Dark matter in dwarf galaxies

Se-Heon Oh

Department of Physics and Astronomy
Sejong University

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- Small-scale challenges to the ΛCDM paradigm: Cusp/core problem
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Small-scale problems of ΛCDM based simulations at galaxy scales

- ΛCDM simulations have provided a framework for understanding the observed structure formation of the universe across scales, ranging from the horizon (~15,000 Mpc) to the typical spacing between galaxies (~1 Mpc)

- At scales below ~1 Mpc, specifically at individual galaxy scales, certain observational challenges have been encountered:

  1) missing satellites problem
  2) cusp/core problem
  3) angular momentum problem
  4) too big to fail problem

Small-Scale Challenges to the ΛCDM Paradigm (Bullock & Boylan-Kolchin, ARAA, 2017)

Missing satellites problem

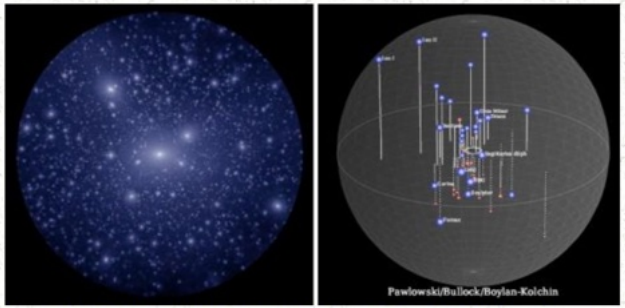


Figure 7. The Missing Satellites Problem: Predicted ΛCDM substructure (left) vs. known Milky Way satellites (right). The image on the left shows the ΛCDM dark matter distribution within a sphere of radius 250 kpc around the center of a Milky-Way size dark matter halo (simulation by V. Robles and T. Kelley in collaboration with the authors). The image on the right (by M. Pawlowski in collaboration with the authors) shows the current census of Milky Way satellite galaxies, with galaxies discovered since 2015 in red. The Galactic disk is represented by a circle of radius 15 kpc at the center and the outer sphere has a radius of 250 kpc. The 11 brightest (classical) Milky Way satellites are labeled by name. Sizes of the symbols are not to scale but are rather proportional to the log of each satellite galaxy's stellar mass. Currently, there are ~ 50 satellite galaxies of the Milky Way compared to thousands of predicted subhalos with $M_{\rm peak} \geq 10^7\, M_\odot$.

Cusp/core problem

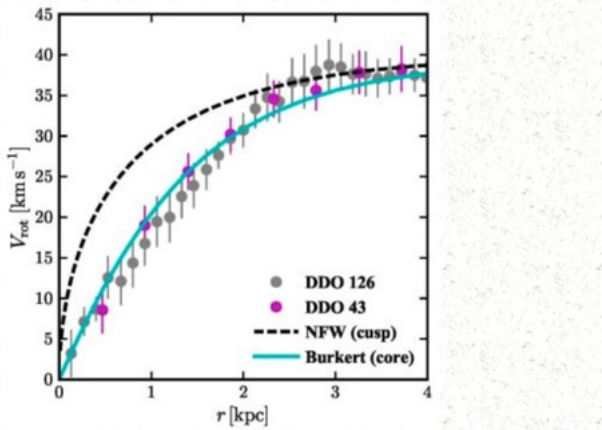


Figure 9. The Cusp-Core problem. The dashed line shows the naive ΛCDM expectation (NFW, from dark-matter-only simulations) for a typical rotation curve of a $V_{\rm max} \approx 40$ km s^{-1} galaxy. This rotation curve rises quickly, reflecting a central density profile that rises as a cusp with $\varrho \propto 1/r$. The data points show the rotation curves of two example galaxies of this size from the LITTLE THINGS survey (Oh et al. 2015), which are more slowly rising and better fit by a density profile with a constant density core (Burkert 1995, cyan line).

Too big to fail problem

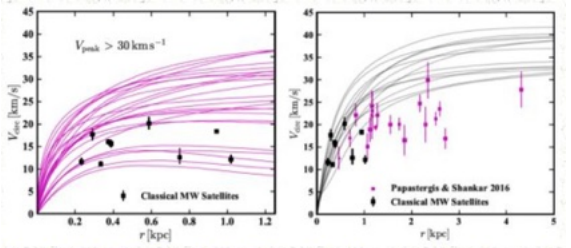
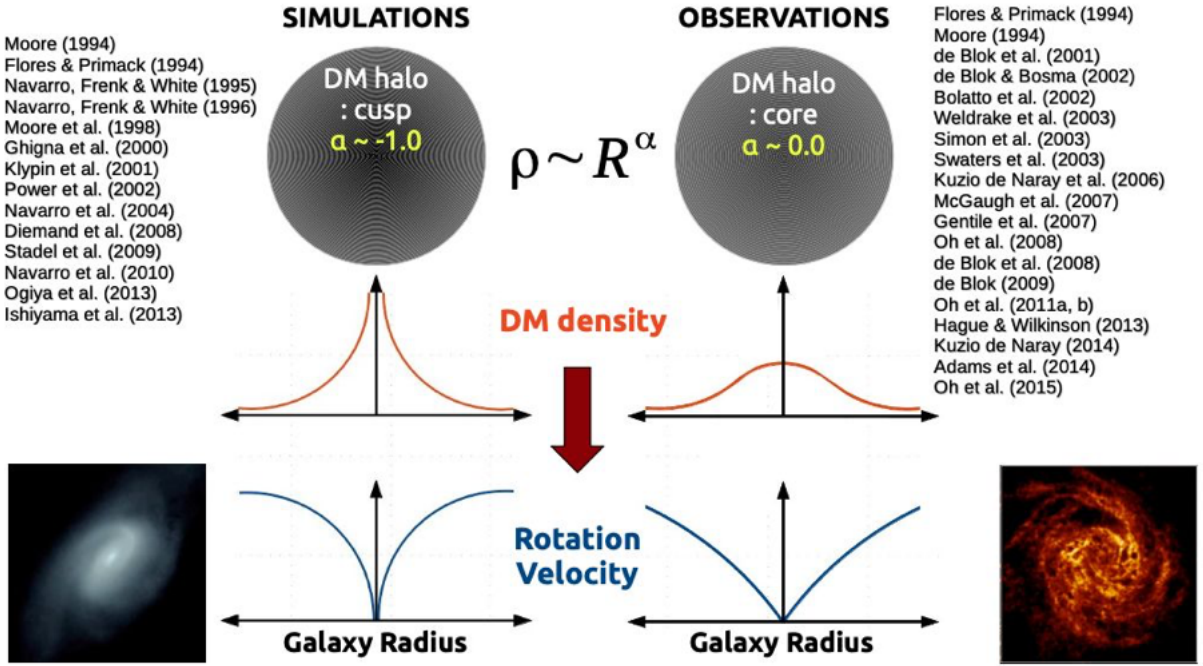


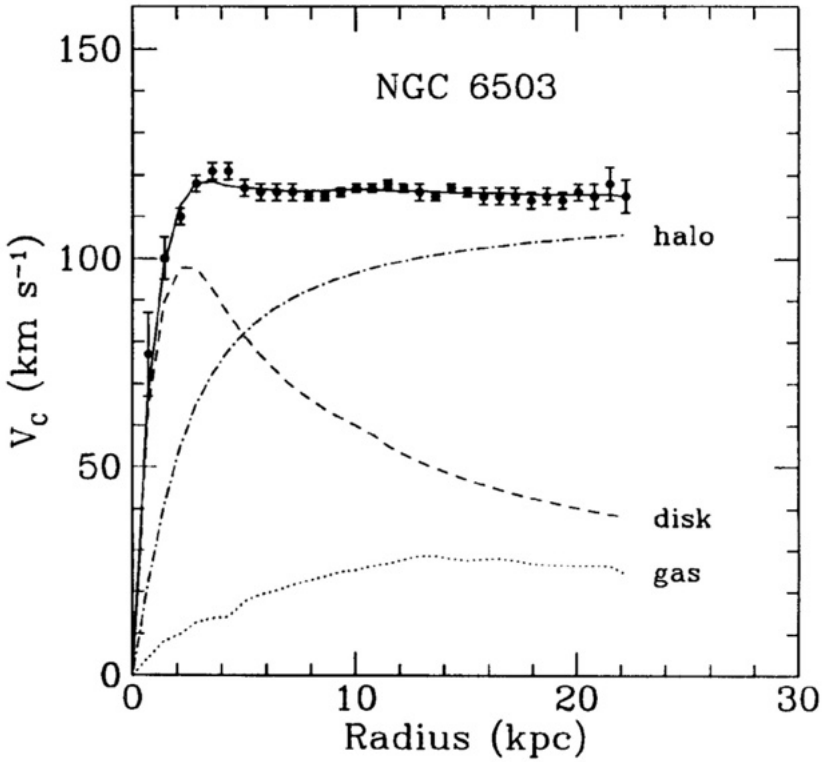
Figure 10. The Too-Big-to-Fail Problem. *Left:* Data points show the circular velocities of classical Milky Way satellite galaxies with $M_* \approx 10^{5-7}\, M_\odot$ measured at their half-light radii $r_{1/2}$. The magenta lines show the circular velocity curves of subhalos from one of the (dark matter only) Aquarius simulations. These are specifically the subhalos of a Milky Way-size host that have peak maximum circular velocities $V_{\rm max} > 30$ km s^{-1} at some point in their histories. Halos that are this massive are likely resistant to strong star formation suppression by reionization and thus naively too big to have failed to form stars (modified from Boylan-Kolchin, Bullock & Kaplinghat 2012). The existence of a large population of such satellites with greater central masses than any of the Milky Way's dwarf spheroidals is the original Too-Big-to-Fail problem. *Right:* The same problem – a mismatch between central masses of simulated dark matter systems and observed galaxies – persists for field dwarfs (magenta points), indicating it is not a satellite-specific process (modified from Papastergis & Ponomareva 2017). The field galaxies shown all have stellar masses in the range $5.75 \leq \log_{10}(M_* / M_\odot) \leq 7.5$. The gray curves are predictions for ΛCDM halos from the fully self-consistent hydrodynamic simulations of Fitts et al. (2016) that span the same stellar mass range in the simulations as the observed galaxies.

DM cusps? or DM cores?



1) Observational systematics?
   - centre offset
   - non-circular motions
   - beam smearing?
2) If not, what causes DM cores?
   - Baryon-induced DM cores? (e.g., SNe-driven gas outflows over cosmic time)
   - Even mild star formation is capable of erasing the cusp over an extended period of time

DM in galaxies (at kpc scales): flat rotation curves



- Flat rotation curves (RCs) of spirals traced by

  1) Hot ionized emissions or stellar absorptions (Ford & Rubin etc.)

  2) Cold neutral hydrogen gas (25 spirals; Bosma etc.)

  → This V_c=const (i.e., M~R, $\rho \sim R^{-2}$) is in sharp contrast to the prediction of the Keplerian decline of $R^{-0.5}$

- can examine the internal DM structure, especially at the centers of galaxies

Tracers for galaxy dynamics

1) Spirals

- ➔ stars (absorptions, e.g, carbon stars)
- ➔ hot ionized gas (emissions, e.g., H-alpha)
- ➔ cold gas (emissions, e.g., HI, CO)



2) Ellipticals

- ➔ stars (absorptions)
- ➔ PNs
- ➔ cold gas (HI) in the outer parts
- ➔ stellar velocity dispersions

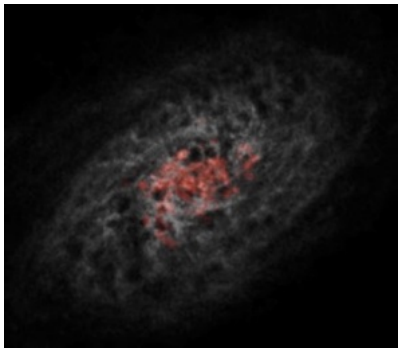


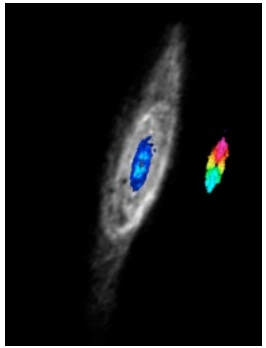
3) Dwarfs

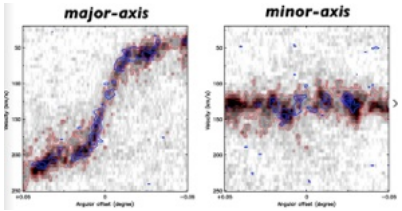
- ➔ stars (absorptions)
- ➔ cold gas (emissions, HI)
- ➔ hot ionized gas (emissions, e.g., H-alpha)

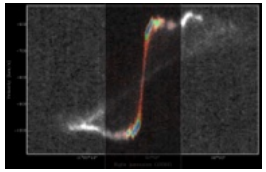


Spiral galaxies (circular rotation dominated)







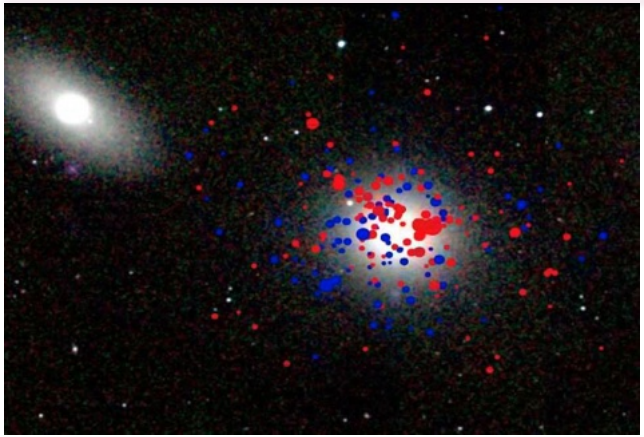


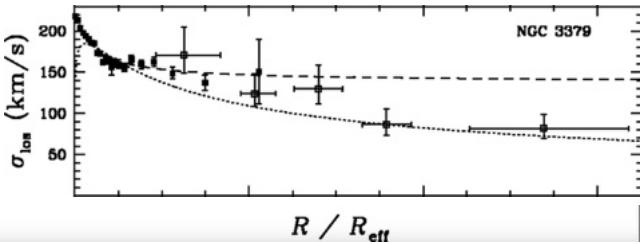
Frank et al. (2012)

Leroy et al.

- Stars (absorptions, e.g, carbon stars)
- Hot ionized gas (emissions, e.g., H-alpha)
- Cold gas (emissions, e.g., HI, CO)

Elliptical galaxies (velocity dispersion dominated)





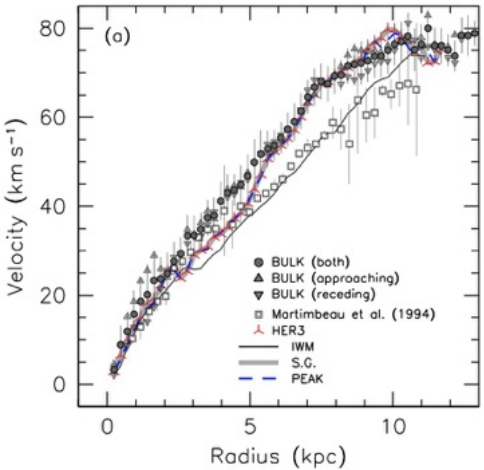
Romanowsky et al. (2003)

- Planetary Nebulae (PNs)
- Cold gas (HI) in the outer parts
- Stellar velocity dispersions

Dwarf galaxies (circular rotation dominated)







- Stars (absorptions)
- Cold gas (emissions, HI)
- Hot ionized gas (emissions, e.g., H-alpha)

Oh et al. (2010)

Dwarf galaxies?



- Dwarf Irregulars (dIrrs)

  → gas rich / on-going star formation
  → circular rotation dominated
  → no bulge / spiral structures, fewer stars



- Dwarf Spheroidals (dSphs)

  → lack of gas / star formation
  → stellar dispersion-supported systems
  → lack of gas
  → typically, satellites

1) Bright dwarfs
   - M_* : $10^{7\text{-}9}$ Msun
   - Mvir: 10^{11} Msun

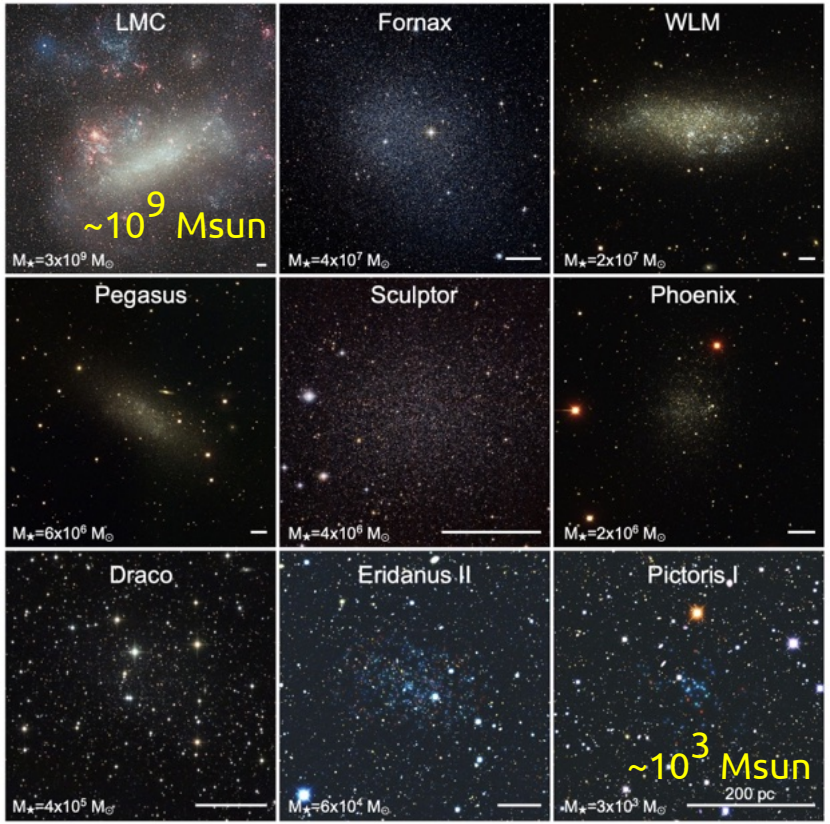
2) Classical dwarfs
   - M_* : 10^{6} Msun
   - Mvir : 10^{10} Msun

3) Ultra-faint dwarfs
   - M_* : 10^{4} Msun
   - Mvir : 10^{9} Msun

Dwarf galaxies

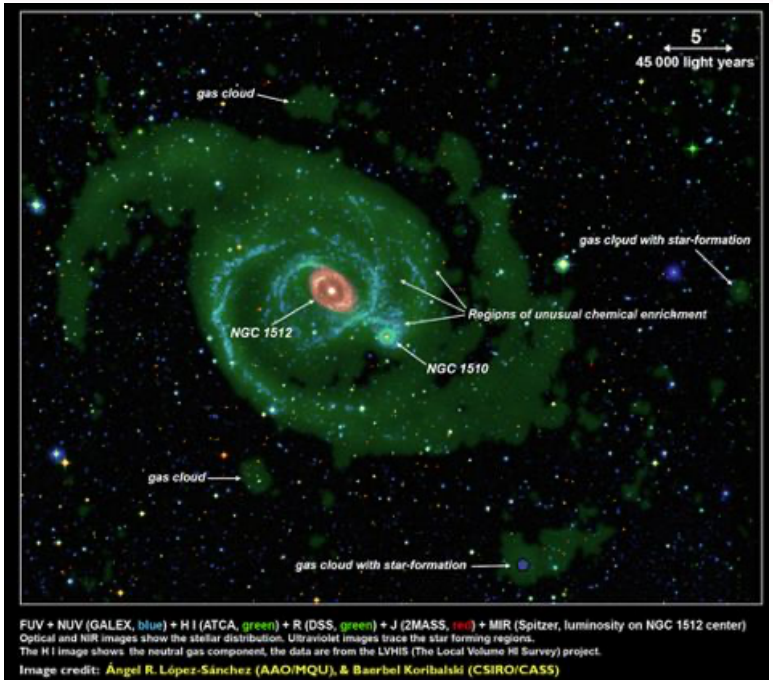
Dwarf Irregulars
(gas rich, star forming)

Dwarf Spheroidals
(gas poor, quiescent)



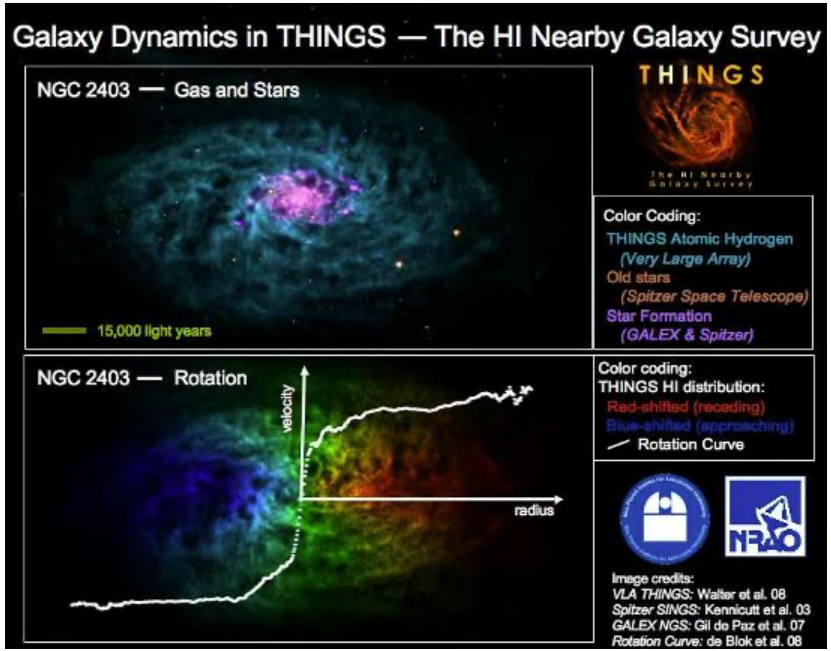
Bullock & Boylan-Kolchin (2017)

Neutral hydrogen (HI) gas in galaxies



- The fuel supply for star formation in galaxies
- Important gas reservoir for star formation in galaxies

Neutral hydrogen (HI) gas in galaxies



- A powerful probe of the mass distribution in galaxies (dark matter)
  (de Blok, Oh et al. 2008, Oh et al. 2008, 2010, 2011, 2015, 2018, 2022)
- Further extended than stars in the disk (typically > 3 times)

Neutral hydrogen (HI) gas in galaxies

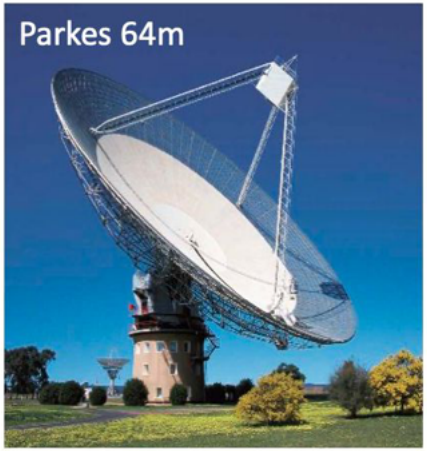
- Observational aspects of HI 21cm radiation
  - HI 21cm emission decay half life: ~10 million years
  - HI 21cm emission ~10^7 times less power than Hα emission
    - Total HI gas in galaxies ~ 10^7 to 10^{10} Msun

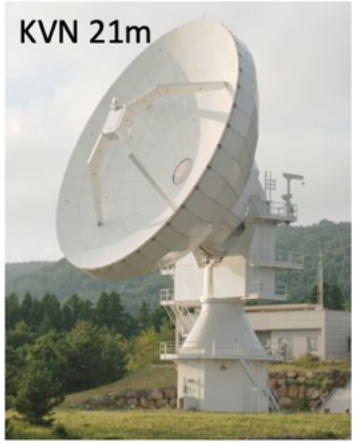
    (1 Msun ~ 2.0 x 10^{33}g → 1.2 x 10^{57} hydrogen atoms)

    → HI 21cm luminosity of ~2 x 10^{32} to 2 x 10^{35} ergs/s

    →For typical star forming galaxies: H-alpha emission luminosity ~ 3 x 10^{39} to 3 x 10^{42} ergs/s

Single dish radio telescope

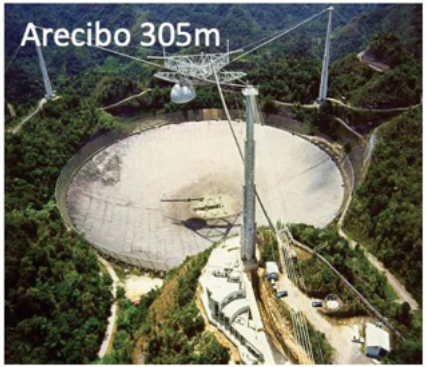












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Arecibo telescope collapses, ending 57-year run

Heavy instrument platform falls before engineers can perform controlled demolition

1 DEC 2020 • BY ERIC HAND



Engineers are concerned other cables could also break at any time, making any attempt at repair excessively dangerous. Photo: Reuters





Arecibo Observatory staff believe one of the remaining suspension cables broke on 1 December, sending the 900-ton instrument platform crashing into the dish.

❑ FAST 500m dish





❑ Radio interferometers

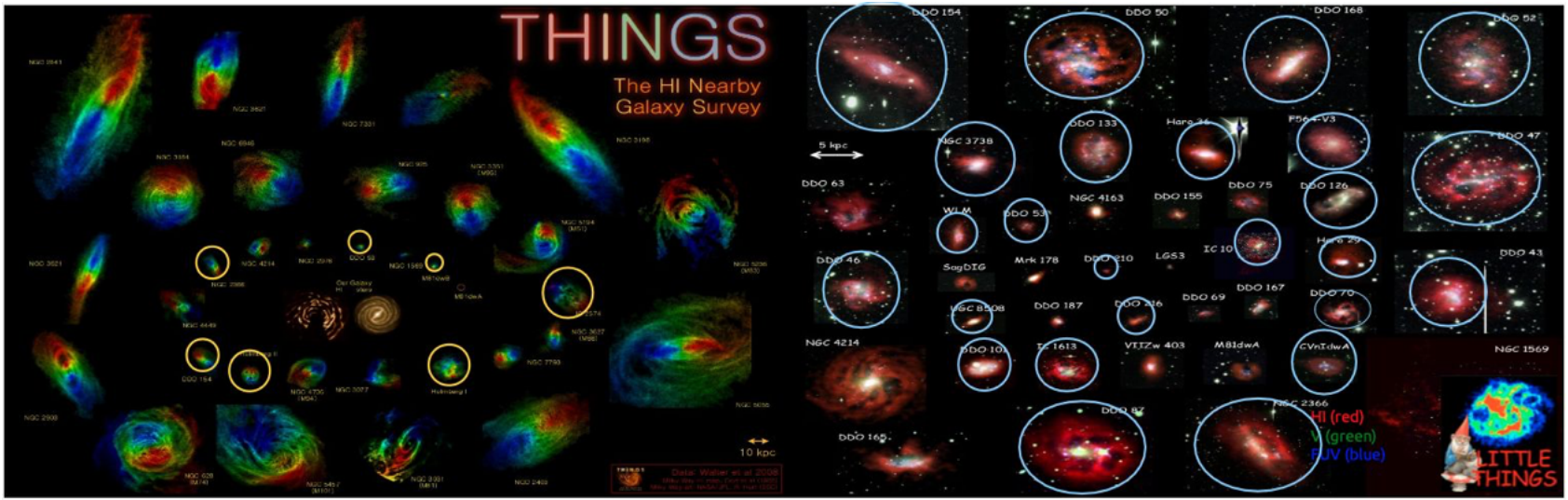


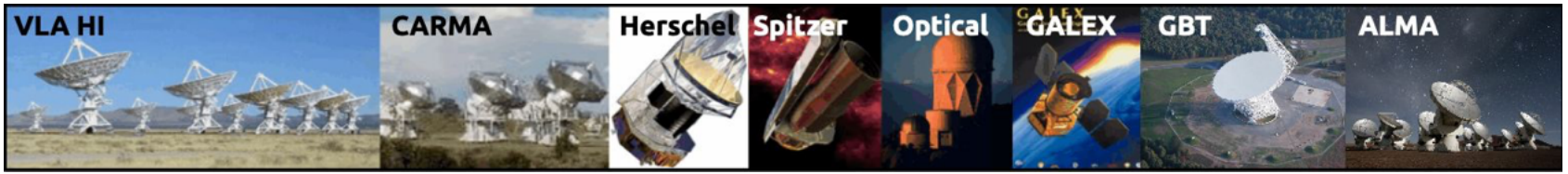






High-resolution HI observations of dwarf galaxies in the local Universe





Galaxy rotation curve analysis



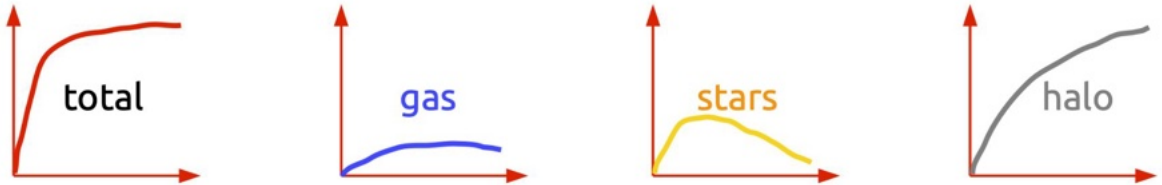
$M_{total} = M_{gas} + M_{star} + M_{halo}$

$V^2_{total} = V^2_{gas} + V^2_{star} + V^2_{halo}$

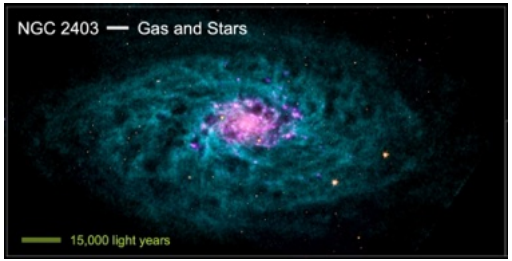
1.4 M_{HI}

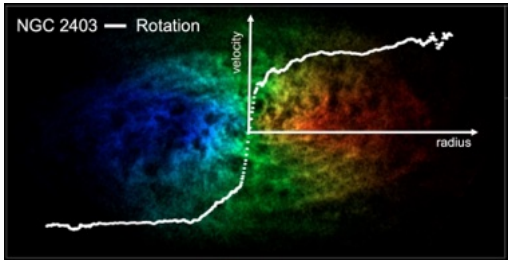
M/L based on 3.6m Spitzer

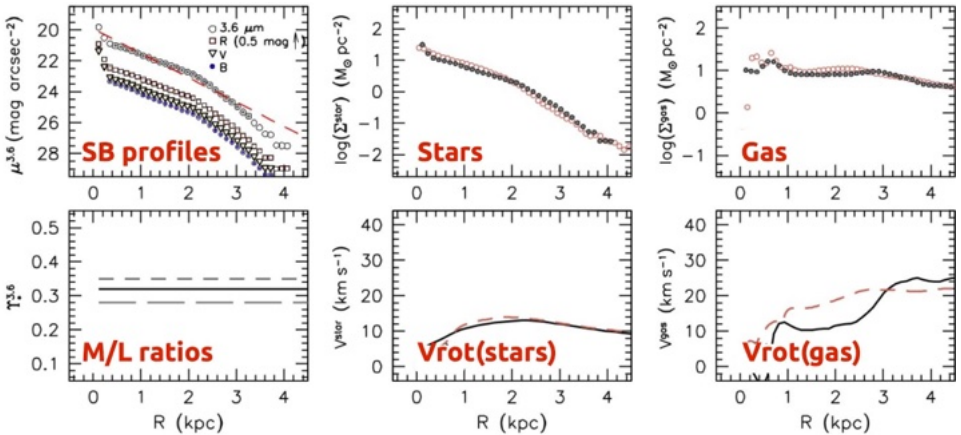
cusp or core?

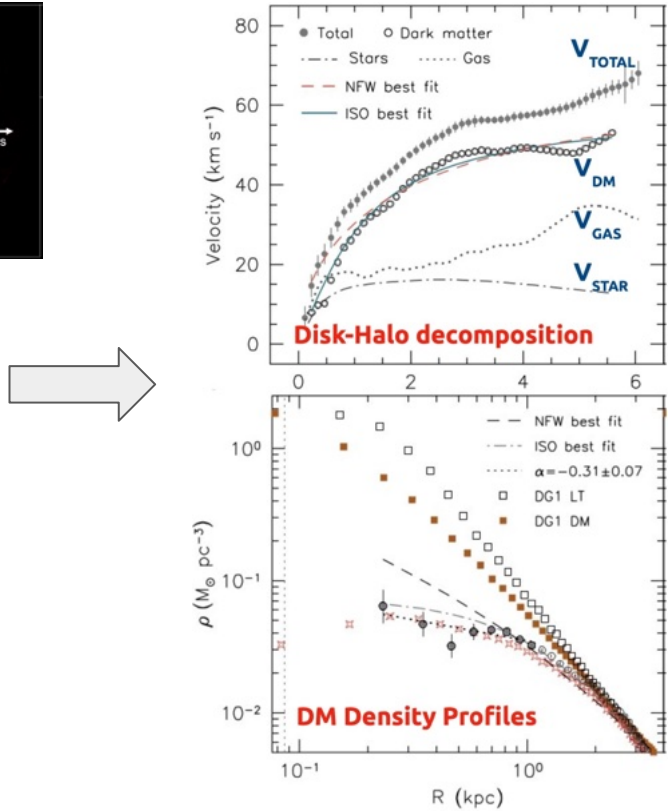


Galaxy rotation curve traced by HI 21cm emission line



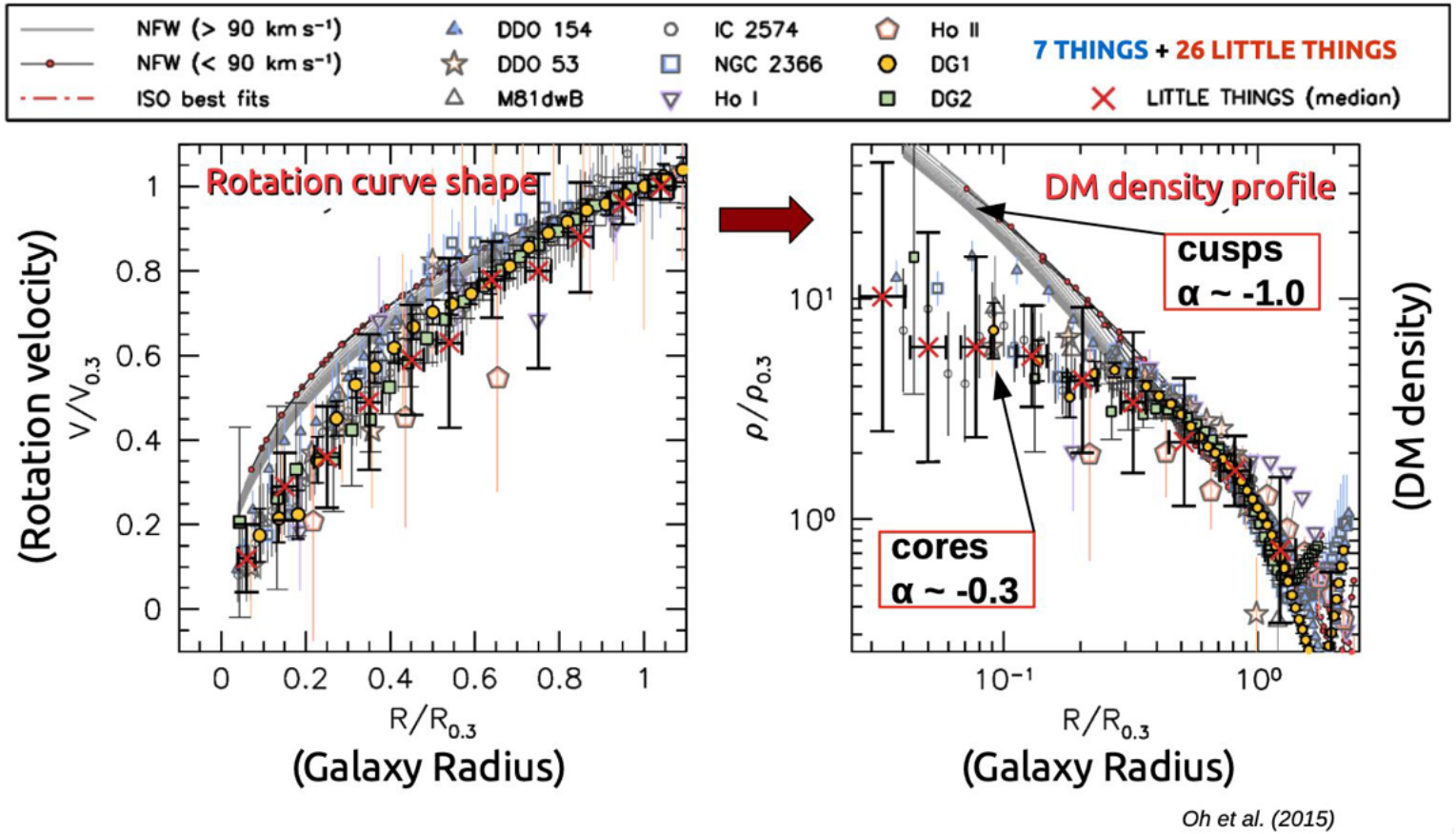






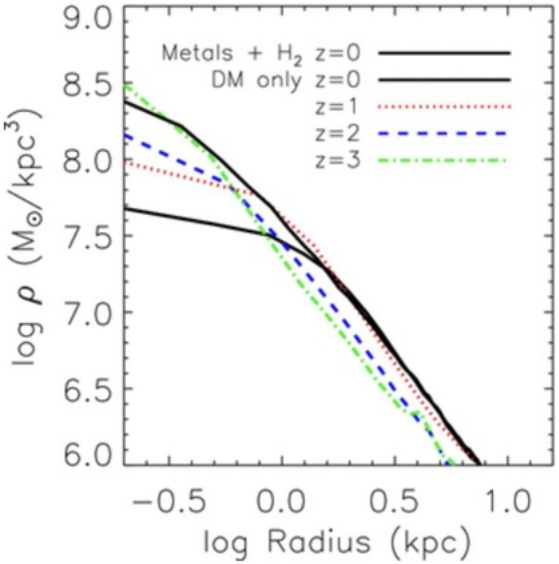
Dark matter distribution in dwarf galaxies

: THINGS + LITTLE THINGS + SPH+N-body ΛCDM simulations

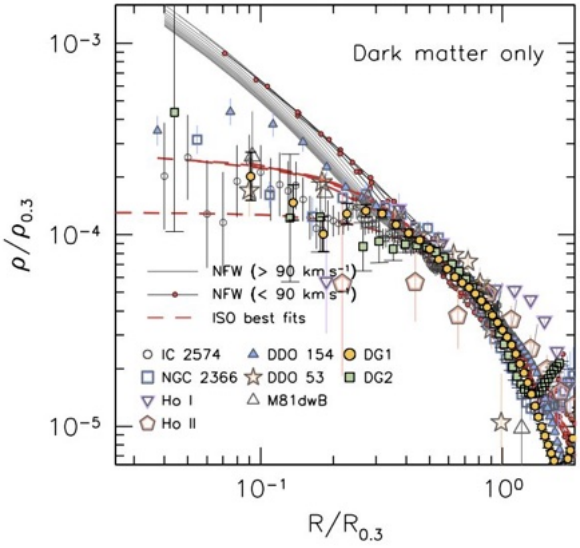


Oh et al. (2015)

Solutions within the LCDM paradigm



Governato et al. (2012)



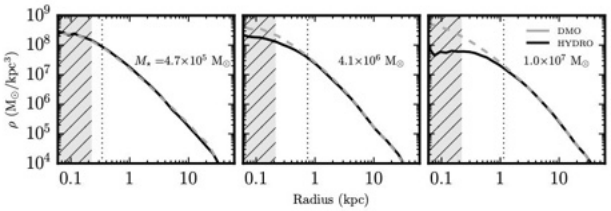
Oh + Governato et al. (2012)

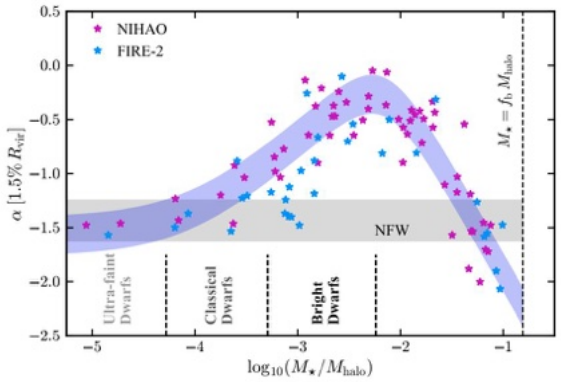
- Baryon induced DM cores in low mass galaxies

→ Repeated gas outflows driven by supernova explosions can displace baryons with low angular momentum outward

→ The gravitational response to the dark matter (DM) halo induces the formation of DM cores over cosmic time

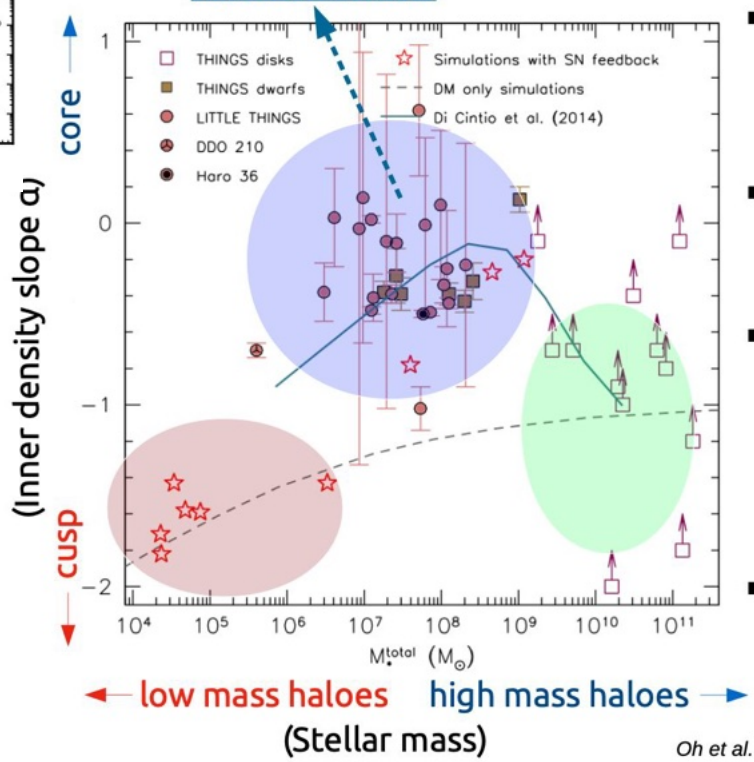
SN-feedback on the central cusps in CDM haloes
: Observations vs. simulations





Bullock & Boylan-Kolchin (2017)

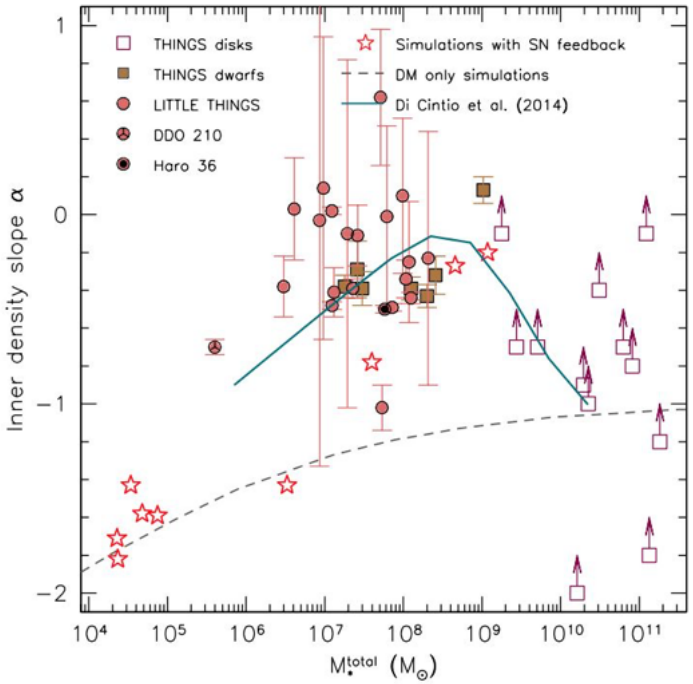
Observational selection effect?



- **In low mass haloes:** SN-feedback gets less efficient so cores at fixed radius get smaller (cuspy)
- **In intermediate mass haloes:** SN-feedback is efficient enough to change the cusps into cores
- **In high mass haloes:** SN-feedback is surpassed by the deep gravitational potential caused by stars in the central region (*halo contraction rather than expansion*)
- *Low-mass dwarfs are the key for the ultimate test of the SN-feedback scenario in ΛCDM simulations*

Oh et al. (2015); see also Pontzen & Governato (Nature, 2014)

Near-field cosmology with low mass dwarf galaxies



1) Usually, DM dominated (low Mbar fraction)

2) No spiral arms and bulge, which reduces the d.o.f of mass modelling

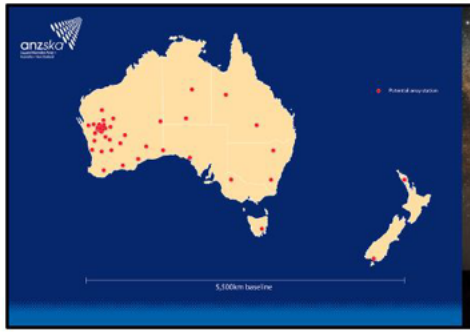
3) Irregular rotation pattern in velocity fields (easily stirred up by hydrodynamical processes like SF)

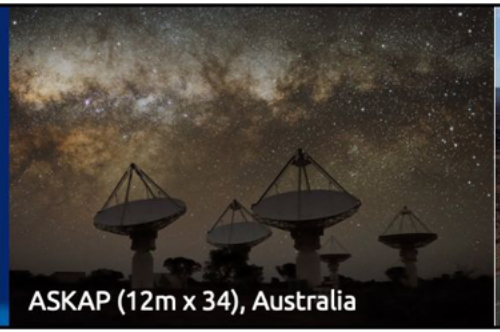
4) Shallow velocity gradient across the major axis

5) Still rising even at the outermost part

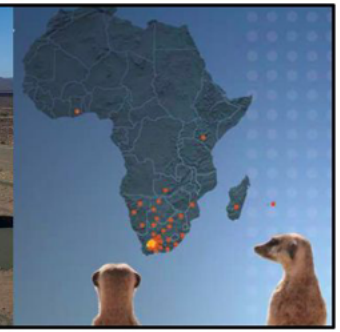
6) Low HI column densities

Square Kilometre Array (SKA): the next generation radio interferometry











Square Kilometre Array (SKA): the next generation radio interferometry

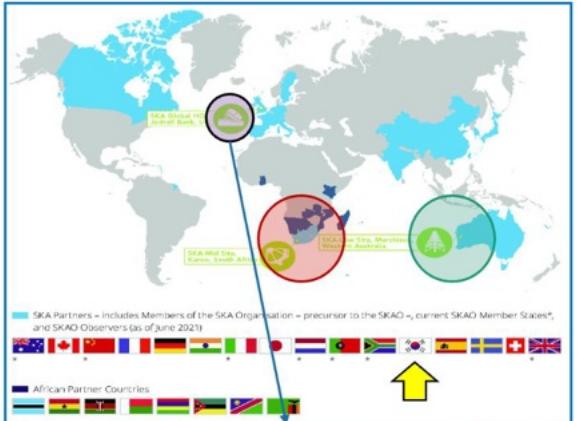
❑ 국제공조 거대 전파망원경 프로젝트 | SKA : Square Kilometre Array



- SKA1 저-주파수(50 ~ 350 MHz) 전파망원경 배열 (13만개)
- 서호주 머치슨 사막지역 설치



- SKA1 중-주파수(0.35 ~ 15 GHz) 전파망원경 배열 (200개)
- 남아공 카루 사막지역 설치

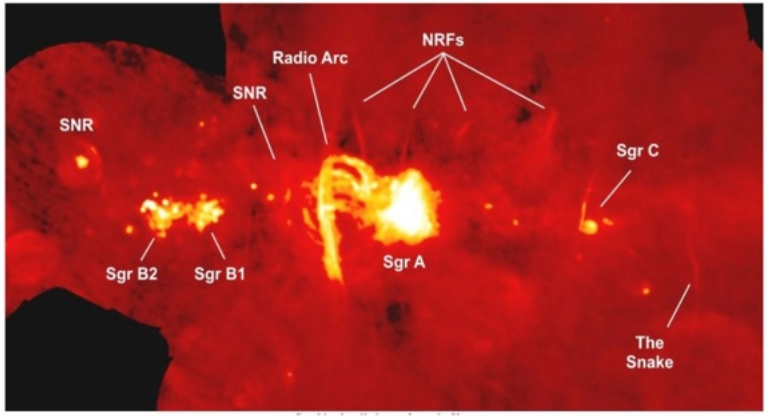




- 국제 SKA 본부
- 영국 맨체스터 조드럴뱅크 전파천문대
- SKA 건설/운영 및 연구 총괄

- 우주에서 방출되는 저/중-주파수 전파영역의 전자기파 관측을 통한 천문우주 연구
- 현존하는 최고 성능의 전파망원경들을 압도하는 탁월한 관측 성능
- 총 사업비용: ~1.5조원
- SKA1 구축 일정: 2021년 ~ 2027년
- 2025년부터 관측 시작 / 금세기 동안 운영
- 2022년 8월 현재 11개국이 정식으로 참여

- SKA-Korea 워킹 그룹 (2009년 ~ 현재)
  - 30여명의 국내 연구자들로 구성
  - 지난 10여년 동안 한국의 SKA 참여방안 논의와 SKA 과학연구활동 지속



VS



현존하는 최고 성능의 전파망원경 (VLA-미국)을
이용한 중-주파수 대역 전파 관측

SKA 프리커서 전파망원경 (MeerKAT - 남아공)을
이용한 중-주파수 대역 전파 관측





