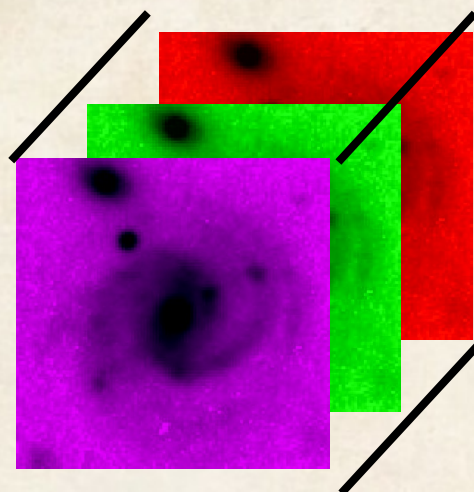
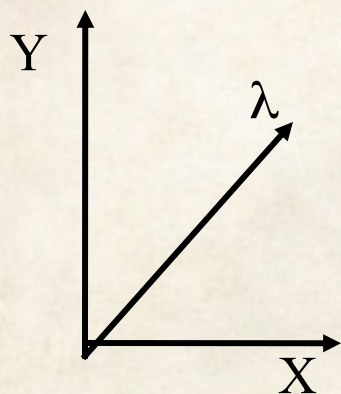


Методы панорамной спектроскопии

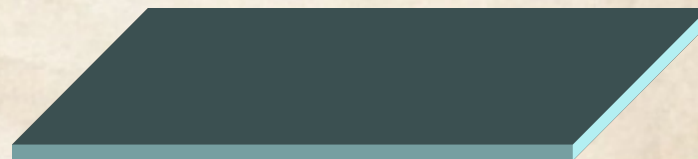
Лекция 4.

Сканирование щелью. Резатели изображений. Панорамные спектрографы в ближнем ИК. Работа с системами АО.
Спектрографы: PIFS, KCWI, OASIS, OSIRIS, SINFONI, KMOS, MUSE, KMOS, приборы JWST.

Куб данных



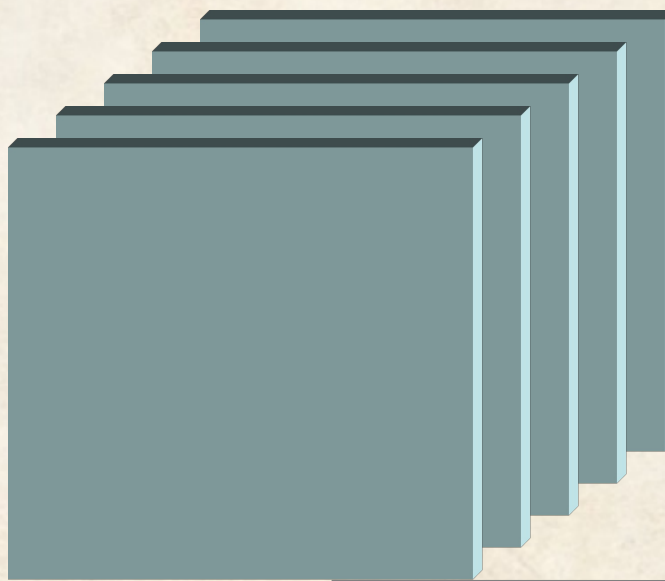
Длинная щель



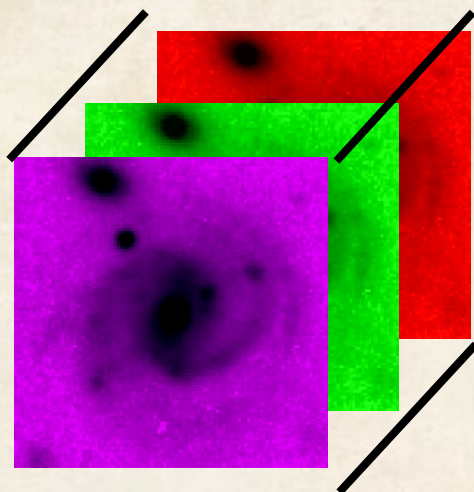
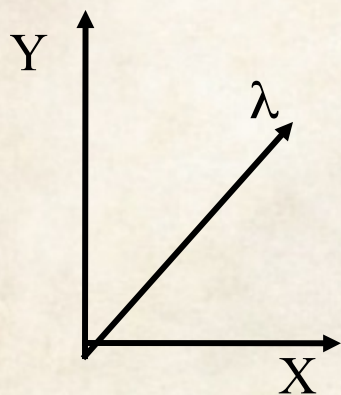
Спектрографы
Интегрального
поля



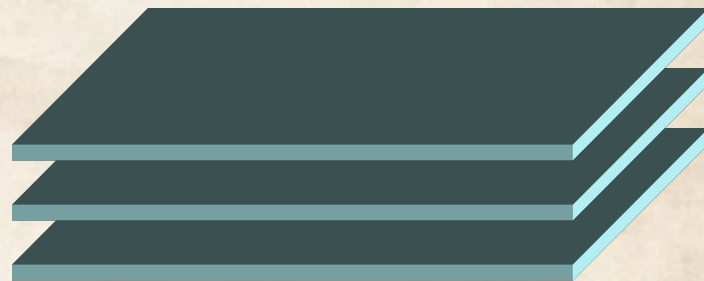
Интерферометр Фабри-Перо



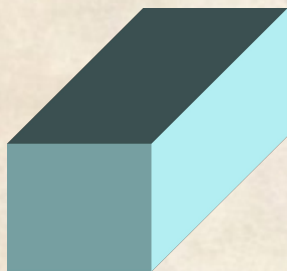
Куб данных



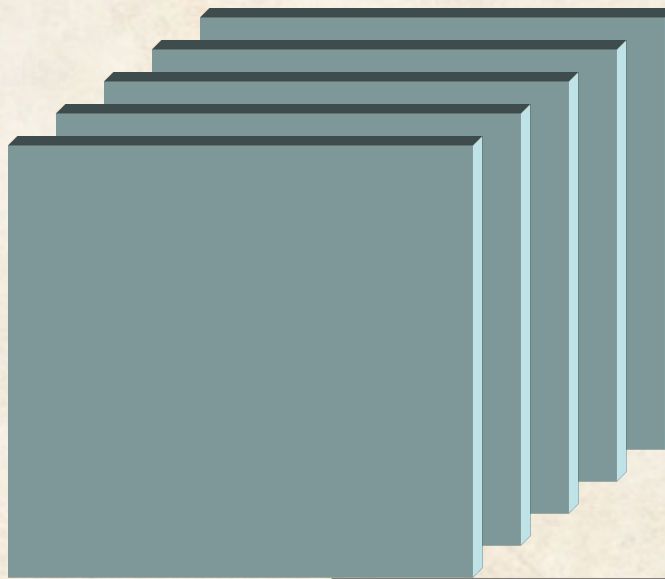
Длинные щели



Спектрографы
Интегрального
поля



Интерферометр Фабри-Перо



Сканирование щелью.

Ohtani 95

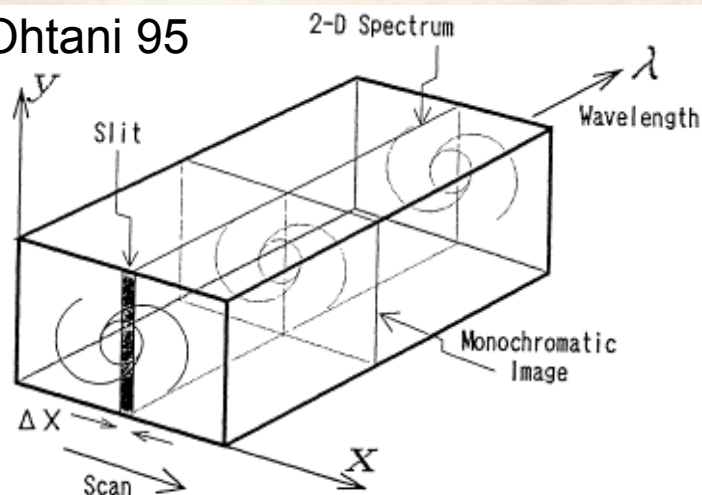


Figure 1. The concept of SNG observations.

Spectronebulagraph (SNG)
1.88-m Okayama Astroph. Observatory

Щель шириной 1.8", точность
установки < 0.3"

Проблемы вариаций атмосферных
условий решается добавлением
наблюдений с поворотом на 90°

Kosugi +95

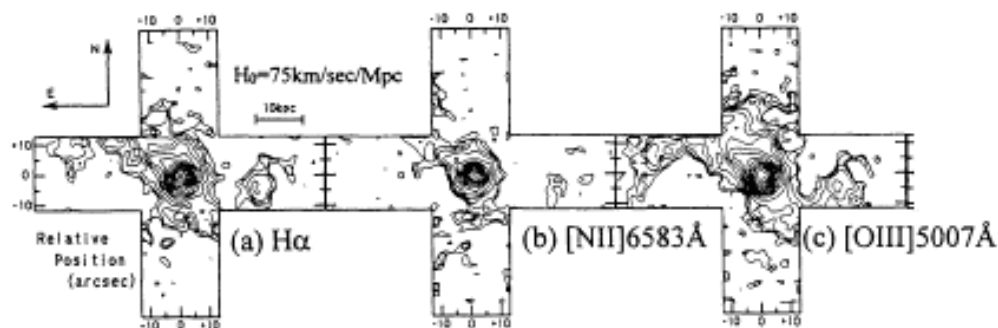


Figure 1. The pure narrow-line images. (a) $H\alpha$, (b) $[NII]6583\text{\AA}$, (c) $[OIII]5007\text{\AA}$ and (d) integrated sections.

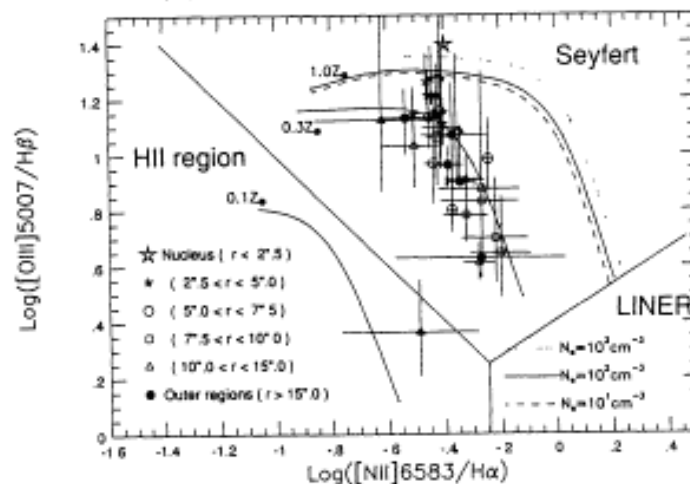


Figure 2. The VO diagram of 3C 120. Each plot shows the line ratios of integrated spectra at the regions shown in Fig.1(d). The solid lines

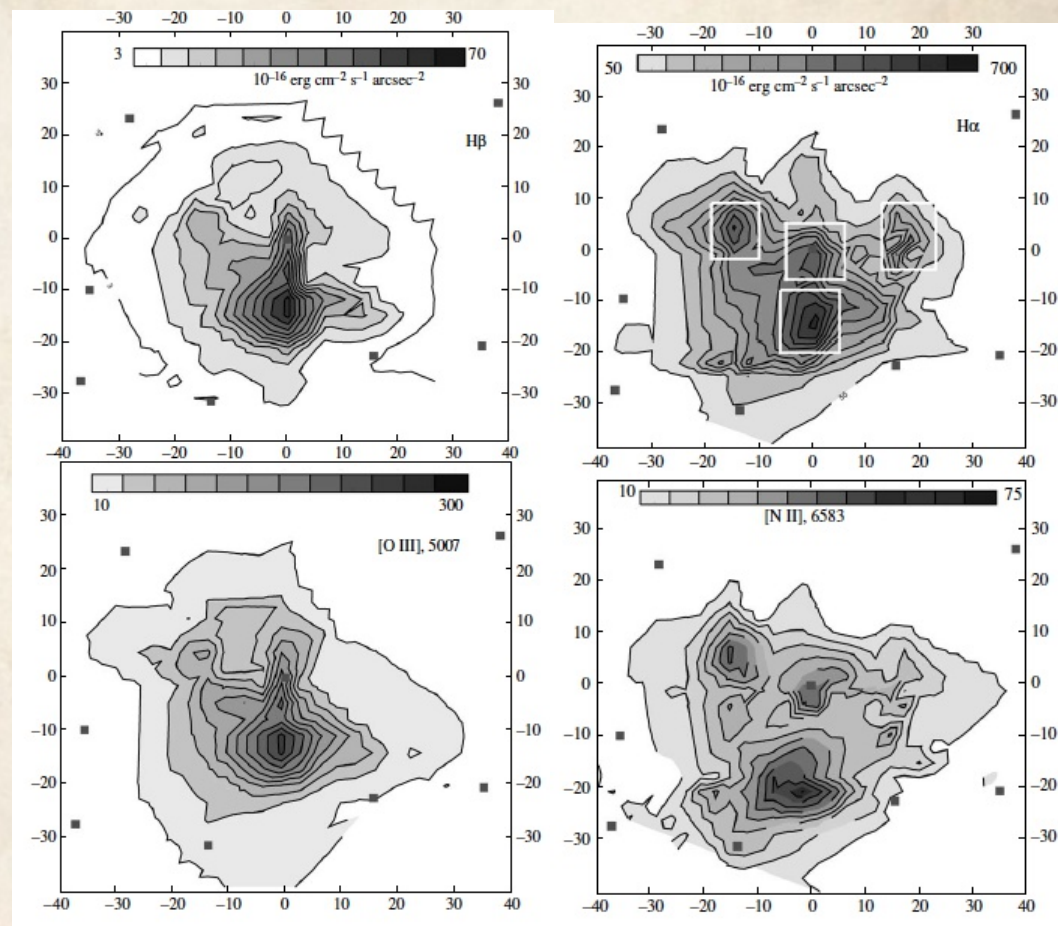
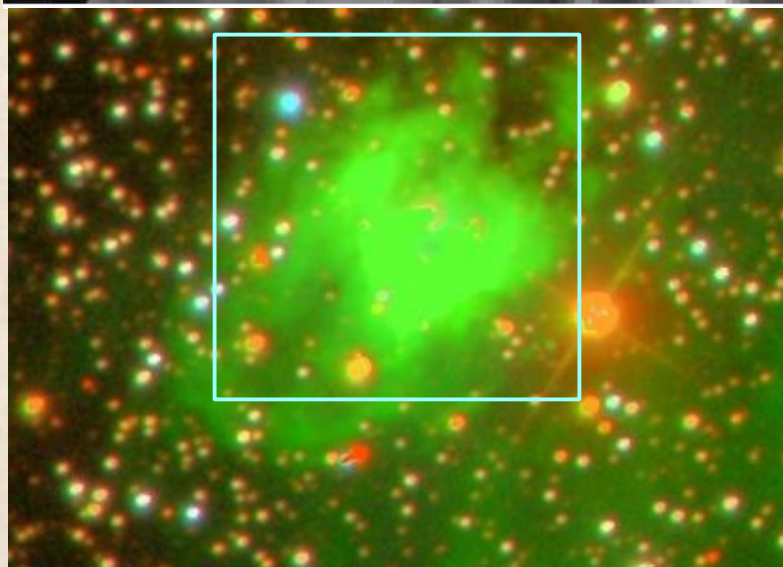
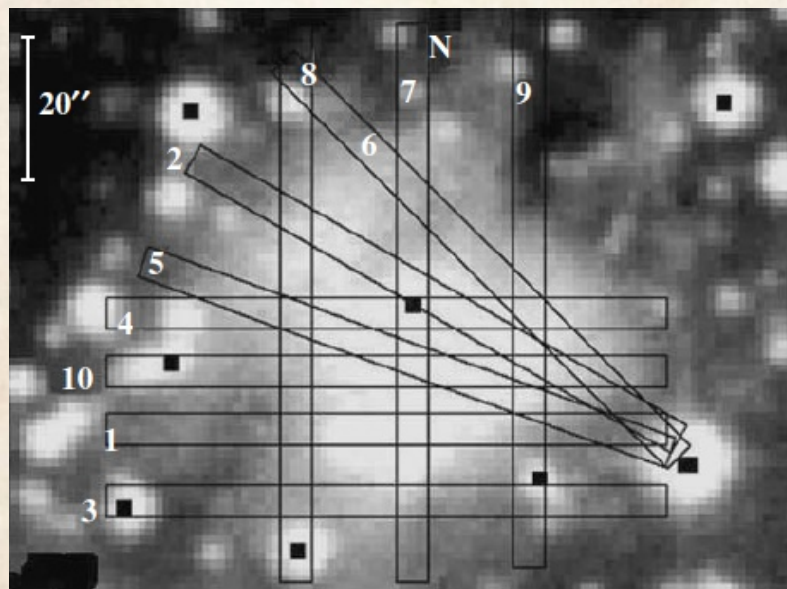
Сканирование щелью: NGC 6857

Цейсс-1000 + 0.7 м АЗТ-8

Щель 4.5"

Построены карты в основных линиях
излучение туманности, карты A_v и pe

(Кондратьева и др. 2014)



NGC 185 co SCORPIO



O.B. Erolov

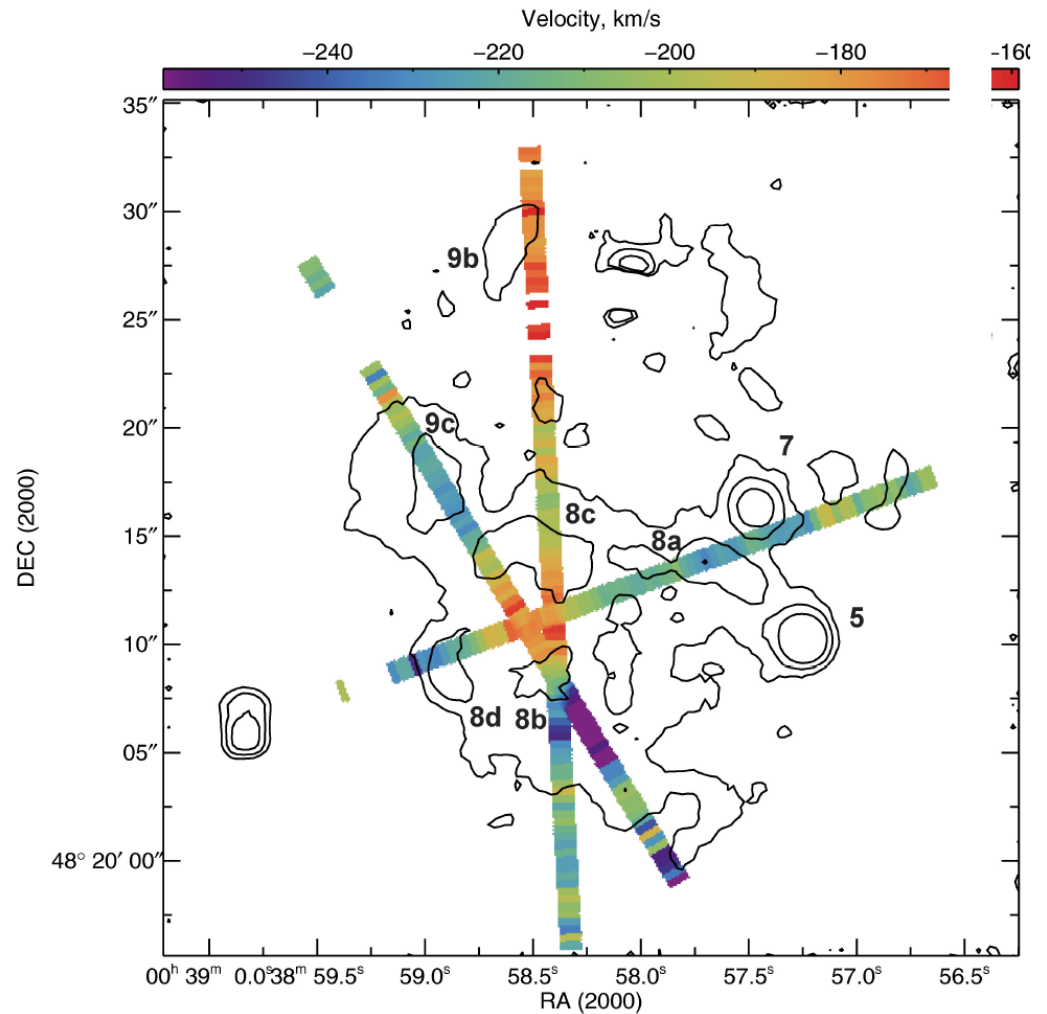
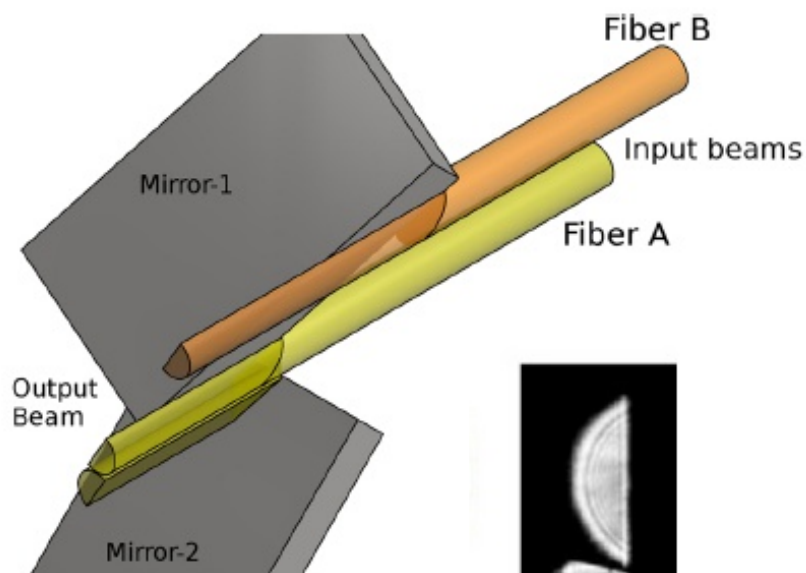


Fig. 10. Two-dimensional velocity map in the $H\alpha$ line of the central $40'' \times 40''$ of NGC 185, constructed from three slit positions for high-resolution spectra, with objects denoted as in Fig. 2. Contours denote $H\alpha$ intensity from narrowband imaging. Assuming that heliocentric velocity of the galaxy is -203.8 km s^{-1} (McConnachie 2012),

M. M. Vučetić et al.: Revealing the nature of emission nebulae in dwarf galaxy NGC 185

“Резатели” - давно используются в спектроскопии высокого разрешения

Системы зеркал или призм



Tala et al 2017

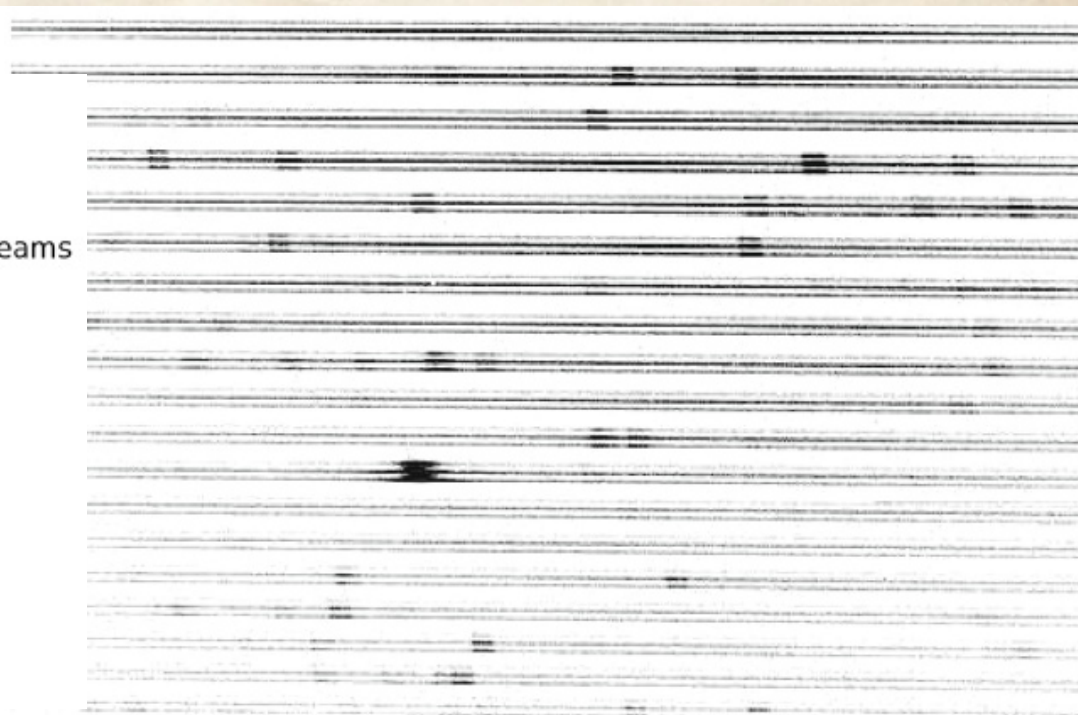


image of an echelle spectrum of CI Cam obtained with the image slicer at λ

НЭС БТА (призменный резатель)
Найденов и др 2007;Панчук и др 2007

Резатели для 3D спектроскопии

Weitzel et al. (1996)

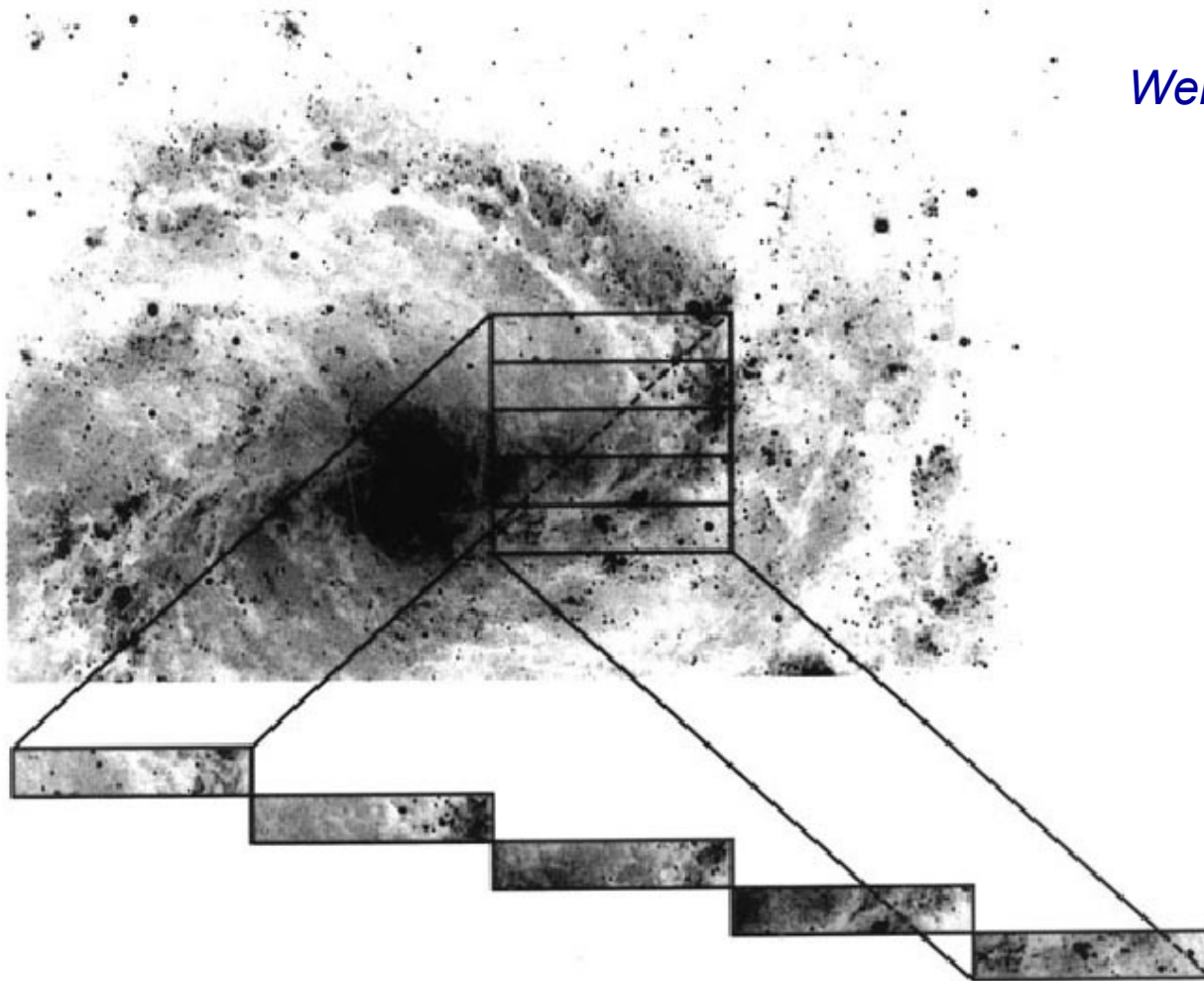
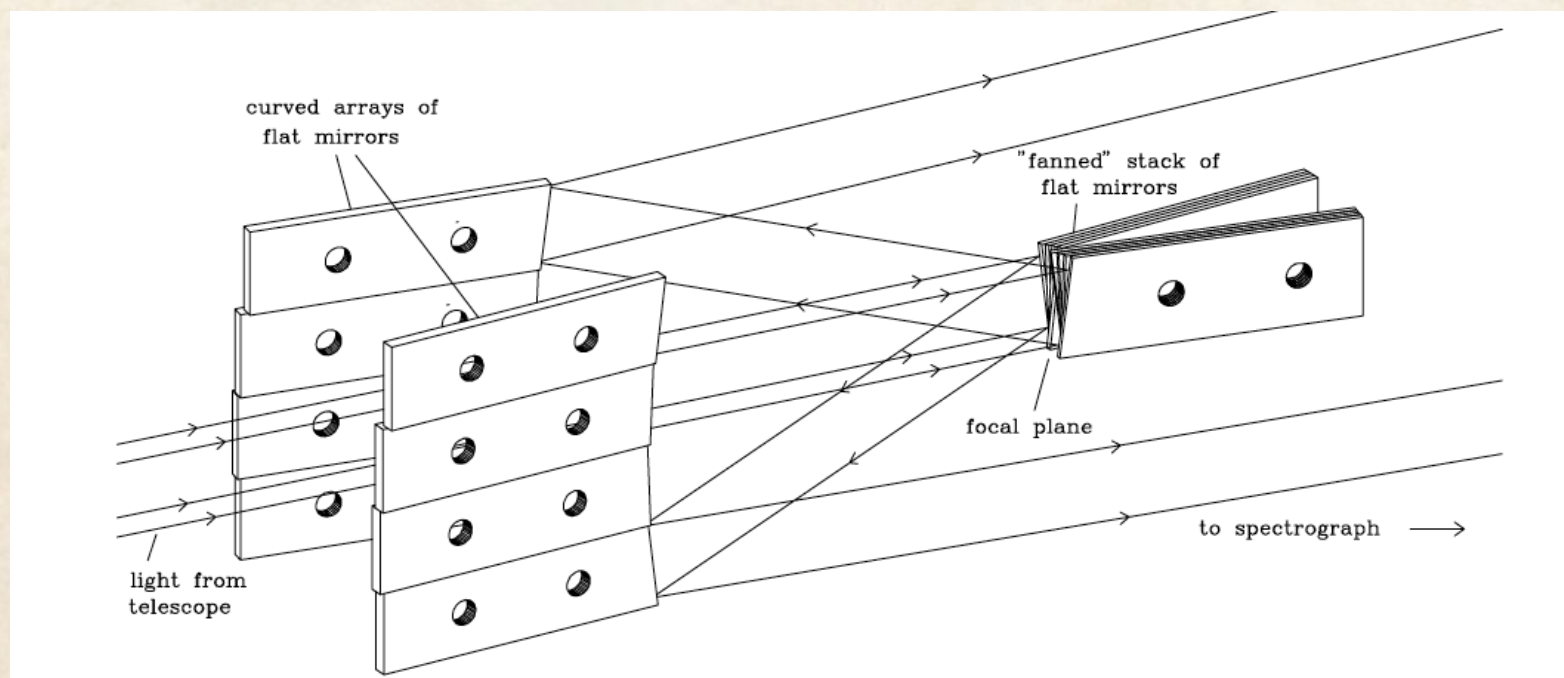


Fig. 1. The working principle of the 3D image slicer. The upper box represents the field of view with the original image. The image is horizontally cut into 16 strips, demonstrated here with 5 strips only. The single strips are then optically rearranged in the way shown to form a stair-like long slit

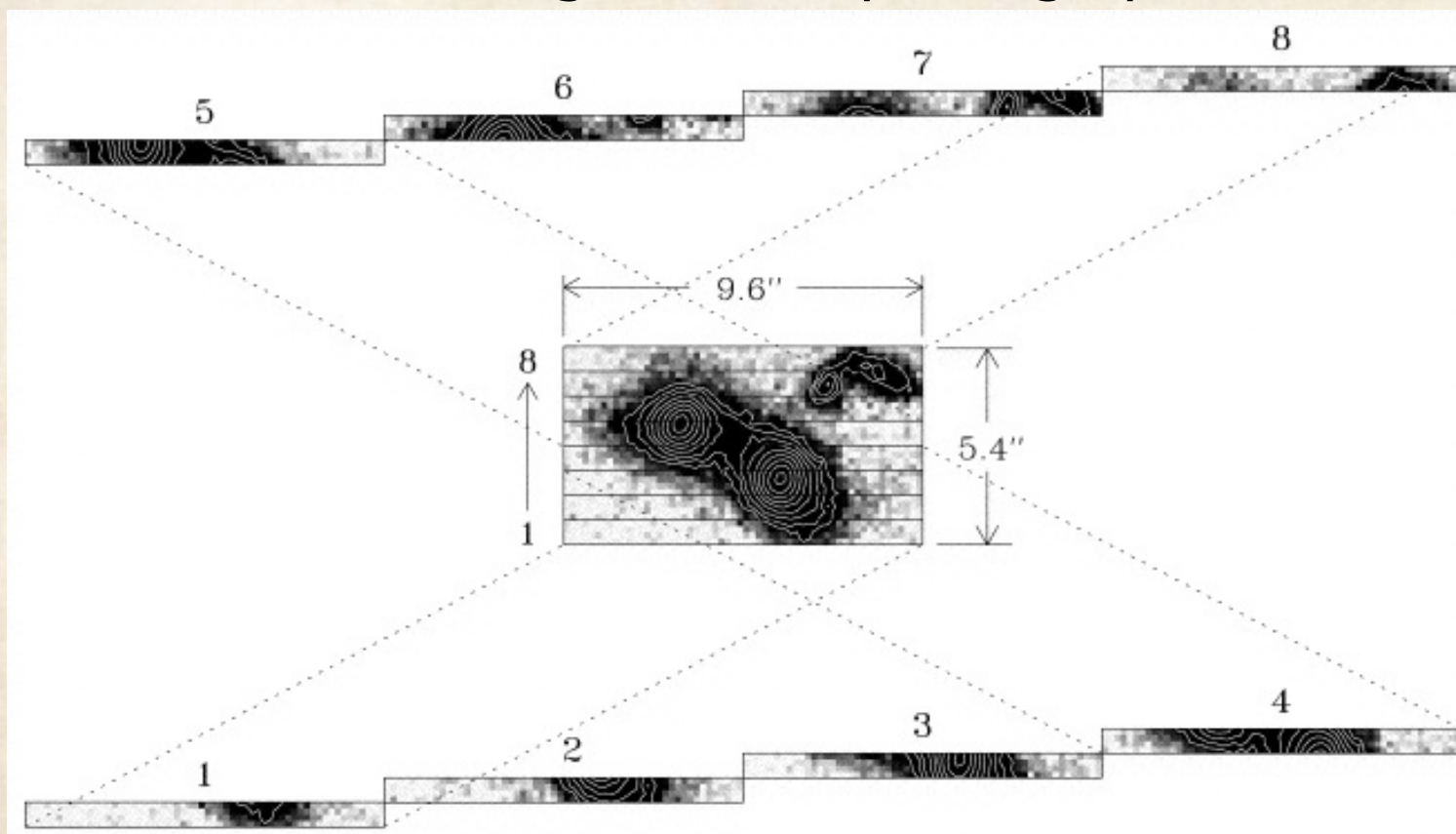
PIFS: Palomar Integral Field Spectrograph

Охлаждаемый щелевой блок оптимален для наблюдений в ИК.
Плата за это – трудности изготовления (прецизионная алмазная обработка) и юстировки тонких пластин.



Murphy +99

PIFS: Palomar Integral Field Spectrograph



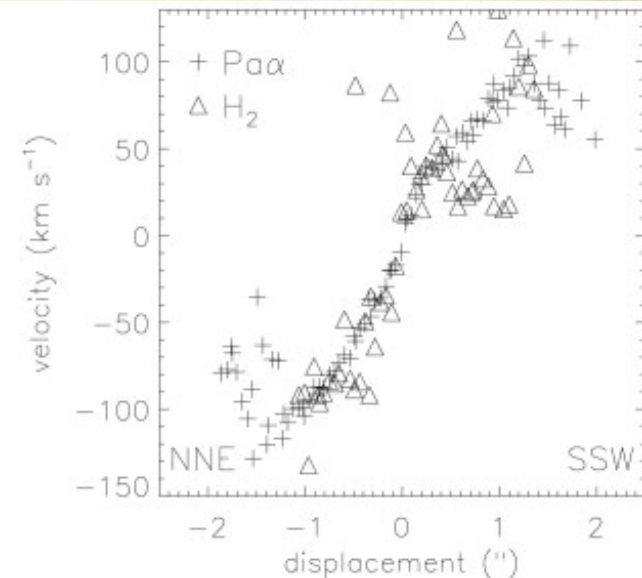
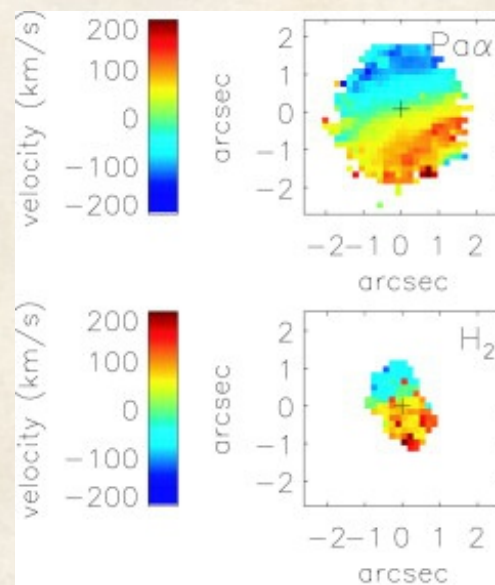
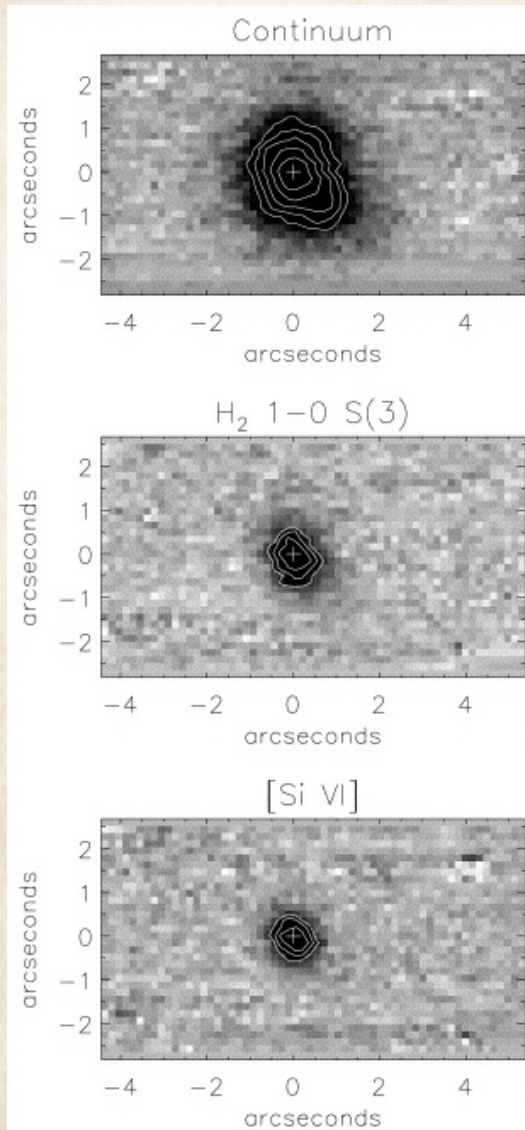
Ширина отдельных щелей – 0.67"

Murphy +99

PIFS: observations of IRAS 08311-2459

Near InfraRed observations of the
Ultraluminous Infrared galaxy IRAS 08311-2459

Murphy et al. (2000)



KCWI: Keck Cosmic Web Imager Integral Field Spectrograph

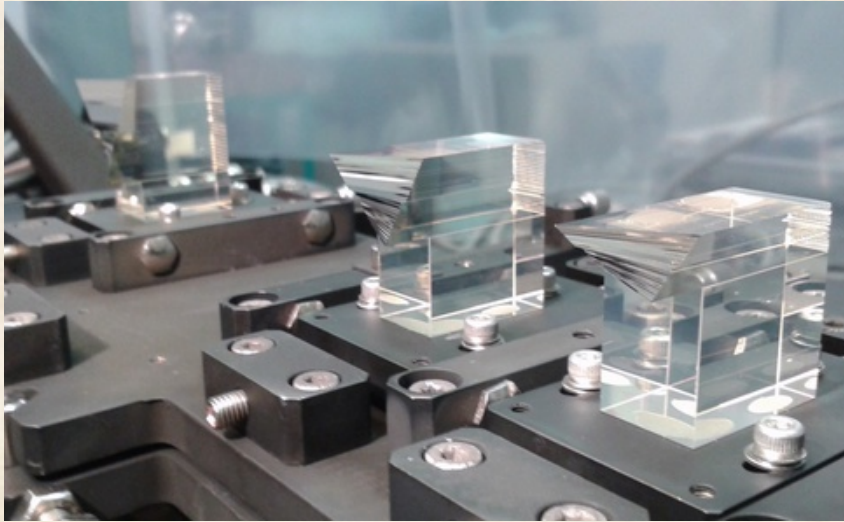
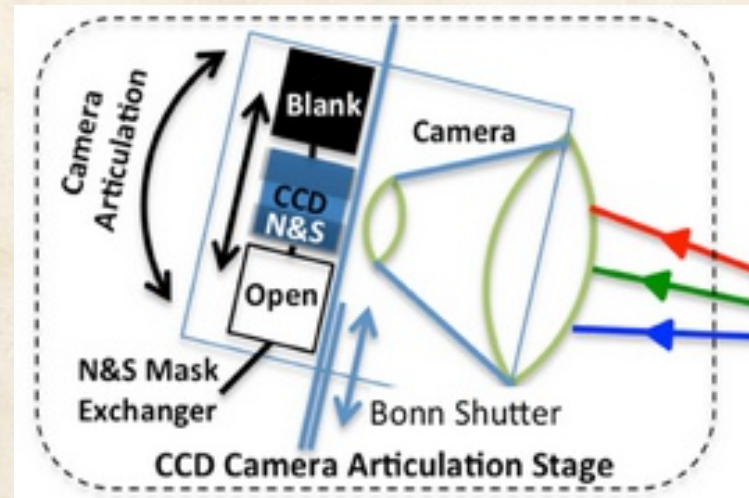


Table 3. KCWI Slicer-Grating Spectral Resolution Table

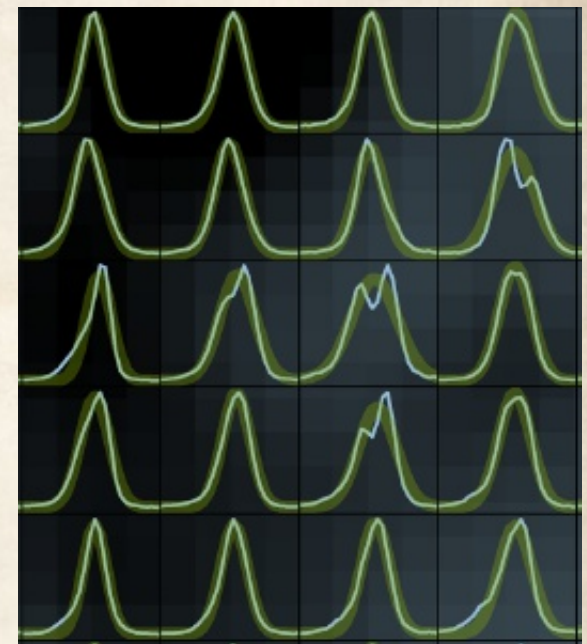
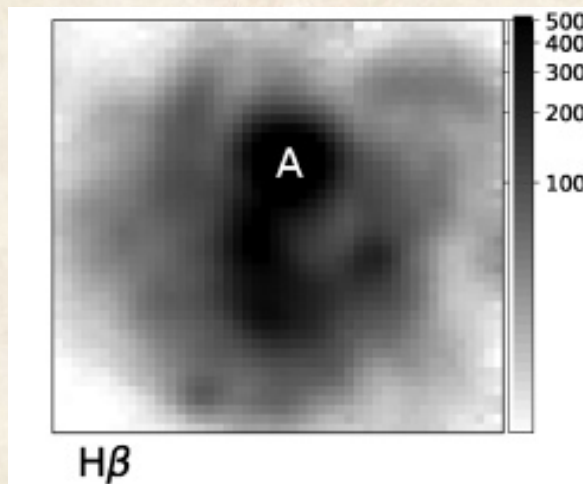
Grating	Slicers		
	Small 8.25" x 20"	Medium 16.5" x 20"	Large 33" x 20"
BL	5000	2500	1250
BM	10000	5000	2500
BHx	20000	10000	5000

Notable features of KCWI include:

- very high efficiency
- extremely accurate sky subtraction (nod-and-shuffle)
- flexible image resolution
- flexible spectral resolution
- officially supported Python pipeline

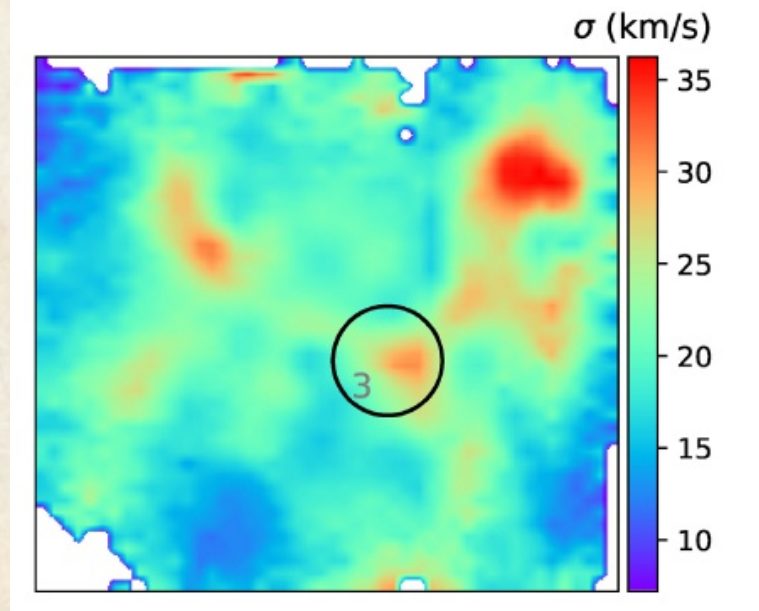


KCWI: HII region NGC 5455 and NGC 5471 in M101

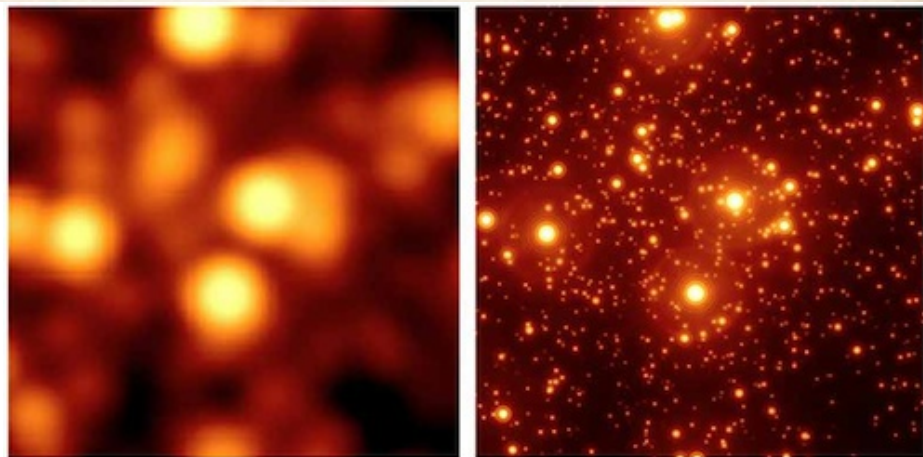
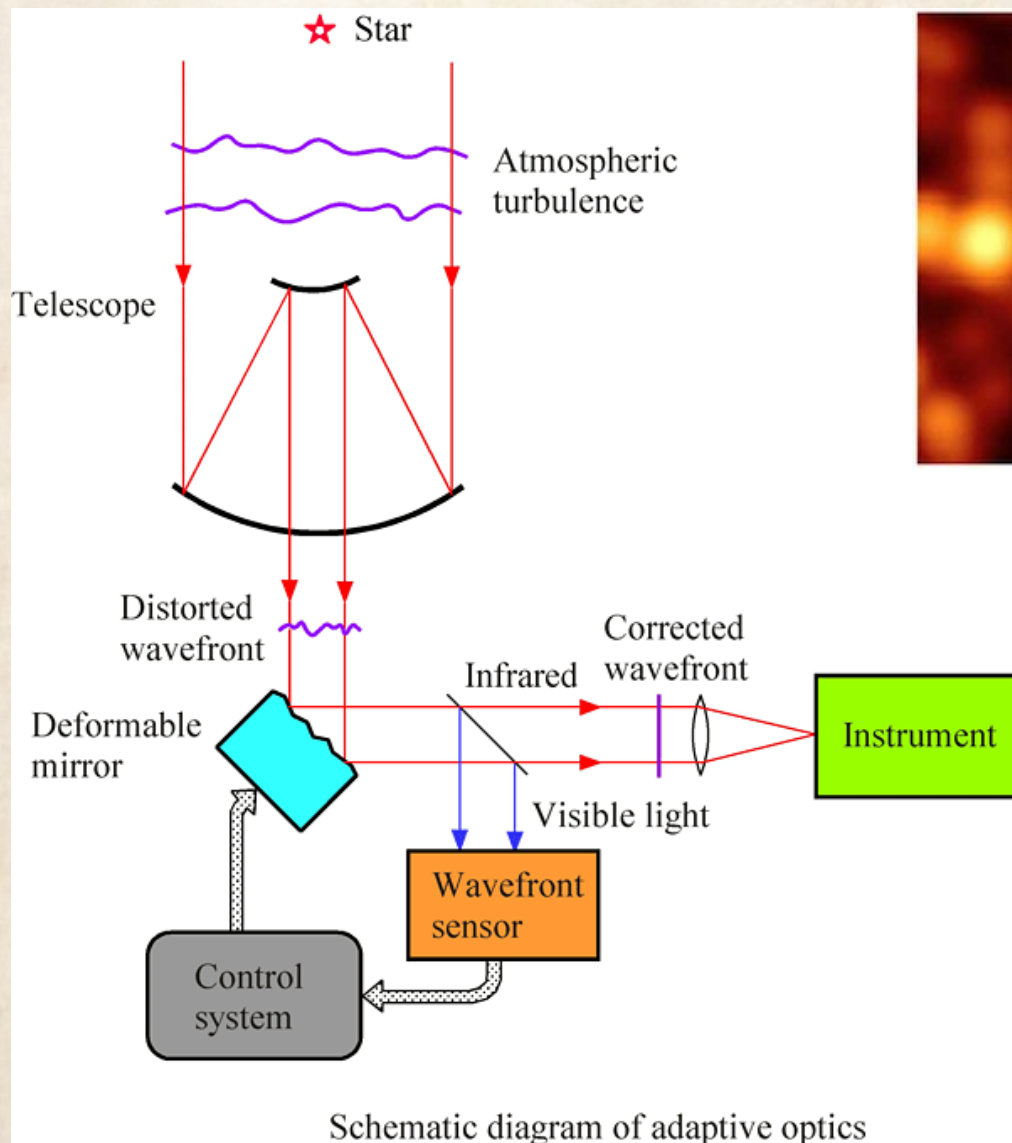


-120 and +120 km s⁻¹

R~16700
(FWHM 0.3A at 5000)
slice width 0.35"
FOV 3x(8.4*20.4)



Спектроскопия с системами адаптивной оптики



- АО работает преимущественно в ИК
- Спектроскопия с длинной щелью здесь нерациональна (потеря пространственной информации + сложность позиционирования + PSF меняются сильнее
($\sim \lambda^{-1}$ vs $\sim \lambda^{-0.2}$ in seeing-limited))



3D-спектроскопия
(в ИК оптимальна с резателем)

OASIS (3.6 m CFHT) - “старший брат SAURONa”



(Optically Adaptive System for Imaging Spectroscopy)

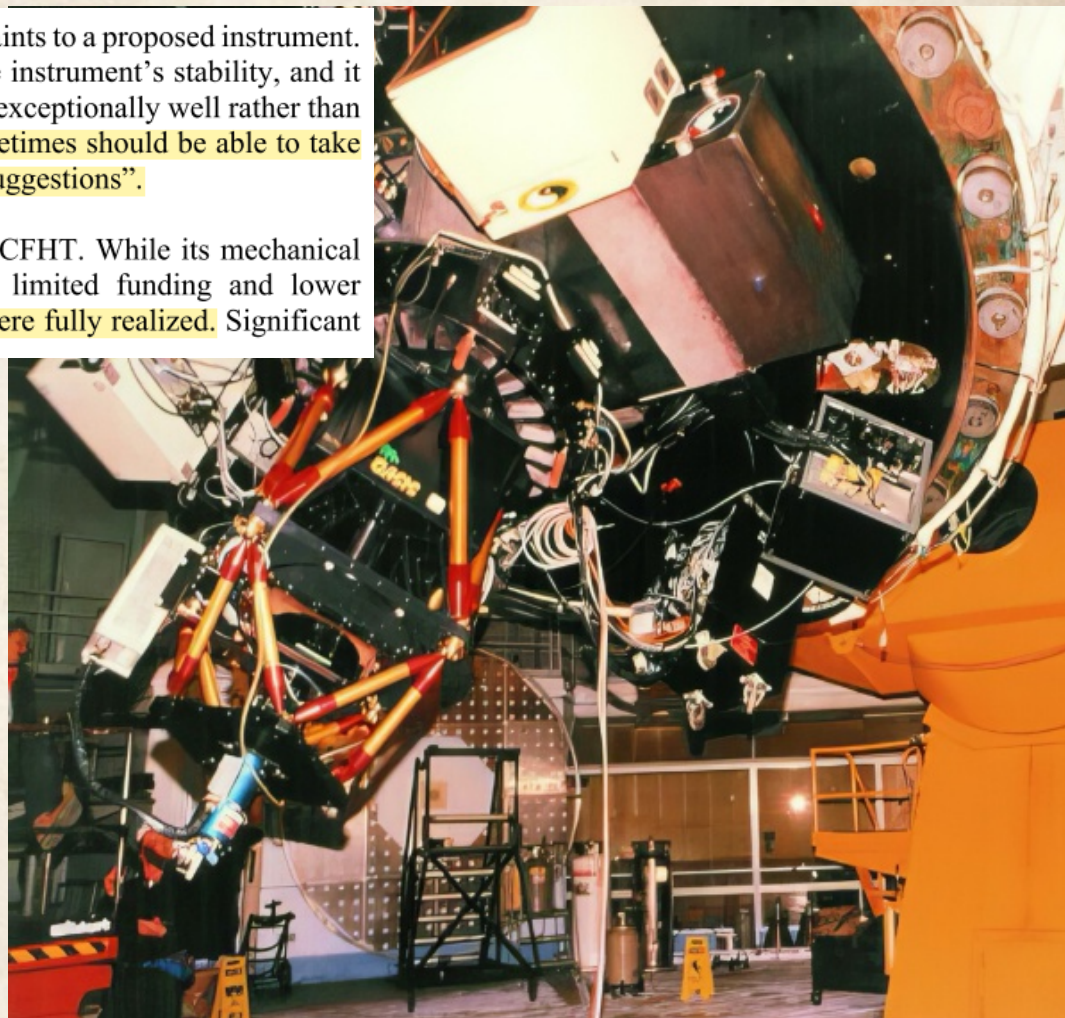
Today, I would be much more cautious before adding new constraints to a proposed instrument. I have learned that apparent “flexibility” often compromises the instrument’s stability, and it is always better to build an instrument that performs a few tasks exceptionally well rather than many tasks poorly. A PI must have his/her own vision and sometimes should be able to take some distance with “committee recommendations” or “friends suggestions”.

OASIS was built at the Lyon observatory with oversight from CFHT. While its mechanical structure was designed to support all the requested modes, limited funding and lower prioritization meant that only the imaging and TIGER modes were fully realized. Significant (Bacon 2024)

TIGER-mode Bacon et al 2001

Spatial configurations

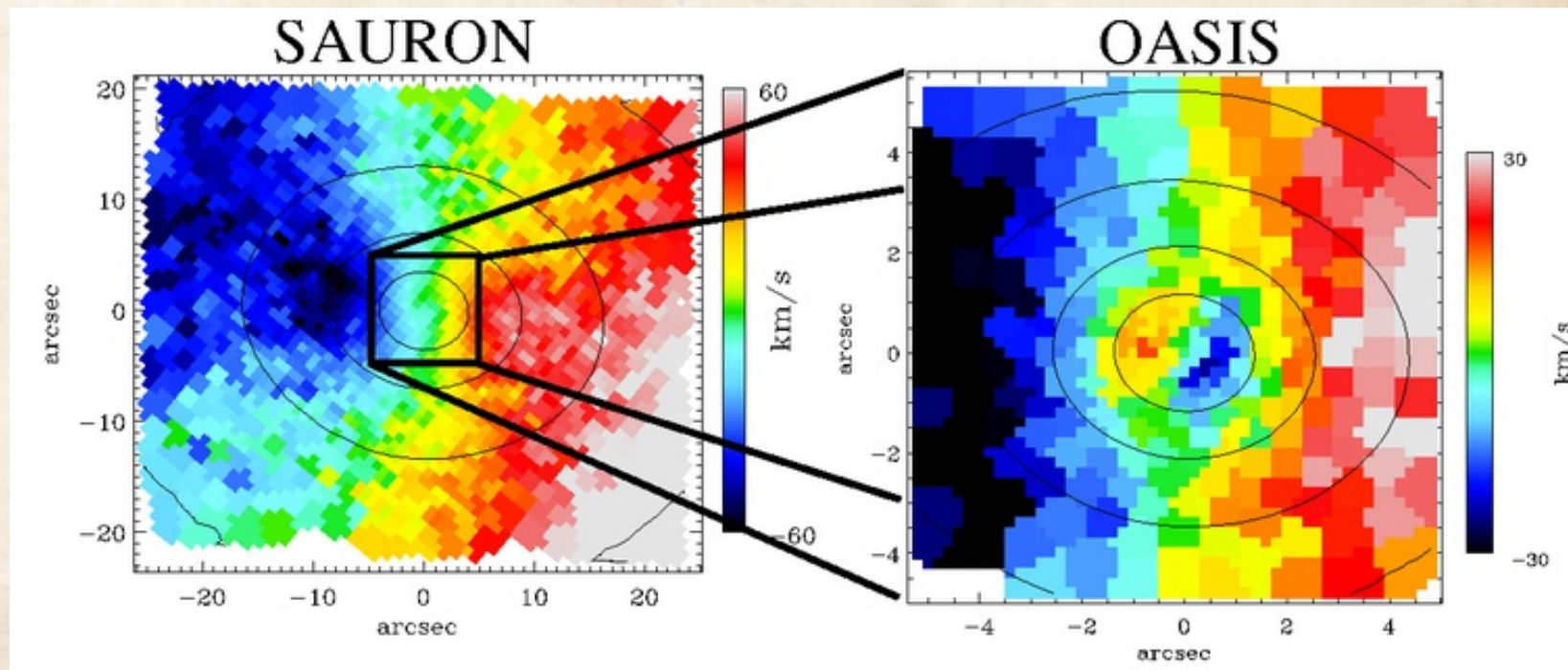
Spatial sampling	Field of view
0.09"	2.7" x 3.7"
0.14"	4.0" x 5.5"
0.26"	7.4" x 10.3"
0.42"	12.0" x 16.7"



OASIS (3.6 m CFHT) - "старший брат SAURONa")

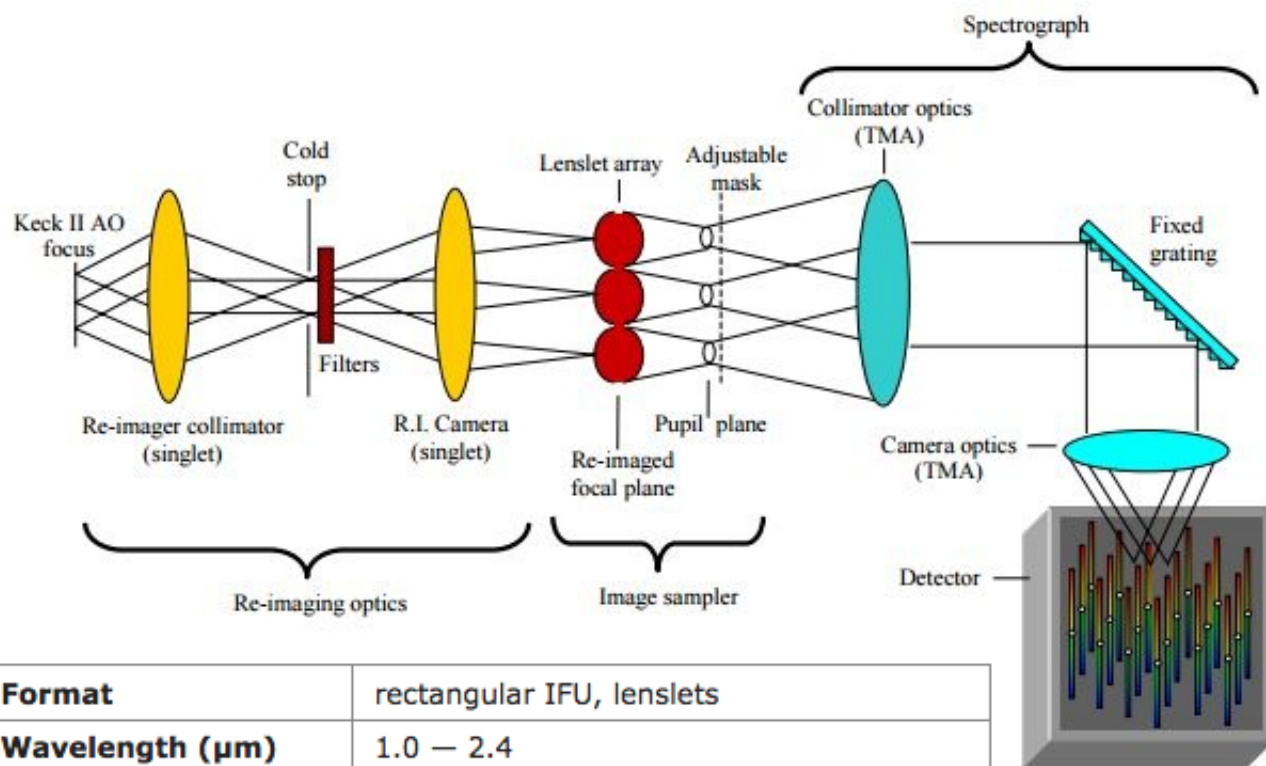


(Optically Adaptive System for Imaging Spectroscopy)



are manifold. The primary issue was the overly optimistic performance expectations for PUEO, the adaptive optics system. Commissioning measurements showed a two-fold improvement in FWHM in the visible range (Veran et al. 1997), but in practice, such performance was rarely achieved with OASIS. The lack of bright natural guide stars was often the culprit, and guiding on galaxy nuclei did not yield good results. The PUEO system introduced 30% throughput losses, and with the small spatial sampling, we were working in a detector noise-limited regime, which is far from ideal. Additionally, the time required to set up PUEO and close the loops was significant, leading to efficiency losses. A critical analysis of the expected PUEO performance

Keck OSIRIS (OH-Suppressing InfraRed Imaging Spectrograph)



Титан:
стратосфера



поверхность:



0.9 arcsec

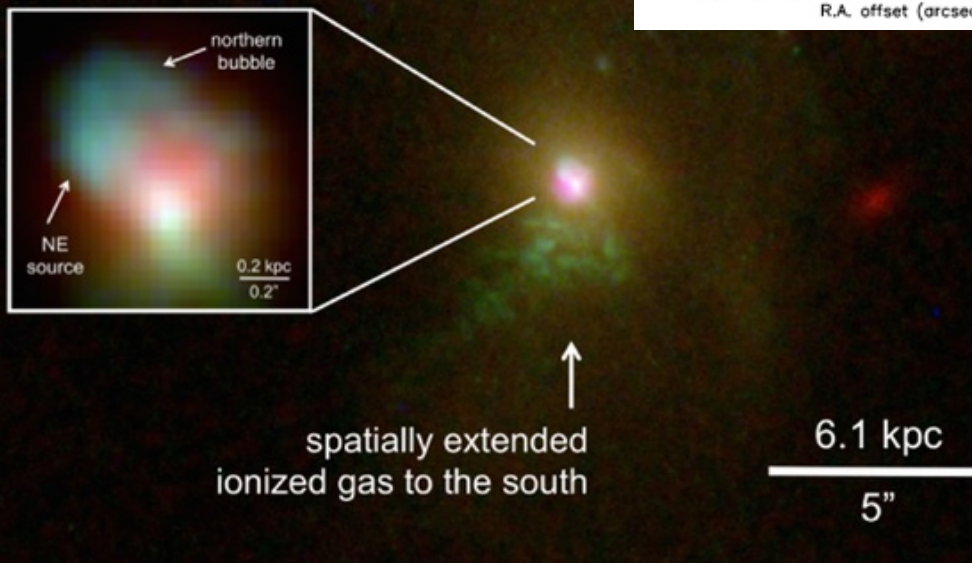
Format	rectangular IFU, lenslets
Wavelength (μm)	1.0 — 2.4
Spectrograph resolution (R)	~ 3800
Simultaneous sky coverage	none in the IFS itself, though there is a simultaneous imager channel
Field of view	0.32"x1.28" — 4.8"x6.4" depending on camera setting
Spatial element size	0.020", 0.035", 0.050", 0.100"

Larkin + 2006

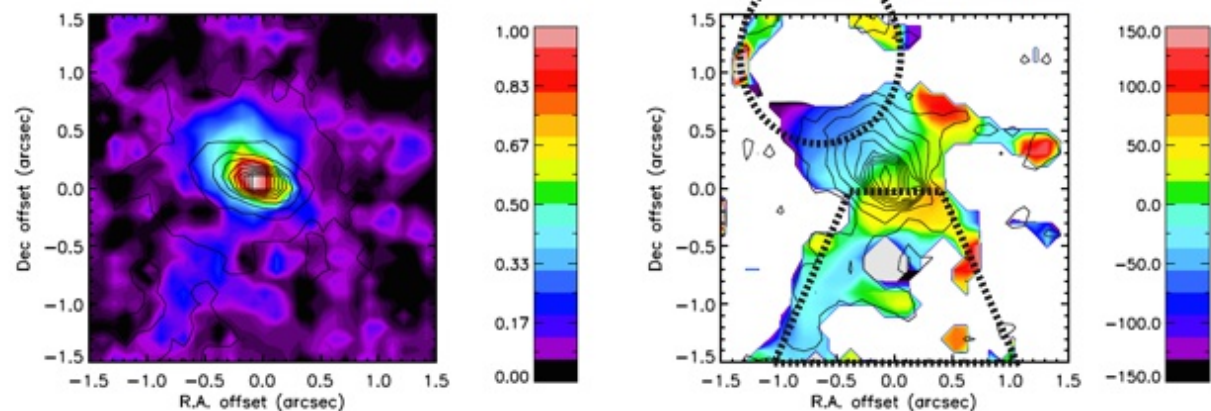
Keck OSIRIS

Comerford et al 2017: галактика в момент переключения активности

HST + Chandra



Pa α flux distribution (top middle), and Pa α velocity (top right)

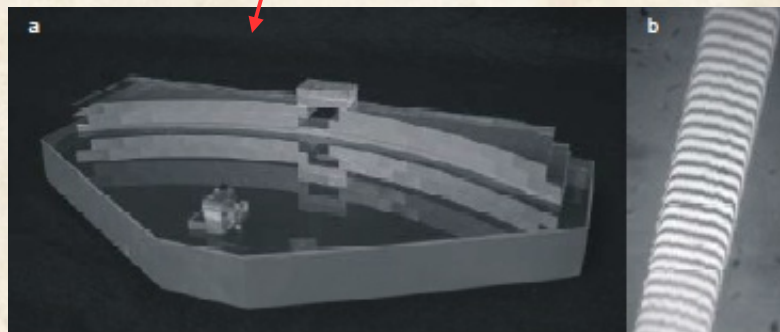
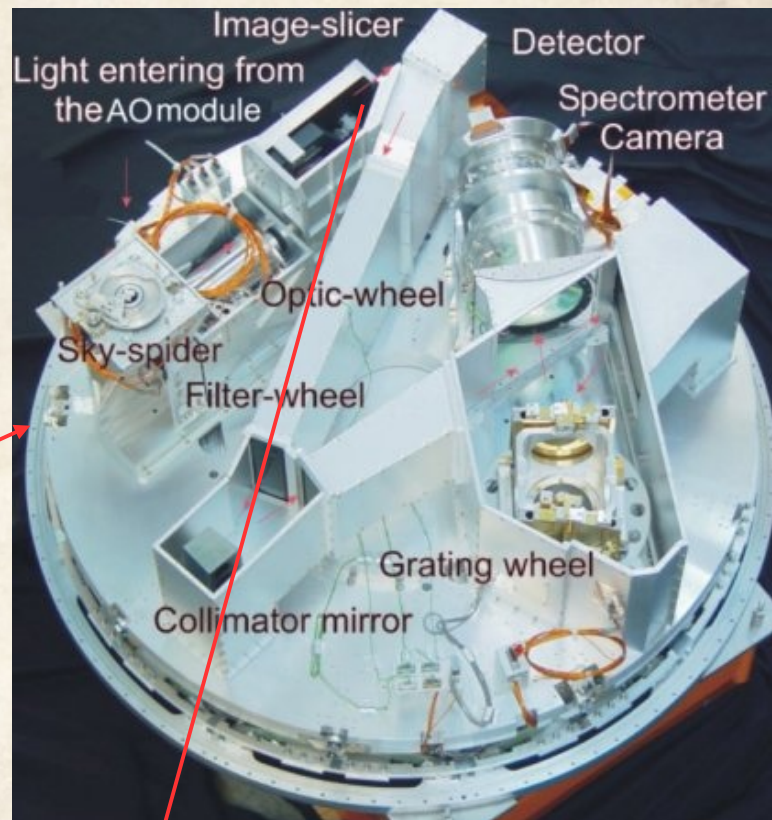
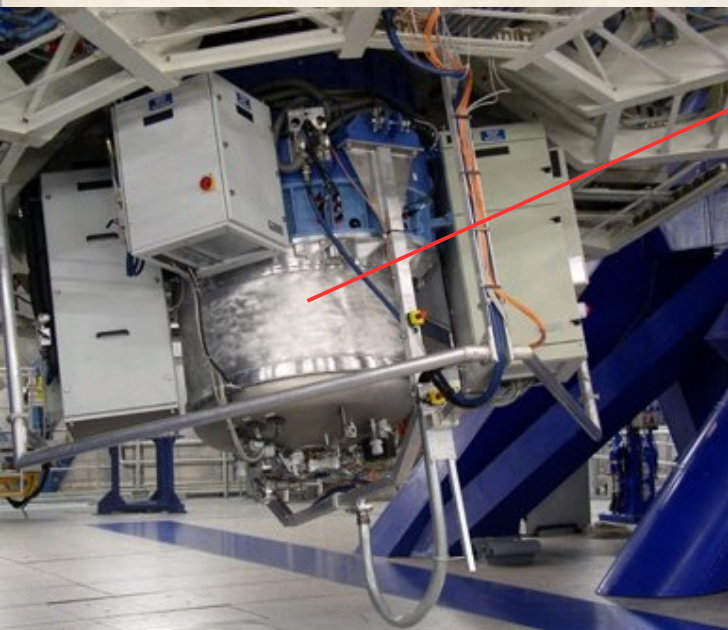


“Конус” и “пузырь” - на разных этапах включения AGN
(100 000 лет)

SINFONI - Spectrograph for INtegral Field Observations in the Near Infrared (VLT)

Spectral range: (1.1 - 2.45 μm)

Field of View	Spatial Scale	Mode	Limiting Magnitudes
8"x8"	125x250mas	noAO	J=20.2 H=19.9 K=17.9 H+K=19.6
3"x3"	50x100mas	NGS	J=19.4 H=19.6 K=18.8 H+K=19.8
0.8"x0.8"	12.5x 25mas	NGS	J=17.8 H=18.7 K=18.3 H+K=19.2

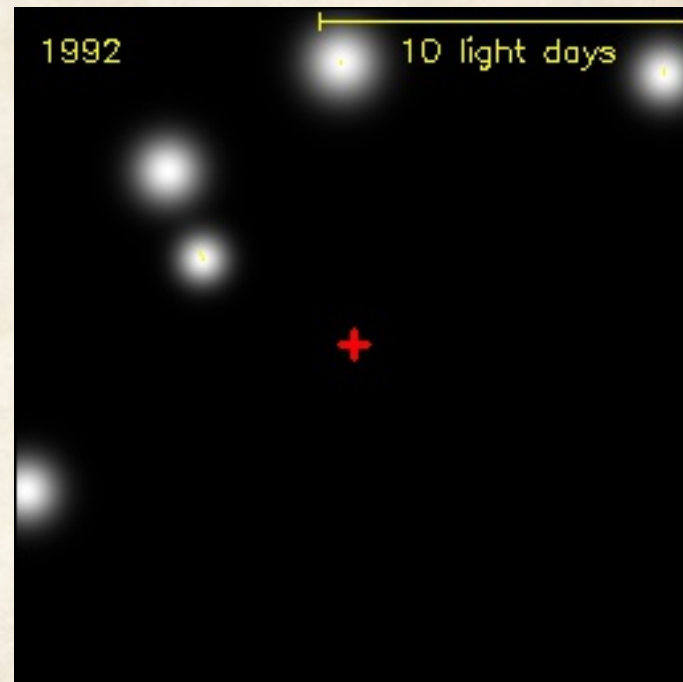


Eisenhauer + 2003

Центр Галактики в инфракрасном диапазоне



Combined H- K- and L-band adaptive optics image of the Galactic Center obtained with

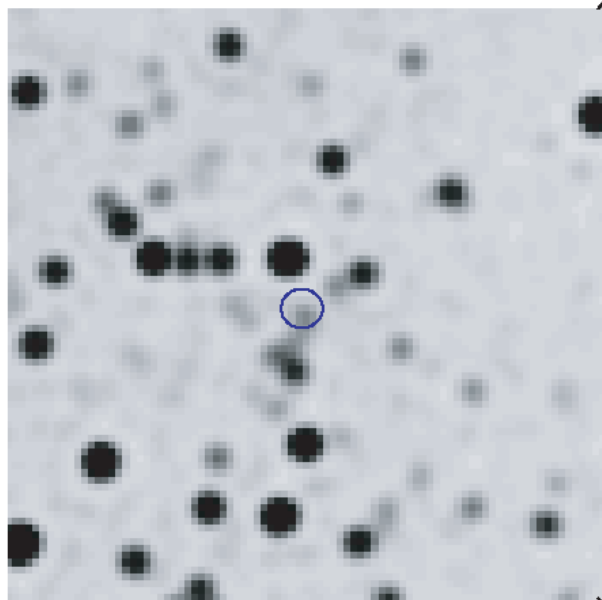


<http://www.mpe.mpg.de/ir/GC>

SINFONI: галактический центр

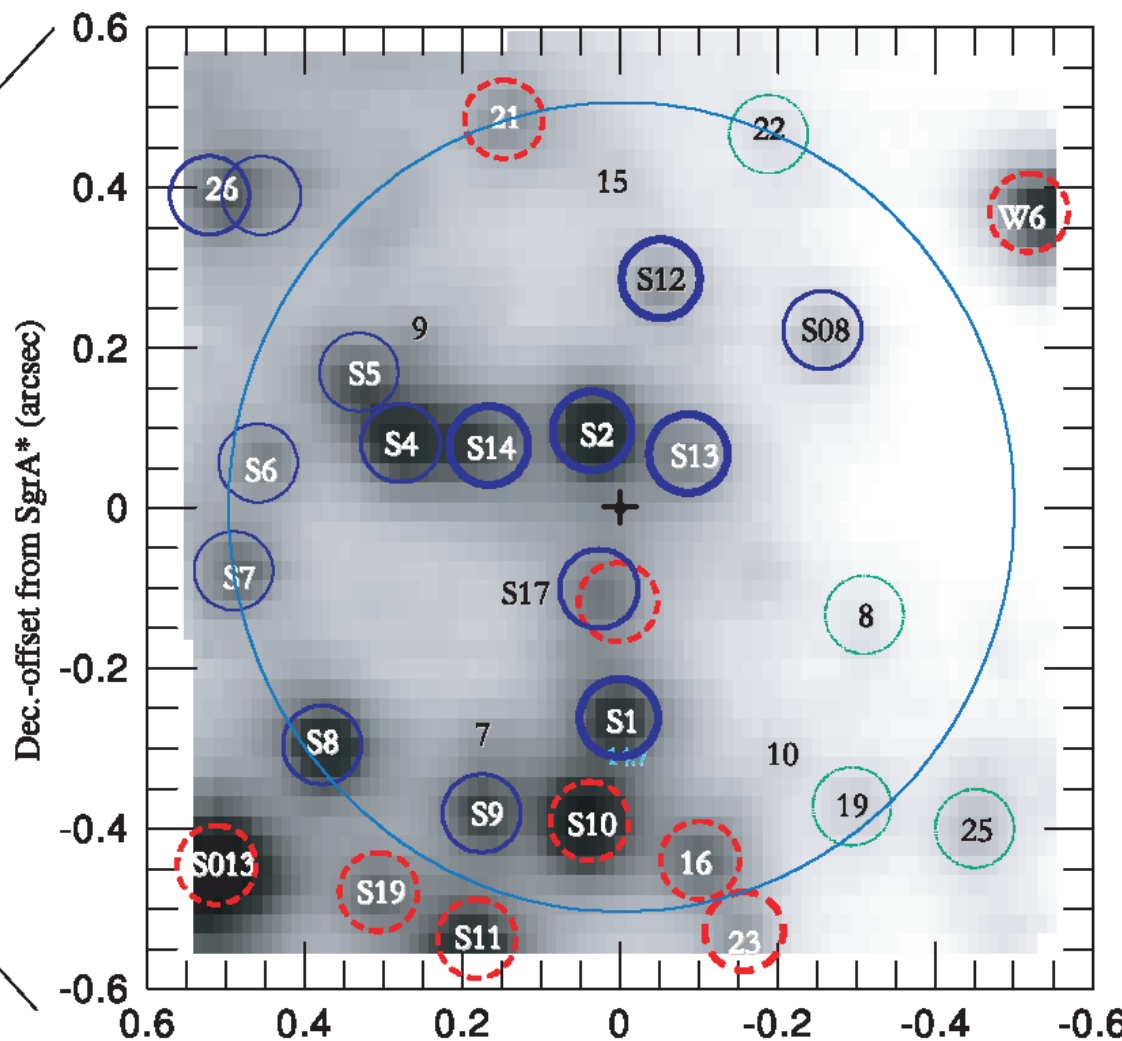
Eisenhauer et al. (2005),

NACO 10.06.04: H (40mas)



0.5" (23 light days)

SINFONI 18.08.04: K(75 mas)



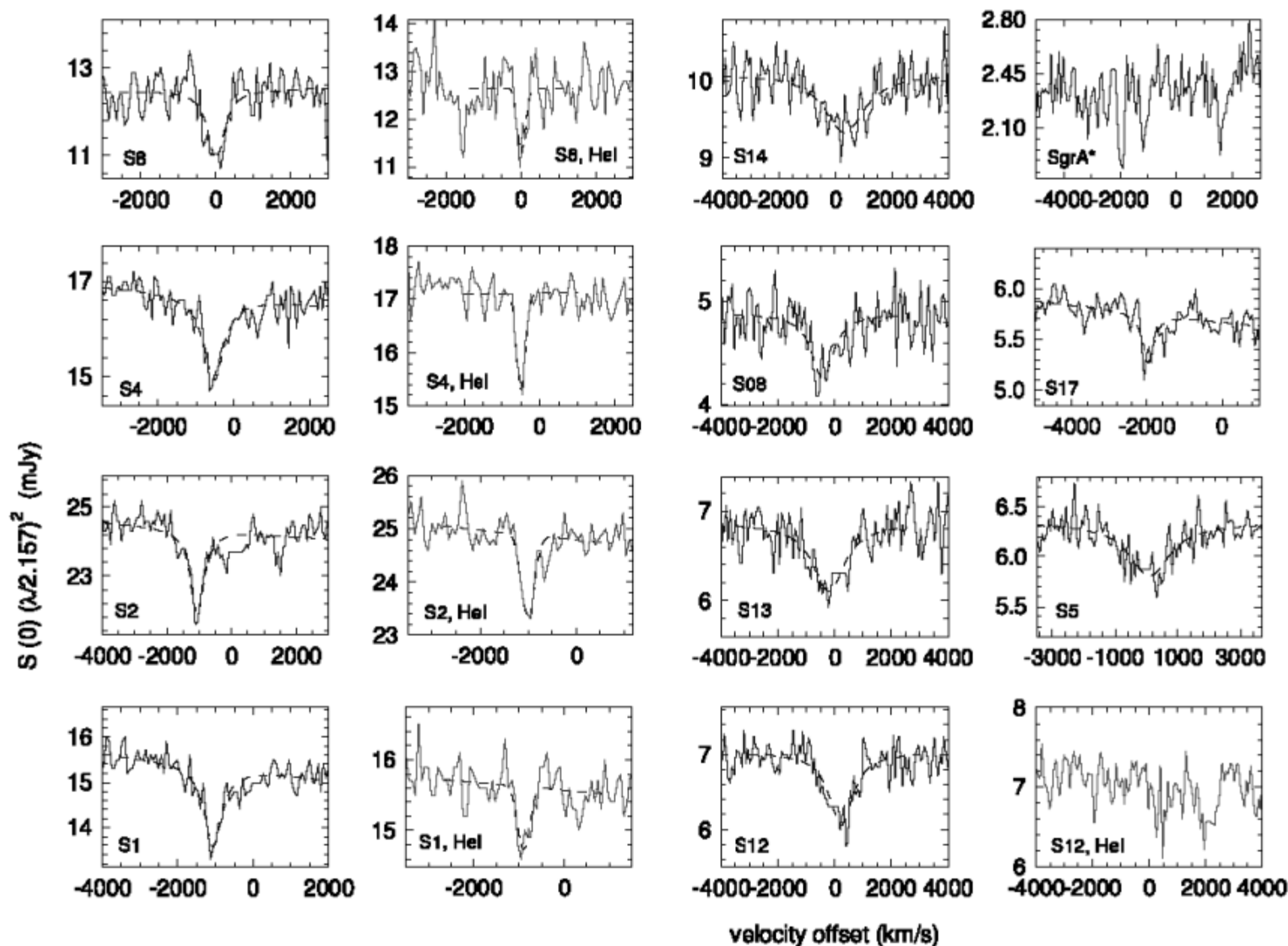
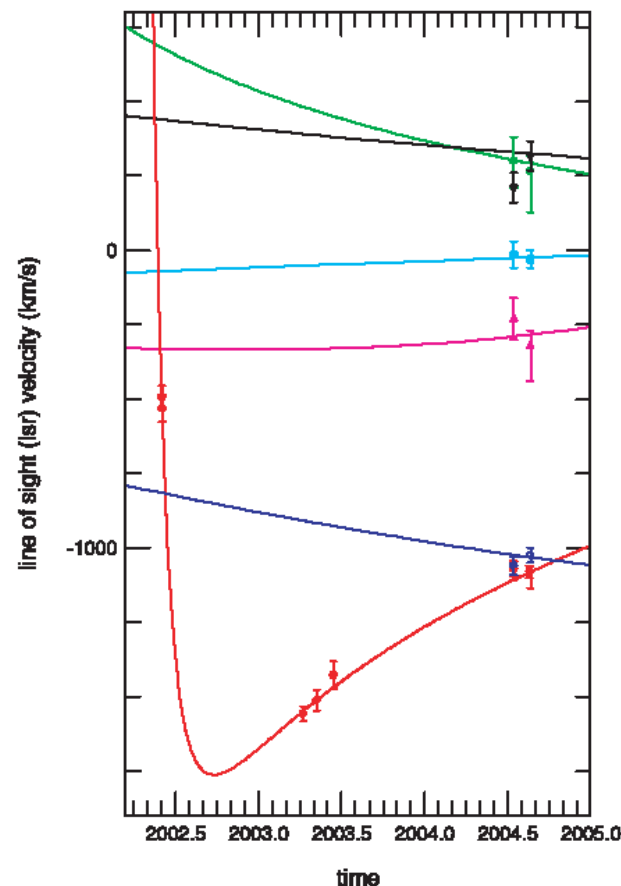
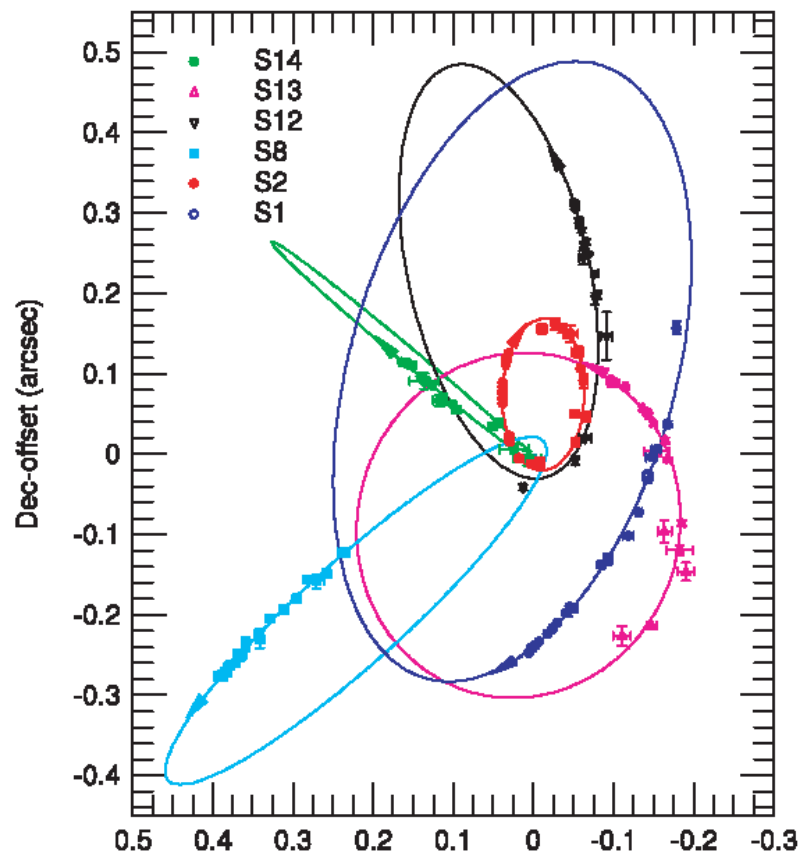


FIG. 2.—Extracted spectra near the $2.1661 \mu\text{m}$ H I Br γ (7–4) line and the $2.1127 \mu\text{m}$ He I line (labeled) for 10 of the 11 $K < 16$ mag stars in the central $\sim 0''.5$, plus a

SINFONI: к астрометрии добавлены лучевые скорости

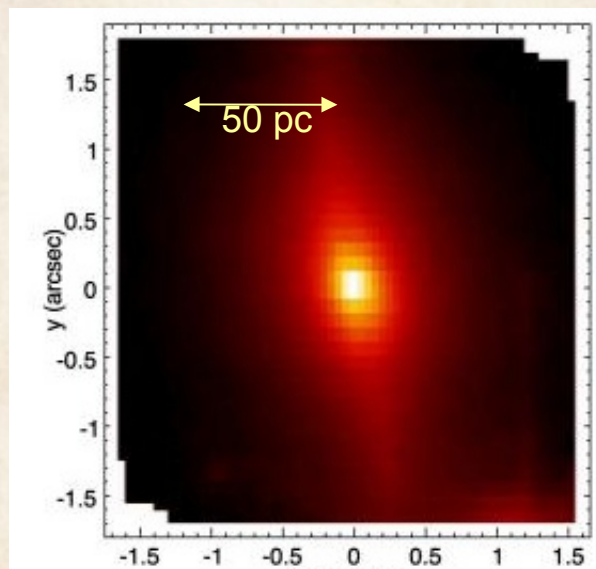


Данные SINFONI в комбинации с прямыми снимками в разные эпохи использовались для построения трехмерной модели звездных орбит в центре Галактики, уточнения массы ЧД и расстояния до неё

(see also Schödel et al. 2003). The measured radial velocity data of S1, S2,

SINFONI: массы черных дыр в других галактиках

NGC 4486A (Nowak +07)



Параметры звездной кинематики

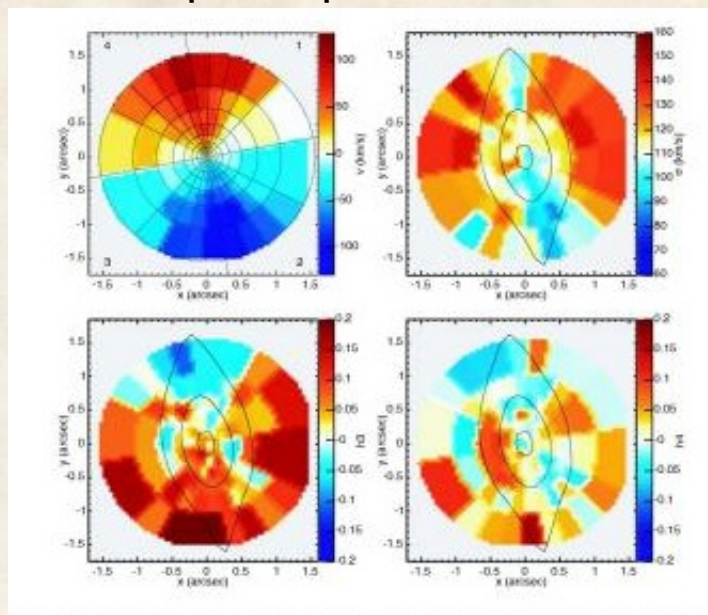
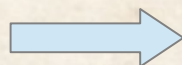
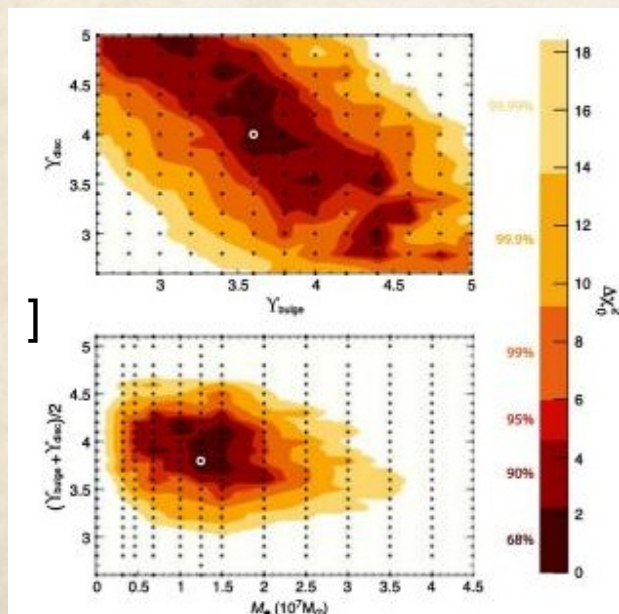


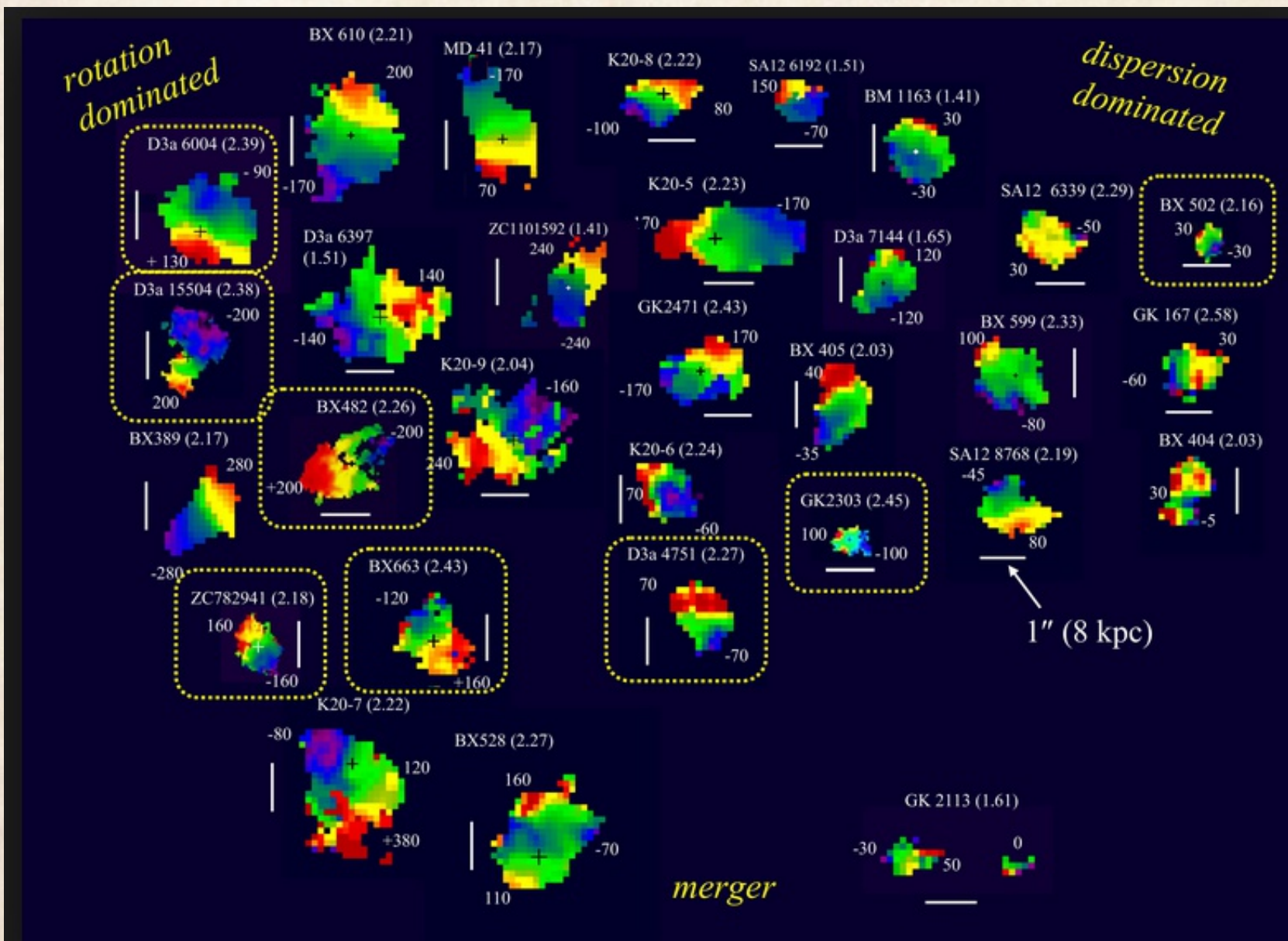
Figure 3. Stellar kinematic fields (v , σ , h_3 , h_4) of NGC 4486a. The binning



Подгонка наблюдений моделью,
масса центральной ЧД (M^*) - один
из параметров

АО: seeing < 0.1"

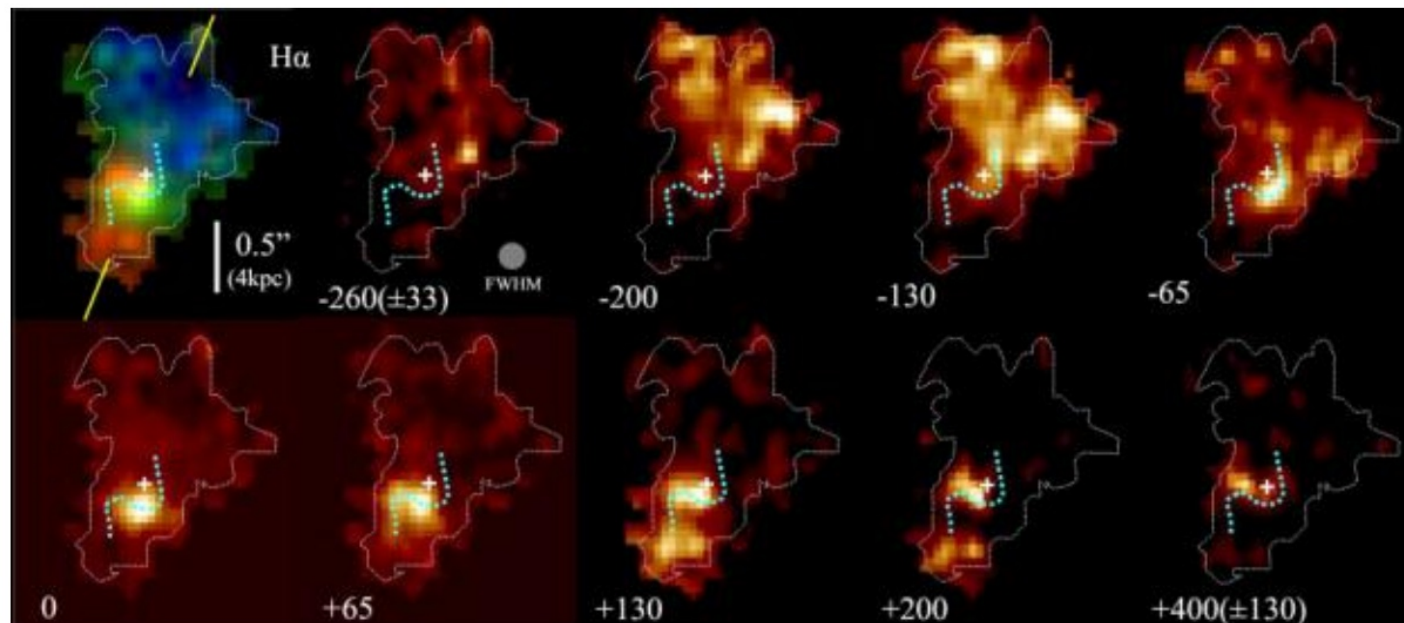
SINFONI: обзор галактик на $z \sim 2$ (SINC, 62 galaxies in Ha)



SINFONI/SINS

Звездообразование в линии H α на $z=2.38$ с разрешением 1.2 кпк – возможность прямого сравнения с близкими галактиками.

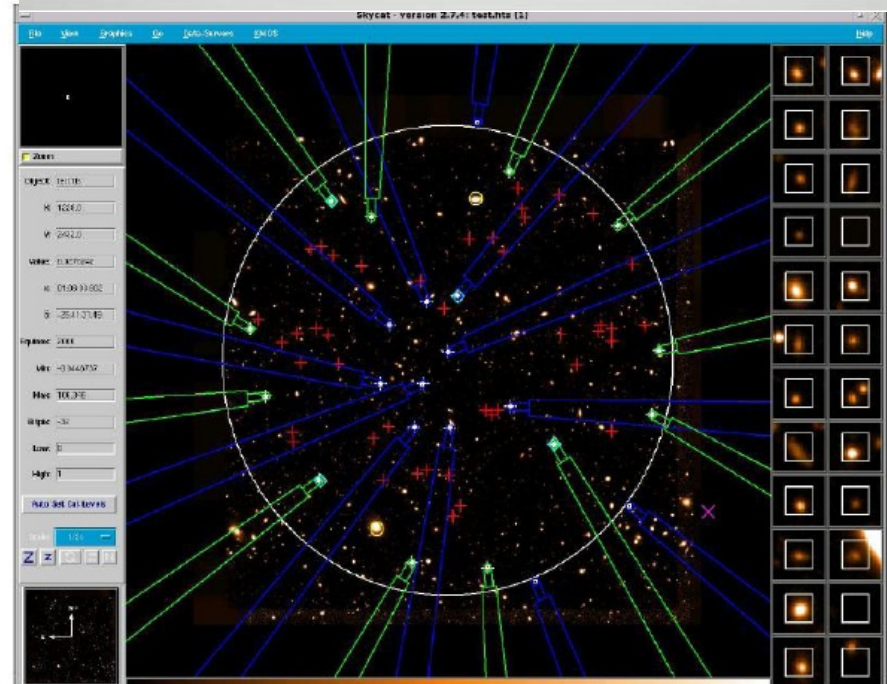
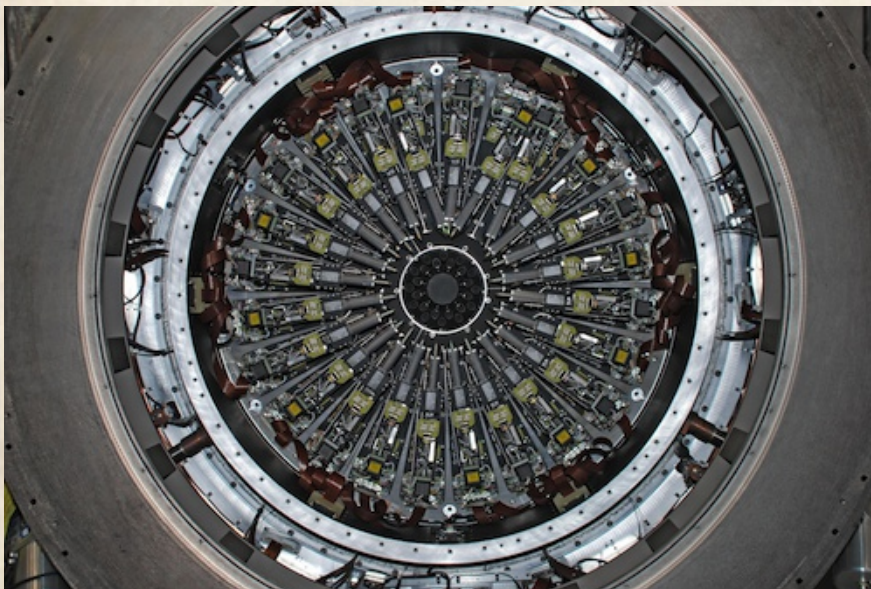
BzK-15504: SFR=150 Msun/yr



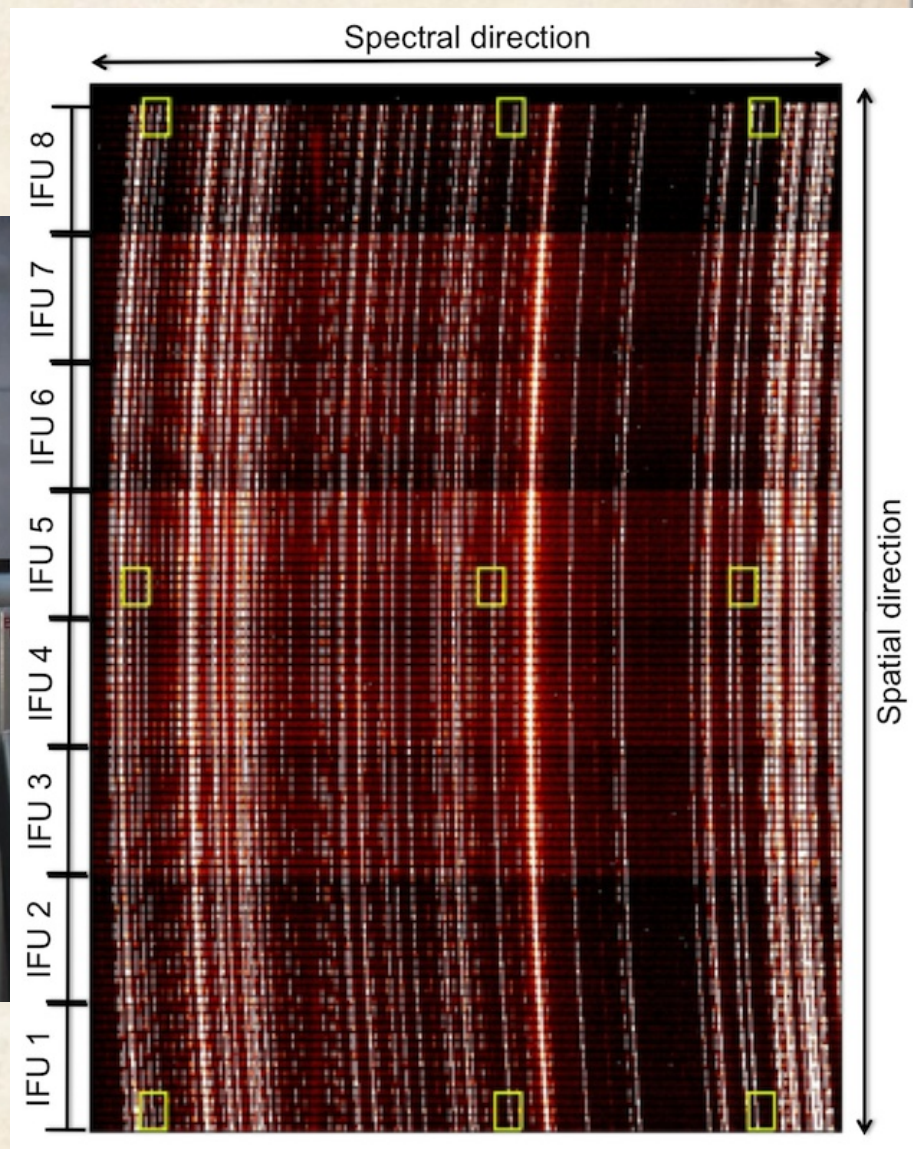
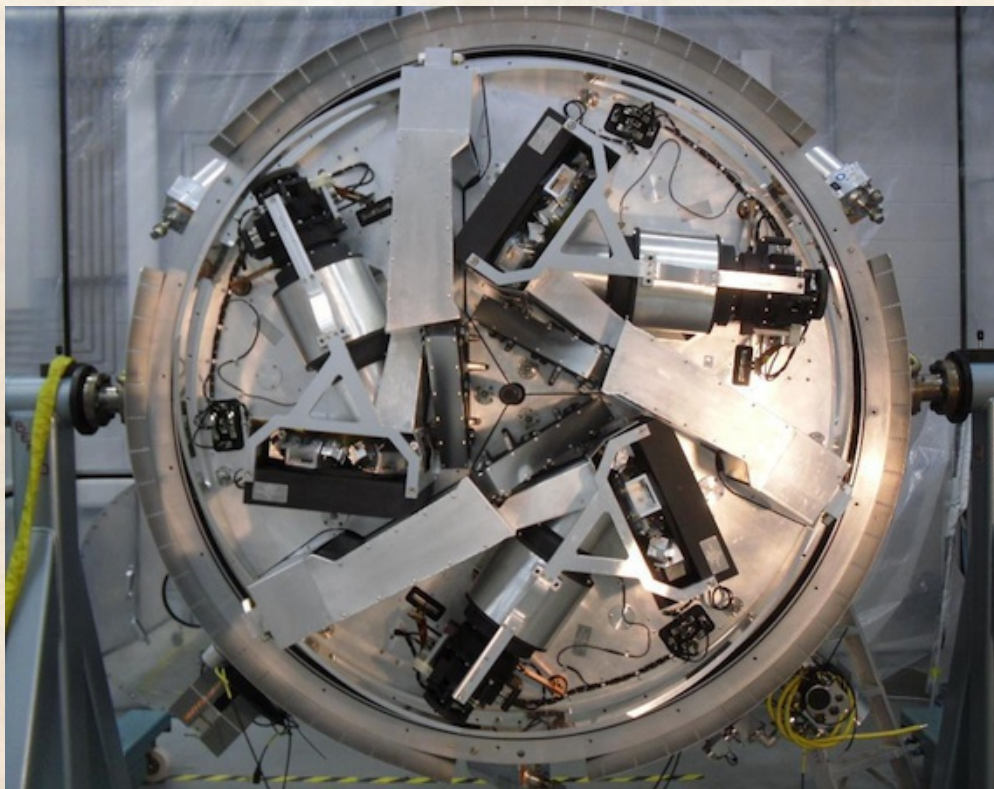
Hydrogen recombination line emission of H α of the massive star-forming galaxy BzK-15504 eleven billion light-years away (redshift $z = 2.38$). The observations were carried out with SINFONI in adaptive-optics mode, resulting in an angular resolution of ≈ 0.15 arcsec, or a mere 1.2 kpc (4000 light-years; indicated by the grey filled circle) at the redshift of BzK-15504. The top left panel is a color-composite map of the integrated H α line emission, showing from blue to red the ionized gas that is blueshifted to redshifted relative to the systemic velocity of the galaxy. The other panels are channel maps showing the spatial distribution of the H α emitting gas moving at different velocities (given in km/s) relative to

KMOS: K-band Multi-Object Spectrograph

- Instrument capabilities
 - VLT 8m
 - 24 MOS probes, 2.8×2.8 arcsec each, sampled at 0.2 arcsec (14 slices)
 - 4704 spatial elements total (188 arcsec^2)
 - 7.2 arcmin diameter patrol field
 - $0.8\text{--}2.5 \mu\text{m}$ range
 - 1000 spectral elements ($R \sim 3600$)
 - $\epsilon = 0.3 \times \text{telescope} \times \text{atmosphere}$

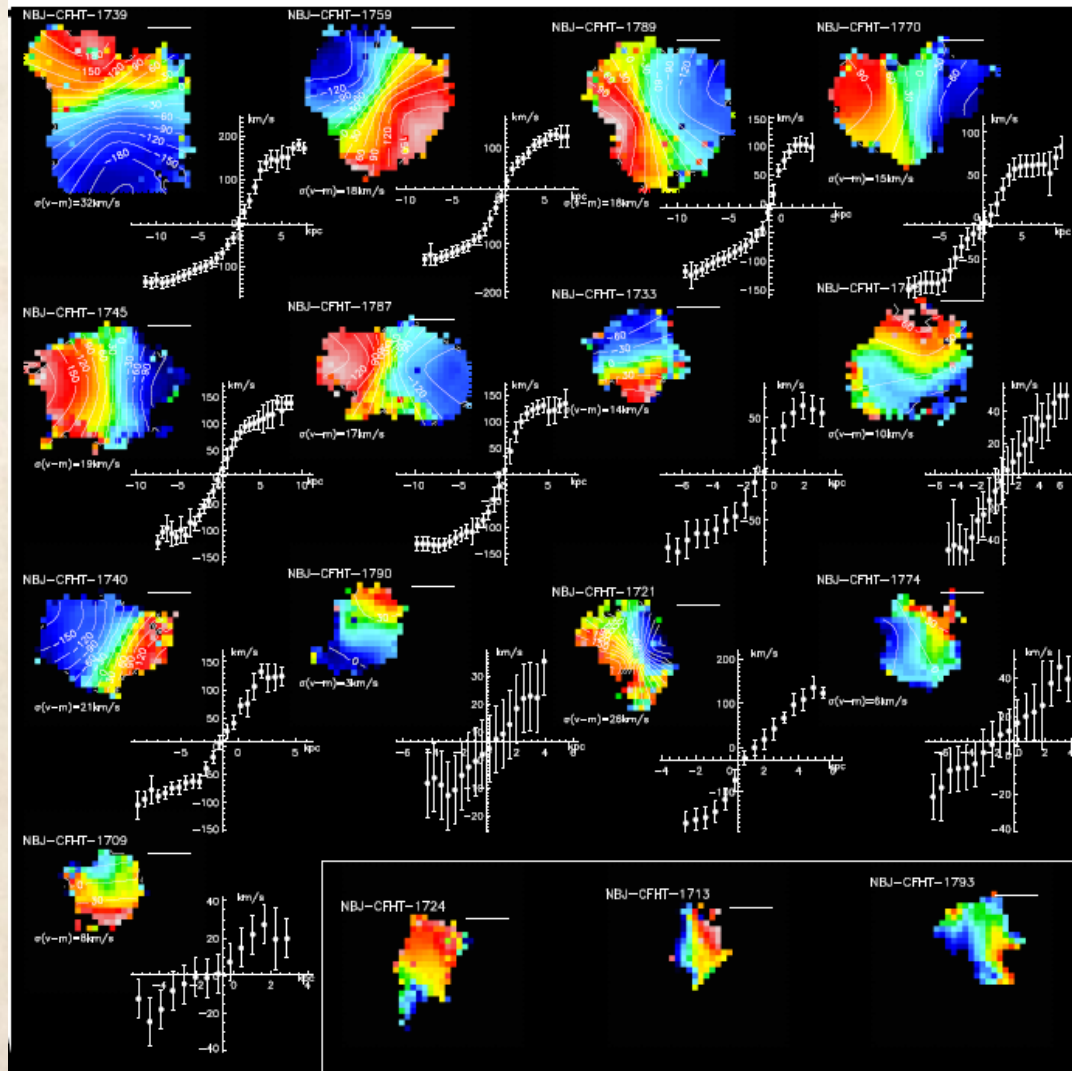


KMOS: три спектрографа, по 8 IFU в каждом



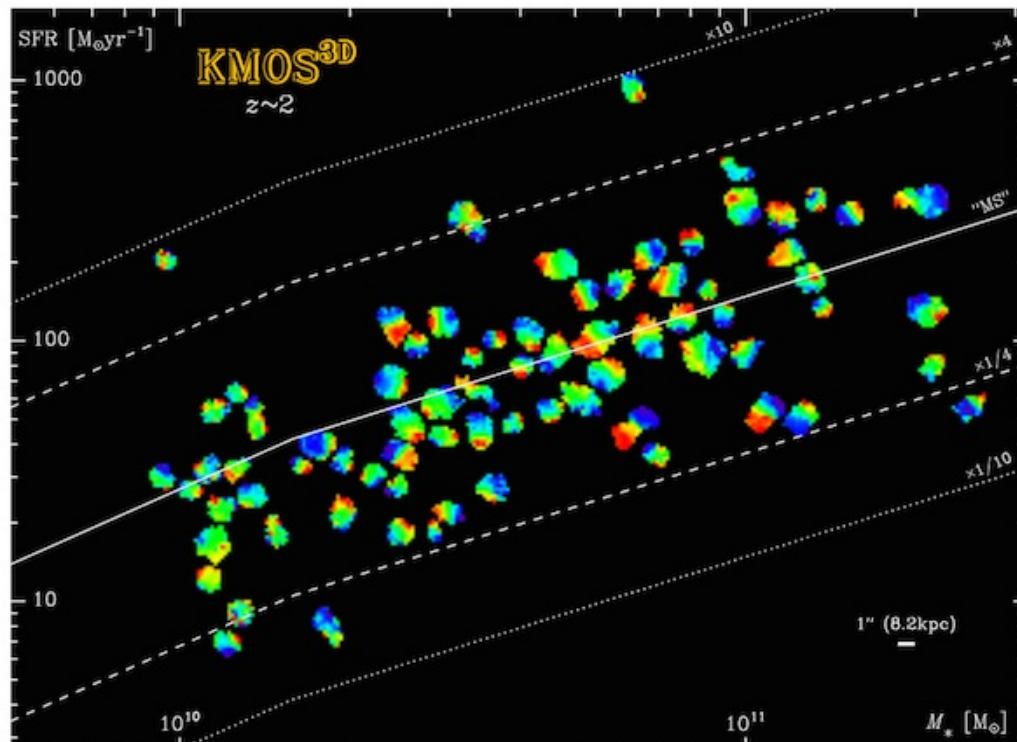
KMOS: многократное увеличение числа объектов

2 hours of VLT time



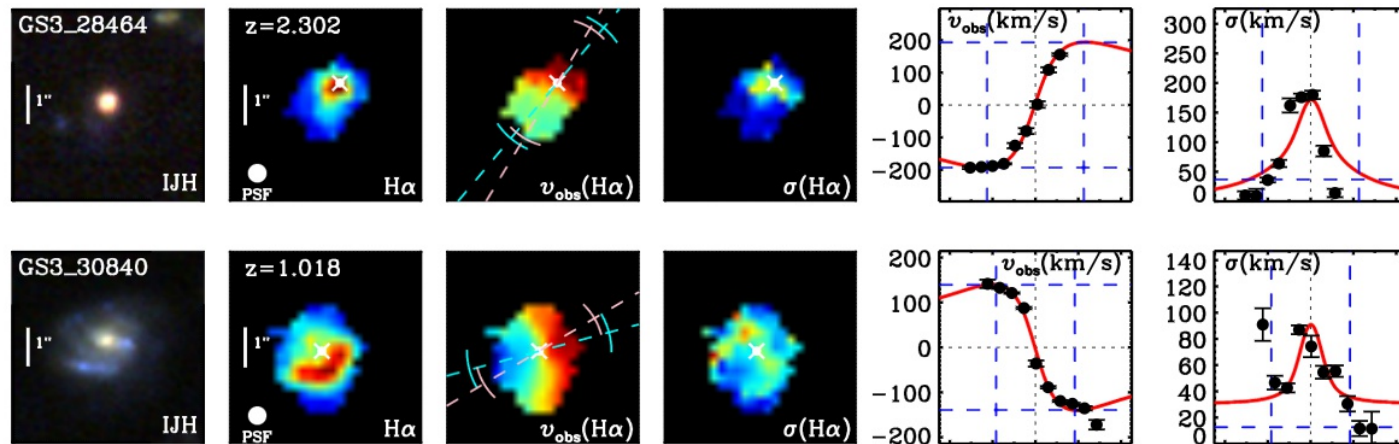
KMOS 3D

550 галактик на $0.6 < z < 2.7$

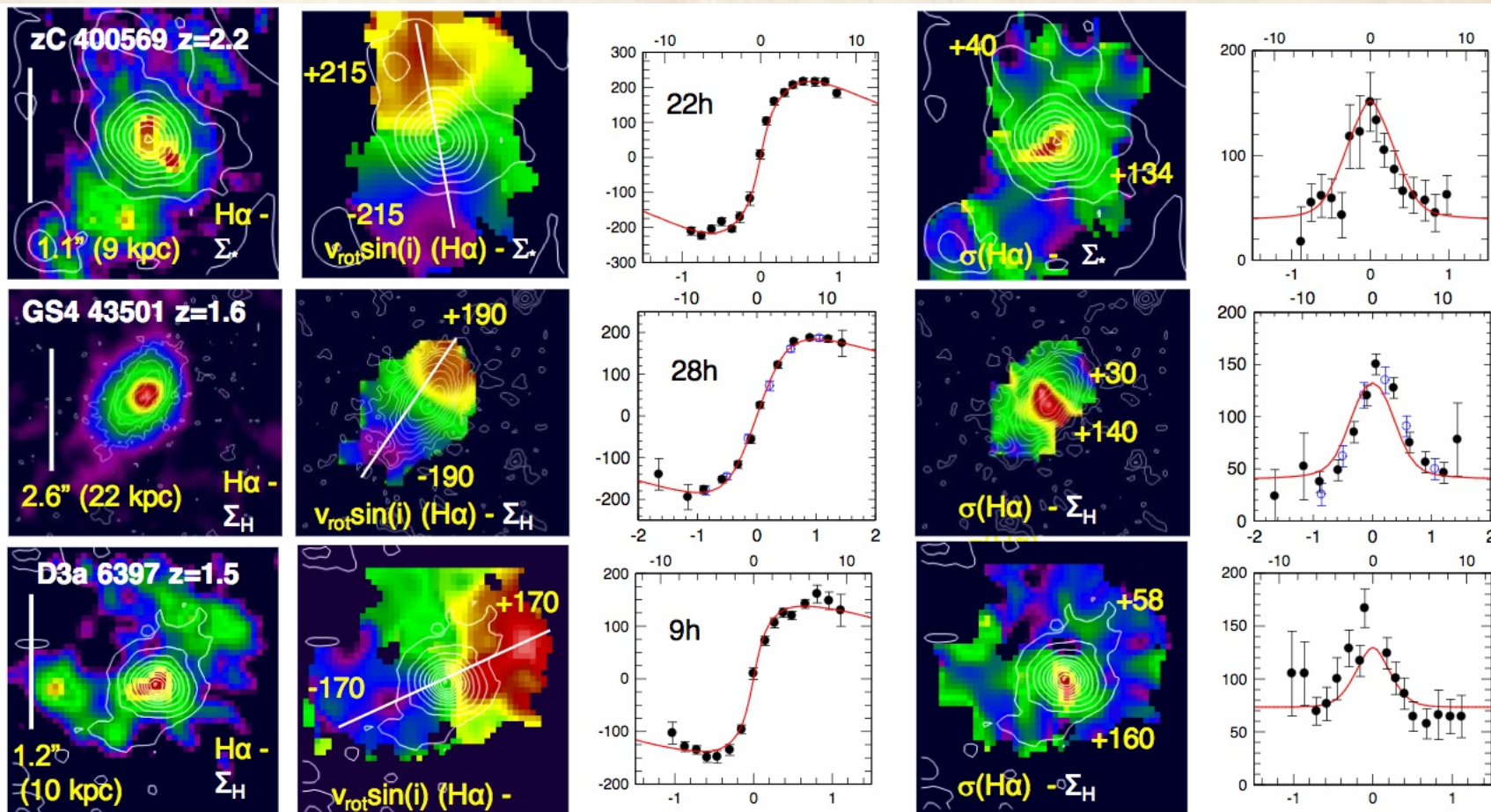


На $z=1-2$ большинство галактик “главной последовательности” - регулярно вращающиеся диски

(Wisnioski + 2015)

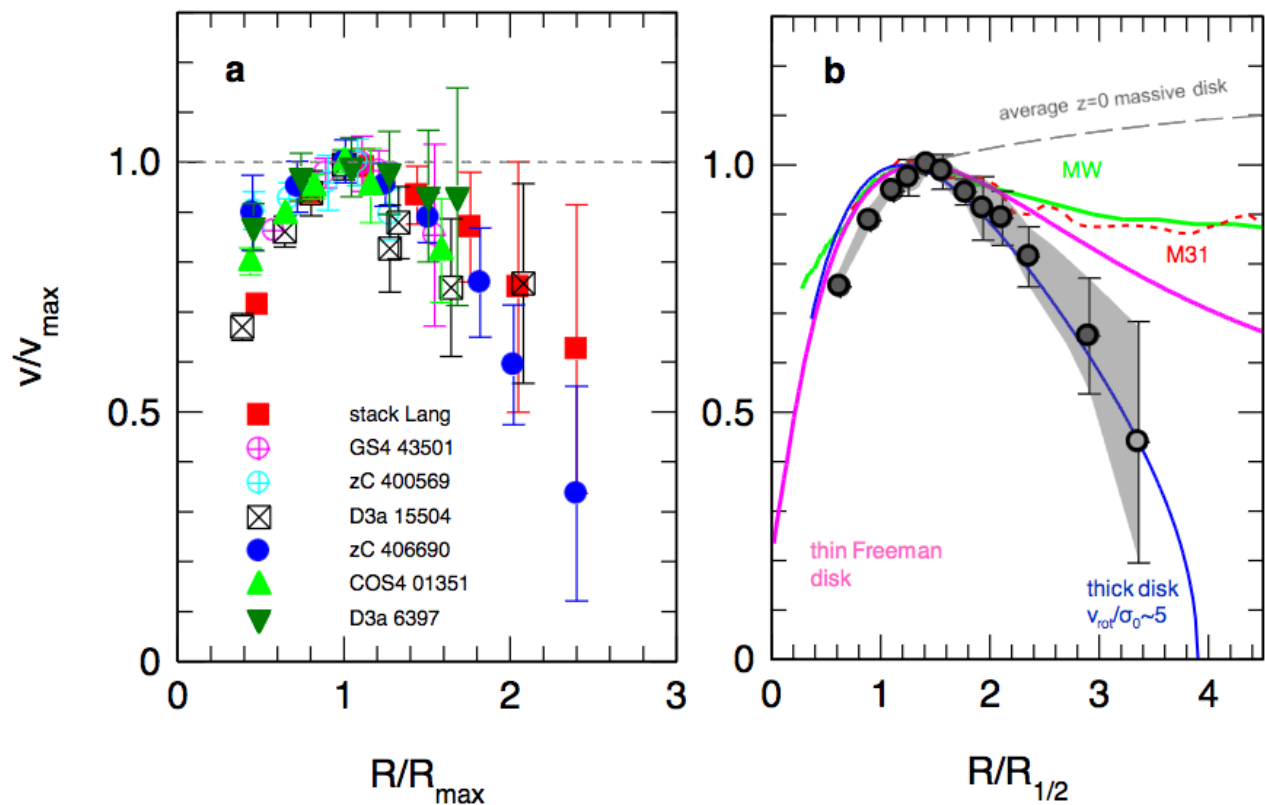


KMOS: в далеких галактиках меньше темной материи?



Genzel et al., 2017, Nature

KMOS: в далеких галактиках меньше темной материи?



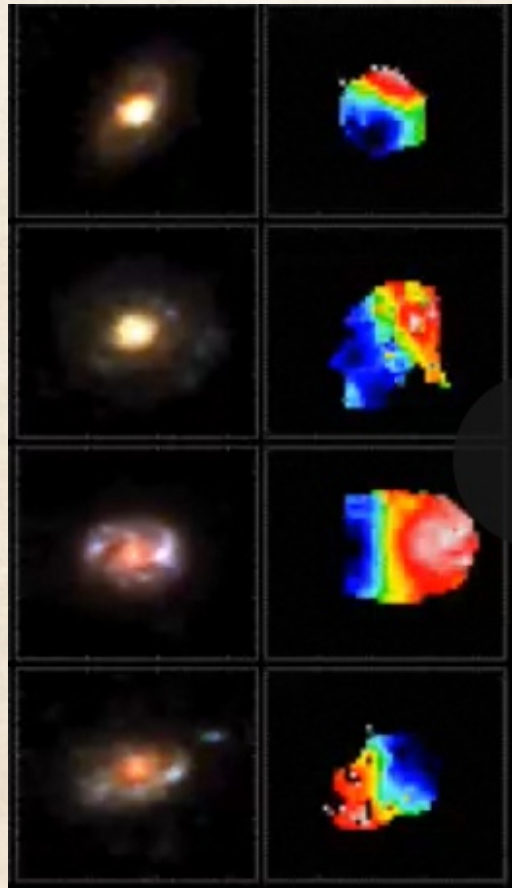
Reinhard Genzel



Awards

Otto Hahn Medal (1980)
Balzan Prize (2003)
Shaw Prize (2008)
Crafoord Prize (2012)
Tycho Brahe Prize (2012)
Fellow of the Royal Society
Harvey Prize (2014)
Nobel Prize in Physics (2020)

Genzel et al., 2017, Nature



Datacubes and Data Products

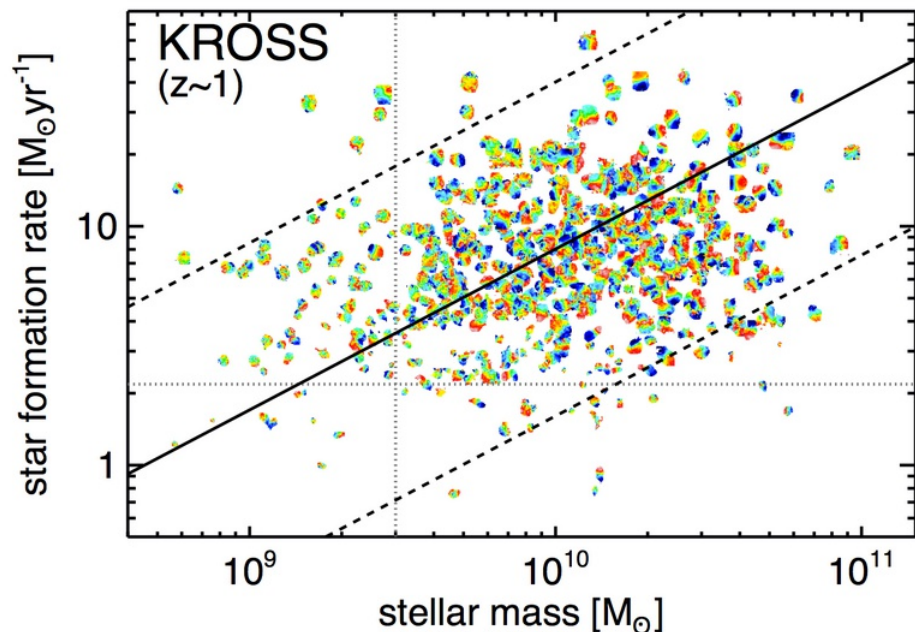
Datacubes and data products for the 586 H-alpha detected galaxies in the KROSS survey

- [Datacubes for all 586 galaxies \[1.2Gb\]](#) (posted: 24/04/2019)
- [H-alpha intensity maps \[2.7Mb\]](#)
- [H-alpha velocity maps \[1.0Mb\]](#)
- [H-alpha line-of-sight velocity dispersion \(sigma\) maps \[1.3Mb\]](#)

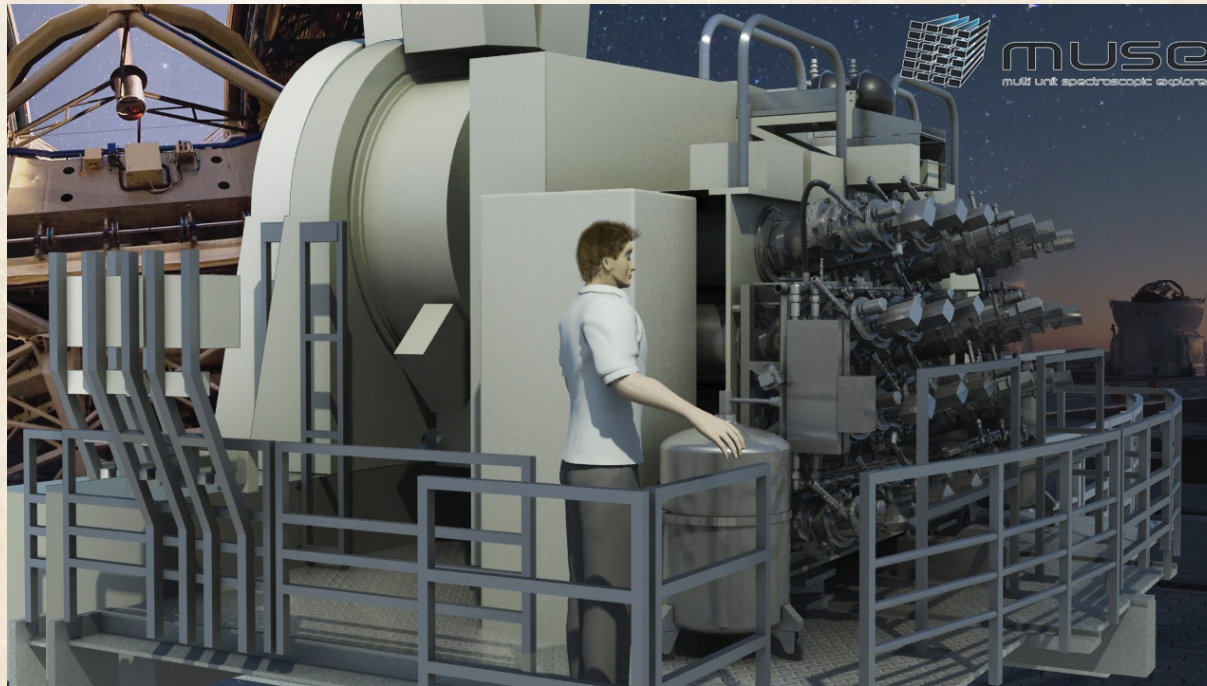
Catalogs (Version 2)

Johnson et al. 2018 ([arXiv:1707.02302](#)) combined with Harrison et al. 2017 ([arXiv:1701.05561](#))

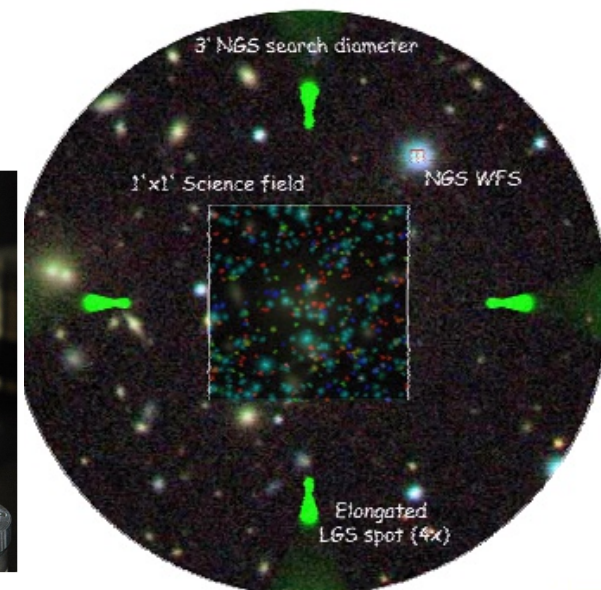
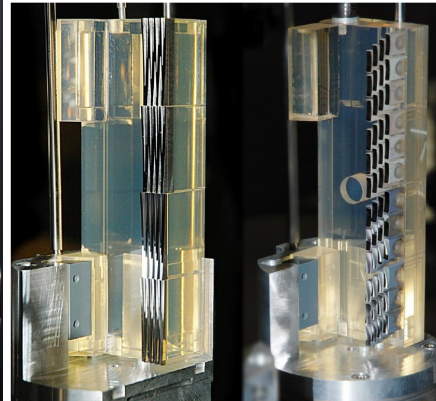
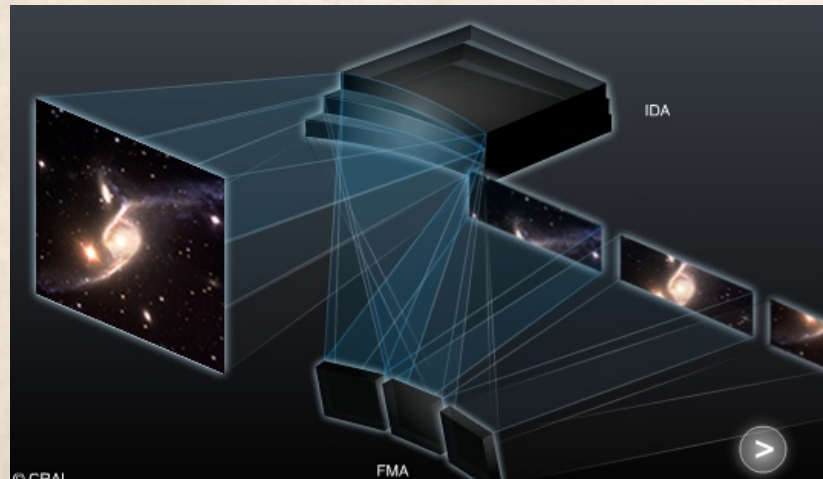
- [Version 2 \(fits table\)](#) (posted: 17/07/2017)



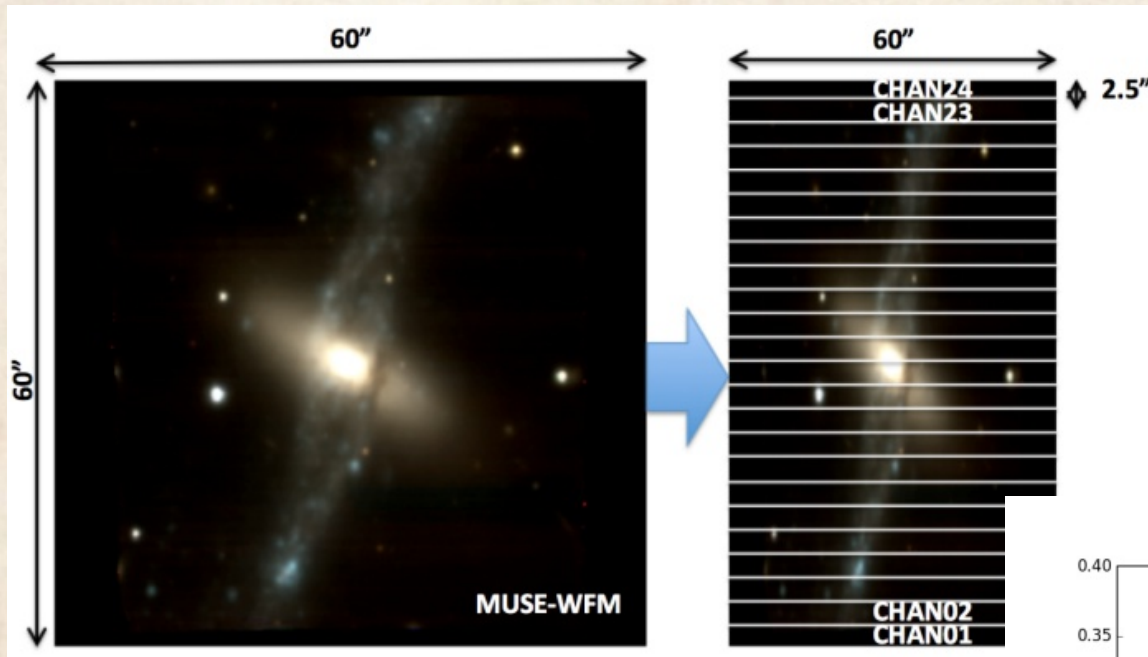
MUSE = Multi Unit Spectroscopic Explorer (VLT)



Observational Parameters	
Spectral range (simultaneous)	0.465-0.93 μm
Resolving power	2000@0.46 μm
	4000@0.93 μm
Wide Field Mode (WFM)	
Field of view	1x1 arcmin ²
Spatial sampling	0.2x0.2 arcsec ²
Spatial resolution (FWHM)	0.3-0.4 arcsec
Gain in ensquared energy within one pixel with respect to seeing	2
Condition of operation with AO	70%-ile
Sky coverage with AO	70% at Galactic Pole
Limiting magnitude in 80h	I _{AB} = 25.0 (R=3500)
	I _{AB} = 26.7 (R=180)



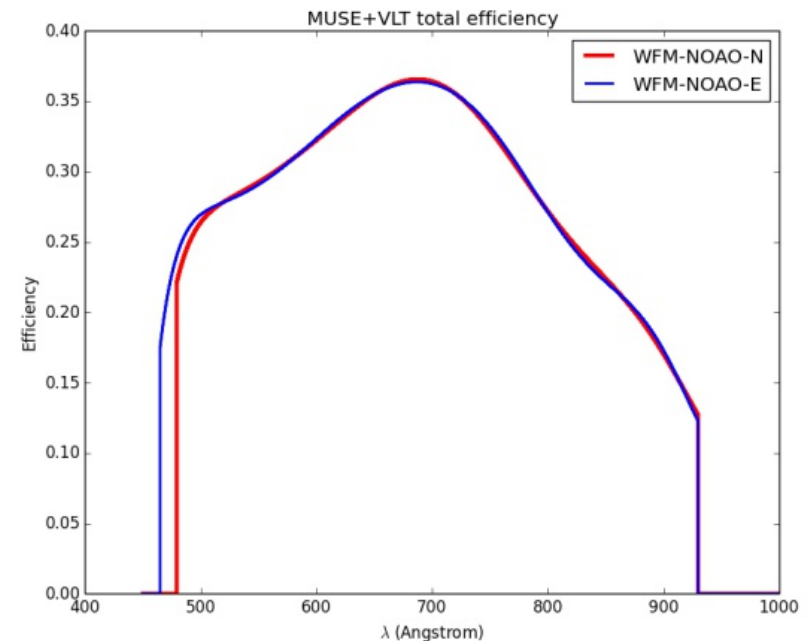
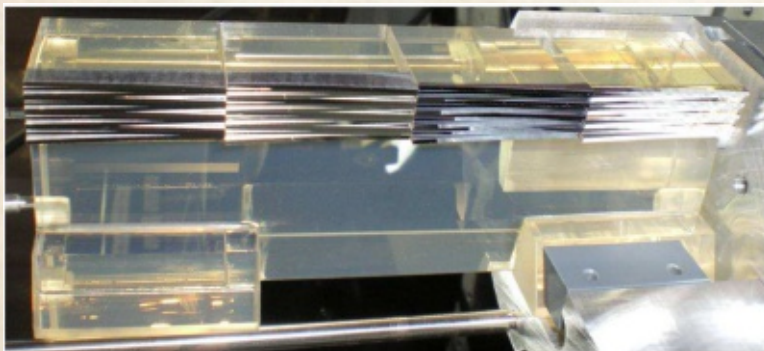
MUSE: slicer & spectrograph



Почти нет подвижных элементов (только решетка)

Рекордная квантовая эффективность на VLT

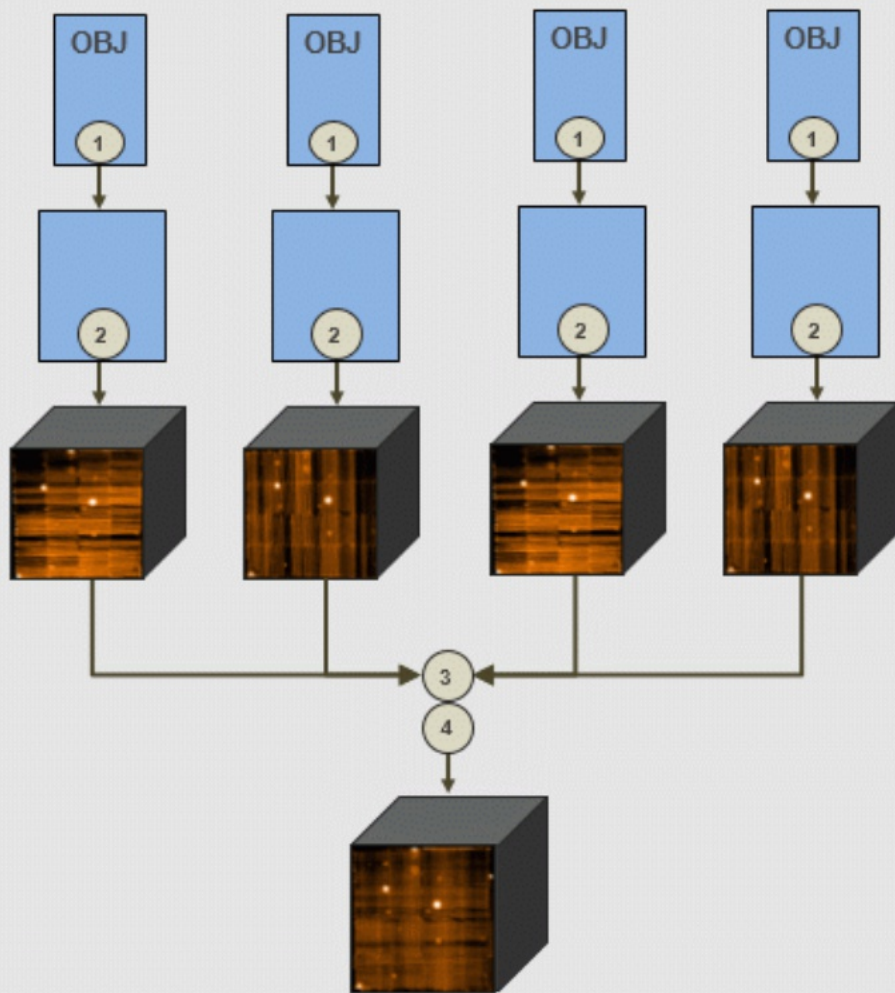
48 щелей в одном “канале”



Roland Bacon & K

MUSE: работа с данными

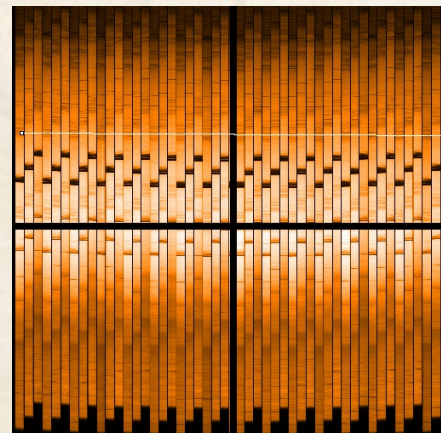
N=4 stack, no SKY



24 кадра с ПЗС 4x4
собираются в один куб
Сырые данные – 820 Мб
Итоговый размер:
315x315 x 3680 px - 2.6 Gb

Рабочая станция:
32 cores
256 GB RAM
Disks: 2x11 Tb

Вычитание неба – построение
модели по измеренной LSF

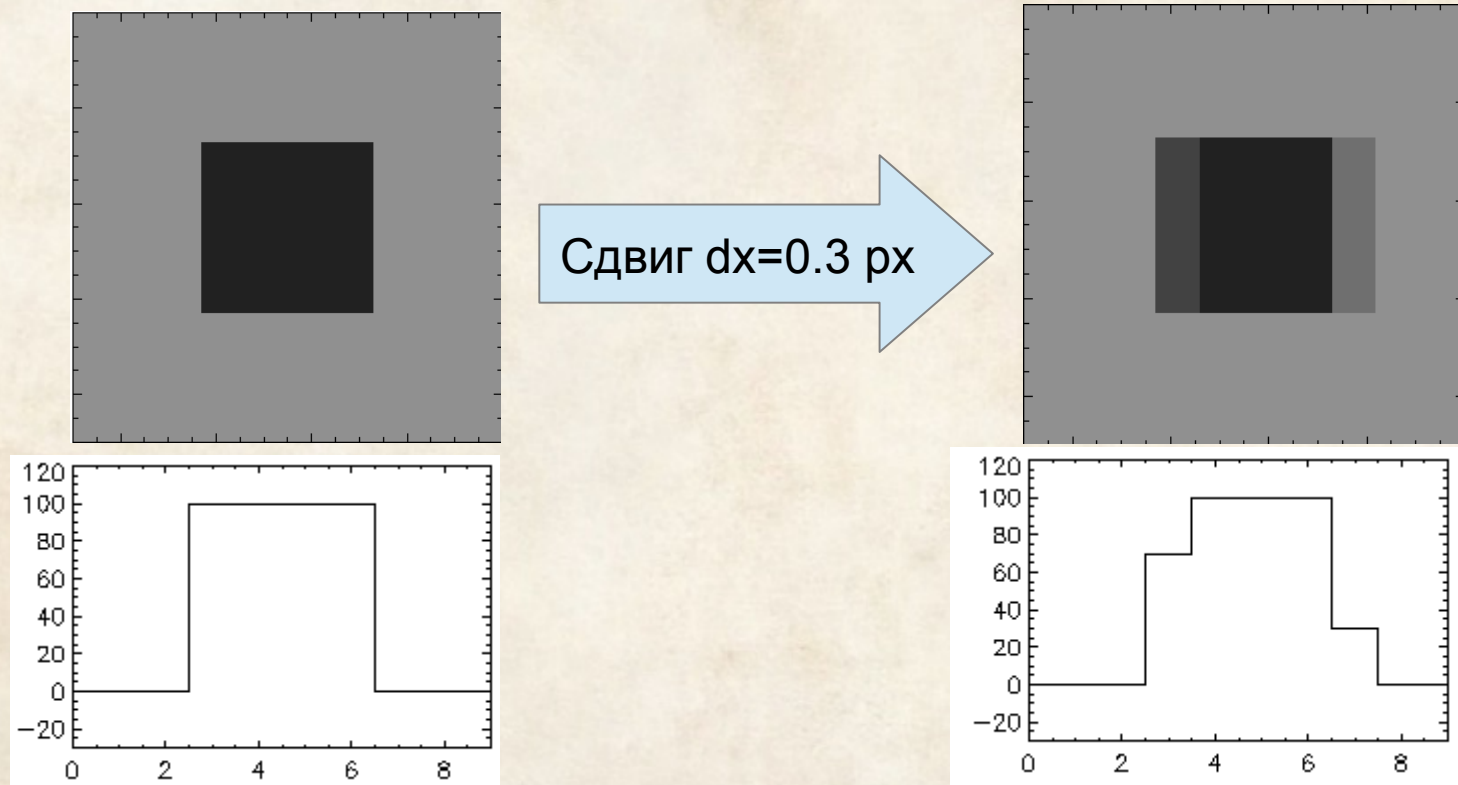


Проблема интерполяции

Лекция 4

“Многорежимный фокальный редуктор...”

Геометрические преобразования — портят исходное изображение, так как выполняется интерполяция на фиксированную координатную сетку

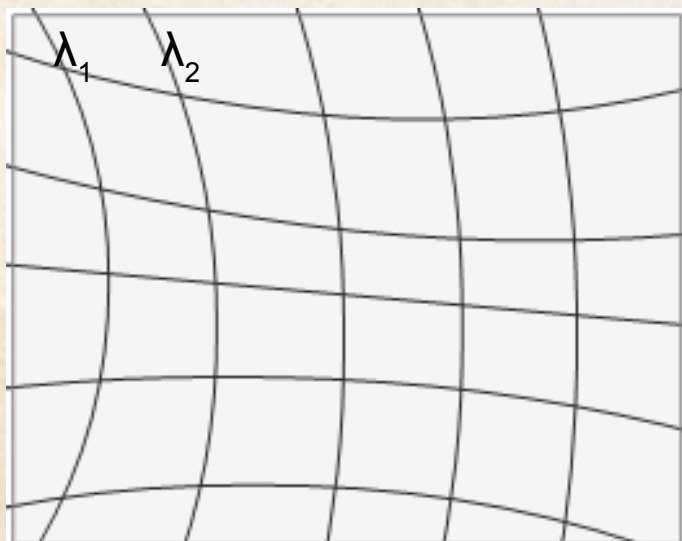


Искусственное разбиение на более мелкие пиксели — лишь частично решает проблему, сильно загружая вычислительные ресурсы

Не объект к калибровкам, а калибровки к объекту!

Обработка современных IFU (MUSE/VLT и т. д.) - идея сохранения первоначальной дискретизации

Т.е. вместо 2D FITS-изображения (запись I в каждом пикселе) — переход к таблицам, где кроме I , в каждом пикселе еще записаны преобразованные координаты (x', y')

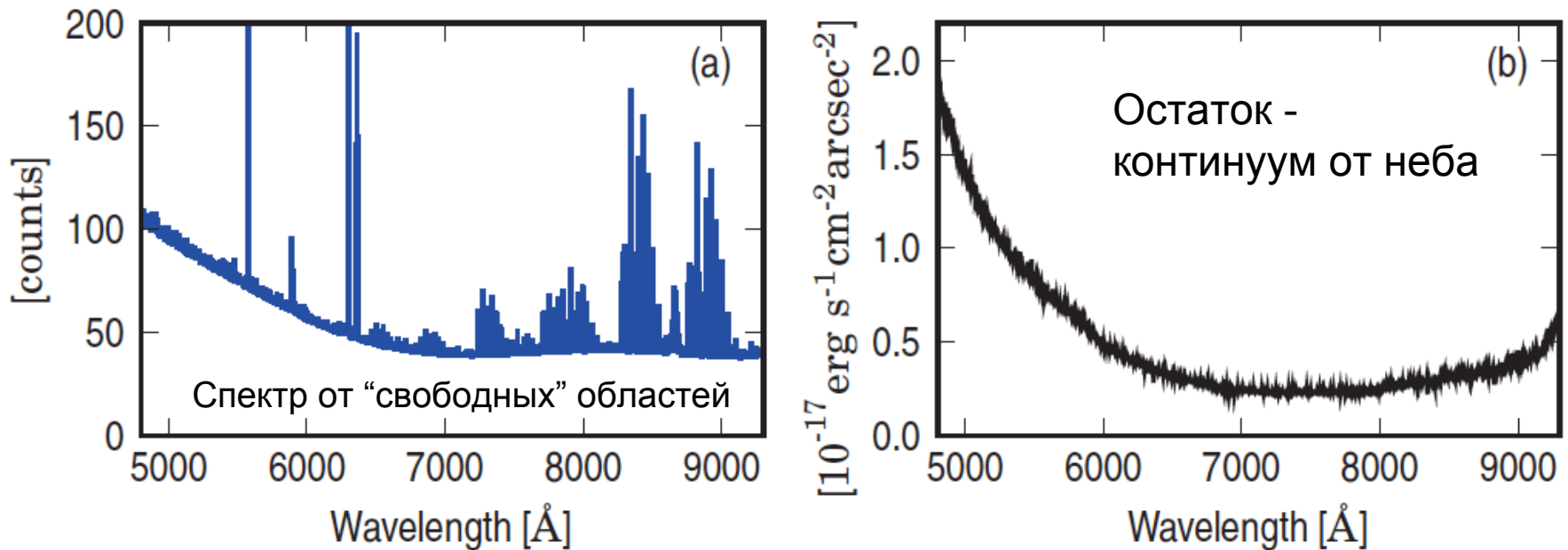


В итоге, лишь одно преобразование — экстракция линейаризованного спектра, после вычитания неба и исправления за кривые пропускания!

Но требуется специализированный софт, в том числе и для визуализации на разных этапах обработки

(Лекция 4 “Многорежимный фокальный редуктор...”)

Вычитание фона неба: моделирование спектра



- знаем LSF, построена адекватная численная модель спектрографа
- подгонка потоков в группах линий:

For the determination of the emission line fluxes, the known atmospheric emission lines (van der Loo & Groenenboom 2007; Osterbrock et al. 1996) are grouped by the originating molecules (OH, [O I], Na I, O₂) and the upper transitional level into twelve groups. Within each group, the emission flux ratio is fixed. The line fluxes for each group are then taken into a fit routine, minimizing the error of the differences between neighboring bins:

$$s^2(p) = \sum_{\lambda} \left(\frac{\Delta I(\lambda, p)}{\Delta \lambda} - \frac{\Delta I_0(\lambda)}{\Delta \lambda} \right)^2.$$

Вычитание фона неба: моделирование спектра

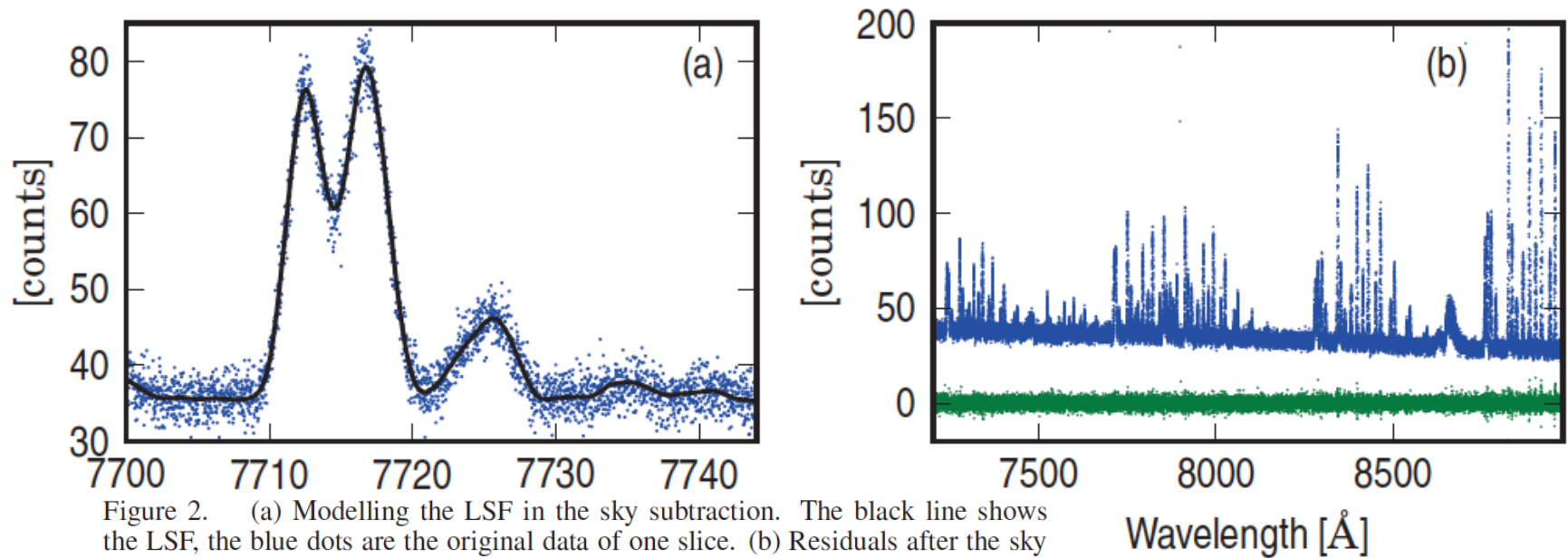
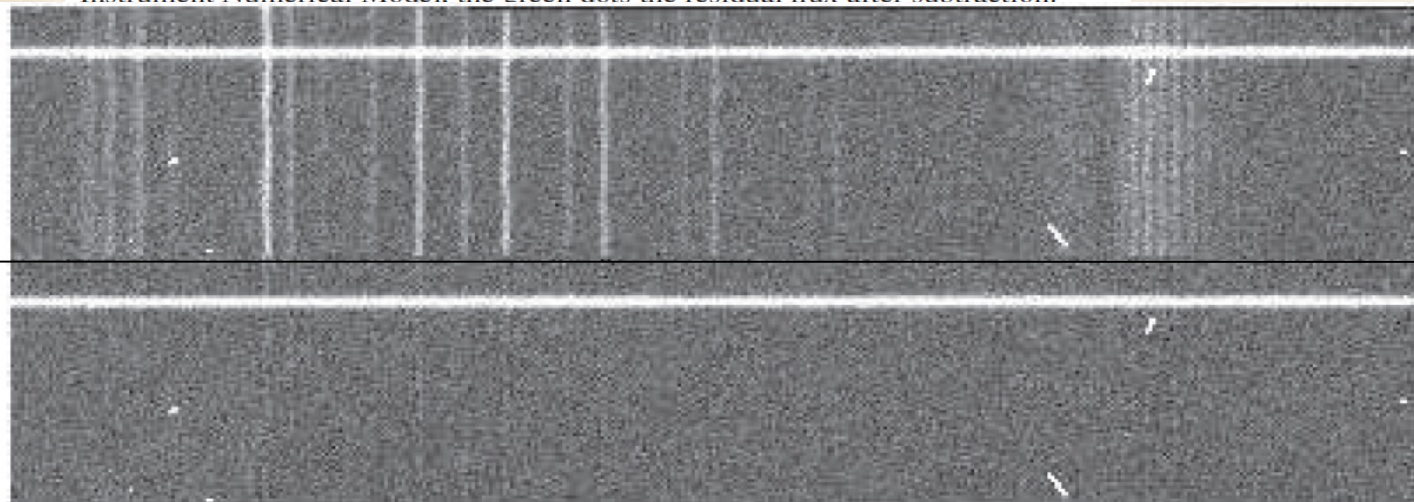


Figure 2. (a) Modelling the LSF in the sky subtraction. The black line shows the LSF, the blue dots are the original data of one slice. (b) Residuals after the sky subtraction for one slice. The blue dots show the original simulated data from the Instrument Numerical Model, the green dots the residual flux after subtraction.



MUSE views the Orion Nebula



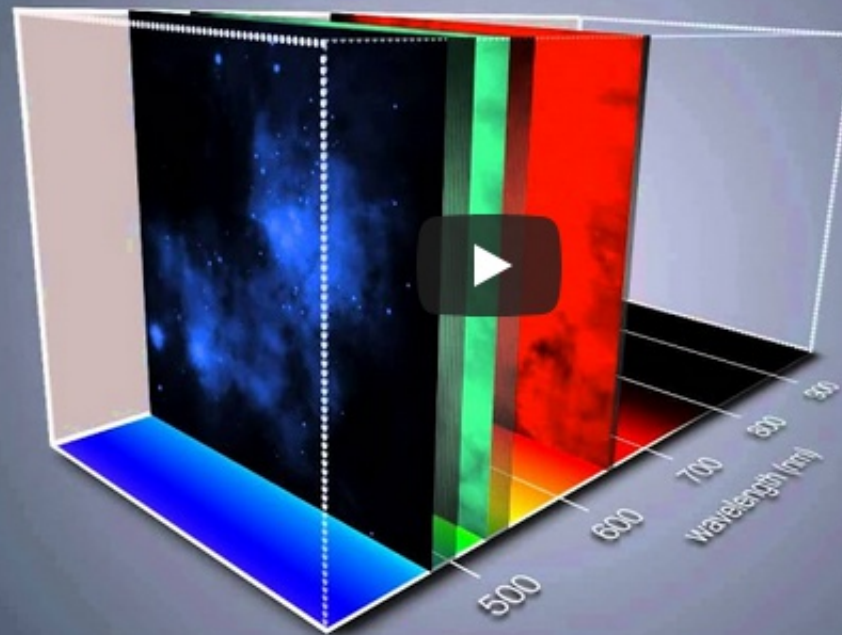
MUSE views the Orion Nebula



Watch later



Share



Watch on YouTube

MUSE: Туманность Ориона

6 x 5 arcmin
Weilbacher et al 2015

<http://muse-vlt.eu/science/m42/>

red: [S II] 6731
blue: Hbeta,
green: [N II] 6584



R. Bacon et al.

TIGER the first map:1988

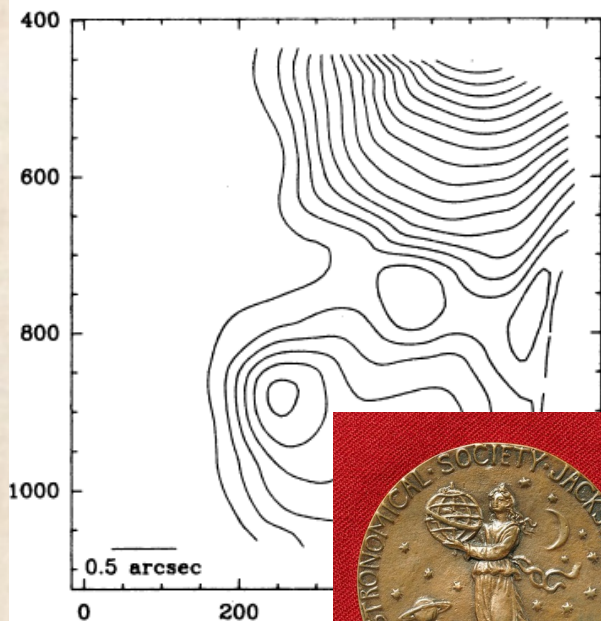
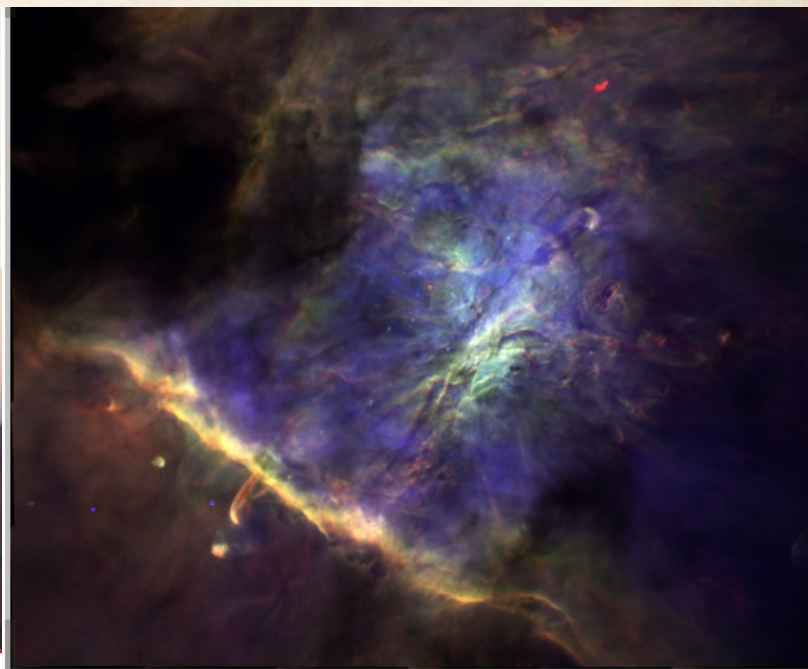


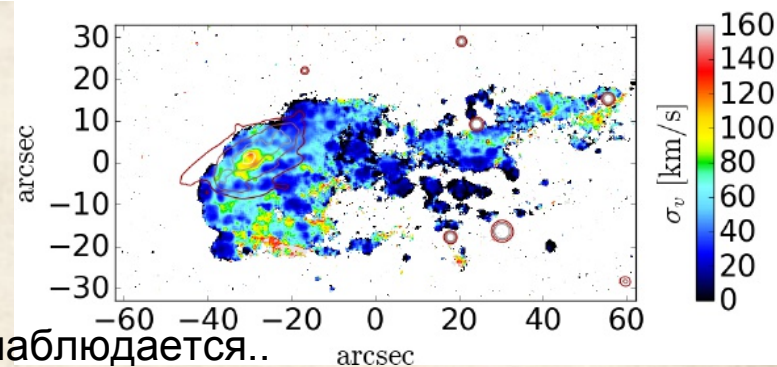
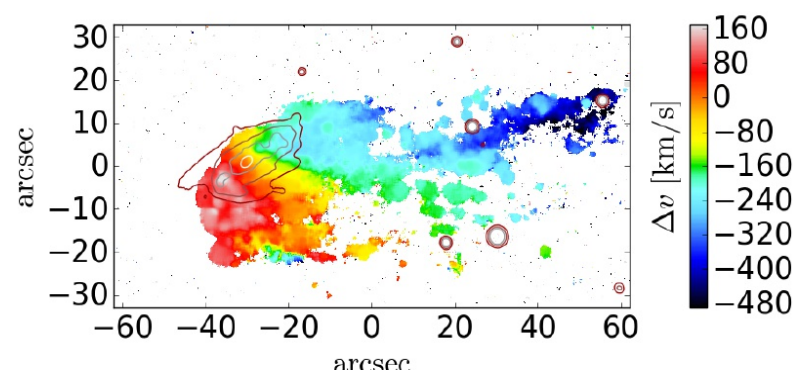
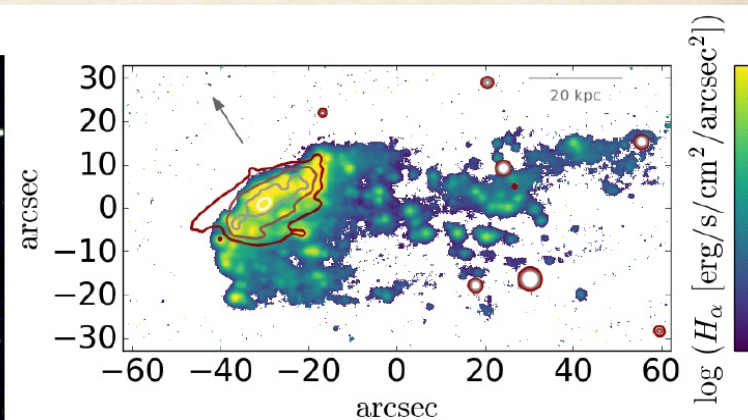
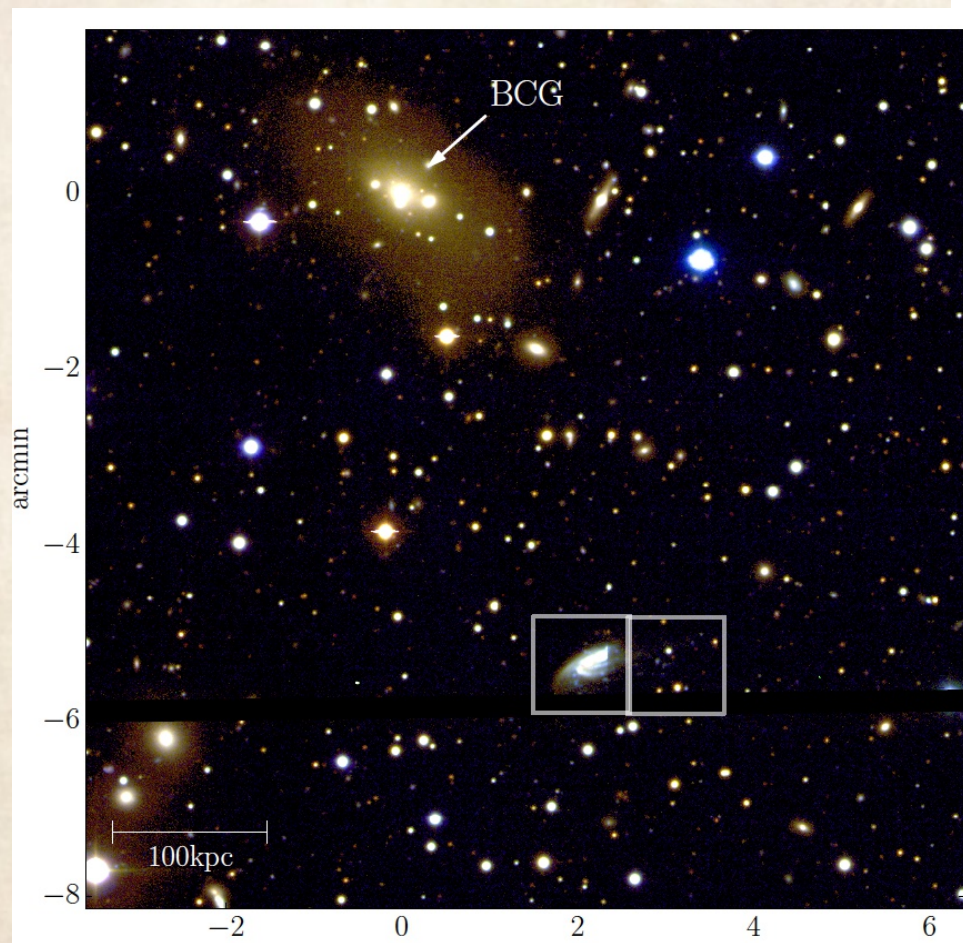
Figure 7 : Monochrom
of the nucl

red: [O III] 5007
green: [O II] 7320
blue: [O I] 6300



Roland Bacon is awarded the Jackson-Gwilt 2020 Medal

“Медузы” в скоплениях галактик (ram pressure stripping)



Poggianti+17:

Расчет удерживающих сил и лобового давления, выметание возможно, только для $r > 20$ кпк, что и наблюдается..
Примерно 15% газа покинуло галактику

MUSE: глубокий обзор

Wisotzki + 15

1'x1' поля внутри UHDFS

27 часов экспозиций: 54x30 мин, seeing 0.66"

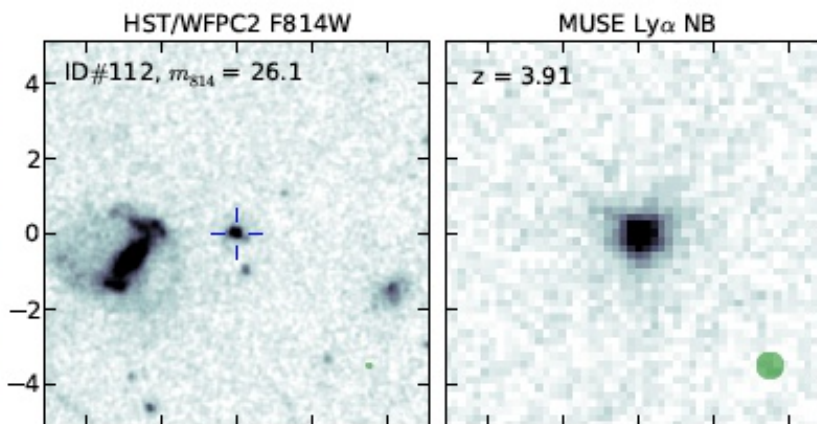
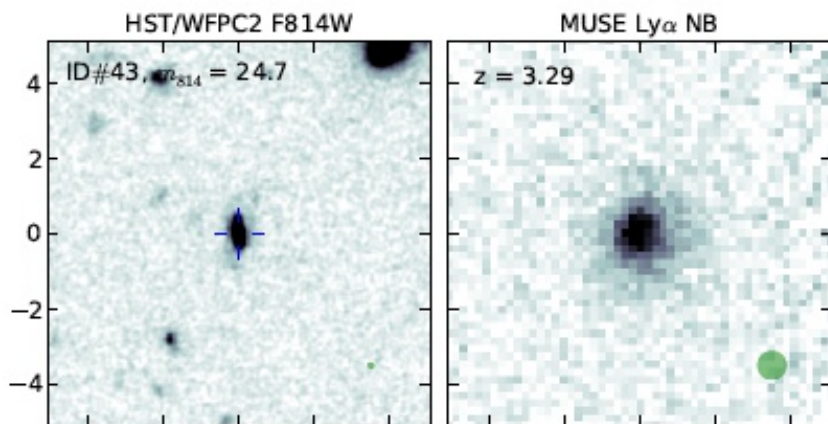
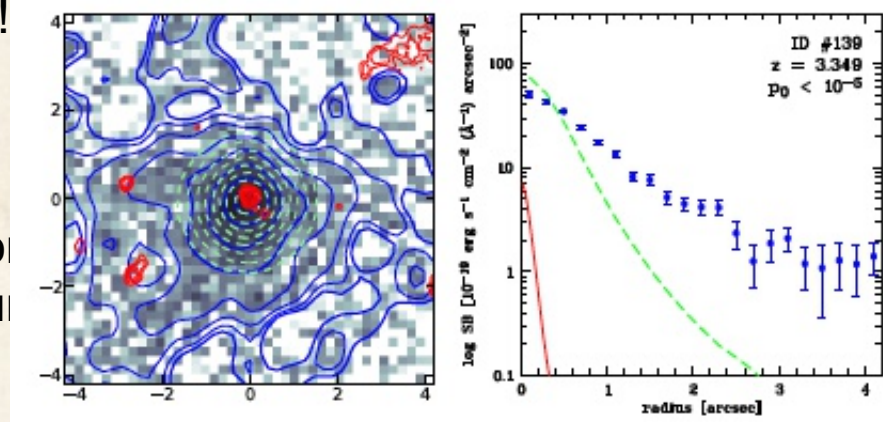
- Разные ориентации поля, тщательное построение PSF по звездам

Неожиданно: $\text{Ly}\alpha$ – гало большие и круглые!

Происхождение гало:

Рассеяние фотонов от галактики

на частично нейтральной межгалактической среде. Ранее подозревалось по наблюдениям абсорбциям от квазаров, теперь видно и в ЭМИССИИ.



Bacon 2024:

Сразу говорили о том, что можно заниматься спектроскопией глубоких полей, избегая пре-селекции объектов, как в MOS, но:

reviewed, together with technical documentation and the management plan. The science referees were quite supportive of the nearby galaxy science case but were much less convinced by our high- z proposal. Their main objection was that MUSE wouldn't be competitive with MOS because it wouldn't have deeper capabilities and would have a much smaller field of view, where most of the spaxels would just capture the sky. This skepticism was probably shared by a large fraction of the high- z community, and MUSE, until its first light, was seen as a perfect machine for the study of extended nearby objects, but not more.

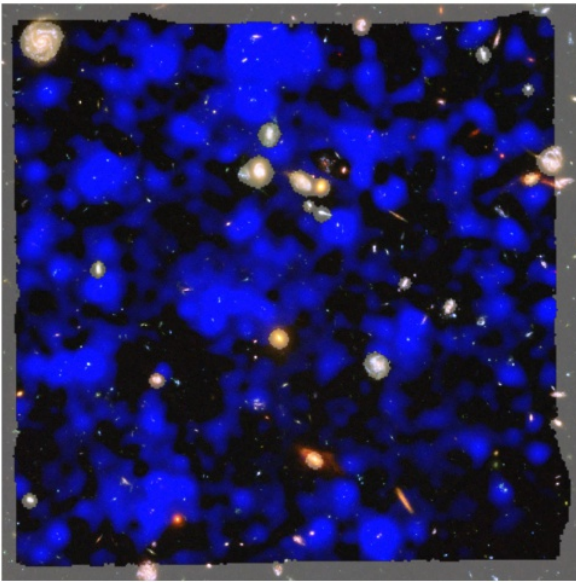


Fig. 1 | Distribution of the observed Ly α emission in the HUDF. The underlying image is a colour composite obtained by the HST¹⁹ restricted to the $1' \times 1'$ section observed with MUSE. The extended Ly α emission detected by MUSE is superimposed in blue, summed over the redshift range $3 < z < 6$ and spatially filtered to suppress the noise. The grey

Wisotzki + 2018
(лекция 1)



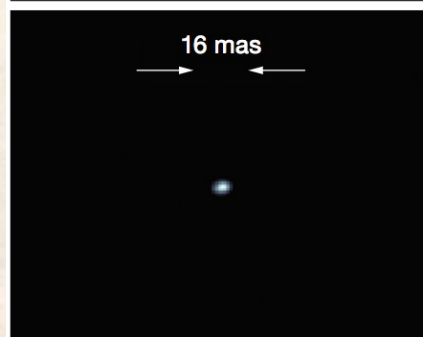
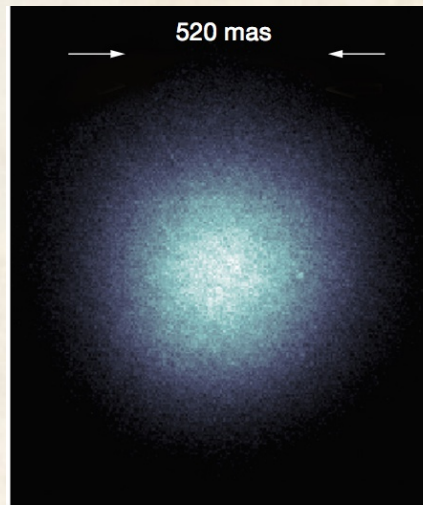
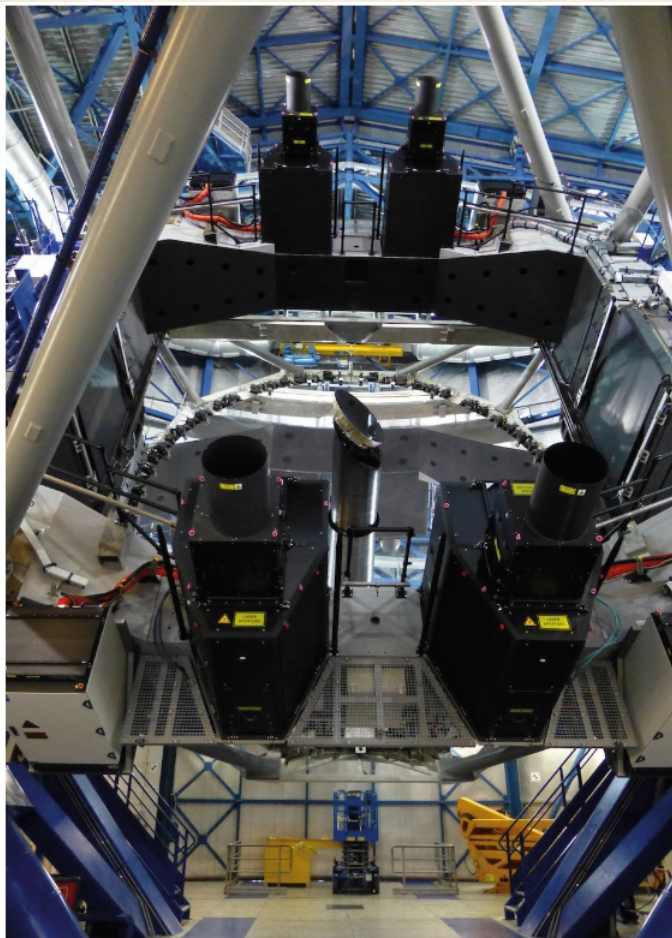
Figure 9: MUSE "landed" on the UT4 Nasmyth platform on January 19, 2014.

MUSE: адаптивная оптика в "оптике"!

4 лазерных звезды в поле

Narrow Field Mode (Not offered yet. To be offered with GALACSI)

Field of view	7.42" x 7.43"
Spatial Sampling	0.025" / pixel
Spatial resolution(FWHM)	0.03" -- 0.05"



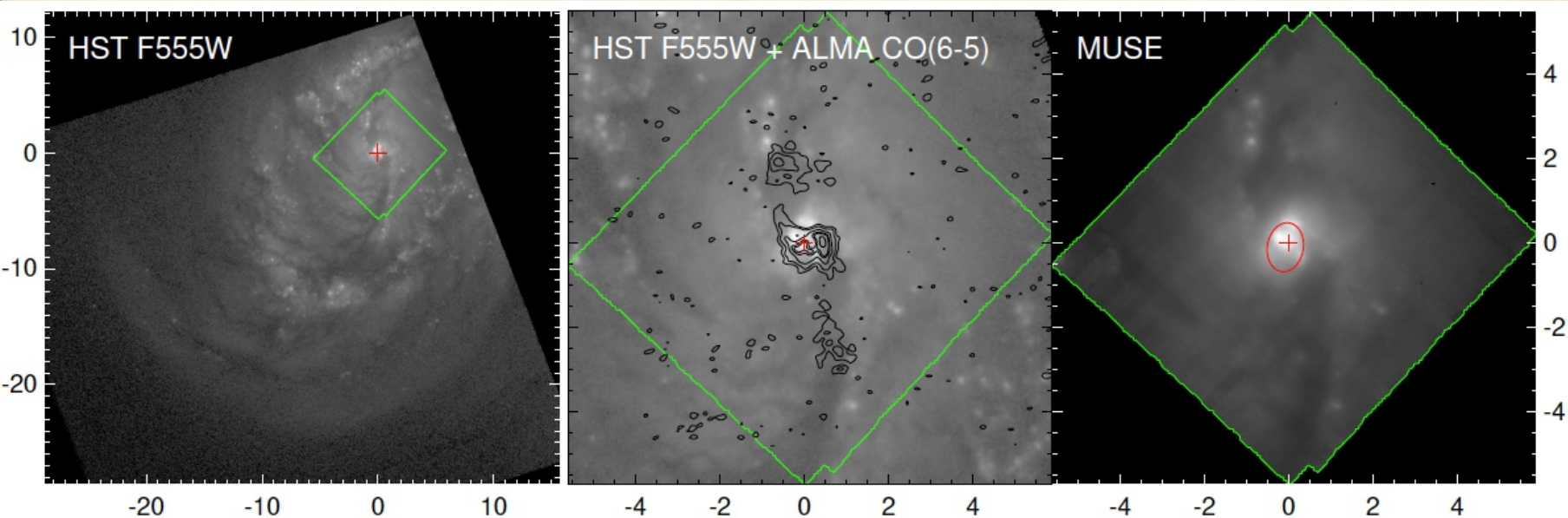
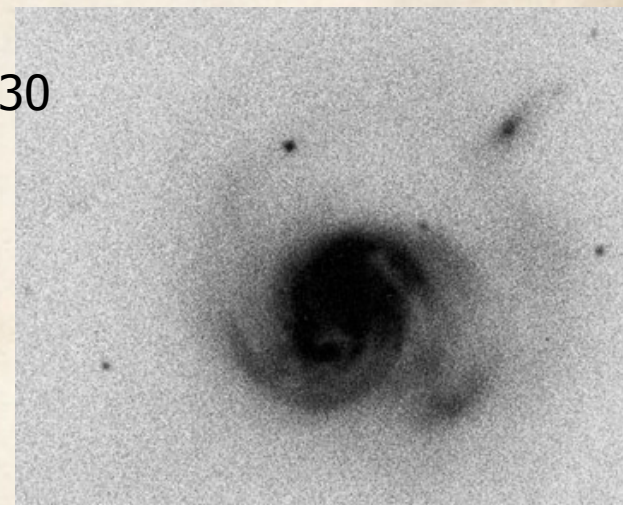
MUSE: адаптивная оптика в "оптике"

arXiv:1812.00809

MUSE-AO view of the starburst-AGN connection: NGC 7130

J. H. Knapen^{1,2,3}, S. Comerón⁴, and M. K. Seidel⁵

MUSE Narrow-field mode (NFM) + AO GALASCI
FOV 7.6" 0.025"/px
Seeing 0.6-1" => AO made: 0.15-0.5"



Не только галактики: B[e] супергигант MWC 137

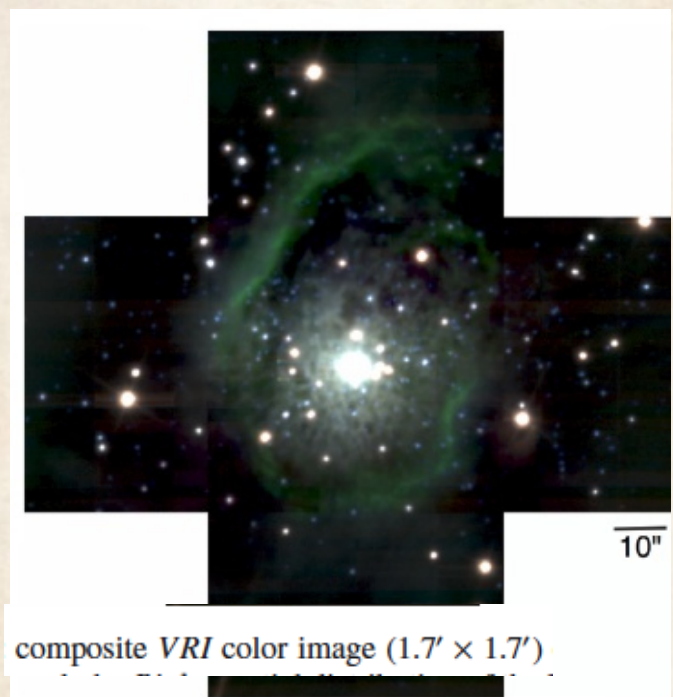
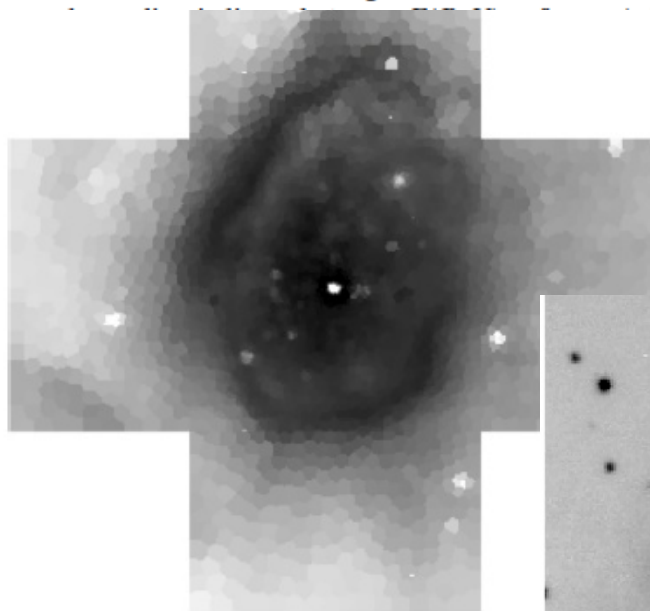
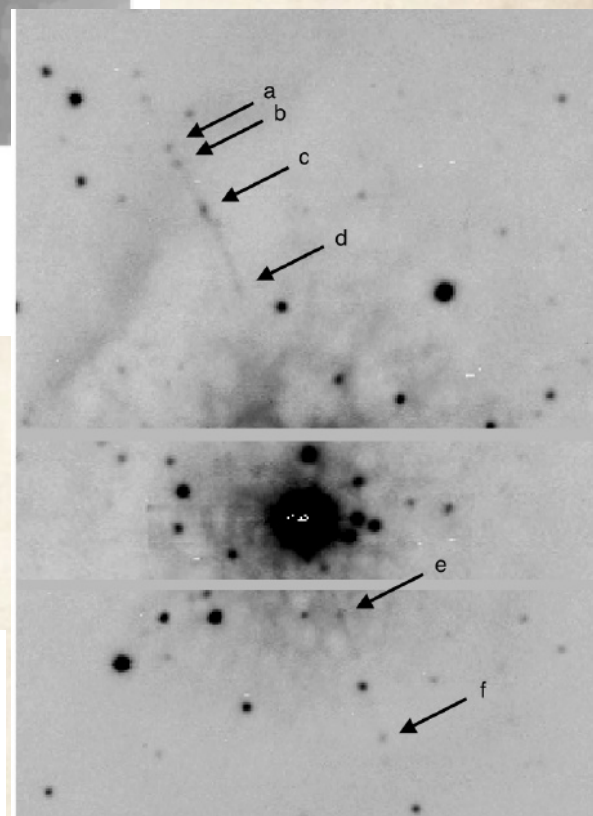


Fig. 2. Voronoi diagram of $E(B-V)$ based on the extended nebular $H\alpha/H\beta$ ratio, binned to a signal-to-noise ratio of 200 per polygon. The

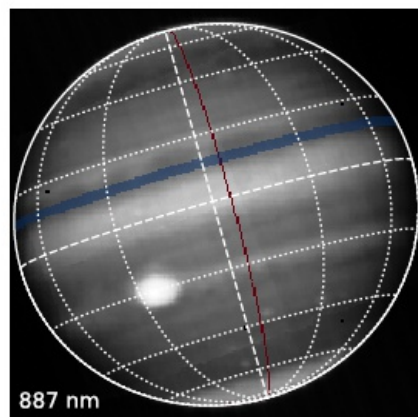
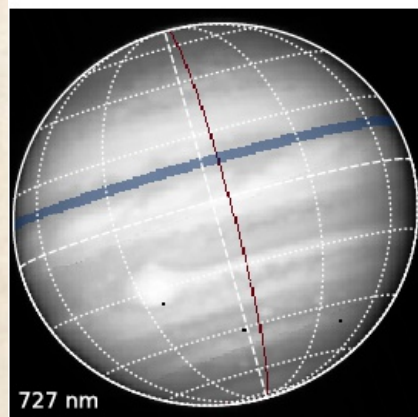
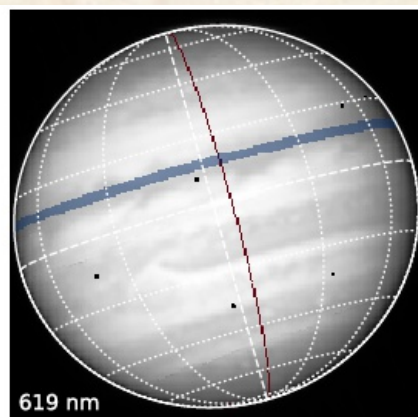
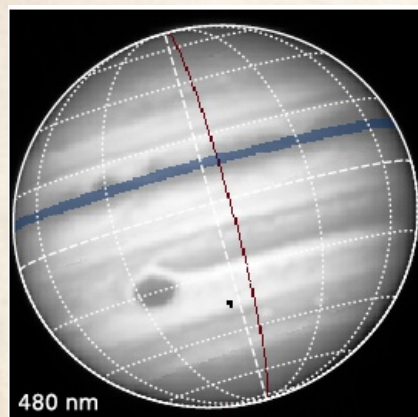


VLT/MUSE discovers a jet from the evolved B[e] star MWC 137 (Mehner + 2017)

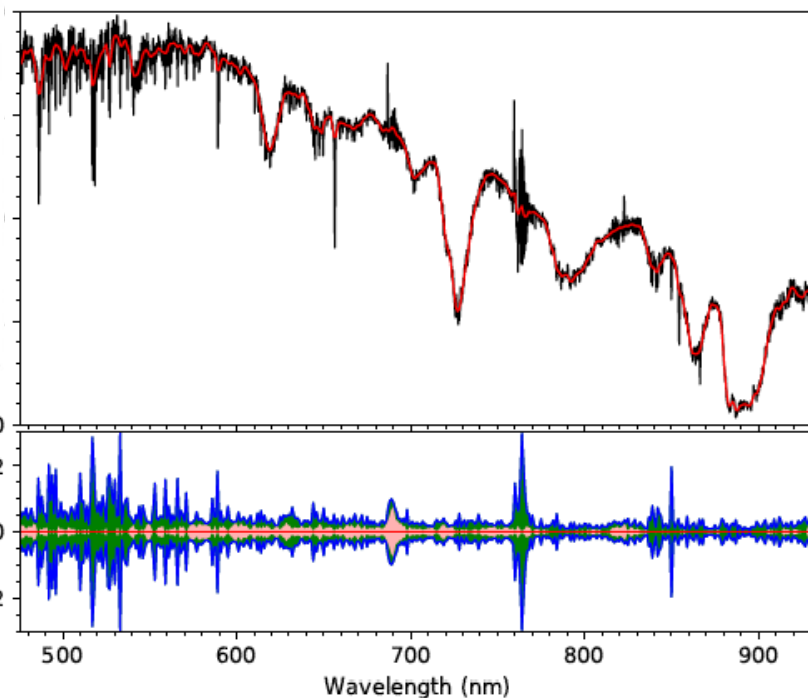
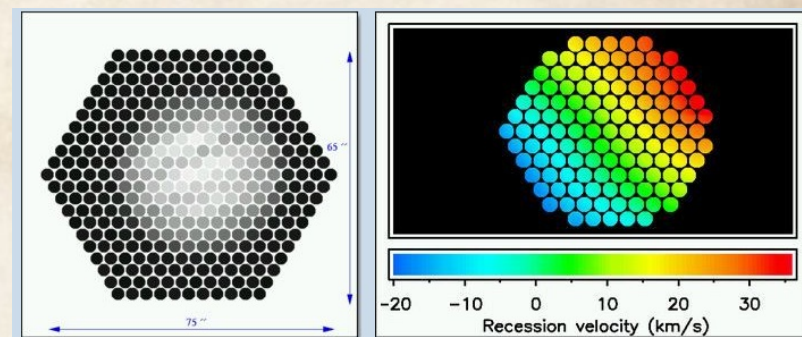
Fig. 8. Composed image showing the jet in [NII] 6583. The *upper* and *lower panels* are velocity-binned images from 600 s exposures (-405 km s^{-1} to -234 km s^{-1} for the *upper* and 336 km s^{-1} to 507 km s^{-1} for the *lower panel*). The *middle panel* is one channel map (at -376 km s^{-1}) of a 300 s exposure. Knots along the jet trace are



Не только галактики: аммиак на Юпитере



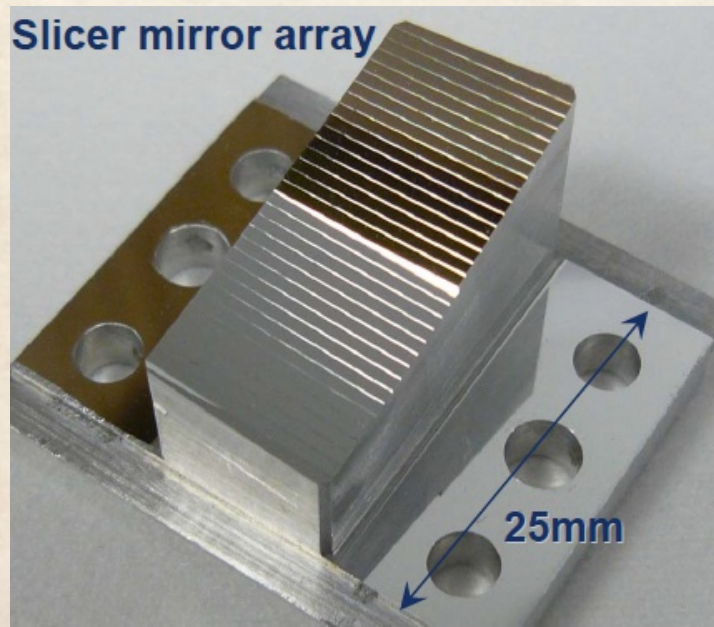
PPAK (2004)



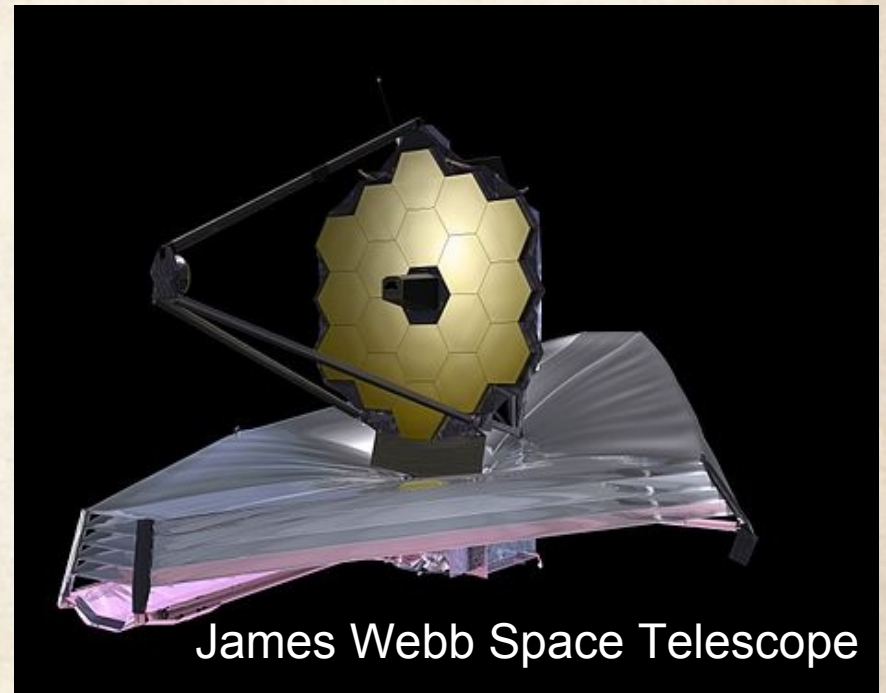
Braudea + 2020

Near-Infrared Spectrometer (NIRSpec): в космосе с 2021

Performance wavelength range	0.7 – 5.0 μm (functional range 0.6 – 5.0 μm)
Operating temperature range	30 – 44K (but with full performance at 293K)
Throughput	>50% (8 reflections)

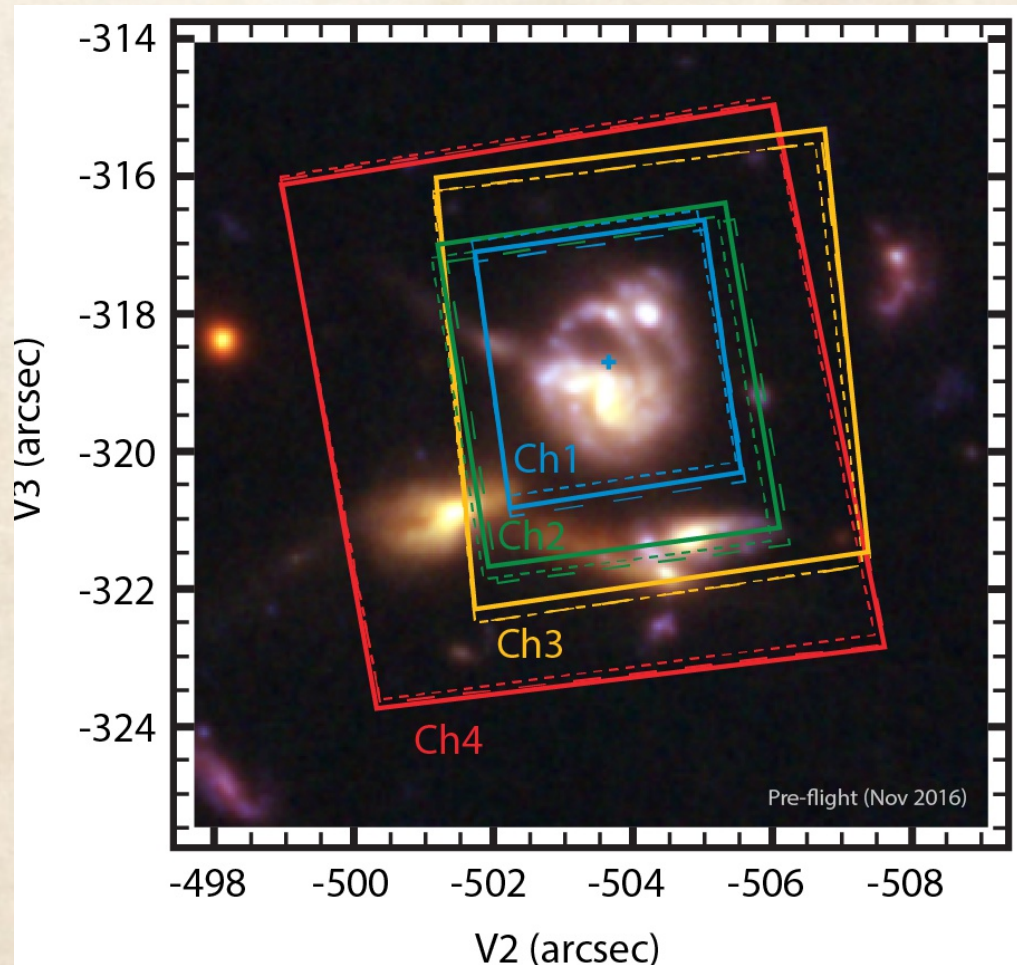


IFU – один из режимов наблюдений
3"x3" с разбиением 0.1"



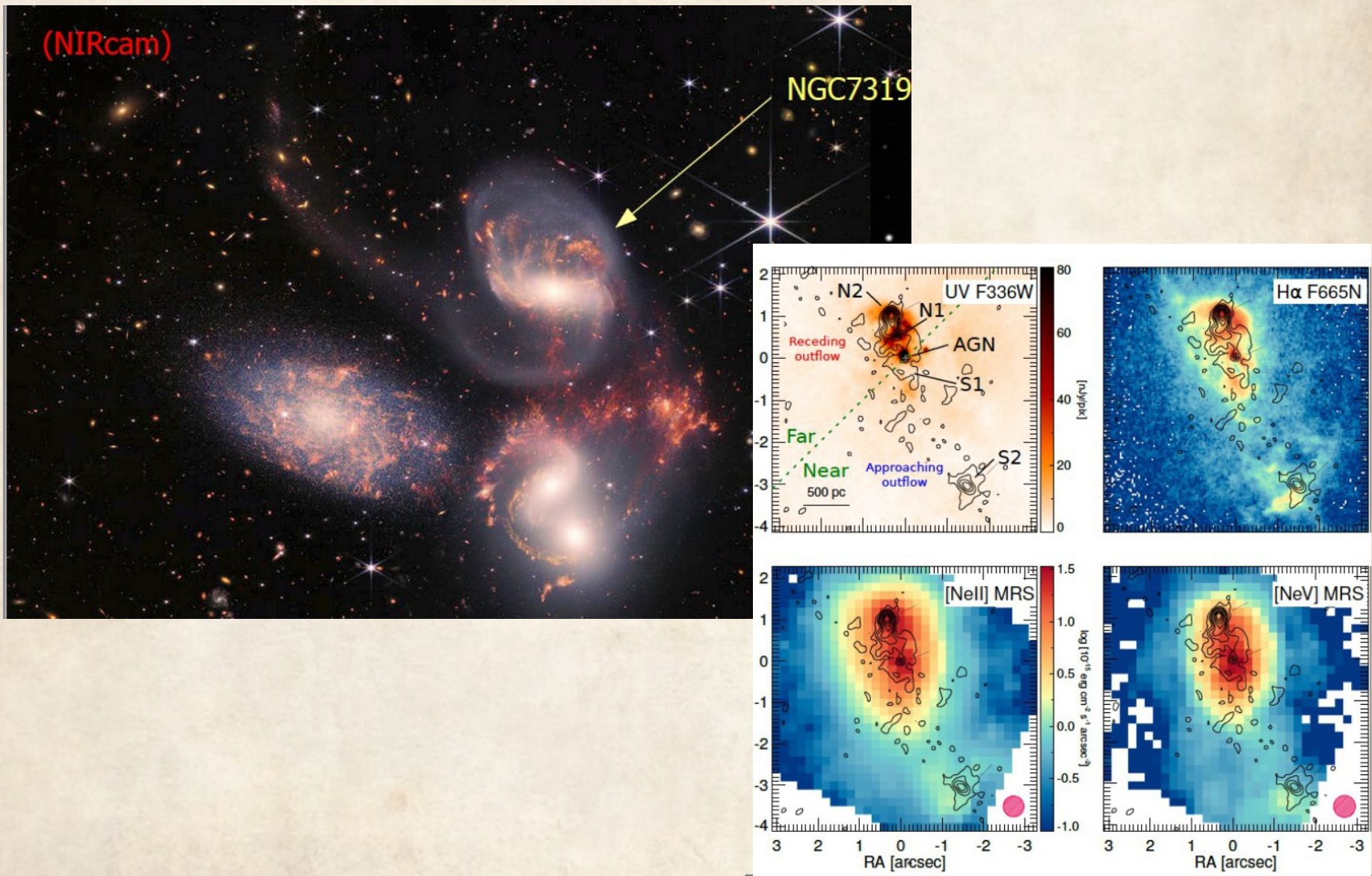
Mid-Infrared Instrument (MIRI)

4 IFU – отдельно для разных диапазонов в области 4.9- 28.8 μm



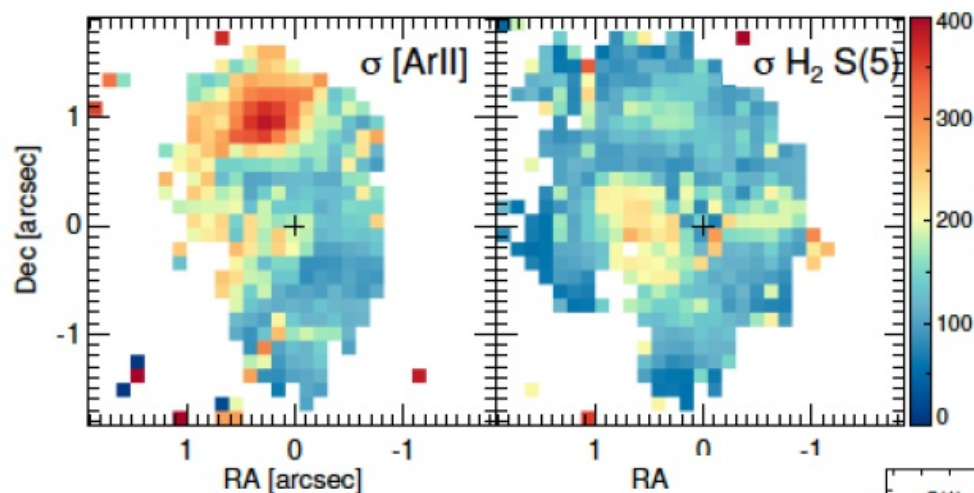
FOV name λ -range (μm)	FOV (arcsec)
Channel 1 4.89–7.66	3.3×3.7
Channel 2 7.49–11.71	4.2×4.8
Channel 3 11.53–18.05	5.6×6.2
Channel 4 17.66–28.45	7.2×7.9

Low power jet-ISM interaction in NGC 7319 revealed by JWST/MIRI MRS (Pereira-Santaella + 2022)



Массовое изучение H_2 в галактиках

Ионизованный газ – более турбулентный, чем молекулярный (300 vs 150 км/с)



Оценка масса газа обеих фракций:

(2021). The ratio between $\text{H}\alpha$ and $\text{H I } 6-5 \text{ } 7.46 \mu\text{m}$ ($\text{P}\alpha$) is 112 at 10000 K (Storey & Hummer 1995). We assume that the electron density, n_e , in the ionized gas in the shock is between 100 cm^{-3} and the upper limit, $n_e < 500 \text{ cm}^{-3}$, obtained from the $[\text{Fe II}] 5.34 \mu\text{m} / [\text{Fe II}] 4.89 \mu\text{m} > 60$ ratio (Fig. D.1). The resulting mass range is $M_{\text{ion}} = (2.4-12) \times 10^5 M_{\odot}$.

lot et al. 1999), so we can assume local thermodynamic equilibrium (LTE) conditions. Under this assumption, the S(1) to S(6) transitions can be fit with a two temperature model: a warm component with $T_w = 330 \pm 40 \text{ K}$ and $M_{\text{H}_2, w} = (6.0 \pm 1.4) \times 10^5 M_{\odot}$ which dominates the S(1) and S(2) emission; and a hotter component with $T_h = 900 \pm 60 \text{ K}$ and $M_{\text{H}_2, h} = (0.44 \pm 0.12) \times 10^5 M_{\odot}$ which dominates the S(3)–S(6) emission (Fig. 5). The higher J transi-

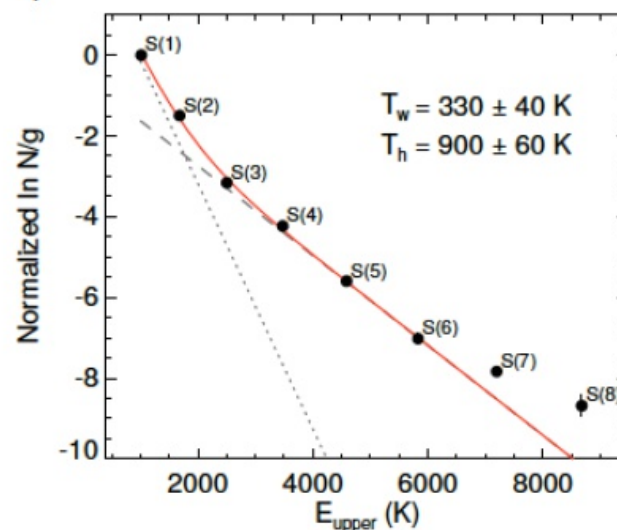


Fig. 5: Rotational diagram showing the H_2 0–0 S(1) to S(8) transitions measured at the northern radio hotspot N2 assuming an ortho-to-para ratio of 3 expected for $T_{\text{rot}} > 200 \text{ K}$ (Burton et al.