



上海交通大学

SHANGHAI JIAO TONG UNIVERSITY



宇宙结构形成和大型光谱巡天

景益鹏

天文系

物理与天文学院



内容

- ④ **宇宙结构形成：进展和问题**
- ④ **大型光谱巡天：回顾、现状和展望**



现代宇宙学—爱因斯坦

宇宙学原理：宇宙是均匀和各向同性的

- 宇宙时空可以用简单的几何模型来描述，即 Robertson-Walker 度规

时空与物质联系由广义相对论决定

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu}$$

- 时空（左边）是由能动量张量（右边）决定，即宇宙的时空是由宇宙的物质决定

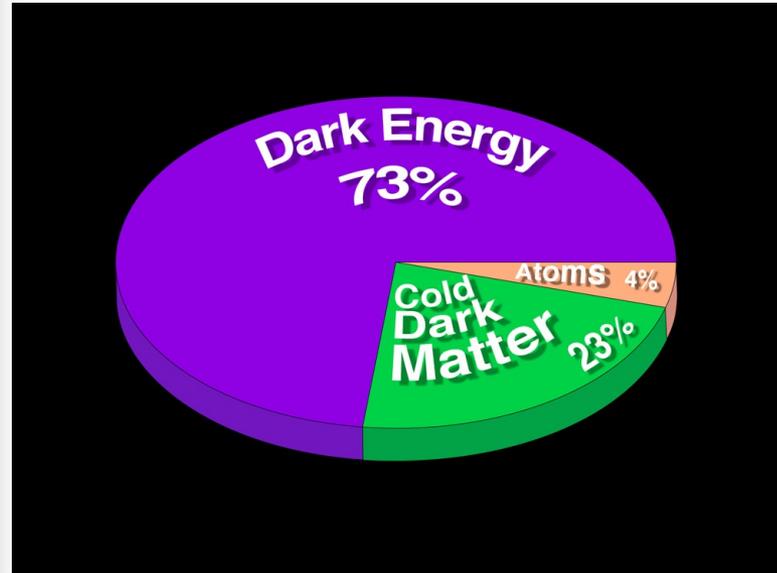
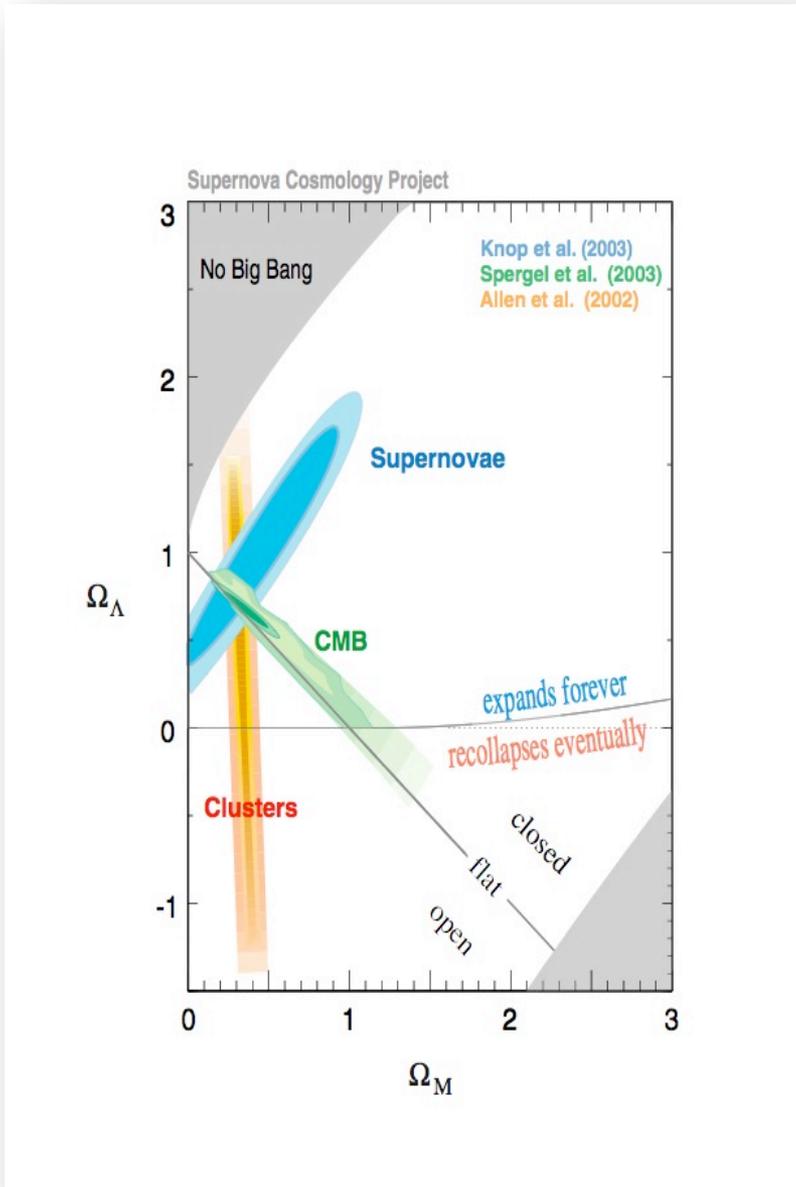


宇宙物质成分

- ④ 原子物质（包括离子、分子），通常也称为重子物质
- ④ 光子（宇宙微波背景等）
- ④ 中微子
- ④ 暗物质
- ④ 暗能量
- ④



现代宇宙学模型



只有6个物理参量：

重子物质密度 Ω_b

冷暗物质密度 Ω_{dm}

(真空) 暗能量密度 Ω_λ

哈勃常数 h

原初扰动谱 (n_s, σ_8)



最新的Planck卫星测量结果（综合了其他观测）

Planck Collaboration: Cosmological parameters

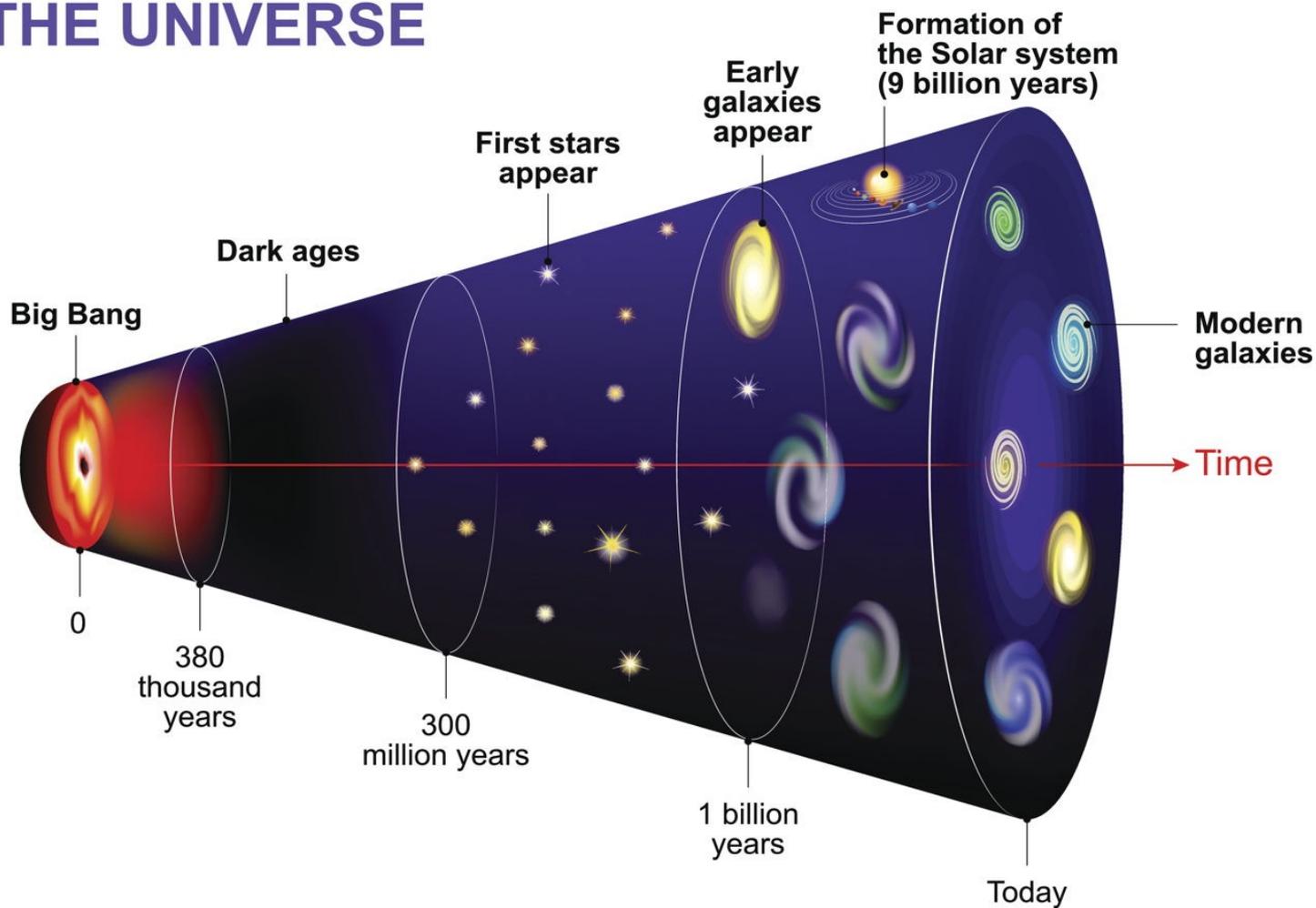
总行也...
新项目。

Parameter	<i>Planck</i>		<i>Planck+lensing</i>		<i>Planck+WP</i>	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2



天文学家的宇宙演化历史

EVOLUTION OF THE UNIVERSE



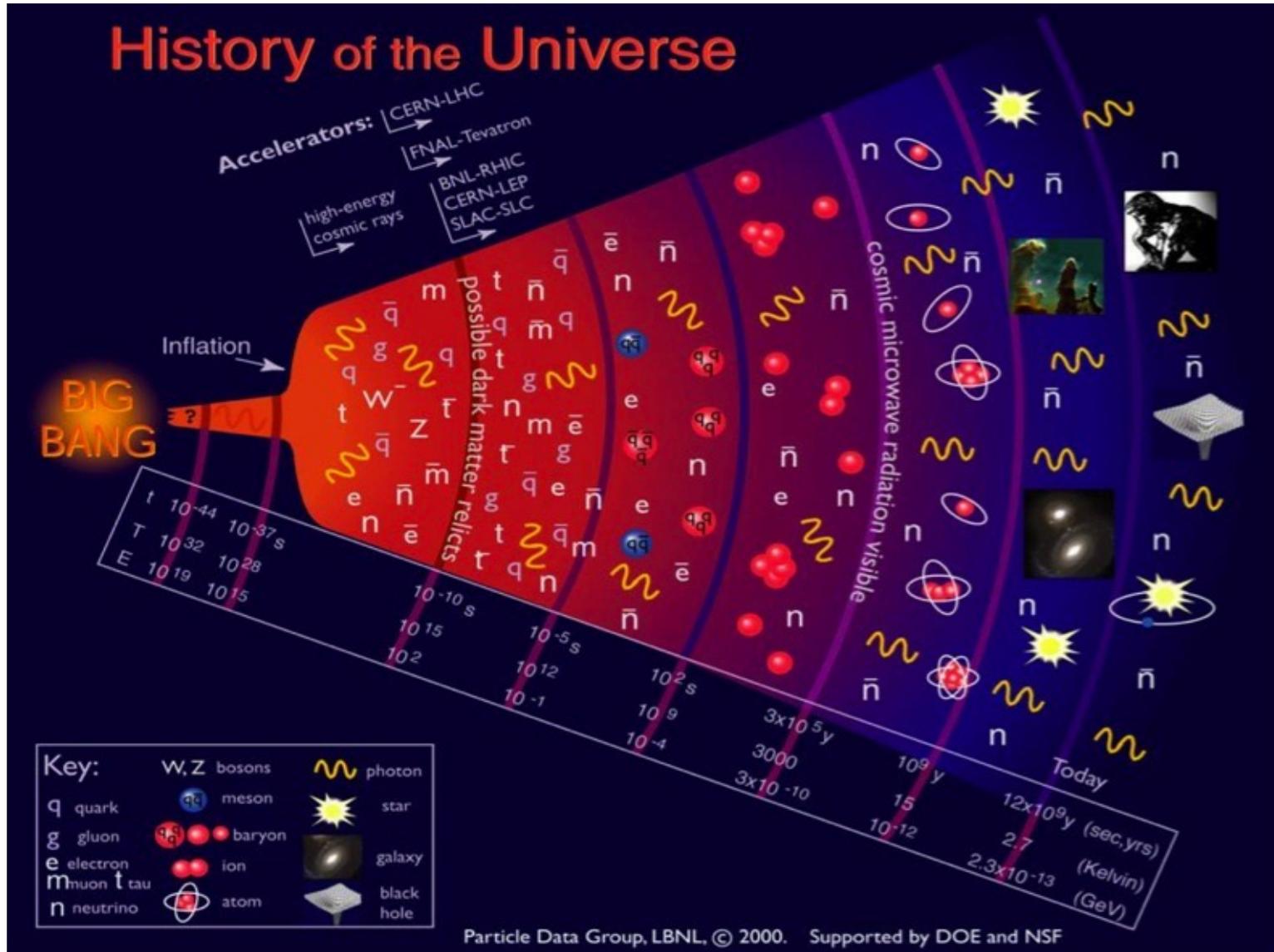


宇宙结构及其演化

- ① 宇宙结构的形成——引力不稳定性（理论）
- ② 宇宙的网络结构（理论）
- ③ 宇宙结构——斯隆数字巡天（观测）



天体（粒子）物理学家的宇宙演化历史





宇宙学研究前沿

- ④ **暗物质：是冷暗物质？粒子性质？**
- ④ **暗能量：是真空能量吗？引力理论有问题吗？**
- ④ **中微子：中微子的质量**
- ④ **宇宙微波背景：极化与宇宙暴涨物理**
- ④ **重子物质：星系（恒星）是如何形成？银河系是如何集成的？**

- ④ **这些问题相互关联, 宇宙、物质、天体的起源成为从第一性物理原理出发研究的问题**



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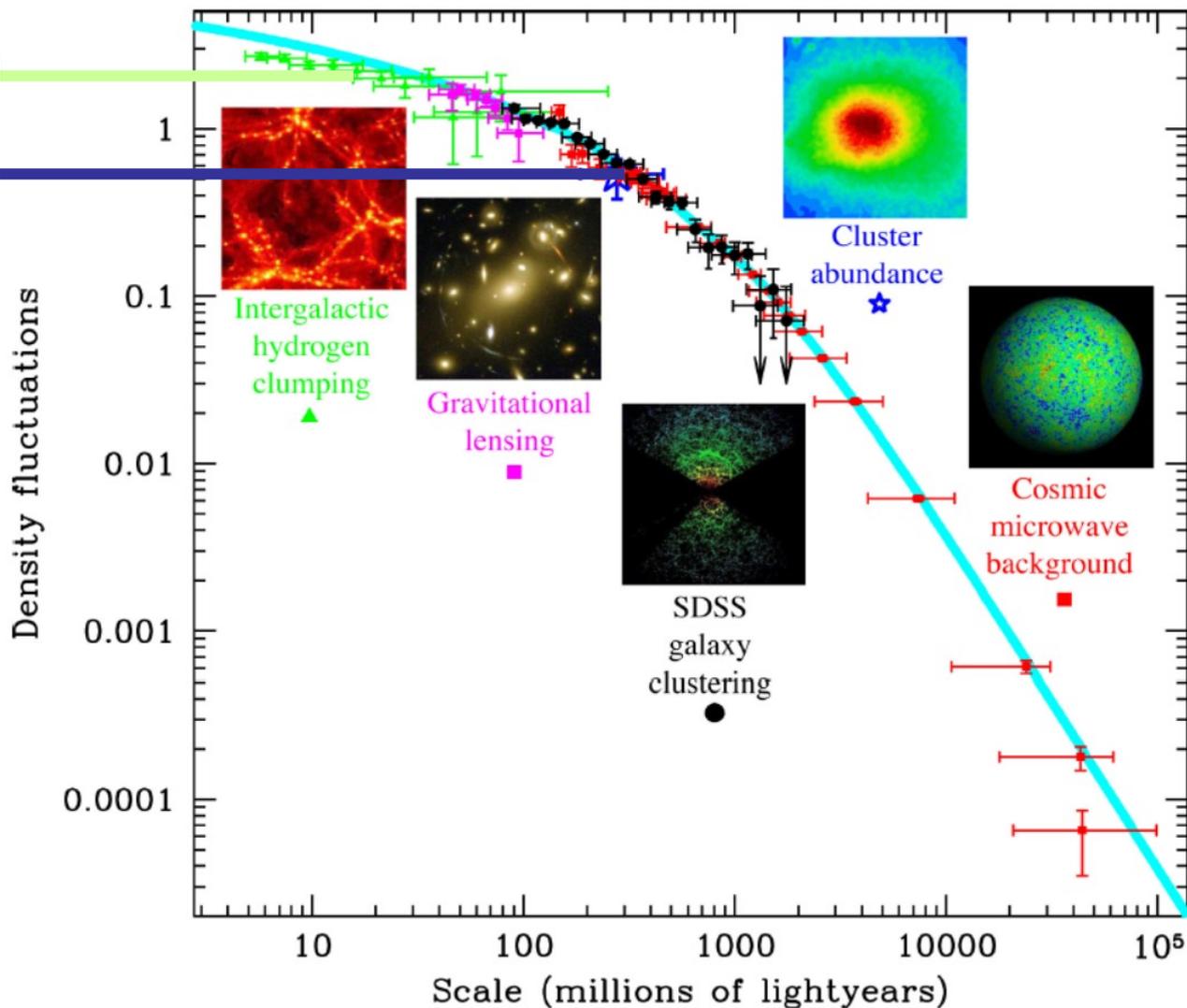


Current status from observations

The Tegmark representation of power spectrum data (2006)

Warm

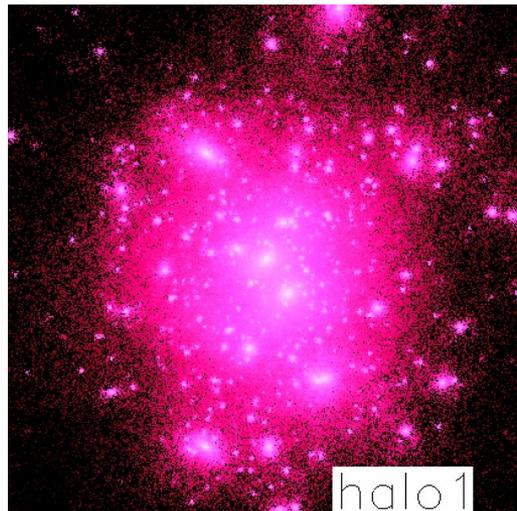
Hot



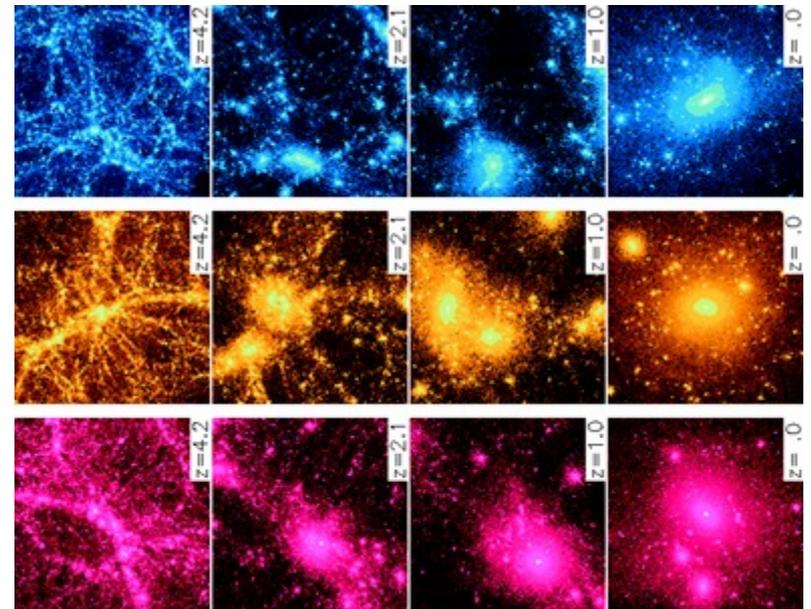


Cold DM and Hierarchical Formation

- Generic Prediction:
abundant small
objects within
(subhalos) and
around (small halos)
big objects (host
halos)



Time →





冷暗物质和温暗物质模型中银河系暗物质晕

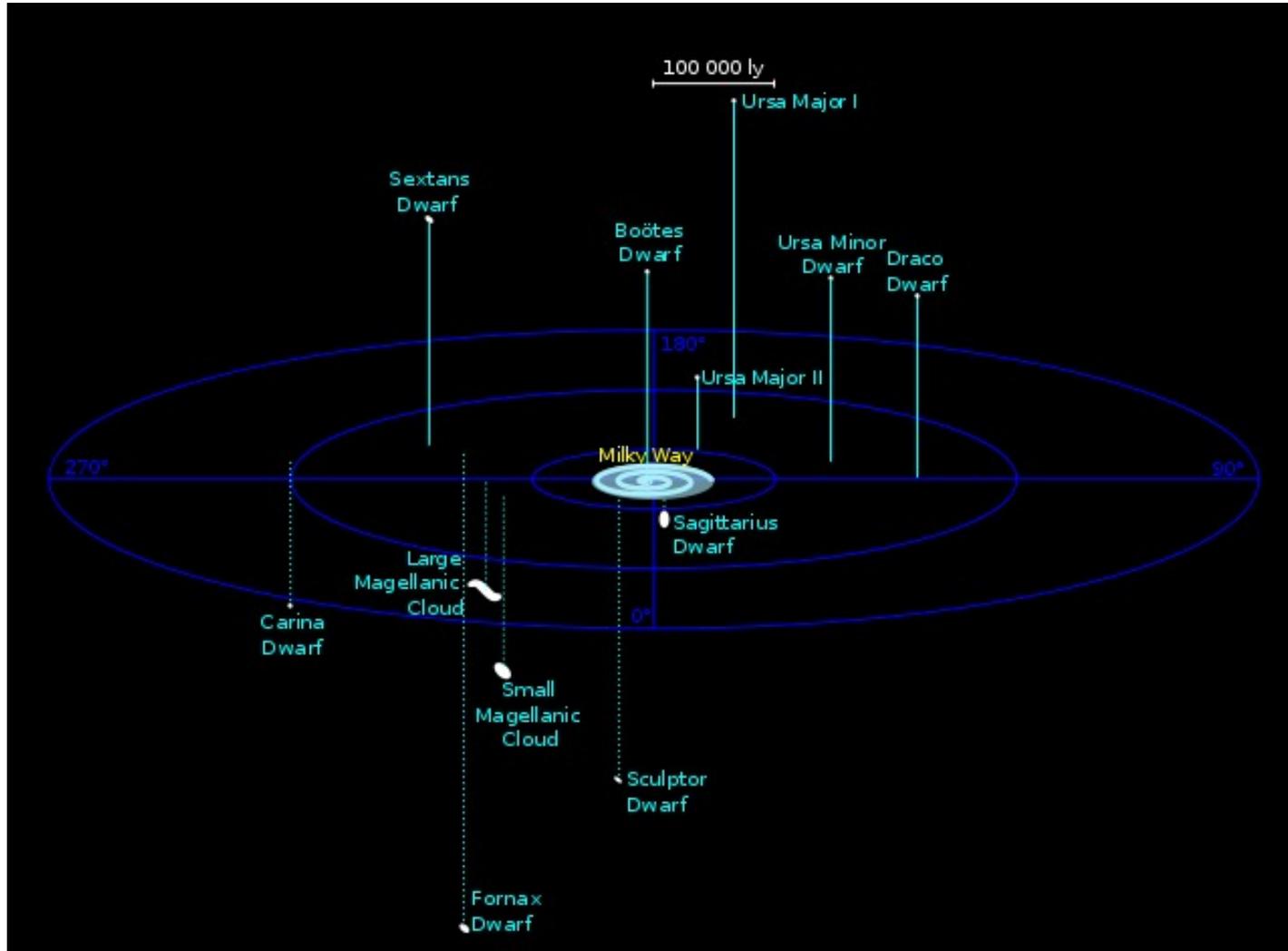
GX_WDM

GX_CDM

Jing 2001



The satellites of the MW





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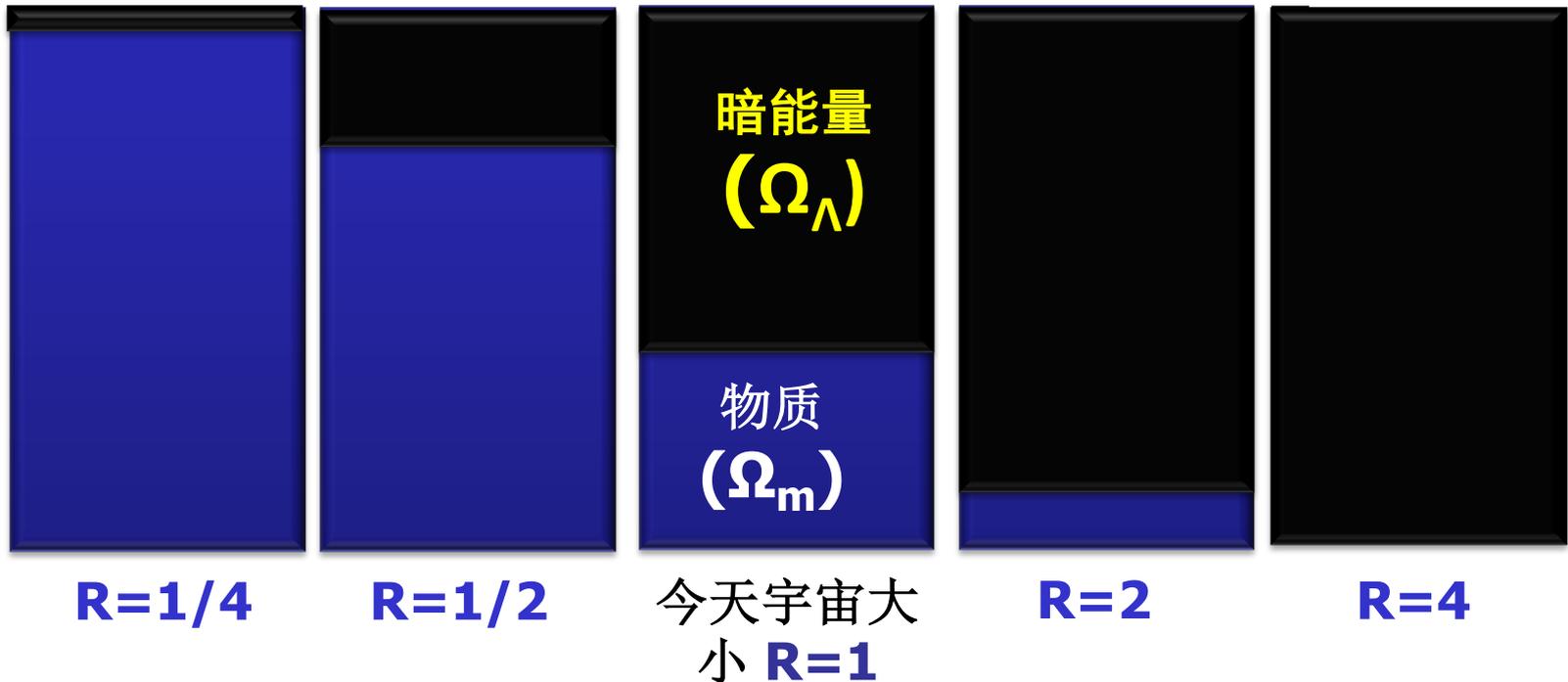
- ④ 这些问题相互关联，宇宙、物质、天体的起源成为从第一性物理原理出发研究的问题



为什么不喜欢真空能：宇宙学巧合问题！

1. 观测对应的真空能量只是通常粒子场论预言 10^{-120} ，为什么它这么小而不等于0？
2. 为什么只在今天，真空能对应的能量与物质对应的能量相当，而在以前它小的可忽略，它以后是主导

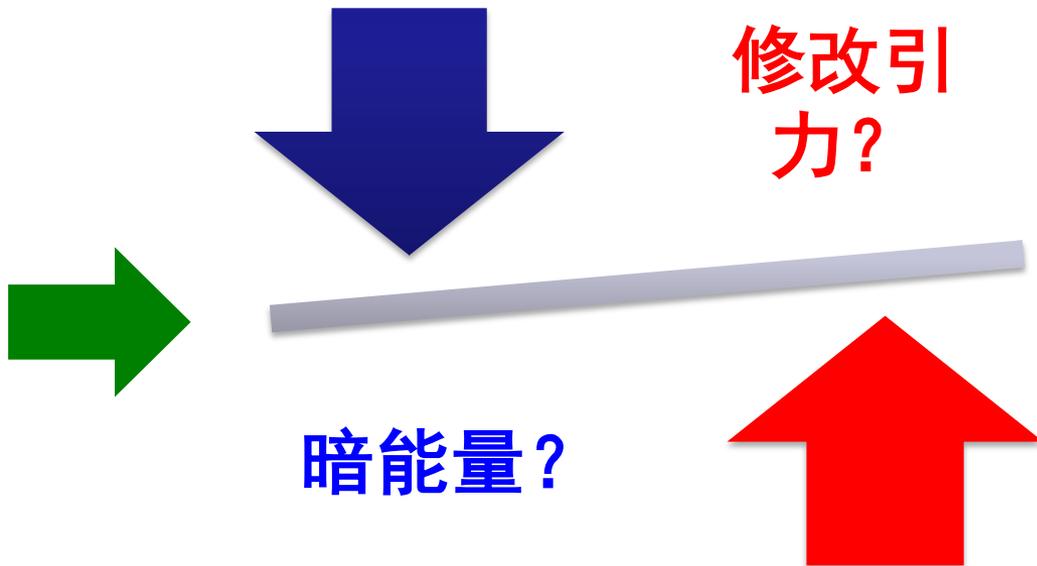
解决的**可能方法**：1) 动力学暗能量模型 $w(z)$ ；2) 暗物质与暗能量的相互作用；...N)等等





暗能量 PK 修改引力论

宇宙加速膨胀



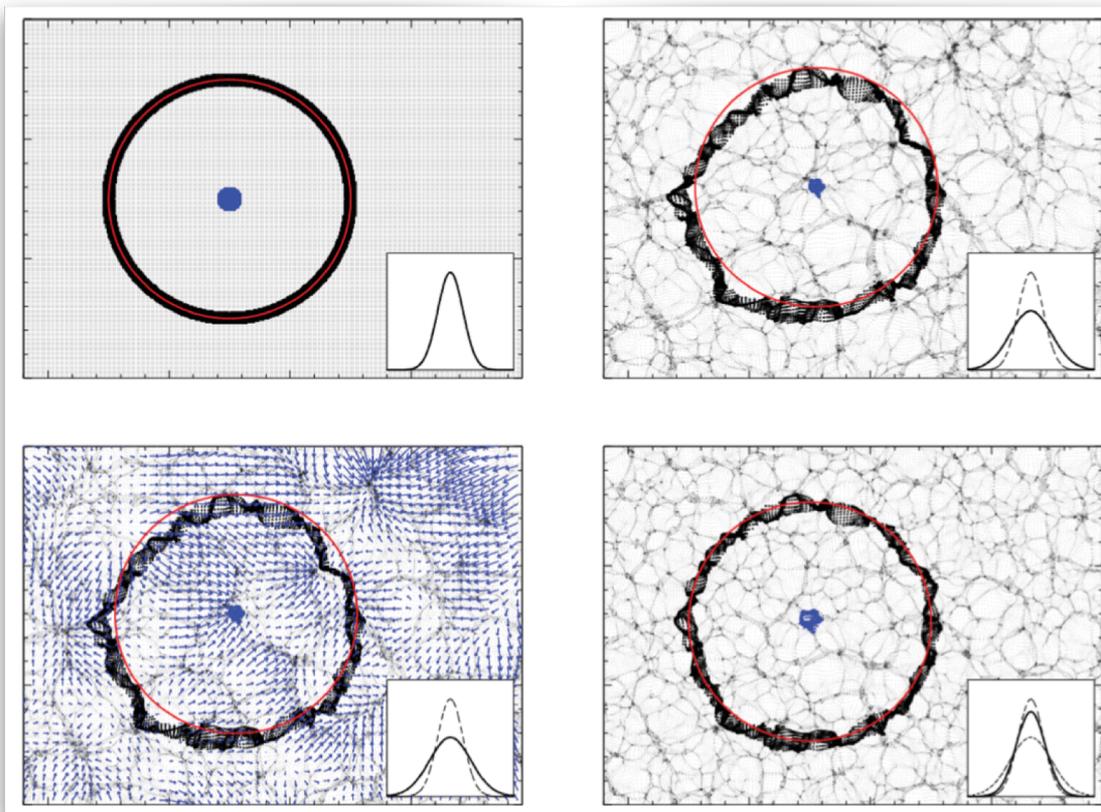
暗能量特别工作组报告（2006）

天文与粒子物理学界关于暗能量研究的权威咨询报告

“宇宙加速膨胀、表明基本粒子和引力理论或不正确、或不完备。大多数专家相信需要基础物理革命来全面理解宇宙加速膨胀”

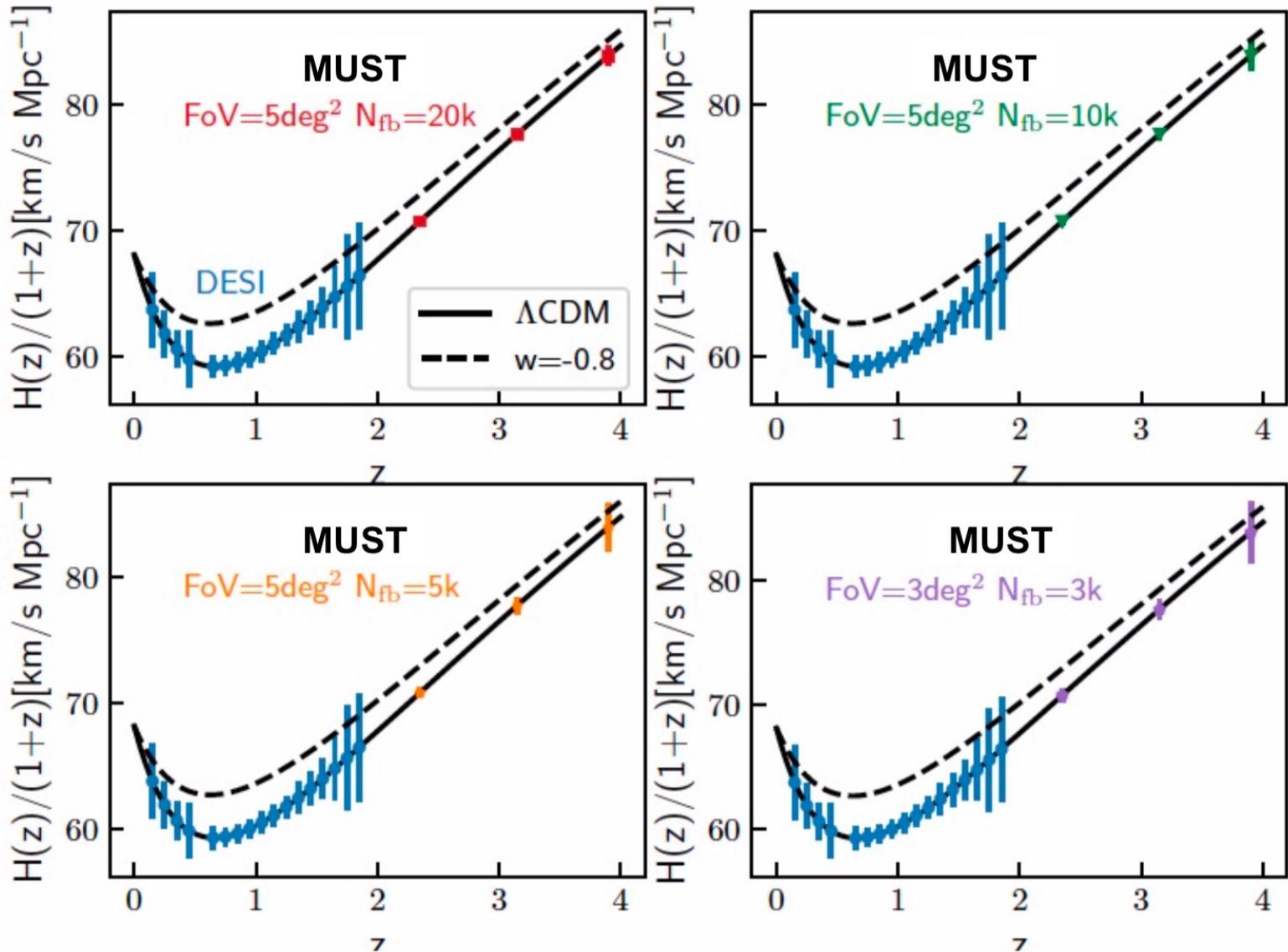


红移空间星系分布：重子声波震荡和红移畸变





重子声波震荡在视线方向的特征尺度

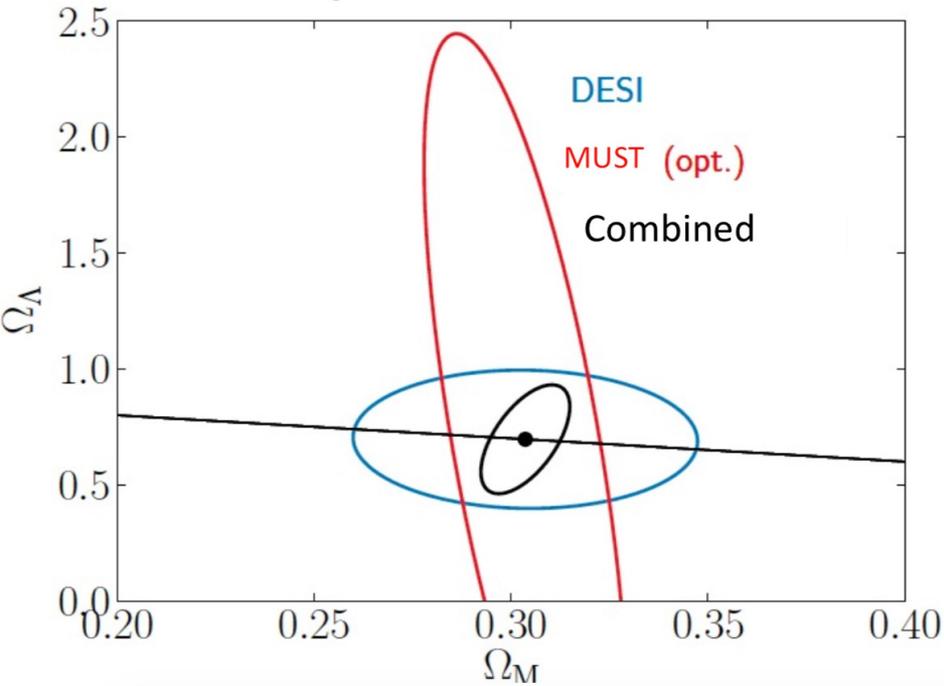




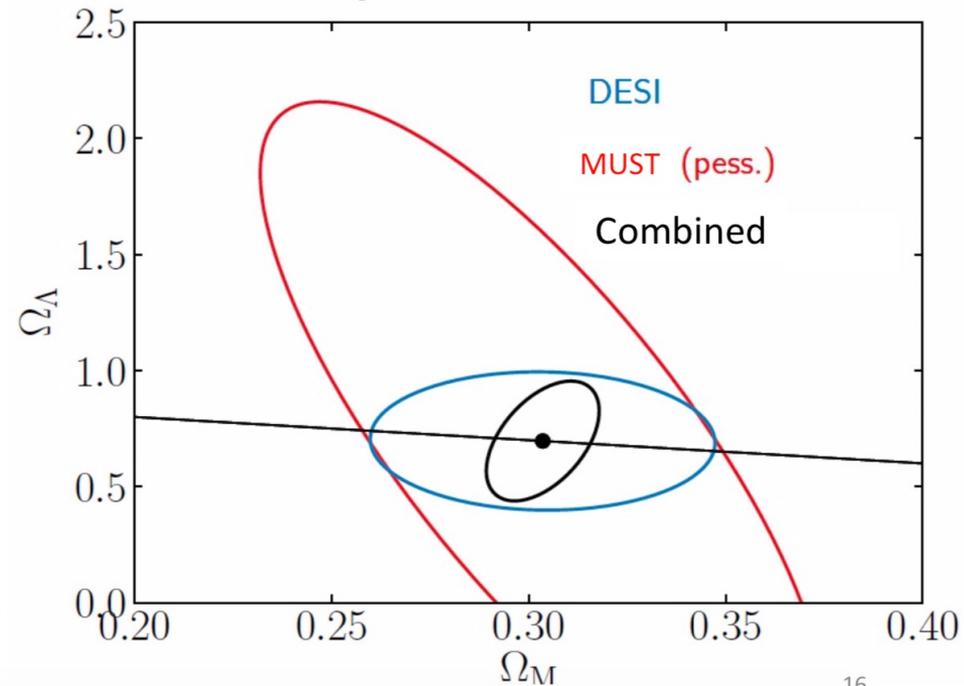
高红移大尺度结构很有用

What do **we** MUST do for dark energy?

(5 deg², 20000 fibres)

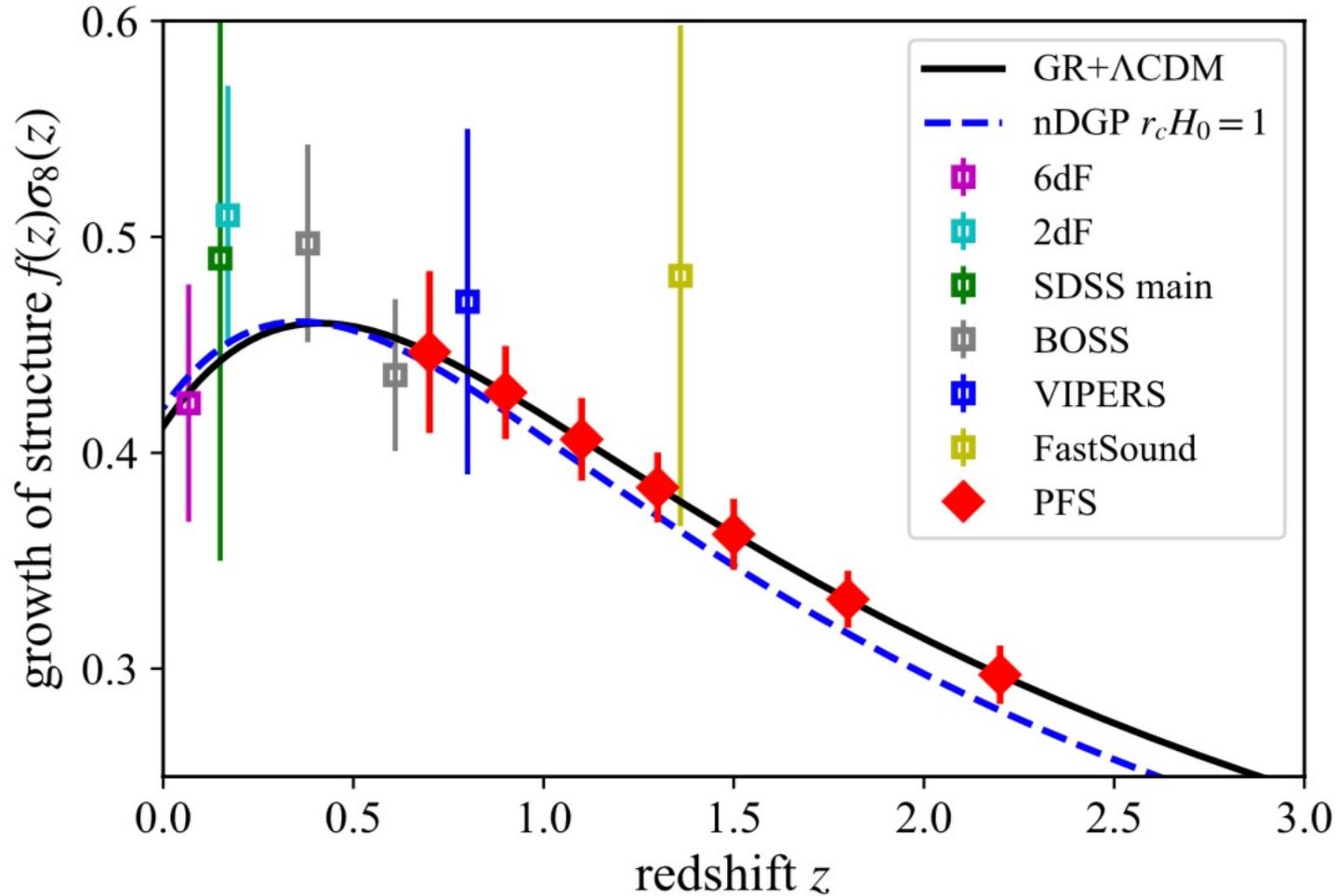


(3 deg², 3000 fibres)





星系分布在红移空间的畸变





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中微子质量

- 中微子发现： β 衰变的粒子能谱是连续，泡利提出中微子的存在
- 粒子标准模型：自旋1/2, 质量为0的轻子 (修改前)
- 中微子振荡：1998年日本超级神冈中微子探测器发现中微子振荡 (中微子转换), 表明中微子质量不为0

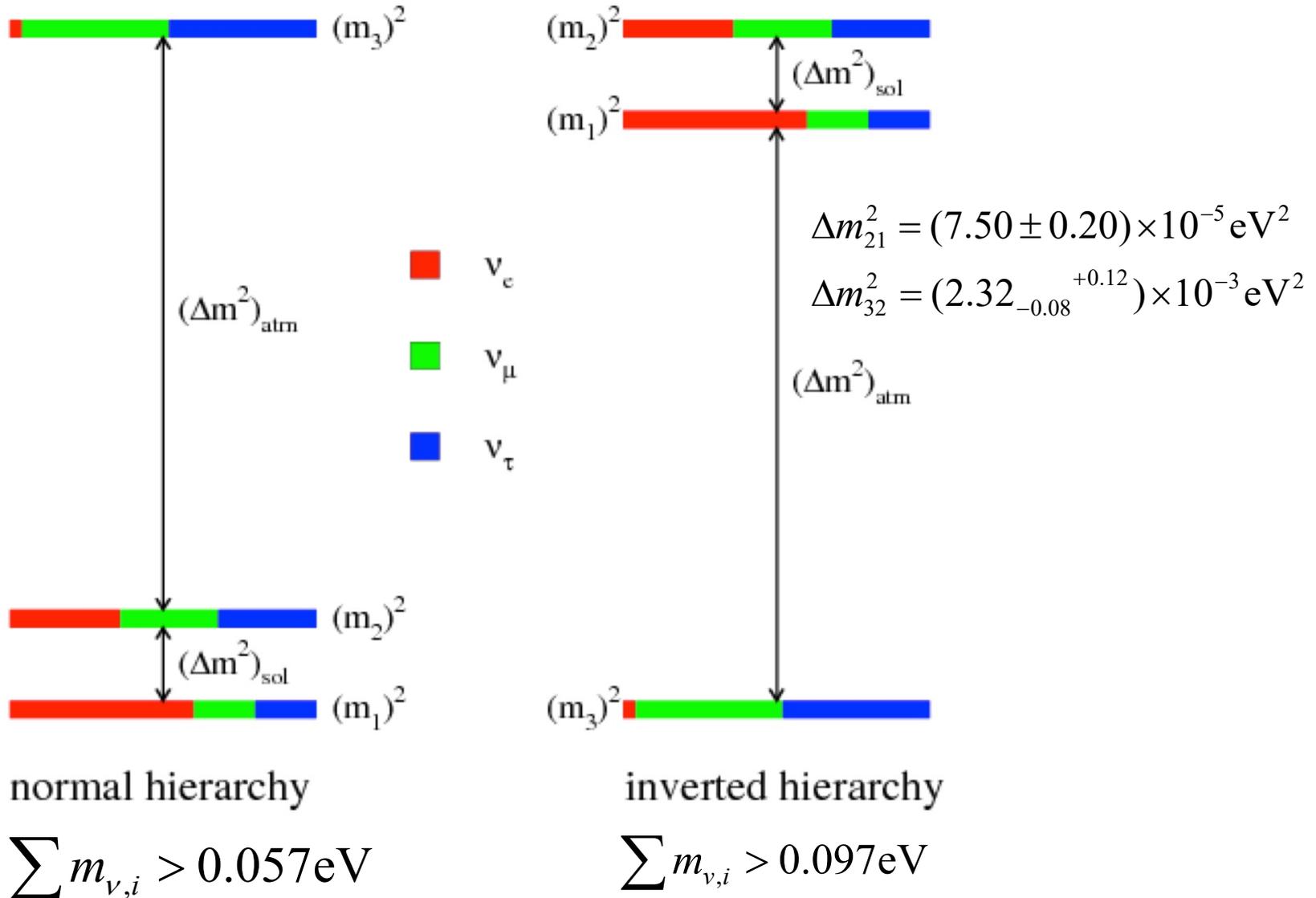
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Source: AAAS

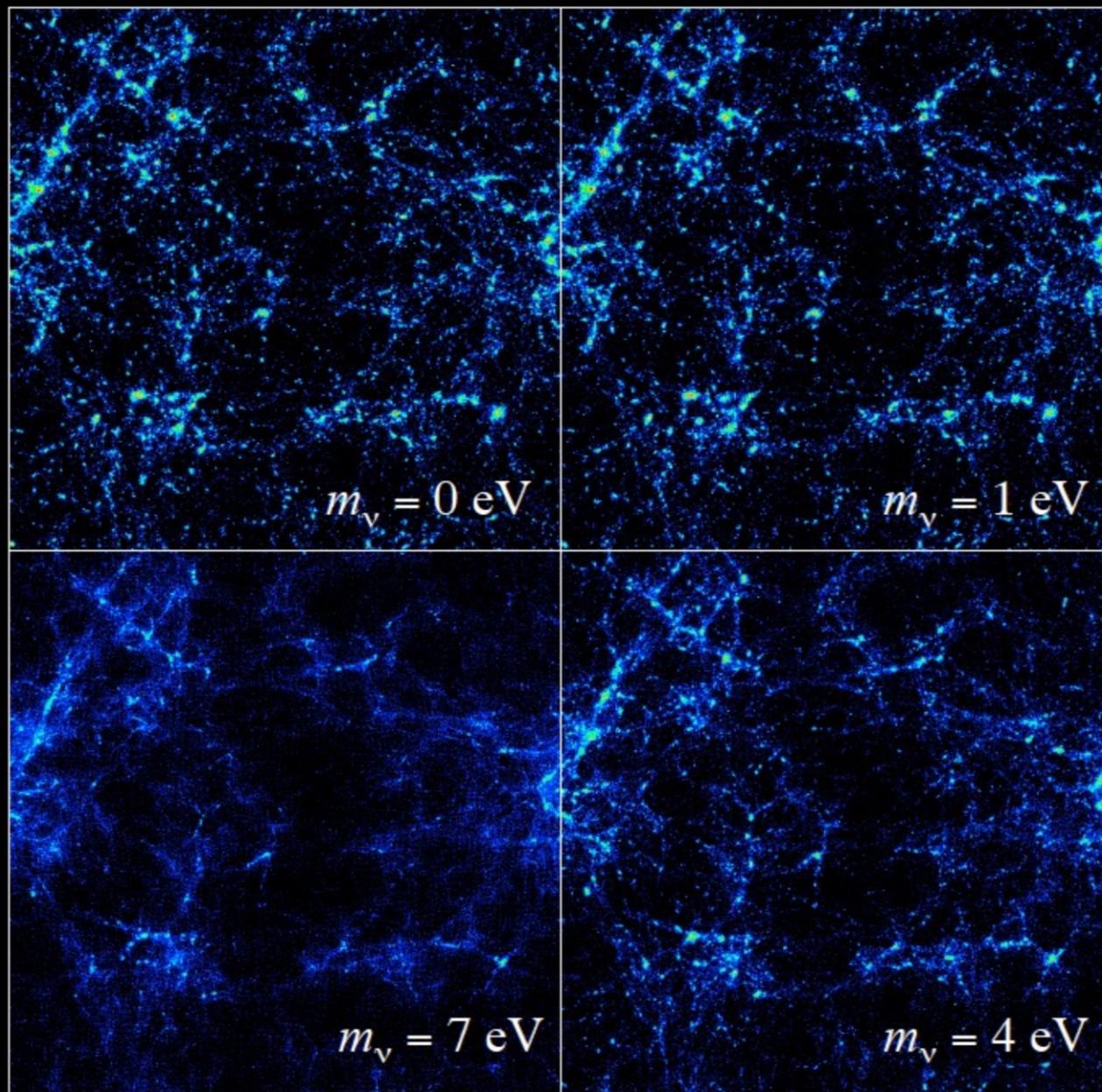
$$|\nu_e\rangle = c_1 |\nu_e\rangle + c_2 |\nu_\mu\rangle + c_3 |\nu_\tau\rangle$$



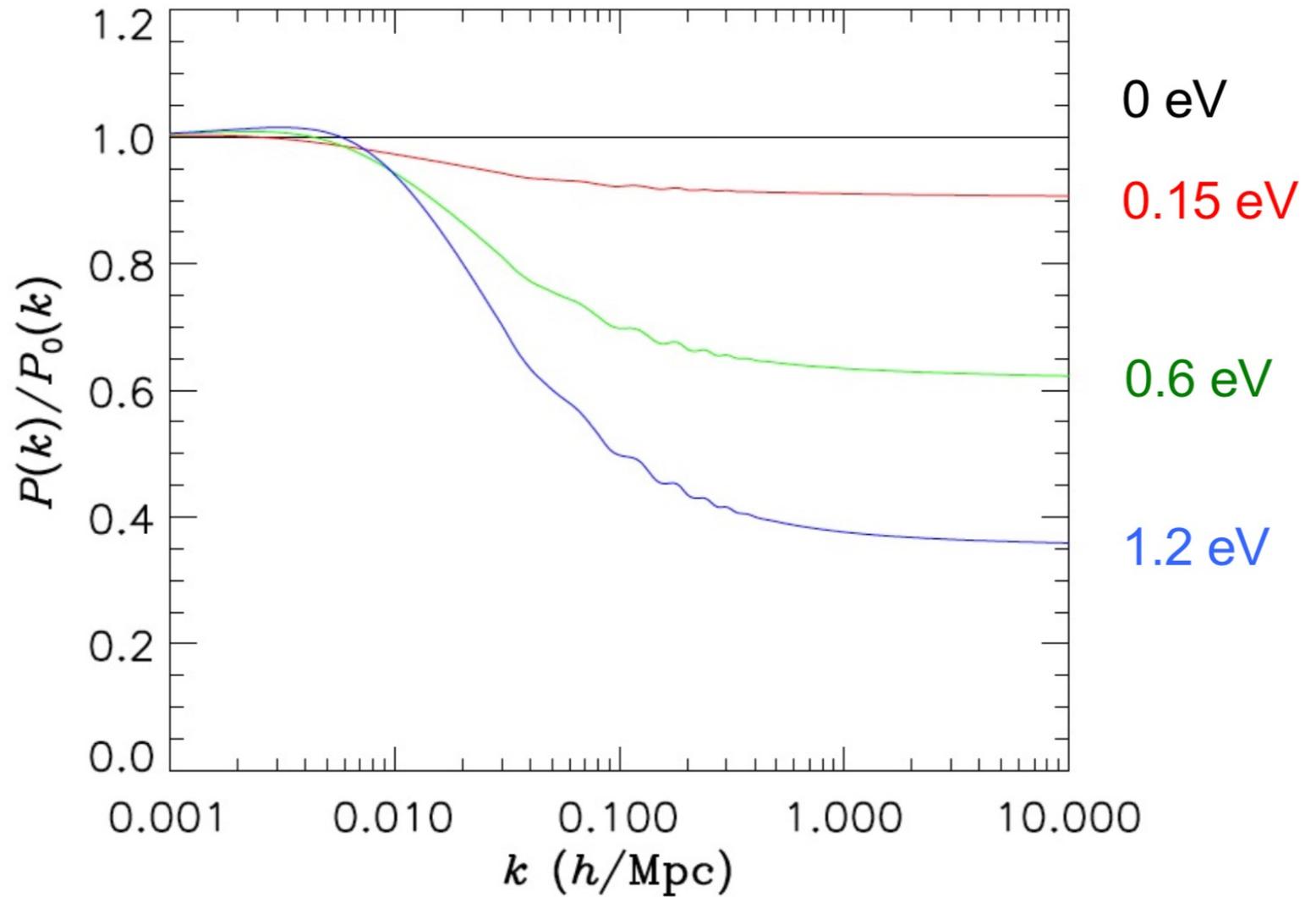
关键科学问题：测量中微子质量



Weighing the neutrinos using redshift surveys



Ma '96





Extending to $z=1.6-2.5$

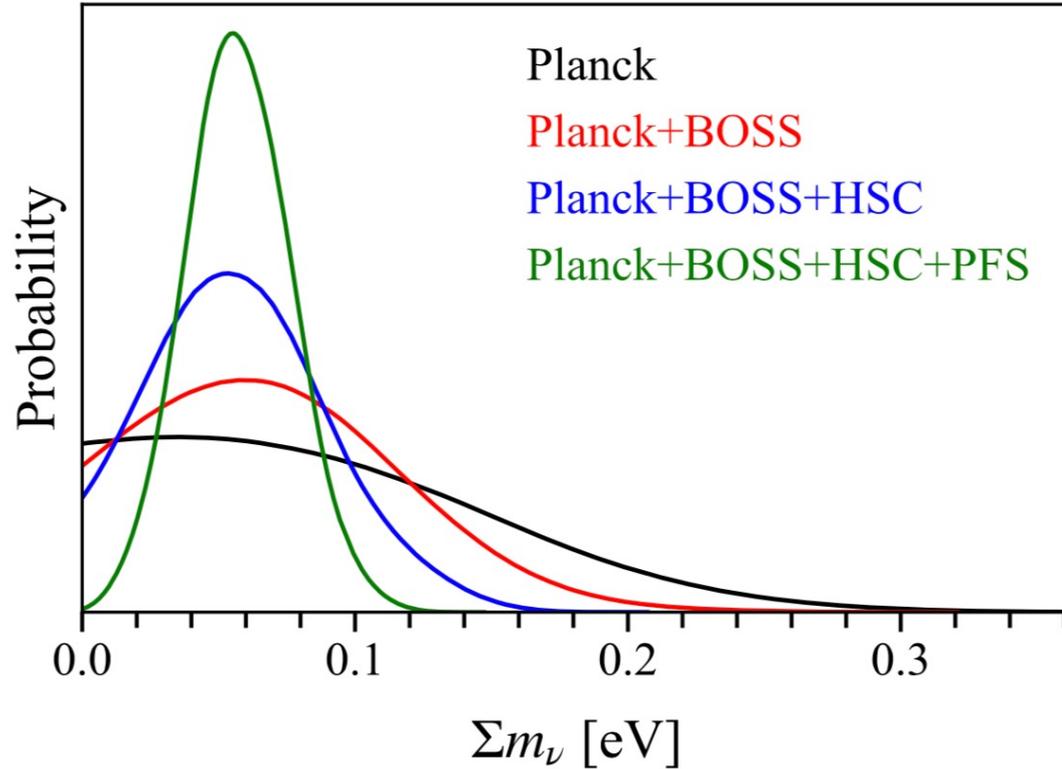


Figure 3. Marginalised posterior distribution of neutrino mass constraints from Planck 2018 only (black), Planck 2018+BOSS (red), Planck+BOSS+HSC forecast (blue), and Planck+BOSS+HSC+PFS forecast (green). Here we assume $\sum m_\nu = 0.06$ eV for the input neutrino mass, which corresponds to the lower limit of the normal mass hierarchy. We will constrain the sum of neutrino masses to 0.02 eV and 0.04 eV to the 68% and 95% confidence, respectively, from Planck+BOSS+HSC+PFS. The power spectrum and bispectrum are used for the PFS forecast.



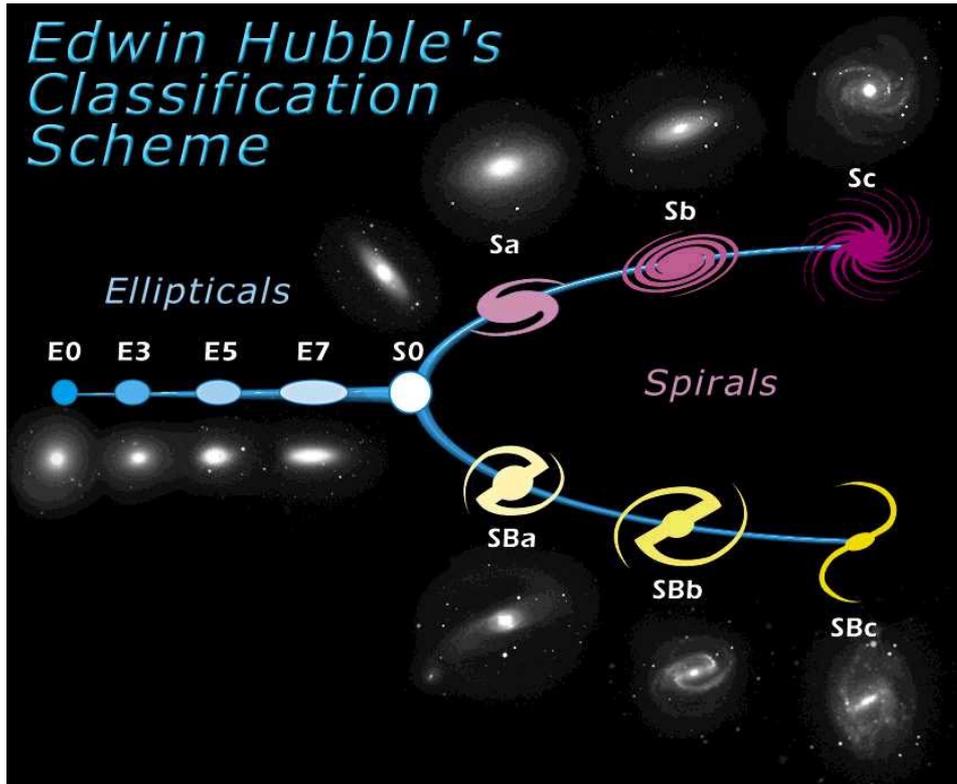
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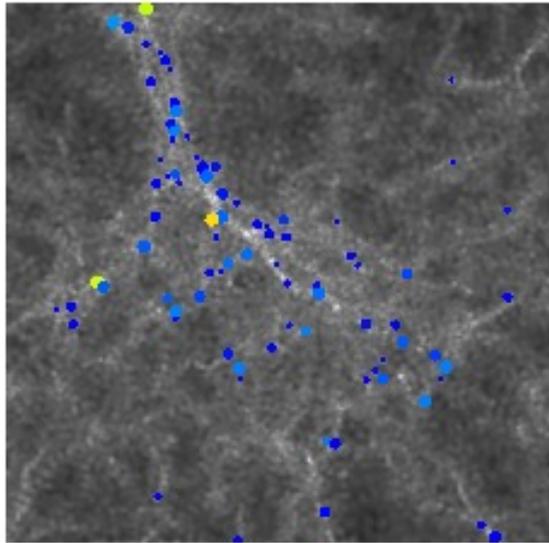
星系形态的分类 (Hubble)

⊙ E, S0, S, S-Bar, Irr.....

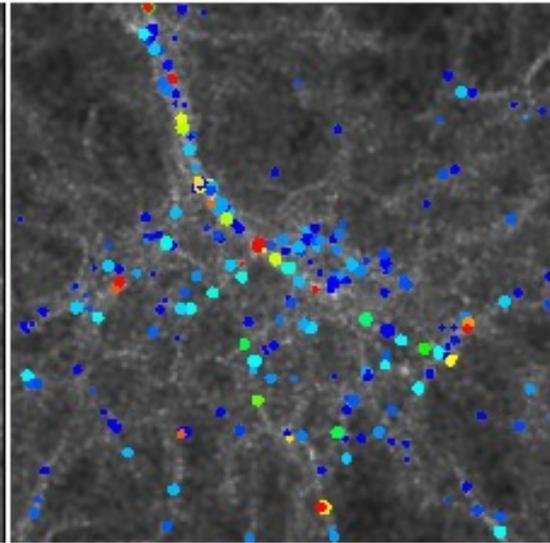




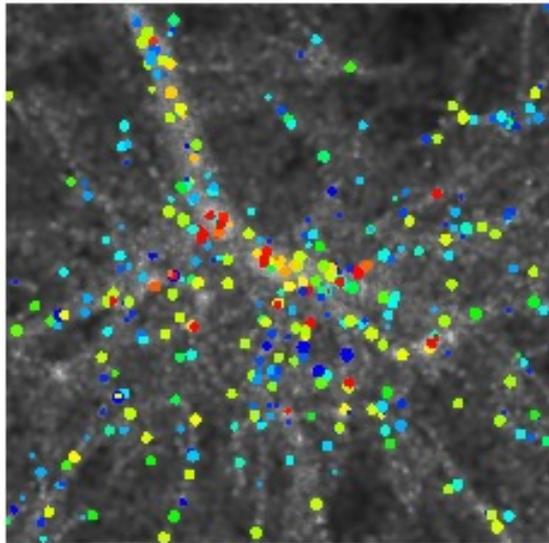
$z=3$



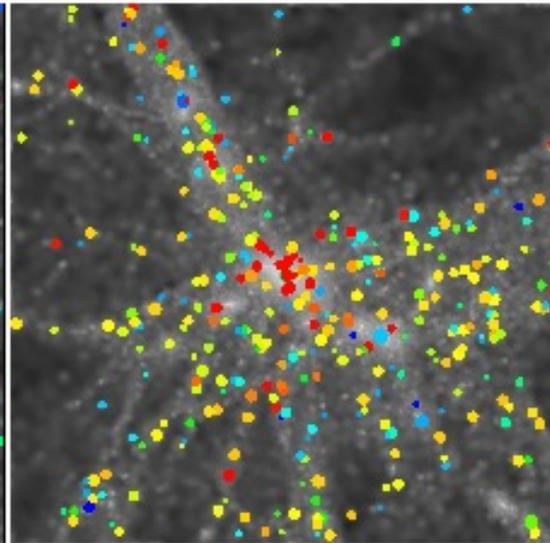
$z=2$



$z=1$

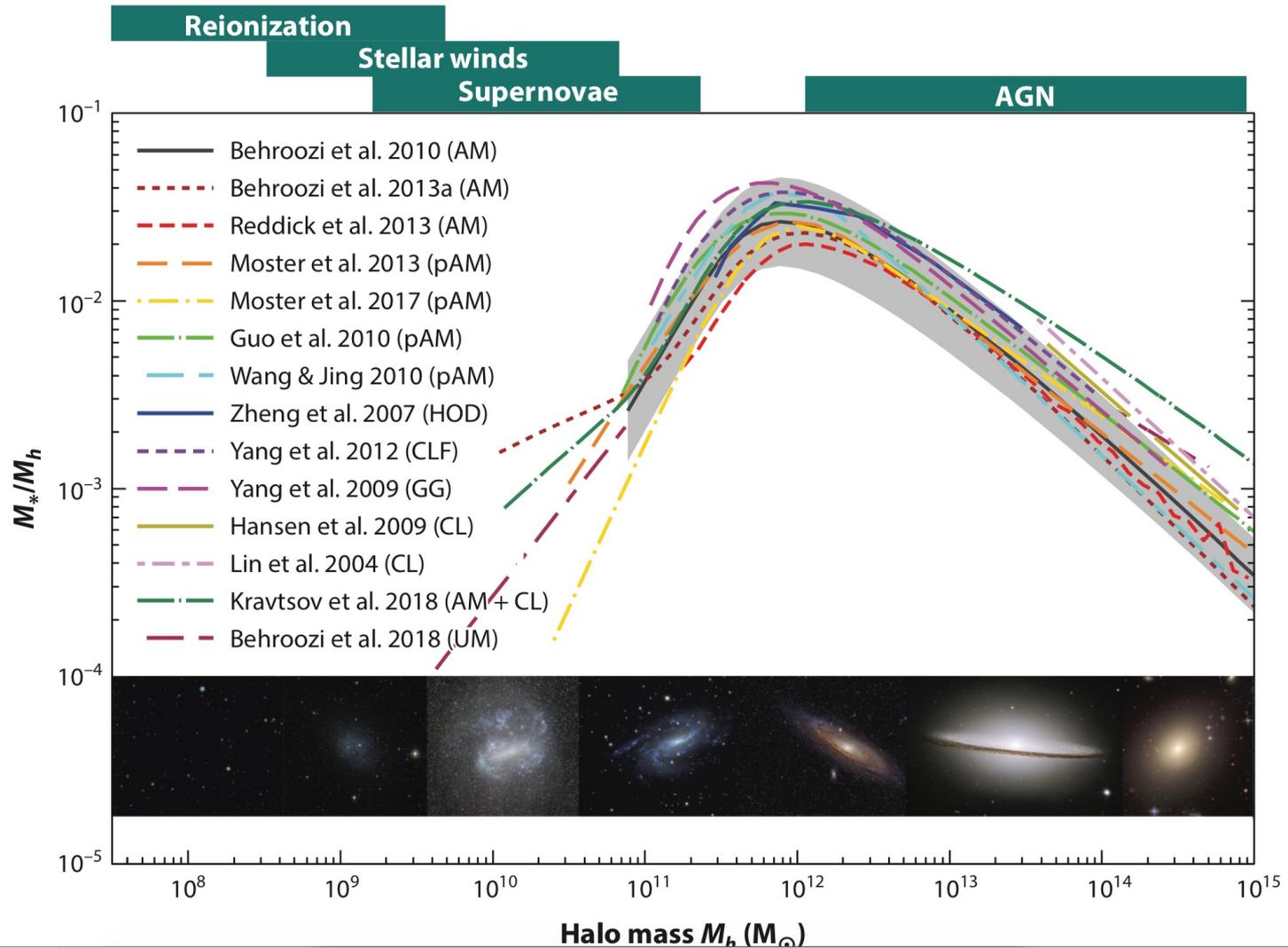


$z=0$



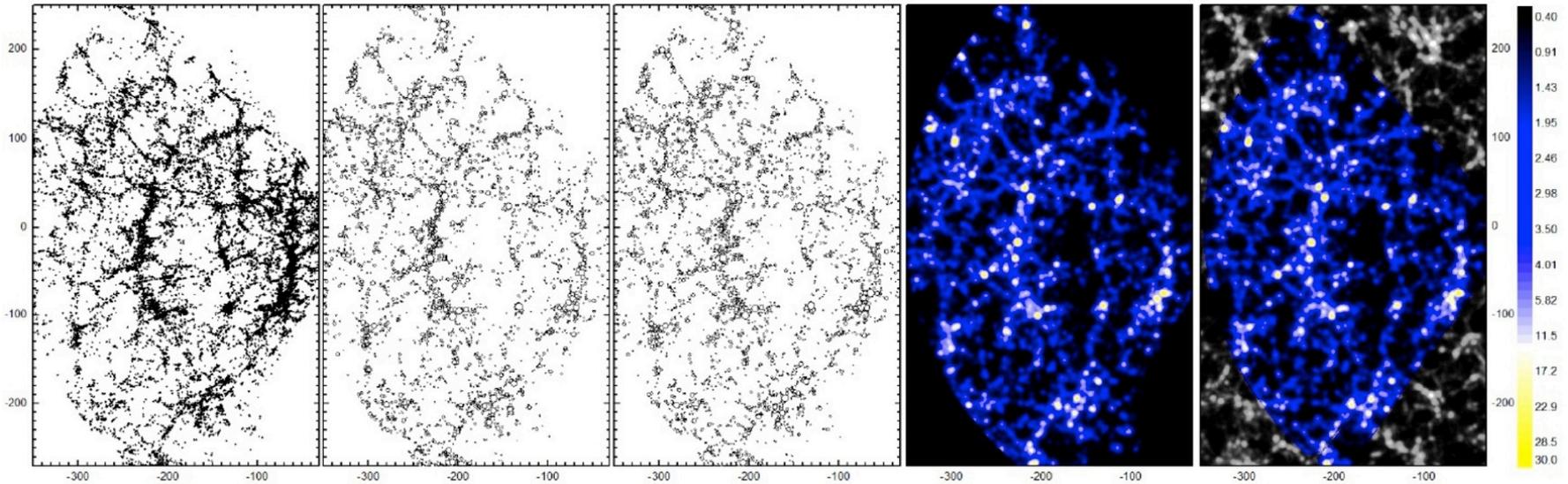


Galaxy formation: how quenched





Detailed map of dark matter around galaxies, and the evolution history

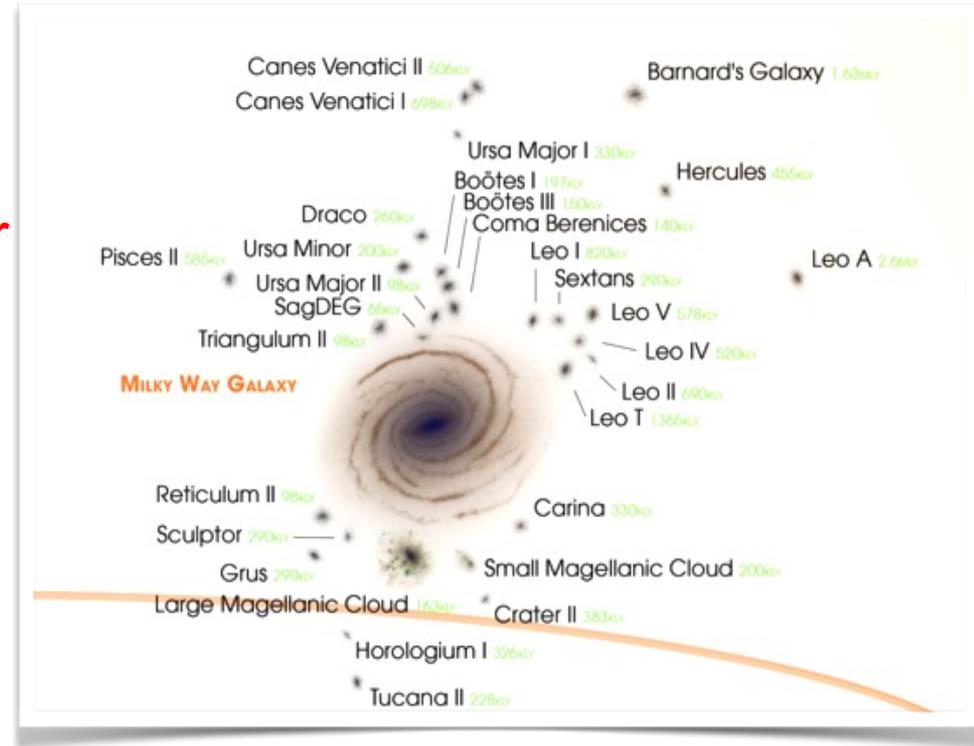


**WANG, Huiyuan et al 2016;
Elucid Project**



MW satellites from DES and GAIA

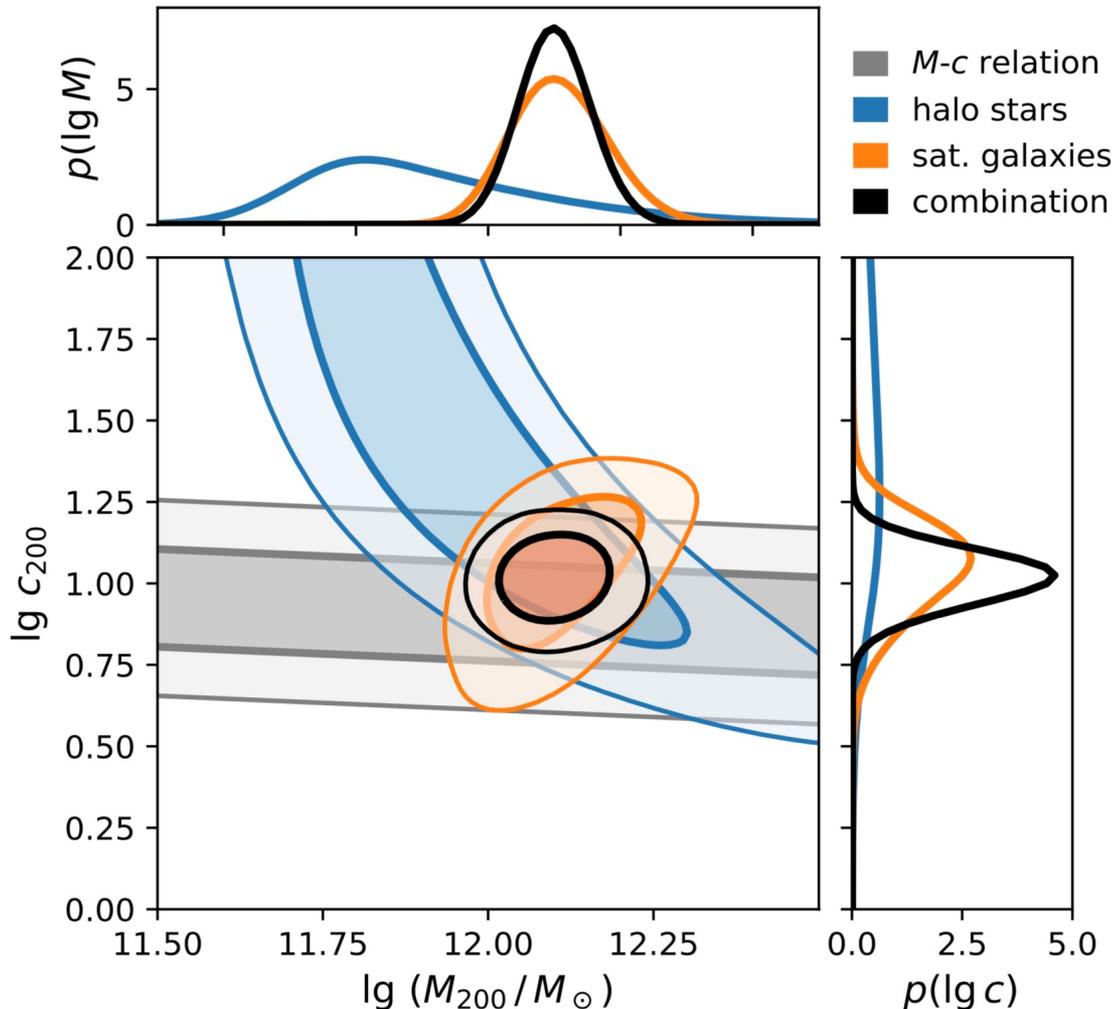
- 60 satellite galaxies found
- extended distribution
- the only tracers beyond 100 kpc or farther
- We will use a sample of 28 satellites with Gaia DR2 Proper motion (pm) measurements in [40, 280] kpc



Andrew Z. Colvin



Joint constraint with satellites and halo stars



Without M-c relation

$$M = 1.27_{-0.15}^{+0.17} \times 10^{12} M_{\odot}$$

$$c = 11.7_{-2.5}^{+3.2}$$

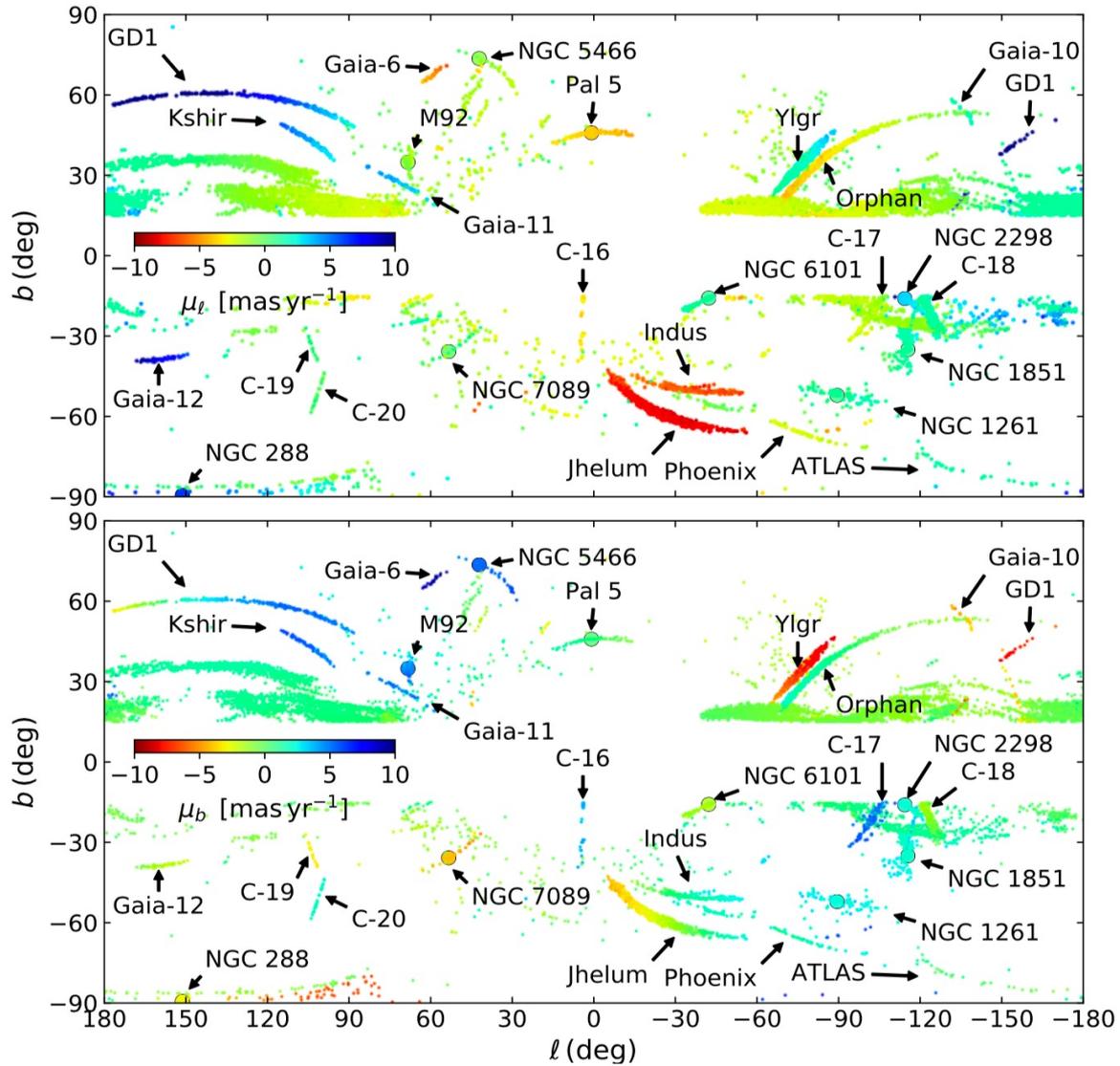
With M-c relation as prior

$$M = 1.26_{-0.15}^{+0.17} \times 10^{12} M_{\odot}$$

$$c = 10.4_{-1.9}^{+2.3}$$

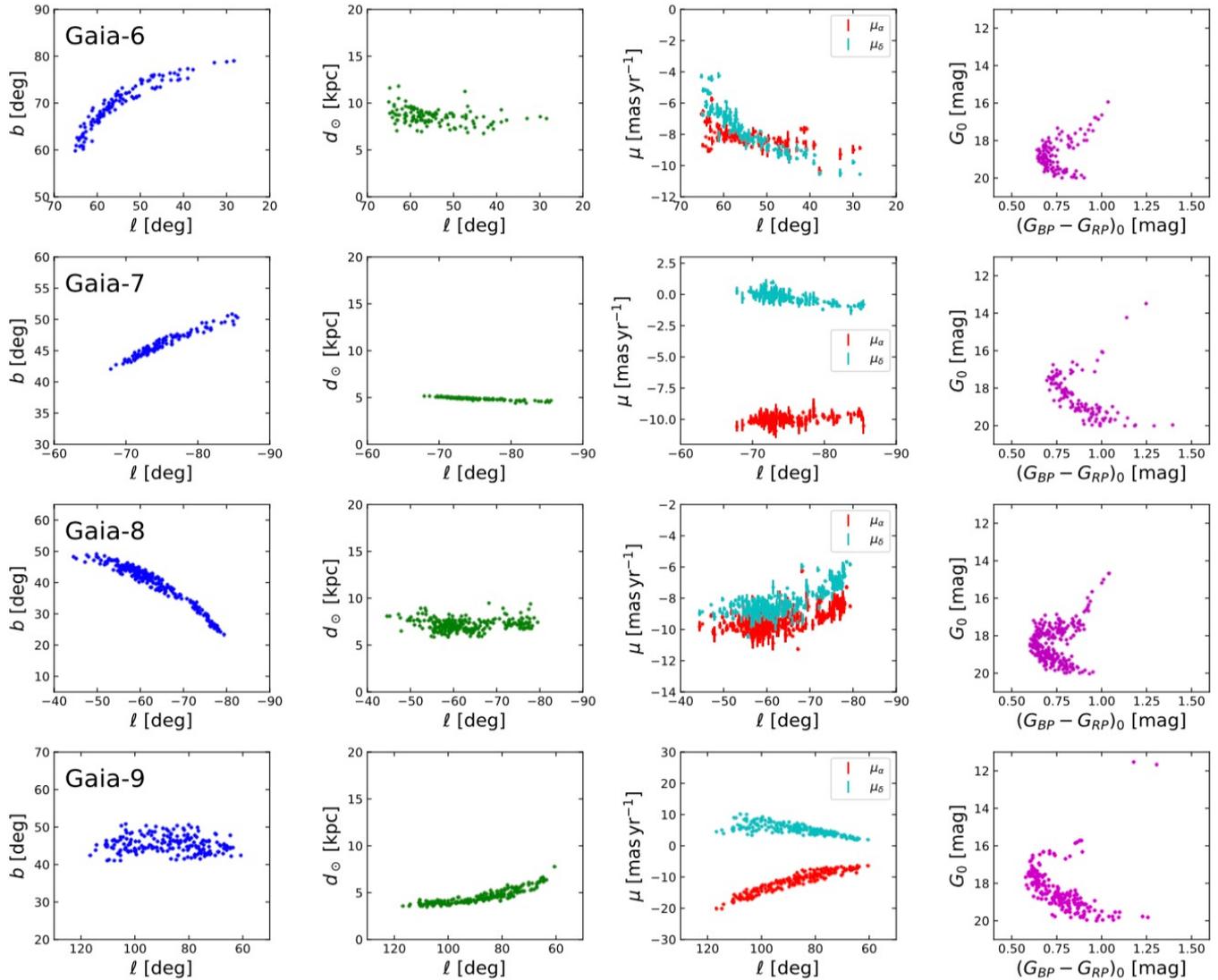


Gaia EDR3 detections, [10, 30] kpc





A SEARCH FOR STELLAR STREAMS WITH GAIA DR2 AND DR3





对深度、广度光谱巡天的需求

- ④ **暗物质**: density profile around dwarf galaxies
- ④ **暗能量 vs 修正引力论**: 大尺度分布; 跨越较大的红移
- ④ **中微子质量**: 大尺度分布; 高红移的非线性效应小
- ④ **宇宙网络中星系形成**: 高红移处宇宙网络中的星系分布
- ④ **银河系集成**: outer disk; survey of streams; dwarf galaxies



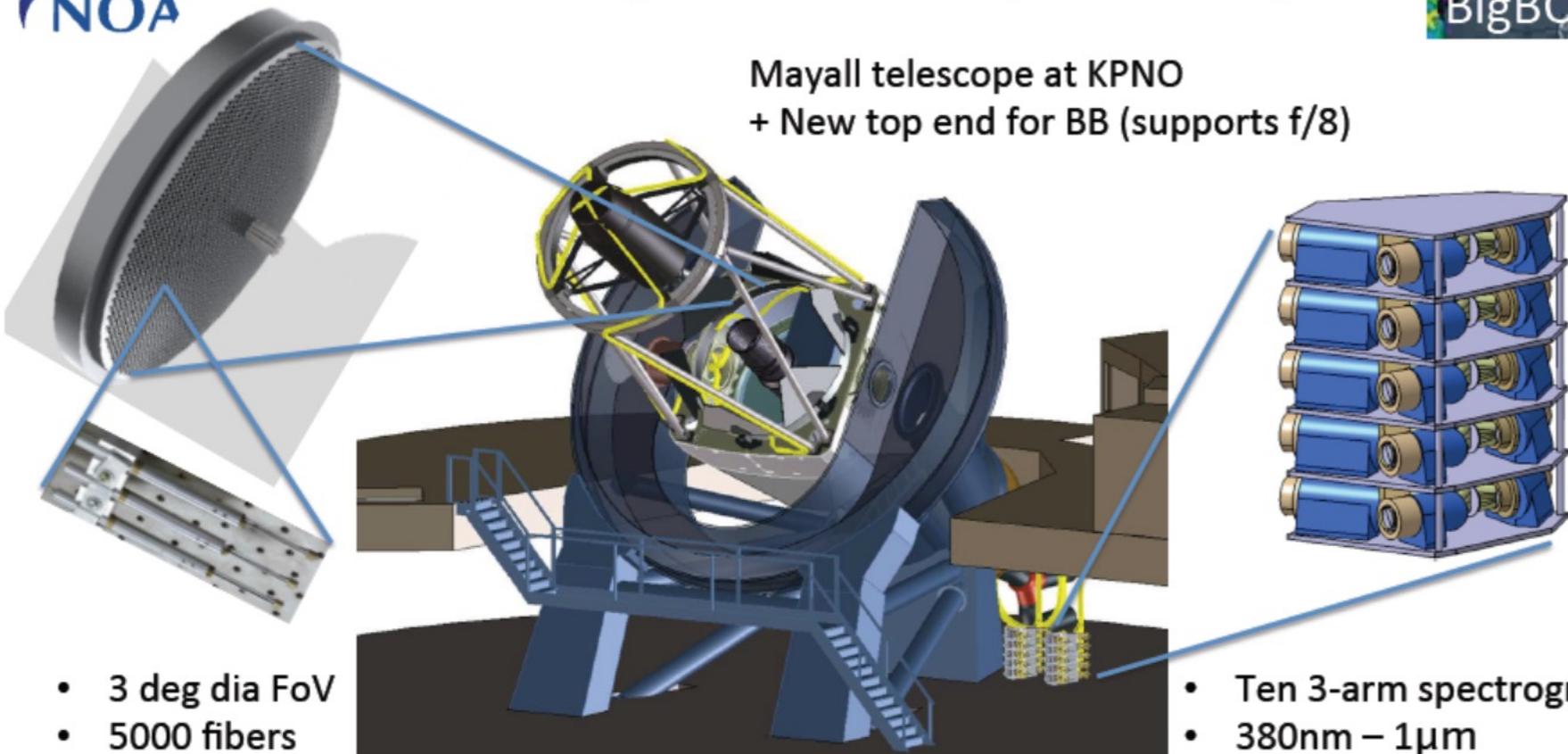
DESI—Dark Energy Spectroscopic Instrument



DESI Capability



Mayall telescope at KPNO
+ New top end for BB (supports f/8)



- 3 deg dia FoV
- 5000 fibers

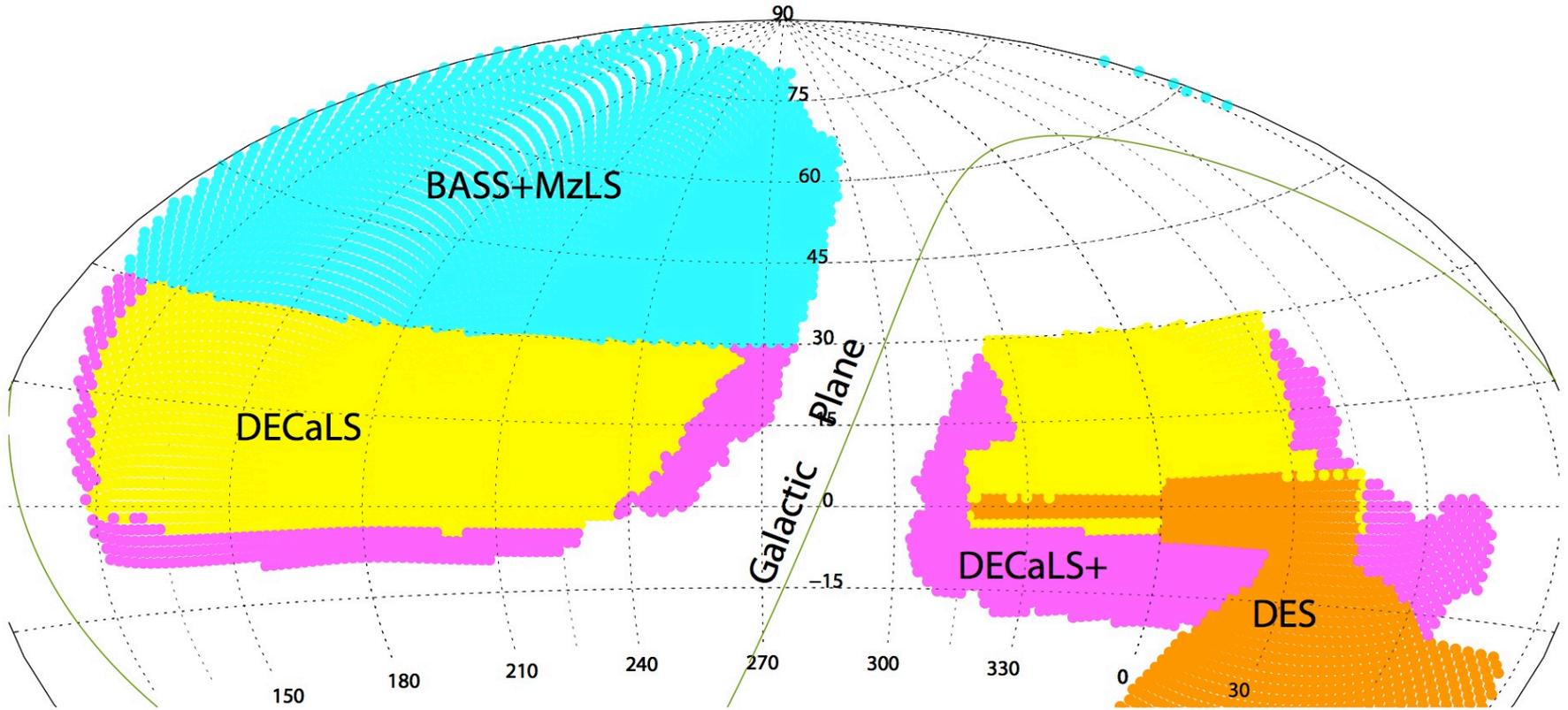
- Ten 3-arm spectrographs
- 380nm – 1 μ m

Nearly 40,000 spectra per night!!

See Natalia Roe's talk!



DESI Sky Coverage



Total 9000 + 5000 deg^{2c}



DESI : started on 15 May 2021

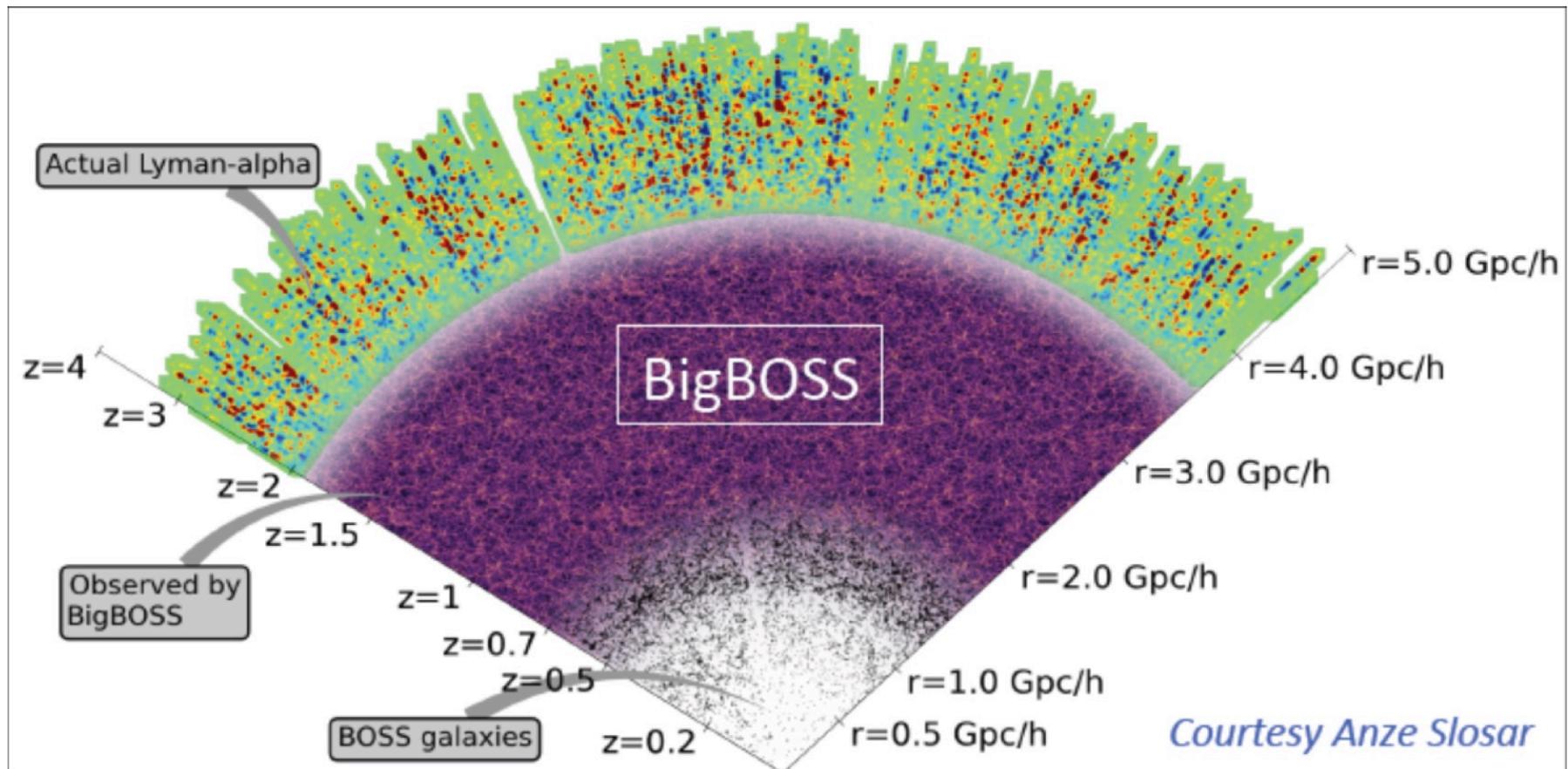
Summary: A new baseline

SV3 LRG	0.3–1.0	$g,r,z,W1$	600	565	500	7.0 M
SV3 ELG	0.6–1.6	g,r,z	1950	1420	910	12.7 M
SV3 QSO (tracers)	< 2.1	$g,r,z,W1,W2$	210	210	140	1.96 M
SV3 QSO (Ly- α)	> 2.1	$g,r,z,W1,W2$	100	295	60	0.84 M
Total in dark time			2860	2490	1619	22.5 M
SV3 BGS	0.05–0.4	r (Gaia G)	860	688	678	9.5 M
SV3 BGS–Faint	0.05–0.4	r (Gaia G)	540	324	317	4.4 M
SV3 MWS	0.0	g,r (Gaia μ)	800+	720	720	10.1 M
Total in bright time			2200+	1732	1715	24.0 M



DESI光谱巡天

- 覆盖1/3天区（14000平方度）、100亿年前星系，共有3千多万星系，具有距离和运动速度信息





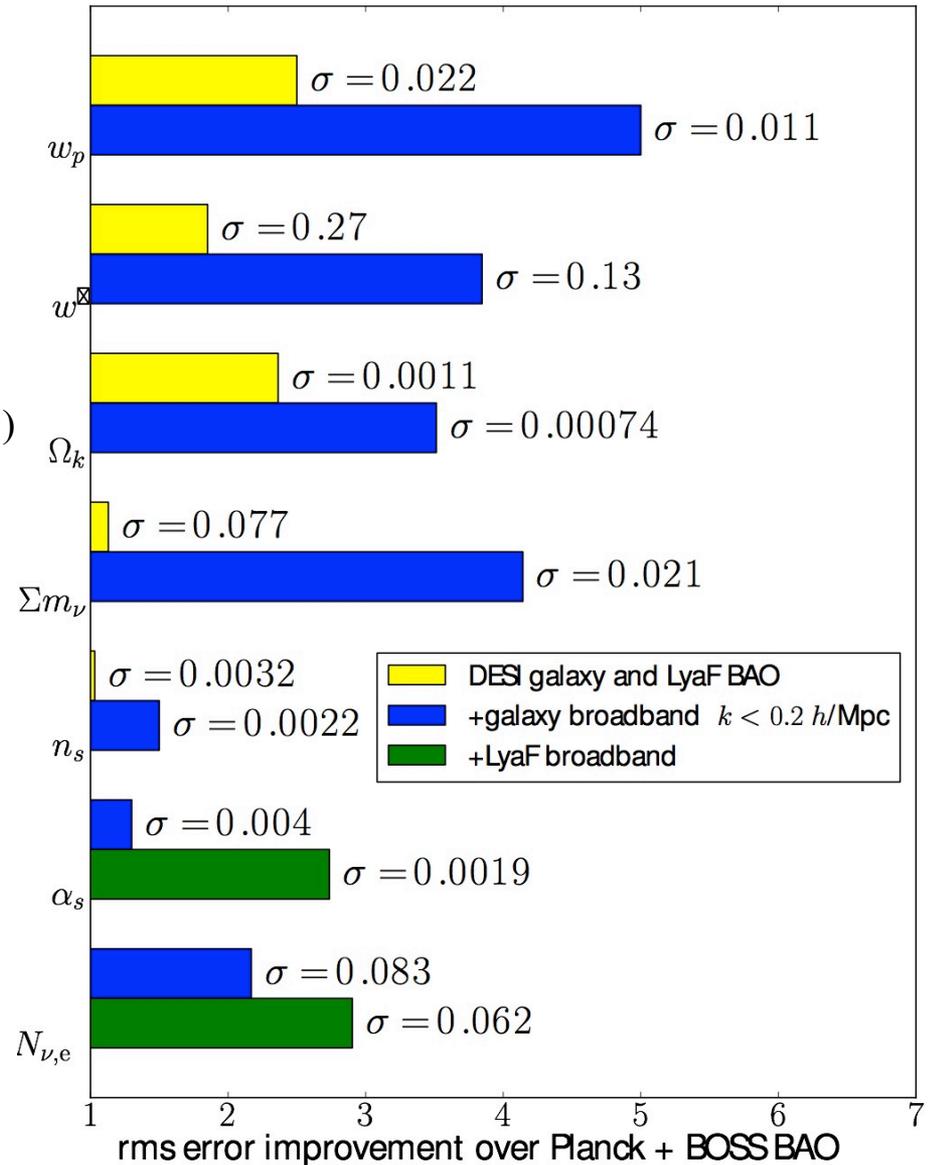
预计：高精度测量宇宙学参量

+Planck CMB data

$$w = w_0 + w_a (1 - a)$$

$$P(k) = P(k_0) (k/k_0)^{n_s(k_0) + 1/2 \alpha_s \ln(k/k_0)}$$

$$k_0 = 0.05 \text{Mpc}^{-1}$$





星系形成和银河系

- 宇宙网络的星系形成：BGS是SDSS Main survey的20倍； **local reference**
- 小质量（矮）星系的形成
- 银河系的质量；银河系的streams



PFS Instrument on Subaru

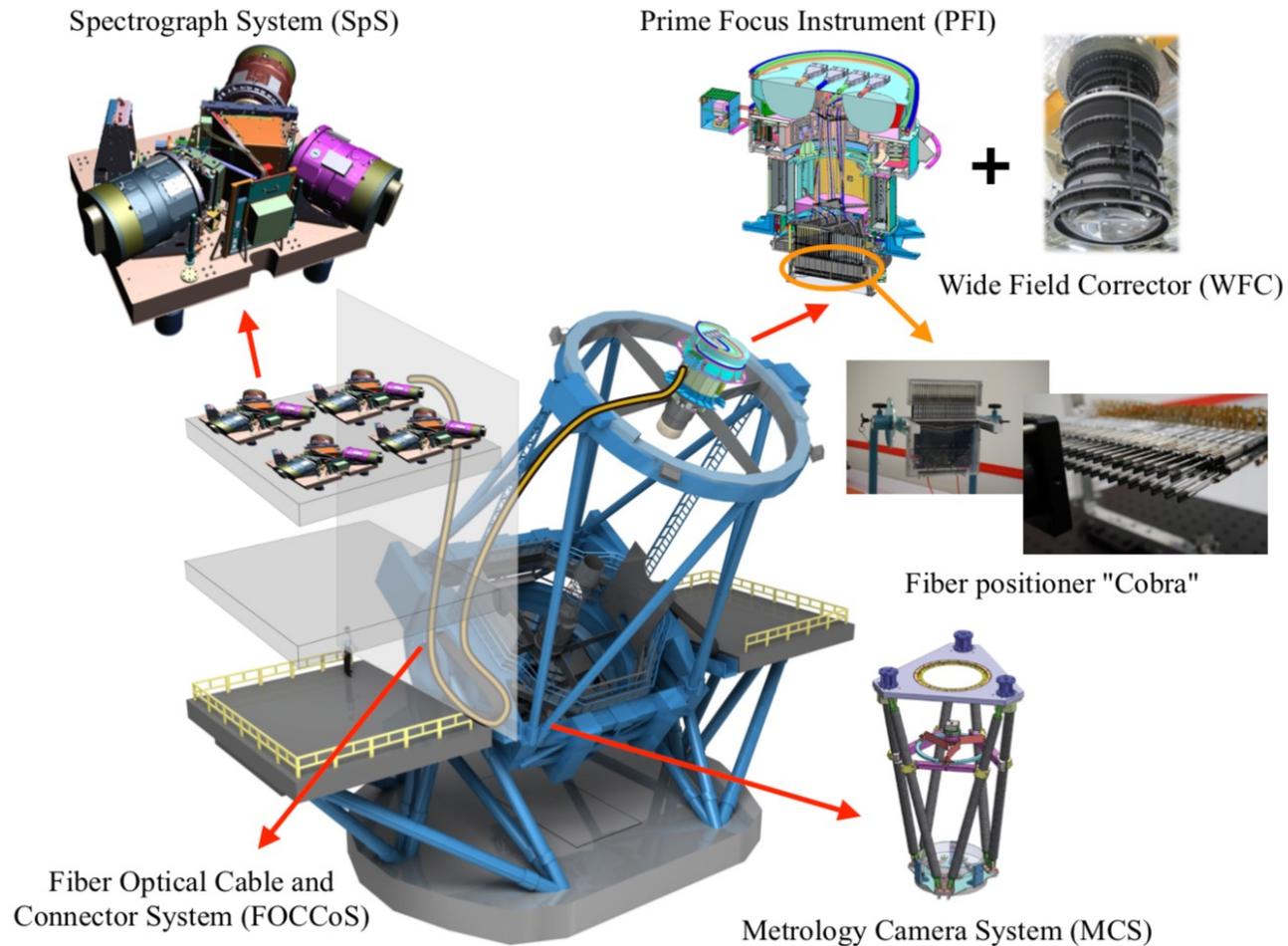


Figure 2. A schematic overview of PFS instruments (see text for details).



Table 1
Instrumentation parameters

Prime Focus Instrument				
Field of view	~ 1.38 deg (hexagonal - diameter of circumscribed circle)			
Field of view area	~ 1.25 deg ²			
Input f number to fiber	2.8			
Fiber core diameter ^a	127 μm (1.12 arcsec at the FoV center, 1.02 arcsec at the edge)			
Positioner pitch	8 mm (90.4 arcsec at the FoV center, 82.4 arcsec at the edge)			
Positioner patrol range	9.5 mm (107.4 arcsec at the FoV center, 97.9 arcsec at the edge)			
Minimum fiber separation ^b	~ 30 arcsec			
Fiber configuration time	~ 60–120 sec			
Number of fibers	Science fibers	Fixed fiducial fibers		
	2394	96		
Fiber density	~ 2000 deg ⁻² or ~ 0.6 arcmin ⁻²			
Spectrograph				
Spectral arms	Blue	Red		NIR
		Low Res.	Mid Res.	
Spectral coverage	380 – 650 nm	630 – 970 nm	710 – 885 nm	940 – 1260 nm
Dispersion	~ 0.7Å/pix	~ 0.9Å/pix	~ 0.4Å/pix	~ 0.8Å/pix
Spectral resolution	~ 2300	~ 3000	~ 5000	~ 4300
Detector type/read-out mode	CCD	CCD		HgCdTe/SUTR
Spectrograph throughput ^c	~ 53% (@500nm)	~ 52% (@800nm)	~ 47% (@800nm)	~ 34% (@1100nm)

^a This is a diameter of the sky projected onto the fiber core through the microlens with a magnification of 1.28.

^b The minimum separation includes a physical limitation and a margin for collision avoidance.

^c These values include detector QEs. The typical total throughput including primary mirror reflectivity, WFC, fiber systems, spectrograph optics, detector QE, etc. in blue, red, NIR, and medium resolution arms are ~22% (@500nm), ~26% (@800nm), ~19% (@1100nm), and ~23% (@800nm), respectively



PFS fields

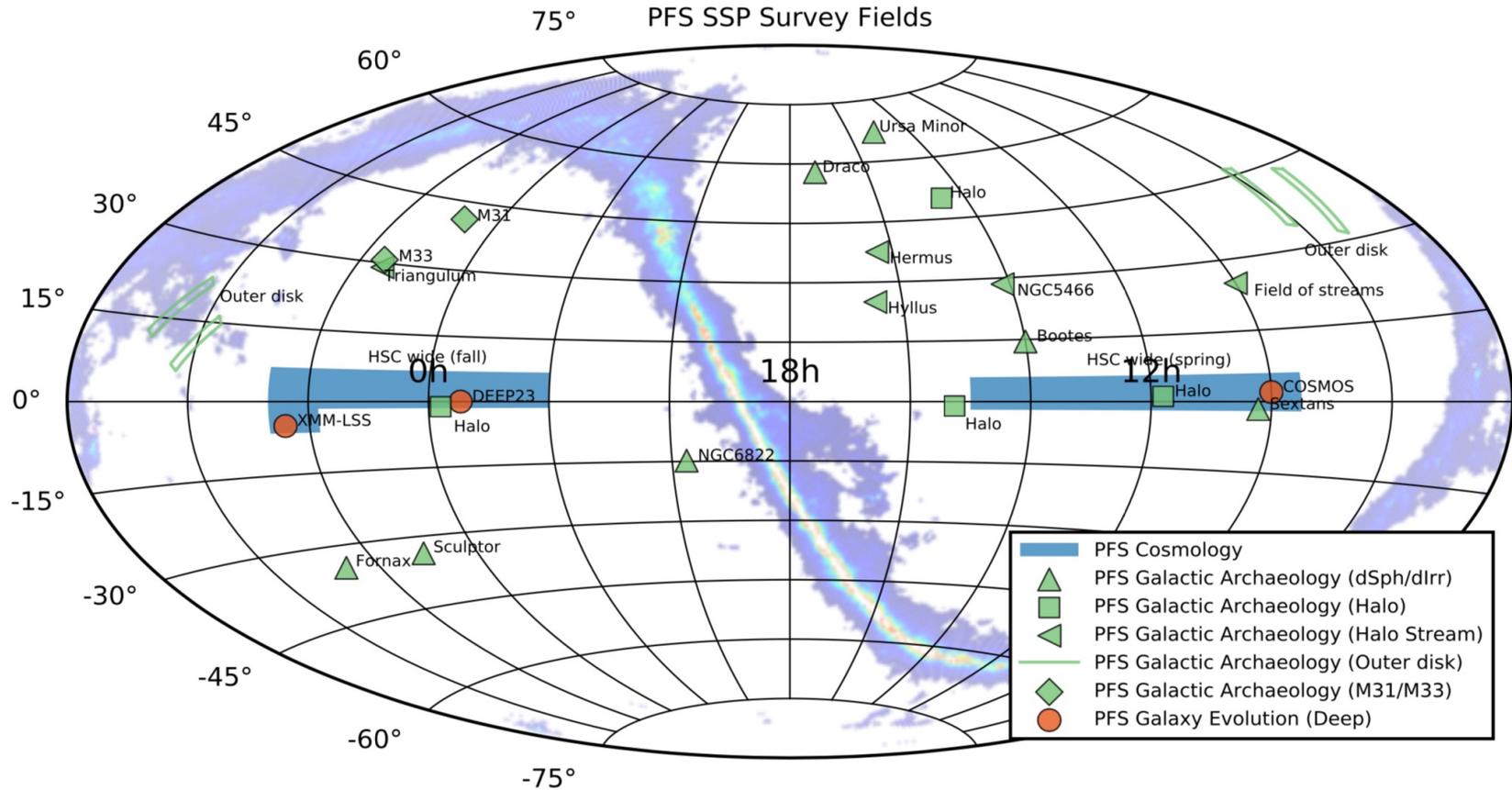


Figure 14. Sky distribution of the PFS survey fields. All targets are drawn from multi-color HSC data.



Table 2
Sample and Depths

Layer	Field	Selection	exp. time ^a	# of FoVs ^b	nights ^c	# of spectra	Requirement(s) ^d	Main science ^e
Cosmology	HSC-W	<i>grizy</i>	15min	~ 1100	~70	~ 4M	redshift ([O II])	BAO, RSD, LSS
ancillary targets	HSC-W	<i>gri(zY)+ext. data (Gaia, etc.)</i>	15-30min	~ 1100	–	~ 100K	–	GA (stars, WDs), GE (e.g., QSOs)
gals $z \lesssim 1$	HSC-D	$i < 23$	2 hrs	11	~ 3.5	~ 28K	spectral features	GE (control sample, deep)
gals $0.7 < z < 1$	HSC-D	$y < 22.5 + z_{\text{ph}}$	2 hrs	11	~ 8.5	~ 68K	spectral features	GE ($0.7 < z < 1$)
gals $1 < z < 2$	HSC-D	$y < 22.5 + z_{\text{ph}}$	2 hrs	11	~ 8.7	~ 69K	spectral features	GE ($1 < z < 2$)
	HSC-D	$y > 22.5, J < 22.8 + z_{\text{ph}}$	2 hrs	11	~ 12	~ 96K	spectral features	GE ($1 < z < 2$, main)
gals $0.7 < z < 2$	HSC-D	$J < 22.8 + z_{\text{ph}}$	12 hrs	11	~ 16	~ 14K	spectral features	GE ($0.7 < z < 2$, deep)
gals $2.1 < z < 2.5$	HSC-D	$y < 24.3 + z_{\text{ph}}$	6 hrs	11	~ 8.3	~ 22K	spectral features	GE (IGM/foreground)
gals $2.5 < z < 3.5$	HSC-D	$y < 24.3, g < 24.2 + z_{\text{ph}}$	6 hrs	11	~ 3.1	~ 8.3K	spectral features	GE (IGM/background)
	HSC-D	$y < 24.3, 24.2 < g < 24.7 + z_{\text{ph}}$	12 hrs	11	~ 10.5	~ 14K	spectral features	GE (IGM/background)
gals $3.5 < z < 7$	HSC-D	$y < 24.5 + z_{\text{ph}}$	6 hrs	11	~ 8.3	~ 22K	spectral features	GE (high-z)
$z \sim 2.2$ LAEs ^f	HSC-D	NB387, $L_{\text{Ly}\alpha} > 3 \times 10^{42}$	3 hrs	11	~ 1.4	~ 7.4K	spectral features	GE, cosmic reionization
$z \sim 5.7, 6.6$ LAEs	HSC-D	NB816,921, $L_{\text{Ly}\alpha} > 5 \times 10^{42}$	6 hrs	11	~ 1.7	~ 4.5K	redshift ($\text{Ly}\alpha$)	cosmic reionization
	HSC-D	NB816,921, $L_{\text{Ly}\alpha} = 3 - 5 \times 10^{42}$	12 hrs	11	~ 2.1	~ 2.8K	redshift ($\text{Ly}\alpha$)	cosmic reionization
AGN $0.5 \lesssim z \lesssim 6$	HSC-D	$i < 24(\text{grizy})$	1-4hrs	11	~ 1.8	~ 9.7K	spectral features	GE, CGM, IGM
MW-dSphs/dIrr ^g	HSC ^h	$g < 23$	3hrs	40 ⁱ	30.5	~ 60K	$S/N _{\text{cont.}} > 10$	DM profiles, [Fe/H] and $[\alpha/\text{Fe}]$ dist.
M31 ^g	HSC ^h	$g < 23$	5hrs	47	29.4	~ 13K	$S/N _{\text{cont.}} > 10$	accretion history, DM subhalos, M33
MW ^g	HSC	$g < 22$	3hrs	83	31.1	~ 26K	$S/N _{\text{cont.}} > 10$	MW grav., macro DM (incl. PBH)

Notes – ^a) The total exposure time for each sample on source. ^b) The number of pointings (roughly corresponding to survey area). ^c) The primary requirement on spectroscopic observation for each sample. ^d) The primary science drivers. ^e) The main science. ^f) The units of $L_{\text{Ly}\alpha}$ are [erg s^{-1}]. ^g) Medium-resolution mode spectroscopic observation is included. ^h) Including NB515 narrow-band imaging to discriminate member giants from foreground dwarf stars. ⁱ) Two visit observation of each pointing to identify binary stars.



Galaxy formation in cosmic webs at $z > 1$

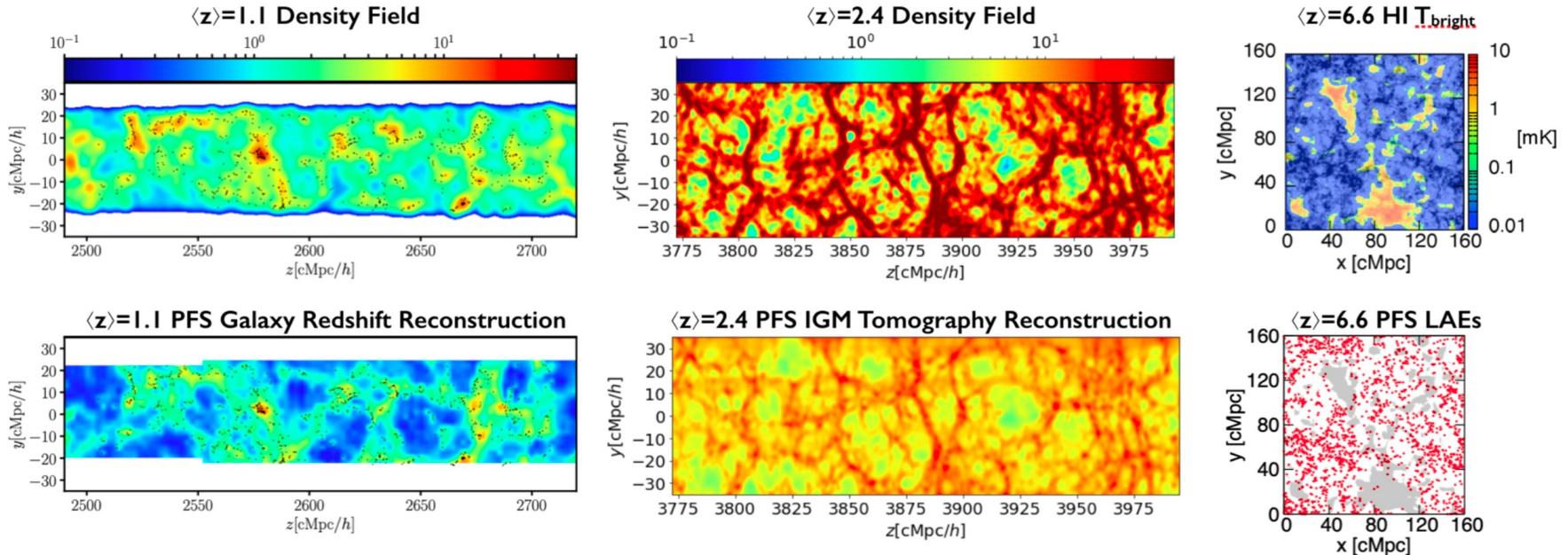


Figure 11. Recovery of cosmic structures from the PFS SSP at $\langle z \rangle = 1.1, 2.4$ and 6.6. The top left and middle shows the simulated density fields from the Horizon AGN simulation at $\langle z \rangle = 1.1$ and $\langle z \rangle = 2.4$, while bottom left and middle show the reconstructed density from the PFS galaxy redshift distribution and IGM absorption data using the algorithms, ARGO (Ata et al. 2015) and TARDIS (Horowitz et al. 2019). The top right panel shows reionization bubbles in the HI 21cm brightness temperature distribution from Kubota et al. (2019), while the bottom panel shows the LAE distribution observed by PFS spectroscopy, which is anti-correlated with the ionized bubbles in this particular model.



PFS 优势

- ④ 宇宙学（暗能量、中微子）：较desi更高的红移，很强的互补
- ④ 暗物质：银河系矮星系的暗物质分布
- ④ 星系形成：红移 $z=1-6$ ；星系周围气体的性质
- ④ 银河系：streams, outer disk; M31; M33



展望



The Maunakea Spectroscopic Explorer



- ④ **11.25 m aperture**
- ④ **4,332 fibers**
- ④ **1.5 square degree field of view**
- ④ **spectral resolutions, from $R \sim 3,000$ to $R \sim 40,000$**
- ④ **near-IR wavelength range of 0.36–1.8 microns**



6.5m宽场巡天望远镜

MULTIplexed SURvey Telescope
(MUST)

MUST科学工作组



主要性能指标：

光纤定位器：theta/phi、tilt-spline 是基础方案； 关注更加灵活的starbug定位

视场： 初步建议 7 deg^2 可允许一定视场边缘渐晕

波长范围： 对光学优化，先考虑 $0.36\text{--}1.0\mu\text{m}$ ，未来争取扩展到 $1.7\mu\text{m}$ ，兼顾近红外接口

光纤数： 1万根光纤

光谱分辨率（bright/dark是否两套仪器）：

暂时不需要两套， $R \sim 4000$ ； $R \sim 20,000$ ($40,000?$)，两种光纤数比例未定
(e. g., $\sim 3:1$)

天光减除： 关注日本 PFS 1%的 sky subtraction technique

光纤的大小： 最优S/N的计算、包括包含可能的光学系统误差、跟踪精度（e. g., $1.3 \cdot \text{seeing}$ ） 再对比货架产品

积分视场光谱仪（成像光谱仪）、个数： 看技术风险，优选 starbug 定位器。

观测模式： 在同一套仪器基础上优化。

新的参数空间： 口径*视场； 光谱时域； 可否实现 fiber 能不能追踪？ 近红外探测器的进展？



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- ① **a five square degree field of view**
- ① **15,000 robotically-controlled fibers**
- ① **Wavelength 360-1330 nm**
- ① **Low, medium, high resolution 3000---**
- ① **EU based**



Megamapper: NG of DESI

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- ④ **3.0 deg diameter field-of-view**
- ④ **20,000 zonal fiber positioners**
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- ④ **David Schlegel**