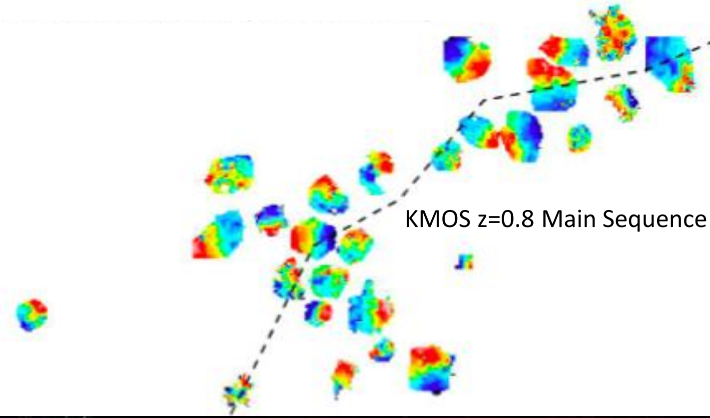
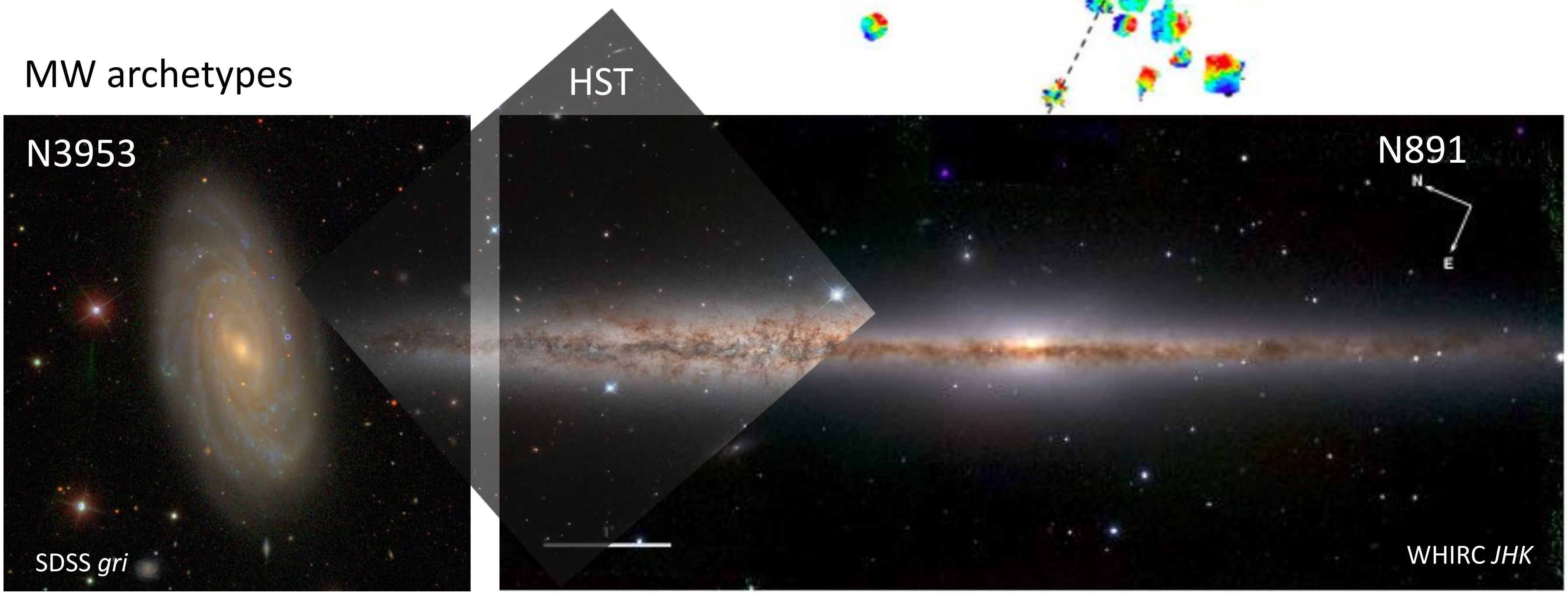
Galaxy Evolution: Current Surveys and Instrumentation


KMOS z=0.8 Main Sequence (Stott+14)

MW archetypes



Credits:
DiskMass Survey team
SDSS-IV/MaNGA team

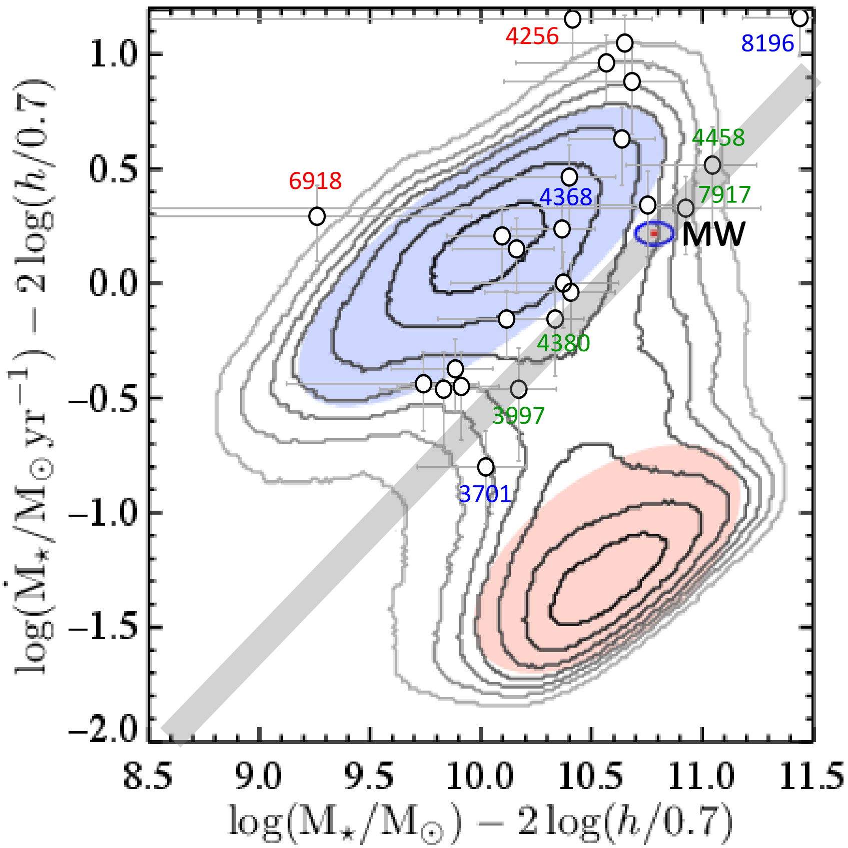
Matthew Bershady
University of Wisconsin-Madison

Outline

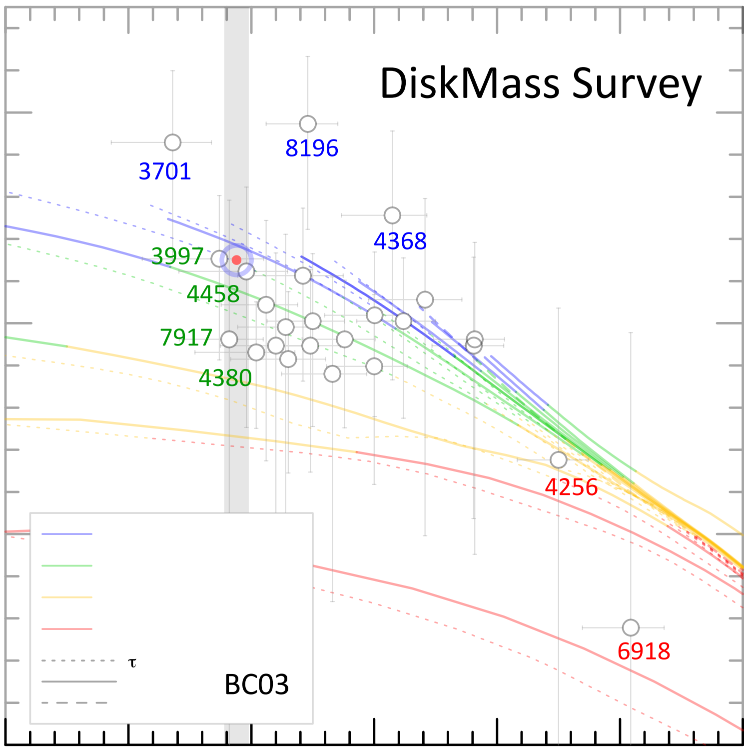
- Theme:
  - *Is the MW a typical spiral galaxy?*
- State of the Art Instrumentation
  - Monoliths, Megaliths & MOS
- Key topics
  - ✓ Heating and cooling of disks
  - dwarfs and the galactic periphery

I. Is the Milky Way a typical galaxy?

M/L and star-formation: MW and the DiskMass Survey



Licquia & Newman (2014)



Bershady+2015
DMS: Bershady+10, Martinsson+2013

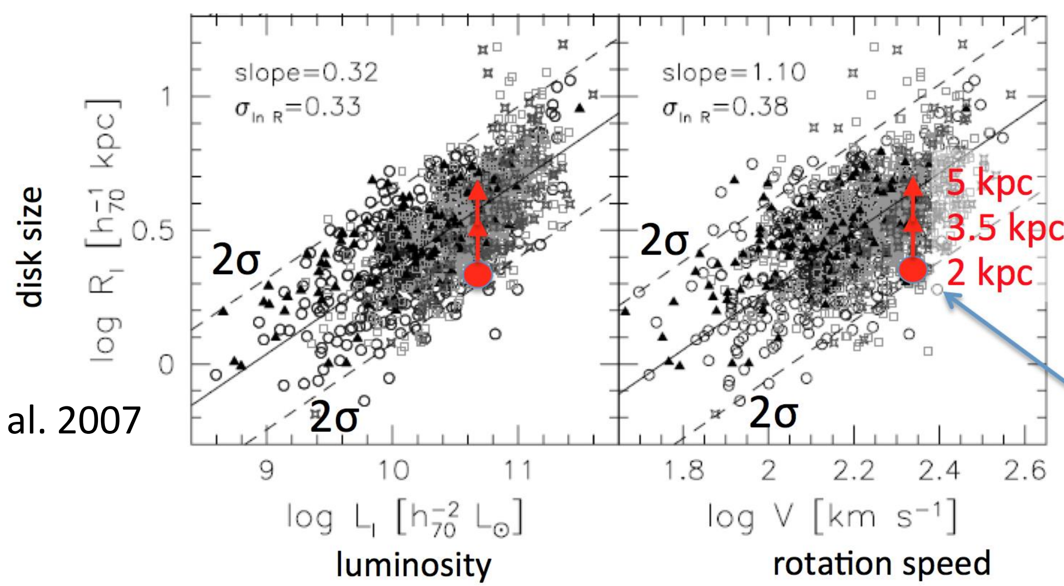
Outstanding issues

- The Milky Way appears to have a *maximal* disk and a very small size for its rotation speed.
- DiskMass Survey spirals have *submaximal* disks.

Bovy+14
cf Iocco+15

Bersshady+11
Martinsson+13

> Do we really live in an unusual galaxy?
> …or are different vantage points leading to observational bias? e.g., mass *vs* light weighting…



Courteau et al. 2007

MW

2 < R_d/kpc < 5

Recent estimate from SEGUE G-dwarfs (Bovy & Rix'13; 2.15 kpc)

II. State of the Art *is* IFS

- *The future just arrived*
  - MUSE – VLT 8m
  - VIRUS – HET 10m
  - MOS
    - KMOS – VLT 8m
    - SAMI – AAT 3.9m
    - MaNGA – Sloan 2.5m

Wide-field (SAMI, MaNGA)

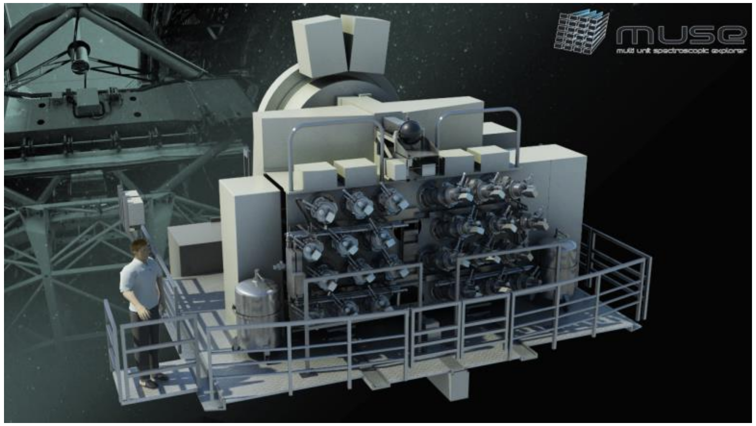
- Common themes:
  - Large AΩ ← instrument multiplex
  - Few have large specific grasp AdΩ
  - **object multiplex**: different solutions
    - *KMOS and MUSE: slicers*
    - *VIRUS, SAMI, MaNGA: fibers*
  - **instrument multiplex**: cost-driven
    - *Economies of scale*
    - *Limited camera field*

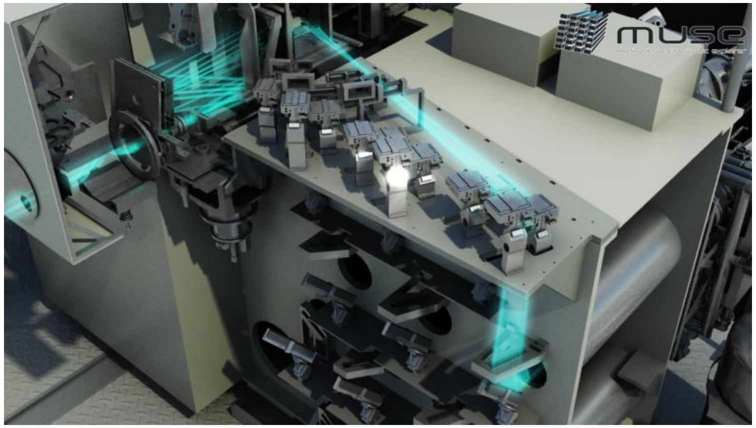
MUSE

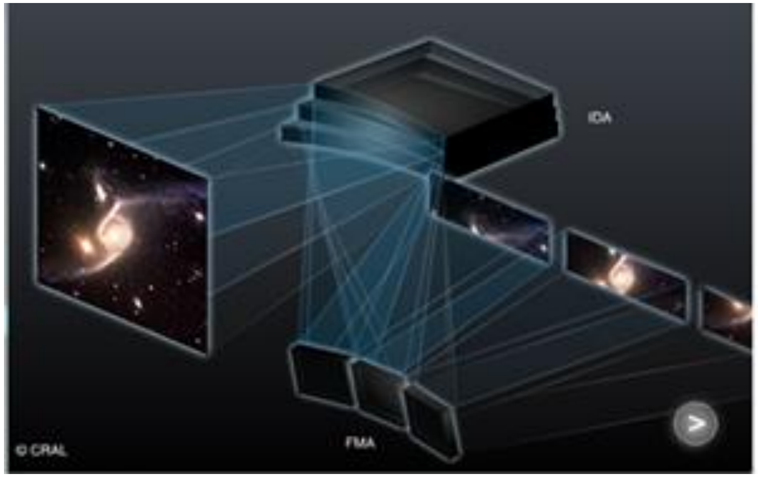
AMAZING

- Science goals
  - Detailed study of high-redshift galaxies, structure formation, discovery.
- Technical approach
  - Replicate 24 modest-resolution spectrographs fed with advanced (catadioptric) images slicers.
  - Premium on image quality / information.
  - Ground-layer AO (GLAO) assisted.
- Instrument capabilities
  - VLT 8m
  - Two scales:
    - 1 $arcmin^2$ FoV, (0.04 $arcsec^2$ elements)
    - 56 $arcsec^2$ FoV, (6.3×10^{-3} $arcsec^2$)
  - integrally sampled
  - 0.465-0.93 nm range (one shot)
  - ~2000 spectral elements (R~3000)
  - $\varepsilon \sim 0.24$

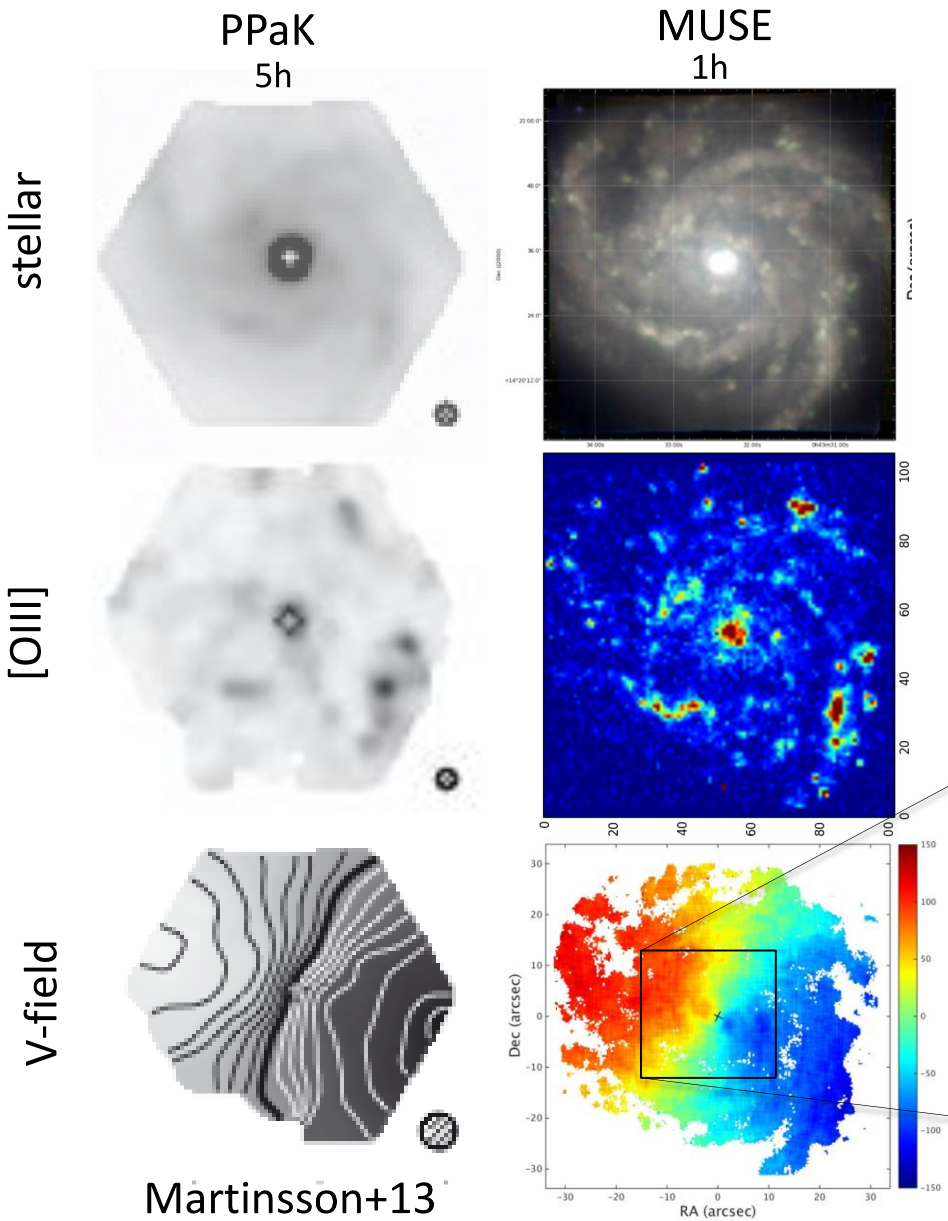
Bacon et al. ‘04



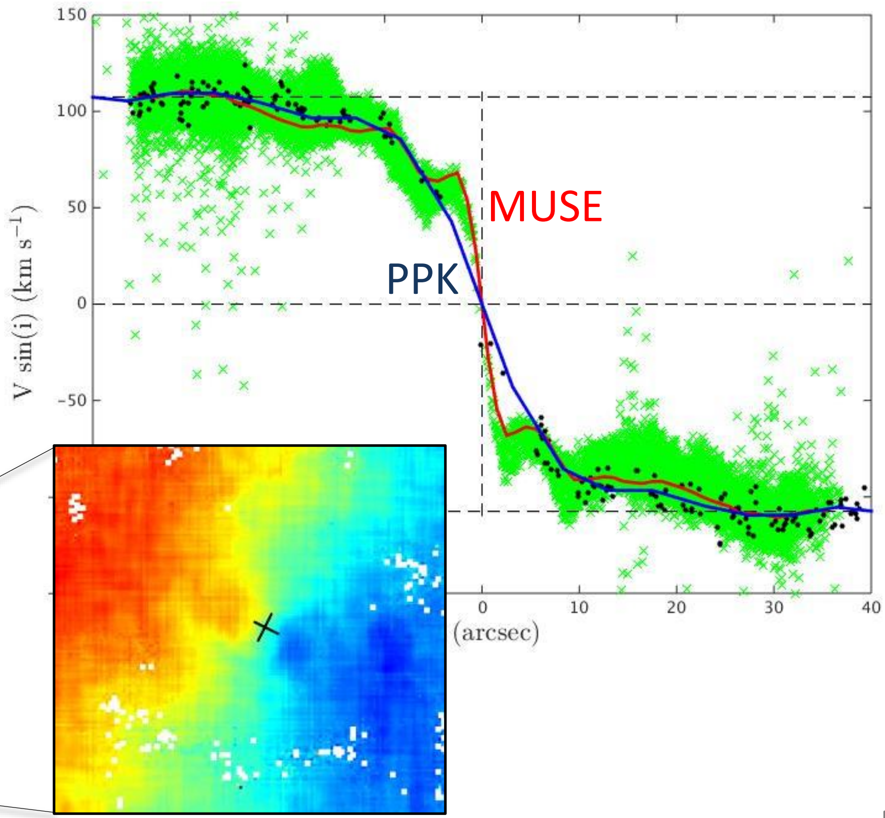




MUSE: great contributions at low-z



Martinsson+13

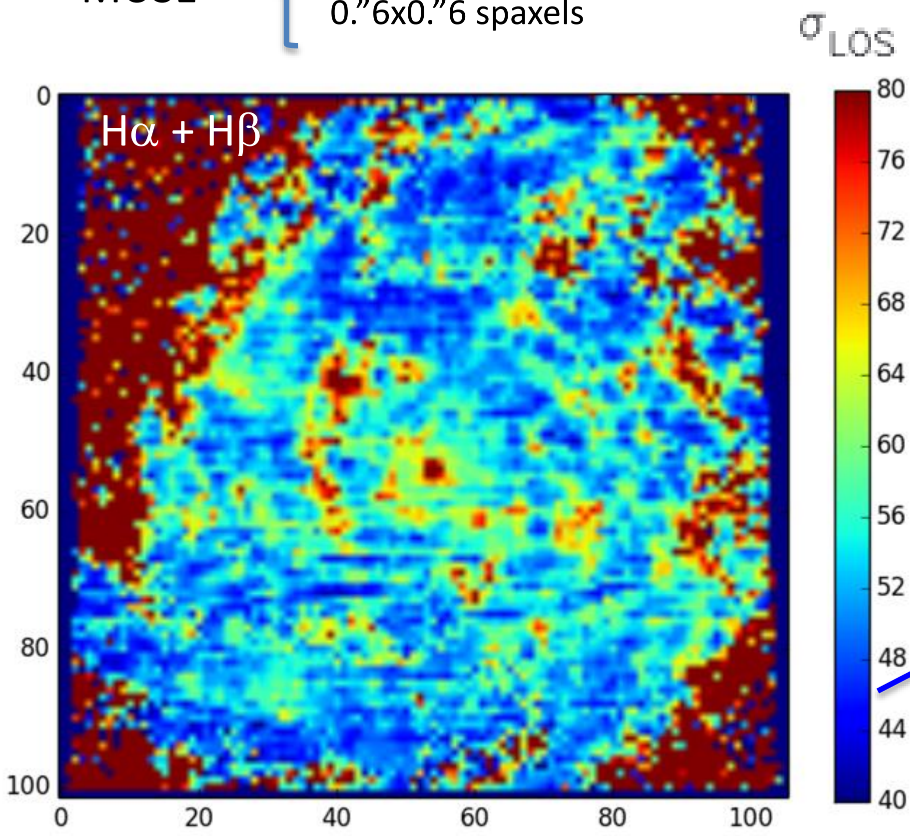


Martinsson & Brinchmann+15

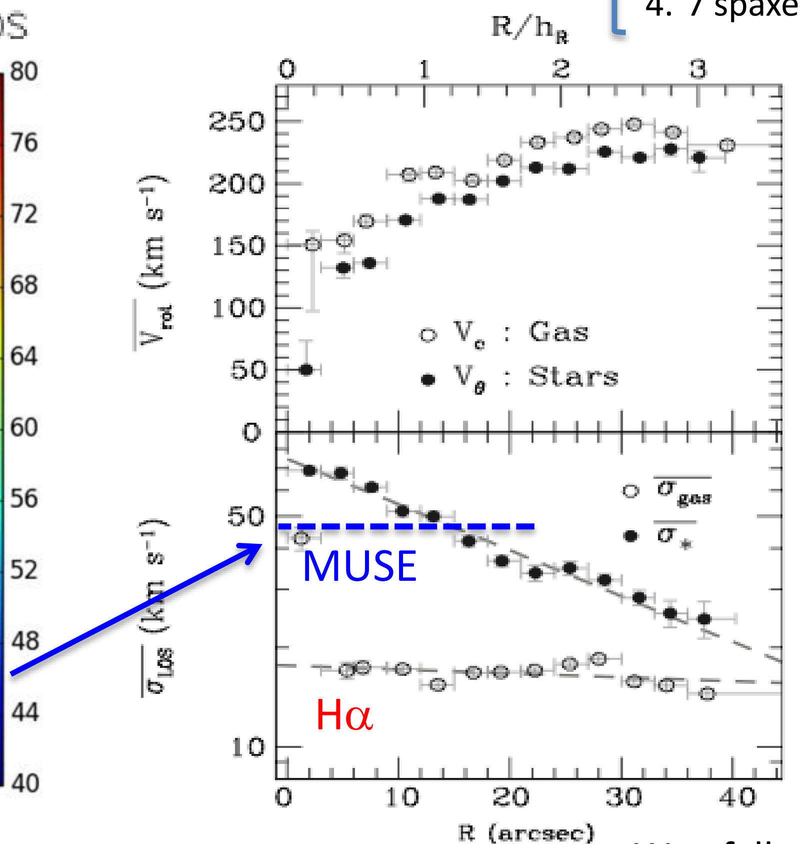
MUSE: great contributions at low-z

MUSE
- 1 x 15min
- 0.”6x0.”6 spaxels

SparsePak
- 1h Hα
- 10h MgI
- 4.”7 spaxels



Martinsson & Brinchmann+15

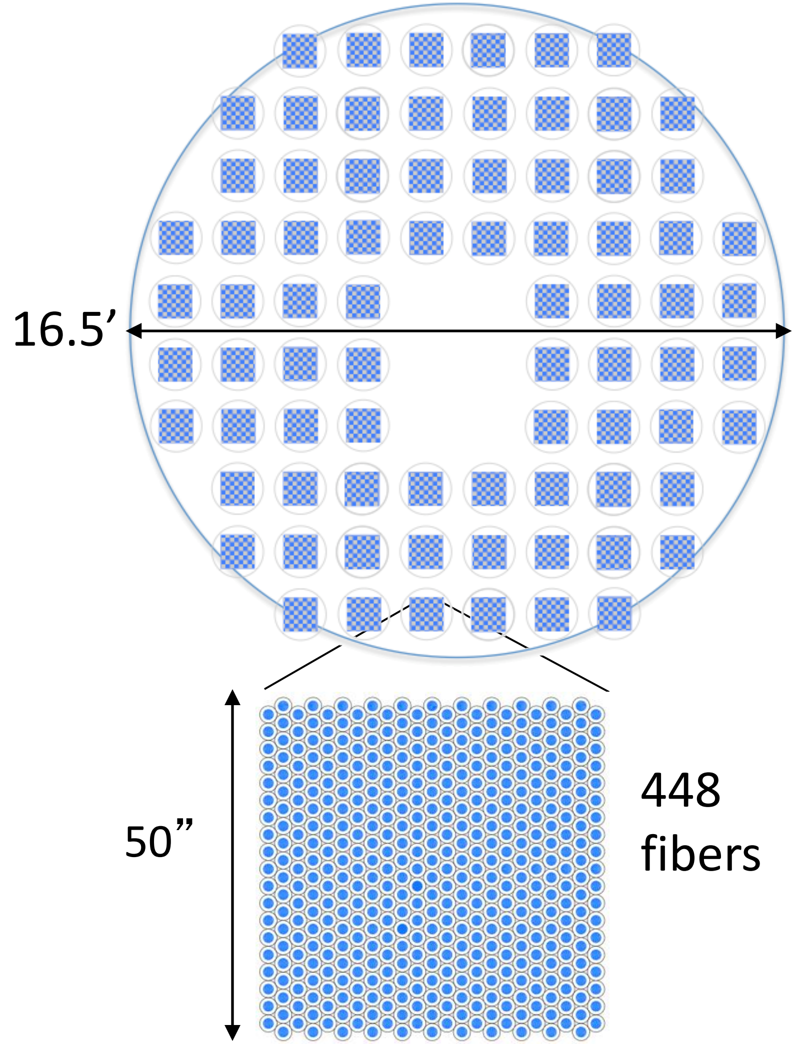


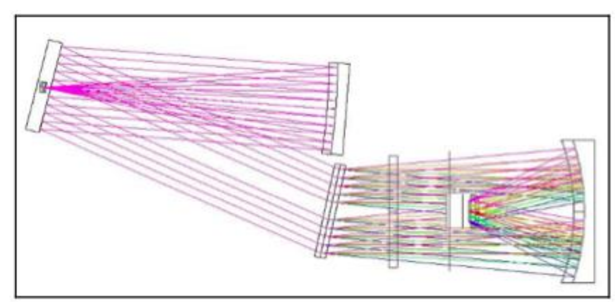
Westfall+11

But there’s a real need for better ***spectral*** resolution:
MUSE can’t ***kinematically*** resolve gas dispersions in normal disks

VIRUS

- Science goals
  - Measure BAO from Lyα-e's at 1.8<z<3.7: **HETDEX**
- Technical approach
  - Replicate 150, small, cheap, low resolution bare-fiber fed spectrographs
- Instrument capabilities
  - HET 10m + new corrector
  - 16.5' field, sparsely sampled
  - 75 IFUs, 16.5 arcmin^2 coverage
  - 33600 fibers (1.5" diam.)
  - 350-550 nm range (one shot)
  - 410 spectral elements (R~700)
  - ε ~ 0.15





Hill+12a,b

KMOS

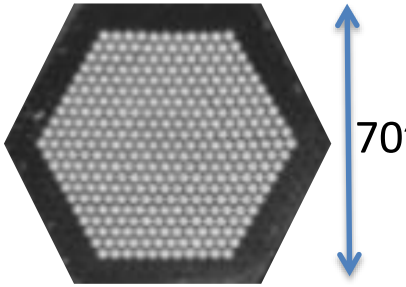
- Science goals
  - Investigate physical properties driving galaxy formation/evolution; measure comoving star-formation rate.
- Technical approach
  - Multi-object image slicer feeding cryogenic spectrographs (3).
- Instrument capabilities
  - VLT 8m
  - 24 MOS probes, 2.8x2.8 arcsec each, sampled at 0.2 arcsec (14 slices)
  - 4704 spatial elements total (188 arcsec^2)
  - 7.2 arcmin diameter patrol field
  - 0.8-2.5 μm range
  - 1000 spectral elements (R~3600)
  - ε = 0.3 * telescope * atmosphere

Sharples+12

CALIFA, SAMI and MaNGA

- Science goals
  - Dissect nearby galaxy population to determine dynamics *and* composition physical properties driving galaxy formation/evolution;
- Technical approach
  - Multi-object fiber IFUs feeding dual-beam spectrographs.
- Instrument capabilities

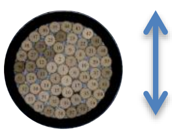
	CALIFA	SAMI	MaNGA
D_{TEL}	CA 3.5m	AAO 3.9m	SDSS 2.5m
Patrol FoV		1 deg	3 deg
# IFU	1	13	17
# fibers	382	819	1423
D_{fiber}	2.7”	1.6”	2.0”
IFU FoV	70”	15	12-32”
spectrograph	PMAS	AAOmega	BOSS
λ coverage (nm)	380-730	370-570, 625-735	350-1050
R=λ/dλ	1500,1100	1730,4500	1400-2700
Efficiency, ε	0.13	0.09,0.14	0.30



CALIFA:
Sanchez+12
PPK: Verheijen+’04, Kelz+’06
PMAS: Roth+’05

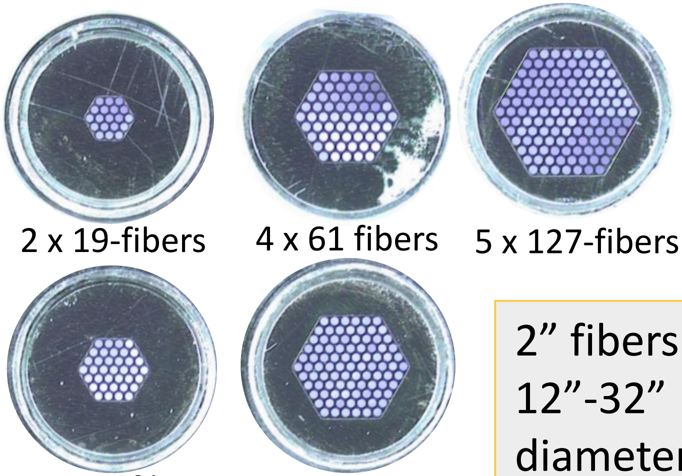
SAMI: Croom+12

13 x 61 fibers



15”
1.6” fibers

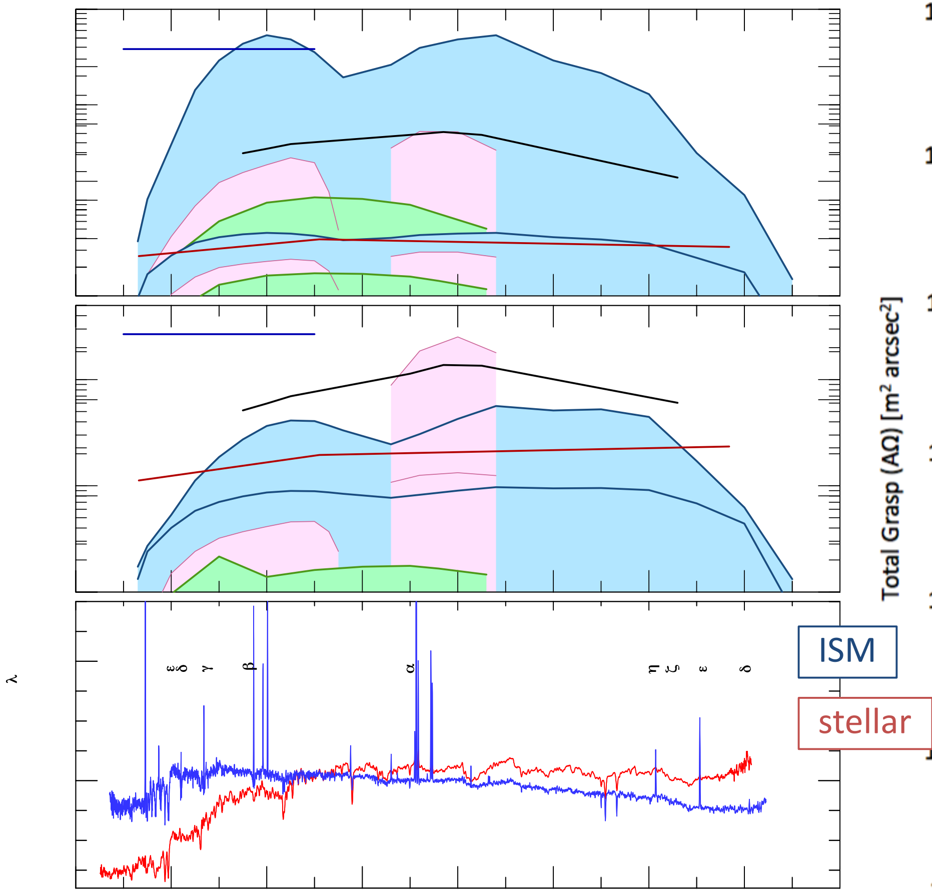
MaNGA: Bundy+15



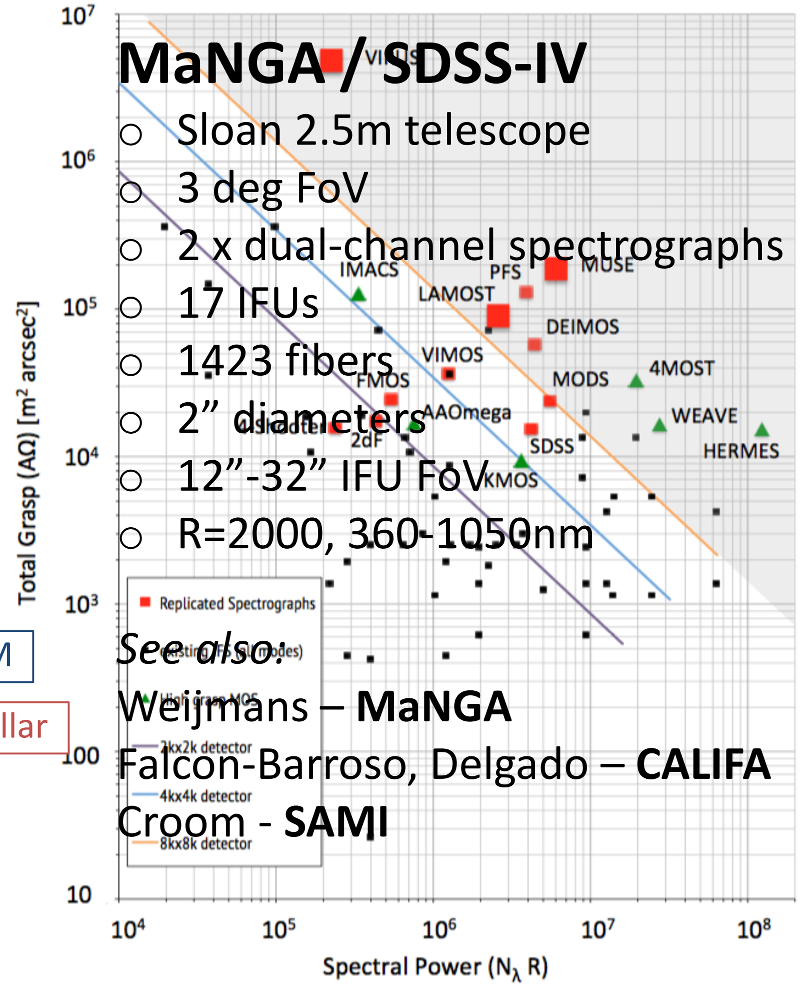
2 x 19-fibers
4 x 61 fibers
5 x 127-fibers
4 x 37-fibers
2 x 91-fibers

2” fibers
12”-32”
diameters

Metrics



Bundy+2015 (MaNGA PI)



MaNGA / SDSS-IV

- Sloan 2.5m telescope
- 3 deg FoV
- 2 x dual-channel spectrographs
- 17 IFUs
- 1423 fibers
- 2” diameters
- 12”-32” IFU FoV
- R=2000, 360-1050nm

See also:

Weijmans – **MaNGA**

Falcon-Barroso, Delgado – **CALIFA**

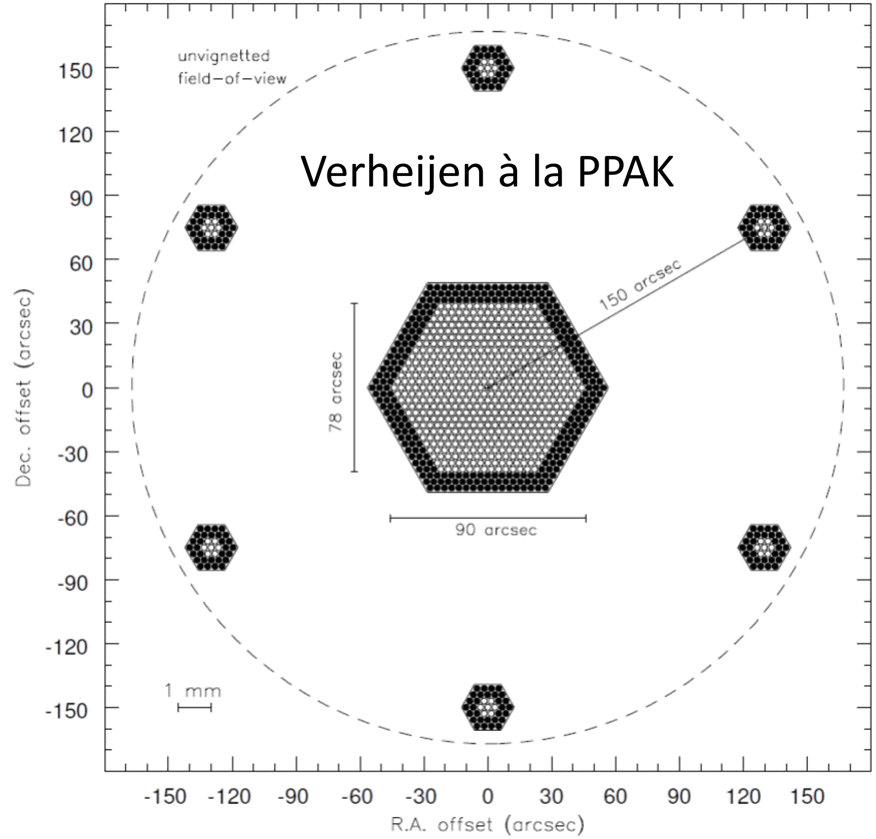
Croom - **SAMI**

Hill 2014

WEAVE / IFUs and key parameters

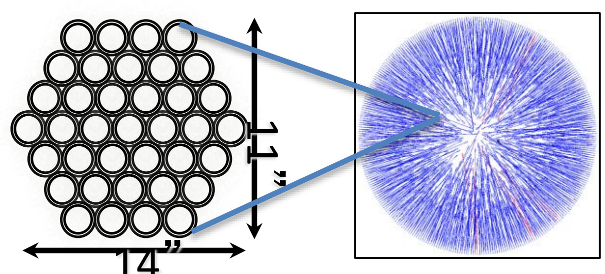
Telescope, diameter	WHT, 4.2m
Field of view	2º
MOS fibers	~1000 x 1.3” diameter
Number of small IFUs, size	20, 10”x14” (1.3” spaxels)
LIFU size	1.5’x1.2’ (2.6” spaxels)
Low-resolution mode	R = 4300–7200 366–984 nm
High-resolution mode	R=18560–21375 404–465, (473–545) 595–685 nm

~~*NB: 32m fiber run – UV attenuation*~~



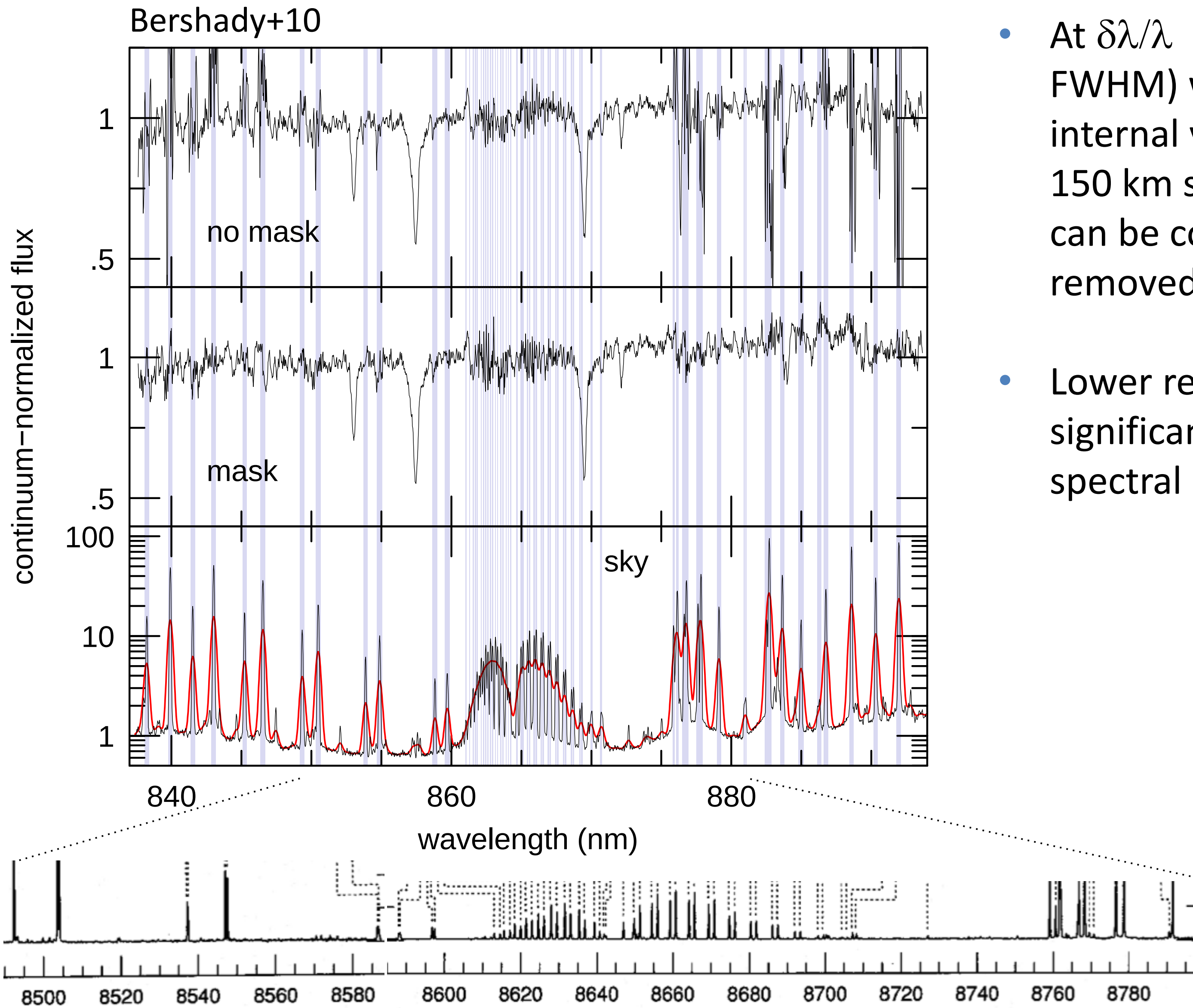
20 mini-IFUs coexist with MOS

20 x



Dalton+’12 (credit also: S. Trager)

Spectral resolution



- At $\delta\lambda/\lambda$ = 9000 (33 km s^{-1} FWHM) with galaxy internal velocity spread of 150 km s^{-1} (5:1) sky lines can be completely removed.
- Lower resolution significantly degrades spectral data.

Sky resolved at:

$\delta\lambda/\lambda$ = 2300

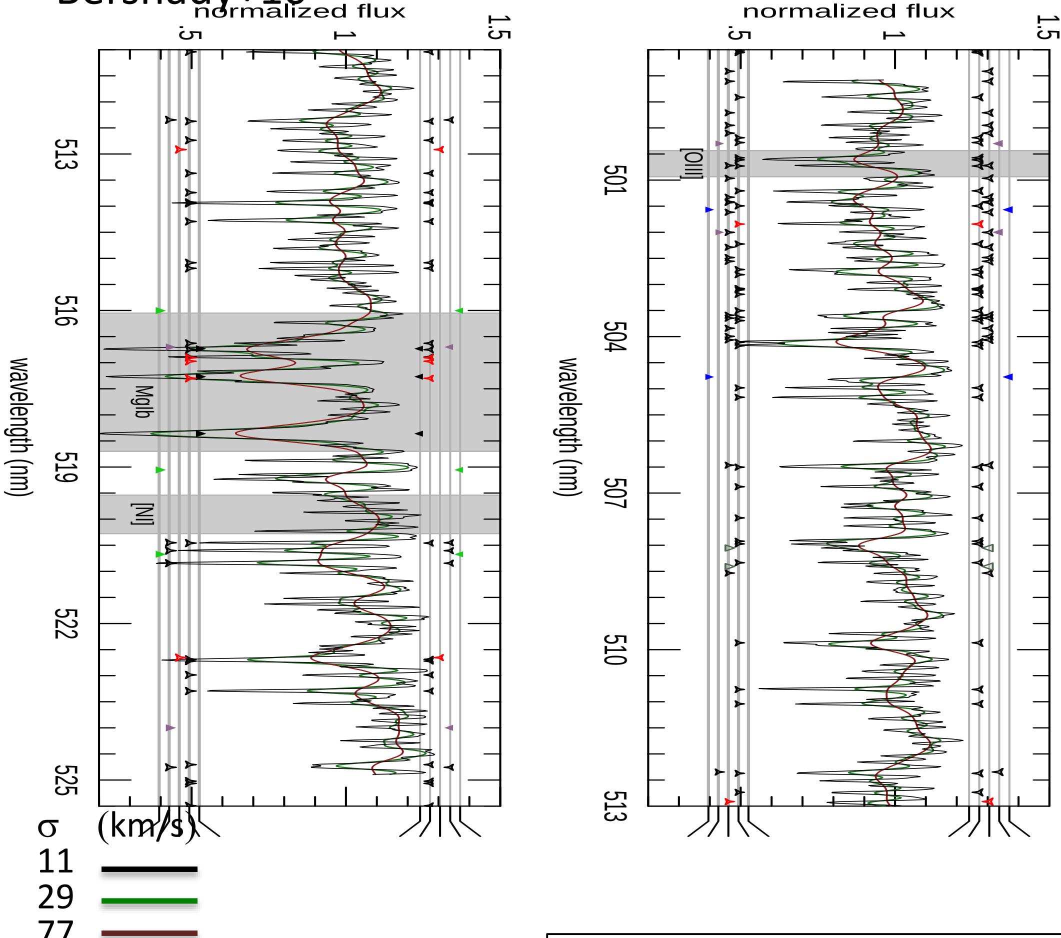
$\delta\lambda/\lambda$ = 9000

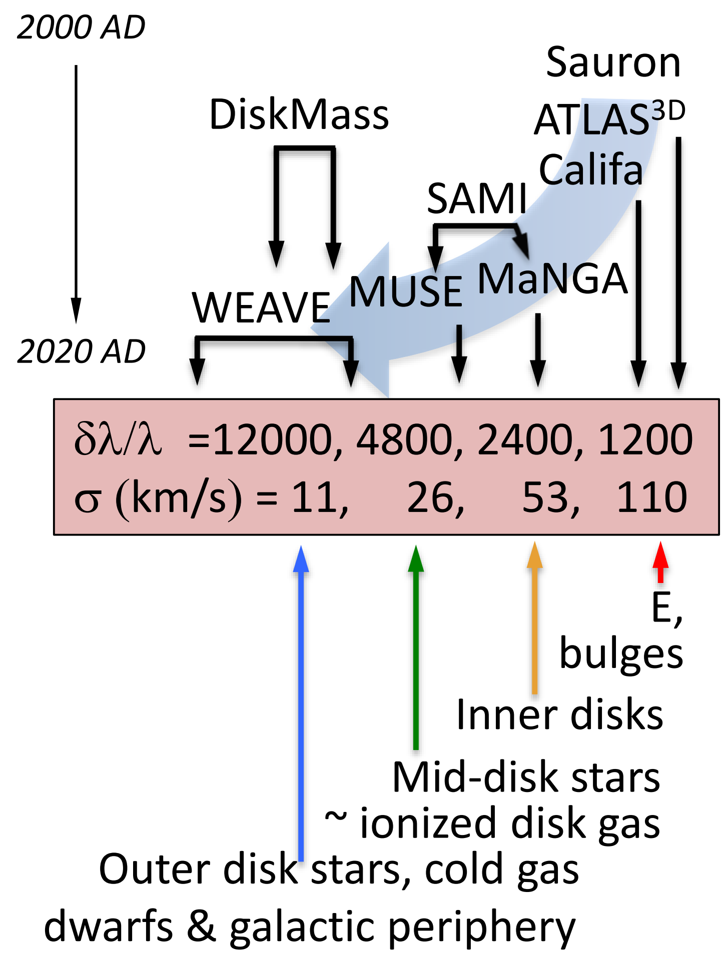
$\delta\lambda/\lambda$ = 35000

(Osterbrock+96)

Spectral resolution

Bershady+10





Best abundance information in dynamically cold systems if you have the spectral resolution.

III. Key questions

Disk assembly: settling, heating or both?

- **Why this question**:
  - Go beyond distributions of integrated properties, e.g., galaxy mass-function, $\phi(M,\ldots)$
  - Directly probe astrophysical processes of mass assembly with *resolved maps* of mass, kinematics, and composition for *galaxy populations*
  - Couple to full chemo-dynamical phase-space for gas and stars *uniquely accessed in MW*

Disk assembly: settling, heating or both?

1. The Milky Way as a Galaxy
2. The look-back record: distant galaxies
3. Breakthroughs very nearby: M31 & NGC 891
4. Statistical studies of low-z galaxies
5. Concluding challenges

Disk assembly: settling, heating or both?

1. The Milky Way as a Galaxy

- Historical debate on origin stellar disk heating

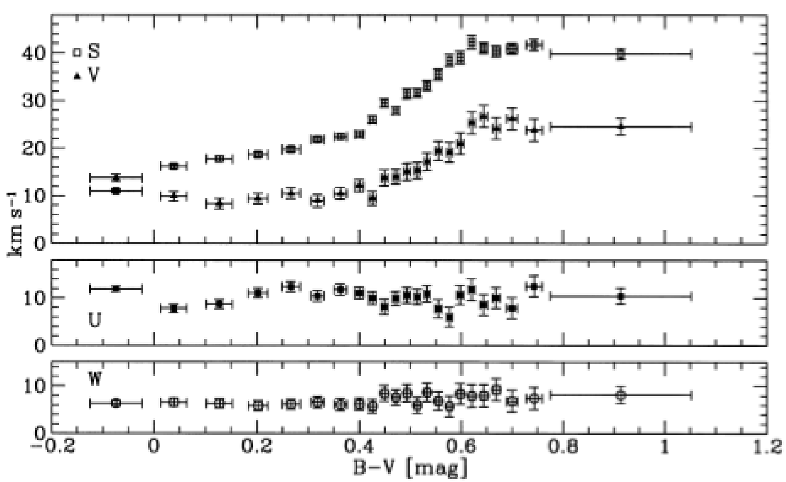
  e.g., Spitzer & Schwarzchild+51, Weilen’77, Ostriker’86, Binney+’00

- Thick disk controversy

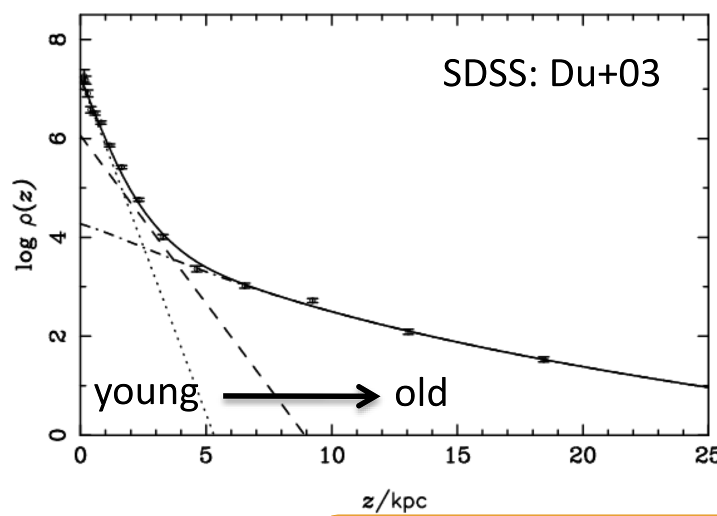
  cf Gilmore & Reid’83, Bovy+12;

  see also Brook+04, Forbes+12, Bird+13, Martig+14, Minhchev+13,14

- Data renaissance: RAVE (Steinmetz+06), SEGUE (Yanny+2009; SDSS-II), GALAH/HERMES (De Silva+15), APOGEE-1,2 (Majewski+15; SDSS-III,IV)
- Earth-quake in process: GAIA



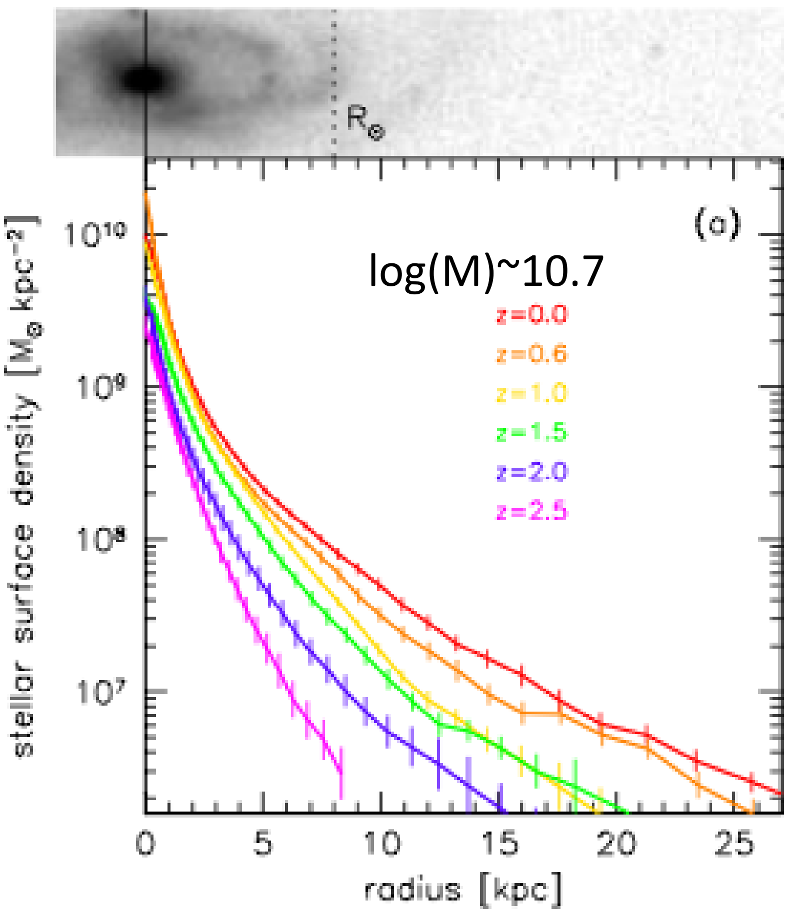
Hipparcos: Binney+00

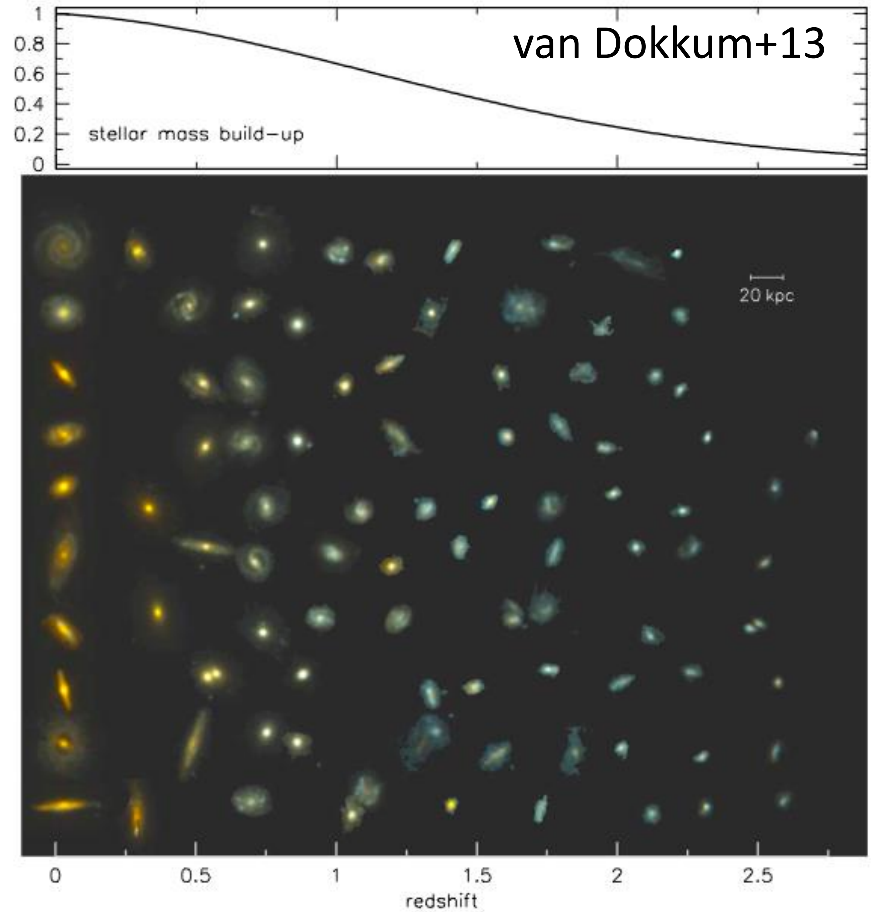


Disk assembly: settling, heating or both?

2. The look-back record: *photometry*

(a) build-up of stellar mass with time and radius in MW-mass galaxies is smooth, inside out, with 90% assembled between $0.4 < z < 2.5$



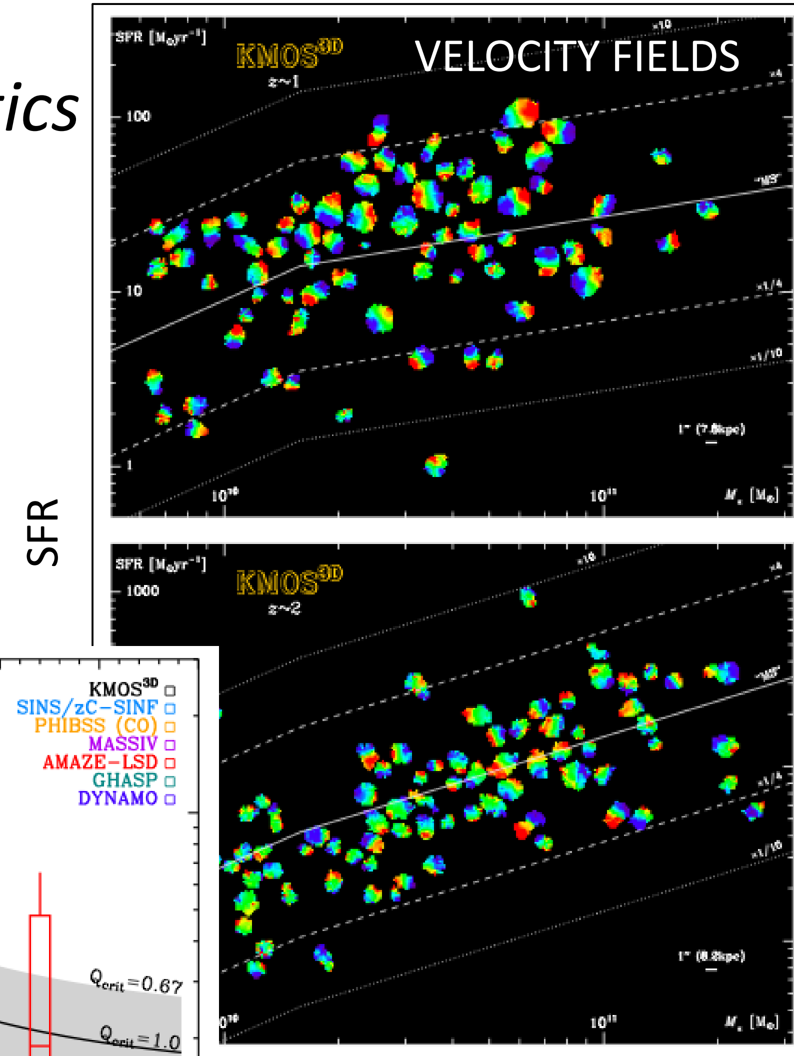


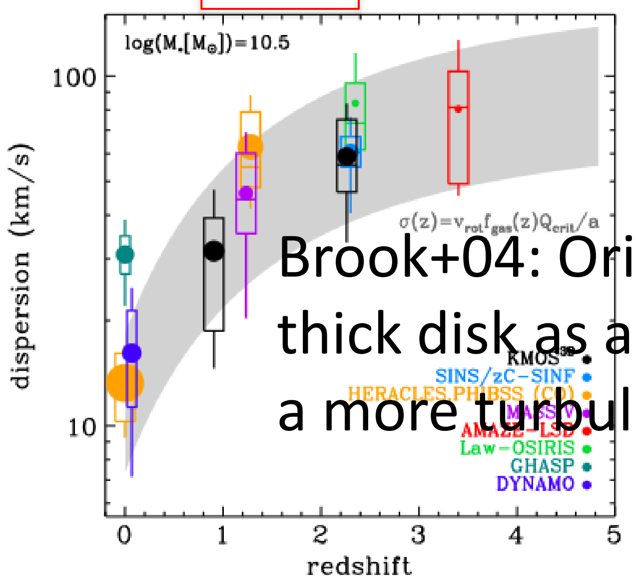
Disk assembly: settling, heating or both?

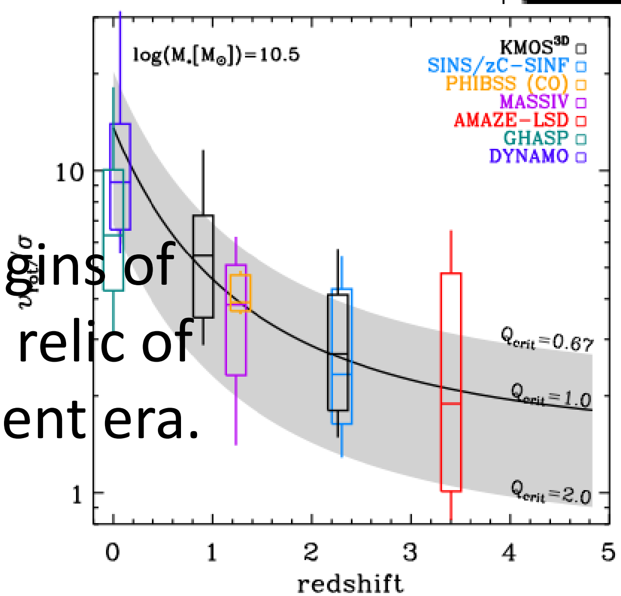
2. The look-back record: *kinematics*

(b) ionized gas disks appear to settle with time

- z<1.2 – DEEP - Kassin+07,12
- z<3 – SINS - Förster Schreiber+09
  - ➔ Bournaud+09
- – KMOS - Wisnioski+15 →





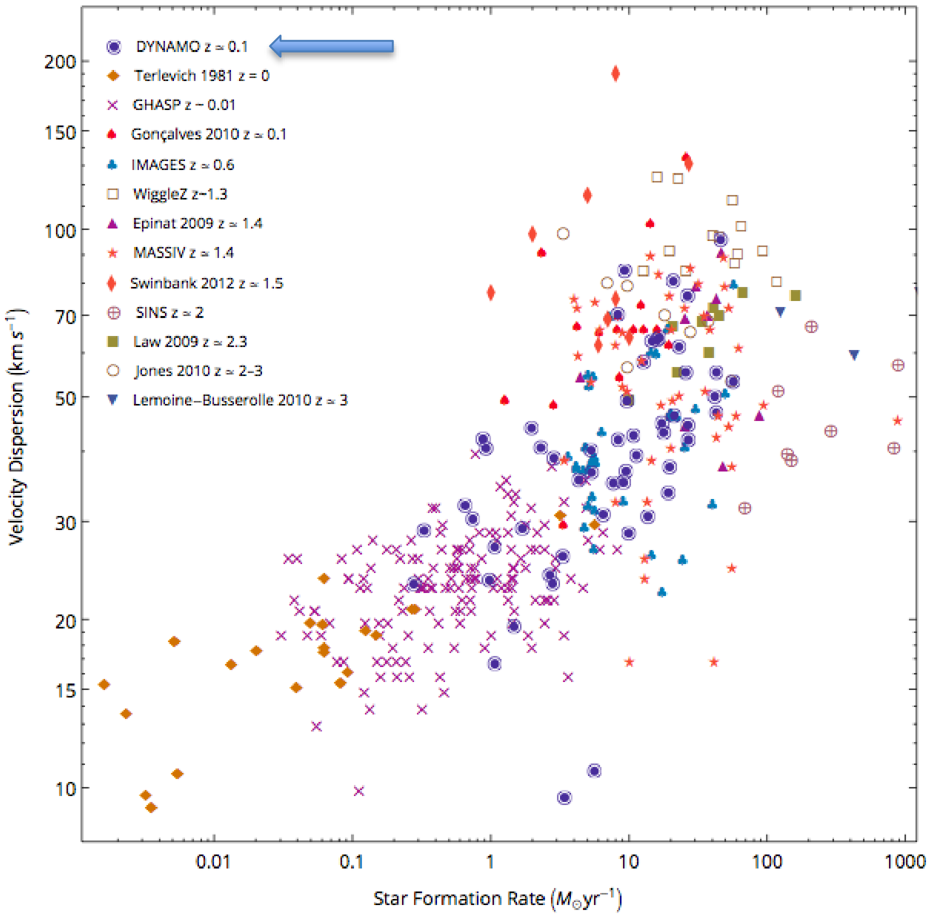


Brook+04: Origins of thick disk as a relic of a more turbulent era.

Disk assembly: settling, heating or both?

2. The look-back record:

(c) settling must be a function of merger and SF history

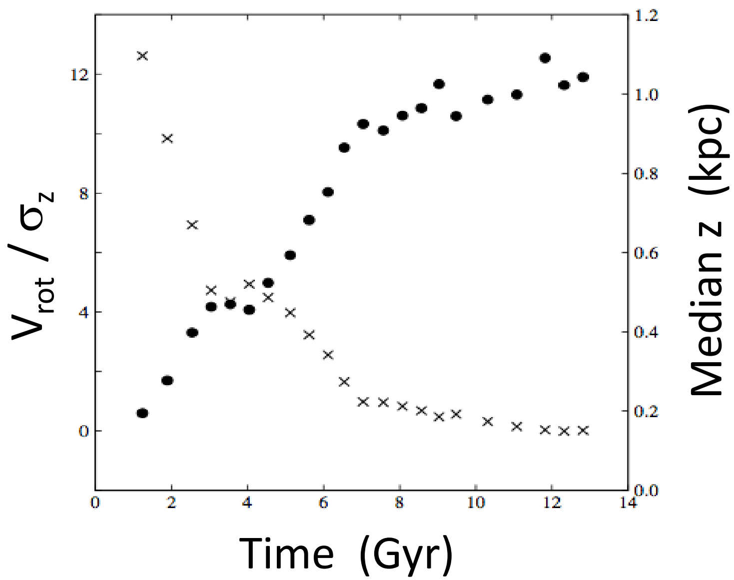


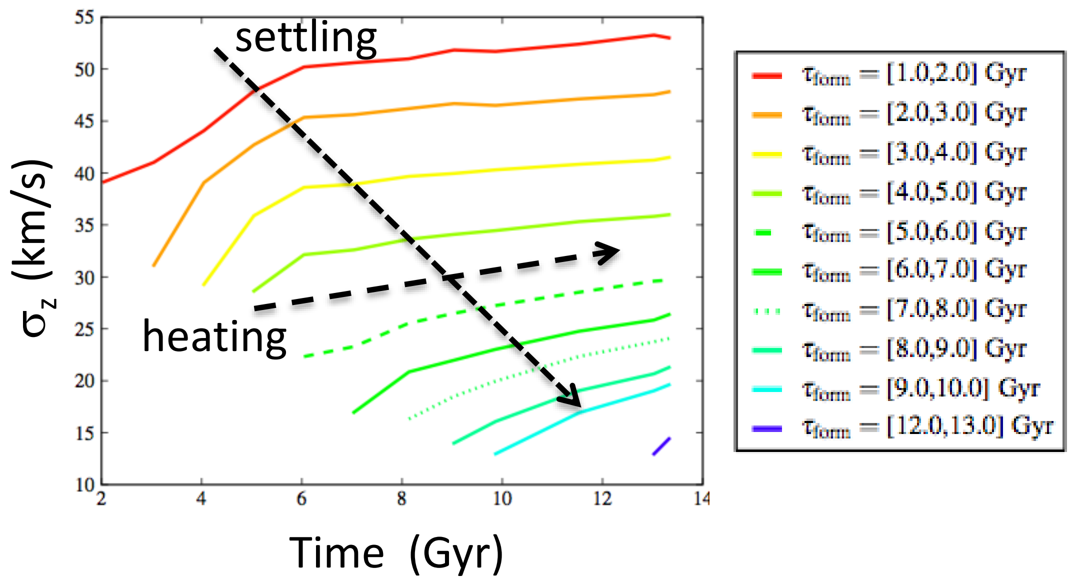
DYNAMO: Green+13

Disk assembly: settling, heating or both?

2. The look-back record: *simulations*

- Heating and cooling/settling of gas disk imprinted on stars observed today
- Establishes ***age-velocity-metallicity relations*** (e.g., Minchev+12,14; Martig+14a,b)
- Relative roles of heating vs settling unclear: *cf* Bird+13, Martig+14a





- Disks form “inside out and upside down”
- Heating relatively unimportant after 1-2Gyr

Bird+13

Disk assembly: settling, heating or both?

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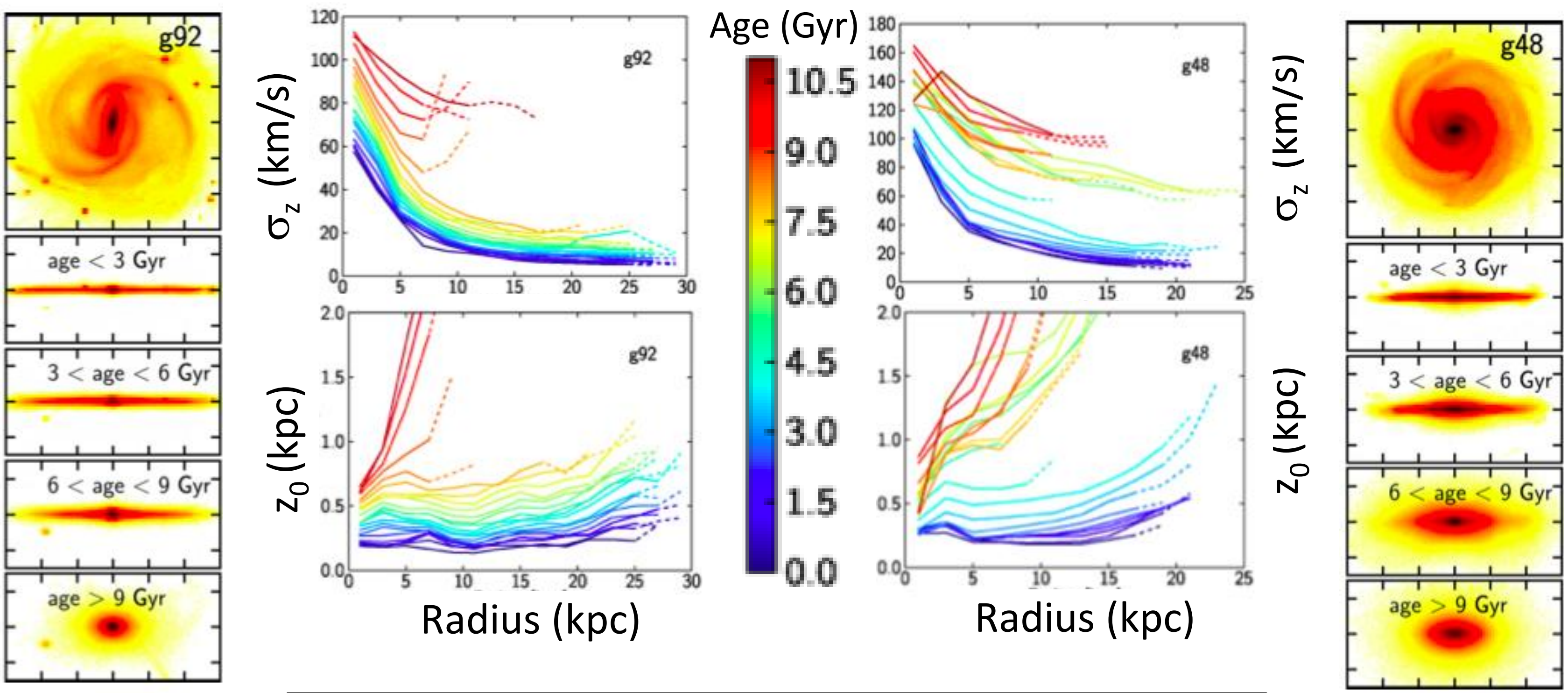


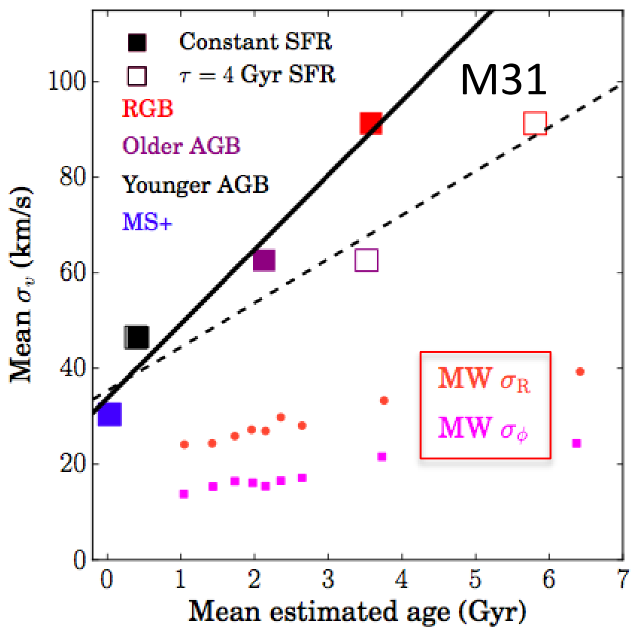
- Different merger histories (heating) *is* important

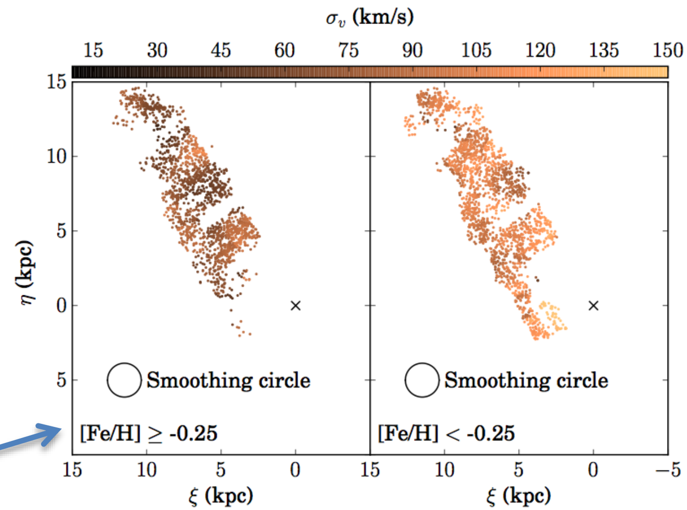
Martig+14a

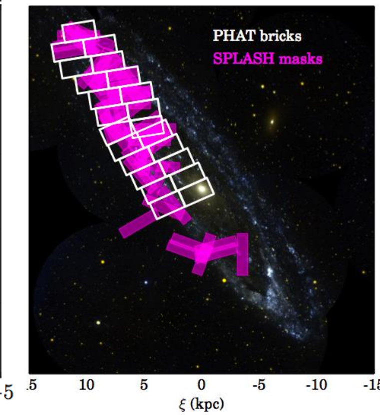
Disk assembly: settling, heating or both?

3. Very nearby: Resolved stellar kinematics in M31

- ***age-velocity-metallicity relations*** not the same for two massive LG spirals

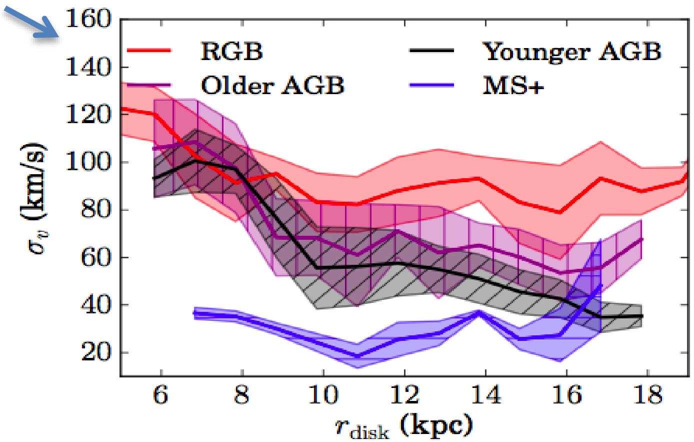






Z

age

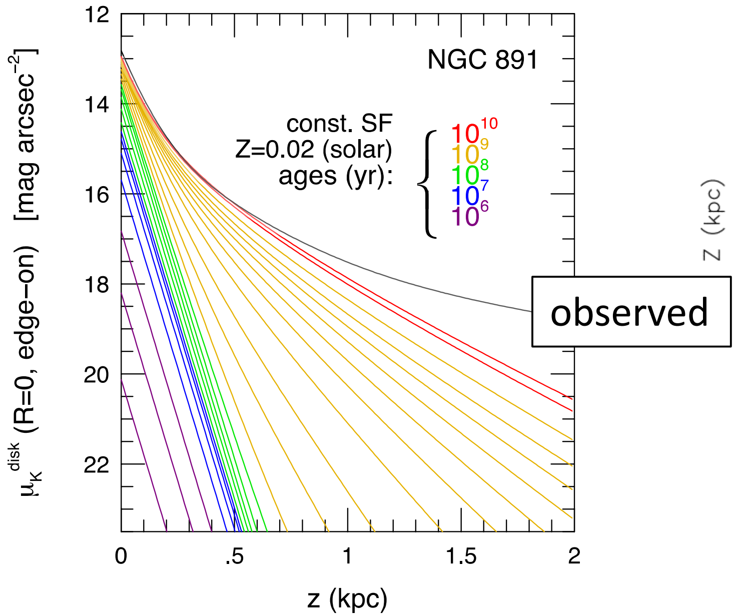


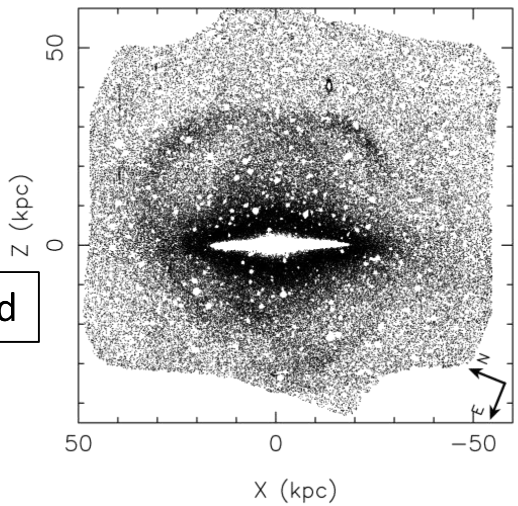
Dorman+15

Disk assembly: settling, heating or both?

3. Very nearby: NGC 891 heating model

Schechtman-Rook et al. 2012c





Mouchine et al. 2010

Subaru star counts

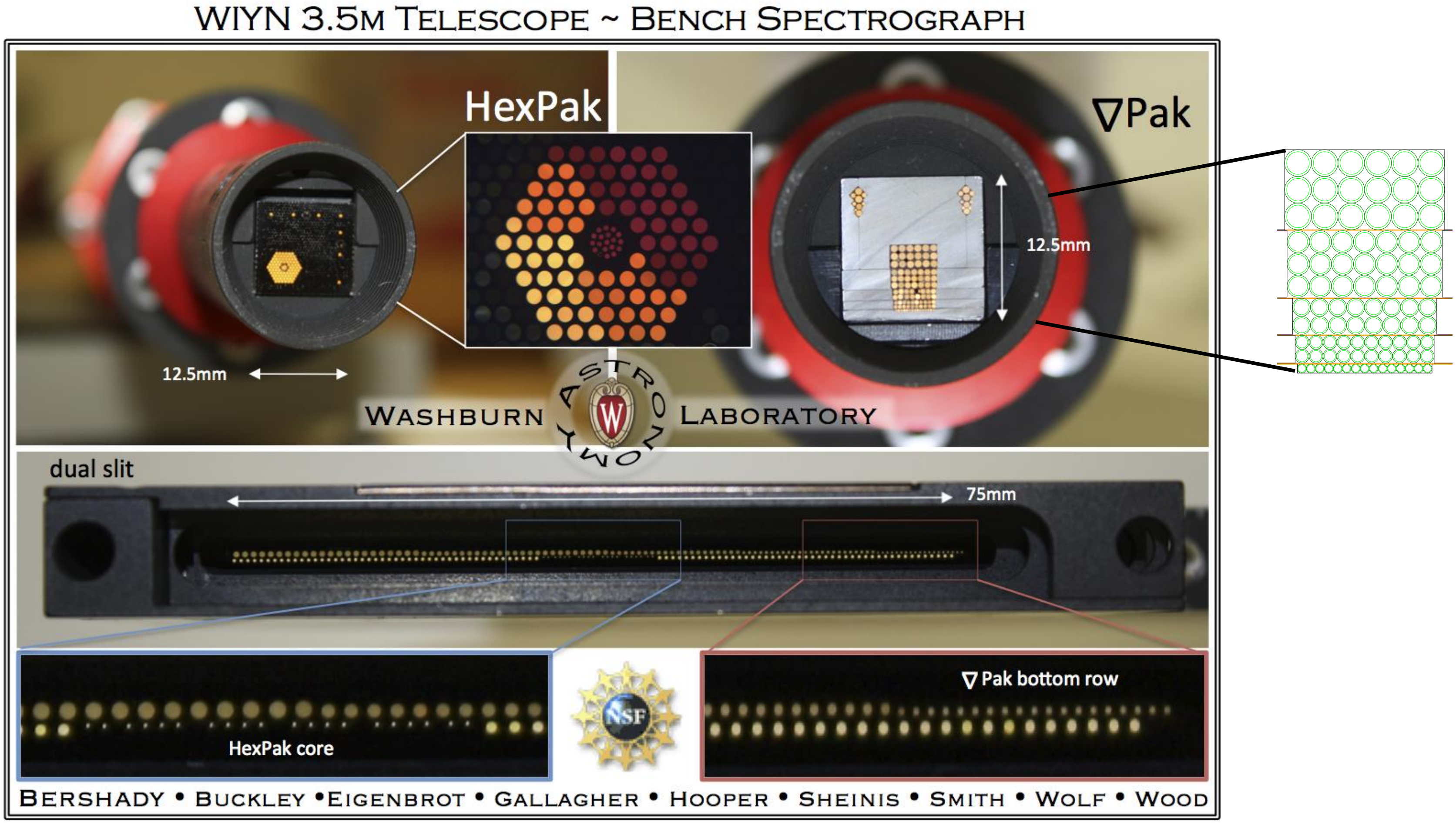
Excess light *above* 1 kpc is 1-2% of total disk light

- NGC 891 K-band vertical light profile well fit by MW heating model and constant SFR for ~9-12 Gyr

Bershady+15

Disk assembly: settling, heating or both?

3. Very nearby: variable pitch IFUs



The universe is logarithmic; why aren't our instruments?

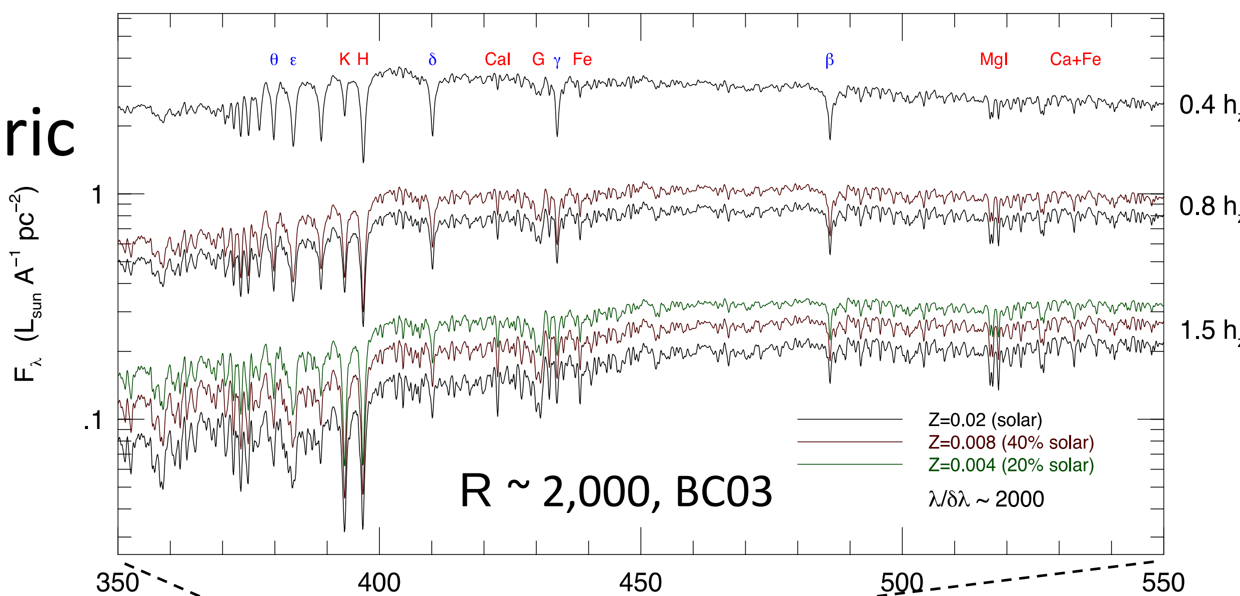
Wood+12

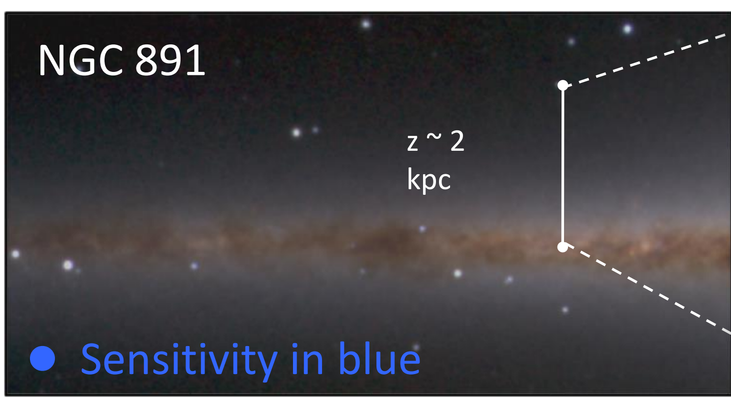
Disk assembly: settling, heating or both?

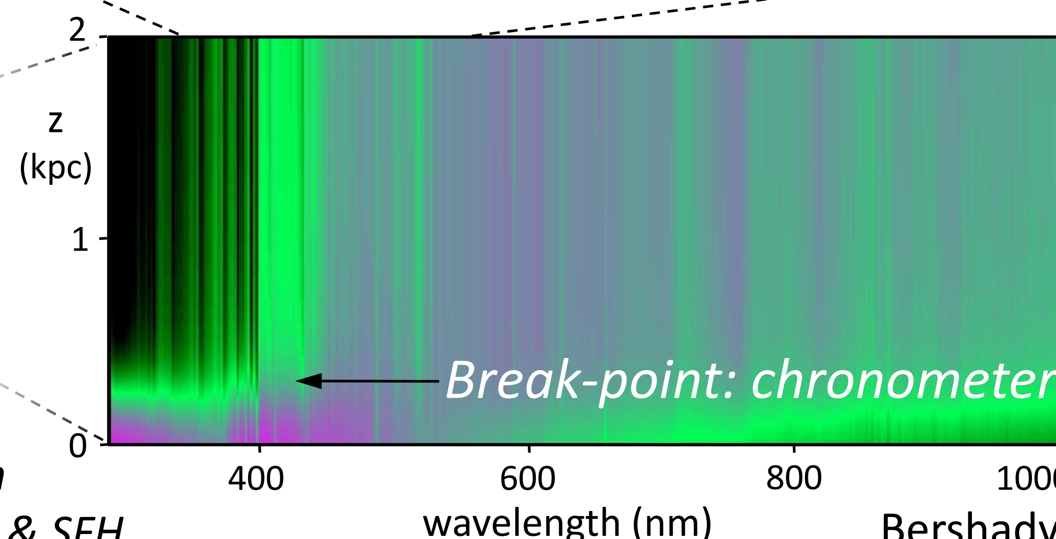
3. Very nearby: spectro-photometric chronometers

- Vertical gradients in spectra
  - … age
  - … metallicity

N891–like edge–on massive spiral, MW disk–heating, const. SFR





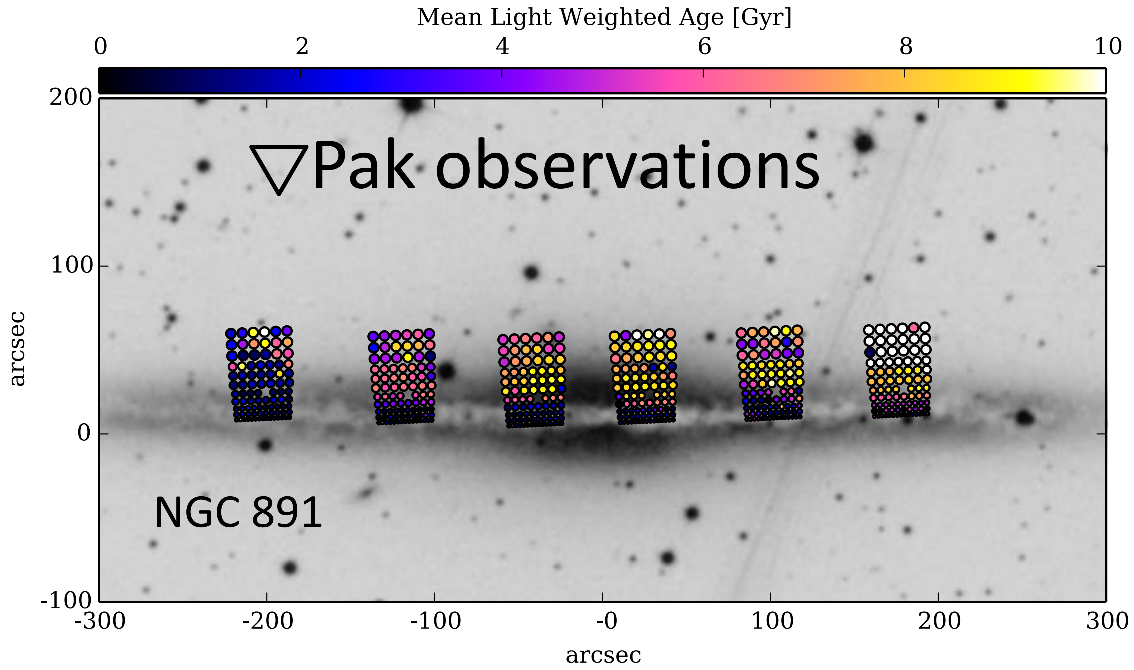


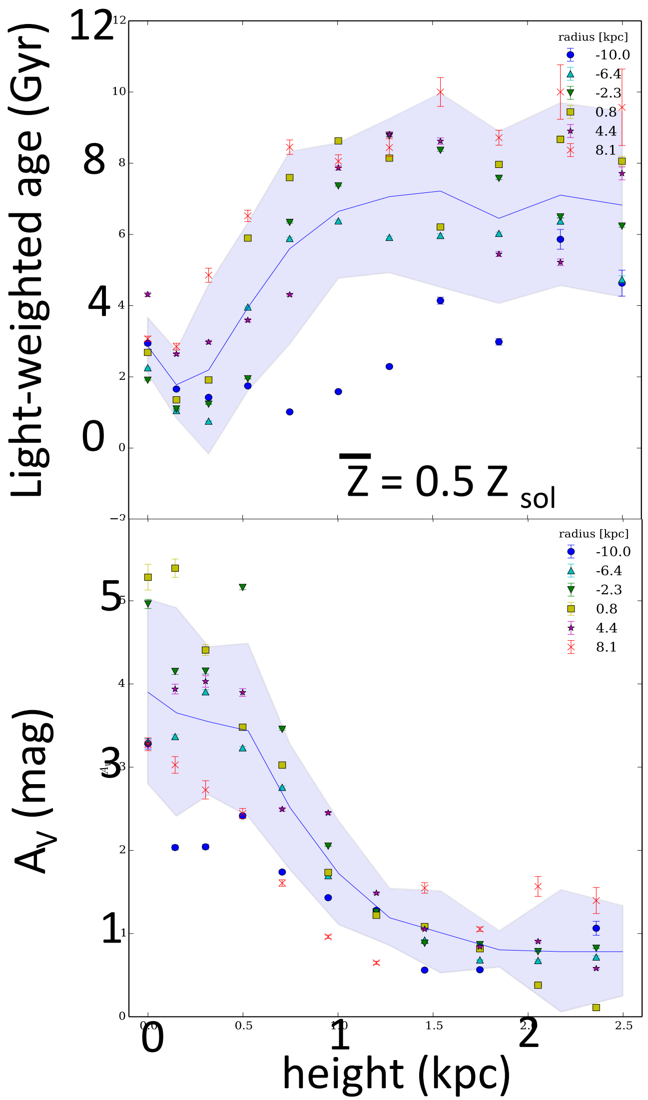
➢ *Break-point height and width measures heating time-scale & SFH*

Bershady+15

Disk assembly: settling, heating or both?

3. Very nearby: vertical population gradients



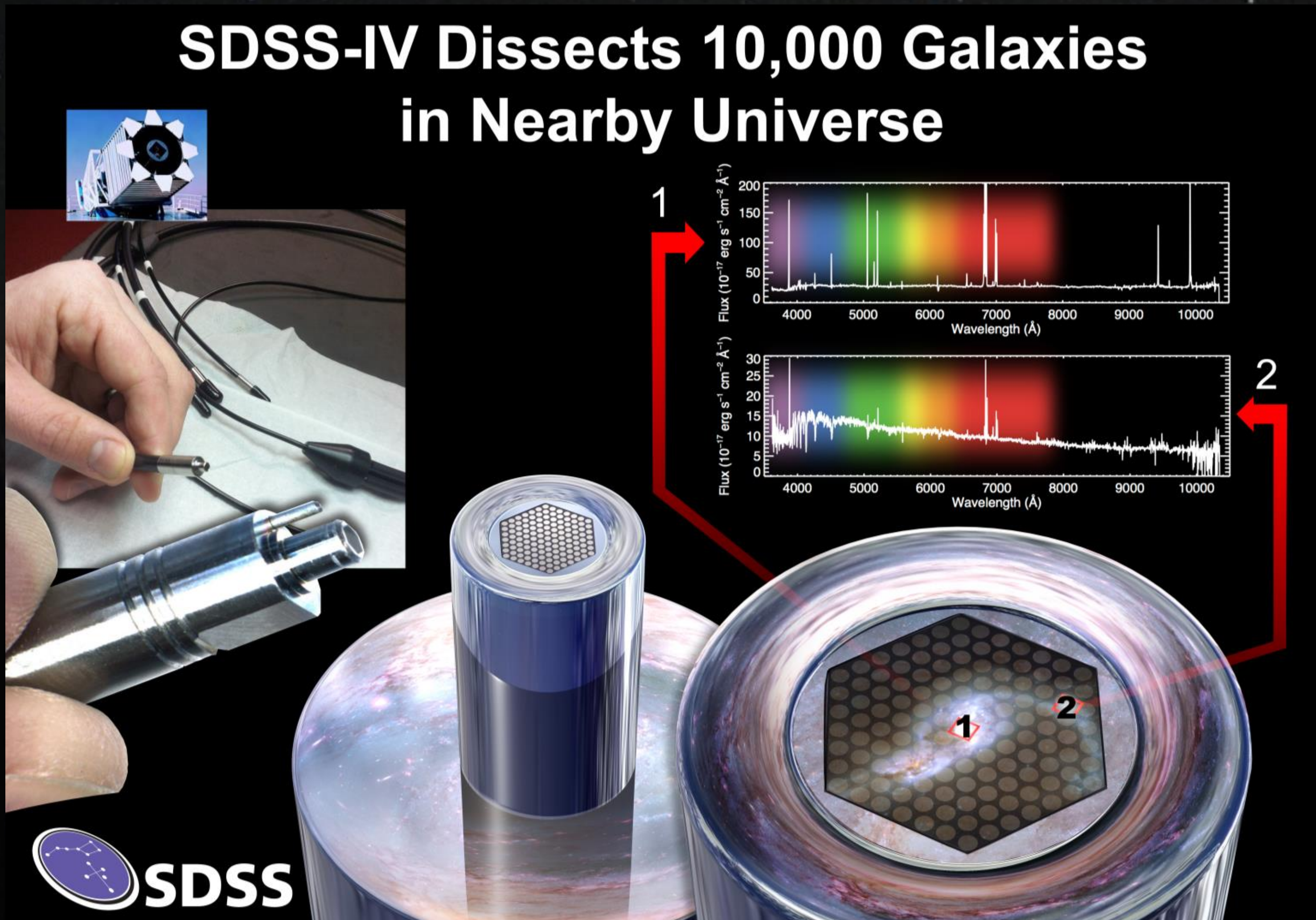


- Can be applied to large samples
- NB: must account for different LOS depth w/height

Eigenbrot+15

Disk assembly: settling, heating or both?

4.



- Cover 350 - 1050nm at resolution of 60 km/s
- Sample all galaxy types and environments
- Multiplex 17 IFUs at once

MaNGA

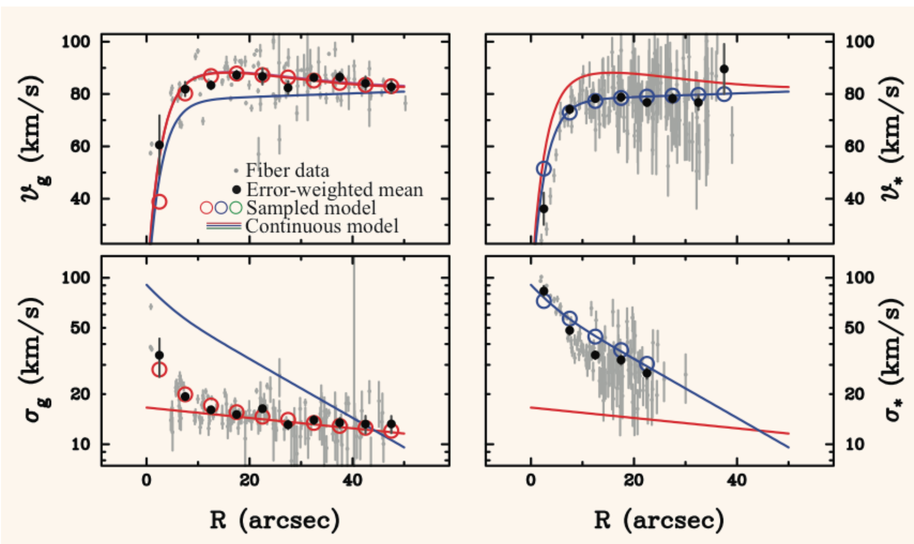
Bundy et al. 2015

David R. Law

Disk assembly: settling, heating or both?

Measuring stellar velocity dispersions with only velocities

Projected tangential velocities ("rotation curves") of gas and stars show **A**symmetric **D**rift



1. measure V_g, V_*
2. infer σ_*
3. calibrate with DiskMass Survey

Asymmetric drift (AD) depends on in-plane σ_* (σ_R, σ_ϕ), radial derivatives of V and σ, and shape of σ-ellipsoid.

AD

$$v_c^2 - \overline{v_\phi}^2 = \sigma_\phi^2 - \sigma_R^2 - \frac{R}{\nu}\frac{\partial(\nu\sigma_R^2)}{\partial R} - R\frac{\partial(\overline{v_r v_z})}{\partial z}$$

$$\frac{\sigma_\phi^2}{\sigma_R^2} = \frac{1}{2}\left(\frac{\partial \ln \overline{v_\phi}}{\partial \ln R} + 1\right)$$

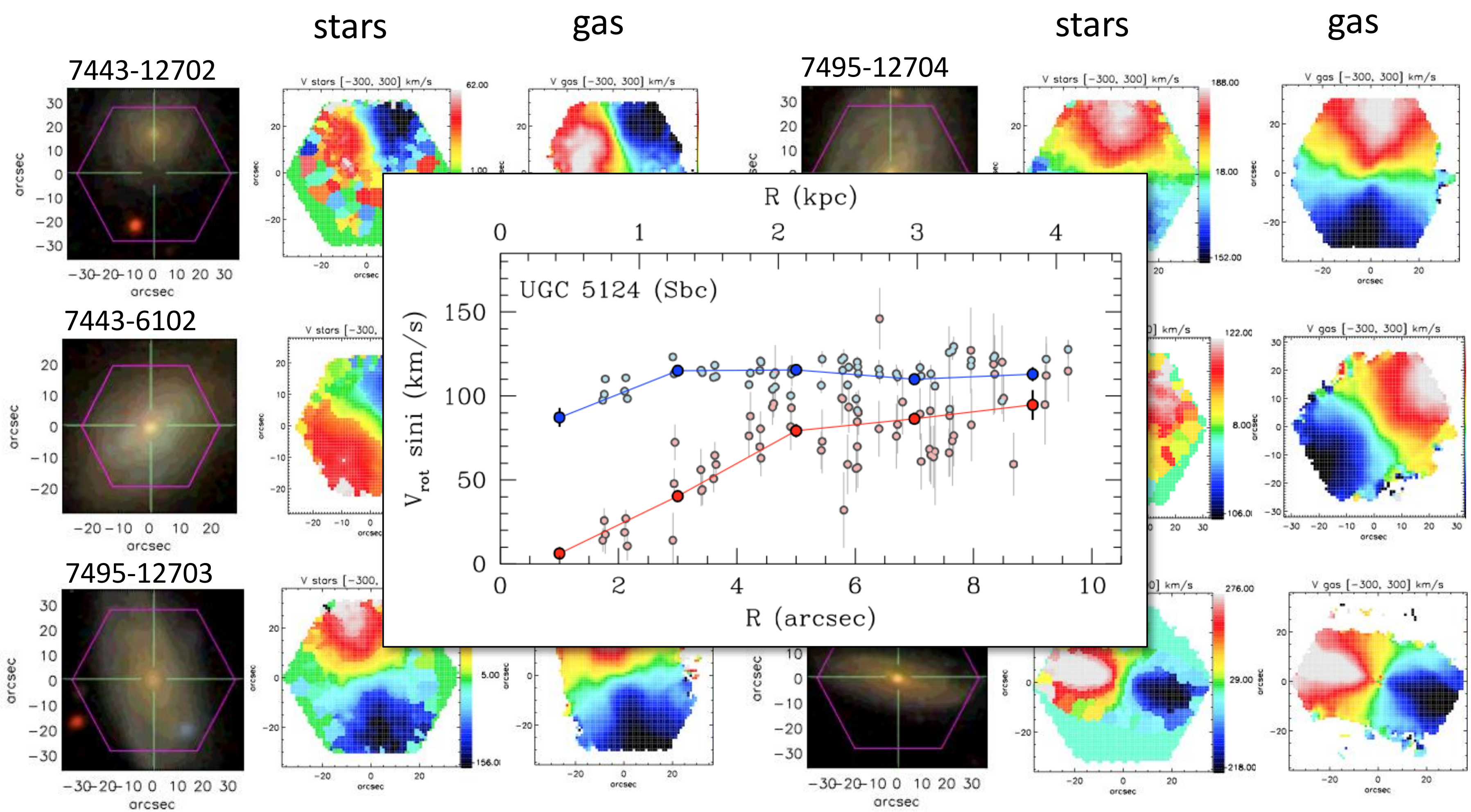
Epicycle approximation

v_R and $v_R v_\phi$ moments of the collisionless Boltzman equation

Westfall+ 2014

Disk assembly: settling, heating or both?

4. MaNGA: Asymmetric Drift



Bundy+15, Westfall+15

Summary Charge to the Community

Disk assembly: settling, heating or both?

5. Challenges:
   a) Measure stellar disk dynamics, ages, and abundances outside of the local group
      - *How*: large-grasp IFUs with broad spectral coverage and high spectral resolution
   b) Define the observational test distinguishing between disk settling (cooling) and stellar heating.
      - *Make this a well-posed problem.*