Mira

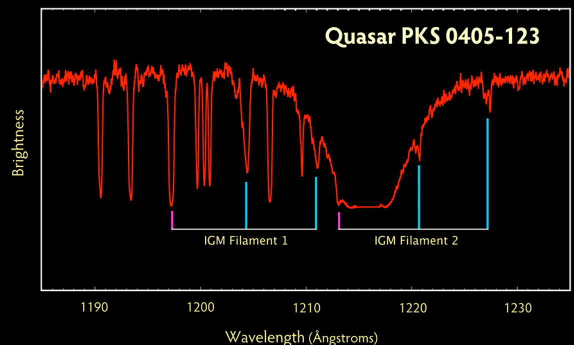
Mira

Applications for UV Photon Counting Detectors

Mapping the Hidden Cosmic Web of Baryons

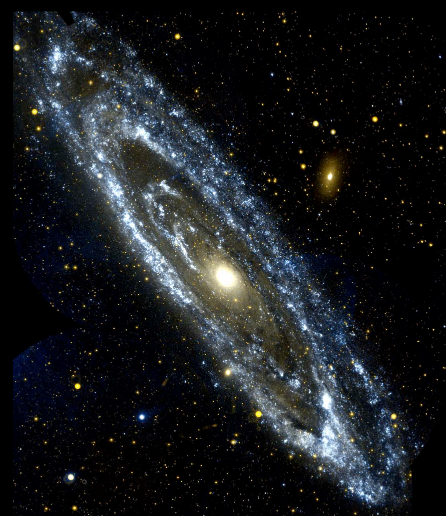
Christopher Martin, Caltech + CWI/FIREBALL Teams

IGM UV absorption spectroscopy

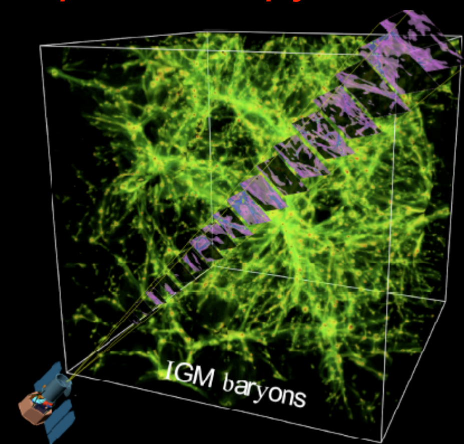


HST/COS/StScI

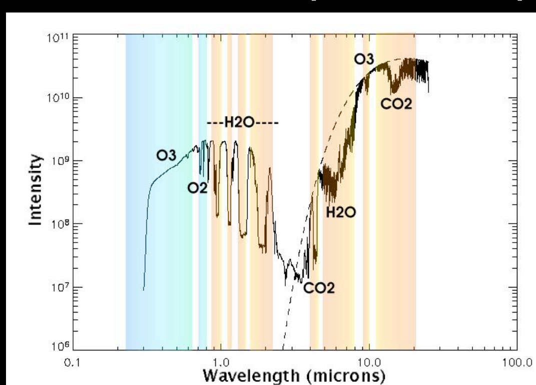
UV Imaging



UV Imaging Spectroscopy of IGM

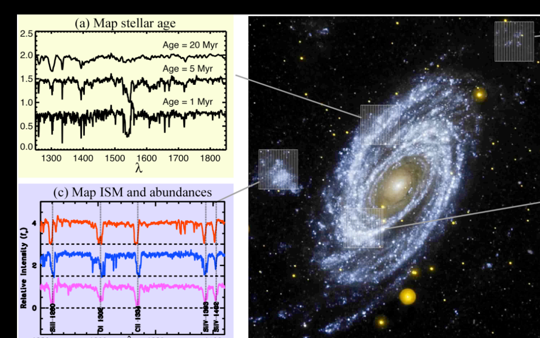


Exoplanet Emission & Transmission spectroscopy

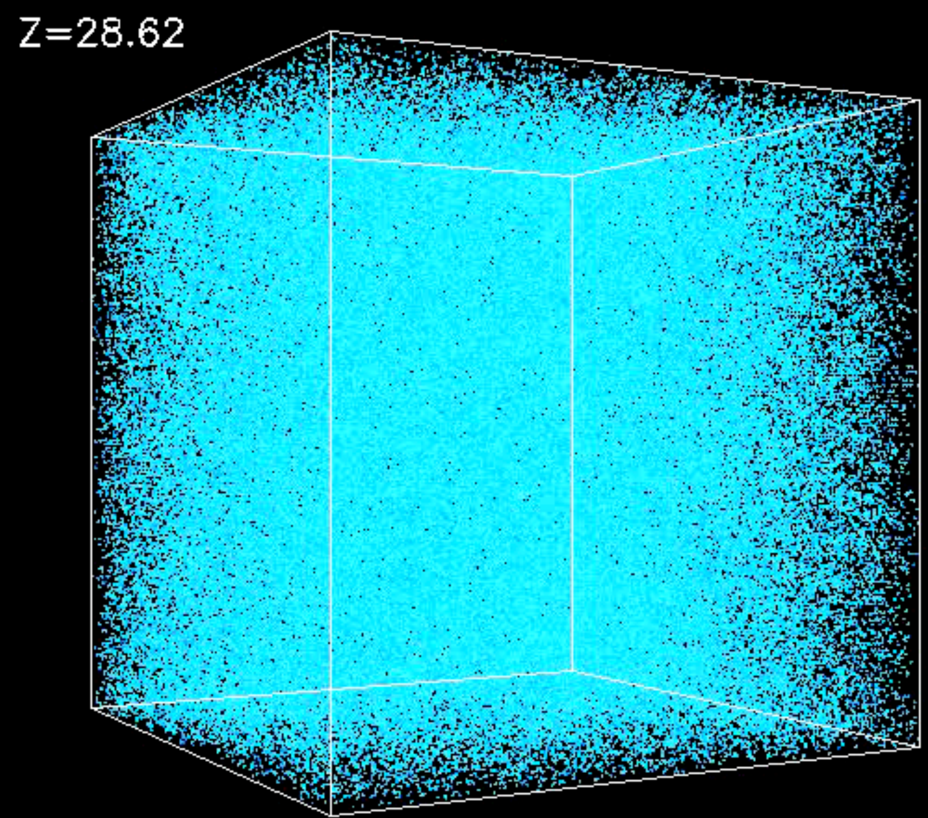


Allard+ 2004

UV Imaging Spectroscopy



Growth of Structure



140 million light years

Andrey Kravtsov

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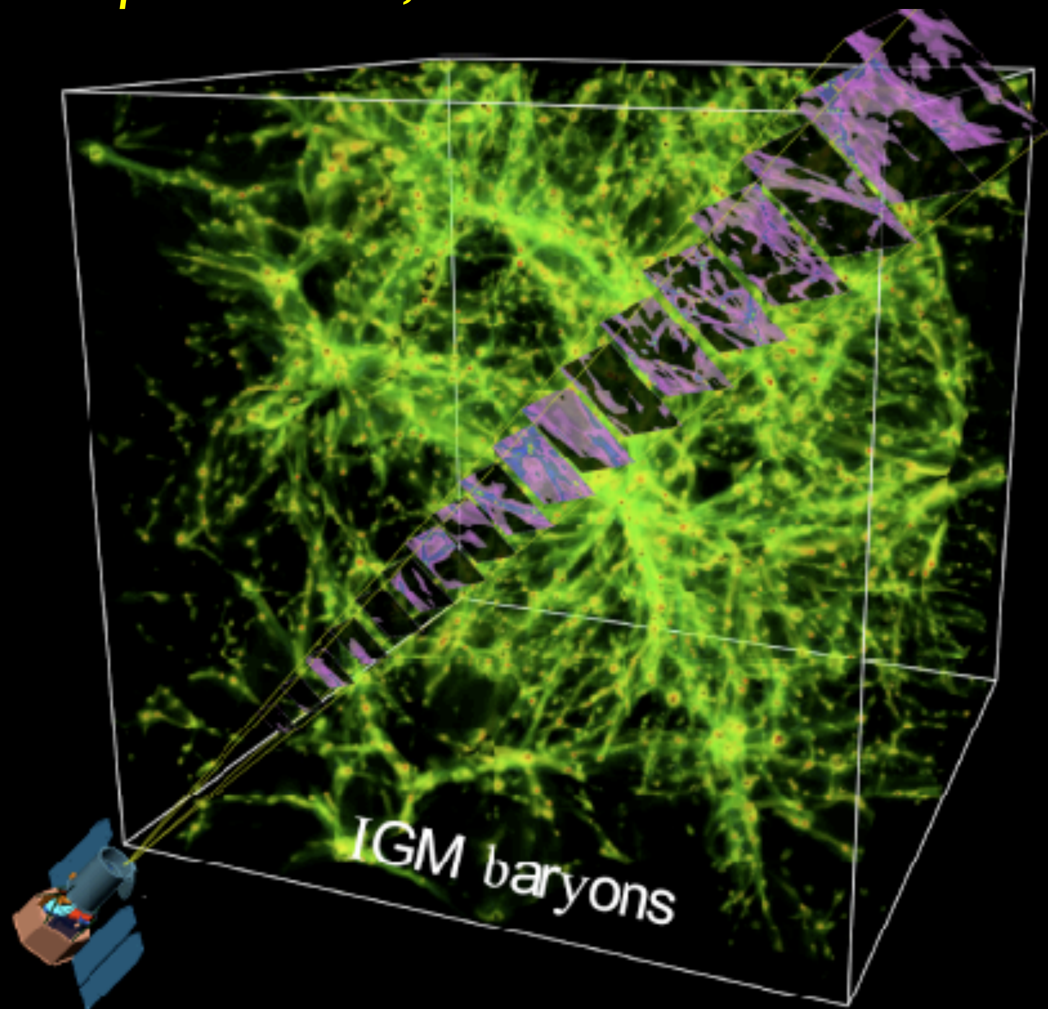


IGM Project

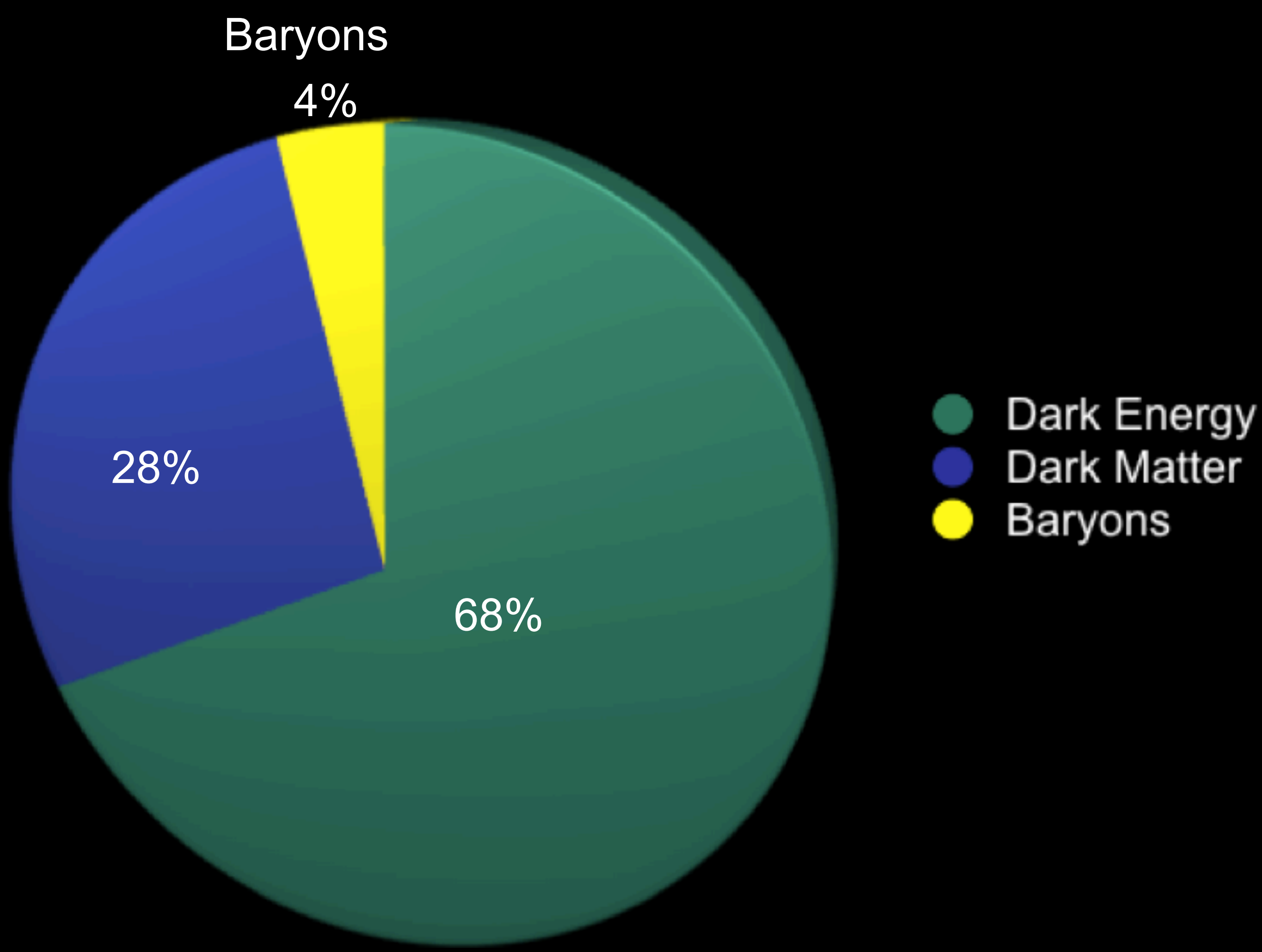
Co-Investigators

- **FIREBALL:** D. Schiminovich, S. Tuttle (Columbia University); B. Milliard, J.-M. Deharveng, R. Grange, C. Peroux (LAM), J. Evrard (CNES); C. Martin, M. Matuszewski, S. Rahman, R. McLean (Caltech)
- **Gen-2 Detectors:** P. Morrissey (Caltech), S. Nikzad (JPL), D. Schiminovich, E. Hamden (Columbia)
- **ISTOS:** D. Schiminovich, G. Bryan (Columbia), B. Milliard, J.-M. Deharveng, C. Peroux, L. Tresse (LAM), C. Martin, P. Morrissey, A. Moore, R. McLean, C. Steidel (Caltech); S. Nikzad, J. Trauger (JPL), T. Heckman (JHU), C. Leitherer (StScI), S. Charlot (IAP), R. Kennicutt, C. MacKay (Cambridge), J. Blaizot (Lyon), C. Martin (UCSB), R. Cen, J. Ostriker (Princeton), J. Schaye (Leiden), J. Kollmeier (CIW)
- **CWI/KCWI/ACWI:** C. Martin, A. Moore, M. Matuszewski, P. Morrissey, S. Rahman, D. Chang (Caltech)

Key Questions Answerable by Mapping IGM Emission

- Census: Where are the Baryons?
- Fuel: How does gas get into galaxies? Where do galaxies form in the cosmic web?
- Feedback: How does feedback control the structure and evolution of galaxies?
- Structure: What is the structure of the Universe & how does it evolve with time?

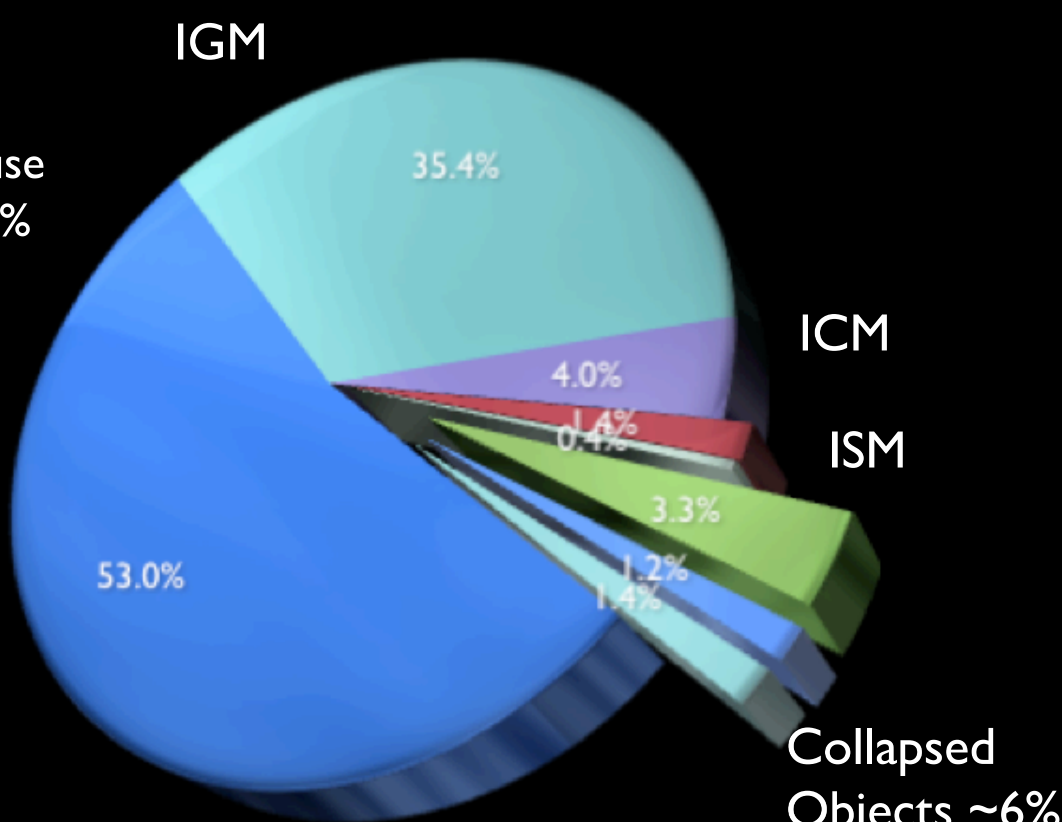
Census: Mass/Energy Budget of Universe

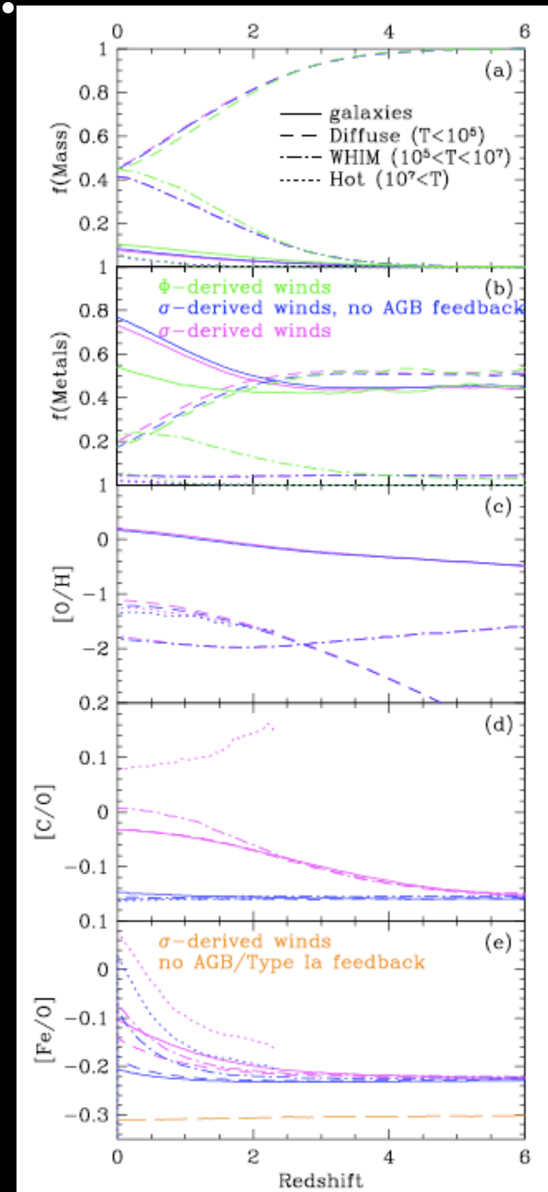


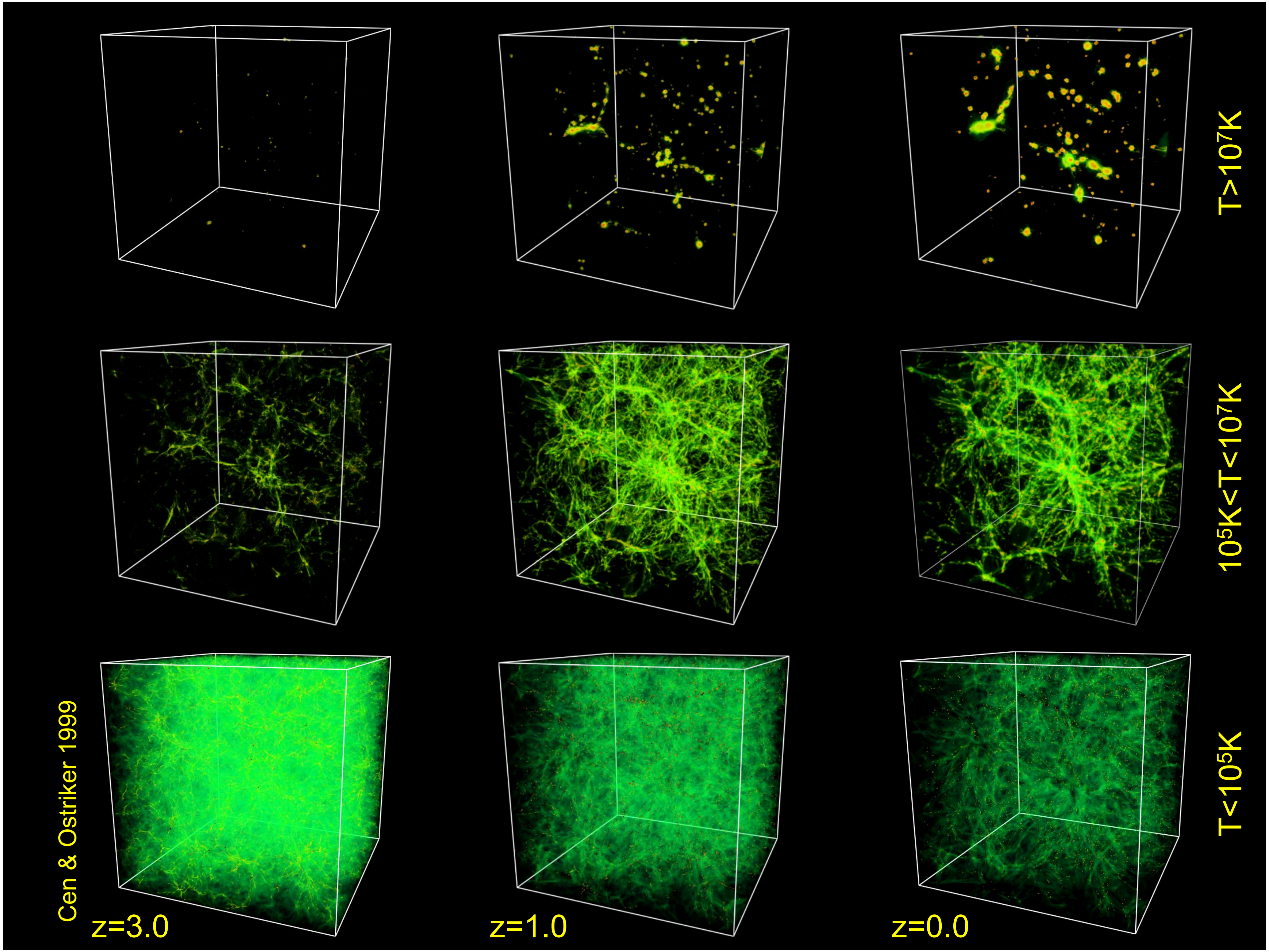
Census: Where are the Baryons?

- Fukugita & Peebles (2004)

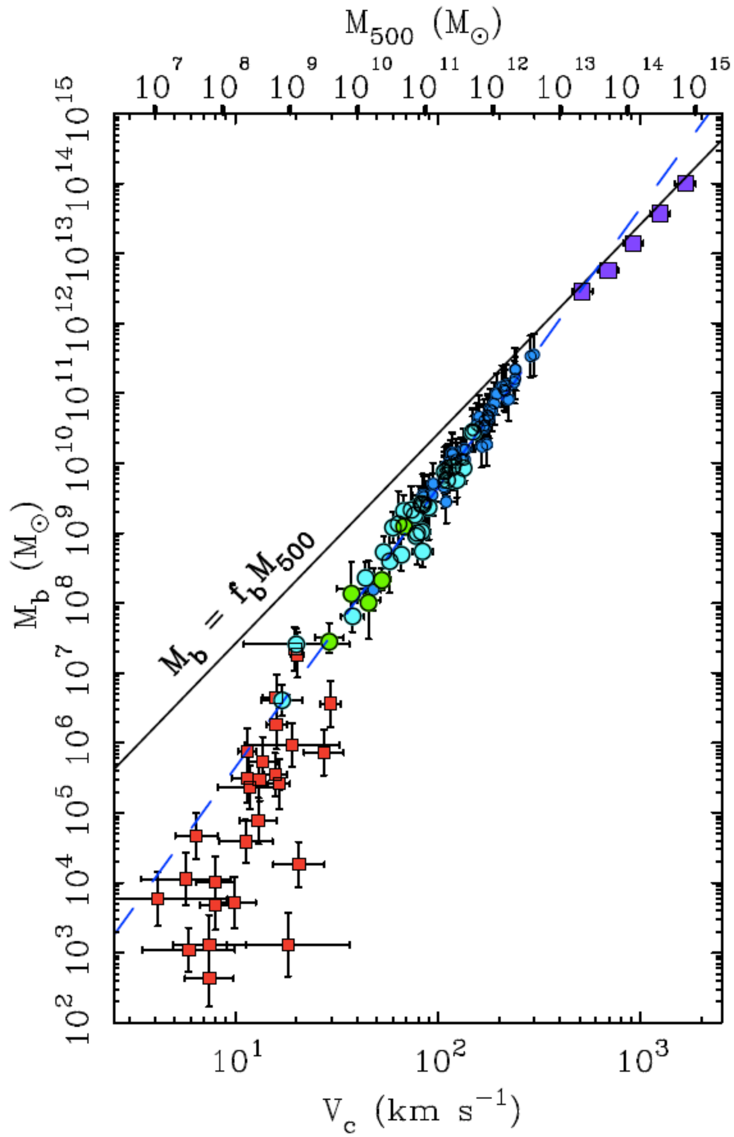
- "Virialized" IGM
- Intracluster Plasma (ICM)
- Molecular Gas
- Stars (disks)
- "Cosmic Web" IGM
- HI+HeI
- Stars (bulges)
- Degenerate/substellar





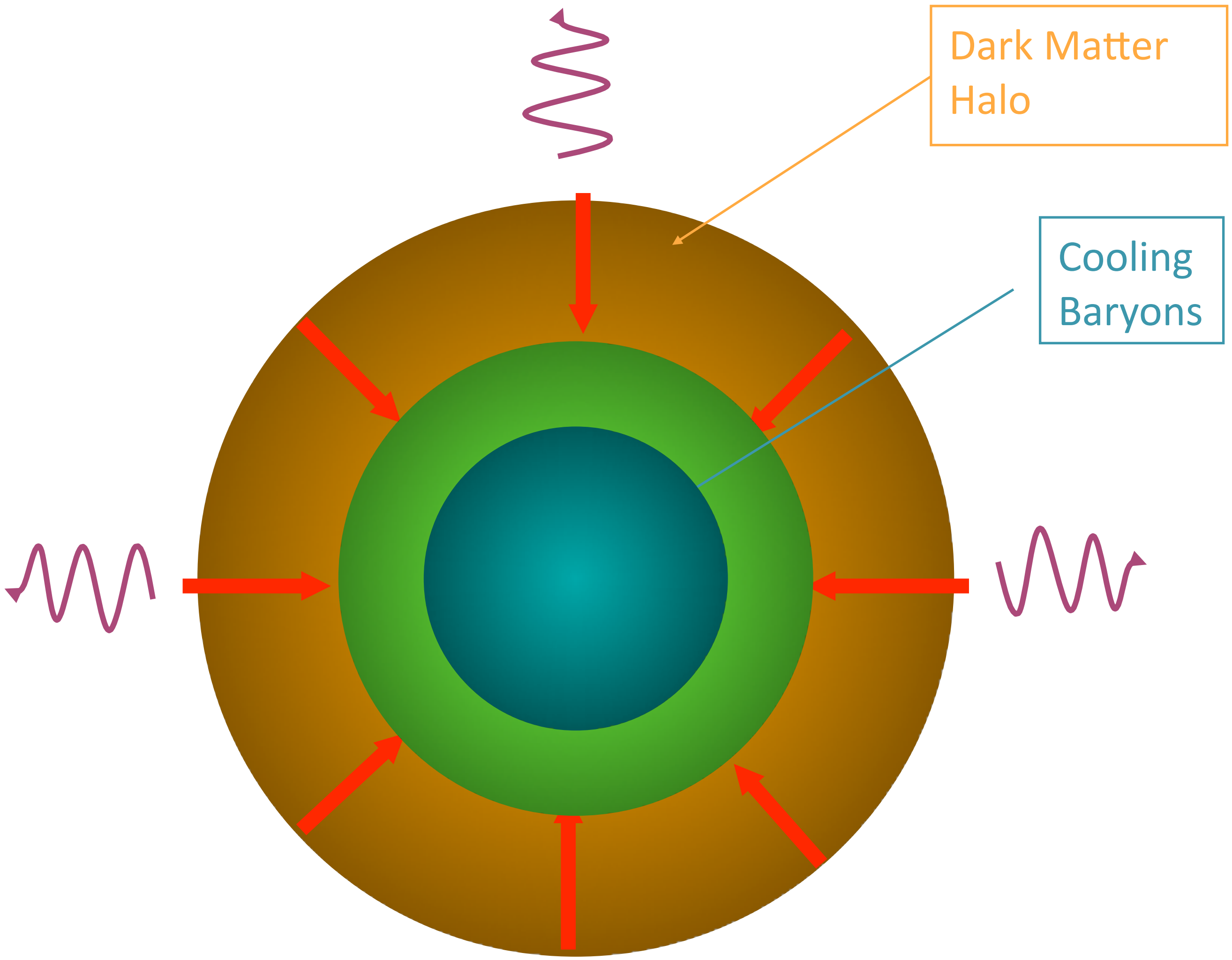

T>10^{7}K
10^{5}K<T<10^{7}K
T<10^{5}K
Cen & Ostriker 1999
z=3.0
z=1.0
z=0.0

Census: Where are the baryons? (in low mass galaxies)



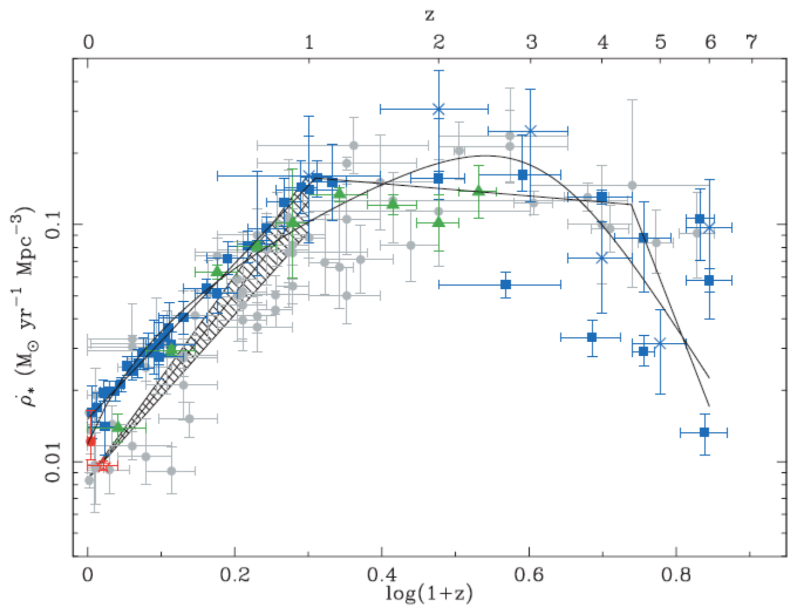
McGaugh+2010

Fuel: How does Gas get into Galaxies?



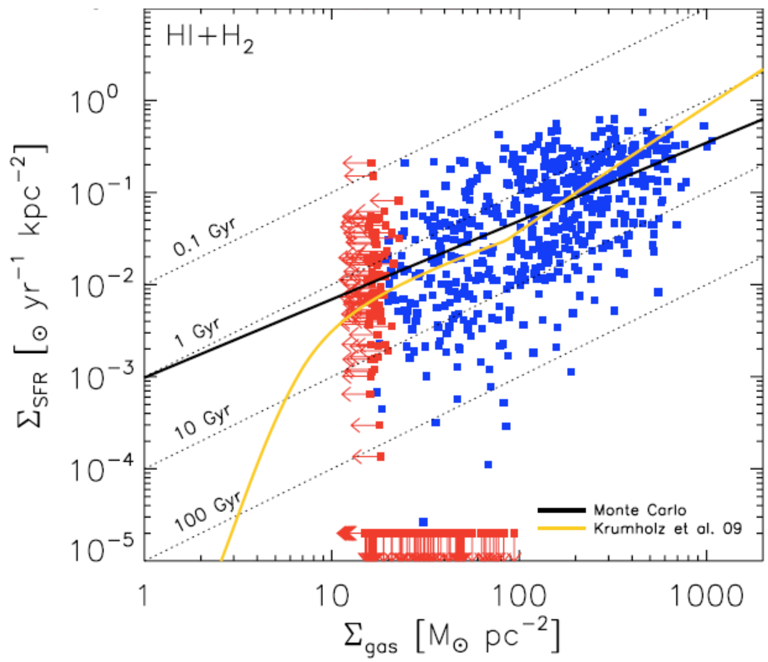
Fuel: How does Gas get into Galaxies? Issues

Cosmic SFR History



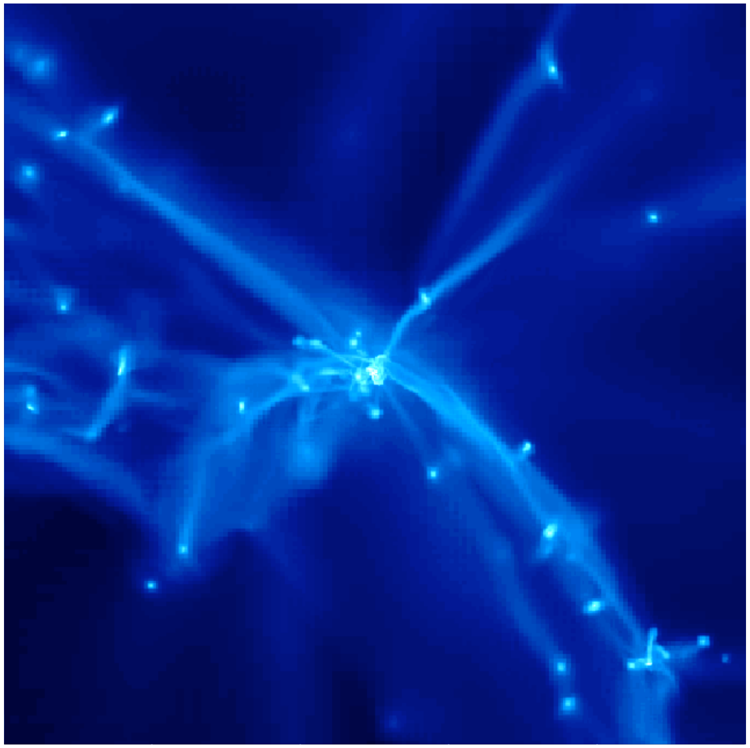
Hopkins & Beacom 2006

Gas Depletion Timescales

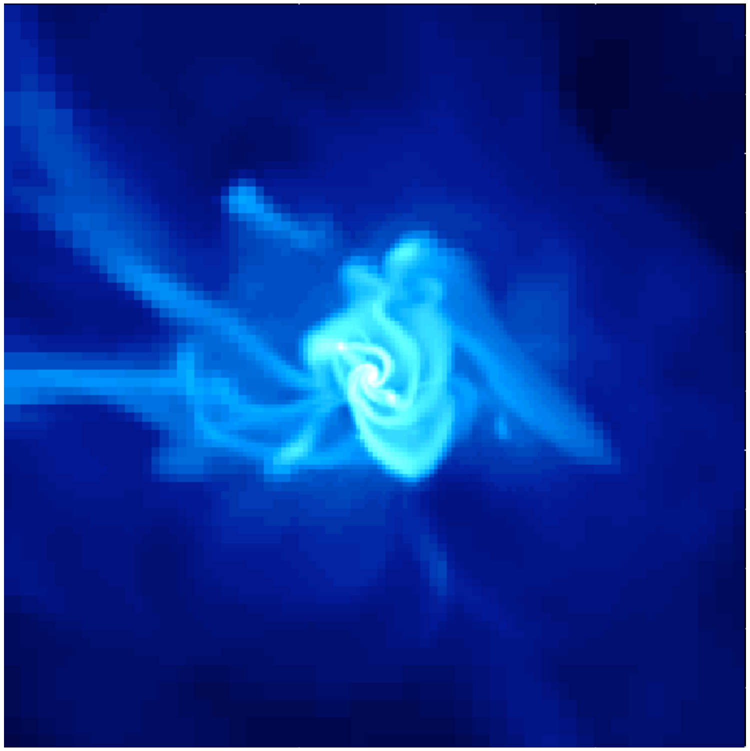


Blanc+2009

Fuel: How does Gas get into Galaxies?



300 kpc

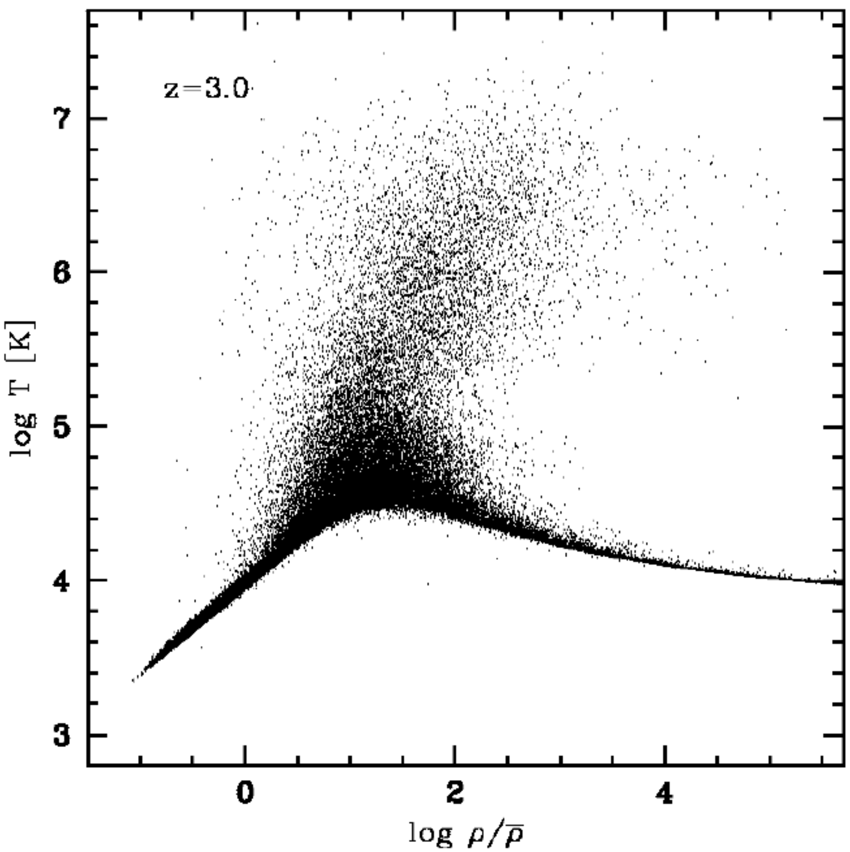


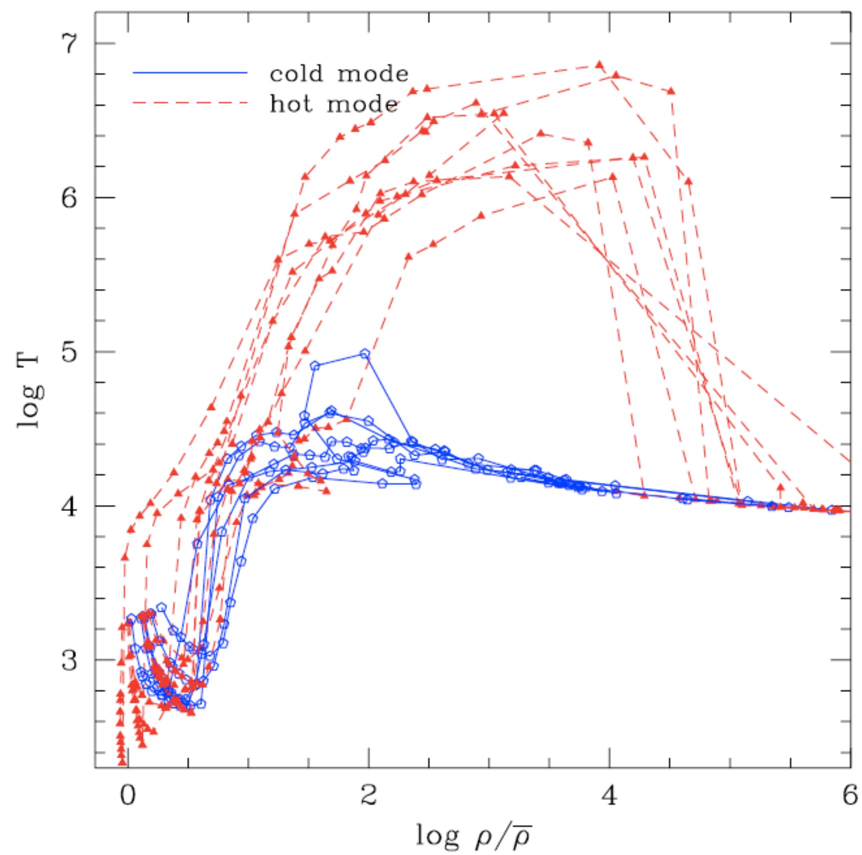
40 kpc

Andrey Kravtsov

Fuel: How does Gas get into Galaxies?

Hot & Cold Accretion

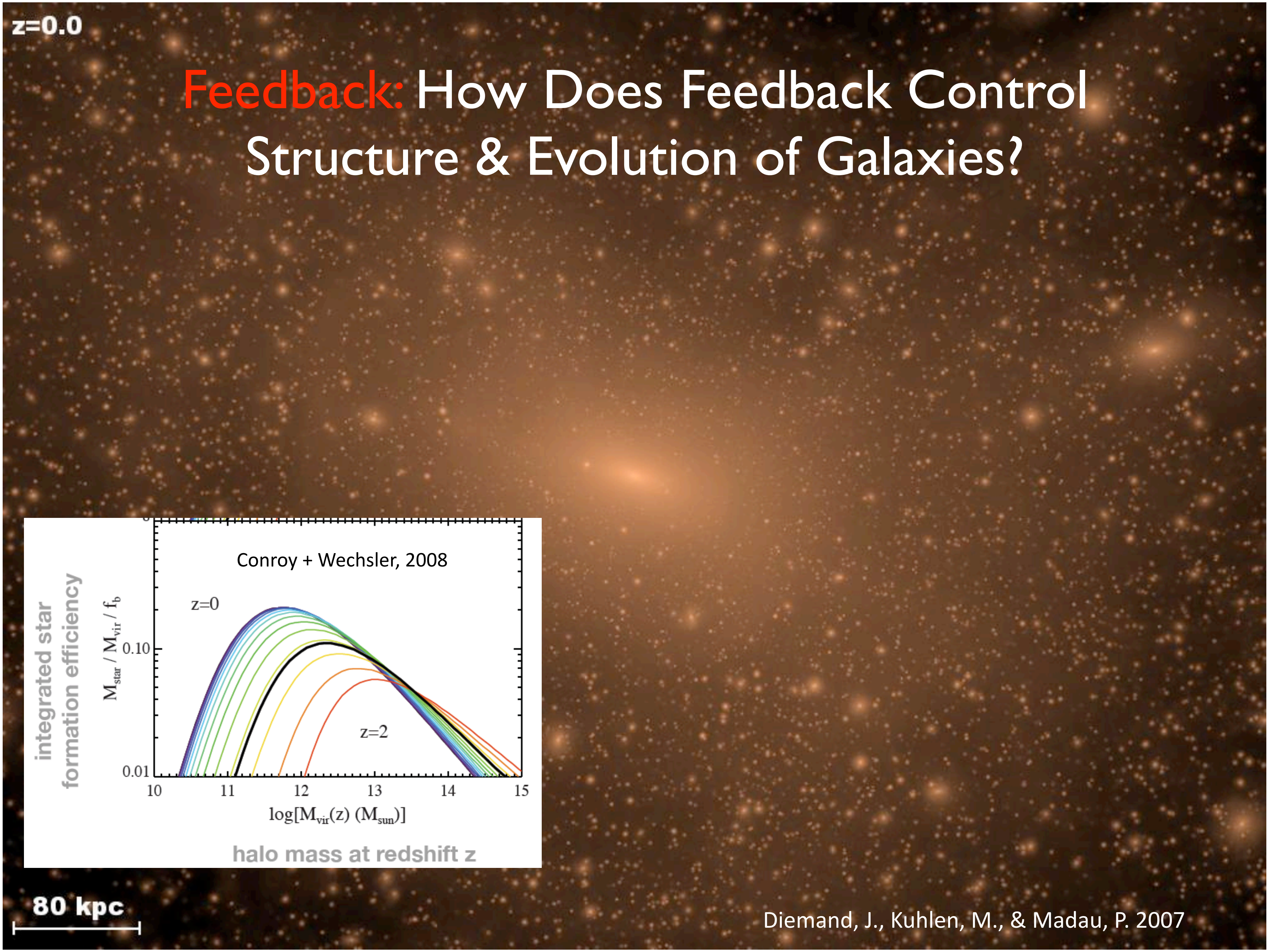




Keres+ 2004

Feedback: How Does Feedback Control Structure & Evolution of Galaxies?

Feedback: How Does Feedback Control Structure & Evolution of Galaxies?

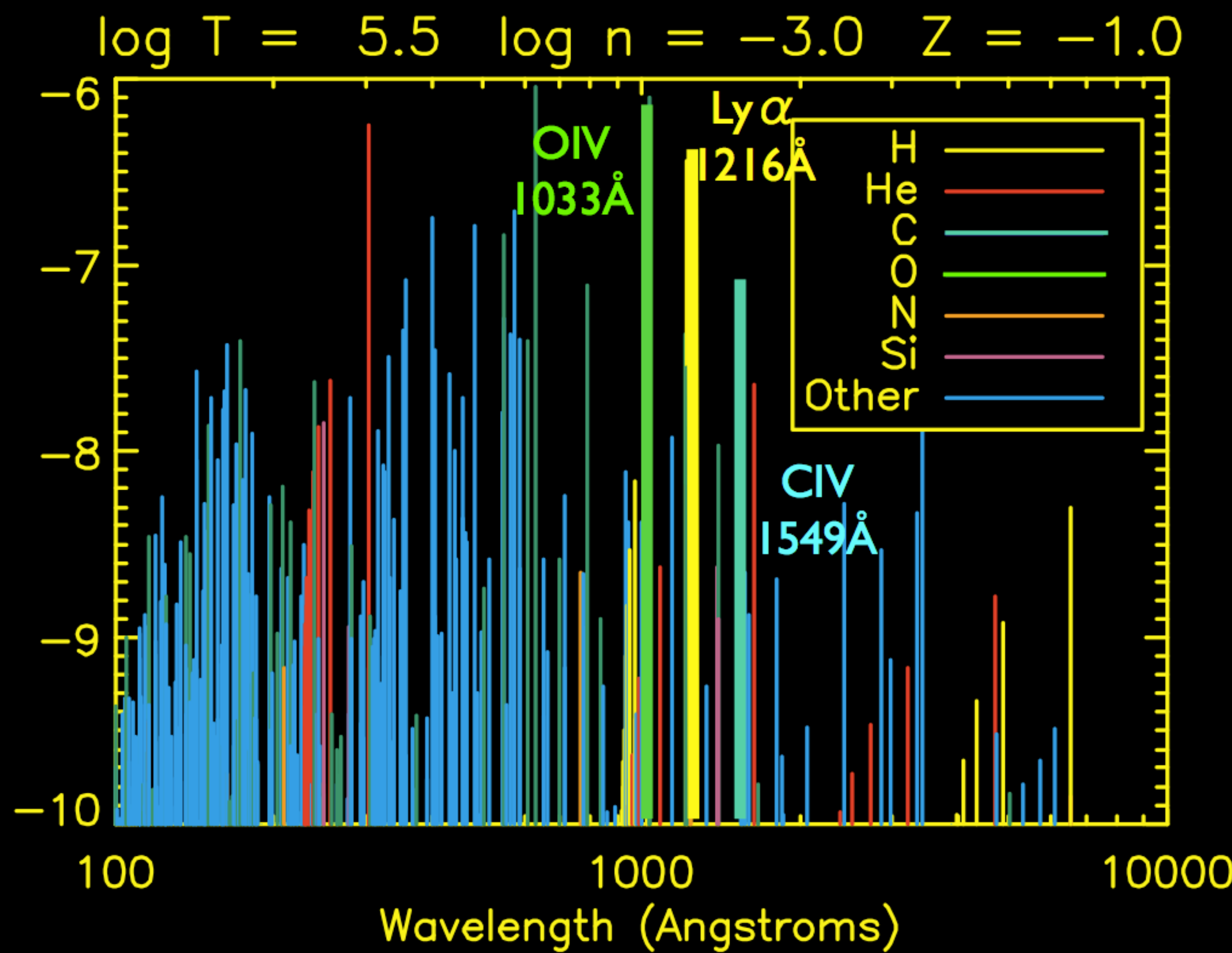


Diemand, J., Kuhlen, M., & Madau, P. 2007

Why Emission?
(as opposed to Absorption…)

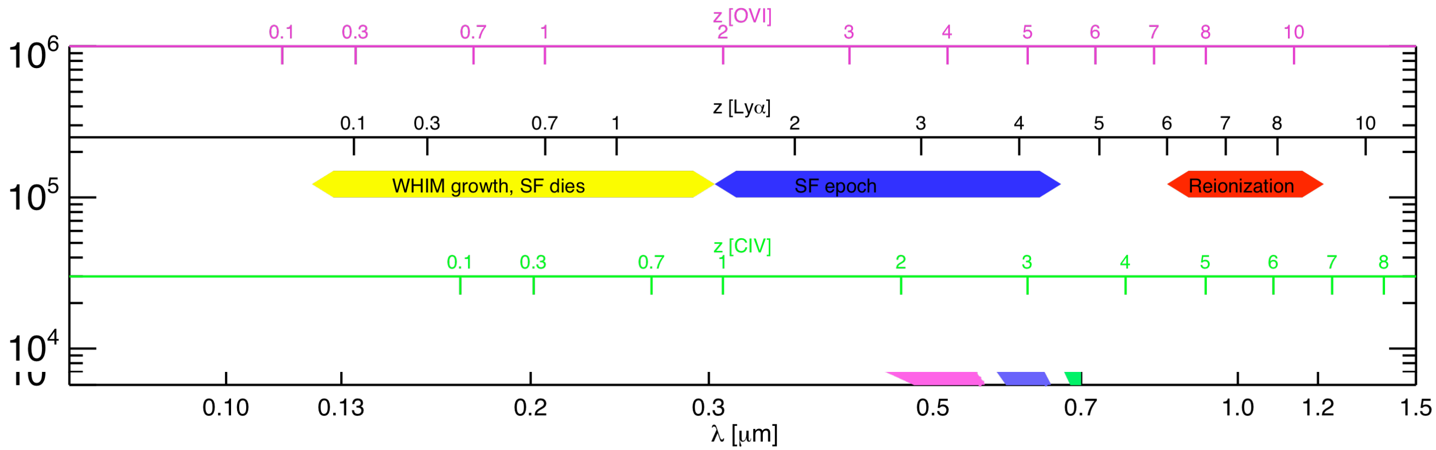
- Scale θ
  - Size $L = \theta D$
  - Mass M
  - Overdensity δ
- Density $n_i = N_i/L$
  - Ionization Γ/n
  - Total density $n = f(\Gamma, n_i)$
  - Pressure $p=nkT$
  - Filling Factor f
- Temperature T
  - pressure
  - Heating/cooling balance
- Timescales
  - cooling $t_{cool} \sim T/nL$
  - Collapse time $t \sim d^{-1/2}$
- Morphology
  - outflows/inflows
  - shocks, filaments
- Gas Kinematics
  - Divergence $\nabla \cdot \vec{v}$
  - Rotation $\nabla \times \vec{v}$
- Large Scale Structure Mapping
  - large scale structure statistics
  - P(k)
  - d_k phases (non-Gaussian?)
- Correlation of IGM w/ galaxies, AGN
  - Circum-galactic medium
  - Gas reservoirs
  - Inflow, accretion
  - Outflow, feedback

Why (rest) UV?


log T = 5.5 log n = −3.0 Z = −1.0
−6
−7
−8
−9
−10
100
1000
10000
Wavelength (Angstroms)
log Flux
OIV
1033Å
Lyα
1216Å
CIV
1549Å
H
He
C
O
N
Si
Other

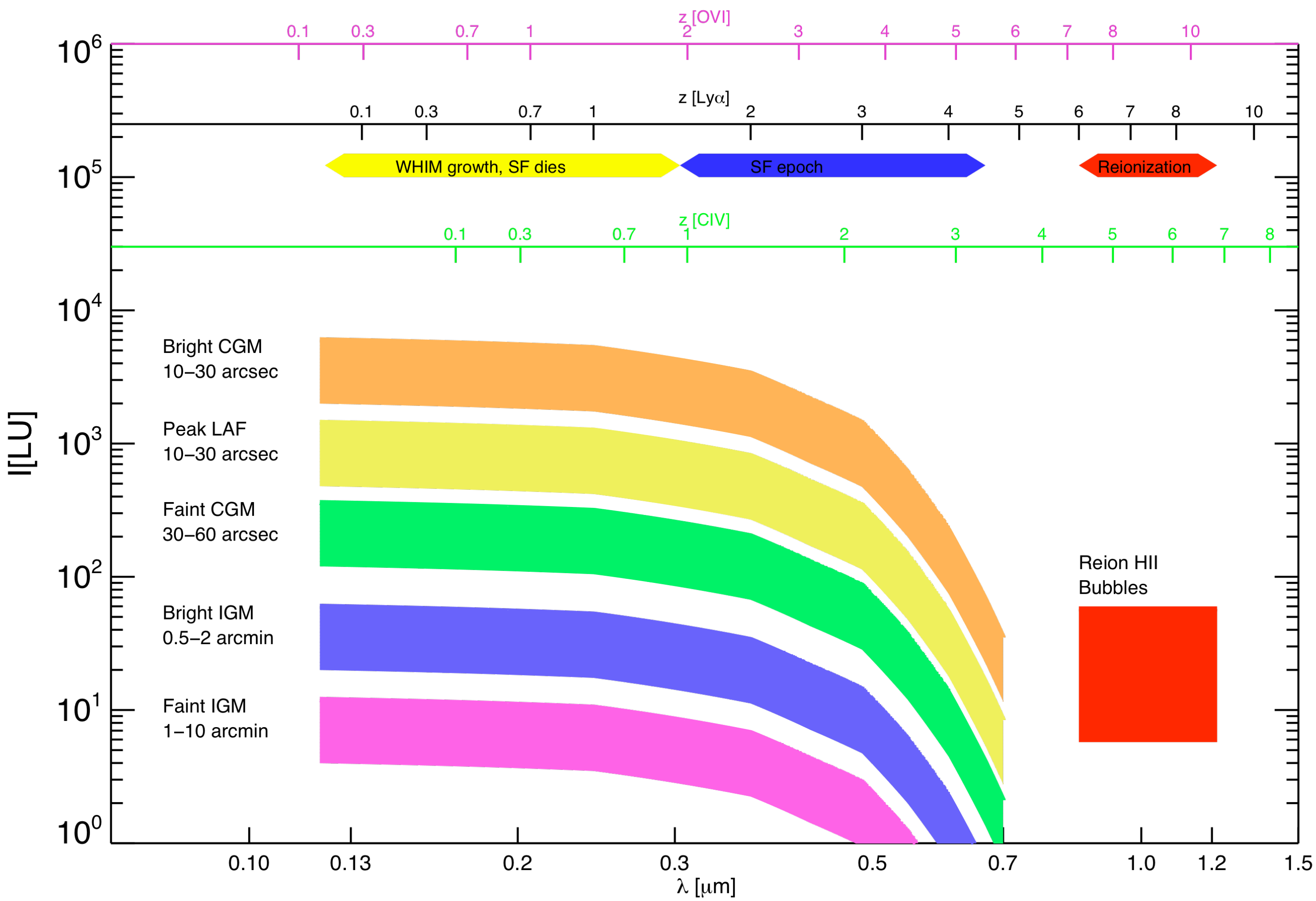
Why UV? Dark Sky!

Why UV? Key redshift range



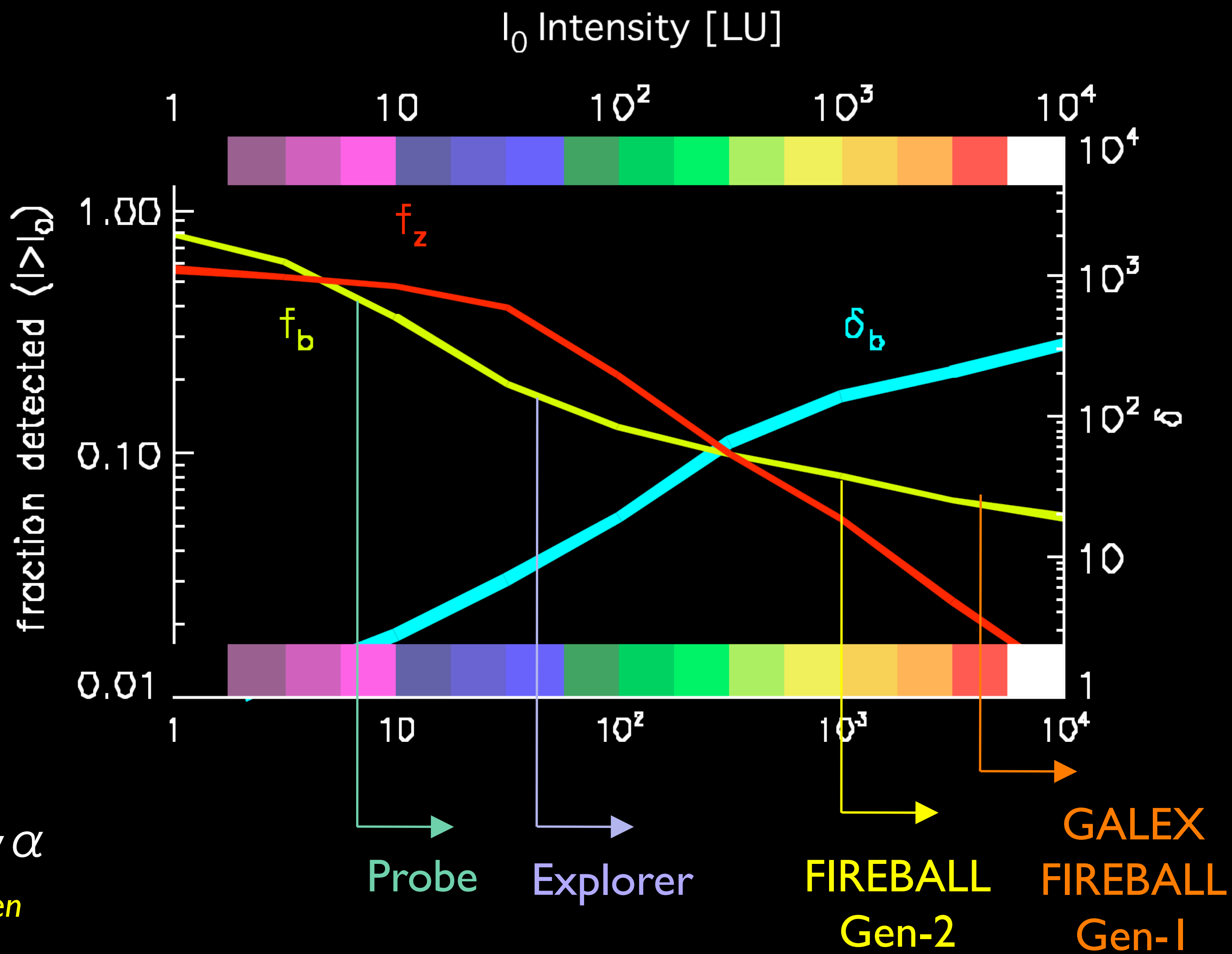
- End of star formation epoch
- Growth of Warm-Hot Ionized Medium

IGM Emission: Flux vs. Wavelength



Where are the Baryons?

Baryon fraction vs. Flux

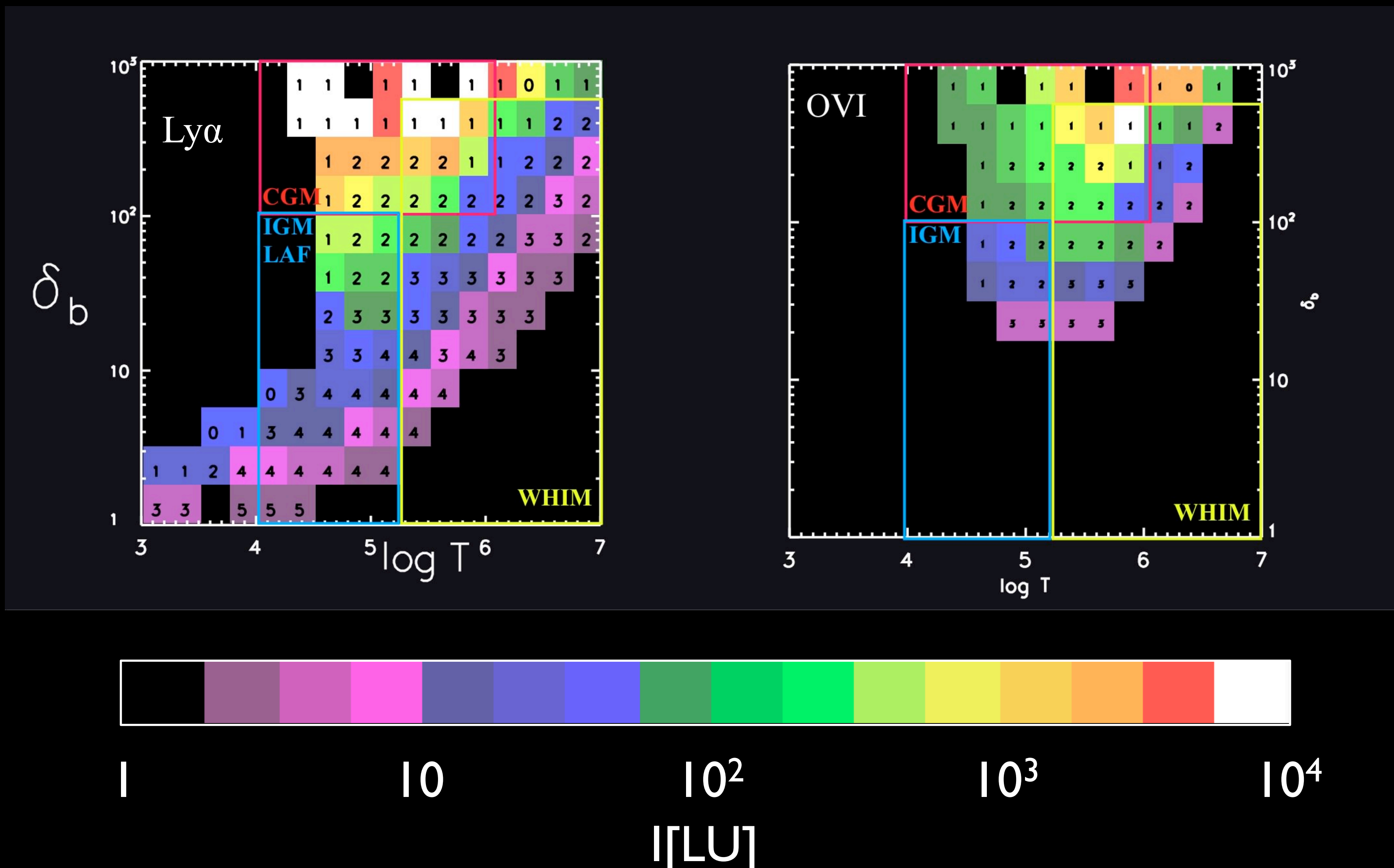


z~0.5 Lyα

SIM-1 Cen

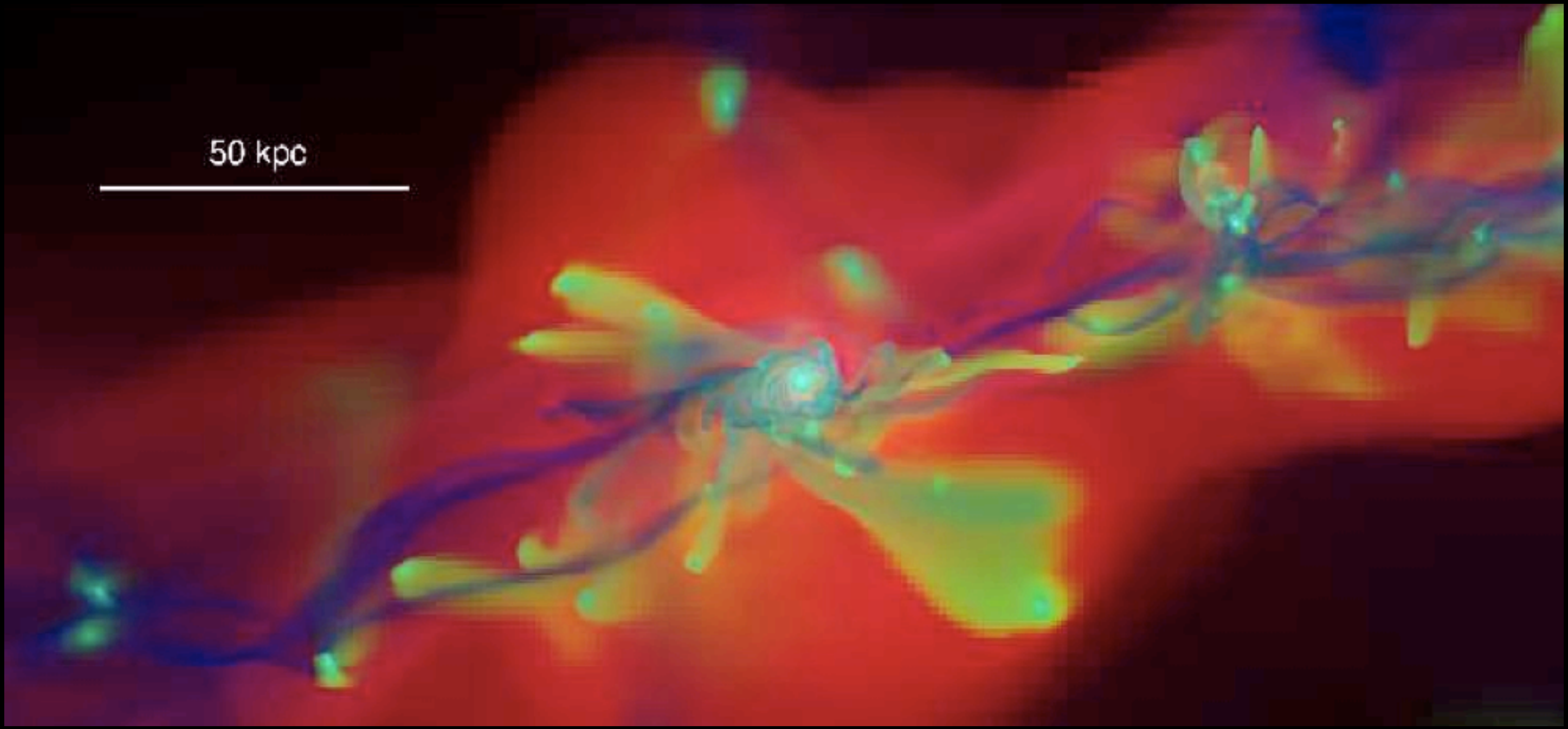
Where are the Baryons?

Density, Temperature vs. Flux



IGM Emission Traces Gas Infall

Cold & Hot Accretion Flows



Agertz, Teyssier, Moore 2009

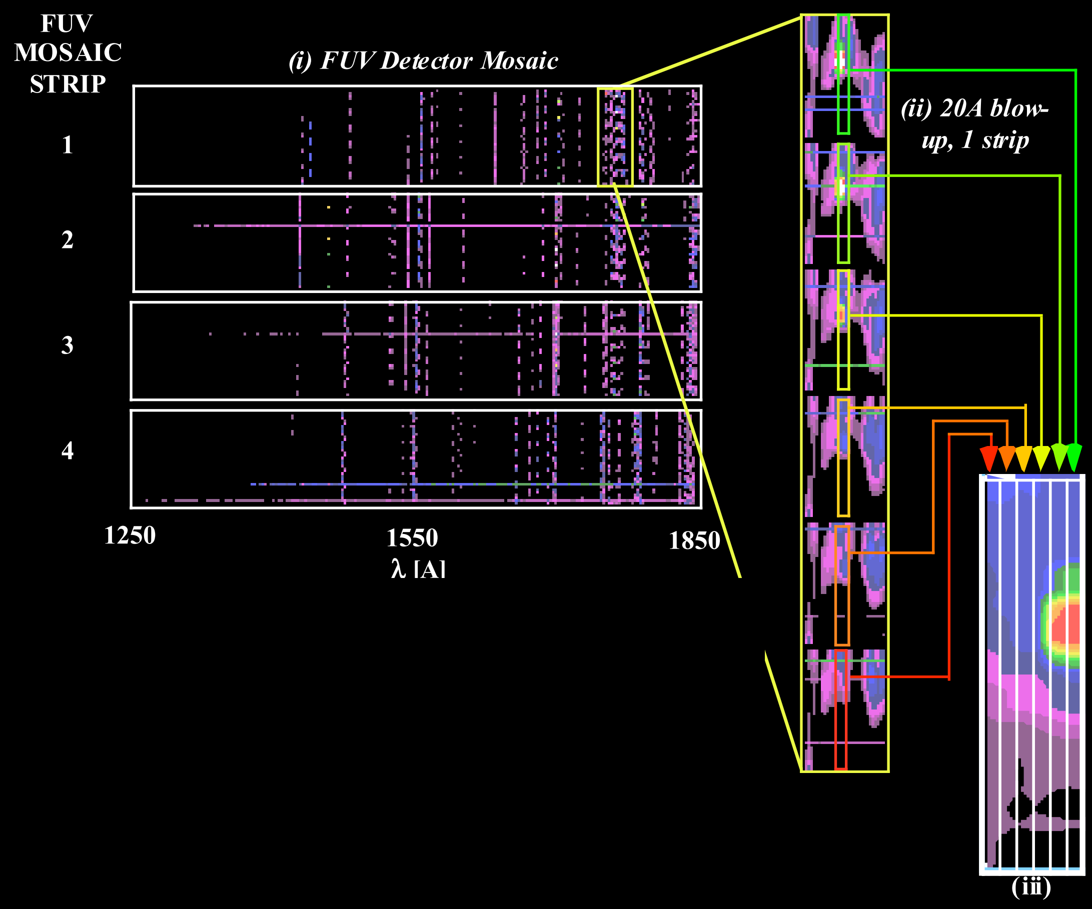
$L_{Ly\alpha} \sim 0.8\ L_{grav}$

IGM Project

Long-term Requirements

Requirement	Rationale
(1) Sensitivity to major baryon, metal fraction	trace majority of unseen baryons, metals
(2) 2D spectral mapping	Relate IGM/CGM/galaxies/QSOs Maximize sensitivity
(3) Spectral range →cosmic evolution →simul: Lyα, OVI, CIV	measure T, ρ, δ, Z space UV: $0<z<1.5$ ground UV: $2<z<4$
(4) Cosmic volume	representative meas.
(5) Spectral resolution	velocity resol $\delta v<300$ isolate foregrounds
(6) Spatial resolution	resolve gals/CGM
(7) Remove foregrounds	IGM low contrast

ISTOS 3D Spectroscopic Mapping



IGM Project

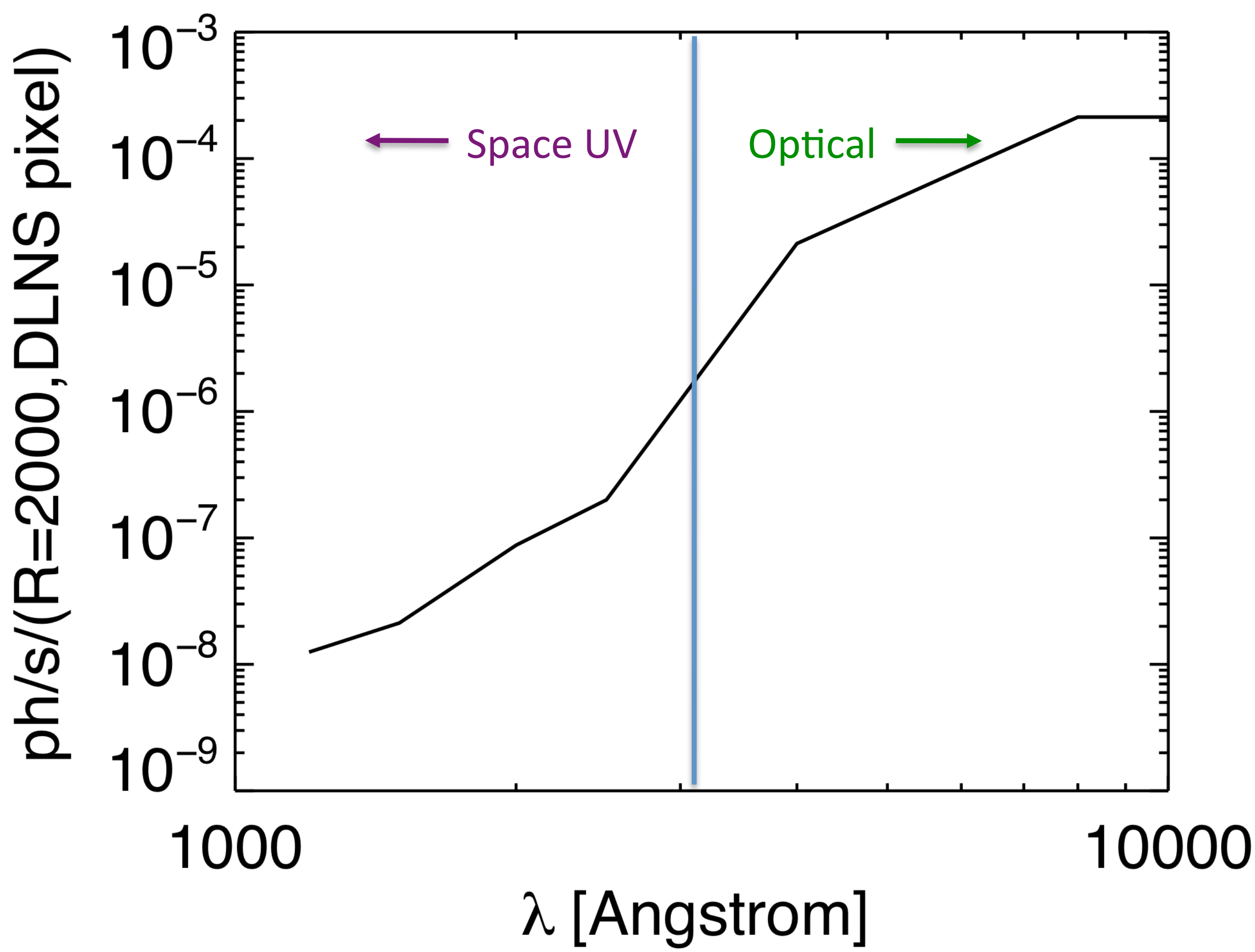
Detector Requirements

Requirement	Detector Requirements
(1) Sensitivity to major baryon, metal fraction	High QE Sky-limited → Photon-counting Low internal background
(2) 2D spectral mapping	Large formats; Lots of pixels
(3) Spectral range →cosmic evolution ($0 < z < 1.5$) →simul: Lyα, OVI, CIV	UV/Optical (1000-3000Å) Large formats; Lots of pixels
(4) Cosmic volume	Lots of pixels; larger pixels
(5) Spectral resolution	Lots of pixels
(6) Spatial resolution	Lots of pixels
(7) Remove foregrounds	Low internal background; Low red leak ($<10^{-3} – 10^{-4}$)

Detector Requirements

Detector Requirement	Current Technology	IGM Emission Requirement
Technology	Microchannel Plates + Photocathode in sealed tube	UV photon-counting CCD with red block filters
QE	5-10%	50-70%
Background (Read noise + Dark Noise + Spurious Noise)	~1 ct/s/cm^2	<0.1 ct/s/cm^2 * (QE/0.5) ~ 2 x 10^{-4} e$^-$/1000s/(15 µm)^2
# of pixels	~4 x 10^6	4 * (10-100)^2 * 2000 ~ 10^6-10^8
Red rejection (systemic)	10^{-3} – 10^{-5}	10^{-3} – 10^{-4}
Time resolution	microsecond	0.1-10 sec for aspect reconstruction
Dynamic range	<100 ct/s	

Photon rate UV/optical Space Sky Background in DL pixel dispersed



Sky Background in Diffraction-Limited Pixel

Photon background [ph s^{-1} $pixel^{-1}$]

$$P_\lambda = I_\lambda * \lambda * \left(\frac{\lambda}{D}\right)^2 * D^2 = I_\lambda \lambda^3 \sim \lambda^7$$

$$CR / pixel \simeq 2.5 \times 10^{-5} \frac{f_b \lambda_{\mu m}^3 \varepsilon \Delta^2}{R_{1000}}$$

$$f_b = [0.5, 1, 30] \quad \lambda = (0.13, 0.25, 0.5 - 1.0)\mu m$$

$$\Delta = \frac{\text{image size}}{DL}$$

$$T_{SL} = \text{time to sky-limited} = (10 hrs) f_b^{-1} \lambda_{\mu m}^{-3} R_{1000} \varepsilon^{-1} \Delta^{-2}$$

Detector Background

$$\frac{B_{DET}}{B_{SKY}} \neq f\left(D_{TEL}\right)$$

CCD READ NOISE

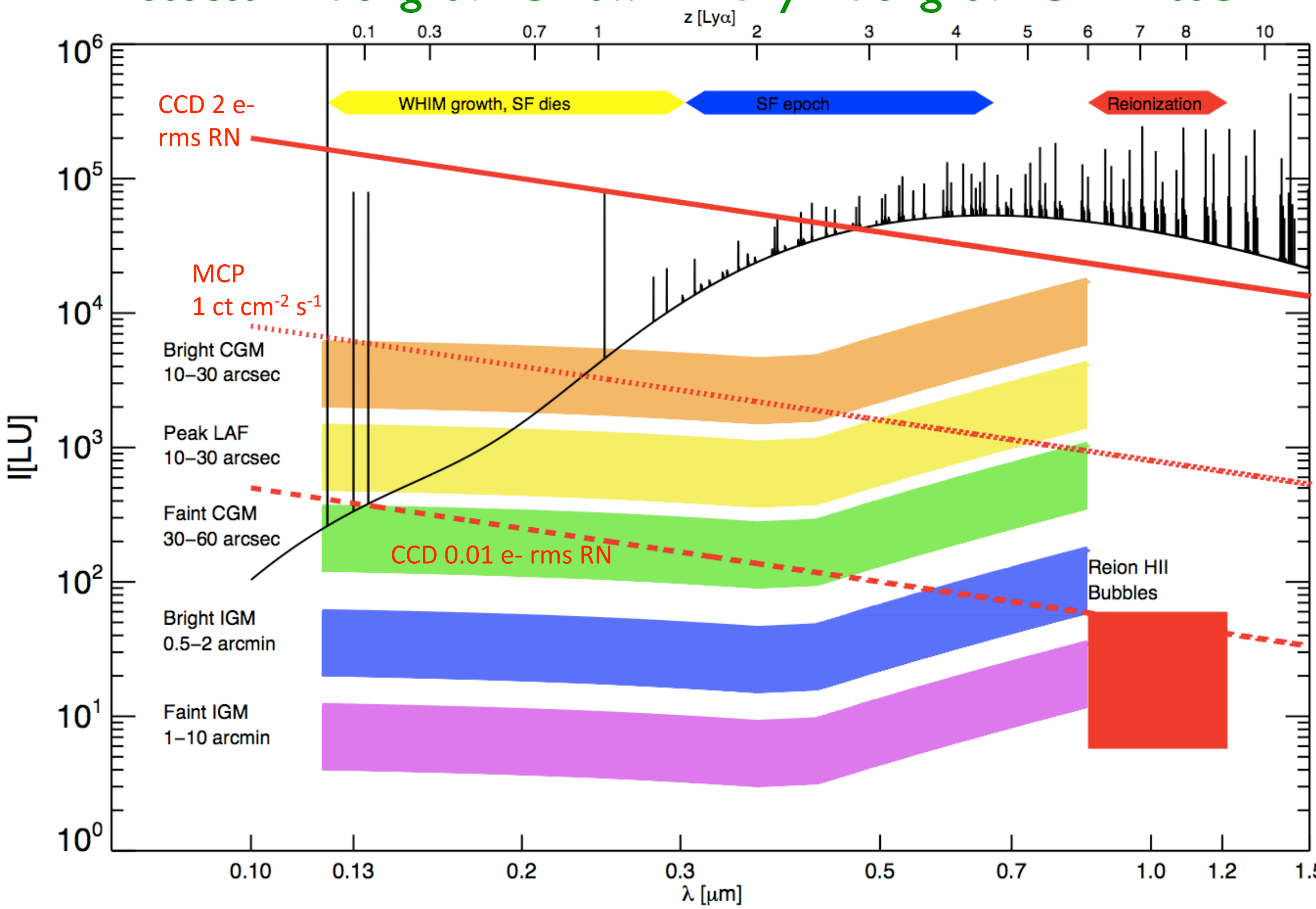
$$B_{CCD}[LU] = 4 \cdot 10^{5} \left(\frac{r}{2e^{-}}\right)^{2} \left(\frac{f_{\#}}{4}\right)^{2} \left(\frac{R}{2000}\right) \left(\frac{\varepsilon}{0.1}\right)^{-1} \left(\frac{\Delta x}{15\mu}\right)^{-2} \left(\frac{\lambda}{200nm}\right)^{-1}$$

MCP DETECTOR BACKGROUND

$$B_{MCP}[LU] = 4 \cdot 10^{3} \left(\frac{b}{1\,ct\ cm^{-2}\,s^{-1}}\right) \left(\frac{f_{\#}}{4}\right)^{2} \left(\frac{R}{2000}\right) \left(\frac{\varepsilon}{0.01}\right)^{-1} \left(\frac{\lambda}{200nm}\right)^{-1}$$

IGM Project

Detector Background Low → Sky Background Limited



IGM Emission SNR Calculation

- SNR w/ MCP, 10% QE, 1 ct/cm^2/sec
  - 10^6 sec, 1600Å, 200LU, 10" x 10", S/N=1.4

	MCP		
Telescope Diameter	2.3		
Mission Cost	1.2B		

IGM Emission SNR Calculation

- SNR w/ MCP, 10% QE, 1 ct/cm^2/sec
  - 10^6 sec, 1600Å, 200LU, 10" x 10", S/N=1.4
- SNR w/ 2 e$^-$ CCD, 70% QE
  - 10^6 sec, 1600Å, 200LU, 10" x 10", S/N=0.4

	MCP	**CCD (2 e-)**	
Telescope Diameter	2.3	8 m	
Mission Cost	1.2B	9B	

IGM Emission SNR Calculation

- SNR w/ MCP, 10% QE, 1 ct/cm^2/sec
  - 10^6 sec, 1600Å, 200LU, 10" x 10", S/N=1.4
- SNR w/ 2 e$^-$ CCD
  - 10^6 sec, 1600Å, 200LU, 10" x 10", S/N=0.4
- SNR w/ photon-counting CCD, 70% QE
  - 10^6 sec, 1600Å, 200LU, 10" x 10", S/N=6

	MCP	**CCD (2 e-)**	**CCD (0 e-)**
Telescope Diameter	2.3	8 m	0.5 m
Mission Cost	1.2B	9B	0.1B

FIREBall

Faint Intergalactic Redshifted Emission Balloon

Probing Circum-Galactic Medium Emission

Goals

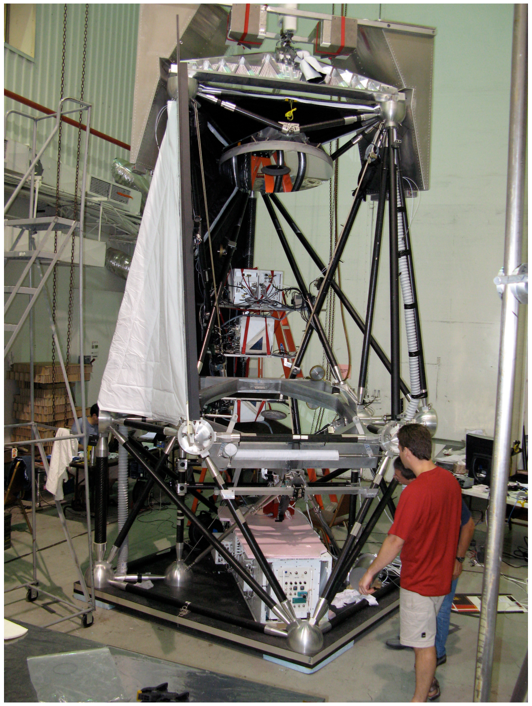
(1) Discover & map Circum-galactic medium to explore IGM-galaxy co-evolution

(2) Pathfind UV integral field spectroscopy

(3) Pathfind next generation high performance UV detectors

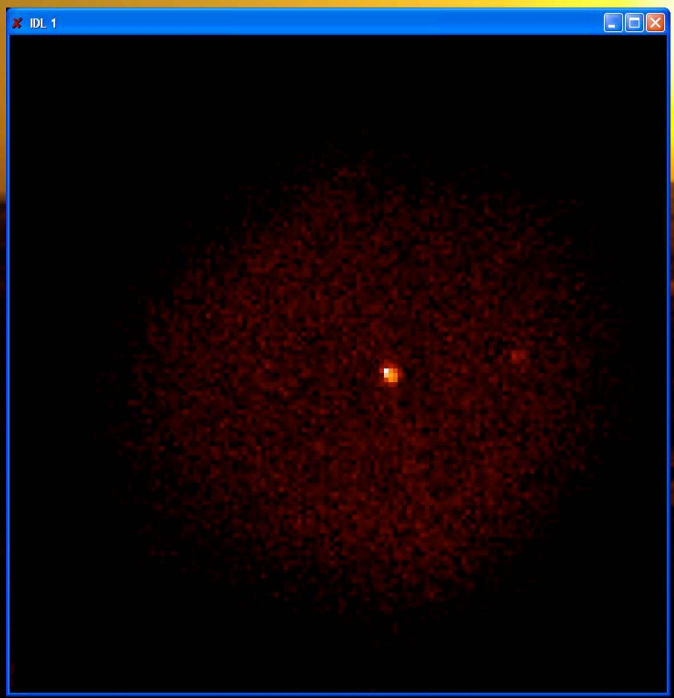
Design

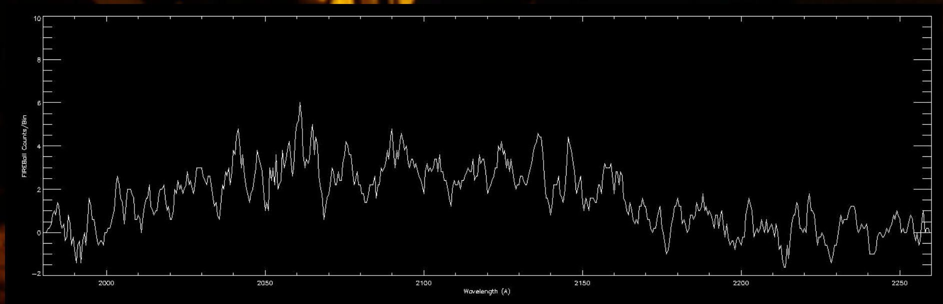
- ✓ 1 meter f/2.5 paraboloid+sidereostat
- ✓ CNES gondola & pointing system
- ✓ Fine guidance with ~3 arcsec pointing
- ✓ Fiber IFU (400 8" fibers, 3 arcmin field of view)
- ✓ High resolution R~5000 Offner spectrometer
- ✓ Bandpass balloon UV window: 2000-2250Å
- ✓ Gen-1 detector: GALEX NUV spare
- ✓ 1^{st} flight 7/07, 2^{nd} flight 5/09 (1^{st} science flight)



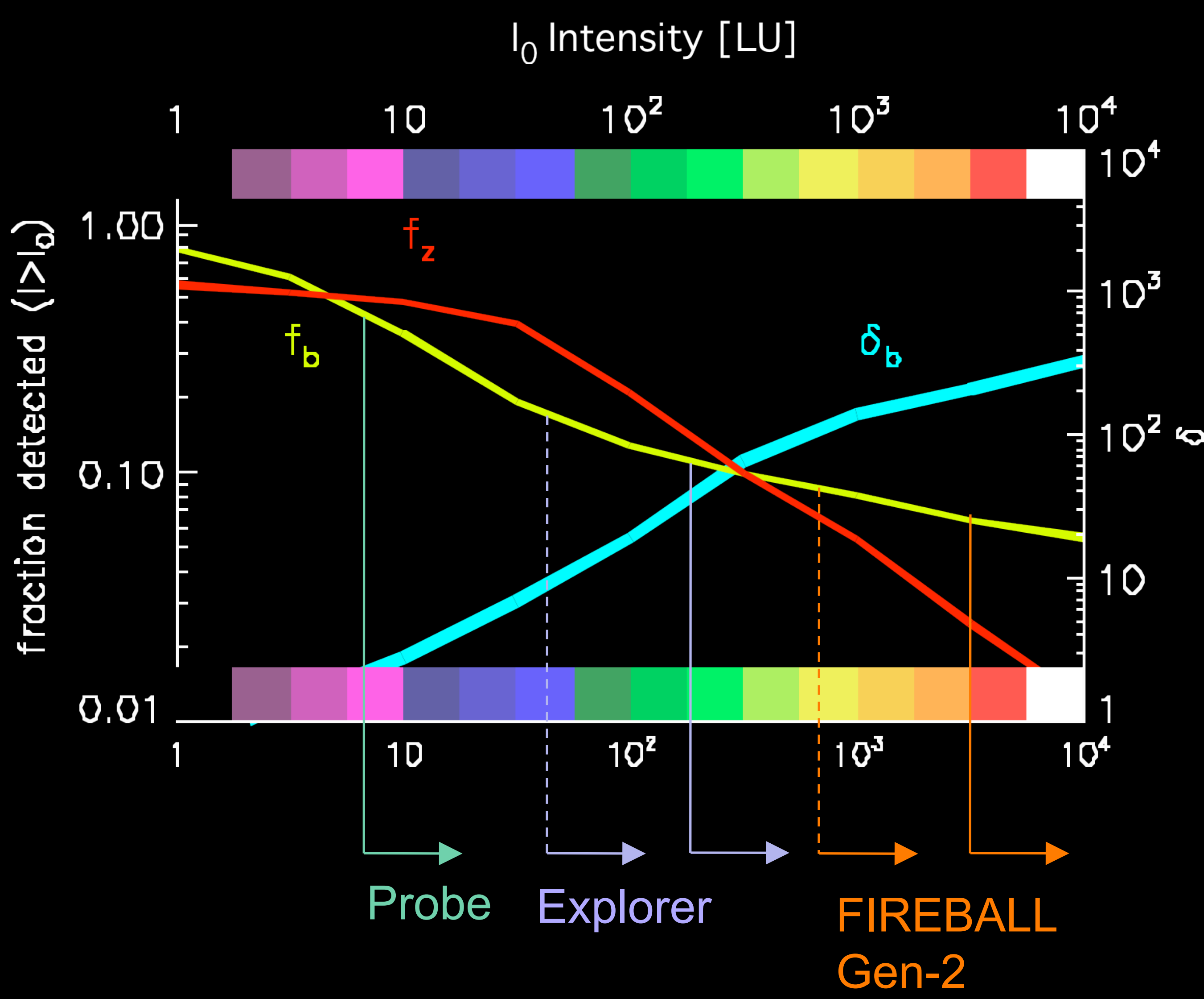
FIREBALL

- Flight #2 demonstrated precision pointing platform and 1st integral field spectroscopy
- Flight #2 obtained ~6 hours of science integration on 3 targets
- Flight #2 altitude was low (~115 kft) reducing throughput
- Brighter CGM emission may be detected by stacking galaxies
- New constraints will be put on gas in CGM and WHIM (assuming no detection)
- Future flights will deploy Gen-2 detector, higher altitude, and additional target types: Factors of 30-100 better sensitivity.





A Program for Discovery & IGM Baryon Mapping



z~0.5 Lyα

Baryon Mapper

Probe

MODEL SIMULATED DATA