Intensity Mapping of Hα, Hβ, [OII] and [OIII] lines at z<5

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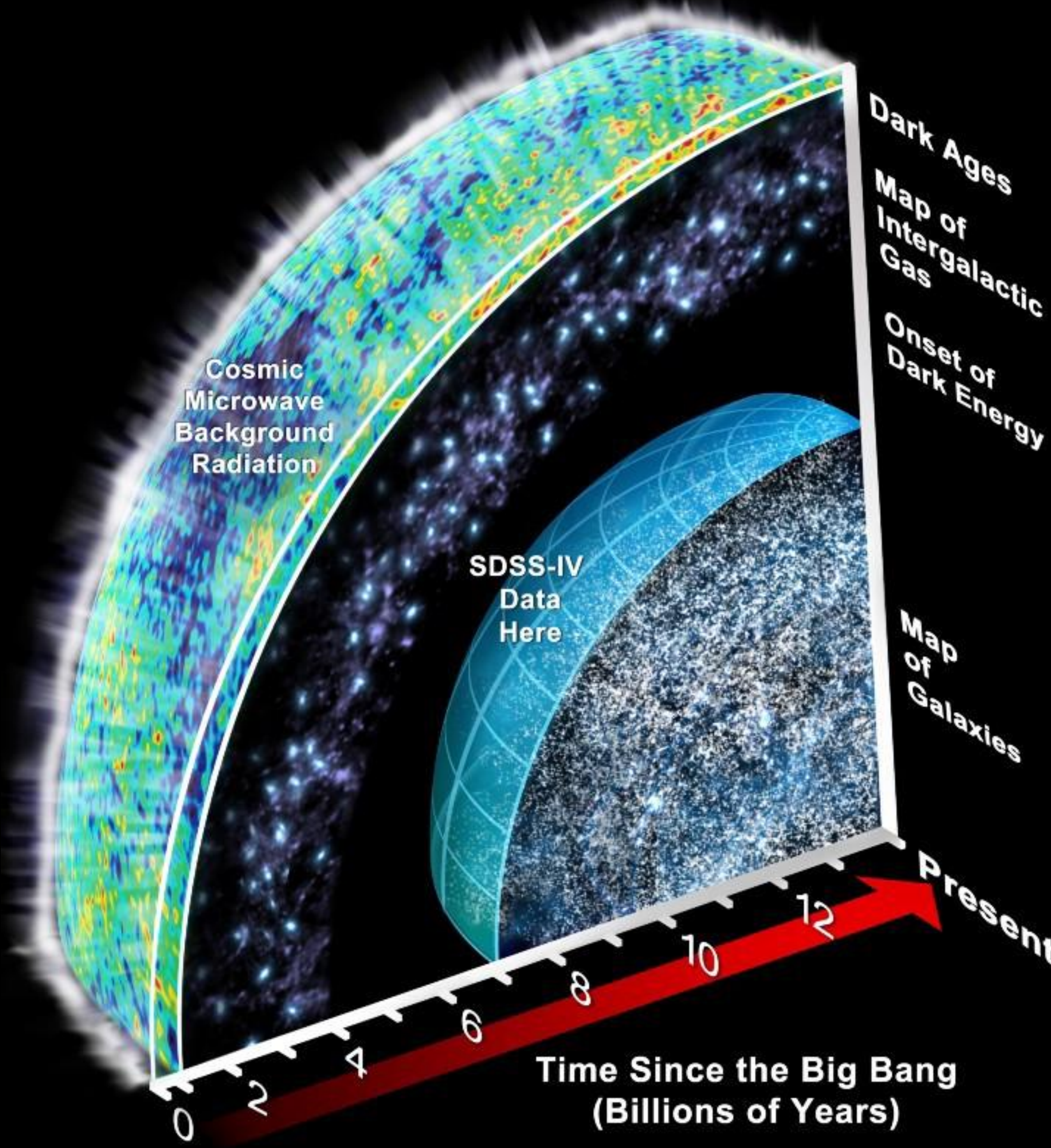

Cosmic Microwave Background Radiation
SDSS-IV Data Here
Dark Ages
Map of Intergalactic Gas
Onset of Dark Energy
Map of Galaxies
Present
0
2
4
6
8
10
12
Time Since the Big Bang (Billions of Years)

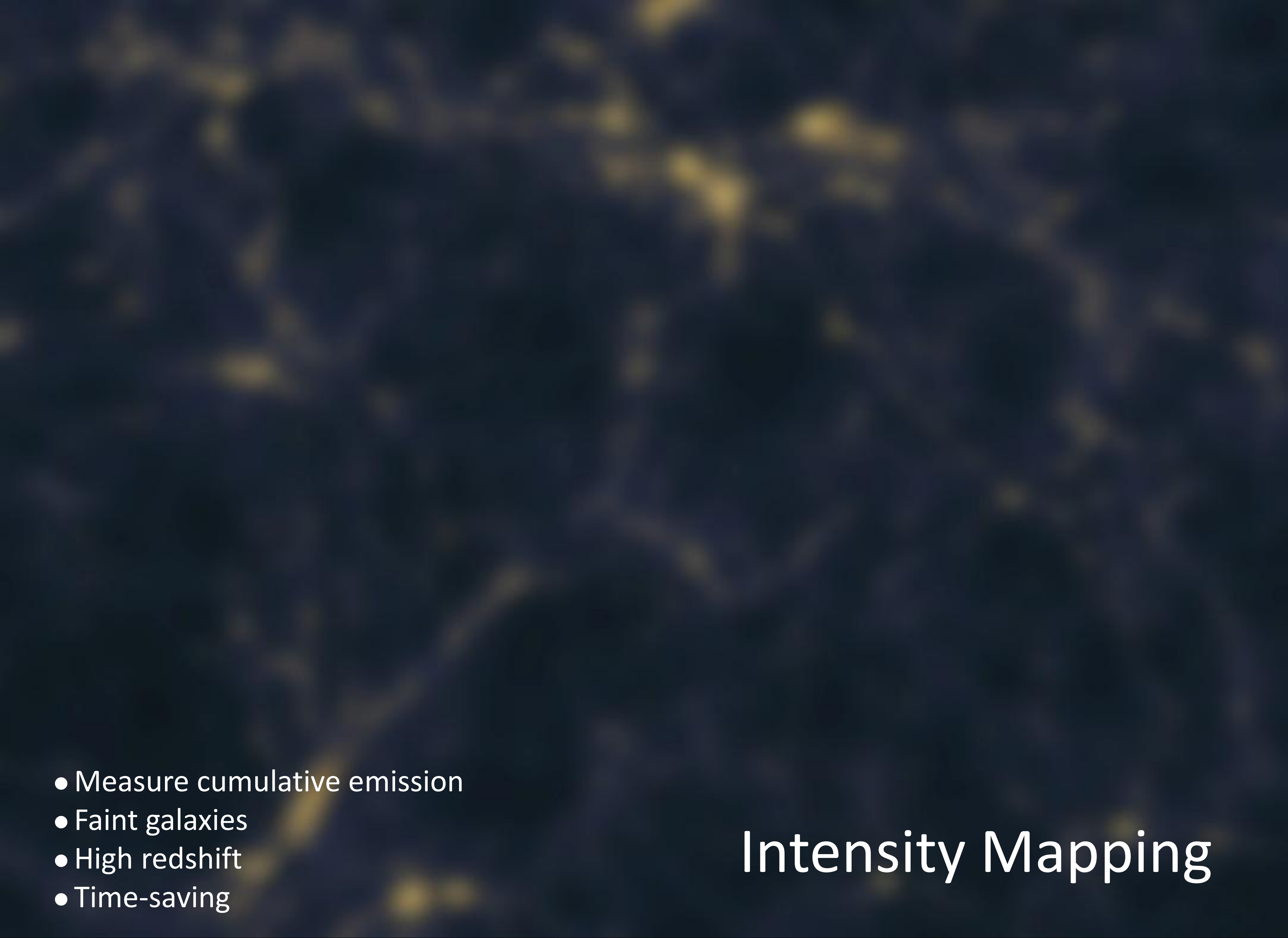
Credit: SDSS

Galaxy Survey

- Resolve individual galaxies
- Bright galaxies
- Low redshift
- Time-consuming

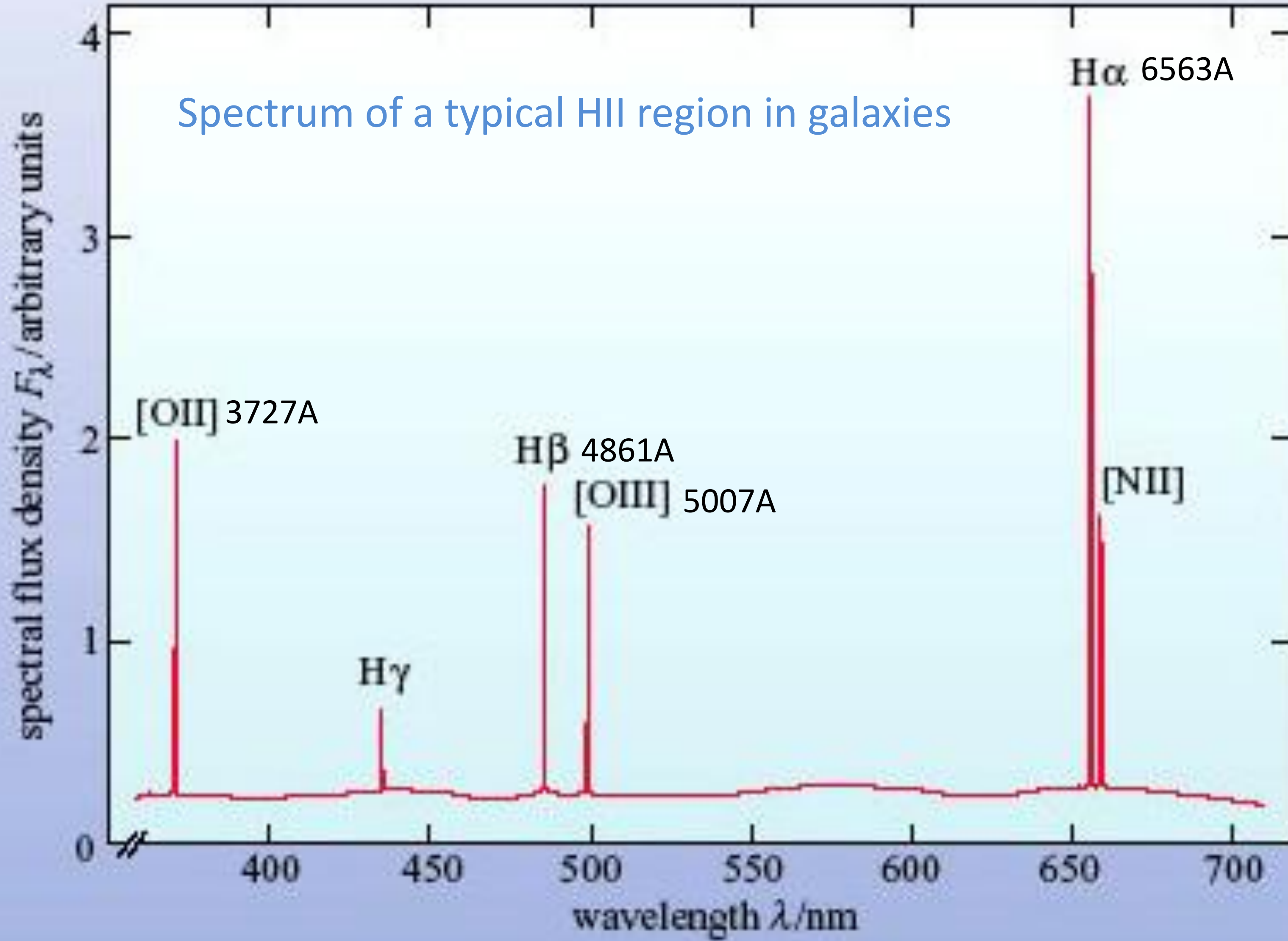
credit: Andrew Pontzen/Fabio Governato

Intensity Mapping



- Measure cumulative emission
- Faint galaxies
- High redshift
- Time-saving

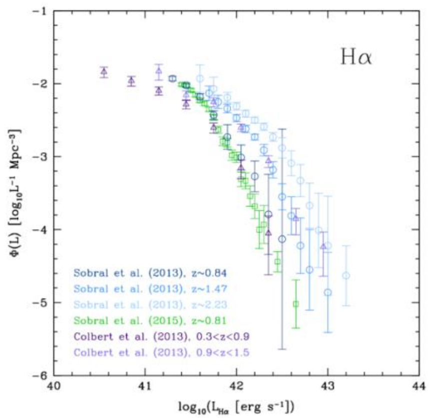
Hα, Hβ, [OII] and [OIII] emission lines as IM tracers



http://www.open.edu/openlearn/ocw/mod/oucontent/view.php?printable=1&id=2462

Line luminosity function

- Observed LFs

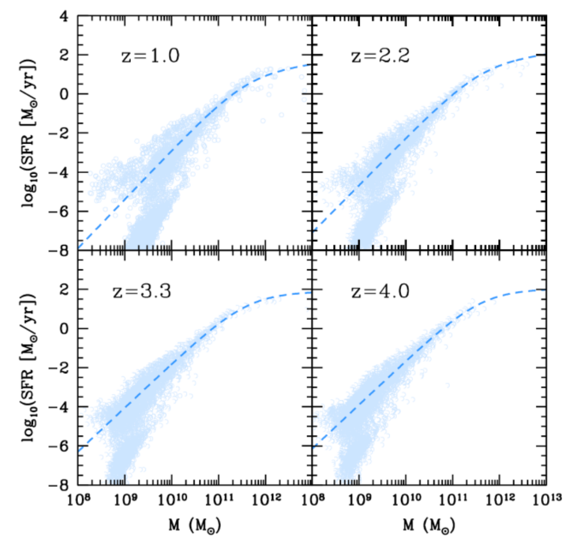


$$\Phi(L)dL = \phi_* \left(\frac{L}{L_*}\right)^\alpha \exp\left(-\frac{L}{L_*}\right)\frac{dL}{L_*}$$

(Schechter function)

Dust extinction included!

- SFR simulations (Guo et al 2013)



$$\mathrm{SFR}\,(M) = 10^a \left(\frac{M}{M_1}\right)^b \left(1+\frac{M}{M_2}\right)^c$$

$$\mathrm{SFR}\,(M_\odot \mathrm{yr}^{-1}) = (7.9 \pm 2.4) \times 10^{-42} L_{\mathrm{H}\alpha},$$
$$\mathrm{SFR}\,(M_\odot \mathrm{yr}^{-1}) = (7.6 \pm 3.7) \times 10^{-42} L_{[\mathrm{OIII}]},$$
$$\mathrm{SFR}\,(M_\odot \mathrm{yr}^{-1}) = (1.4 \pm 0.4) \times 10^{-41} L_{[\mathrm{OII}]}.$$

- SFRD function from Obs.

(Hopkins & Beacom 2006; Madau & Dickinson 2014)

$$\mathrm{SFRD}(z) = \int dM (dn/dM) \mathrm{SFR}(M, z) \Rightarrow \mathrm{SFR}(M, z) = f_*(z)\frac{\Omega_b}{\Omega_M}\frac{1}{t_s}M$$

$A_{\mathrm{H}\alpha} = 1.0$ mag, $A_{[\mathrm{OIII}]} = 1.32$ mag, $A_{[\mathrm{OII}]} = 0.62$ mag, and $A_{\mathrm{H}\beta} = 1.38$

Line mean intensity and power spectrum

- Line mean intensity

$$\bar{I}_\nu(z) = \int_{L_{\rm min}}^{L_{\rm max}} dL\, \Phi(L) \frac{L}{4\pi D_L^2} y(z) D_A^2$$ (For LFs)

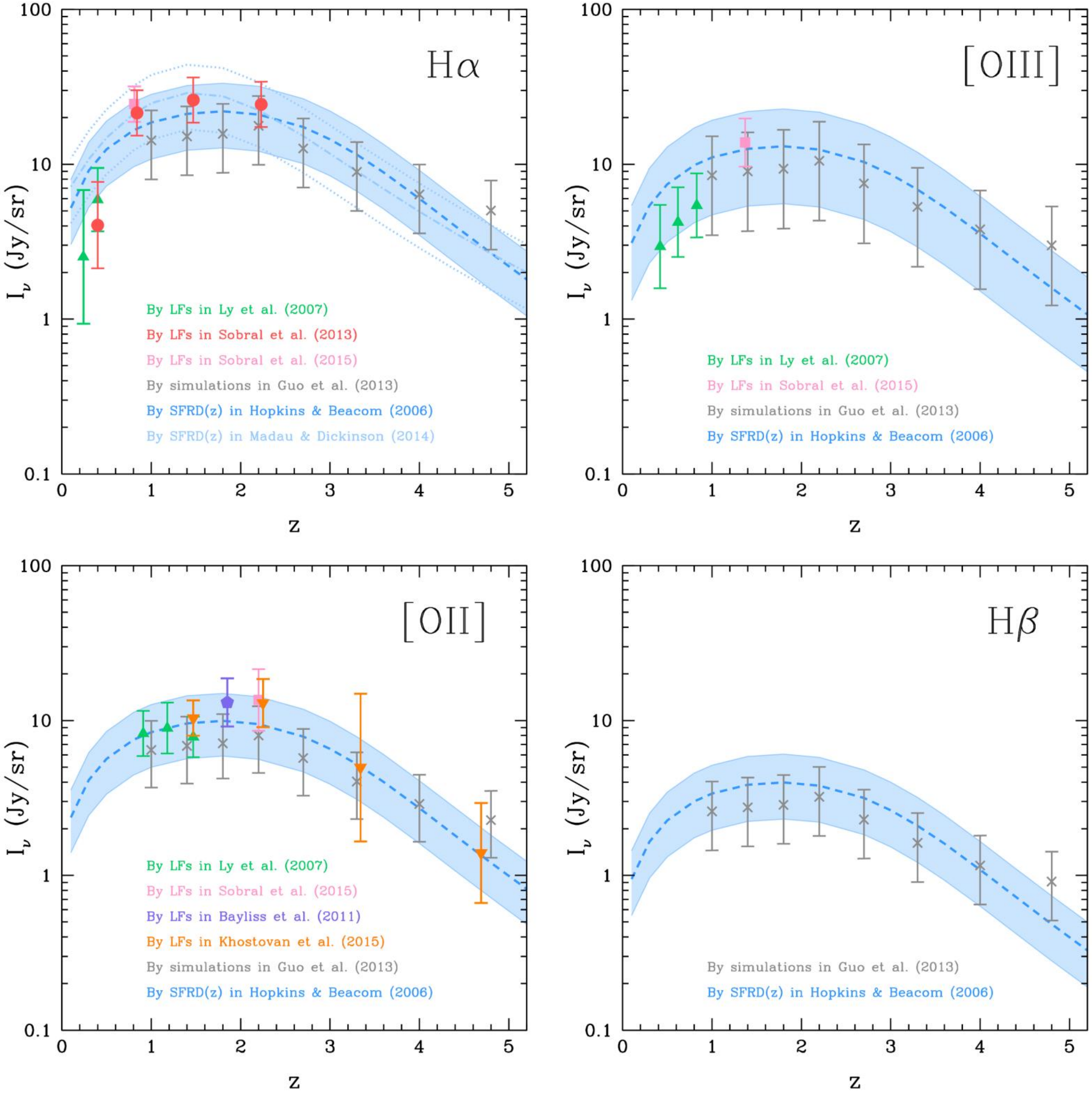
$$\bar{I}_\nu(z) = \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} \frac{L_{\rm line}(M,z)}{4\pi D_{\rm L}^2} y(z) D_{\rm A}^2$$ (For SFR)

- Line intensity power spectrum:

$$P^{\rm clus}_{\rm line}(k,z) = \bar{b}^2_{\rm line}\, \bar{I}^2_{\rm line}\, P_{\delta\delta}(k,z)$$ (Clustering power)

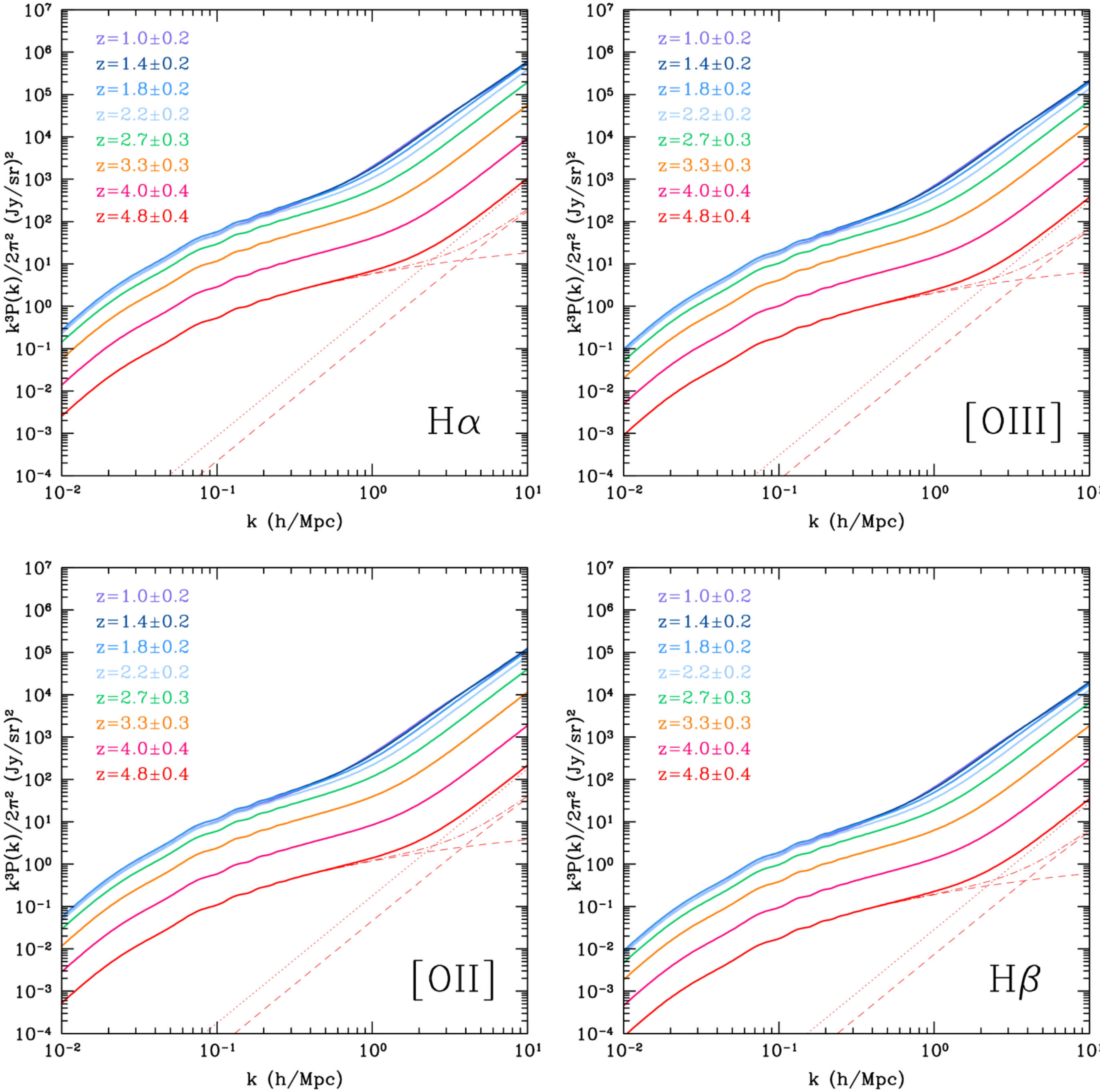
$$P^{\rm shot}_{\rm line}(z) = \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} \left[\frac{L_{\rm line}}{4\pi D_{\rm L}^2} y(z) D_{\rm A}^2 \right]^2$$ (Shot-noise power)

$$\bar{b}_{\rm line}(z) = \frac{\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}\, L_{\rm line}\, b(M,z)}{\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}\, L_{\rm line}}$$ (line bias)



Line mean intensity at 0<z<5

Ha>[OIII]>[OII]>Hb

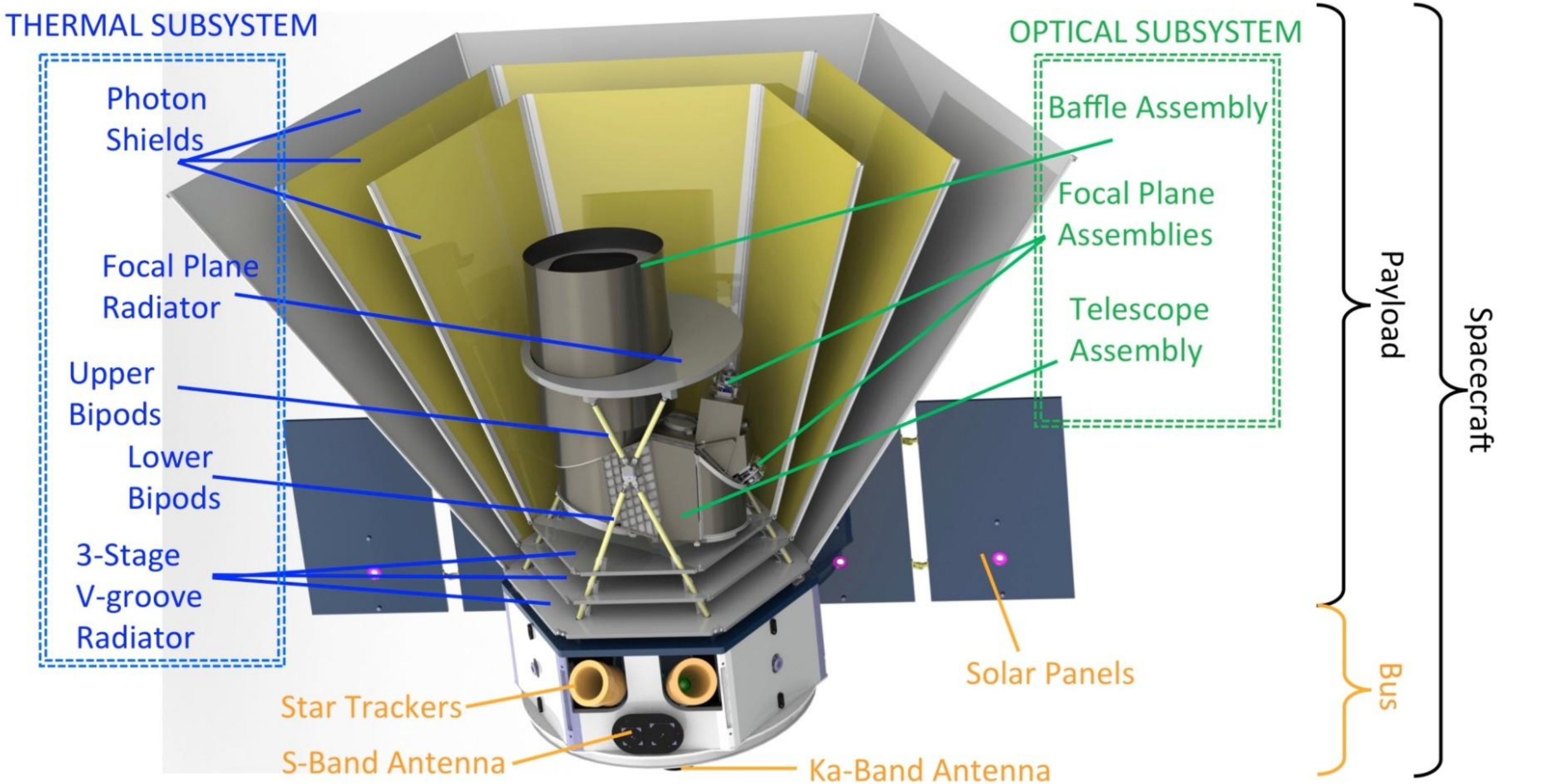


Line intensity power spectra at 1<z<5

Ha>[OIII]>[OII]>Hb at the same z

Detectability

SPHEREx experiment



Credit: http://spherex.caltech.edu/

A small NASA space explore mission

SPHEREx instrument parameters

Telescope Effective Aperture	20 cm
Pixel Size	6.2" x 6.2"
Field of View	2 x (3.5° x 7.0°); dichroic
Resolving Power and Wavelength Coverage	λ= 0.75- 4.18 μm; R=41.4 λ= 4.18 - 5.00 μm; R=135
Arrays	2x Hawaii-2RG 2.5 μm 2x Hawaii-2RG 5.3 μm
Point Source Sensitivity	18.4 AB mag (5σ) per frequency bin referenced at 2 μm. Sensitivity has 380% total margin to science requirement
Cooling	All-Passive
2.5 μm Array and Optics Temperature	80K
5.3 μm Array Temperature	55K
Payload Mass	68.7 kg

http://spherex.caltech.edu/

- Foreground line contamination:

$$P_{\rm obs}(k,z) = P_s(k,z) + \sum_{i=1}^{N} P_f^{p,i}(k_f,z)$$ (Total power spectrum)

$$P_f^p(k_f,z) = A_\perp^2 A_\| P_f(k_f,z_f)$$ (Foreground line power spectrum)

$$k = \sqrt{k_\perp^2 + k_\|^2} \qquad k_f = \sqrt{A_\perp^2 k_\perp^2 + A_\|^2 k_\|^2}$$

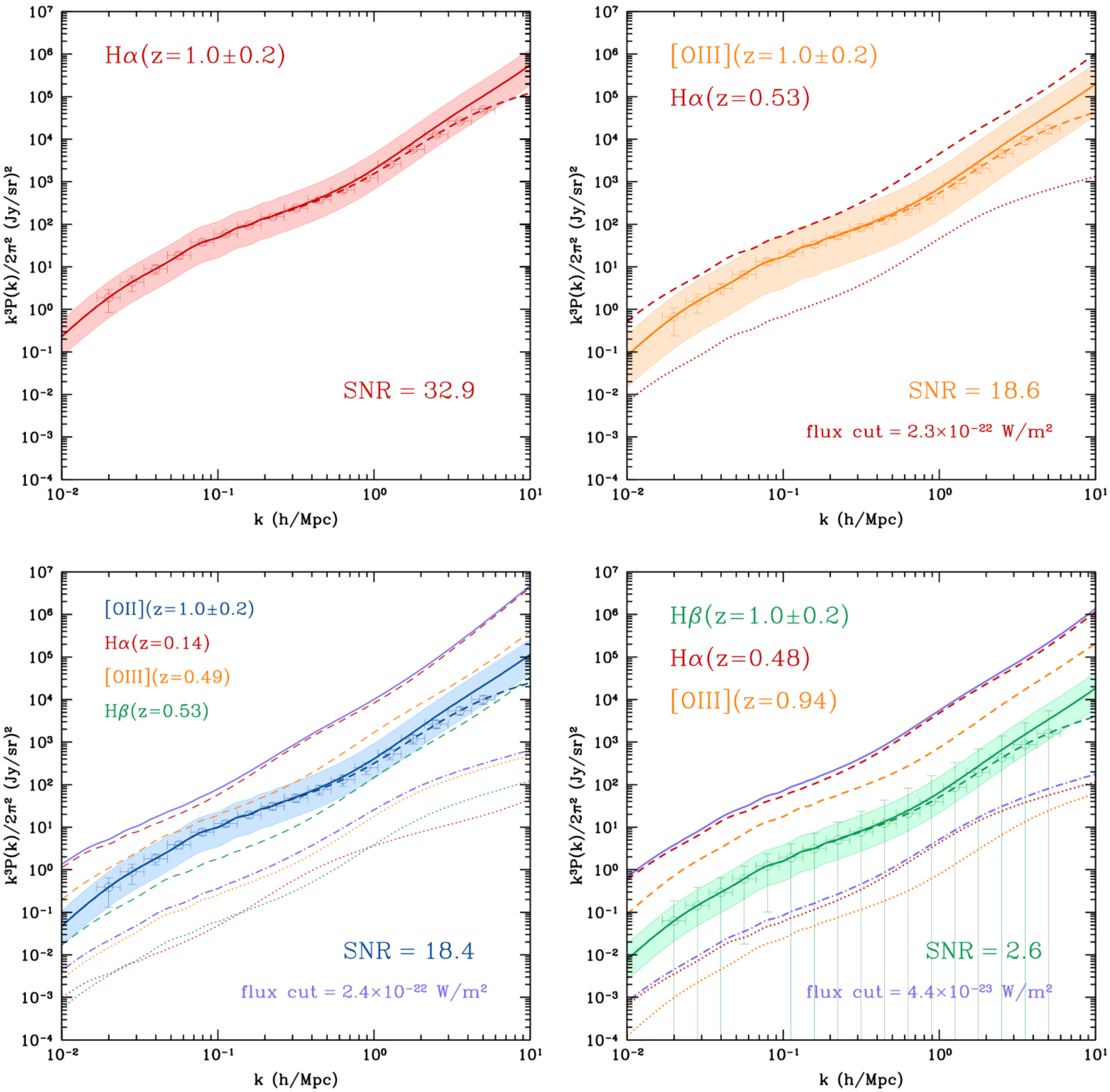
$$A_\perp = r_s/r_f \qquad A_\| = y_s/y_f$$

- Detected Signal to Noise Ratio (SNR):

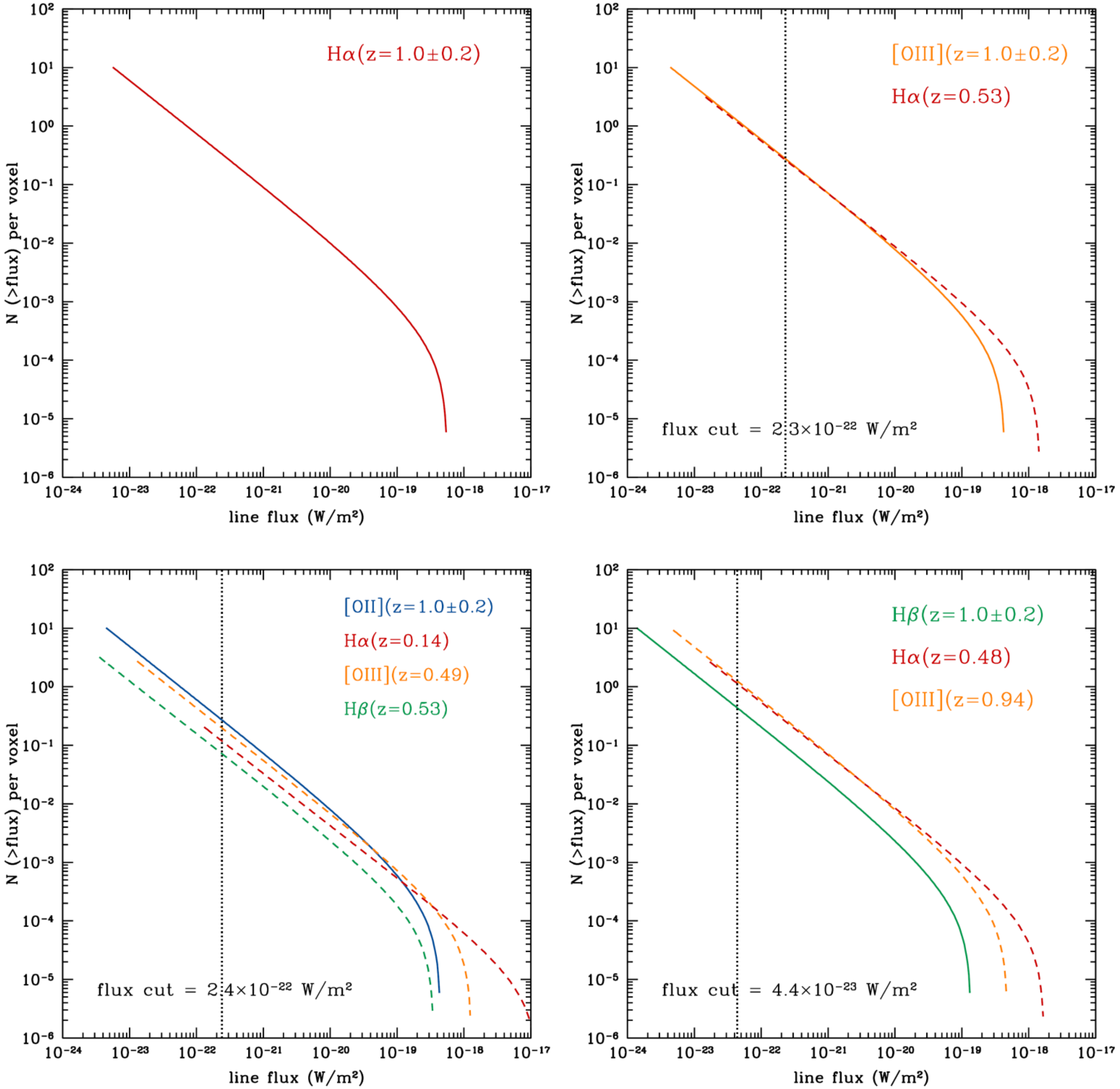
$$\Delta P_{\rm line}(k)^2 = \frac{\left[P_{\rm line}(k) + P_N^{\rm line}(k)\right]^2}{N_m(k)}$$ (Variance of the power spectrum)

$$P_N^{\rm line}(k) = \frac{V_{\rm pix}\,\sigma_{\rm pix}^2}{t_{\rm pix}}$$ (noise power spectrum)

$$\mathrm{SNR} = \sqrt{\sum_{k\ \rm bin}\left[\frac{P_{\rm line}(k)}{\Delta P_{\rm line}(k)}\right]^2}$$



Detectability of line intensity power spectra at z~1



Number of sources per voxel at z~1

SNRs, flux cuts, and % of removed pixels for SPHEREx

Line		$z \sim 1.0$	$z \sim 1.4$	$z \sim 1.8$	$z \sim 2.2$	$z \sim 2.7$	$z \sim 3.3$	$z \sim 4.0$	$z \sim 4.8$
Hα	SNR	32.9	44.0	33.6	29.4	39.6	20.0	7.1	1.3
	flux cut (W/m^2)	-	-	-	-	-	-	-	-
	% of rem. pix.	-	-	-	-	-	-	-	-
[OIII]	SNR	18.6	13.0	19.7	14.4	11.5	4.8	2.6	0.5
	flux cut (W/m^2)	2.3×10^{-22}	1.4×10^{-22}	8.4×10^{-23}	6.0×10^{-23}	2.4×10^{-23}	6.8×10^{-24}	2.8×10^{-24}	1.3×10^{-24}
	% of rem. pix.	3%	4%	5%	6%	10%	21%	42%	55%
[OII]	SNR	18.4	11.4	8.2	6.4	8.4	3.2	0.8	0.1
	flux cut (W/m^2)	2.4×10^{-22}	8.6×10^{-23}	4.0×10^{-23}	2.5×10^{-23}	9.9×10^{-24}	4.6×10^{-24}	2.4×10^{-24}	9.9×10^{-25}
	% of rem. pix.	3%	5%	9%	20%	32%	43%	53%	67%
Hβ	SNR	2.6	1.8	2.9	2.1	1.4	0.5	0.3	< 0.1
	flux cut (W/m^2)	4.4×10^{-23}	2.6×10^{-23}	1.3×10^{-23}	9.2×10^{-24}	5.2×10^{-24}	3.0×10^{-24}	1.6×10^{-24}	8.8×10^{-25}
	% of rem. pix.	12%	15%	21%	27%	38%	48%	65%	87%

- Ha is the best tracer (no strong interloper lines, SNR>7 at z<4)
- [OIII] is better than [OII] (SNR_[OIII]>11 and SNR_[OII]>8 at z<3)
- Hb is challenging to measure (strong contamination, SNR<3 for all z)

Cross correlation with 21-cm line

CHIME and Tianlai 21-cm experiments

CHIME and Tianlai specs

	CHIME	Tianlai	Unit
Survey area A_s	10000	10000	deg^2
Total int. time t_{tot}	10^4	10^4	hour
Total bandwidth	400-800	400-1420	MHz
Redshift range	0.8-2.5	0.0-2.5	-
Sys. Temp. T_{sys}	50	50	K
FoV N-S	$\sim$150	$\sim$150	deg
FoV E-W	$\sim$1.9	$\sim$1.6	deg
Cylinder size	100×20	120×15	m^2
Num. of cylinders	5	8	-
Tot. Collecting area	10000	14400	m^2
Num. of feeds	256×5	275×8	-
Freq. resolution $\Delta\nu$	$\sim$1	$\sim$0.1	MHz

- Cross power spectrum:

$$P_{\rm cross}^{\rm clus}(k,z) = \bar{b}_{\rm 21cm}\bar{b}_{\rm line}\bar{T}_{\rm 21cm}\bar{T}_{\rm line}\, P_{\delta\delta}(k,z)$$ (Cross clustering power)

$$P_{\rm cross}^{\rm shot} = \sqrt{P_{\rm line}^{\rm shot} P_{\rm 21cm}^{\rm shot}}$$ (Cross shot-noise power)

$$P_{\rm 21cm}^{\rm shot}(z) = \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM}\left(\bar{T}_{\rm 21cm}\frac{M_{\rm HI}}{\rho_{\rm HI}}\right)^2$$ (21-cm shot-noise power)

$$\bar{b}_{\rm 21cm}(z) = \frac{\int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} M_{\rm HI}\, b(M,z)}{\rho_{\rm HI}}$$

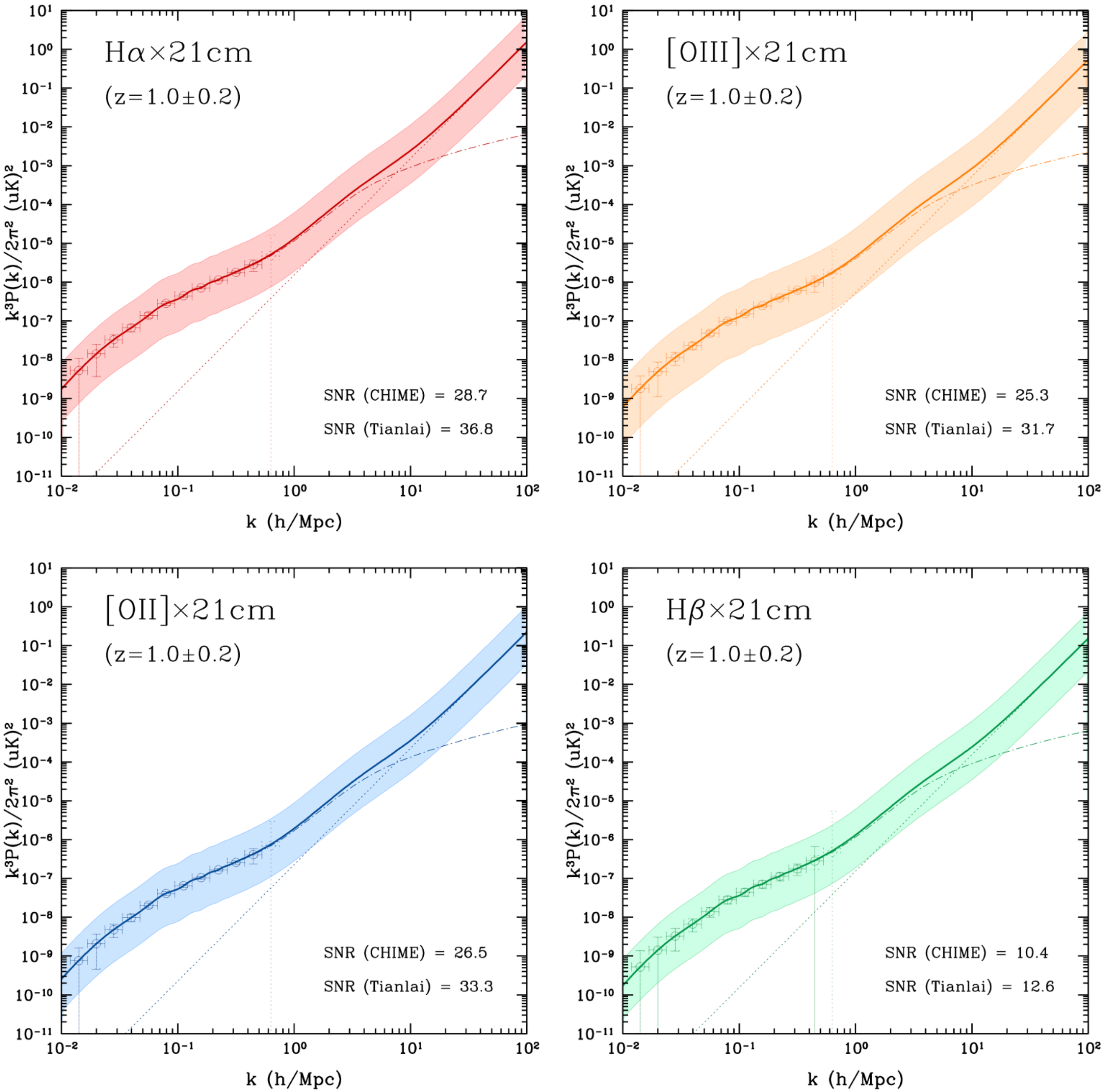
$$\bar{T}_{\rm 21cm}(z) = 248\left(\frac{\Omega_{\rm HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{1+z}{1.8}\right)^{0.5}\left[\frac{\Omega_M+\Omega_\Lambda(1+z)^{-3}}{0.37}\right]^{-0.5}\mu{\rm K}.$$

- Variance of the cross power spectrum:

$$(\Delta P_{\rm cross})^2 = \frac{P_{\rm cross}^2 + (P_{\rm line}+P_N^{\rm line})(P_{\rm 21cm}+P_N^{\rm 21cm})}{2\,N_m^{\rm cross}(k)}$$ (Variance)

$$P_N^{\rm 21cm} = r_c^2\, y(z)\frac{\lambda^2\, T_{\rm sys}^2}{A_e\, t_k}$$ (21-cm noise power spectrum)

$$t_k = t_0(A_e/\lambda^2)n(\mu_\perp) \qquad \mu_\perp = k\sin(\theta)r_c/2\pi$$



Cross power spectra of optical lines and 21-cm line at z~1

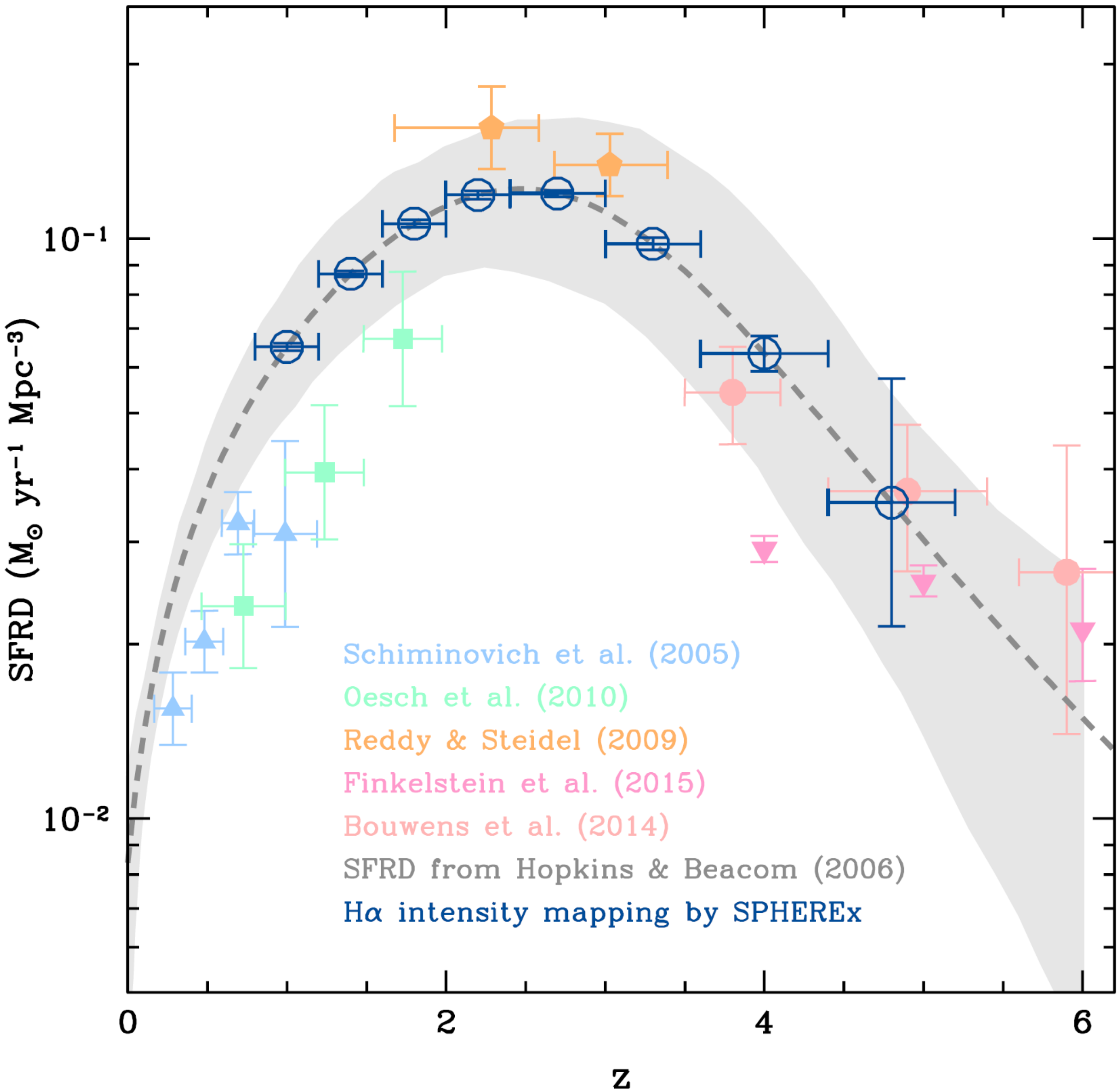
SNRs of SPHEREx $\times$ CHIME and Tianlai

Line	21-cm expt.	$z = 1.0 \pm 0.2$	$z = 1.4 \pm 0.2$	$z = 1.8 \pm 0.2$	$z = 2.2 \pm 0.2$
Hα	$\times$CHIME	28.7	26.9	18.9	15.2
	$\times$Tianlai	36.8	36.1	26.6	22.0
[OIII]	$\times$CHIME	25.3	16.7	17.8	12.2
	$\times$Tianlai	31.7	21.6	18.4	17.4
[OII]	$\times$CHIME	26.5	17.2	11.7	8.8
	$\times$Tianlai	33.3	22.2	15.8	12.4
Hβ	$\times$CHIME	10.4	6.8	7.8	5.2
	$\times$Tianlai	12.6	8.5	10.5	7.3

HIRAX has similar SNR; SKA1-mid as single dishes has smaller SNR (SNR~5.7 at z=1)

Cross correlation is a good method for extracting IM signal!

Constraints on SFRD(z) by SPHEREx



Error<7% at z<4, better than the measurements from galaxy LFs

Derived by Fisher matrix, no degeneracy between other parameters.


IM is a powerful tool to explore high-z Universe!
https://www.nas.nasa.gov/SC14/demos/demo27.html#prettyPhoto

Thanks!