From TIGER to WST: scientific impact of four decades of developments in integral field spectroscopy

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This paper traces the 37 years of my career dedicated to the development of integral field spectroscopy (IFS)

MUSE is amazing...

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

TIGER the first map:1988

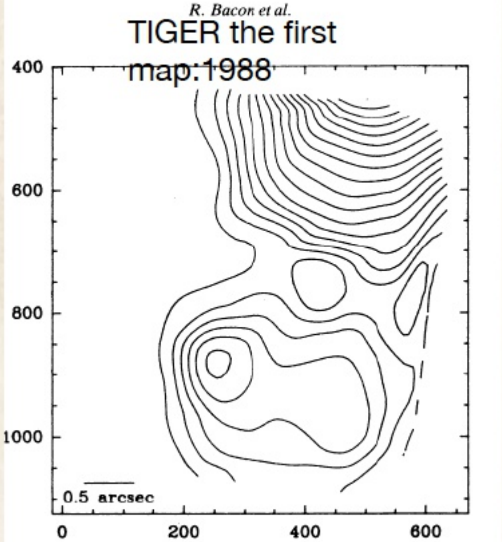
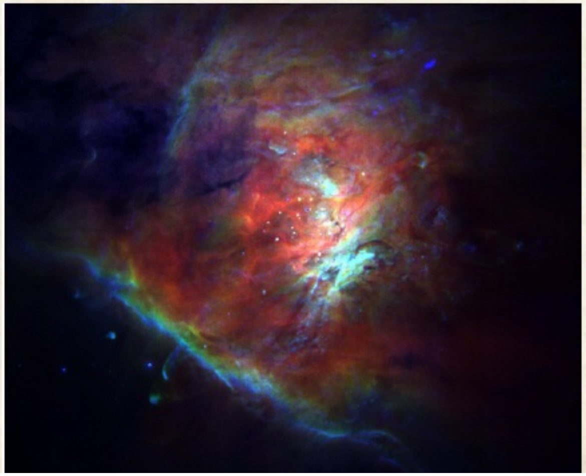


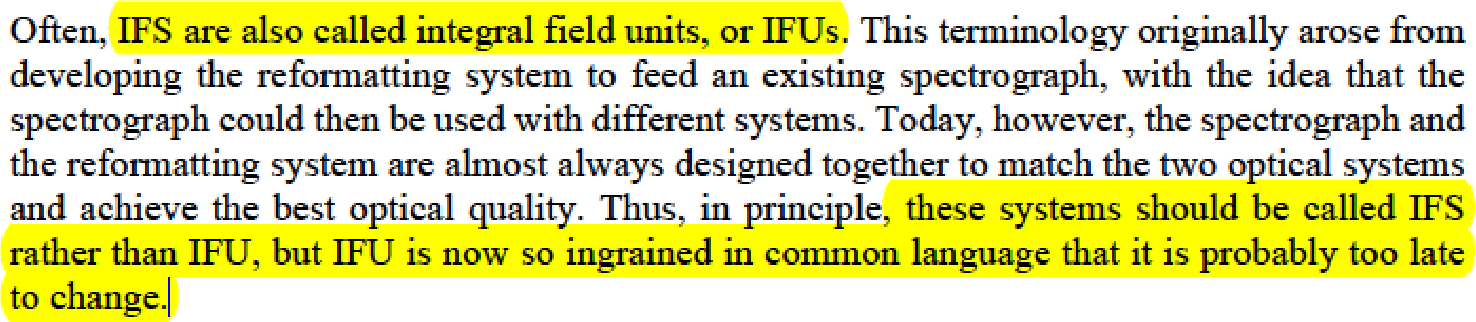
Figure 7 : Monochromatic map in [NII]–Hα of the nuclear region of M 51



M 42
red: [S II] 6731
blue: Hbeta,
green: [N II] 6584

Моисеев/ВАК-2024

О терминологии...


Often, IFS are also called integral field units, or IFUs. This terminology originally arose from developing the reformatting system to feed an existing spectrograph, with the idea that the spectrograph could then be used with different systems. Today, however, the spectrograph and the reformatting system are almost always designed together to match the two optical systems and achieve the best optical quality. Thus, in principle, these systems should be called IFS rather than IFU, but IFU is now so ingrained in common language that it is probably too late to change.

Путь к первому IFS:

1982 – начал писать диссер у Guy Monnet о динамике E-галактик, анизотропия...
Проблема сравнения моделей с наблюдениями, начали на CFHT с длинной щелью:
I quickly realized how inefficient this method was.
Основной проблемой считал точный учет PSF [то, что сейчас делает Ваня Катков]

Попытка использовать CIGALE в абсорбции – провалилась, даже с высоким S/N о дисперсии скоростей можно забыть [у нас тоже на БТА в 00х, хотя есть отдельные работы...]

Monnet обсудил проблему с Georgies Courtes (бывшим его руководителем), самая концепция – Courtes (1980) примерно тогда же – реализация с волокнами на 2.2м (Vanderriest 1980)

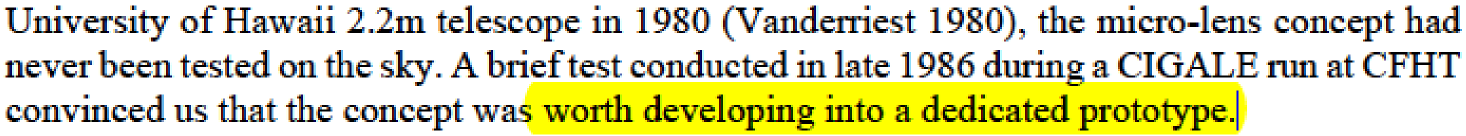

University of Hawaii 2.2m telescope in 1980 (Vanderriest 1980), the micro-lens concept had never been tested on the sky. A brief test conducted in late 1986 during a CIGALE run at CFHT convinced us that the concept was worth developing into a dedicated prototype.

Figure 3: TIGER first light at CFHT in June 1987. From let to right: Georges Courtès, Roland Bacon, Guy Monnet and Yvon Georgelin.

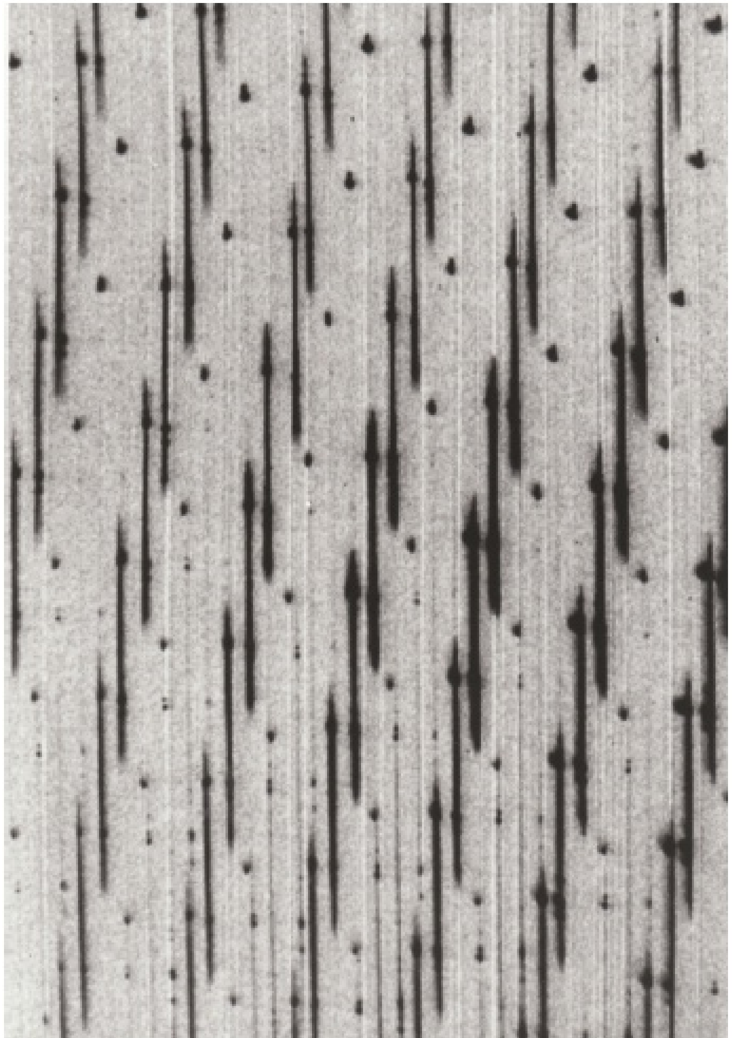


Figure 4: *This raw image of the nucleus of M51 was the first science exposure obtained by TIGER during first light at CFHT in June 1987.*

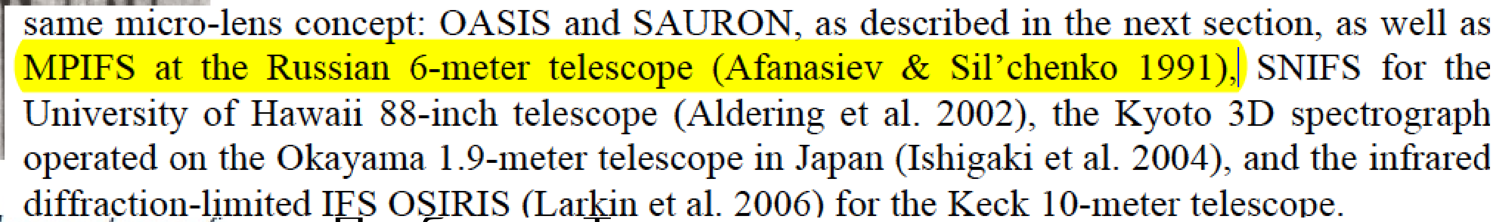
TIGER: быстро собрали из того, что было

Первый свет: 1987 (Courtes+1988; Bacon+1988)
Первая рецензируемая публикация (по integral-field) вообще:
Крест Эйнштейна (Adam + 1989)
[рецензируемость – как критерий нового результата]

Сперва 1024*640 px, потом 1Кx1К @570 линз

Первое поле скоростей и дисперсии скоростей звезд – Bacon+1994   [Что с MPFS?]

1996 TIGER снят с вооружения:
38 publ/12 refereed from Mars to AGNs



same micro-lens concept: OASIS and SAURON, as described in the next section, as well as MPIFS at the Russian 6-meter telescope (Afanasiev & Sil'chenko 1991), SNIFS for the University of Hawaii 88-inch telescope (Aldering et al. 2002), the Kyoto 3D spectrograph operated on the Okayama 1.9-meter telescope in Japan (Ishigaki et al. 2004), and the infrared diffraction-limited IFS OSIRIS (Larkin et al. 2006) for the Keck 10-meter telescope.

Проблемы Тигра:
- сменный детектор
- турель вращалась руками
- долгое наведение
- гнутия

OASIS себя не оправдал....

Хотя и первая попытка использовать АО

resolution improves. The second reason is that the spatial PSF evolution with wavelength (λ) is much more pronounced in diffraction-limited mode ($\propto \lambda^{-1}$) than in seeing mode ($\propto \lambda^{-0.2}$), making it difficult to optimize the slit width for a wide wavelength range.

Проблемы на стадии проектирования, хотели еще и ИФП, PYTHEAS..., а в итоге потребовали ARGUS и, сюрприз-сюрприз... длинную щель: *“As a young PI with little experience, I did not try to argue and said yes to all these new requirements....A PI must have his/her own vision and sometimes should be able to take some distance with “committee recommendations” or “friends suggestions”*

Сделали только image & IFU,
CFHT :1997-2003, только 8 статьей

Проблемы АО: большие потери света (30% забирает), так что работали в ограничении по шумам считывания, не везде есть яркие звезды для нее:

Перенесли на WHT где работали до 2008 (еще 13 статей), так как на CFHT ставили Megaprime
Но уже без АО
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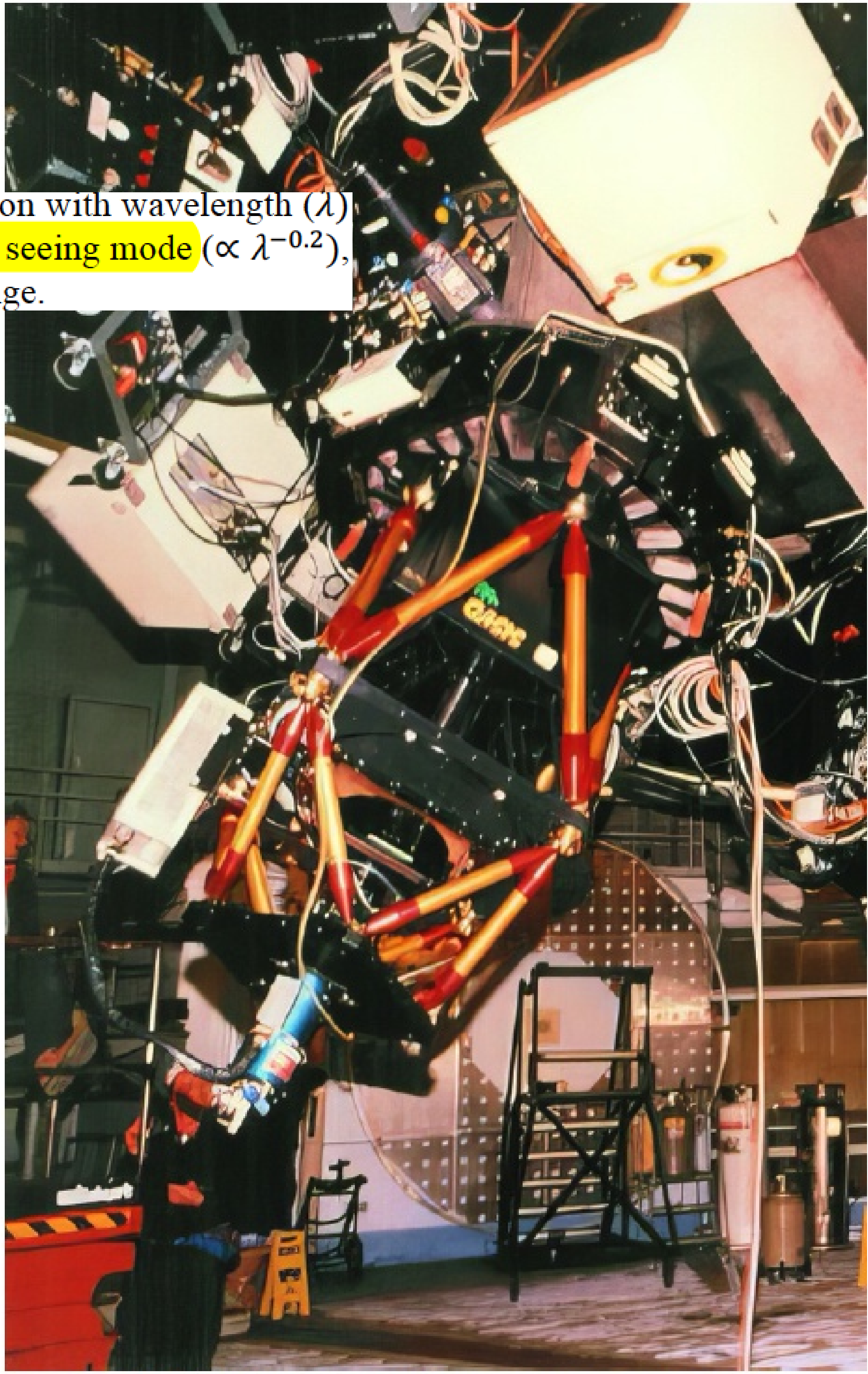


Figure 5: OASIS at CFHT Cassegrain focus (1997).

SAURON: переход на большое поле

I was convinced that significant new scientific discoveries could be made with a large field-of-view IFS, something that OASIS would not be able to achieve.

33x41arcsec @ 0.94” минимум подвижных элементов, построили < 2.5 года
SAURON: 9 PhD theses , series 21 peer-reviewed papers, 6,250 citations
ATLAS-3D (2007-08): 31 peer-reviewed papers, a total of 7,200 citations

Figure 7: The SAURON team in Leiden (July 2001). From left to right : Roger Davies, Jesus Falcon-Barroso, Davor Krajnovic, Michele Cappellari, Tim de Zeeuw, Fabien Wernli, Roland Bacon, Martin Bureau, Bryan Miller, Marc Sarzi, Yannick Copin and Eric Emsellem.

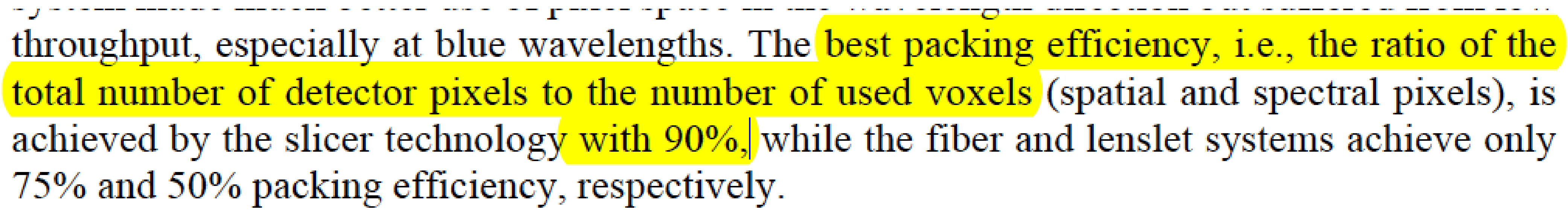
MUSE – начался в 2001, сбор идей для второго поколения инструментов VLT:

Только начался SAURON, но : such an opportunity to build a new IFS for the VLT could not be missed...

My idea was to design a "true 3D instrument" that combines the expected performance of an imager — large field of view, high spatial resolution, and excellent throughput

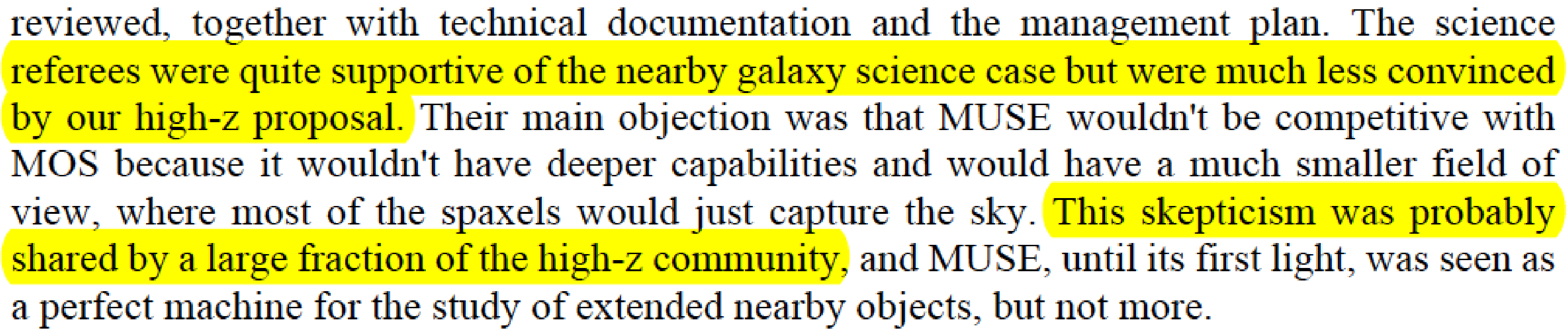
Image reconstruction needs to account for all the imperfections of the various optical elements involved in this reformatting. This is not an easy task and may explain why the imaging capabilities of the first generation of IFS were not at the level expected for an imager.

Paradigm shift was required, leading to the concept of multi-units



throughput, especially at blue wavelengths. The best packing efficiency, i.e., the ratio of the total number of detector pixels to the number of used voxels (spatial and spectral pixels), is achieved by the slicer technology with 90%, while the fiber and lenslet systems achieve only 75% and 50% packing efficiency, respectively.

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

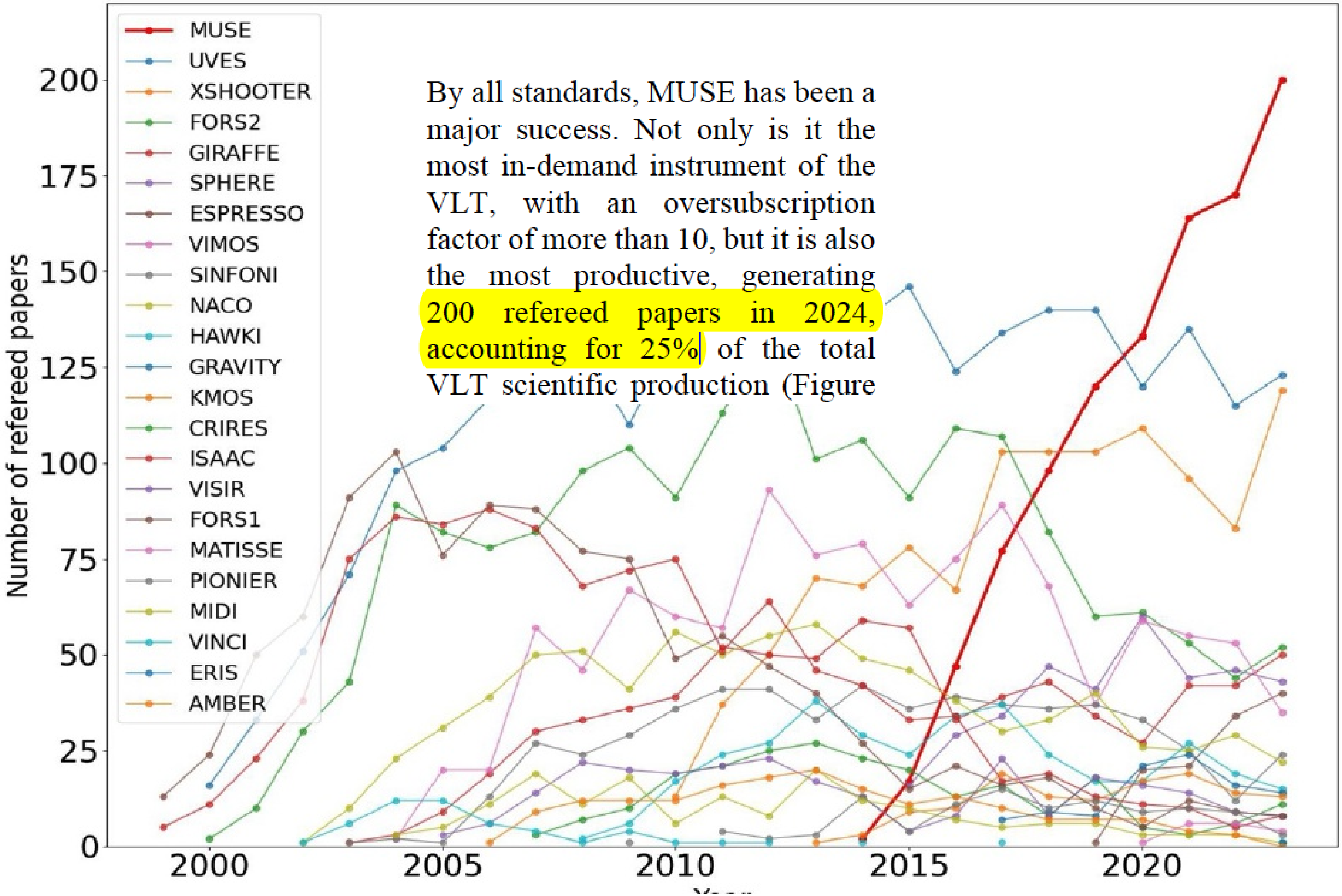


reviewed, together with technical documentation and the management plan. The science referees were quite supportive of the nearby galaxy science case but were much less convinced by our high-z proposal. Their main objection was that MUSE wouldn't be competitive with MOS because it wouldn't have deeper 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.

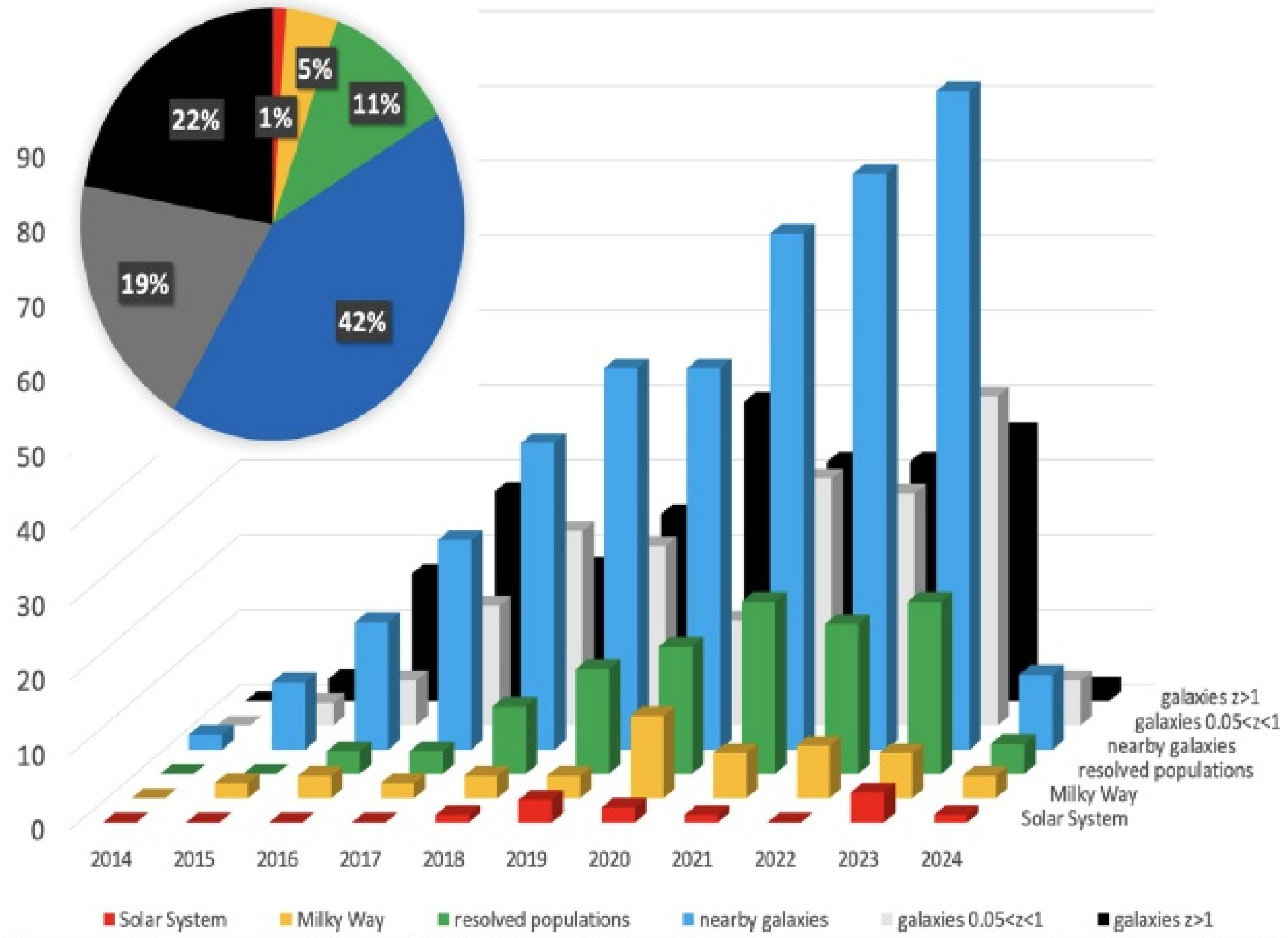
2002 pre-phase A
2004 Phase A
2013 – прибор отправлен на Параналь
(на 2 года позже планов)
И занял всю несмитовскую платформу

Опирался на позитивный опыт SAURON
и негативный OASIS – меньше подвижных
элементов

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



By all standards, MUSE has been a major success. Not only is it the most in-demand instrument of the VLT, with an oversubscription factor of more than 10, but it is also the most productive, generating 200 refereed papers in 2024, accounting for 25% of the total VLT scientific production (Figure



This example highlights another reason for MUSE's success: its discovery power. The concept of obtaining spectroscopy of everything within a field of view has led to many unexpected discoveries. This is a fundamental feature of a game-changing facility. The number of publications that rely solely on data from the MUSE ESO archive is a testament to this.

BLUE MUSE

Пишет, что KCWI – единственный хоть как-то сравнимый прибор, хотя поле в 20 раз меньше и спаксель 0.35, а его единственный выигрыш – голубая граница 350 нм, а MUSE – 480 нм
[не упоминает про R!]

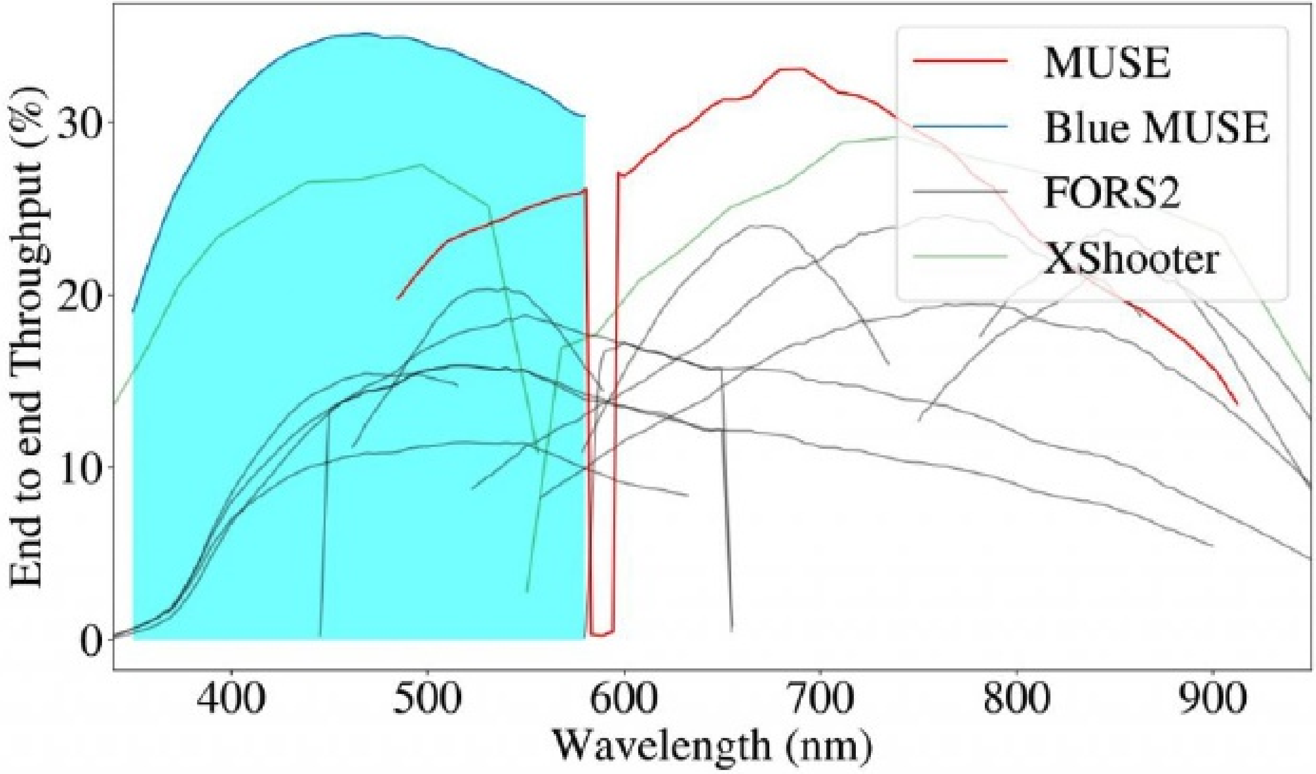


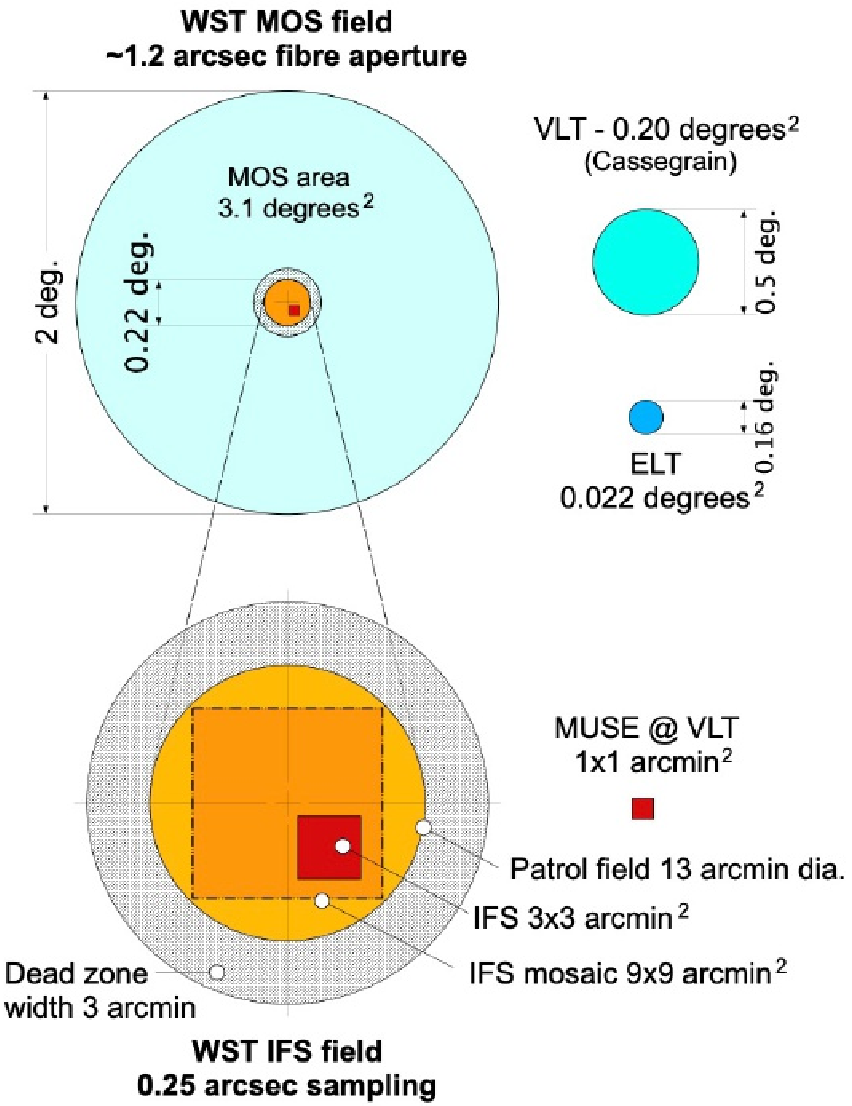
Figure 15: Comparison of the BlueMUSE (predicted) and MUSE (measured) end-to-end transmissions with other VLT instruments. A 15% is included for slit spectrographs to account for slit losses (from Richard et al. 2019).

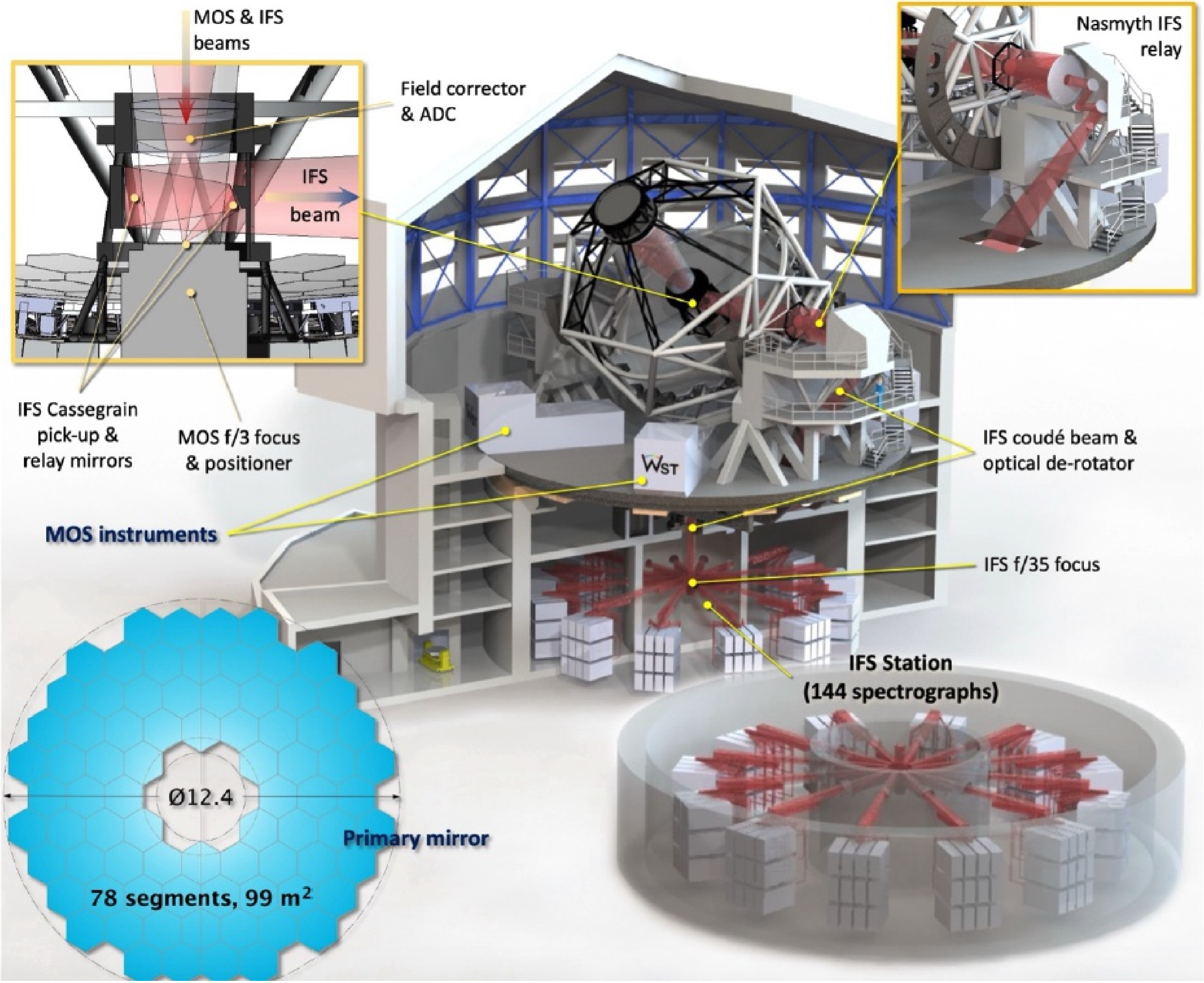
WST=Wide-field Spectroscopic survey telescope (Bacon +24)

Инструмент для следующей эпохи:

post-ELR era, ESO+Australia

12 м
MOS+IFU




MOS & IFS beams
Field corrector & ADC
IFS beam
Nasmyth IFS relay
IFS Cassegrain pick-up & relay mirrors
MOS f/3 focus & positioner
IFS coudé beam & optical de-rotator
WST
MOS instruments
IFS f/35 focus
IFS Station (144 spectrographs)
Ø12.4
Primary mirror
78 segments, 99 m²