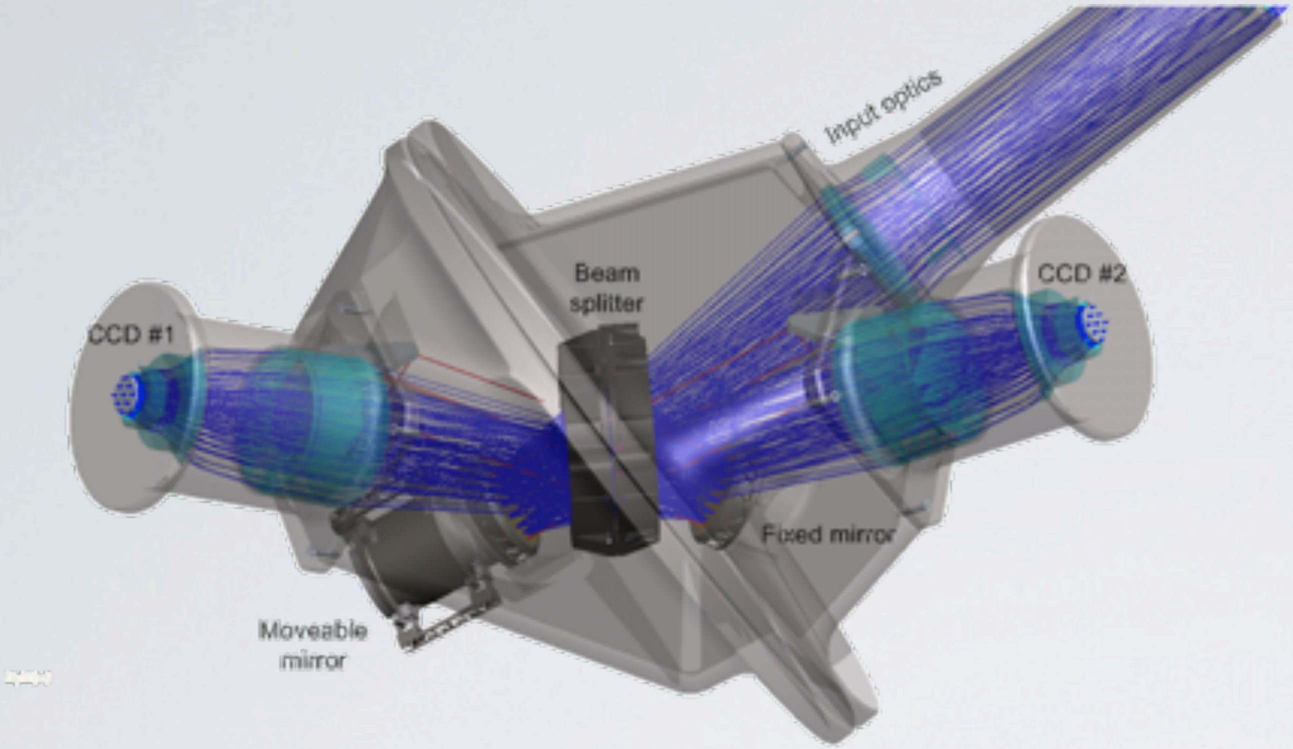


SITELLE: An Imaging FTS for the **C**anada-**F**rance-**H**awaii **T**elescope

CFHT Users Meeting, Campbell River, May 2013

Laurent Drissen (Université Laval) et al.

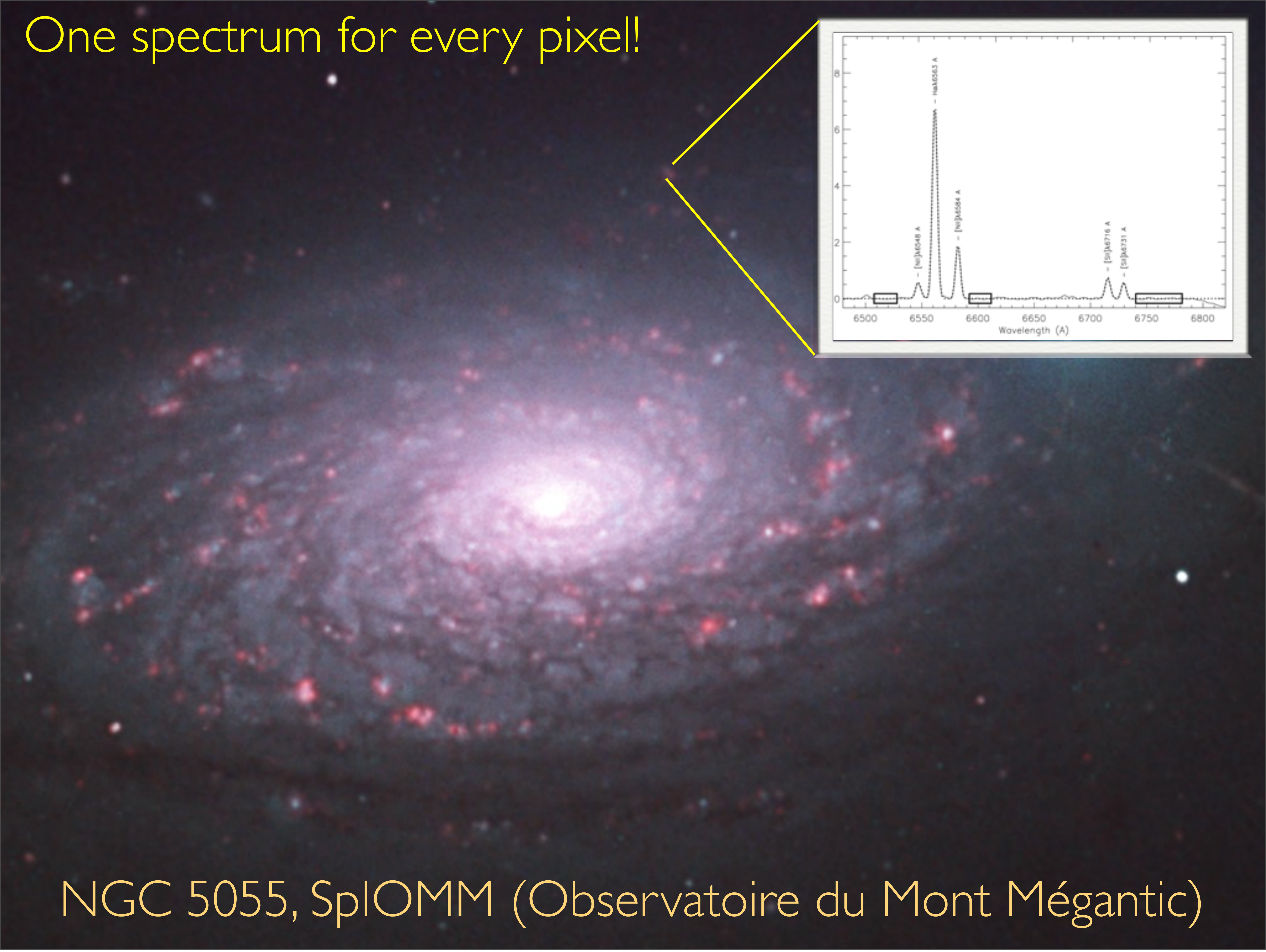
SITELLE in a nutshell

* Imaging Fourier transform spectrometer

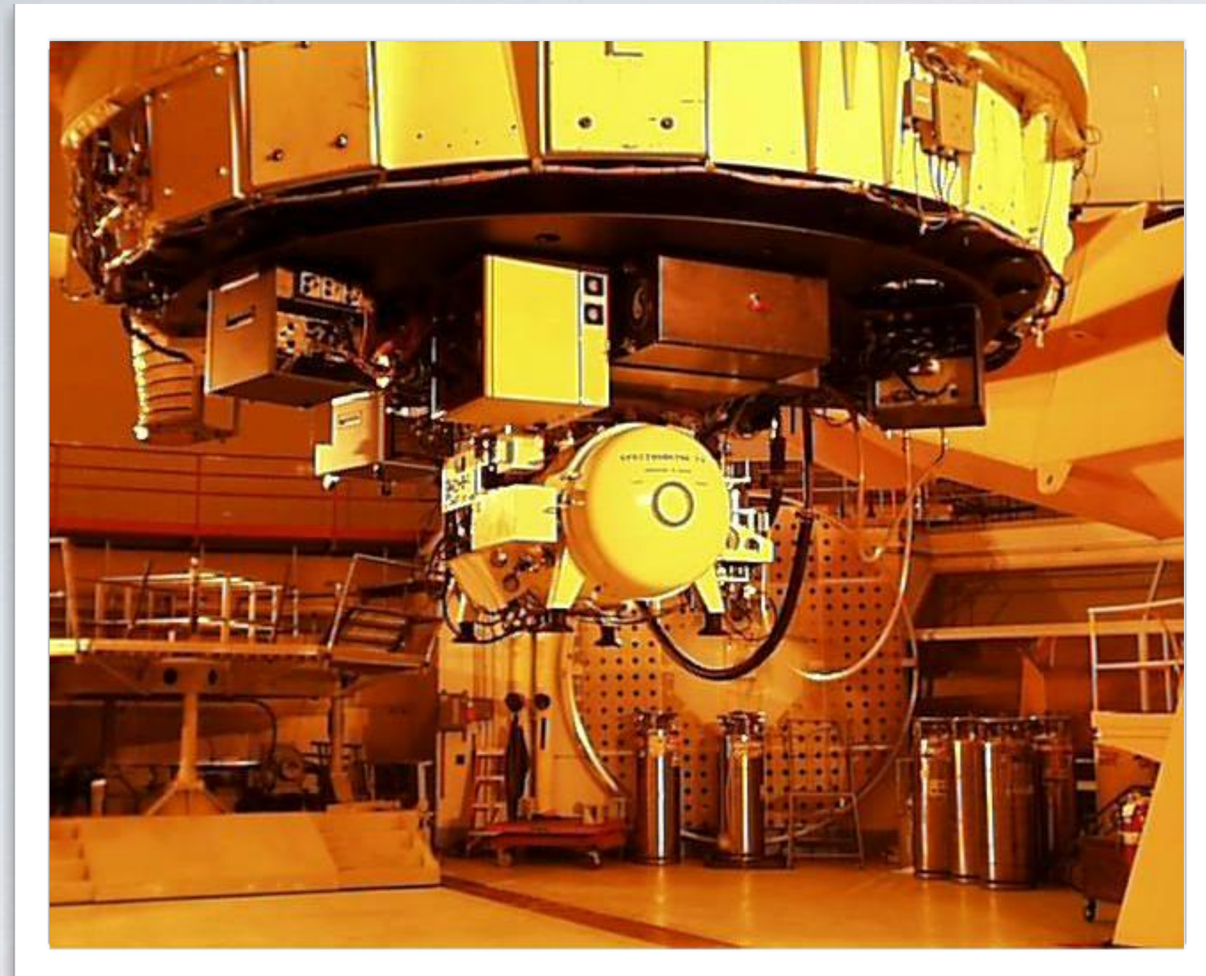
* FoV: 11 x 11 arcminutes
* R = 1 ~ 20 000
* Filter-selected bandpasses
* 350 - 900 nm [50% CCD]

* Detectors: e2v CCDs
* 2048 x 2064 pixels, 0.32''

=> 4.2 million spectra

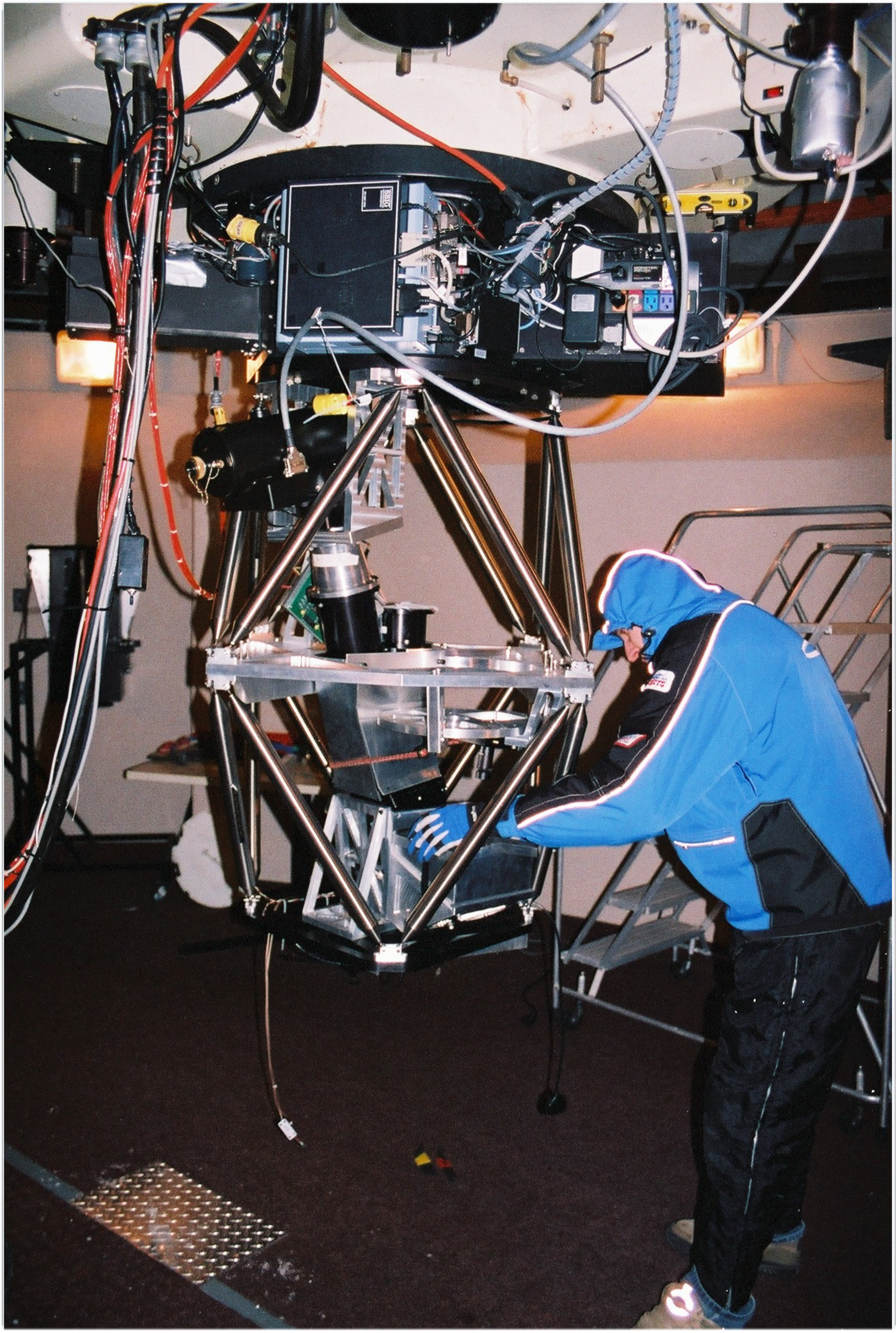

One spectrum for every pixel!
[NII]λ6548 A
Hαλ6563 A
[NII]λ6584 A
[SII]λ6716 A
[SII]λ6731 A
0
2
4
6
8
6500
6550
6600
6650
6700
6750
6800
Wavelength (A)
NGC 5055, SpIOMM (Observatoire du Mont Mégantic)

Other Imaging FTS on Mauna Kea



BEAR (CFHT ~ 1992 Maillard & Simons)

SCUBA2-FTS2 (2012 / Naylor et al.)

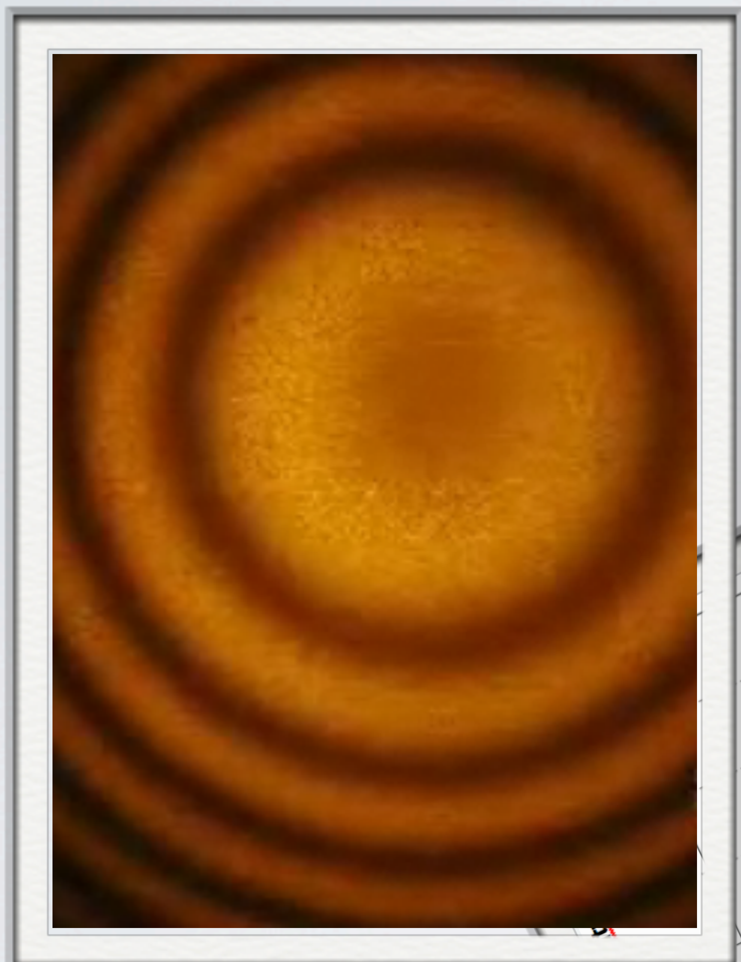


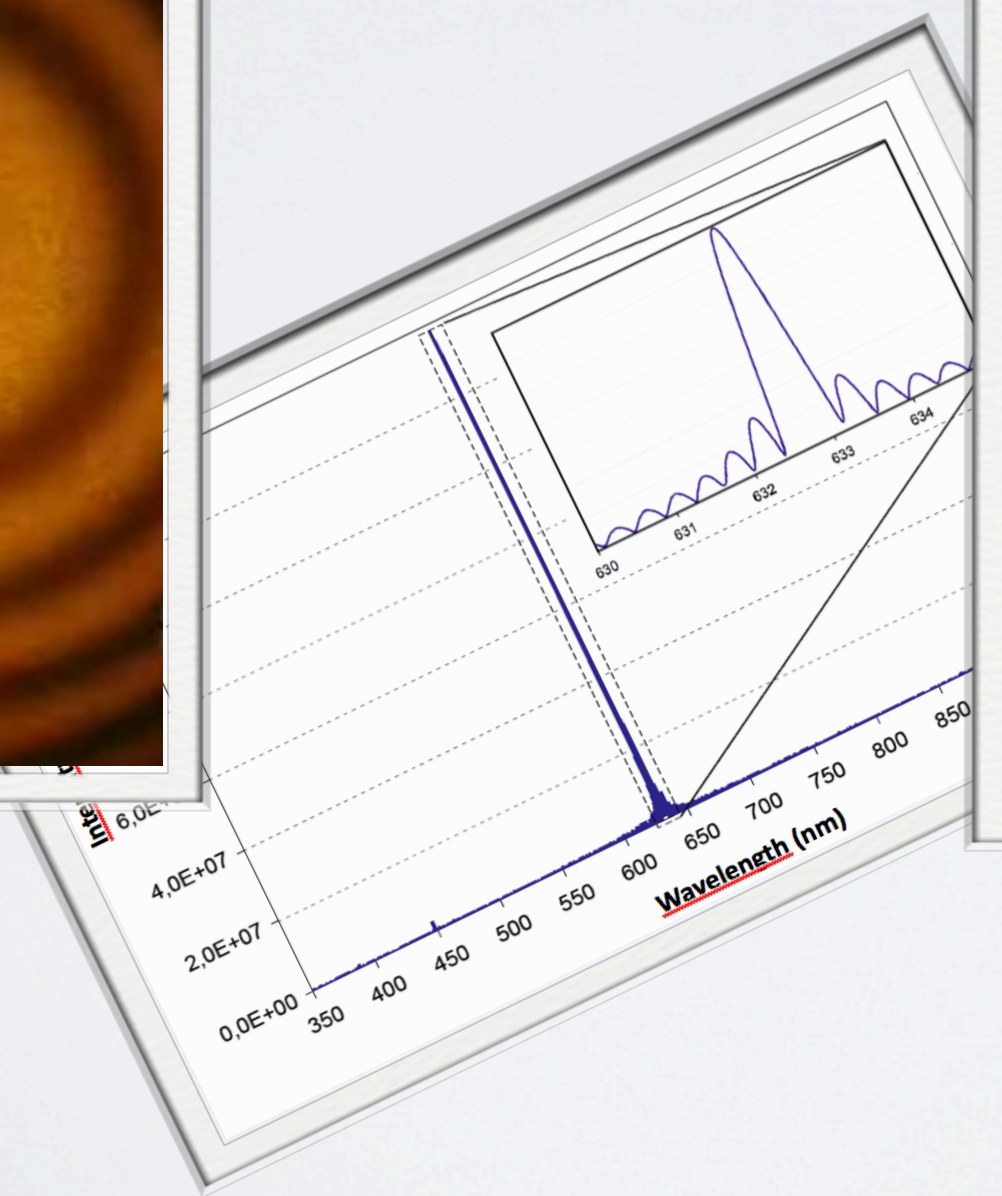
SpIOMM: a prototype for SITELLE Observatoire du Mont Mégantic (1.6-m)

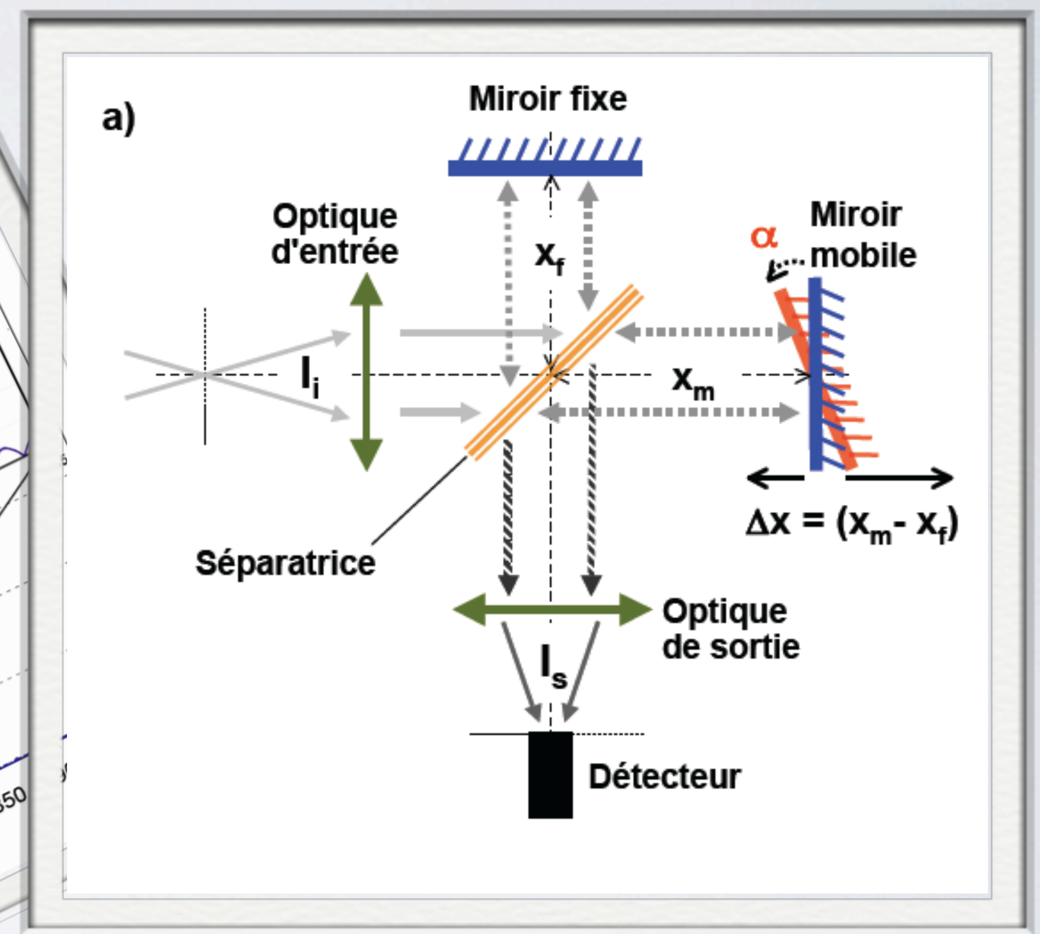
FOV: 12' x 12'
0.55''/pixel

CHAPTER I -

A (BRIEF) TECHNICAL INTRODUCTION





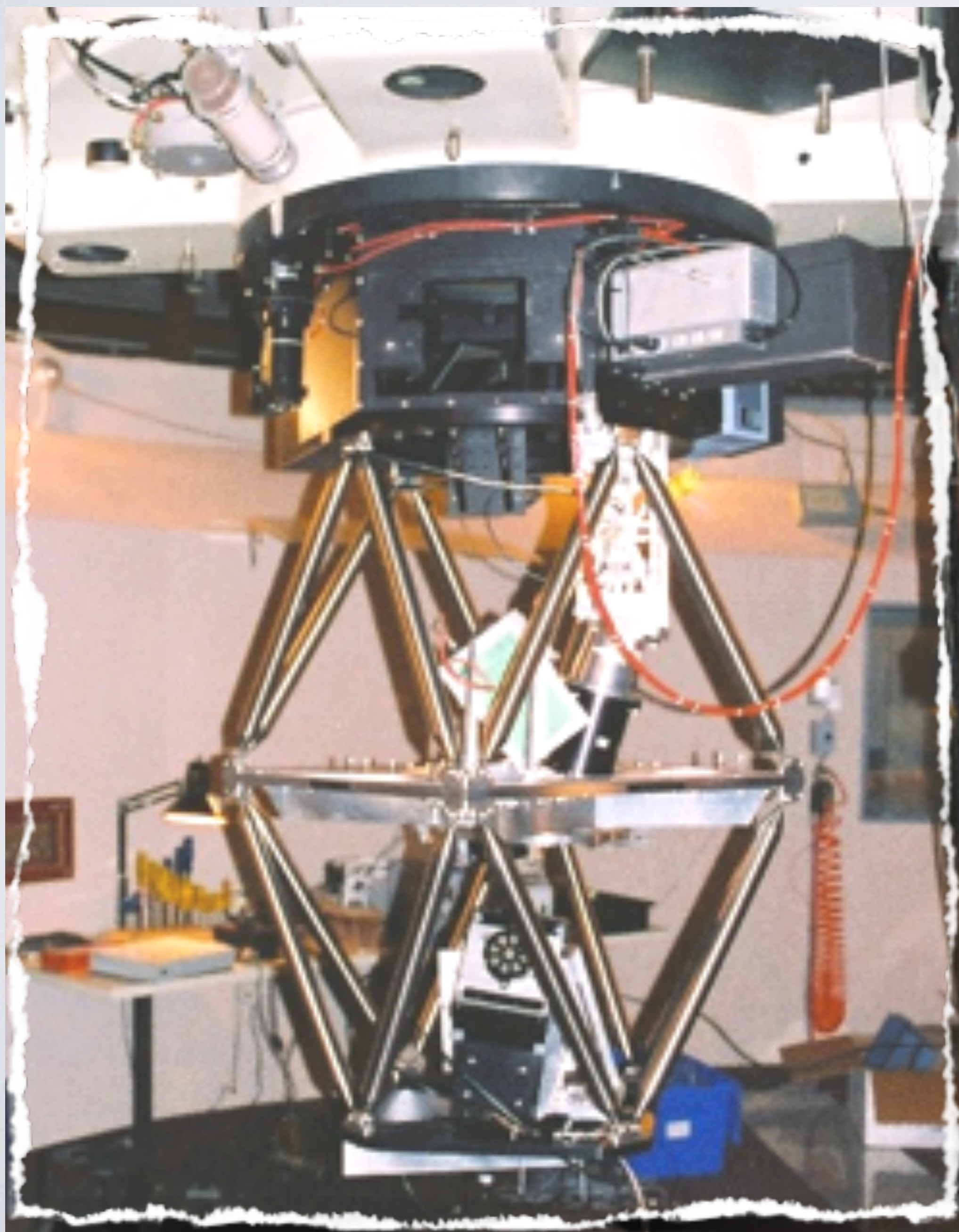


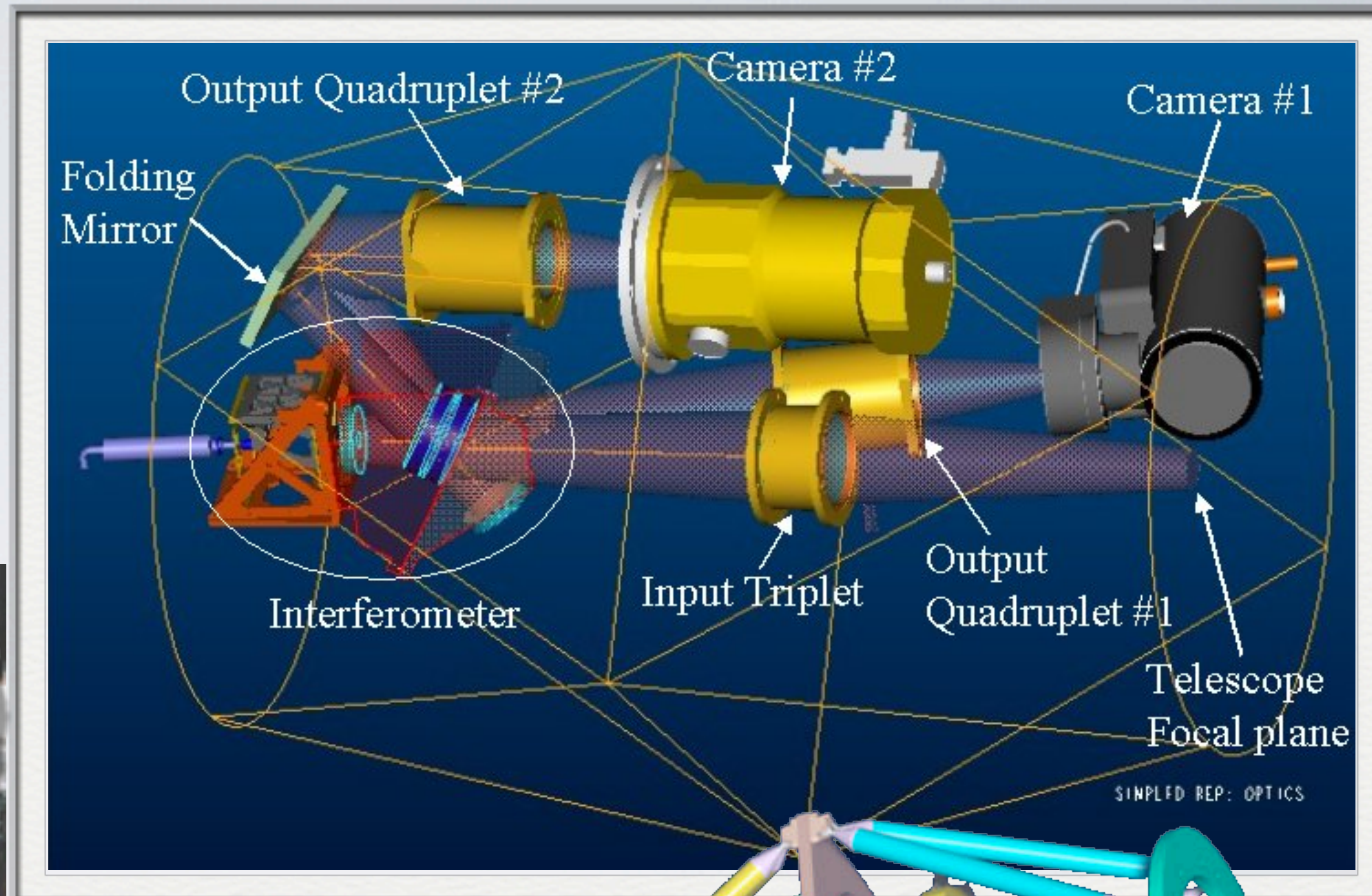
Imaging FTS =

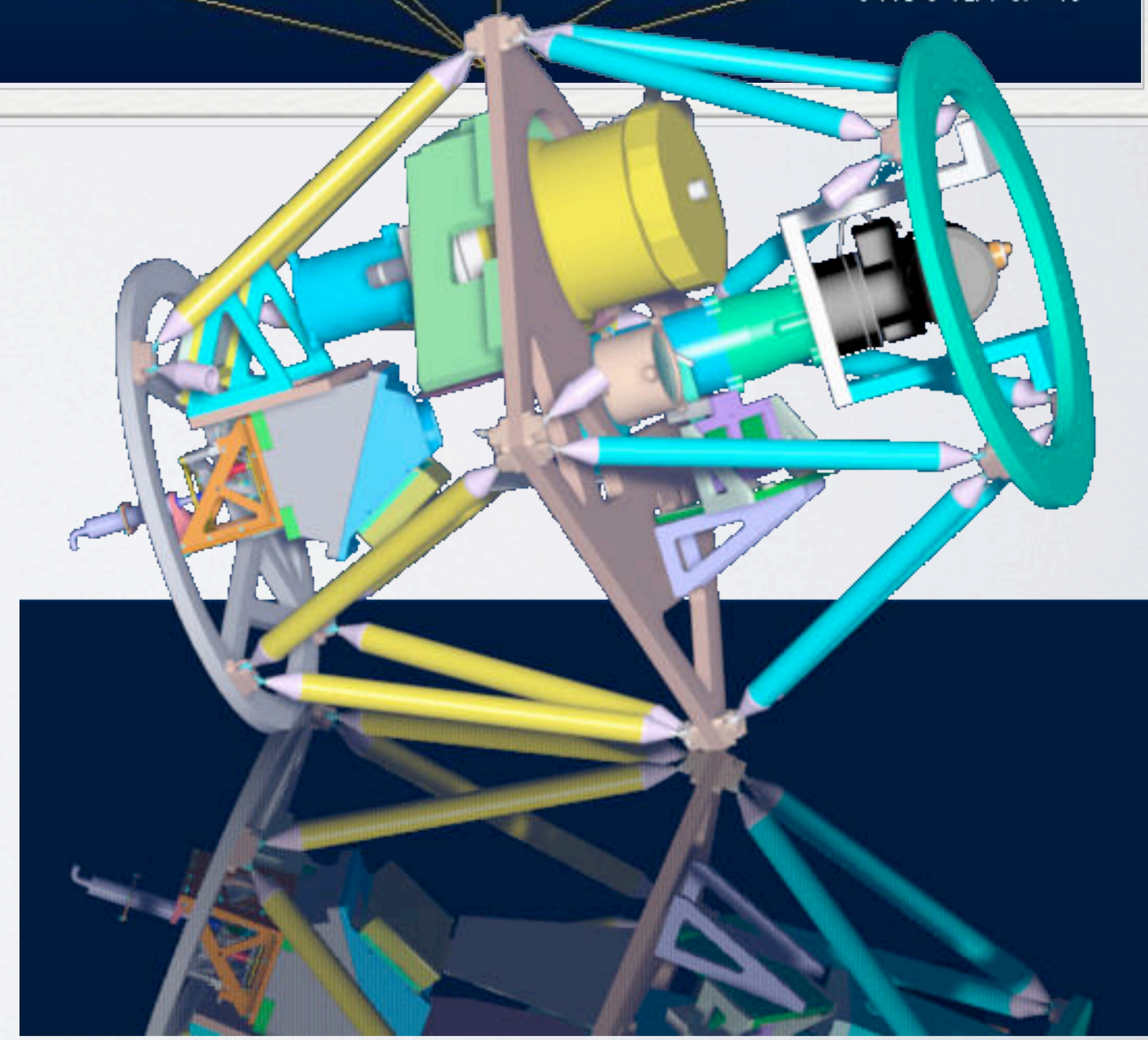
Michelson

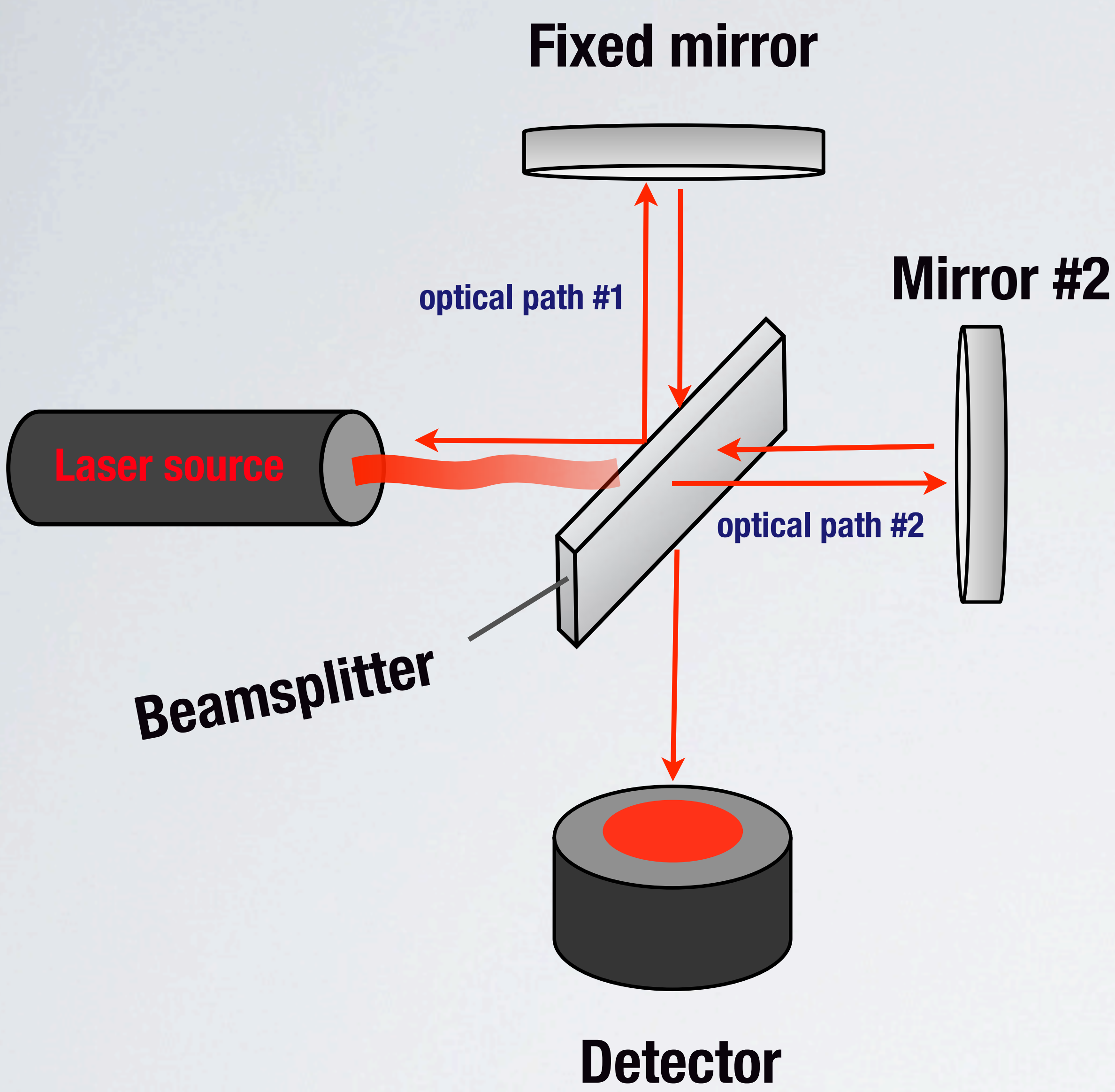
interferometer +

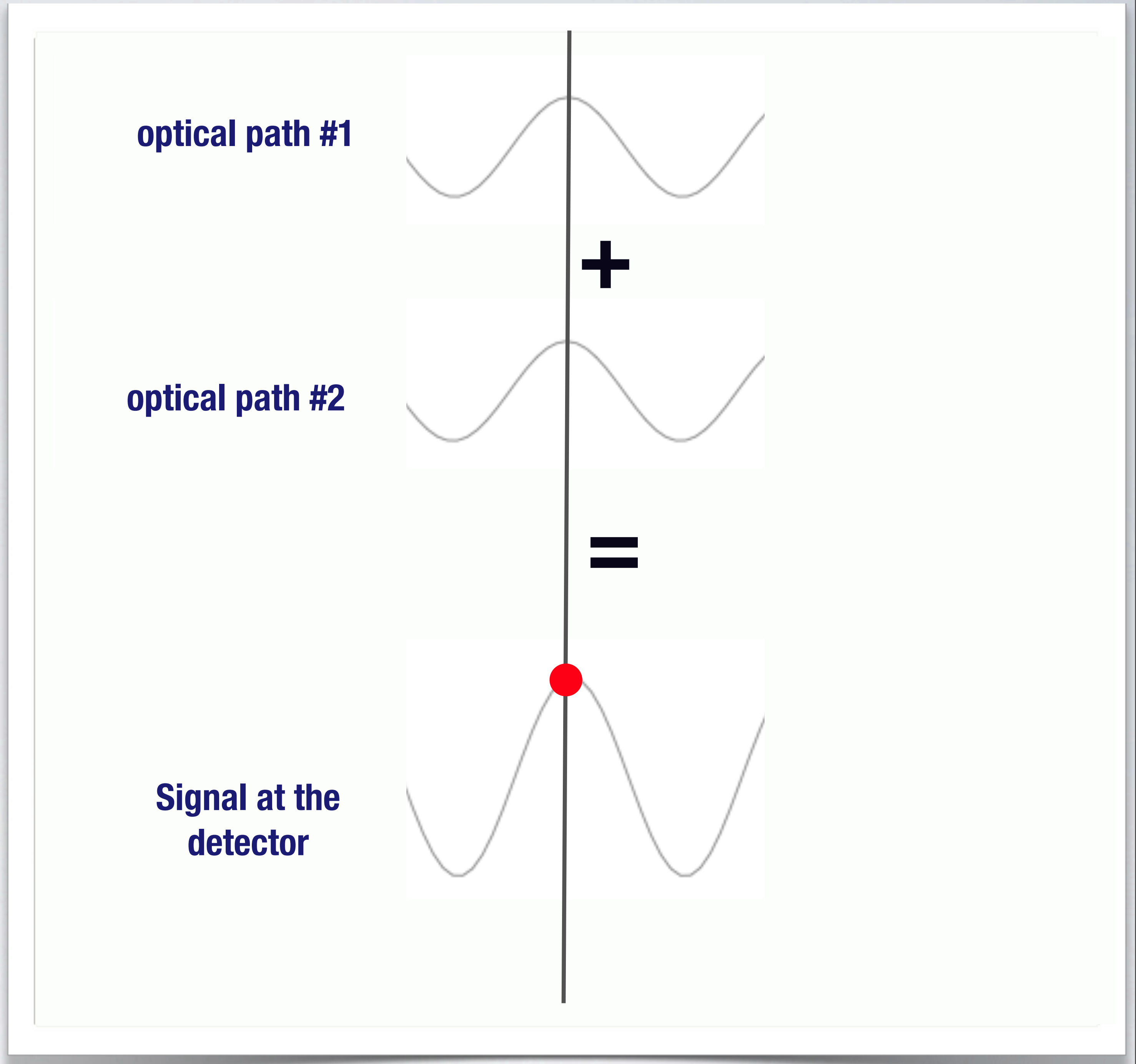
imaging optics



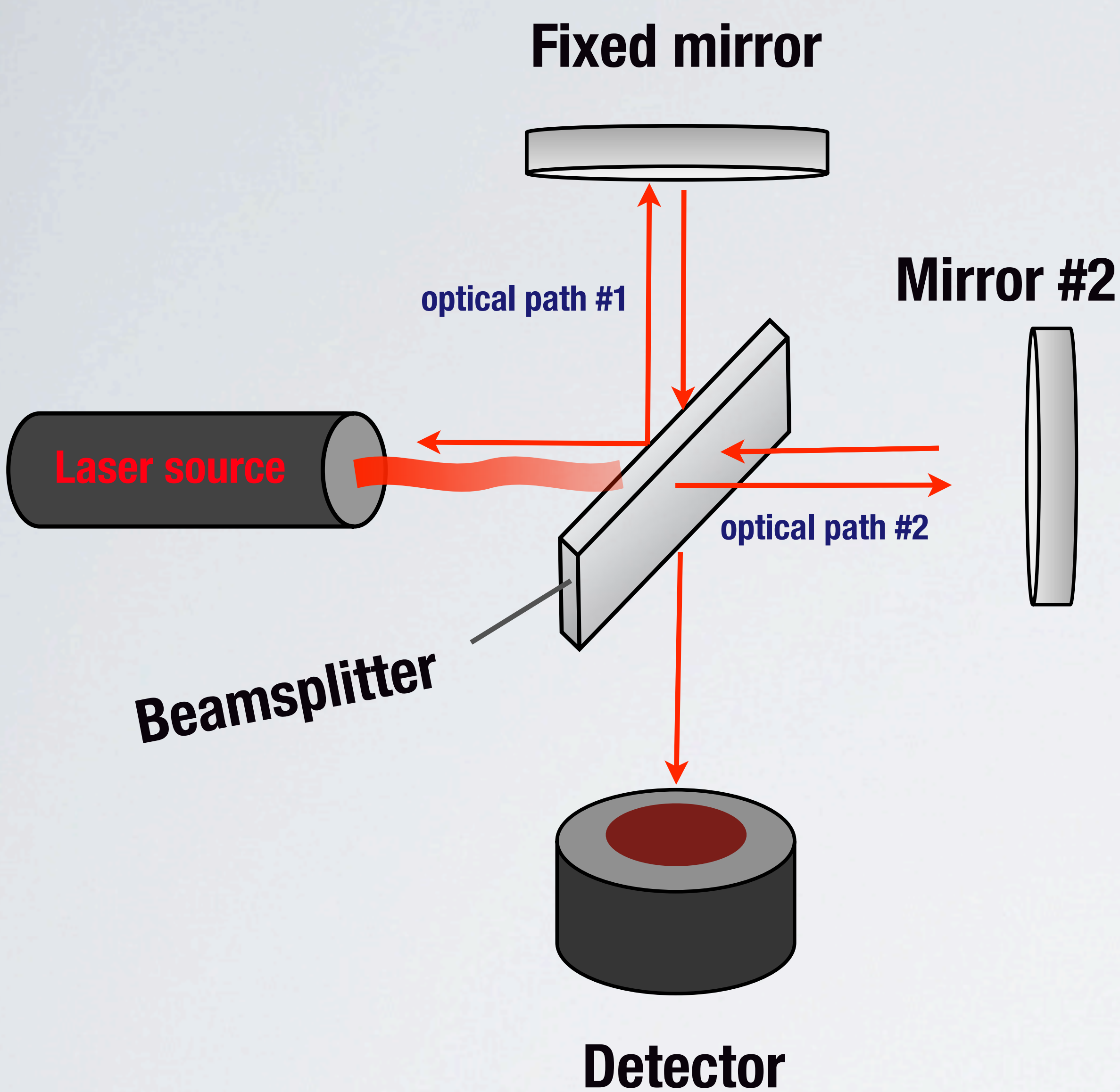


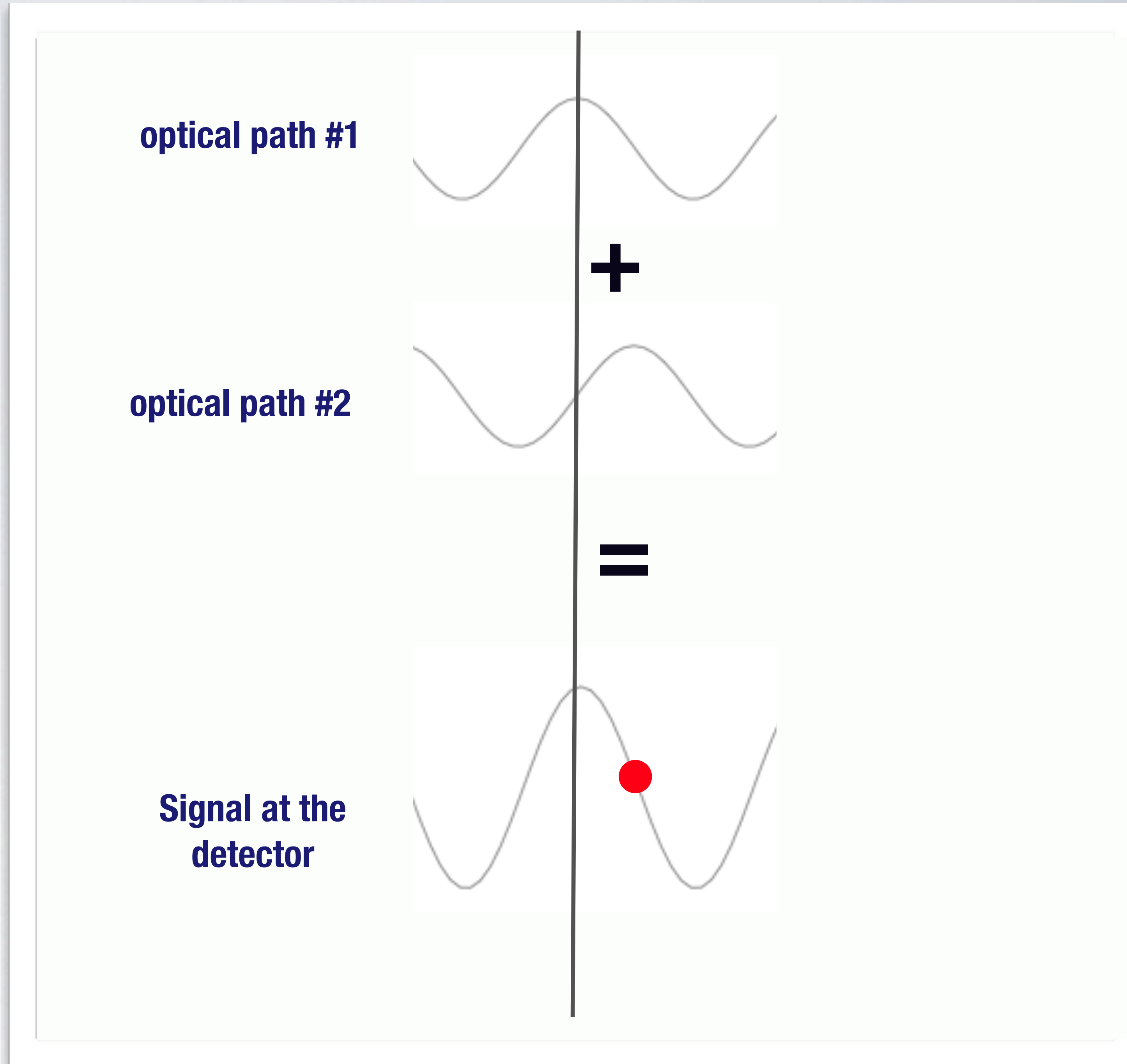




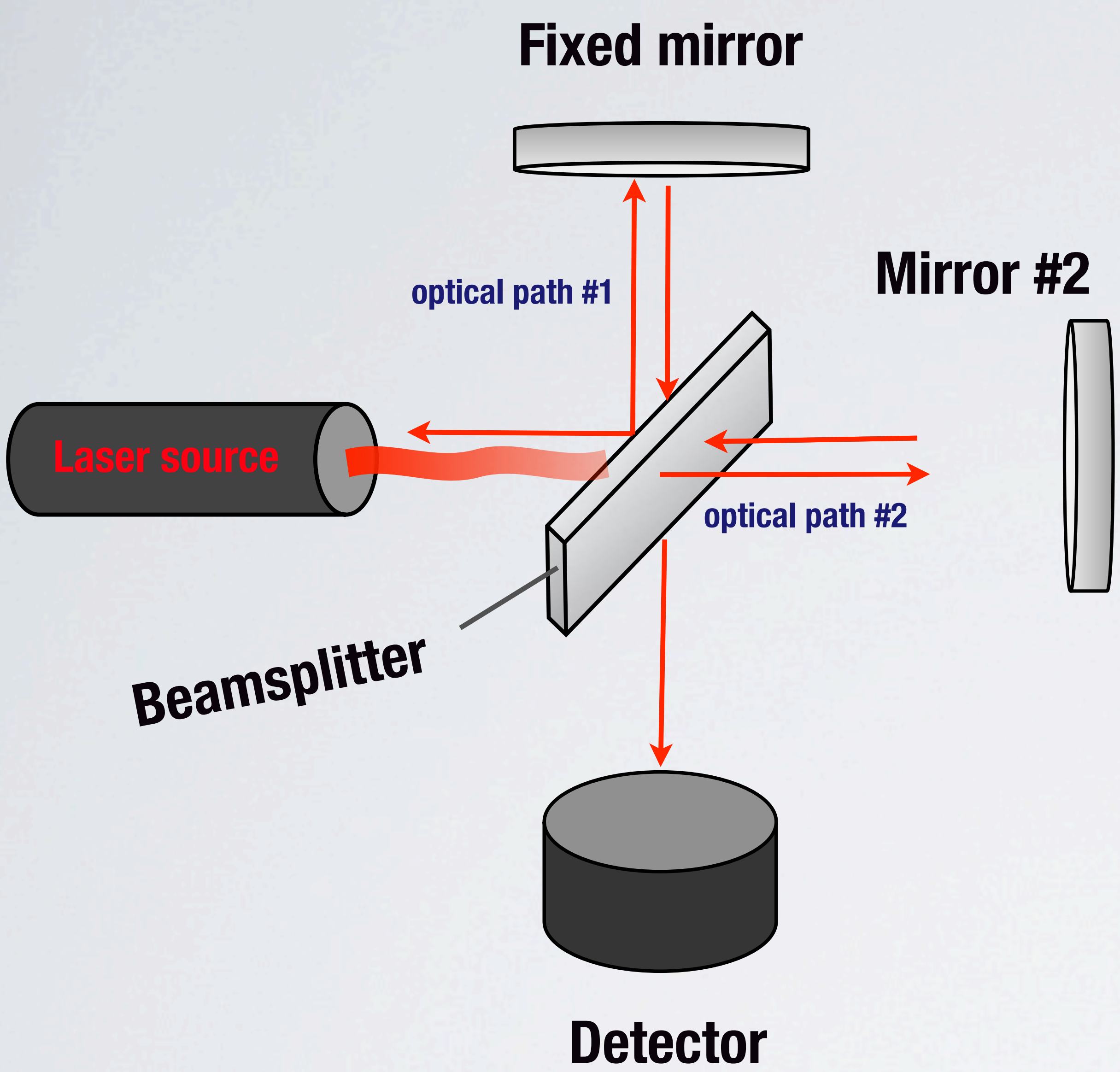


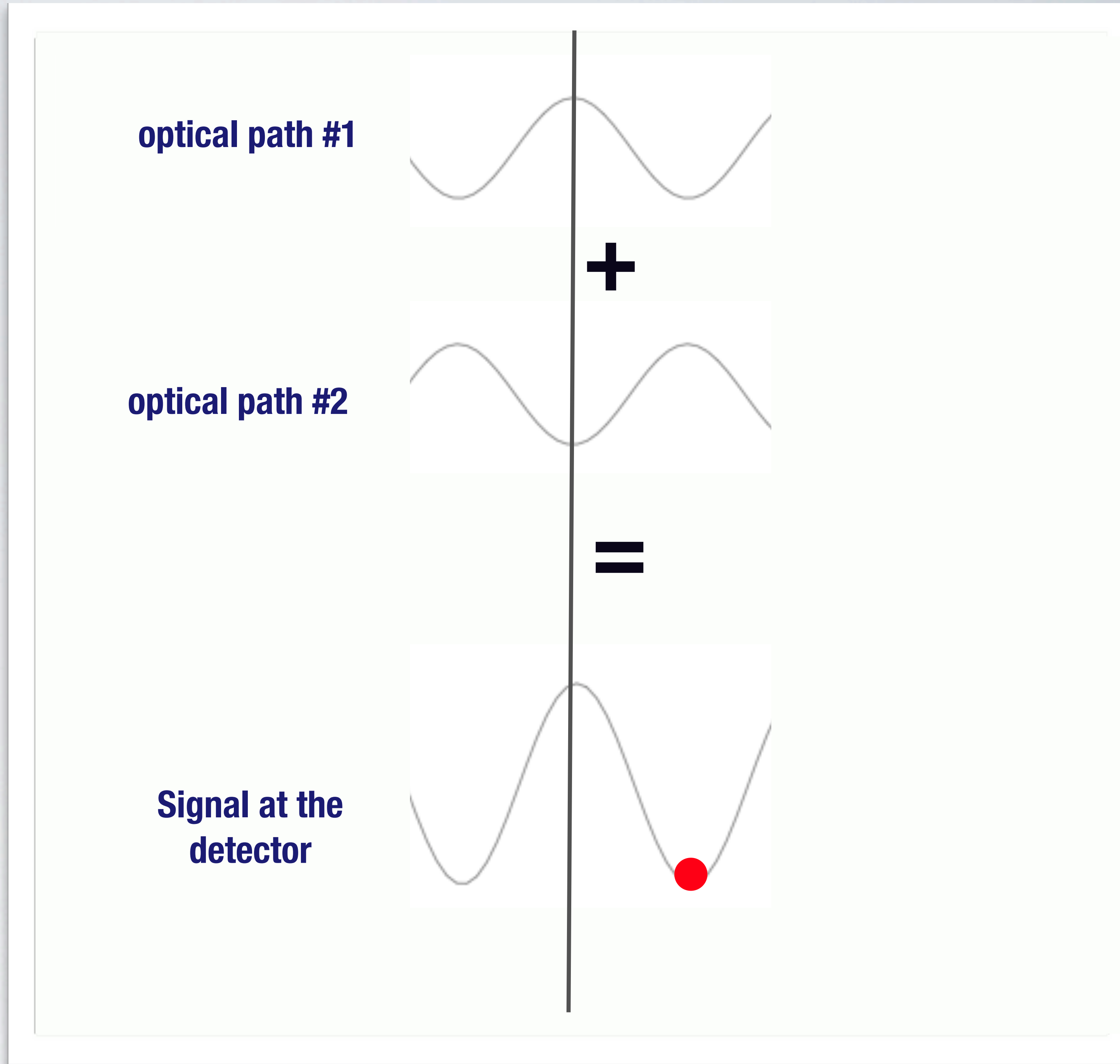
At the core of a Fourier transform spectrometer: a Michelson interferometer





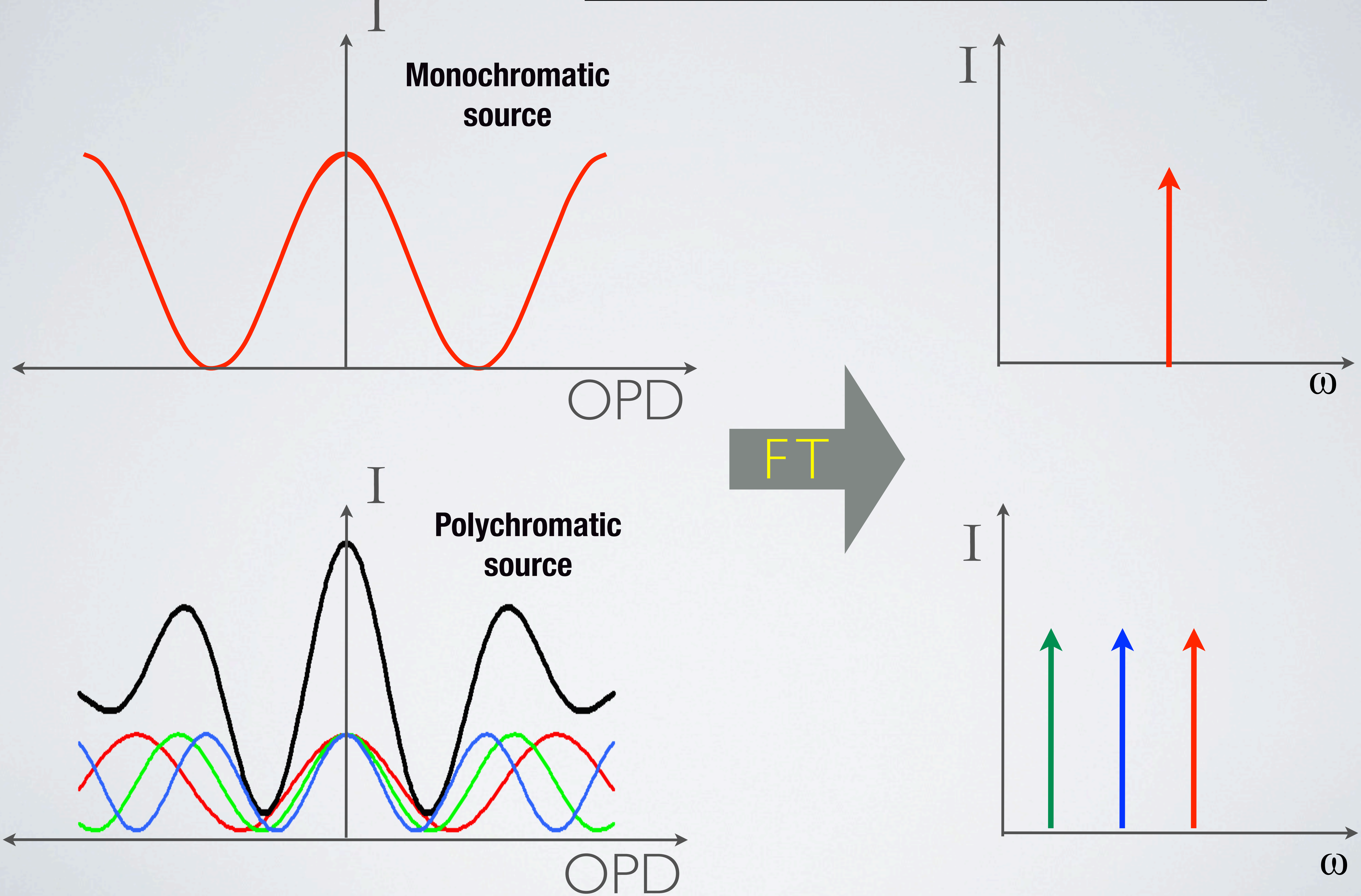
At the core of a Fourier transform spectrometer: a Michelson interferometer



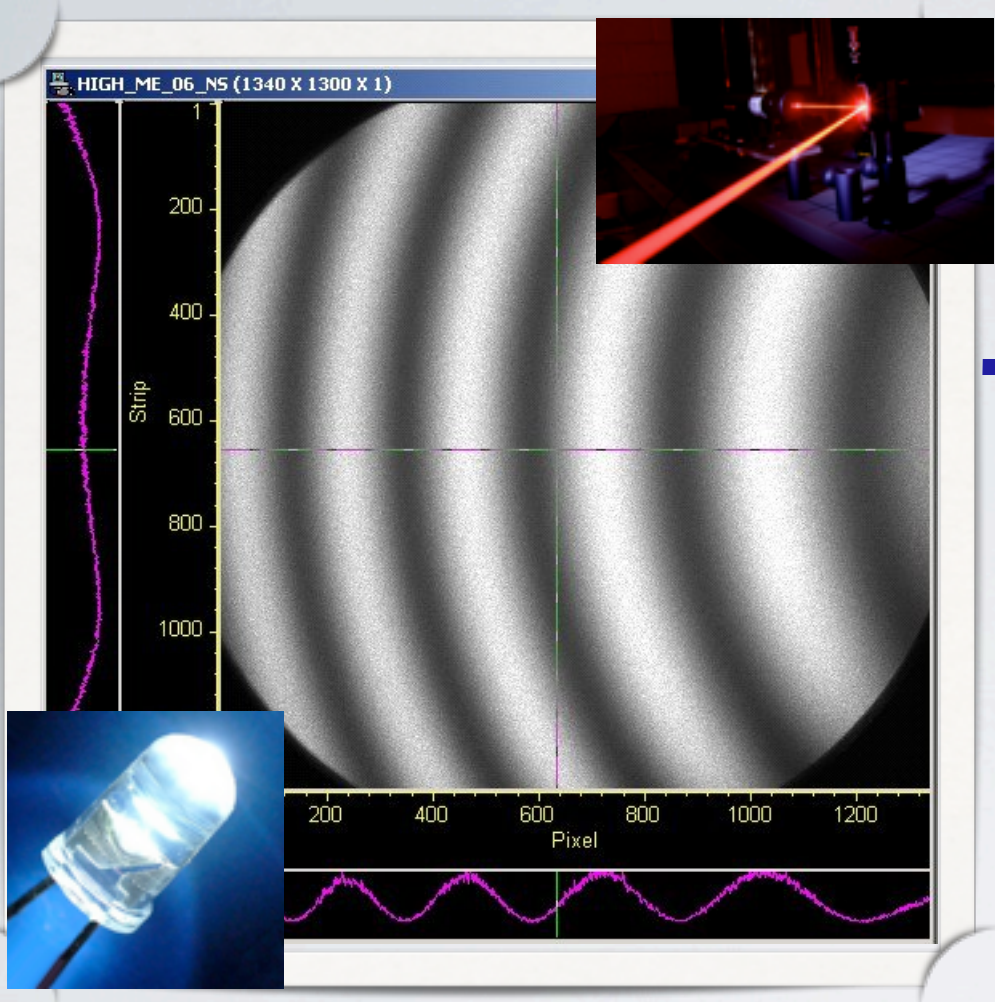


At the core of a Fourier transform spectrometer: a Michelson interferometer

$$\mathcal{F}(f) : \omega \mapsto \hat{f}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t}\, dt$$

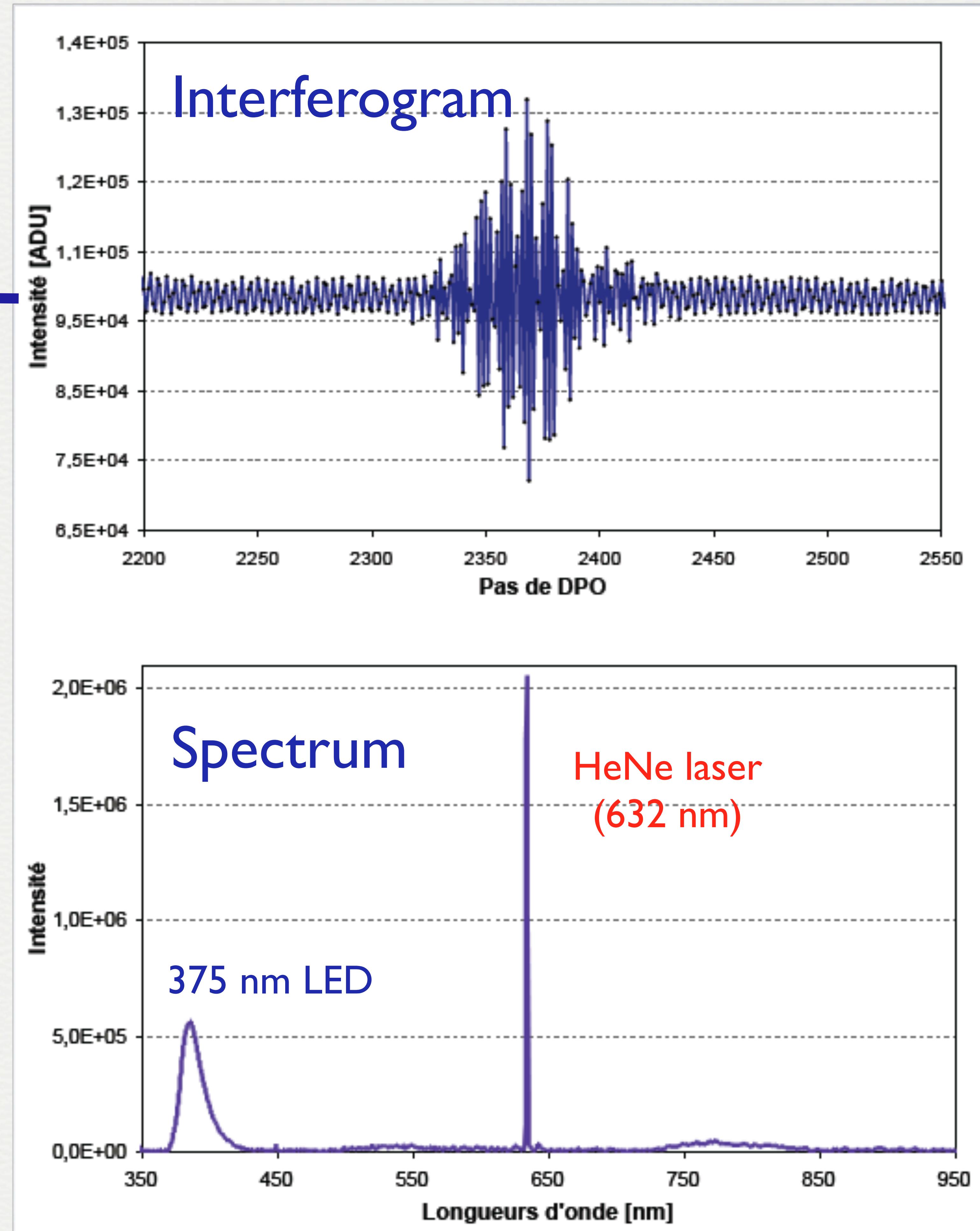


Tests in the lab

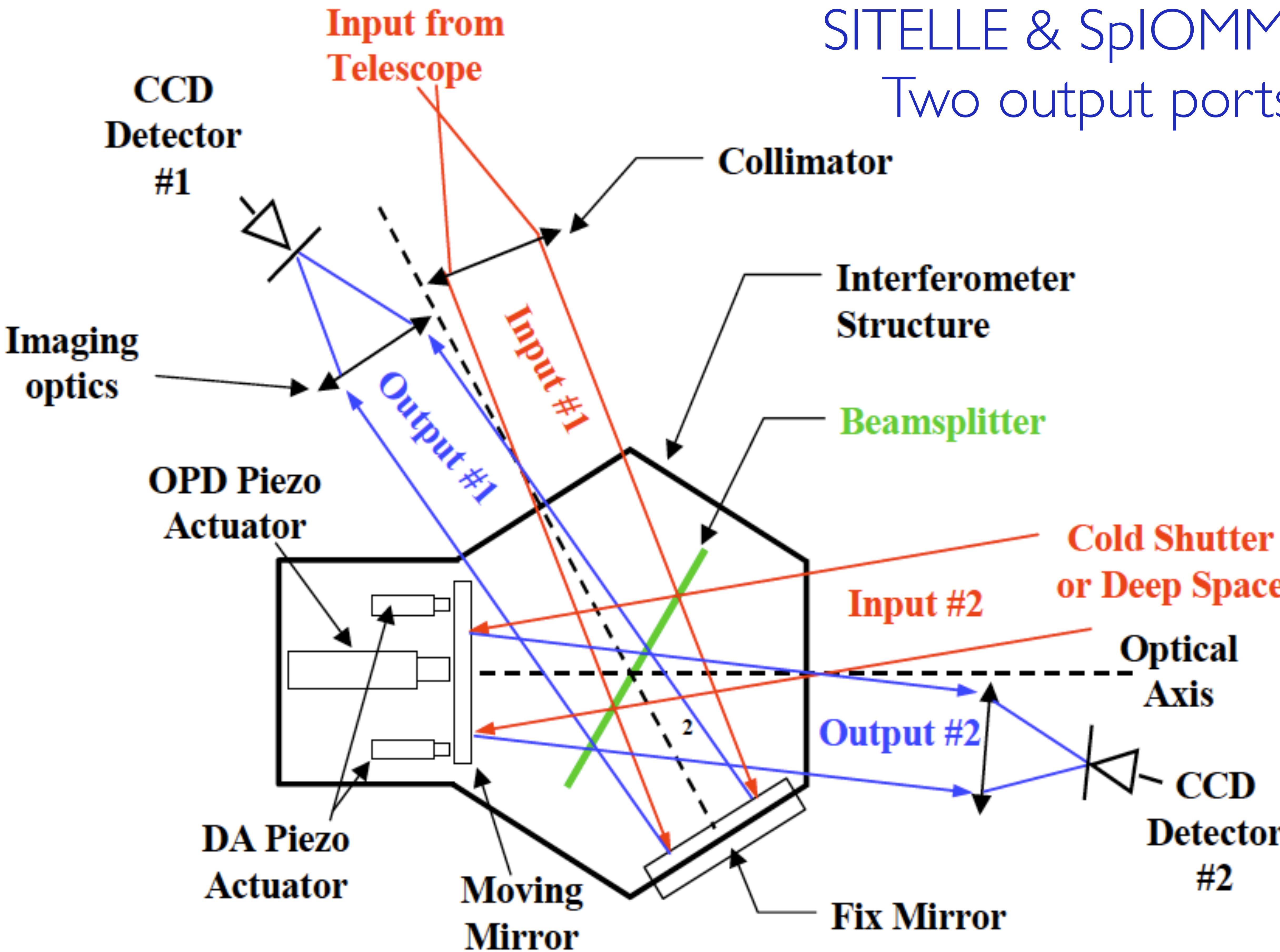


Integration sphere

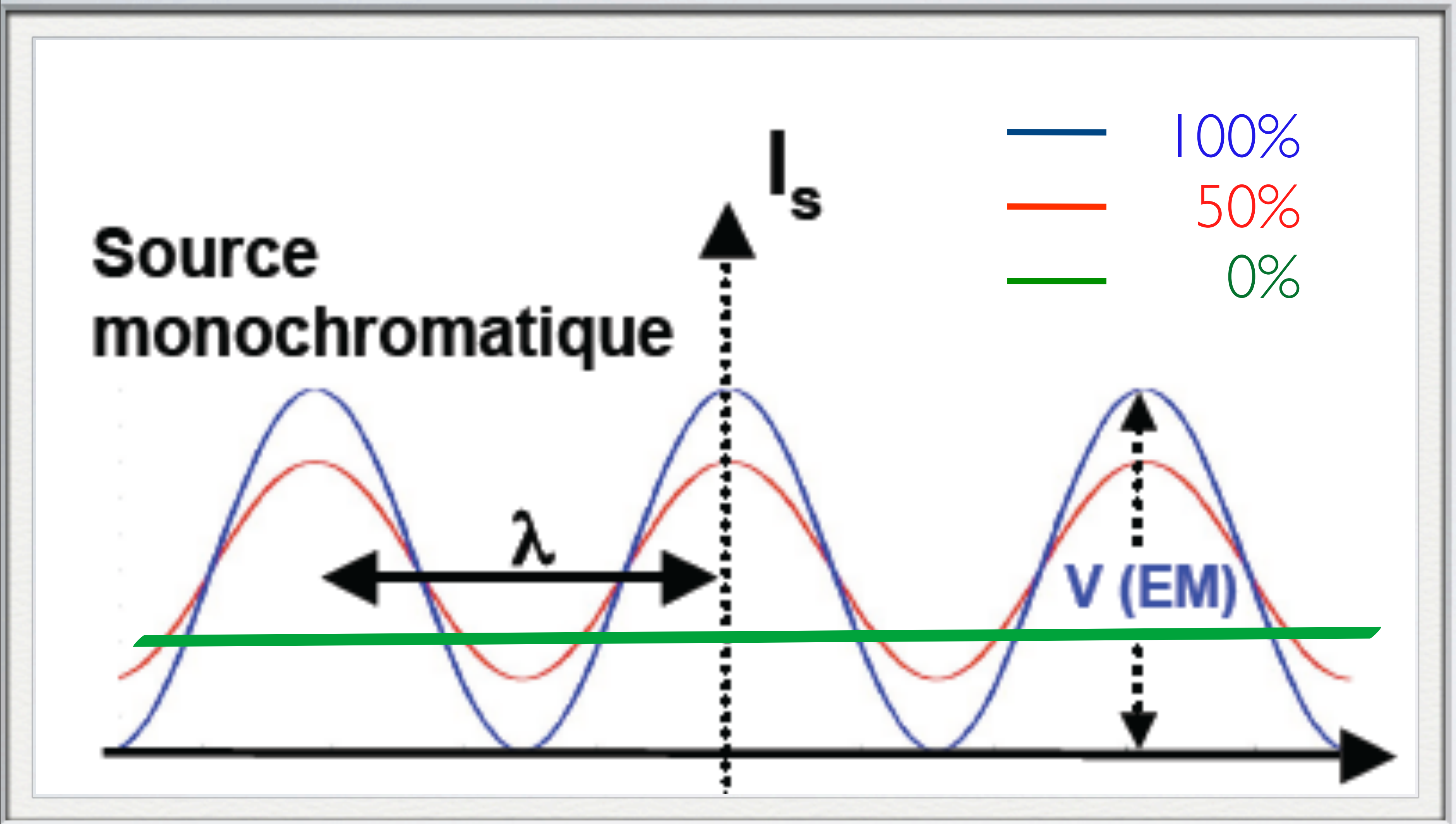
Fourier transform



SITELLE & SpIOMM: Two output ports

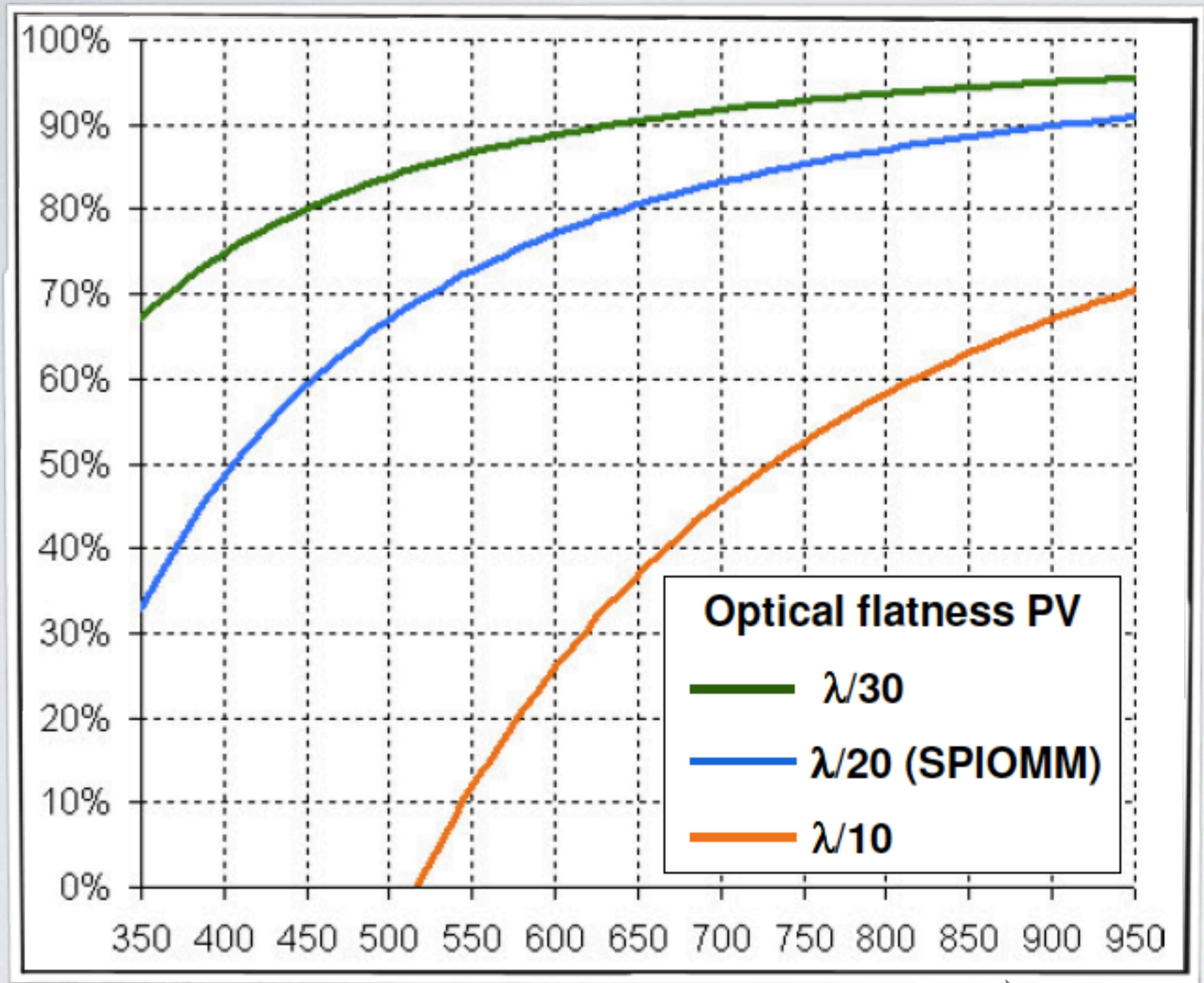


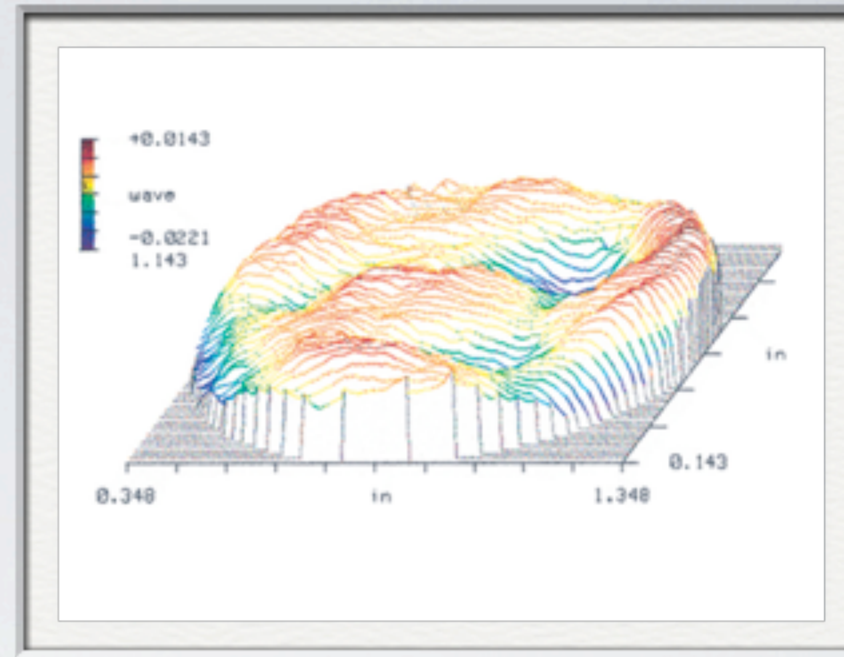
Modulation efficiency: definition



If ME = 0%, spatial information remains but no spectral information can be extracted from the cube.

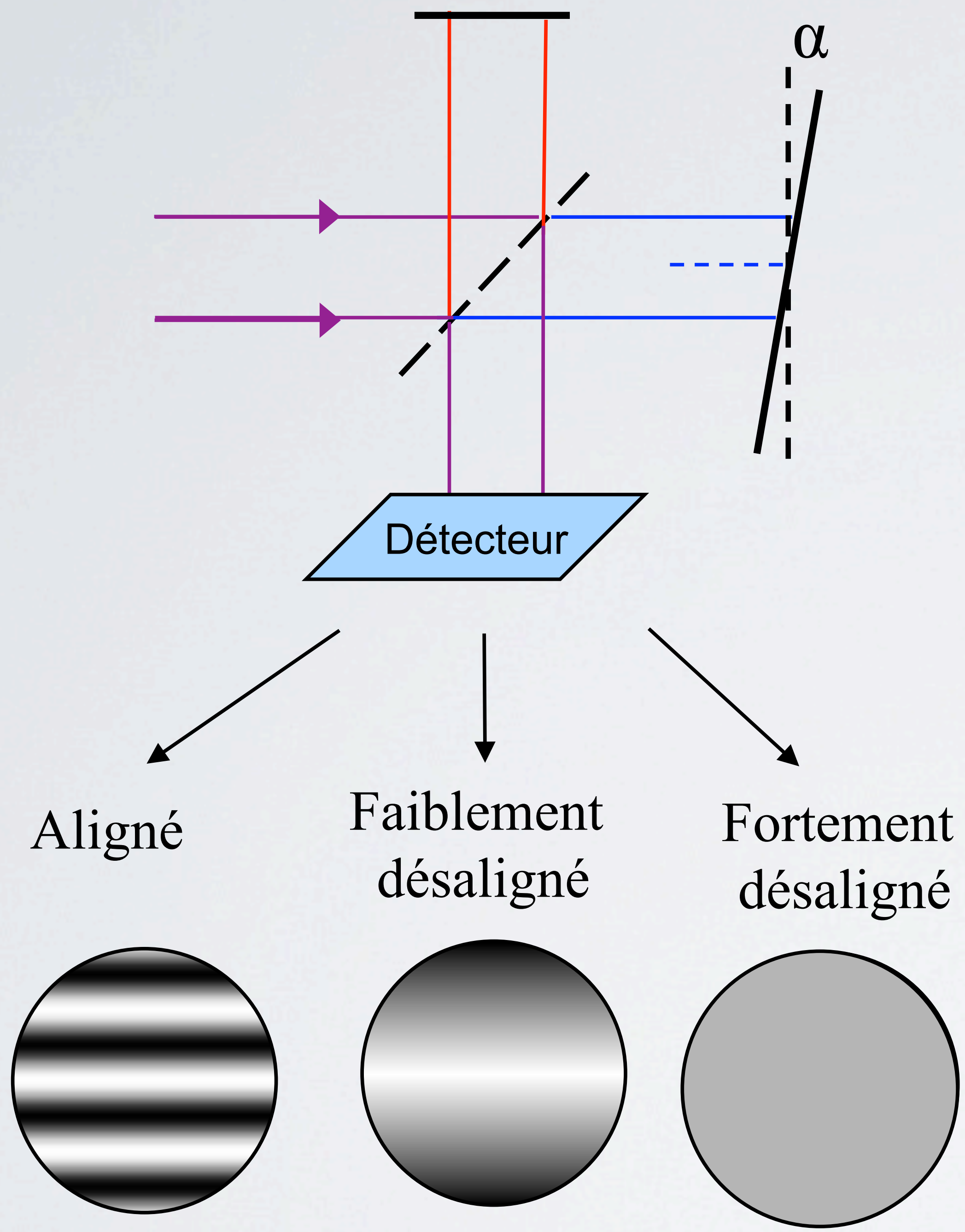
Modulation efficiency: optics quality



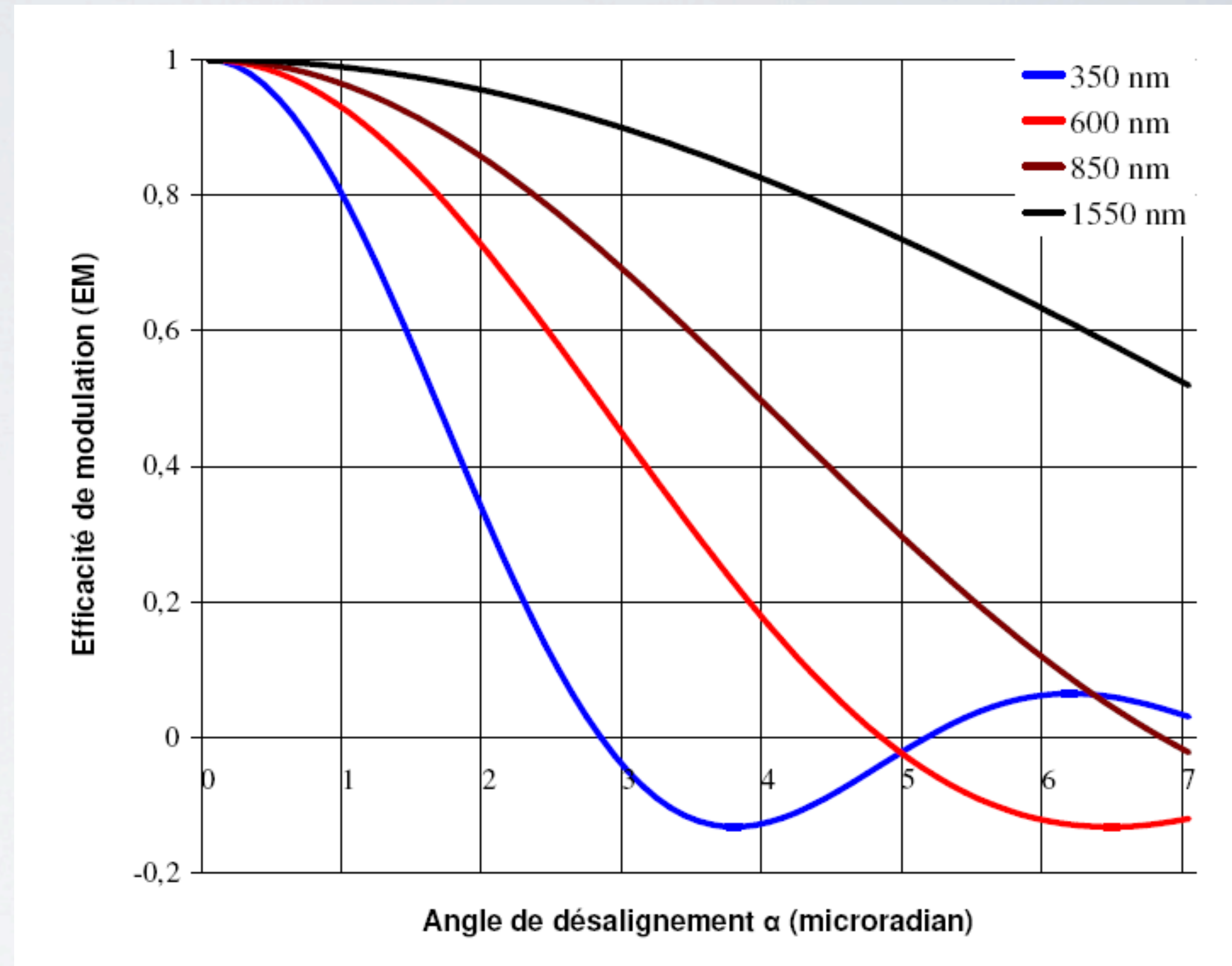


Much easier in the infrared!

Modulation efficiency: mirror alignment



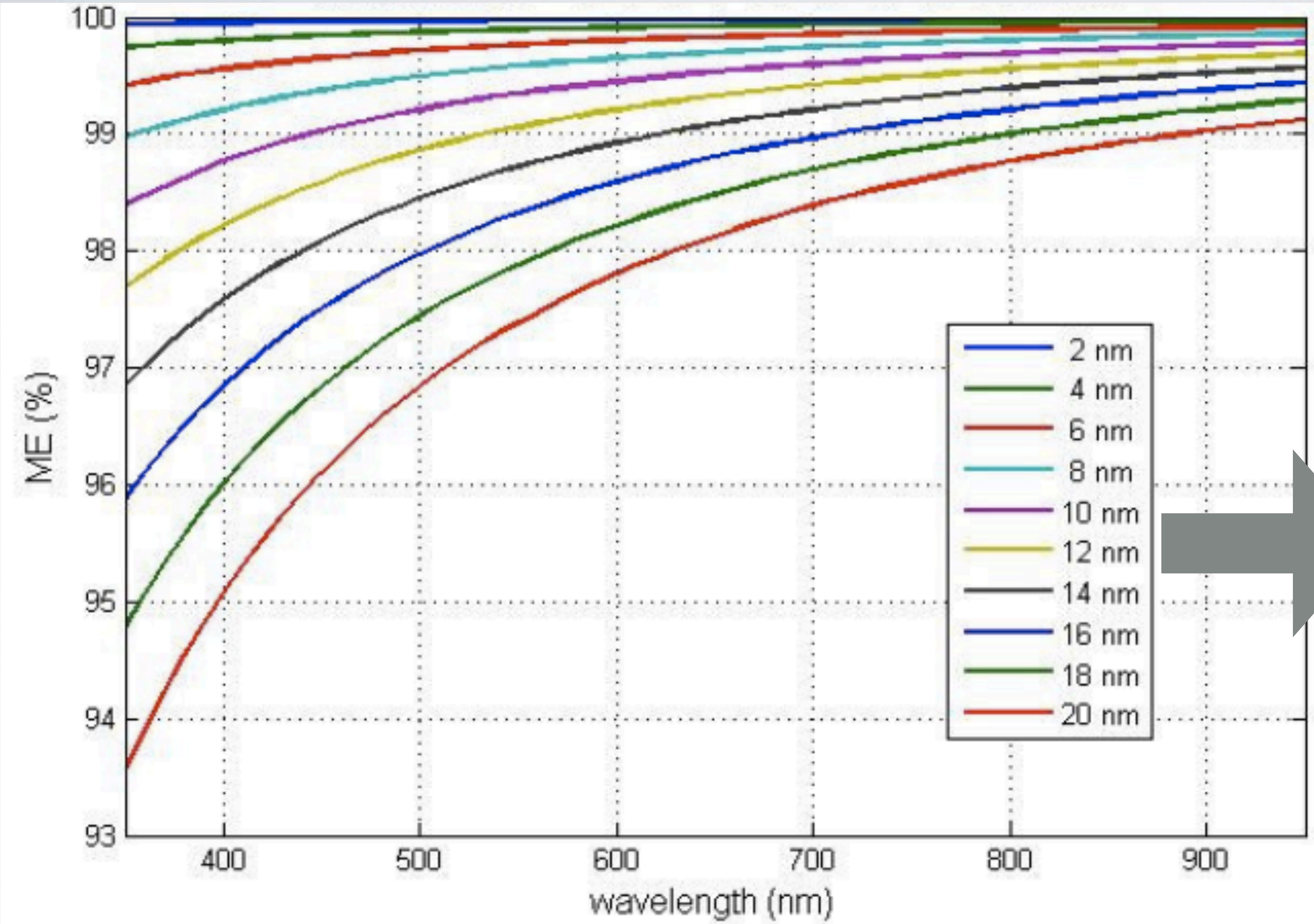
Bon contraste
des franges



$$EM = \frac{2J_1(\frac{4\pi}{\lambda}\alpha r)}{\frac{4\pi}{\lambda}\alpha r}$$

Much easier in the infrared!

Modulation efficiency: mirror jitter



Maximum mirror position jitter during an exposure

Much easier in the infrared!

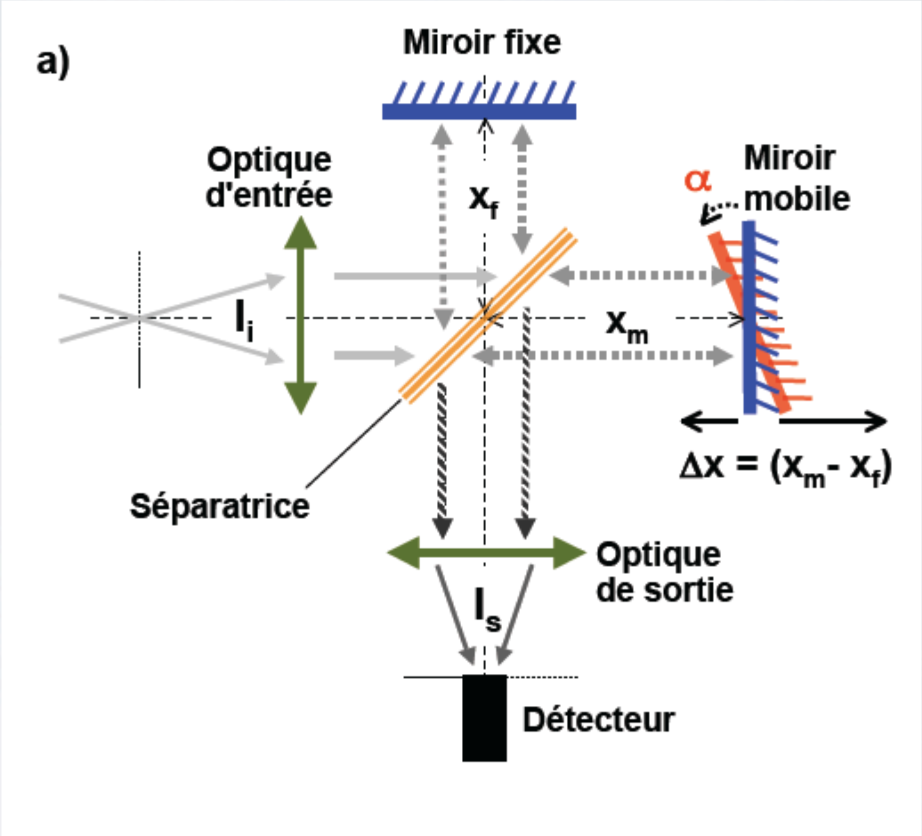
Modulation efficiency: summary

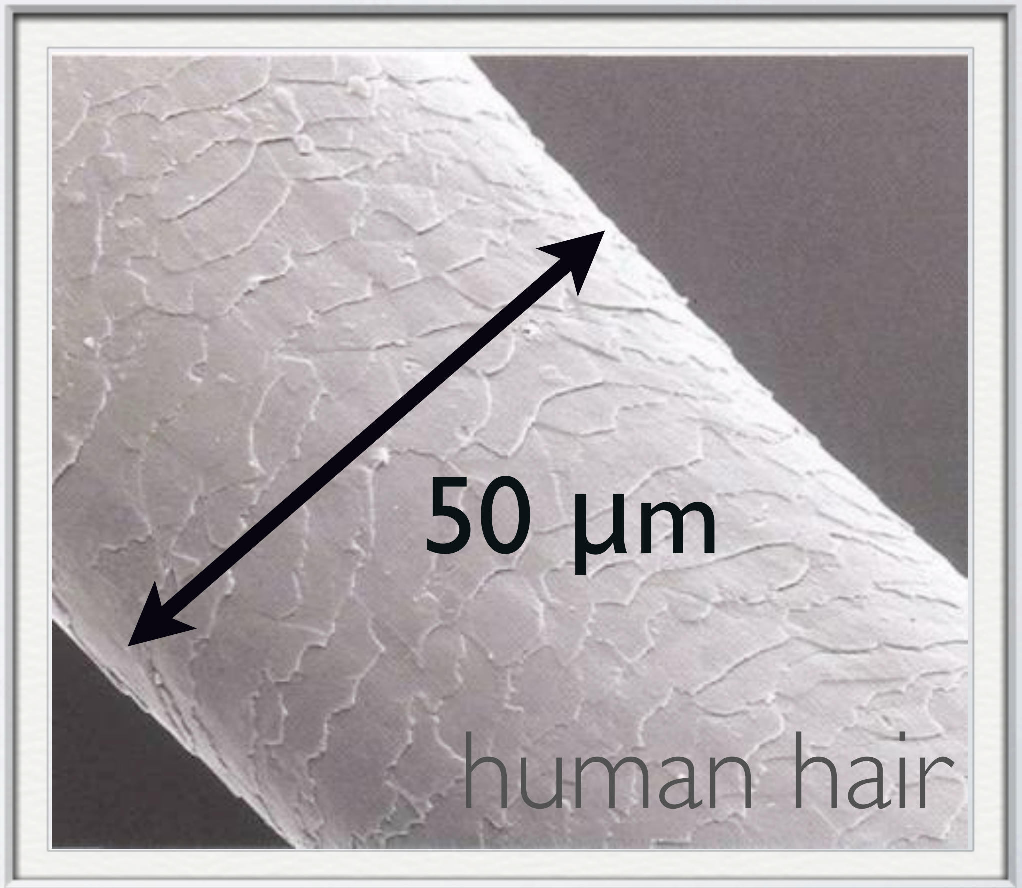
Although the principle behind an imaging FTS is simple, it is very difficult to obtain a good efficiency in the visible & near UV:

* Excellent **surface quality** for the optical components (~ 10 nm);

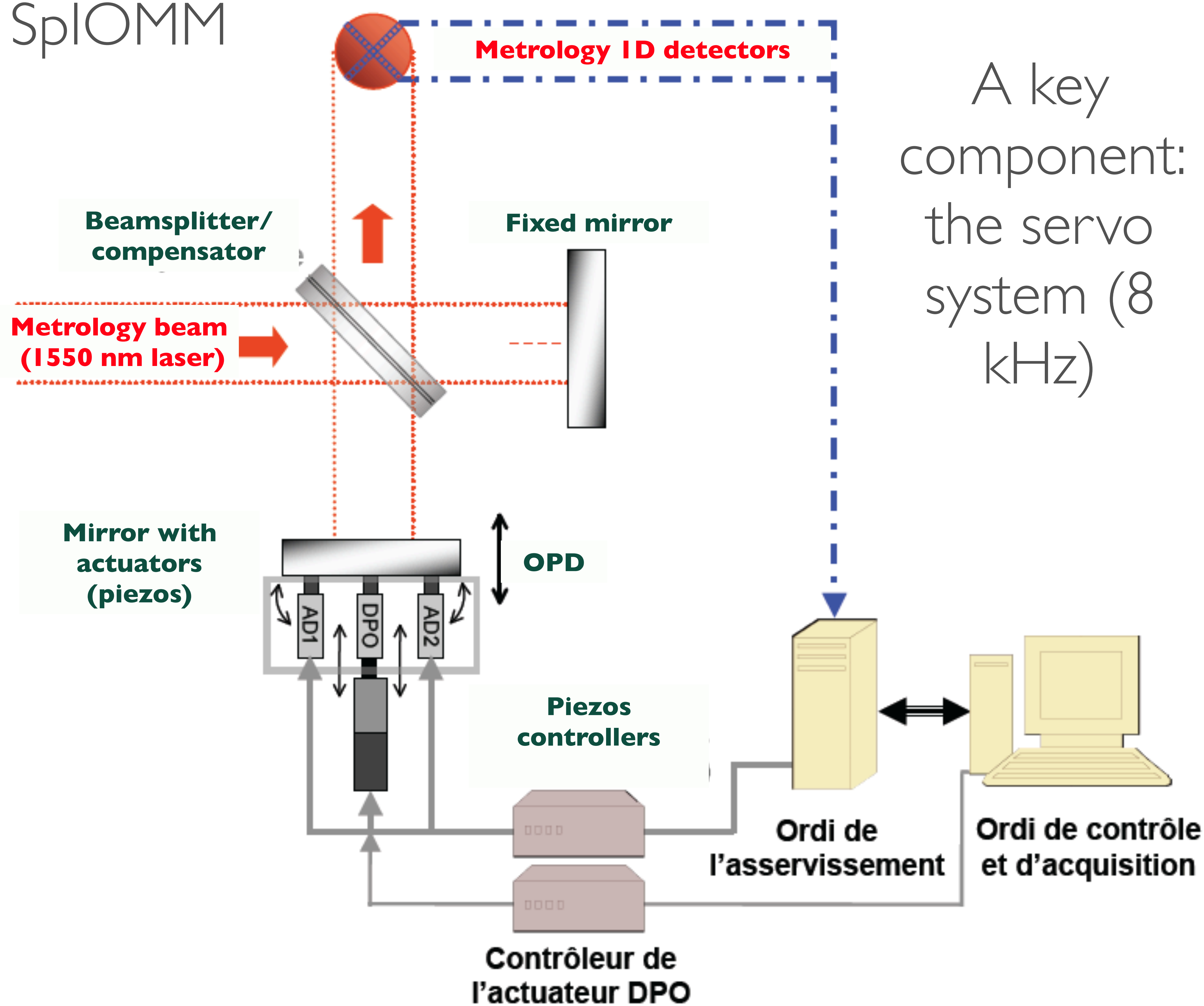
* Precise and **stable mirror alignment** (0.2 µrad = 0.04'');

* Maintain their **relative distance**, during an exposure, to better than ~ 10 nm (1/5000th the diameter of a human hair.



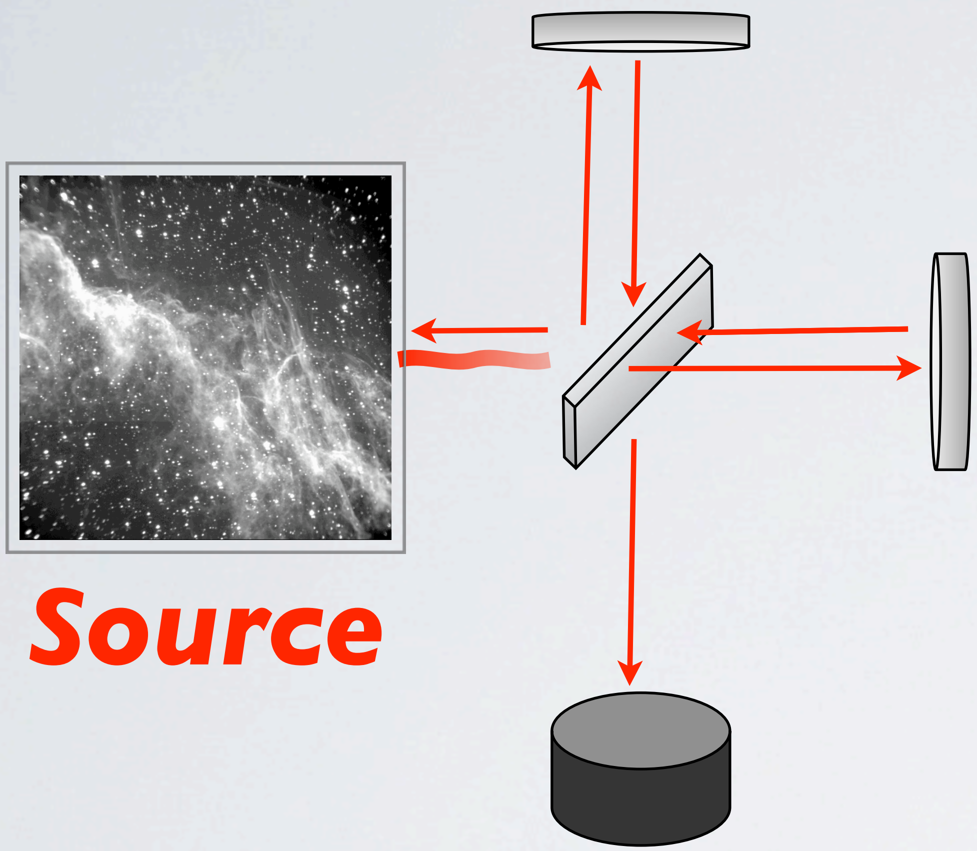


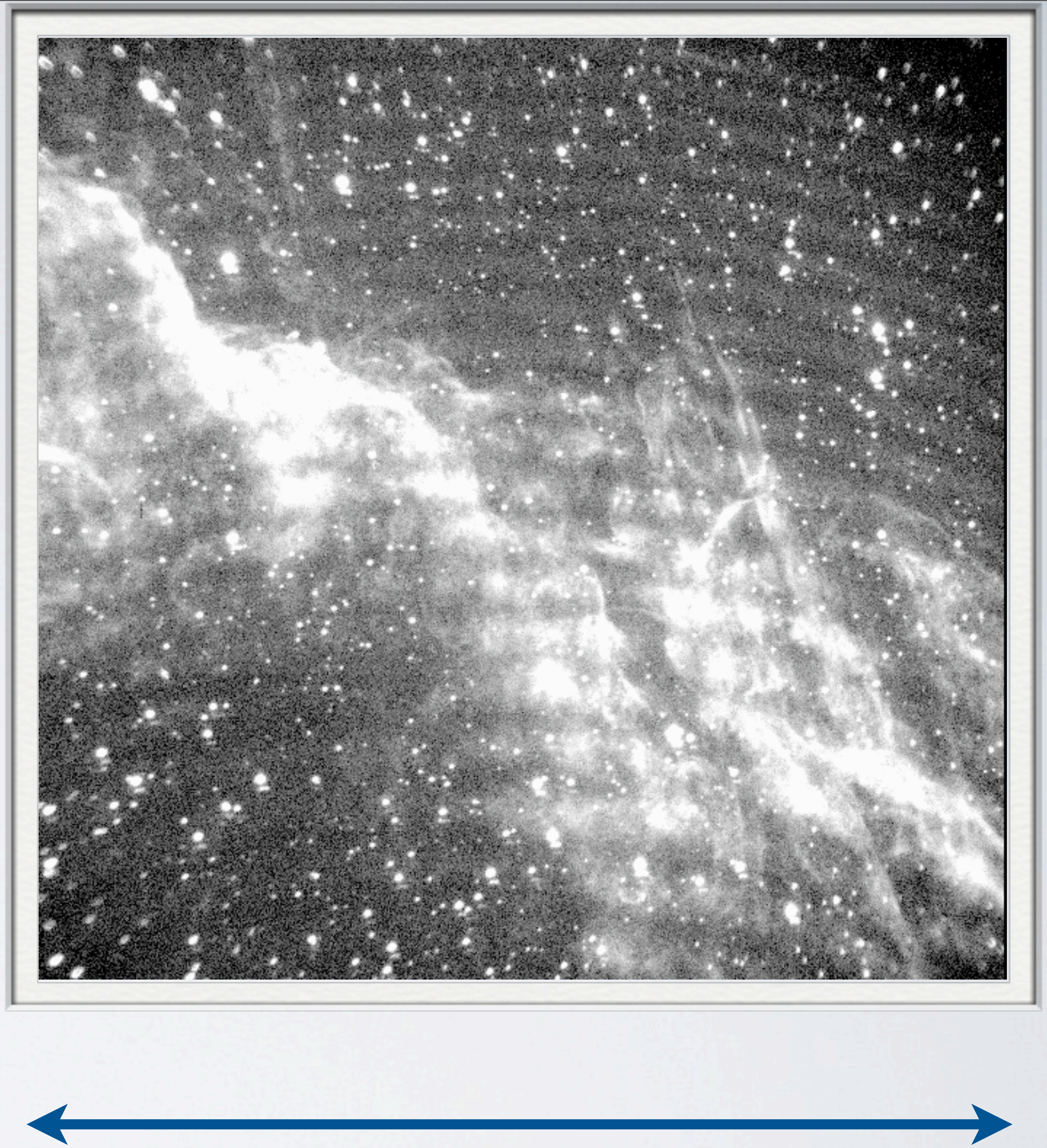
SpIOMM



A key component: the servo system (8 kHz)

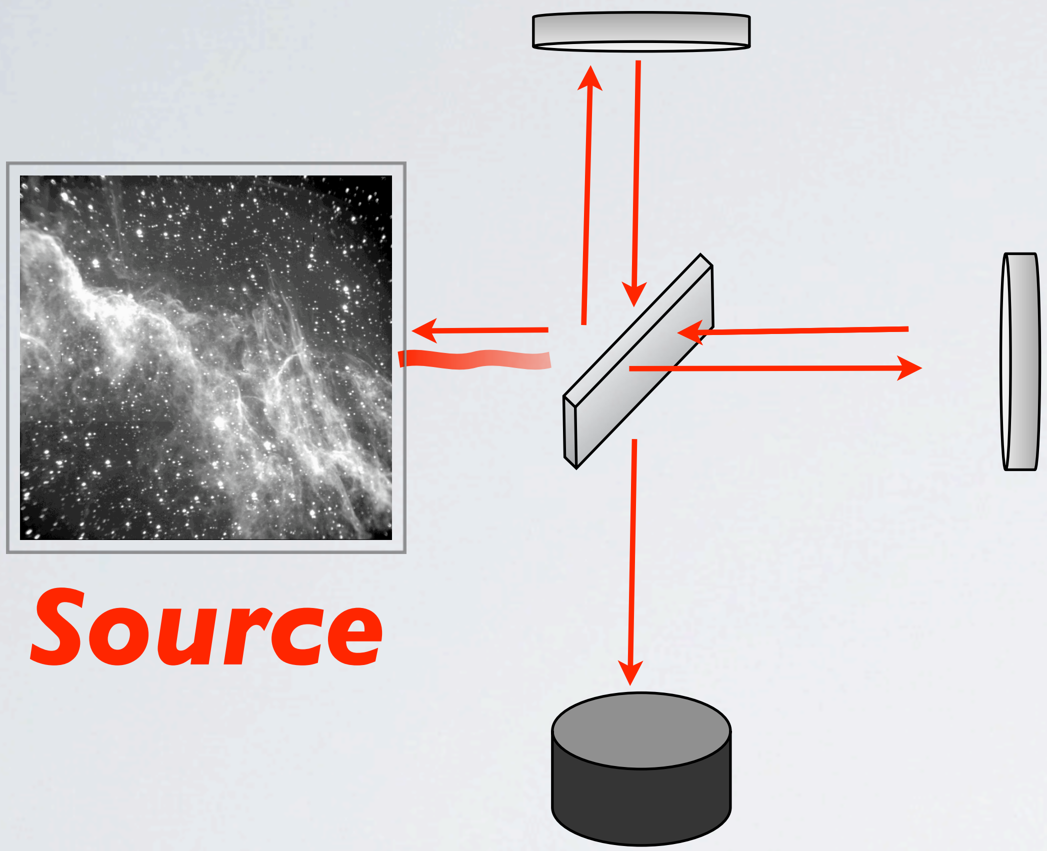
Michelson + imaging optics + CCD = Imaging FTS

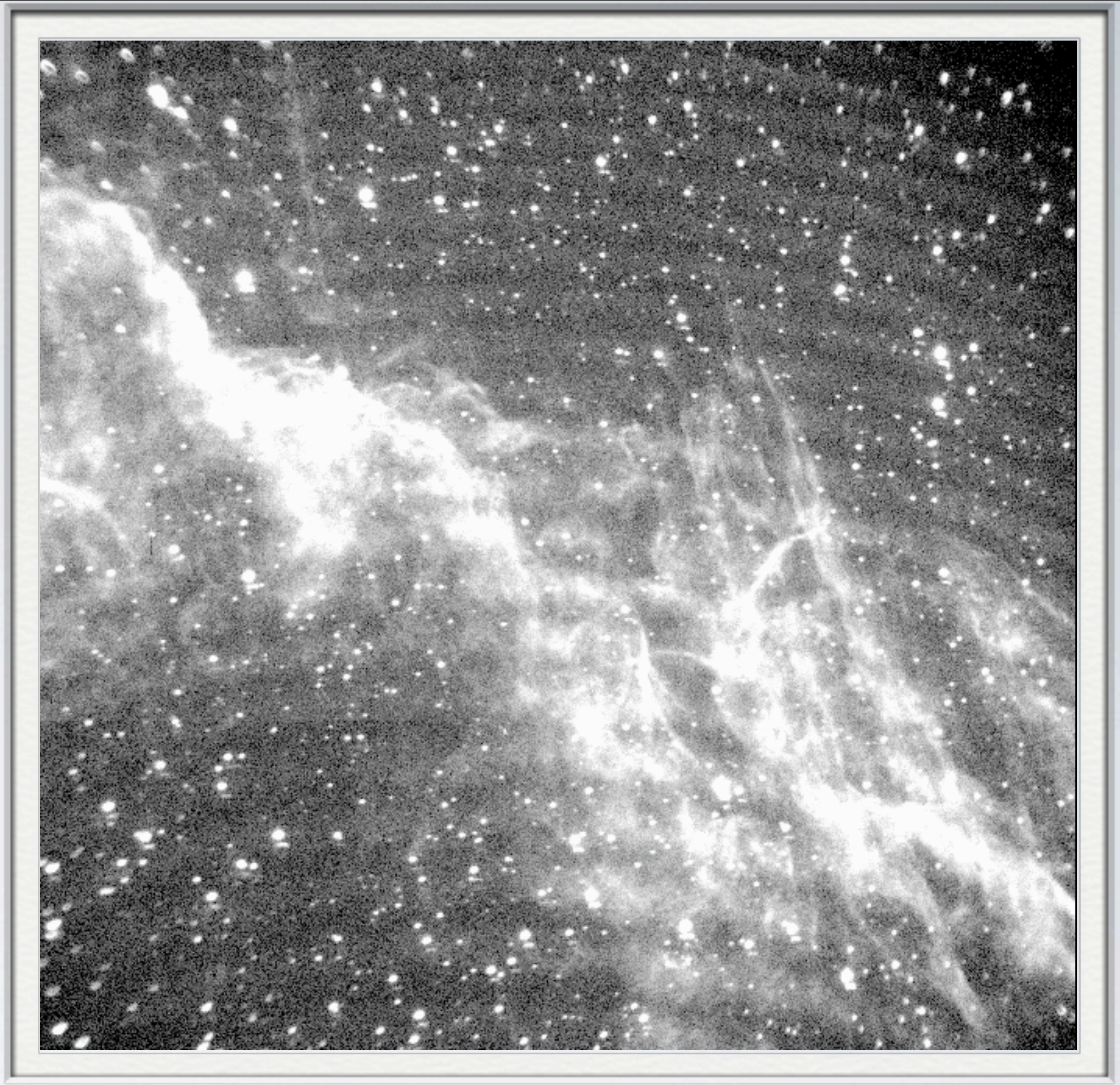




The spectral range is NOT scanned. The entire waveband is observed at every step.

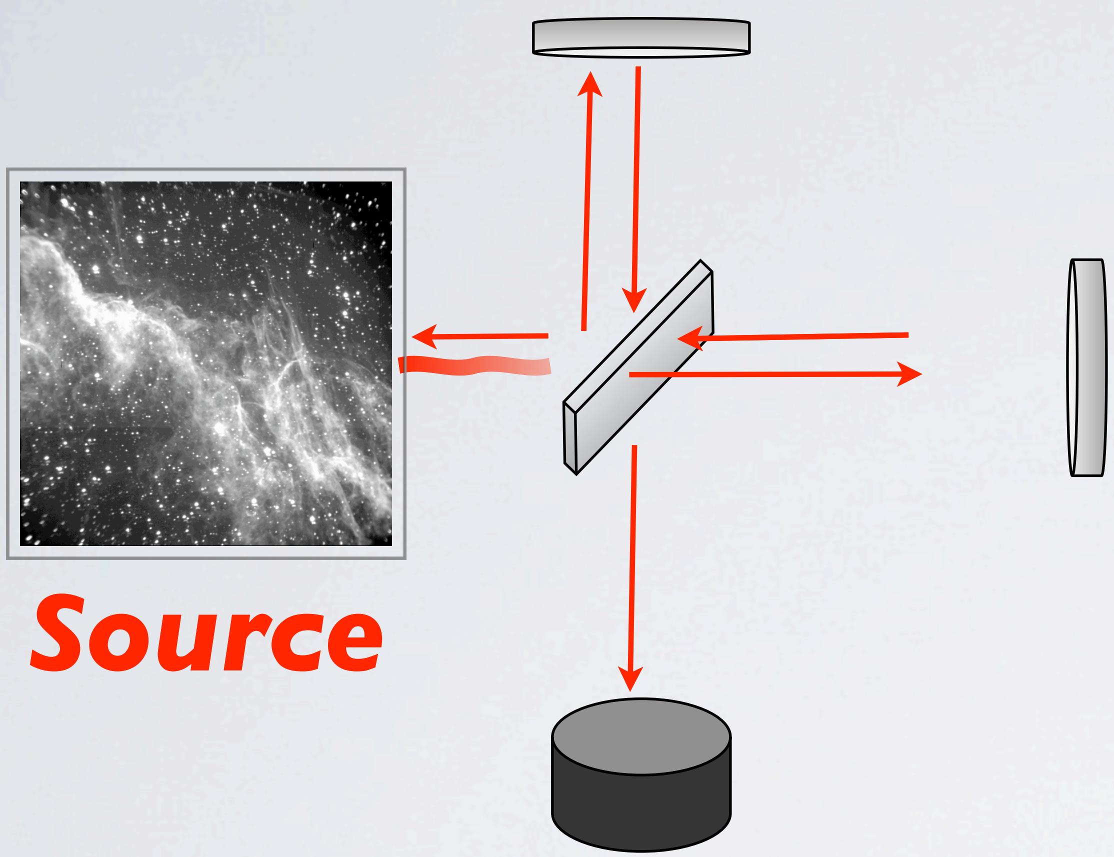
Michelson + imaging optics + CCD = Imaging FTS

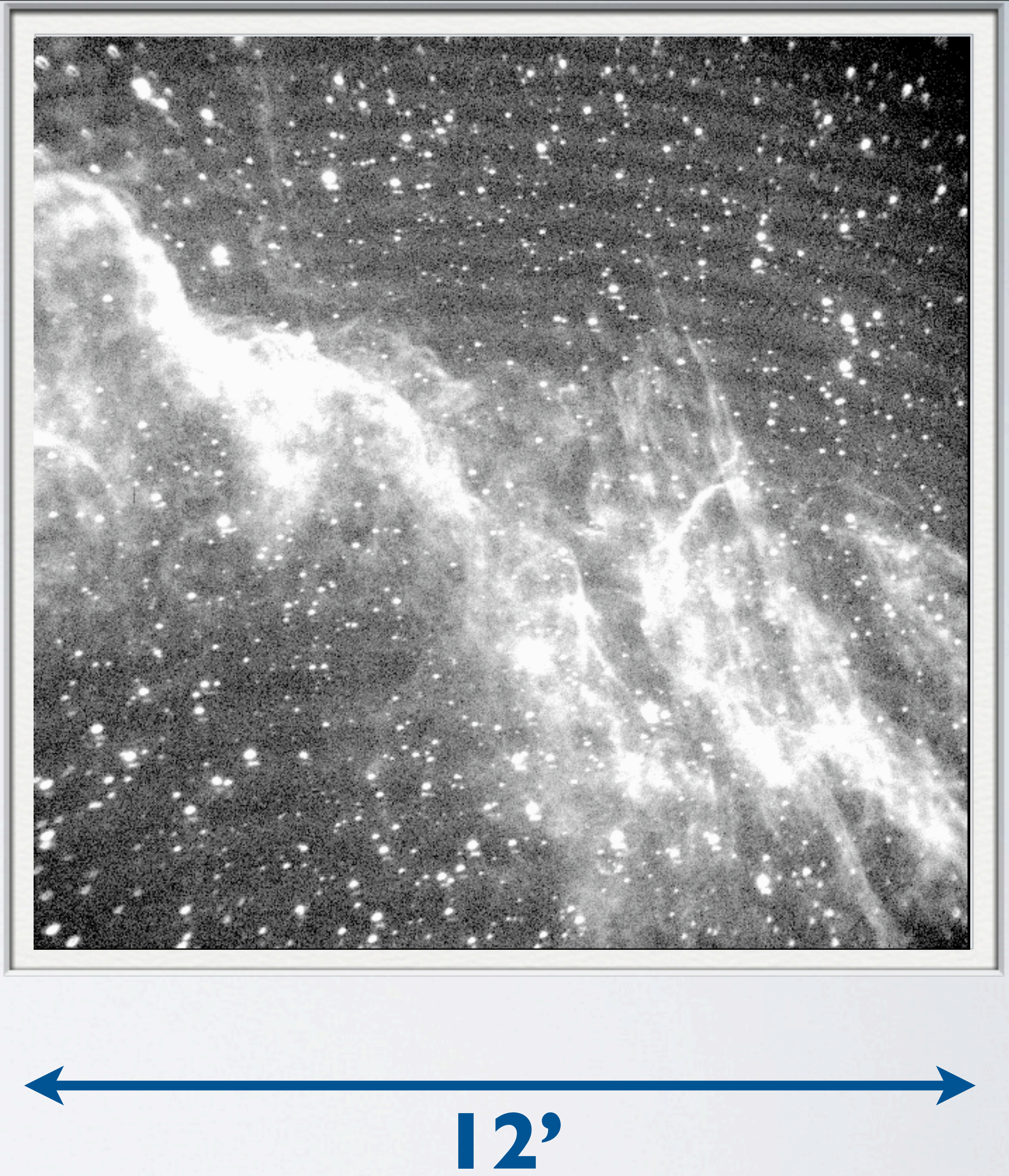




The spectral range is NOT scanned. The entire waveband is observed at every step.

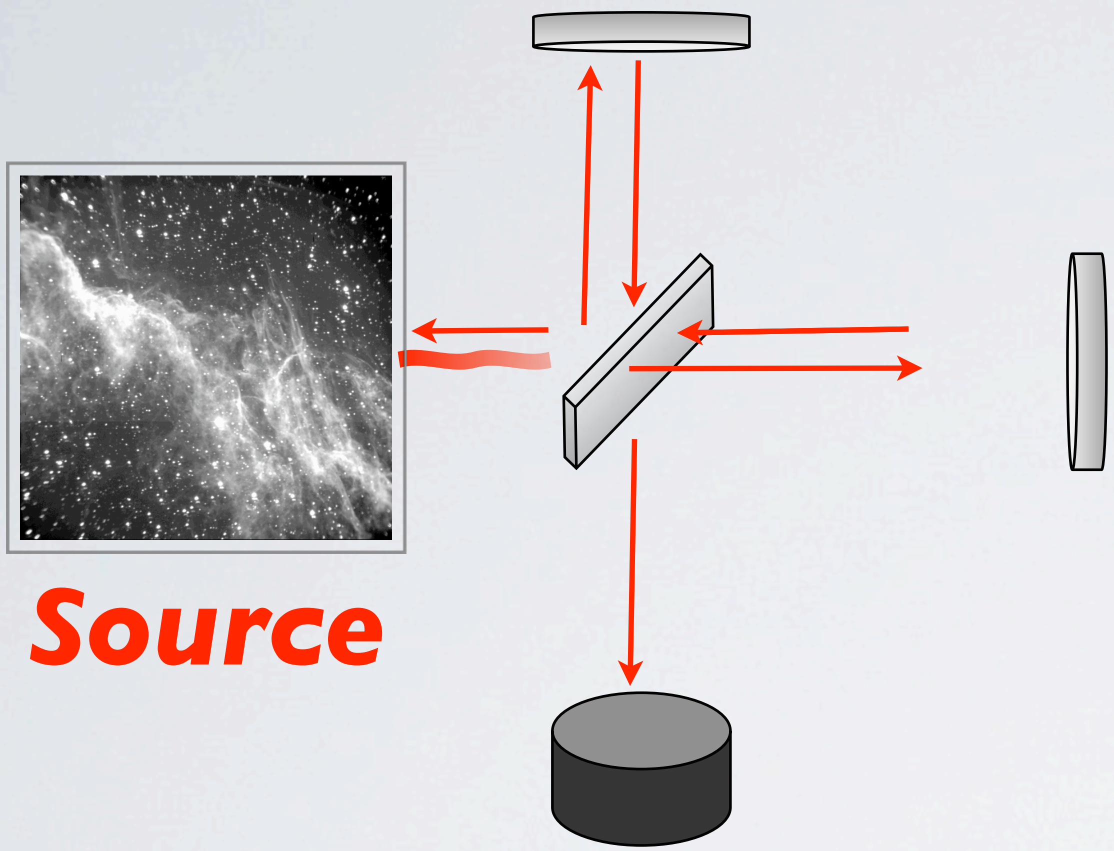
Michelson + imaging optics + CCD = Imaging FTS





The spectral range is NOT scanned. The entire waveband is observed at every step.

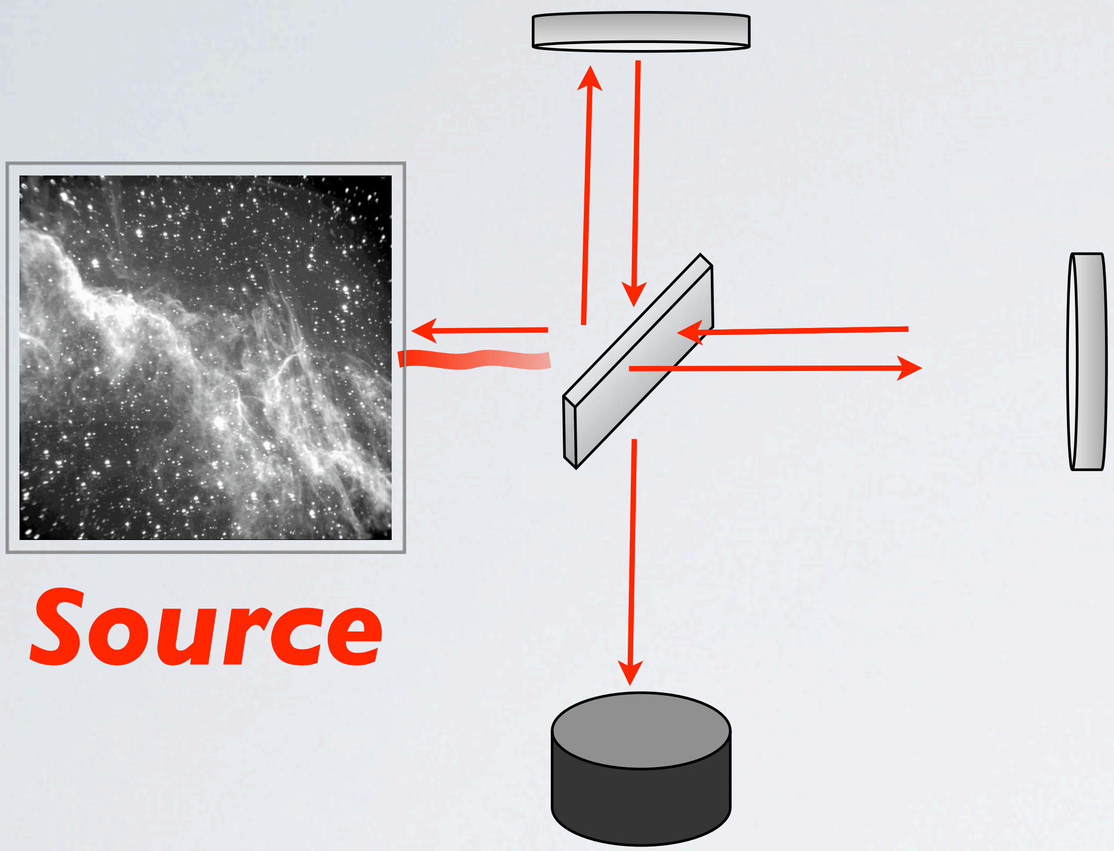
Michelson + imaging optics + CCD = Imaging FTS

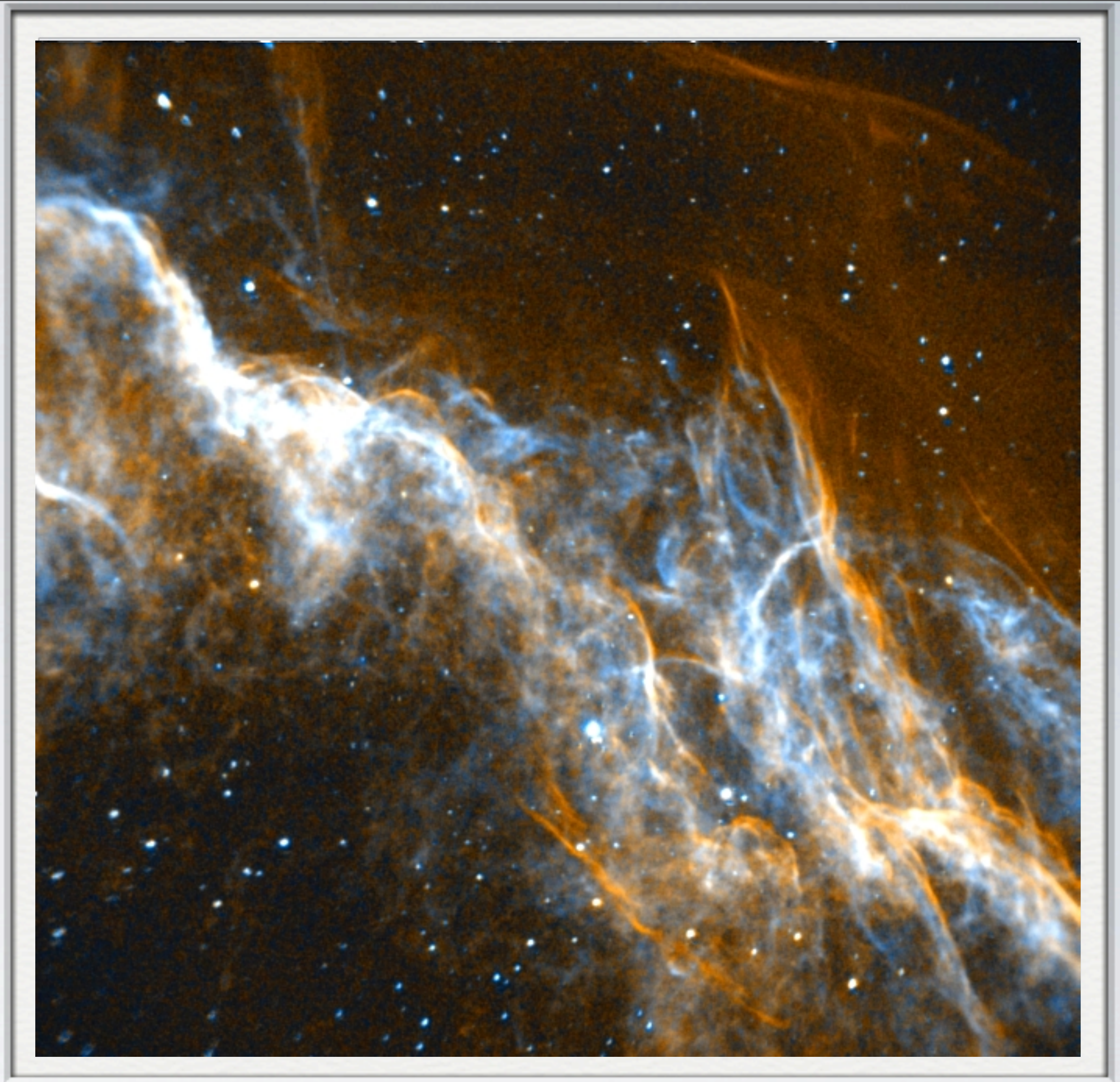


12’

The spectral range is NOT scanned. The entire waveband is observed at every step.

Michelson + imaging optics + CCD = Imaging FTS



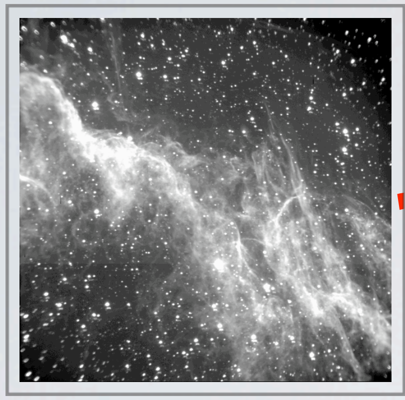


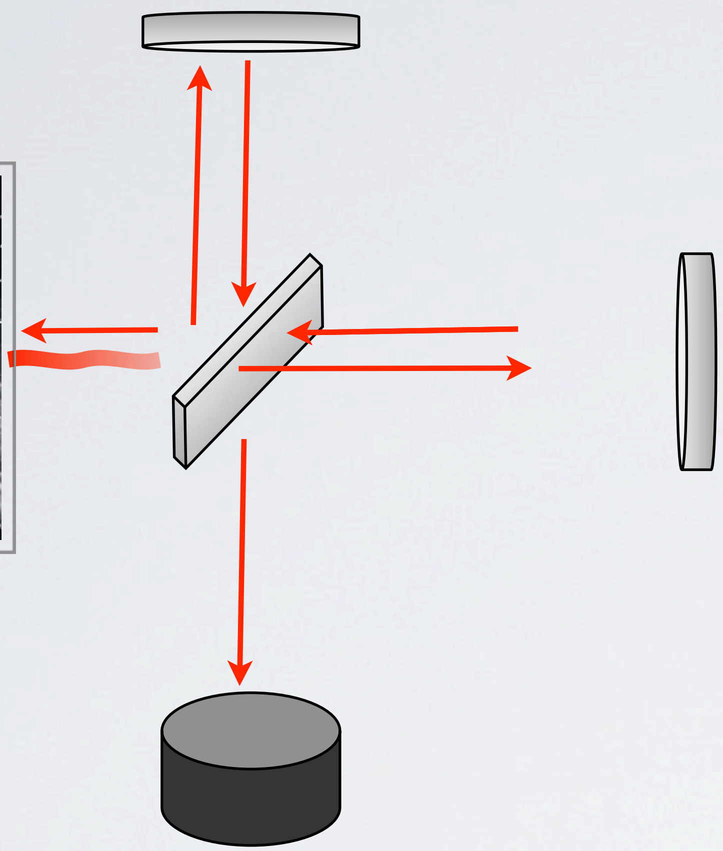
Cygnus Loop SNR Hα & [NII]

12’

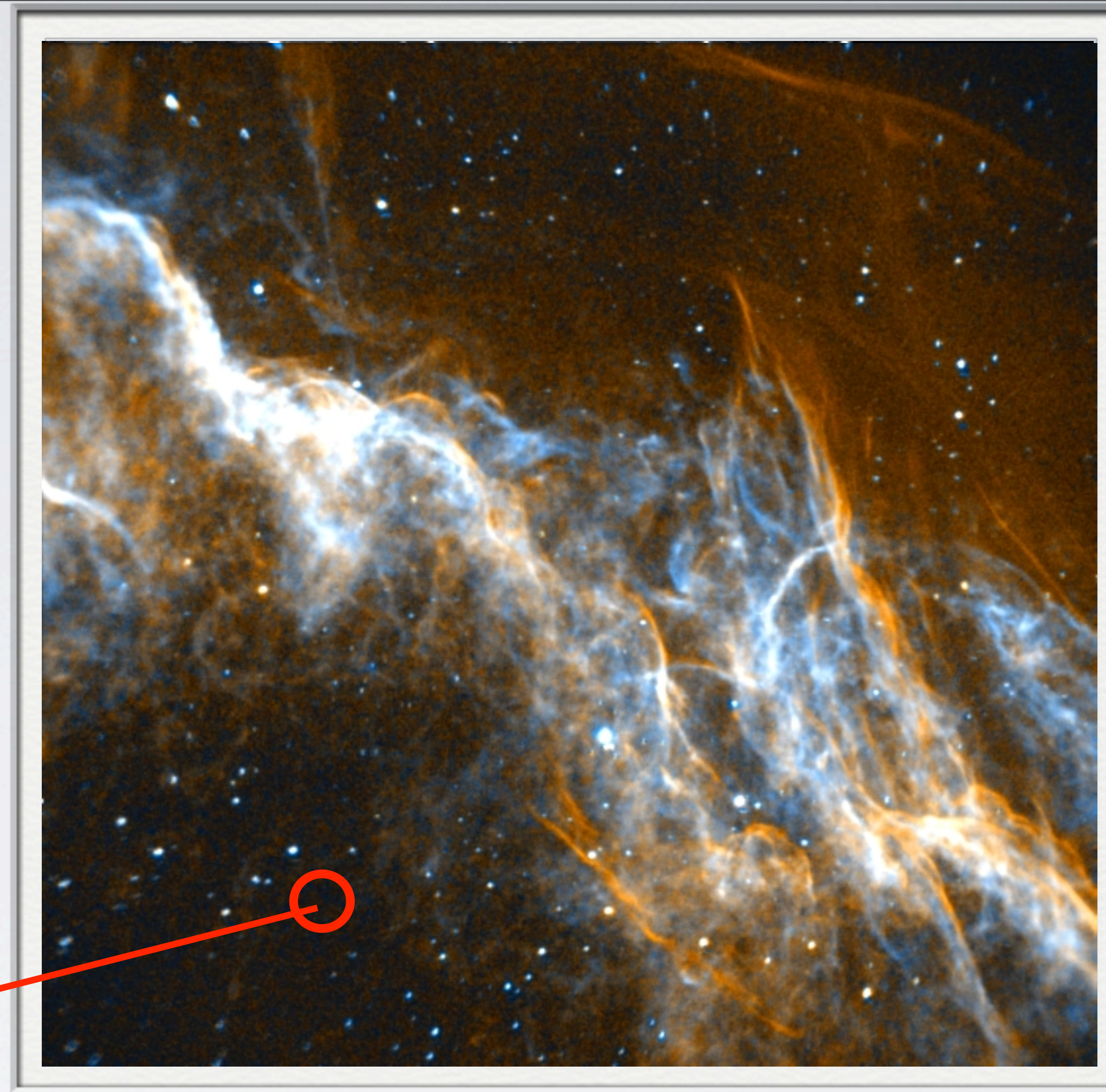
The spectral range is NOT scanned. The entire waveband is observed at every step.

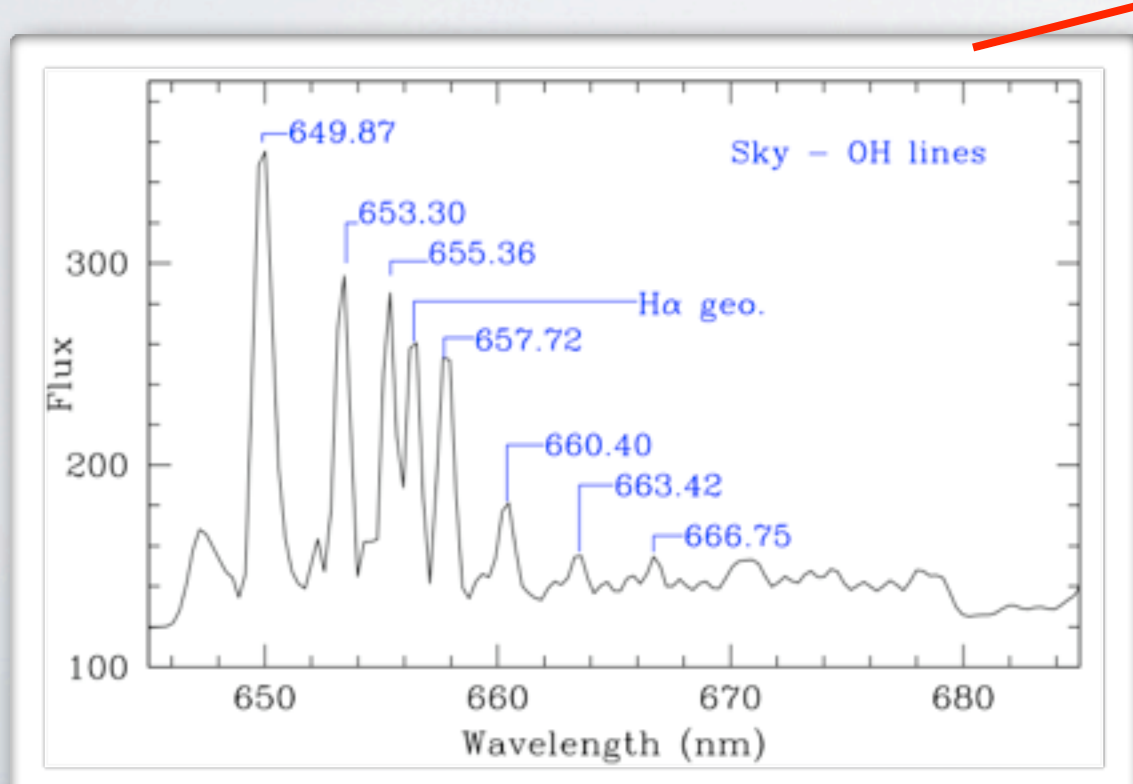
Michelson + imaging optics + CCD = Imaging FTS





Source



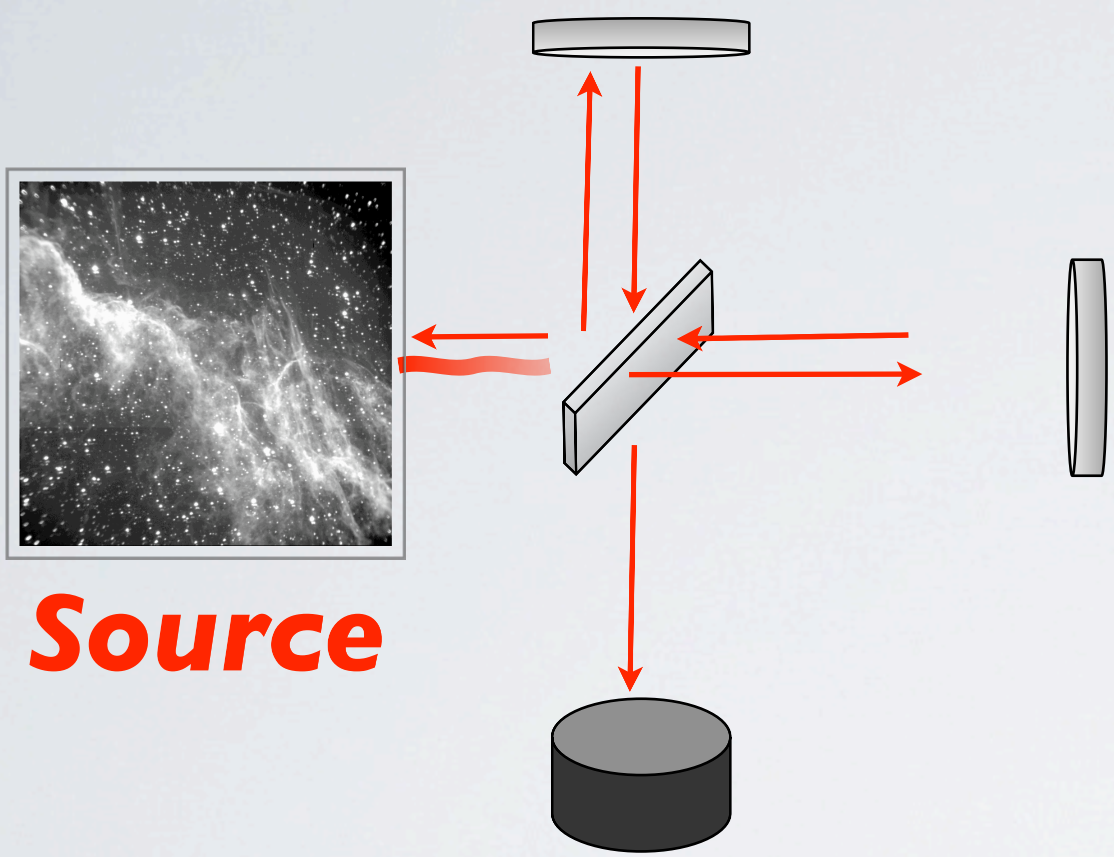


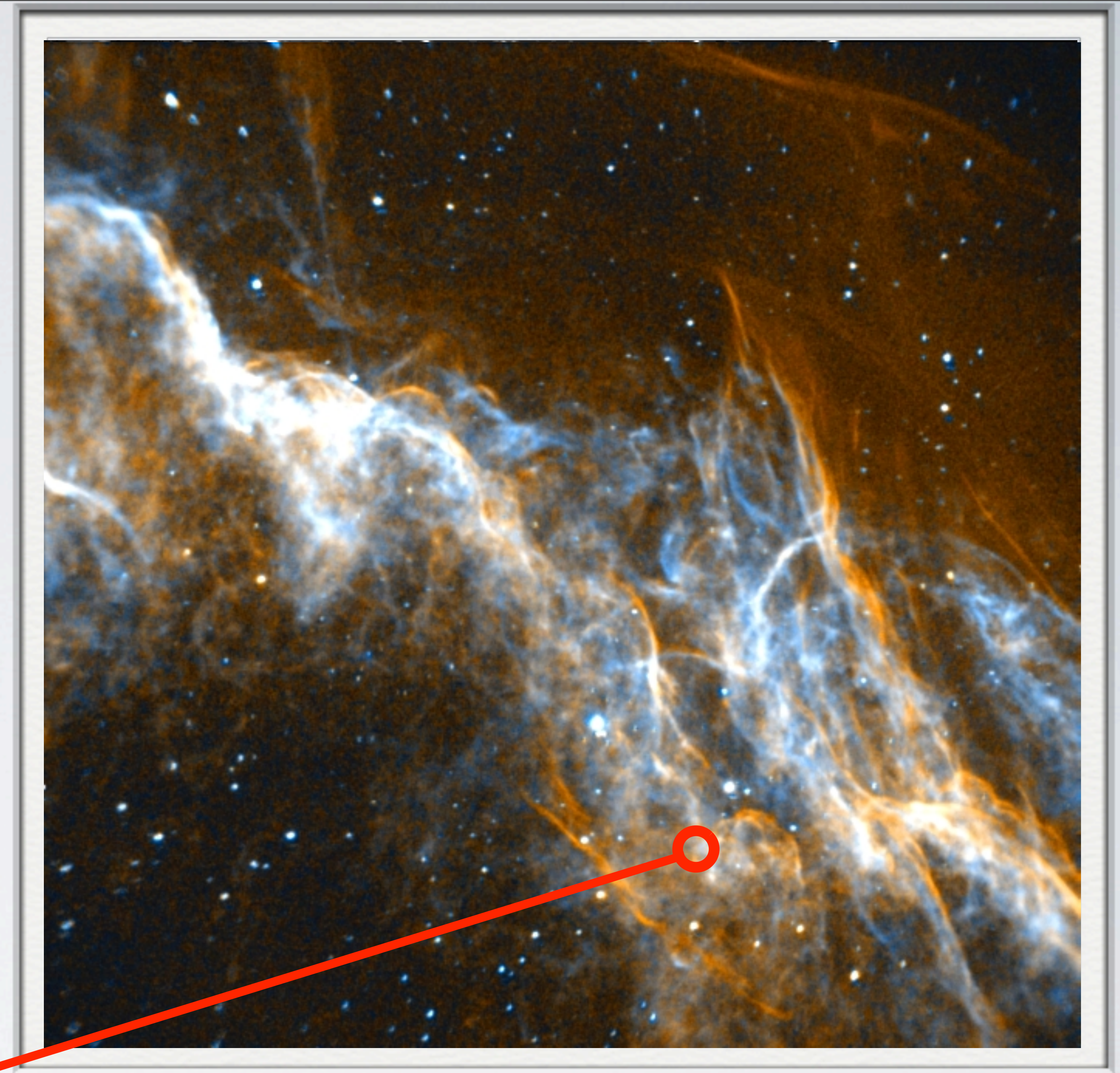
Cygnus Loop SNR Hα & [NII]

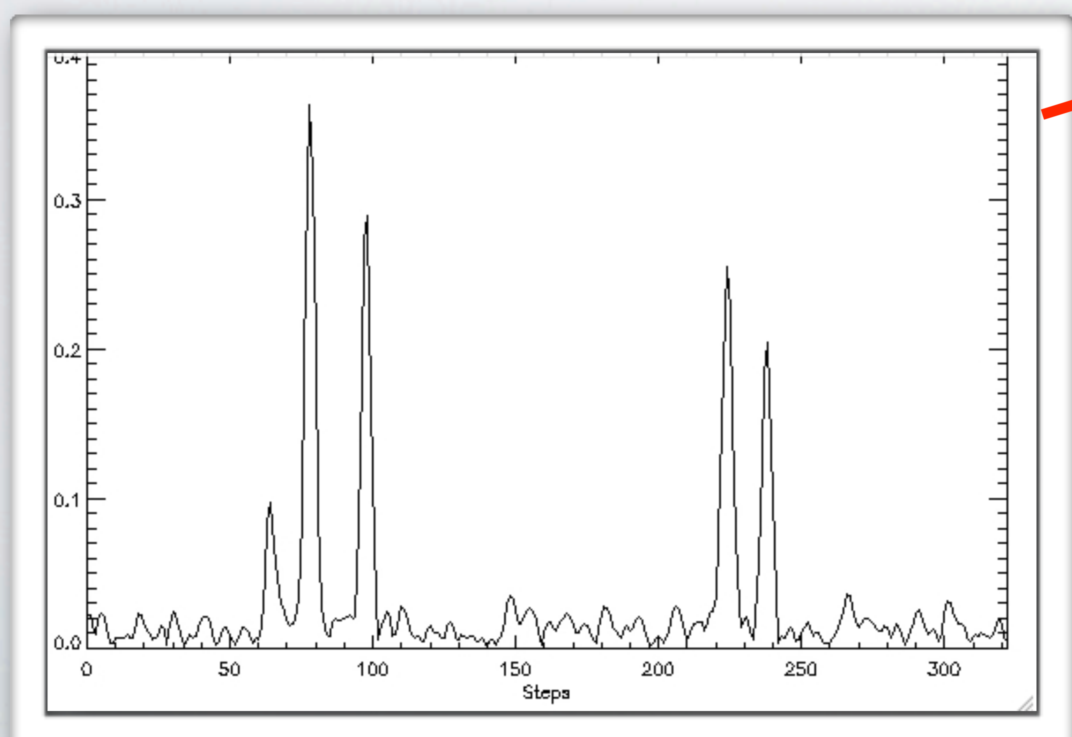
12’

The spectral range is NOT scanned. The entire waveband is observed at every step.

Michelson + imaging optics + CCD = Imaging FTS



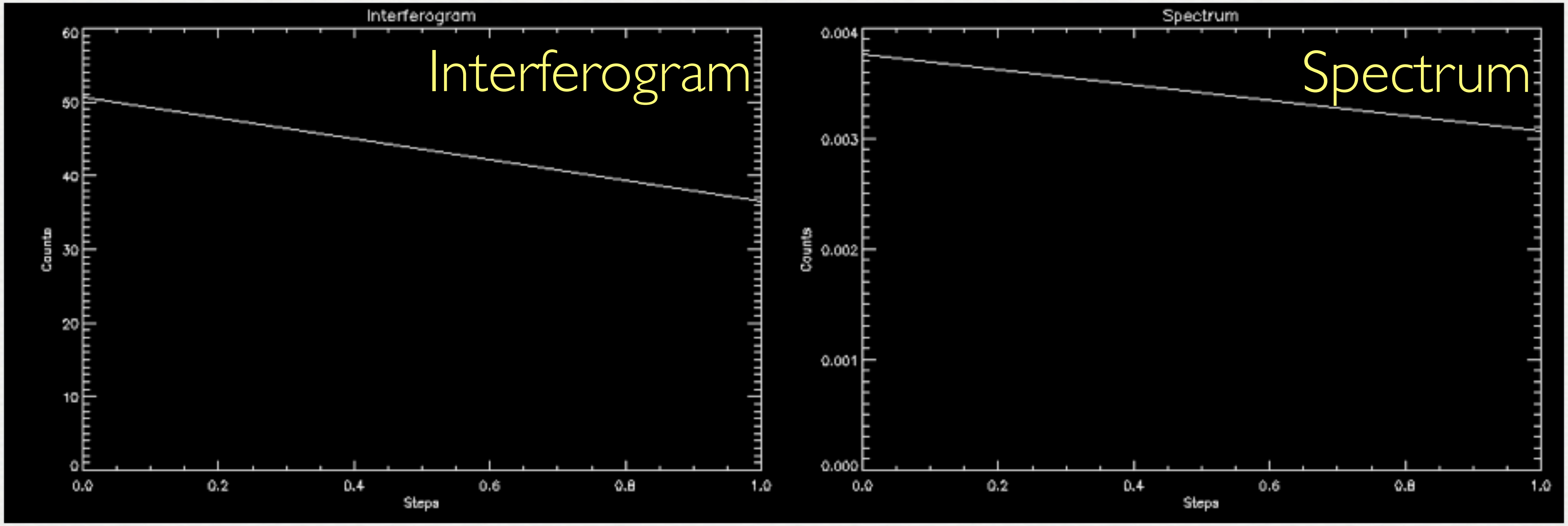




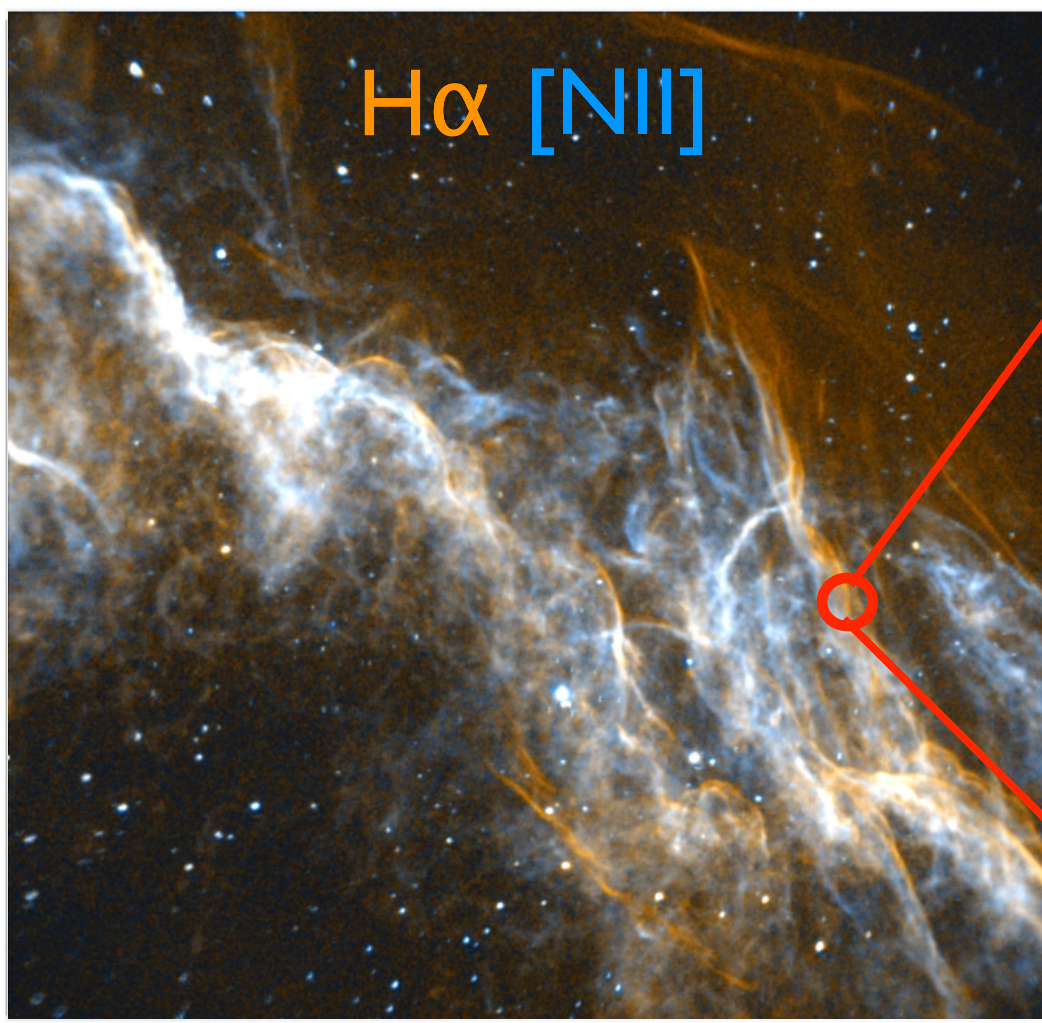
Cygnus Loop SNR Hα & [NII]

12’

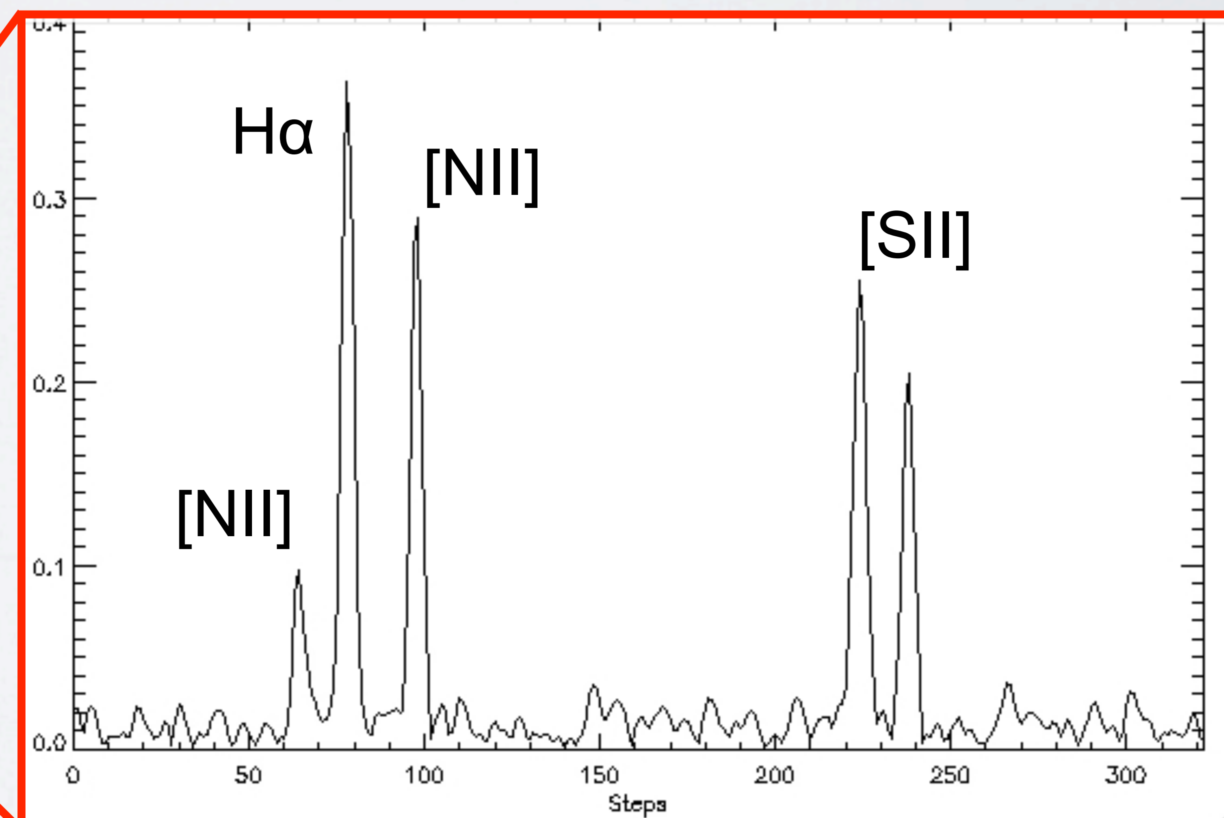
The spectral range is NOT scanned. The entire waveband is observed at every step.



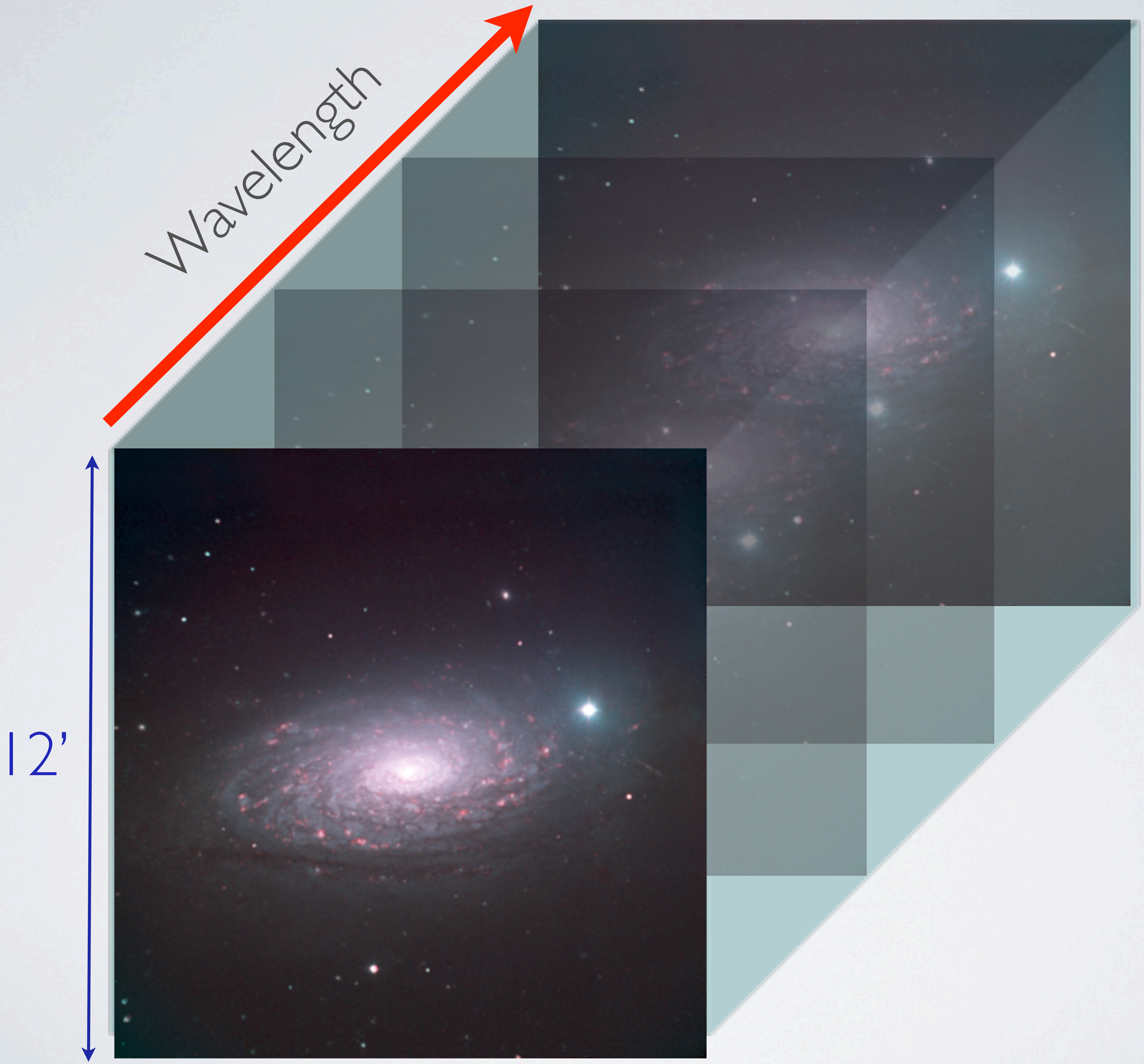
Interferogram
Spectrum
Interferogram
Spectrum
Counts
Steps

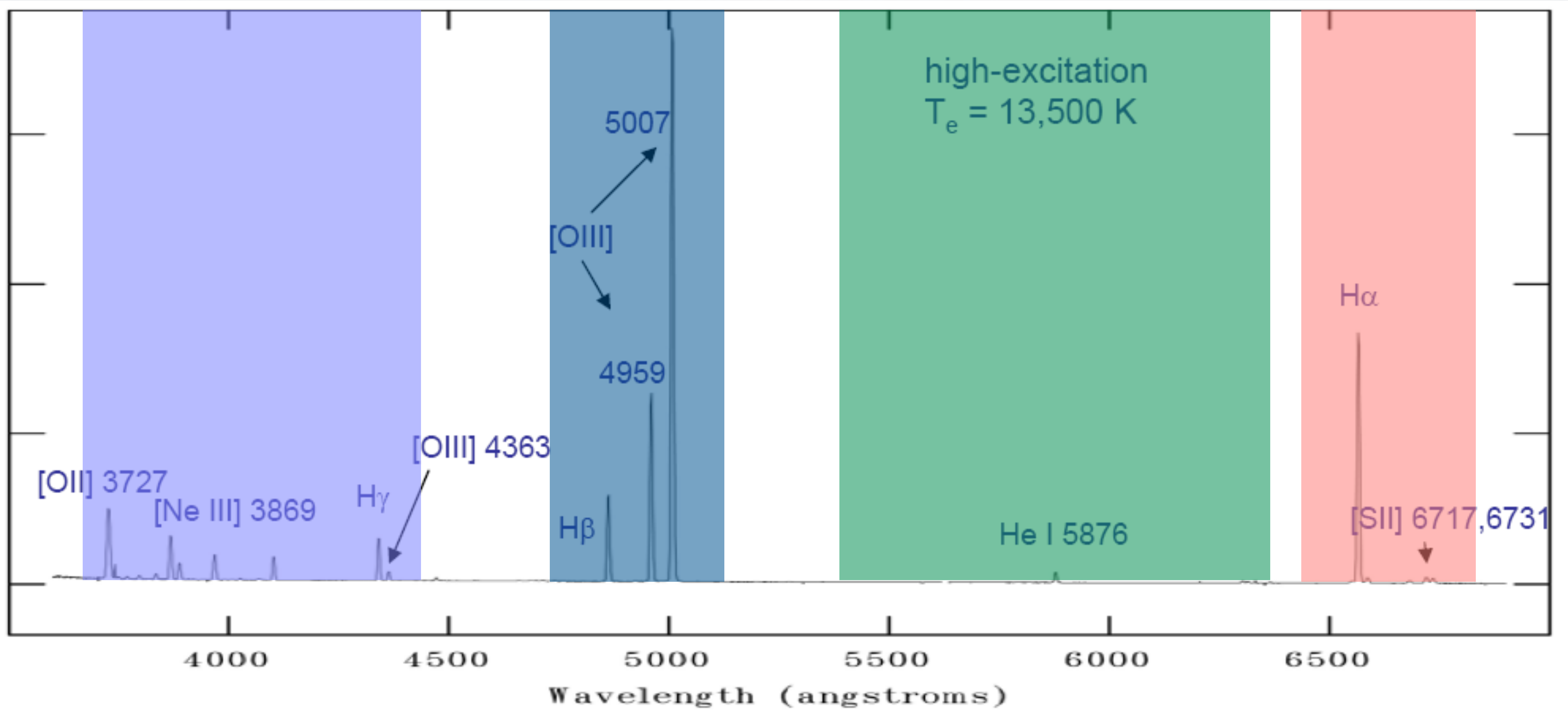


Hα [NII]



Hα
[NII]
[NII]
[SII]
Steps

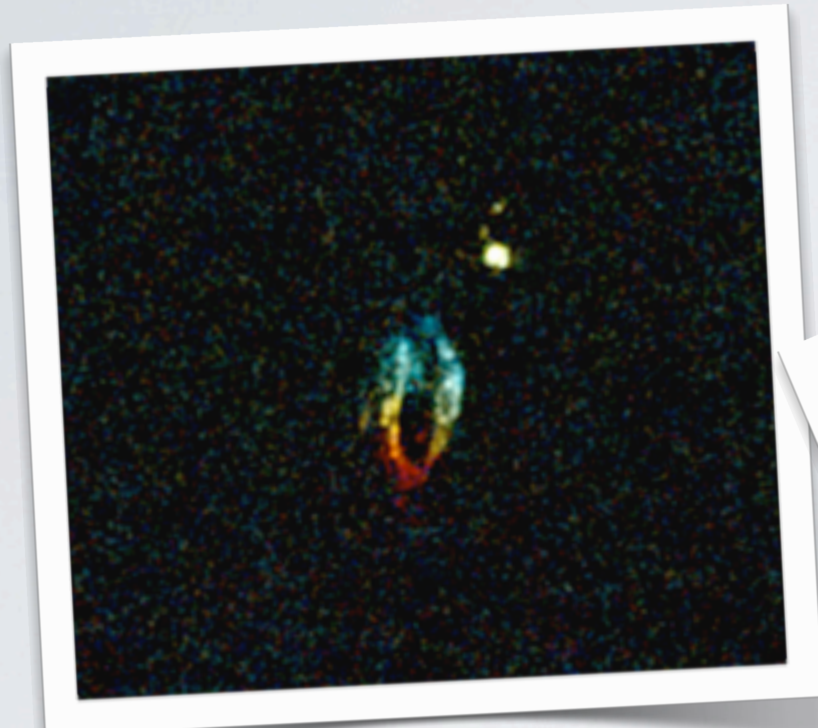

Wavelength
12'

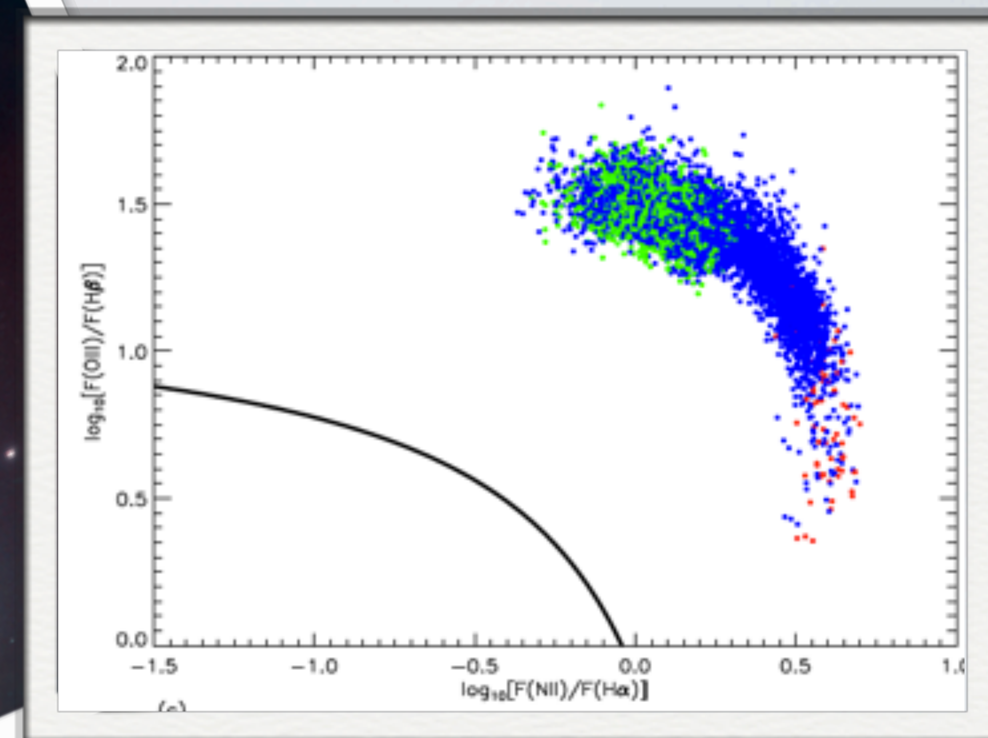


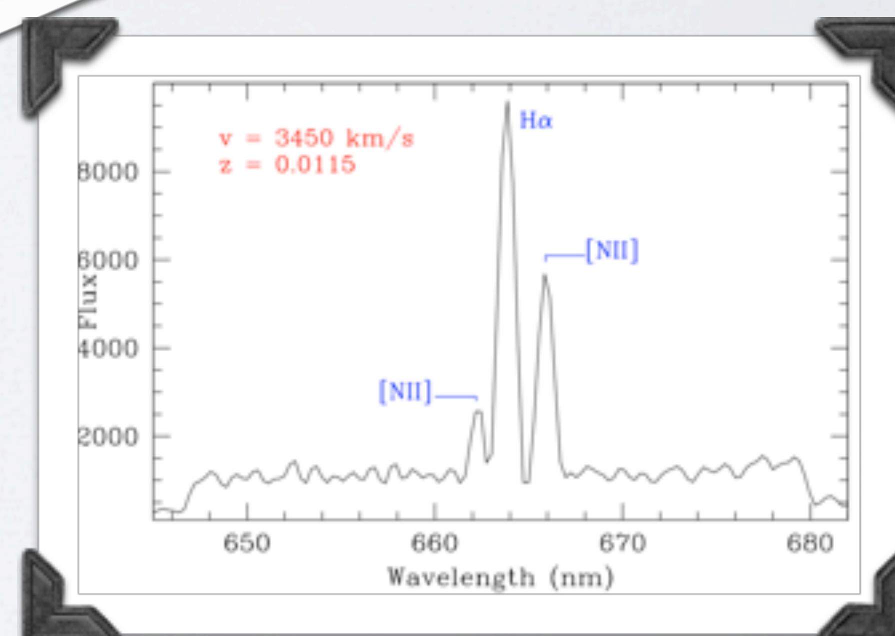
Typical observations:

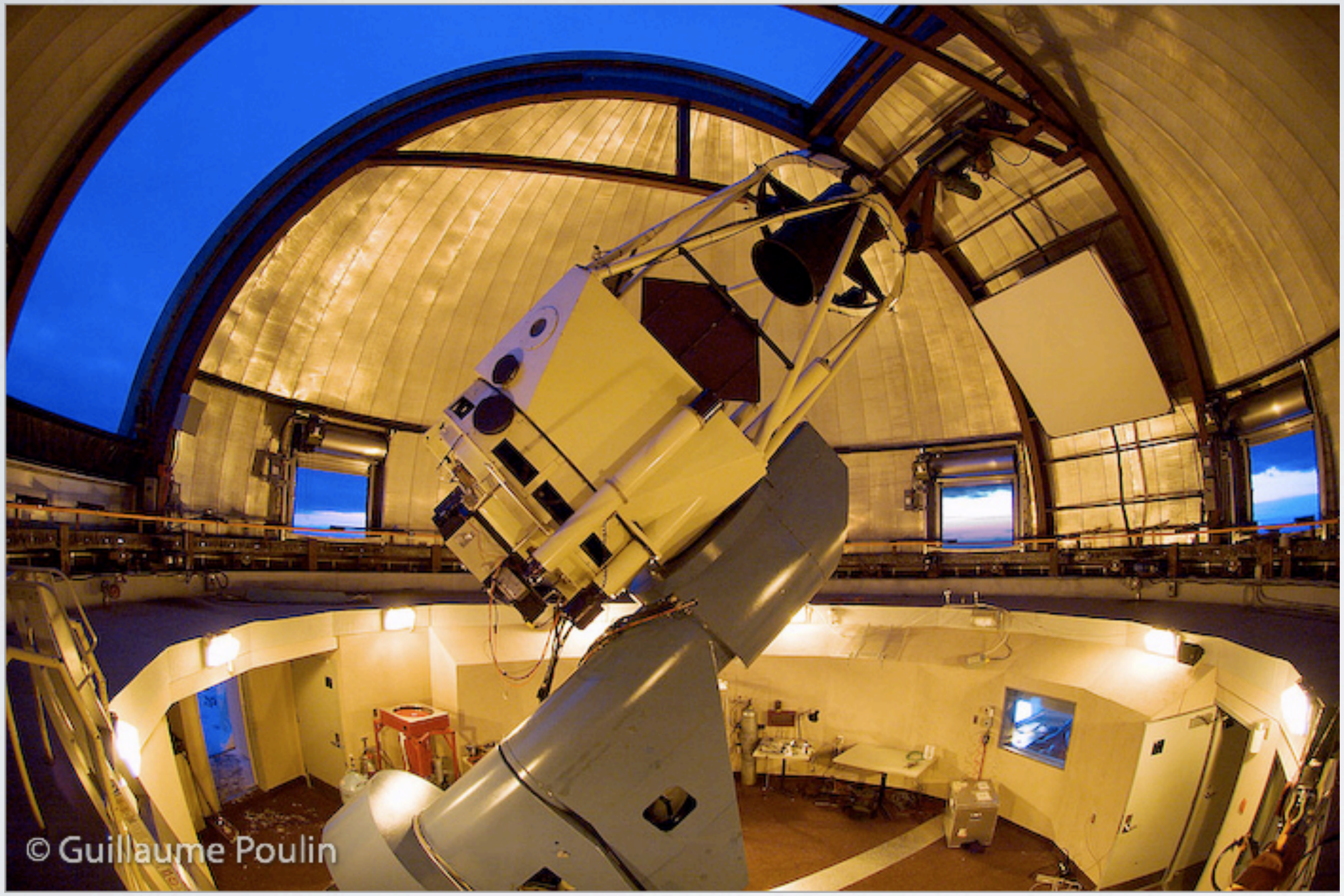
* Red filter (650 - 680 nm): 350 steps - R ~ 2000
* Blue filter (475 - 510 nm): 150 steps - R ~ 600

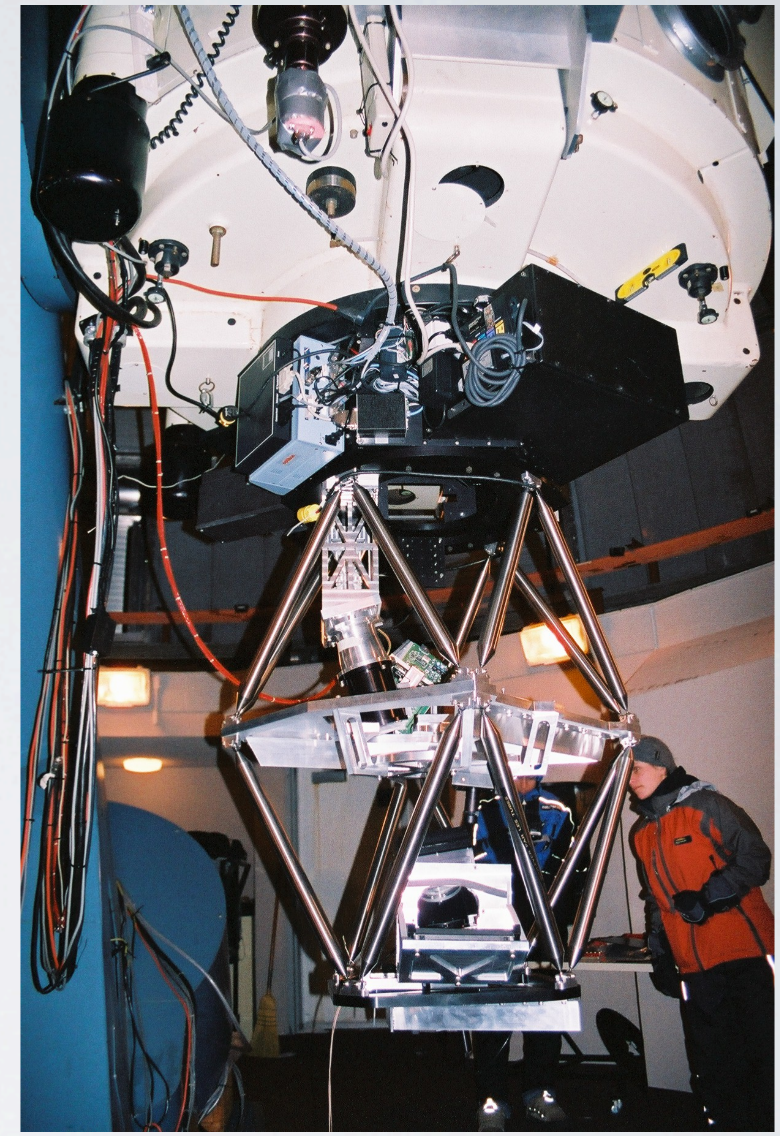
CHAPTER II - RECENT HIGHLIGHTS FROM SPIOMM











Mont Mégantic Observatory, 1.6-m
SpIOMM: 12' x 12' FOV
Two CCDs (1340 x 1300; 2k x 2k)
Spectral resolution: R ~ 1 - 20 000

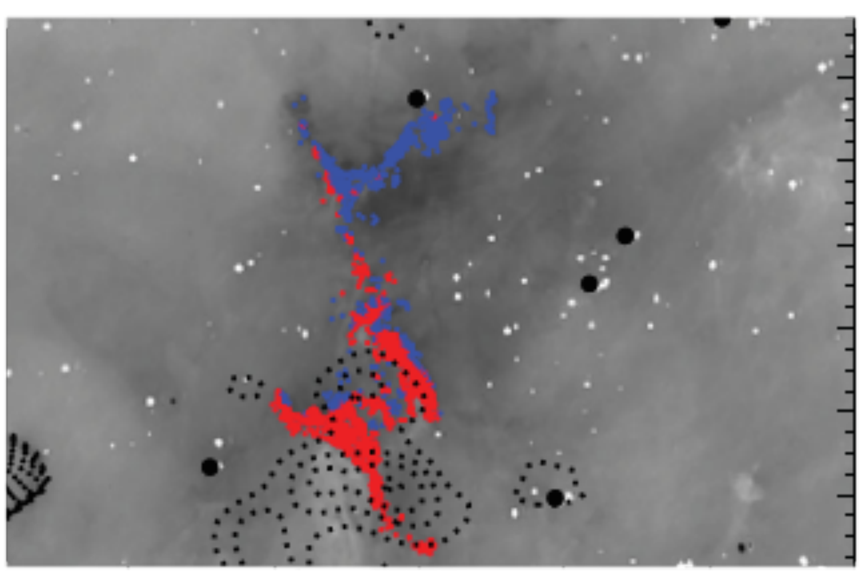
Diagnostic line ratios in the IC 1805 optical gas complex

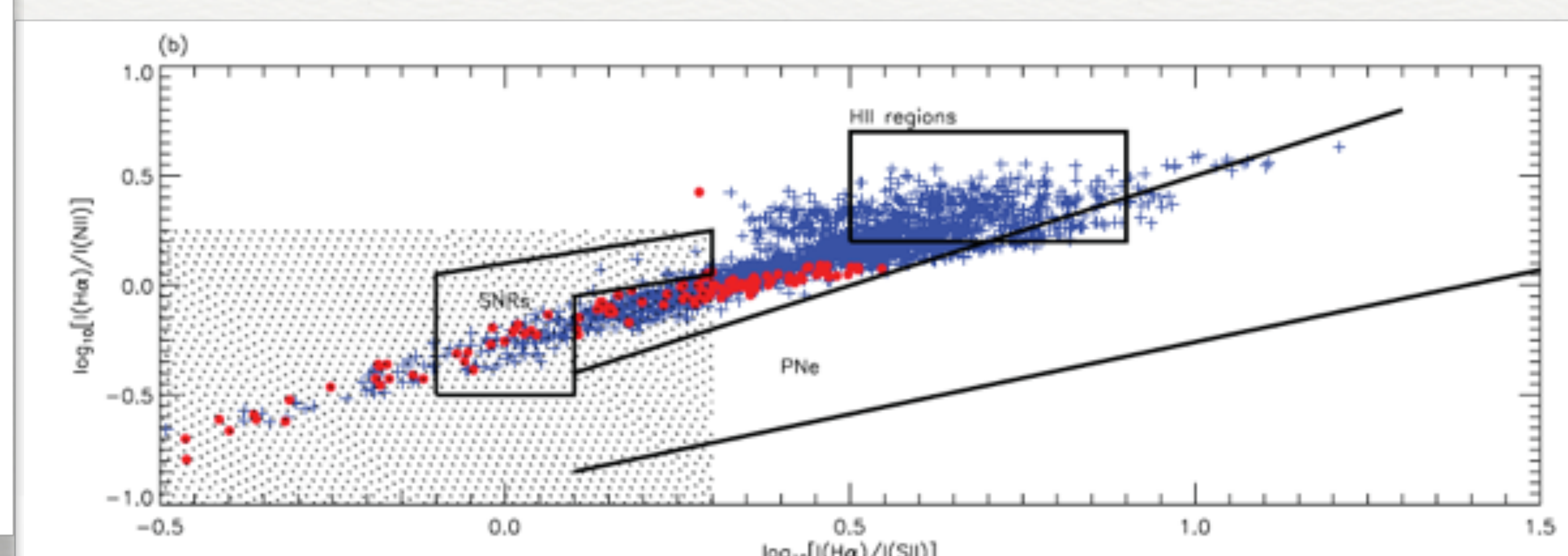
Dominic Lagrois,[1,2*] Gilles Joncas[1,2] and Laurent Drissen[1,2]

MNRAS, 420, 2280 (2012)

Hα/[NII]

Impacts of stellar winds and UV radiation on the ISM

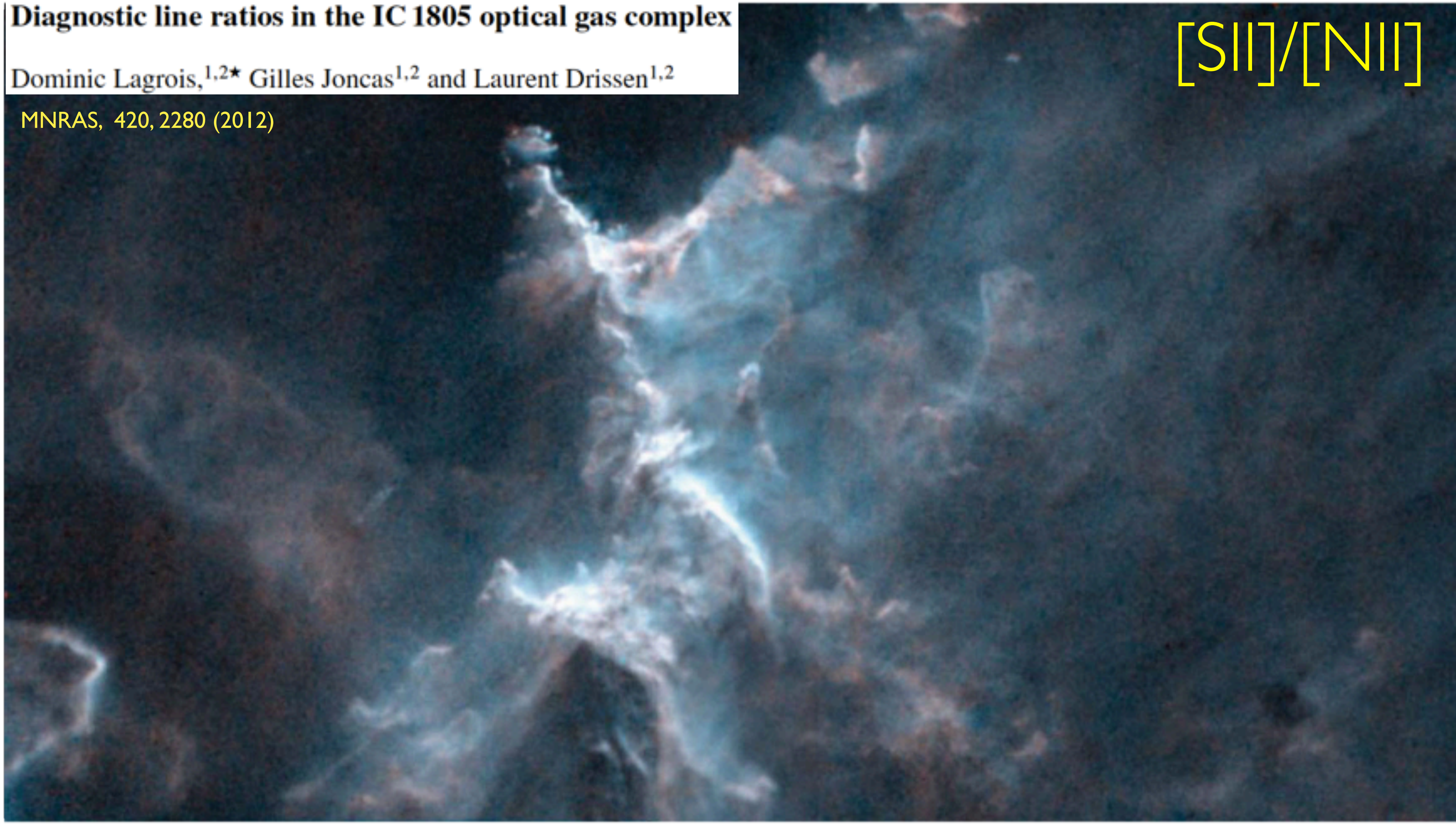


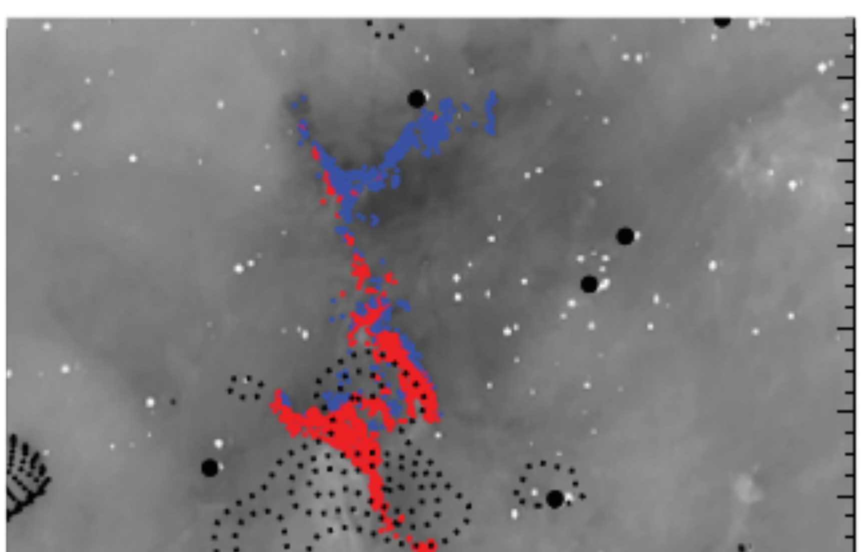


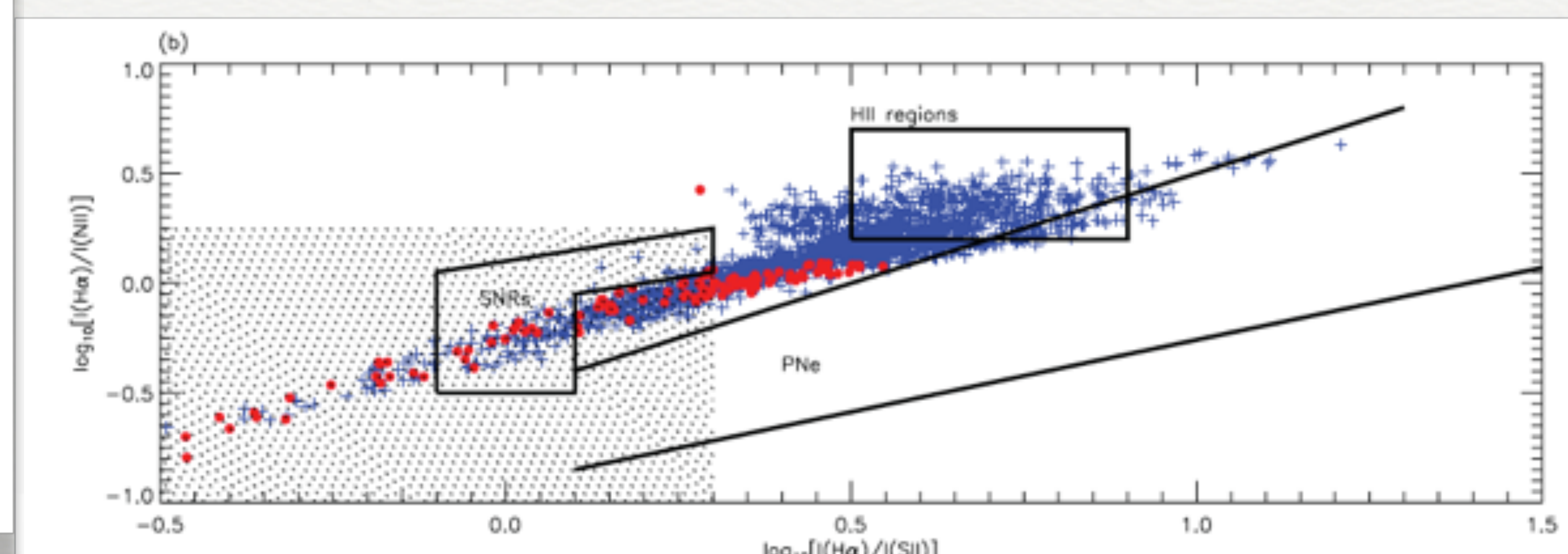
Diagnostic line ratios in the IC 1805 optical gas complex

Dominic Lagrois,[1,2★] Gilles Joncas[1,2] and Laurent Drissen[1,2]

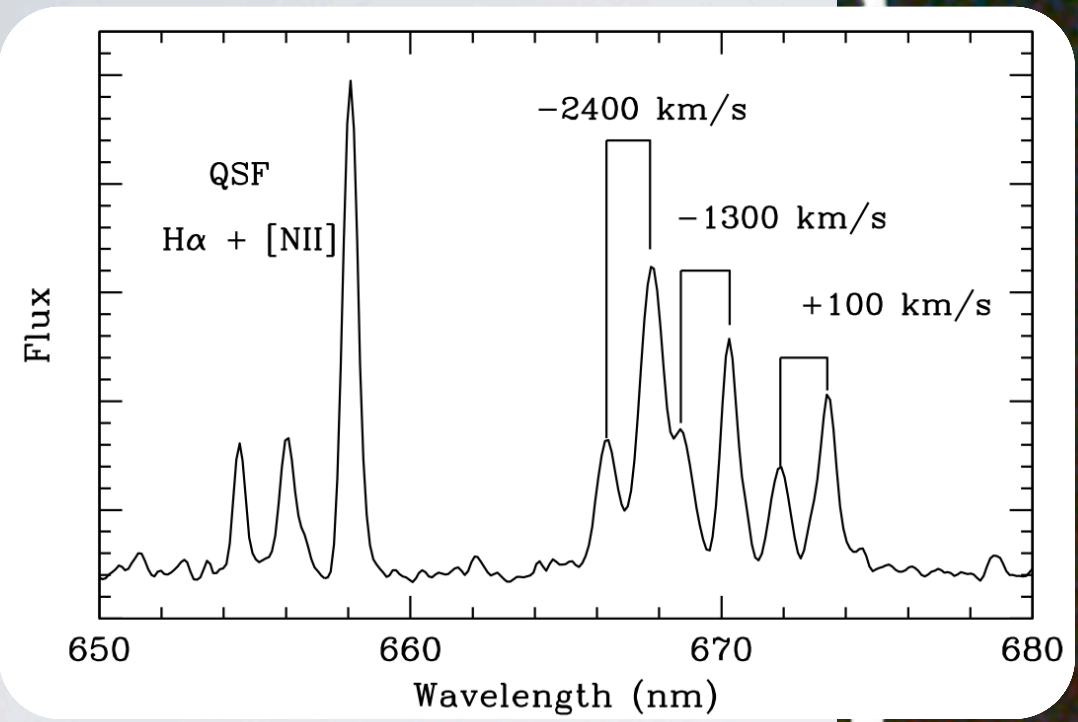
MNRAS, 420, 2280 (2012)

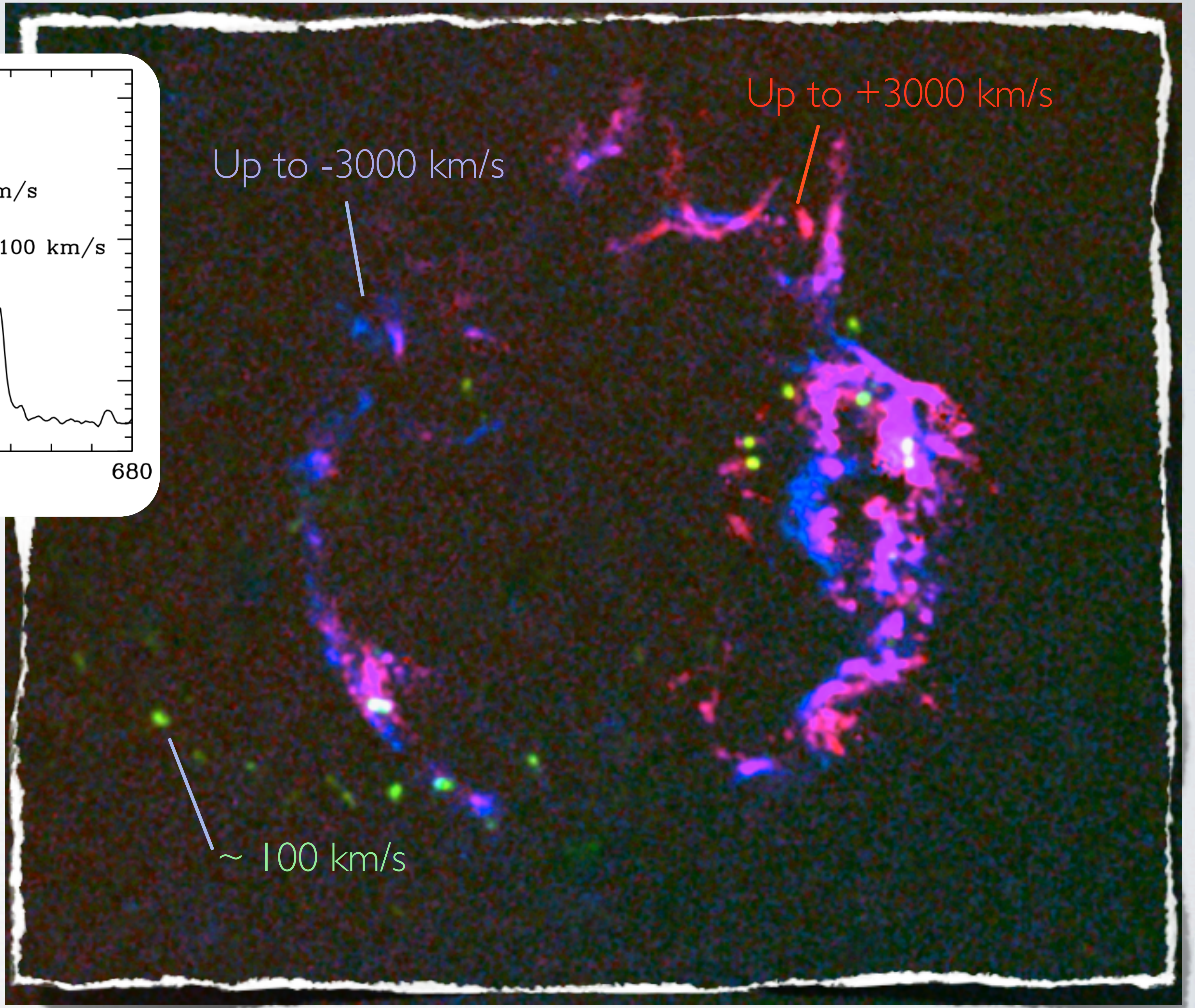






Cas A supernova remnant



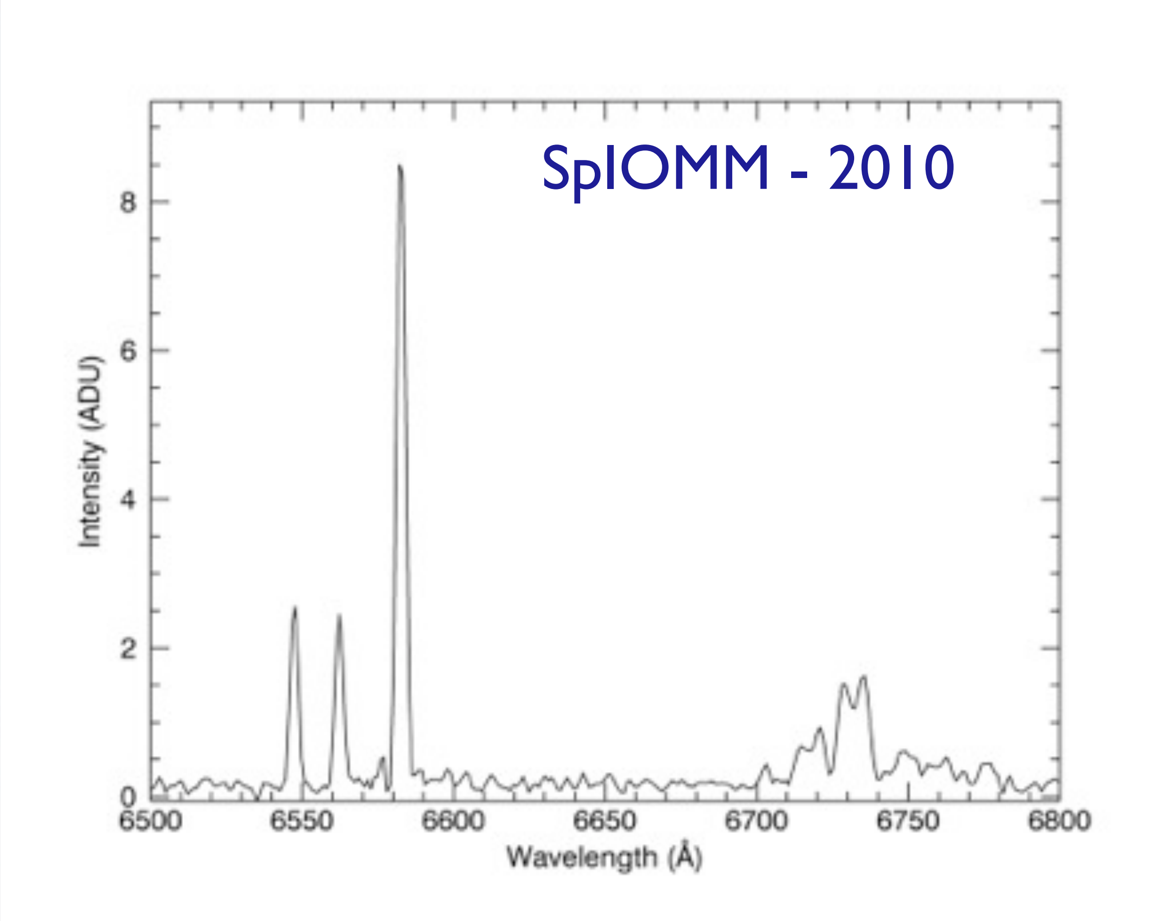


Alexandre Alarie, Ph. D.

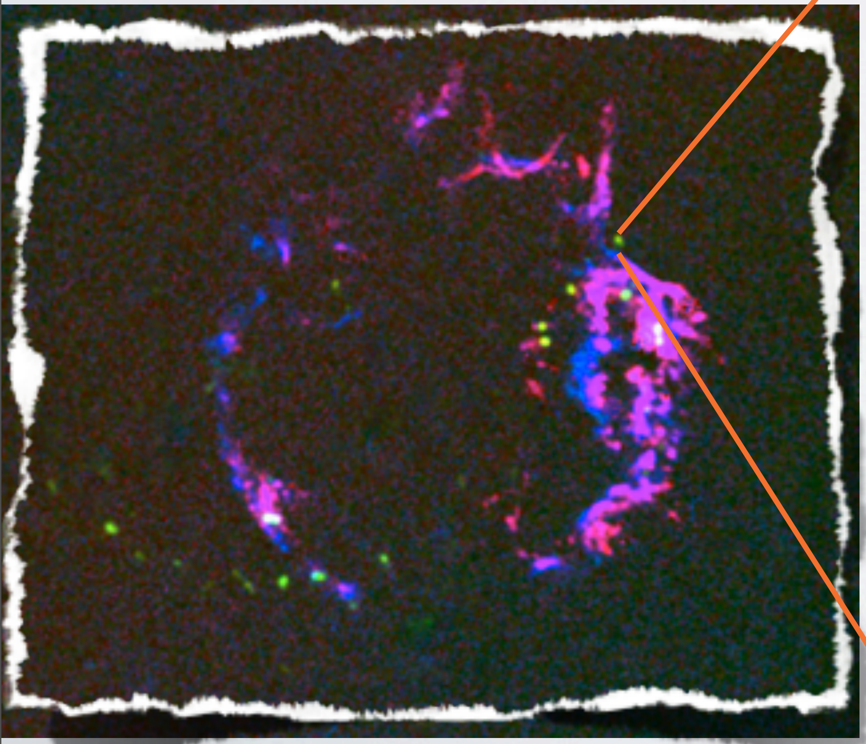
Doppler image

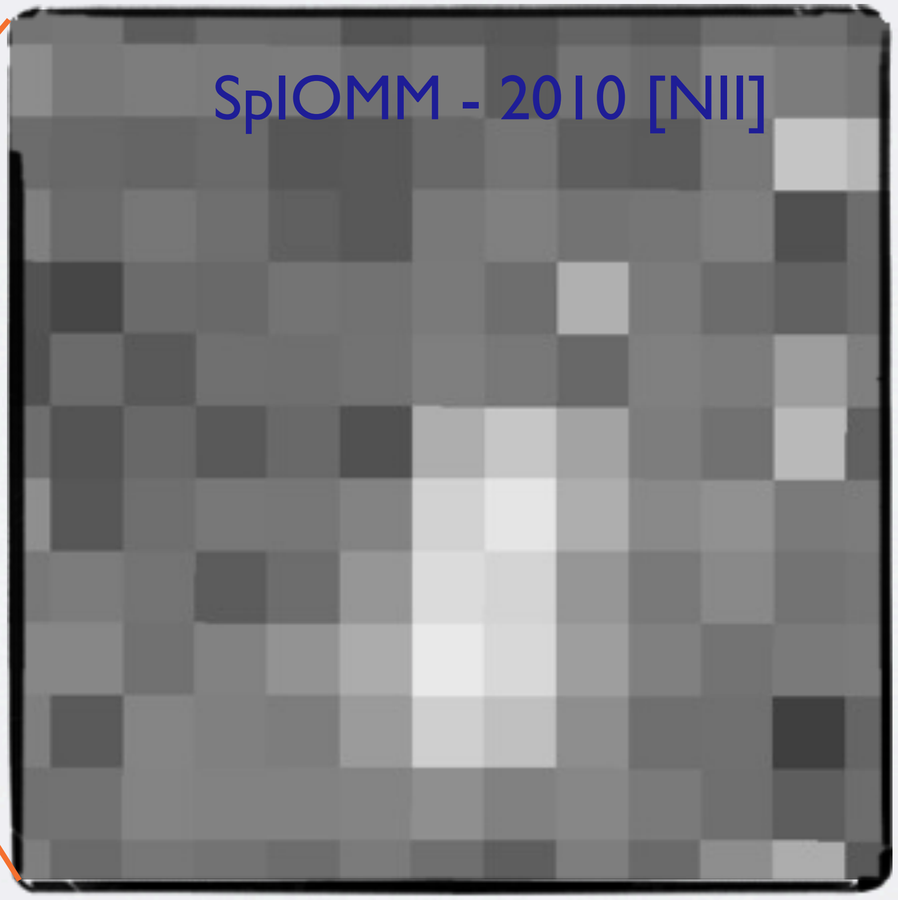
SpIOMM: radial velocity

Hubble: tangential velocity (proper motions)



SpIOMM - Doppler

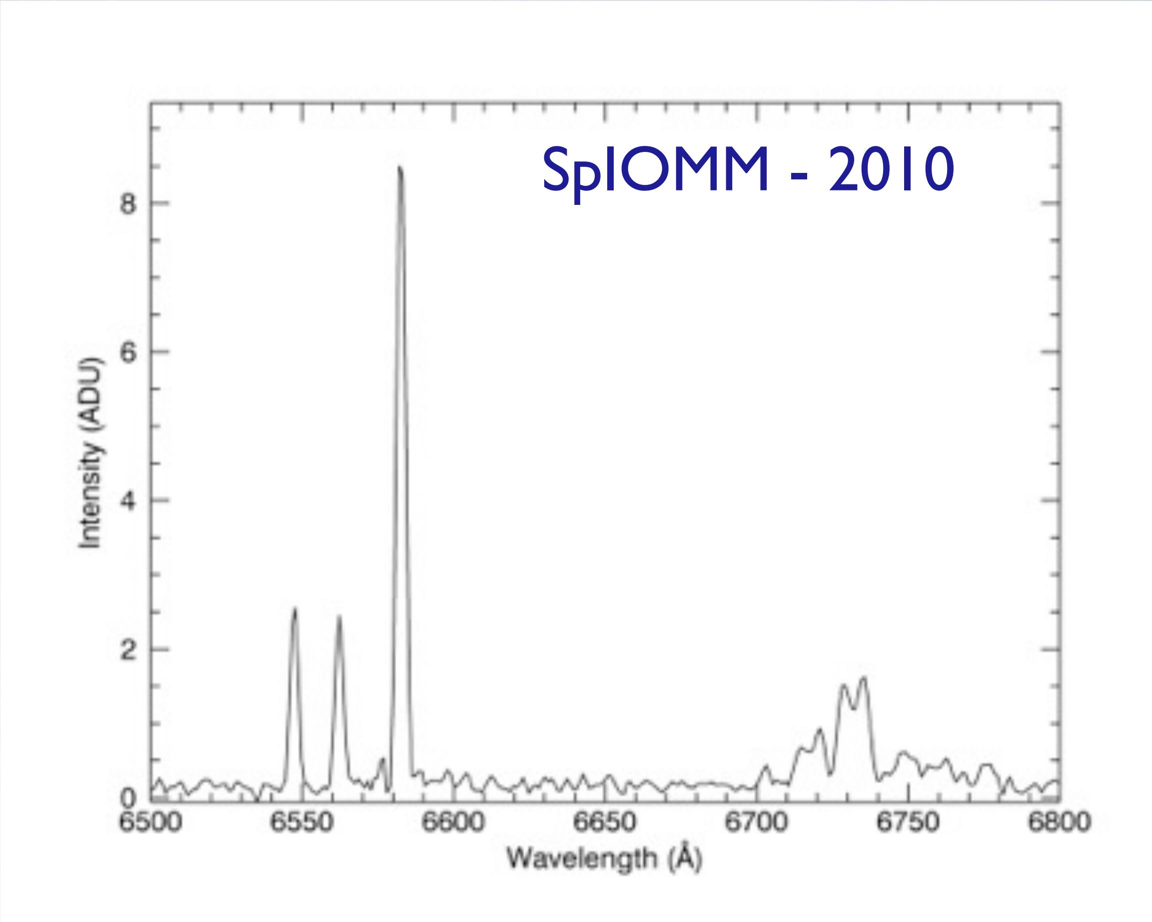




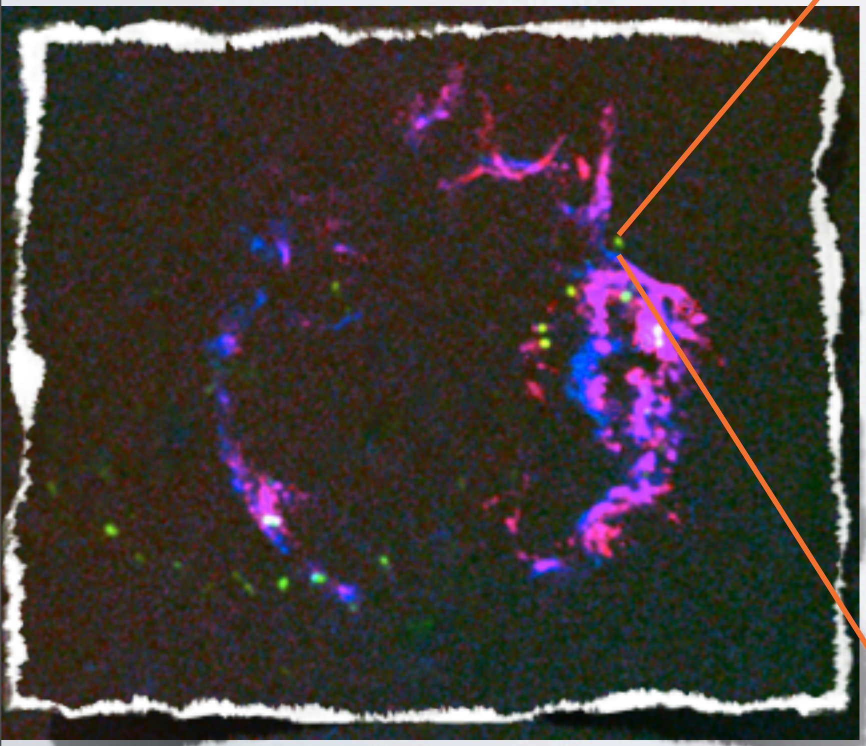
Hubble/WFPC2
2001/2009

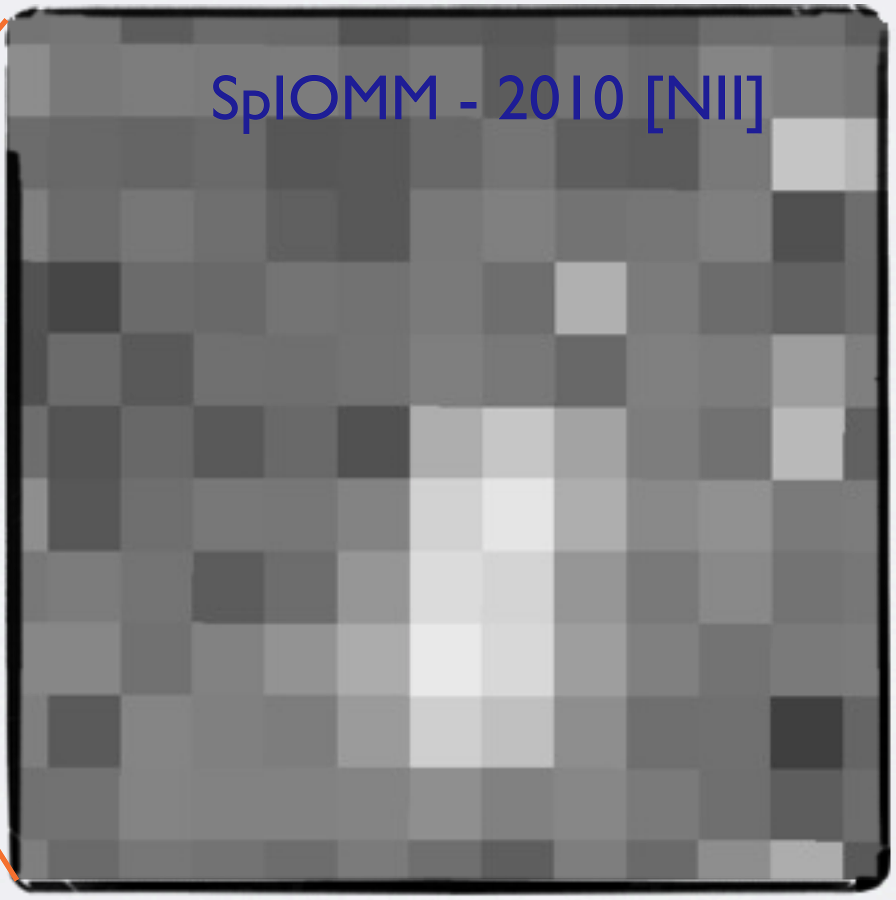
SpIOMM: radial velocity

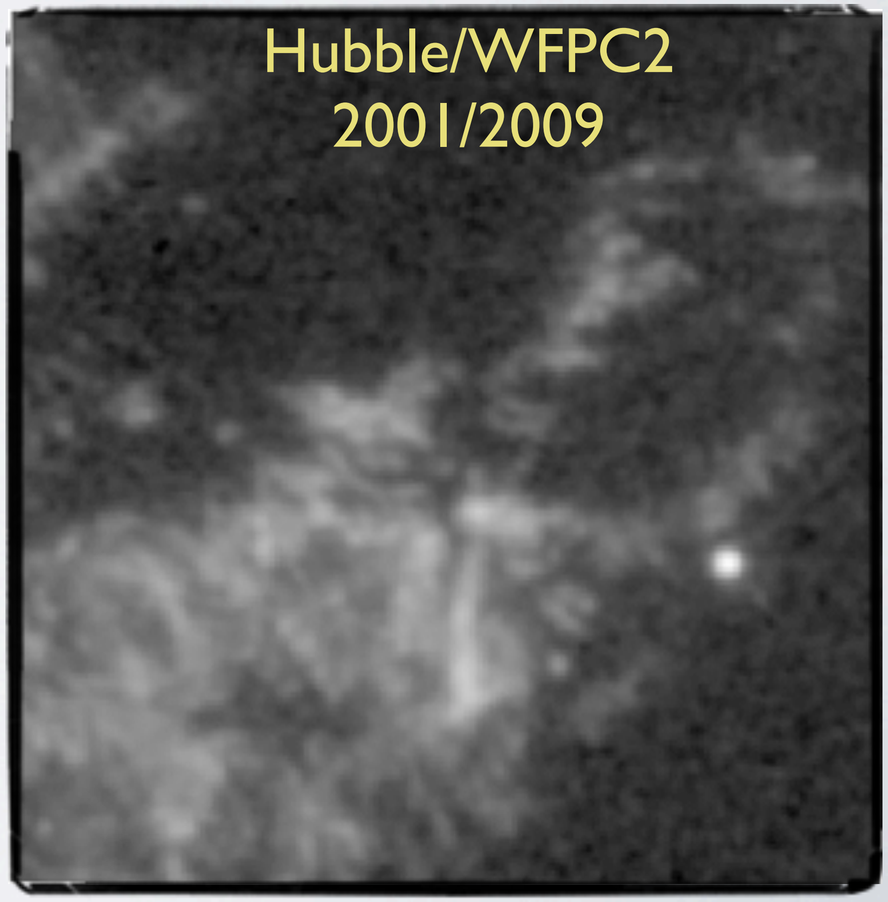
Hubble: tangential velocity (proper motions)

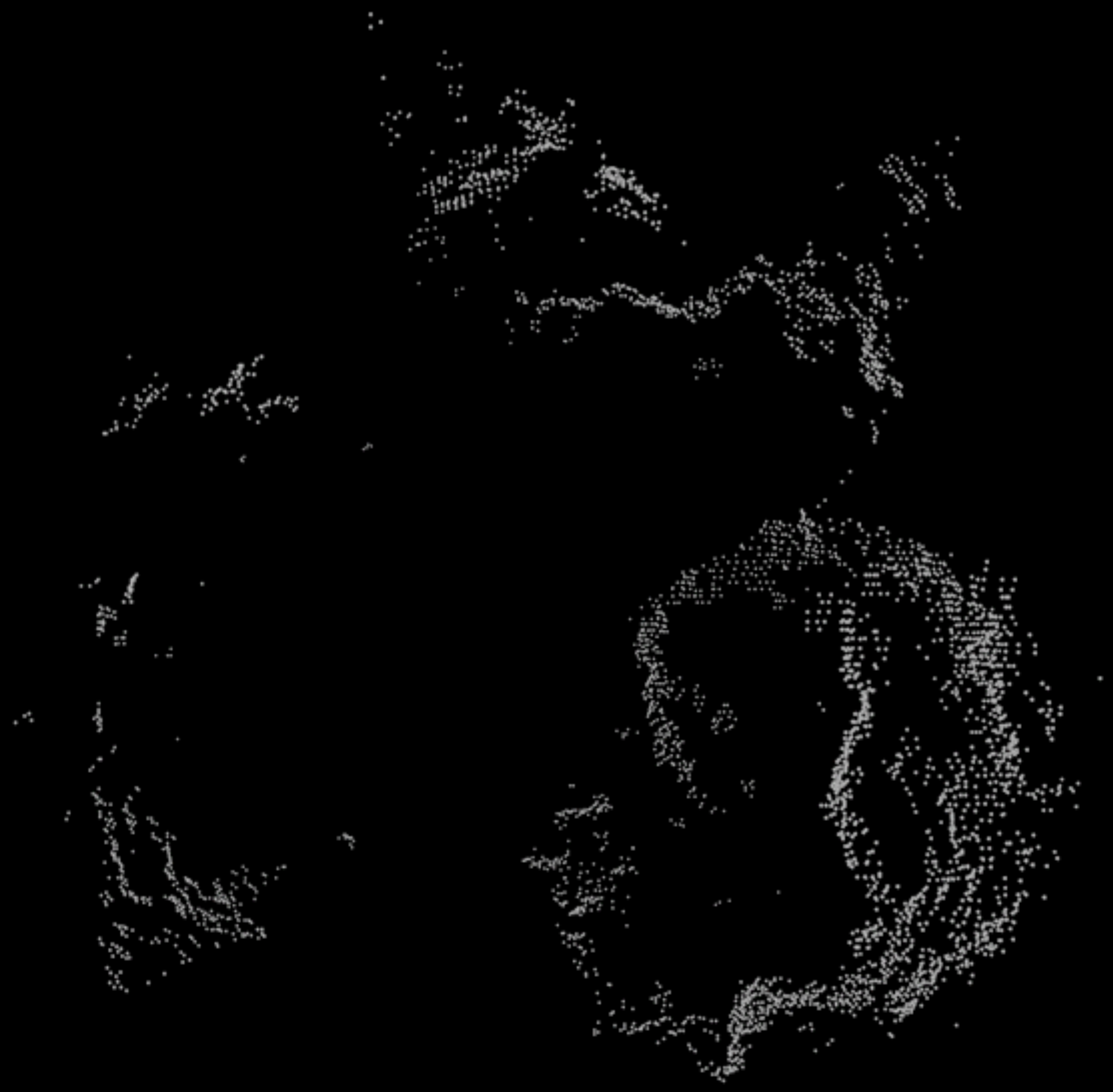


SpIOMM - Doppler





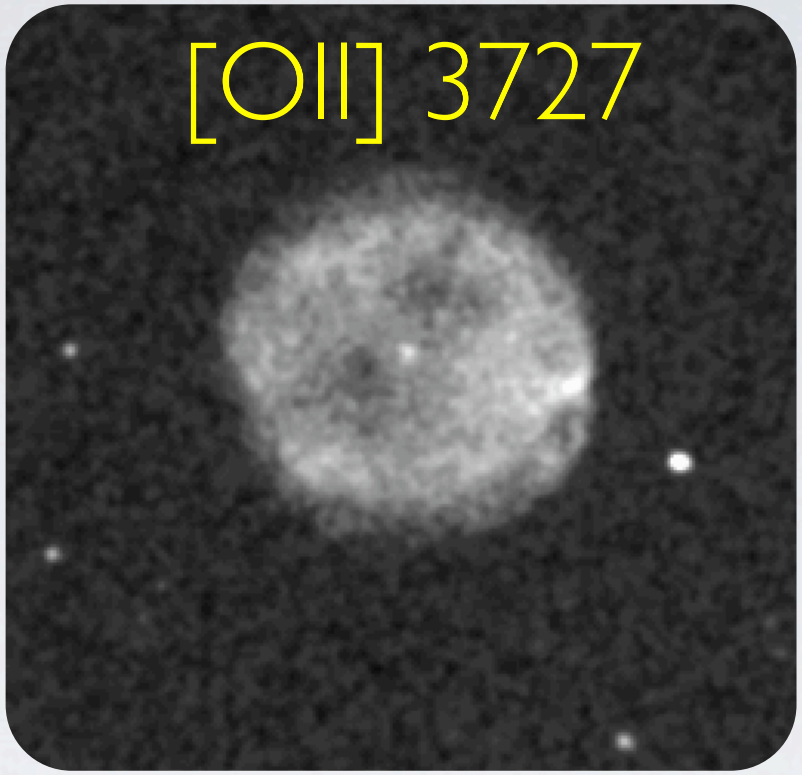


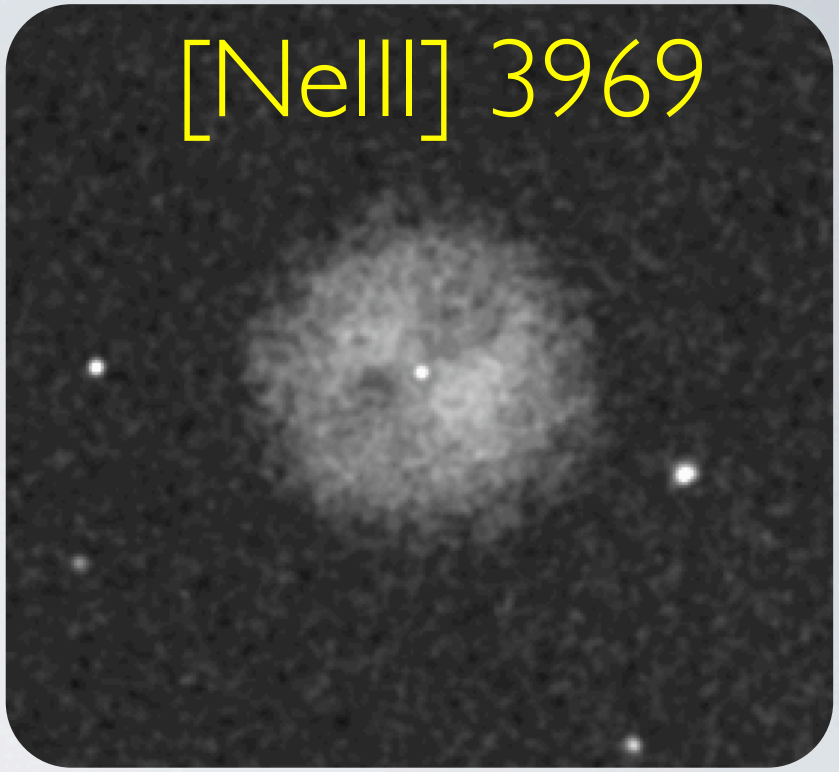


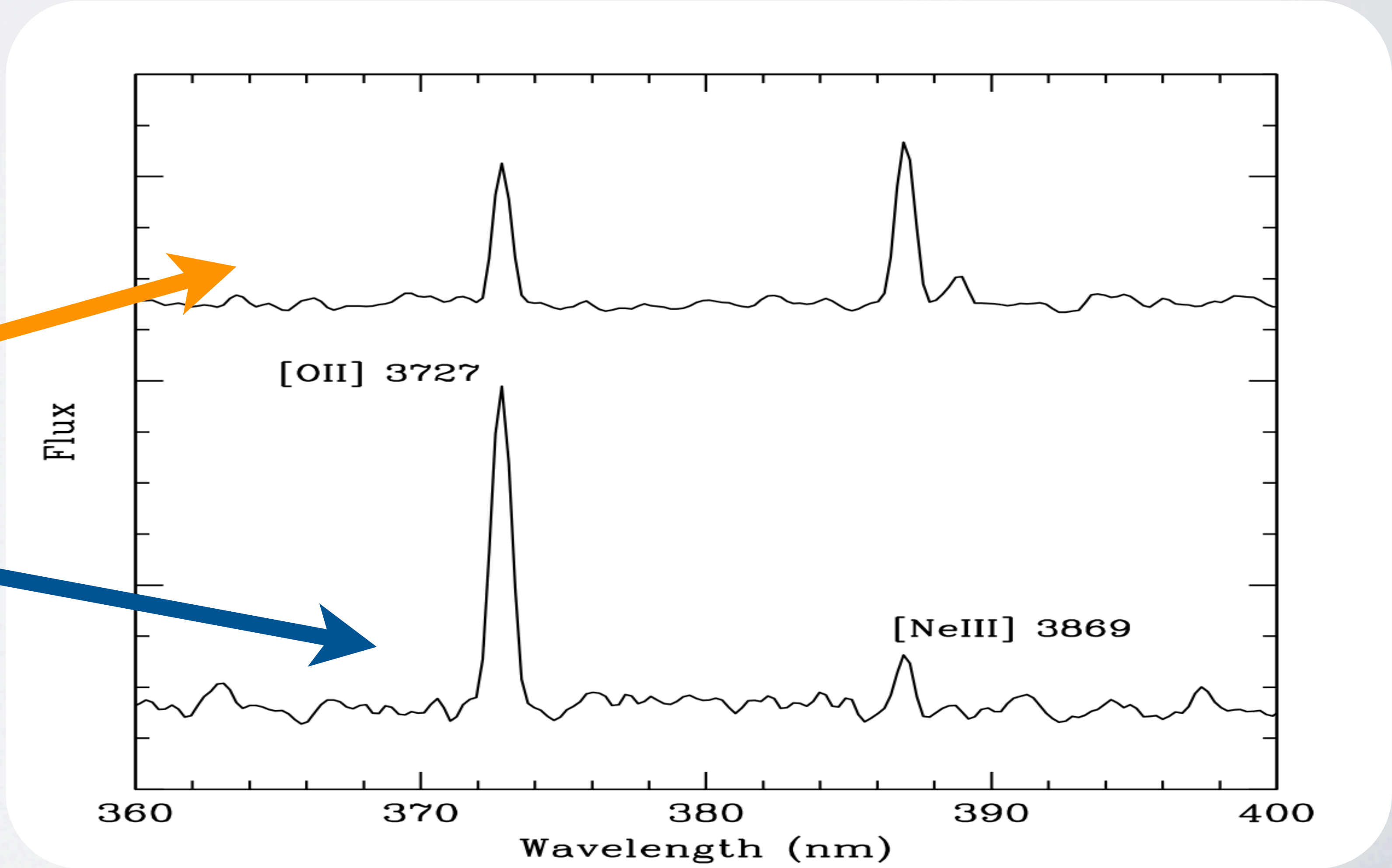
SpIOMM - 3D (from [SII] doublet)

Works in near UV as well!

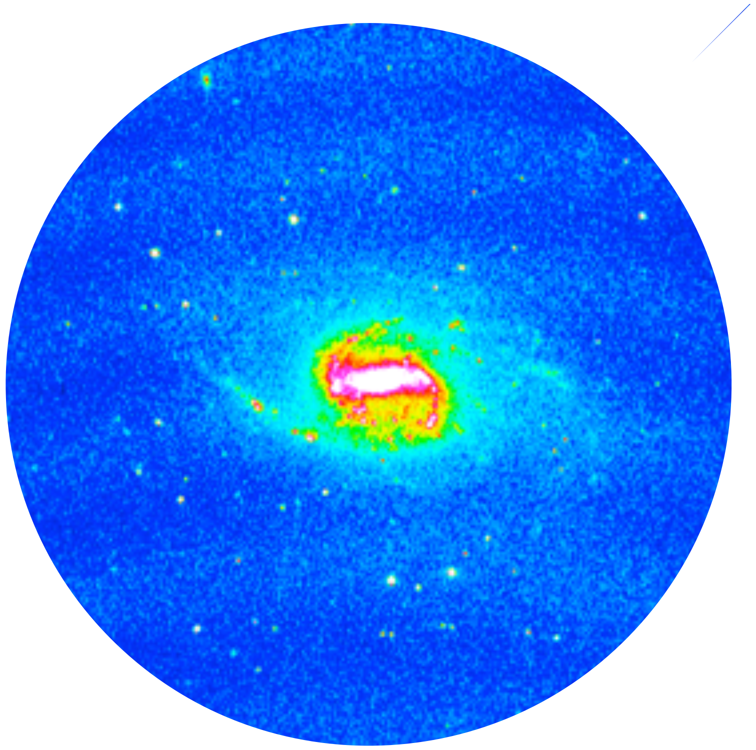
SITELLE will be ~ 20 times more sensitive in the UV than SpIOMM

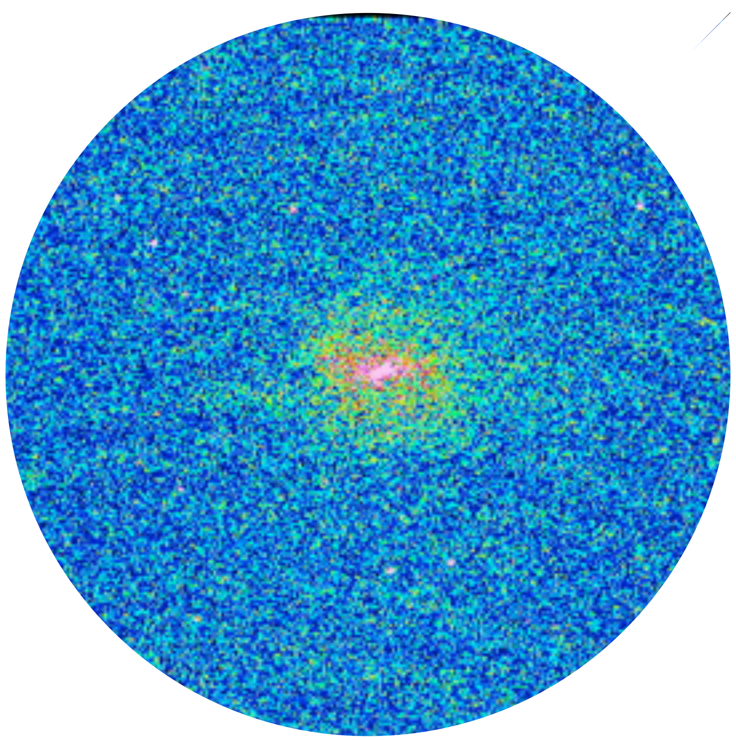






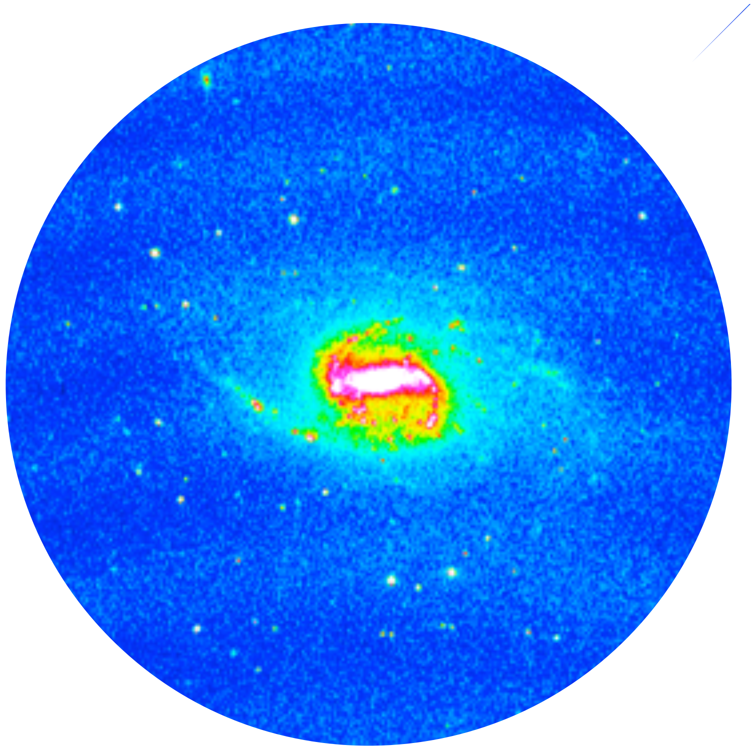

Galaxies
Laurie Rousseau-Nepton (Ph. D.)

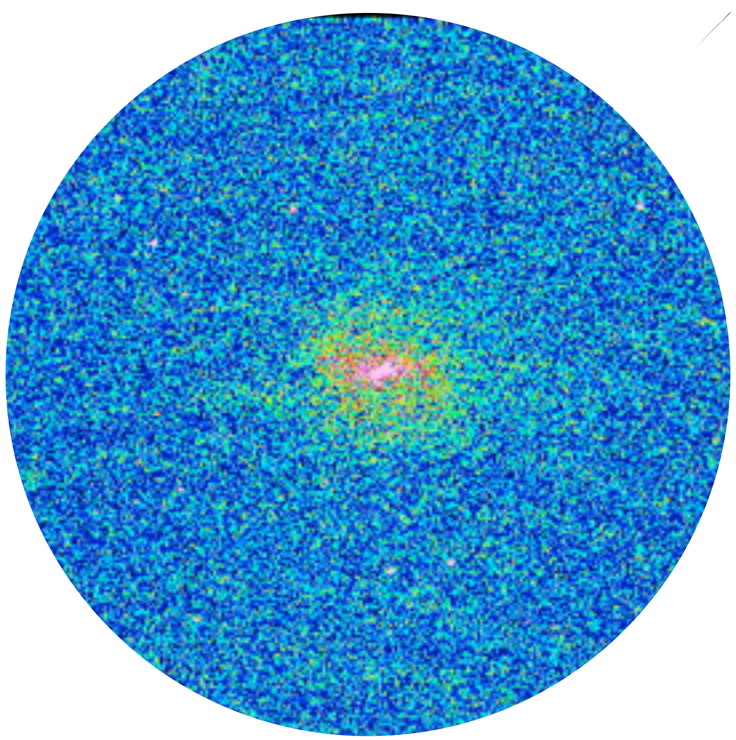




Galaxies

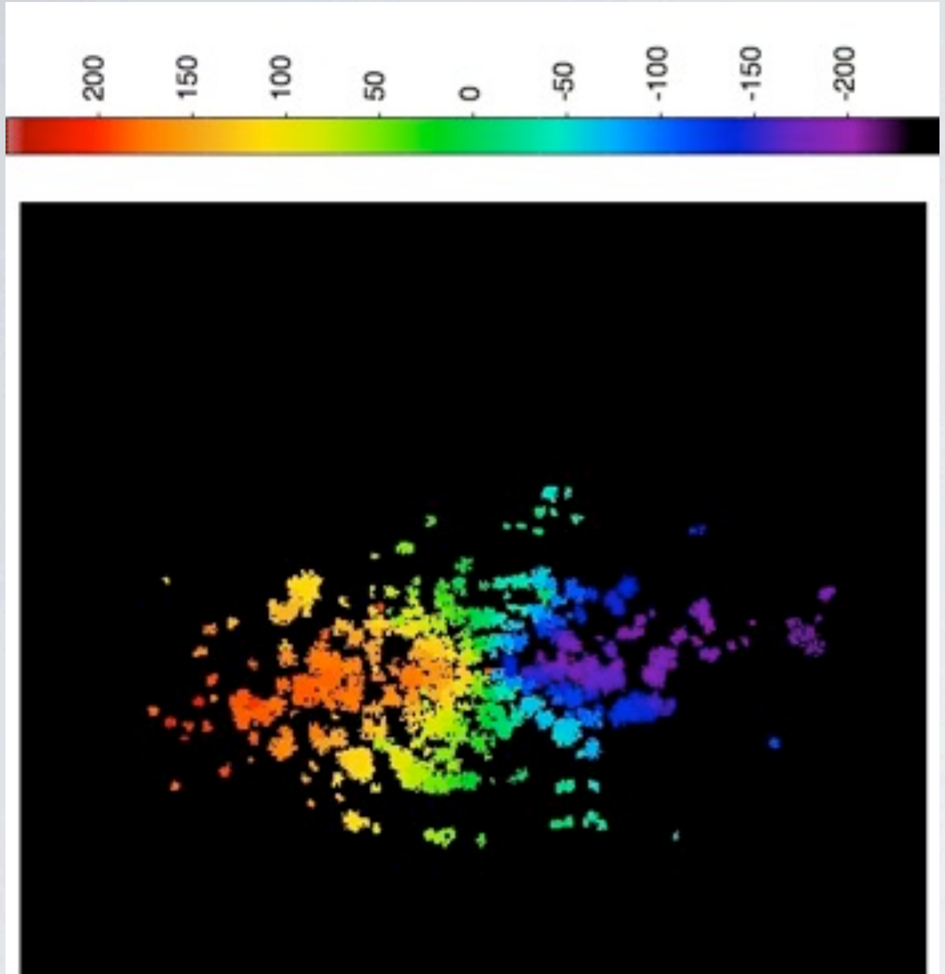
Laurie Rousseau-Nepton (Ph. D.)

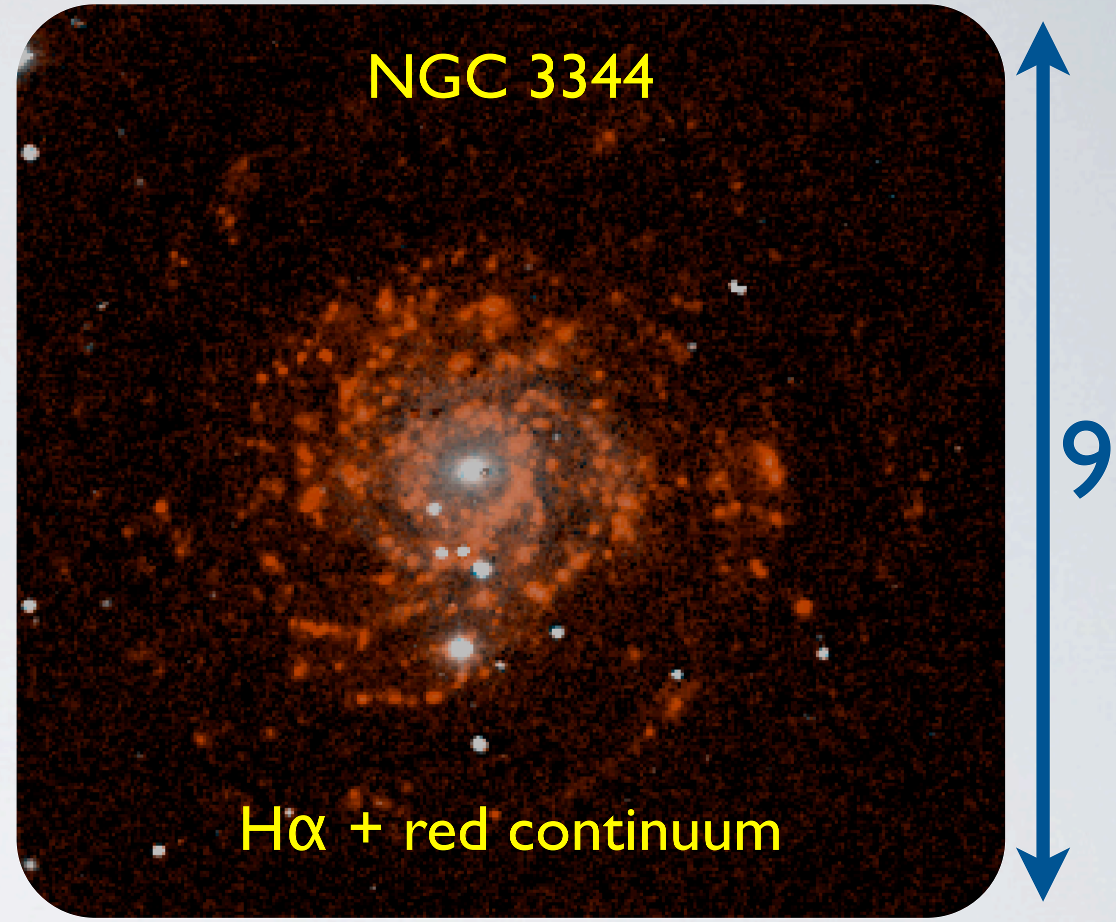


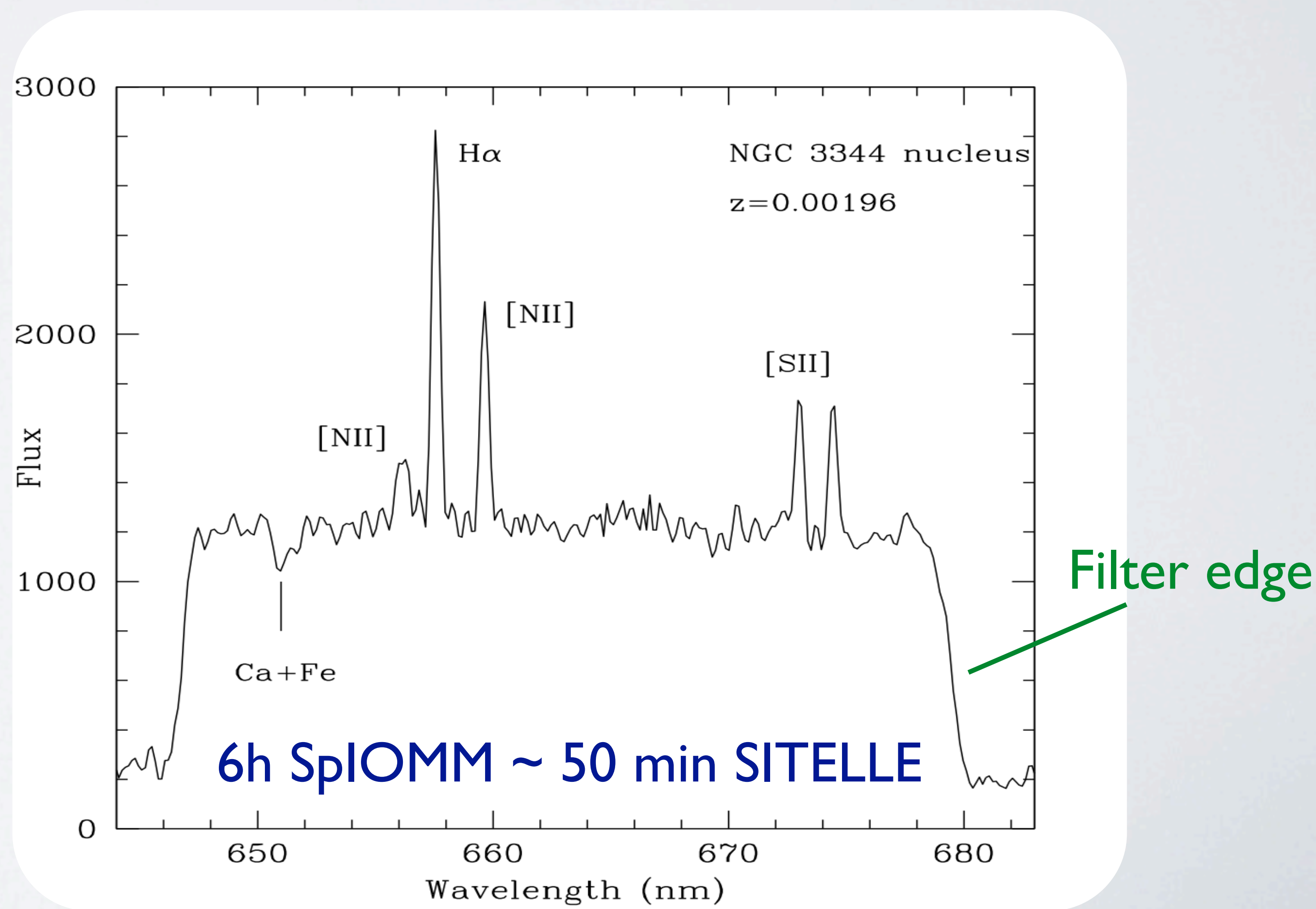


Galaxies

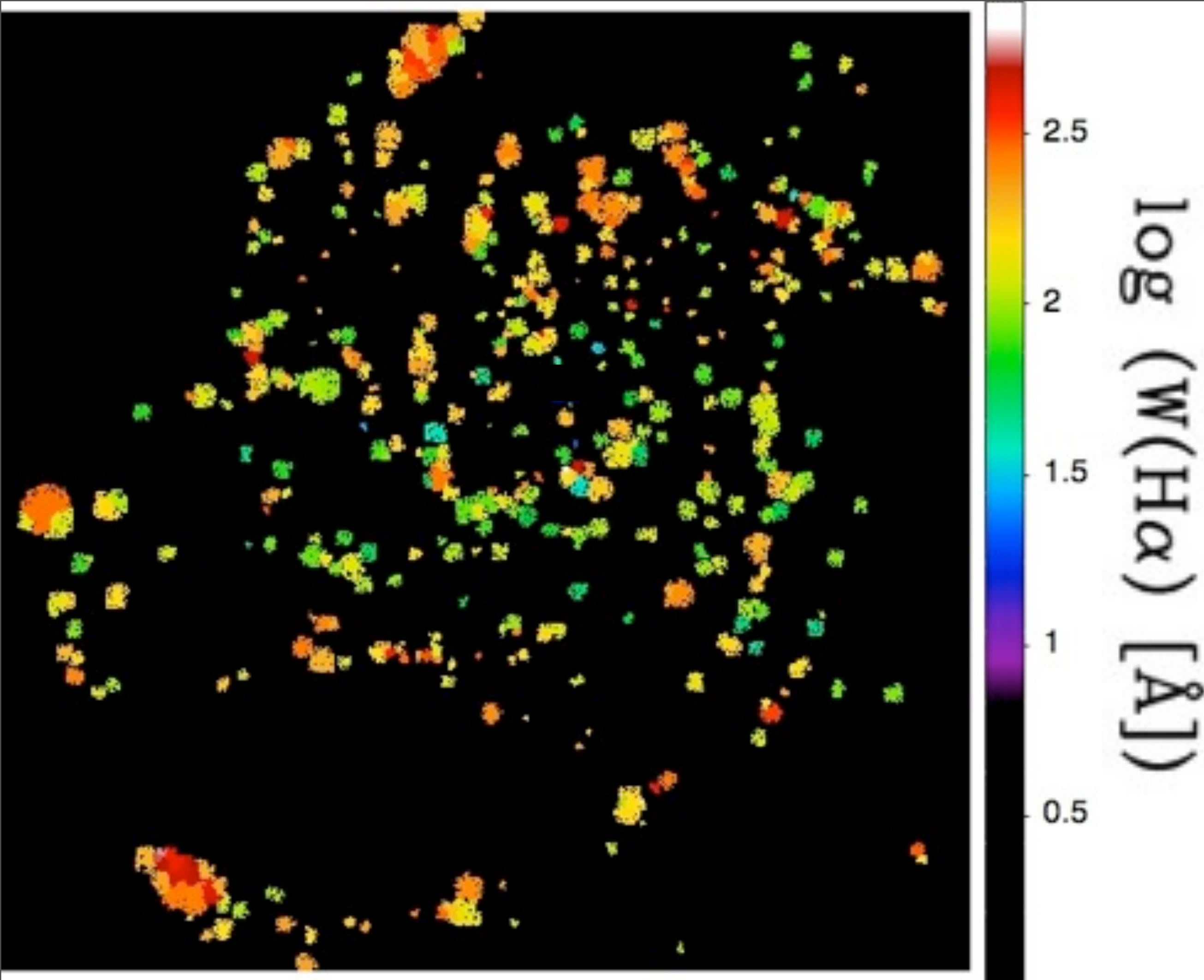
Laurie Rousseau-Nepton (Ph. D.)


200
150
100
50
0
-50
-100
-150
-200

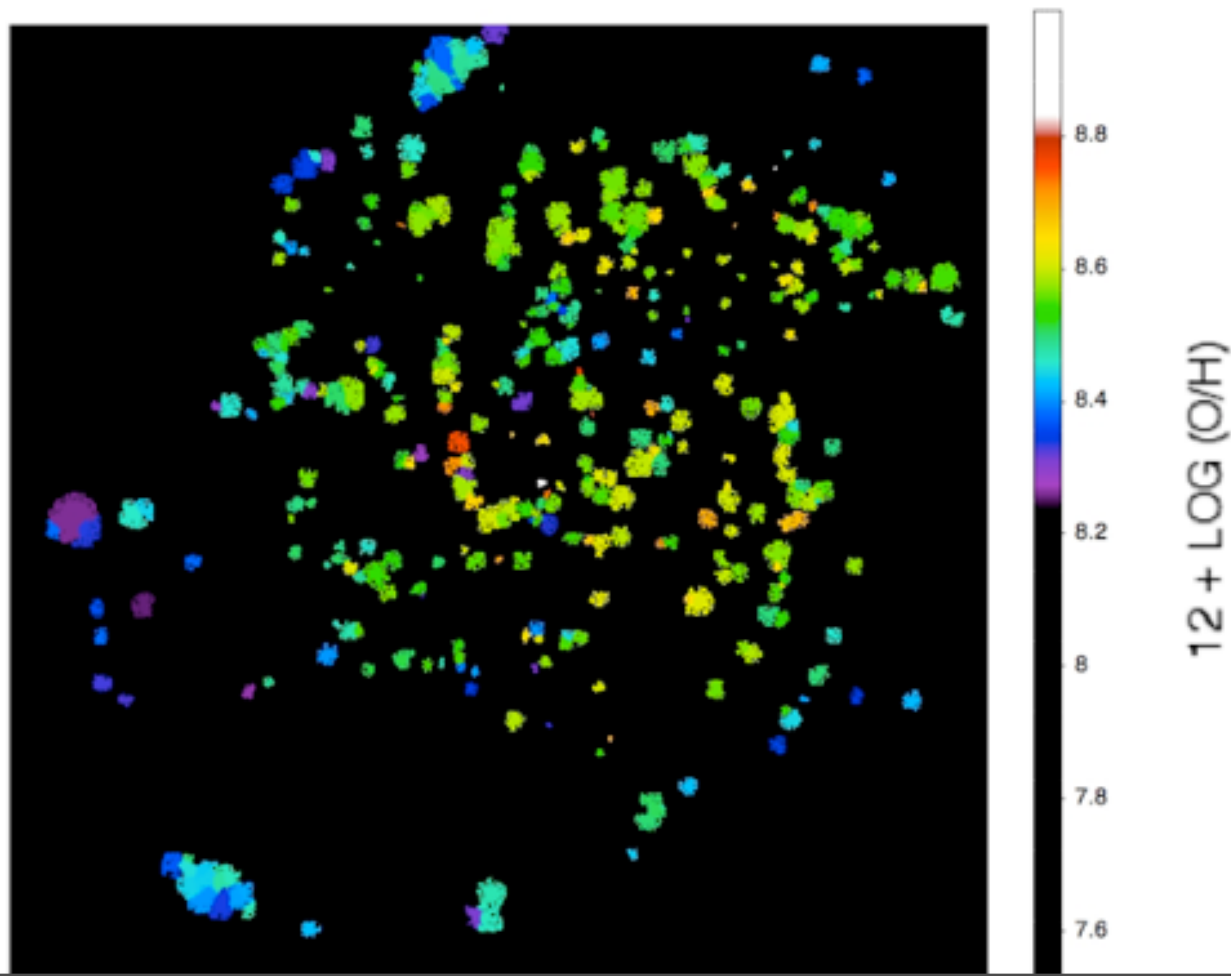

NGC 3344
Hα + red continuum
9’


Hα
NGC 3344 nucleus
z=0.00196
[NII]
[NII]
[SII]
Ca+Fe
Flux
Wavelength (nm)
3000
2000
1000
0
650
660
670
680
Filter edge
6h SpIOMM ~ 50 min SITELLE

M101

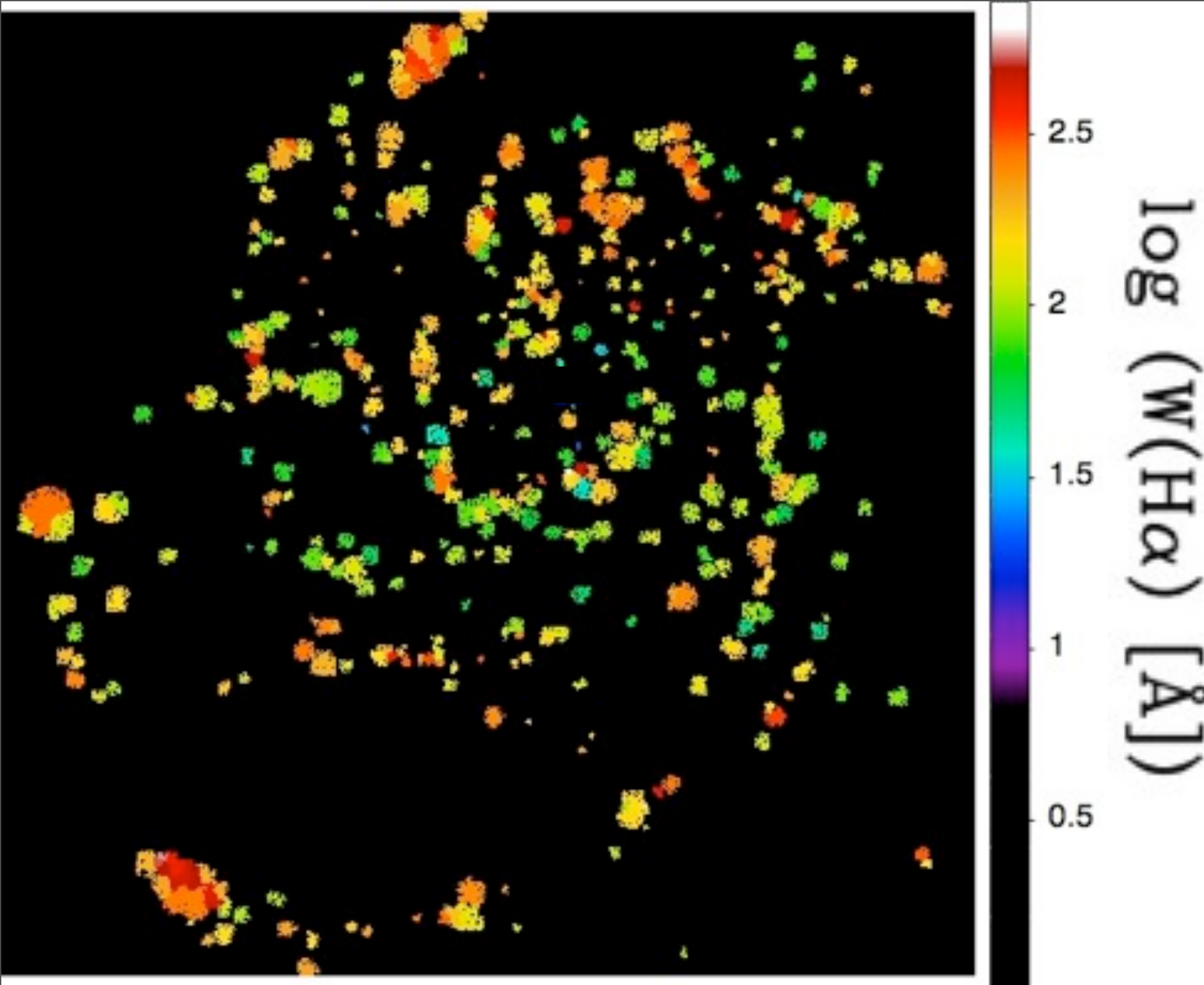


Age

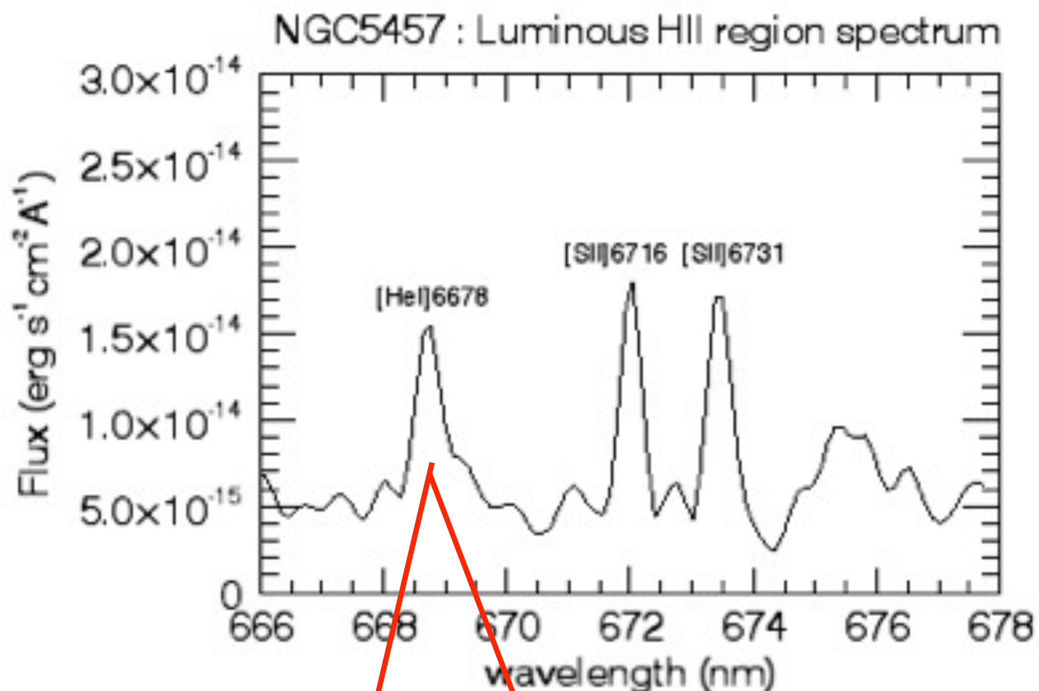


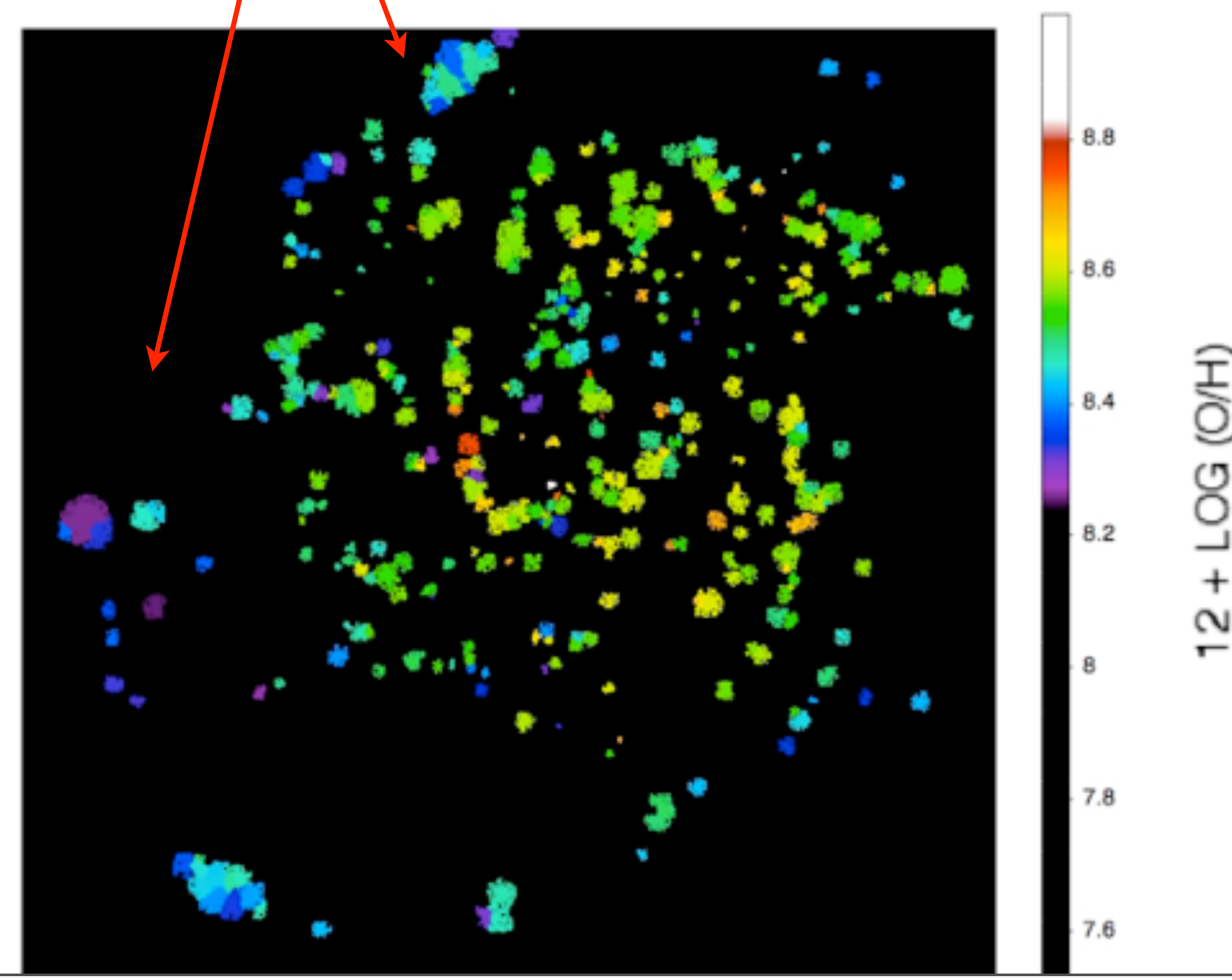
Metallicity

M101



Age

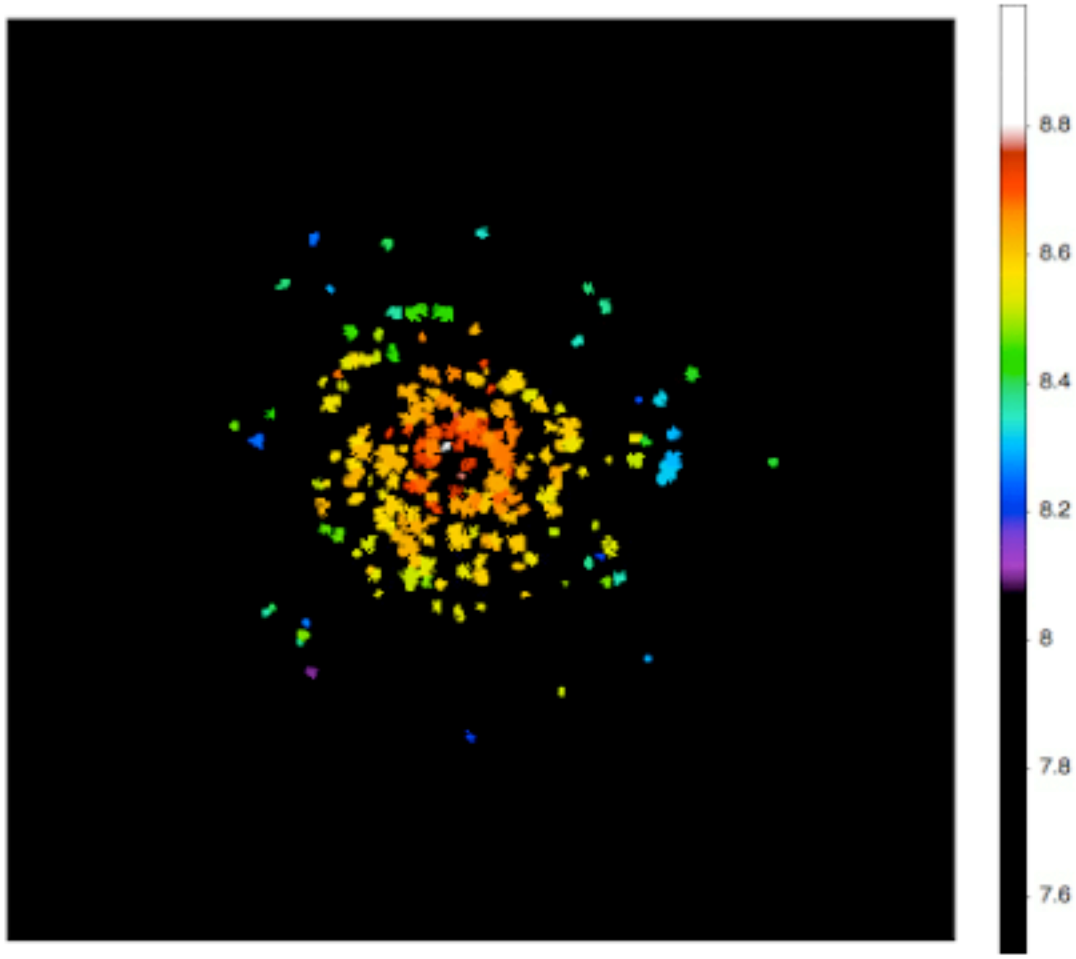




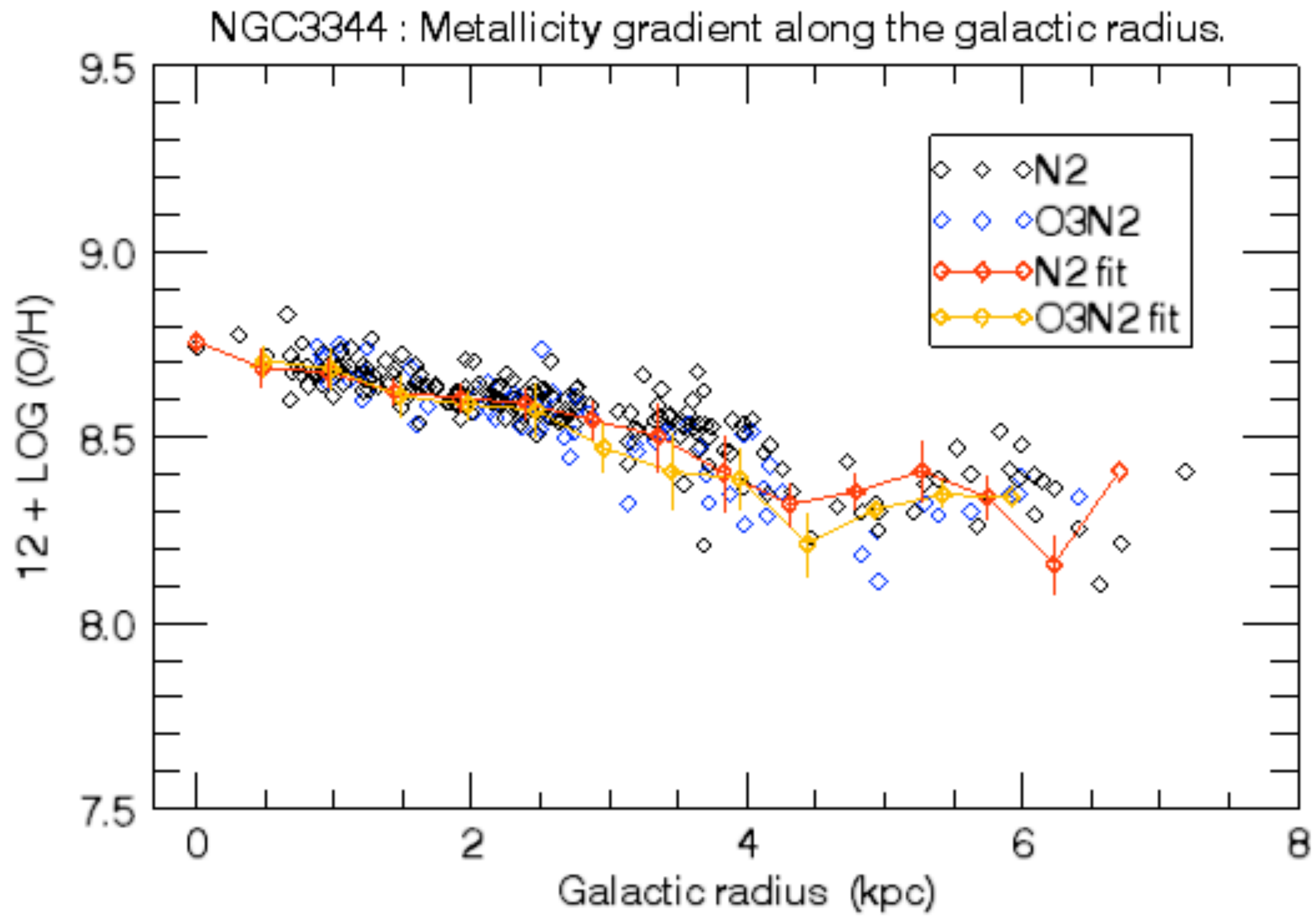
Metallicity

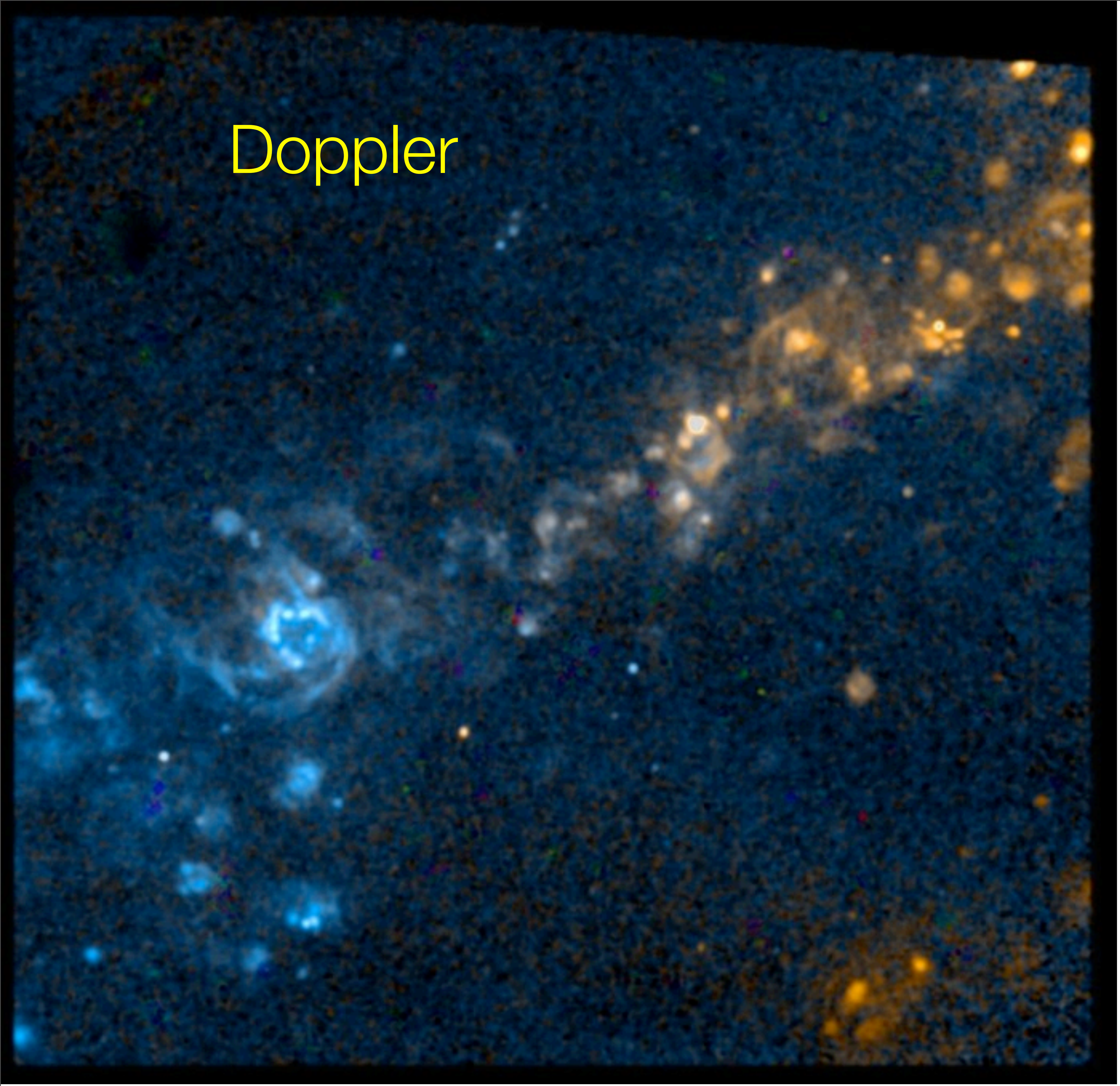
Results

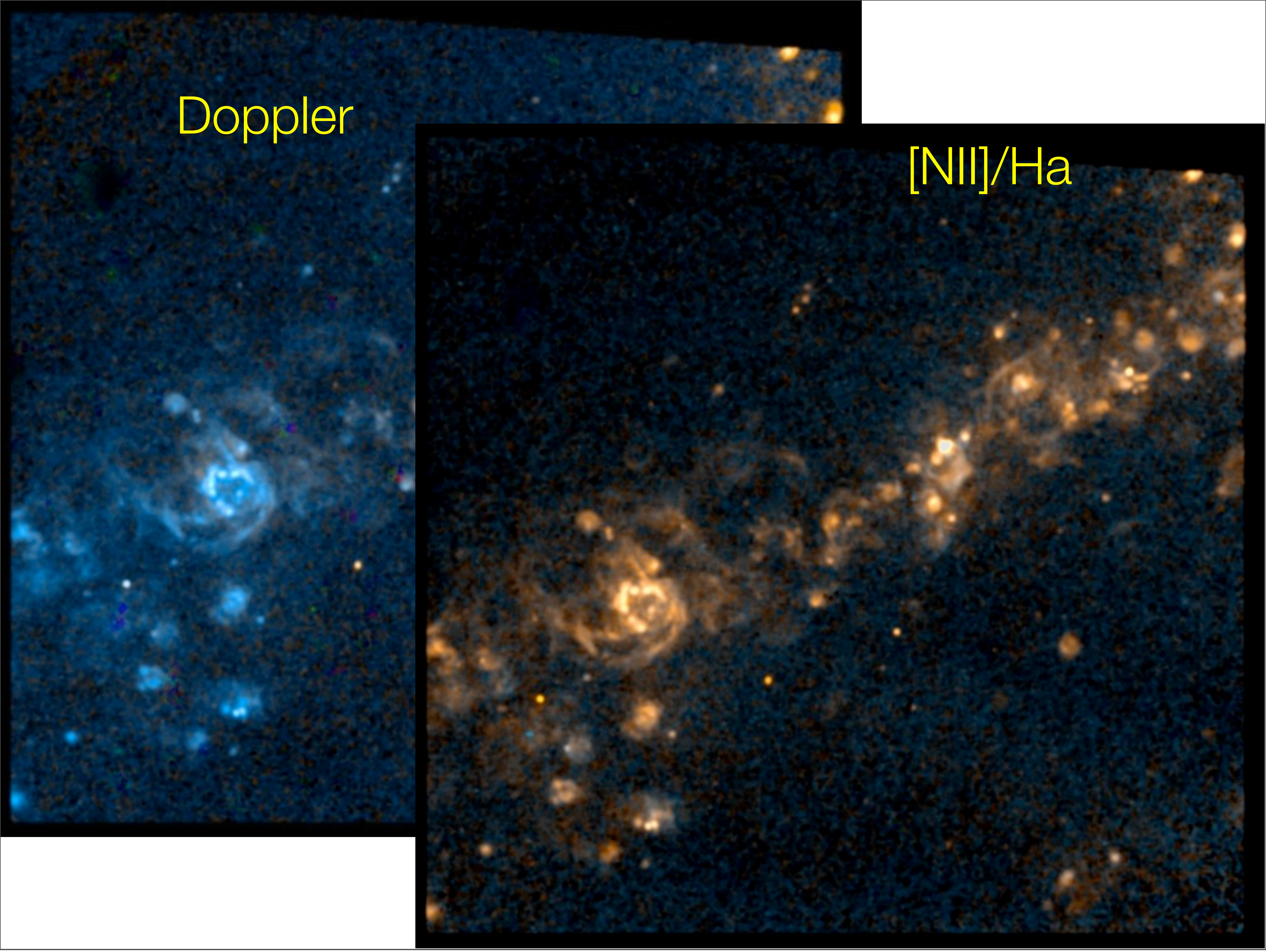
- Metallicity map

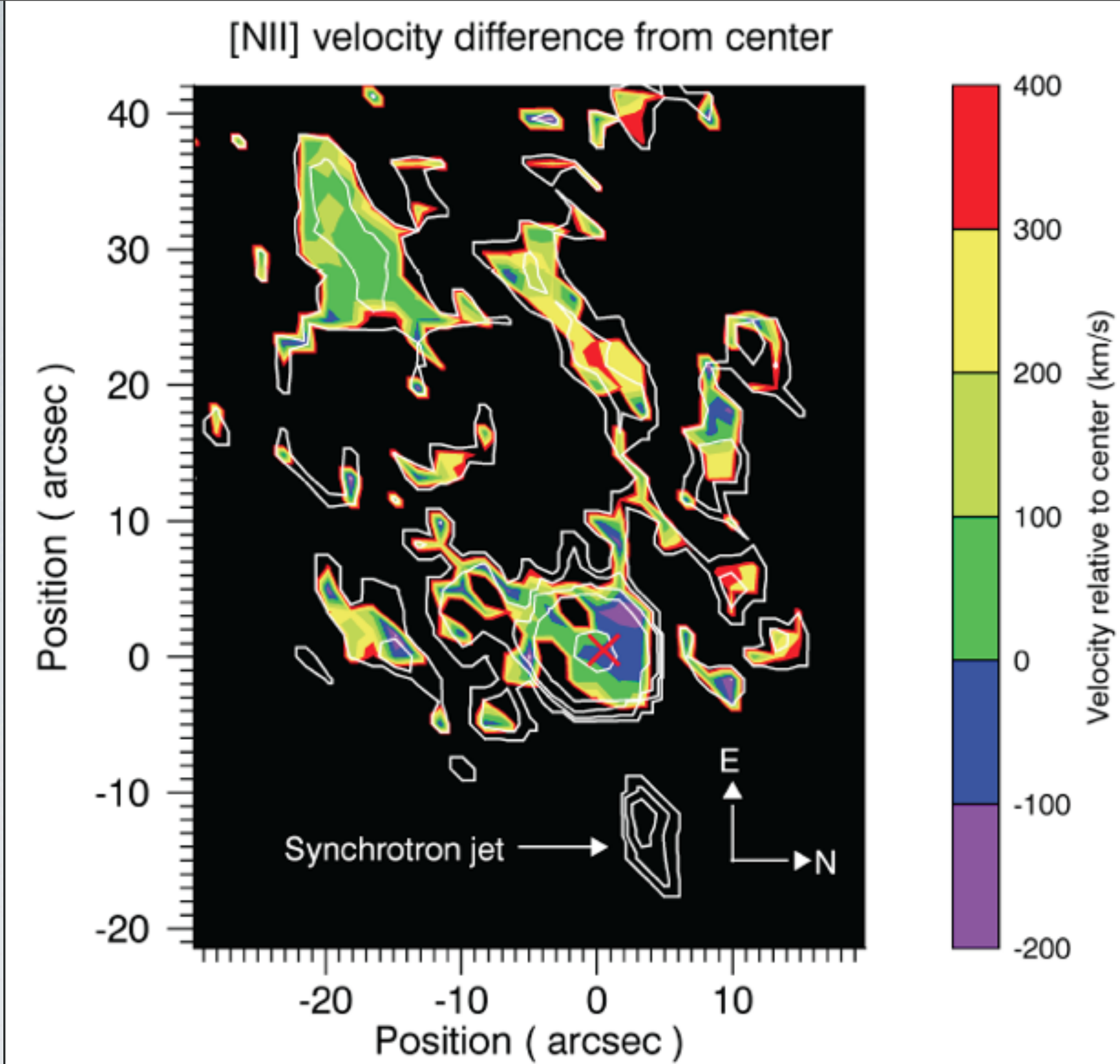


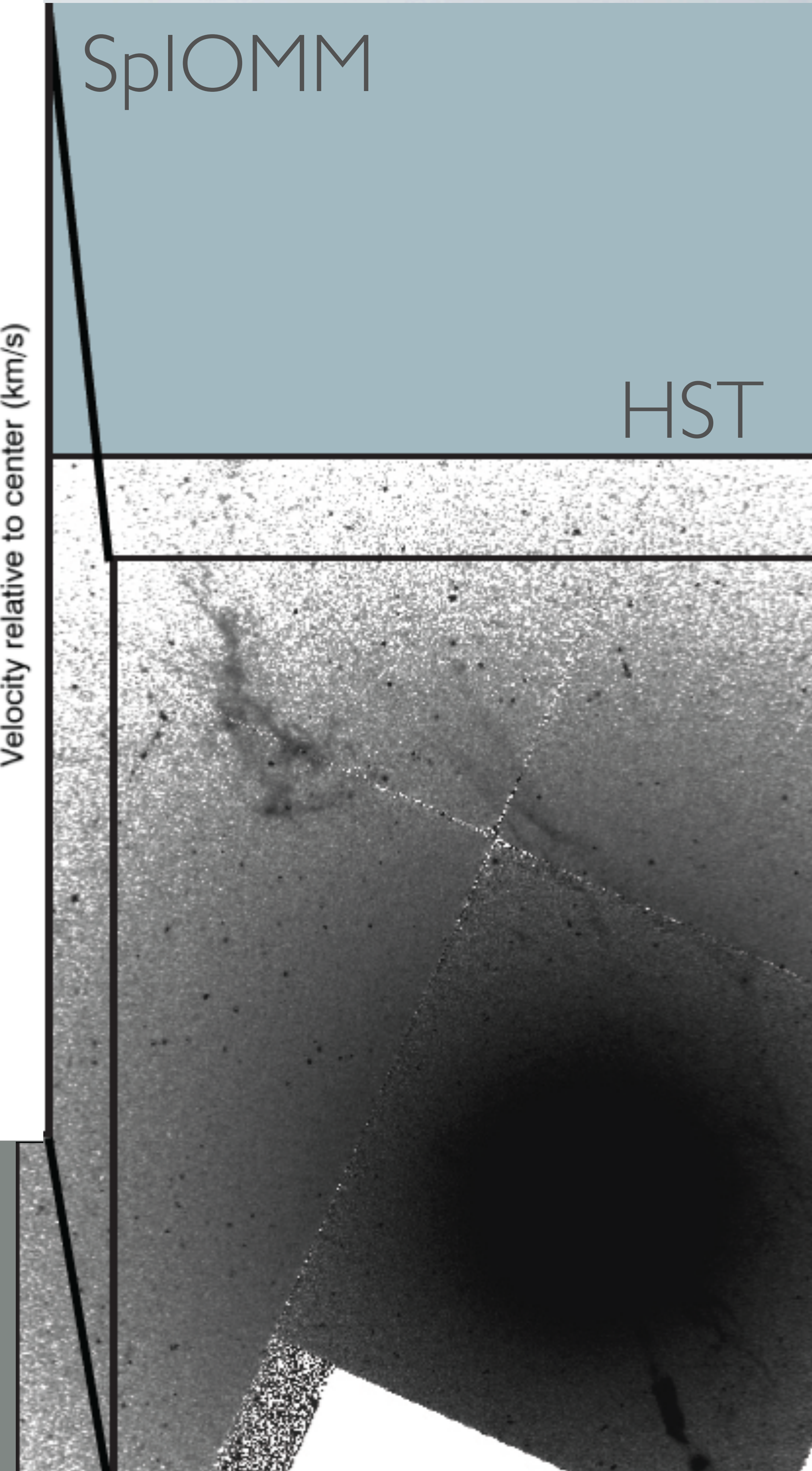
12+log(O/H)=8.90+0.57*LOG(NII/Hα)
12+log(O/H)=8.73-0.32*LOG((OIII/Hβ)/(NII/Hα))
(Pettini & Pagel 2004)




Doppler

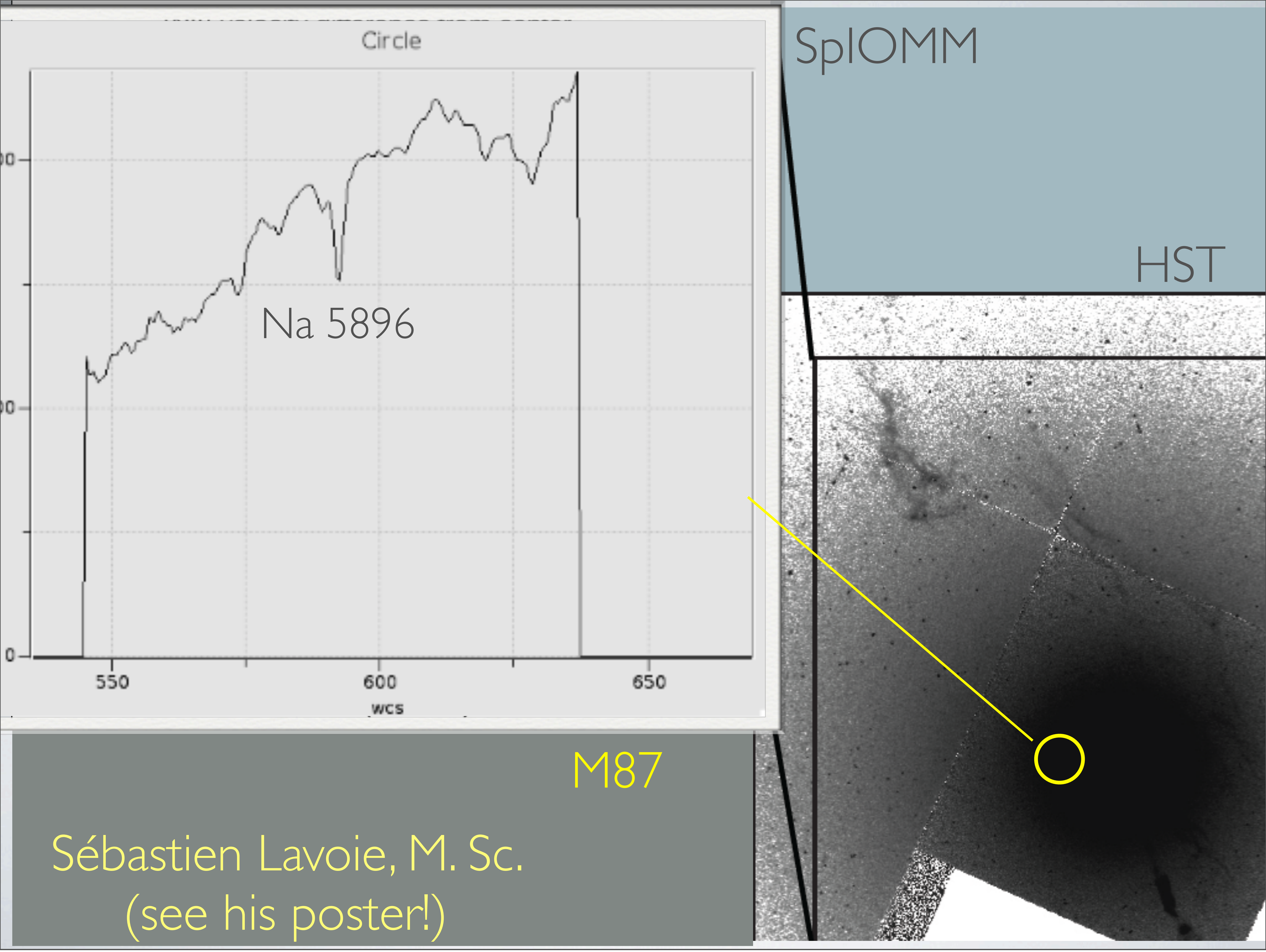

Doppler
[NII]/Ha





M87

Sébastien Lavoie, M. Sc.
(see his poster!)



Circle
Na 5896
550
600
650
wcs
0
SpIOMM
HST
M87
Sébastien Lavoie, M. Sc.
(see his poster!)

CHAPTER III - SITELLE

Spectromètre **I**mageur à **T**ransformée (de Fourier) pour l'**E**tude en **L**ong et en **L**arge (de raies d') **E**mission

SITELLE team

Université Laval

Laurent Drissen (PI)
Simon Thibault (opt. design)
Thomas Martin (software)
Carmelle Robert
Gilles Joncas
Denis Brousseau
Alexandre Alarie, Sébastien Lavoie, Antoine Bilodeau

ABB

Julie Mandar (Syst. Eng.)
Frédéric Grandmont (Syst. Eng.)
Guillaume Thériault (PM)
Éric Carbonneau, Marie-Ève Duplain, Louis-Philippe Bibeau, Fabien Lalisse,Martin Larouche, Patrick Gilbert, Sylvio Laplante, Hugo Savard, Steve Lévesque, Stéphane Lemelin

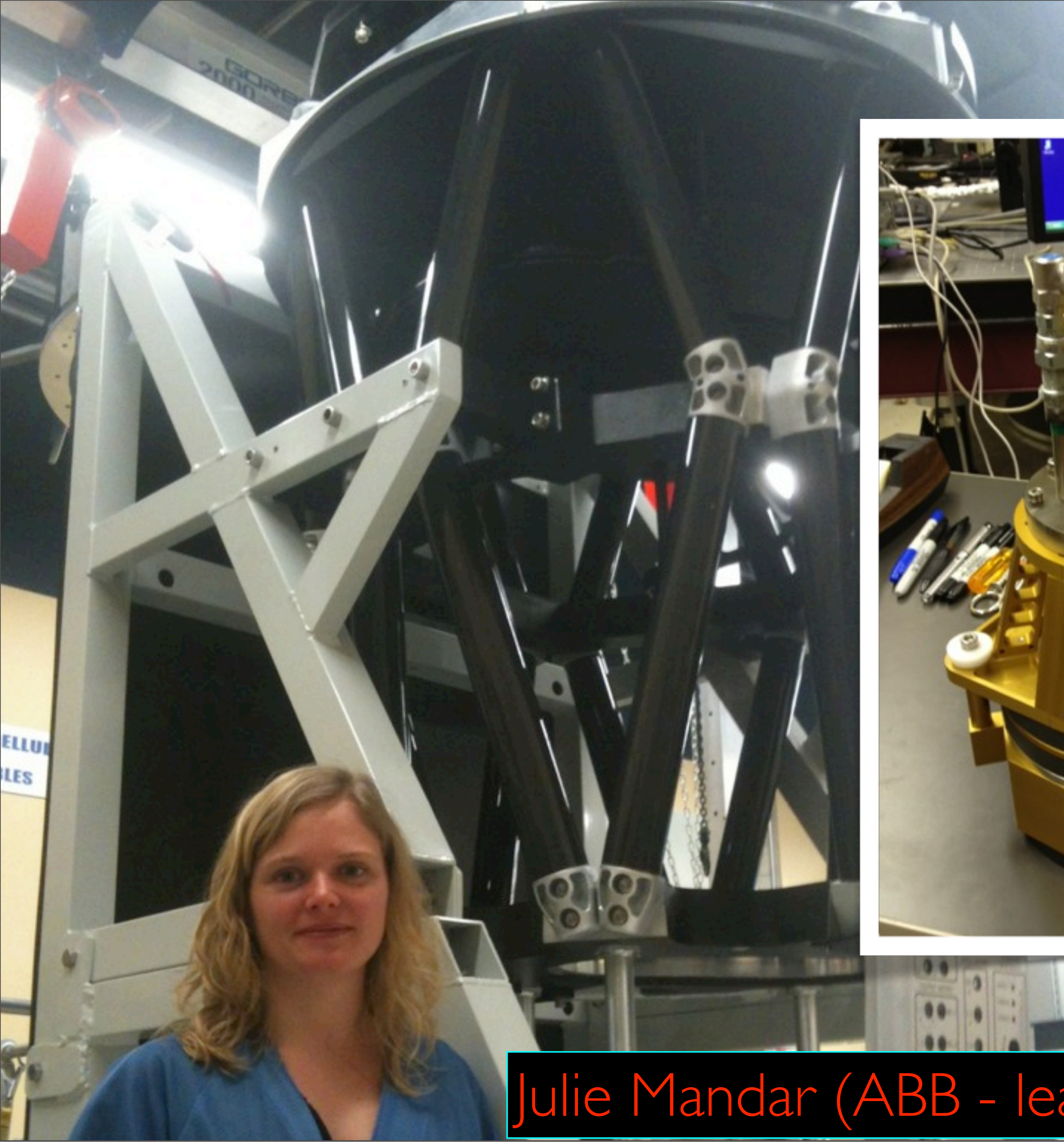
Université de Montréal

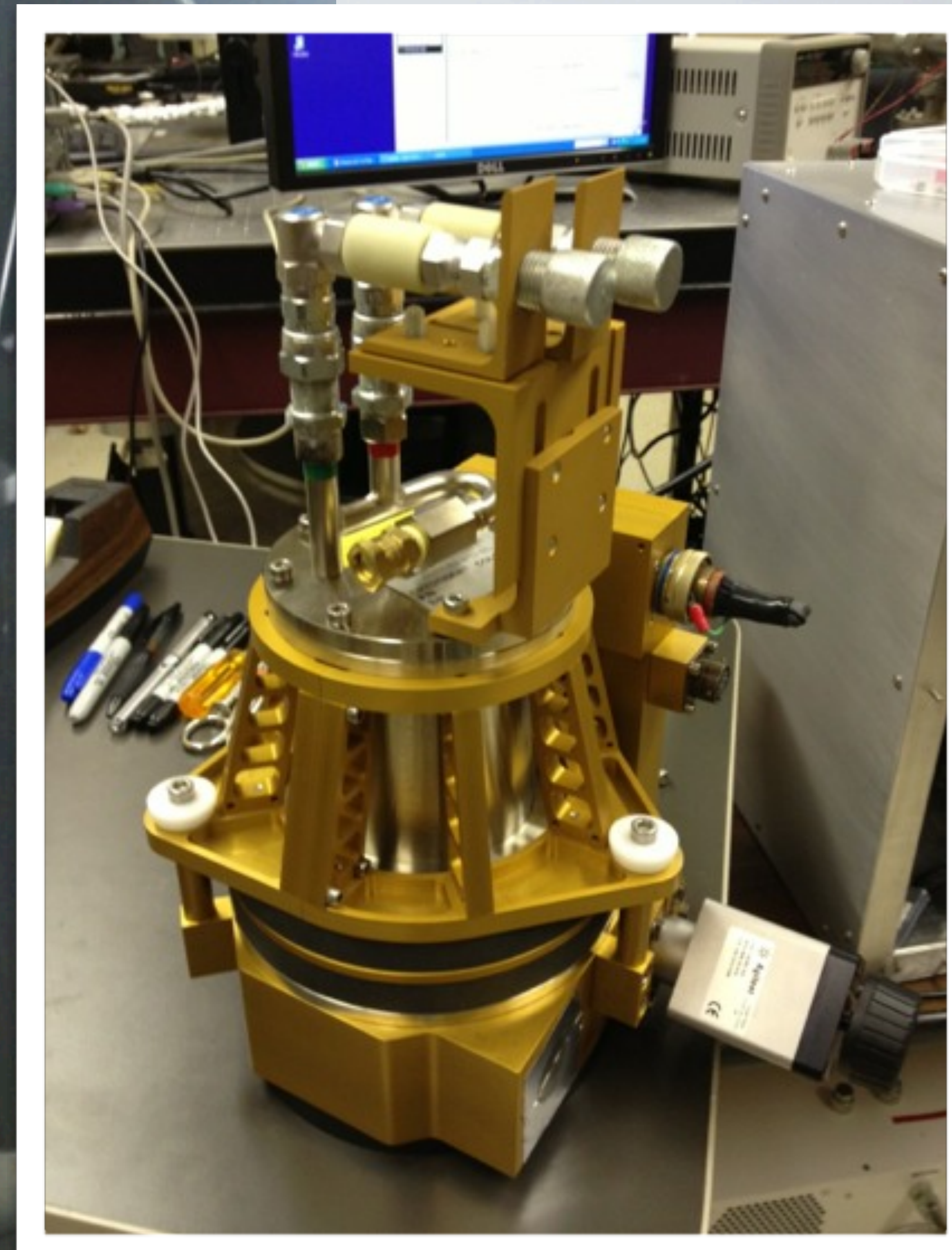
Philippe Vallée (opto-mechanics)
Olivier Hernandez ($$$)

CFH

Marc Baril
Kevin Ho
Tom Benedict
Greg Barrick
Glenn Morrison, Jim Thomas
Kanoa Withington,Daniel Devost

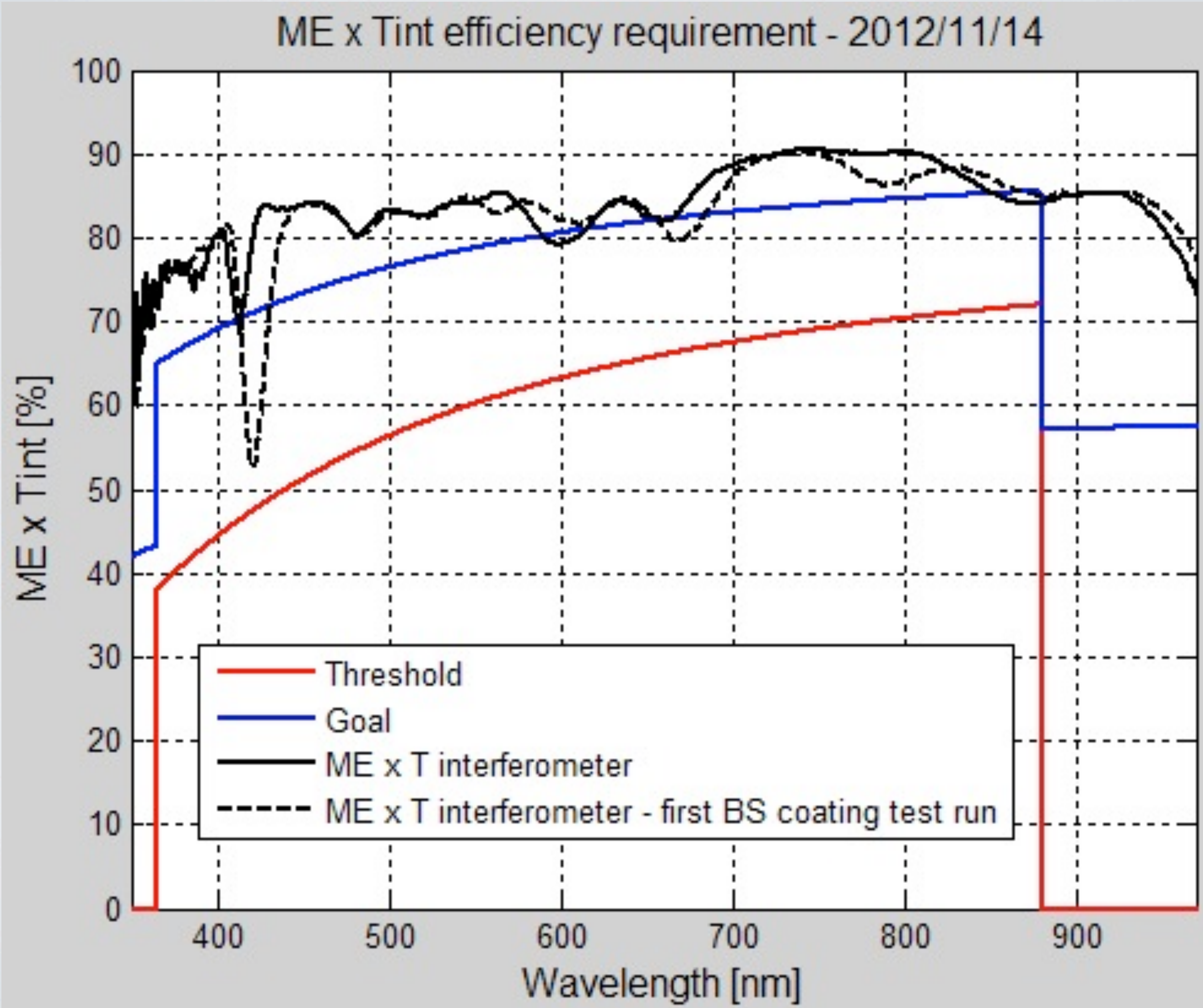
Julie Mandar (ABB - lead engineer)

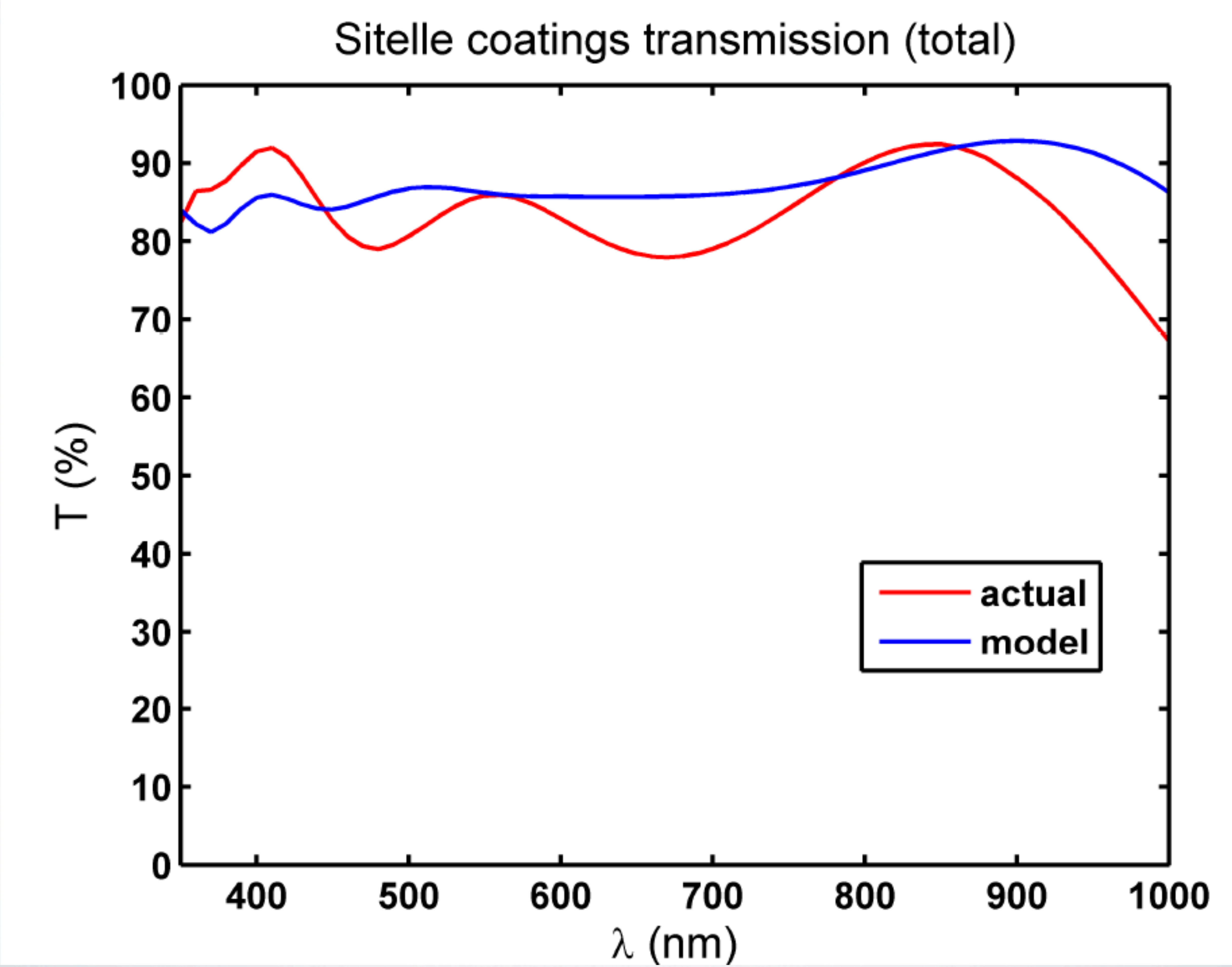




Julie Mandar (ABB - lead engineer)

Modulation efficiency





Sitelle coatings transmission (total)
T (%)
λ (nm)
actual
model
0
10
20
30
40
50
60
70
80
90
100
400
500
600
700
800
900
1000

e2v technologies

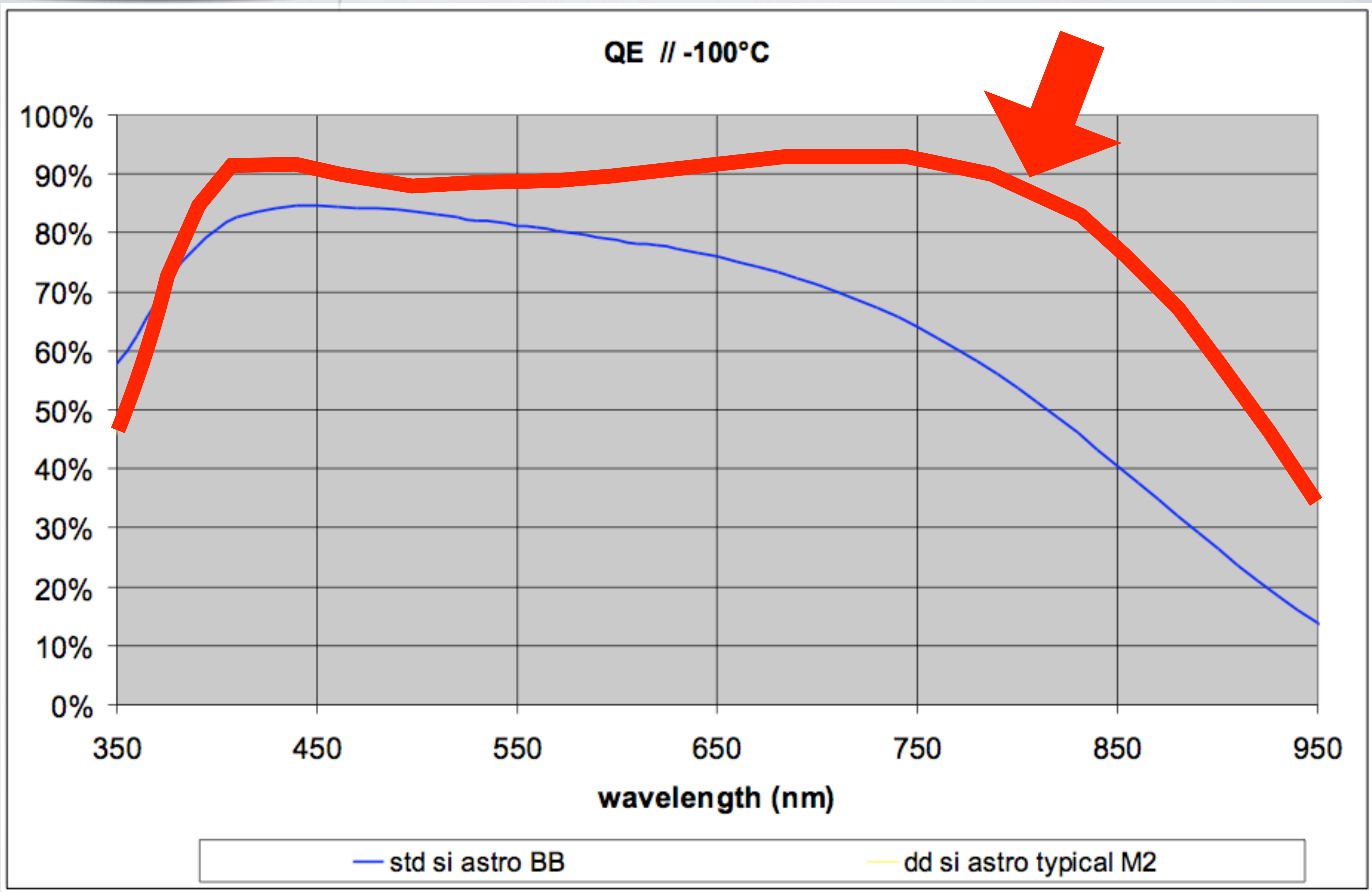
2k x 2k

ron: <4e

read time: 3s

QE @ 370 nm: 60%

low fringing in the red



2k x 2k
ron: <4e
read time: 3s

QE @ 370 nm: 60%
low fringing in the red

Olivier Hernandez
À : Laurent Drissen <Laurent.Drissen@phy.ulaval.ca> , Marc Baril , Julie A Mandar , Frederic Grandmont
Cc: sitelle-internal@cfht.hawaii.edu
CCD e2v ....

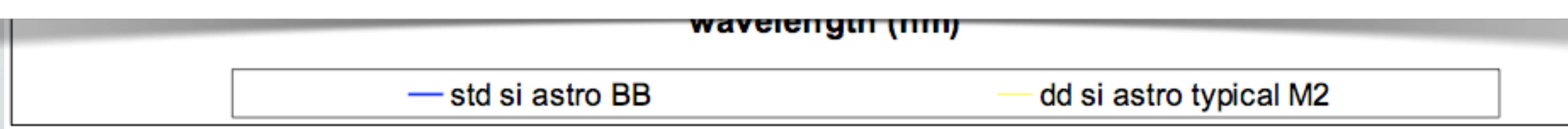
30 avril 2013 10:07
Boîte de réception - Compte POP

Dear All,

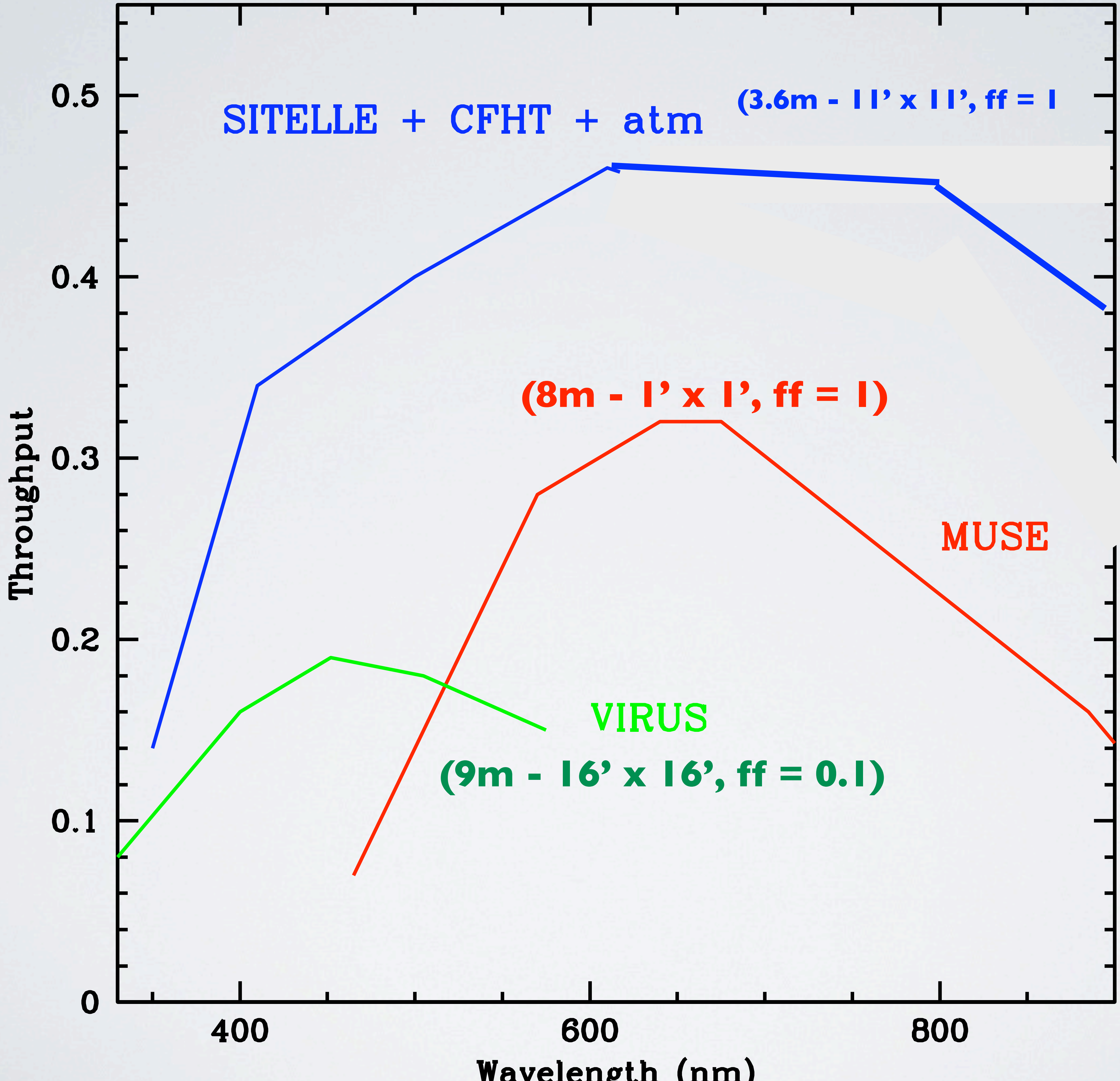
I hope that you did not have a heart attack while reading the subject of my email (;-)) but I'm happy to tell you that I have 2 brand new CCDs with the right coating in front of me ! The final destination was supposed to be CFHT but they are in Montréal. So I suggest either to bring them at the SITELLE workshop and to give them to Marc or to sent them directly to CFHT. What is your choice ?

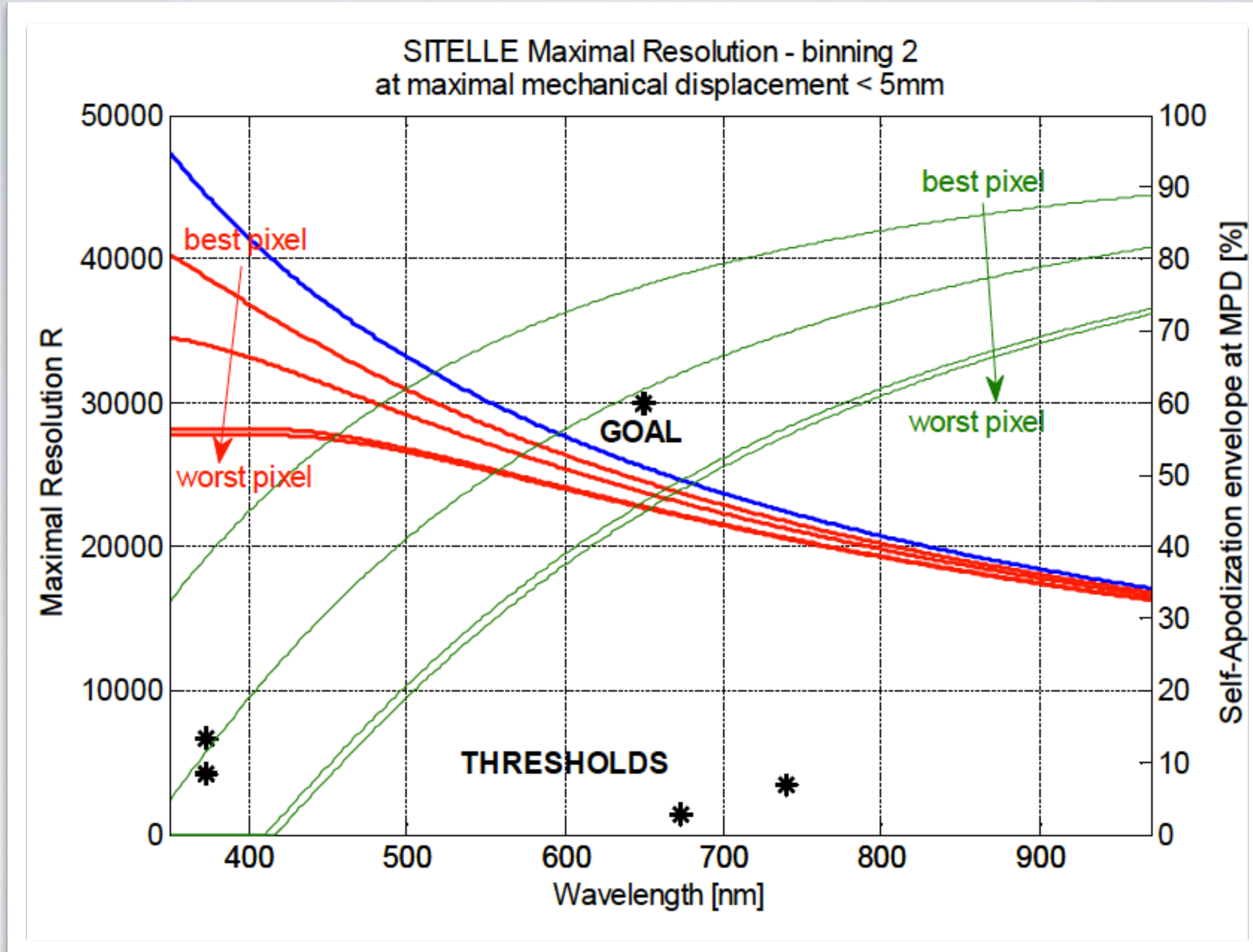
Cheers
Olivier

Dr Olivier Hernandez
Université de Montréal
CRAQ - Dep. Physique
CP 6128 succ. centre ville
Montréal H3C 3J7
Québec, Canada
Tél : 1-514-343-6111 #4681
P Avant d'imprimer, pensez à l'environnement.

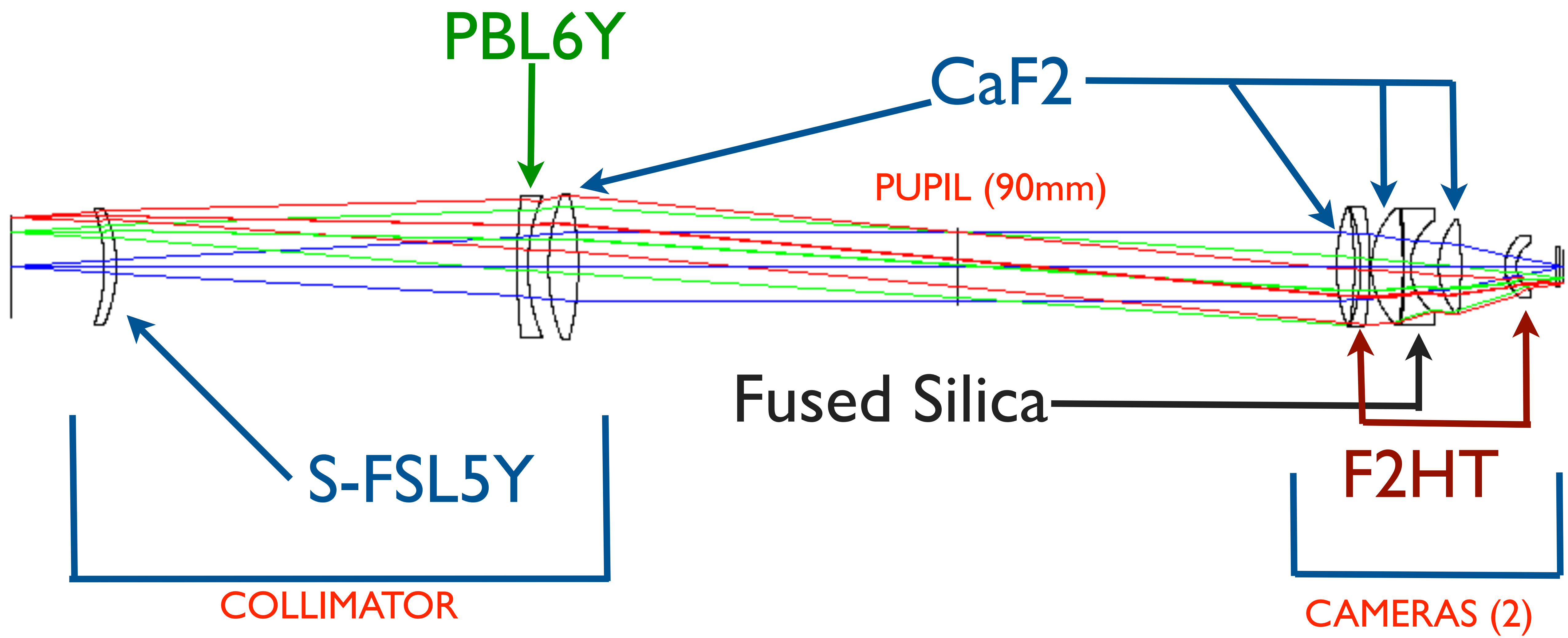


Comparison - throughput

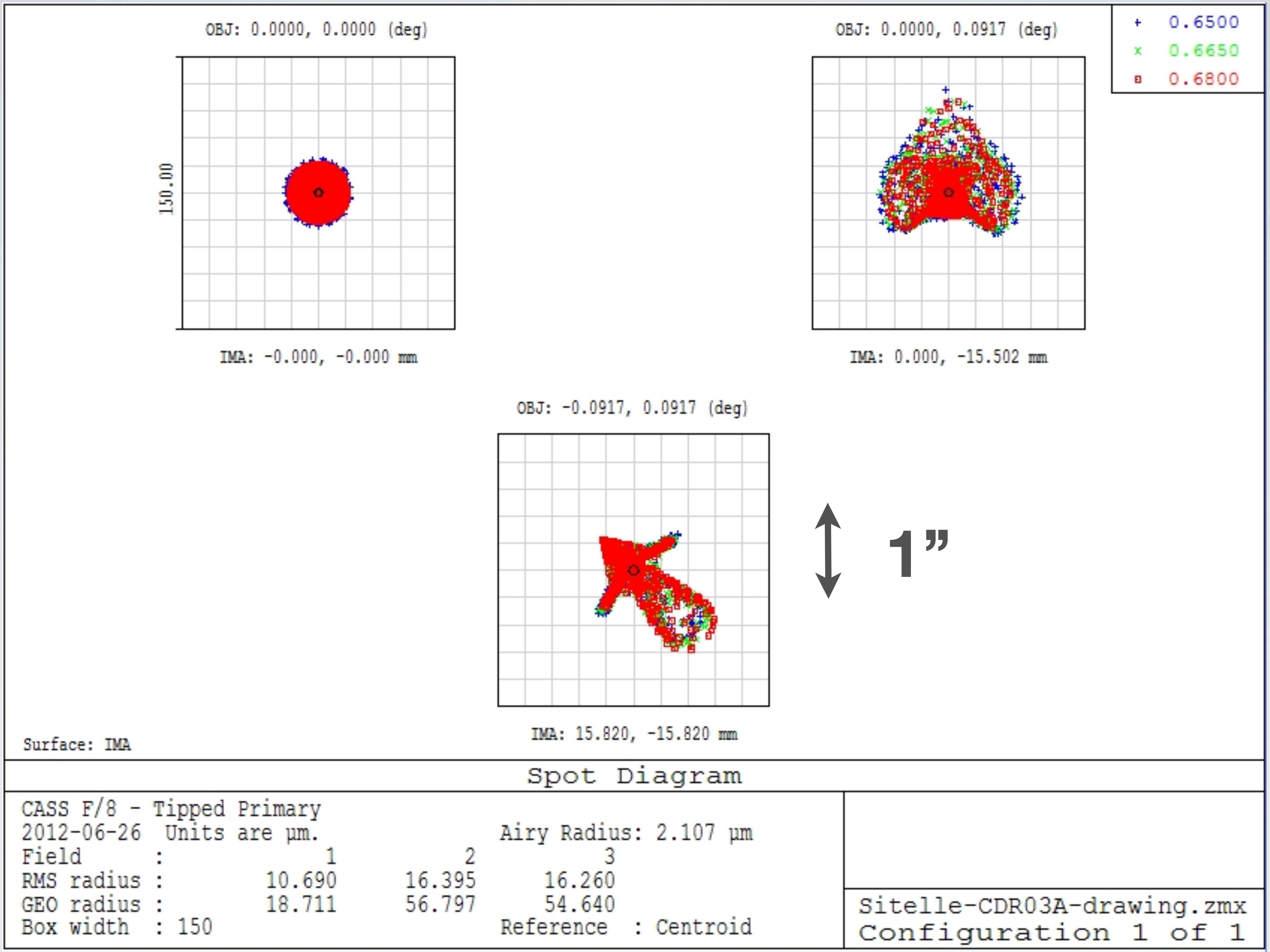



SITELLE Maximal Resolution - binning 2
at maximal mechanical displacement < 5mm
Maximal Resolution R
Self-Apodization envelope at MPD [%]
Wavelength [nm]
best pixel
worst pixel
best pixel
worst pixel
GOAL
THRESHOLDS
50000
40000
30000
20000
10000
0
400
500
600
700
800
900
100
90
80
70
60
50
40
30
20
10
0

Optical design (Simon Thibault, U. Laval)



FBFL: 43mm (BFL = 62mm)
Collimated space: 510mm/510mm
Collimator: 752mm
Camera: 319mm

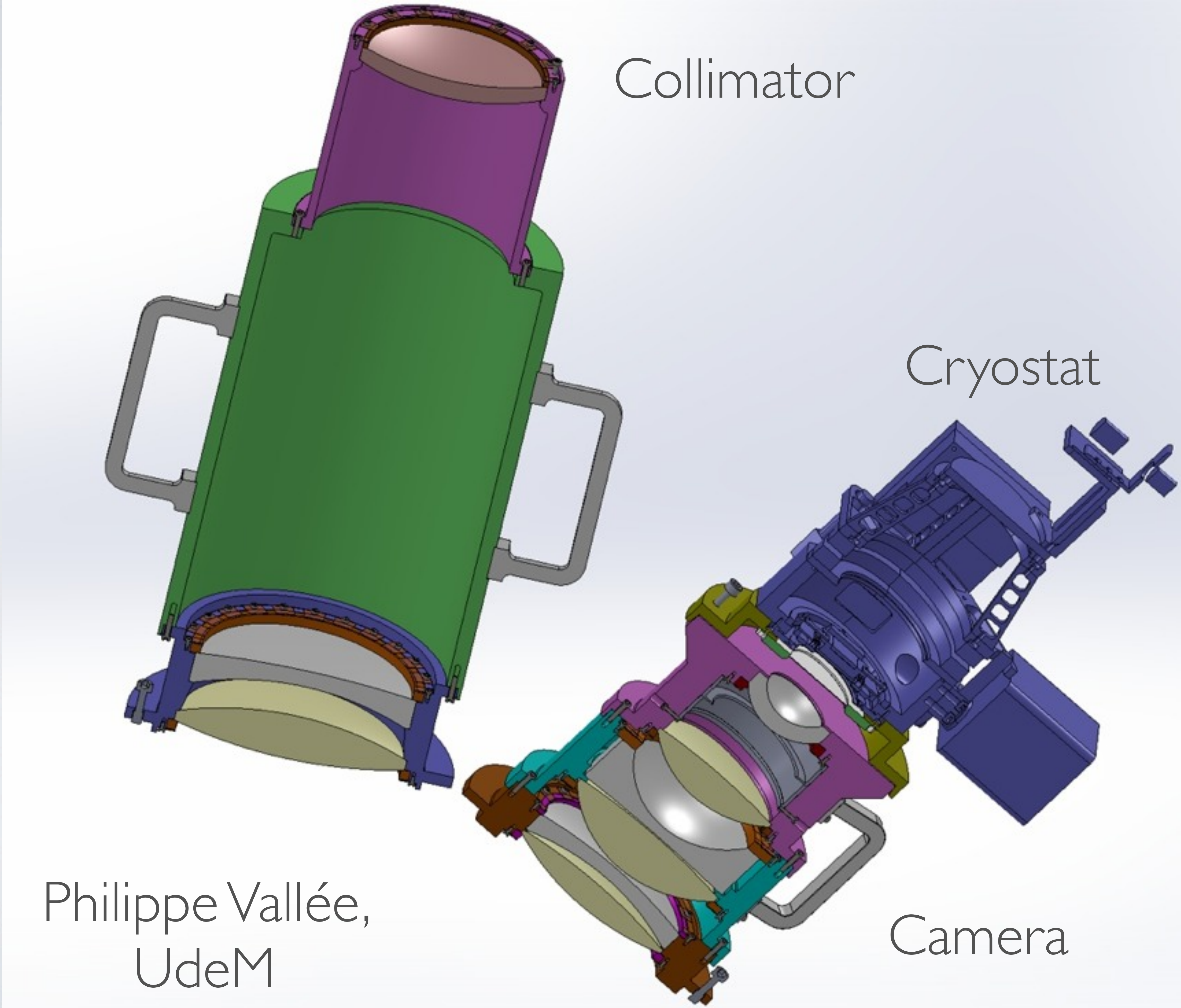


10 pixels X 10 pixels

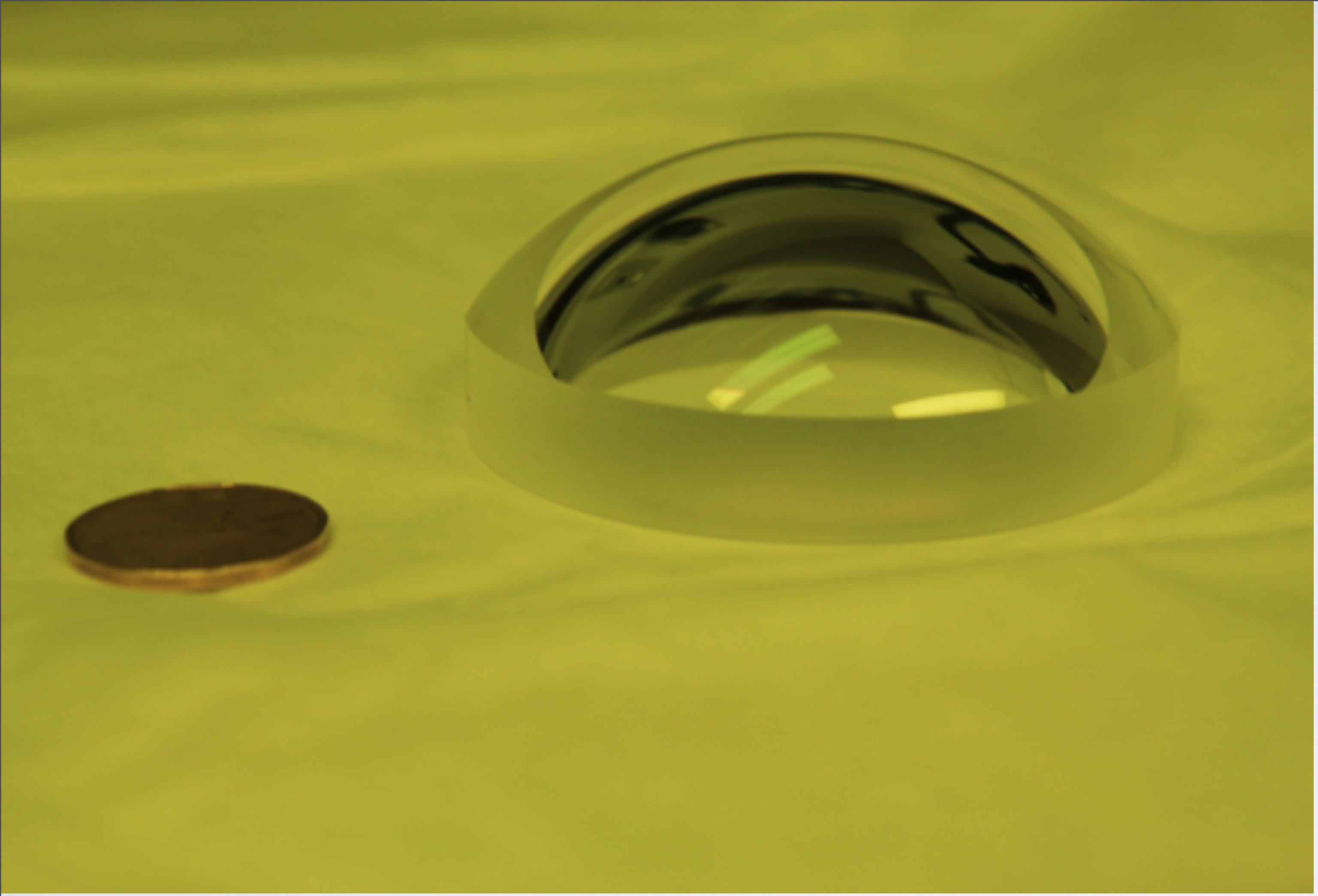
Waveband 650-680nm

FHWM < 0.4″ — <0.7'' for wide bands (200 nm) across the visible

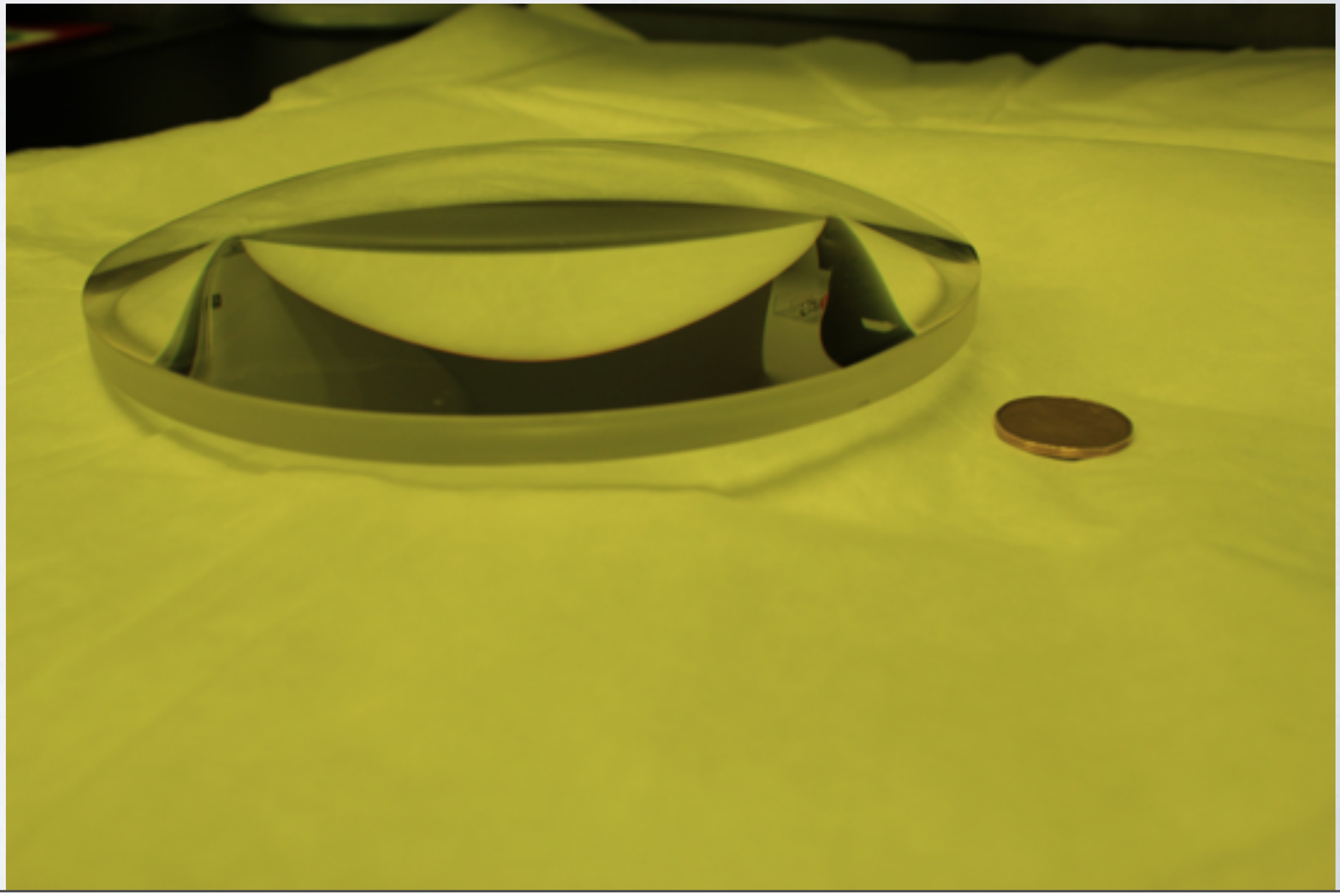
FOV: 11′X11′


Collimator
Cryostat
Camera
Philippe Vallée,
UdeM

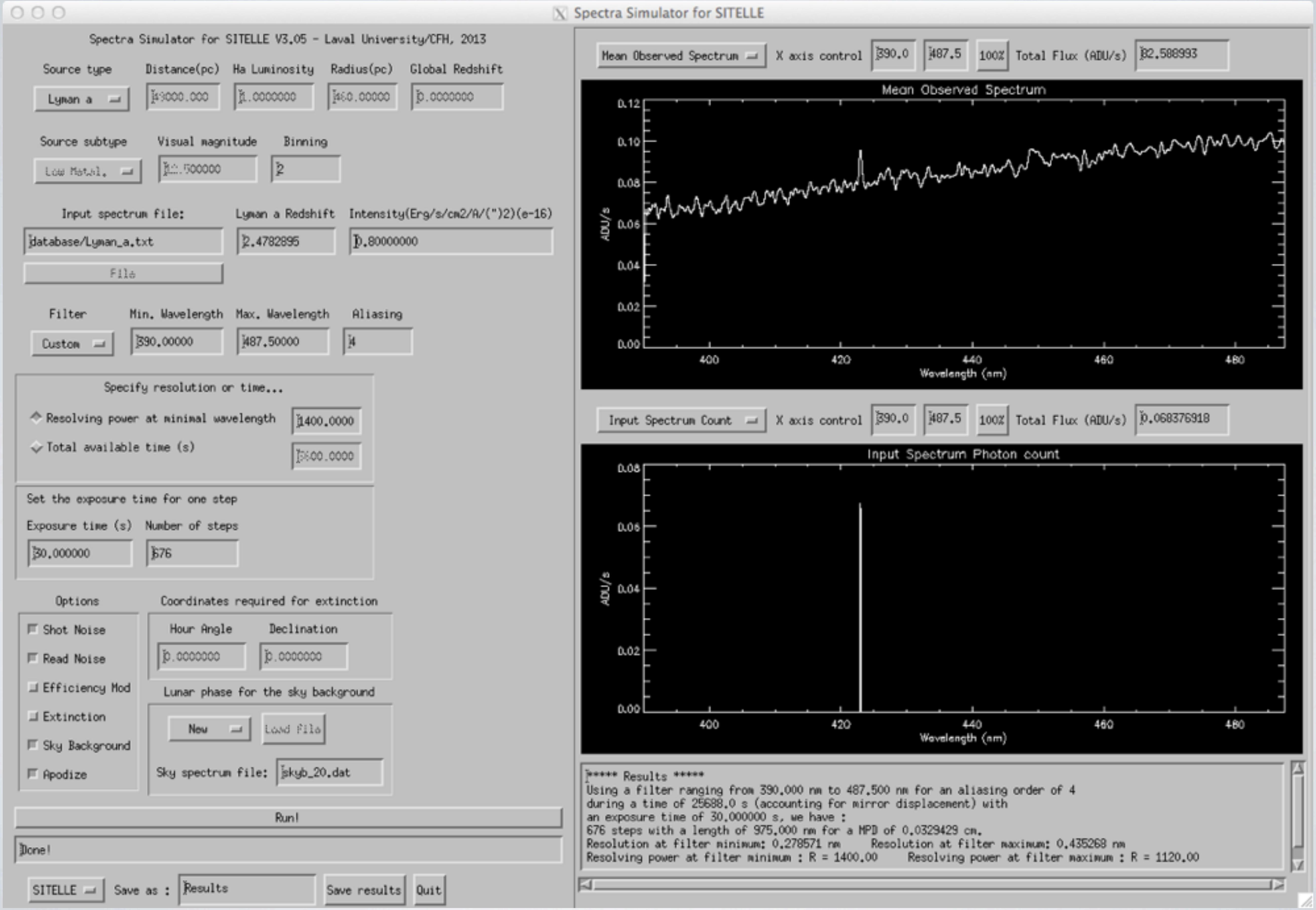
In the lab at UdeM, April 30th



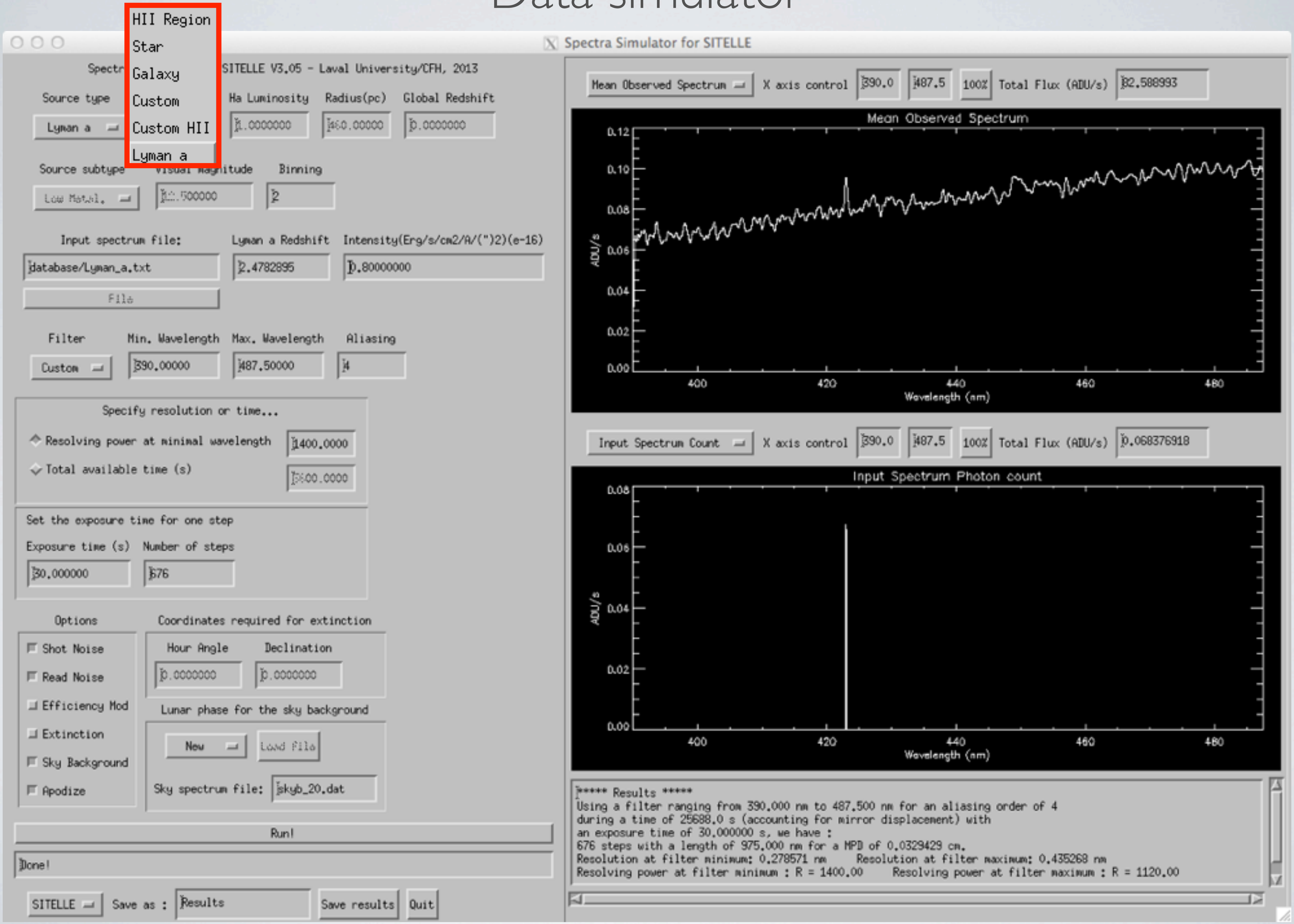
Some lenses...
(Laval, COPL)



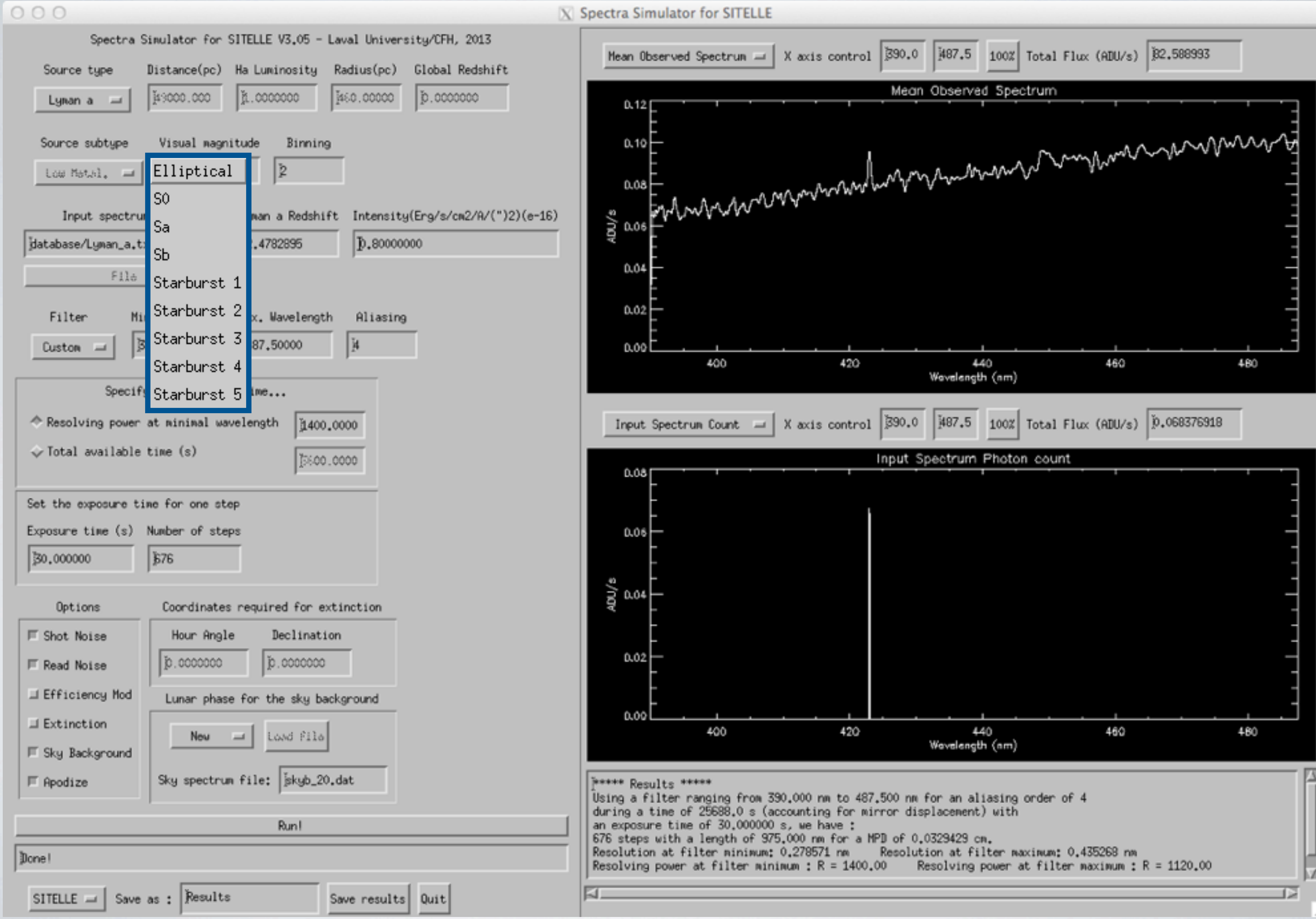
Data simulator



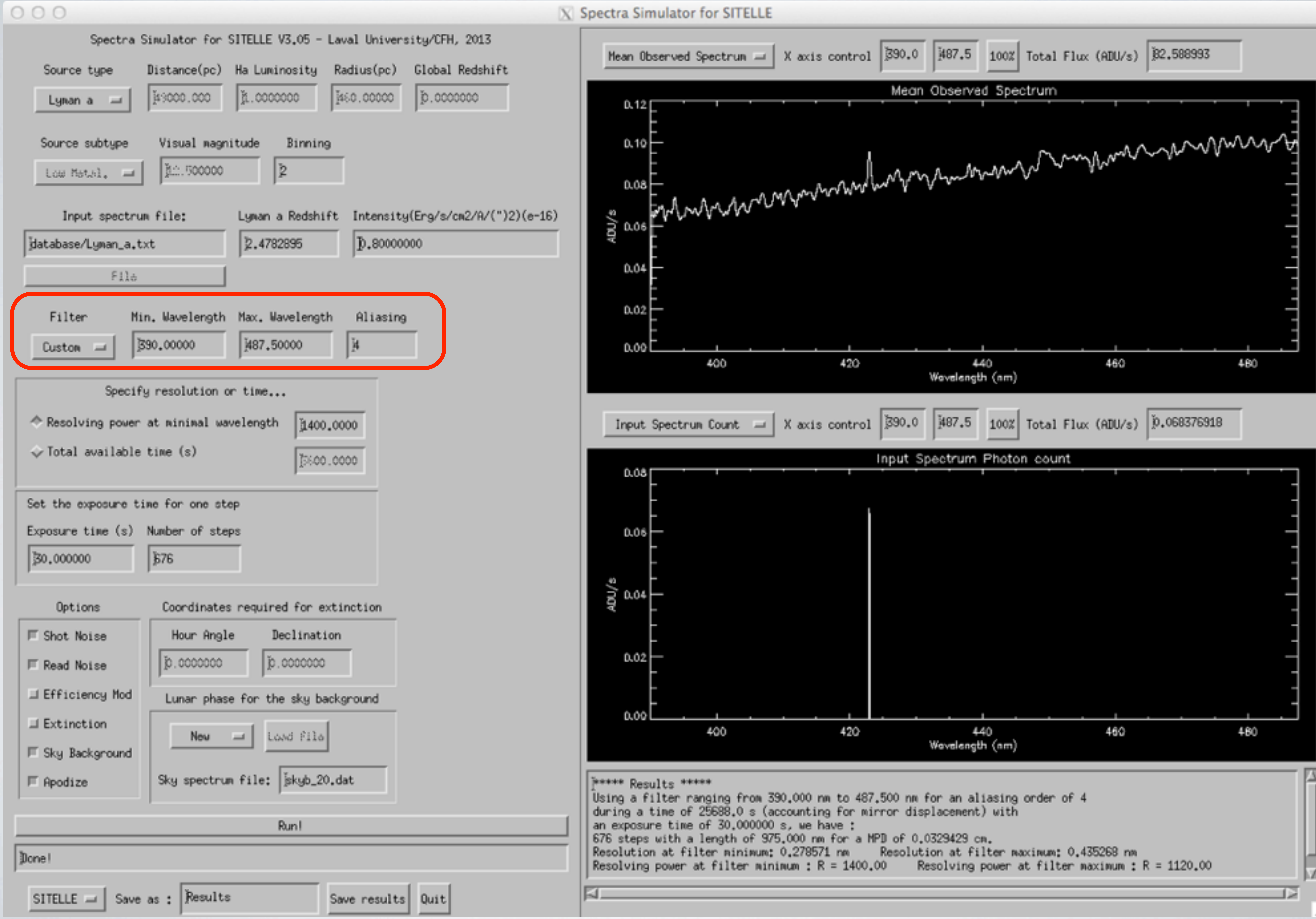
Data simulator



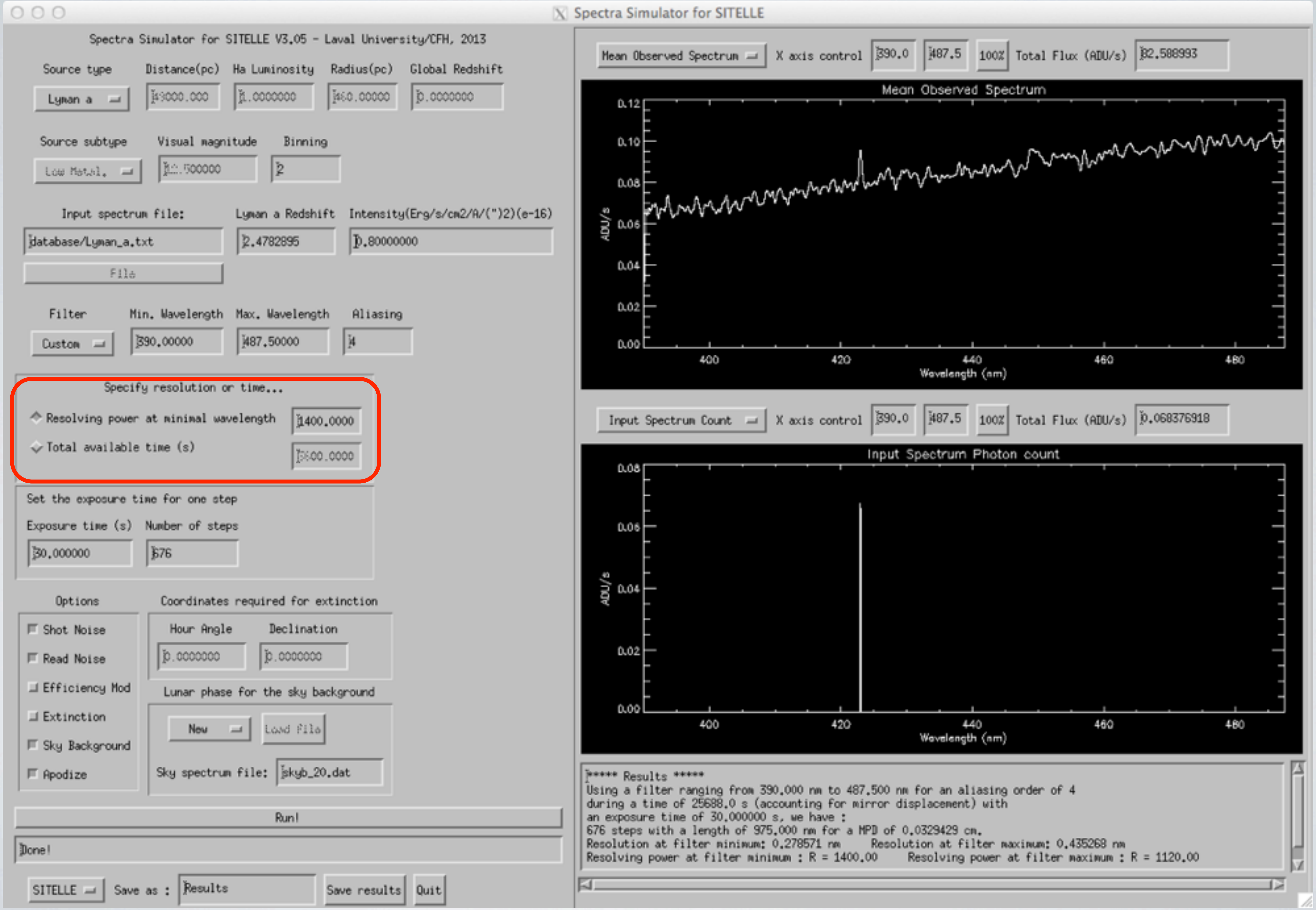
Data simulator



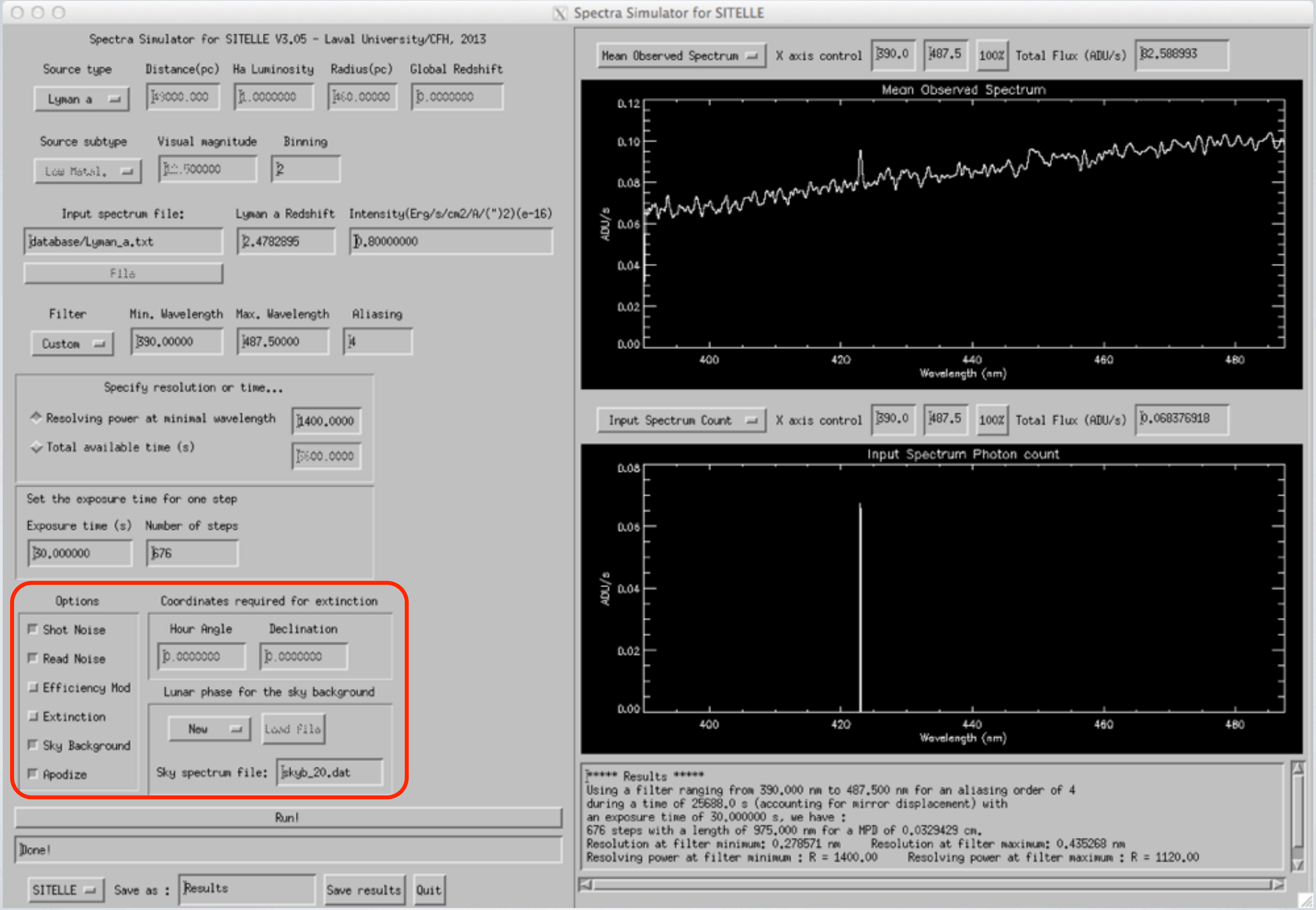
Data simulator



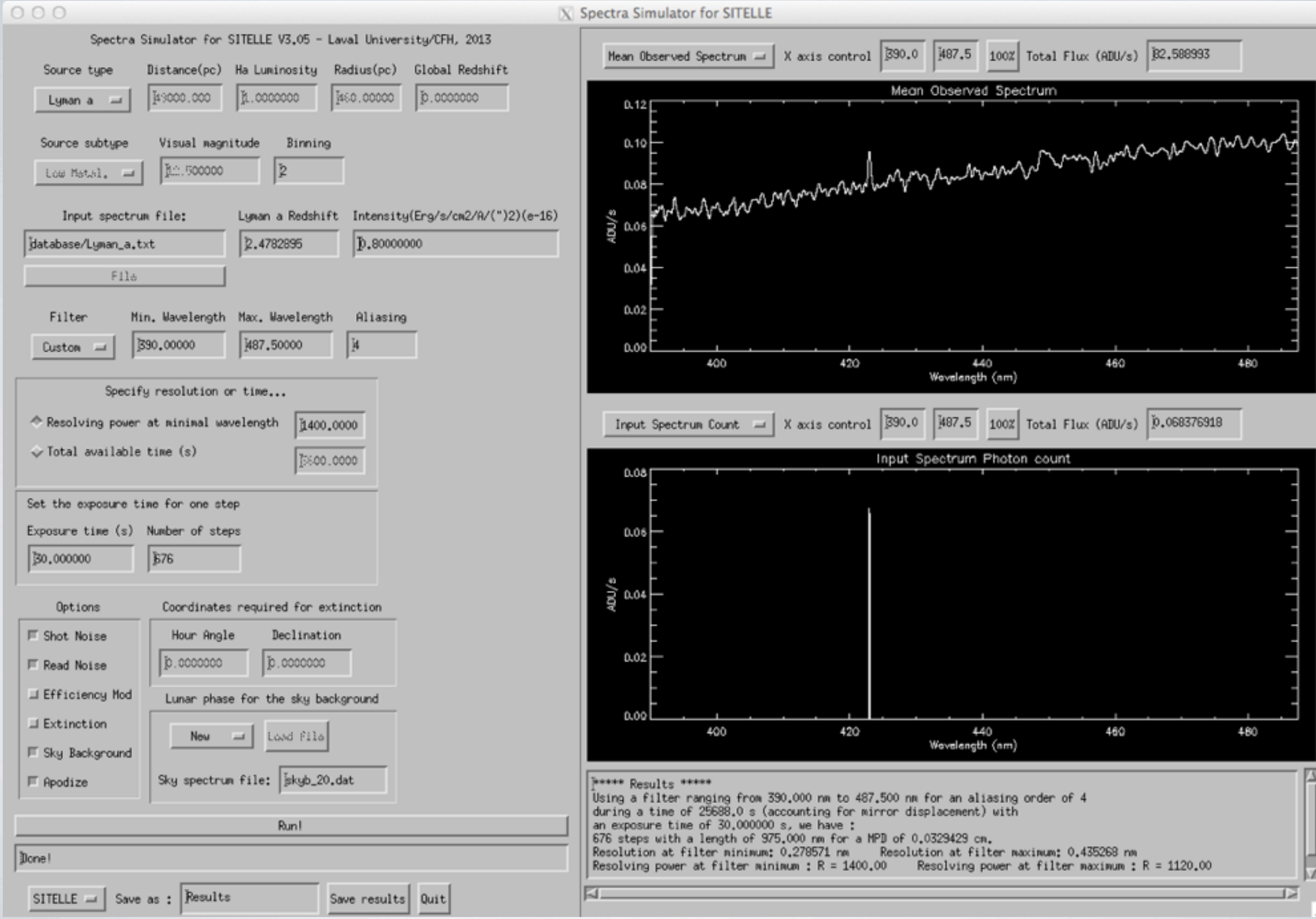
Data simulator



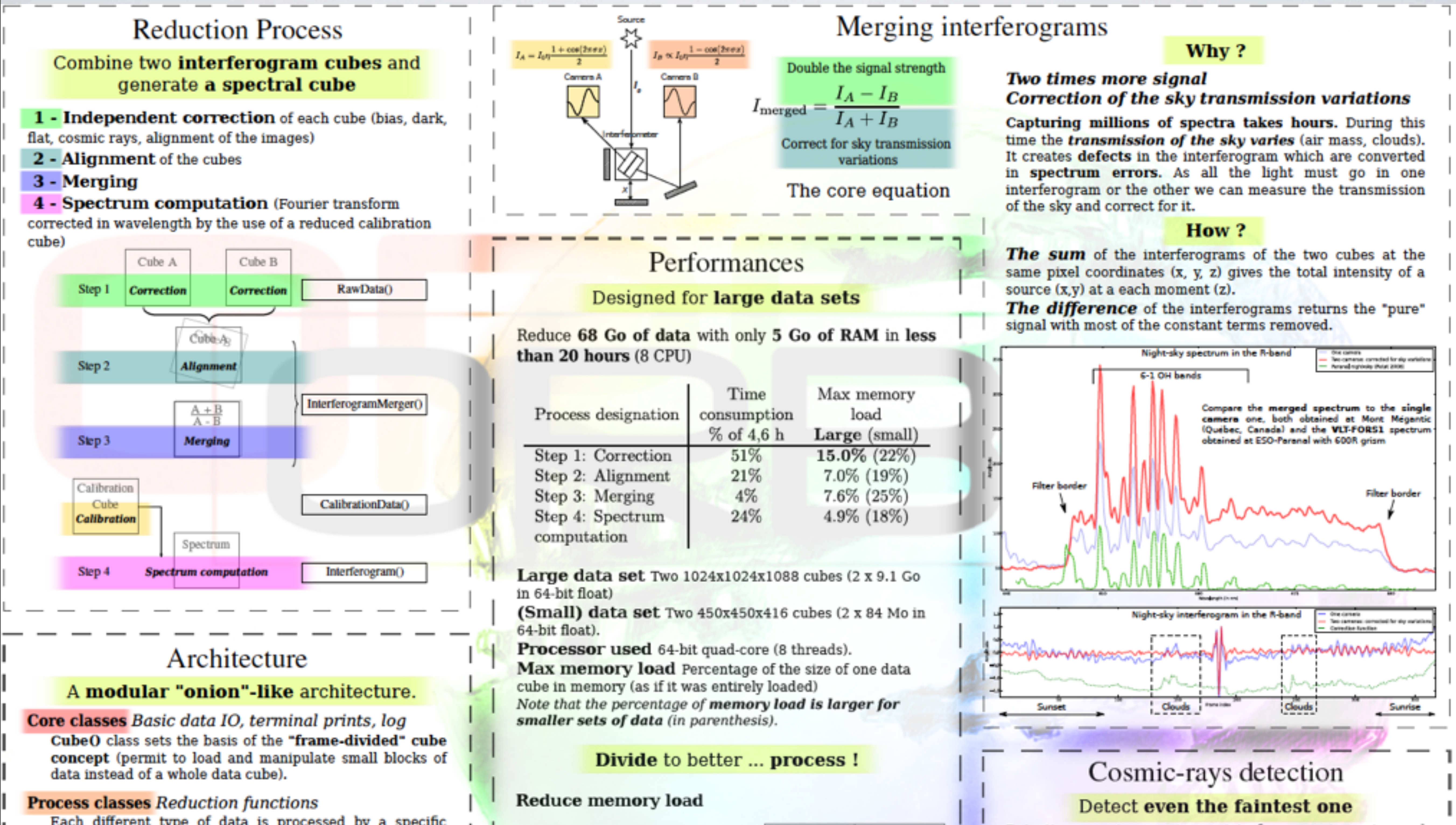
Data simulator



Data simulator



Data reduction: ORBS (Thomas Martin, Laval)



Reduction Process

Combine two **interferogram cubes** and generate **a spectral cube**

1 - Independent correction of each cube (bias, dark, flat, cosmic rays, alignment of the images)

2 - Alignment of the cubes

3 - Merging

4 - Spectrum computation (Fourier transform corrected in wavelength by the use of a reduced calibration cube)

Architecture

A **modular "onion"-like** architecture.

Core classes *Basic data IO, terminal prints, log*

Cube() class sets the basis of the **"frame-divided" cube concept** (permit to load and manipulate small blocks of data instead of a whole data cube).

Process classes *Reduction functions*

Each different type of data is processed by a specific

Merging interferograms

$I_A = I_{(\sigma)}\frac{1+\cos(2\pi\sigma x)}{2}$ $I_B \propto I_{(\sigma)}\frac{1-\cos(2\pi\sigma x)}{2}$

Double the signal strength

$$I_{\text{merged}} = \frac{I_A - I_B}{I_A + I_B}$$

Correct for sky transmission variations

The core equation

Why ?

Two times more signal

Correction of the sky transmission variations

Capturing millions of spectra takes hours. During this time the ***transmission of the sky varies*** (air mass, clouds). It creates **defects** in the interferogram which are converted in **spectrum errors**. As all the light must go in one interferogram or the other we can measure the transmission of the sky and correct for it.

How ?

The sum of the interferograms of the two cubes at the same pixel coordinates (x, y, z) gives the total intensity of a source (x,y) at a each moment (z).

The difference of the interferograms returns the "pure" signal with most of the constant terms removed.

Performances

Designed for **large data sets**

Reduce **68 Go of data** with only **5 Go of RAM** in **less than 20 hours** (8 CPU)

Process designation	Time consumption % of 4,6 h	Max memory load **Large** (small)
Step 1: Correction	51%	**15.0%** (22%)
Step 2: Alignment	21%	7.0% (19%)
Step 3: Merging	4%	7.6% (25%)
Step 4: Spectrum computation	24%	4.9% (18%)

Large data set Two 1024x1024x1088 cubes (2 x 9.1 Go in 64-bit float)

(Small) data set Two 450x450x416 cubes (2 x 84 Mo in 64-bit float).

Processor used 64-bit quad-core (8 threads).

Max memory load Percentage of the size of one data cube in memory (as if it was entirely loaded)

*Note that the percentage of **memory load is larger for smaller sets of data** (in parenthesis).*

Divide to better ... **process !**

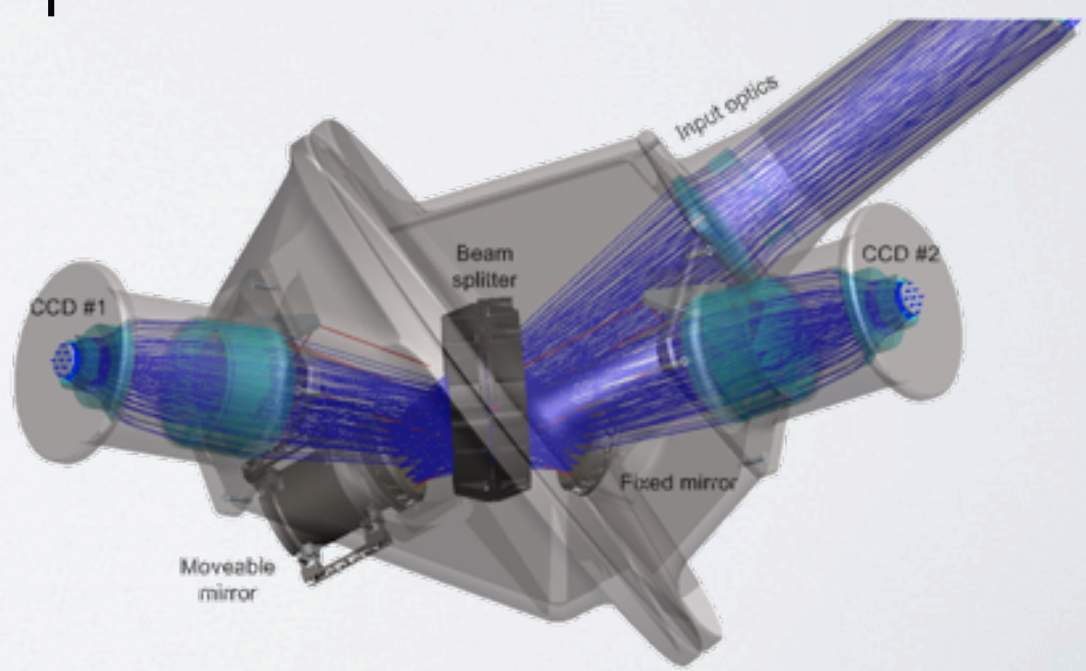
Reduce memory load

Cosmic-rays detection

Detect **even the faintest one**

Status of SITELLE

* Funded by CFI (2.8 M$ out of 11.7M$, R. Doyon PI) 2009
* Preliminary design review: February 2012 ✓
* Critical design review: 27 - 28 June 2012 ✓
* Assembly started in September 2012 ✓
    - Global structure
    - Interferometer
    - Optics
    - CCDs
    - Software



Status of SITELLE

Canada-France-Hawaii Telescope Corporation
65-1238 Mamalahoa Highway
Kamuela, Hawaii, USA 96743
808 885-7944

Summer 2013!

SITELLE Acceptance Testing and Commissioning Plan

Document revision: April 17, 2013

* Delivery date to CFHT: Early fall 2013
* Commissioning: fall 2013
* Shared-risk : 2014A?

Pros & Cons of SITELLE

[OII] 3727, z ~ 0 - 0.8
Ly alpha, z ~ 1.8 ~ 4

Pros:

* Wide Field of View IFU
* High troughput, from 350 to 950 nm
* No need for image reconstruction
* Deep image + one spectrum for every pixel
* Very flexible in terms of spectral & spatial resolution

[Unbeatable for extended, emission-line sources]

Cons:

* Compromise between simultaneous spectral coverage and spectral resolution
* Distributed noise (not optimal for absorption)

[Not good for individual stars]

SITELLE science workshop
Wendake (Québec), 11 - 14 May 2013

** An introduction to imaging FTS
** SITELLE's capabilities
** CFHT plans for SITELLE (commissionning, shared risk, call for proposals, large projects, ...)
** Science: ISM, nearby galaxies, galaxy clusters, cosmology
** A visit to ABB (SITELLE testing)
** Choice of filters
** Everyone welcome!

SITELLE science workshop
Wendake (Québec), 11 - 14 May 2013

Patrick Côte (NRC, Victoria)
Stellar Systems in the Nearby Universe : Possible Opportunities for **SITELLE**

Anne-Laure Melchior (LERMA)
Gas Fueling of the Andromeda's Nucleus

Glenn Morrison (CFHT) et al.
Abell 1882: Kpc-scale Spatially Resolved Star formation on a z=0.14 « Proto-cluster »

Vinicius de A. Oliveira (Unipampa, Brasil)
Electron Temperature Fluctuations in Gaseous Nebulae

Eric Peng *Dynamical Studies of Nearby Galaxies*

ADDITIONAL SLIDES


Frédéric Grandmont
(Ph. D. 2006)


Maxime Charlebois
(M. Sc. 2008)


Anne-Pier Bernier
(Ph. D.)


Élaine Brière
(M. Sc. 2009)


Alexandre Alarie
(M. Sc. → Ph. D)


Antoine Bilodeau
(B. Sc.)


Jean-François Rochon
(M. Sc. 2006)


Sébastien Lavoie
(M. Sc.)

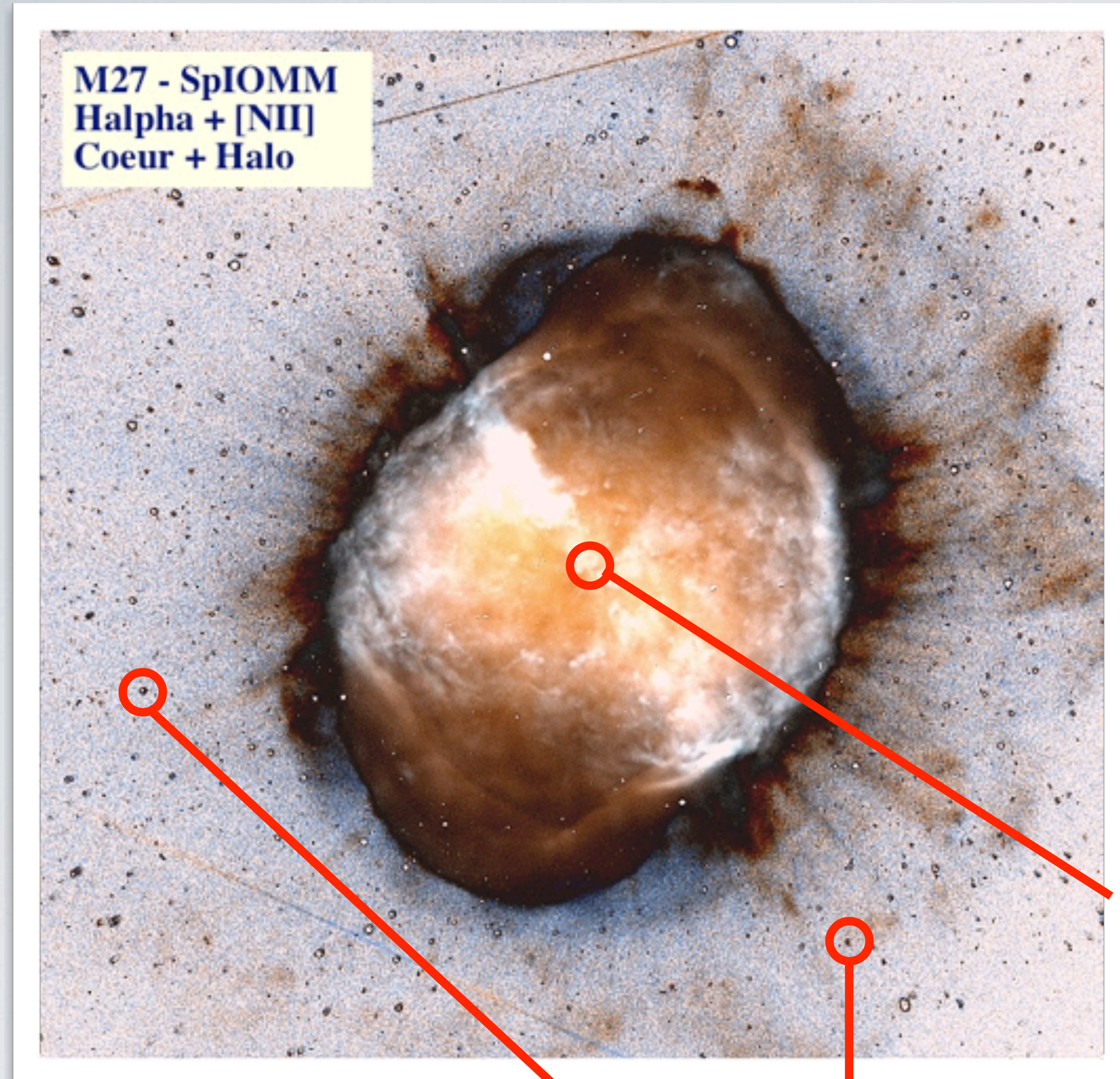

Julie Mandar
(M. Sc. 2011)

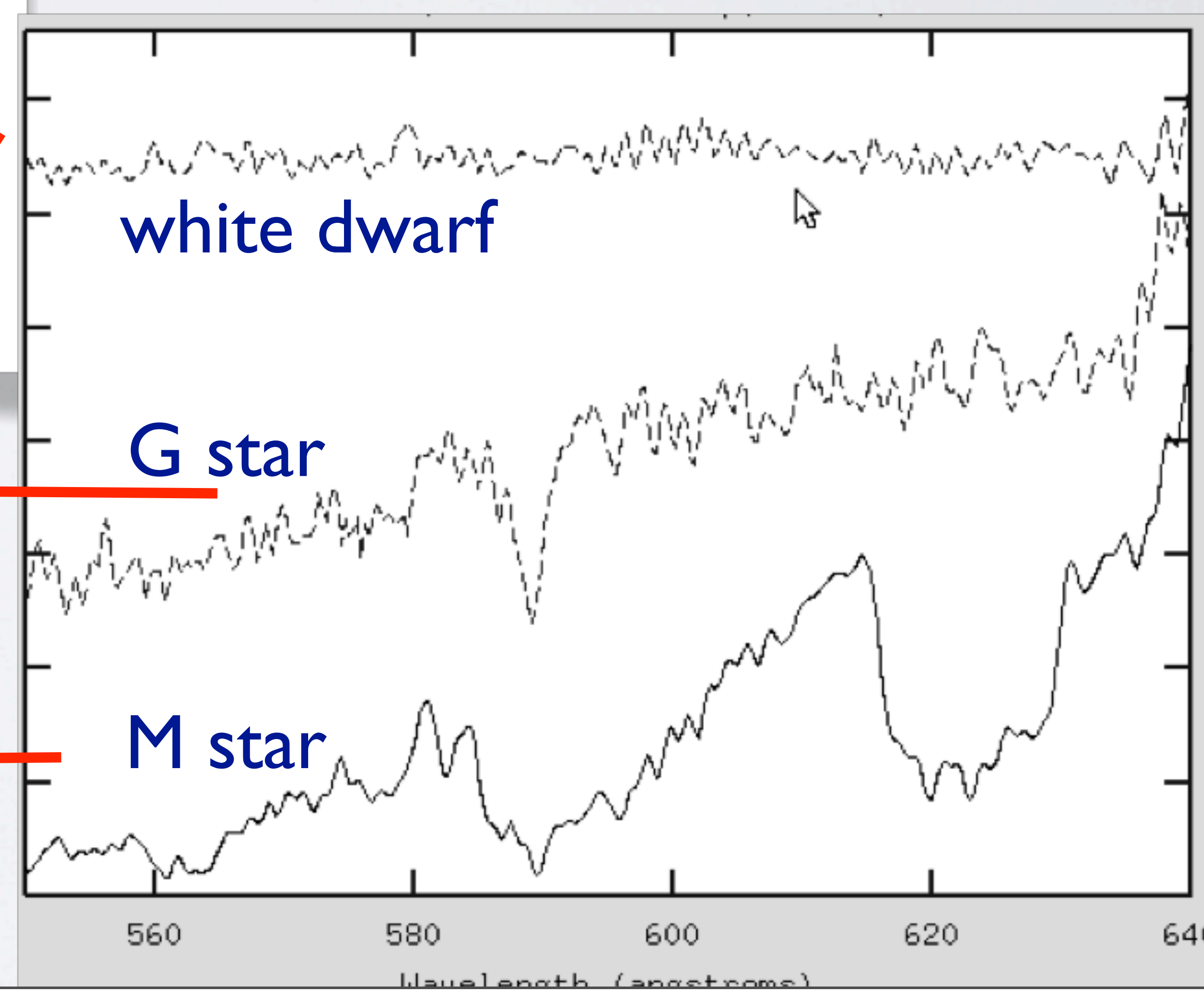

Thomas Martin
(Ph. D.)


Laurie Rousseau-Nepton
(Ph. D.)


Jean-François Lavigne
(M. Sc. 2004)

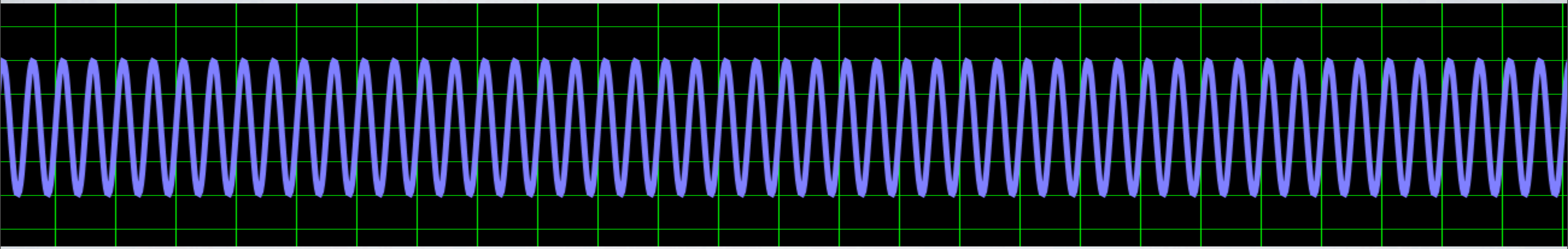
Can FTS do absorption???
Yes, we can!





SpIOMM
V~ 15 field stars
(530 - 630 nm)

FTS: Instrument line function - Spectral resolution



$f(x)$: infinite sine wave

$g(x)$: instrumental function

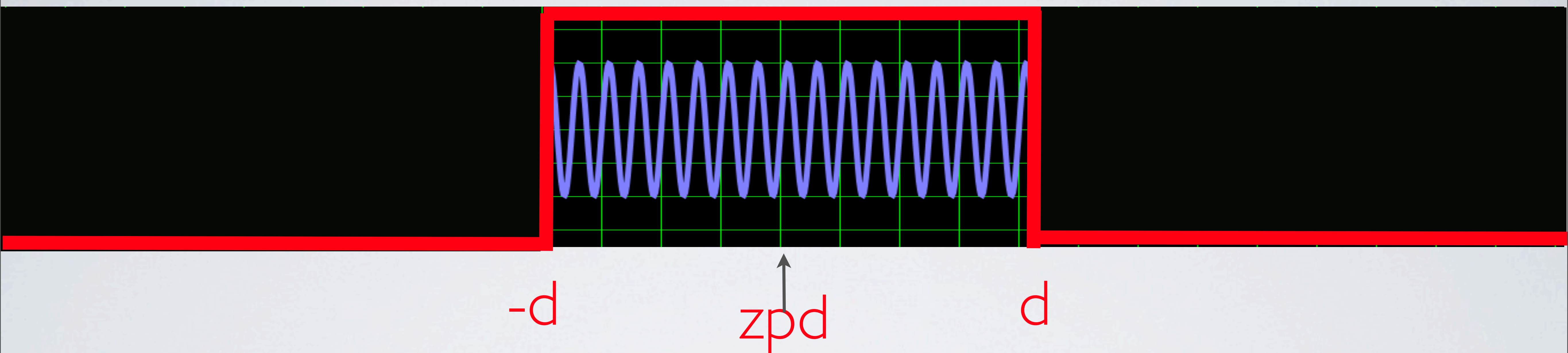
$$FT\left[f(x)\cdot g(x)\right] = \int_{-\infty}^{\infty} f(x)\cdot g(x)\, e^{-i\omega x} dx = F\left(\omega\right) \otimes G\left(\omega\right)$$

convolution of FT(sine wave)
with instrumental function

Contributors to instrument function:

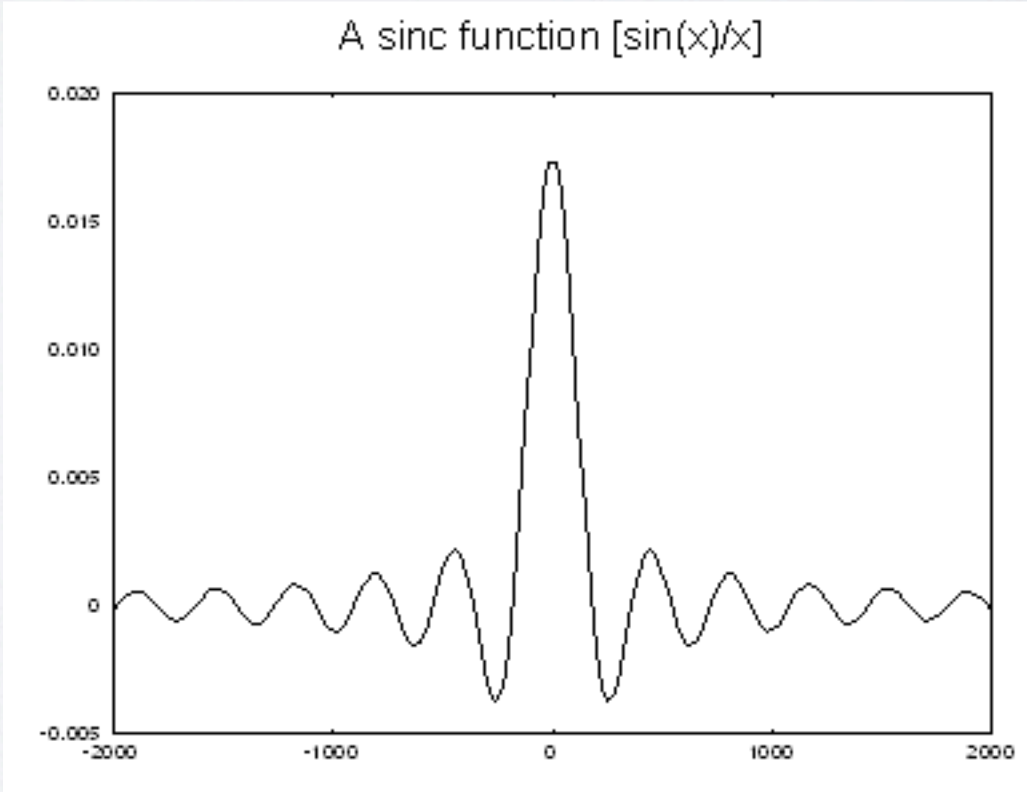
* Sampling errors
* Modulation efficiency variations
* Truncation of interferogram (finite total exposure)

FTS: Instrument line function - Finite interferogram

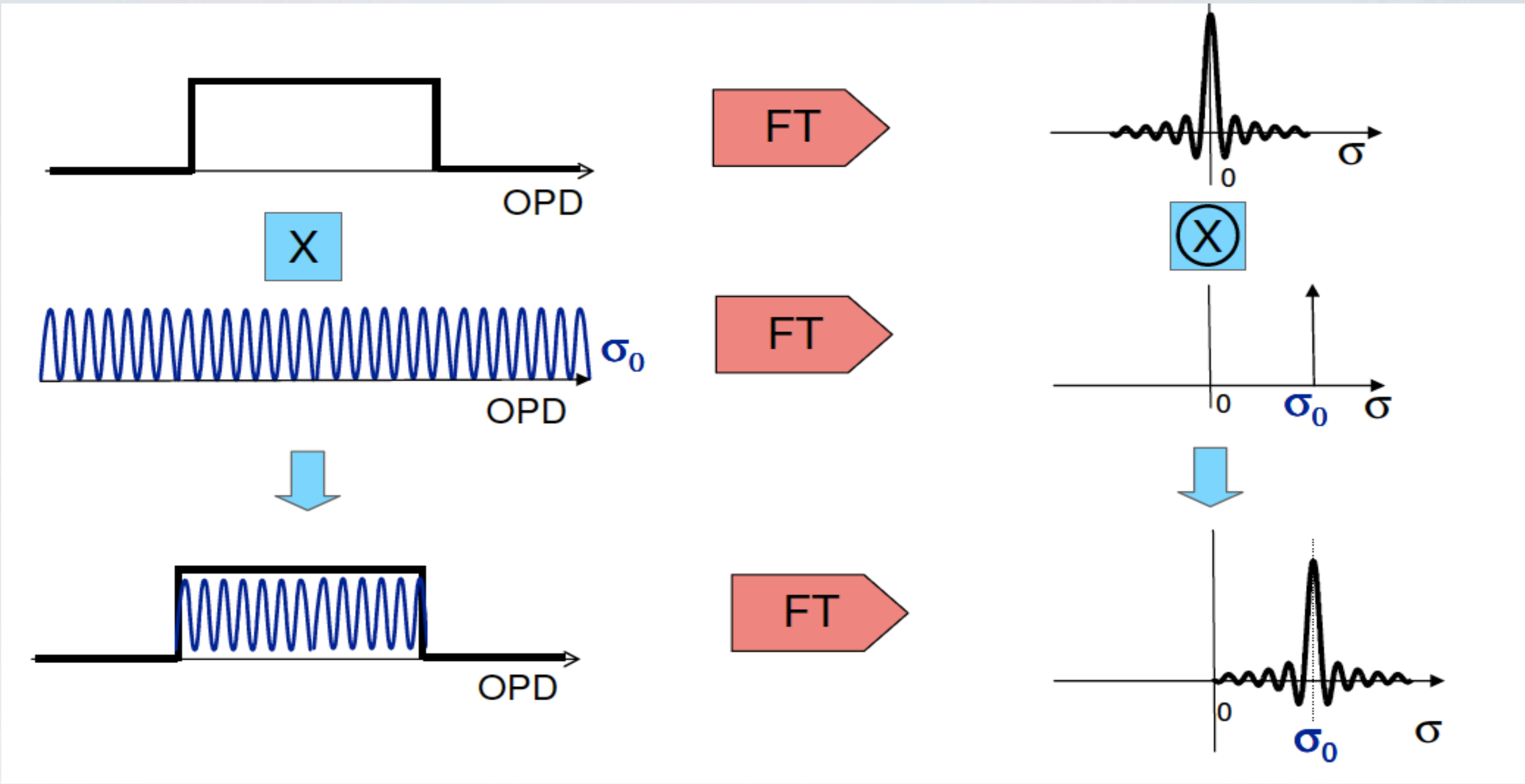


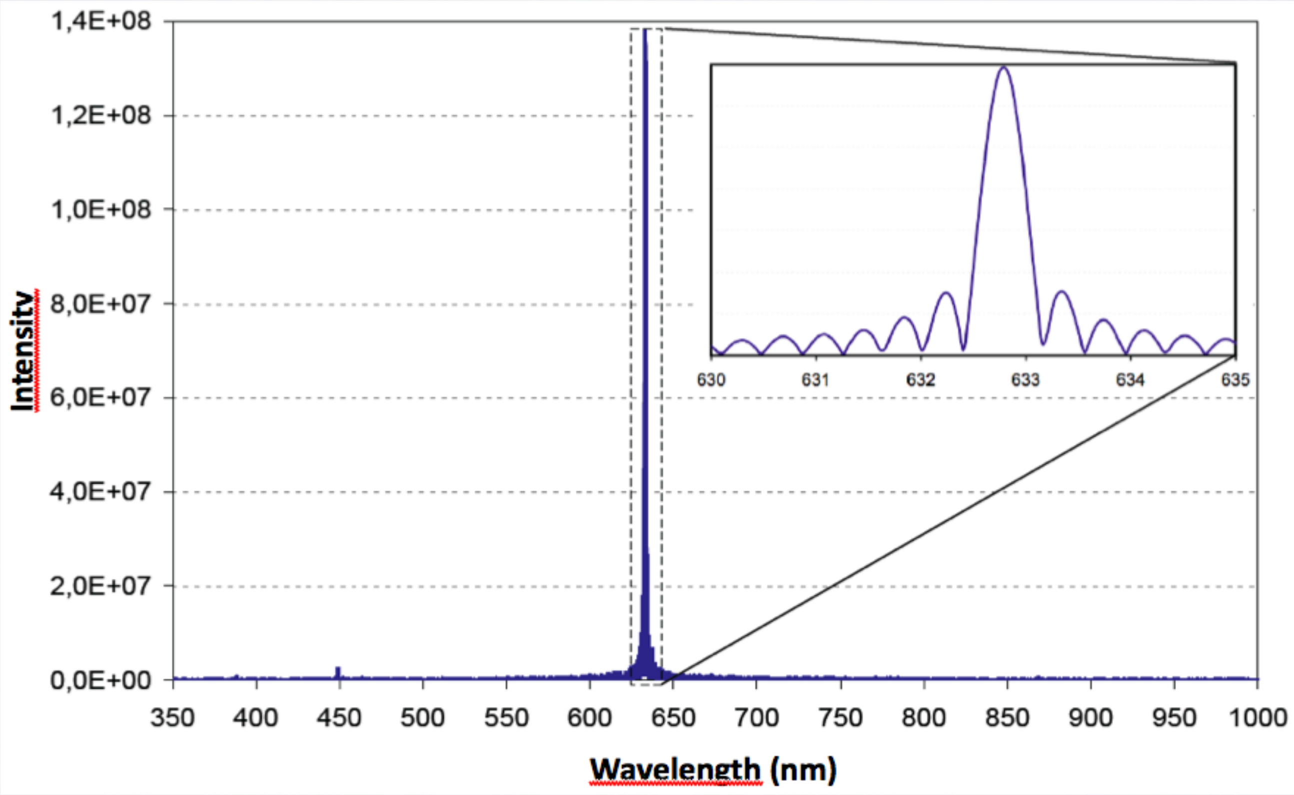
$$\text{Instrument function} = FT\left[boxcar(x)\right] = 2d\frac{\sin(\omega d)}{\omega d}$$

Finite interferogram ==> sinc function

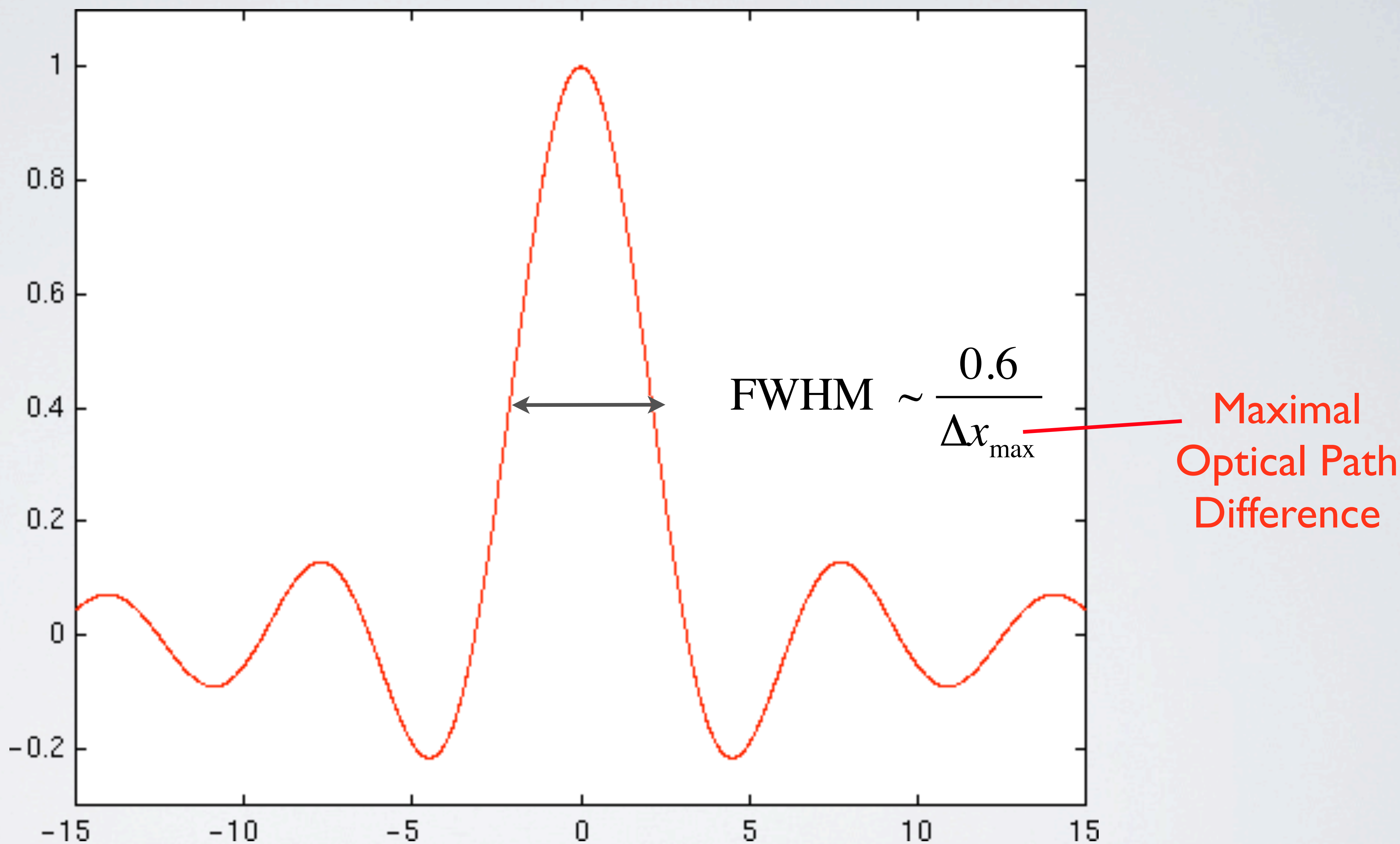


FTS: Instrument line function - Monochromatic source



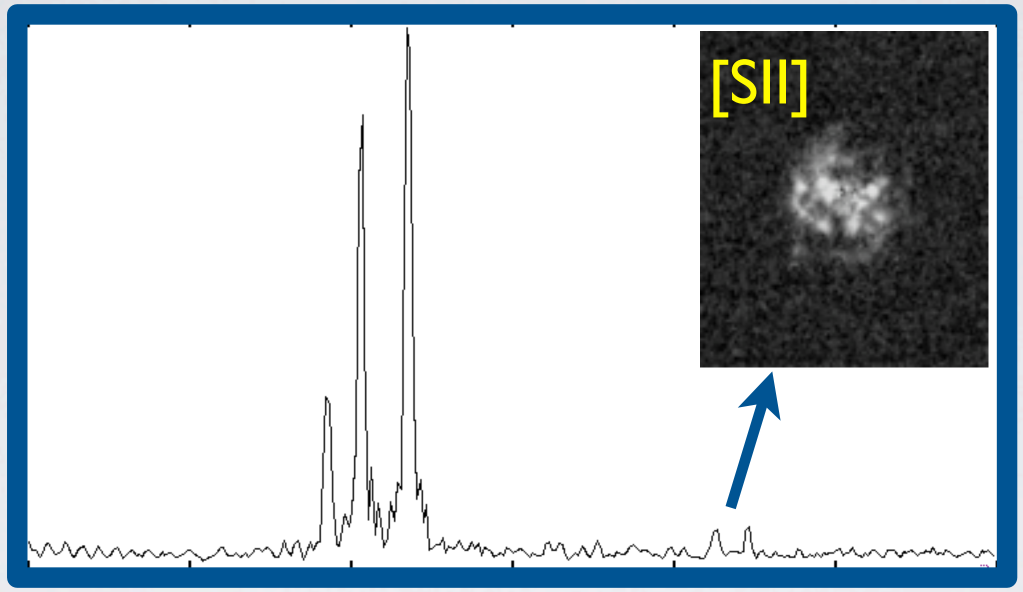


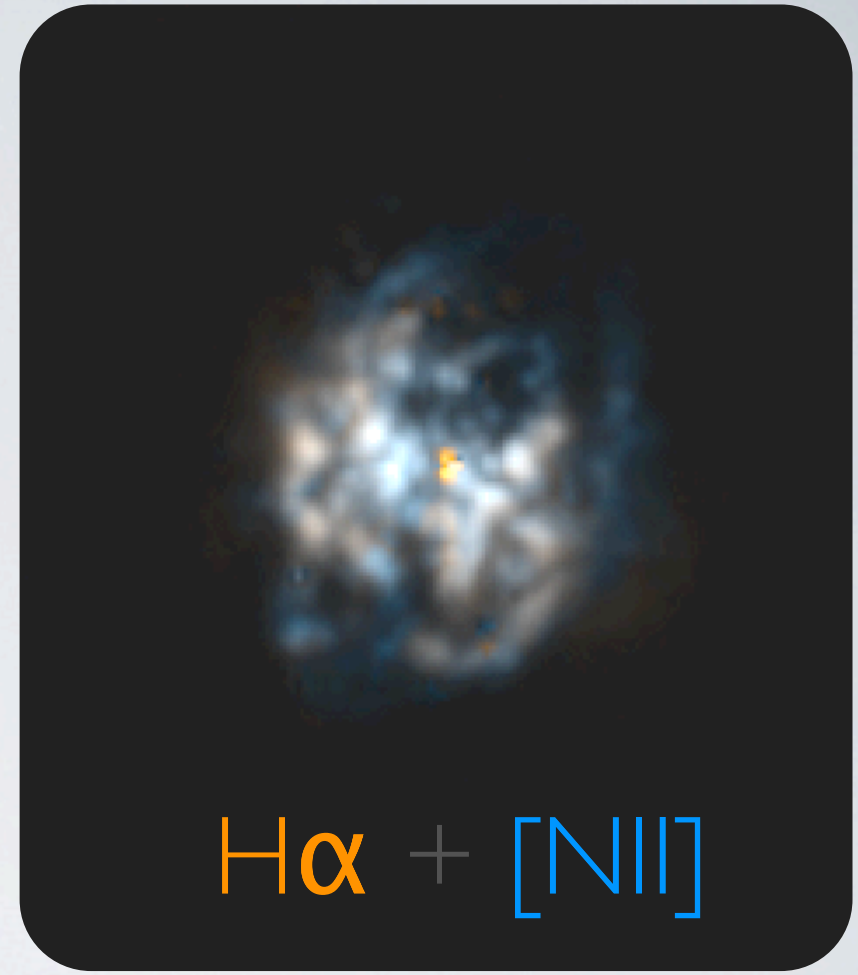
$$\text{Instrument function} = FT\left[boxcar(x)\right] = 2d\frac{\sin(\omega d)}{\omega d}$$

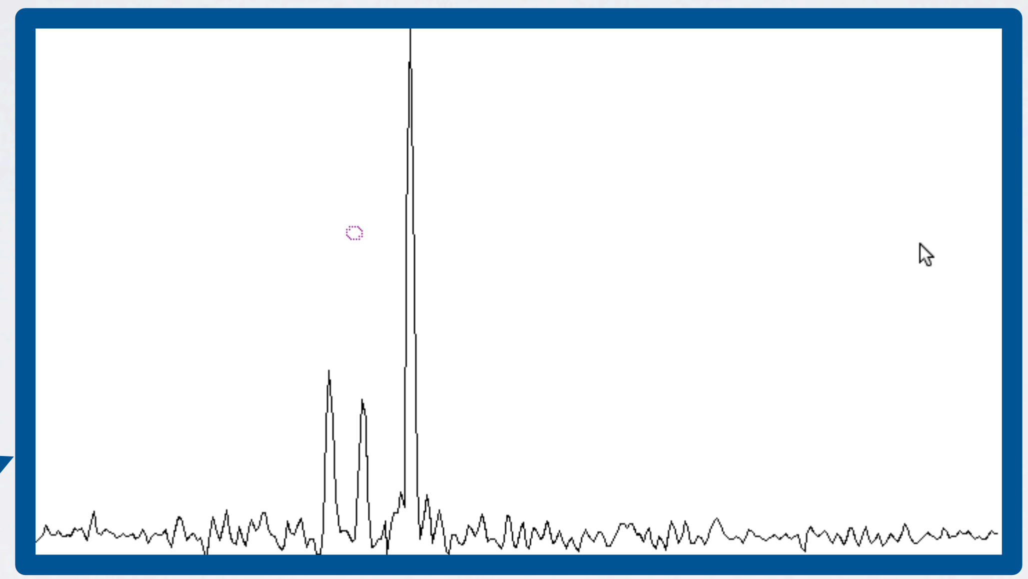


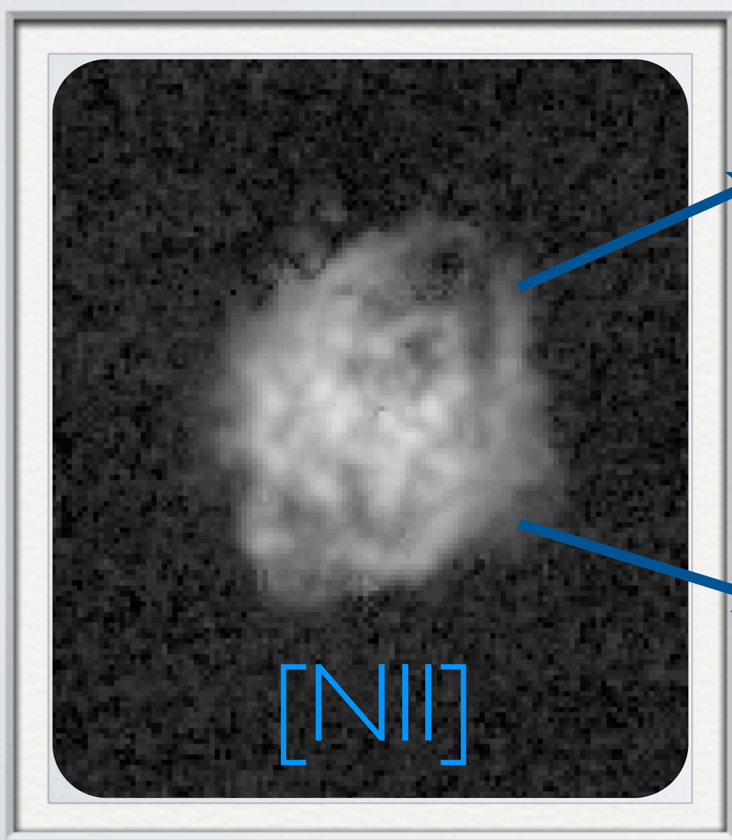
Spectral resolution is directly proportional to the total optical path difference (properly) sampled by the Michelson

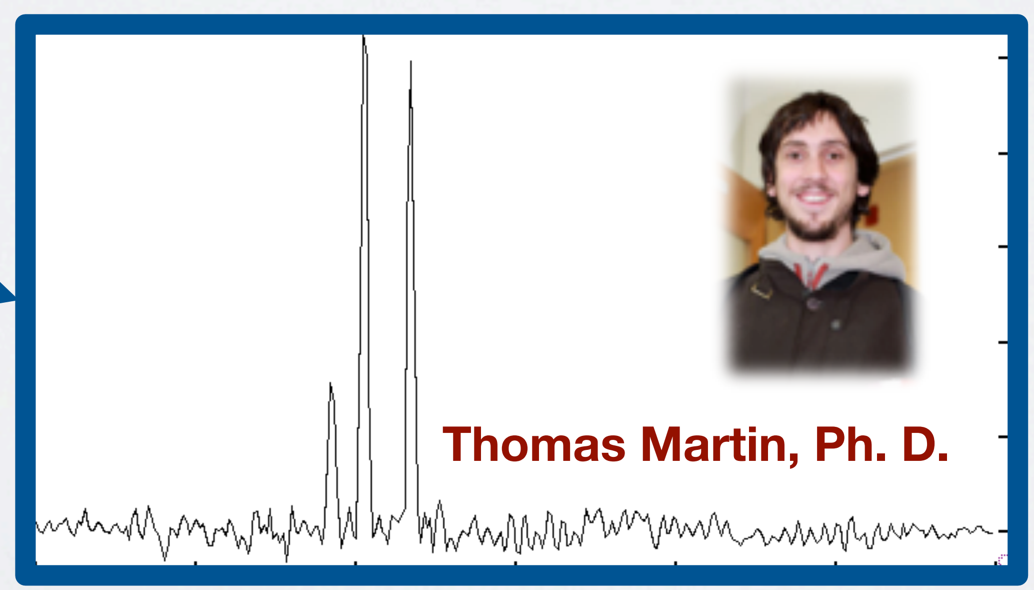
Wolf-Rayet nebula M1-67

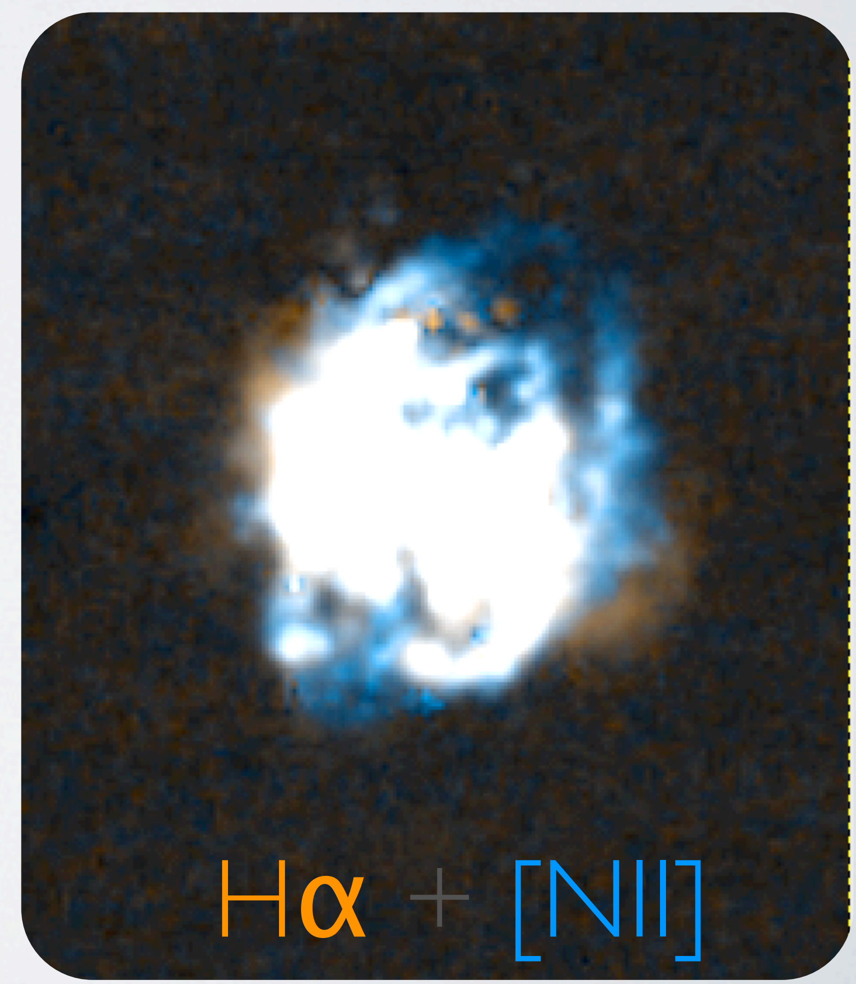




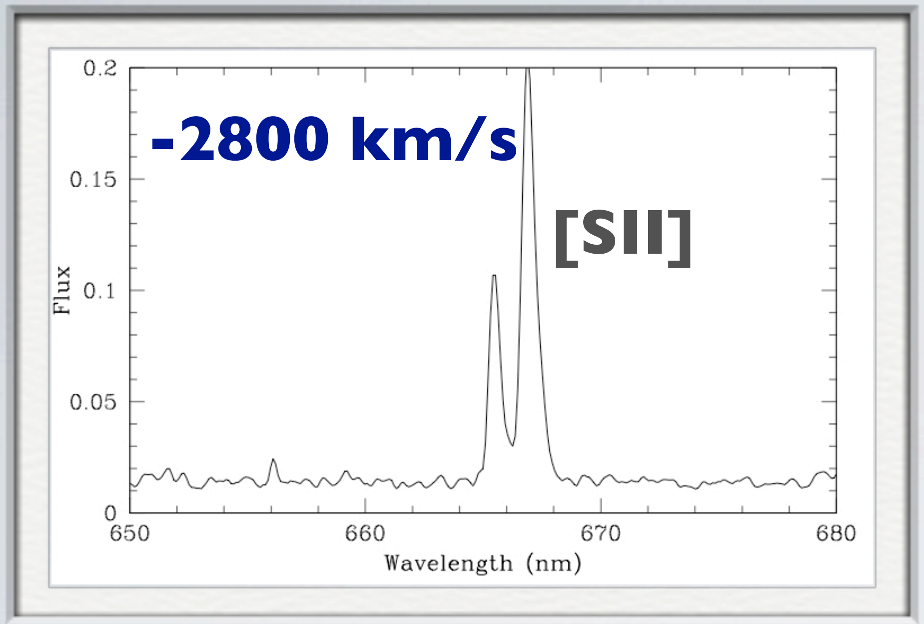


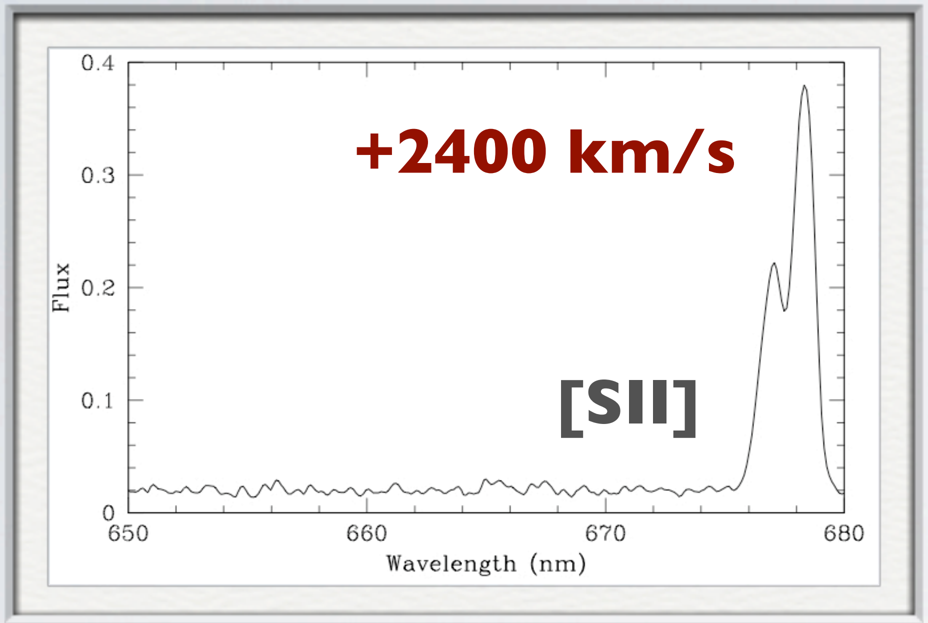


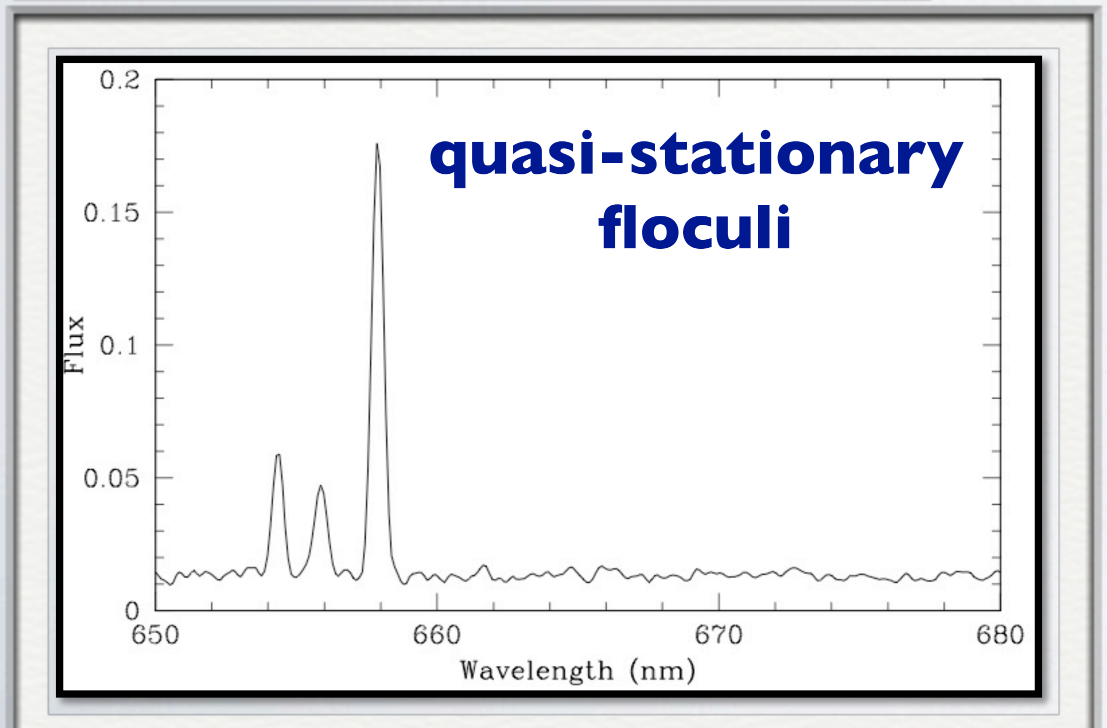


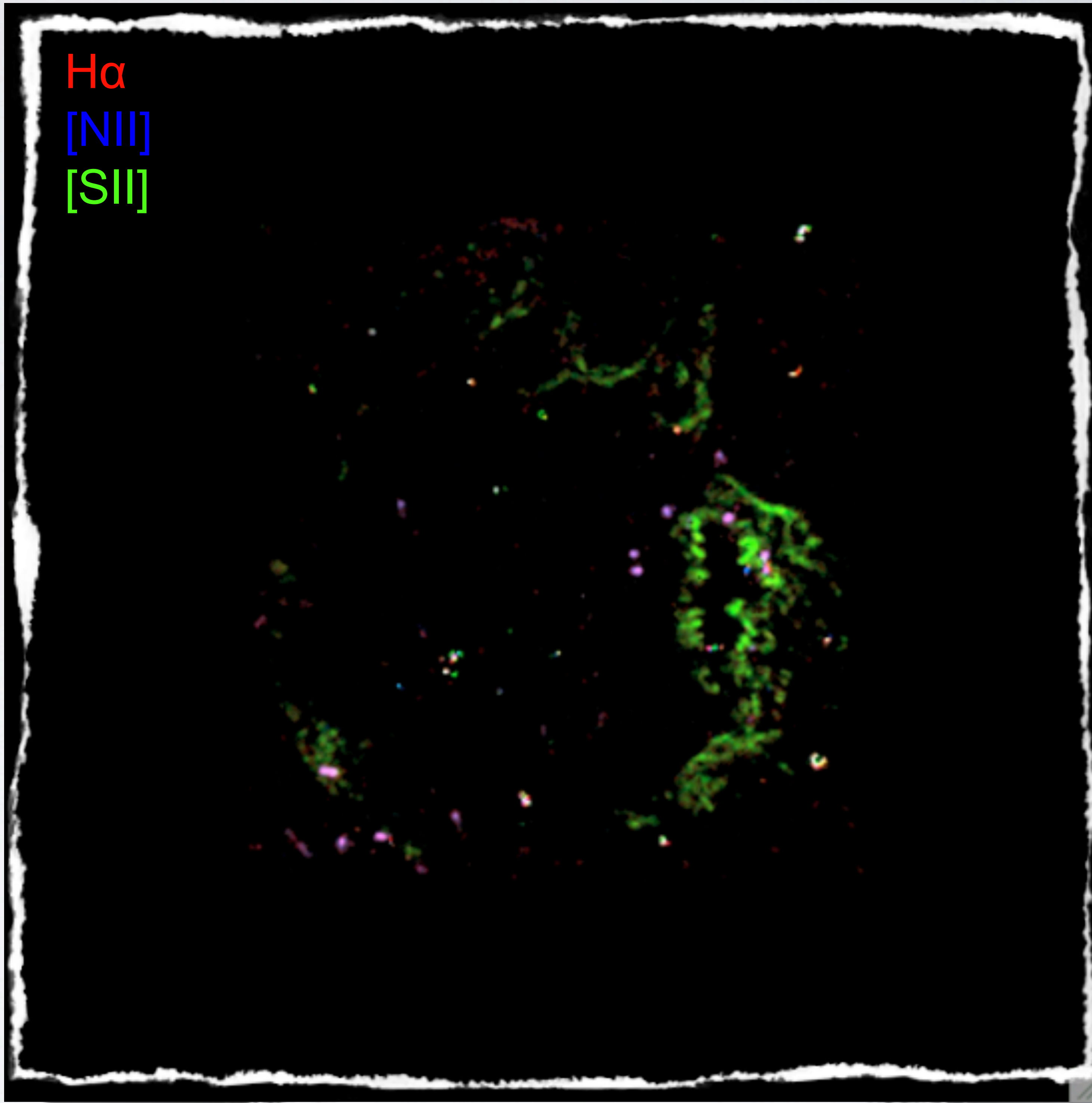


Cas A supernova remnant

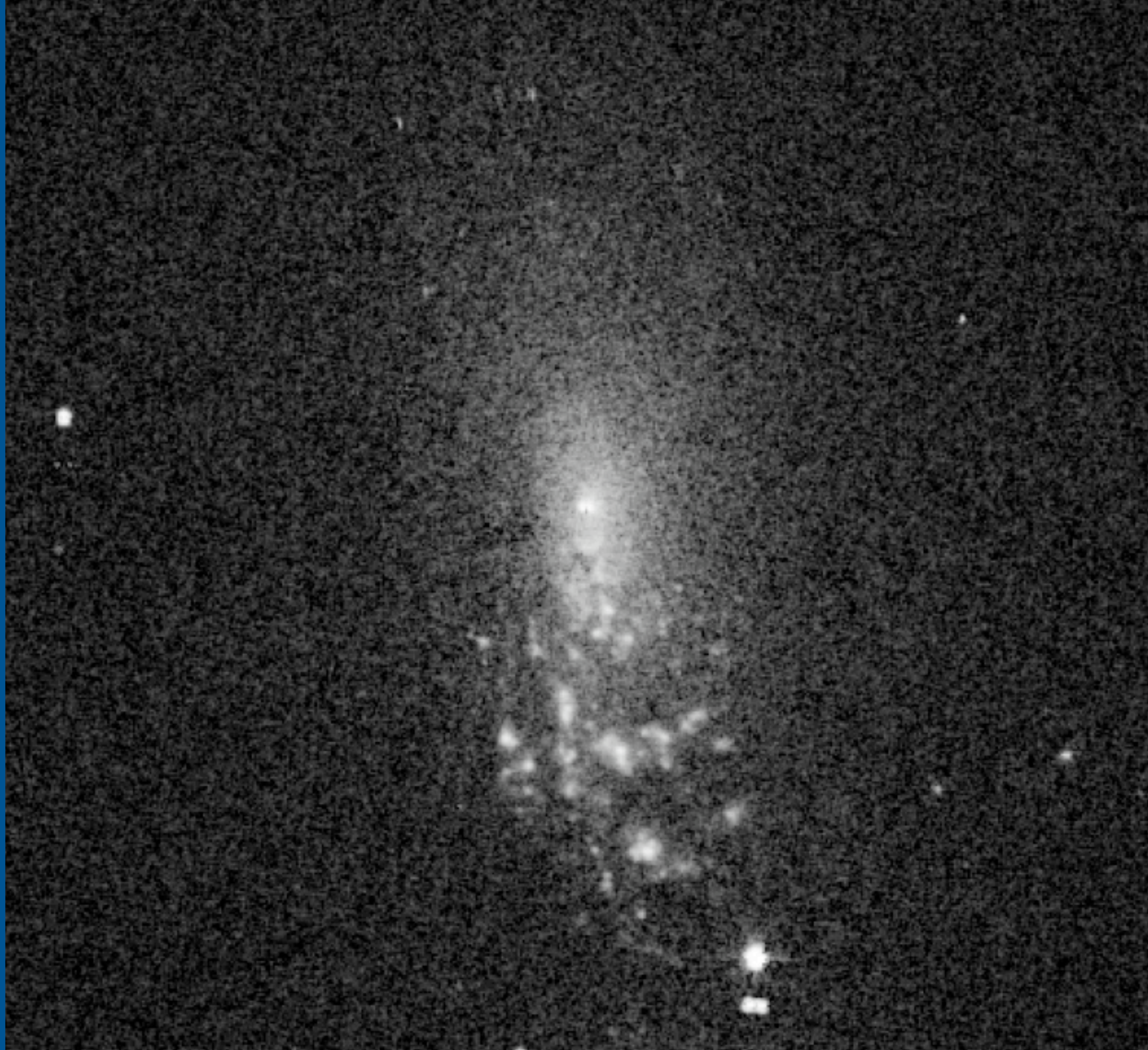


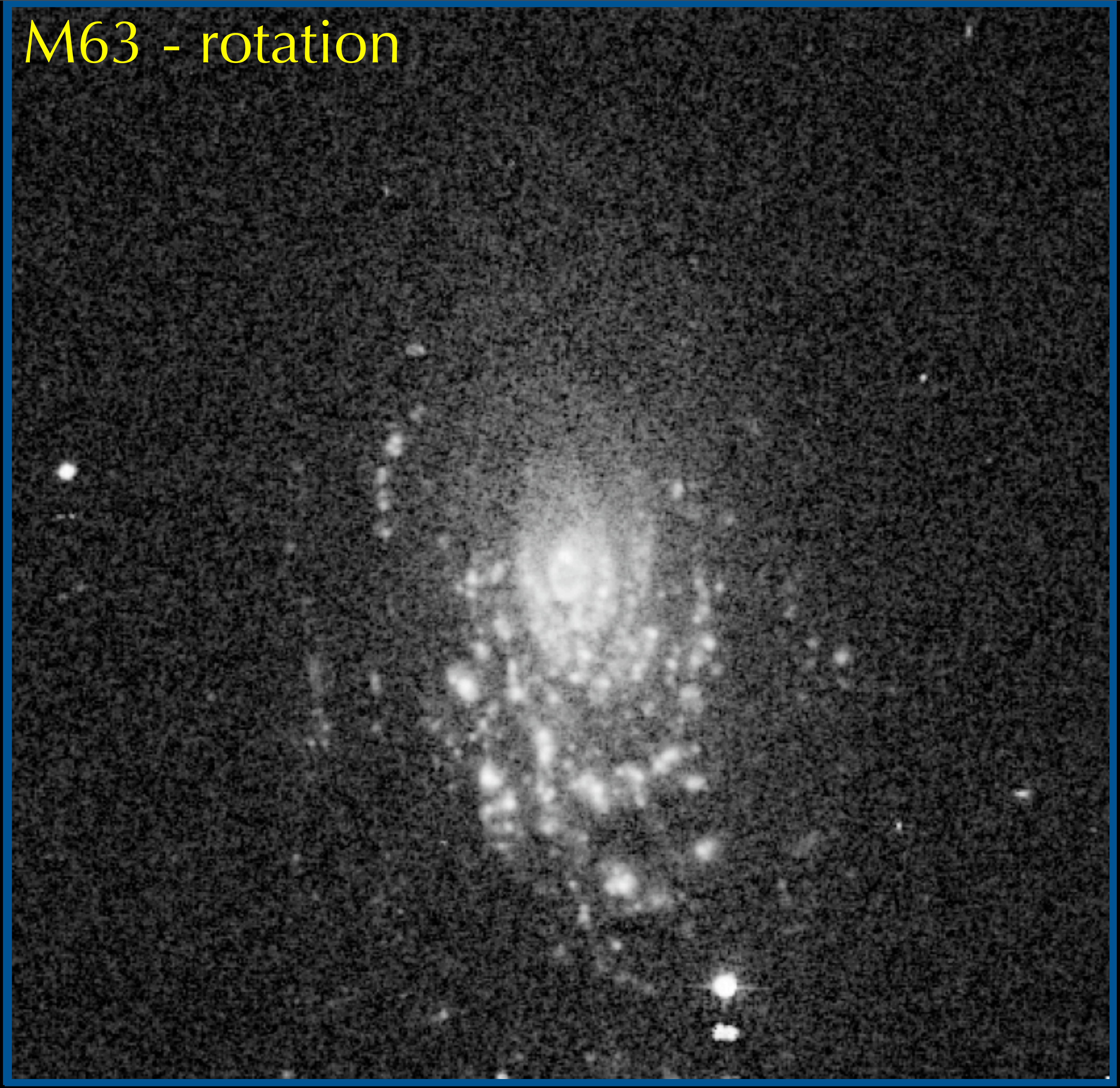


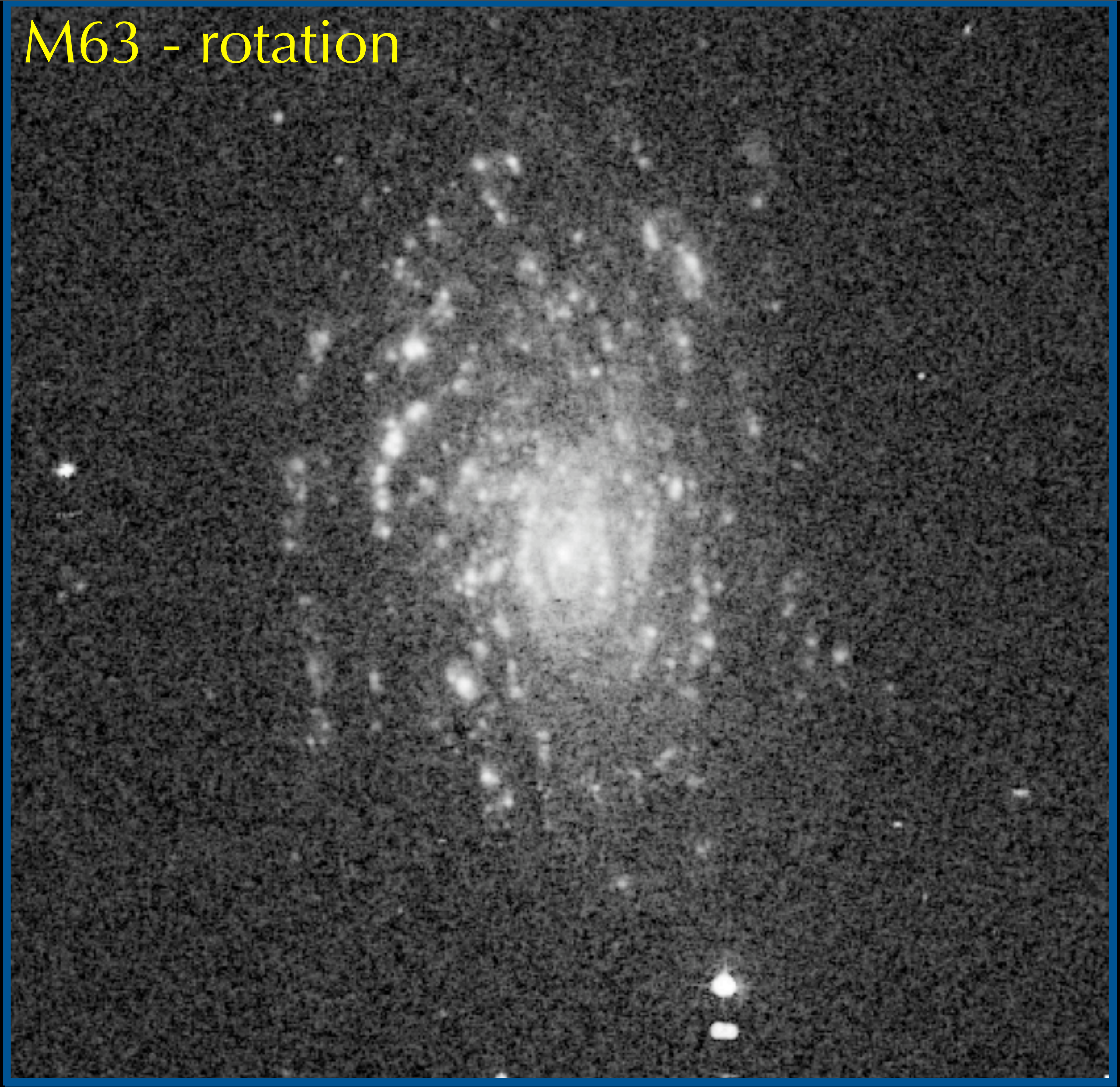




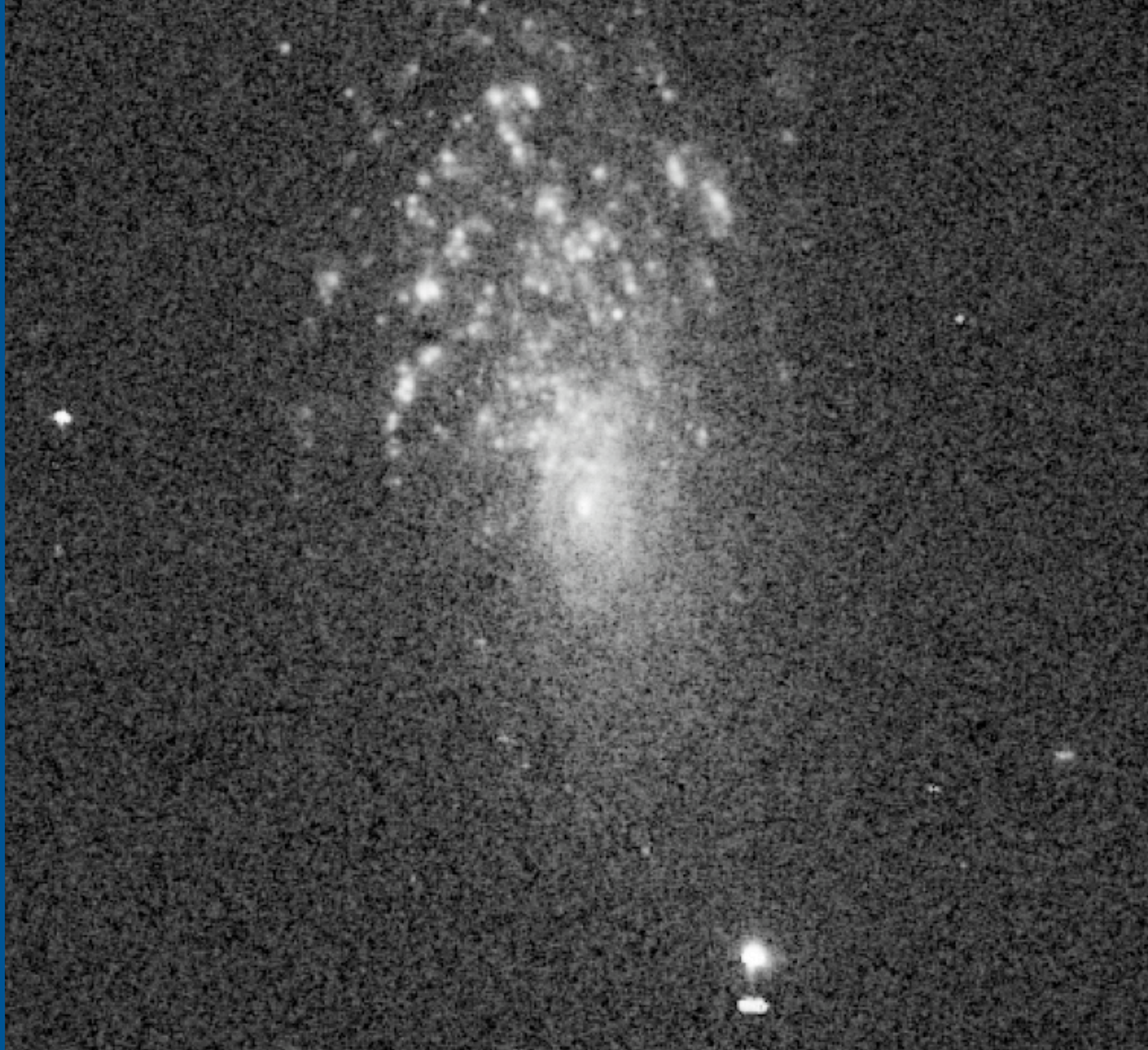
M63 - rotation



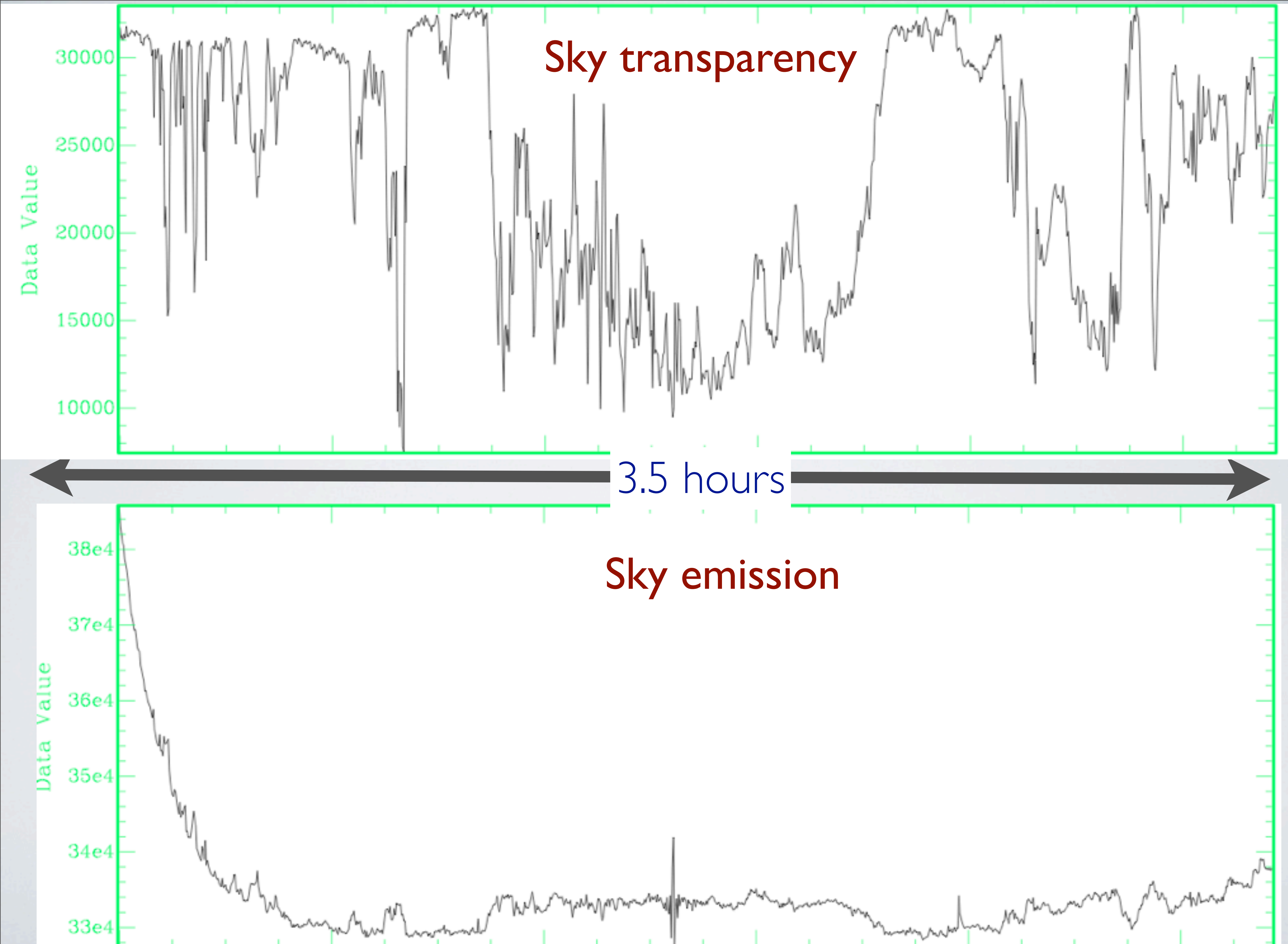

M63 - rotation

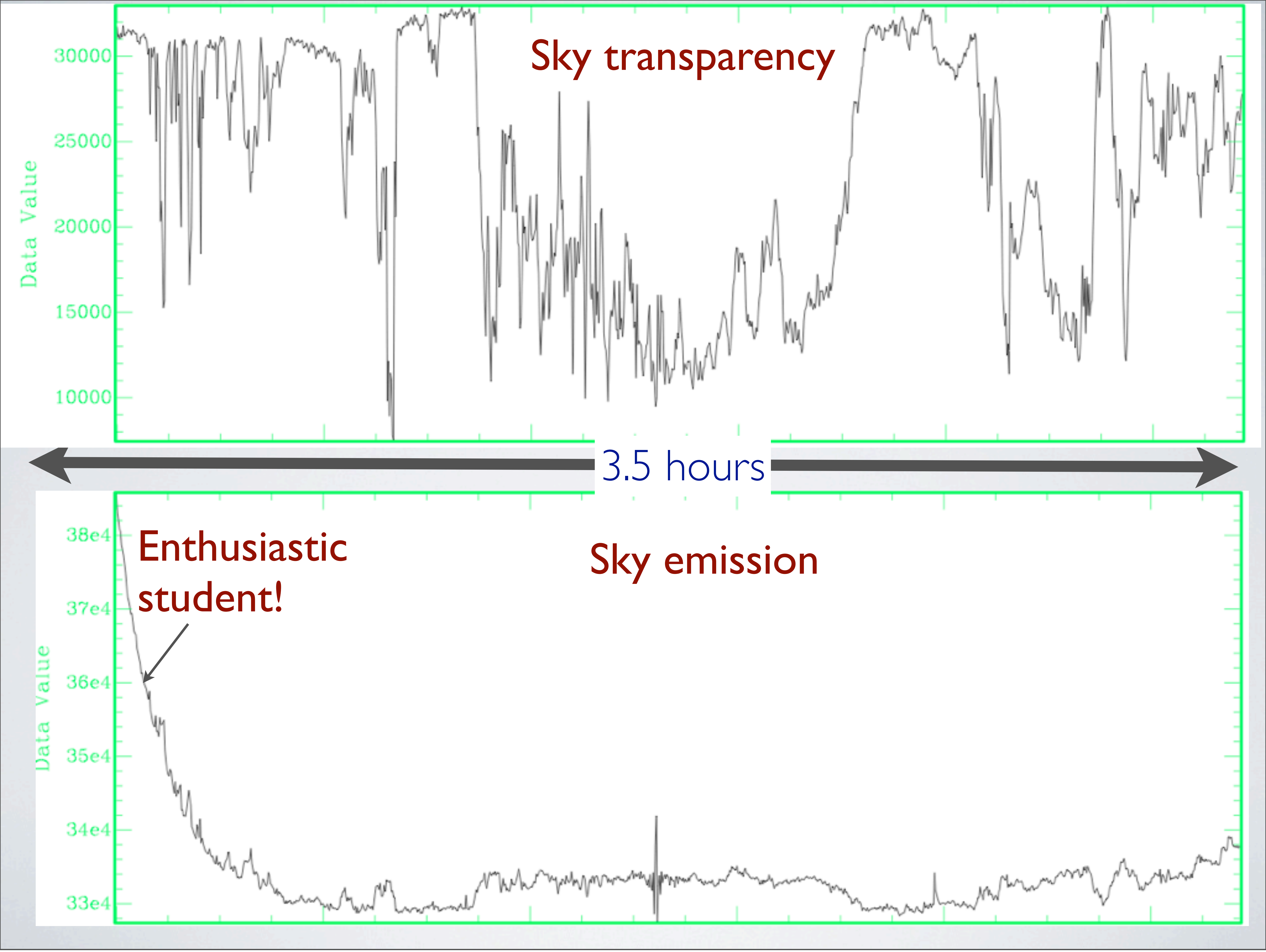

M63 - rotation

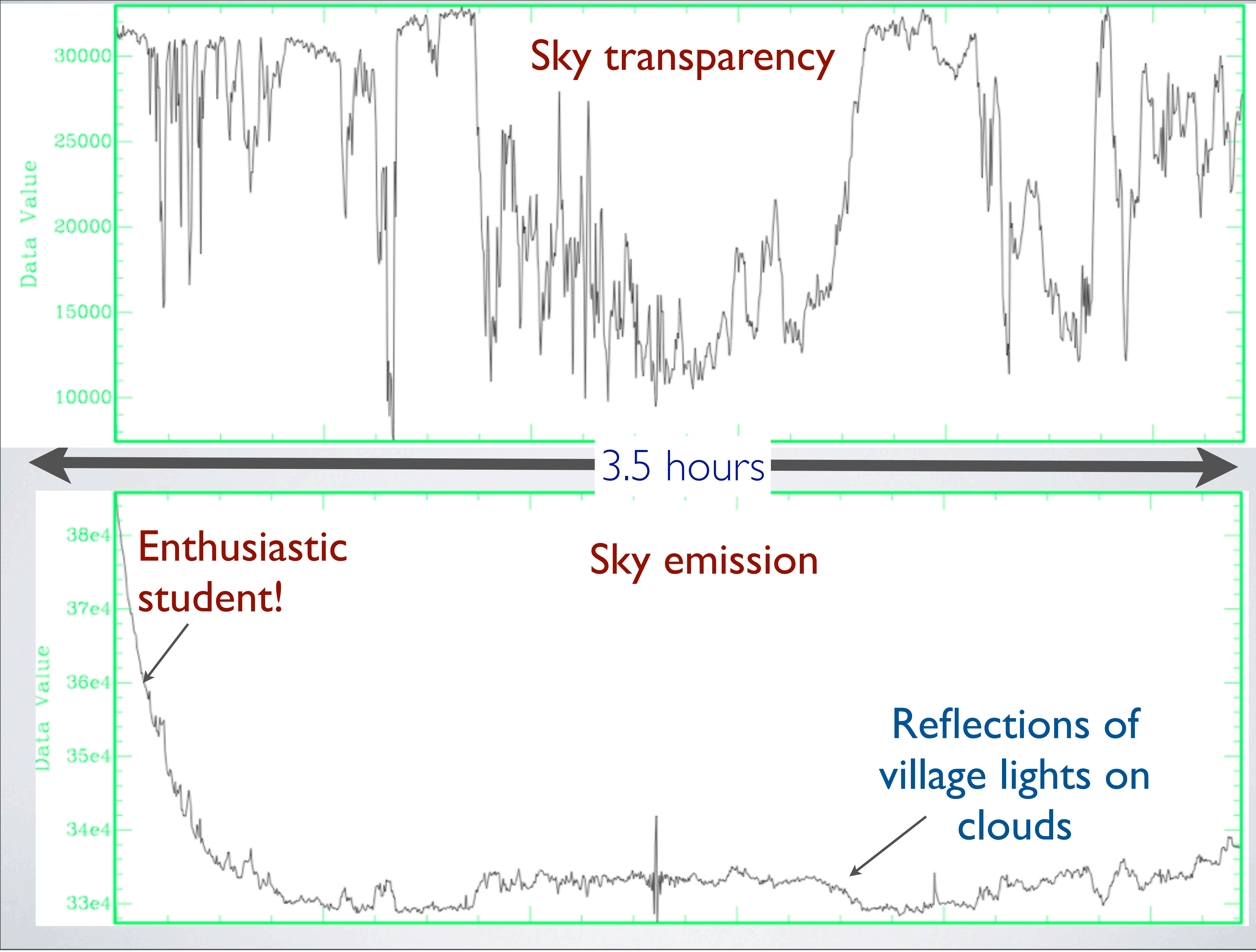
M63 - rotation

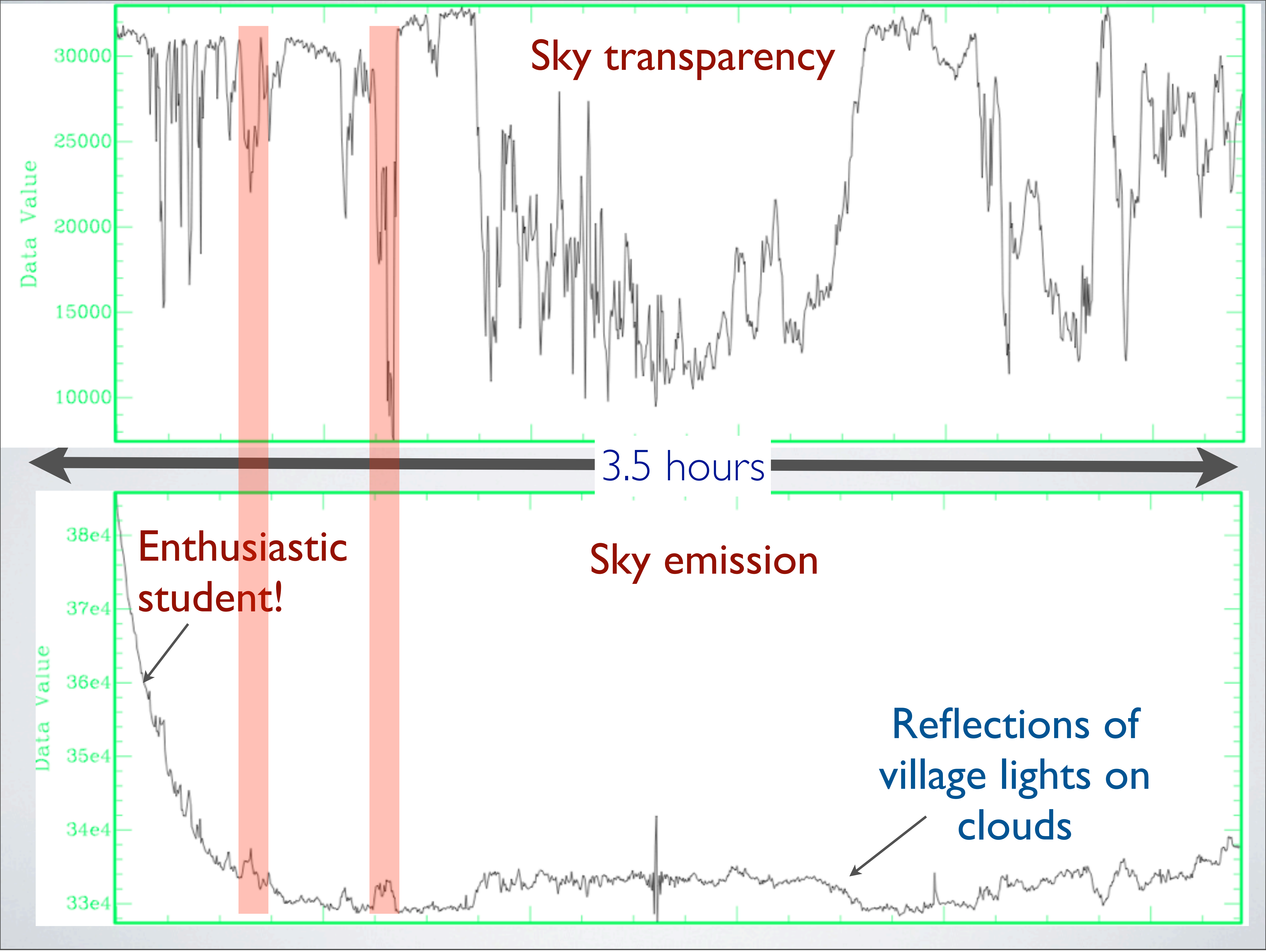


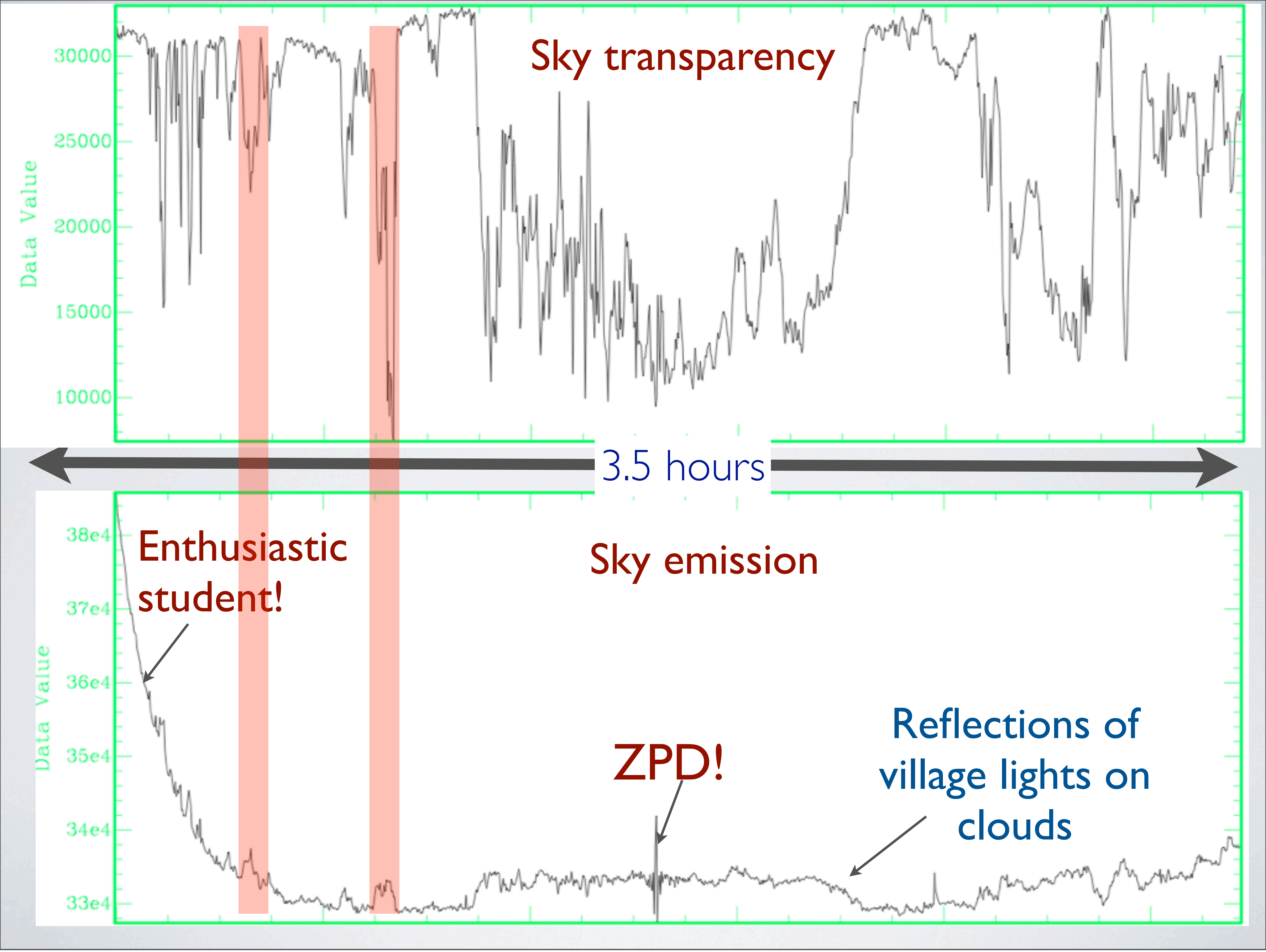

What about variable sky transparency?


Sky transparency
Data Value
30000
25000
20000
15000
10000
3.5 hours
Sky emission
Data Value
38e4
37e4
36e4
35e4
34e4
33e4

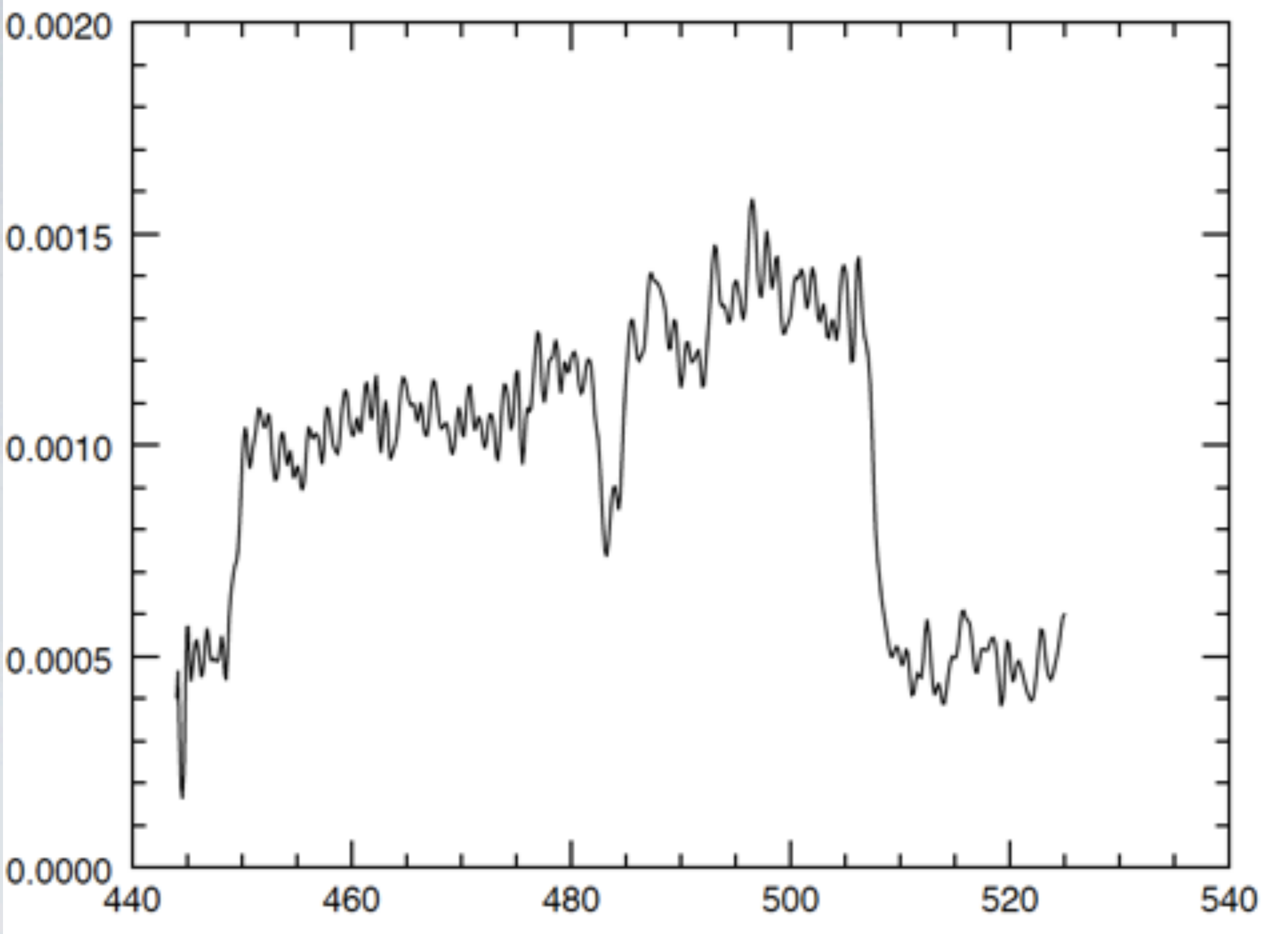

Sky transparency
Data Value
30000
25000
20000
15000
10000
3.5 hours
Enthusiastic
student!
Sky emission
Data Value
38e4
37e4
36e4
35e4
34e4
33e4

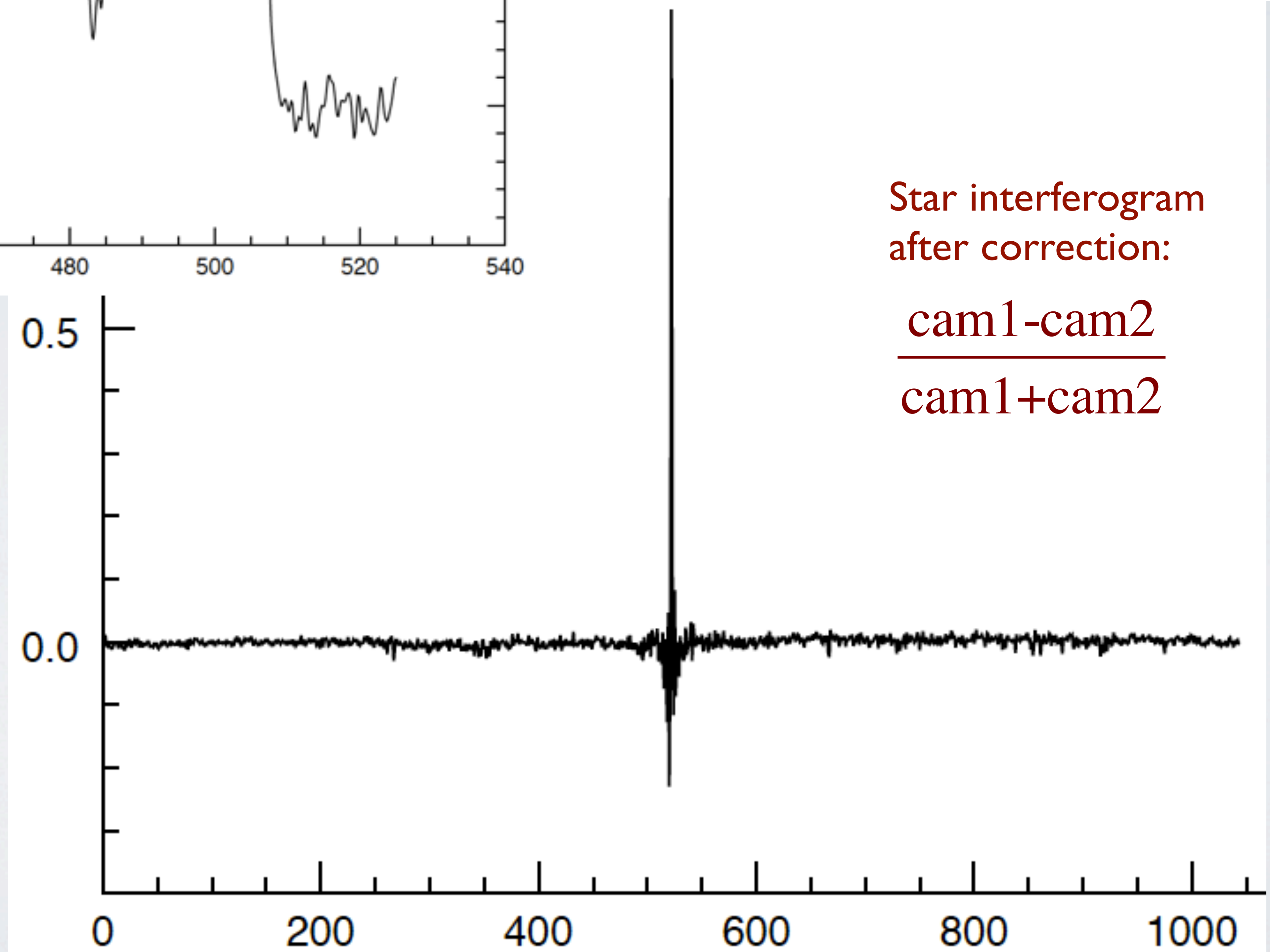

Sky transparency
Data Value
30000
25000
20000
15000
10000
3.5 hours
Sky emission
Enthusiastic
student!
Data Value
38e4
37e4
36e4
35e4
34e4
33e4
Reflections of
village lights on
clouds


Sky transparency
Data Value
30000
25000
20000
15000
10000
3.5 hours
Sky emission
Enthusiastic student!
38e4
37e4
36e4
35e4
34e4
33e4
Reflections of village lights on clouds



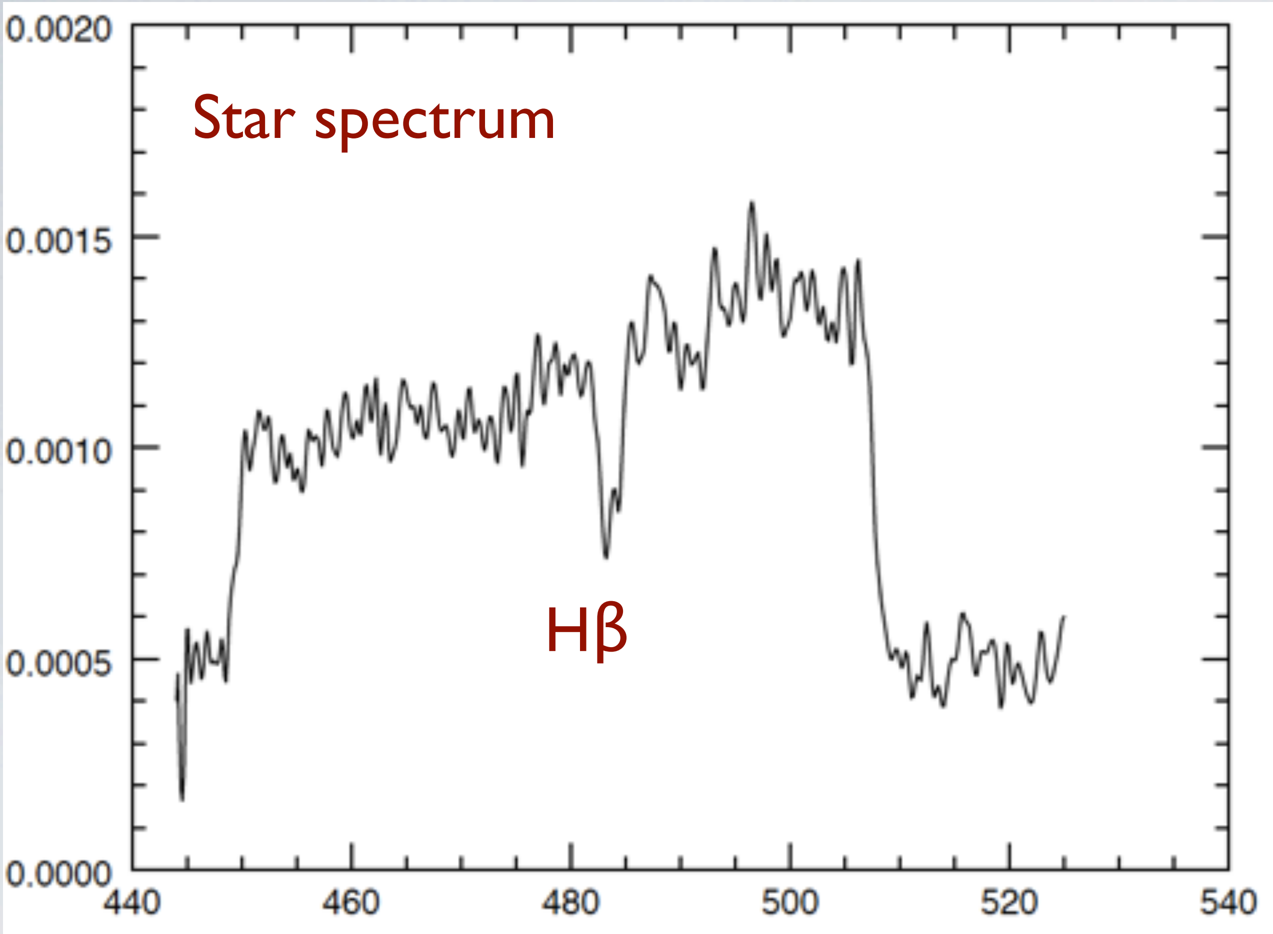
Sky transparency
Data Value
30000
25000
20000
15000
10000
3.5 hours
Sky emission
Enthusiastic student!
ZPD!
Reflections of village lights on clouds
Data Value
38e4
37e4
36e4
35e4
34e4
33e4

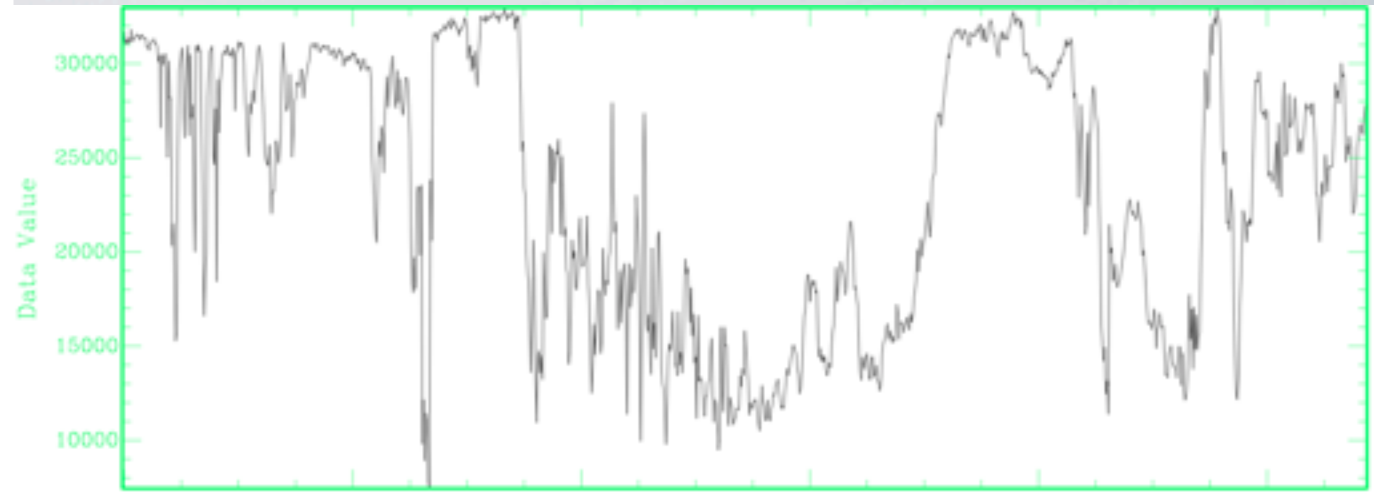


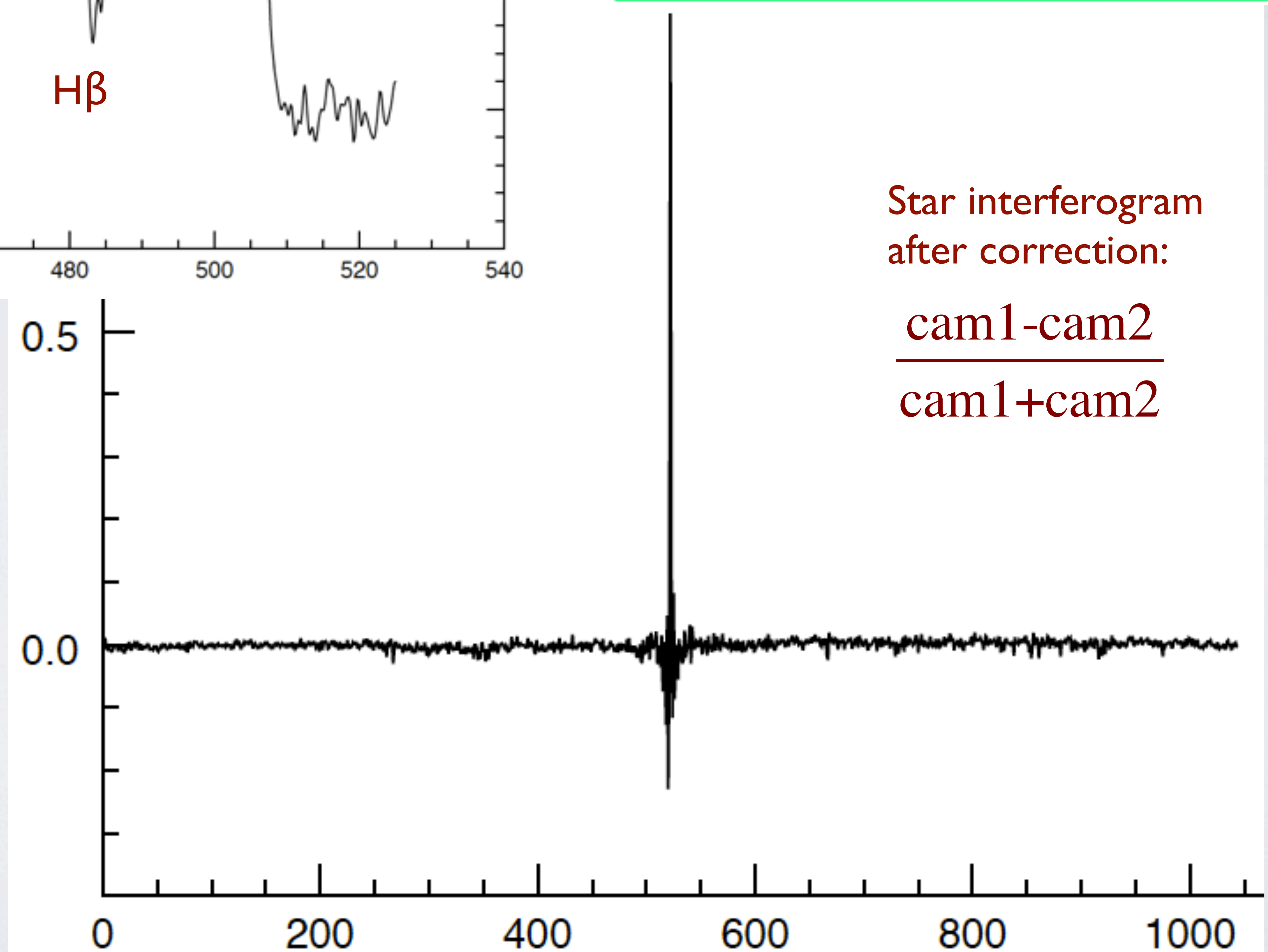


Star interferogram after correction:

$$\frac{\text{cam1-cam2}}{\text{cam1+cam2}}$$


Star spectrum
Hβ
0.0020
0.0015
0.0010
0.0005
0.0000
440
460
480
500
520
540

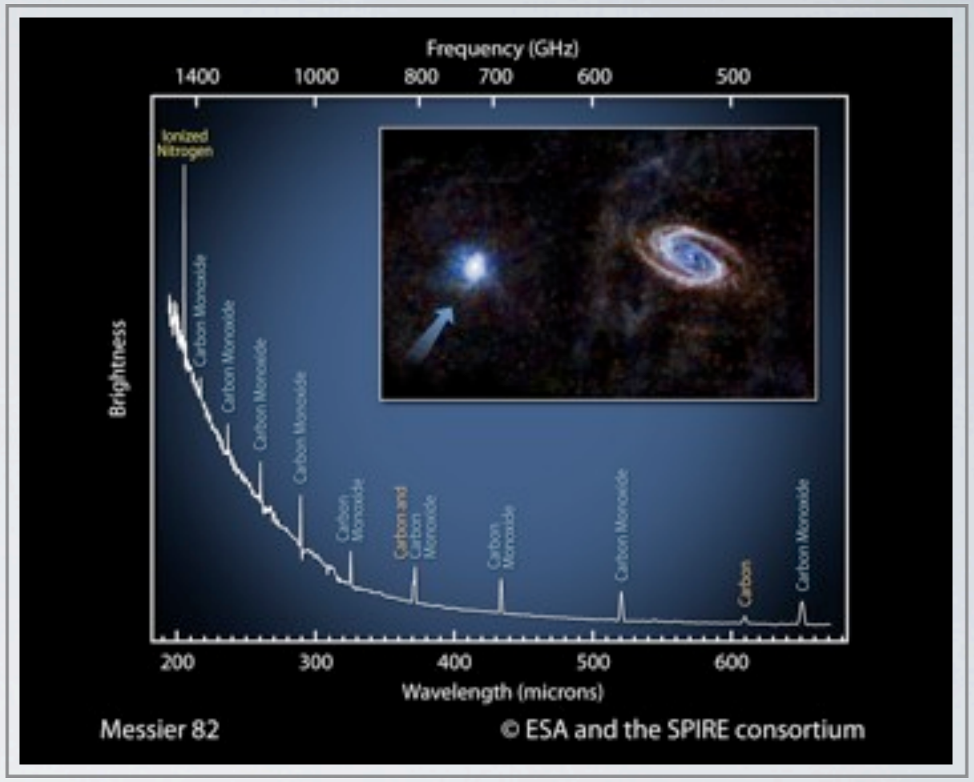

Data Value
30000
25000
20000
15000
10000


Star interferogram
after correction:
$$\frac{\text{cam1-cam2}}{\text{cam1+cam2}}$$
0.5
0.0
0
200
400
600
800
1000

A few Other Imaging FTS

BEAR (CFHT ~ 1992 / Simons & Maillard)

SCUBA2-FTS2 (2012 / Naylor et al.)



Herschel SPIRE-FTS

Simulations of interferograms (175 nm sampling)