@ “prehistory” calculations (2008-2012)
@ MesoPSL (2012 -)
@ Turing/Idris (2016 -)

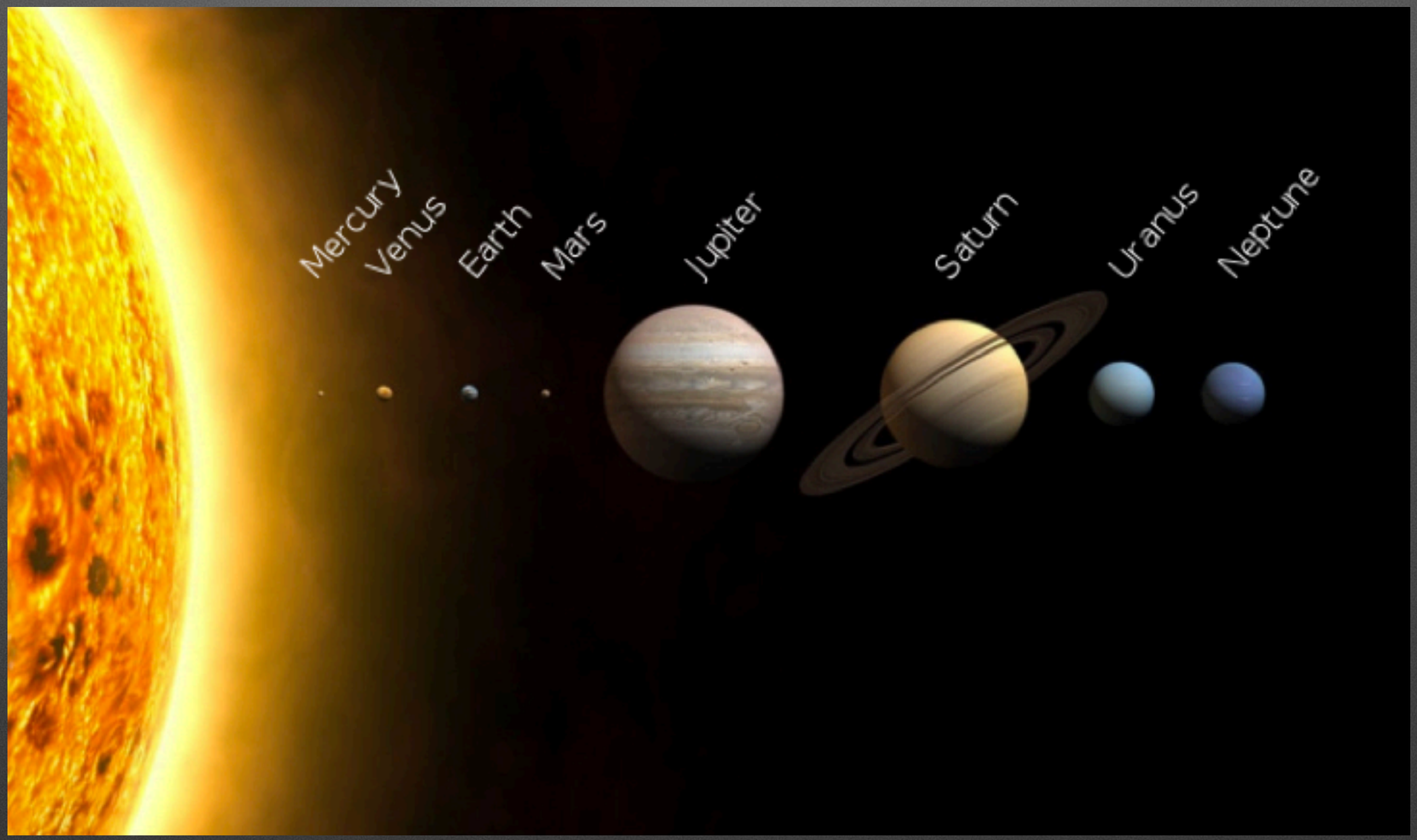
The galactic dynamics in the Local Group
N-body Hydrodynamic simulations

- The origin of the Magellanic Stream System
- The Formation history of M31 (Andromeda galaxy)
- Dwarf galaxies in the Milky way halo
- Hot and diffused gas in the Milky way halo
- The mass profile of the Milky way

Yanbin Yang, Francois Hammer, Jianling Wang*, Hector Flores,
Mathieu Puech, Frederic Arenou, Carine Babusiaux**, Hadi Rahmani

Laboratoire d'Etudes des Galaxies, Etoiles, Physique et Instrumentation (GEPI)
Observatoire de Paris (Meudon) ; CNRS
*National Astronomical Observatories, China (NAOC)
**Université Grenoble Alpes

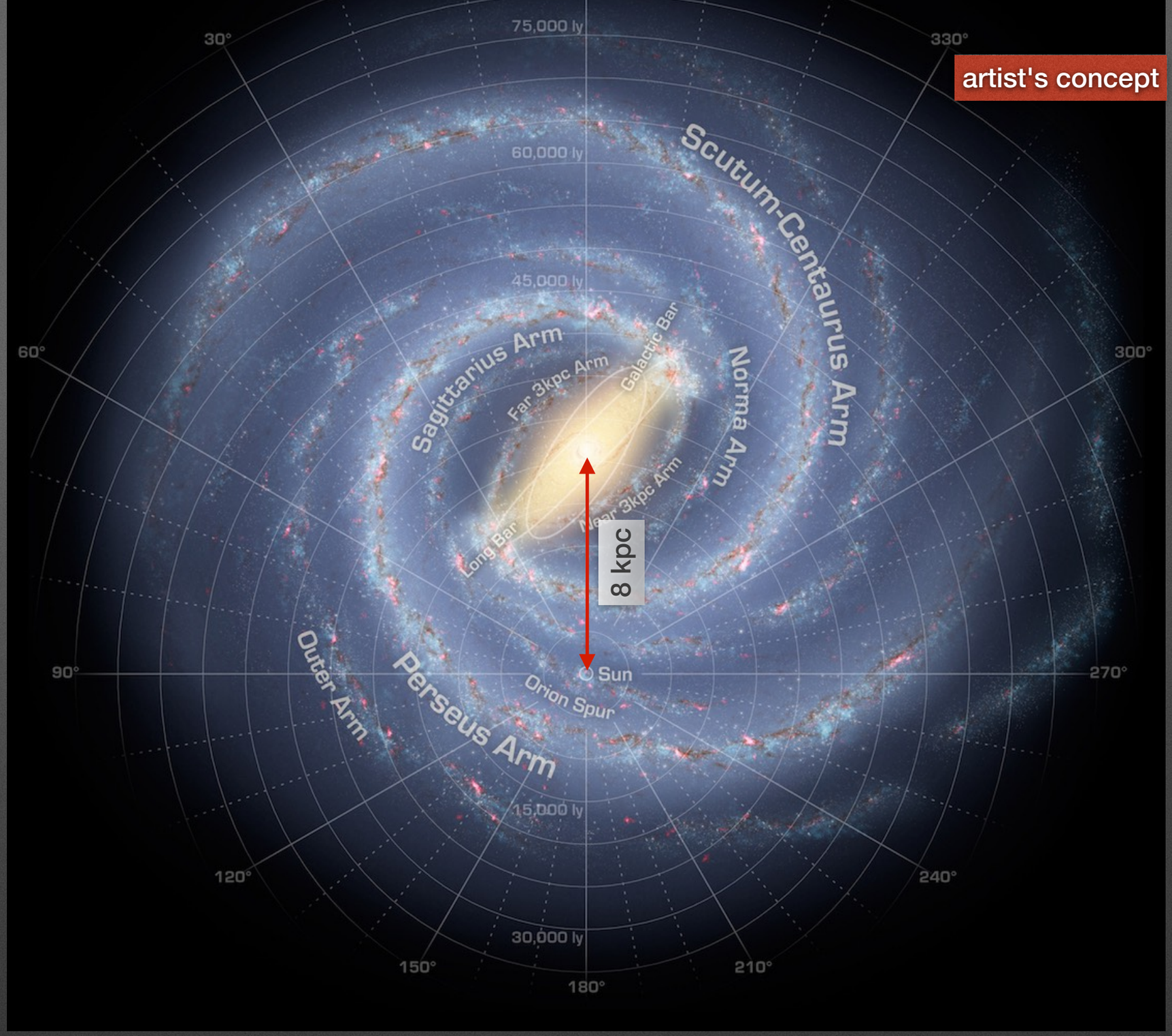
- Scientific motivations
- Methodology & techniques
  - Code : Gadget2 (Springel, 2005)
  - Code : Gizmo (Hopkins, 2014)
  - Star formation module : “Cox06” (Cox et al. 2006)
- Results
  - Publications since 2012
  - M31 and the Challenge on Astro-A 2018
  - Magellanic Stream and Clouds
  - MW dwarf galaxies
- Future work



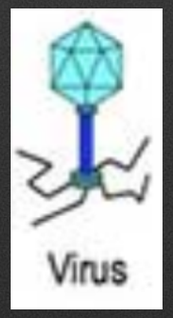
30 AU = 4.5×10^9 km


FloriansPhotographs.blogspot.com

30 m



30 kpc = 9.2 x 10^{17} km



0.14 micron

4.5x10^{9} km

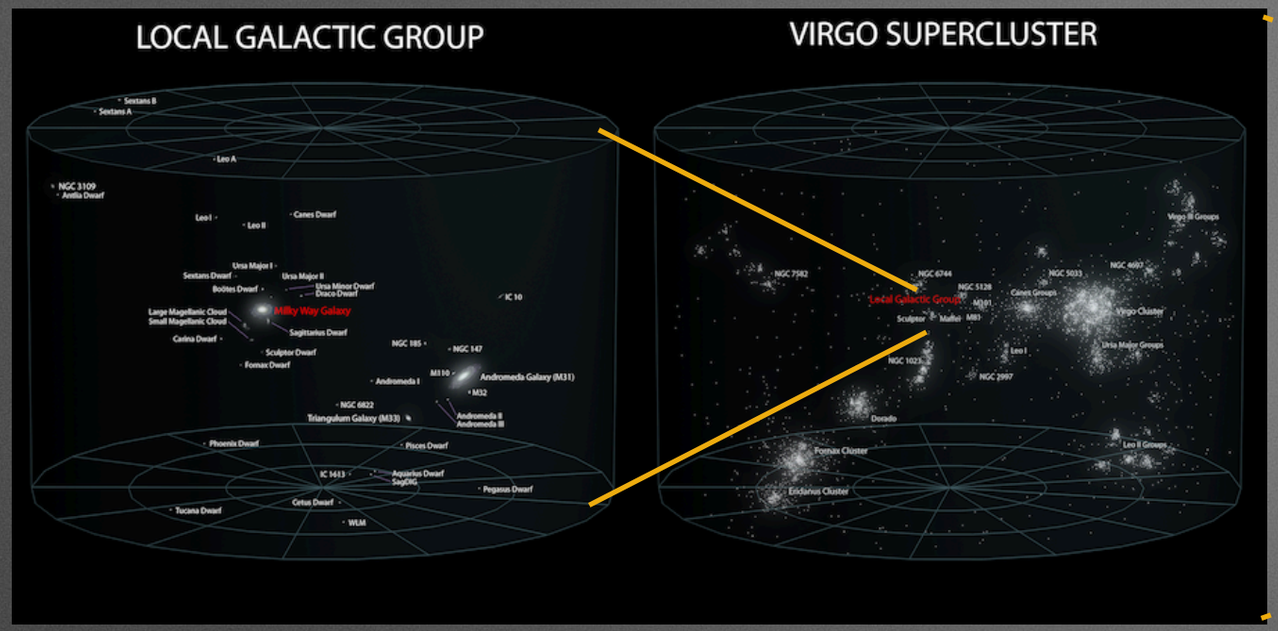
1 pc = 1 parsec = 3.26 light-year
1 kpc = 1000 pc ;

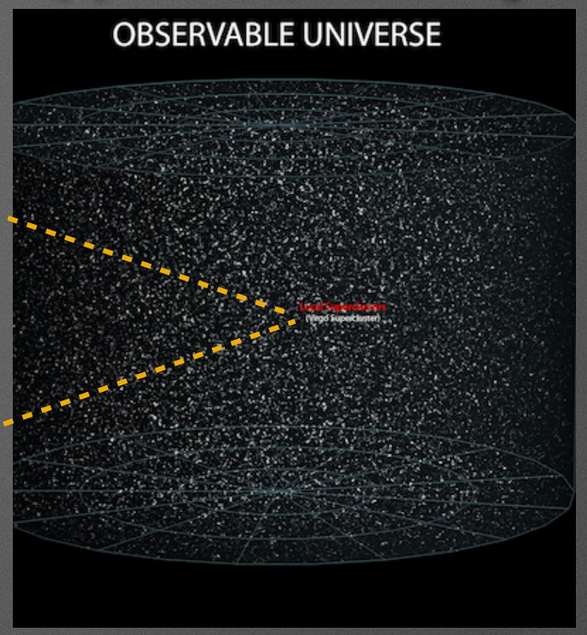
LOCAL GALACTIC GROUP

Sextans B
Sextans A
Leo A
NGC 3109
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
Ursa Major I
Sextans Dwarf
Ursa Major II
Boötes Dwarf
Ursa Minor Dwarf
Draco Dwarf
IC 10
Large Magellanic Cloud
Small Magellanic Cloud
Milky Way Galaxy
Sagittarius Dwarf
Carina Dwarf
780 kpc
NGC 147
Sculptor Dwarf
Fornax Dwarf
M110
Andromeda Galaxy (M31)
Andromeda I
M32
NGC 6822
Triangulum Galaxy (M33)
Andromeda II
Andromeda III
Phoenix Dwarf
Pisces Dwarf
1Mpc (1000 kpc)
IC 1613
Aquarius Dwarf
SagDIG
Pegasus Dwarf
Cetus Dwarf
Tucana Dwarf
WLM

redshift (z) ~ 0.0 , T ~ today

redshift (z) ~ 0.6 , T ~ 8Gyr ago





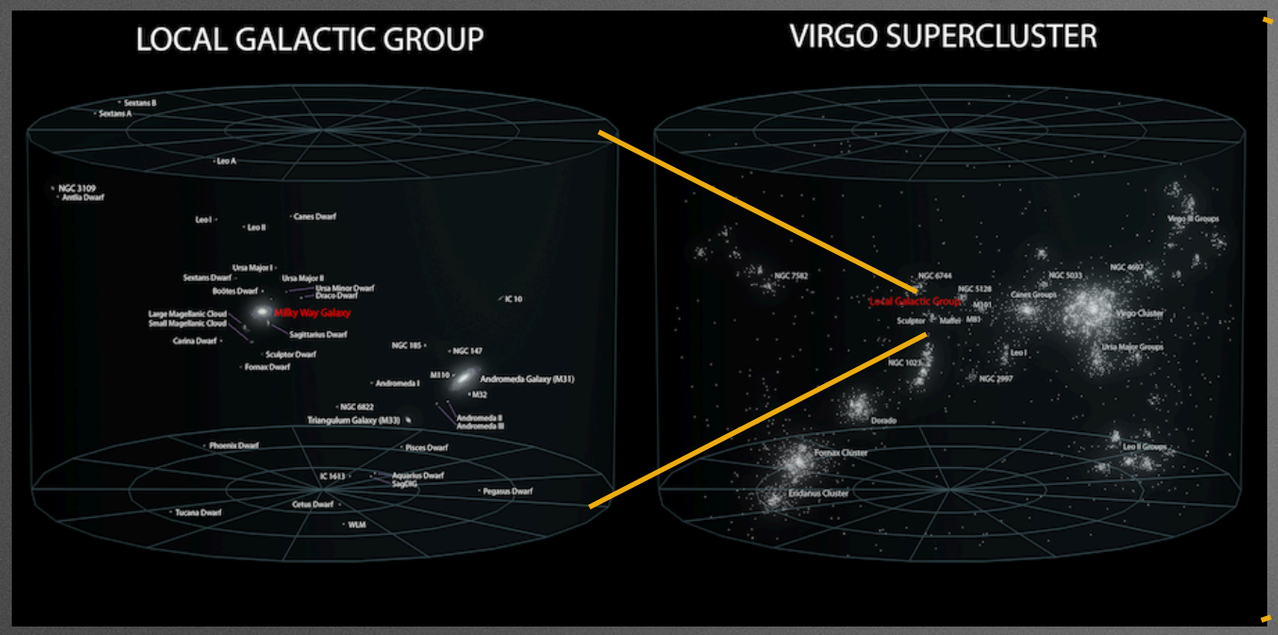
2 Mpc

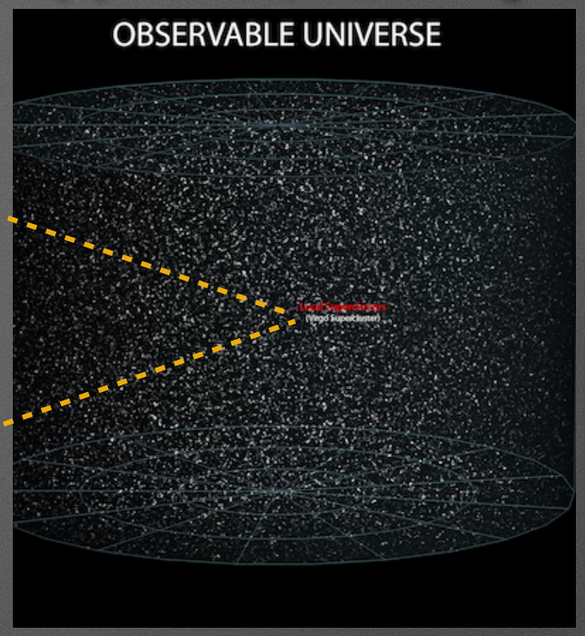
33 Mpc

~3000 Mpc

redshift (z) ~ 0.0 , T ~ today

redshift (z) ~ 0.6 , T ~ 8Gyr ago



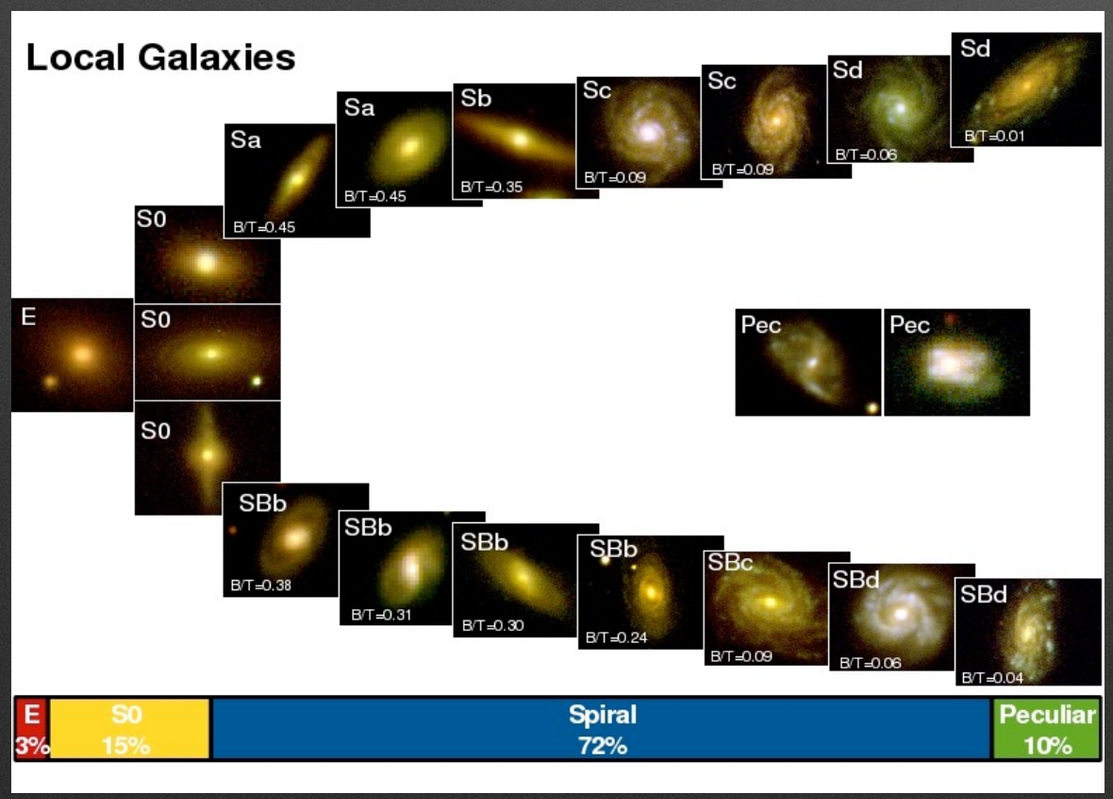


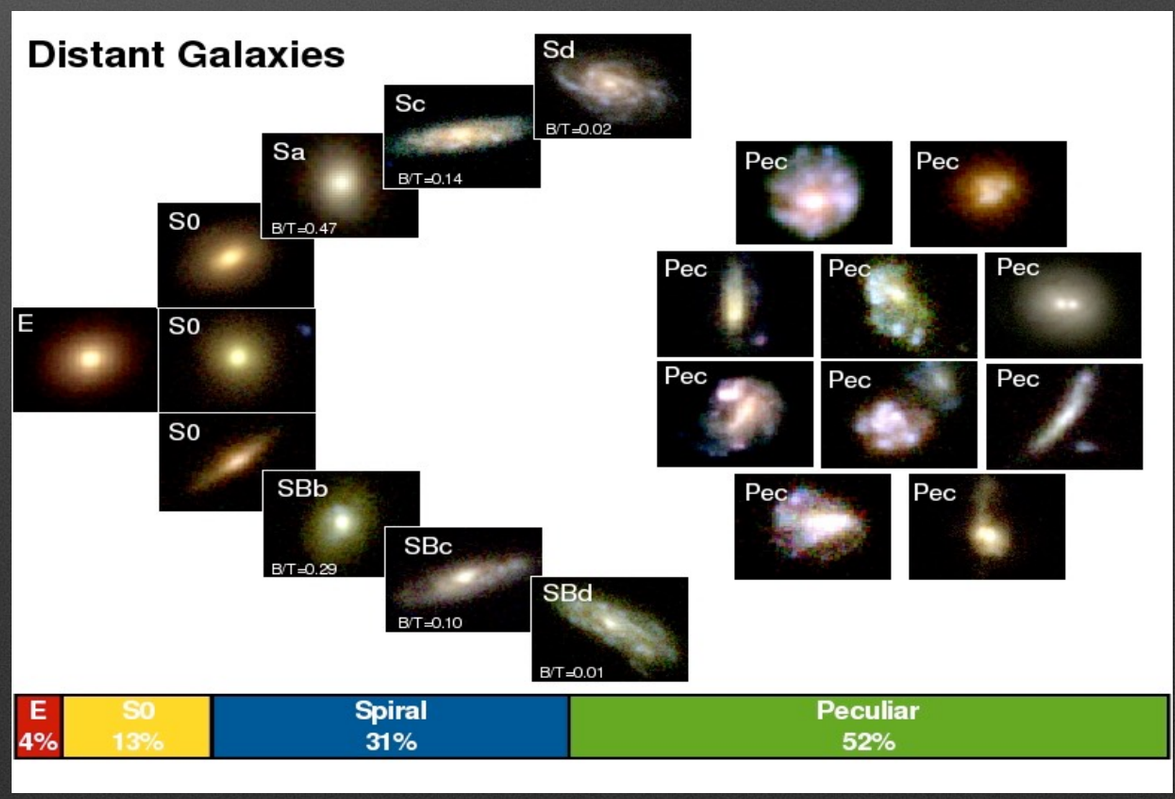
2 Mpc

33 Mpc

~1500 Mpc

Hubble sequence





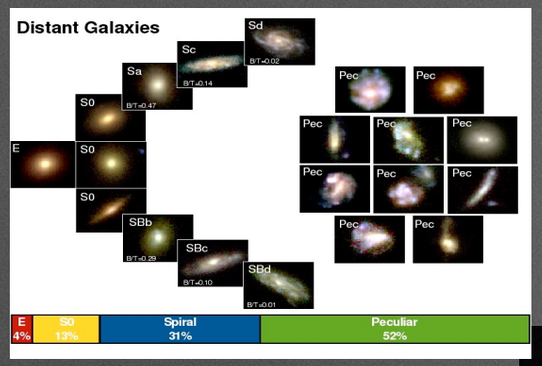
-E/SO were mostly in place
-Half of spirals did not.

Major merger

IMAGES (VLT large program)

- HST **morphology**
- IFU@VLT 2D **kinematics** maps
- N-body/SPH **simulations**

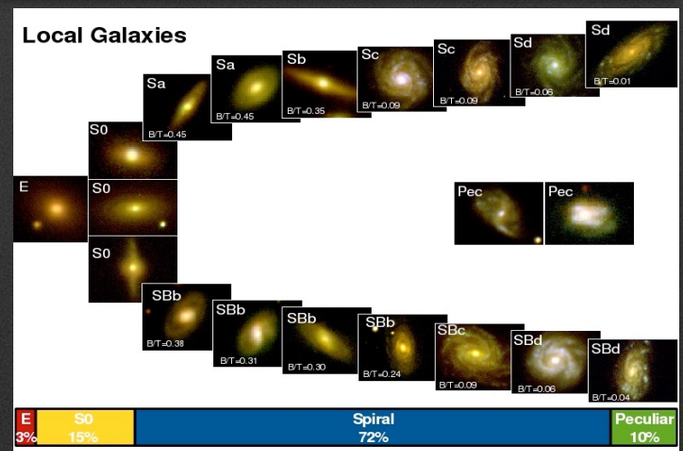
Hammer+05, Flores+06,Yang+08, Nichel+08,Rodrigues+09, Puech+09, Hammer+09,Delgado-Serrano+10



Merge of two galaxies over 6-10 billion years

Gravity & Hydrodynamics & Star formation

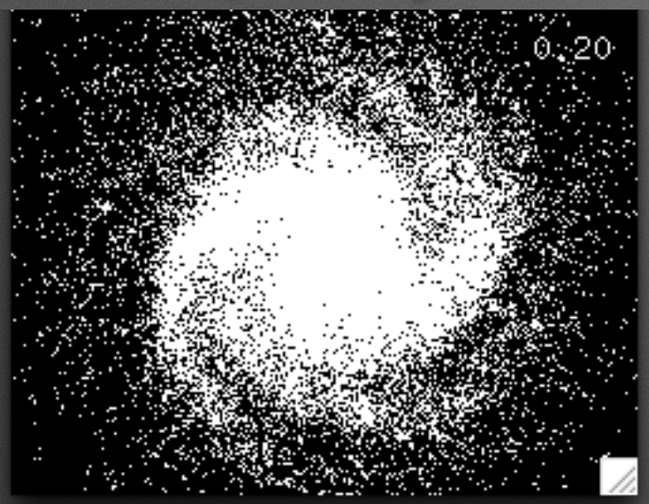
N-body Hydrodynamical simulations



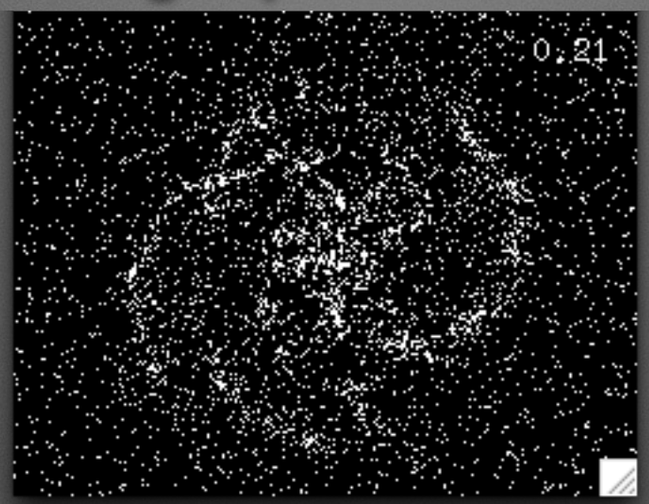
- Scientific motivations
- Methodology & techniques
  - Code : Gadget2 (Springel, 2005)
  - Code : Gizmo (Hopkins, 2014)
  - Star formation module : “Cox06” (Cox et al. 2006)
- Results
  - Publications since 2012
  - M31 and the Challenge on Astro-A 2018
  - Magellanic Stream and Clouds
  - MW dwarf galaxies
- Future work

Methodology : N-body hydrodynamical simulations

dark matter, stars particles



gas particles



Simulate

dark matter, stars, gas

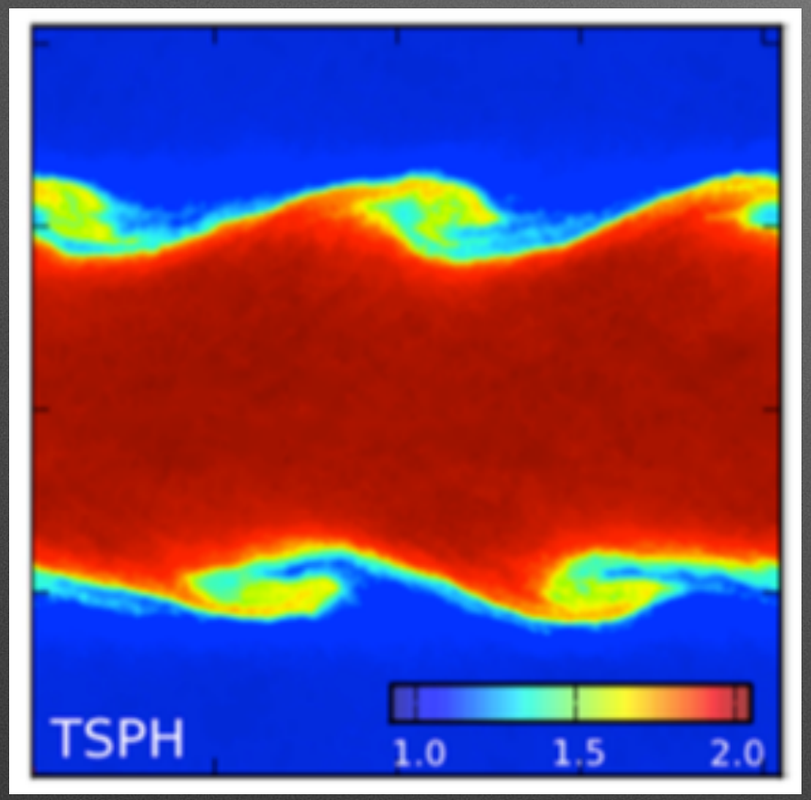
particle *i* : mass, position, velocity, acceleration (density, T …)

> 10 billion stars + plus else

- gravitational dynamics (all particles)
- hydrodynamics (gas particles)
- Star formation process (transform gas into stars)
- Massive parallel calculation (MPI, openMP) (~million particle to ~300 billion particles [presently known])
  - @MesoPSL (1.5M hours since 2012):
    - 1, 2, 6 million particles
    - 2, 4, 8 nodes (32, 64, 128 cores)
    - < 24 hours or 3-5 days per simulation

- hydrodynamics (gas particles)

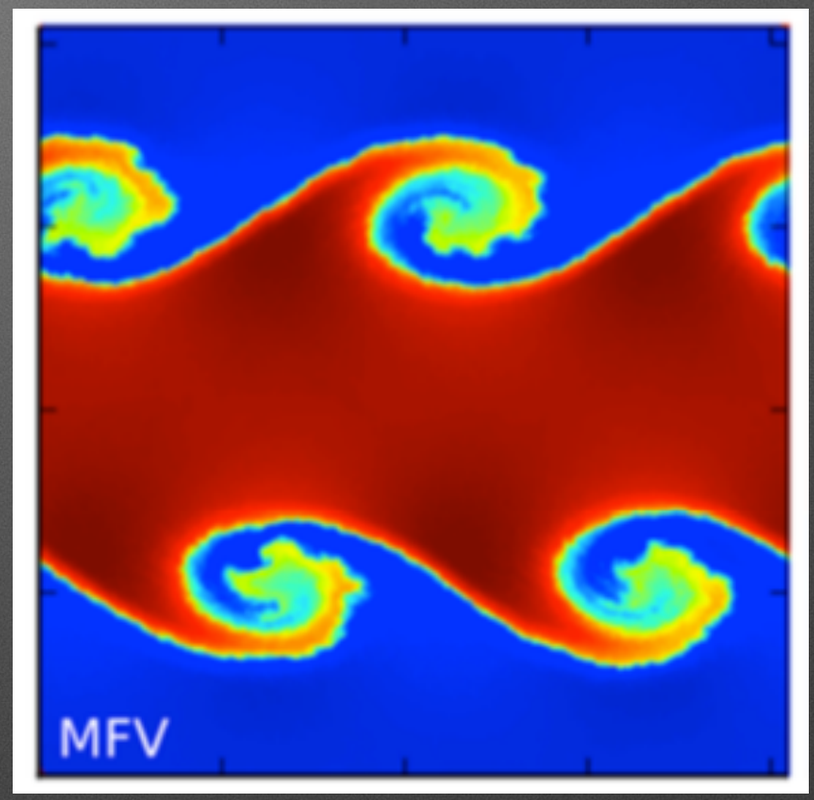
Since 2012 @ MesoPSL



SPH
(Smoothed Particle Hydrodynamics)

Gadget2
Springel (2001, 2005)

Since 2016 @ MesoPSL

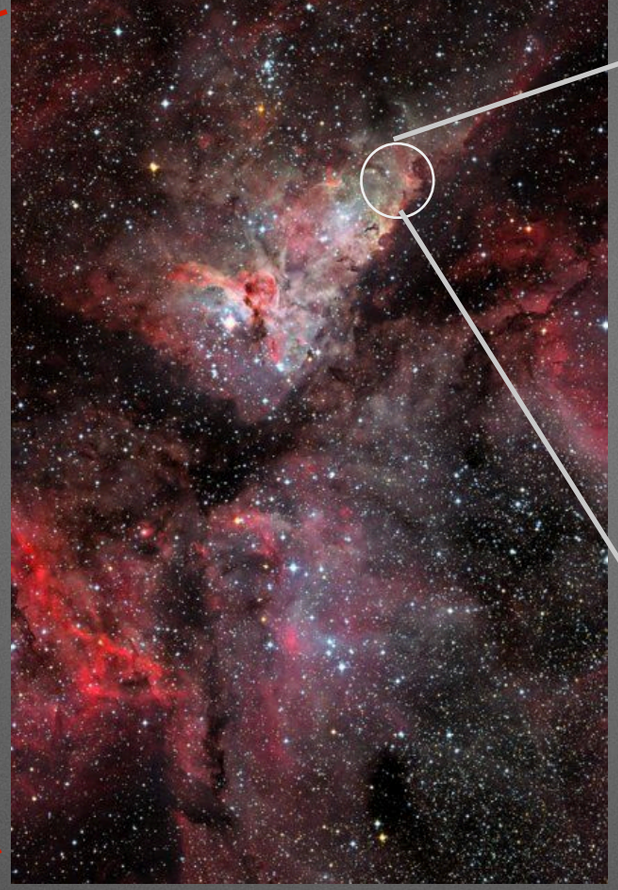


MFM
(Meshless Finite Mass)

Gizmo
Hopkins (2014)

The Southern Cross and Milky Way over a Tree. the Carina Nebula Is the Red Cloud at Top

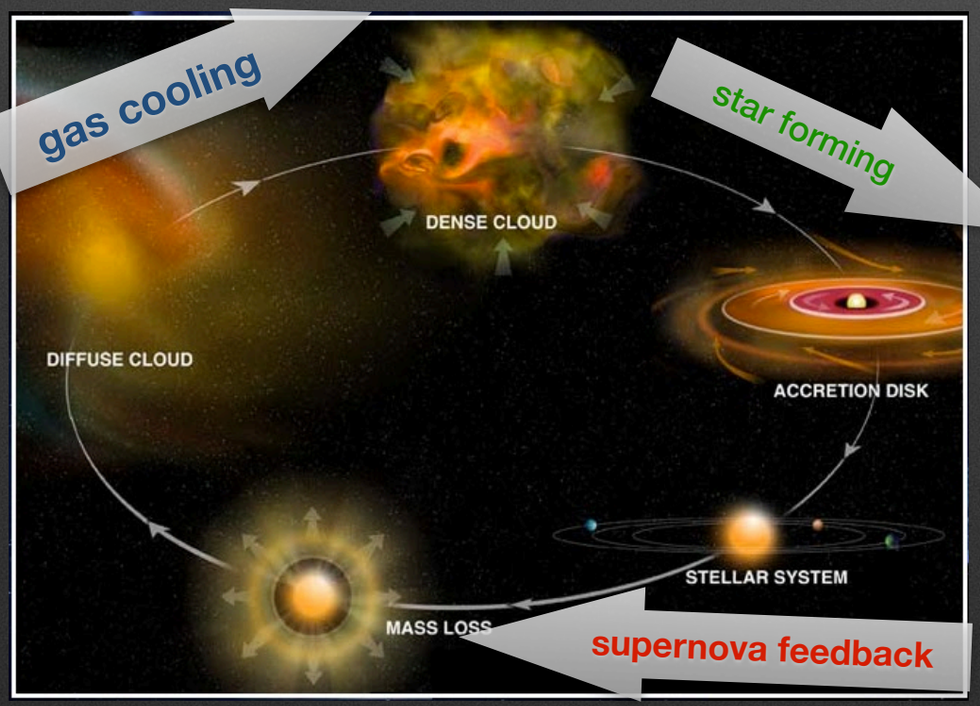
By: Babak Tafreshi Item #: 11985059



For example

extremely complex processes

- Simplistic (kpc-scale) Star formation & SN feedback



CoxSF (Cox et al. 2006)

star forming :
convert gas particle into star particles
when
rho_gas > rho_threshold
to reproduce the observed star formation law

- Scientific motivations
- Methodology & techniques
  - Code : Gadget2 (Springel, 2005)
  - Code : Gizmo (Hopkins, 2014)
  - Star formation modules : “Cox06”
- Results
  - Publications since 2012
  - M31 and the Challenge on Astro-A 2018
  - Magellanic Stream and Clouds
  - MW dwarf galaxies
- Future work

Publications

(1.5M hours @mesopsl since 2012)

- “The Hydrodynamic Nature of Magellanic Stream and Clouds”
  Wang, J., et al. in preparation

- “The origin of MW dwarf galaxies … ”
  Yang et al., in preparation

- “ MW mass profile and its dwarf galaxies …”
  Hammer et al., in preparation.

- “The NGC 891 …. ”
  Wang, J., et al. in preparation

- “Galactic forces rule dynamics of Milky Way dwarf galaxies”
  Hammer, F., Yang, Y., Arenou, F., et al. 2018, arXiv:1805.01469 , accepted for ApJ (will be published 14 June + press release)

- “A 2-3 billion year old major merger paradigm for the Andromeda galaxy and its outskirts”
  Hammer, F., Yang, Y. B., Wang, J. L., et al. 2018, MNRAS, 475, 2754

- “Most pseudo-bulges can be formed at later stages of major mergers”
  Sauvaget, T., Hammer, F., Puech, M., et al. 2018, MNRAS, 473, 2521

- “The Magellanic Stream System. I. Ram-Pressure Tails and the Relics of the Collision Between the Magellanic Clouds”
  Hammer, F., Yang, Y. B., Flores, H., Puech, M., & Fouquet, S. 2015, ApJ. 813, 110

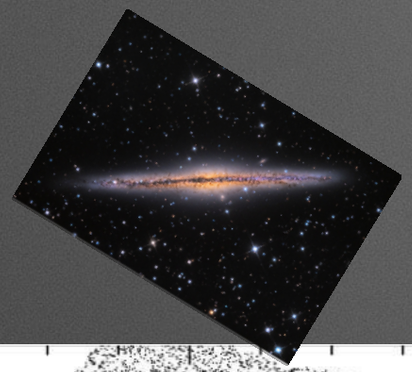
- “The NGC 4013 tale: a pseudo-bulged, late-type spiral shaped by a major merger”
  Wang, J., Hammer, F., Puech, M., Yang, Y., & Flores, H. 2015, MNRAS, 452, 3551

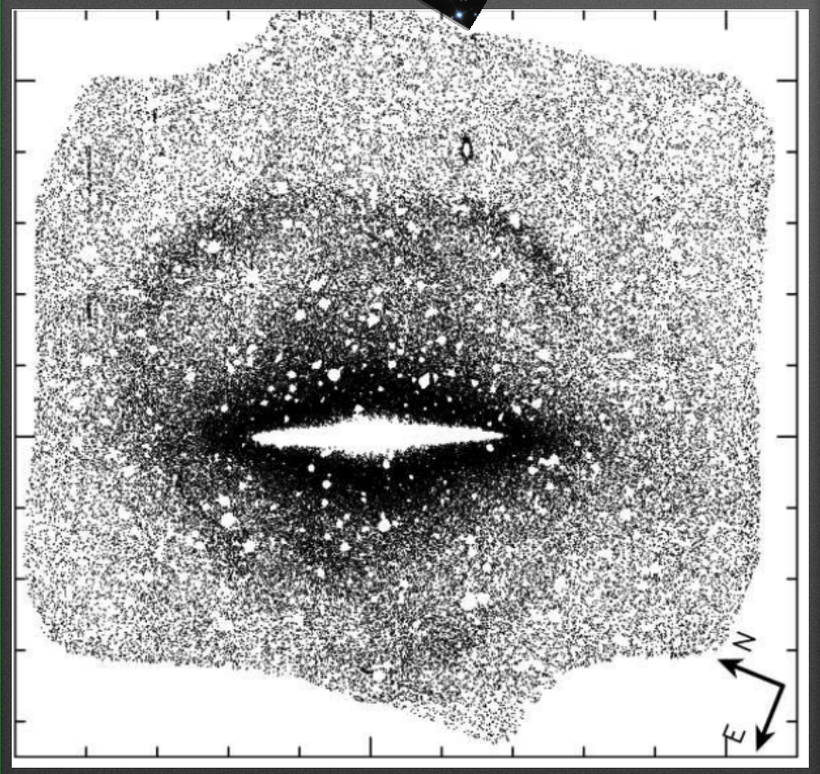
- “Reproducing properties of MW dSphs as descendants of DM-free TDGs”
  Yang, Y., Hammer, F., Fouquet, S., et al. 2014, MNRAS, 442, 2419

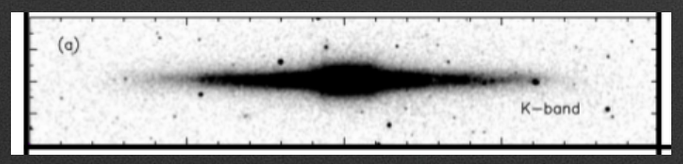
- “The vast thin plane of M31 corotating dwarfs: an additional fossil signature of the M31 merger and of its considerable impact in the whole Local Group”
  Hammer, F., Yang, Y., Fouquet, S., et al. 2013, MNRAS, 431, 3543

Loops formed by major merger:formation of NGC 891
Jianling Wang et al. (in preparation)

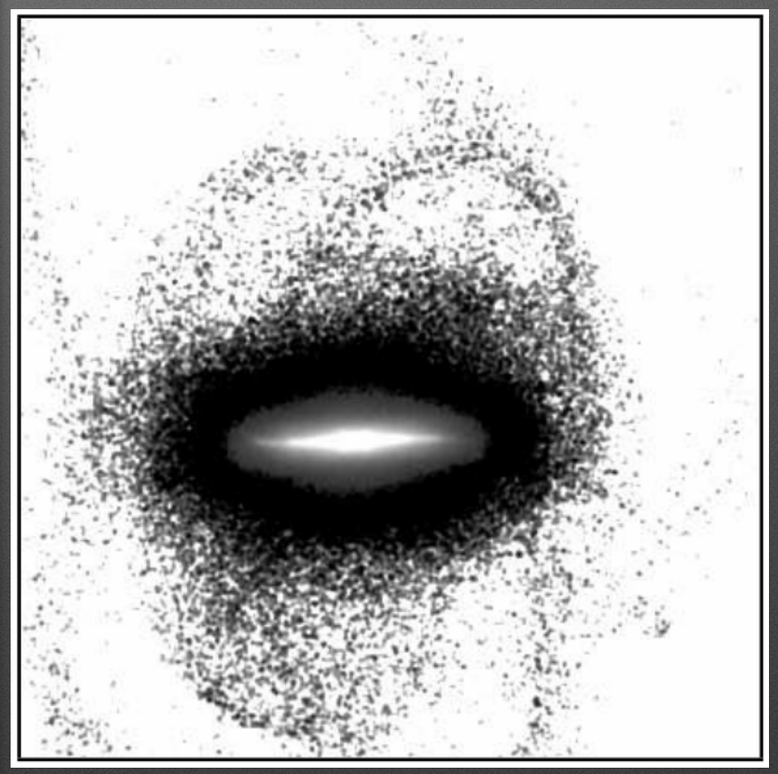
- GIZMO, MFM
- CoxSF
- 2-6 M particles
- 2-4 nodes
- 1-3 days / run
- ~300 simulations

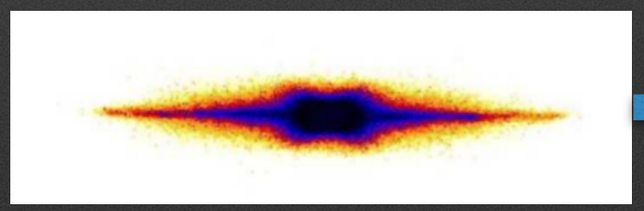




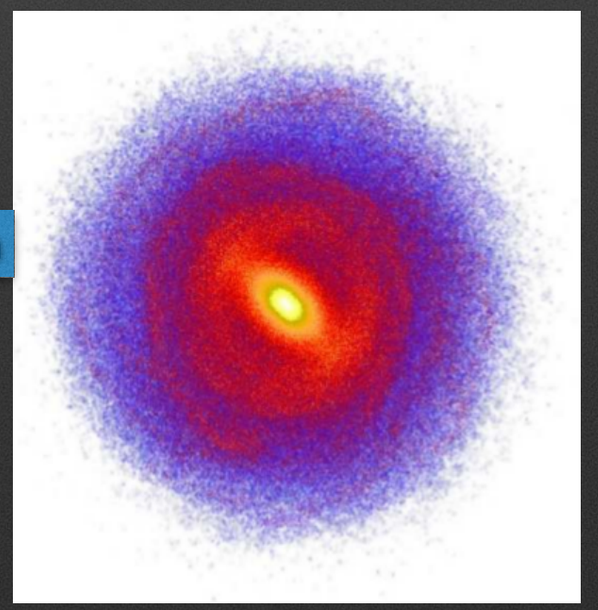


Observation





face on



Simulation

- ✓rotation curve
- ✓pseudo-bulge
- ✓bulge fraction
- ✓disk scale-length
- ✓large scale HI lopsided
- ✓stellar loops
- ✓box-shape halo
- ✓extended stellar halo
- ✓boxy bulge
- ✓super thin star forming disk

LOCAL GALACTIC GROUP

Sextans B
Sextans A
Leo A
NGC 3109
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
Ursa Major I
Sextans Dwarf
Ursa Major II
Boötes Dwarf
Ursa Minor Dwarf
Draco Dwarf
IC 10
Large Magellanic Cloud
Small Magellanic Cloud
Milky Way Galaxy
Sagittarius Dwarf
Carina Dwarf
780 kpc
NGC 147
Sculptor Dwarf
Fornax Dwarf
M110
Andromeda Galaxy (M31)
Andromeda I
M32
NGC 6822
Triangulum Galaxy (M33)
Andromeda II
Andromeda III
Phoenix Dwarf
Pisces Dwarf
1Mpc (1000 kpc)
IC 1613
Aquarius Dwarf
SagDIG
Pegasus Dwarf
Cetus Dwarf
Tucana Dwarf
WLM

A 2-3 billion year old major merger paradigm for the Andromeda galaxy and its outskirts

(Hammer er al. 2018, MNRAS), (First model published in 2010)

- press release (Obspm, CNRS)
- highlight (poster) at the celebration of 10-years GENCI/CNRS
- the emission at France Culture

https://www.youtube.com/watch?v=zz86Dd_L7HY

Crédit : Richard Crisp

- Gizmo, MFM
- CoxSF
- 2-6 M particles (24M for the current video run @ IDRIS)
- 2-4 nodes
- >600 simulations

A 2-3 billion year old major merger paradigm for the Andromeda galaxy and its outskirts

(Hammer er al. 2018, MNRAS)

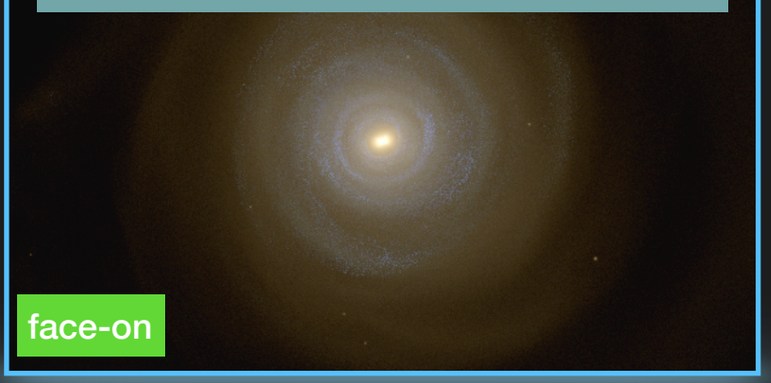
- press release (Obspm, CNRS)
- highlight (poster) at the celebration of 10-years GENCI/CNRS
- the emission at France Culture

https://www.youtube.com/watch?v=exetDytuUYQ

Crédit : Richard Crisp

Challenge 2018, MesoPSL (Astro-A) : the Andromeda galaxy and its outskirts

Formation of the bar

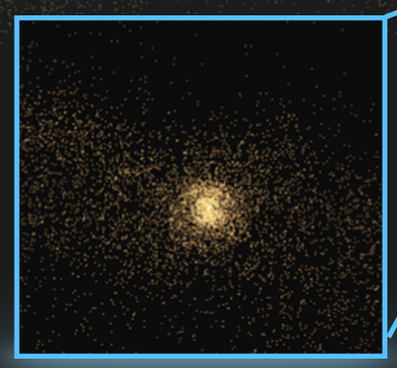


face-on

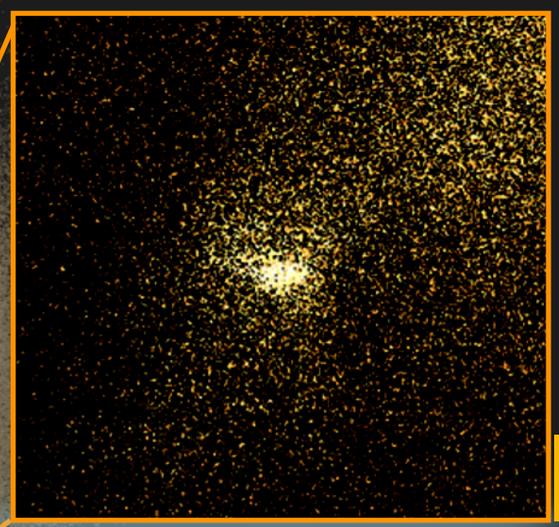
Formation of thin and thick

edge-on

- **144 million particles** (5 GB per snapshot, 1900 snapshot in total is 9TB at the end)
- **512MPI + 2 OMP per MPI** (1024 cores on 11 nodes = 88% of total CPU)
- **RAM 5TB** (about 50% RAM available)



Tidal dwarf galaxies

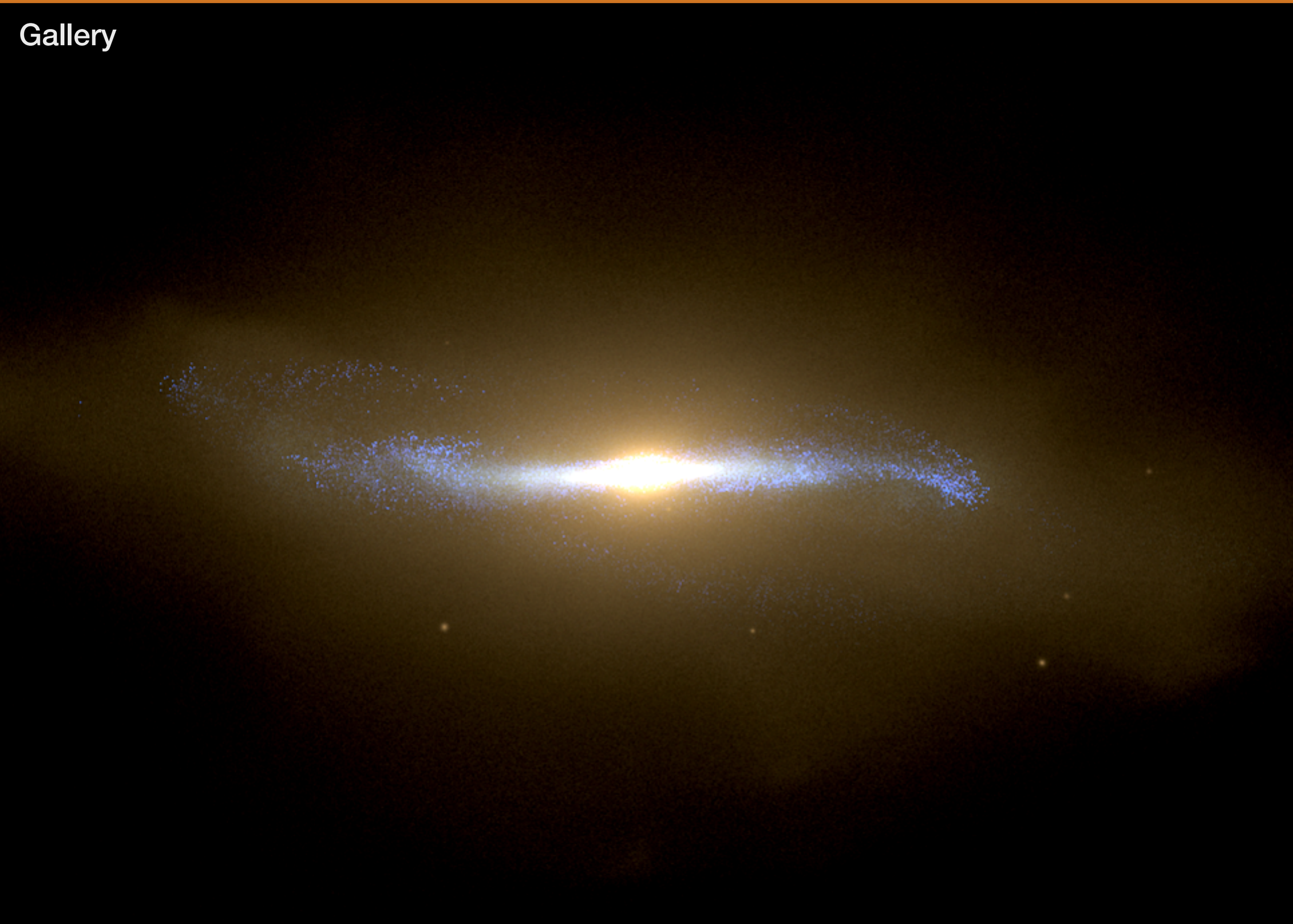


$3x10^7 M_{Sun}$ / $N_{particles}$=105000

In the 2nd tidal tail , this is the **first** unambiguous detection, thanks to the high resolution.

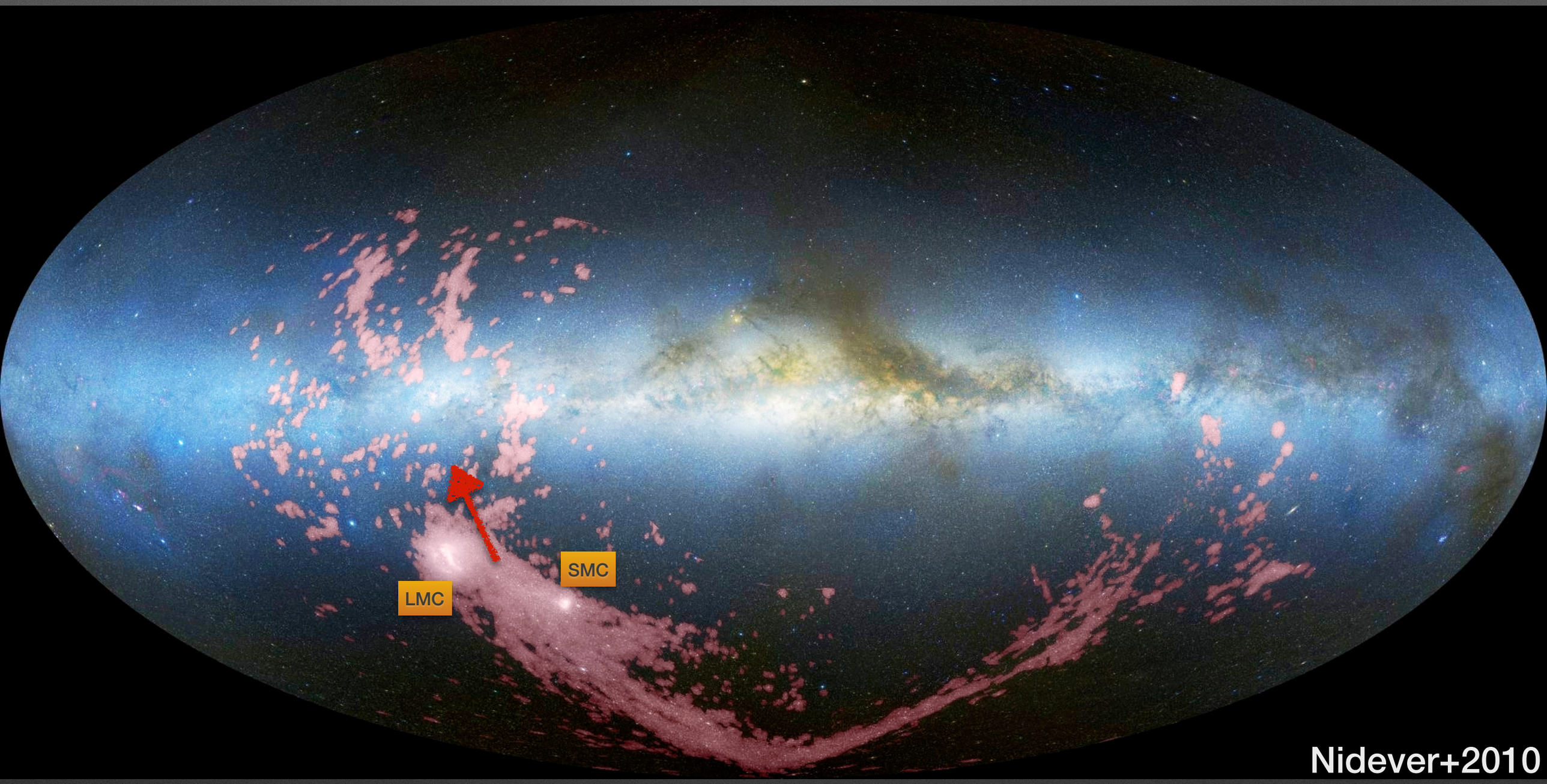
Challenge 2018, MesoPSL (Astro-A) : the Andromeda galaxy and its outskirts

Gallery



The Hydrodynamic Nature of Magellanic Stream and Clouds

- Hammer et al. 2015, ApJ.
- Wang et al. 2018 (with Gizmo) in preparation



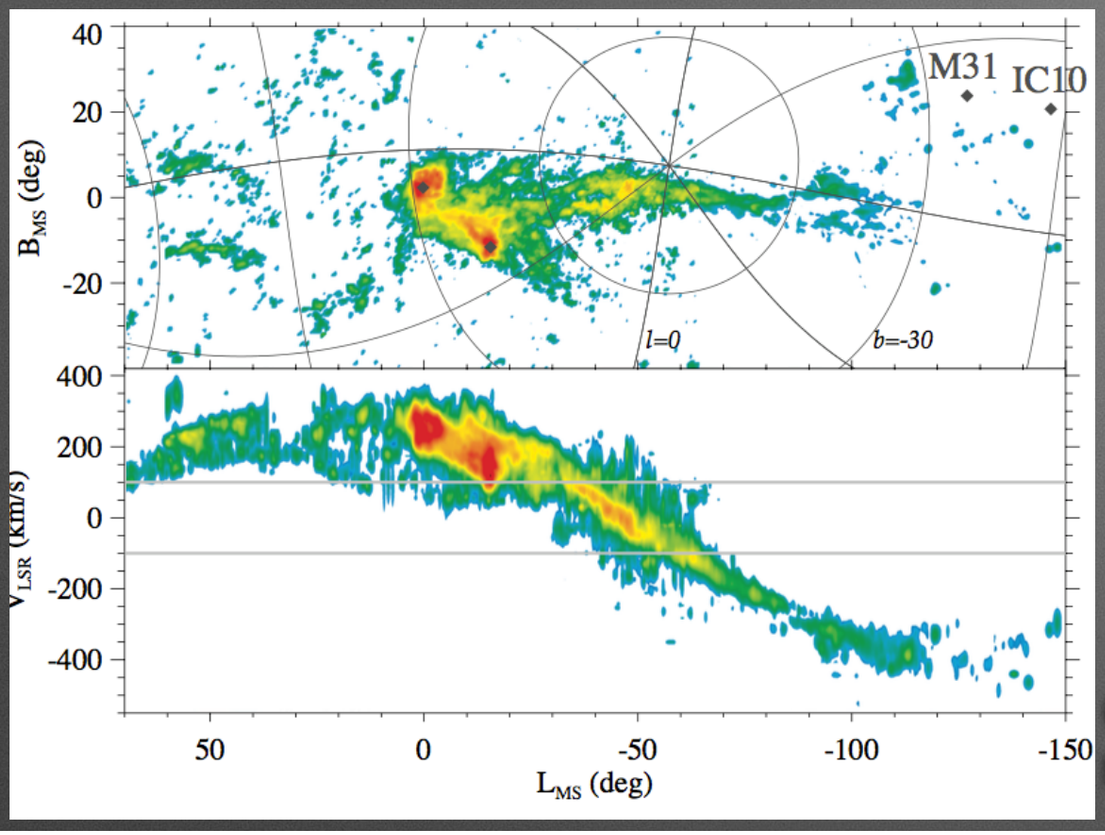
The Magellanics Stream : neutral Hydrogen (H I), 21cm

Firstly identified as the MS by Mathewson+74 after detections by van Kuilenburg and Wannier & Wrixon72

Mathewson (2012): still no satisfactory explanation since 1974

Ram-pressure tails and the relics of the collision between the magellanic clouds

(Hammer+2015)



Observation

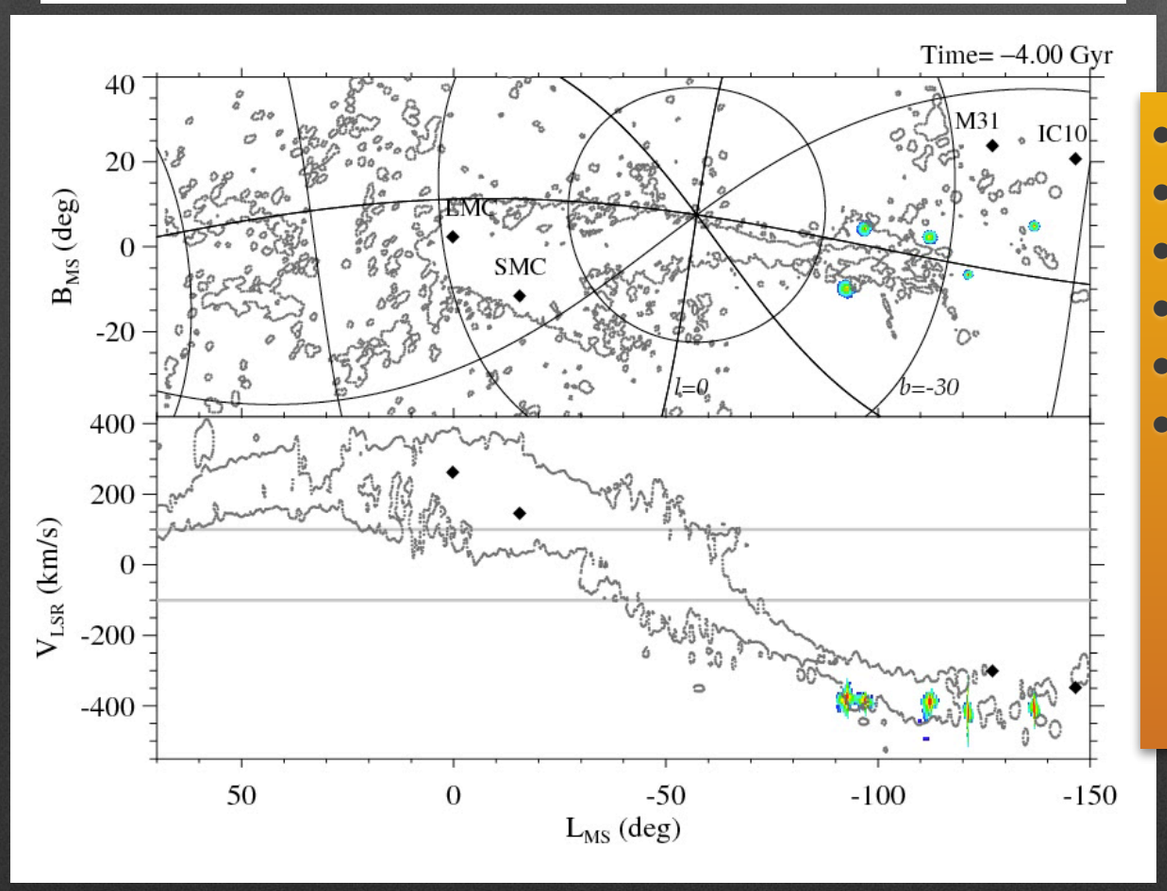
Nidever+2010

Quoting Don Mathewson's email:

.....

Congrats to you and your colleagues on producing a highly sophisticated and well researched piece of work and much,much nearer the truth!

....

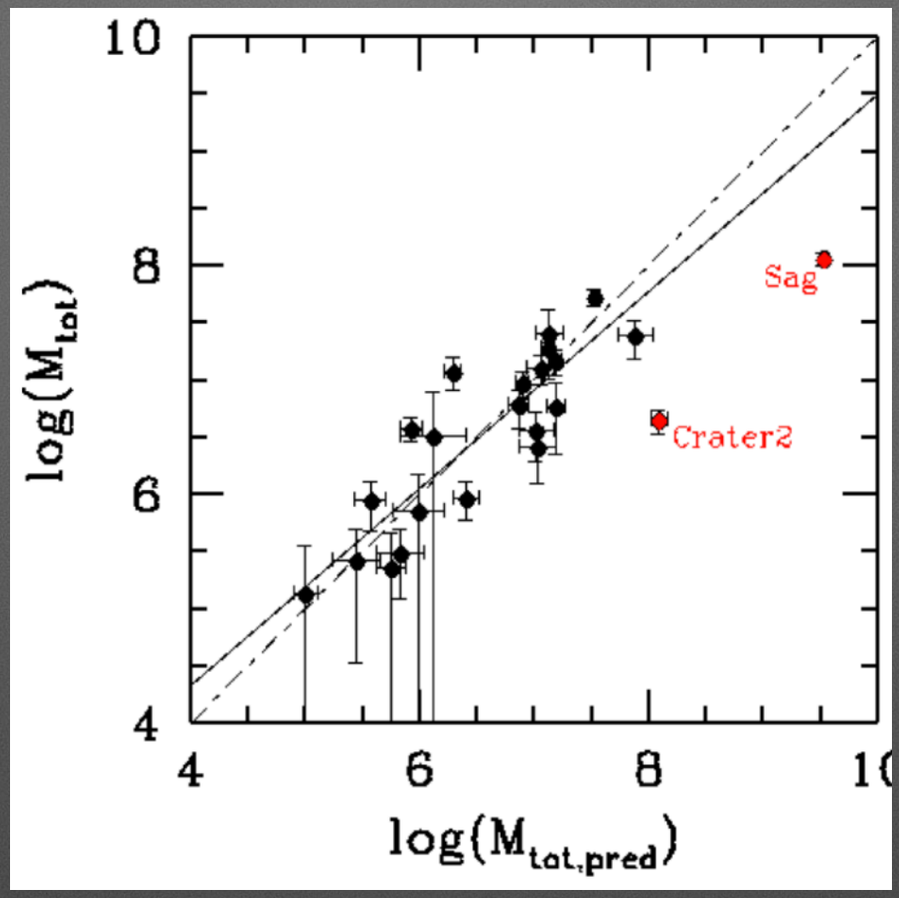


- During 3 years
- Gadget2, SPH
- CoxSF
- 2-6 M particles
- 2-8 nodes
- >1000 simulations
  - stabilize hot gas in MW
  - testing densities of MW hot gas
  - finding orbit of collision, at <1% level

- “Galactic forces rule dynamics of Milky Way dwarf galaxies” Hammer et al. 2018

$$M(r_h) \approx \frac{5 r_h \sigma_V^2}{2G},$$

walker 2011



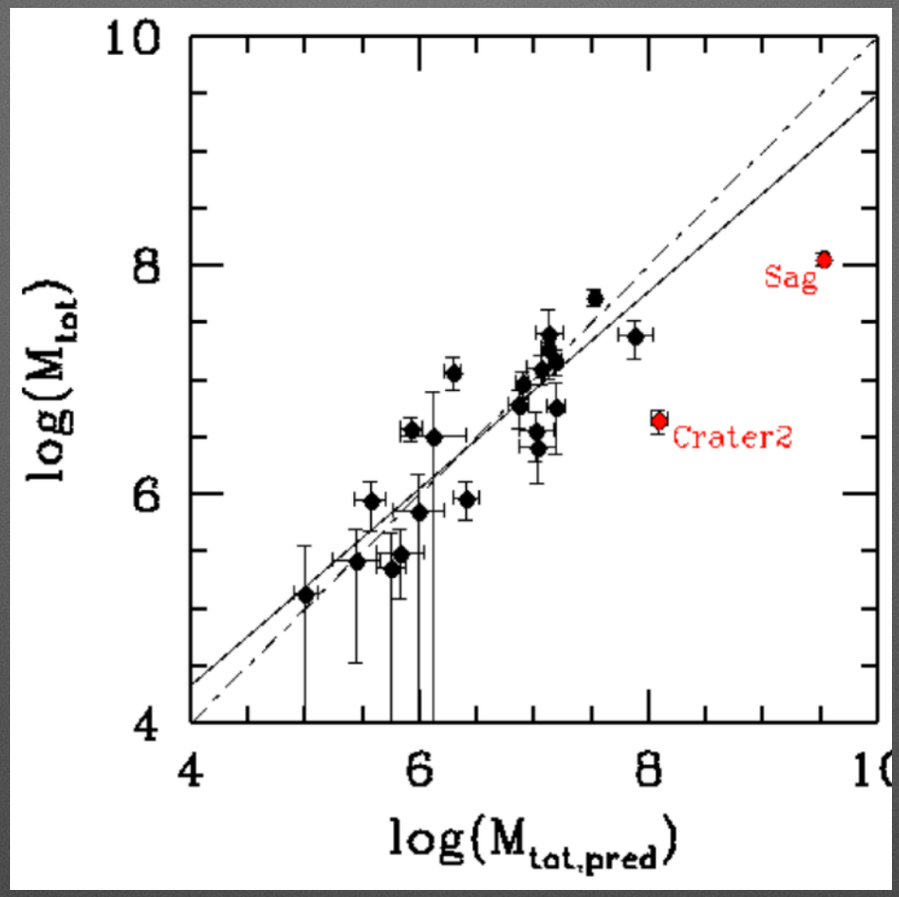
$$M_{tot,pred} \approx 3.529 \times M_{MW}(D_{MW}) \times \left(\frac{r_{half}}{D_{MW}}\right)^2$$

Hammer+2018

- “Galactic forces rule dynamics of Milky Way dwarf galaxies” Hammer et al. 2018

$$M(r_h) \approx \frac{5 r_h \sigma_V^2}{2G},$$

walker 2011



$$M_{tot,pred} \approx 3.529 \times M_{MW}(D_{MW}) \times \left(\frac{r_{half}}{D_{MW}}\right)^2$$

Hammer+2018

No more proof of dark matter in MW dwarf galaxies!

- “Galactic forces rule dynamics of Milky Way dwarf galaxies” Hammer et al. 2018

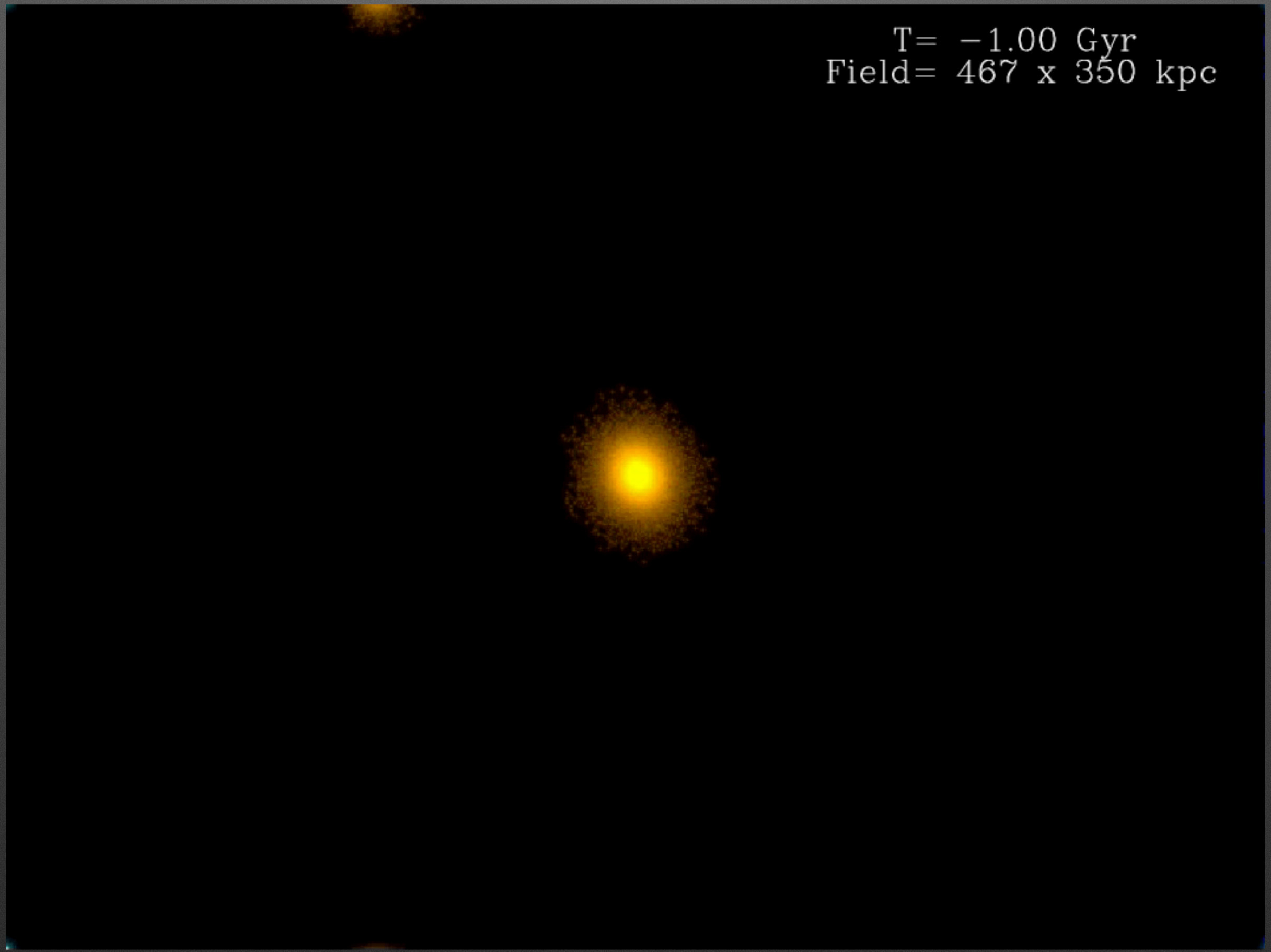
Yang et al. 2014

Physical transformation of a gas-rich dwarf galaxy into dwarf spheroidal during its first passage into the Milky Way halo

Future works

@ MesoPSL (<6M particles)
@ IDRIS (6-300M particles) (4M hours for 2018)

- "The Hydrodynamic Nature of Magellanic Stream and Clouds"
  Wang, J., et al. in preparation
- "The origin of MW dwarf galaxies … "
  Yang et al., in preparation
- " No(?) Dark-matter in MW dwarf galaxies …"
  Hammer et al., in preparation.
- " MW mass profile and its dwarf galaxies …"
  Hammer et al., in preparation.
- "The NGC 891 …. "
  Wang, J., et al. in preparation
- "3D kinematics of MW dwarf galaxies (collaboration with GAIA team)"
- .
- **A full history of the Local Group?**


T= −1.00 Gyr
Field= 467 x 350 kpc

not ended yet

Surprising 3D shape of the small Magellanic cloud (SMC)

Wang et al. 2018, in preparation

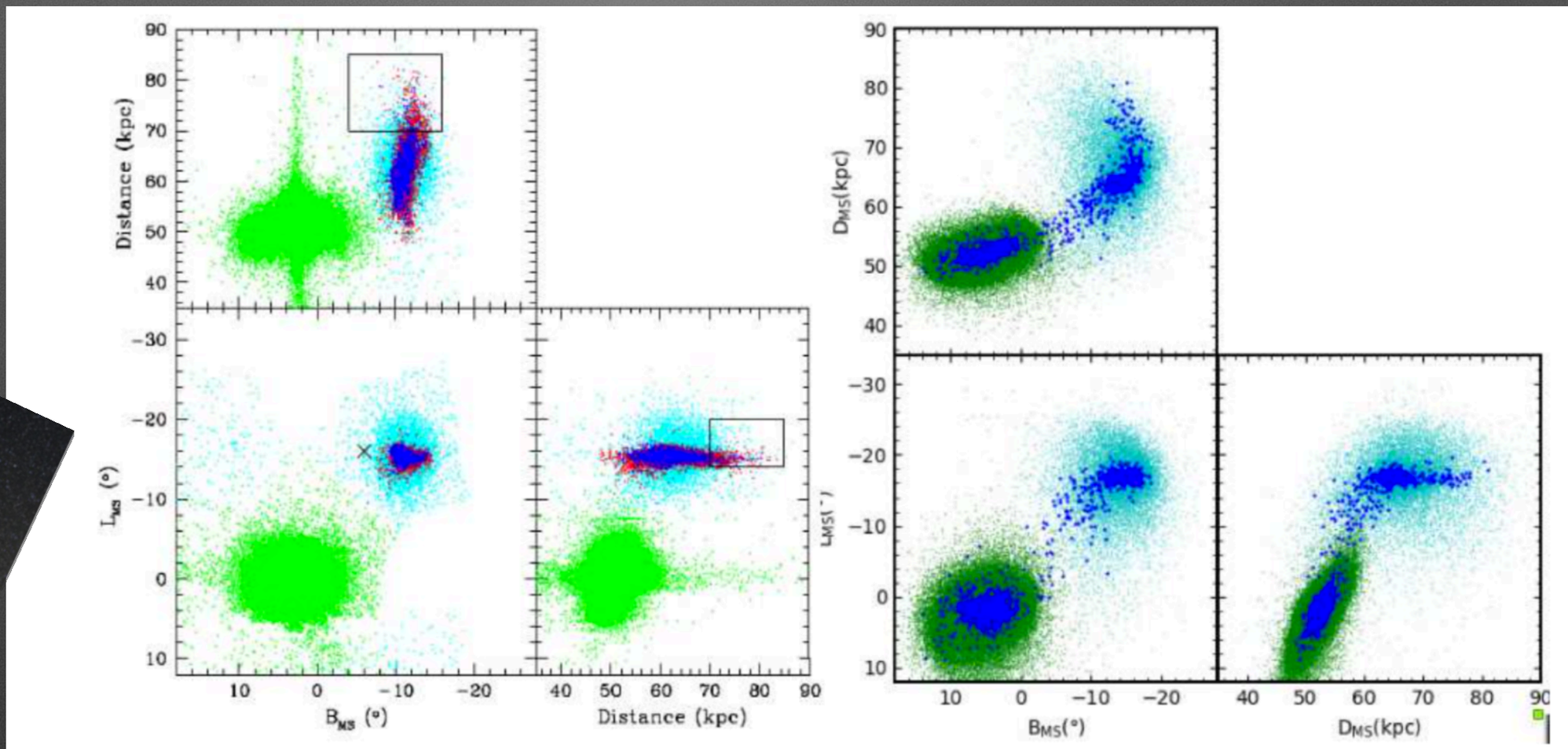
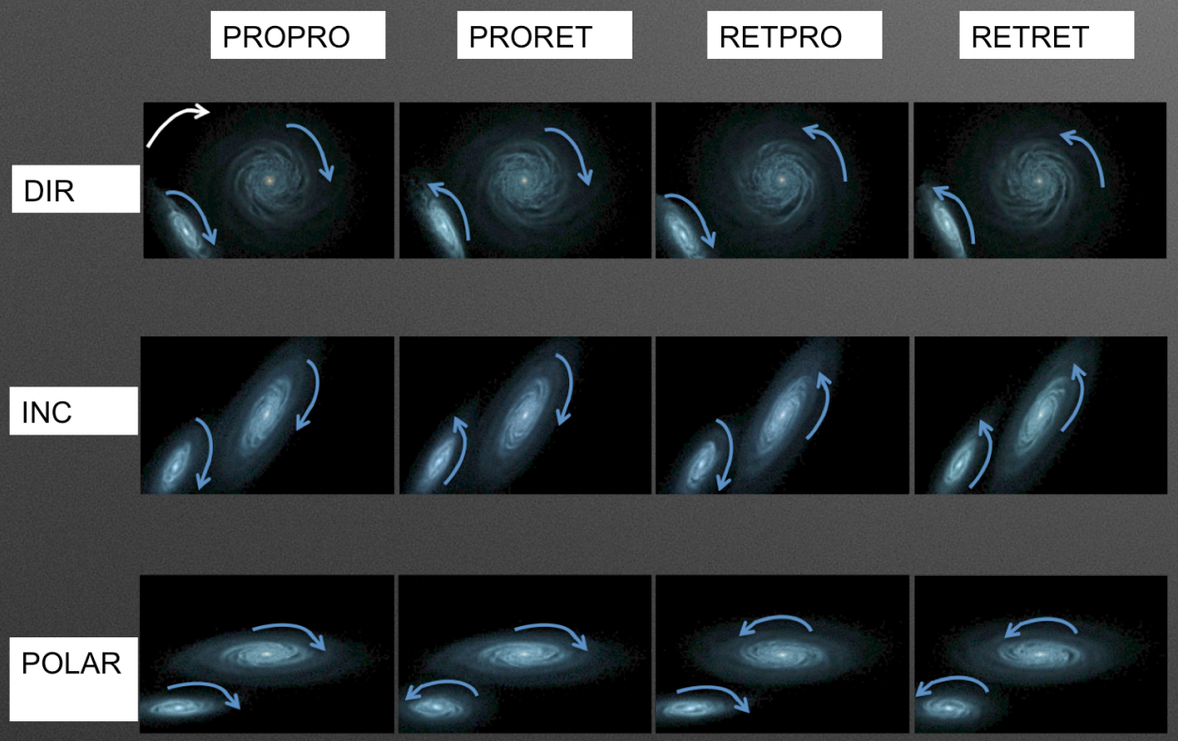


Figure 2: Comparing observed stellar distribution of Magellanic clouds with that of simulation Model-40. The observed data from Ripepi et al. (2017), who select ab-type RR Lyrae stars in the SMC (cyan dots) and in the LMC (green dots),and young and old Classical Cepheids are shown by blue and red dots.

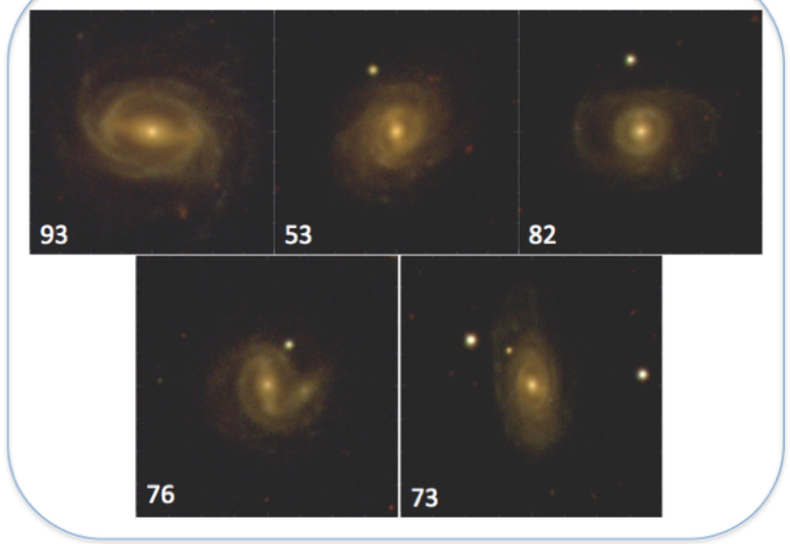
Pseudo-bulge formation in giant spiral local galaxies via gas-rich major mergers
Tabatha Sauvaget (PhD thesis + a paper published in 2018)

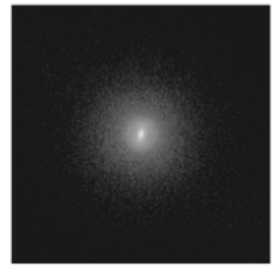
Simulations : 12 orbits



- database
- Gadget2, SPH
- CoxSF
- 2M particles
- 2-4 nodes

Highlights



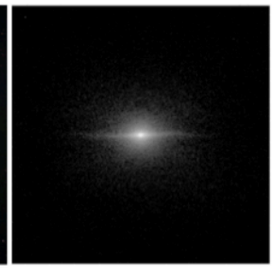


DIR-RETPRO
Feedback 2.5*median

DIR-RETPRO
Pericentre 8 kpc

Highlights

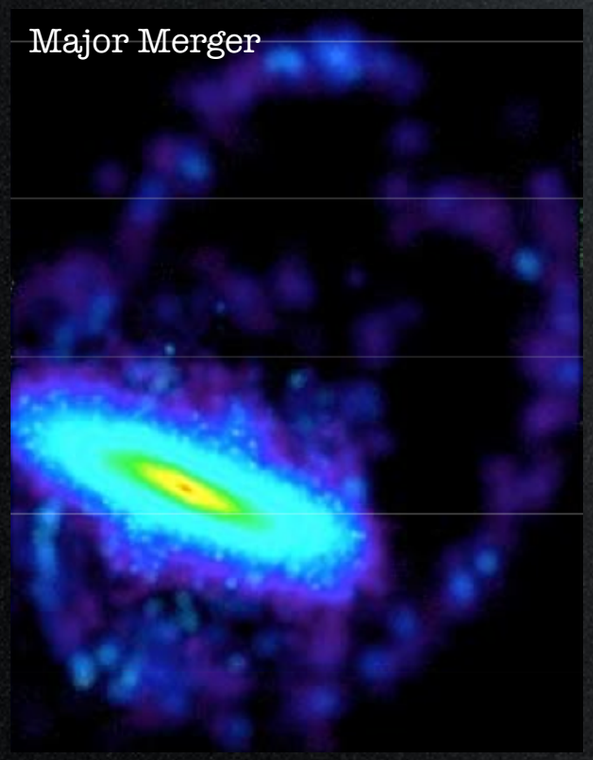
DIR-PRORET
2 millions of particles



POLAR-PRORET
Mass ratio 1:1.5

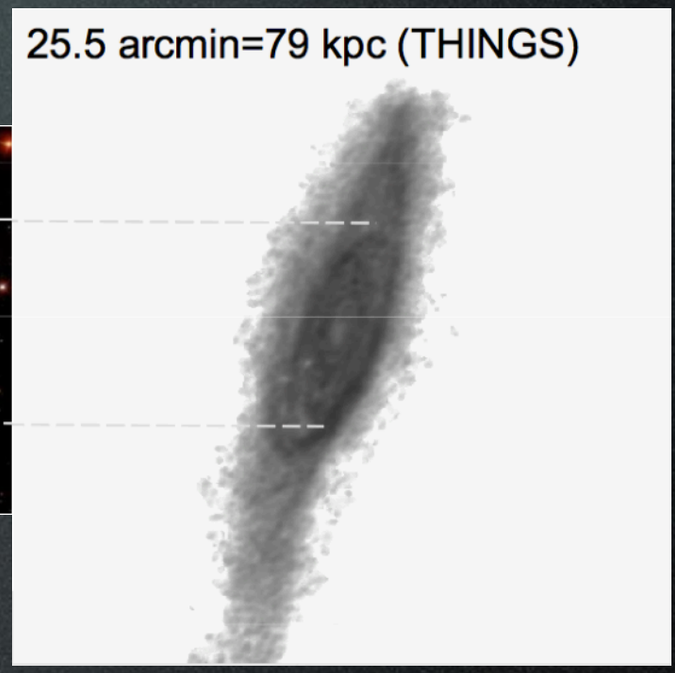
Nearby univers: Faint structures <> signature of mergers

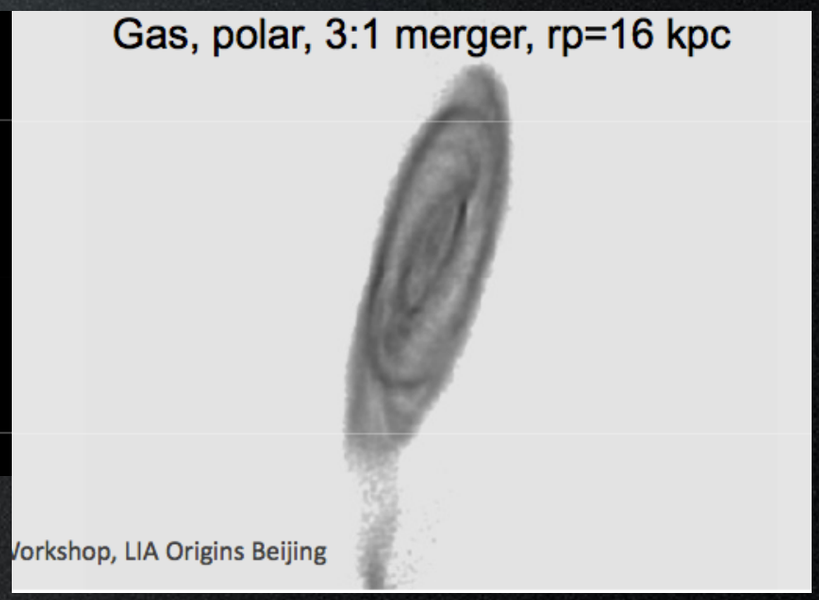
NGC 5907



Wang+2012

NGC 3521





from our library of simulations