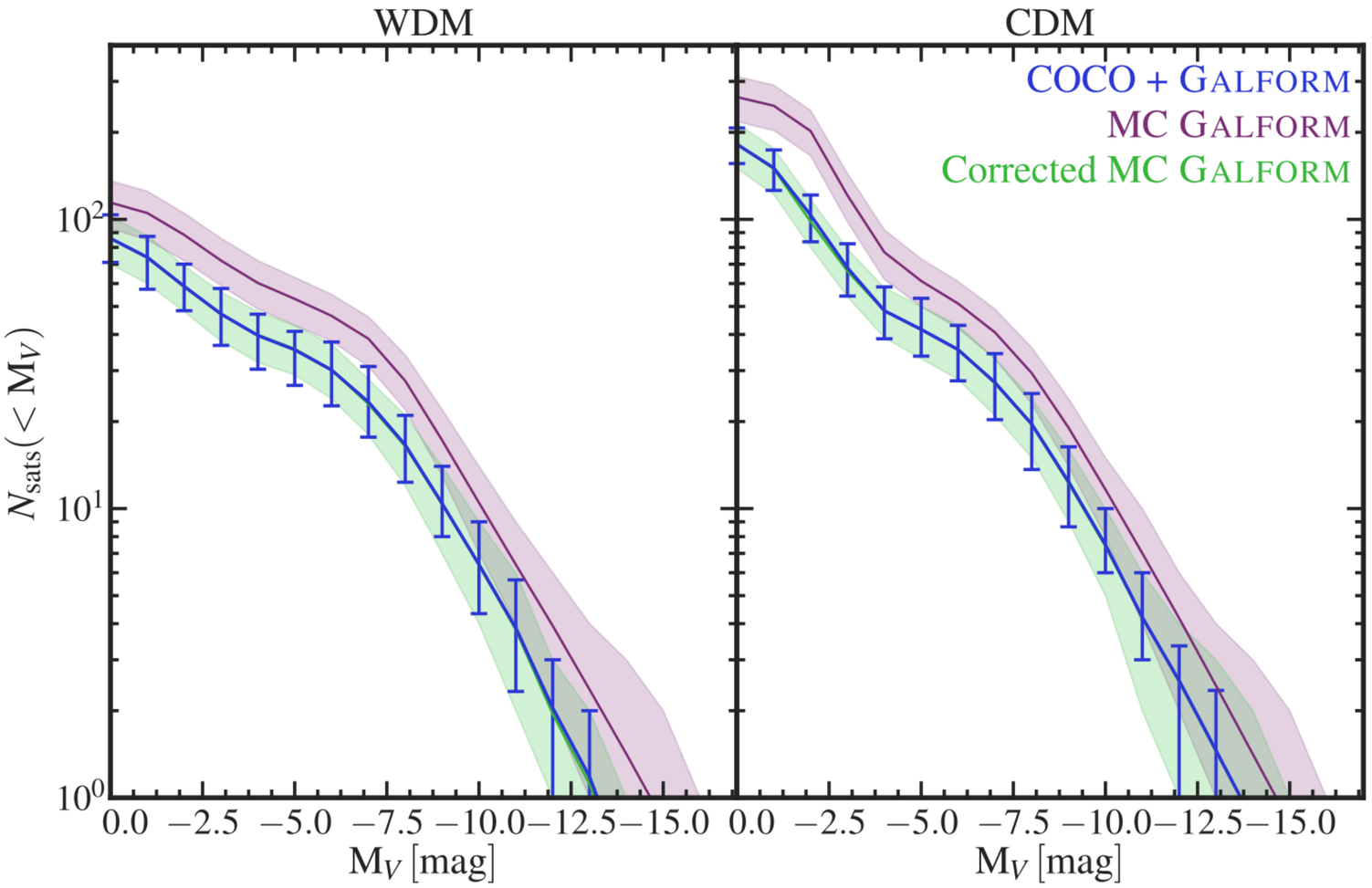
Dwarf Galaxies as dark matter probes with CSST

袁珍 （南京大学）

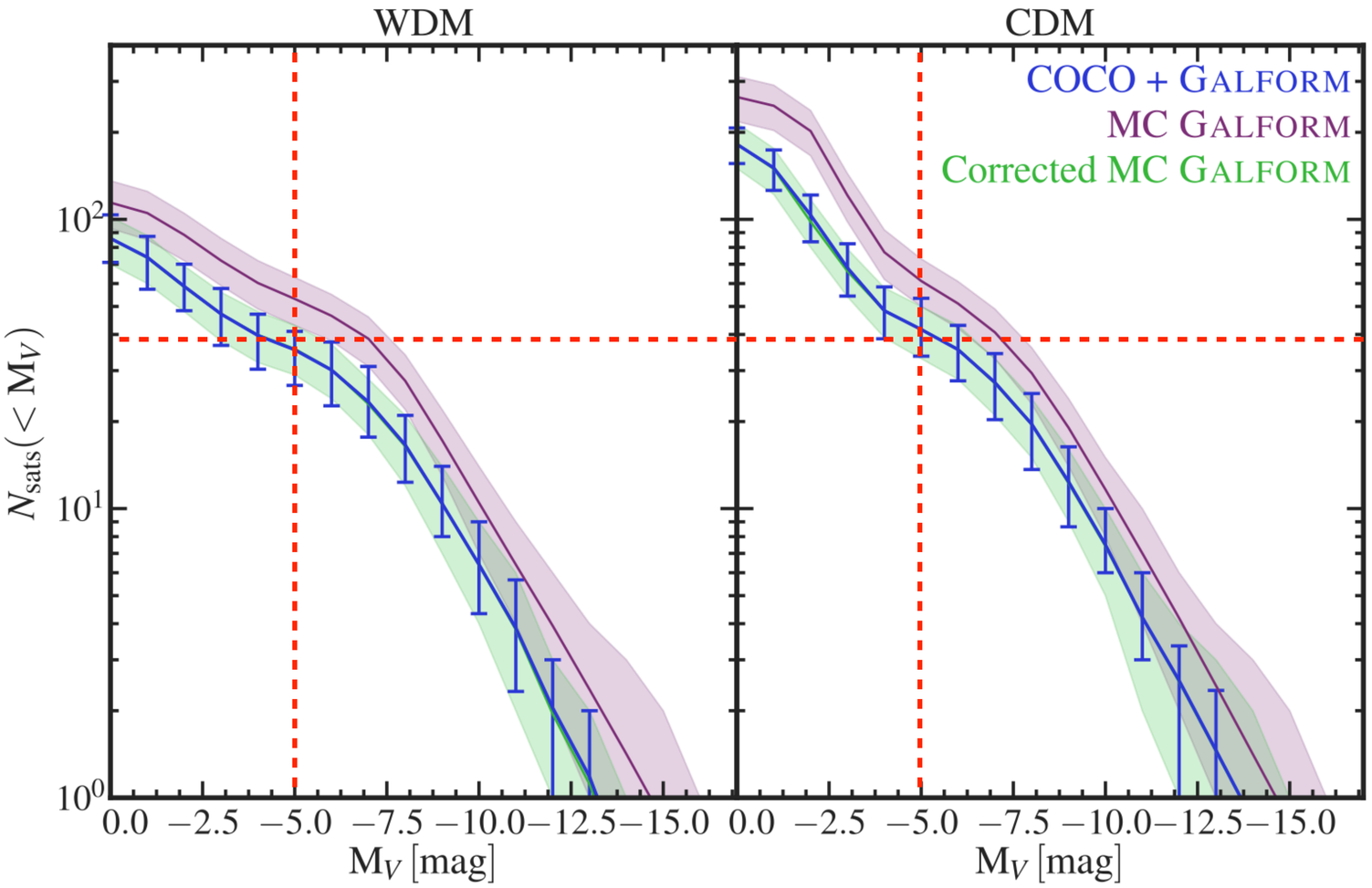
zhen.yuan@nju.edu.cn

Dwarf satellites as probes of dark matter



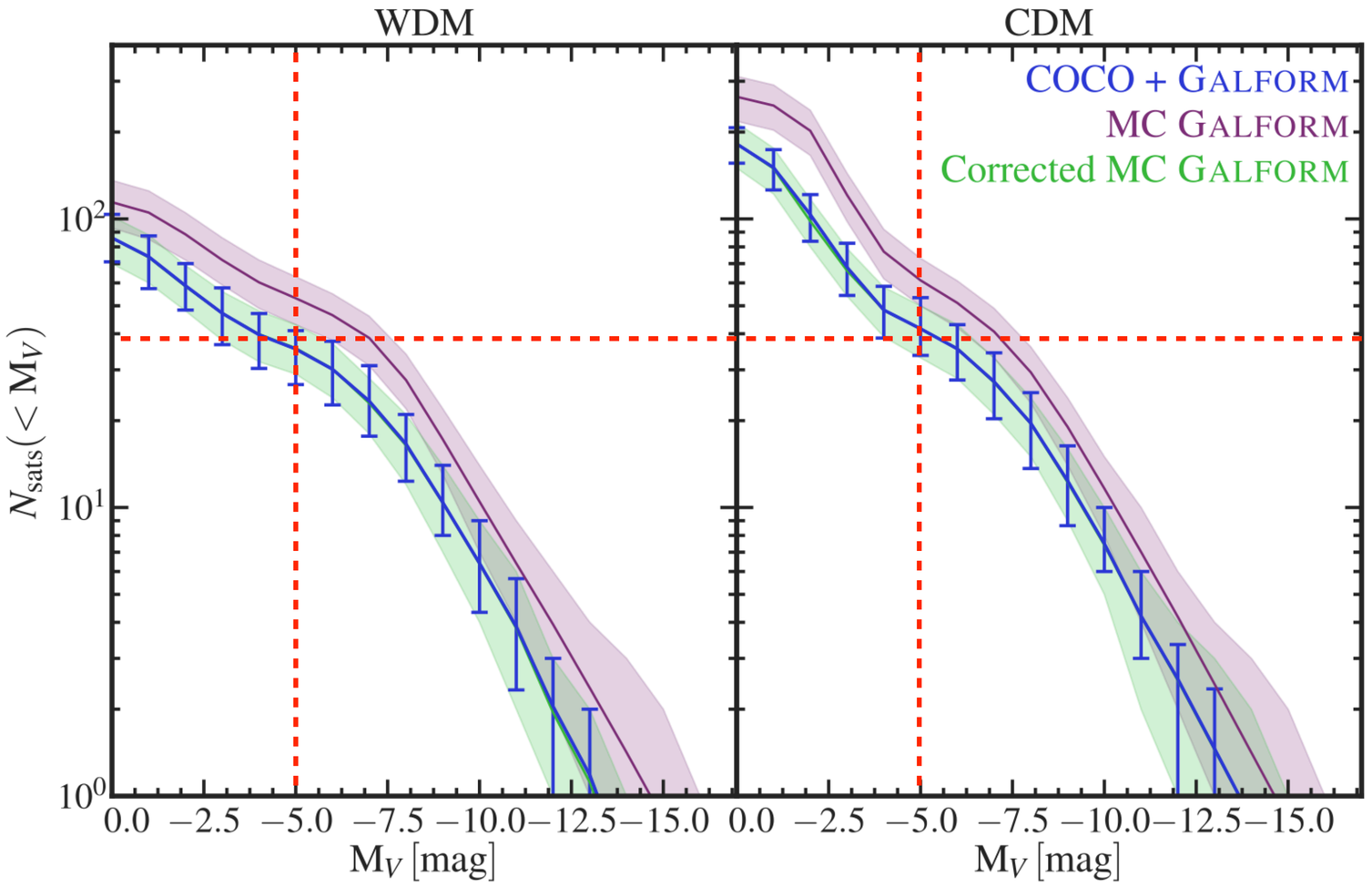
Newton et al. (2021)

Dwarf satellites as probes of dark matter



Newton et al. (2021)

Dwarf satellites as probes of dark matter

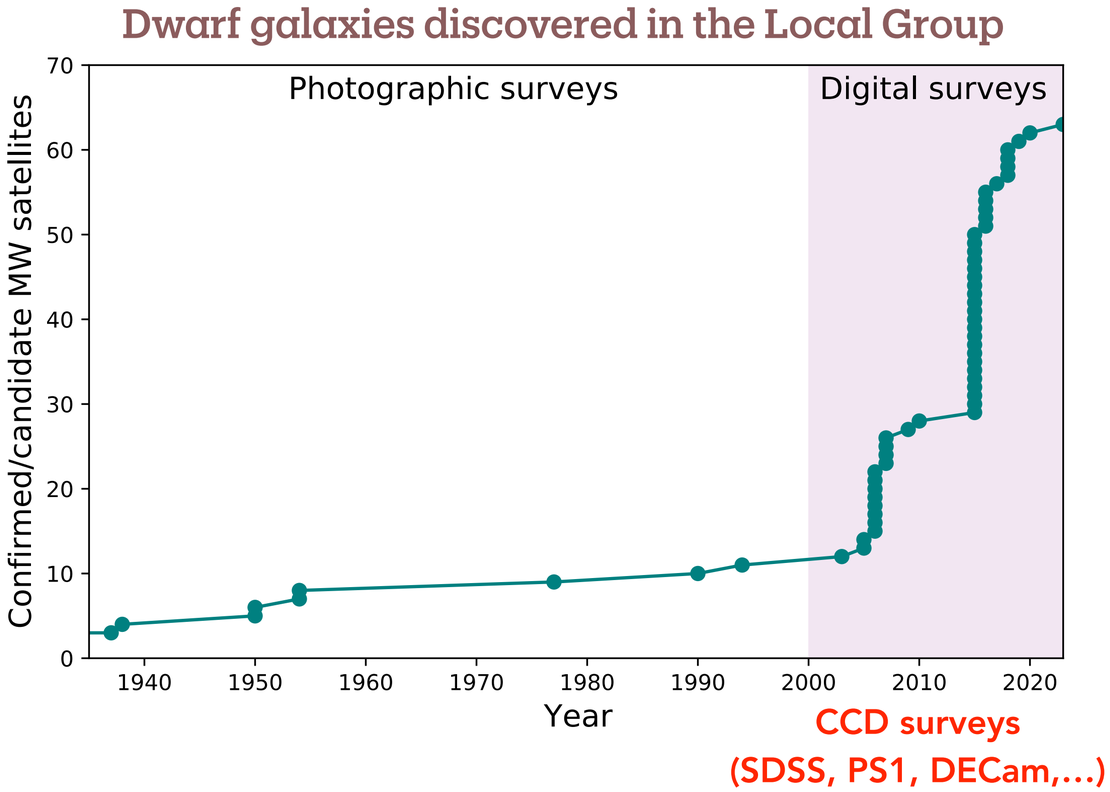


Newton et al. (2021)

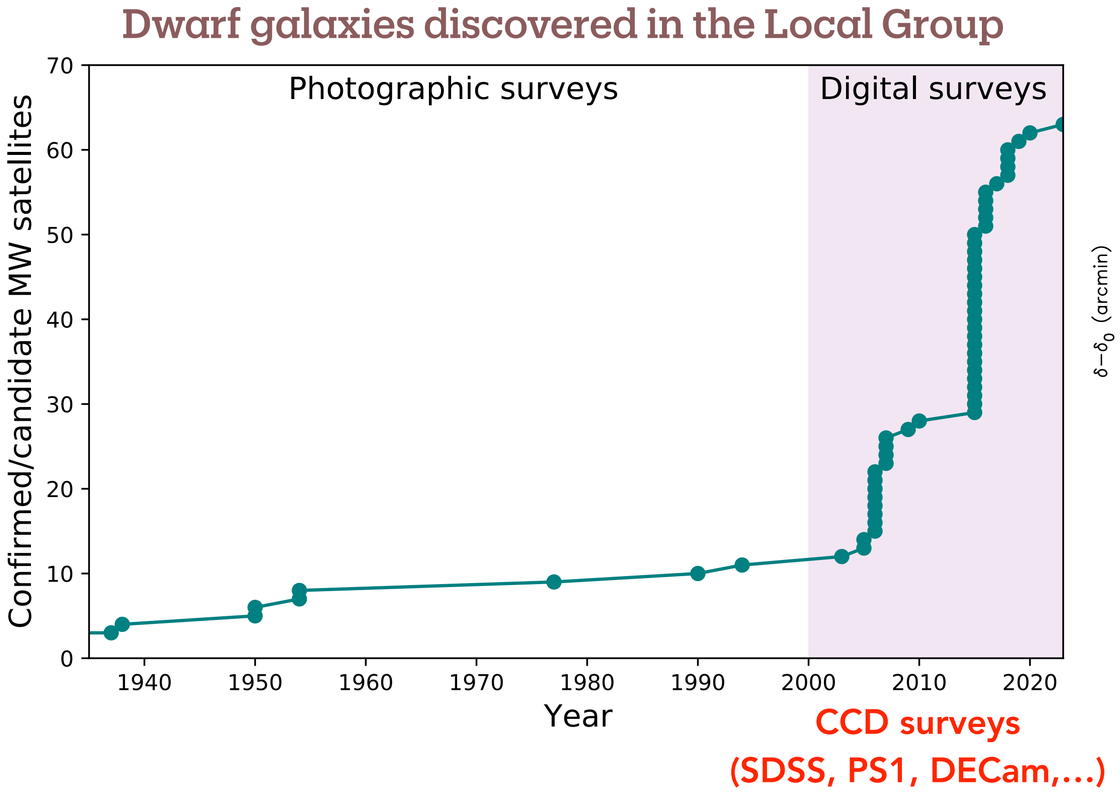
- Small structures (Mv >= -5, Ms <= 1e4 Msun) are sensitive probes of dark matter nature

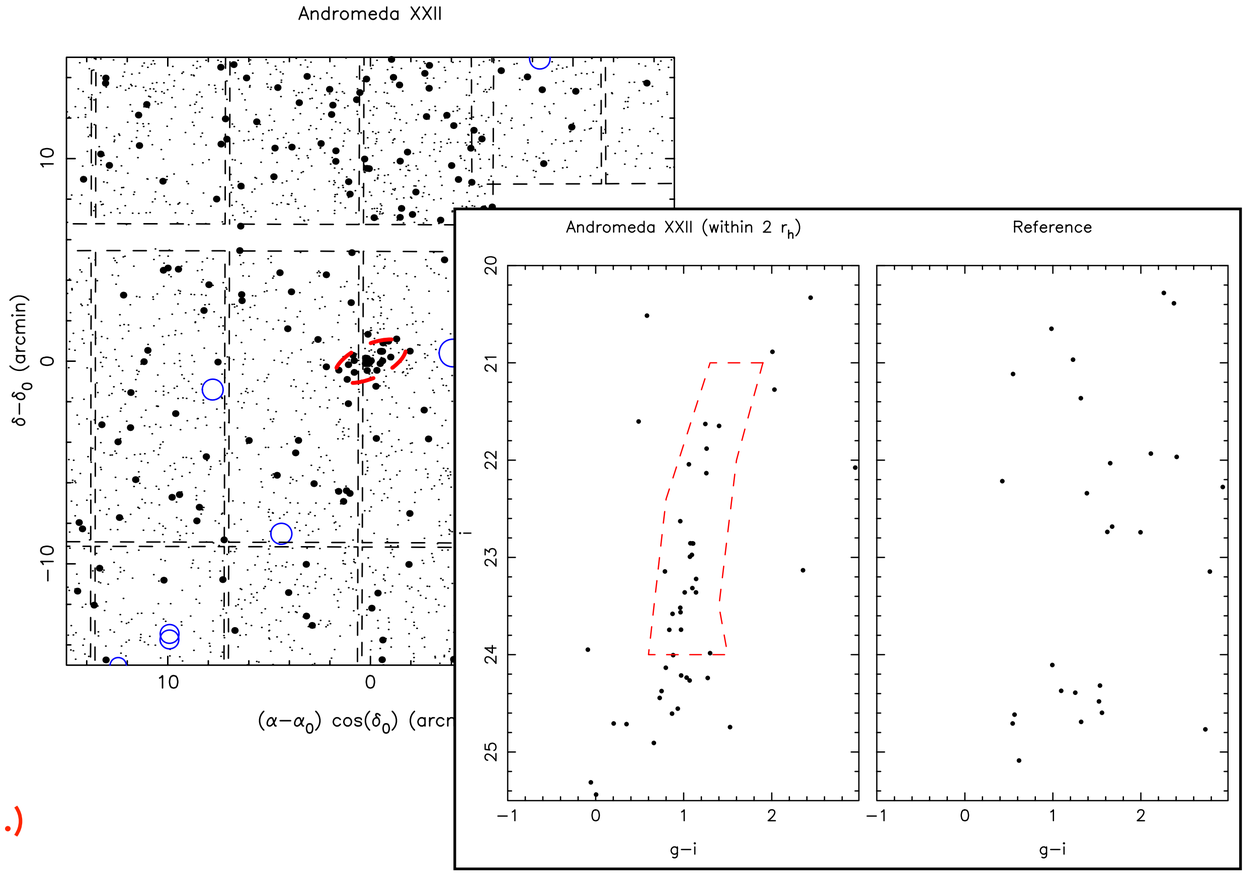
A brief history of dwarf galaxy searching

A brief history of dwarf galaxy searching



A brief history of dwarf galaxy searching

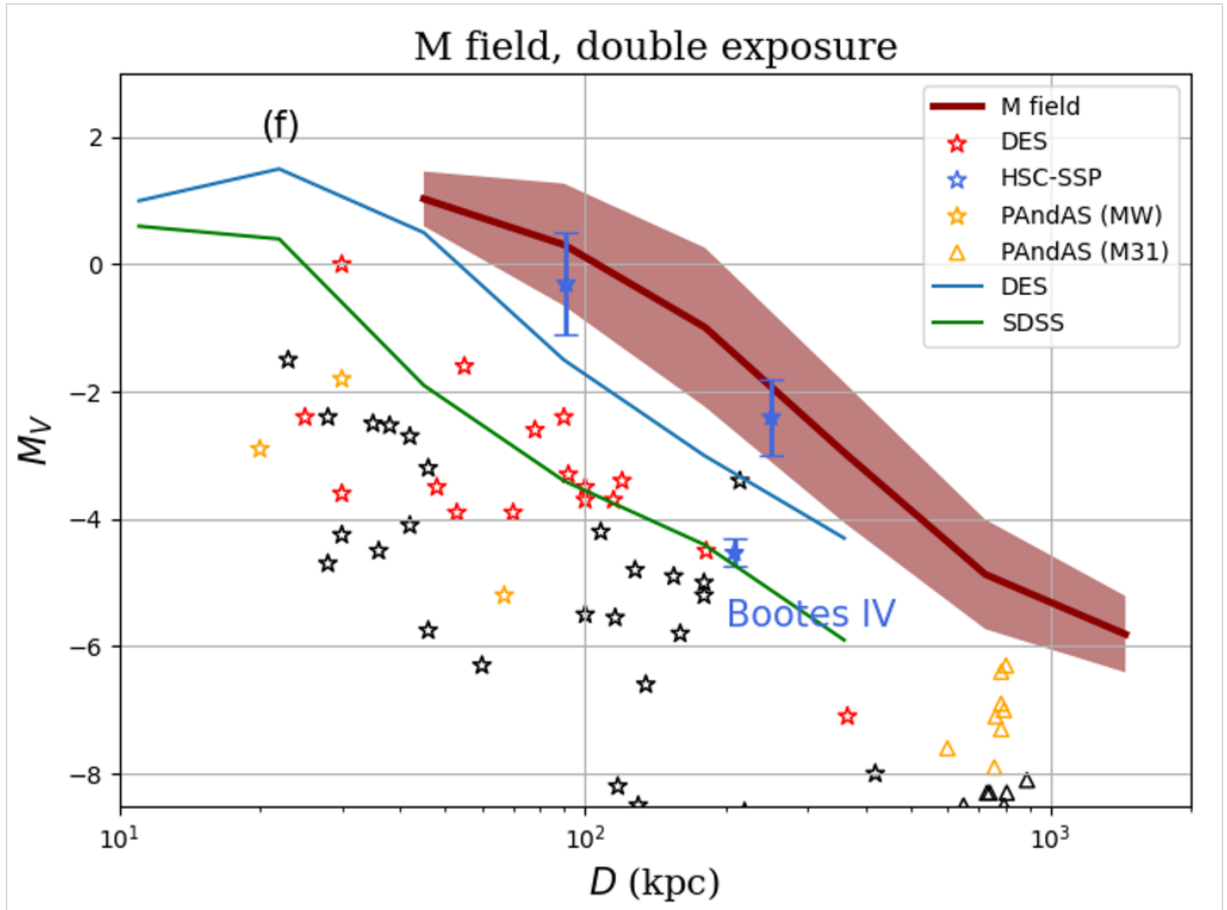


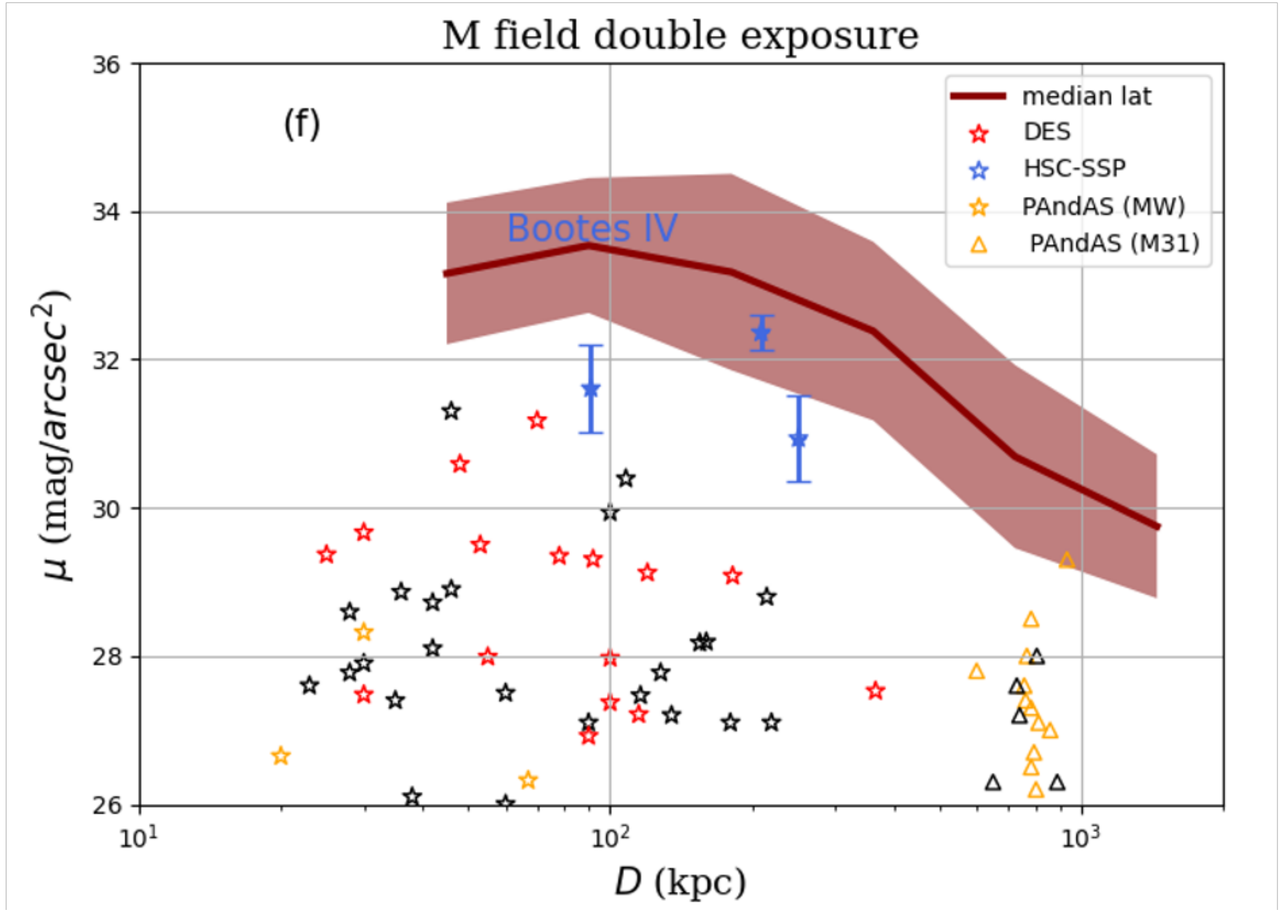


Martin et al. (2009)

Local Group dwarf galaxy detection limit of CSST

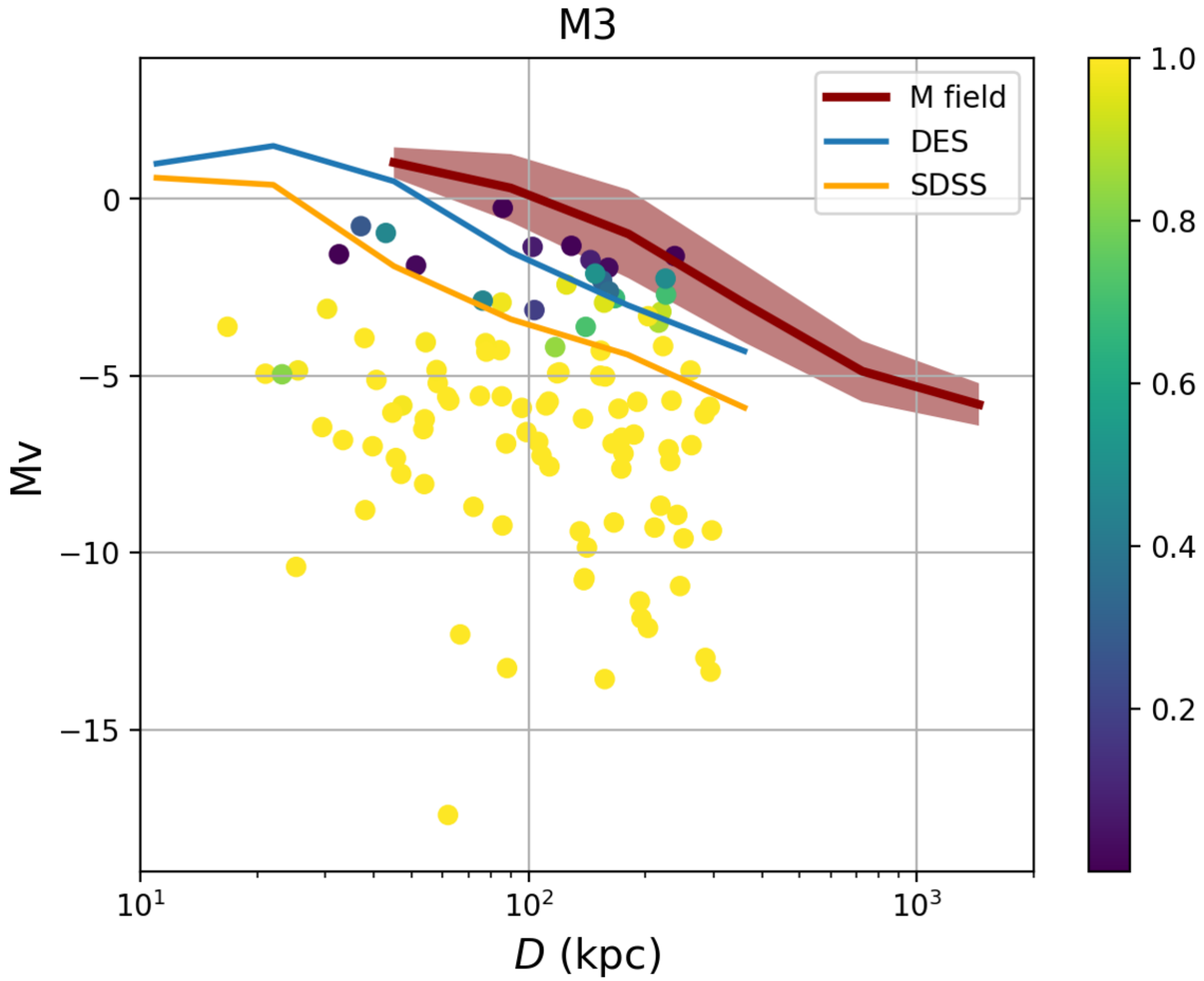
Qu & Yuan et al. (2023, 2025)

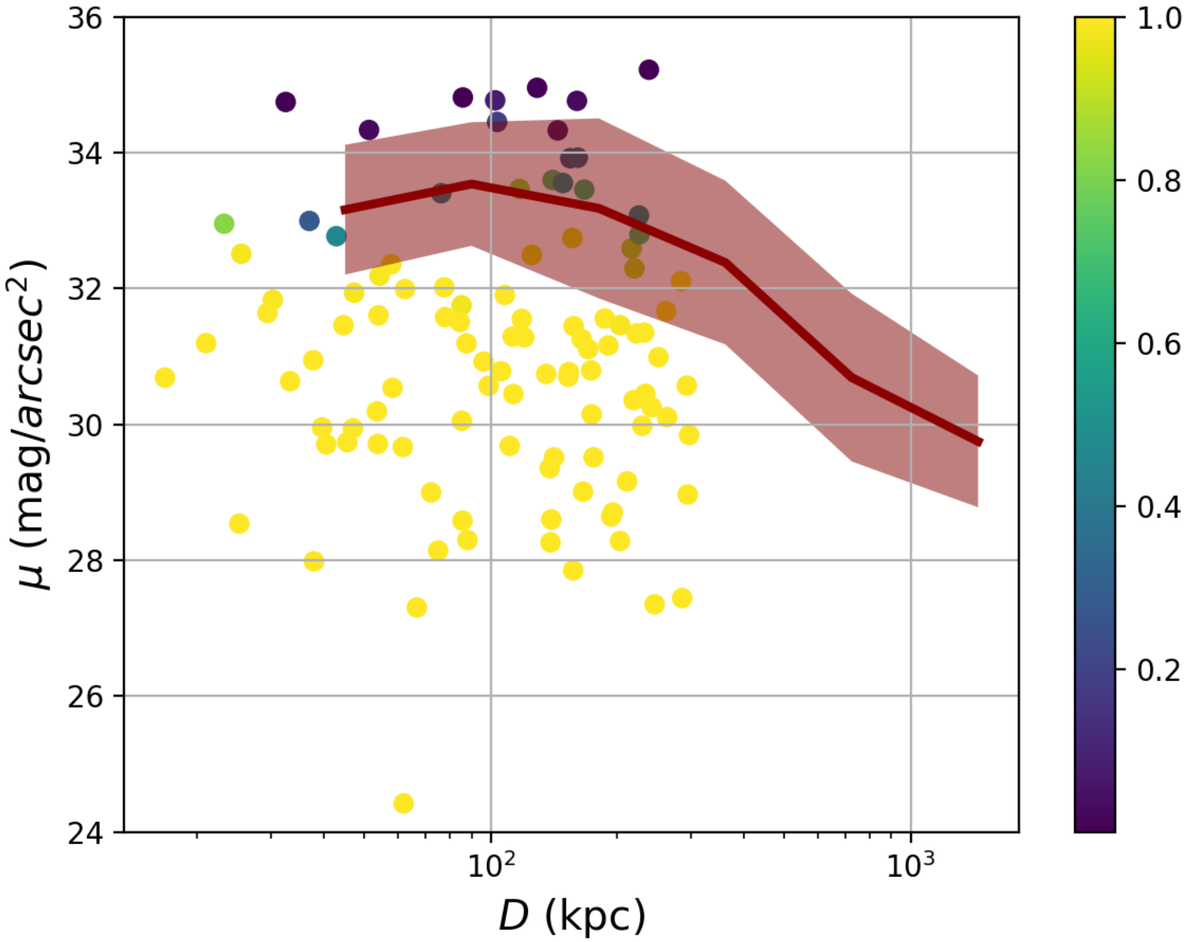




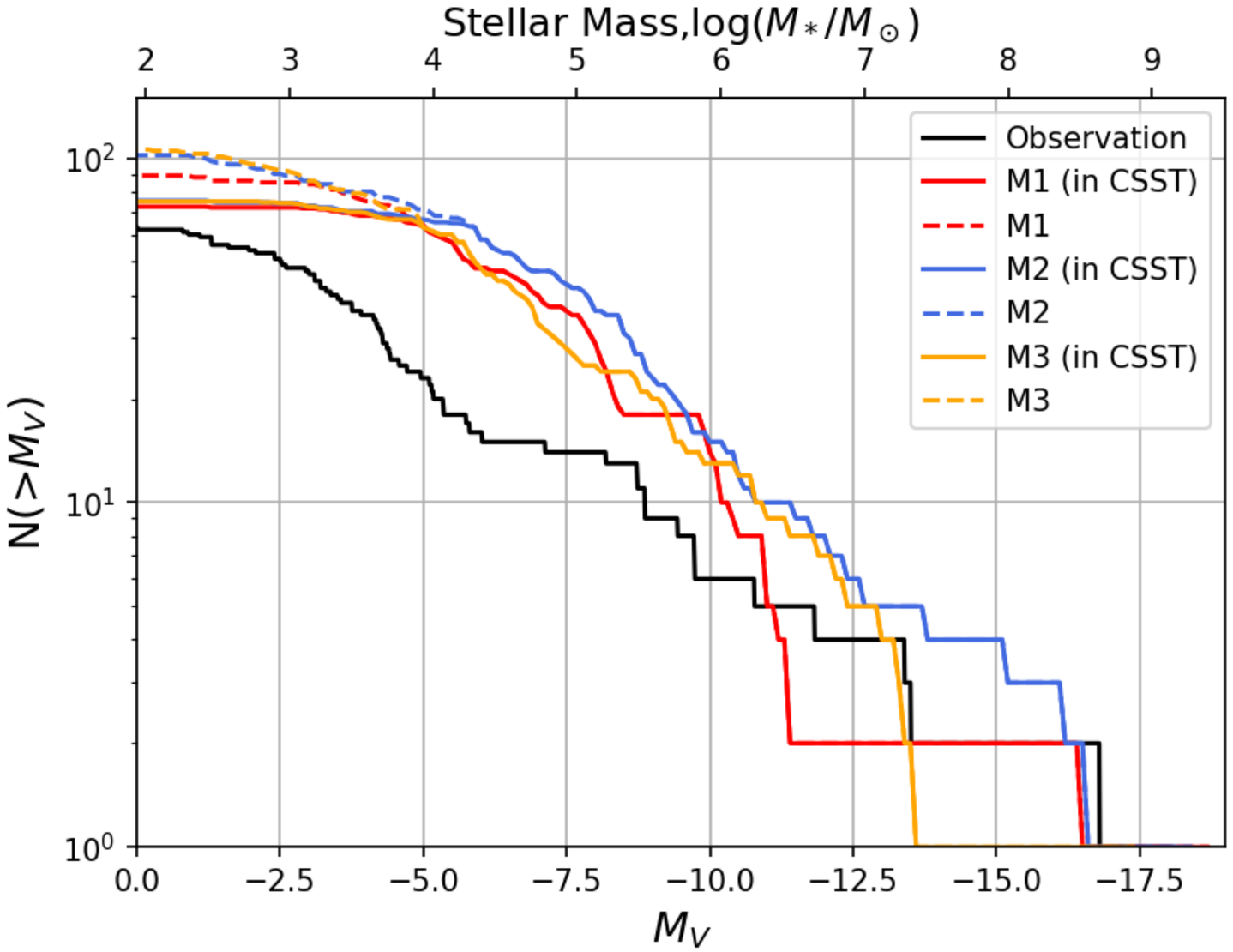
Local Group dwarf galaxy detection in simulated MWs

MagPie zoom-in MW simulation



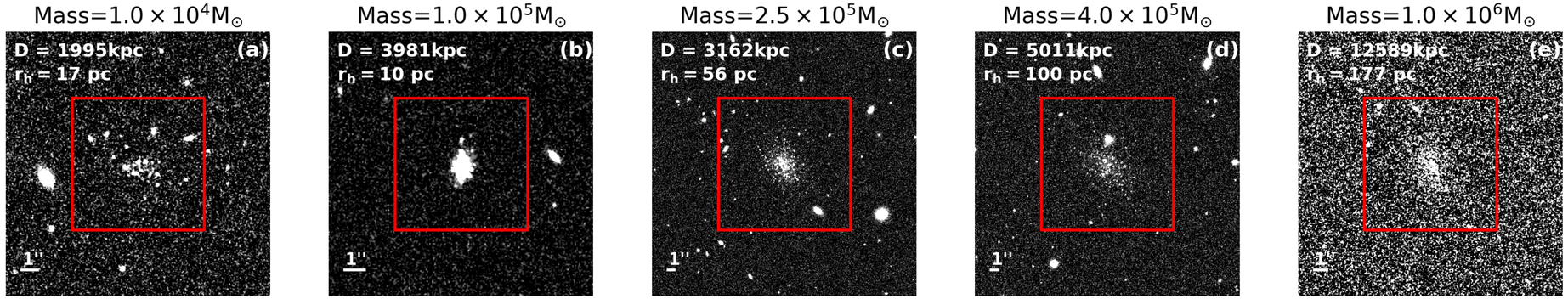


Luminosity function prediction with CSST



Lacking resolved bright giants beyond 5 Mpc …

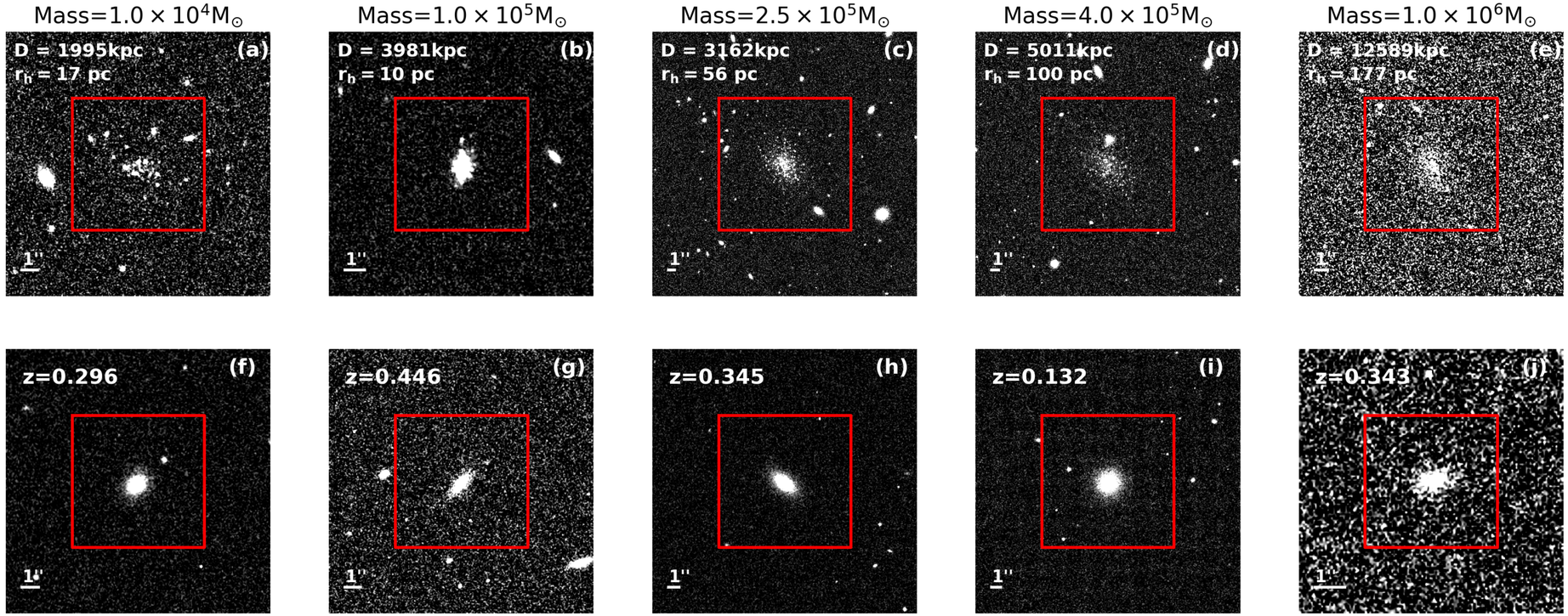
Qu & Yuan et al. (2025 in prep)



We can search dwarf galaxies in images

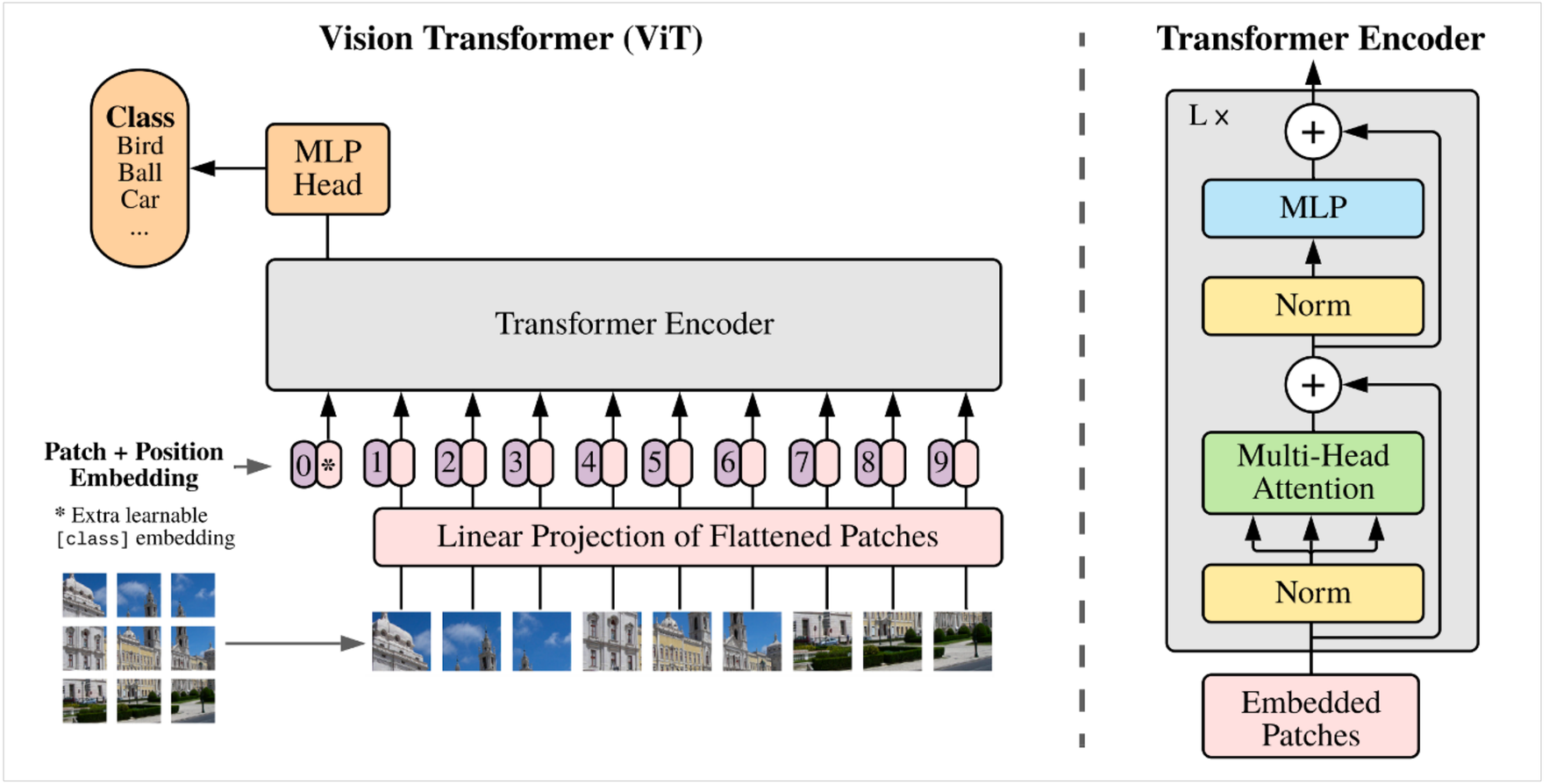
Qu & Yuan et al. (2025 in prep)

Dwarf galaxies



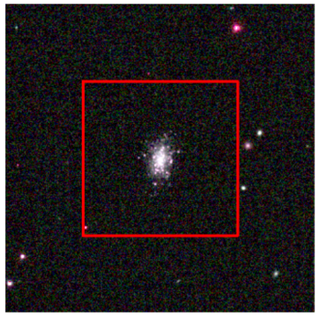
Contaminates from distant galaxies

Vision Transformer model

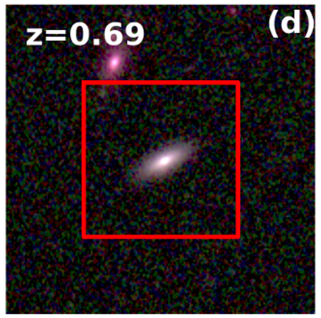


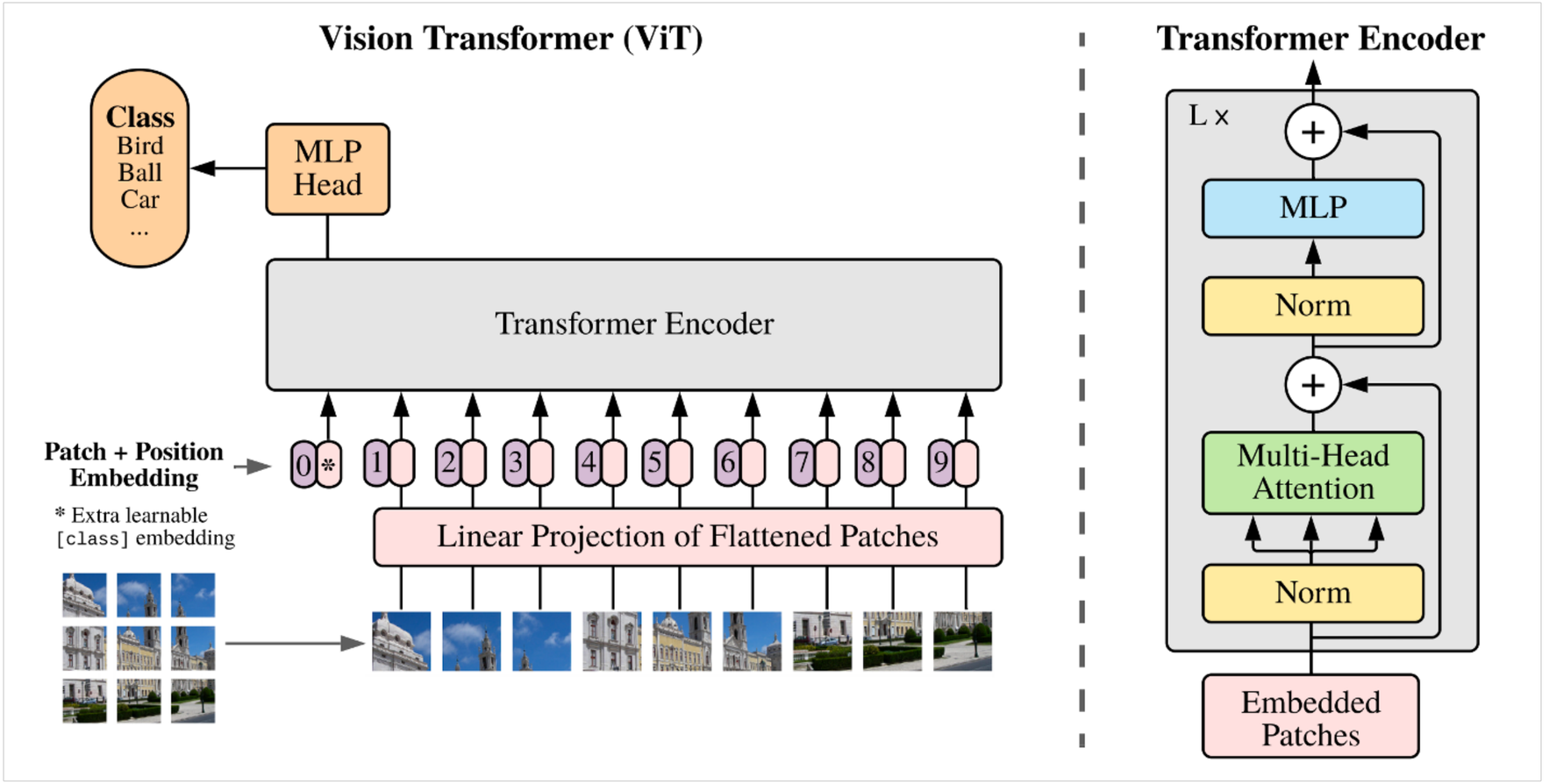
Vision Transformer model

positive



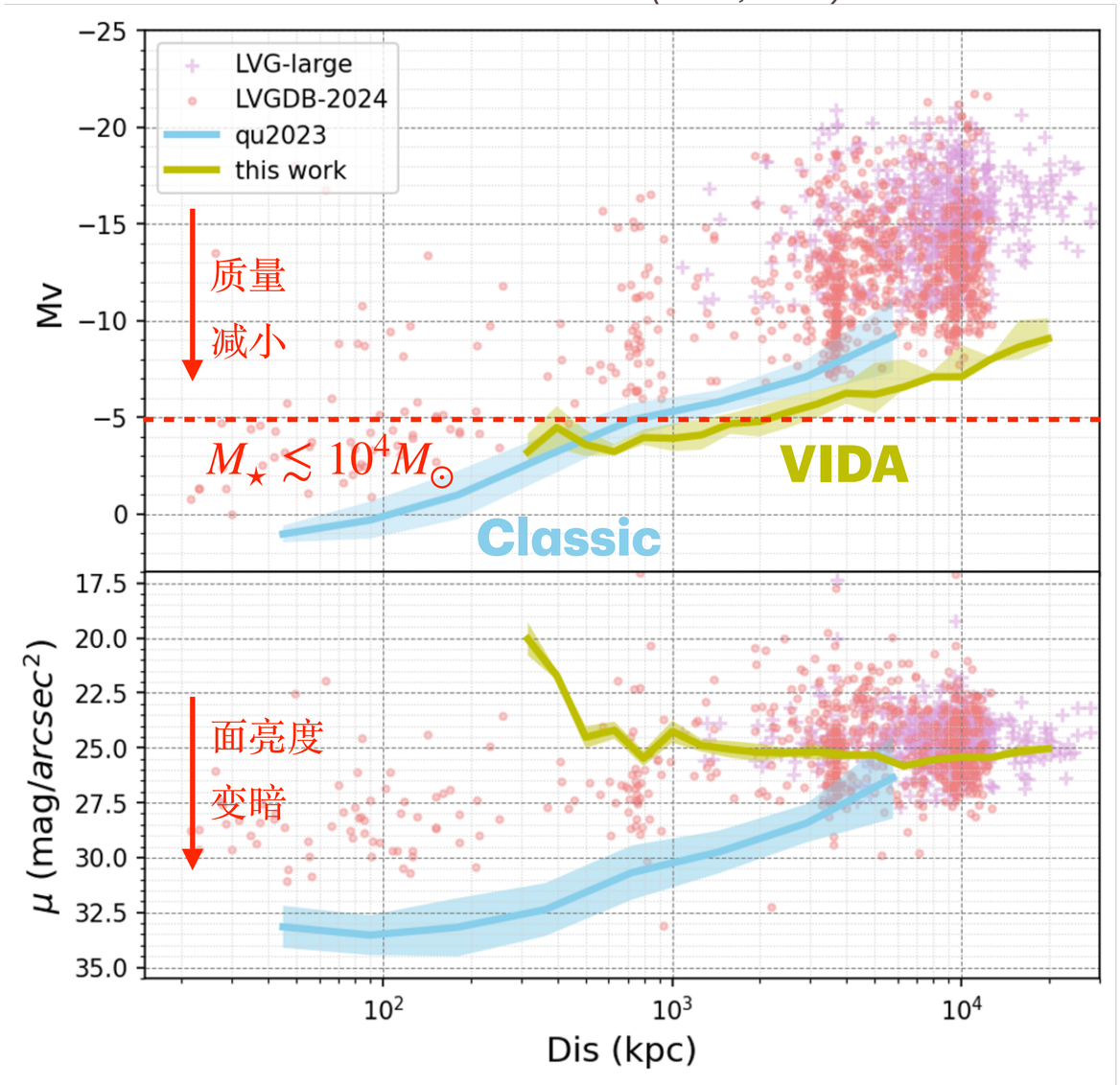
negative





Dwarf galaxy search in the CSST images
- Complementary searching methods up to 20Mpc

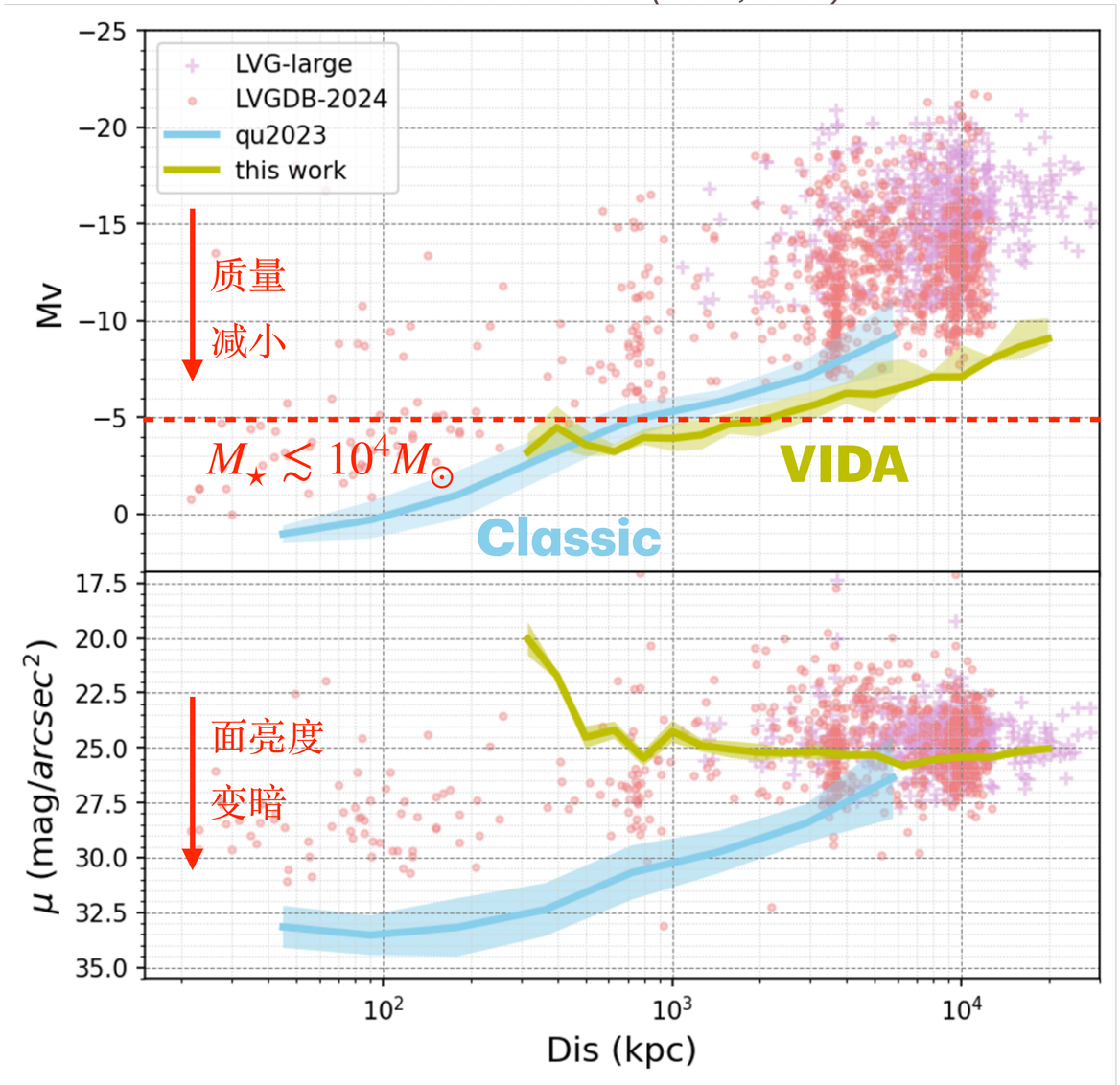
Qu & Yuan et al. (2023, 2025)



- New surface brightness detection limit up to 5Mpc (classic) — fainter objects
- New luminosity detection limit up to 20Mpc (VIDA) — smaller & more distant objects

Dwarf galaxy search in the CSST images
- Complementary searching methods up to 20Mpc

Qu & Yuan et al. (2023, 2025)



- New surface brightness detection limit up to 5Mpc (classic) — fainter objects
- New luminosity detection limit up to 20Mpc (VIDA) — smaller & more distant objects

How to constrain the nature of dark matter?

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\rm particle\ physics} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\rm particle\ physics} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Astronomy

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Astronomy

$$\propto \rho_{\rm DM}^2 D^{-2}$$

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Astronomy

$$\propto \rho_{\rm DM}^2 D^{-2}$$

Jeans equation
(spherical assumptions)

$$\sigma_v^2 \propto \int \frac{M_{\rm DM}(r)}{r^2}\rho_*(r)dr$$

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Astronomy

$\propto \rho_{\rm DM}^2 D^{-2}$

Jeans equation
(spherical assumptions)

$$\sigma_v^2 \propto \int \frac{M_{\rm DM}(r)}{r^2}\rho_*(r)dr$$

Velocity dispersion

Stellar profile

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Astronomy

$\propto \rho_{\rm DM}^2 D^{-2}$

Jeans equation
(spherical assumptions)

$$\sigma_v^2 \propto \int \frac{M_{\rm DM}(r)}{r^2}\rho_*(r)dr$$

Velocity dispersion

Stellar profile

mass-anisotropy degeneracy problem

1.radial orbits & low mass galaxy -> core (low $\rho_{\rm DM}$)

2.tangential orbits & massive galaxy-> cuspy (large $\rho_{\rm DM}$)

Gamma-ray signal flux from dwarf galaxies

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\rm particle\ physics} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r}){\rm d}l{\rm d}\Omega'}_{\rm J-factor}$$

Astronomy

$$\propto \rho_{\rm DM}^2 D^{-2}$$

Jeans equation
(spherical assumptions)

$$\sigma_v^2 \propto \int \frac{M_{\rm DM}(r)}{r^2}\rho_*(r)dr$$

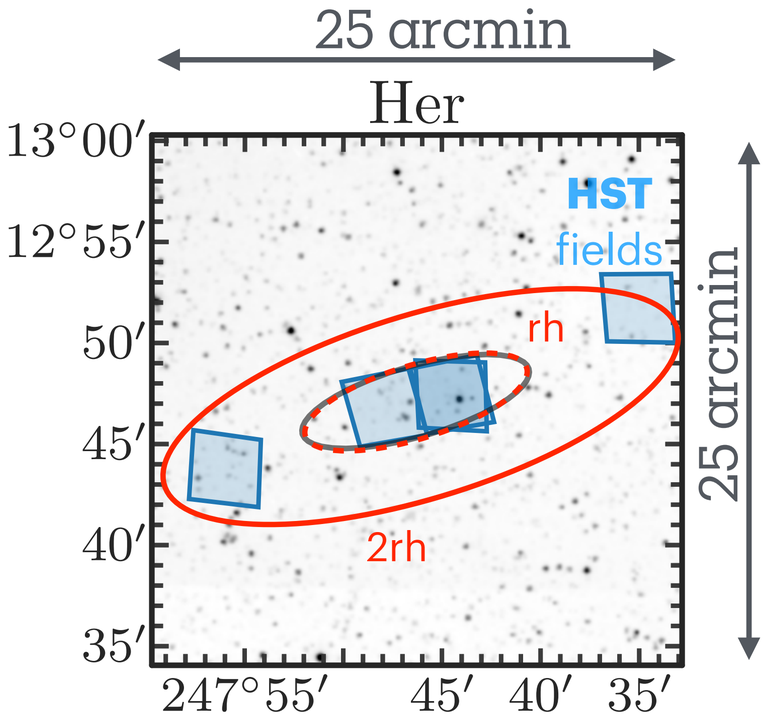
Velocity dispersion

Stellar profile

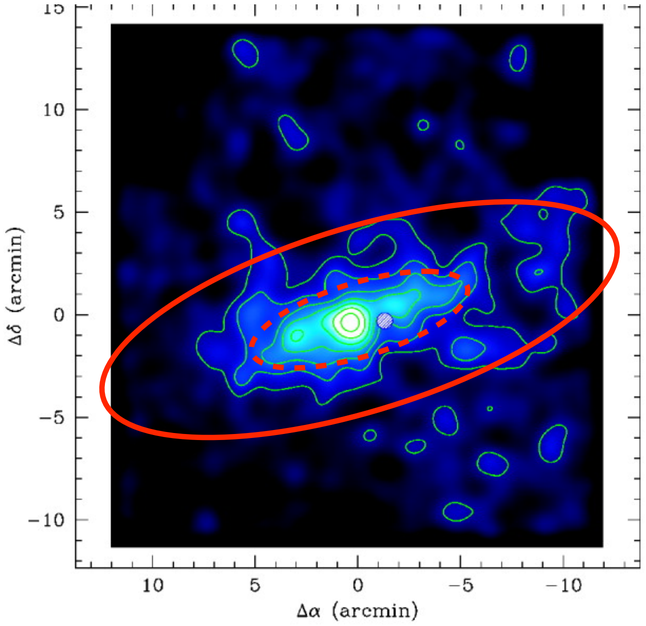
mass-anisotropy (M-β) degeneracy solution

1. proper motion (maybe possible for nearby DG)
2. multi-population decomposition (ref. GravSphere)
3. higher-order velocity moments(ref. GravSphere2)
4. extend the data to the tidal radius (β observed!)

Dwarf galaxy observations with the CSST



Durbin et al 2025



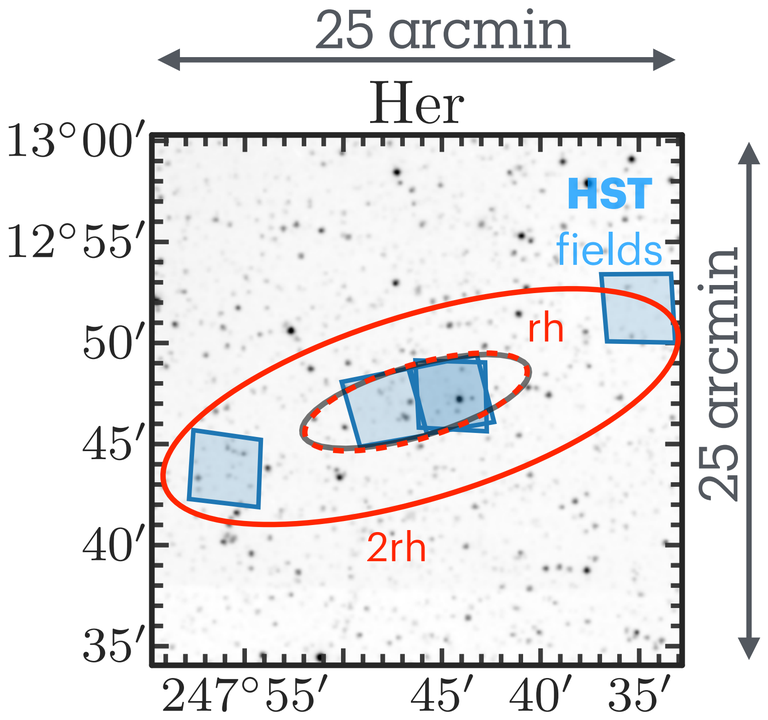
Colman et al 2007

Dwarf galaxy observations with the CSST

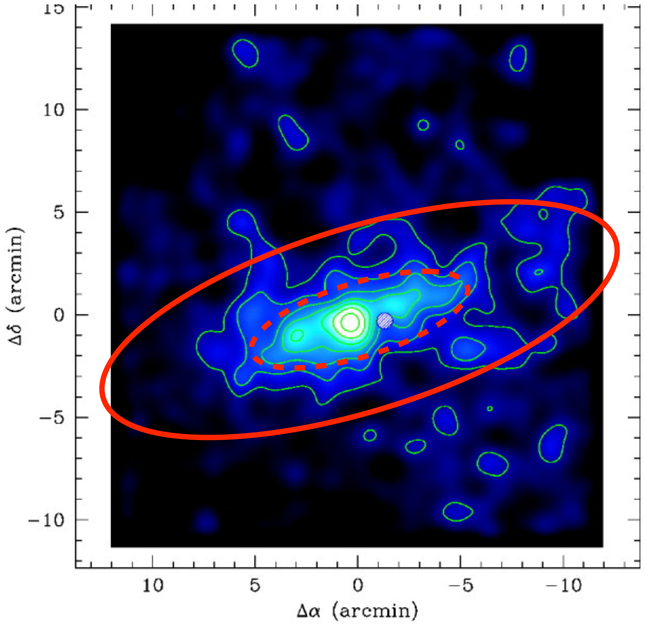
55 arcmin

66 arcmin

g, i	g, r, i	g, r, i	g, r, i	g, r
2NUV, g, i	2NUV, u, g, r, i	2NUV, u, g, r, i	2NUV, u, g, r, i	NUV, u, g, r
3NUV, u, g, i	4NUV, 2u, g, r, i	4NUV, 2u, g, r, i	4NUV, 2u, g, r, i	3NUV, u, g, r
3NUV, u, g, r	4NUV, 2u, g, r, i	4NUV, 2u, g, r, i	4NUV, 2u, g, r, i	3NUV, u, g, i
NUV, g, u, r	2NUV, u, g, r, i	2NUV, u, g, r, i	2NUV, u, g, r, i	2NUV, g, i
g, r	g, r, i	g, r, i	g, r, i	g, i



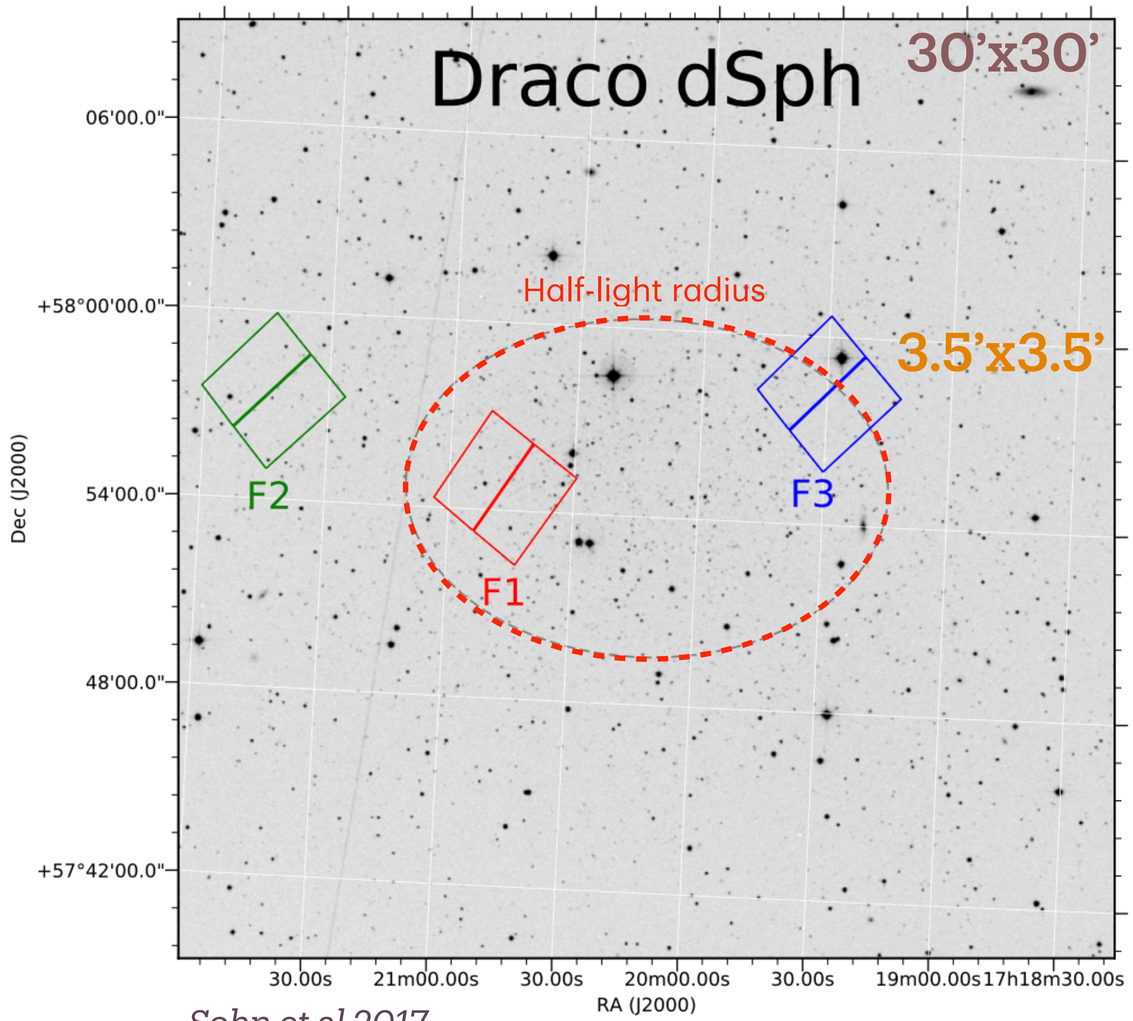
Durbin et al 2025



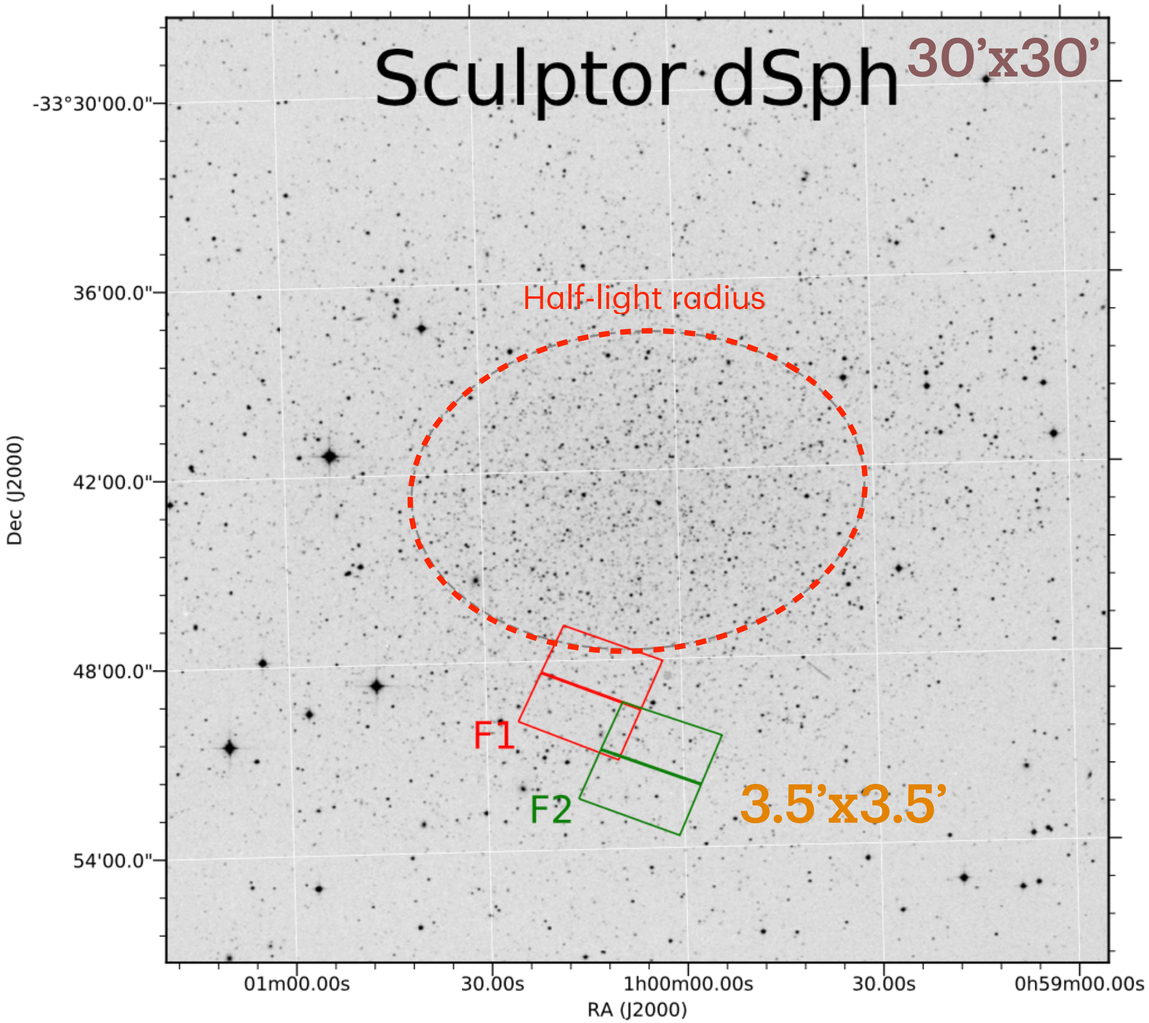
Colman et al 2007

15 pointings for one exposure

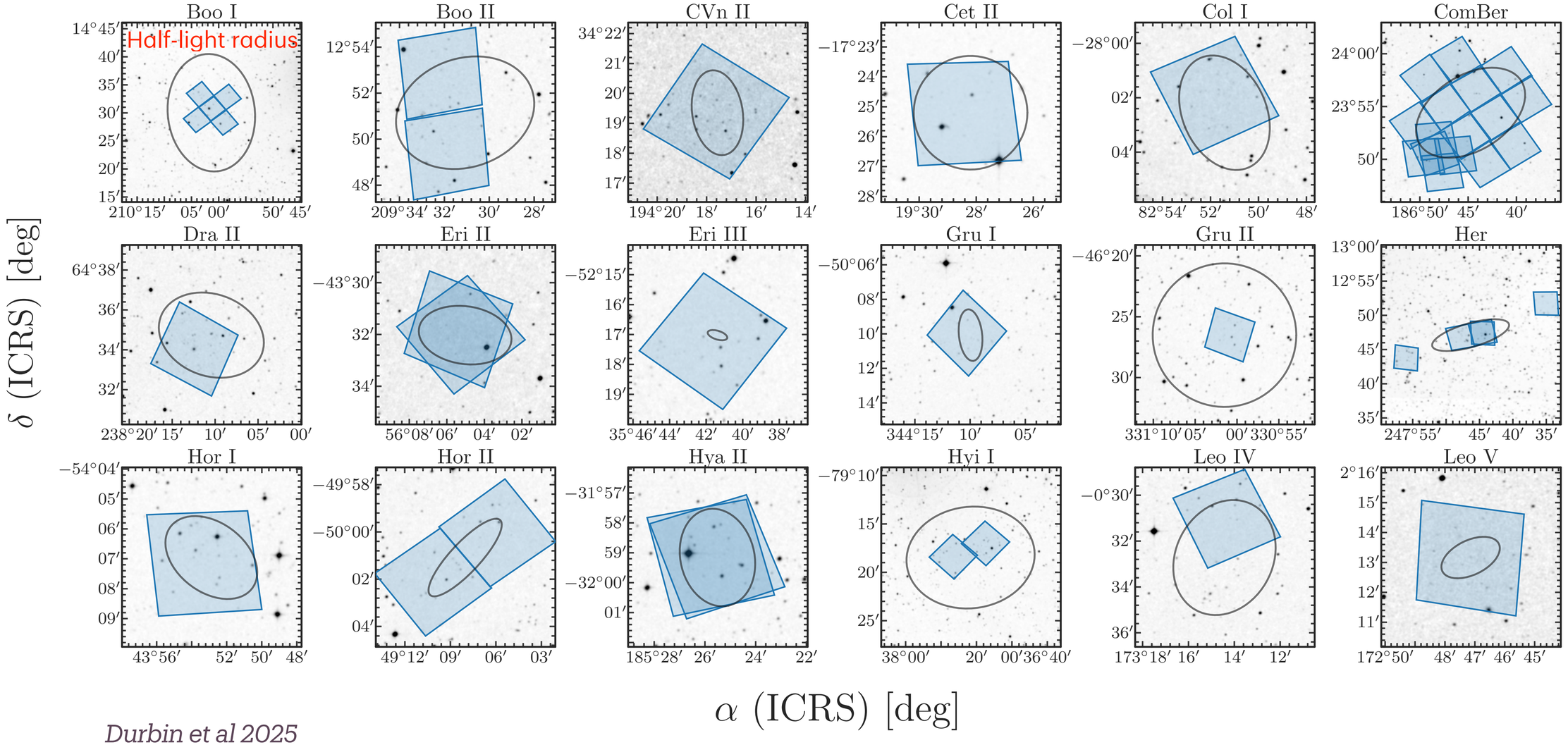
MW dwarf galaxies seen by HST/ACS



Sohn et al 2017

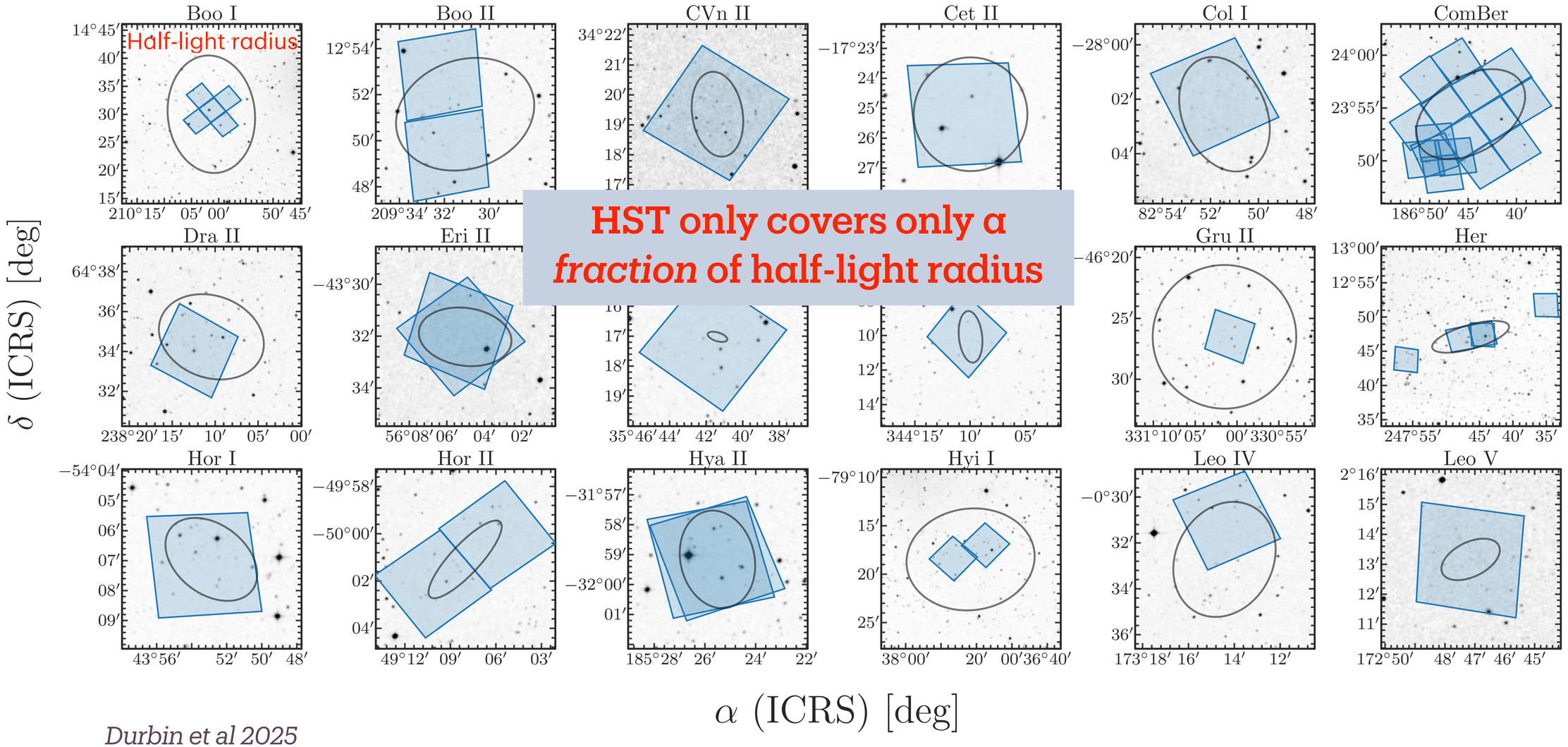


MW dwarf galaxies seen by HST/ACS



Durbin et al 2025

MW dwarf galaxies seen by HST/ACS



HST only covers only a *fraction* of half-light radius

Durbin et al 2025

What we have now:

Stellar density profiles & velocity dispersion up to r_h

of the existing dwarf satellites

What we can have with CSST:

What we can have with CSST:

- Stellar density profiles up to $r_t \approx 5r_h$ of the existing dwarf satellites thanks to the large FoV of CSST

What we can have with CSST:

- Stellar density profiles up to $r_t \approx 5r_h$ of the existing dwarf satellites thanks to the large FoV of CSST
- σ_v from PFS (North) & 4MOST (South) early science programs & WEAVE PI program of dwarf galaxies

CSST-DG20+

银河系矮星系巡天

CSST早期科学提案

袁珍 （南京大学）

Nicolas F. Martin (CNRS/Strasbourg astronomical Observatory)

曲涵，韦成亮，常江，李国亮， 李江涛（紫金山天文台）

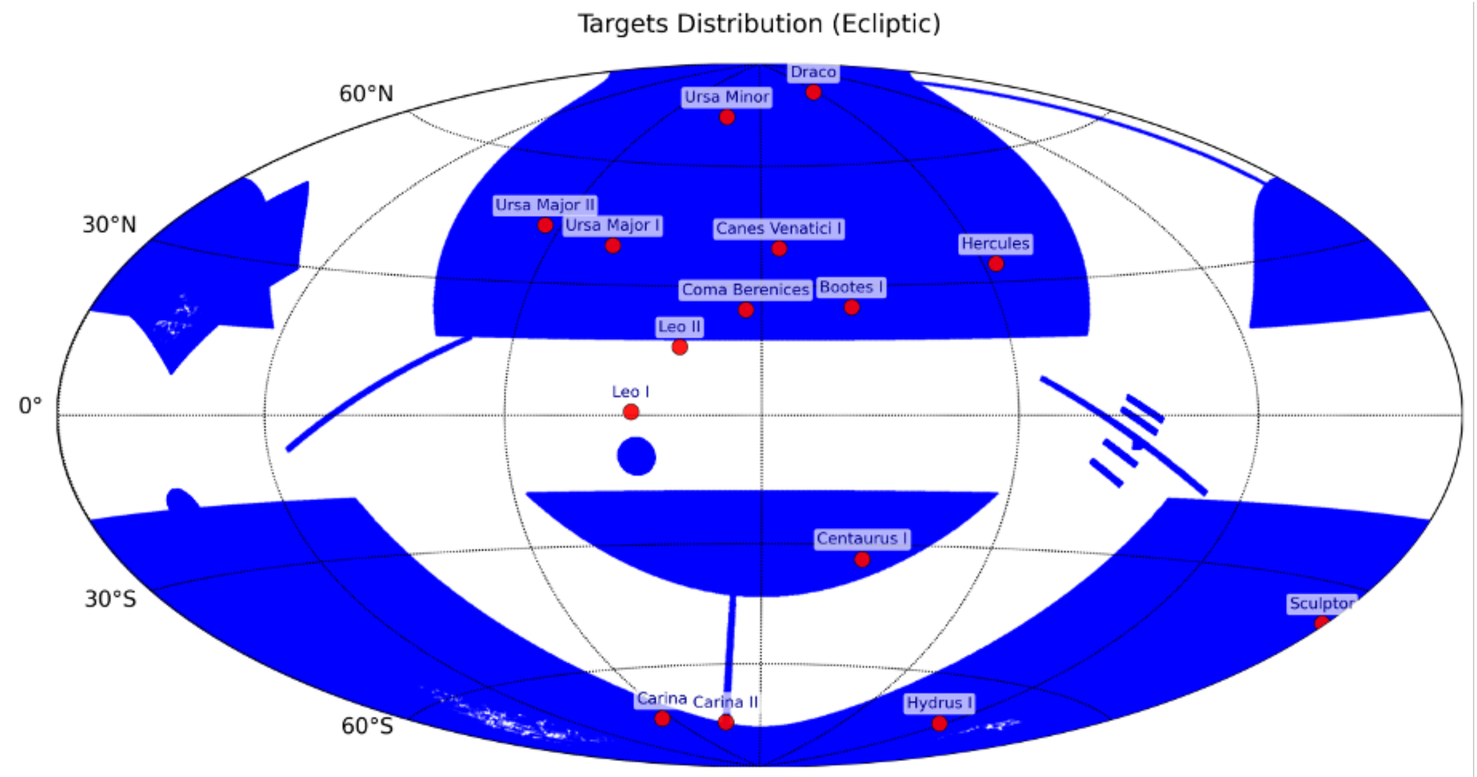
李海宁，赵景昆，王杰，蔡肇伟，张鑫，邵实，范舟，廖世鸿（国家天文台）

韩家信 ，王文婷（上海交通大学），朱玲 （上海天文台），李然（北京师范大学）

郑浩楠，姜方周（北京大学），罗煜（湖南师范大学），康熙（浙江大学）

CSST-DG20+

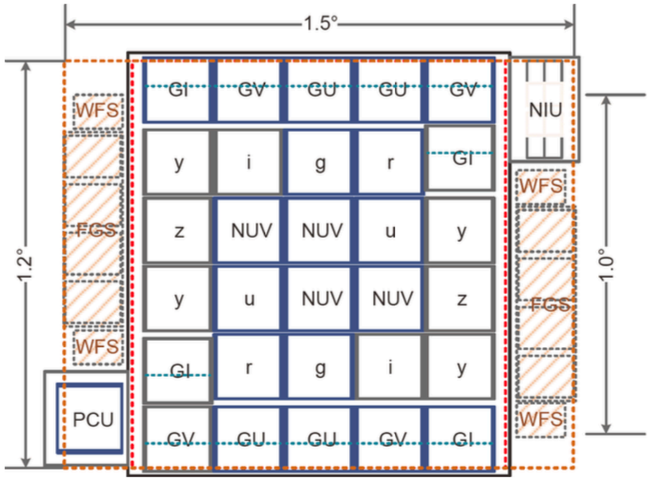
利用CSST观测20+银河系矮星系



	name	rhalf	ns
2	Fornax	19.9	2028349
6	Sculptor	11.17	359022
19	Leo I	3.65	159660
7	Carina	10.1	80062
3	Ursa Minor	18.3	74888
9	Draco	9.67	64187
1	Sextans	22.8	52996
22	Leo II	2.52	28539
13	Canes Venatici I	7.12	14041
8	Bootes I	9.97	5793
12	Hydrus I	7.42	4160
10	Carina II	8.69	2700
4	Ursa Major II	13.8	2520
17	Hercules	5.63	2135
16	Coma Berenices	5.64	1837
11	Ursa Major I	8.31	1701
20	Centaurus I	2.6	1629
5	Tucana II	12.89	844
14	Reticulum II	6.3	821
21	Leo IV	2.54	774
18	Aquarius II	5.1	733
15	Grus II	5.9	682

Key advantages of CSST in searching dwarf galaxies

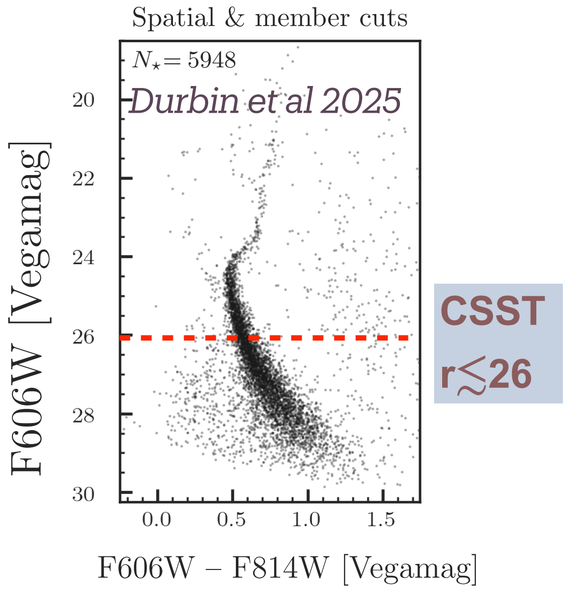
CSST观测矮星系的三大优势



大视场深度测光

Wide field-of-view: 1.1 sq deg

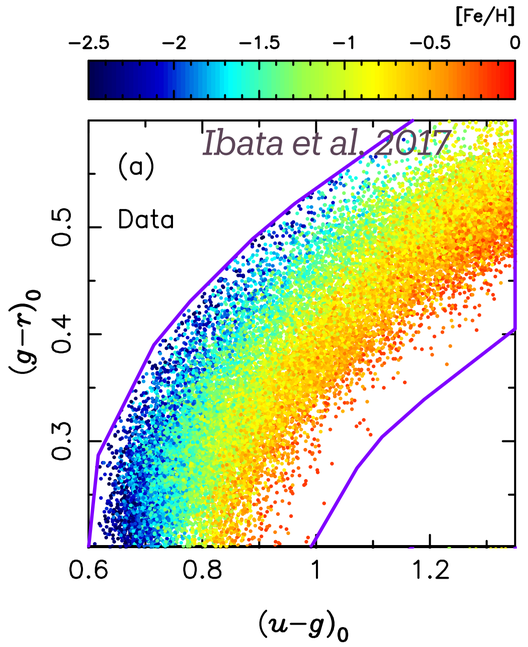
17,500 sq deg (40% of whole sky)



CSST $r \lesssim 26$

有效分辨恒星/星系

Spatial resolution: 0.15”



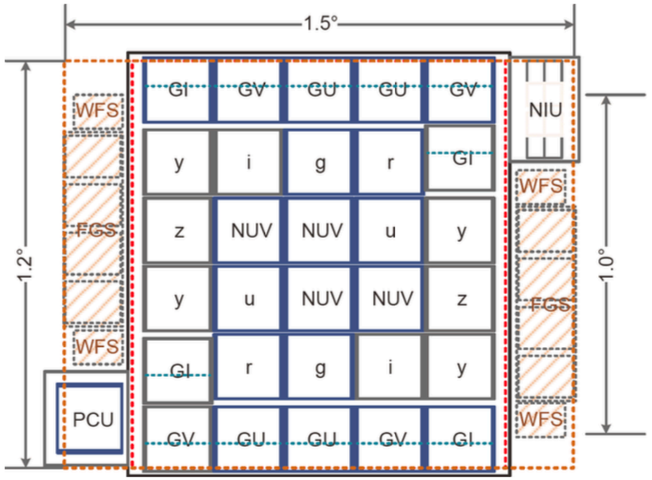
光学波段更易分辨贫金属星族

Optical filters: **nuv+u**grizy

+ CαHK

Key advantages of CSST in searching dwarf galaxies

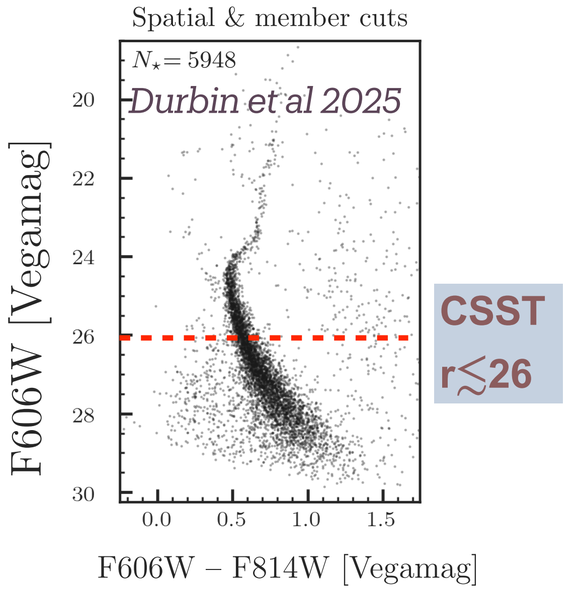
CSST观测矮星系的三大优势



大视场深度测光

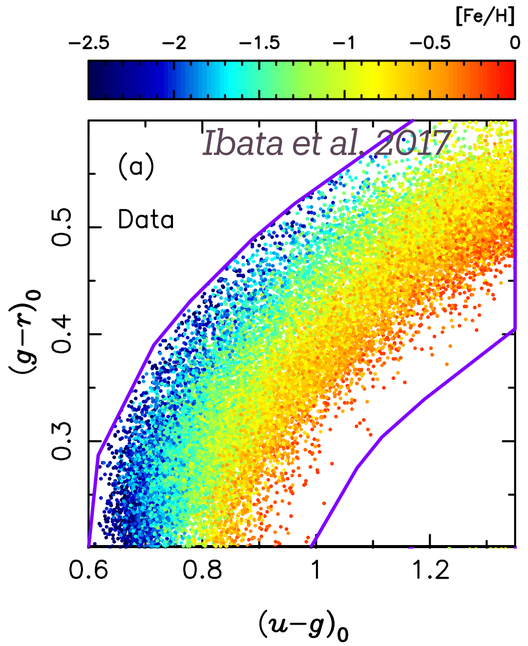
Wide field-of-view: 1.1 sq deg

17,500 sq deg (40% of whole sky)



有效分辨恒星/星系

Spatial resolution: 0.15”



光学波段更易分辨贫金属星族

Optical filters: nuv+ugrizy

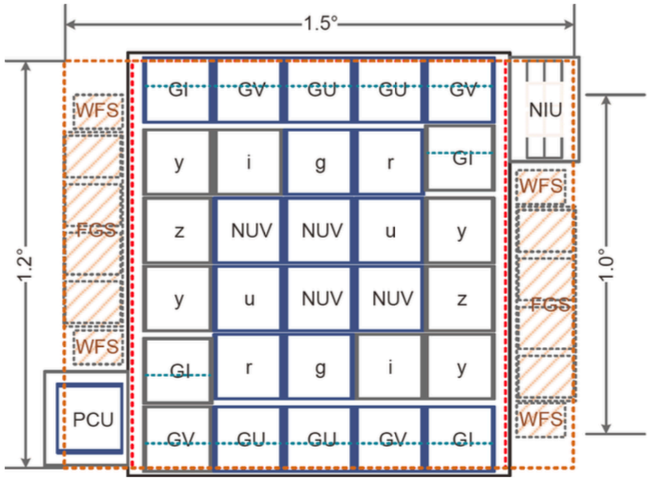
+ CαHK

band and limiting photometric

band	NUV	u	g	r	i	z	y
wavelength($\lambda_{-90} - \lambda_{+90}$nm)	255-420	322-396	403-545	554-684	695-833	846-1000	937-1000
Wide imaging(5σ depth)	25.4	25.4	26.3	26.0	25.9	25.2	24.4
deep imaging(5σ depth)	26.7	26.7	27.5	27.2	27.0	26.4	25.7

Key advantages of CSST in searching dwarf galaxies

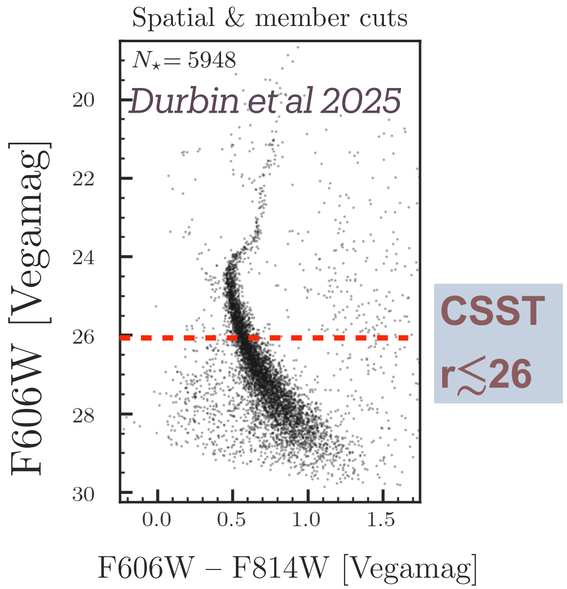
CSST观测矮星系的三大优势



大视场深度测光

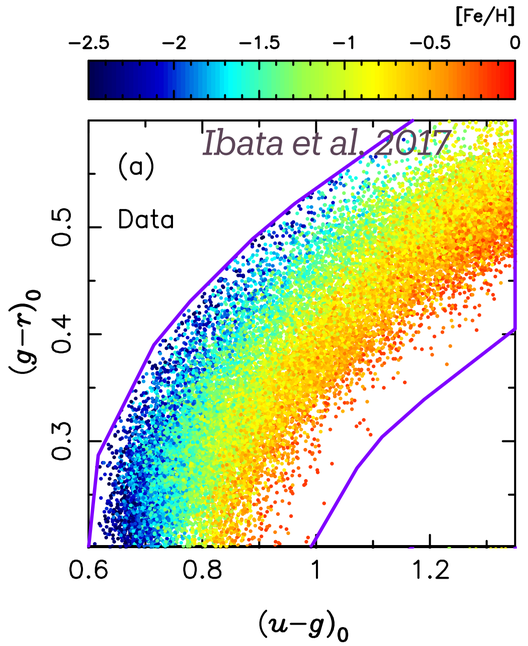
Wide field-of-view: 1.1 sq deg

17,500 sq deg (40% of whole sky)



有效分辨恒星/星系

Spatial resolution: 0.15”



光学波段更易分辨贫金属星族

Optical filters: nuv+ugrizy

+ CαHK

band and limiting photometric

band	NUV	u	g	r	i	z	y
wavelength($\lambda_{-90} - \lambda_{+90}$nm)	255-420	322-396	403-545	554-684	695-833	846-1000	937-1000
Wide imaging(5σ depth)	25.4	25.4	26.3	26.0	25.9	25.2	24.4
deep imaging(5σ depth)	26.7	26.7	27.5	27.2	27.0	26.4	25.7

总结&预期成果

- 系统搜寻20+矮星系矮潮汐半径结构，获得不同半径处
  - 金属丰度&恒星形成历史
  - 构建化学演化历史
- 获得首个epoch位置坐标
  - 结合HST, 获得10年间隔的自行测量(~20μas/yr)
  - 计算Gaia, HST offset
  - 结合主巡天, 将获得独立自行测量
- RRL变星的epoch观测 (~20次/per)

	name	rhalf	ns
2	Fornax	19.9	2028349
6	Sculptor	11.17	359022
19	Leo I	3.65	159660
7	Carina	10.1	80062
3	Ursa Minor	18.3	74888
9	Draco	9.67	64187
1	Sextans	22.8	52996
22	Leo II	2.52	28539
13	Canes Venatici I	7.12	14041
8	Bootes I	9.97	5793
12	Hydrus I	7.42	4160
10	Carina II	8.69	2700
4	Ursa Major II	13.8	2520
17	Hercules	5.63	2135
16	Coma Berenices	5.64	1837
11	Ursa Major I	8.31	1701
20	Centaurus I	2.6	1629
5	Tucana II	12.89	844
14	Reticulum II	6.3	821
21	Leo IV	2.54	774
18	Aquarius II	5.1	733
15	Grus II	5.9	682