Characterisation of the outer Solar System and the Oort cloud

D. Hestroffer[1], E. Pilat-Lohinger[2], M. Fouchard[1,3], M. Saillenfest[1]

[1] Observatoire de Paris, Univ. PSL, CNRS/INSU (FR)

[2] Uni. Wien, Inst. Of Astrophysics (AT)

[1] Univ. Lille (FR)

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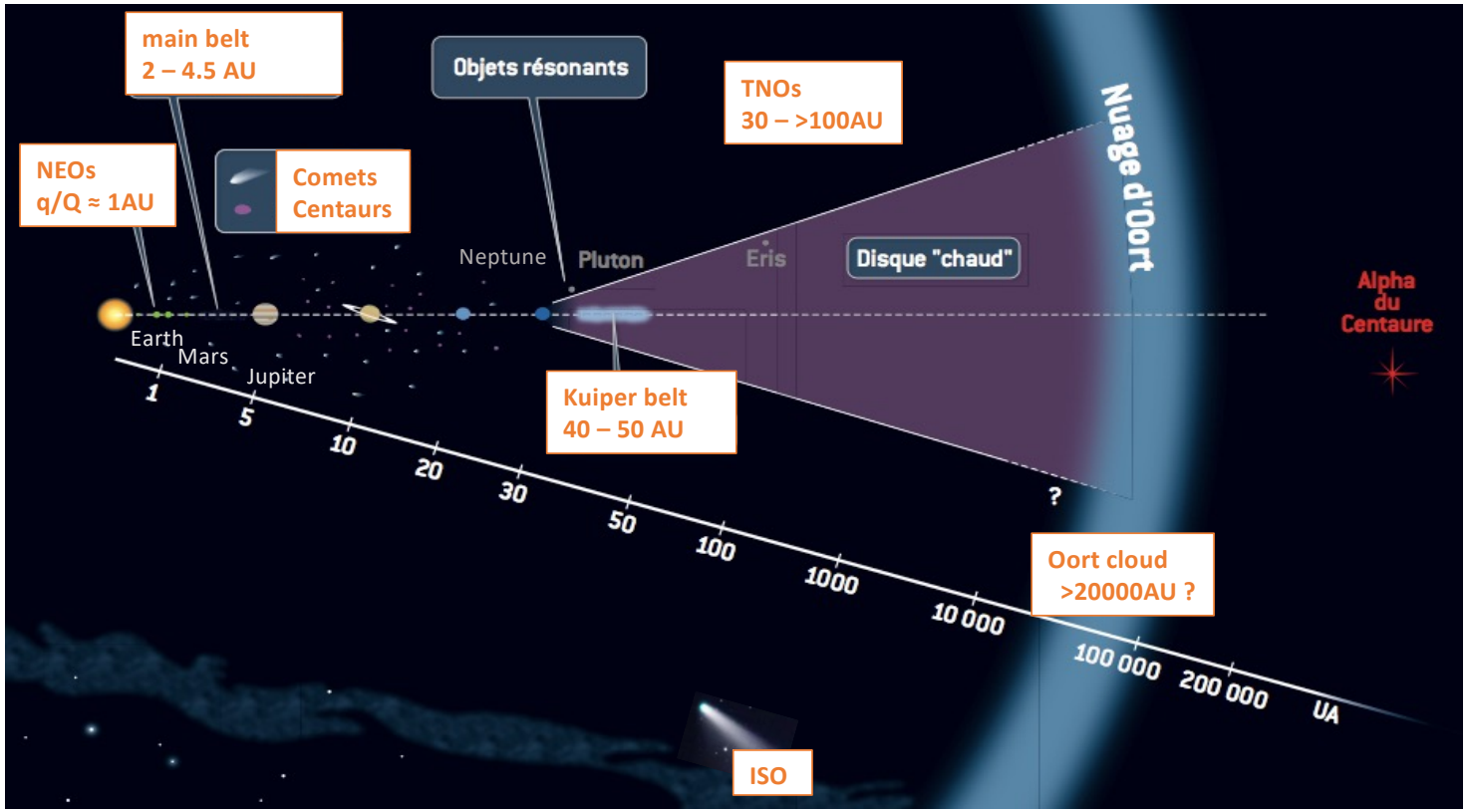
Small Solar System Bodies (SSSBs)

- Various populations in the Solar System – The targets



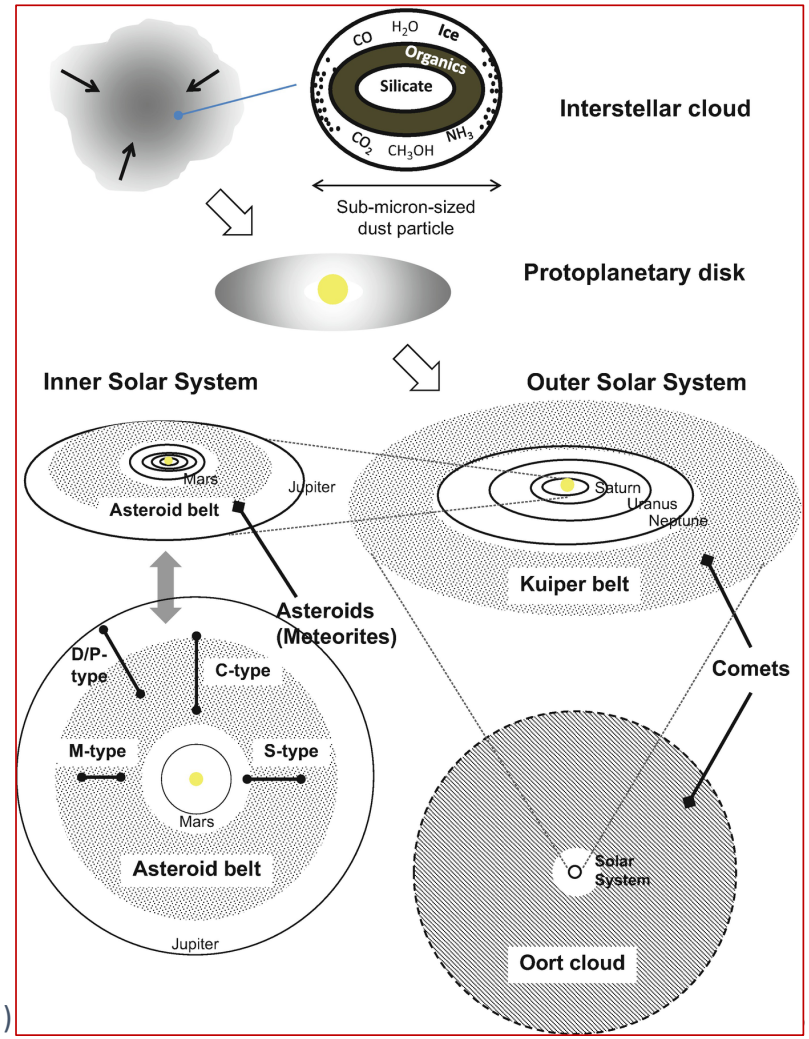
(Doressoundiram & Lellouch 2008)

Small Solar System Bodies (SSSBs)

- **Formation & Evolution the Solar System**
  – The science –

  - ± pristine objects – tracer of the chemistry at formation
    - formation of the Solar system / of planetary systems
    - mineralogy (meteorites, sample return), aging, transport, water on Earth, …

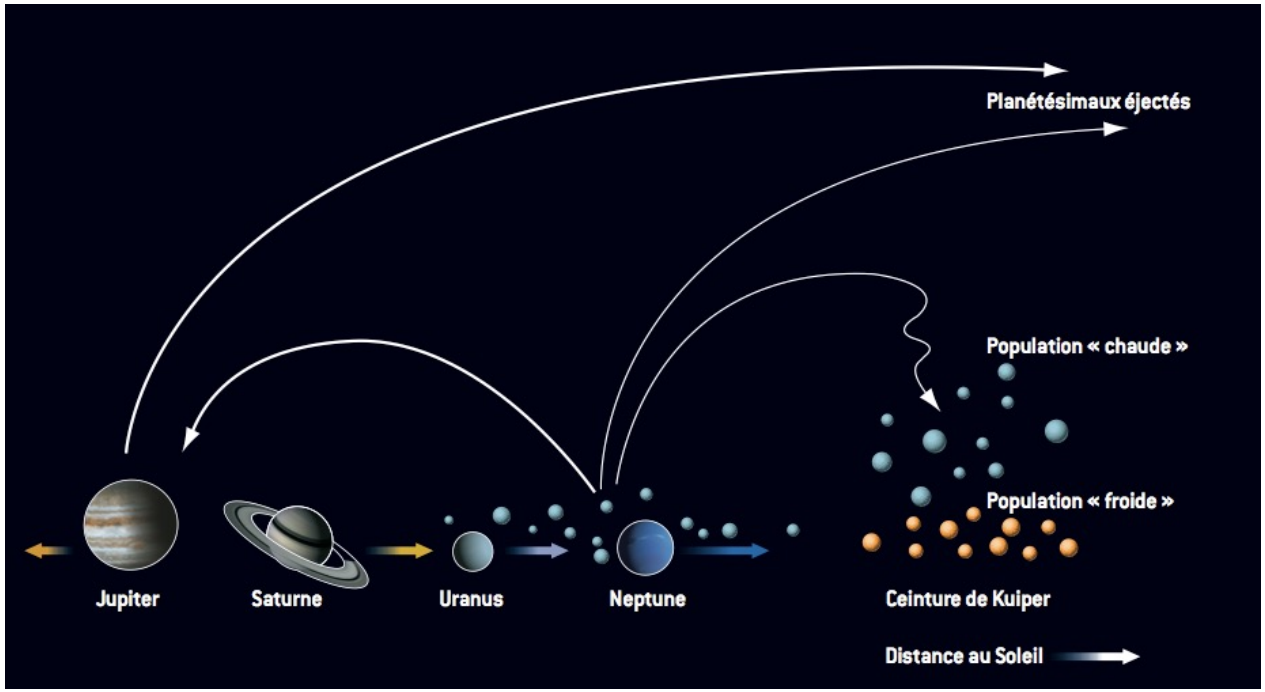
  - dynamical structure – tracer of evolution over time
    - formation of Solar System / of planetary systems
    - dynamical interactions, migrations, …



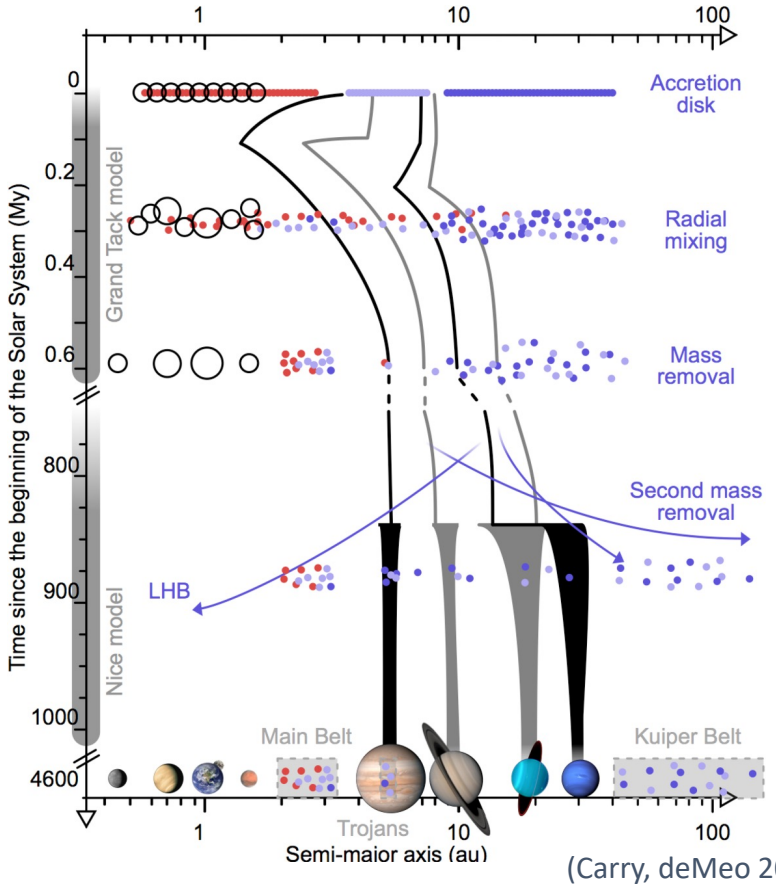
(H. Yabuta – Astrobiology, 2019)

Small Solar System Bodies (SSSBs)

- **Evolution the Solar System – The science**
  - dynamical structure – tracer of evolution amplitude and speed of planet migration



(Doressoundiram & Lellouch 2008)

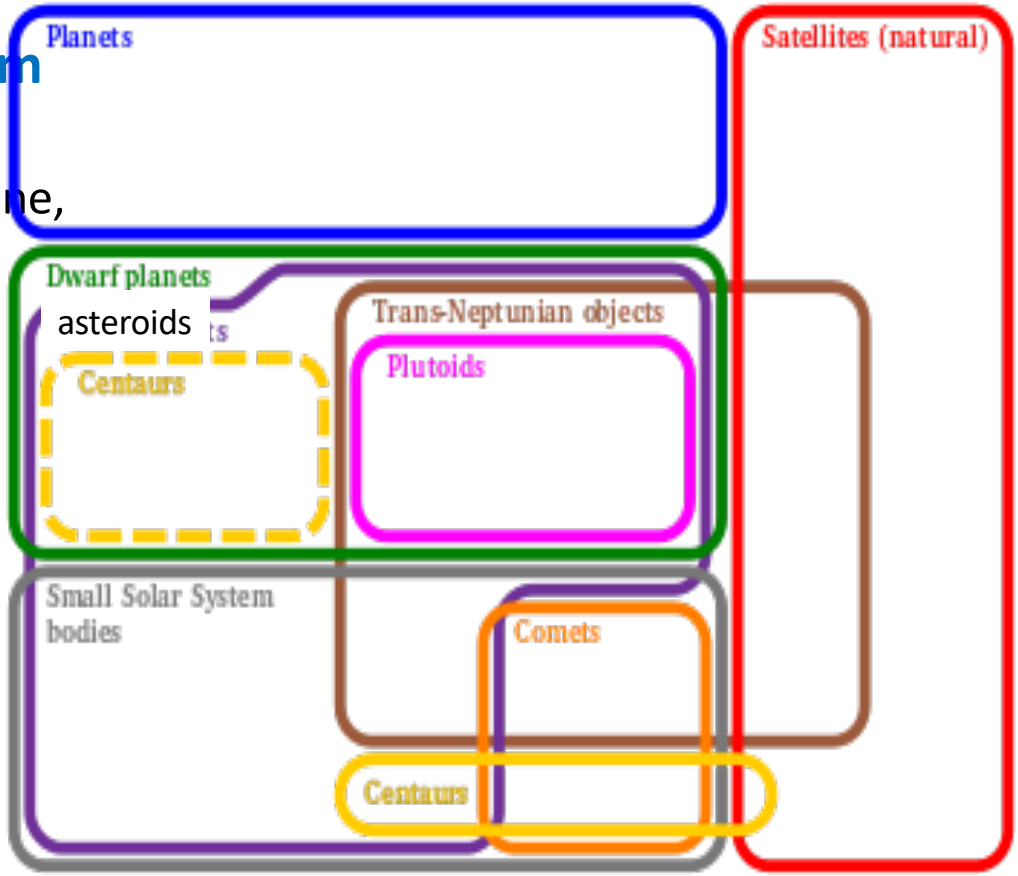


(Carry, deMeo 2014)

LSST – SSSBs

- **Taking a deeper inventory of the Solar System**
  - Asteroids: NEOs, MBAs, Trojans (of Jupiter, Neptune, …), Centaurs, TNOs (different populations), …
  - Comets: SPC, JFC, HFC, LPC, DNC, … Oort cloud
  - Planetary satellites: regular and irregular
  - Meteoroids, Dwarf planets
  - ISOs
  - asteroid-comet-etc continuum

  - Peculiar objects or state: Active asteroids (MBA Centaurs), main-belt comets (MBC), fast rotators, tumbling, multiple, bilobated, rings, …



(wikipedia SSSBs)

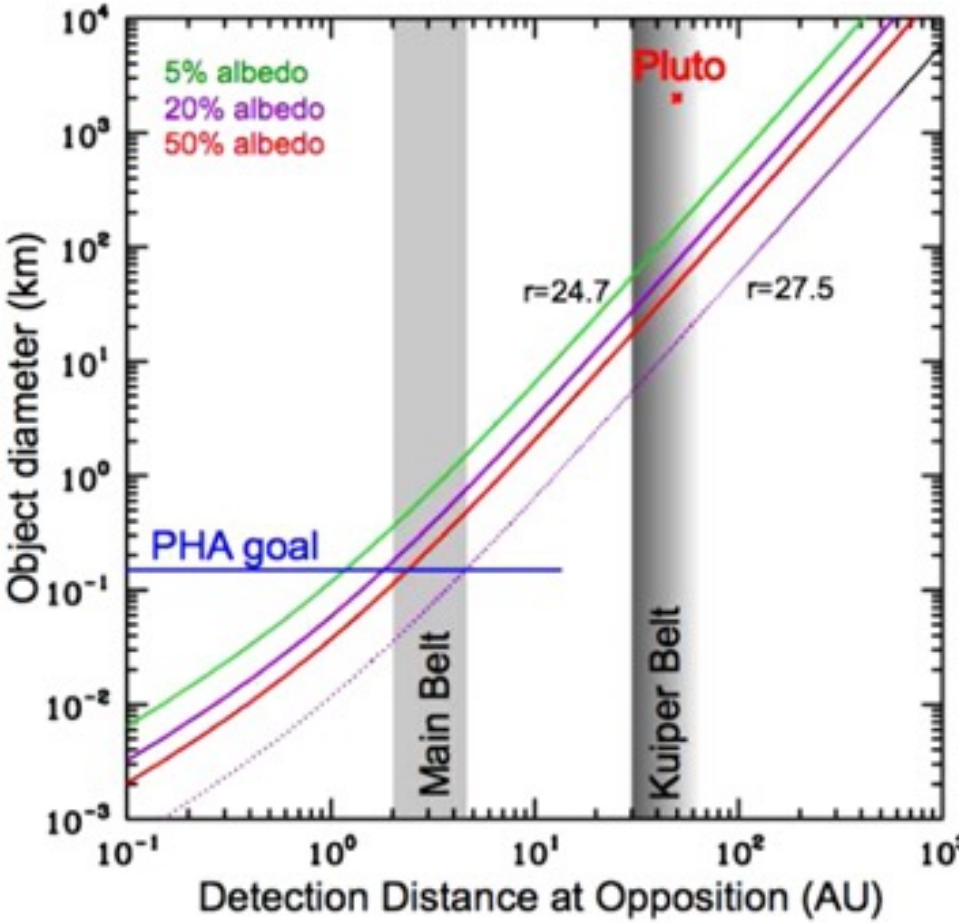
LSST - SSSBs

- **Survey strategy, Cadence, Discoveries, Astrometry, Photometry**
  - *Depends on cadence for proper detection and linking*
  - *epoch-data f,x(t) over 10 years*
  - *Going to faint magnitude => smaller and/or farther*

  - *ugrizy* colour-photometry - taxonomy, lightcurves, size distribution, …
  - imaging - peculiar objects, active, binaries, MBC
  - astrometry - good orbits, dynamics, proper elements, families, masses, non grav. effects, ISOs, …

- **Major Extension of populations**
  - *from r≈21 to r≈24 mag.* - population extension XXL*
  - faint and small objects – in particular for LPCs, TNOs, MBAs, NEOs

(*OSSOS isn't complete)



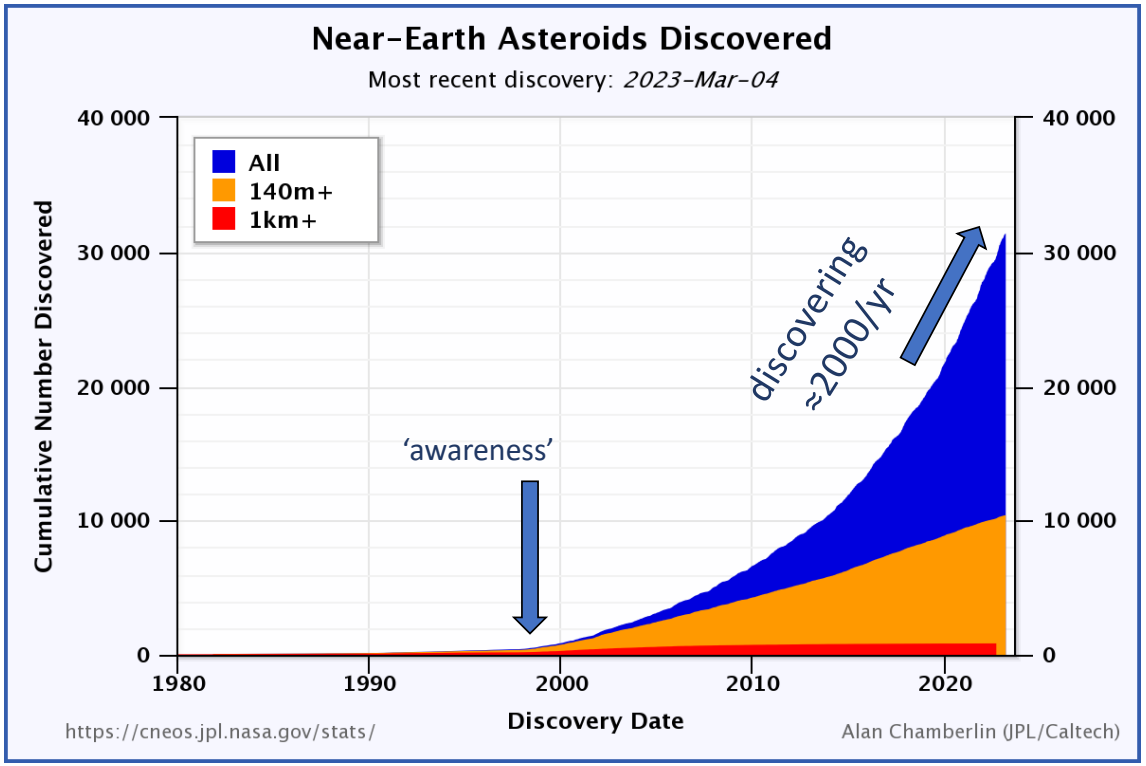
(Ivecic 2015)

The *inner* Solar System

- **NEAs**
  - Reaching goal in detecting more than 90% objects larger than ≈140m
  - good astrometry, long time span in continuation to Gaia
  - fink broker for detecting new objects (see J. Peloton & Co.)

… and more

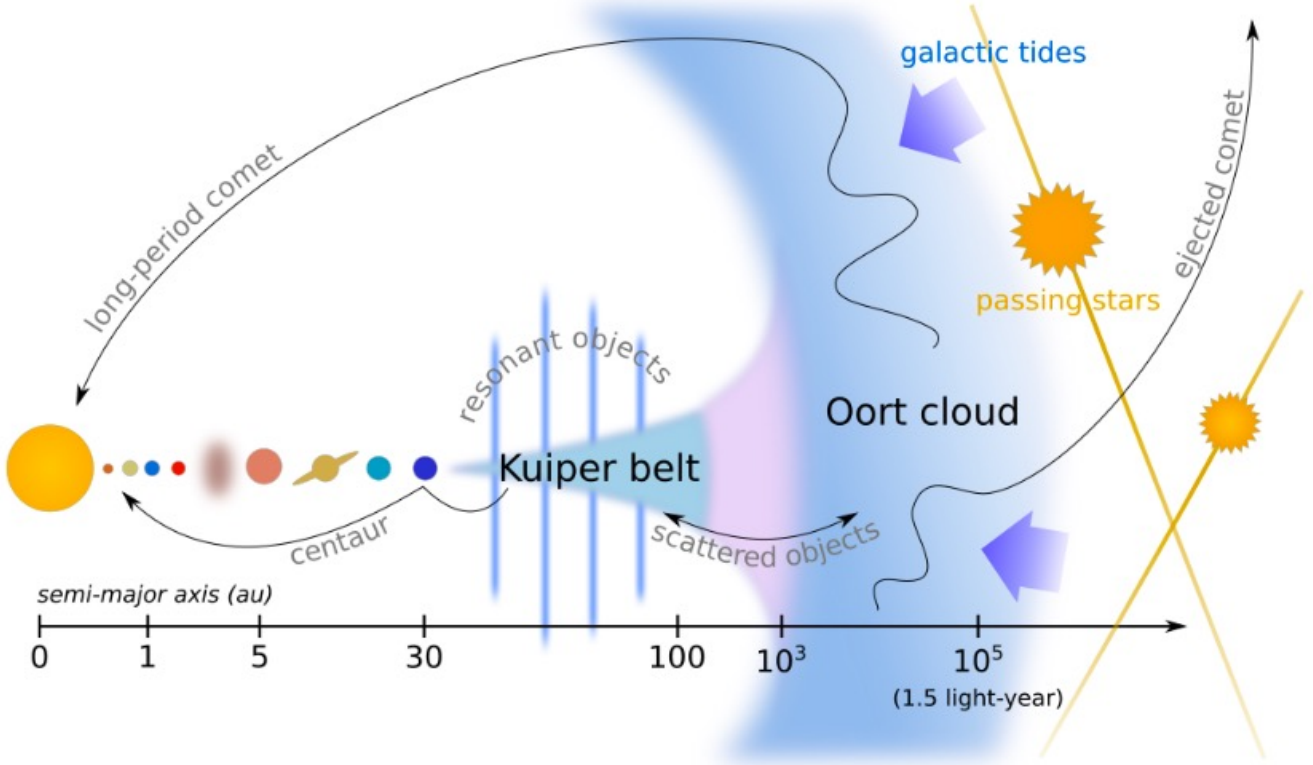
  - Solar System and NEAs part of EPO investigations!



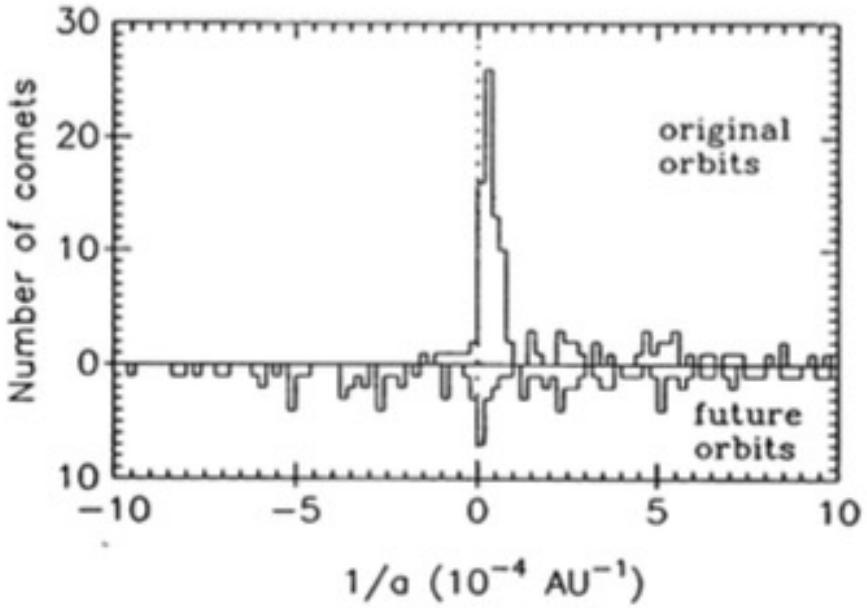
The *outer* Solar System

DYNEGALE: Dynamics beyond Neptune in the galactic environment

- Various dynamical interactions



The Oort cloud hypothesis



Oort (1950):

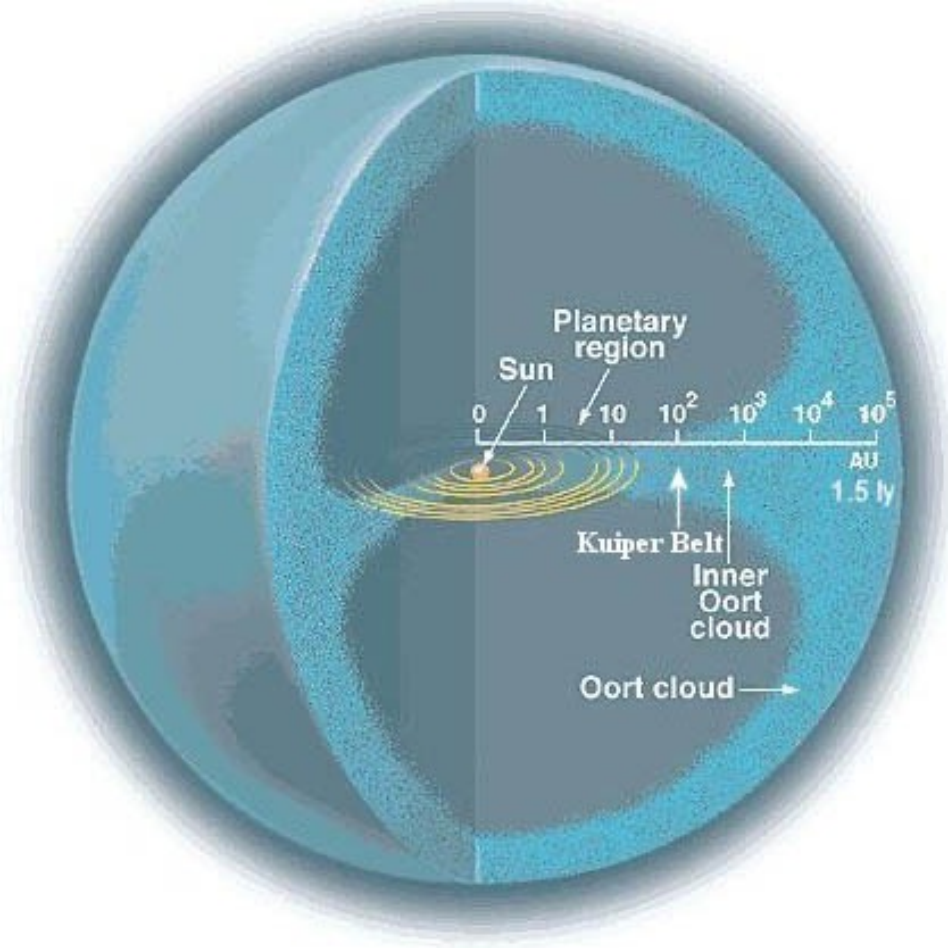
"From a score of well-observed original orbits it is shown that the "new" long-period comets generally come from regions between about 50 000 and 150 000 AU distance. The sun must be surrounded by a general cloud of comets with a radius of this order, containing about 10^{11} comets of observable size; the total mass of the cloud is estimated to be of the order of 1/10 to 1/100 of that of the earth. Through the action of the stars fresh comets are continually being carried from this cloud into the vicinity of the sun."

The Oort cloud hypothesis

- **No direct evidence**
  - Origin of 'long period' comets (HFC, LPC)
  - Perihelion, inclination distribution

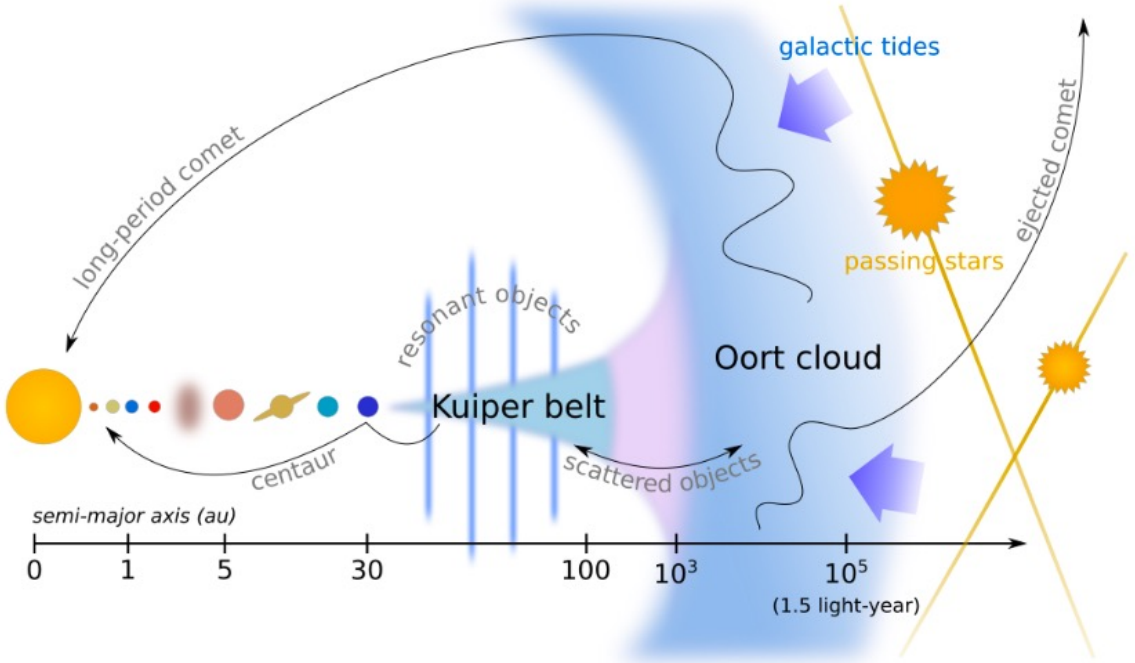
- **What characteristics?**
  - Outer – Inner edge transition?
  - Distribution/shape?
  - Extent inward and outward
  - How/When did it develop?
  - Depletion?
  - Present in other stellar systems?

- **Insight about the Oort cloud**
  - From comparison of initial models
    - to observations of comets
    - with long-term dynamical evolution



The outer Solar System

- **Initial Oort cloud hypothesis**
  - Long-term dynamics simulations
- **Modeling dynamical environment**
  - Galactic potential/tides
  - Passing stars, Molecular clouds
  - Planets
- **Comparison to observed orbit distributions**
  - LSST



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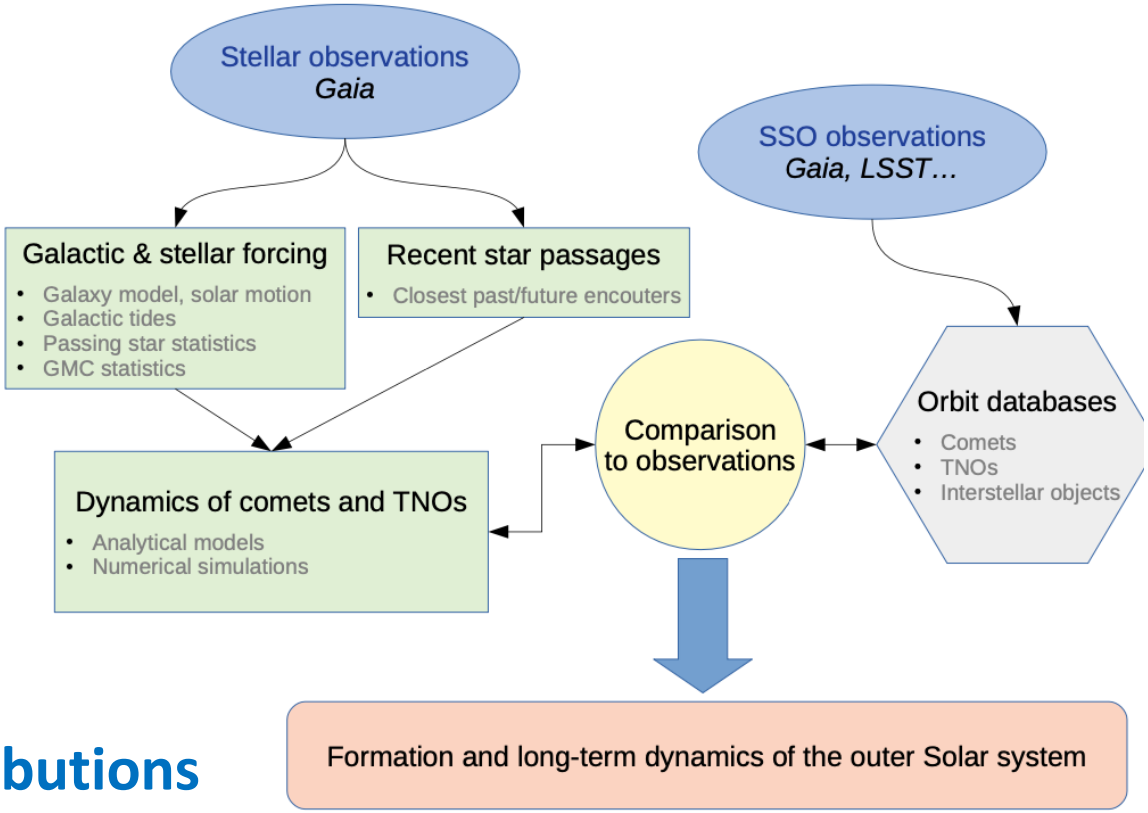
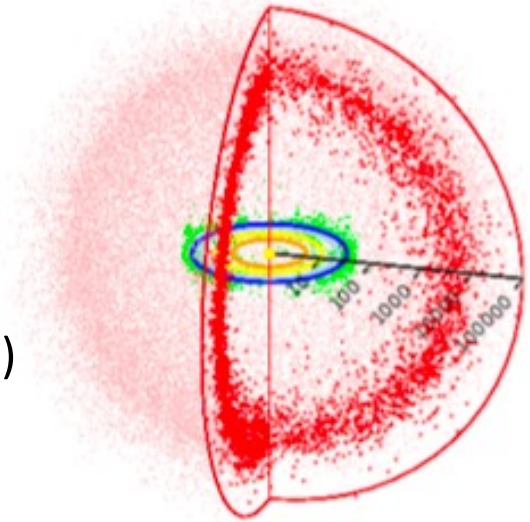


The perturbators & dynamical model

- **Galactic potential/tides**
- **Passing stars and MC**
- **Planets**
  - 4 giant planets when perihelion distance gets small (<70AU)
  - Interplay galactic tides and planetary perturbations (chaotic region)
- **Performing long-term numerical simulations**
  - Proto-Oort clouds hypothesis models
  - Large set (tens of millions) of test particule comets and initial conditions
  - Use of GPU-HPC and quasi-integrable dynamics



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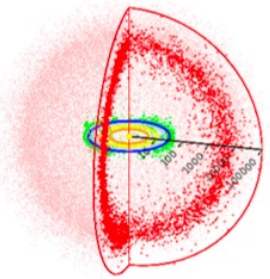
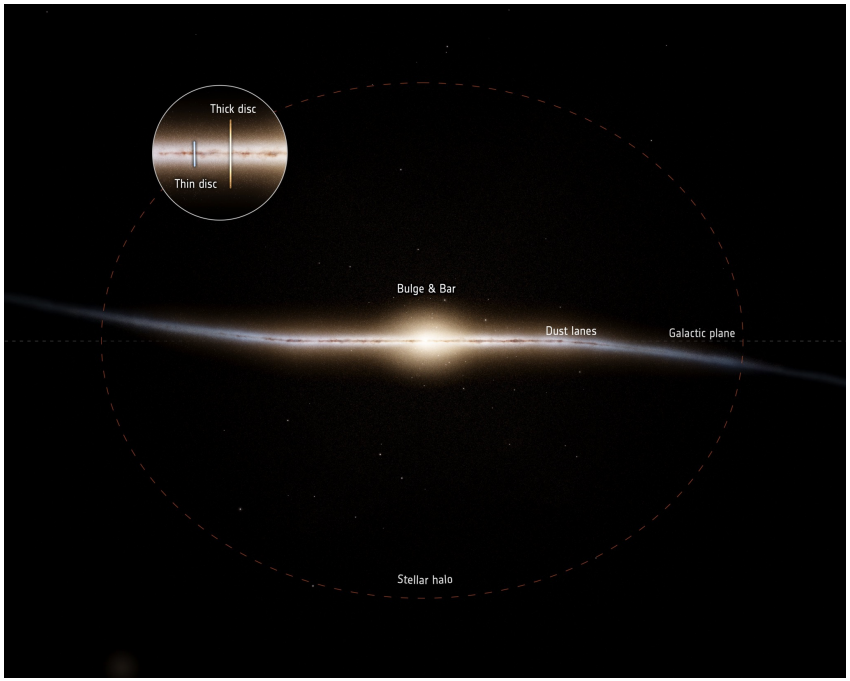
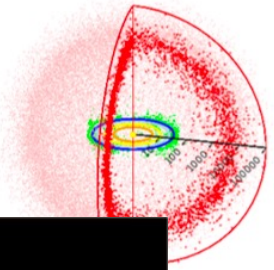


- **Galactic potential/tides**
  - Gravitational attraction by the Milky Way, varies with Solar oscillation on the galactic plane
  - Quasi-integrable dynamics
  - New modeling from Gaia

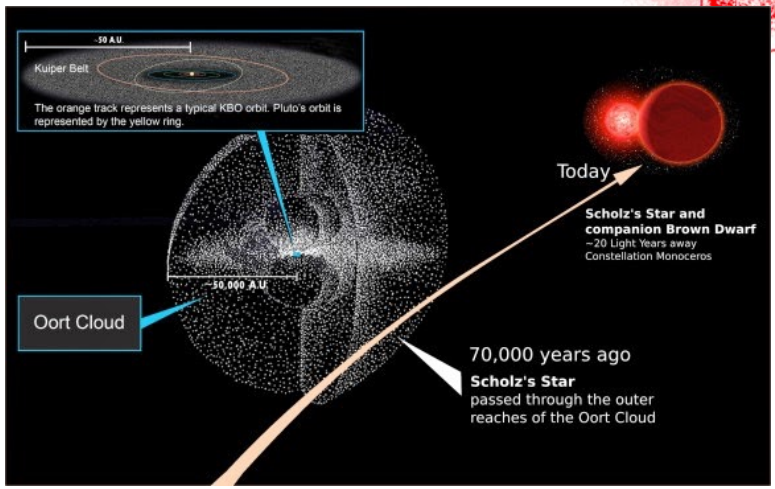
    non axisymetric, non-constant potential



The perturbators & dynamical model



- **Passing stars and MC**
  - Individual stellar fly-by (few Myears timescale) with uncertainty from Gaia
  - Stellar and sub-stellar objects from Galaxy model
  - Effect of Molecular Clouds
  - Statistics on stellar encounters (Gyears timescale)



Type	Mass ($M_\odot$)	Enc. freq.	$\langle V \rangle$ (km/s)	σ_V (km/s)
B0	9	0.005	24.6	6.7
A0	3.2	0.03	27.5	9.3
A5	2.1	0.04	29.3	10.4
F0	1.7	0.15	36.5	12.6
F5	1.3	0.08	43.6	15.6
G0	1.1	0.22	49.8	17.1
G5	0.93	0.35	49.6	17.9
K0	0.78	0.34	42.6	15.0
K5	0.69	0.85	54.3	19.2
M0	0.47	1.29	50.0	18.0
M5	0.21	6.39	51.8	18.3
wd	0.9	0.72	80.2	28.2
gi	4	0.06	49.7	17.5

Observations and orbital database

- **Three database used so far**
  - CODE 163 comets
    - catalogue with full data processing, in particular original orbits with error bar on each orbital elements – not updated
  - MPC 158 comets
    - data bases with original orbital elements and error bar on the orbital energy
  - JPL 327 comets
    - Osculating orbital elements, propagated backward until 250 au from the Sun

- **LSST to come**
  - Astrometry of HFCs, LPCs and detached objects
    - more statistics and less biased
    - need to characterize how many new comets or extreme TNO, in particular with high perihelion

- **Confrontation to modeling**
  - fingerprints in Oort cloud, detecting disk, long-term stability, transport efficiency, …

Connex study

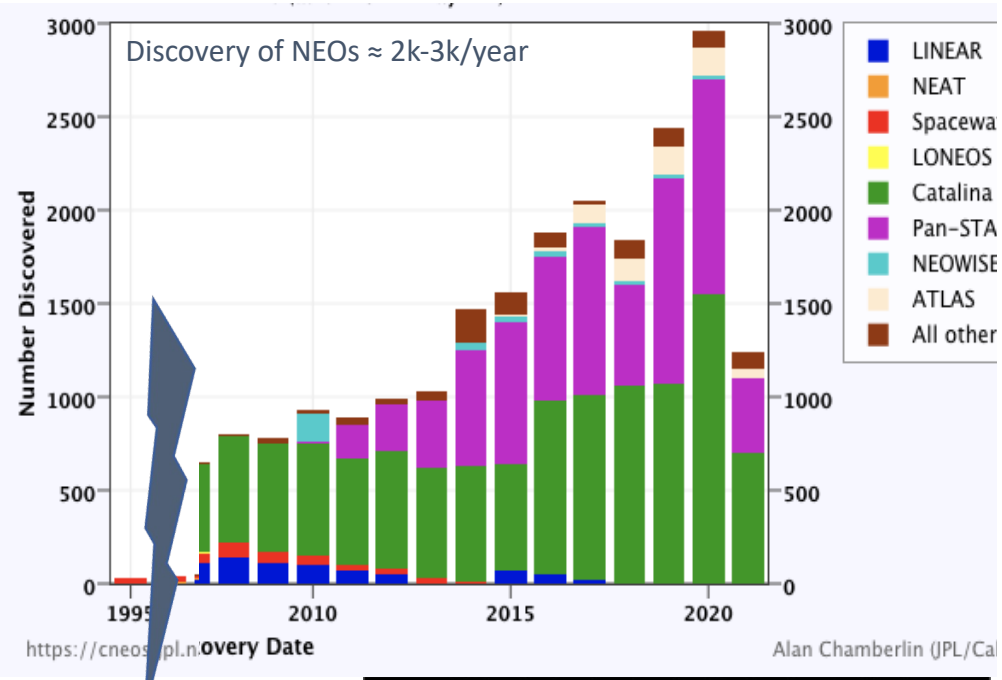
- **Analysis of ISOs**
  - Oort cloud comets on out-bond trajectory (escaping the Solar System)
  - Inbound ISOs (about 10 expected from LSST, S. Eggl priv. comm)

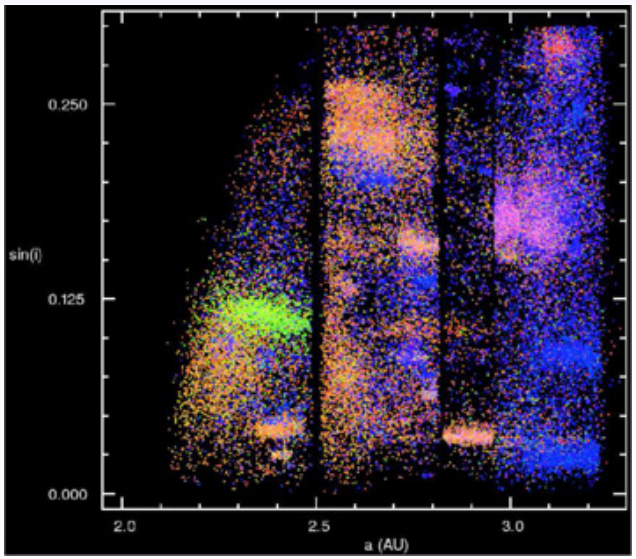
- **Comet interceptor (ESA mission)**
  - ISO or dynamically new comet ideal target
  - characterize the ISO's possible host star
  - analysis of long dynamics to characterize the comet

- **EAS special session SS5** (July 10)
  - The Solar System - from near to far - in its stellar environment at the Gaia & LSST era

Physics & Dynamics

- **Current**
  - Several surveys for detection of NEOs (Space Safety, Planetary Defence) down to V≈21
  - Science programmes legacy
- **SDSS** (2MASS)
  - ugriz images of about a quarter of the sky to r ≈ 22.5
  - colour-photometry
  - color-based asteroid taxonomy
- **CFHT**
  - large programmes on TNOs (CFEPS, OSSOS, ColOSSOS, …)
  - survey along ecliptic down to r≈24
  - about 1000 targets observed in astrometry & colour-photometry
  - discoveries, orbits, colours, resonant and discs, dyn. models, Neptune's migration, …
  - http://www.ossos-survey.org/
- **Gaia**
  - about 350.000 asteroids (+satellites, comets) observed – mostly known (V≈20.7)
  - over 10years (in progress, 2014.5 – 2024.5)
  - high precision astrometry & spectro-photometry (visible)
  - direct or indirect science of SSOs – discovery high inclination bodies
  - https://www.cosmos.esa.int/web/gaia





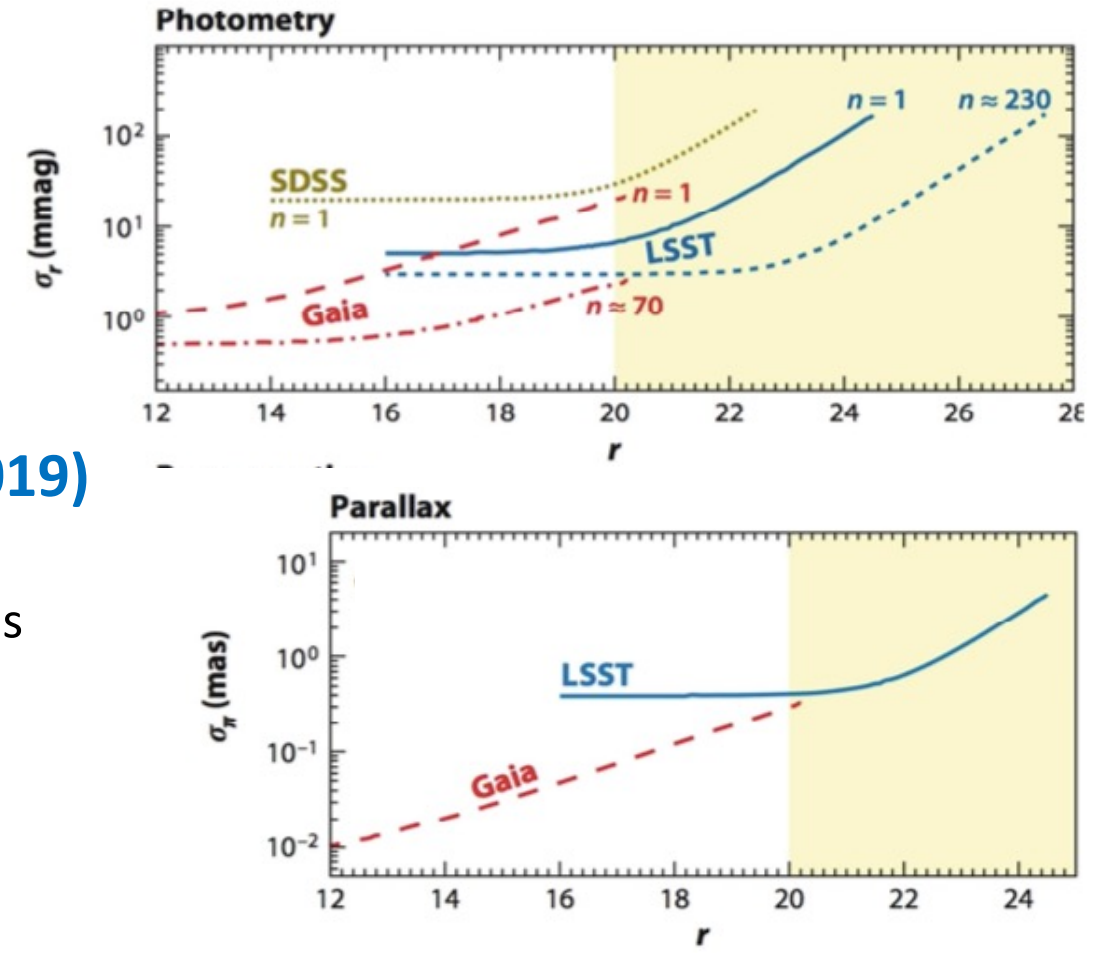
Taxonomy (SDSS Parker *et al.* 2008)
+ proper elements

LSST - SSSBs

- **Science case**
  - See e.g. H. Hsieh et al. SSSC (2019)
- **Gaia-LSST synergy (Ivecic 2015, 2019)**
  - calibration and astrometric catalogue
  - extends Gaia survey by ≈4 magnitudes

  + OSSOS-LSST synergy

- **Dynamical and physical properties**
- **Population characterisation**
- **Testing of formation models**
- **Predictions of events** (occultations)



Gaia-LSST synergy (Ivecic *et al.* 2015)