I. The Nascence of Late-type Galaxies : Angular Momentum and Mass-Size Relation

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National Science Challenge Initiatives
중력파우주연구단

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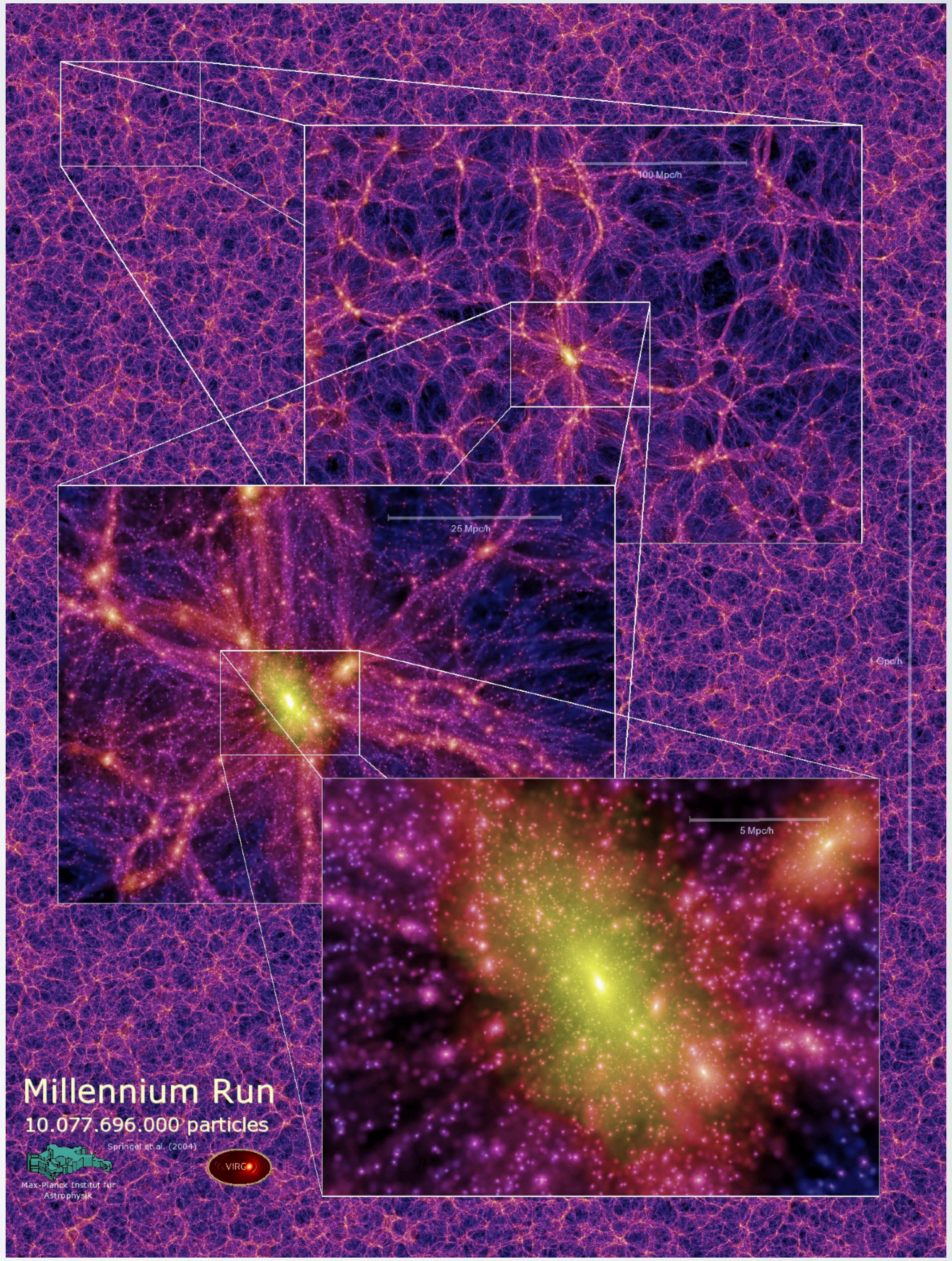
Formation of Late-type Galaxies

- *In the current standard galaxy formation picture within the ΛCDM paradigm,*

  1. *density fluctuation out of primordial gas slowly cools out of hot gaseous halos conserving specific angular momentum, j , and*
  2. *forms disks with stellar and gaseous components at centers of potential well of dark matter halos.*

- *Assumptions :*

  1. *Conservation of Angular Momentum*
  2. *No Angular Momentum Transfer between Baryons and DM*

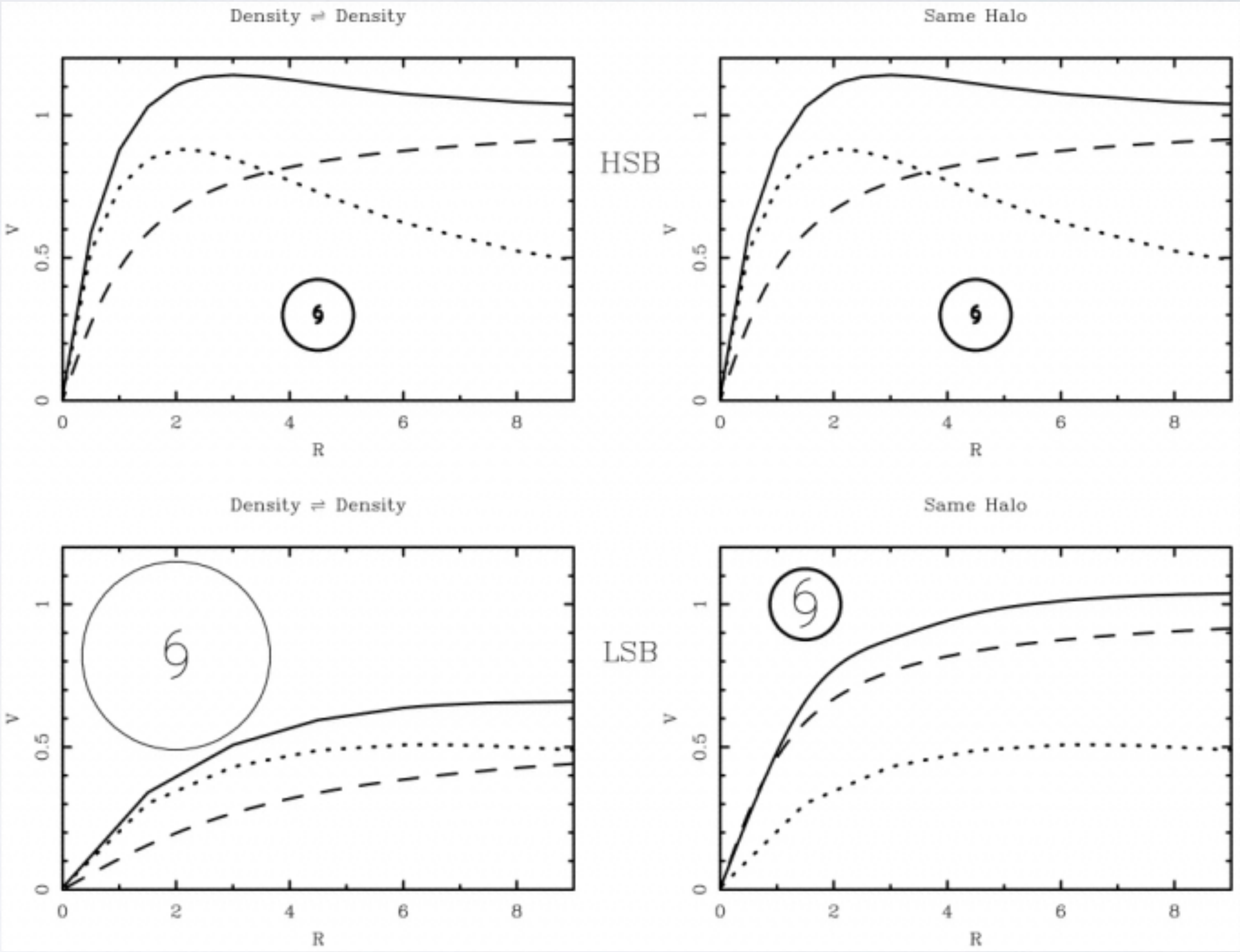


Millennium Run

Formation of Late-type Galaxies

McGaugh & de Blok (1998)

- *The fundamental properties of galactic disks, such as central surface density, and disk scale length, must reflect the physical conditions of their formation.*
- *It is still unclear what regulates these properties.*
- *Leading Hypotheses*
  1. *"Density Begets Density" (DD) : Differences in surface brightness are driven by the differences in the amplitude of the original density fluctuations (e.g. Ho et al. 1994).*
  2. *"Same Halo (SH)" : Differences in surface brightness are driven by differences in the spin parameter (e.g. Dalcanton et al. 1997).*

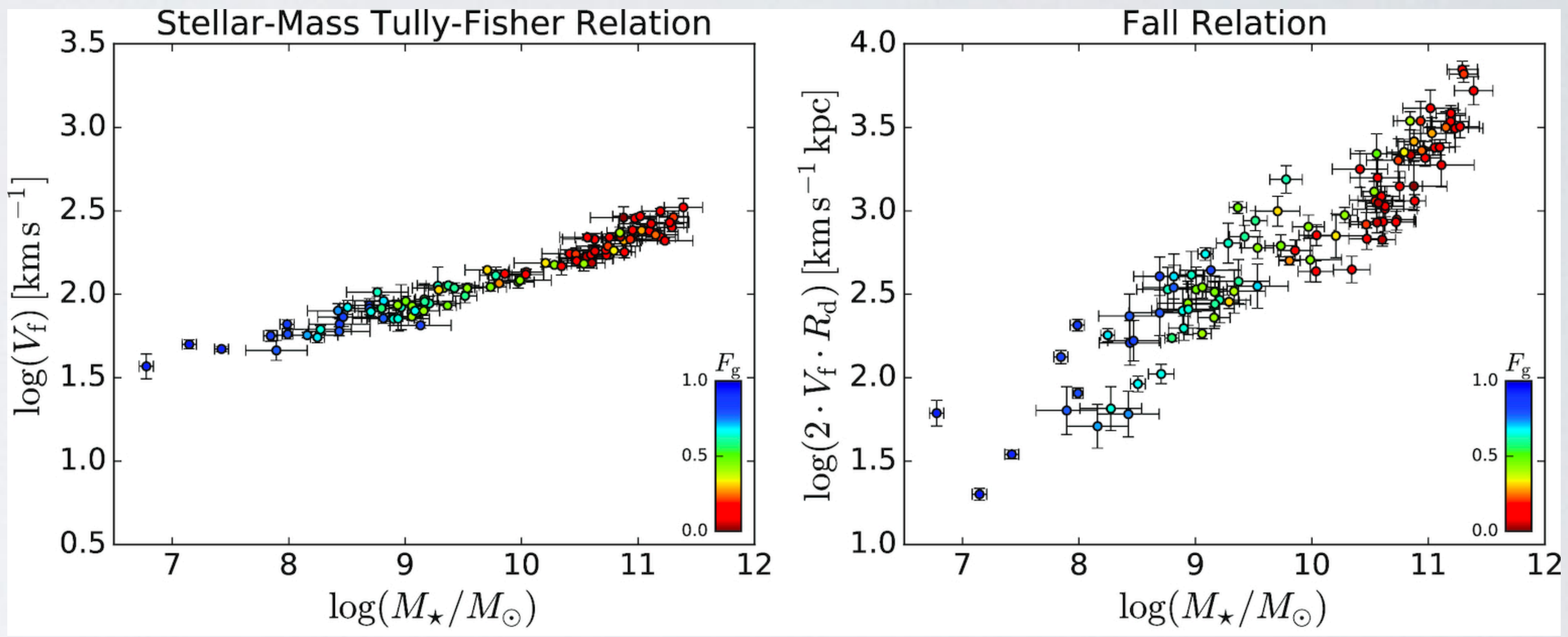


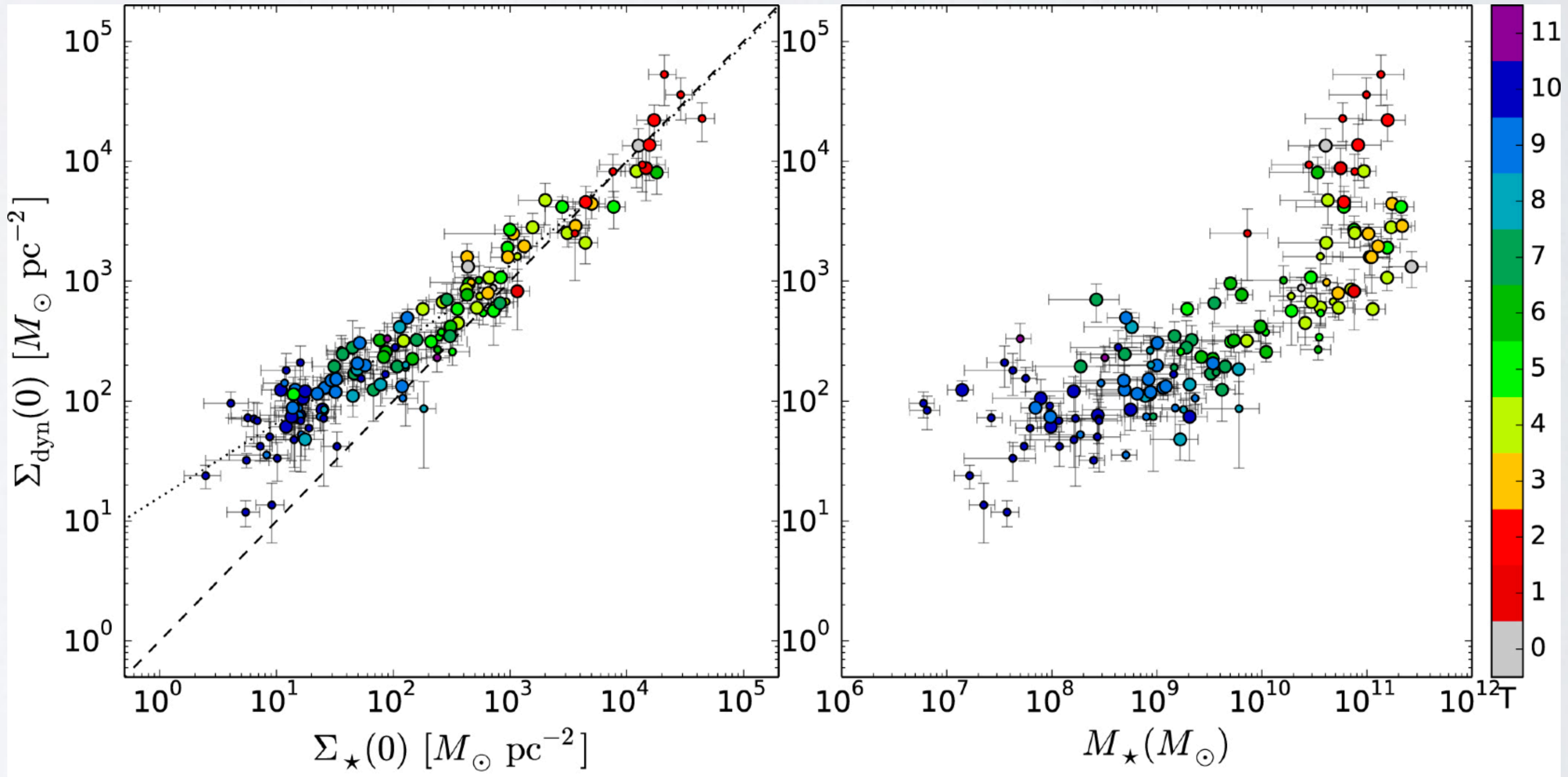
LSBG ≠ UDG, or
Galaxies with low mean surface brightness

Empirical Laws of Galactic Rotation

1. *Flat Rotation Curves (Rubin-Bosma Law)*
   - *Rotation curves tend asymptotically towards a constant rotation velocity that persists to indefinitely large radii :* $V\ (R \rightarrow \infty) \rightarrow V_f$
2. *Tully-Fisher Relation (Luminous, Stellar Mass, and Baryonic TF relations)*
   - *The baryonic mass of galaxies scales as the fourth power of the flat rotation curve :* $M_b = AV_f^4$
3. *Central Density Relation*
   - *Lower surface brightness galaxies exhibit larger mass discrepancies.*

Lelli et al. (2019)





Lelli et al. (2016)

Empirical Laws of Galactic Rotation

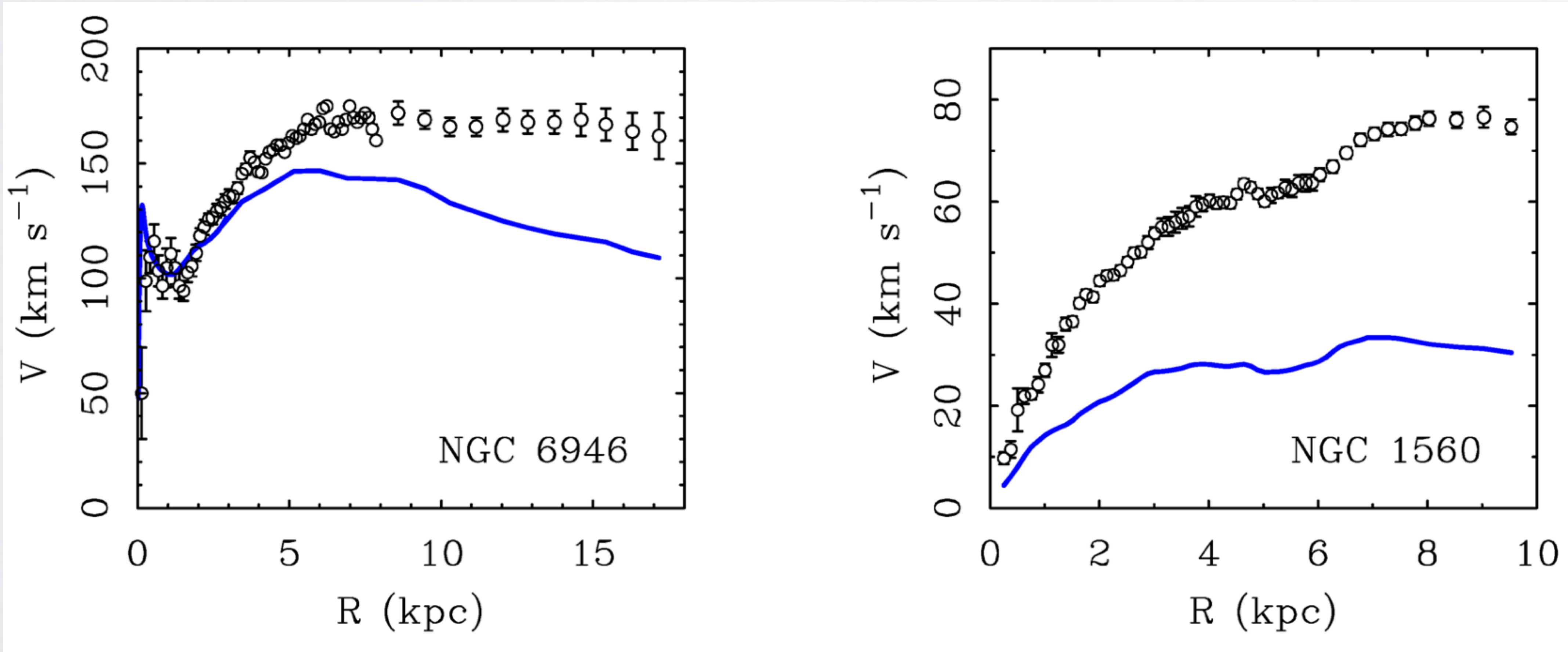
McGuagh et al. (2016)

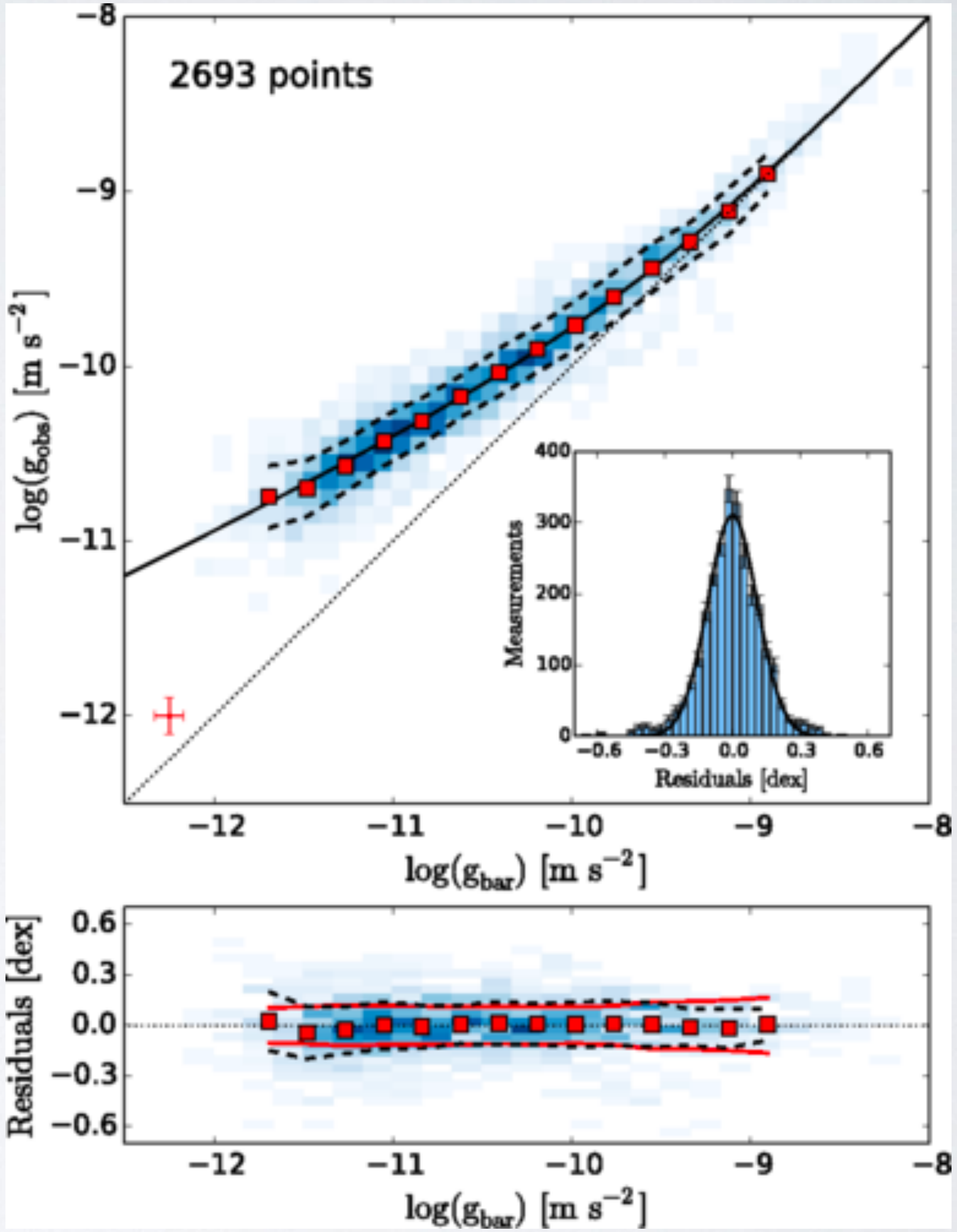
4. *Radial Acceleration Relation*

- *The observed centripetal acceleration is related to that predicted by the observed distribution of baryons :* $g_{obs} = \mathcal{F}(g_{bar})$

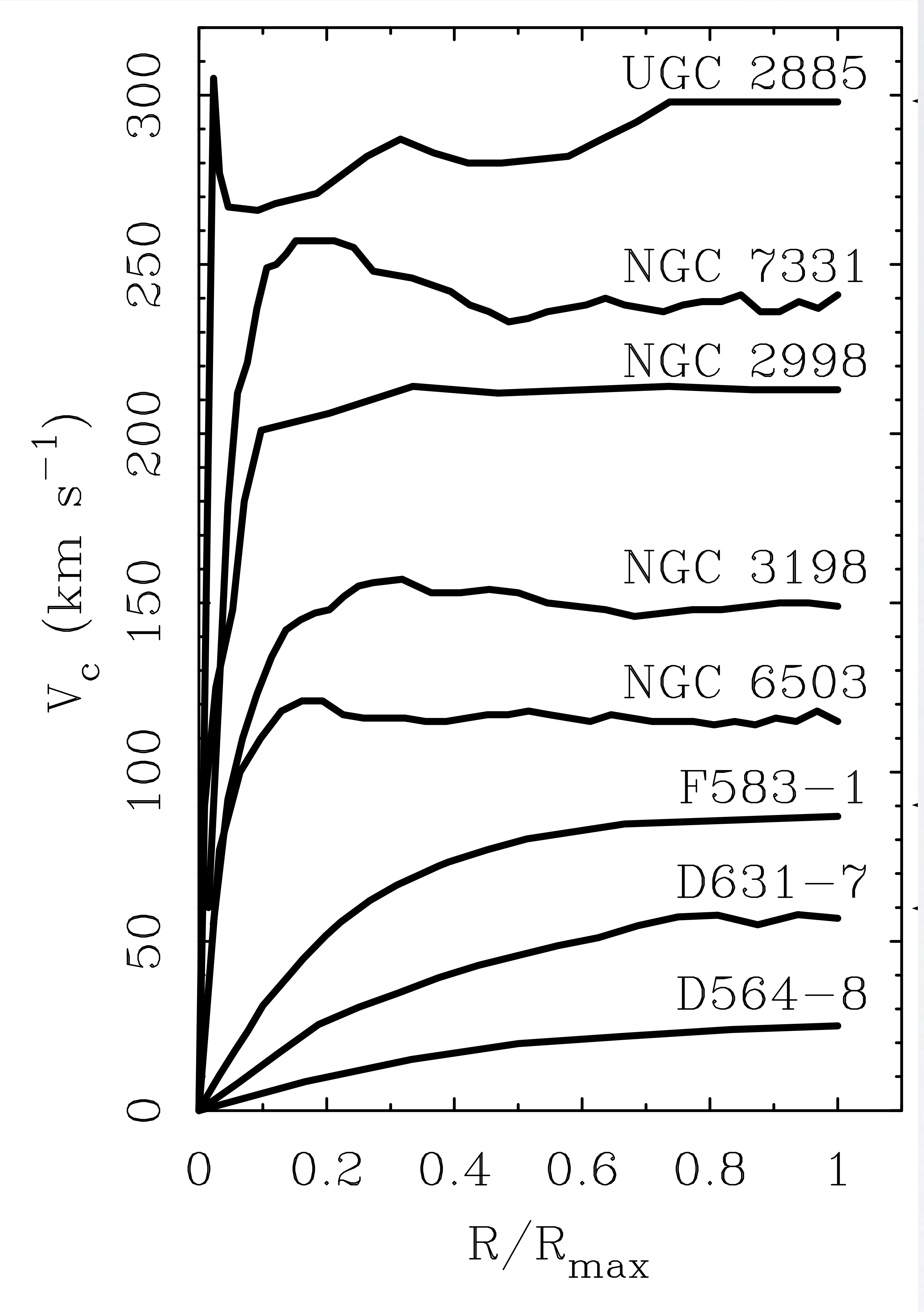
5. *Renzo's Rule (Sancisi's Law)*

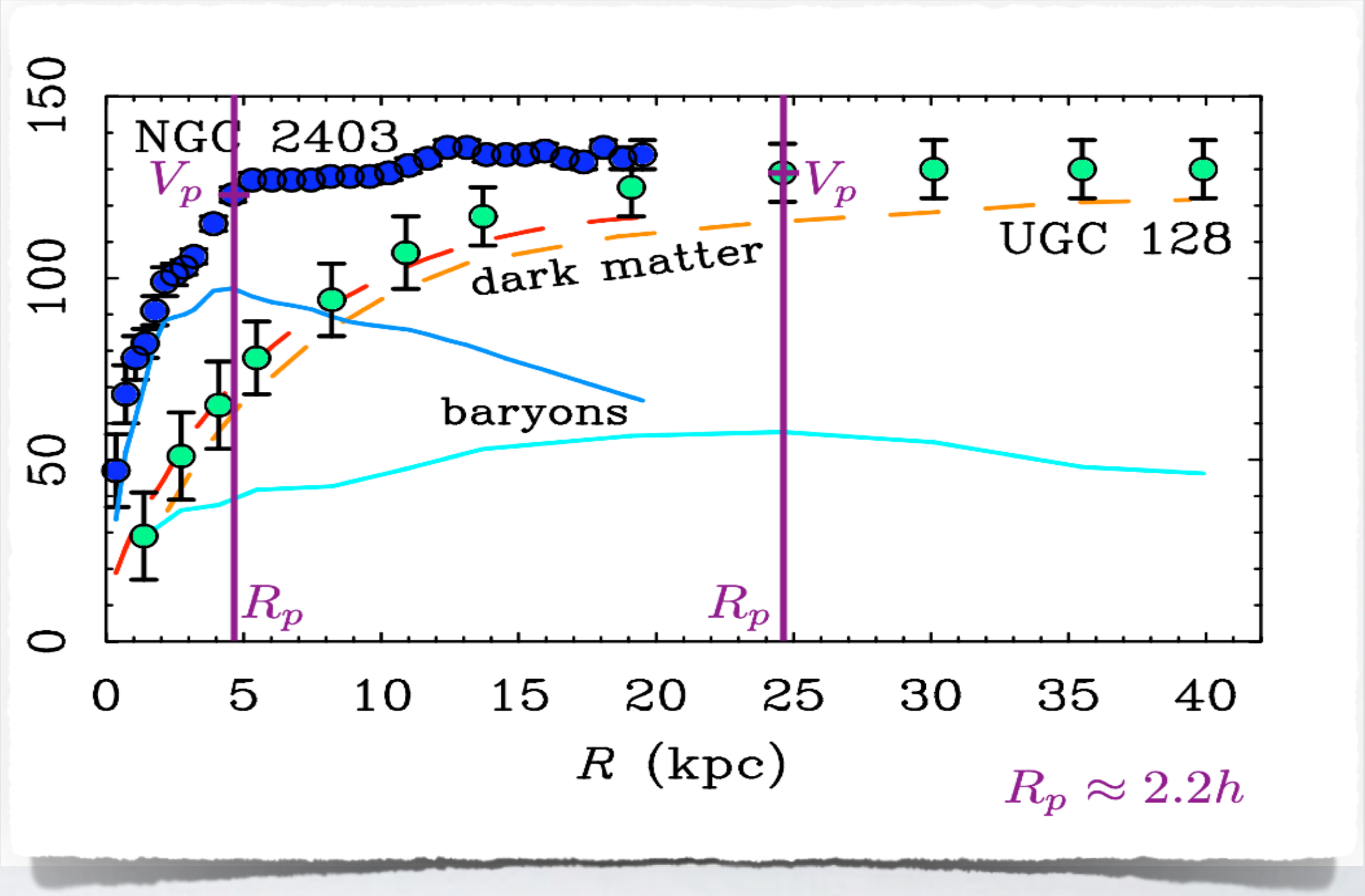
- *"For any feature in the luminous profile there is a corresponding feature in the rotation curve and vice versa."*





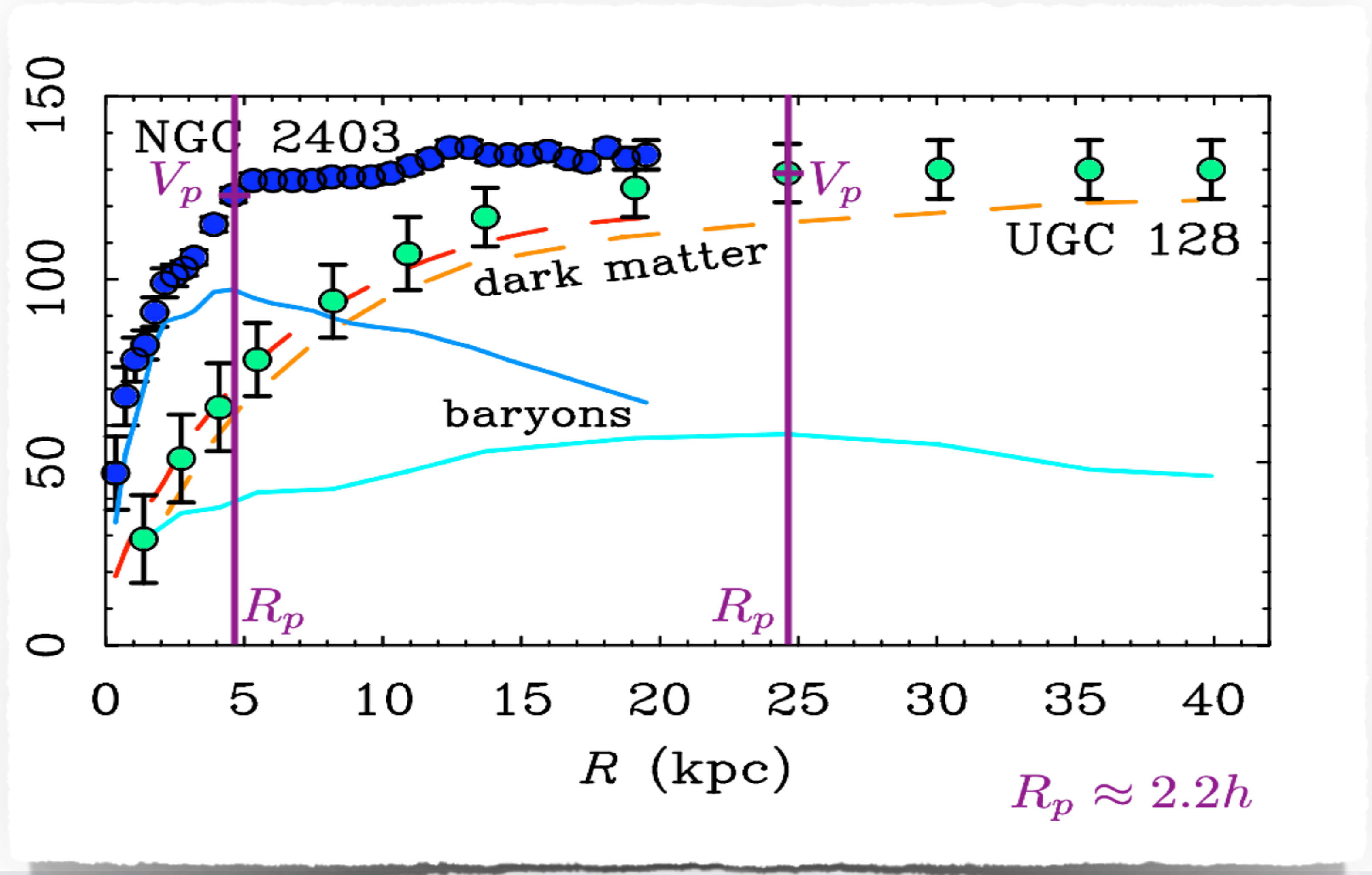
Rotation Curves of Disk Galaxies

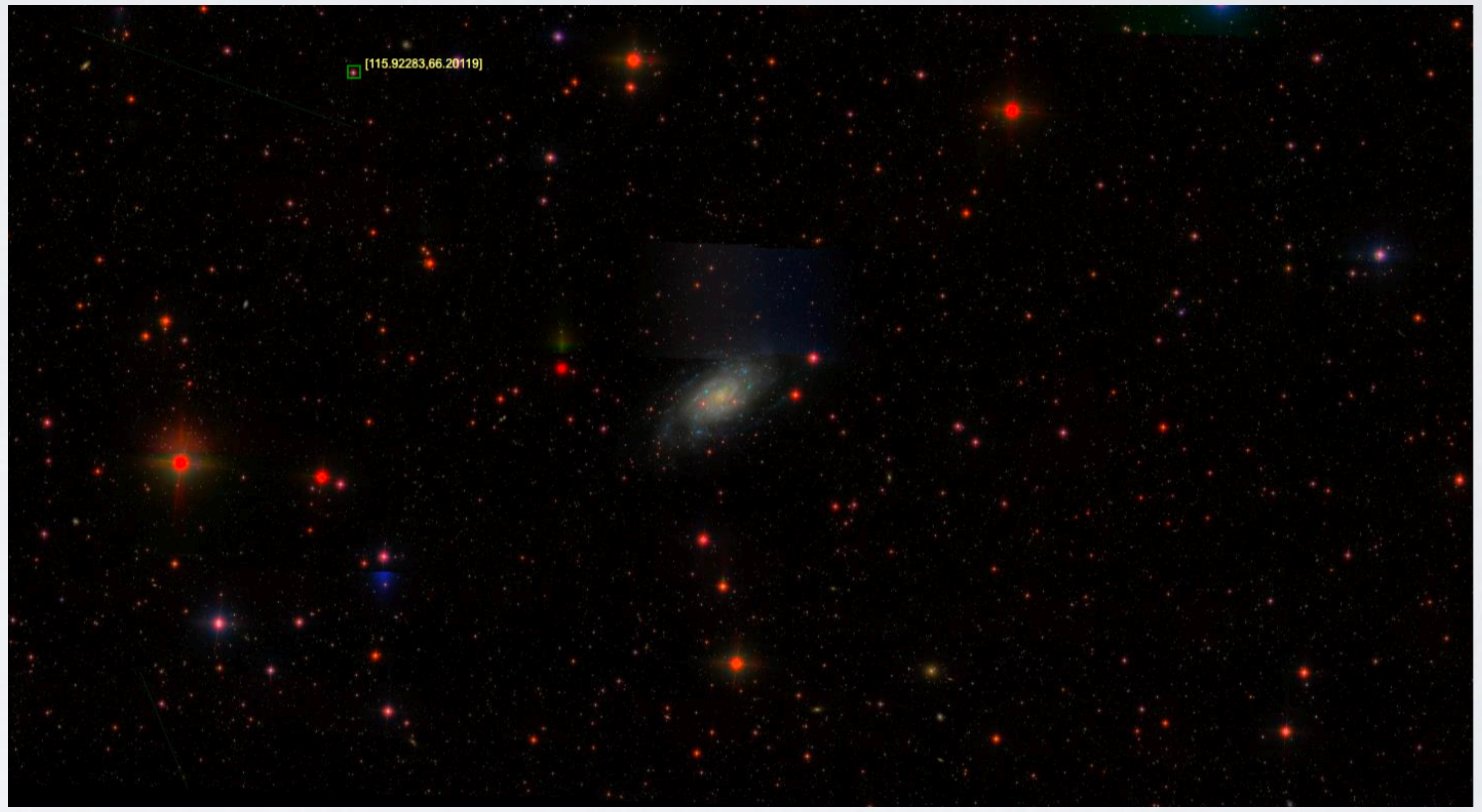




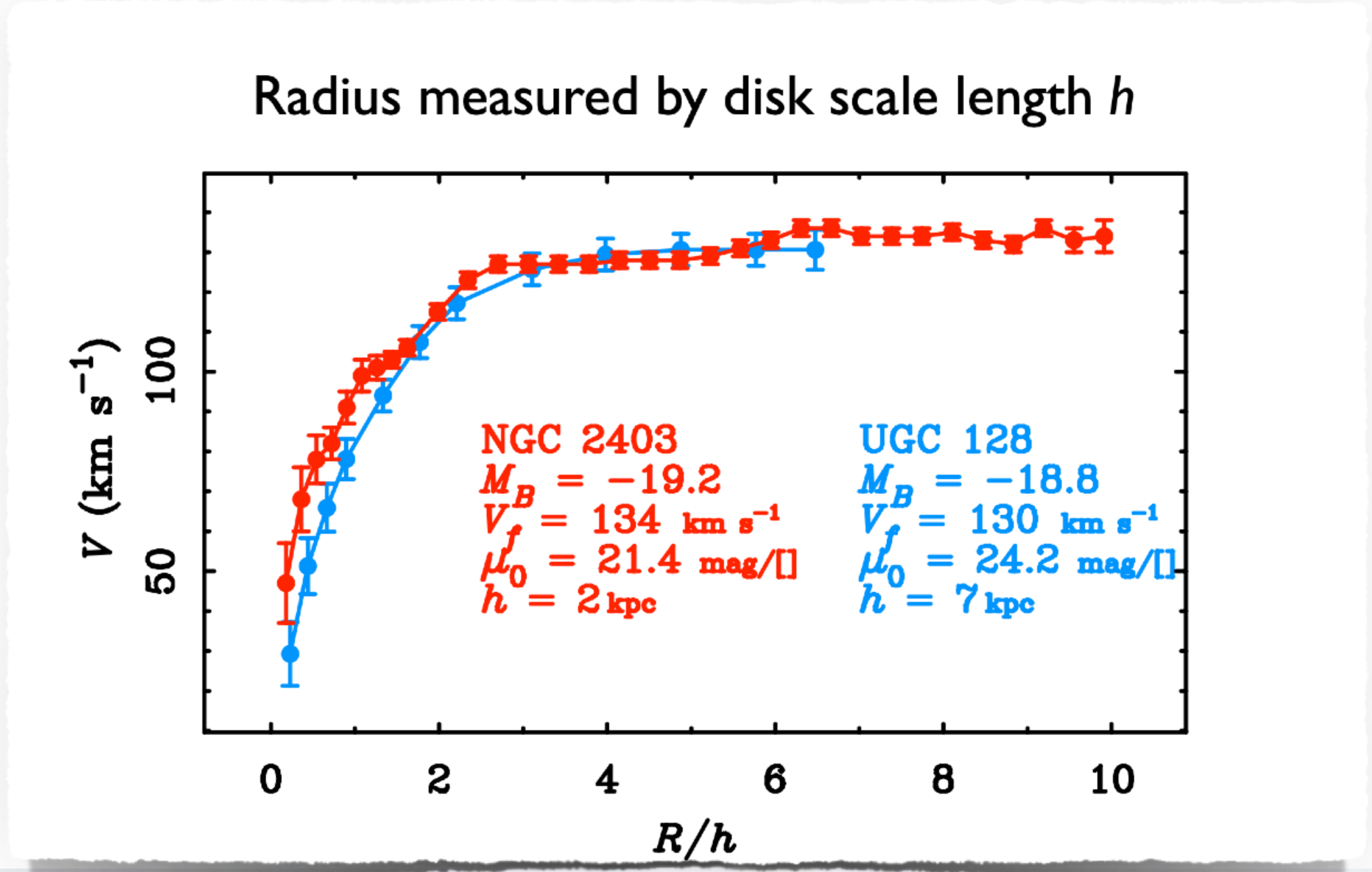
- *Rotation curve amplitude correlates with the mass of stars and gas.*
- *Rotation curve shape correlates with the distribution of stars and gas.*

Rotation Curves of Disk Galaxies





NGC 2403
@ V_h ~ 135 km/s



UGC 128
@ V_h ~ 4535 km/s

Predictions by the Hypotheses

DD

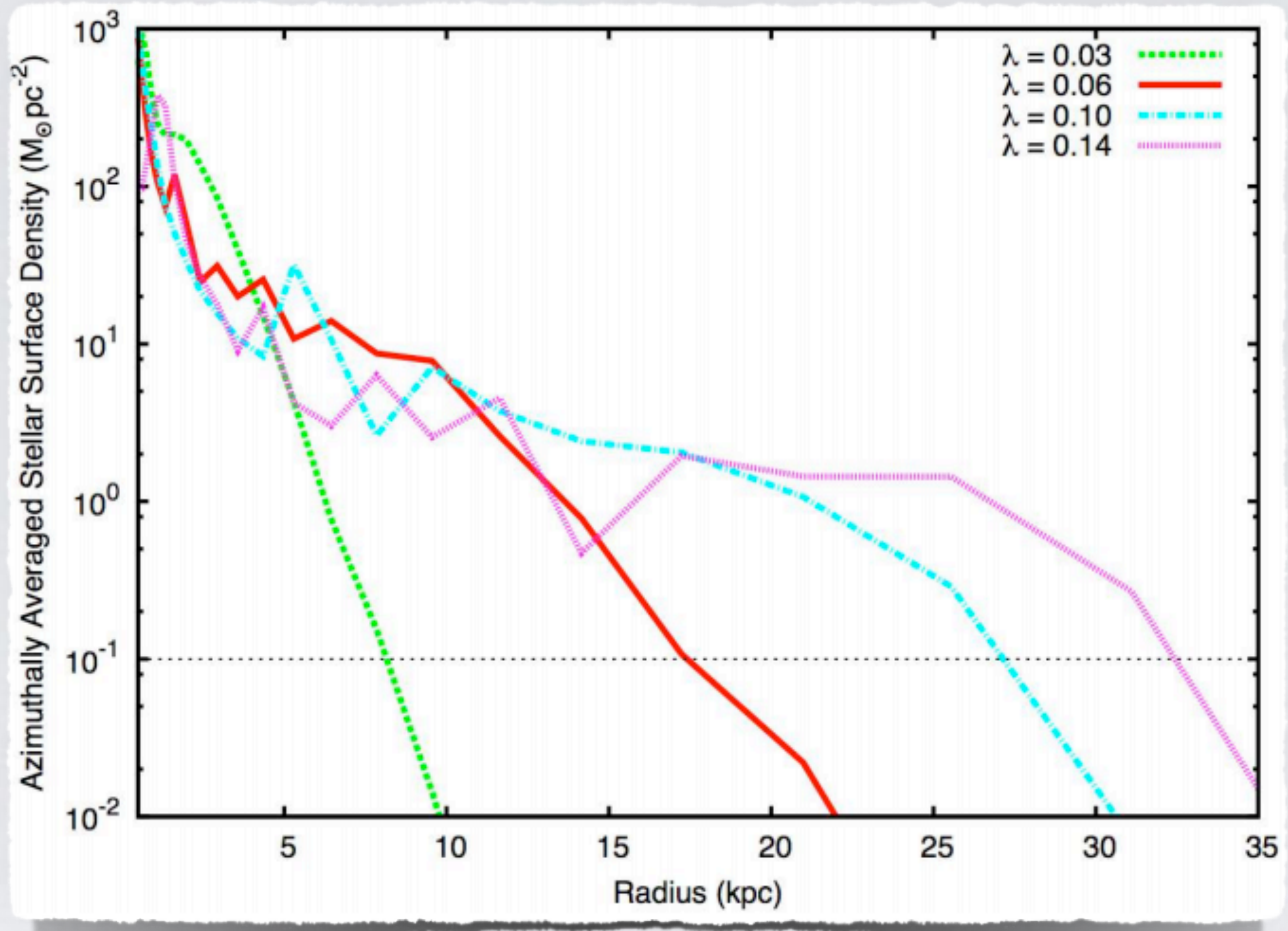
- *Right*
  1. *Clustering Properties : LSBGs should be less clustered than HSBGs*
  2. *Rotation Curve Shapes : LSBGs should have slowly rising rotation curves.*
  3. *Low Surface Density*
  4. *Collapse Time : Collapse time for LSBGs should be later than HSBGs.*
- *Wrong*
  1. *Tully-Fisher Relation : LSBGs and HSBGs should have different TF relations.*

SH

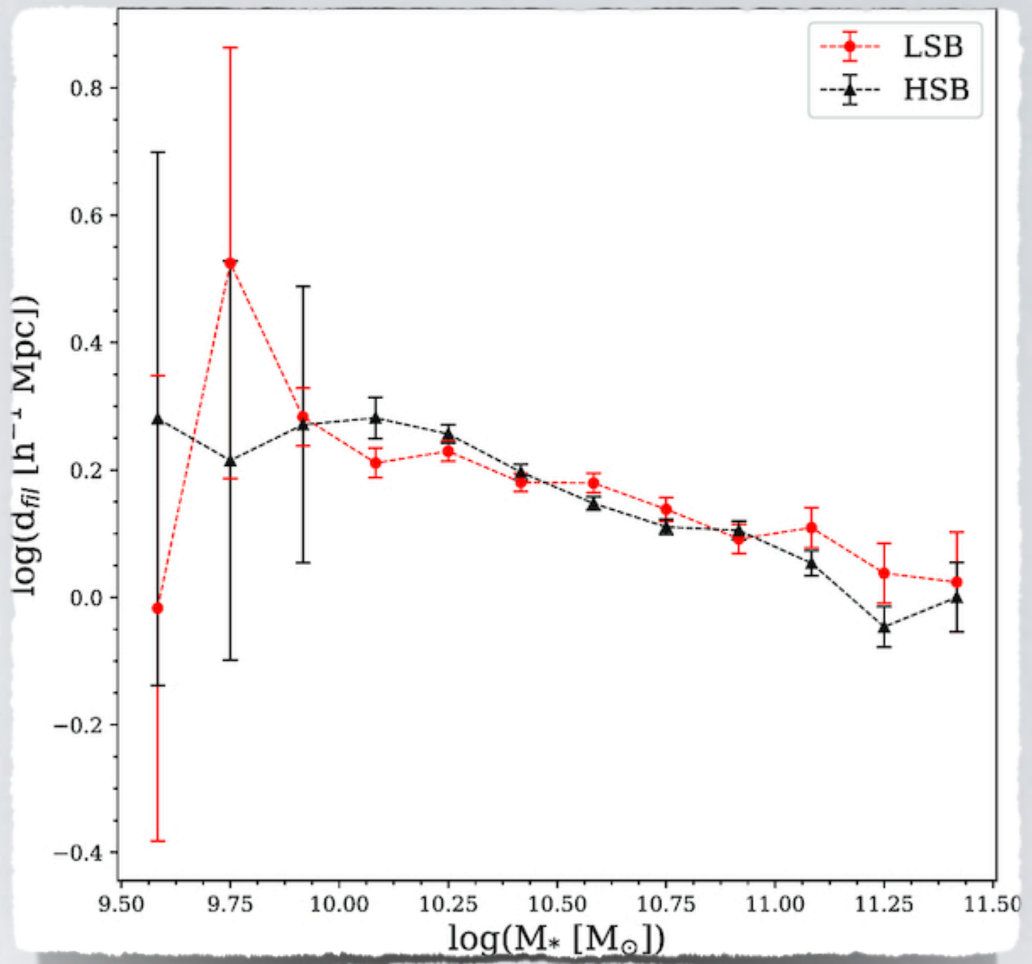
- *Right*
  1. *Tully-Fisher Relation : LSBGs and HSBGs should have a same TF relation.*
- *Wrong*
  1. *Rotation Curve Shapes : There need to be a lot of fine tuning.*
  2. *No Age Difference : It is difficult to distinguish between late collapse and delayed stellar components.*
  3. *Environment : Are spin and environment correlated?*

Questions

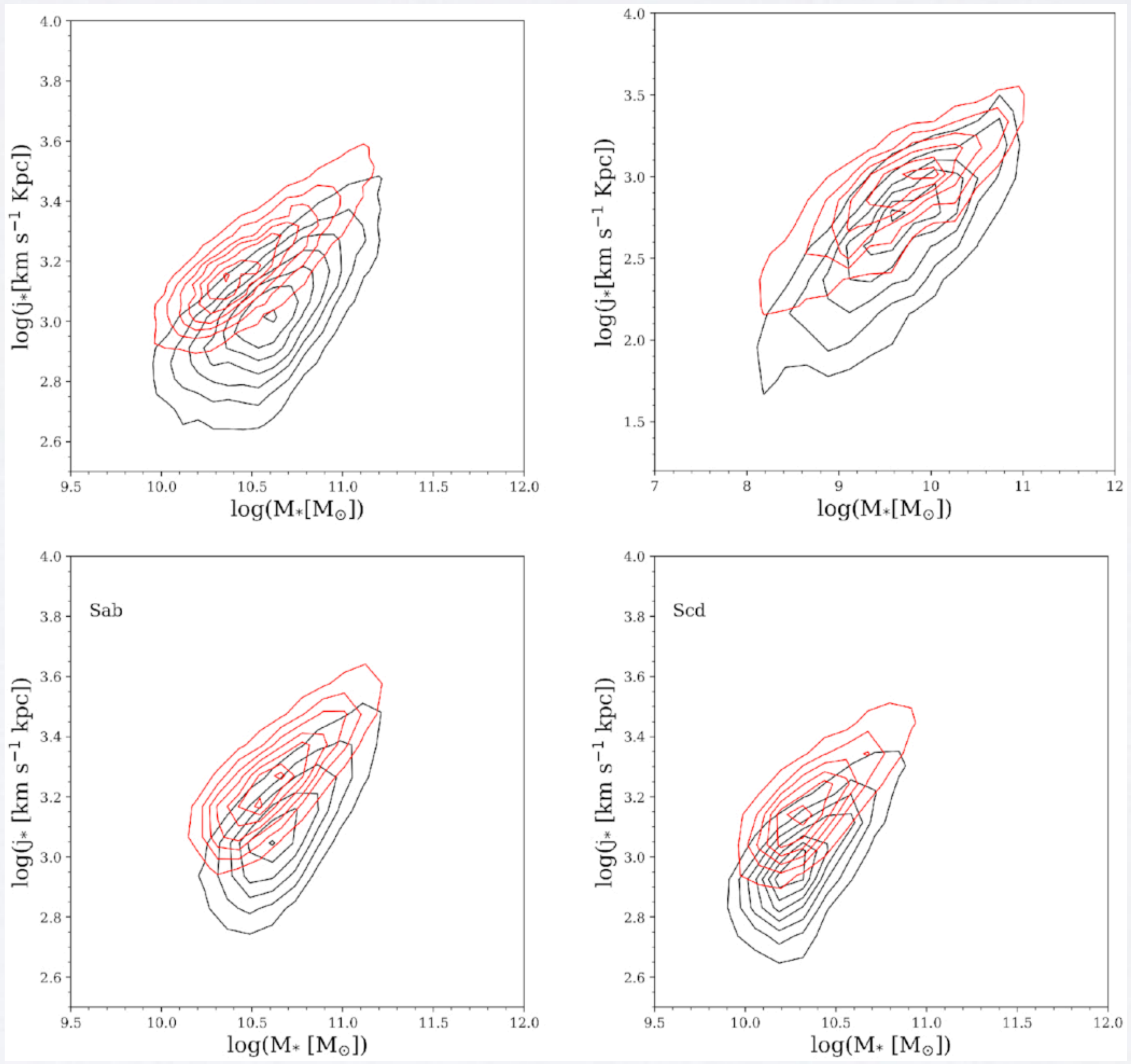
- *What determines surface brightness, or surface density of disk galaxies?*
- *Do LSBGs have higher spin parameters?*
- *Do spin and environment really not correlate?*
- *Can environment affect shapes of rotation curves without impacting TF relation?*
- *Is the surface brightness distribution of disk galaxies similar to one predicted by the theoretical hypotheses?*



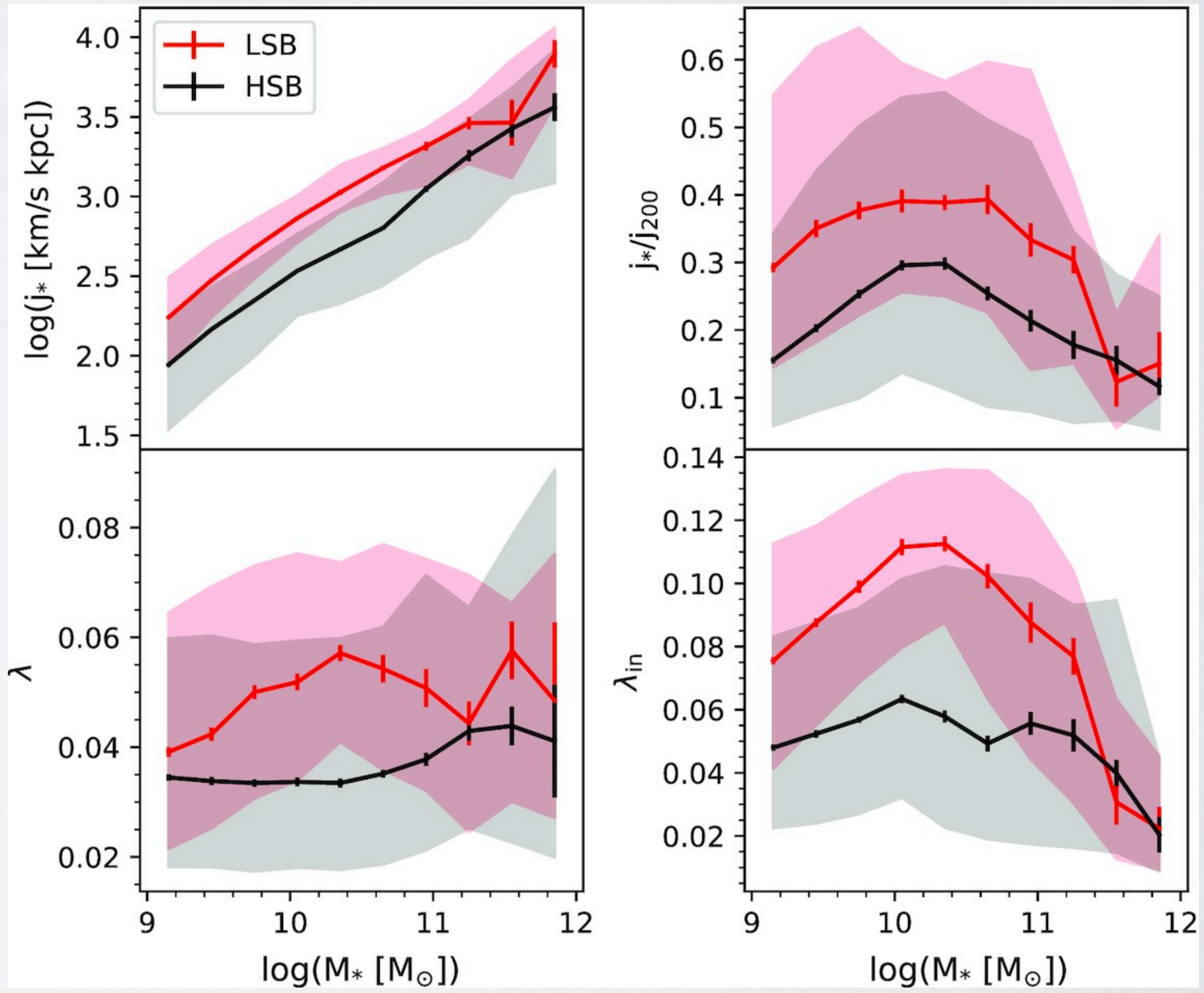
Kim & Lee (2012)



Perez-Montana & Cervantes-Sodi (2019)



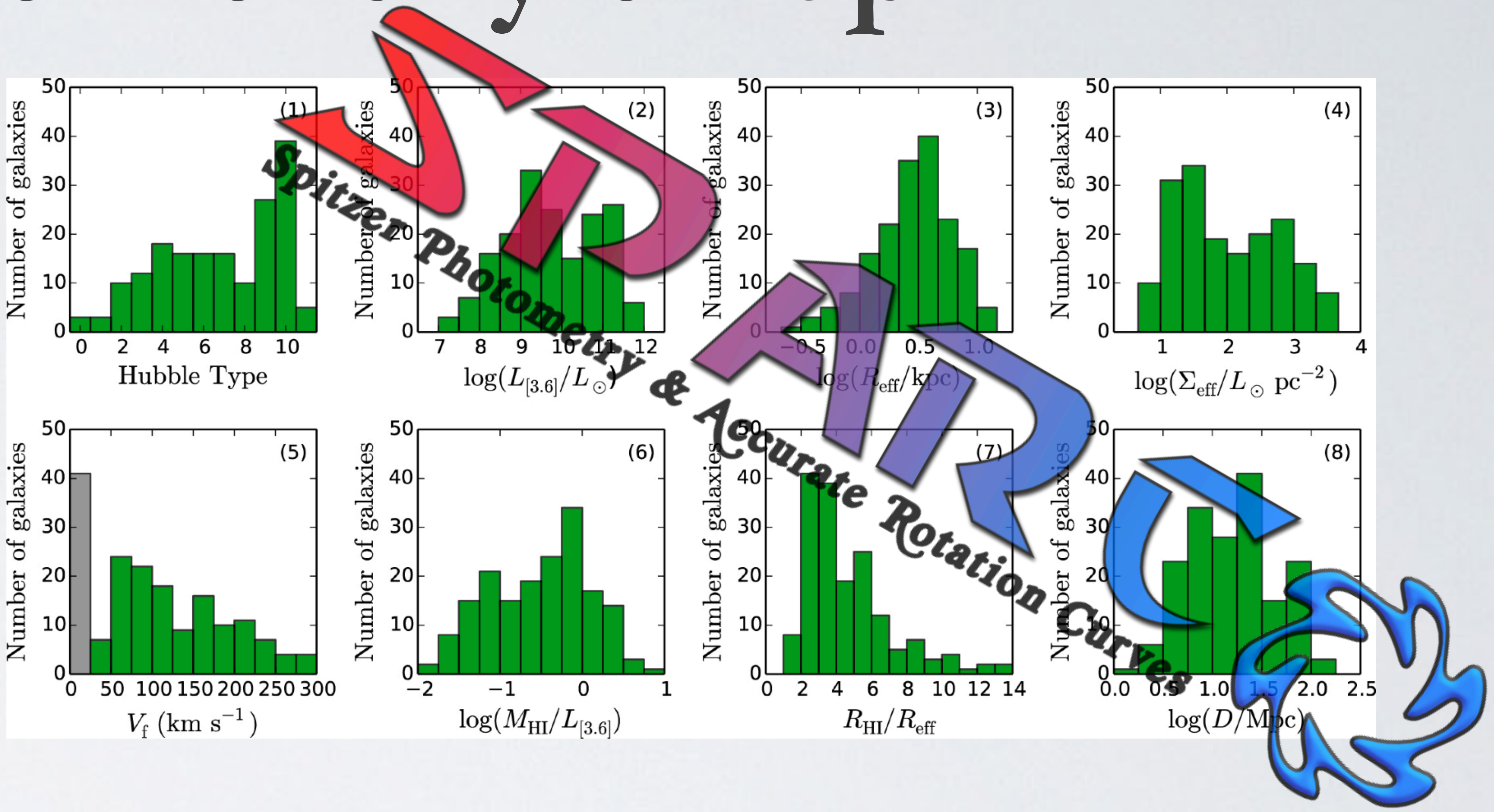
Perez-Montana & Cervantes-Sodi (2019)

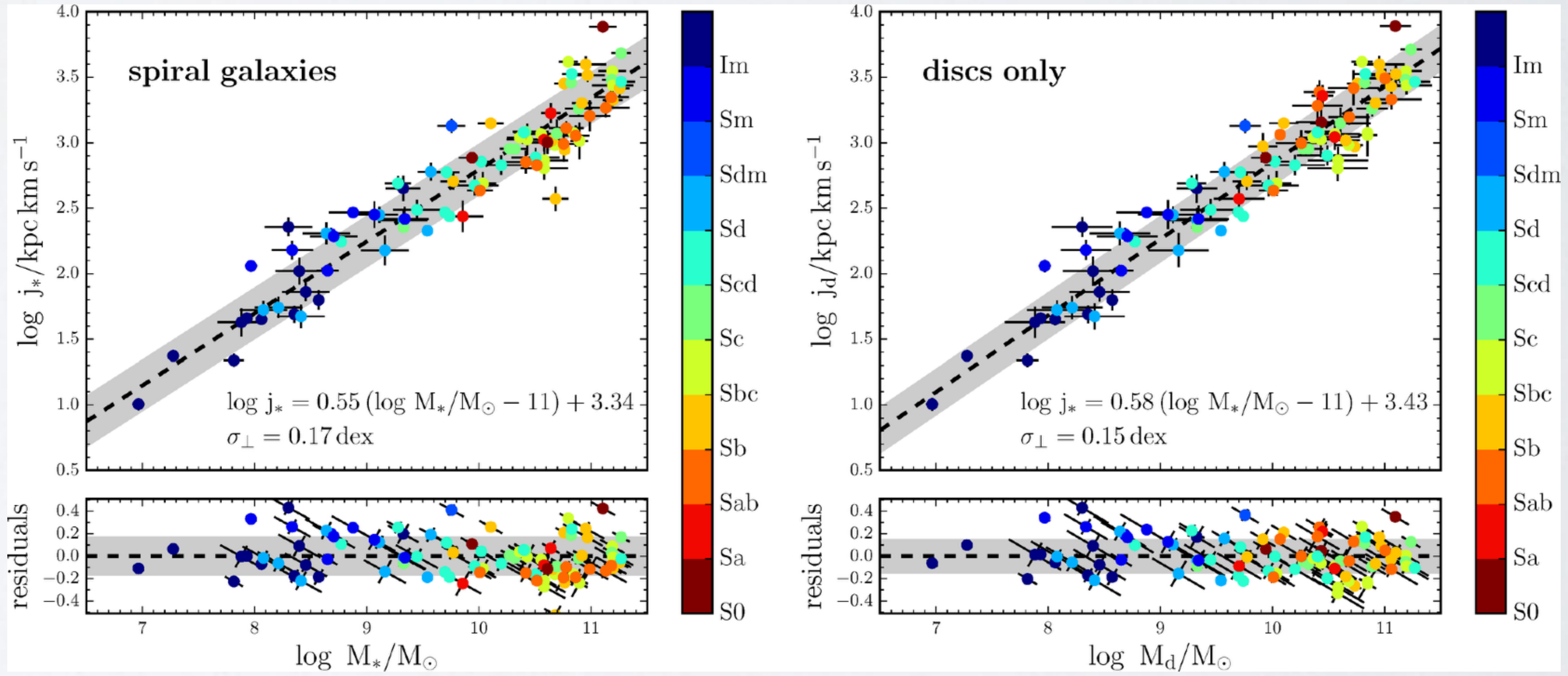


Perez-Montana & Cervantes-Sodi (2019)

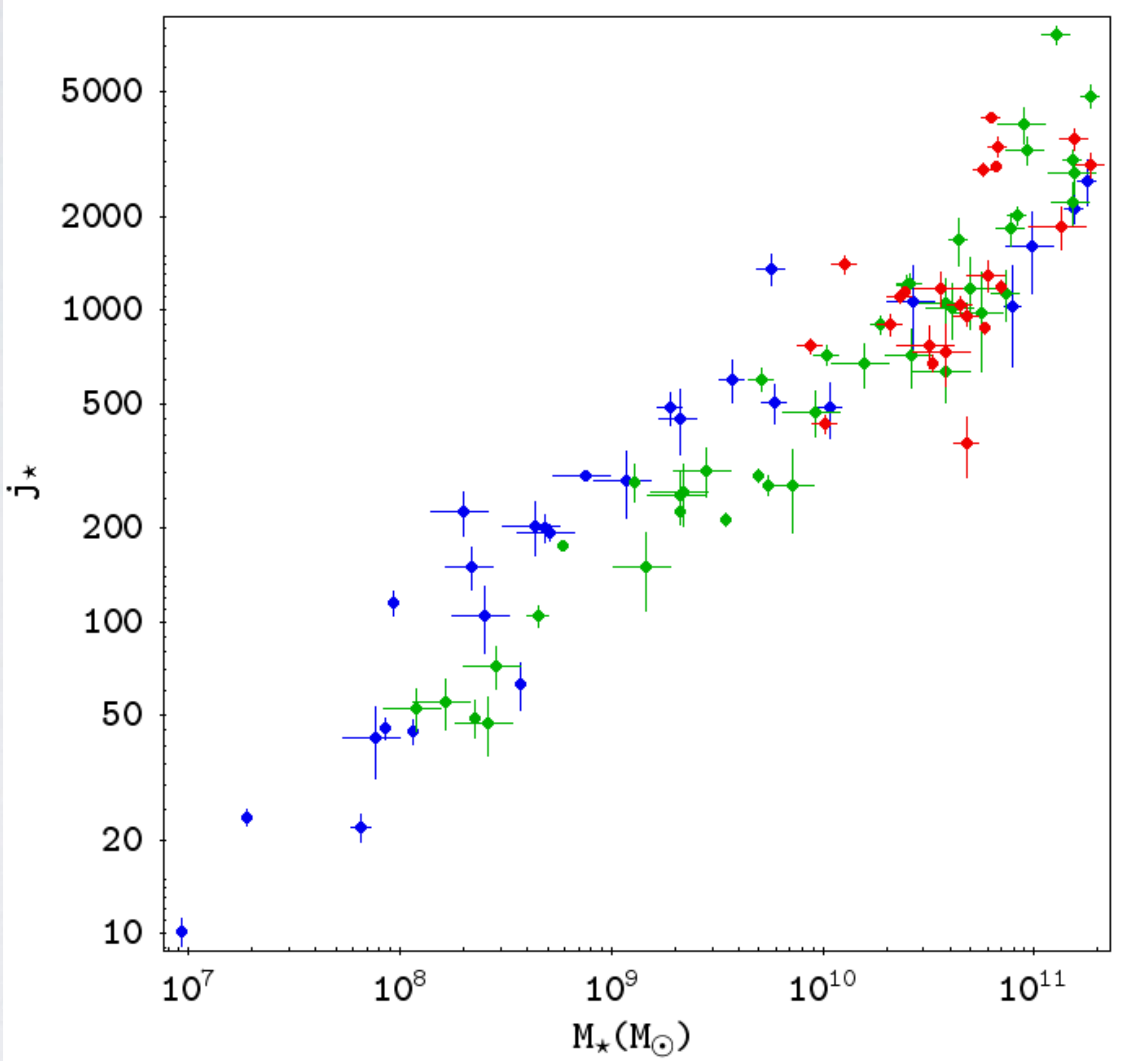
The Dependence of Surface Density on Spin

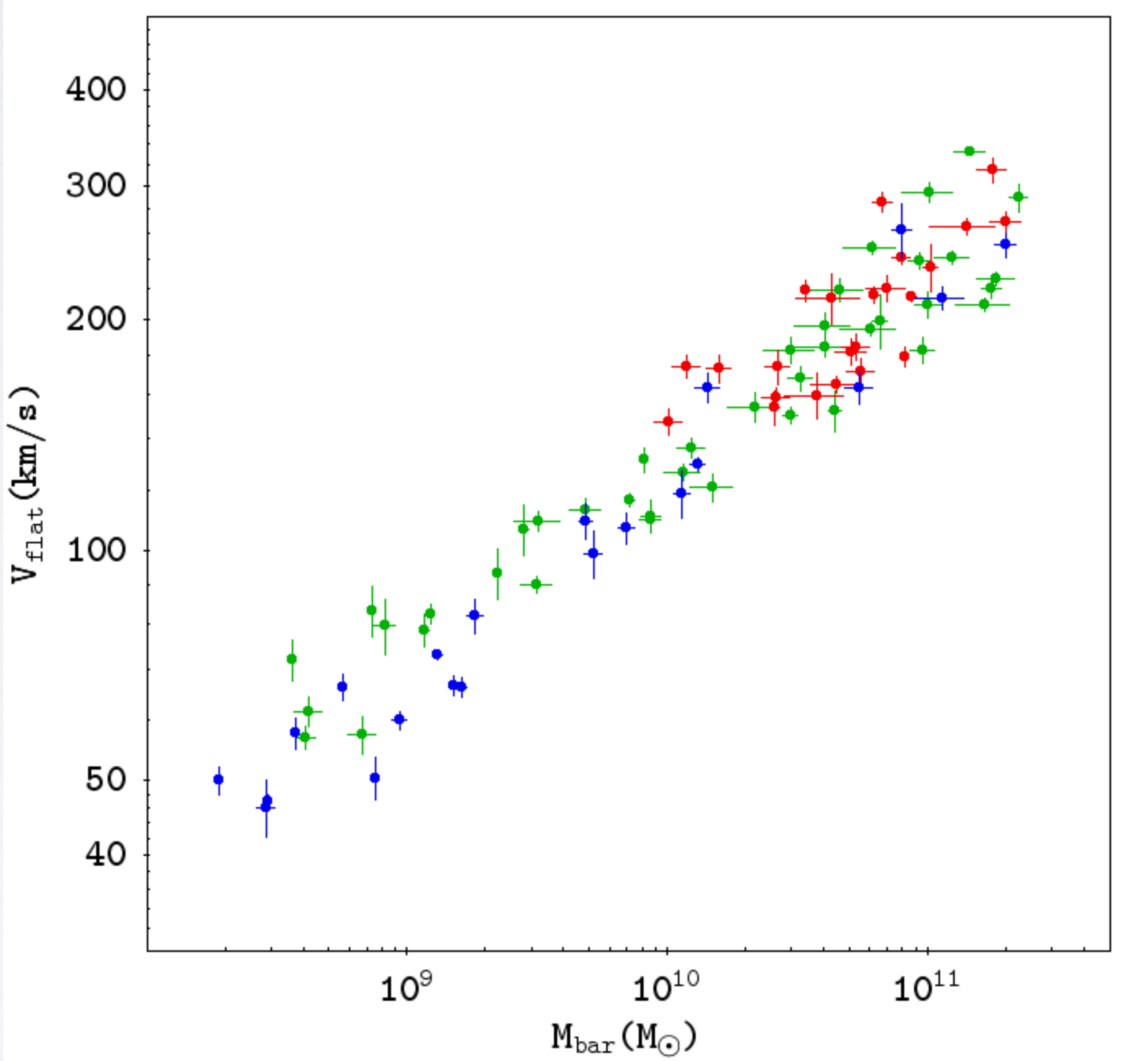
- *SPARC : Spitzer Photometry and Accurate Rotation Curves*
- *the Sample : 175 late-type galaxies*
- *Data : Spitzer photometry at 3.6 μm and high-quality HI+Hα rotation curves*
- *a wide range in stellar masses (5 dex), surface brightnesses (>3 dex), and gas fractions*
- *Posti et al. (2018) calculated specific angular momentum (j=J/M) for 92 out of 172 SPARC sample galaxies.*
- $\lambda = \dfrac{j}{\sqrt{2}RV}$



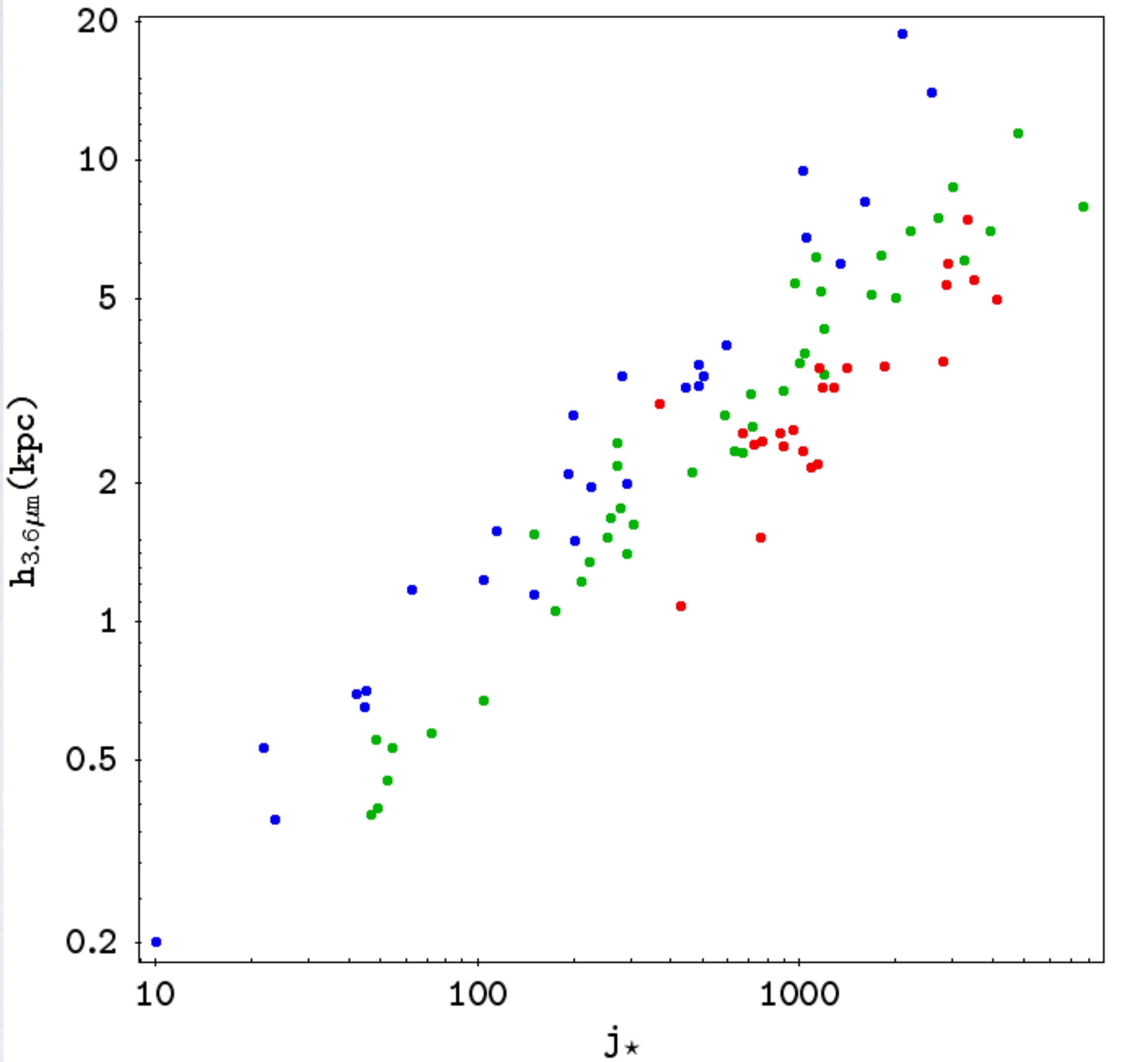


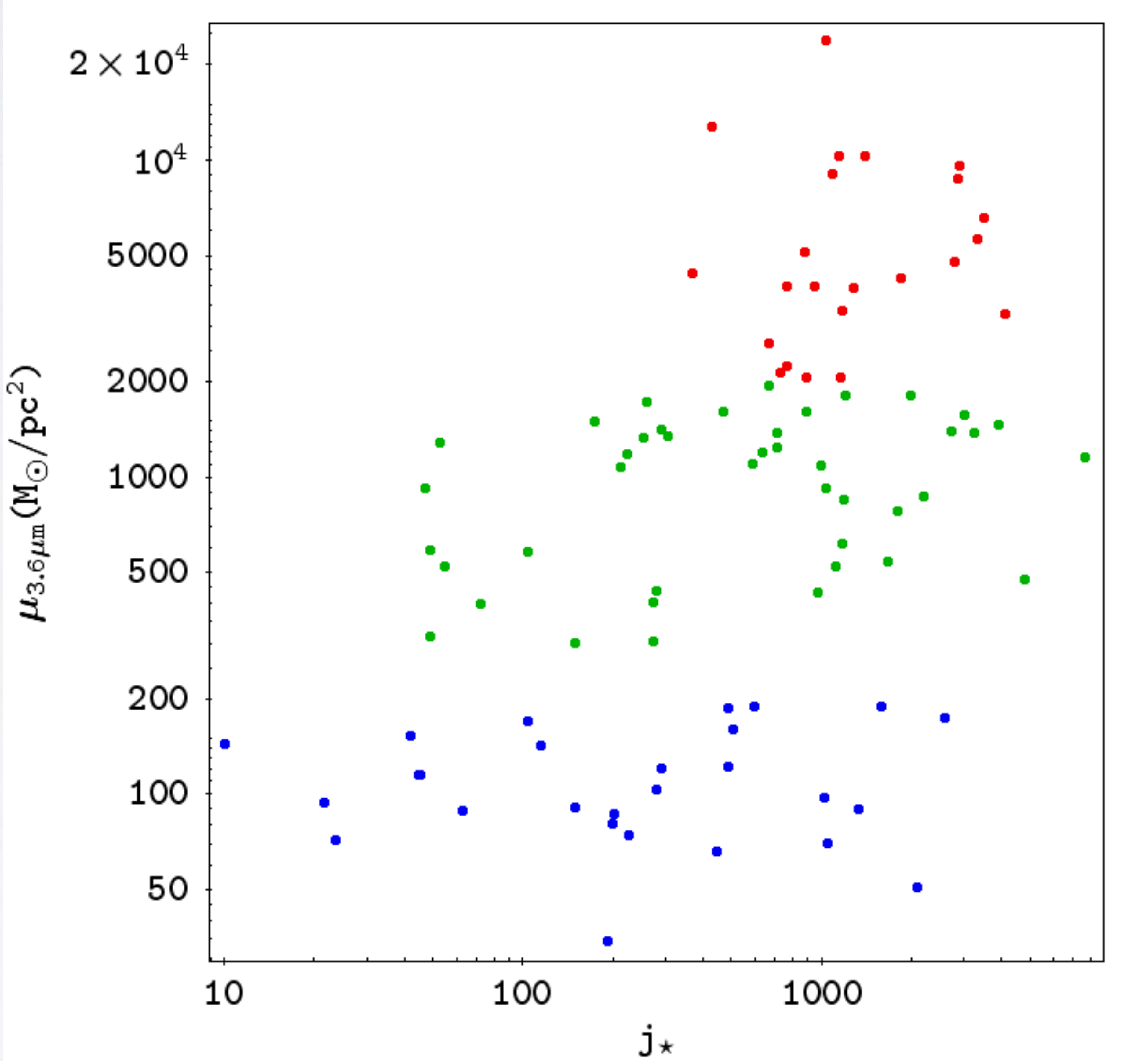
Fall Relation vs Baryonic Tully-Fisher Relation



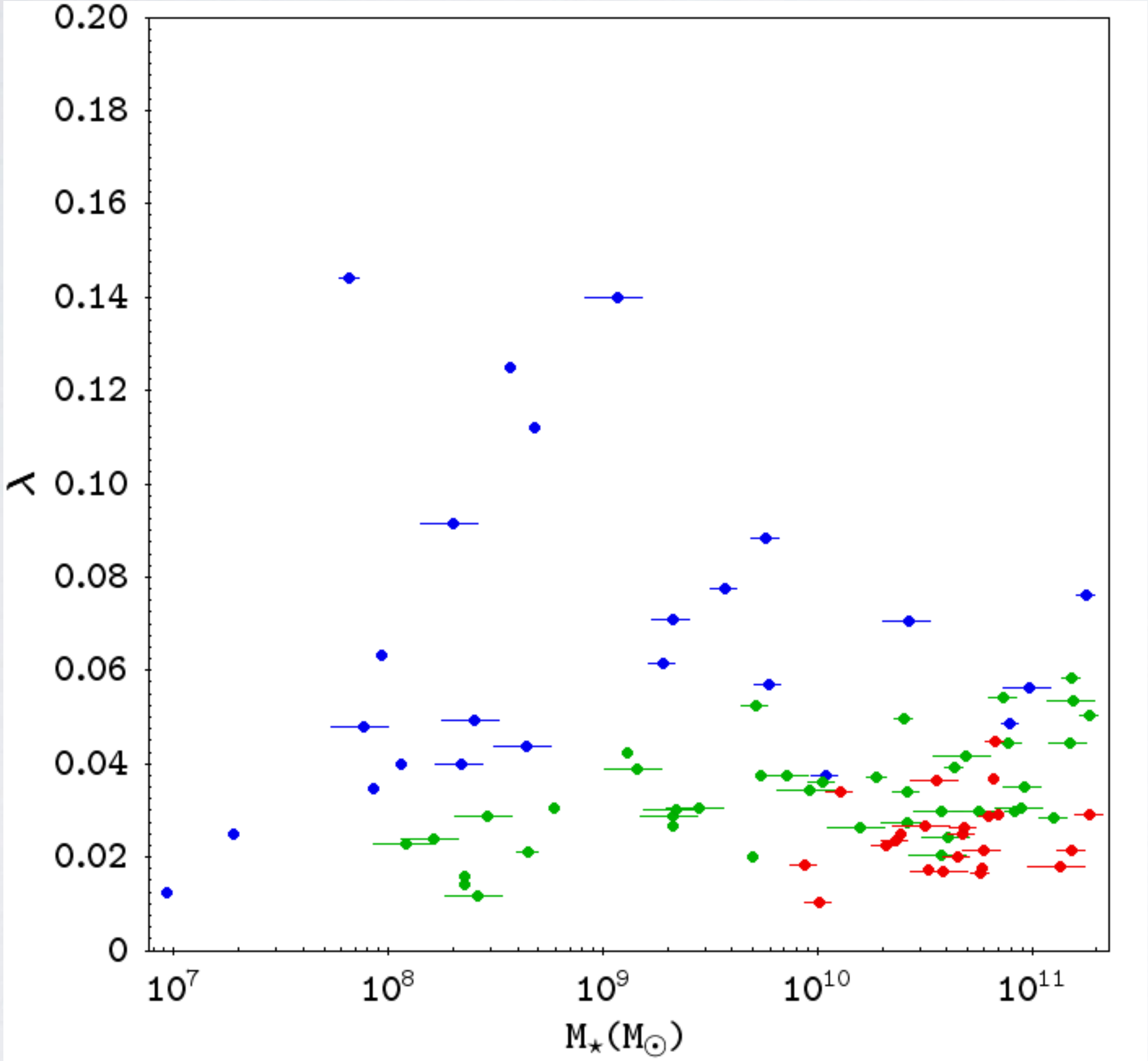


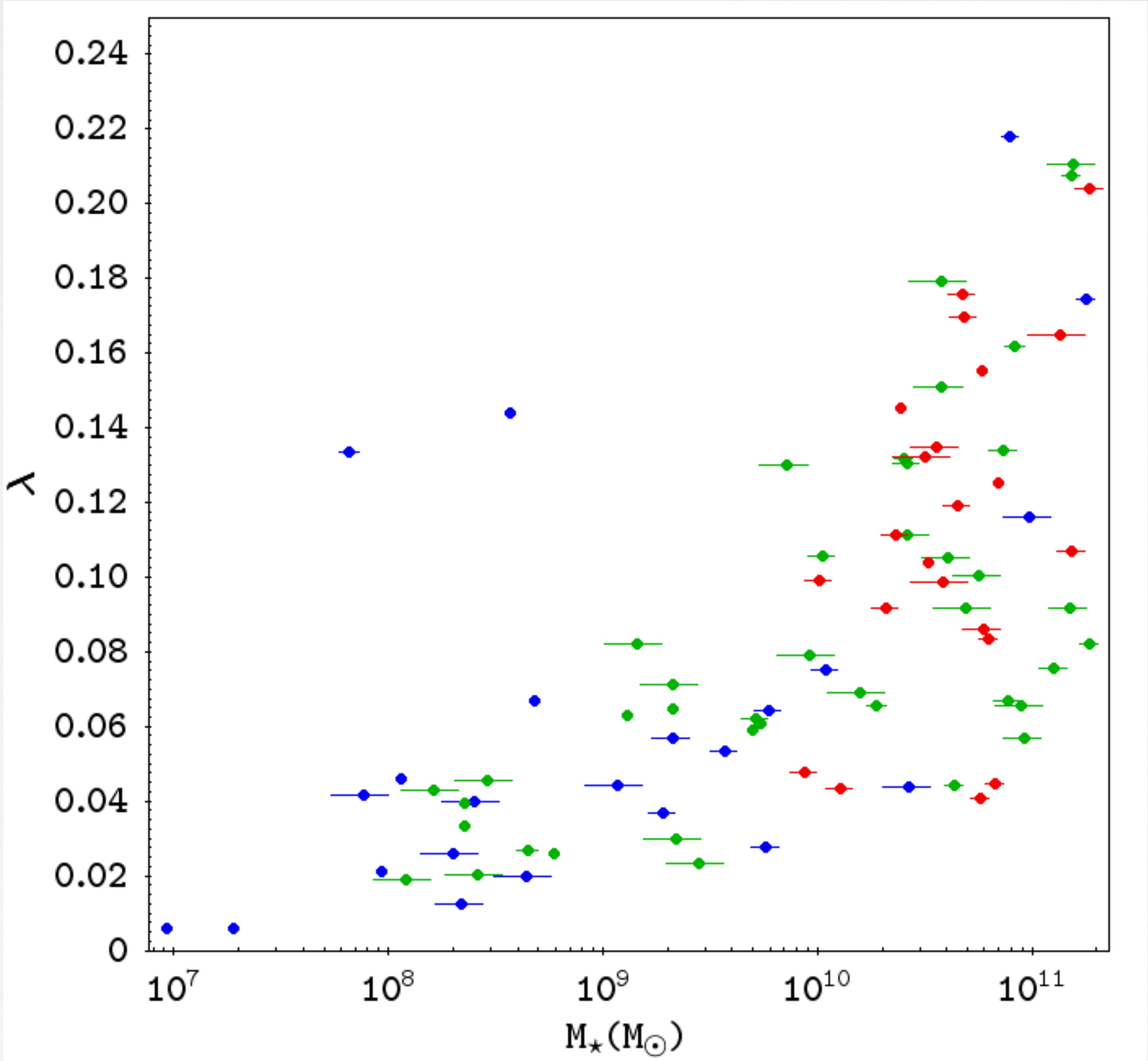
Fundamental Disk Parameters





Spin Parameter



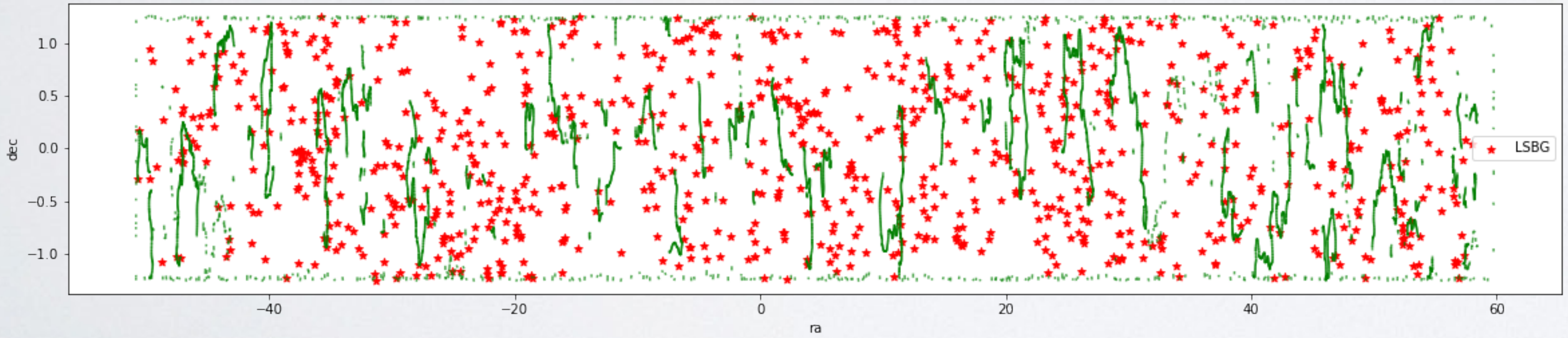


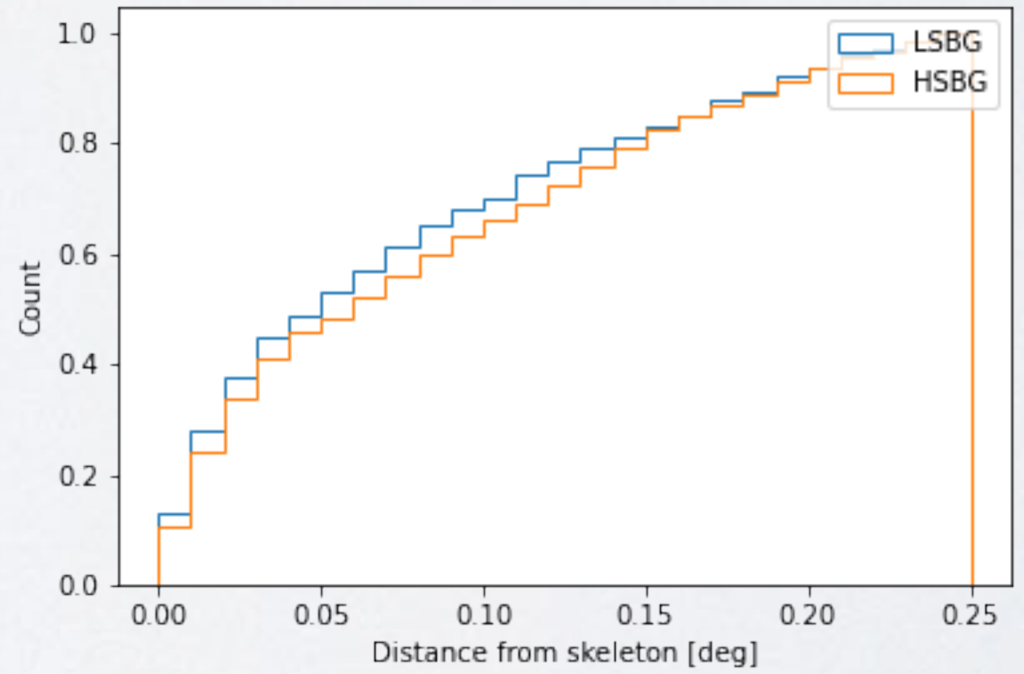
So far…

- *LSBGs may have systematically higher angular momentum for given mass.*
- *There are certainly outliers;*
  1. *No peculiar morphology*
  2. *Not in interaction*
- *LSBGs may not have systematically higher spin parameter, even for given mass.*
- *Spin parameter proxies are messy, therefore consider it as a grain of salt.*

Then, what?

- *We will measure environment parameters:*
  1. *Σ_5, or δ_5*
  2. *Distance to filament structure*
- *We will recalculate spin parameters to calibrate proxies.*
- *We are also carrying out a study on galaxy environment of disk galaxies based on Stripe82 Coadds data.*





By Eunhee Ko

II. Introduction to 7DT/7DS

Center for the Gravitational-Wave Universe team
Seoul National University, Korea Astronomy and Space Science Institute,
Ewha Womans University, and Postech

Hyung Mok Lee

Myungshin Im

Arman Shafieloo

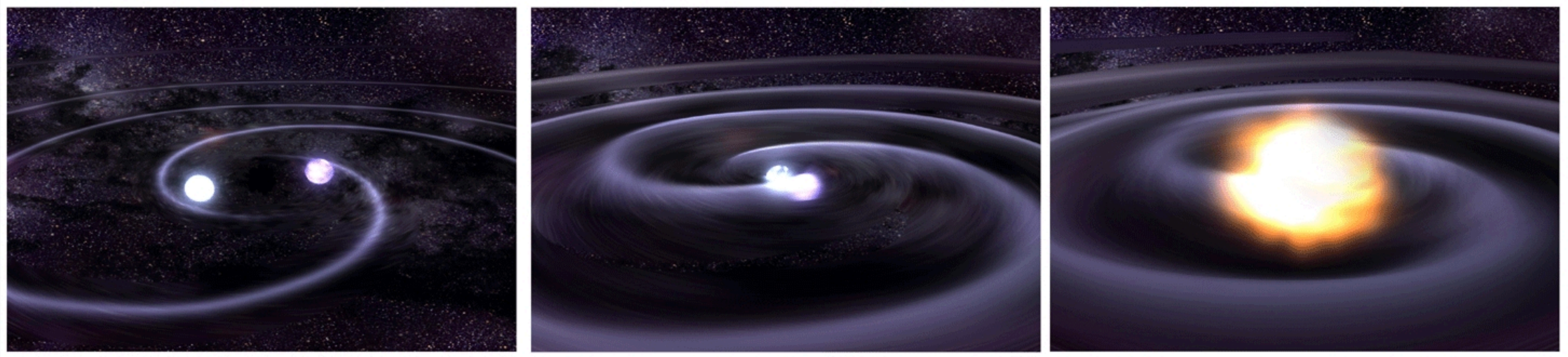
Chunglee Kim

Jae-Hun Jung

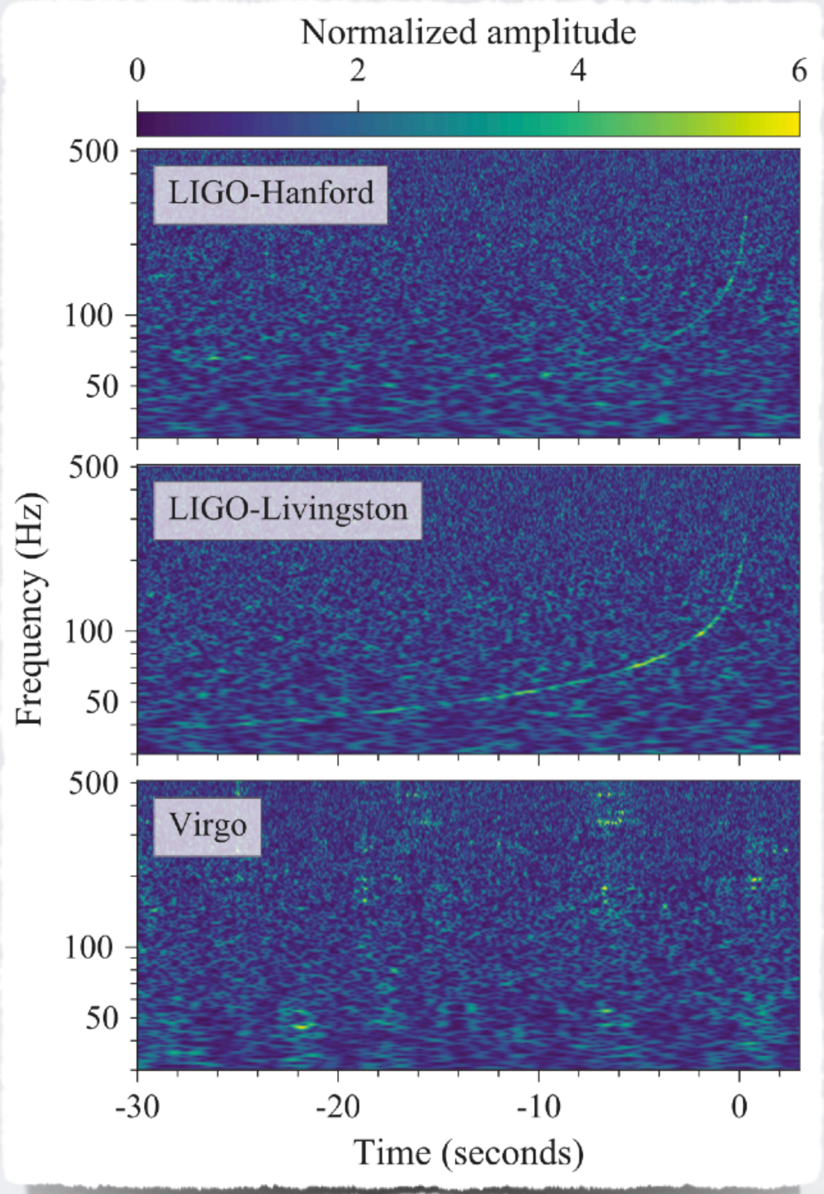
Lucas Uhm

Gravitational-wave EM Counterpart Identification

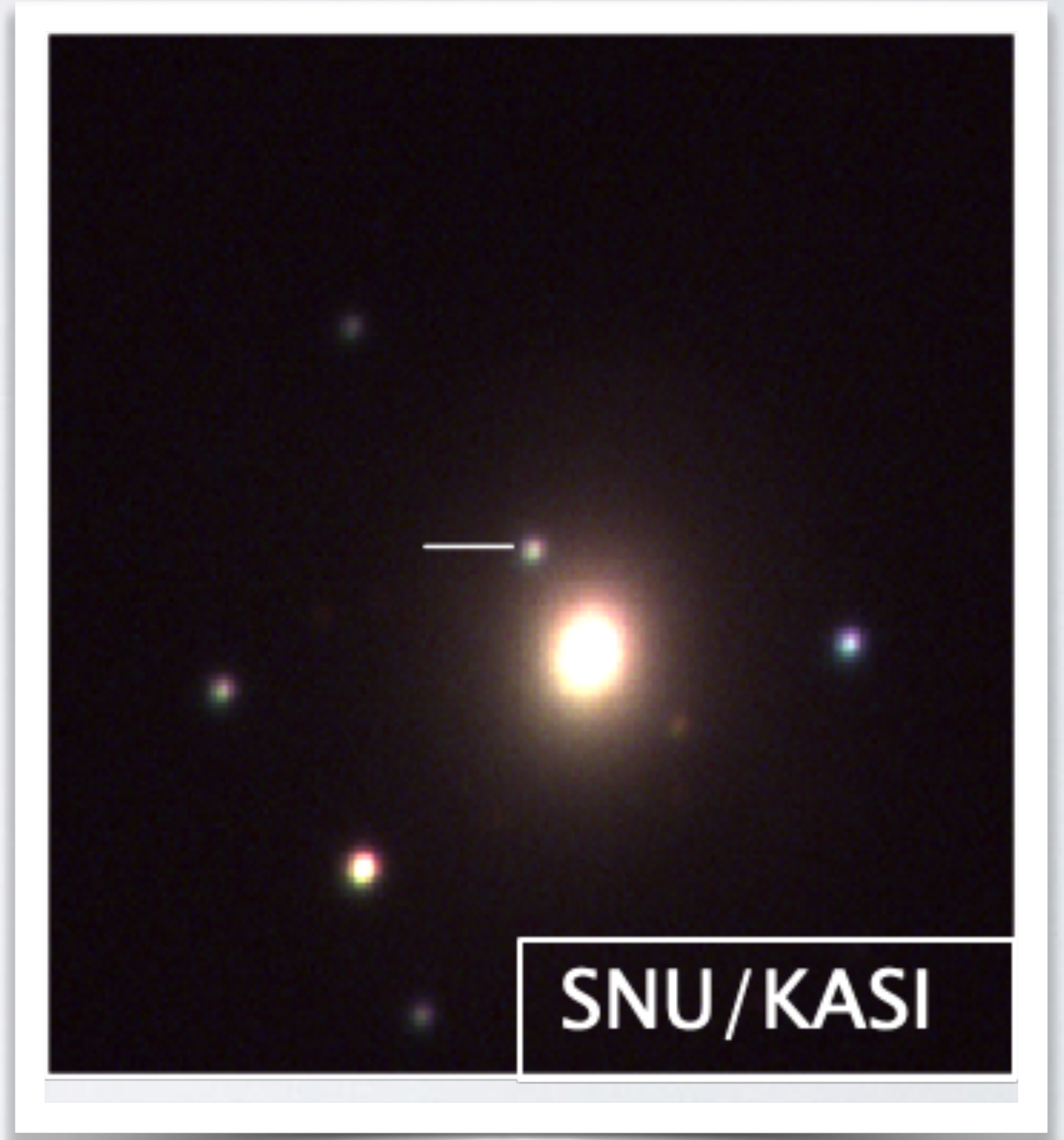
- *4 messengers : photons (electromagnetic wave), cosmic rays (protons and atomic nuclei), neutrinos, and gravitational waves.*
- *Gravitational Wave Astronomy*
  1. *Binary Black Hole Merger*
  2. *Binary Neutron Star Merger*
  3. *Violent Events, such as Supernovae*
  4. *Epoch Prior to Recombination*
  5. *the Properties of GW Sources : mass and distance*
- *GW170817 : a binary neutron star merger*



An artistic rendition of binary neutron star merger (image credit : NASA)

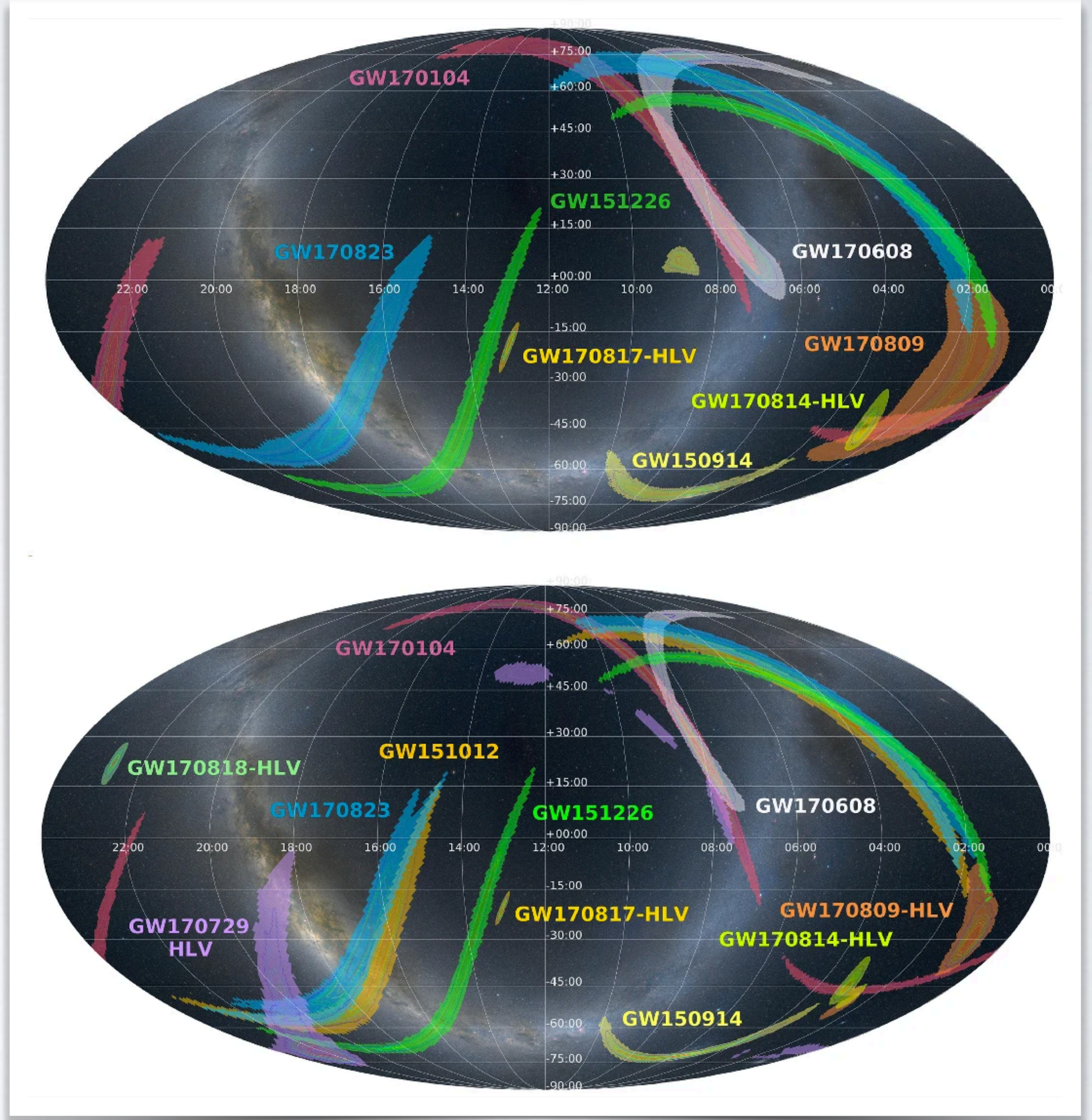


Time-frequency representations of data containing the gravitational-wave event, GW170817 observed by LIGO.



Multi-Messenger Astronomy

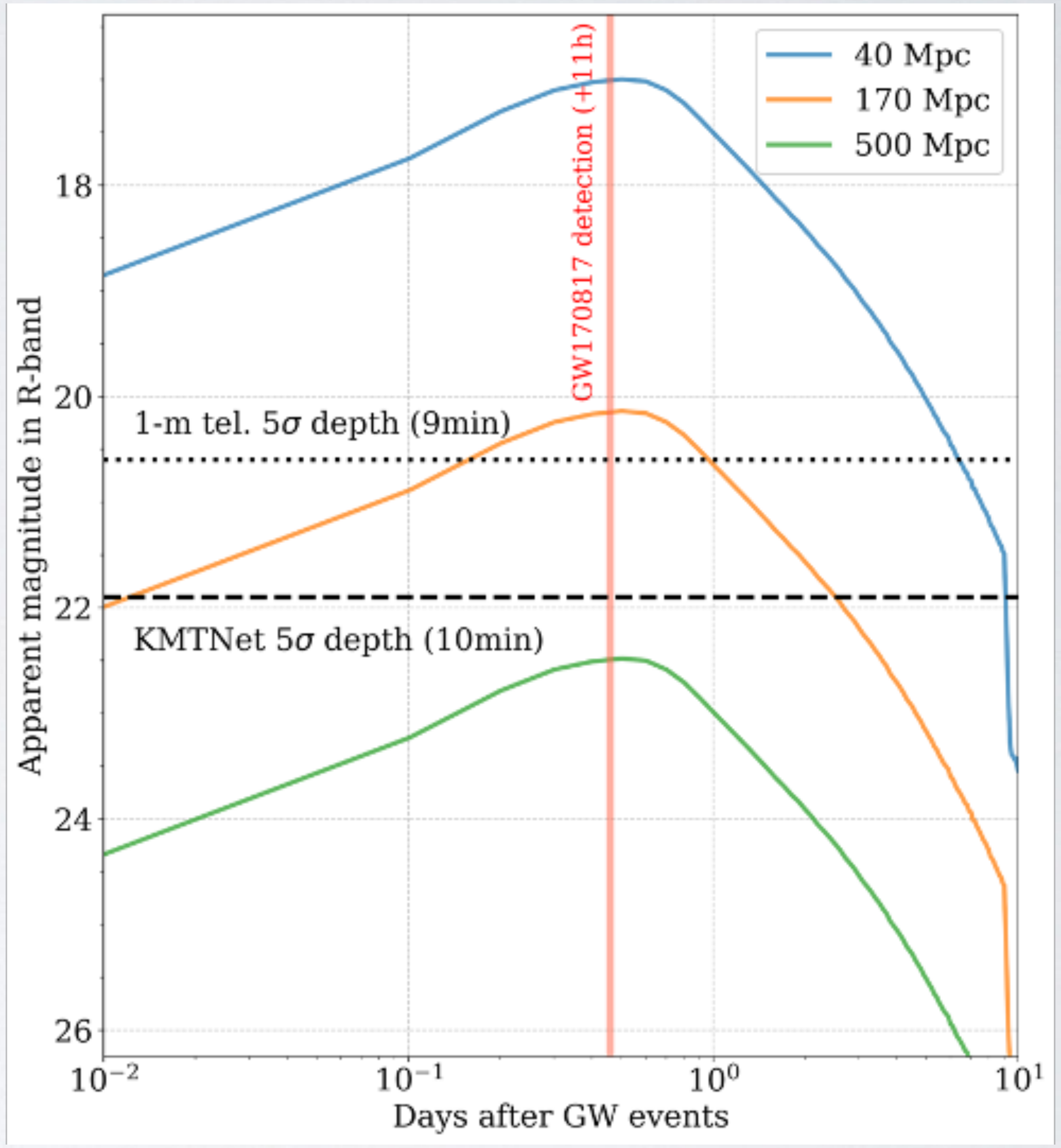
- *3 Challenges to EM Counterpart Identification*
  1. *Wide Localization Area*
     - *a few100's square degrees for O3*
     - *a few10's of square degrees for O4?*
  2. *Faint, Fast-declining Transients (kilonova)*
     - *Peak apparent magnitudes are R = 17 ~ 22.5 mag.*
     - *They become a few mag fainter in several days.*
  3. *Numerous Transients and Bogus Signals in large FoVs*
     - *a few100's transients and/or variable objects in 10 square degrees*
     - *a few10^5's artifacts in 10 square degrees*



Sky locations of GW events confidently detected in O1 and O2
(Fig 5 of Abbot et al. 2020)

Multi-Messenger Astronomy

- *3 Challenges to EM Counterpart Identification*
  1. *Wide Localization Area*
     - *~100's square degrees for O3*
     - *~10's of square degrees for O4?*
  2. *Faint, Fast-declining Transients (kilonova)*
     - *Peak apparent magnitudes are R = 17 ~ 22.5 mag.*
     - *They become a few mag fainter in several days.*
  3. *Numerous Transients and Bogus Signals in large FoVs*
     - *~100's transients and/or variable objects in 10 square degrees*
     - *~10⁵ artifacts in 10 square degrees*



G. Paek, Im, et al. (*in prep*)

Multi-Messenger Astronomy

- *3 Challenges to EM Counterpart Identification*
  1. *Wide Localization Area*
     - *~100's square degrees for O3*
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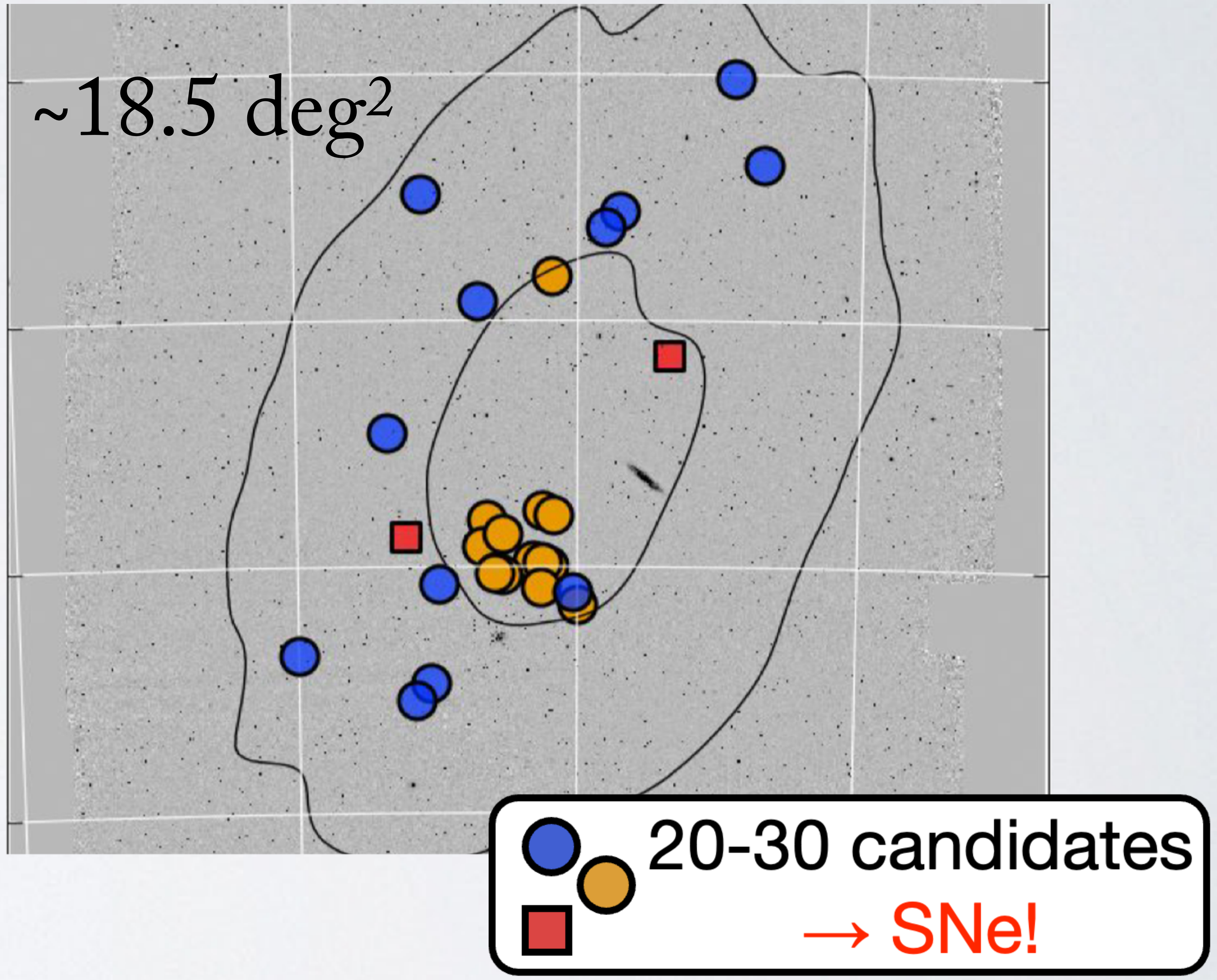
  3. *Numerous Transients and Bogus Signals in large FoVs*
     - *~100's transients and/or variable objects in 10 square degrees*
     - *~10^5 artifacts in 10 square degrees*

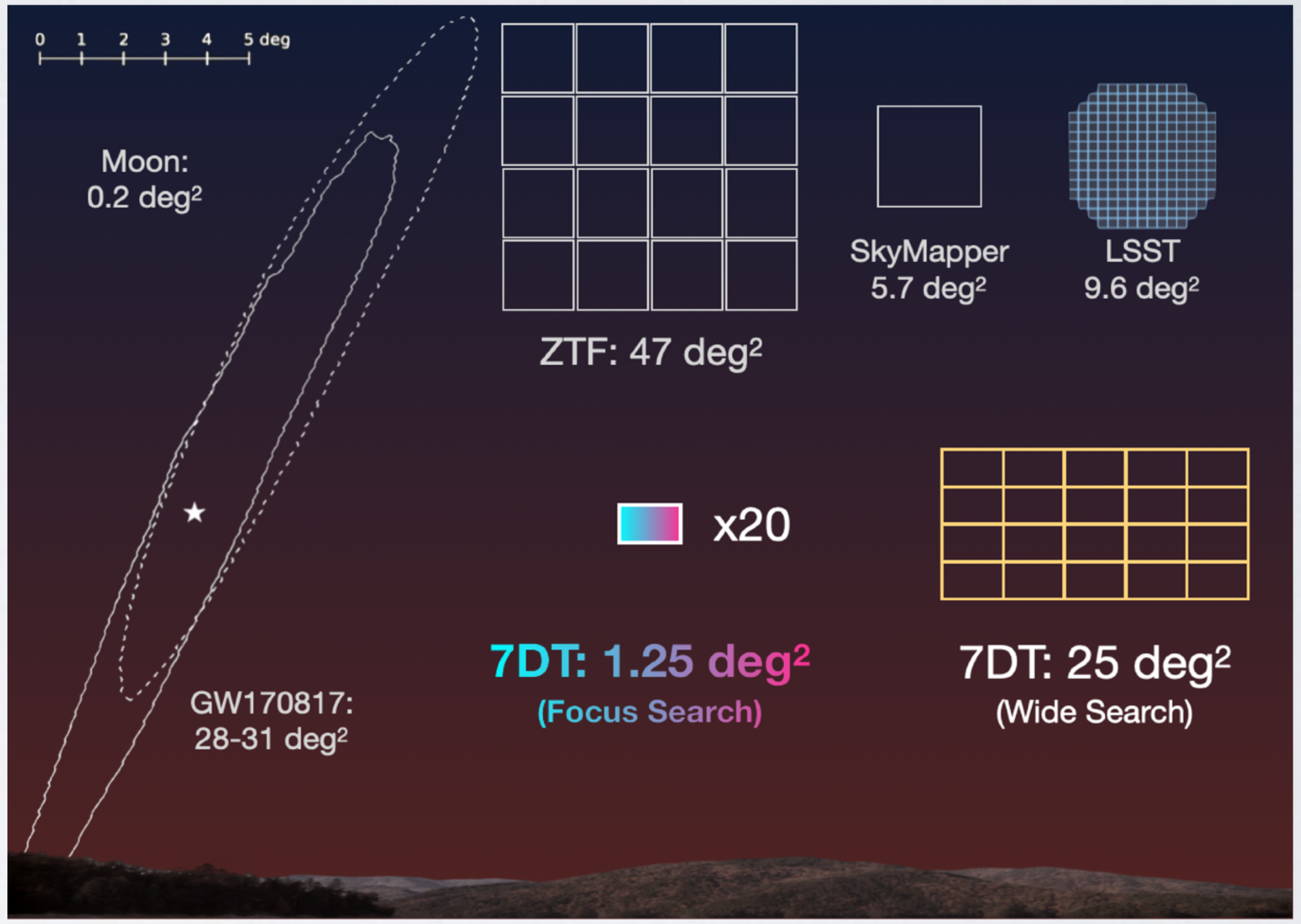
GW 190814 , NSBH (O3)

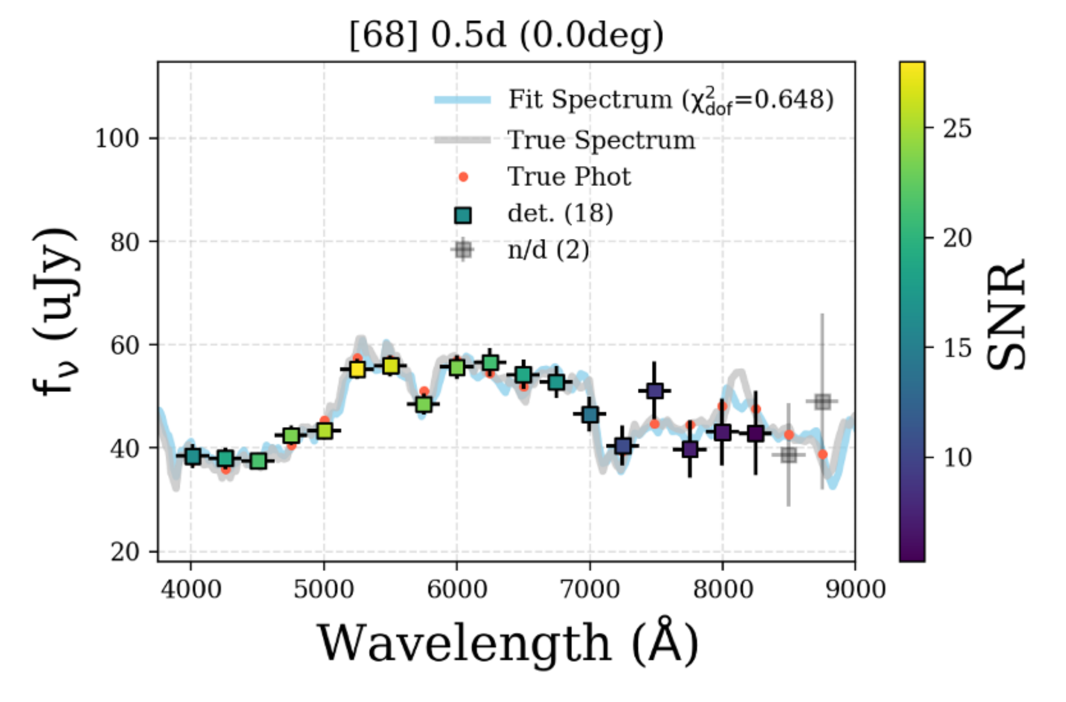


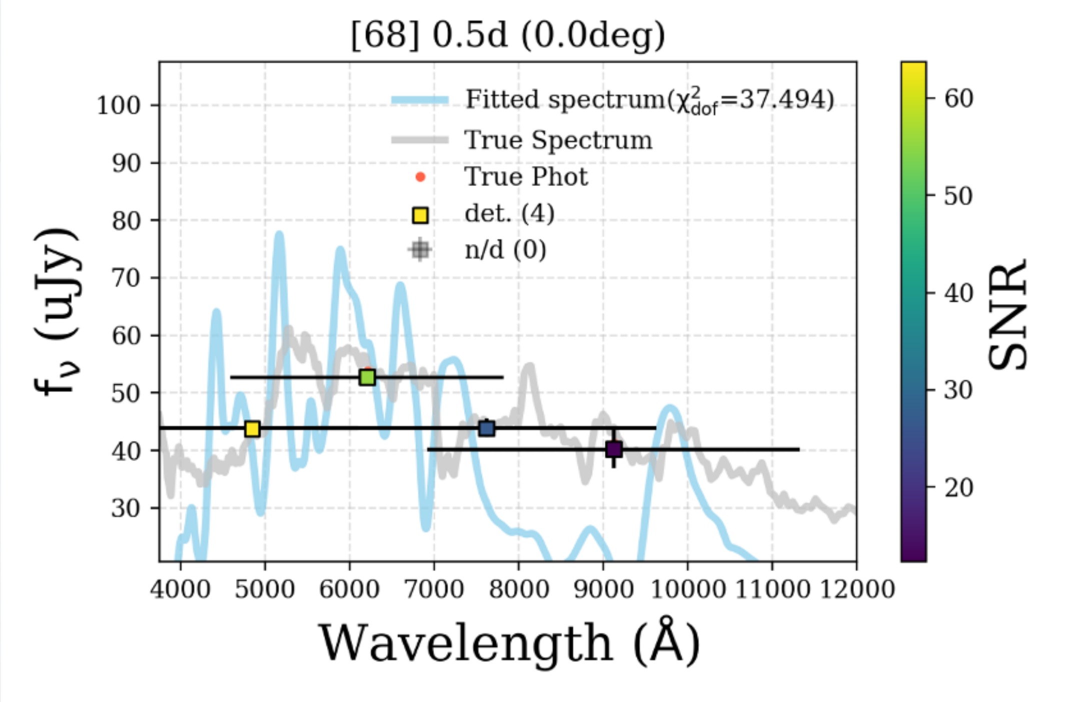
Thakur et al. 2019

What do we need?

1. Wide Field of View
    - Need to cover as much area as possible.
2. Flexible Operation
    - Need to start follow-up as soon as possible.
3. Real Time Analysis
    - Need to distinguish real and bogus objects.
    - Need to keep covering localization areas while analyzing obtained data.
4. Low Resolution Spectroscopy
    - Need to classify among transients.



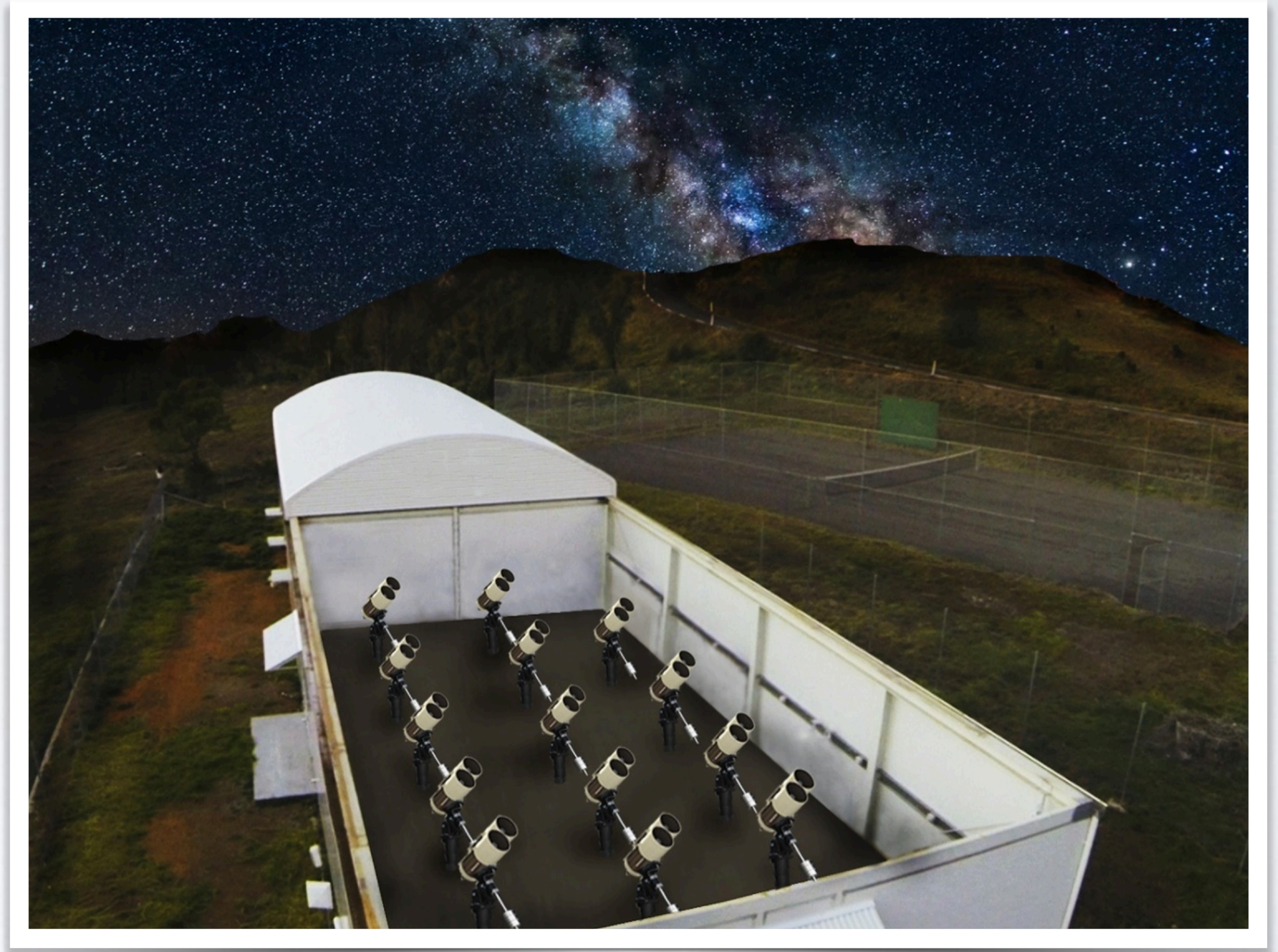




Courtesy of Gregory S. H. Paek

7-Dimensional Telescope in a Nutshell

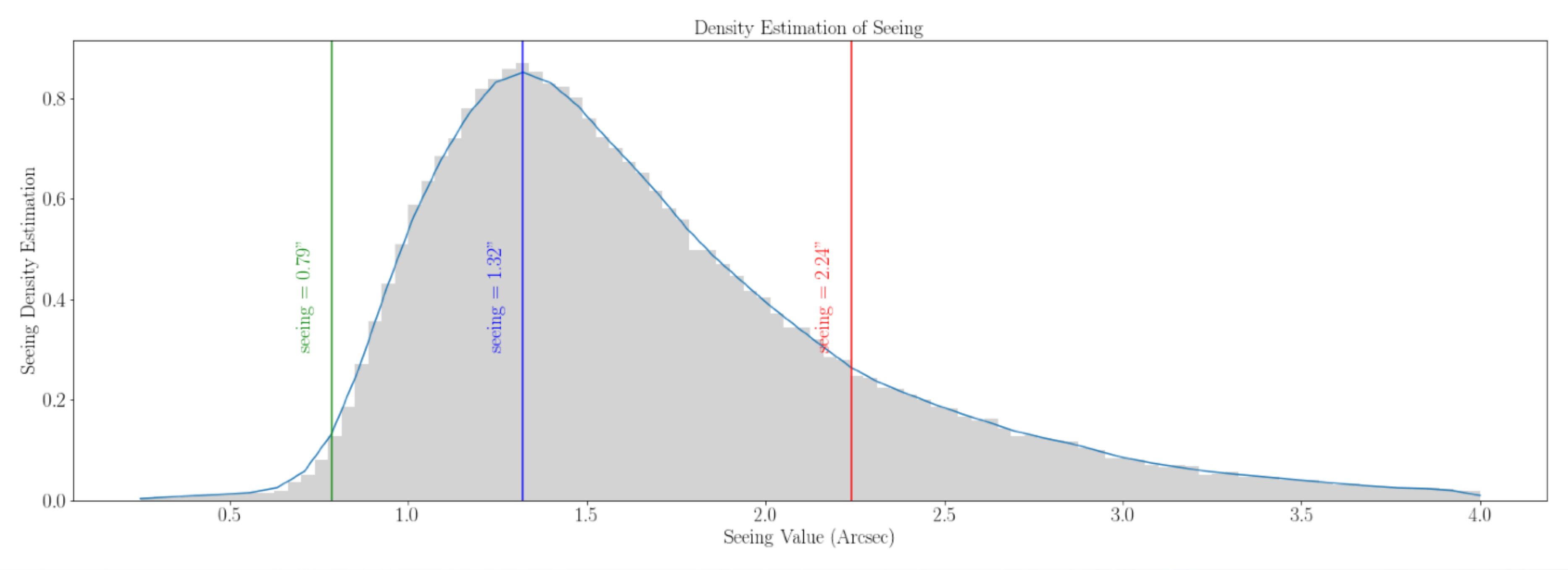
- *7DT is a multi-telescope system of 20 small telescopes with a large FoV and medium-band filters.*
- *7DT will carry out a wide-field survey with high cadence which will produce IFU-style data.*
- *7DT will be located at Observatorio El Sauce situated in the Río Hutardo Valley in Chile.*
- *Science operation will be done remotely. We are developing softwares for fully automated operation, including scheduling, and data reduction pipeline.*



A conceptual view of 7DT (Image Credit : Dr. Hyun, M.)

Site

- *7DT will be installed at Observatorio El Sauce which is located in the Río Hutardo Valley in Chile. Currently, SNU RASA36 is deployed at Observatorio El Sauce.*
- *Science operation will be done remotely, but will be assisted by a hosting company, ObsTech which will provides technical support and infrastructure.*
- *altitude : 1700 m*
- *more than 300 clear nights (up to 320 nights)*
- *the median seeing : 1.3″*
- *the mean sky brightness : ~22 mag/″*



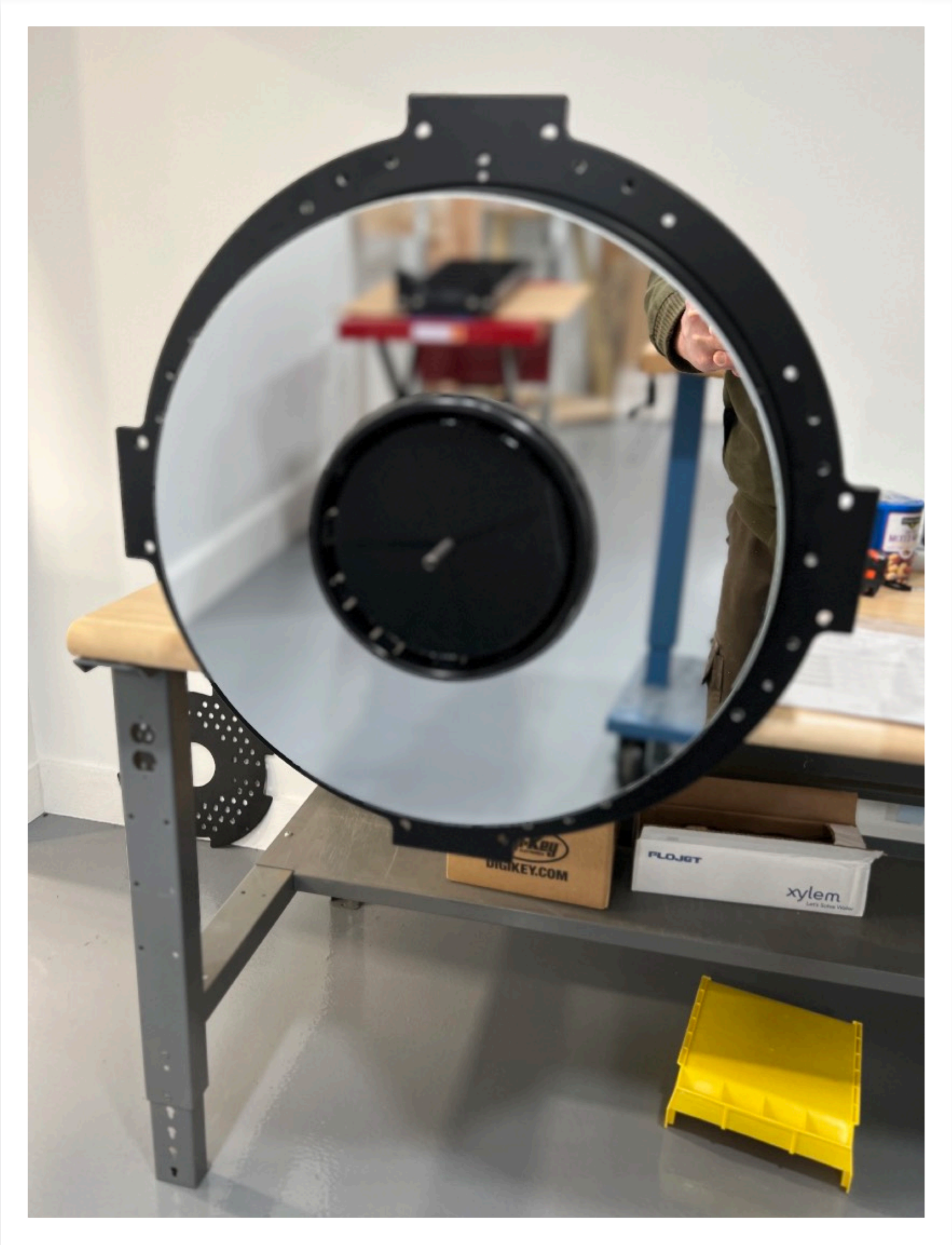
Site

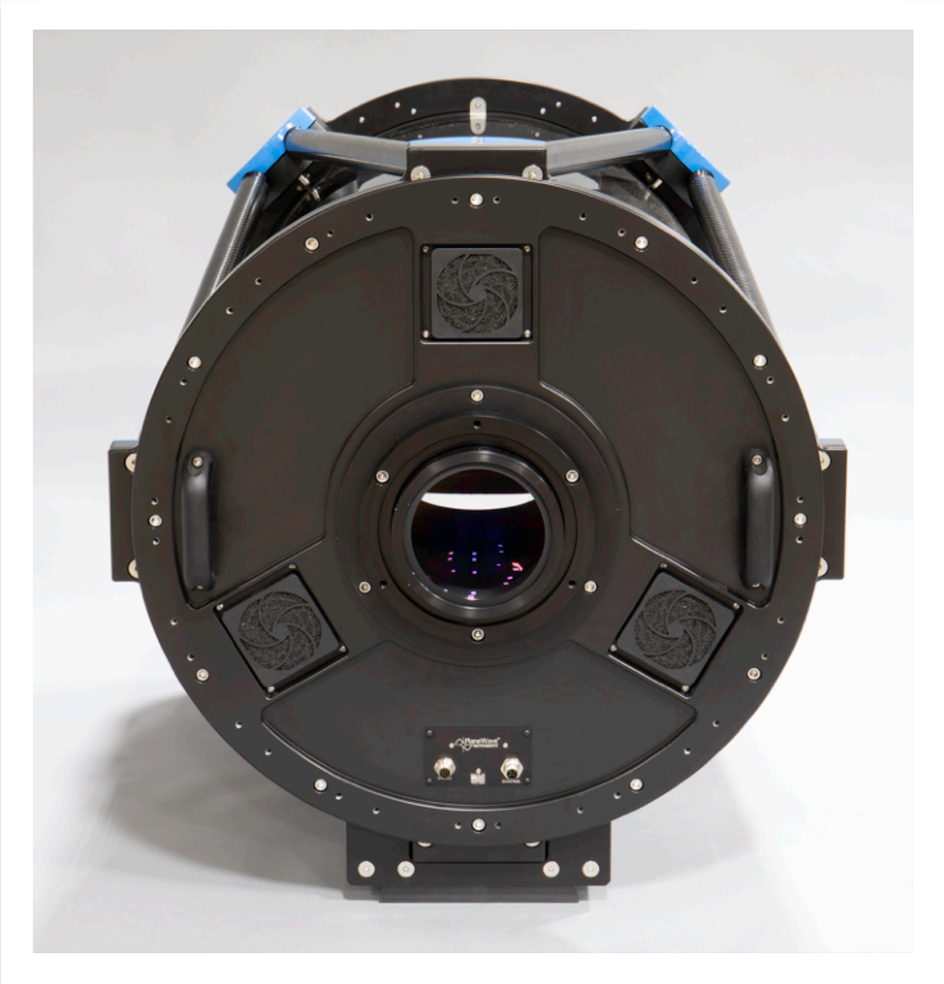
- *The structure is scheduled to be complete by the end of this month.*

Credit : V. Suc @ ObsTech

Instrument : Telescope

- Delta-Rho 500 by PlaneWave Instruments
  1. Primary mirror diameter : 508 mm
  2. Effective focal ratio : f/3.0
  3. Field of view : 2.62 degree
  4. Optical field of view : 70 mm diameter
  5. Back focal length : 232.8 mm
  6. Weight : 75 kg
  7. Central obstruction : 60% by diameter





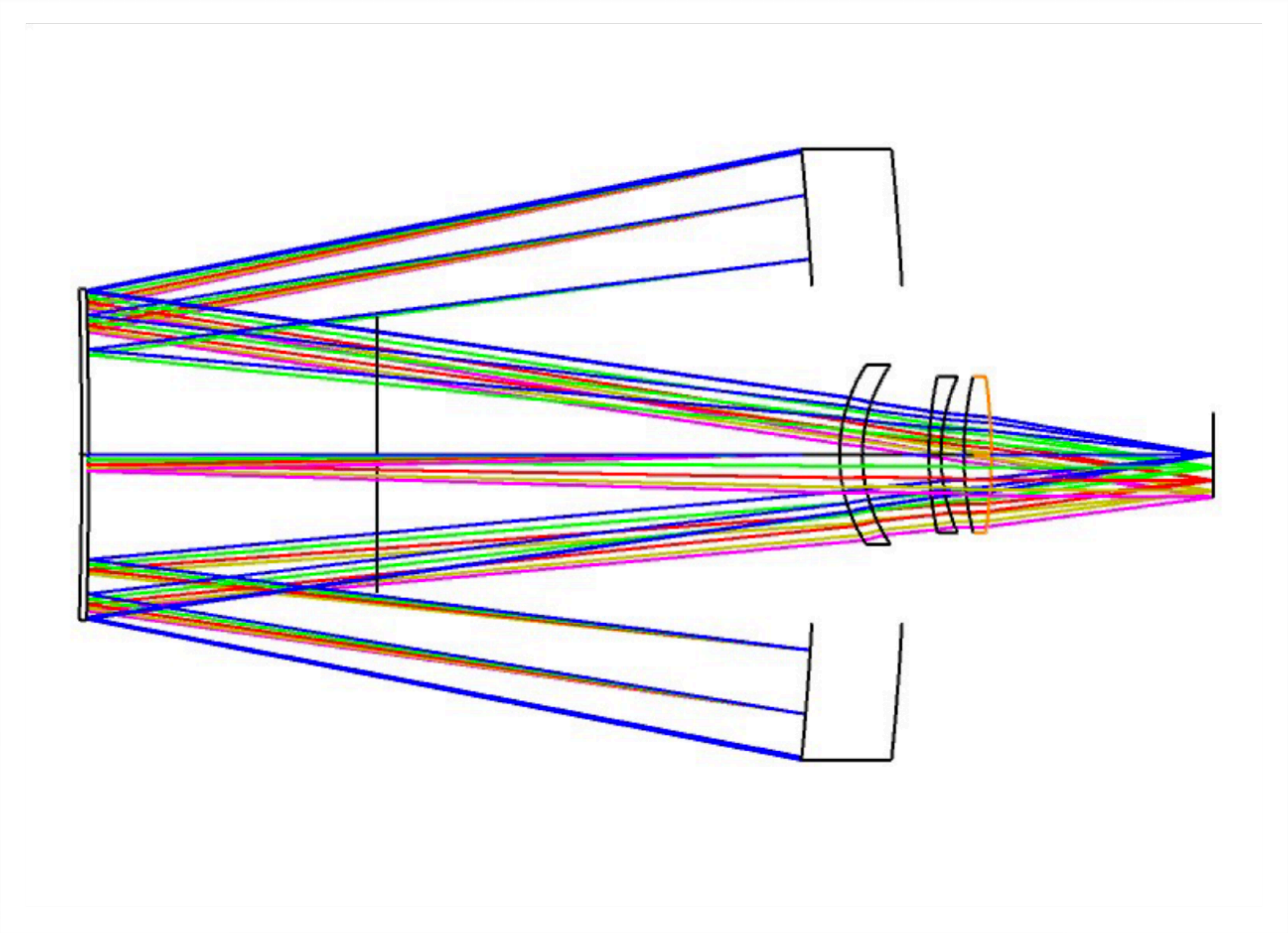
Instrument : Telescope

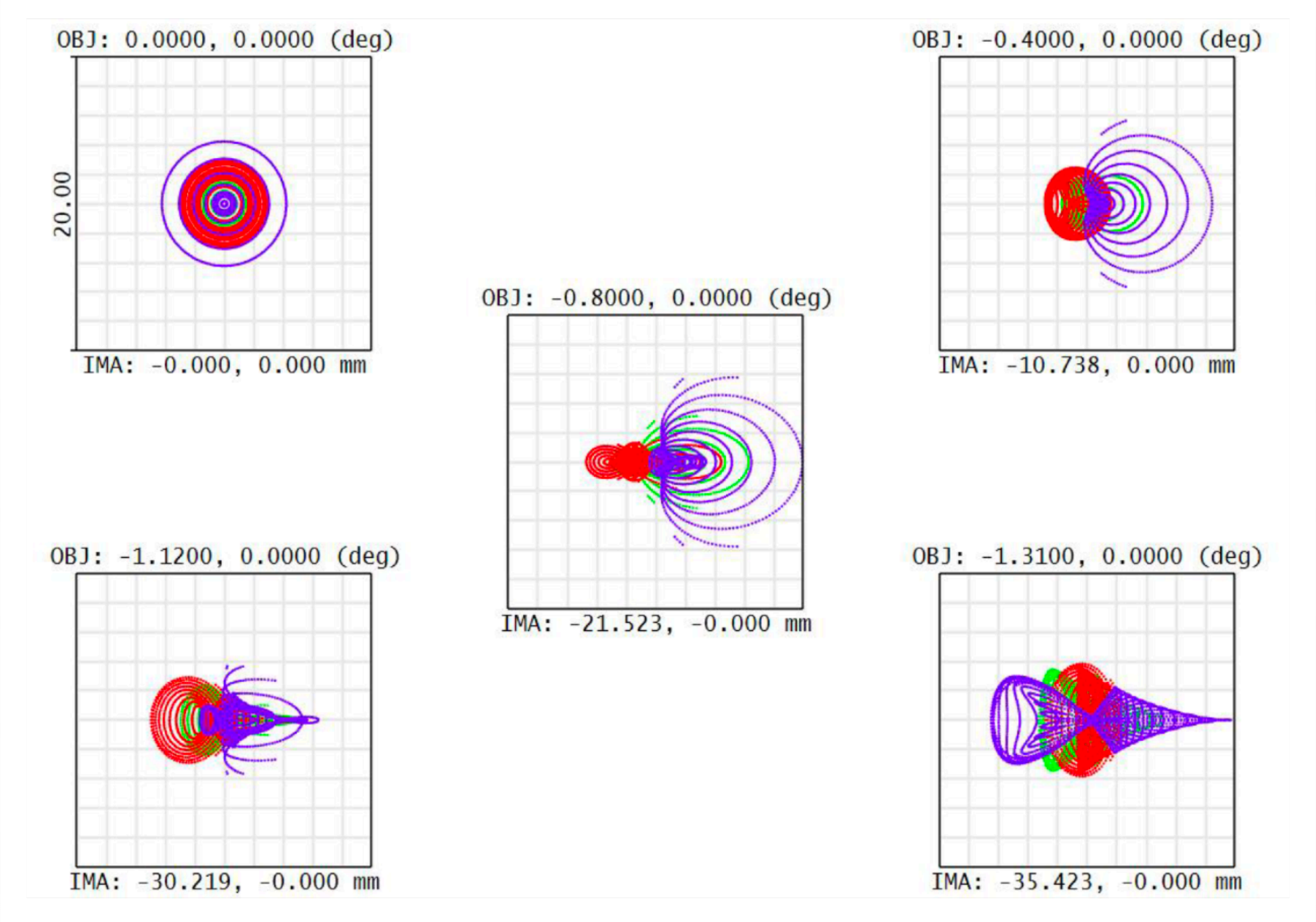
- *Delta-Rho 500 by PlaneWave Instruments*

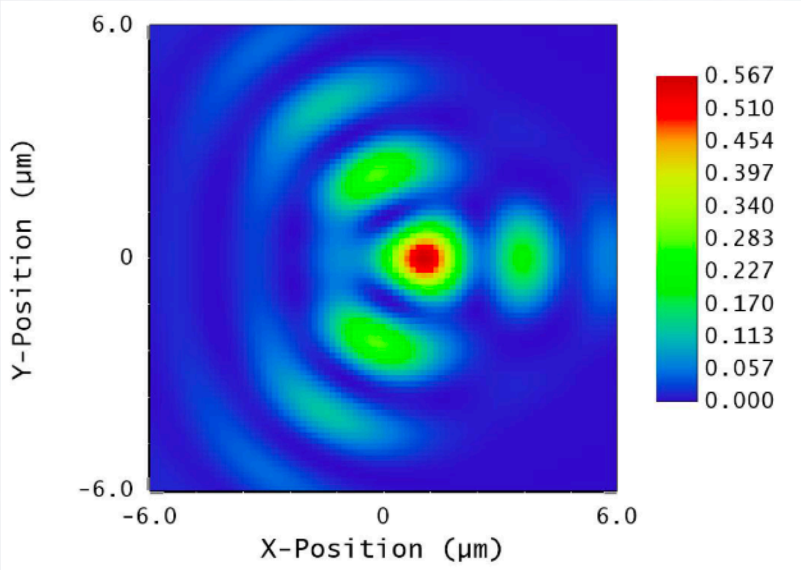
  6. *Optical performance*

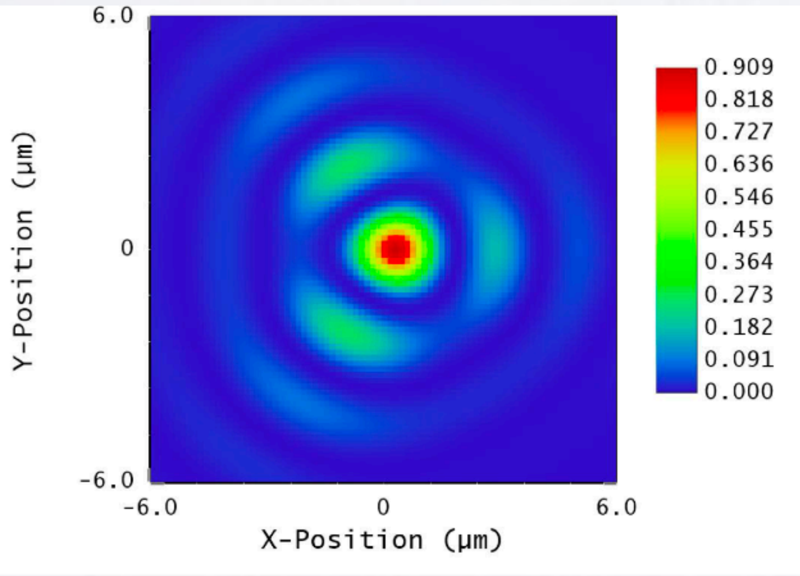
     - *4 micron RMS on-axis*
     - *4.6 micron RMS at 22 mm off-axis*
     - *6.4 micron RMS at 30 mm off-axis*

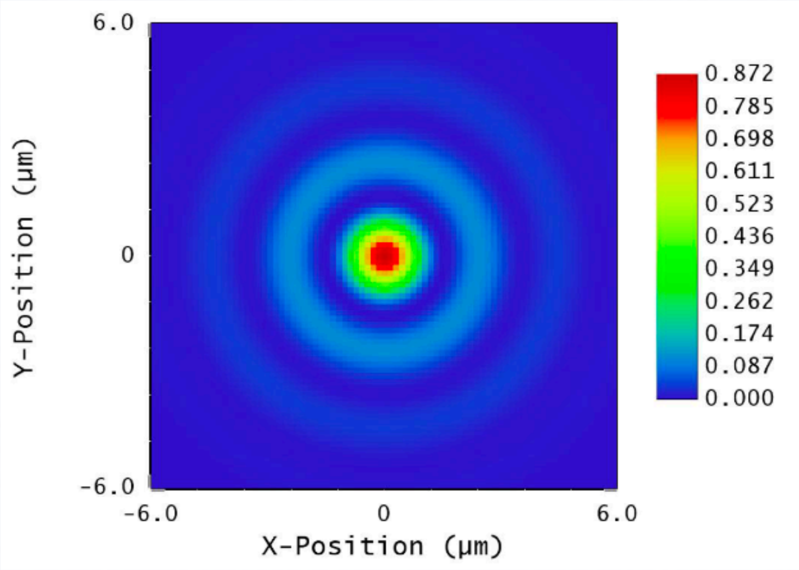
- *20 × DR500 is an equivalent of 2.3-m telescope with focal ratio of 0.67.*









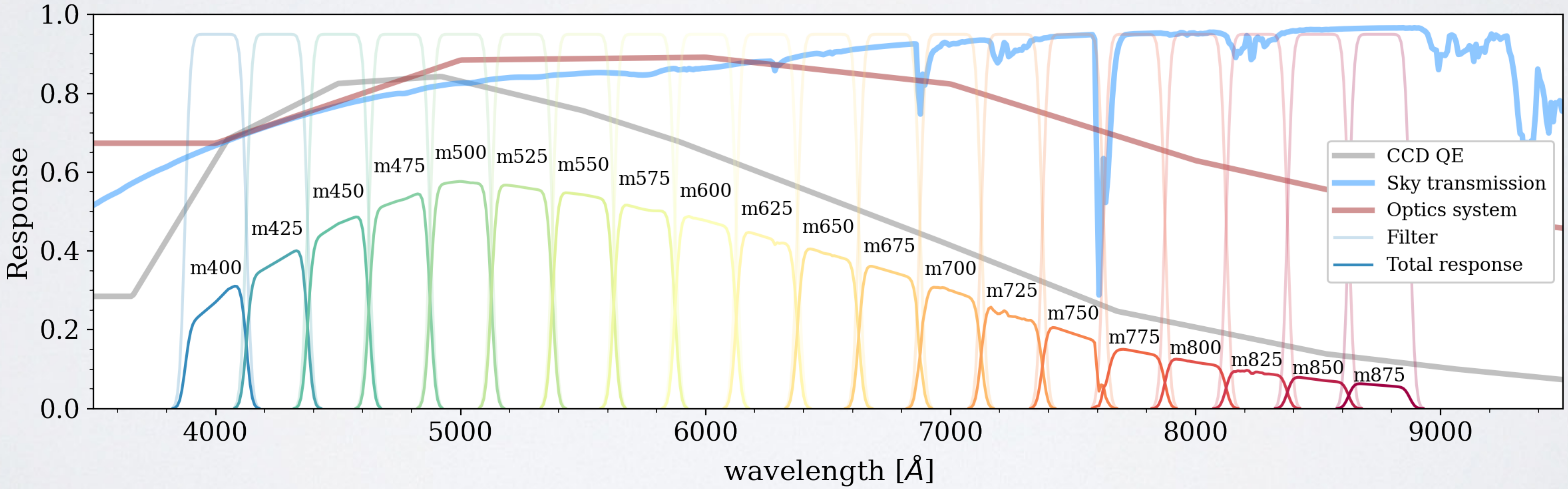


Instrument : Camera

- *C3 61000 Pro by Moravian*
  1. *Sony IMX455 CMOS Sensor*
  2. *9576 x 6388 pixels of 3.76 micron pixel size*
  3. *36 mm x 24 mm (~ 43 mm diagonal)*
  4. *1.4 degree x 0.9 degree on sky*
  5. *All 6 cameras arrived in Chile.*
  6. *We will order 4 more cameras for Batch 2.*
  7. *Upgrade in future : C5A-150M using IMX411 (53.42 mm x 40 mm, 66.7 mm diagonal) is released.*

Instrument : Filter

- *Filter*
  1. *Medium-band filters : Off-the-Shelf filters from Edmund Optics*
     - *20 Medium-band Filters with FWHM of 25nm from 400 nm to 900 nm*
  2. *Sloan Broad-band u-, g-, r-, i-, and z-bands : Off-the-Shelf filters from Chroma Technology*
  3. *Filter transmissivities are being measured.*



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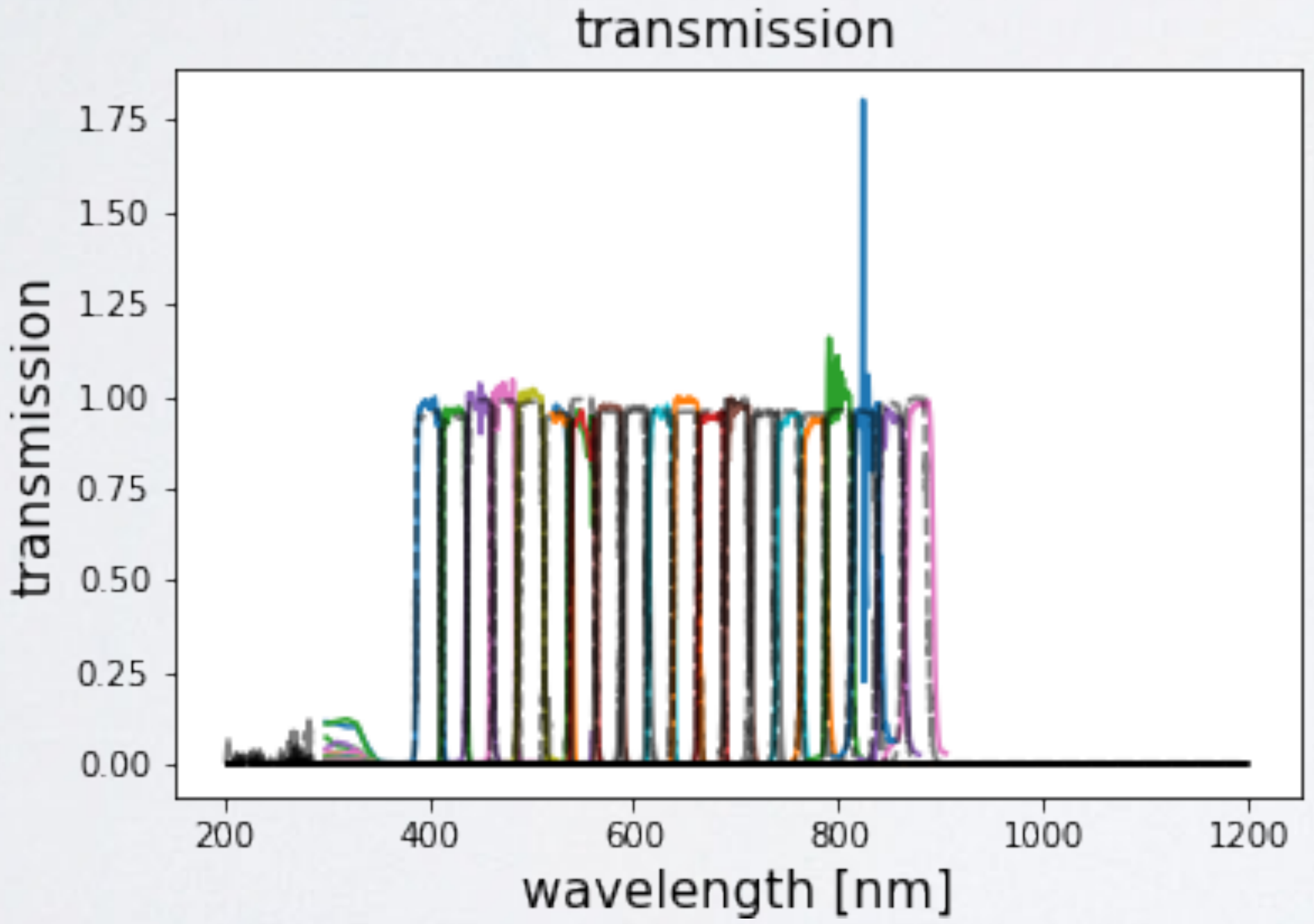
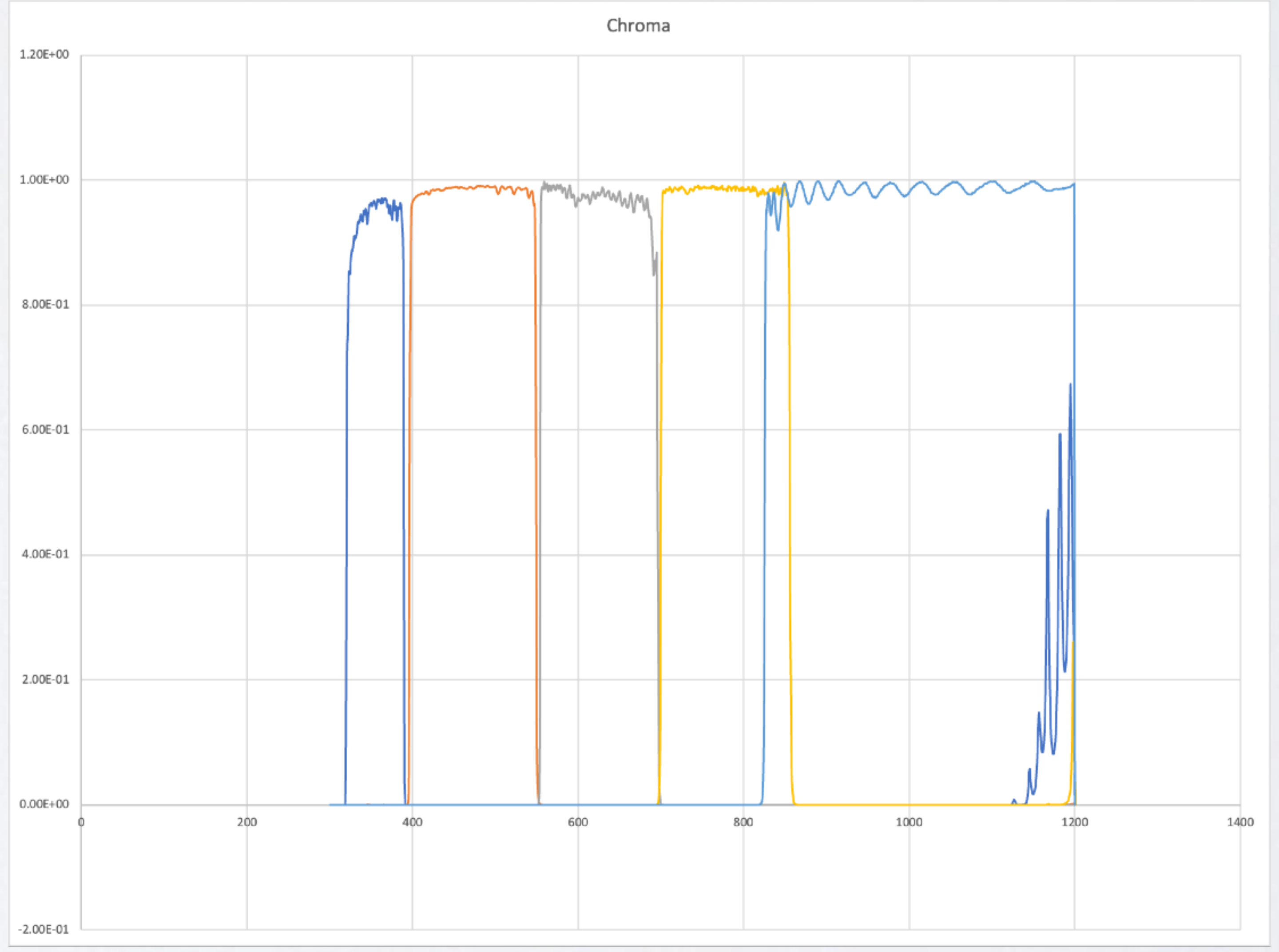
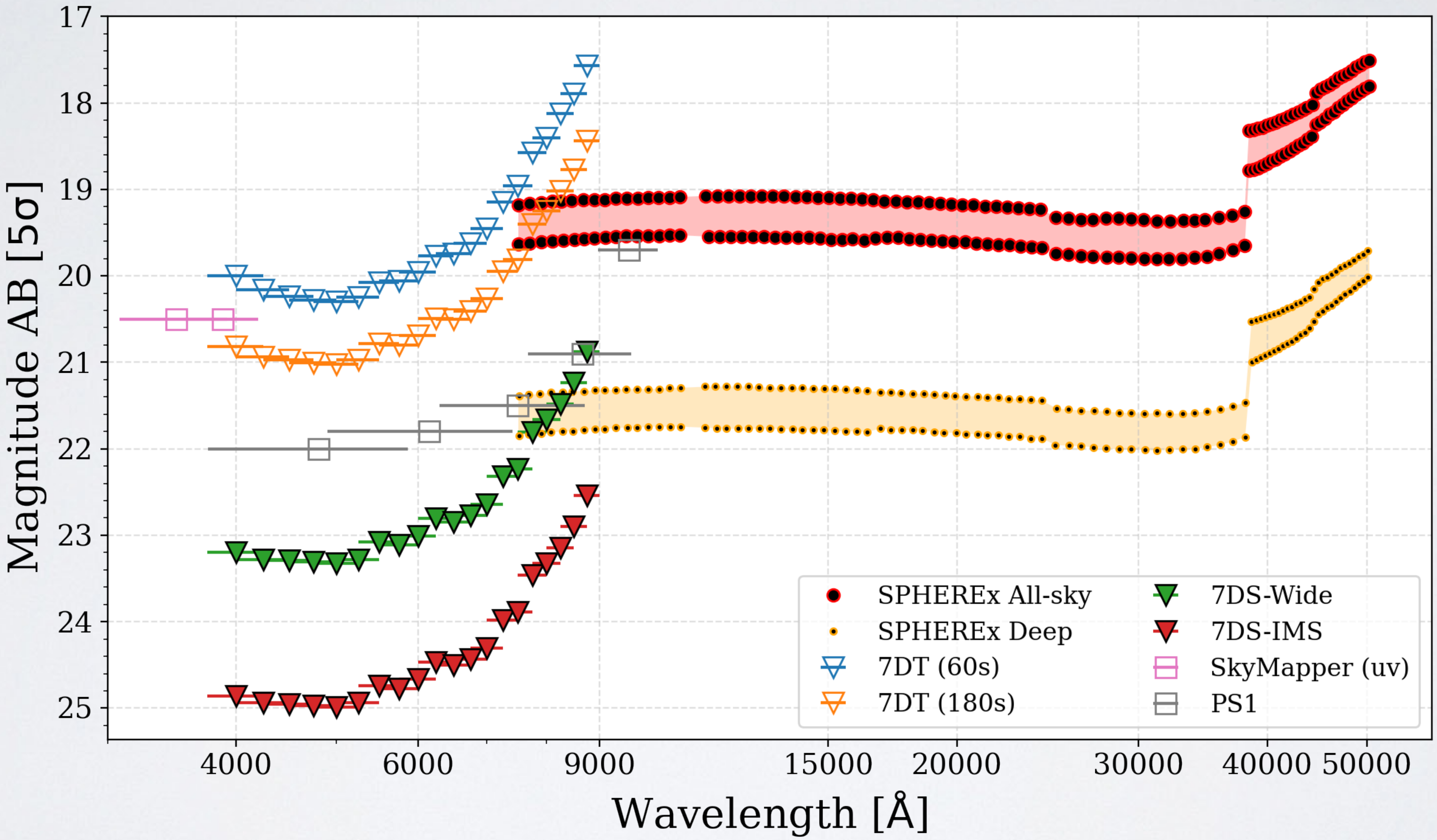




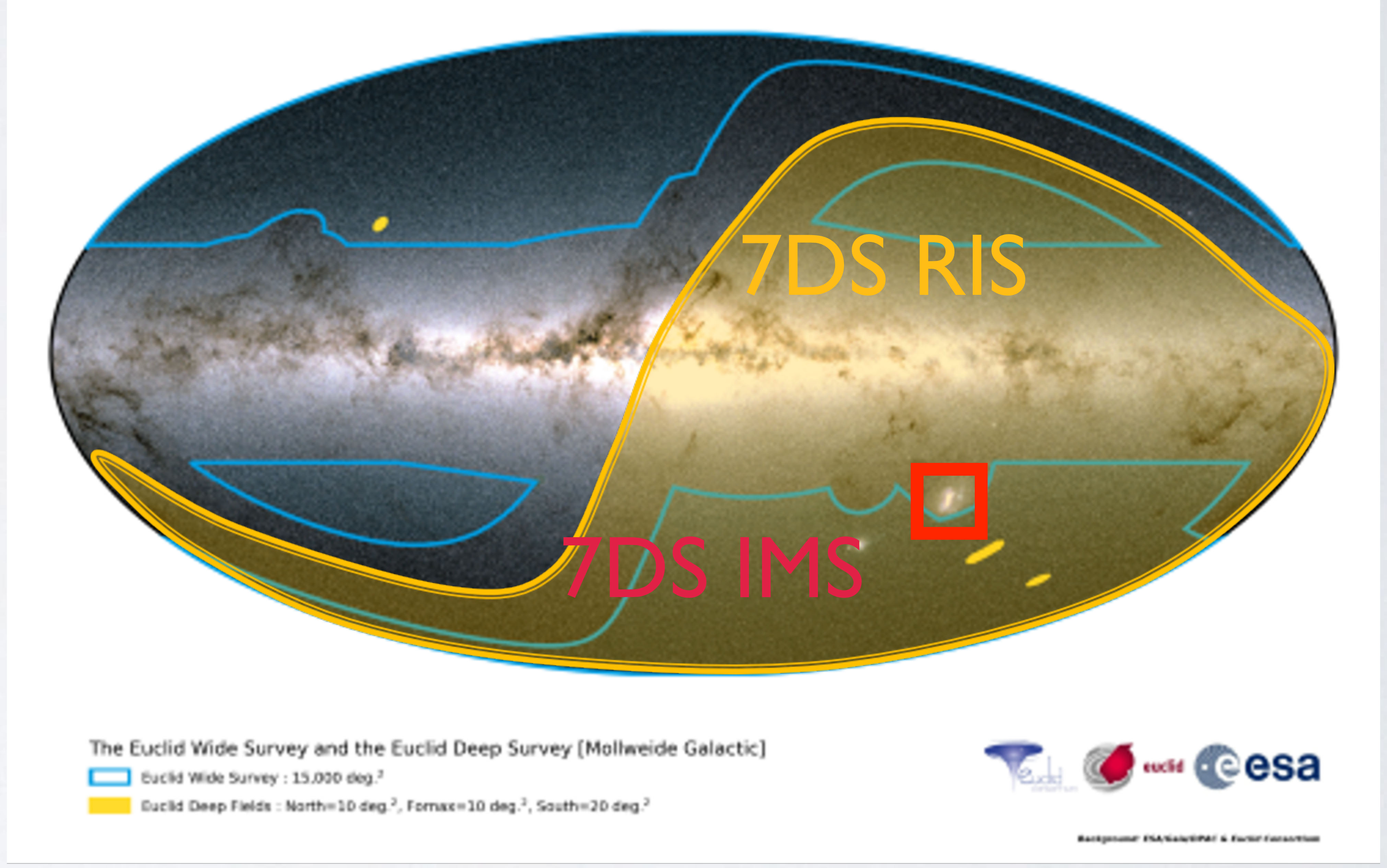
Sensitivity



Survey Strategy

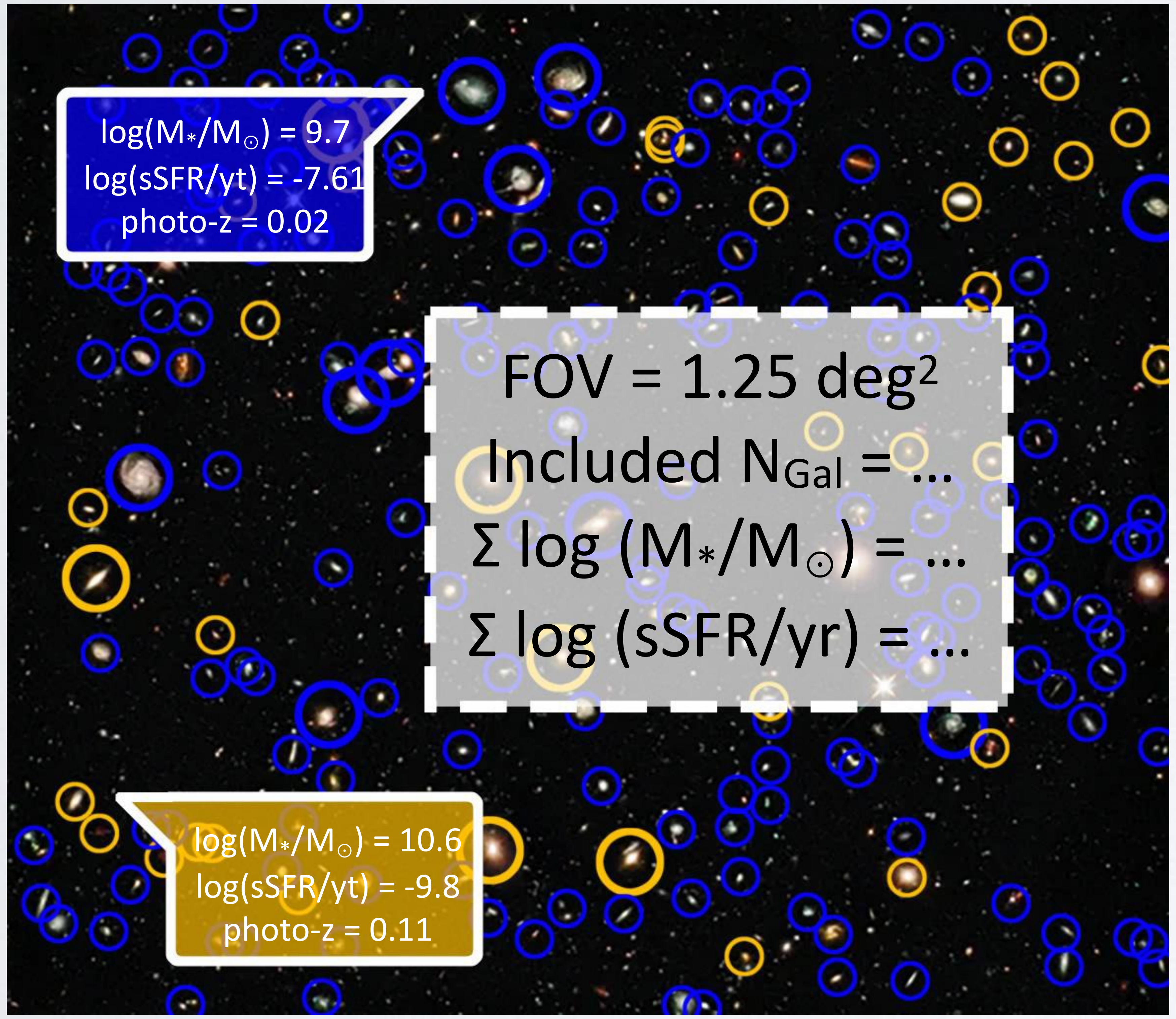
Surveys	Survey Area (deg^2)	Cadence	Depth (5yr)	Exposure Time per epoch per filter
Reference Imaging Survey	20,000	-	20 mag	3 min
Wide-field Survey (WFS)	1,620	14 days	23.3 mag	3 min
Intensive Monitoring Survey (IMS)	12.6	1 day	25.1 mag	3 min

The survey depths are estimated assuming 1.5″ seeing and 70% survey efficiency.



GW Follow-Up & Monitoring Survey Strategy

- *There are two approaches for scanning the sky localization of GW with telescopes:*
  1. *Tiling observation*
  2. *Galaxy-targeting observation*



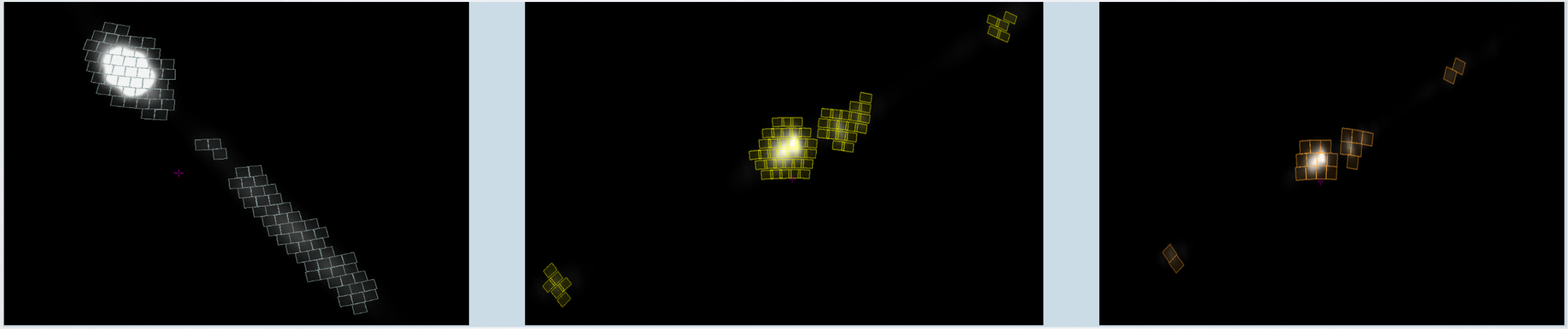
Q | Which field should be observed preferentially to discover a GW counterpart?

A | Find the galactic environment of BNS merger events using short GRB host galaxies.

GW Follow-Up & Monitoring Survey Strategy

1. Tiling Observation

- *Multi-order coverage (MOC) maps are generated based on FoV.*
- *Then, tiles are ranked based on GW probability which is released by LIGO group.*

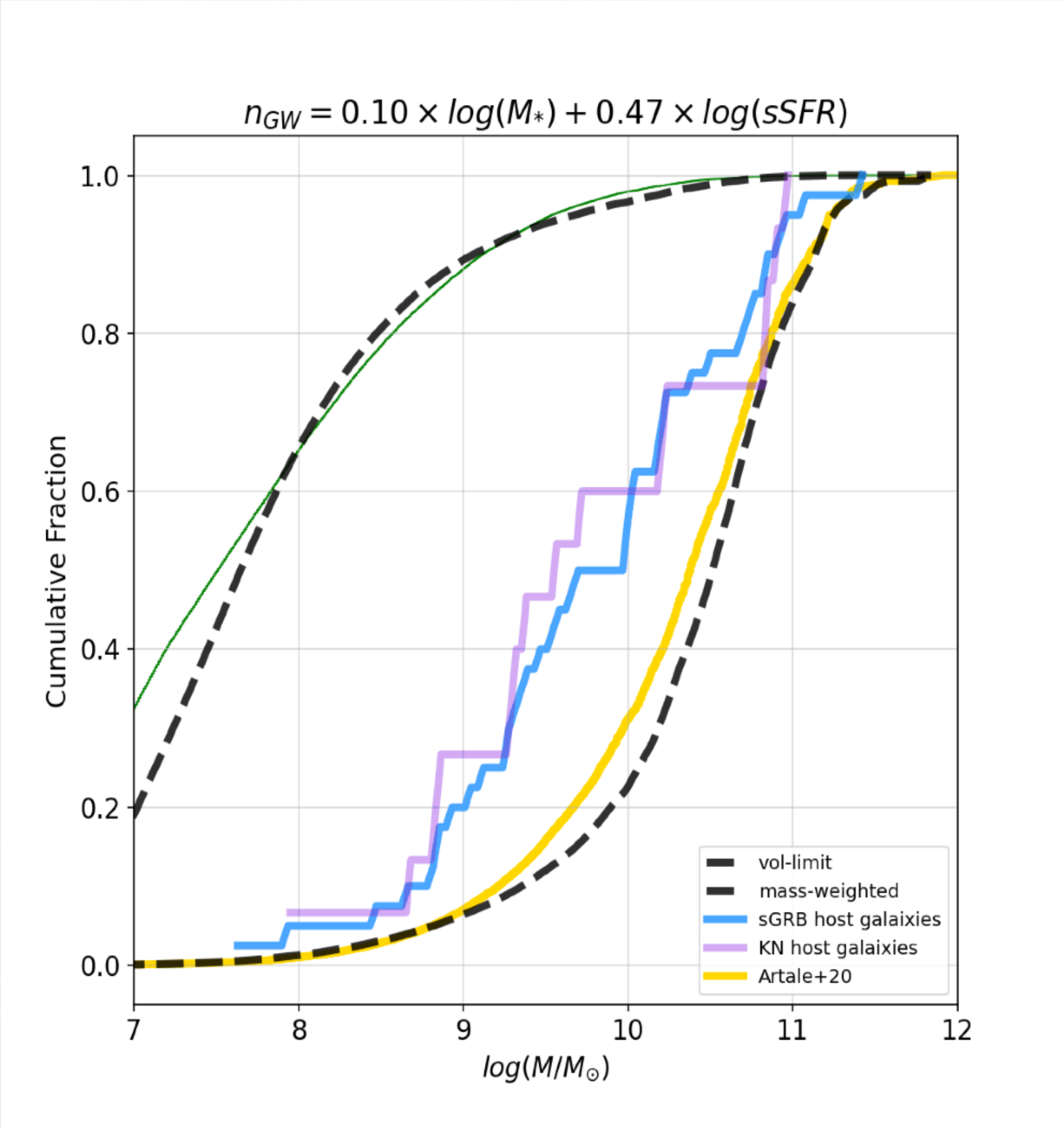


Elahe Khalouei et al. (*in prep*)

GW Follow-Up & Monitoring Survey Strategy

2. Galaxy-targeting Observation

- *Within localization areas for GW events, we identify host galaxy candidates.*
- *Host galaxies are ranked based on BNS merger rate.*



If BNS rate Stellar mass?

⇒ sGRB would follow the mass-weighted distribution

⇒ Emprically, not true.

Then, which "weight" reproduce the observed data?

⇒ the weight would be the proxy of merger rate

⇒ $log(N_{BNS}/Gyr) = 0.82 \times log(M_*) + 0.47 \times log(sSFR) + C$

Mankeun Jeong et al. (*in prep*)

Software Development

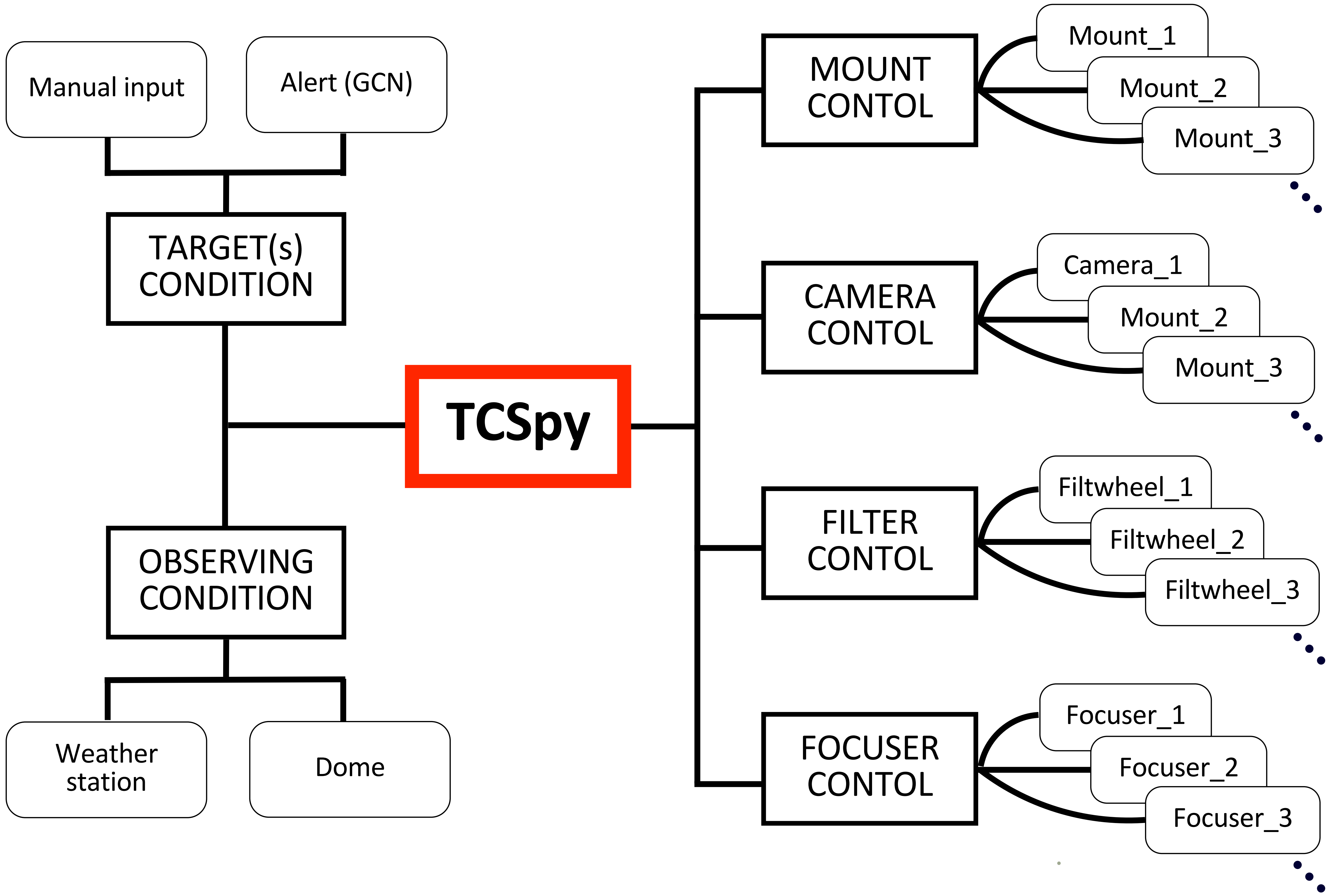
1. *Main Controller/Scheduler :*
    - *Is a backbone frame to control/communicate TCSs of telescopes.*
    - *Needs to accommodate various ToO triggers.*
    - *We are developing TCS + scheduler based on Alpaca Pi suite.*
2. *Data Reduction Pipeline*
    - *Should provide data products for real-time analysis.*
    - *Is expected to carry out transient object classification to trigger ToO observation.*
3. *Data Catalog and Analysis Tool*
    - *Produces open-to-public database (images, and catalogs).*
    - *Provides photometry, or spectra for objects of interest.*

Software Development

Courtesy of Hyunho Choi

TCSpy : Telescope control system for 7DT

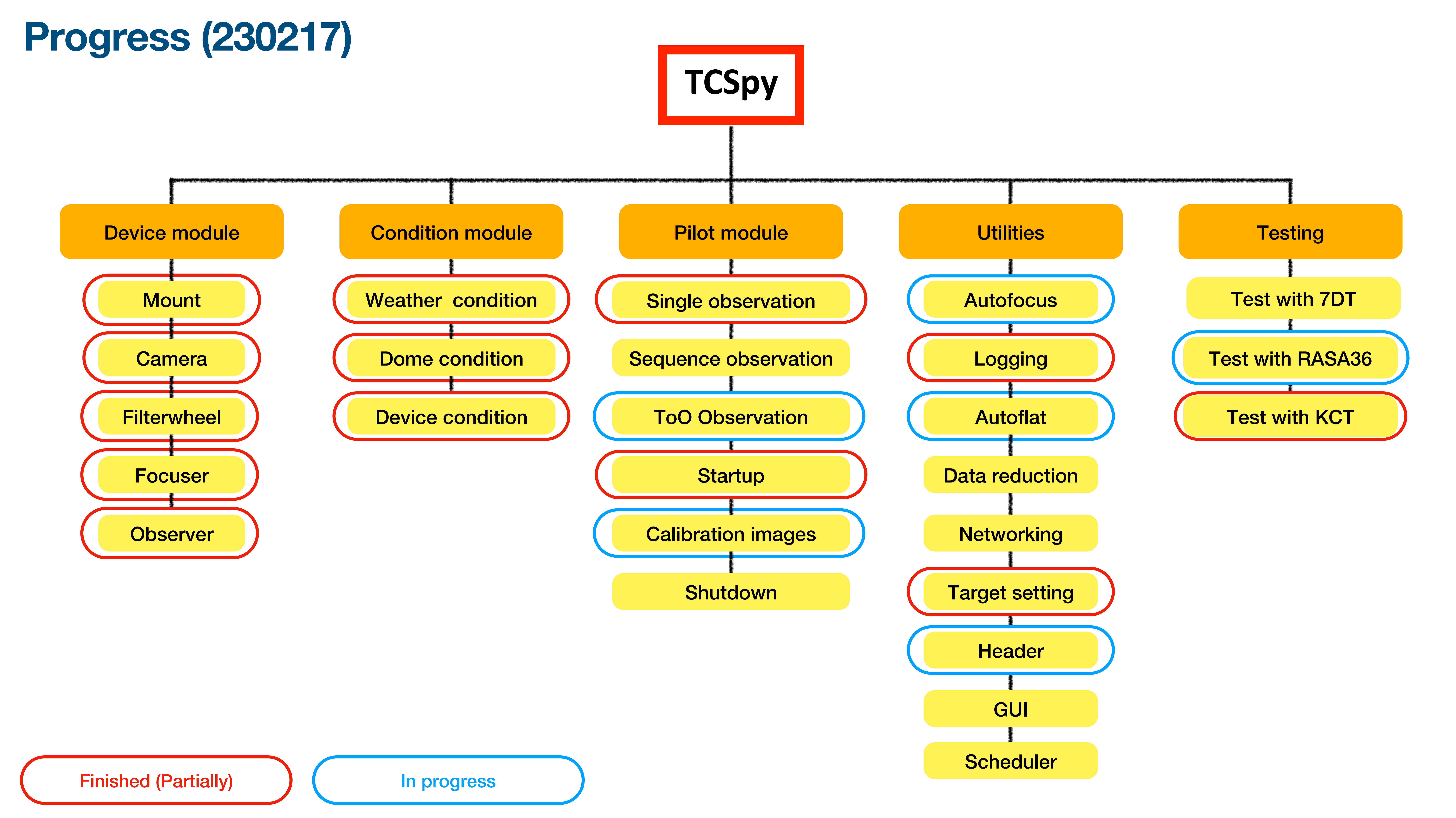
- TCSpy **operates multiple telescopes** with TCP/IP network
- TCSpy **synchronizes** multiple telescopes
- TCSpy will enable
  1. Fast follow-up observation
  2. Focused observation
  3. Tiled observation (large FOV)



Network hosted communication

Software Development

Courtesy of Hyunho Choi



Data Storage and Processing Servers

1. *Data Processing Servers*
    - *Expected Data Inflow Rate : ~1.5 TB per night*
    - *We are expecting to data generation rate of 1.5 PB per year including processed data.*
    - *Up to 12 PB data storage will downlink data via KREONET utilizing 10Gbps data transfer rate.*
    - *1PB storage of NFS will be ready for O4 run, and we will increment the storage by the end of 2024.*
2. *Data Processing Servers*
    - *Needs for either multiprocessing, or multithreading computing servers to expedite data reduction process for real-time data analysis*
    - *We will purchase a GPU-based data processing server soon.*

Science beyond Gravitational-wave Astronomy

Subject	Now	7DS	Scientific Value
Time-series Spectra of Quasars	~1000	>30,000	Complete Census of SMBH AGN Variability
RM Measurement of SMBH Mass	~100	10,000	Growth History of SMBHs
Velocity Maps of Galaxies	~10,000	50,000,000	Galaxy Evolution
Galaxy Clusters	100,000	100,000	Cosmology, Galaxy Evolution
Early Spectra of SNe	~10	>1,000	Physical Mechanism of SNe
Time-series Spectra of Stellar Objects	1,000,000	10^9	Stellar Evolution
Time-series Spectra of Small Bodies of the Solar System	100	>10,000	Origin of the Solar System, Census of Asteroids/Comets

Timeline

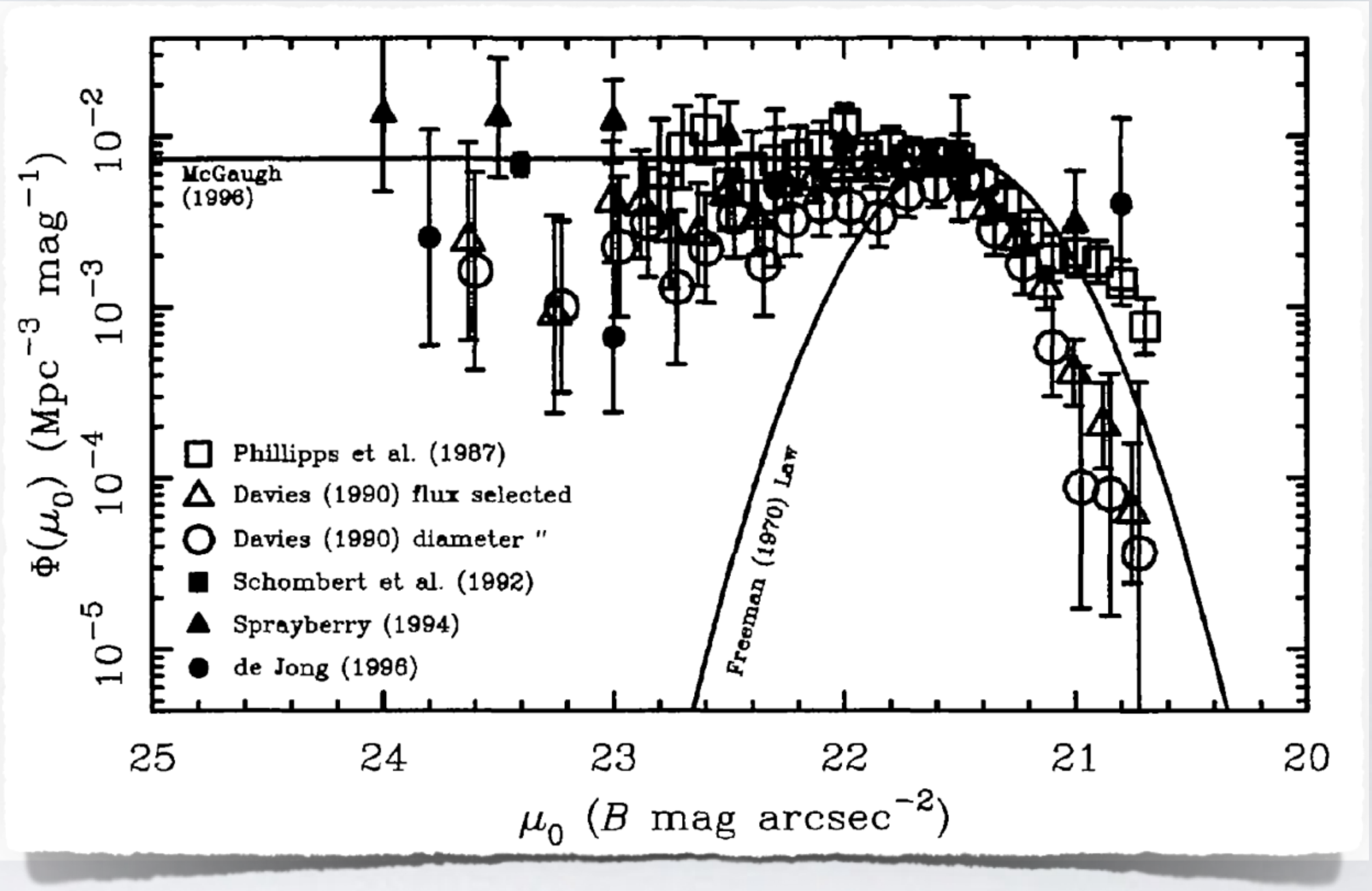
1. *Year 3 : 2023*
    - *March : Completion of Unit #1 and #2*
    - *May ~ : GW ToO during LVK O4*
    - *June : Completion of Unit #3 ~ #10*
    - *December : Completion ?*
2. *Year 4, 5 : 2024 ~ 2025*
    - *Completion of Data Analysis System*
    - *Regular 7DT Operation (7DS + GW ToO)*

Summary on 7DT/7DS

- *7DT provides a wide-field, multi-object spectroscopic capability with high cadence.*
  - *1.4 by 0.9 square degree FoV*
  - *40 medium-band (25 nm) filters*
  - *very fast optics : f/3.0*
- *7DS will carry out 3 layers of survey with various area coverages and depths:*
  - *Reference Imaging Survey, Wide-Field Survey, and Intensive Monitoring Survey.*
  - *pilot operation starts in early 2023; full operation is expected in early 2024.*
- *7DS will benefit various projects beyond GW E&M counterpart identification, including, but not limited to the solar system small body, stellar evolution, galaxy evolution, and cosmology.*
- *The synergy with the NIR coverage of SPHEREx will significantly enhance the scientific value of 7DS.*

Formation of Late-type Galaxies

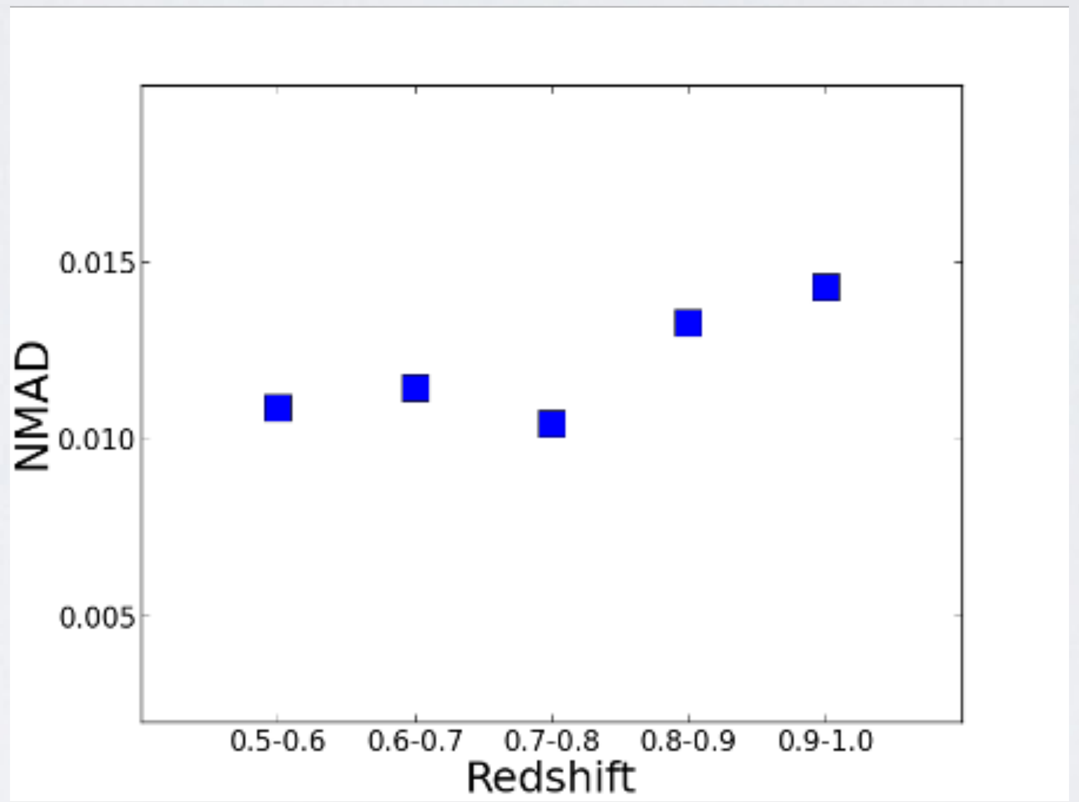
- *The fundamental properties of galactic disks, such as central surface density, and disk scale length, mush reflect the physical conditions of their formation.*
- *Tidal Torque Theory within the ΛCDM paradigm predicts LSBGs to be located in less denser regimes.*
- *The difference in the specific angular momentum of host dark matter halos result in different surface densities of disks.*
- *Does LSBGs have systemically large specific angular momenta, and reside in low density environments?*

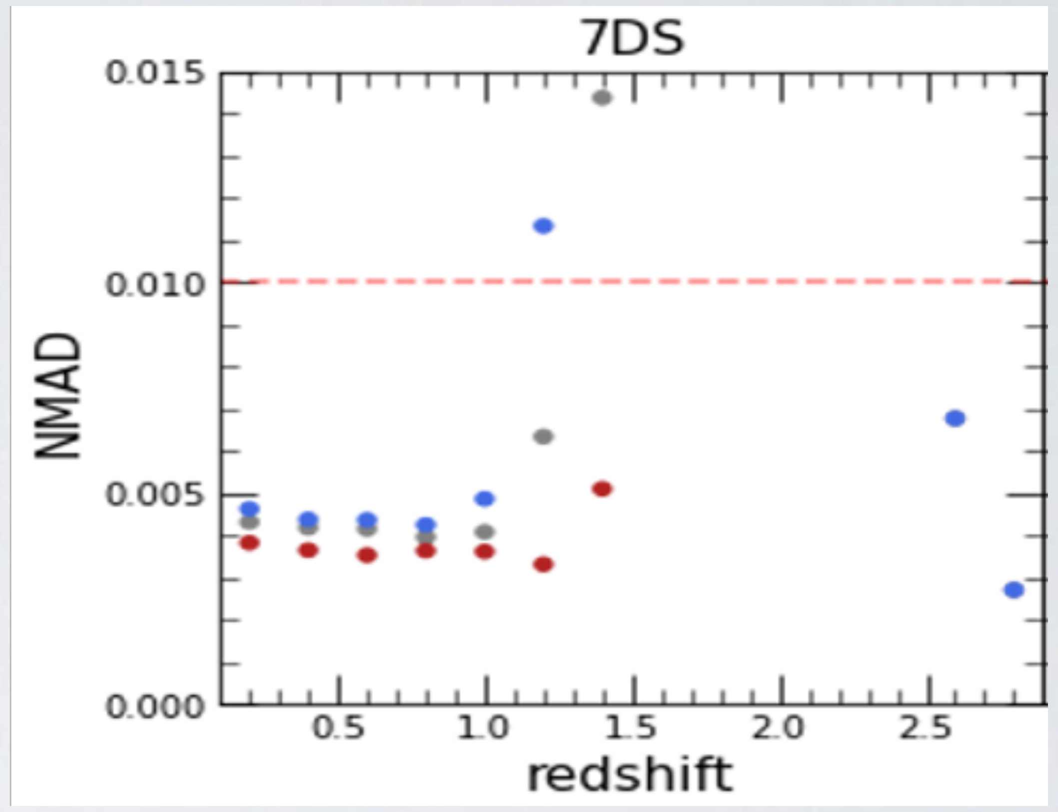


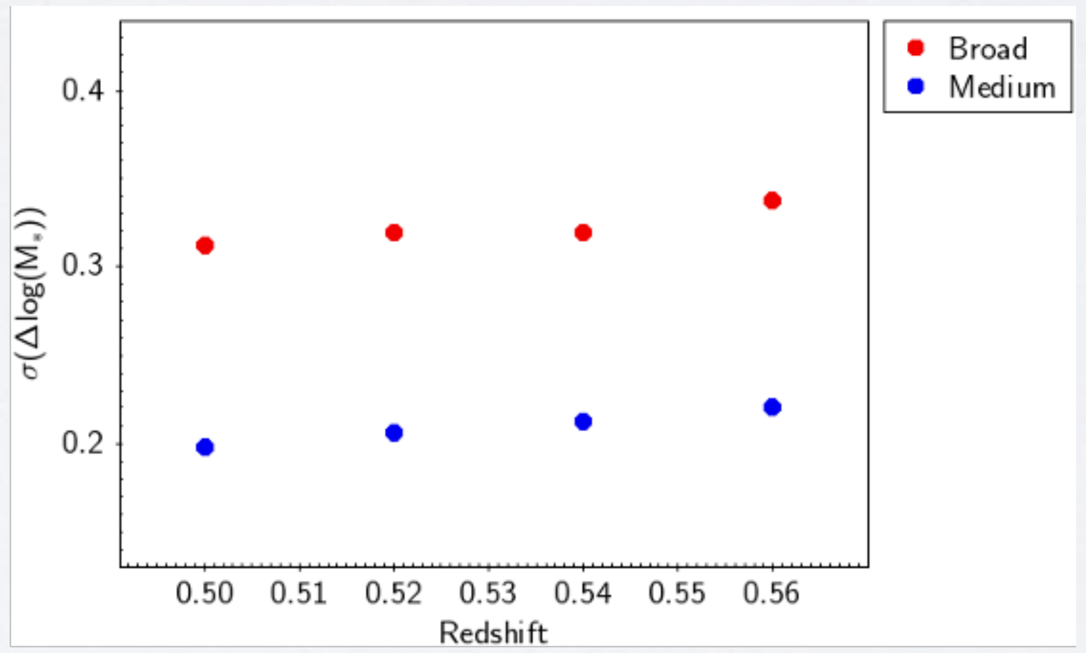
Bothun et al. (1997)

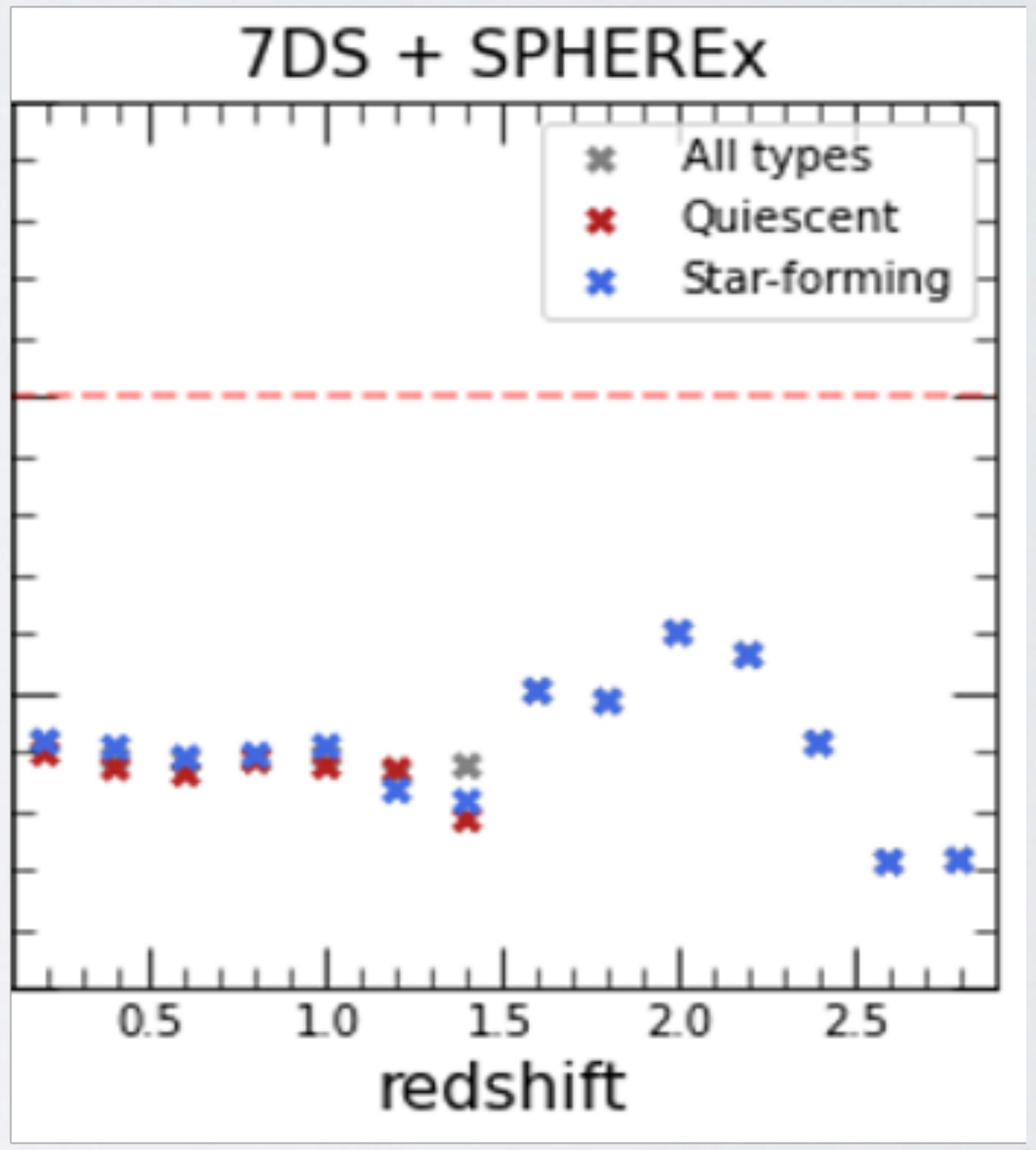
Phototometric Redshift and SED Fitting with 7DS

1. *Photo-z Error Estimation*
   - *With 20 bands : < 1% up to z~0.8*
   - *With 40 bands :< 0.5 % up to z~1.0*
2. *SED Fitting*
   - *Stellar Mass: reduced uncertainty (0.3% to 0.2%)*
   - *SFR: reduced bias*
   - *Age: reduced bias & uncertainty*
3. *7DS+SPHEREx : reduced photo-z uncertainty at z > 1*



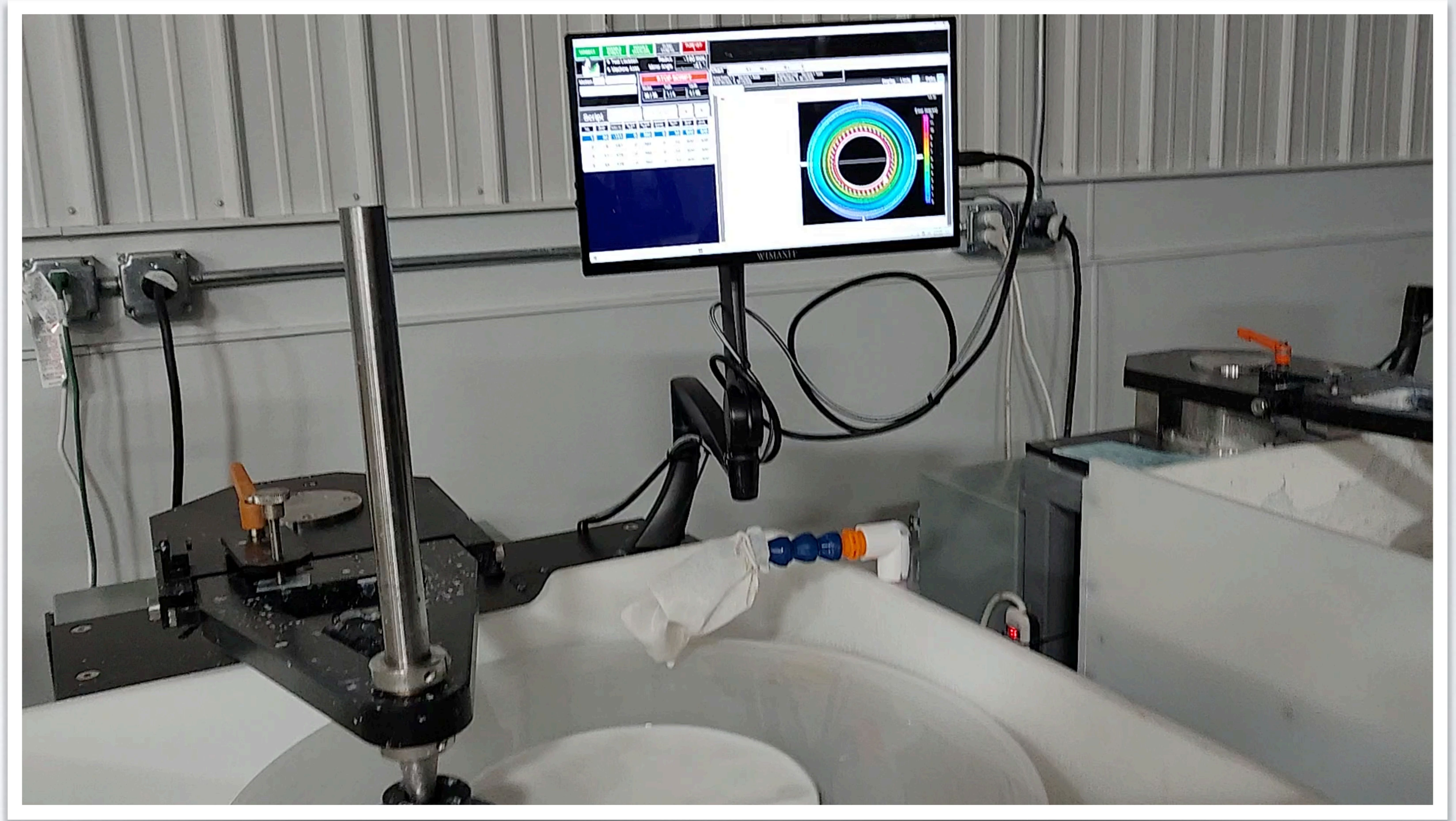




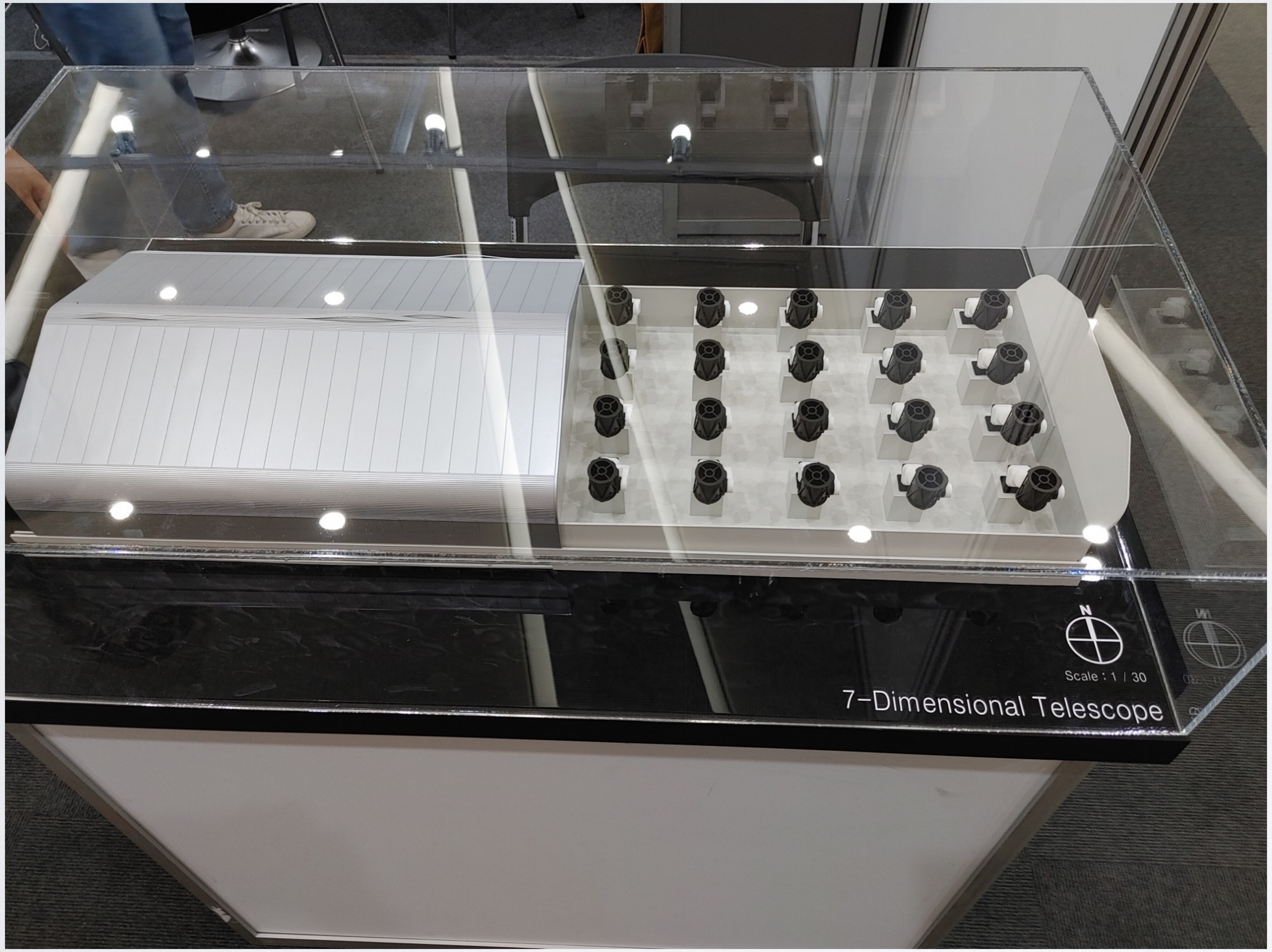


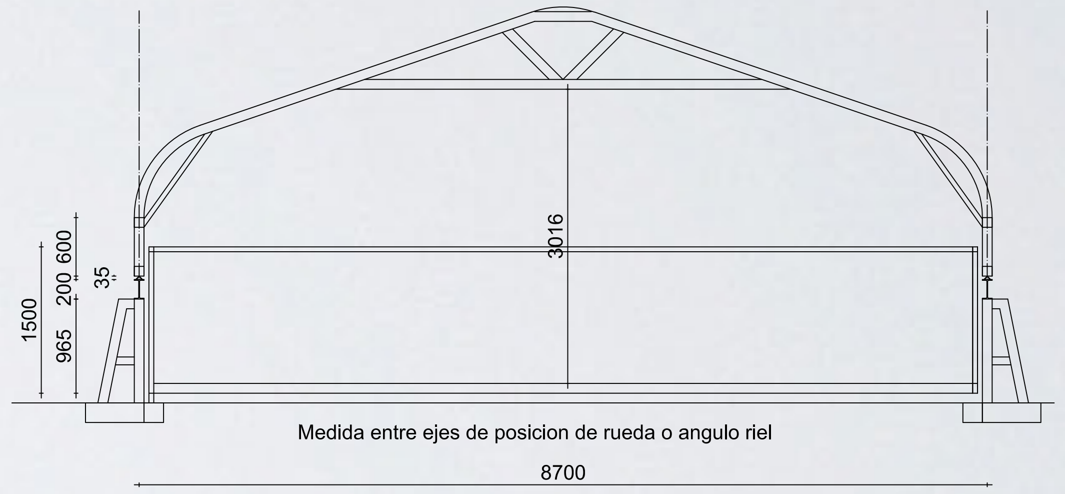
Courtesy of Eunhee Ko and S.-K. Lee

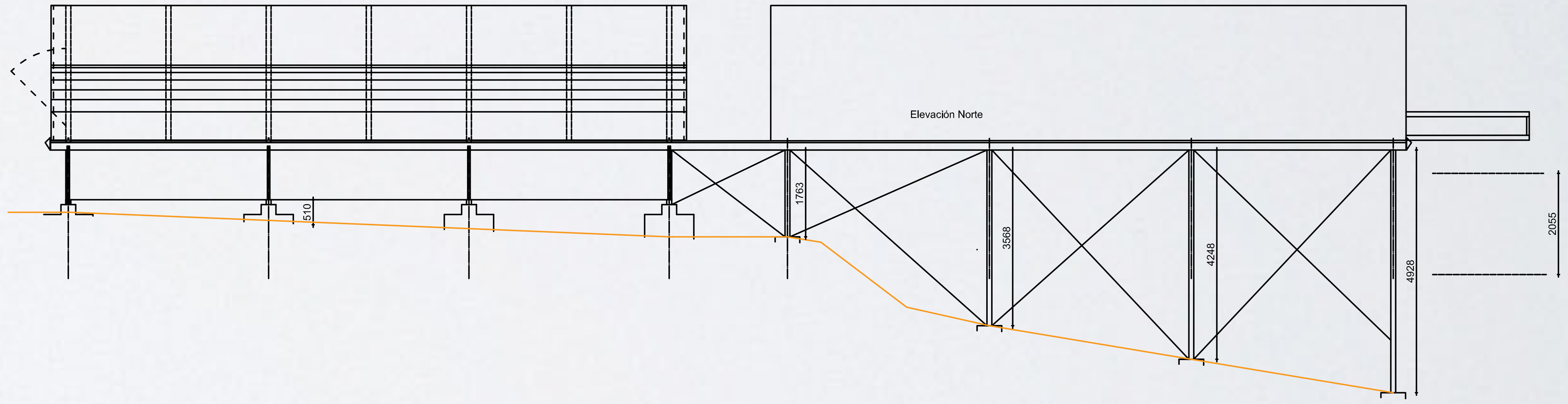
Instrument : Telescope



Site


Scale : 1 / 30
7-Dimensional Telescope


1500
965
200
600
35
3016
Medida entre ejes de posicion de rueda o angulo riel
8700


Elevación Norte
510
1763
3568
4248
4928
2055