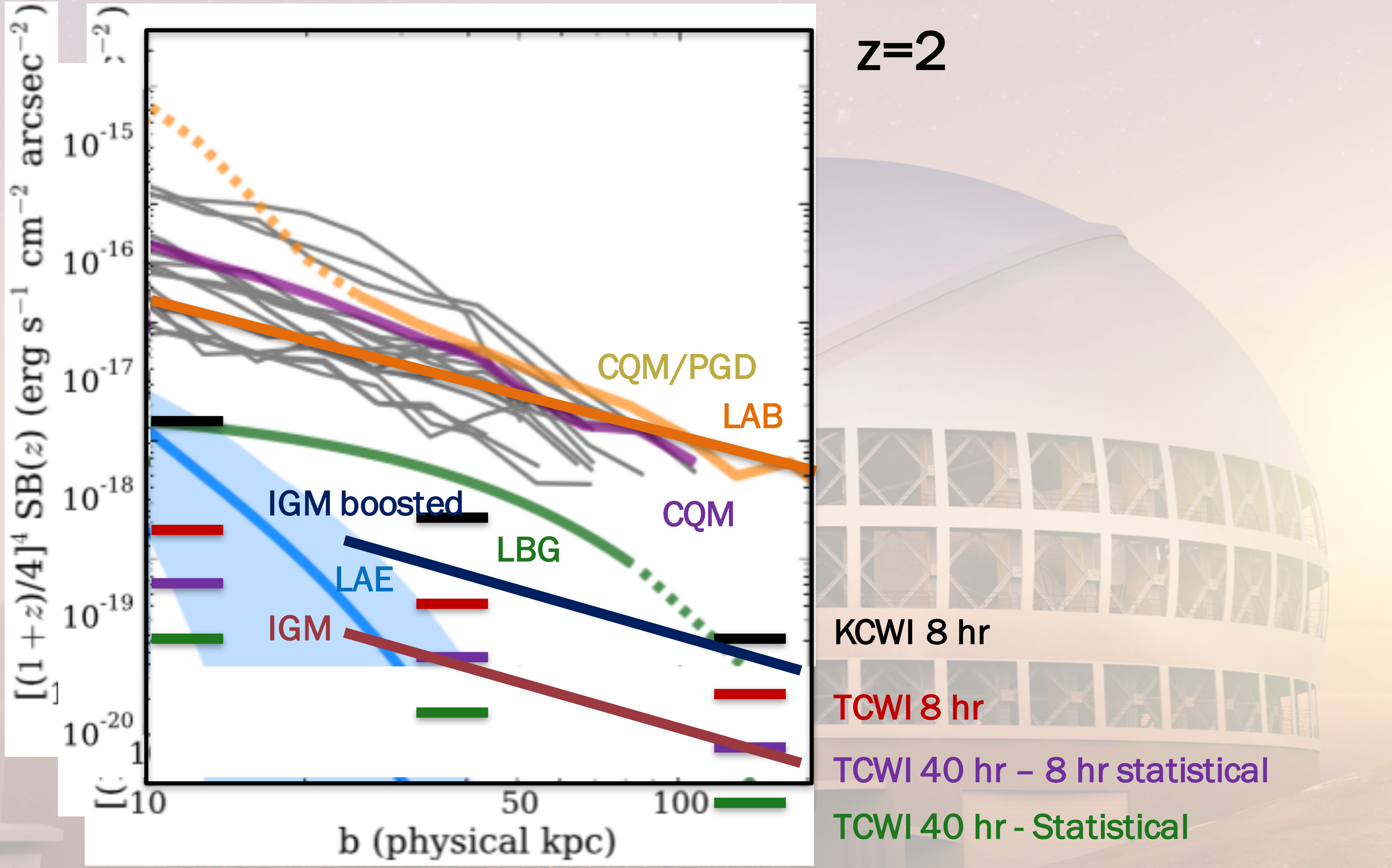
KCWI 8 hr

TCWI 8 hr

CGM Sensitivity



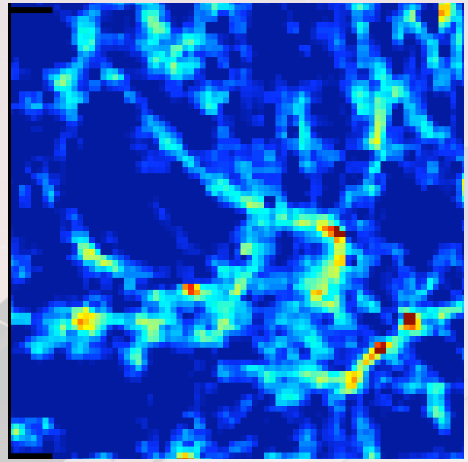
IGM Sensitivity



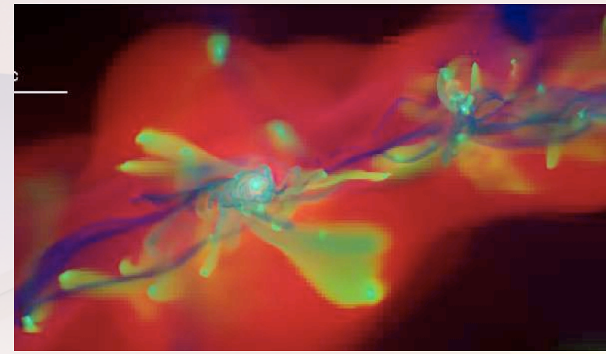
What TCWI May do that PCWI and KCWI Can't

Tidal Stellar Streams

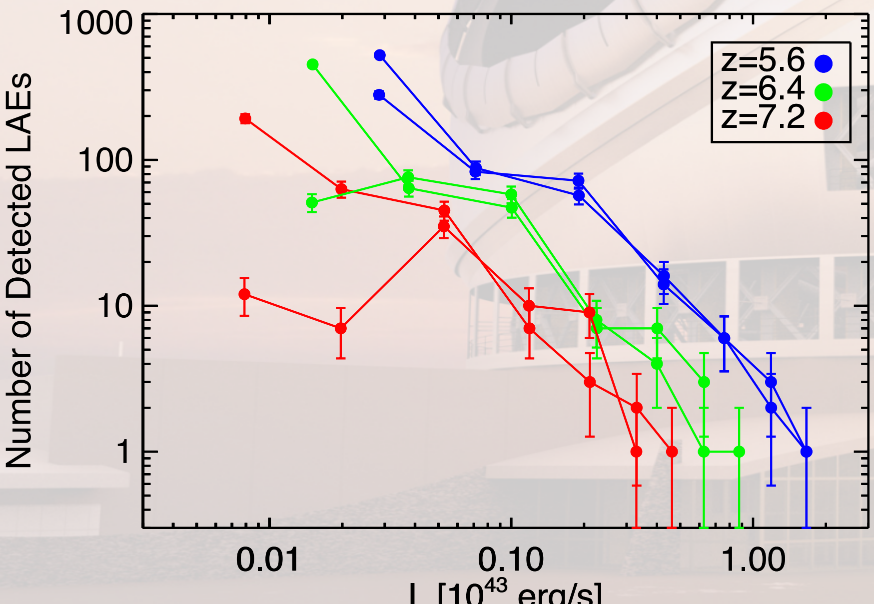
Faint Cosmic Web Emission



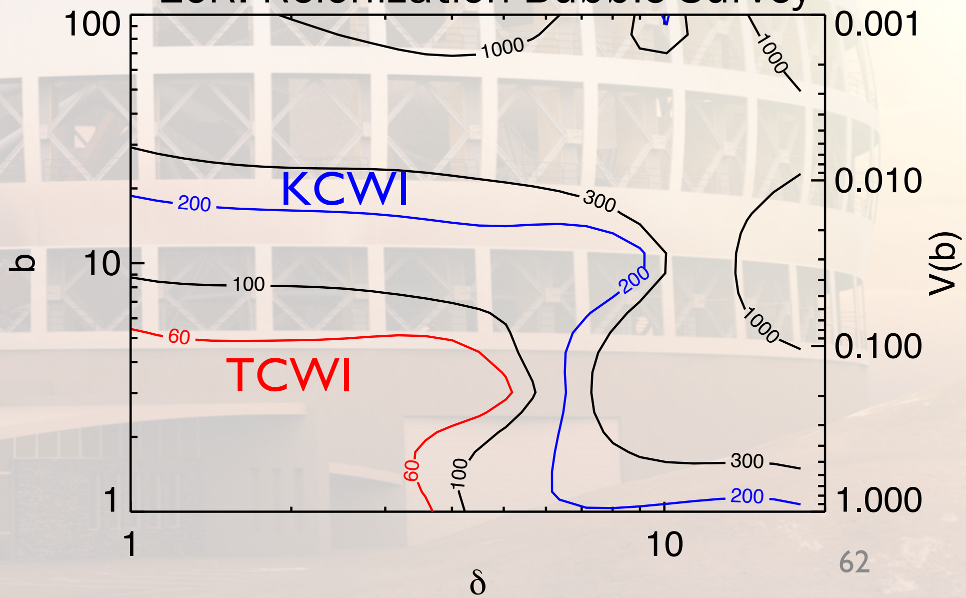
Deconstructing Sources/ Geometry/Detailed Structure



EoR: Lyα Emitter high-z Low L Lum. Func.



EoR: Reionization Bubble Survey



TCWI – Next Steps

- *Now: Expressions of interest from TMT community*
- *Late 2016/Early 2017: Organize science and technical workshop in late 2016*
  - *1st results from KCWI-B available*
  - *Identify possible international instrument partners and science team members*
  - *Develop preliminary concept for proposal to TMT 2nd Generation Concept Study call*
- *Submit concept study proposal*
- *A possible TCWI would build on KCWI design/development and PCWI/KCWI science foundation to perform unique breakthrough science*

本日は、ご清聴ありがとうございました

KCWI Uniqueness

wrt Competing Integral Field Spectrographs

Unique Feature	Science applications	Design Impacts
Flexibility/versatility	ALL	3 slicers Selectable gratings 2 channels.
High spectral resolution	Elliptical galaxies, CGM/IGM	Narrow slit limited imaging performance
High efficiency	Halos, streams, light echoes, CGM, IGM, reionization	High Performance Coatings Operations S/W DRP Simple enclosure
Blue coverage	Halos, z=2-3 CGM and IGM Nearby galaxies.	2 channels, optimized blue CCD, optics
Red coverage	Reionization, z>6-7 universe z<0.5 universe	2 channels, FDCCD, red optimized optics
Precision Sky Subtraction (Nod & Shuffle)	CGM/IGM Galaxy outer limits Stellar streams	Deployable nod & shuffle mask. 4k x 4k CCDs. Control S/W, guider.

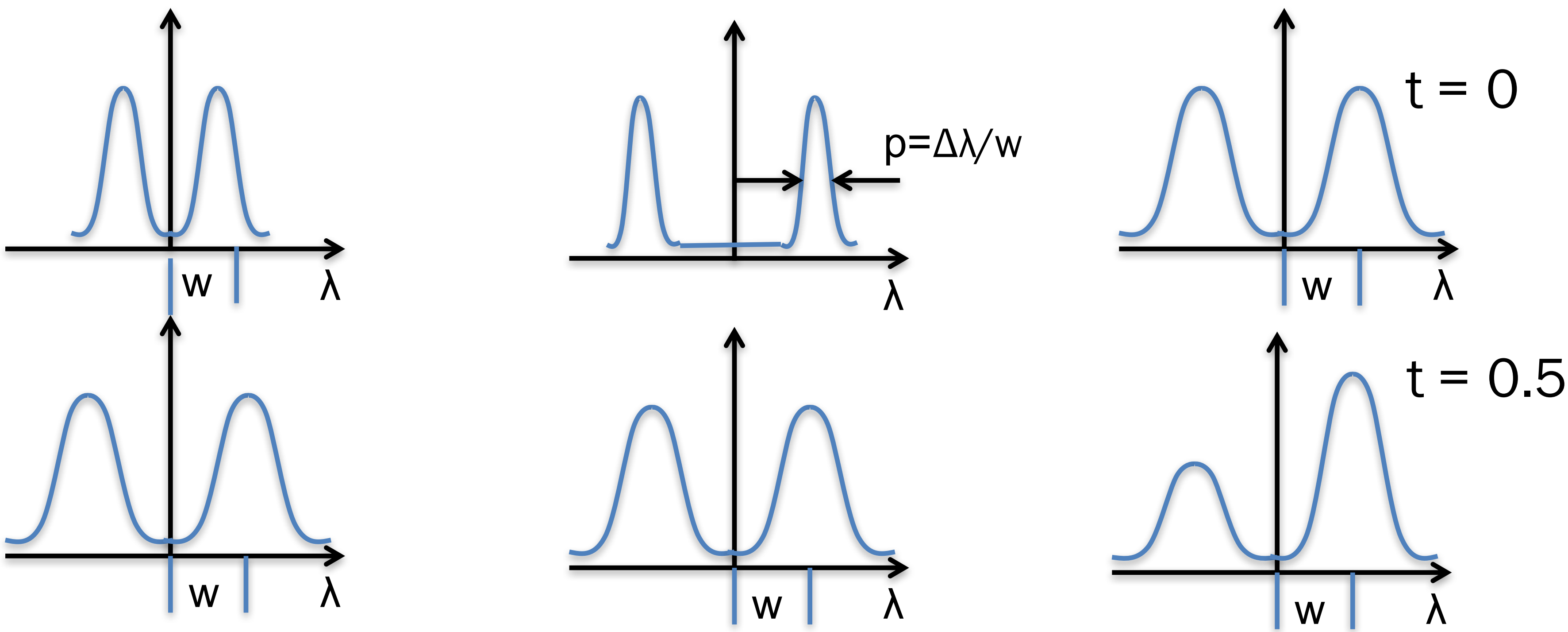
IGM/CGM Lyman α Emission Profile

Physical Diagnostics → N_{HI}, σ, Δv

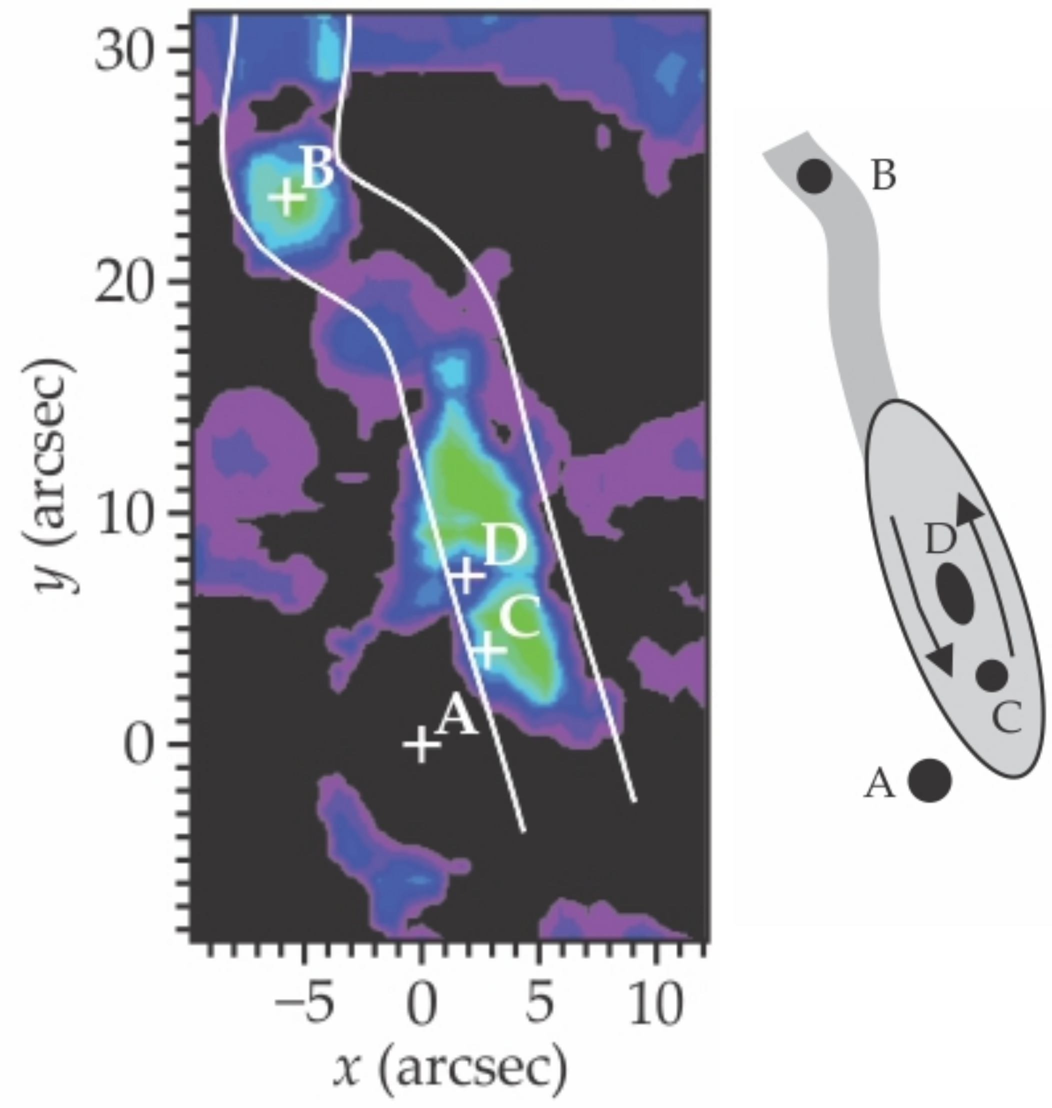
$w = f(N_{HI}, \sigma, \Delta v)$

$p = g(N_{HI}) = \Delta\lambda / w$

$t = h(\Delta v) = \frac{I_+ - I_-}{I_+ + I_-}$

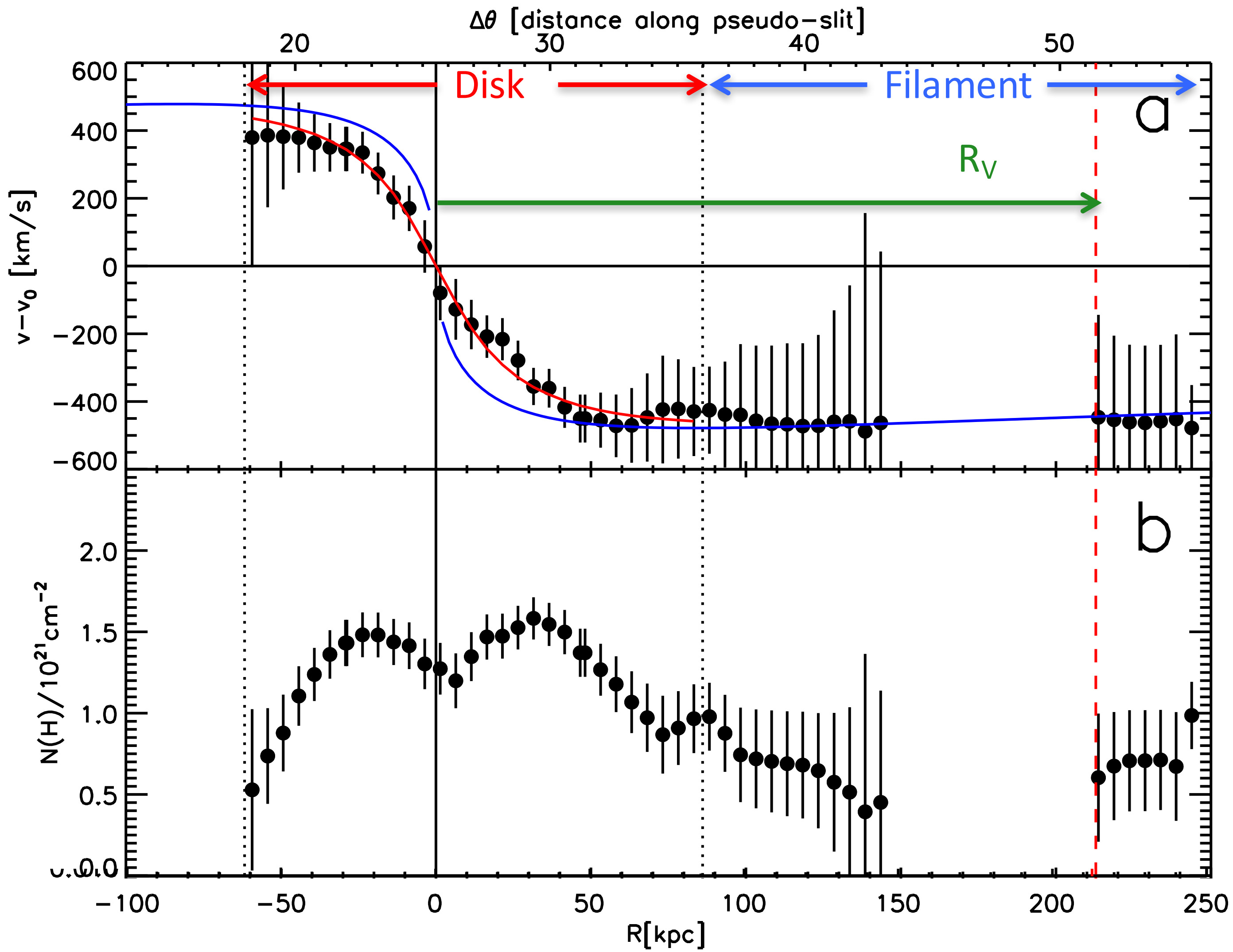


Protogalactic Disk (PGD): Model



Martin+2015, Nature, 524, 192

Protogalactic Disk: Rotation Curve



Martin+2015, Nature, 524, 192

Prospects for Imaging the IGM/CGM with TMT

- *IGM and CGM Emission → New probe of cosmic structure and galaxy formation*
- *PCWI detecting emission and obtaining completely new kind of data and physical insight*
- *KCWI will be a powerful, flexible instrument with superb sky-subtraction precision and low surface brightness sensitivity*
- *A possible TCWI would build on KCWI design/development and PCWI/KCWI science foundation to perform unique breakthrough science*