Long-term variability of AGN: future perspectives

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AGN optical spectral variability

- EVERYTHING VARIES!
  - line flux and continuum flux
  - broad emission line (BEL) profiles

- in some cases extreme:
  AGN even change their type
  - e.g. type 1 -> type 2
  - changing look AGN

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Shapovalova+ 2008

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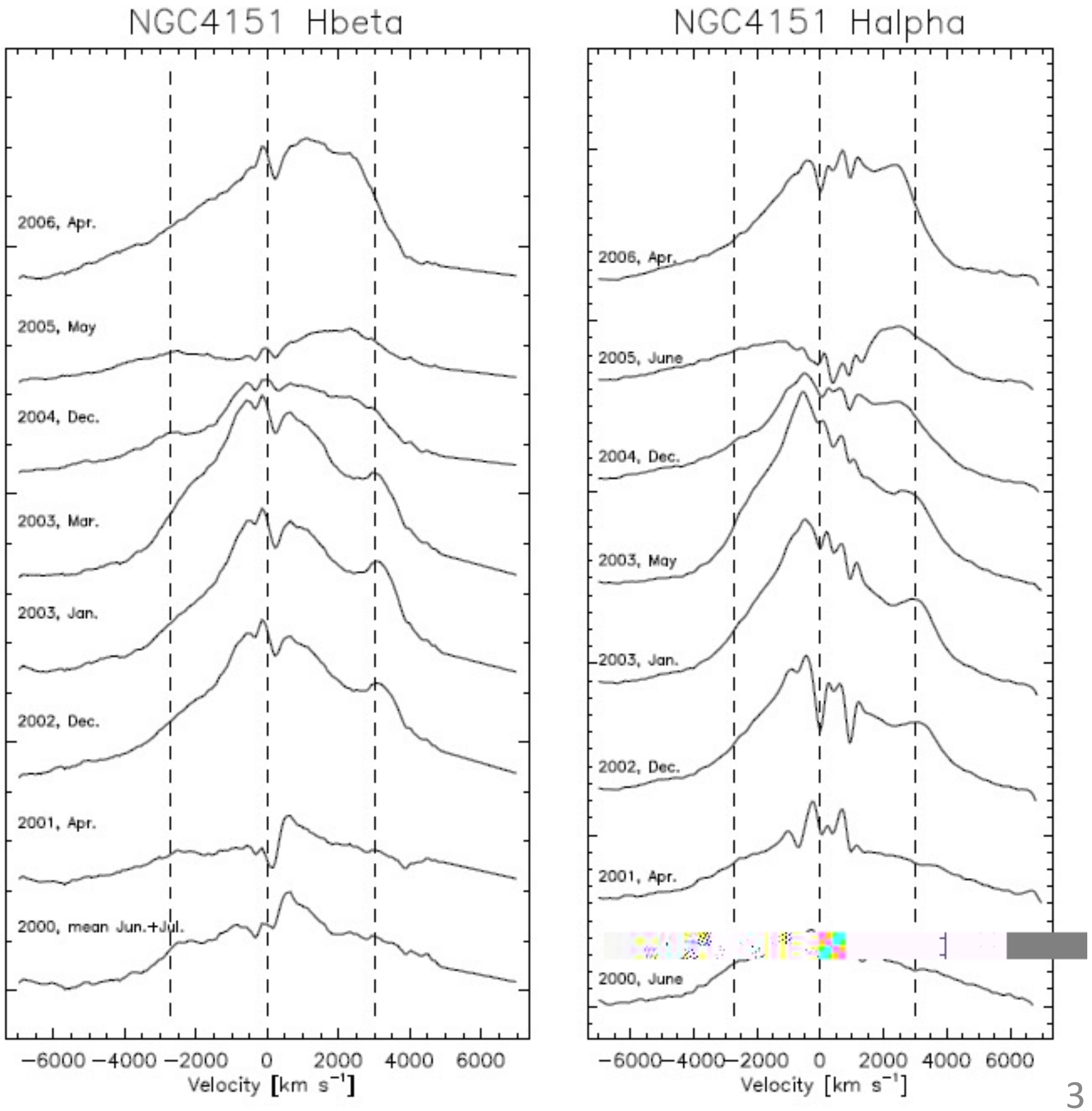
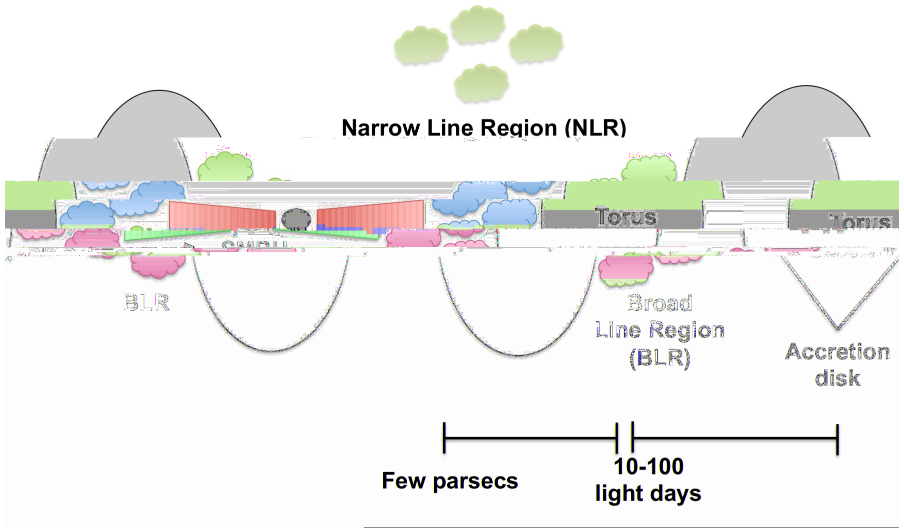
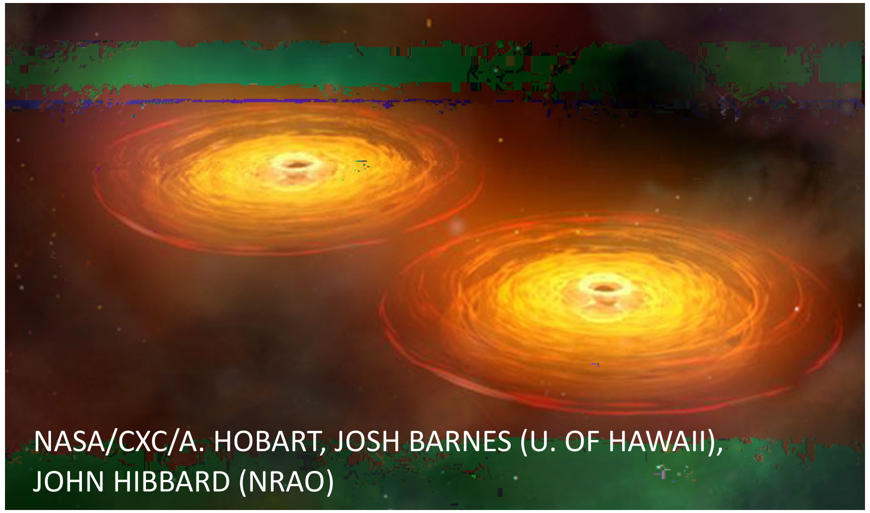


Why study broad lines of AGN?

- reverberation: direct **measure of the unseen (the BLR size) and the SMBH mass**
- the era of multimessenger astronomy: detect **binary supermassive black holes** (SMBH)
  - tricky to detect on parsec-scales (e.g. Popović+12, Komossa+03, Comerford+09, Ge+12, Benitez+18)
  - from spectroscopy (Bon+12,16, Liu+16) or periodicity analysis of photometric light-curves (Graham+09,17)
- the ultimate aim of astronomy today → new tools to **measure distances** with AGN
  - e.g. using optical lines of the BLR (e.g. Watson+11)





1. Reverberation Mapping (RM)

- there is a **time-delay** btwn continuum and line flux

- only for ~100s AGN: direct measure of $\mathbf{R_{BLR}}$
- empirical **Radius-Luminosity relation**
  (e.g. Kaspi+ 2000, Peterson+ 2004, Bentz+2009)

  → can get **SMBH mass** from
  single epoch observation

  → if we directly measure R → L→ **distance**

RM campaigns

QUANTITY

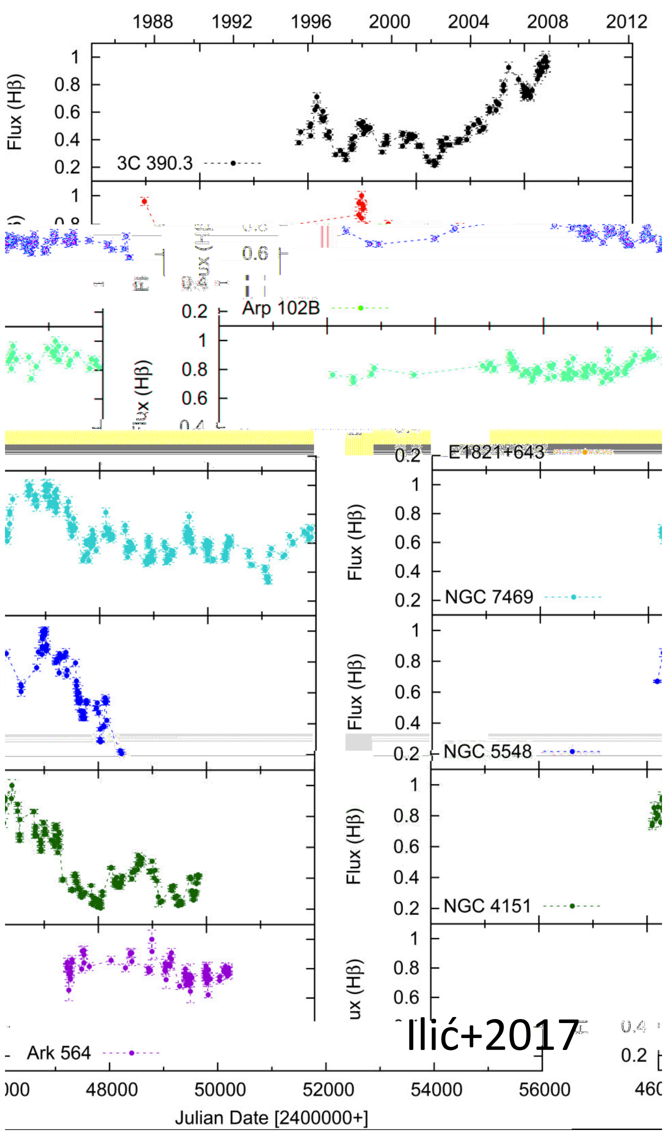
- SDSS reverberation monitoring
  - monitoring 849 quasars, $0.1<z<4.5$ (Shen et al. 2014, 2018)
  - measured for 44 quasars, $z<0.3$ (Grier+2017) and 144 quasars, $z<1$ (Li+2017)
- OzDES

Long-term RM campaign (long=decades)

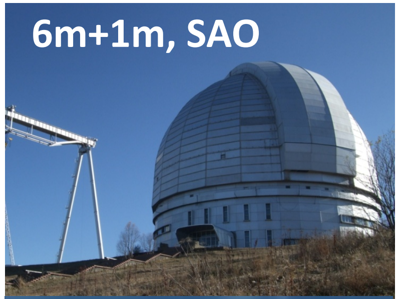
- **Typical Seyfert 1s:**
  NGC 5548 – 9+ years (Shapovalova+ 2004, Ilić 2007, Popović+2008, Bon+2016)
  NGC 4151 – 11+ years (Shapovalova+ 2008, 2010a, Ilić+2010, Bon+ 2012)
  NGC 7469 – 20 years (Shapovalova+2017)
  NGC 3516 – 22 years (Shapovalova+2019)
- **Narrow Line Seyfert 1:**
  Ark 564 – 11 years (Shapovalova+ 2011, Shapovalova+ 2012)

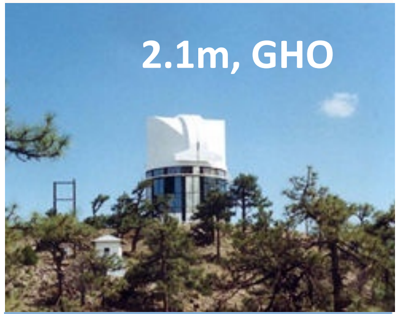
- **Double Peaked Line AGNs (DPLs):**
  3C 390.3 – 13 years (Shapovalova+ 2001, 2010b, Popović+2011, Jovanović+ 2010, Kovačević+ 2014);
  Arp 102B – 12 years (Shapovalova+13, Popović+ 14, Kovačević+ 14, Ilić+15, Rakić+ 17)

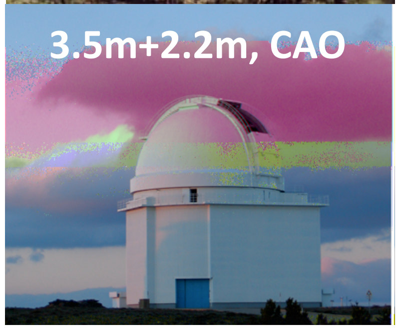
- **Quasar, a binary black hole candidate:**
  E1821+643 – 25 years (Shapovalova+2016, Kovačević+2017, Kovačević+2018)



Ilić+2017

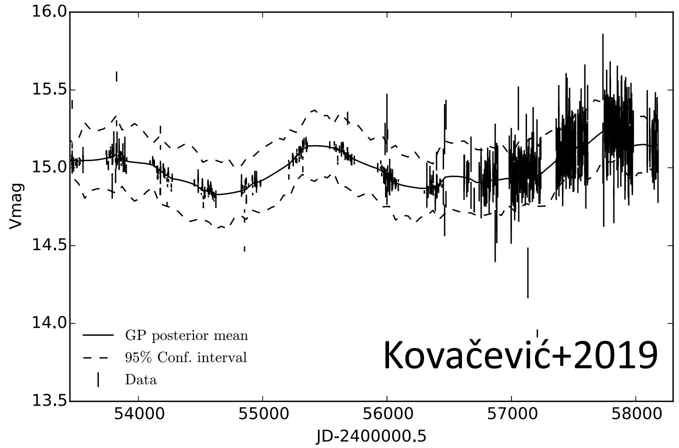


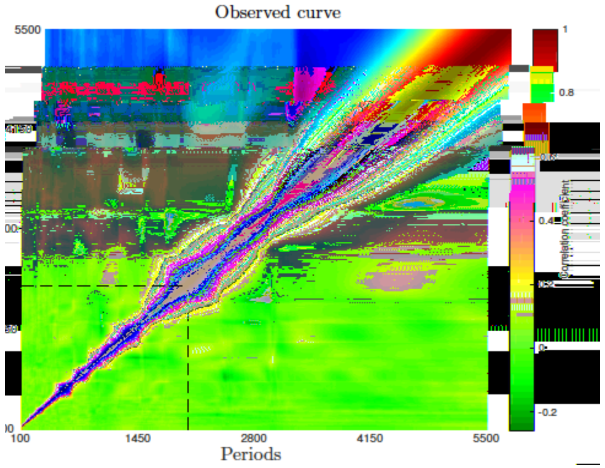




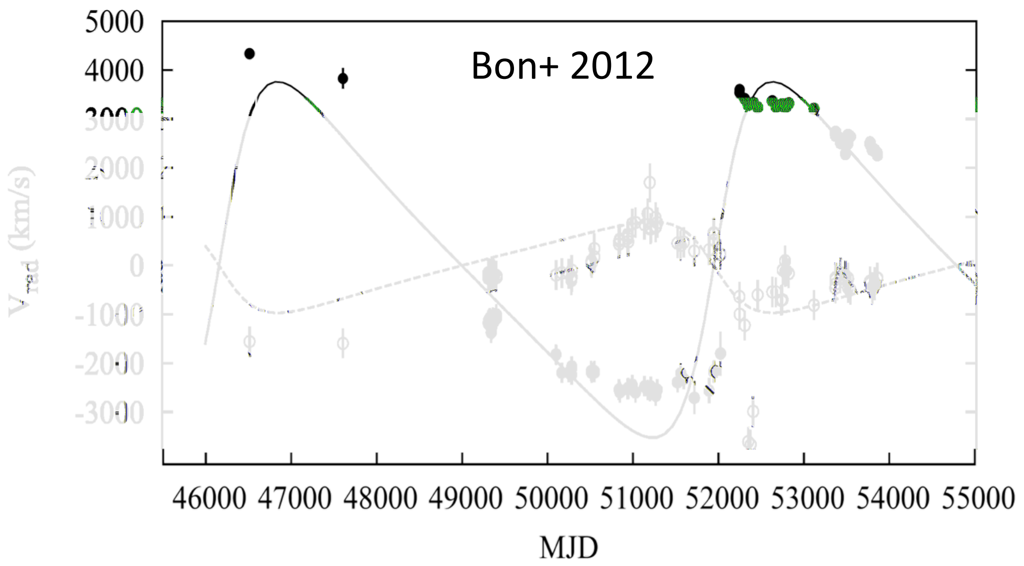
2. Hunt for parsec-scale SMBH binaries

- time-domain photometry of AGN (see e.g. with CRTS, Graham+2017)
  → famous case: binary SMBH candidate PG1302-102 (Graham+2015)
- novel hybrid method to search for periodic oscillatory behavior
  → applies continuous wavelet transform and correlation coefficients on Gaussian-processed light curves (see Kovačević+2018, 2019 for details)





- NGC 4151: the first spectroscopically resolved sub-parsec orbit of SMBH (Bon+2012)
  → orbital period 15.7yr, masses ~ 10^7 M_{sun}

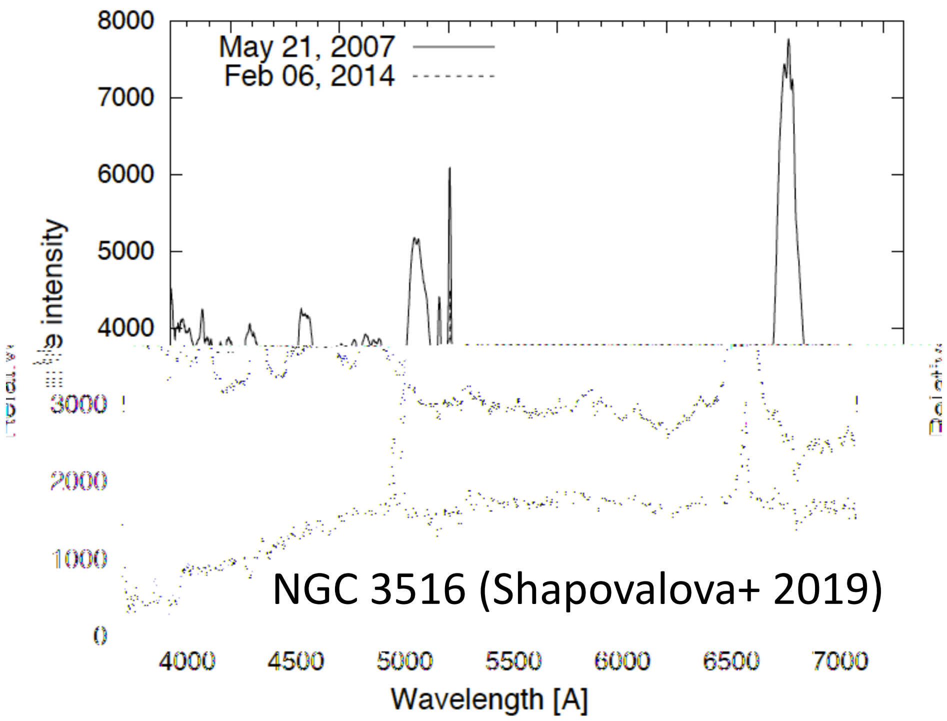


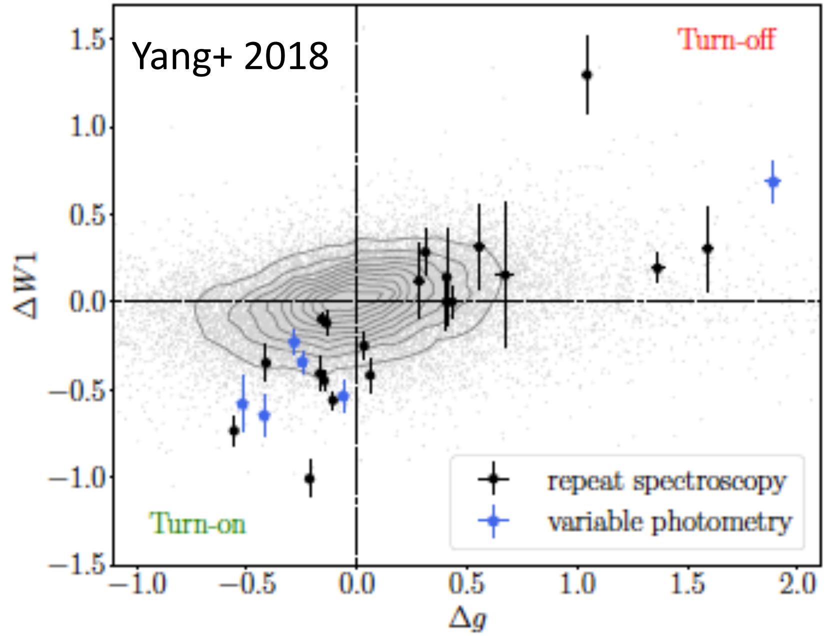
3. Changing-look (CL) AGN

- extreme variability: appearance or disappearance of BELs within a few years
- what is the cause?
  - variable accretion rate
  - variable obscuration
  - tidal disruption event

- LAMOST has found 21 new CL AGN (Yang et al. 2018)

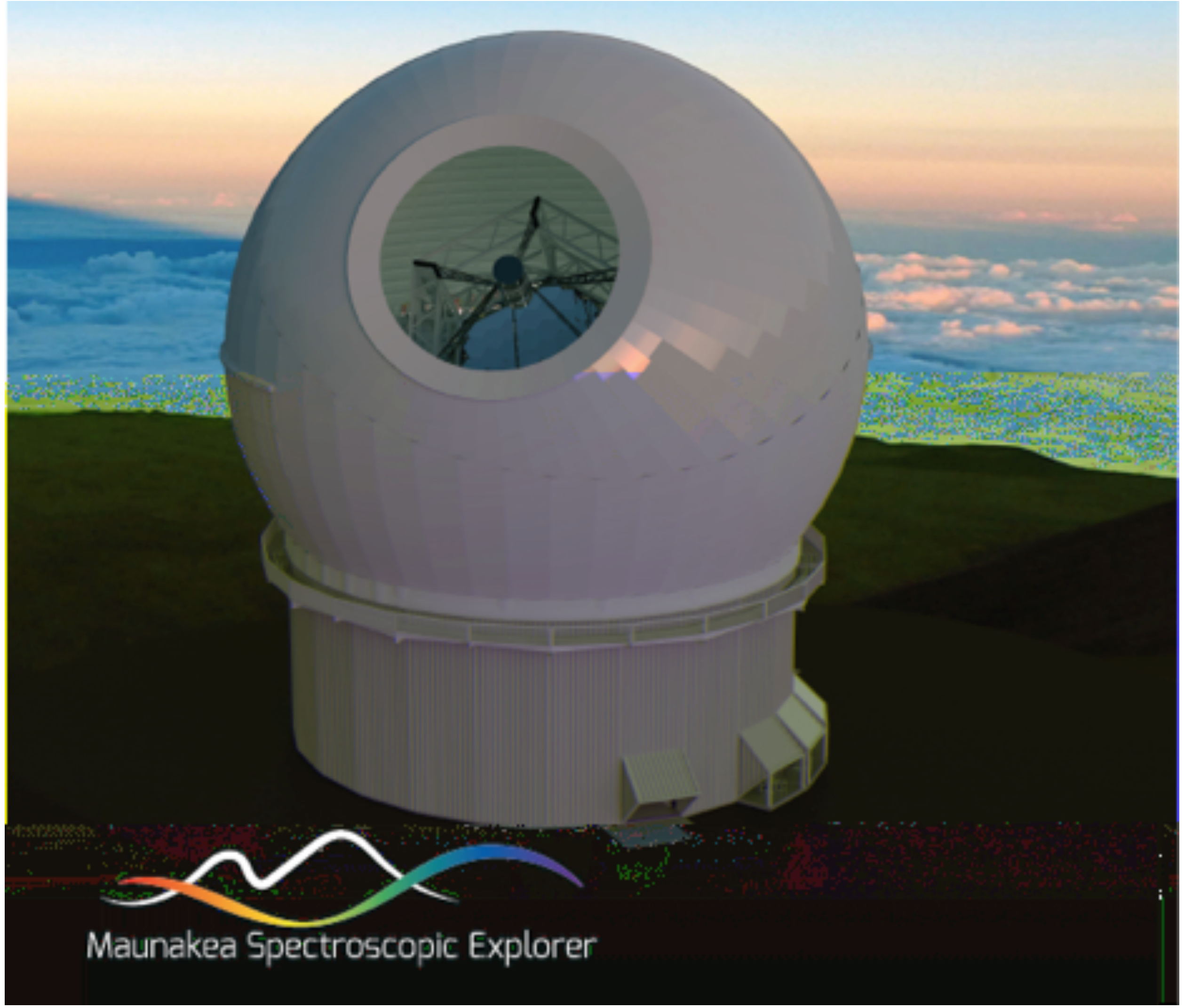
- perfect cases to study the connection between AGN and its host galaxy
- important to understand AGN evolution





MSE Meeting, February 2019, Tucson, Arizona

Massively multiplexed spectroscopy with MSE: Science, Project and Vision

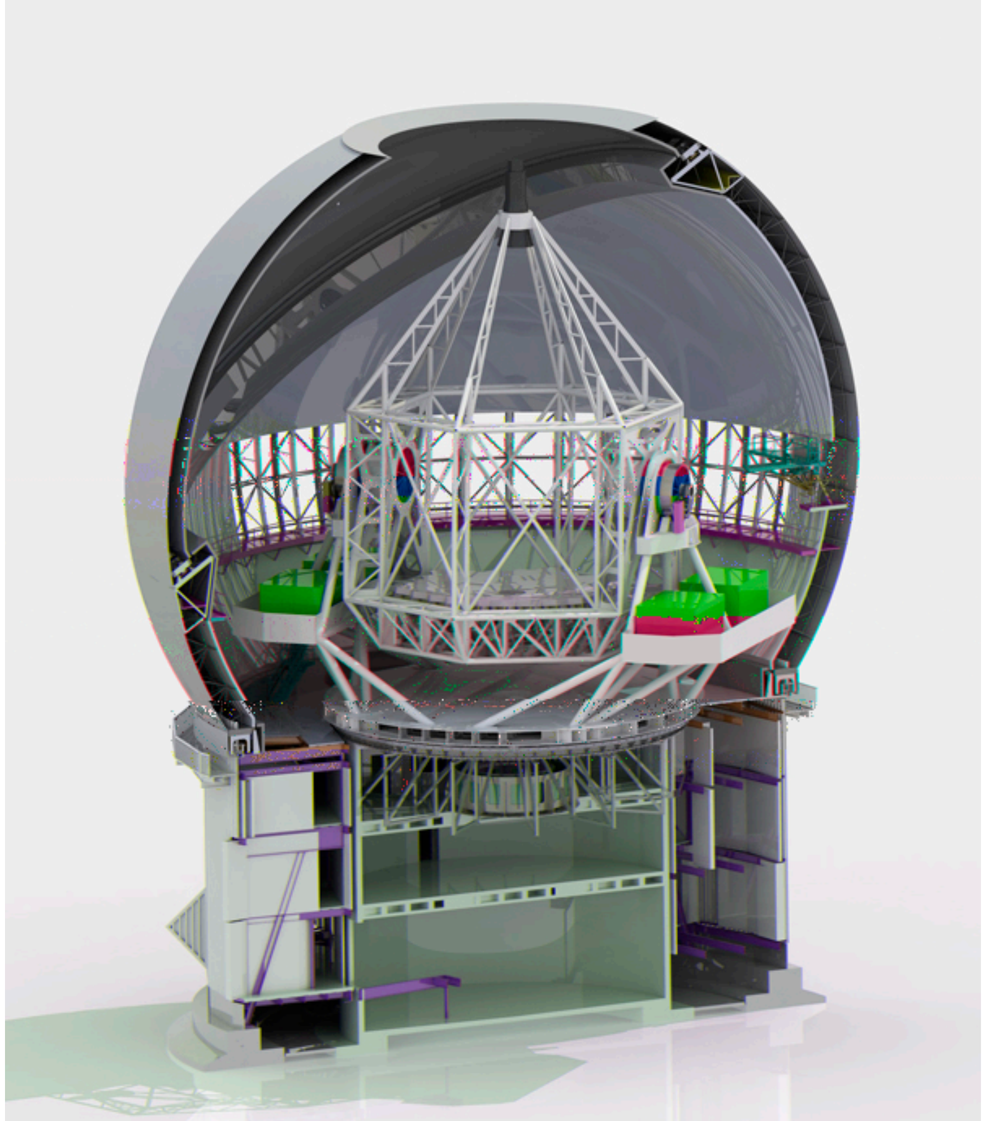


based on slides presented at the meeting https://www.noao.edu/meetings/mse2019/agenda.php

MSE Science Team meeting, Tucson, Feb 2019

Maunakea Spectroscopic Explorer

- **11.25m** telescope that will lead the world in multi-object spectroscopy
  - unique capability to study up to **4,000 astronomical objects** at once
- transform the CFHT 3.6m optical telescope into dedicated facility
- simultaneously observe more than 4000 objects with a spectral resolution range spanning 3,000 to 40,000
- planned for 2029



Maunakea Spectroscopic Explorer

MSE Project Office

Kei Szeto
Project Manager

Alan McConnachie
Project Spokesperson

Jen Marshall
Project Scientist

Andreea Petric
Deputy Project Scientist

Alexis Hill
Deputy Project Engineer

Nicolas Flagey
System and Operation Scientist

Mary Beth Laychak
Outreach Program Manager

Doug Simons
CFHT Executive Director

Science Working Groups

Chemical nucleosynthesis
Sivarani Thirupathi & **David Yong**

Galaxy Formation and evolution
Kim-Vy Tran & **Aaron Robotham**

Astrophysical tests of dark matter
Ting Li & **Manoj Kaplinghat**

Time domain astronomy and transients
Adam Burgasser & Daryl Haggard

Exoplanets and stellar astrophysics
Maria Bergemann & **Daniel Huber**

Milky Way and resolved stellar pops
Carine Babusiaux & Sarah Martell

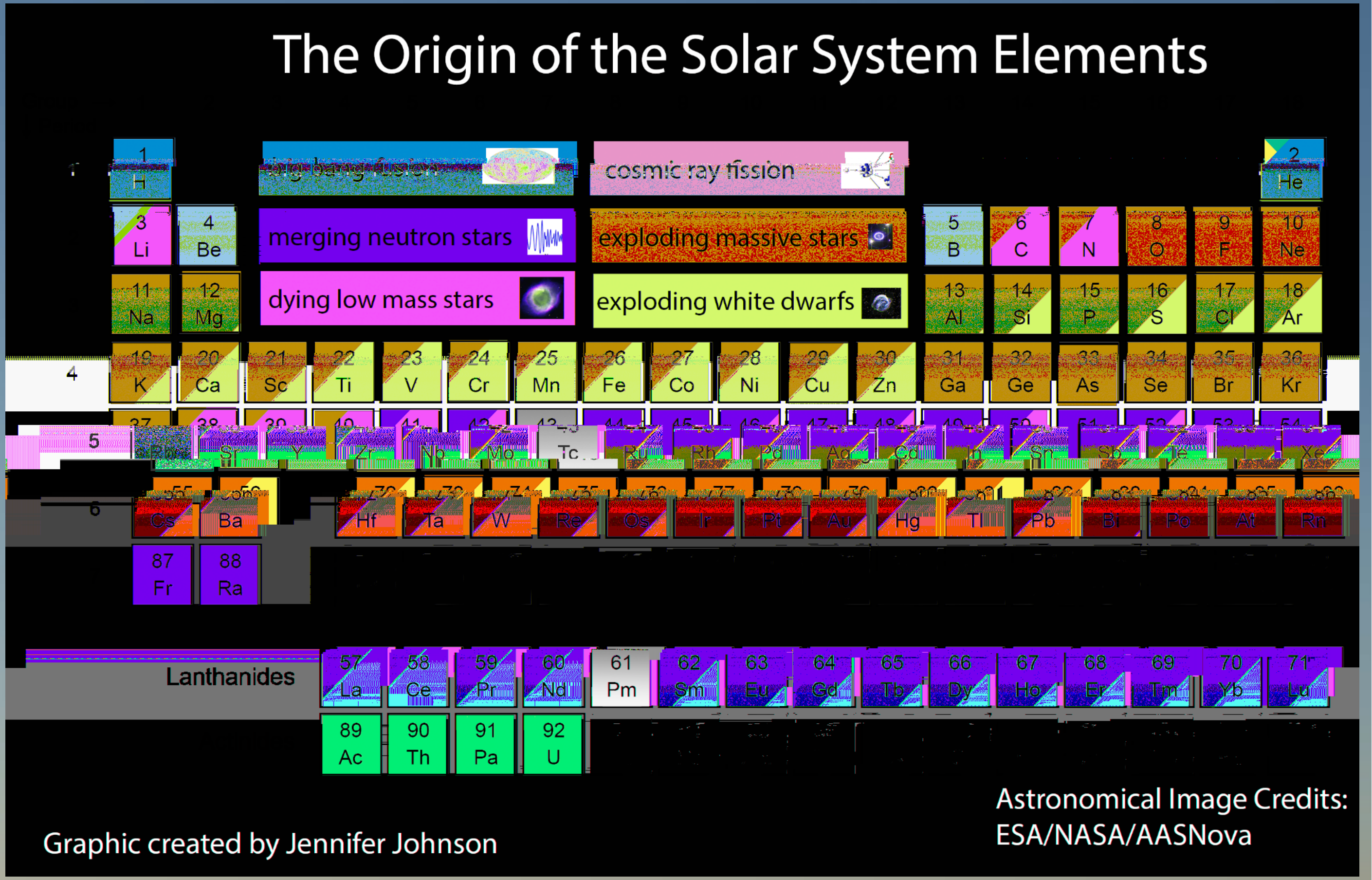
AGN and supermassive black holes
Yue Shen & Sara Ellison

Cosmology
Will Percival & **Christophe Yeche**

Most important Science Cases

Origins of the elements

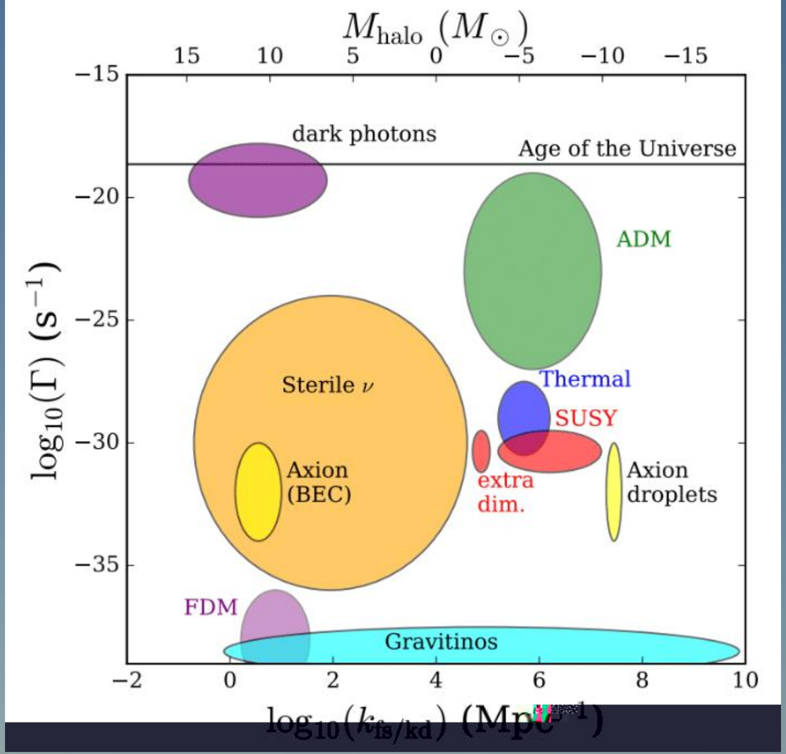
- MSE’s high resolution spectrographs will be able to measure *r*-process element abundances in an unprecedented number of stars, providing the final piece of direct observational evidence of the origins of every element on the Periodic Table

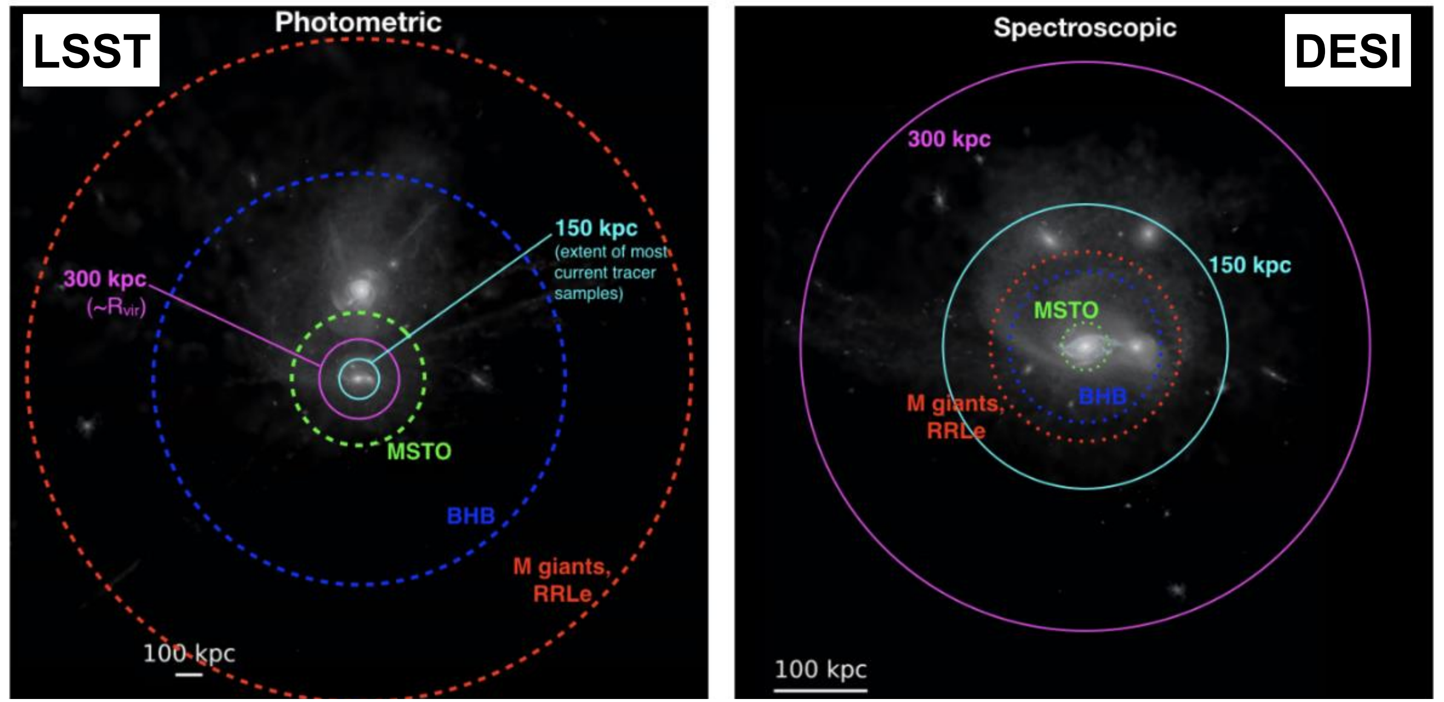


Most important Science Cases

Probing the particle nature of dark matter

- By measuring kinematics of stars in the Milky Way and dwarf galaxies, MSE will be able discriminate between different dark matter particles





MSE is the only planned spectroscopic survey that will be able to study the faintest objects discovered by LSST

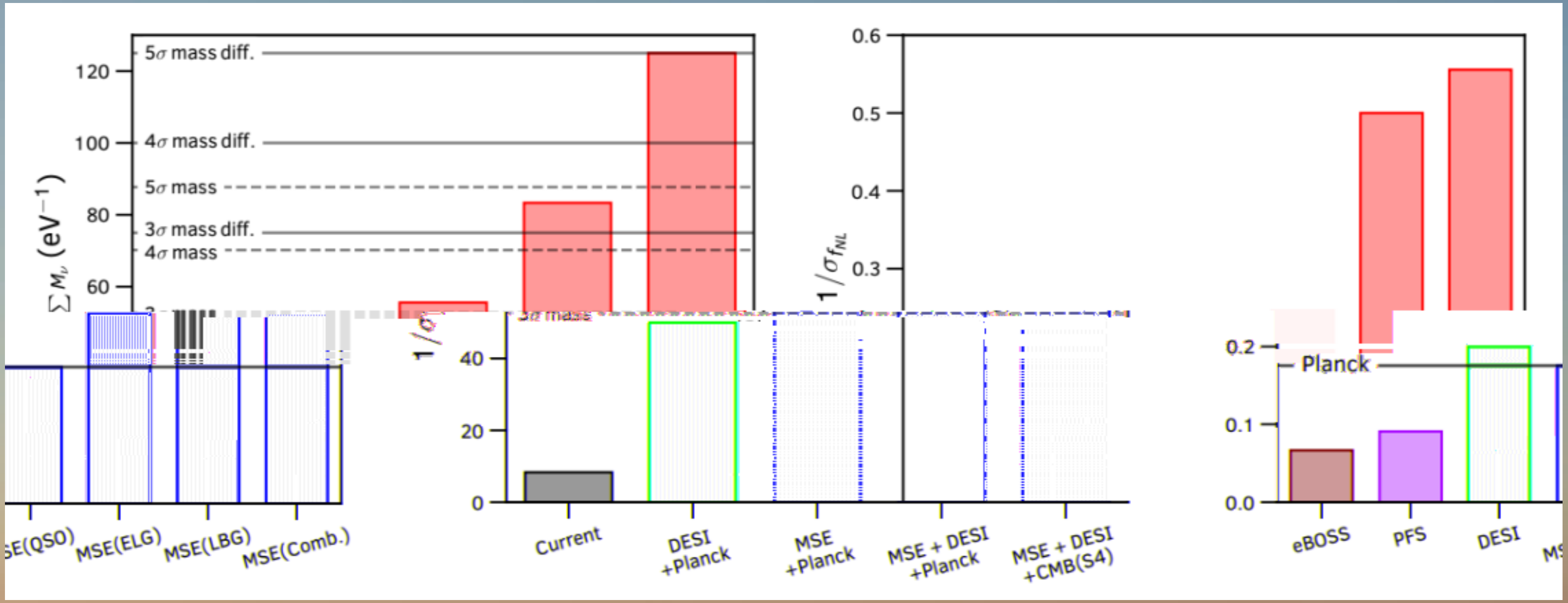
Most important Science Cases

Neutrino mass

- The proposed MSE cosmological large-volume survey of high-redshift galaxies can measure the combined mass of the neutrino better than any other project
- When combined with DESI+CMB(S4), a 5-σ measurement can be made

Primordial non-Gaussianity

- Probe physics of inflation
- Survey covers 10,000 square degrees; enormous volume of 280 Gpc^3 out to z~4
- Countless more science applications
- New regime for galaxy surveys



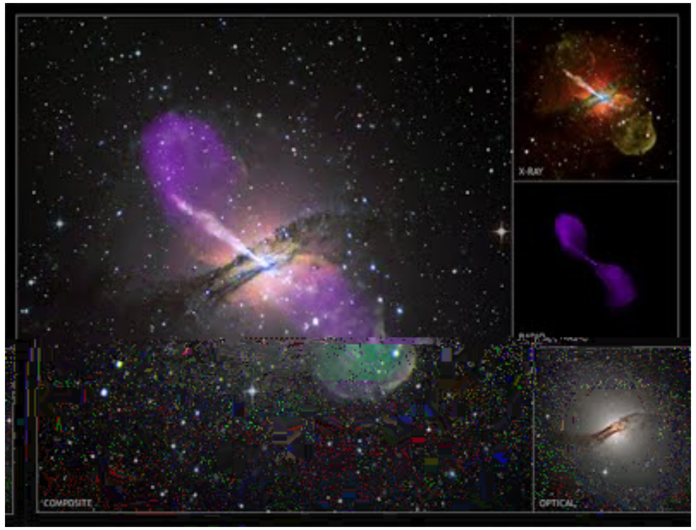
AGN/SMBH Themes

Physics of BH growth

The central engine (<~1-10 pc)

- SMBH seeds
- Reverberation mapping
- Variability
- Close SMBH binaries
- Nuclear outflows

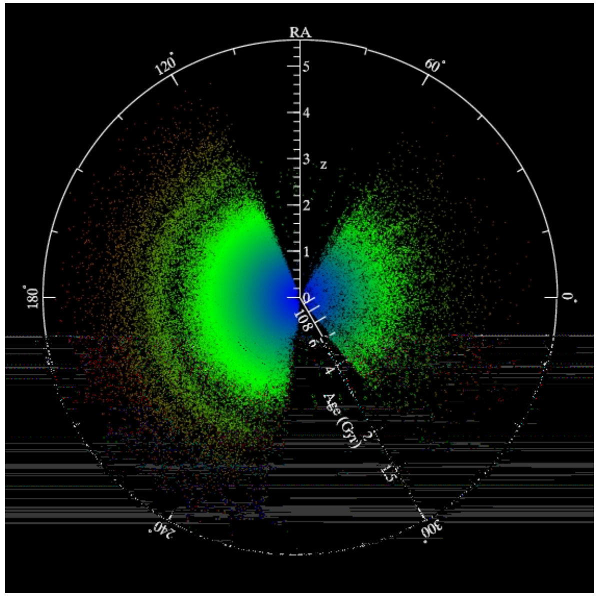
Coevolution with galaxies



The host galaxy

- AGN host properties
- Type-2 (obscured AGN)
- The earliest SMBHs and their hosts
- AGN triggering and mergers
- AGN feedback

As a cosmological probe

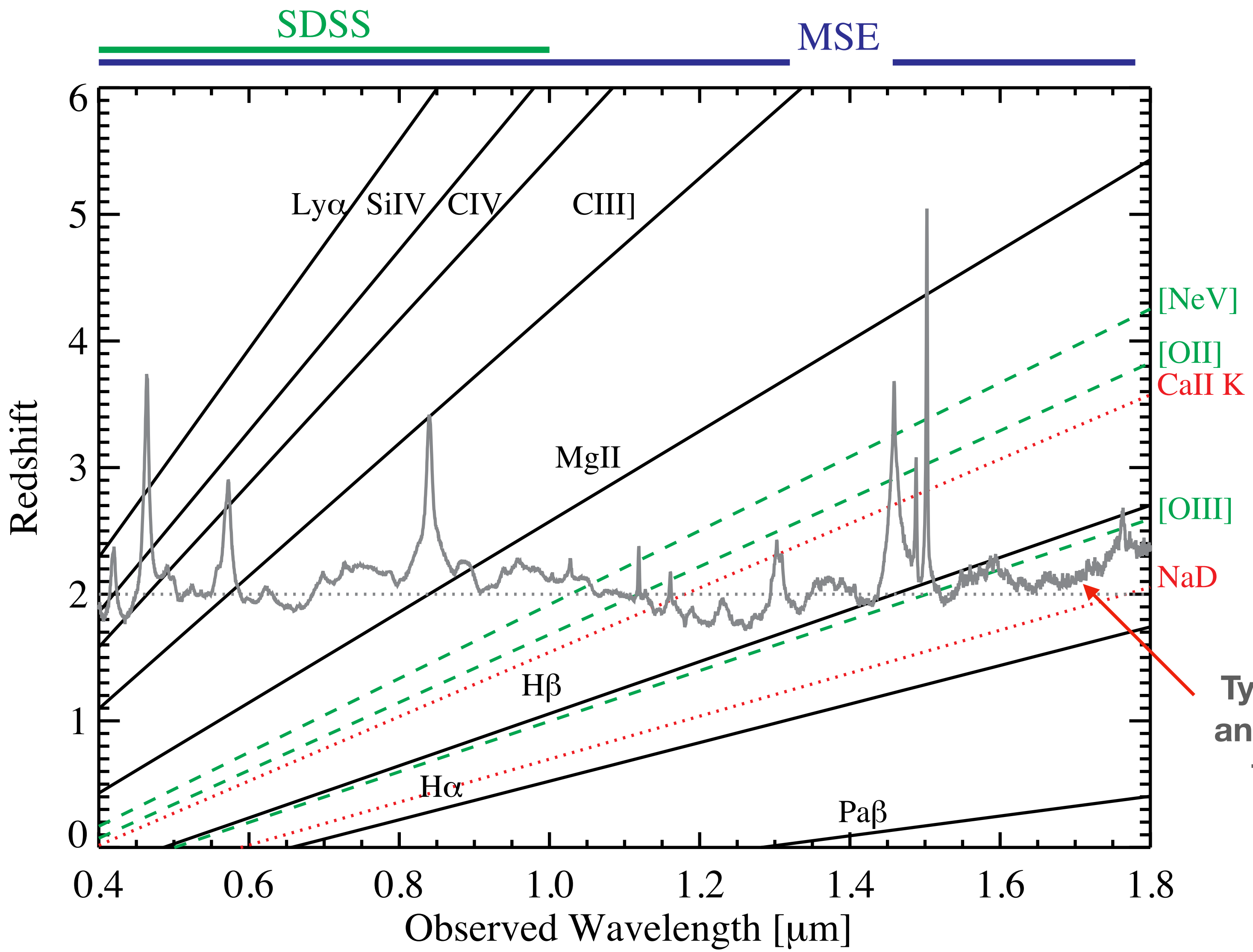


Beyond the galaxy

- Clustering and demography
- Gravitational lensed quasars
- Reionization with high-z quasars
- Intervening absorbers

MSE advantages
Sensitivity
NIR coverage
Multiplex
Survey dedication

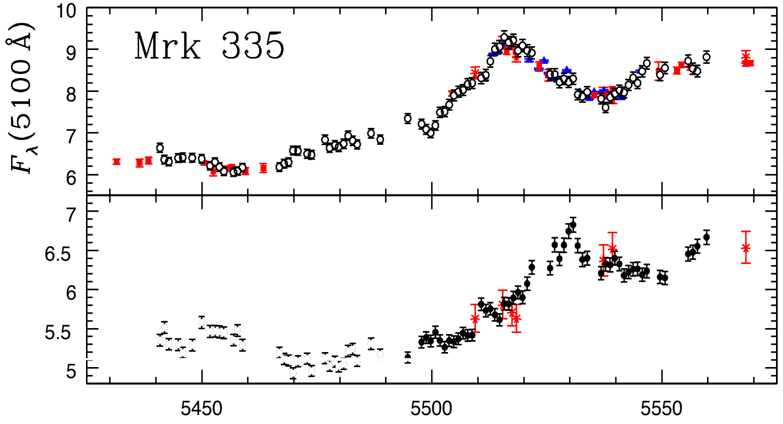
Lots of information in the spectrum, not just a redshift!

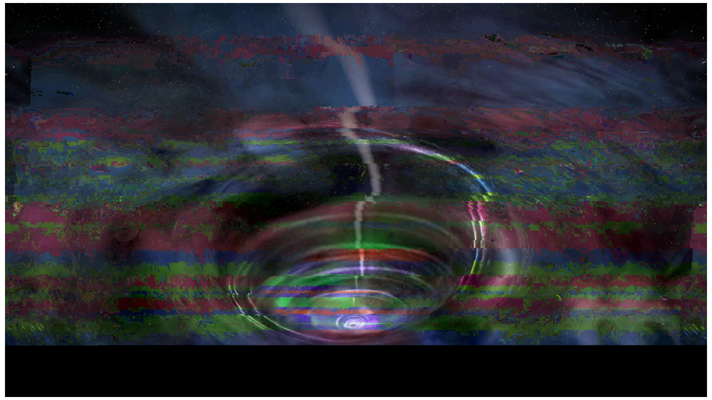


Typical spectrum of an unobscured (type 1) quasar at z=2

Science highlight

SRO-11 Mapping the Inner Parsec of Quasars with MSE



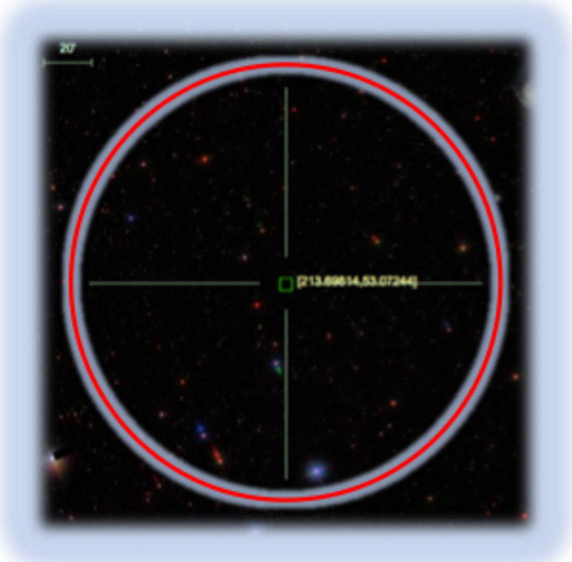


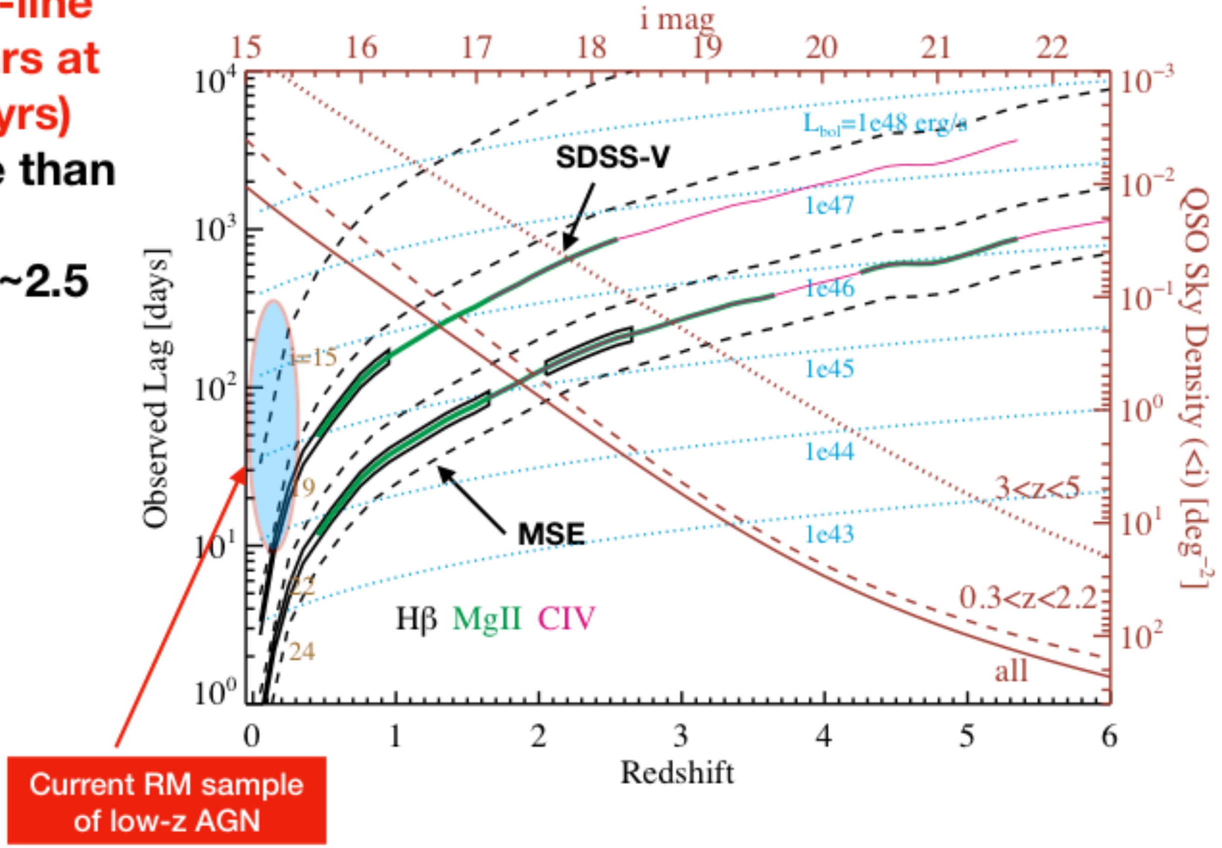
Science highlight

SRO-11 Mapping the Inner Parsec of Quasars with MSE

MSE will try to measure broad-line RM lags for ~2000-3000 quasars at z=0-5 (w/ ~100 epochs over 5 yrs)

- **An order of magnitude more than current MOS-RM programs**
- **NIR arm to cover Hbeta at z~2.5**

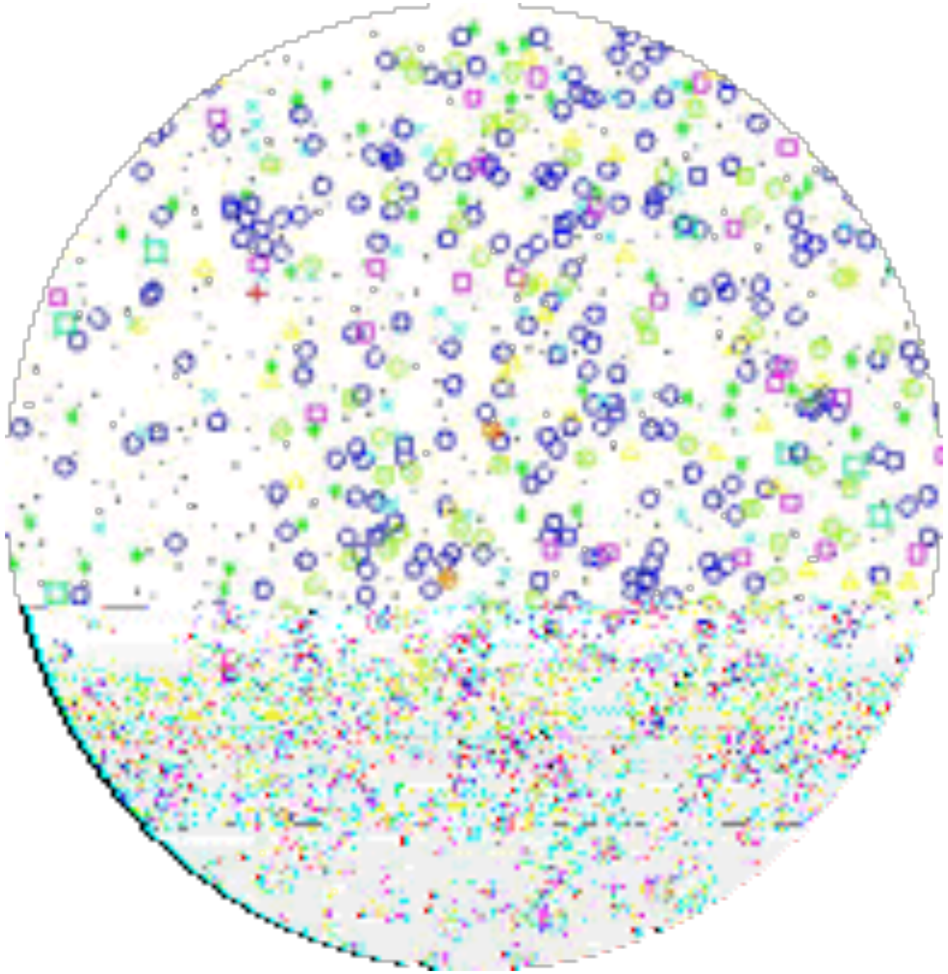


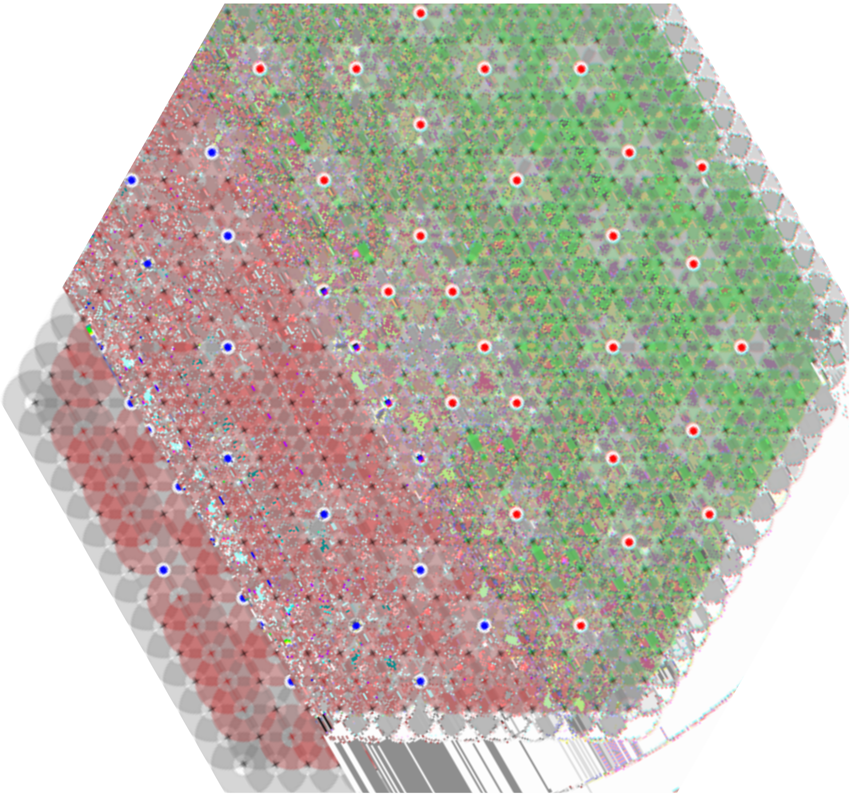


We will learn a lot from the SDSS-V Reverberation Mapping program (2020-2025). Now is a good time to get involved and get prepared.

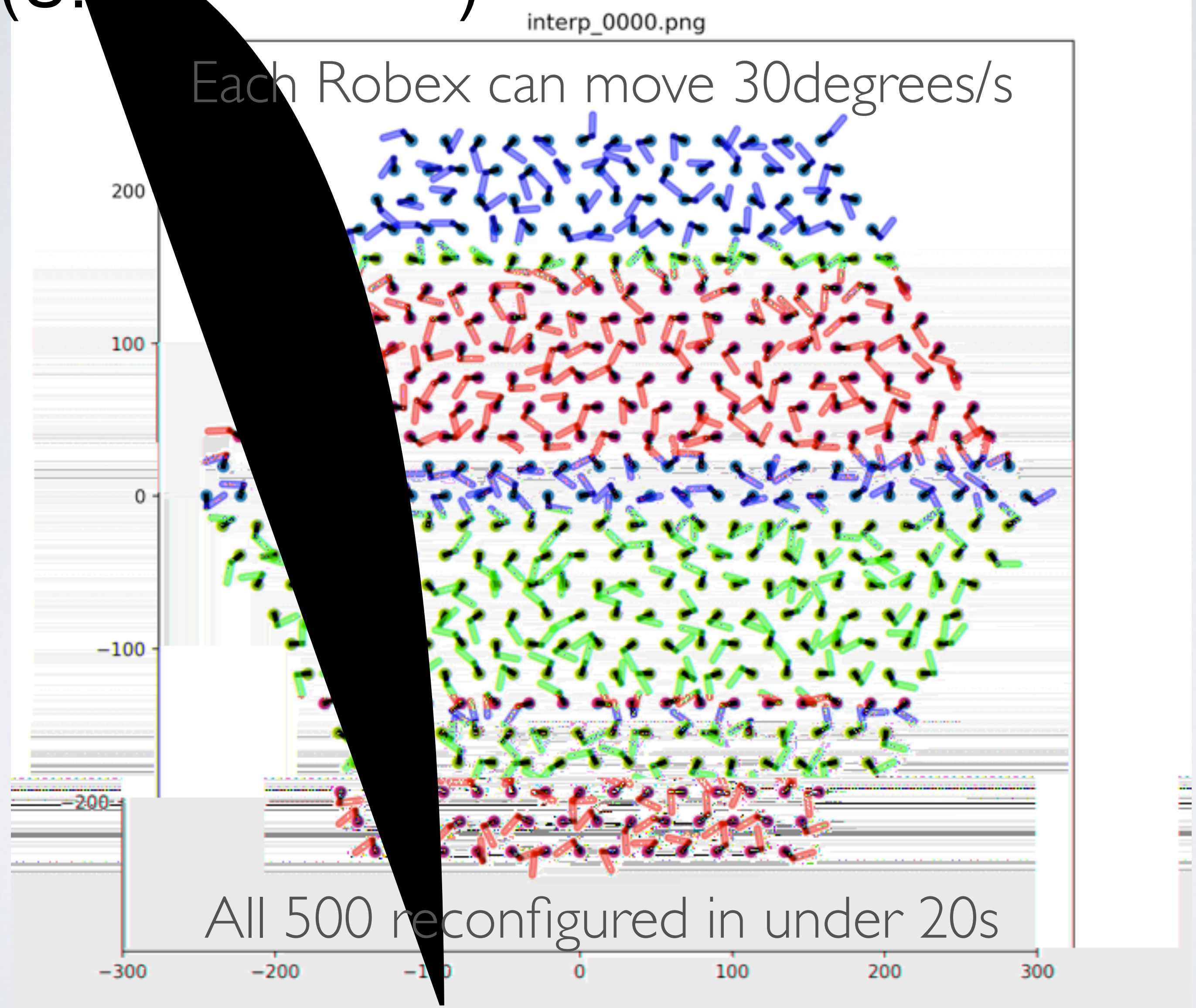
Other MOS surveys
→ Recycling Telescopes

ROBOTIC FIBER POSITIONERS TO FEED SPECTROGRAPHS





Kaiju: A H E C A A SDSS- R F P C S (U.)



Each Robex can move 30degrees/s

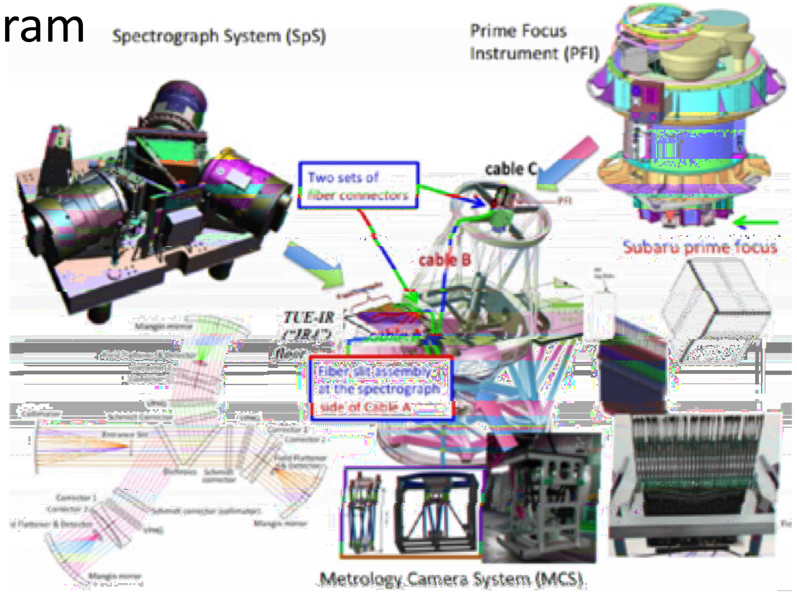
All 500 reconfigured in under 20s

Prime Focus Spectrograph (PFS)

PSF

8m,Subaru Hawaii

- Subaru 8m, D=1.3deg, 1.1deg2, 2400 fibers,
  R~2000-3500 (380-1260nm)
- Main science foci:
  - Cosmology (100n); BAO/RSD @ 0.8<z<2.4, neutrino mass, cosmology w/ join experiment of WL and galaxy clustering (HSC+PFS)
  - GA (100n): MW, M31, dSphs, ~1M stars w/ rad. vel., and chemistry
  - GE (100n): 15deg2, 0.7<z<1.7 J-selected, IGM tom. 2.1<z<3.5, LAEs, UV-sel z<7, AGNs
- Started 2010, 2020 commissioning, 2/2022 start SSP program
- SSP-PFS 300-360 clear nights, 5-6 years
- Operation costs on NAOJ – how about MSE?
- Rules set by SC, principles of operation as SDSS model
- PFS and MSE are actually quite similar
  - except PFS has only 300n, no H, no highR
  - PFS experience will be of key importance for MSE



Danilo Marchesini

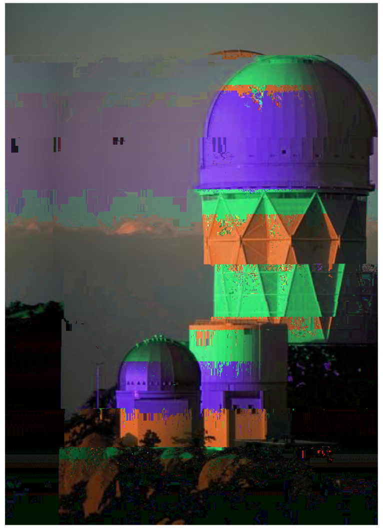
DESI

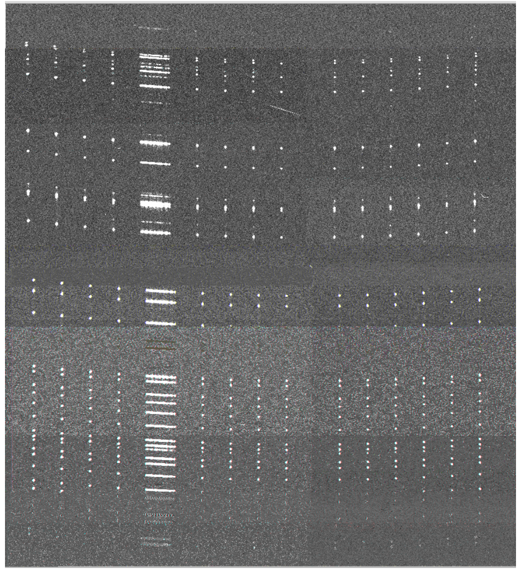
Mayall 4m

Kitt Peak

Dark Energy Spectroscopic Instrument (DESI)

- Mayall 4m telescope, prime focus, 3 deg dia field, 5000 fibers, R~2000-5500 (blue to red)
- Main science foci:
  - cosmology – dark energy (BAO+RSD), neutrino mass, some inflation constraints
  - Galaxies to z ~ 1.6, QSOs and Ly **α** to z ~ 3.5
  - Other science: Milky Way surveys (in bright time)
  - ~35 million galaxies, > 8 million stars
- 10.5 years from start of project to on-sky commissioning
- Survey operations 2020-25 (commissioning 2019 fall)
- Plans beginning for post-2025 ops (10+ before MSE?)





4MOST

VISTA 4m, ESO Chile

Specification	Design value
Field-of-View (hexagon)	**~4.1 degree²** (ø>2.6°)
Multiplex fiber positioner	**2436**
Medium Res Spectrographs (x2) # Fibres Passband Velocity accuracy	R~4000–7500 812 fibres (2x) 370-950 nm < 1 km/s
High Res Spectrograph # Fibres Passband Velocity accuracy	R~20,000 812 fibres 392.6–435.5 nm, 5 < 1 km/s
# of fibers in Ø=2' circle	>3
Fibre diameter	Ø=1.45 arcsec
Area (first 5 yr survey)	>2h x 18,000 deg²
Number of science **spectra** (5 yr)	**~75 million** of 20 r

.6–573 nm, 610–679 nm

Status: ***operations from end 2022 (≥2x 5 year)***

Science:

Cosmology, galaxy evolution, high-energy and Galactic science

Complement large area space missions: Gaia, eROSITA, Euclid, PLATO

Complement ground-based surveys: VISTA, VST, DES, LSST, SKA, etc.

Survey facility:

Instrument, science operations, data products, science

Run all-sky 5 year *public* surveys in parallel with yearly data releases

Key surveys organized by consortium, add-on surveys from community through ESO

No	Survey Name	Survey (Co-)PI
S1	Milky Way Halo LR Survey	Irwin (IoA, Cambridge), Helmi (RuG)
S2	Milky Way Halo HR Survey	Christlieb (ZAH)
S3	Milky Way Disk and Bulge LR Survey	Chiappini, Minchev, Starkenburg (AIP)
S4	Milky Way Disk and Bulge HR Survey	Bensby (LU), Bergemann (MPIA)
S5	Galaxy Clusters Survey	Finoguenov (MPE)
S6	AGN Survey	Merloni (MPE)
S7	Galaxy Evolution Survey (WAVES)	Driver (USW), Liske (HHU)
S8	Cosmology Redshift Survey	Richard (CRAL), Kneib (EPFL)
S9	Magellanic Clouds Survey	Cioni (AIP)
S10	Time-Domain Extragalactic Survey (TiDES)	Sullivan (Southampton)

Science case	S/N / Å	r_{AB}-mags	Targets (Millions)
S1 Milky Way Halo LR Survey	10	16–20.0	1.4
S2 Milky Way Halo HR Survey	140	12–15.5	0.6
S3 Milky Way Disk and Bulge LR Survey	10–30	14–18.5	10.7
S4 Milky Way Disk and Bulge HR Survey	140	14–15.5	2.0
S5 Galaxy Clusters Survey	4	18–22.0	0.8
S6 AGN Survey	4	18–22.0	0.5
S7 Galaxy Evolution Survey (WAVES)	4	18–22.5	1.4
S8 Cosmology Redshift Survey	4	–22.5	10.4
S9 Magellanic Clouds	10–30	-20.0	0.3
S10 Transients Survey (TiDES)	4	–22.5	0.3
Total			>27

SDSS V

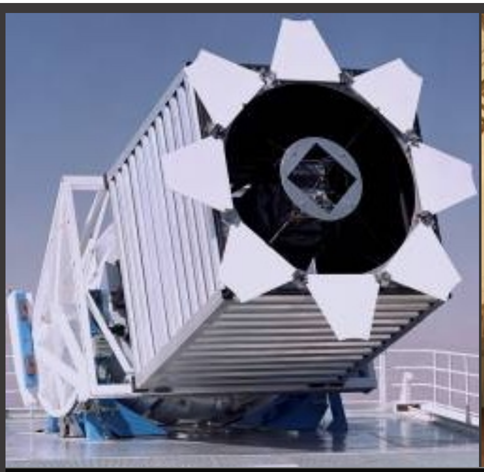
2.5m, New Mexico

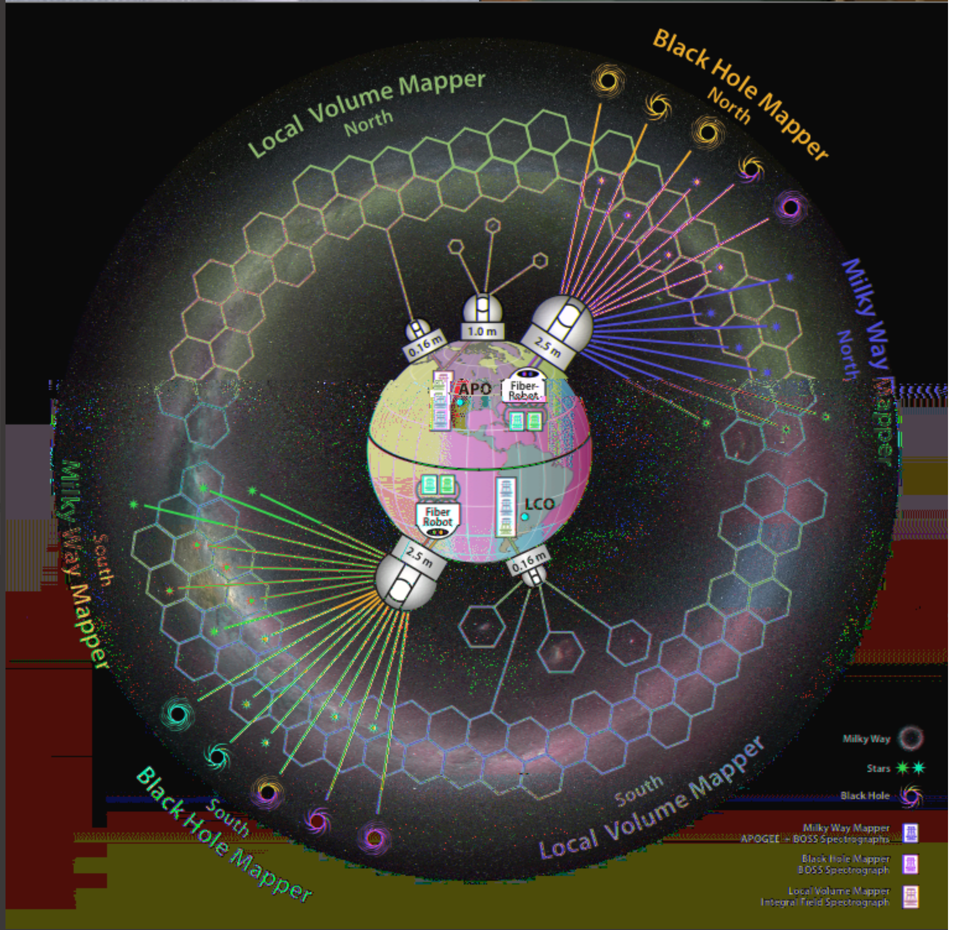
SDSS

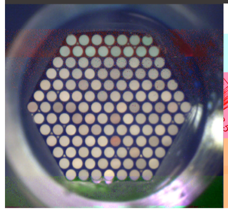
SDSS-III (2008-2014)
SDSS-IV (2014-2020)
SDSS-V (2020-2025)

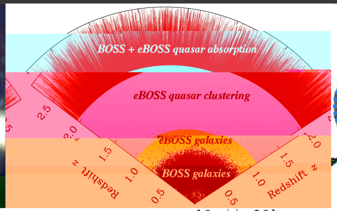
Peter Frinchaboy

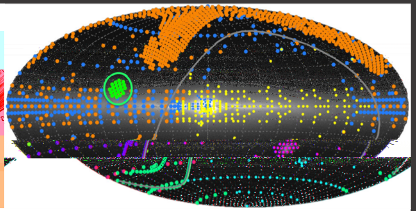
SDSS-III/APOGEE-1 Operations Scientist
SDSS-IV Survey Coordinator
SDSS-IV Survey Implementation Consultant

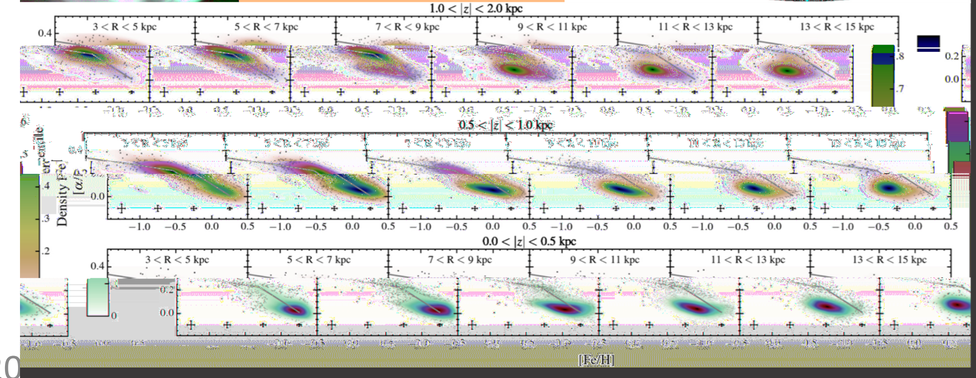












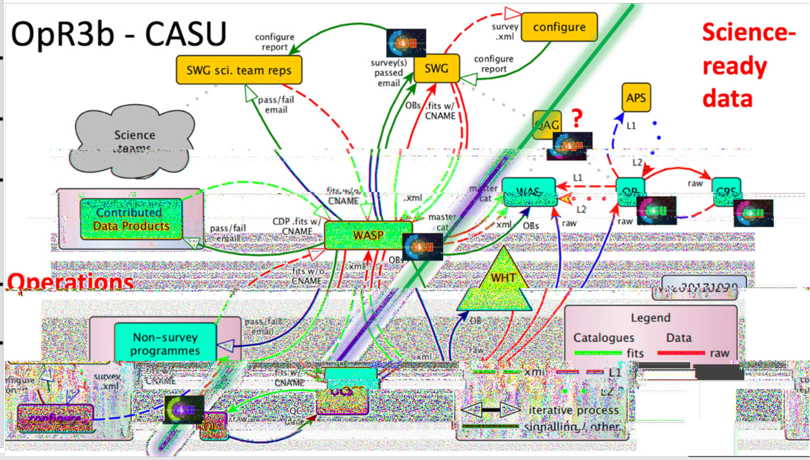
WEAVE

WHT, 4.2m

Canary islands

Telescope, diameter	WHT, 4.2m
Field of view	2º Ø
Number of fibers	960 (plate A)/940 (plate B)
Fiber size	1.3″
Number of small IFUs, size	20 x 11″x12″ (1.3″ spaxels)
LIFU size	1.3′x1.5′ (2.6″ spaxels)
Low-resolution mode resolution	5750 (3000–7500)
Low-resolution mode wavelength coverage (Å)	3660–9590
High-resolution mode resolution	21000 (13000–25000)
High-resolution mode wavelength coverage (Å)	4040–4650, 4730–5450 5950–6850

WEAVE Summary



Galactic Archaeology

LR-highlat, LR-disc, HR, Open Cluster

Stellar, Circumstellar, and Interstellar Physics

Galaxy Clusters

WEAVE-Apertif

StePS (Stellar Populations at intermediate redshifts

WEAVE-LOFAR

WEAVE-QSO

White Dwarfs

~1000 fibres (+mIFU and IFU)
over ~π deg^2
at R up to 25,000
for λ ~366-959nm

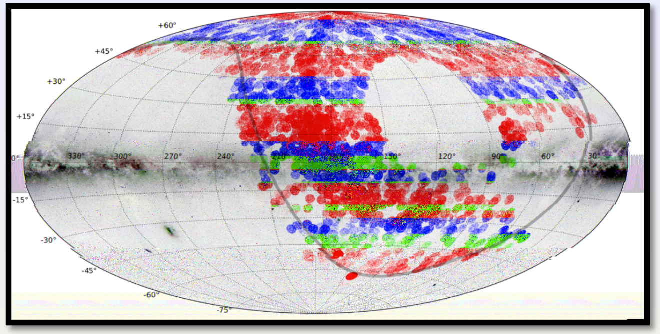
WEAVE 5 year surveys
commence Q2/ **2020**

http://www.ing.iac.es/weave

LAMOST

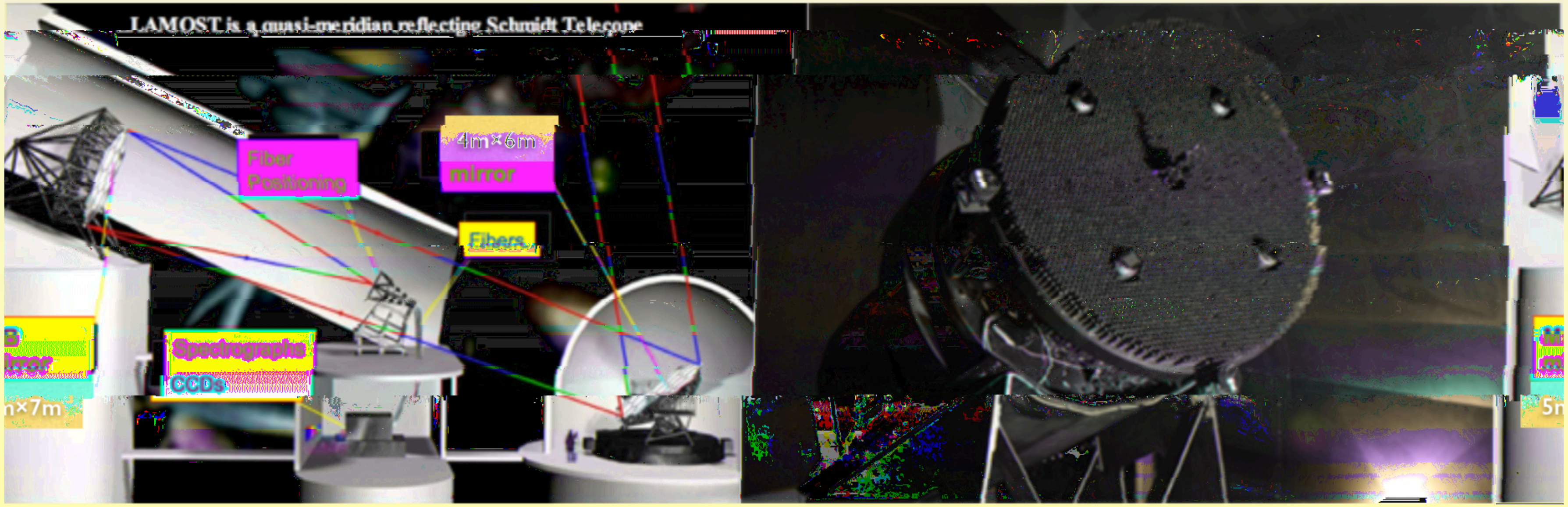
4m,China

LAMOST



- Pilot survey: 2011.10 - 2012.5
- Phase-I Regular survey: 2012.10 – 2017.6
- Phase-II Pilot survey: 2017.9-2018.6
- Phase-II Regular survey: 2018.9-present (low- + intermediate-resolution)
- Phase II development (a new fiber system + a new site)?

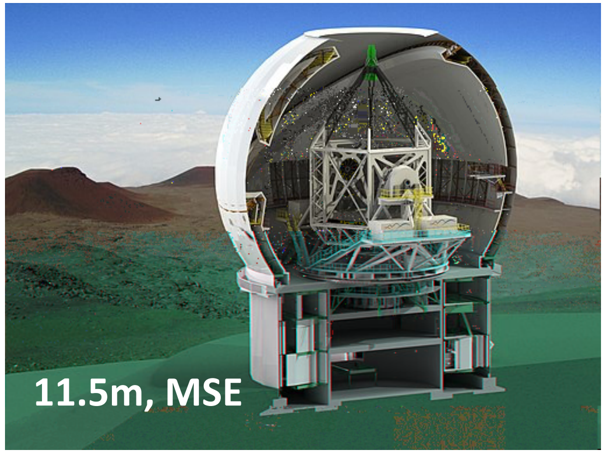
In pilot survey and phase-I regular survey, LAMOST has collected nearly 9 million spectra, including over two hundred thousand spectra of extra-galactic objects (galaxy and qso) and nearly 7.5 million qualitied (SNR > 10) spectra of star.



MSE will make a difference

- **reverberation mapping** campaign of 5000 quasars up to z~3

  → robust estimates of time lags → accurate SMBH mass for the largest sample of quasars to date



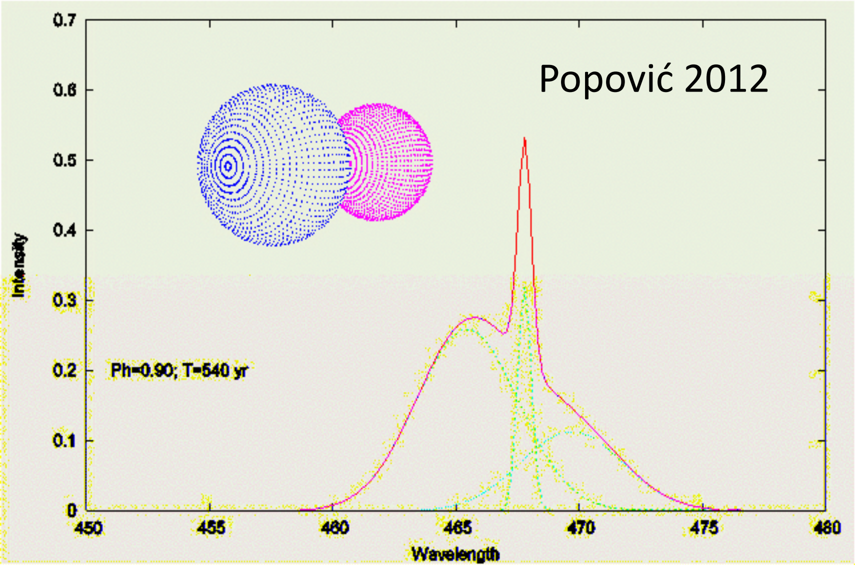
- identify **new changing look AGN** -- synergy with other missions (e.g. LSST, Pan-STARRS)

- high-resolution high-performance spectroscopy

  → velocity resolved reverberation mapping

  → mapping of the central regions

  → resolve the **binary SMBH**



Summary

- spectral monitoring still crucial for the AGN and emission line region investigations
- the optical spectral **variability** can be used for:

  → reverberation, i.e. measuring the unseen → the radius of the BLR

  → the mass of the SMBH

  → constrain the radius-luminosity relation

  → discover more changing-look AGN

  → hunt for SMBH binaries

→ constrain the physics and geometry of the BLR

Maunakea Spectroscopic Explorer