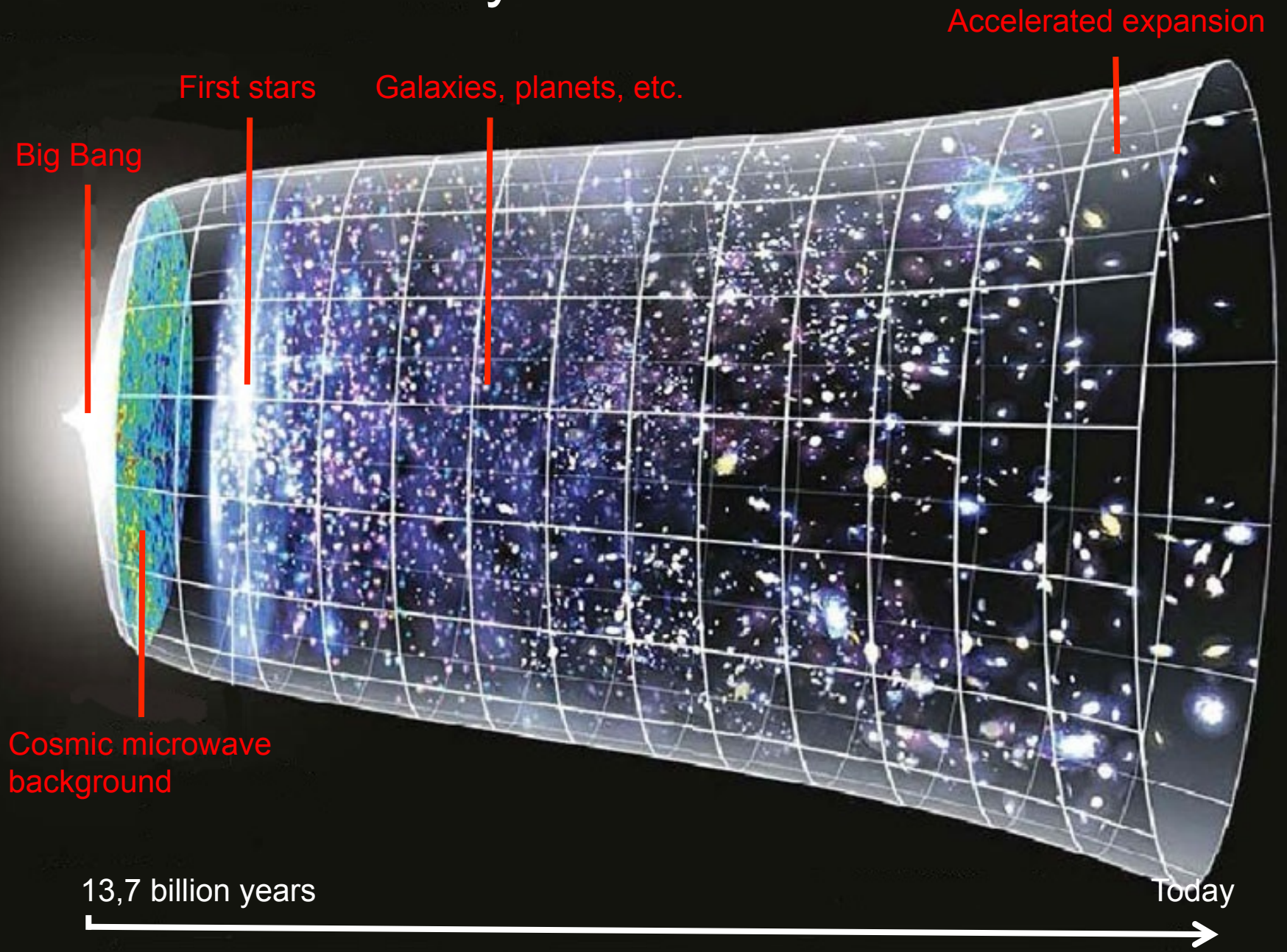
Understand the formation of structures at all scales

1. Mathilde Gaudel (Irfu/DAp)
2. Dimitri Chuard (Irfu/DAp)
3. Pauline Zarrouk (Irfu/DPhP)
4. Clément Leloup (Irfu/DPhP)

History of our universe



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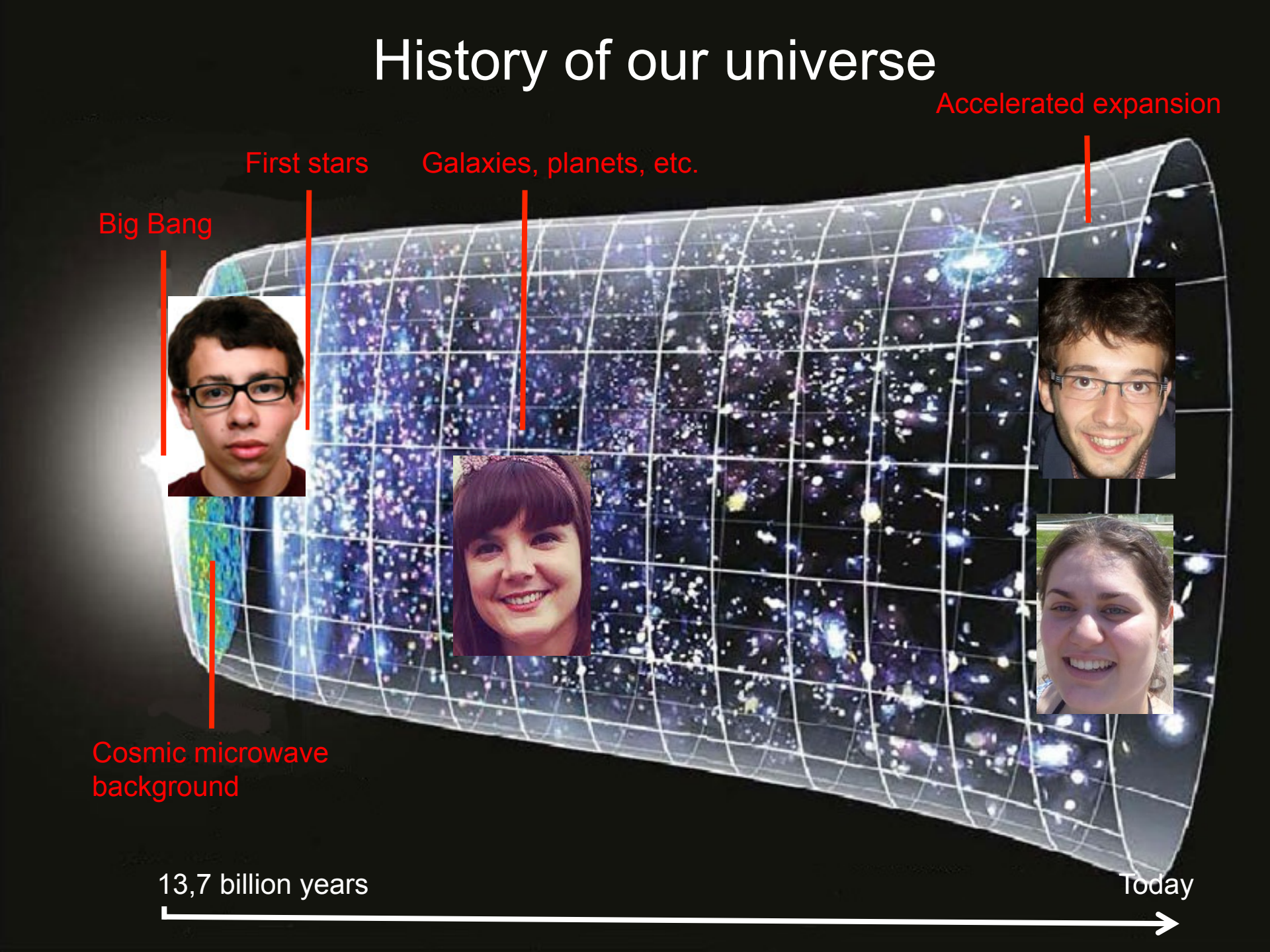
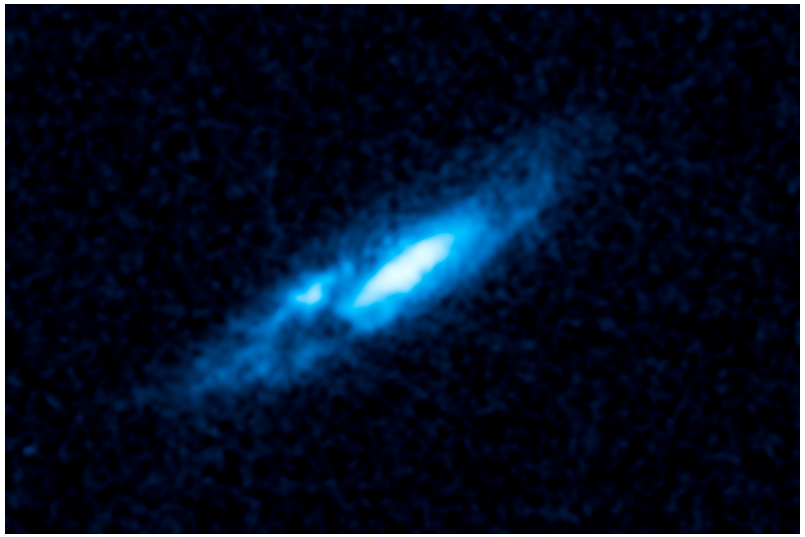


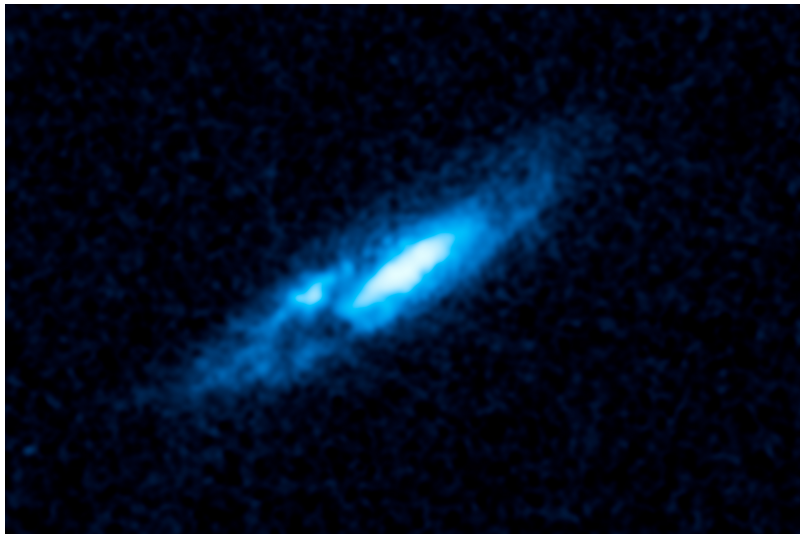
Mechanisms of accretion

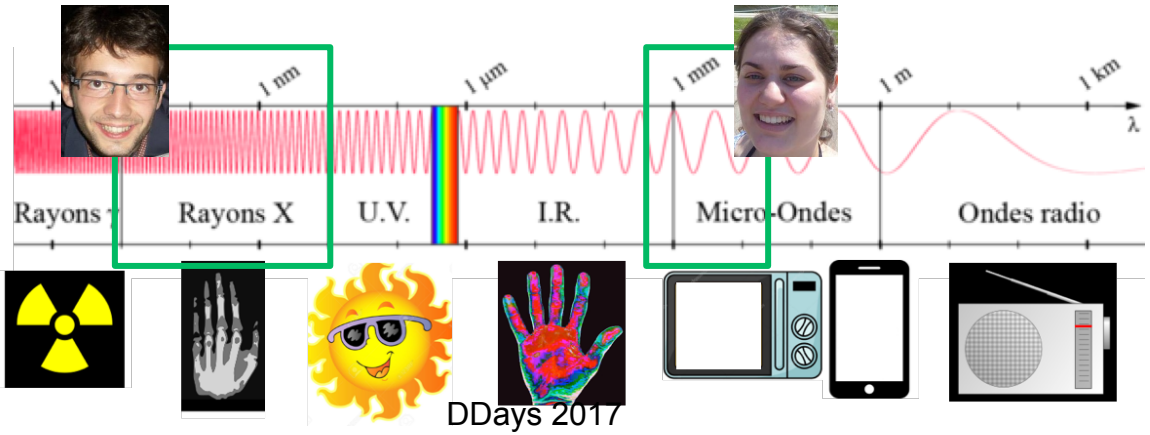


Disk of gas around an bright star in the Milky Way (2013).
Credit:NASA, ESA, and J. Mauerhan (University of California, Berkeley)

Accretion disk and jets around a black hole.
Artist view.

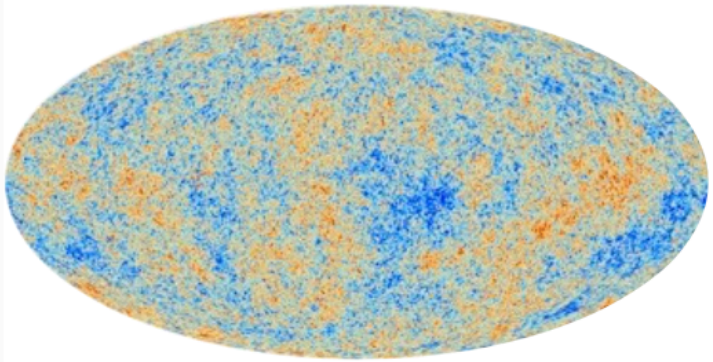
Mechanisms of accretion





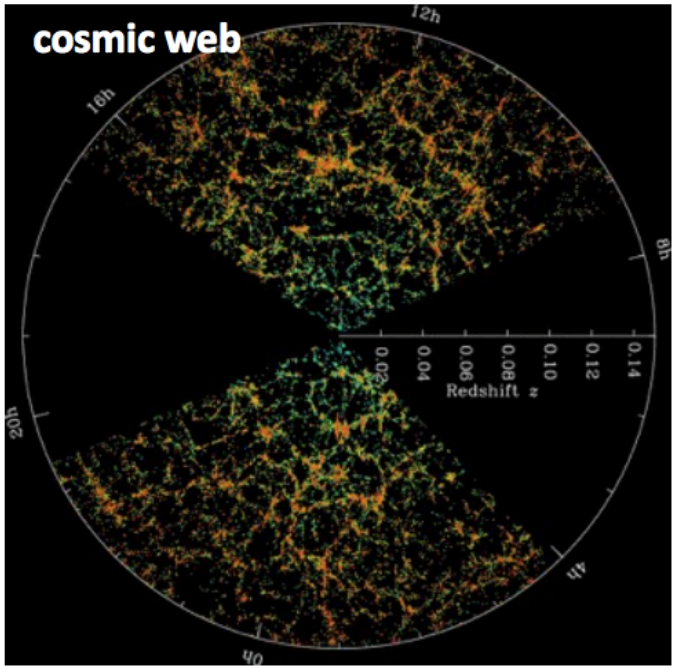
Formation of largest structure in the universe

Gaussian primordial fluctuations



gravity

expansion

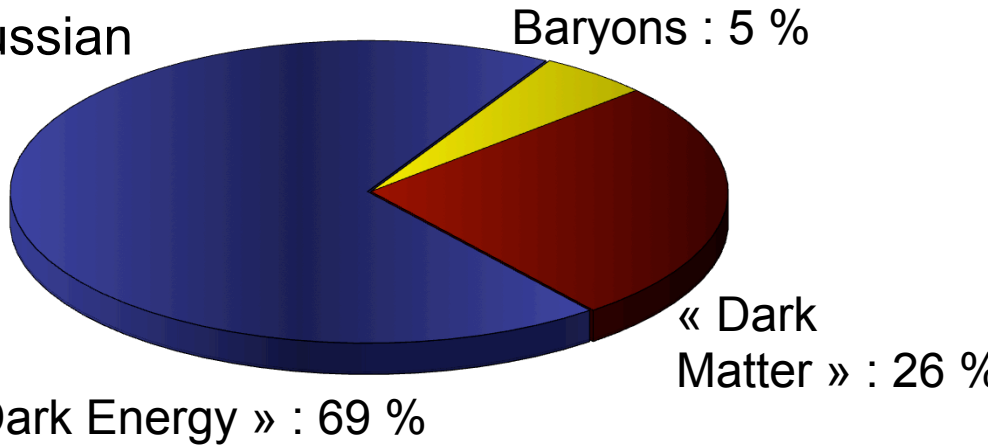


Concordance model

Key ingredients (simplified) :

- Inflation produces a scale invariant perturbation spectrum : initial Gaussian fluctuations
- **Assumes General Relativity**
- Baryon density
- Cold dark mater (CDM) density
- Dark energy (L) density

→ **Cosmological constant**



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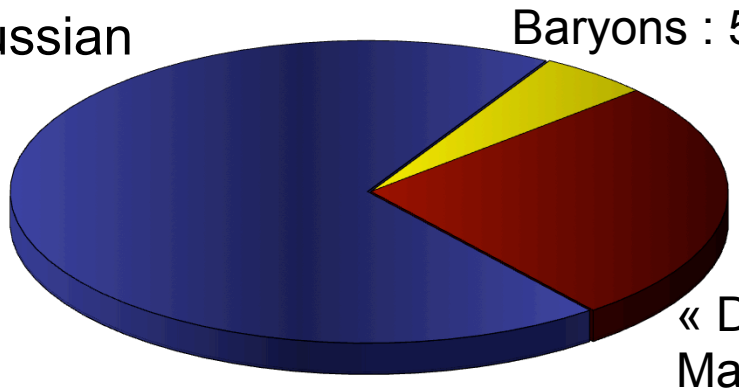
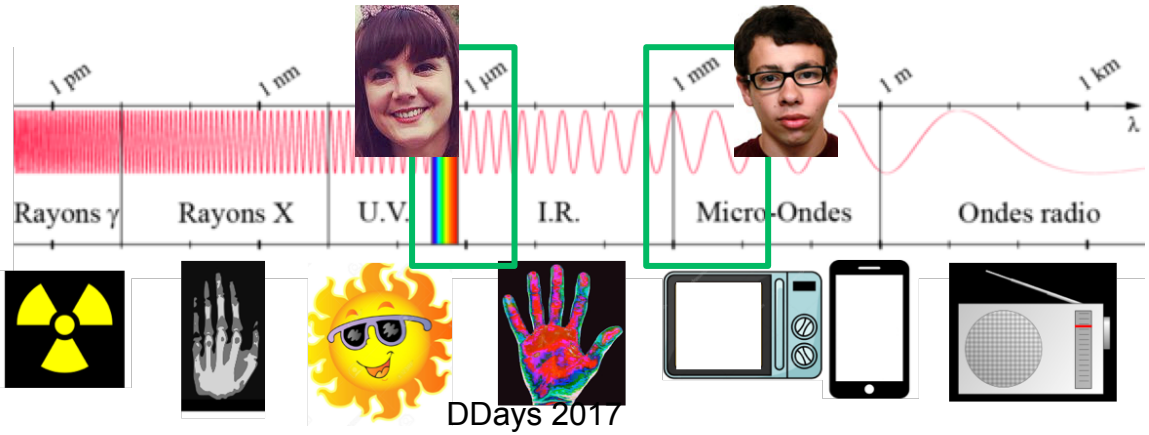
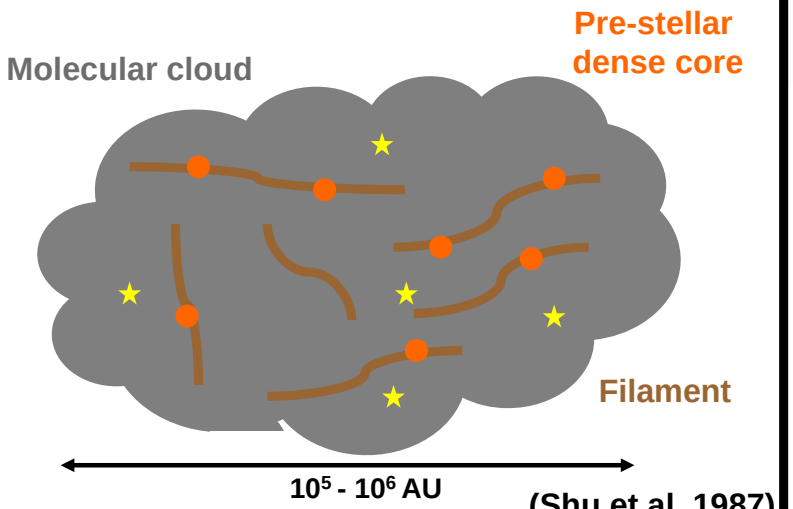




1. Angular momentum problem in star formation

Mathilde Gaudel (DAp)

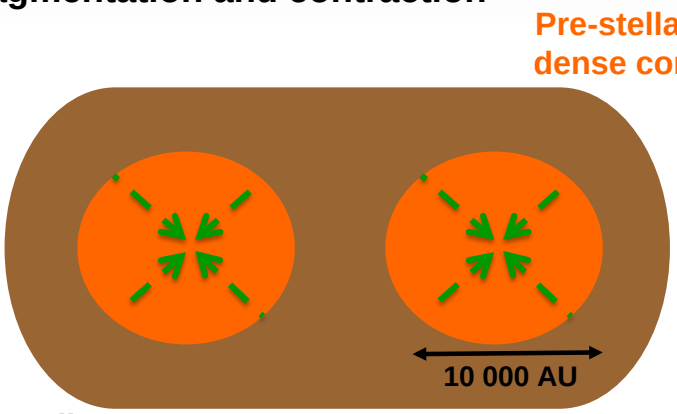
Introduction: formation of solar-type stars



(Shu et al. 1987)

Pre-stellar phase

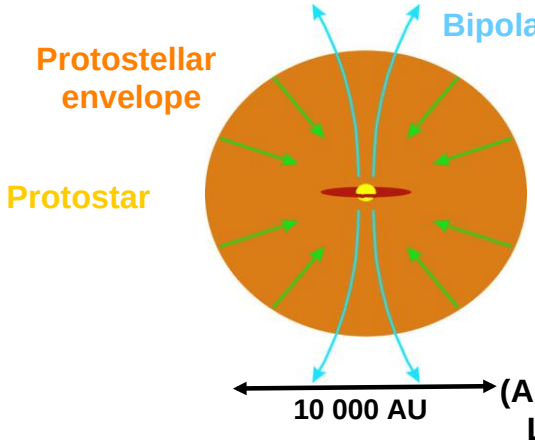
Fragmentation and contraction



(Ward-Thompson et al. 1997)

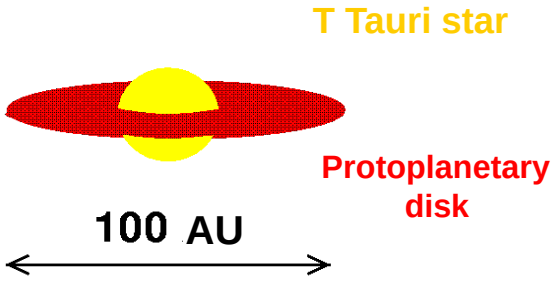
Protostellar phase

Accretion and ejection



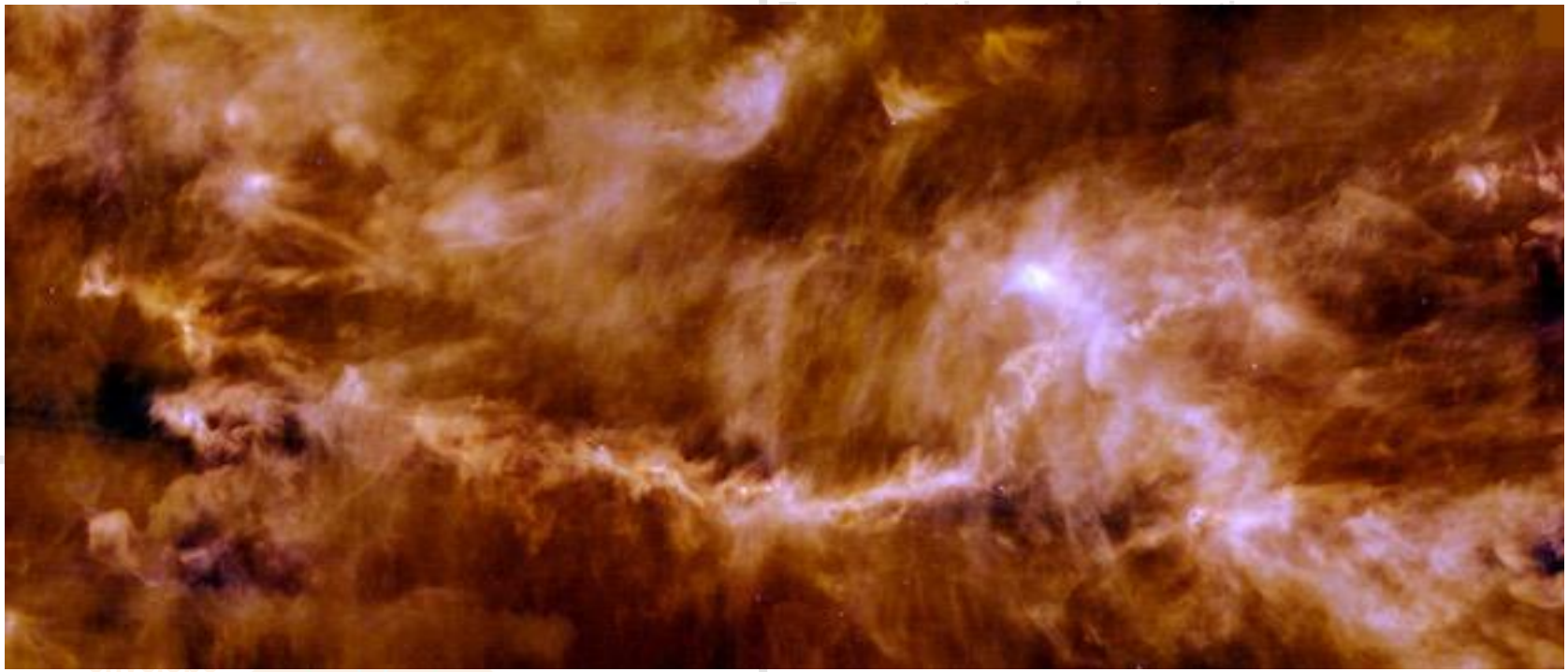
(André et al. 1993, Lada et al. 1995)

Pre-main sequence phase



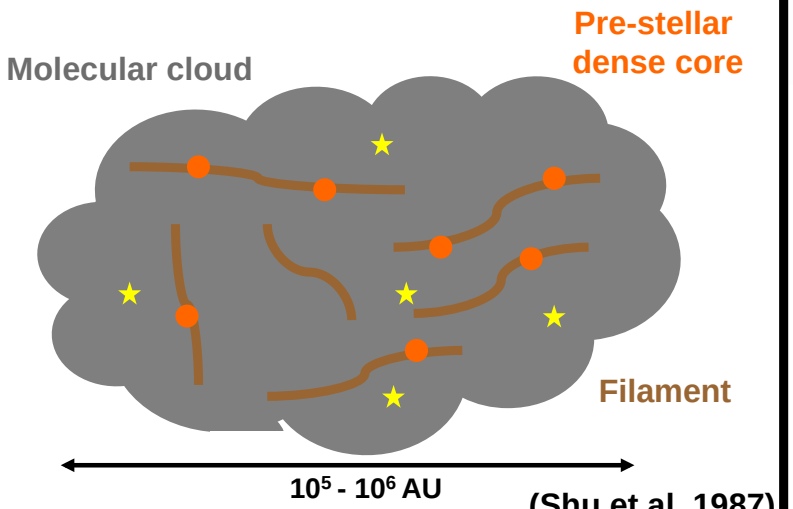
(Kenyon et al. 1995)

Introduction: formation of solar-type stars



The B211/B213 filament in the Taurus Molecular Cloud (2013).
Credit: ESA/Herschel/PACS, SPIRE/Gould Belt survey Key Programme/Palmeirim et al. 2013

Introduction: formation of solar-type stars



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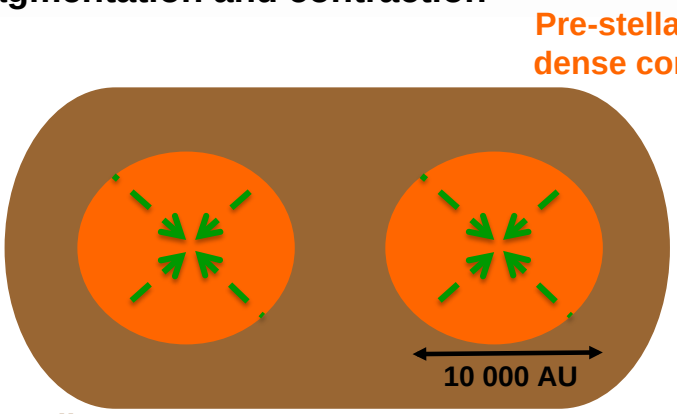

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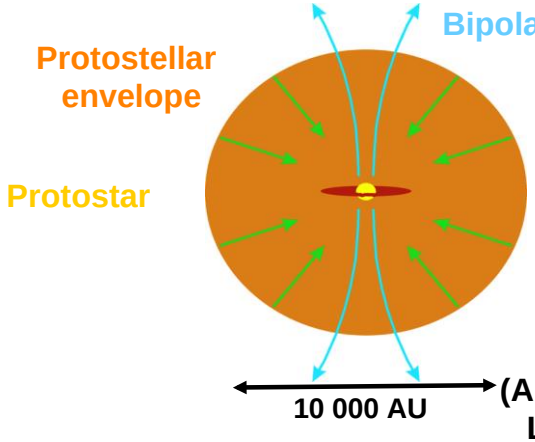

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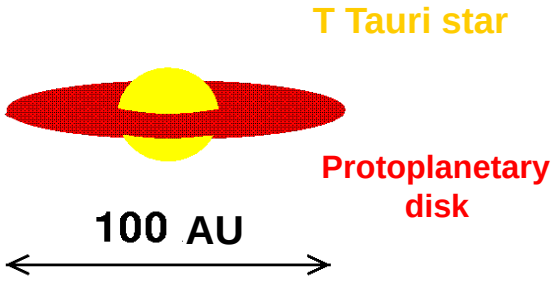

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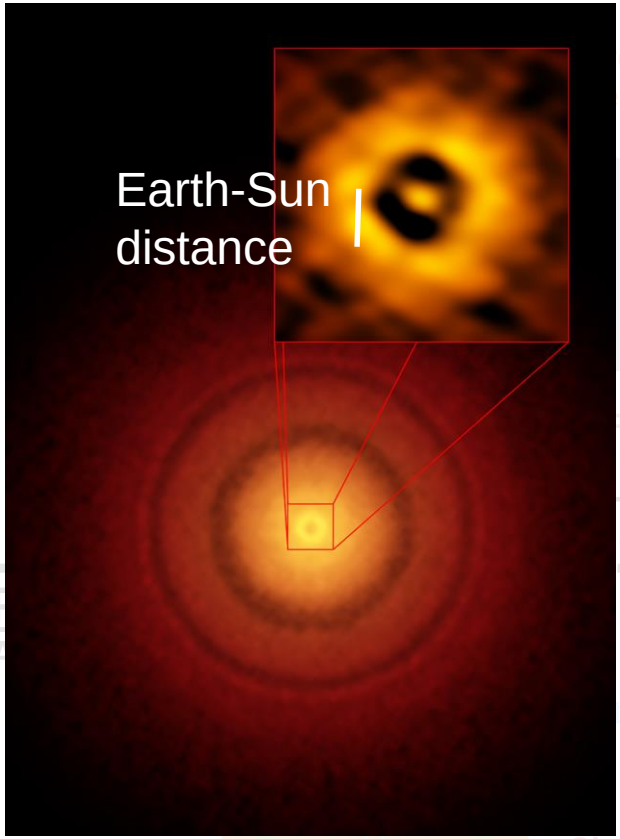
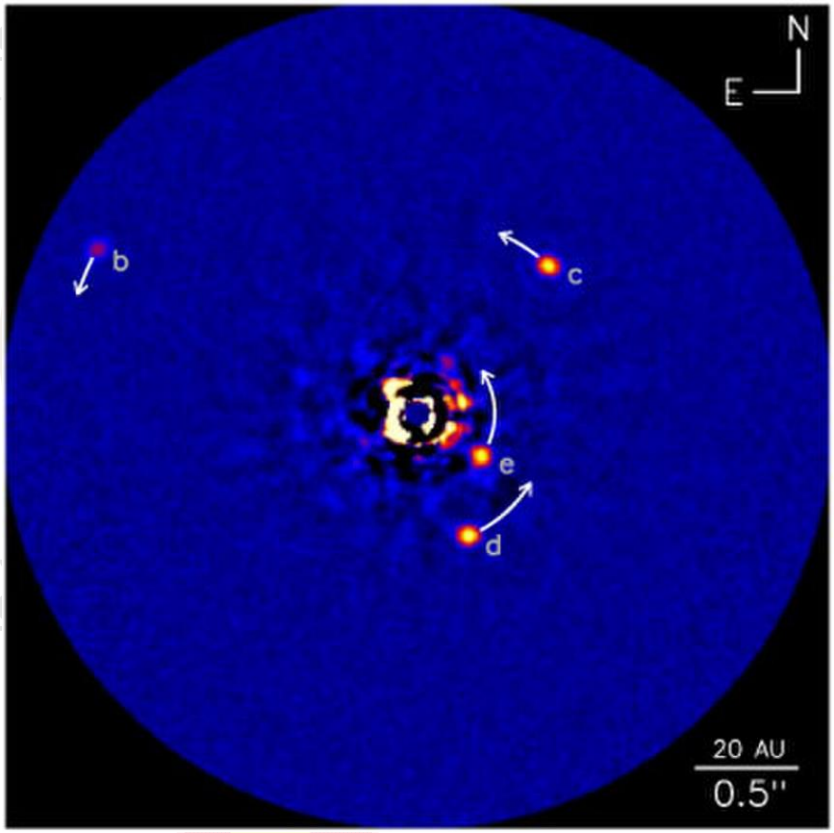
Introduction: formation of solar-type stars



ALMA image of the planet-forming disk around the young, Sun-like star TW Hydrae (2014).

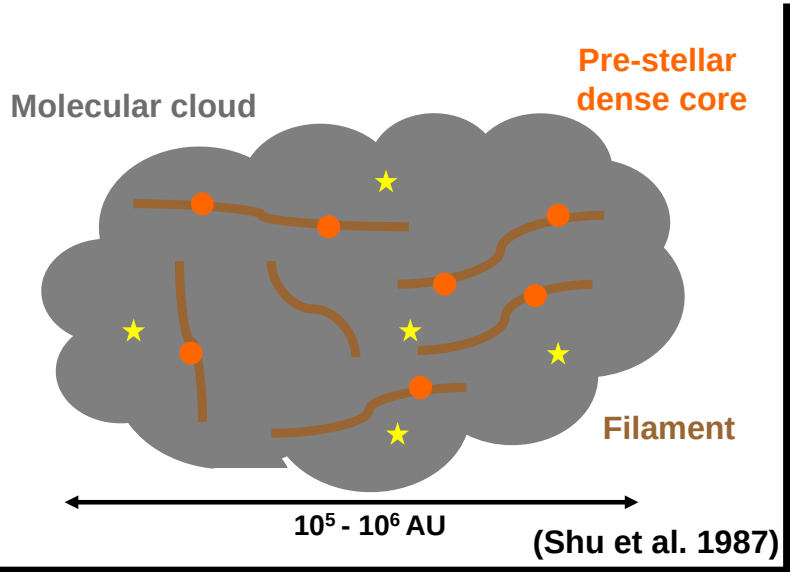
Credit: S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)



Four planets in the HD 8799 star environment directly imaged in the infrared (2008).

Credit: NRC-HIA, C. Marois, and Keck Observatory

Introduction: formation of solar-type stars



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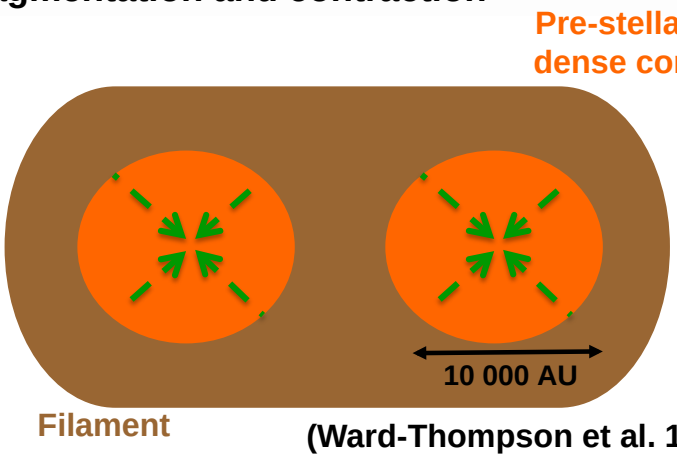
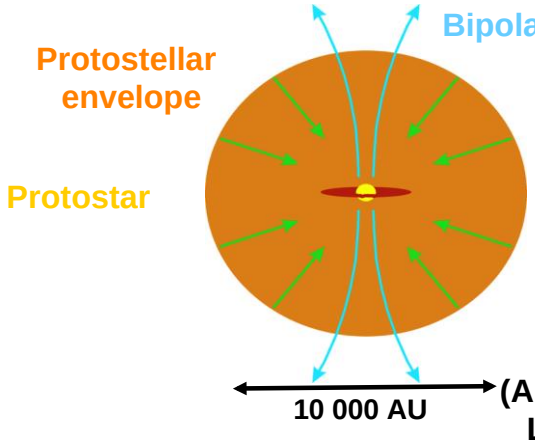


(Ward-Thompson et al. 1997)

Protostellar phase

Accretion and ejection



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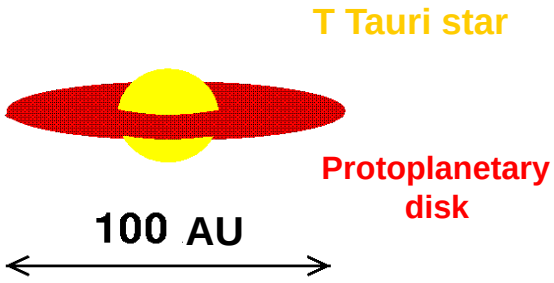

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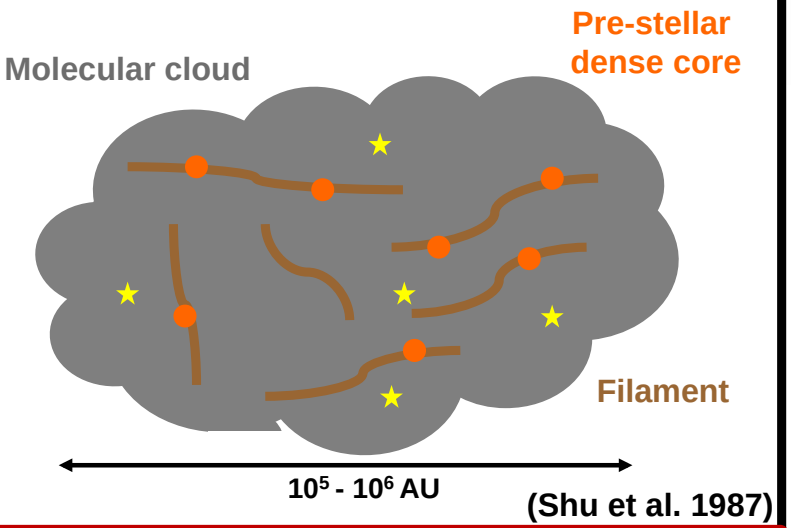

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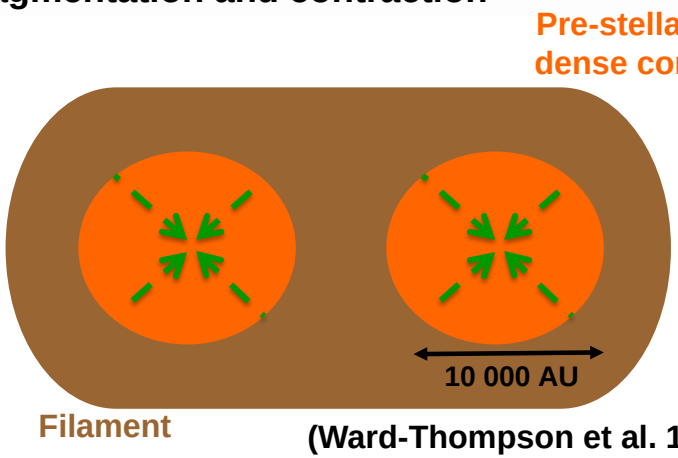

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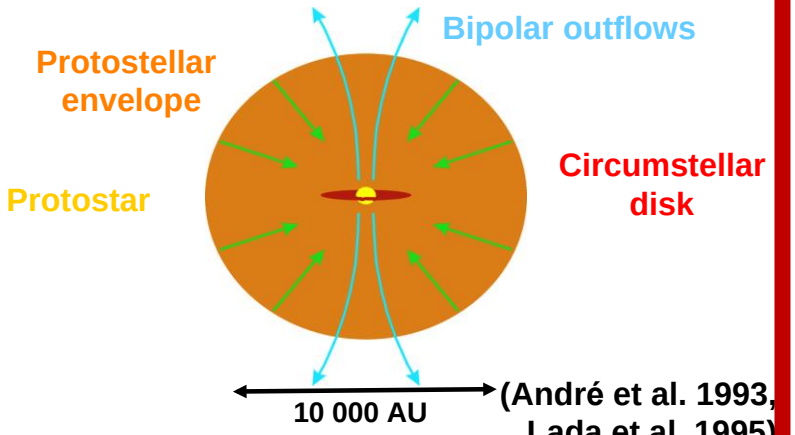

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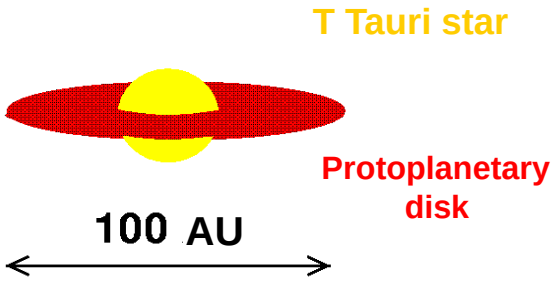
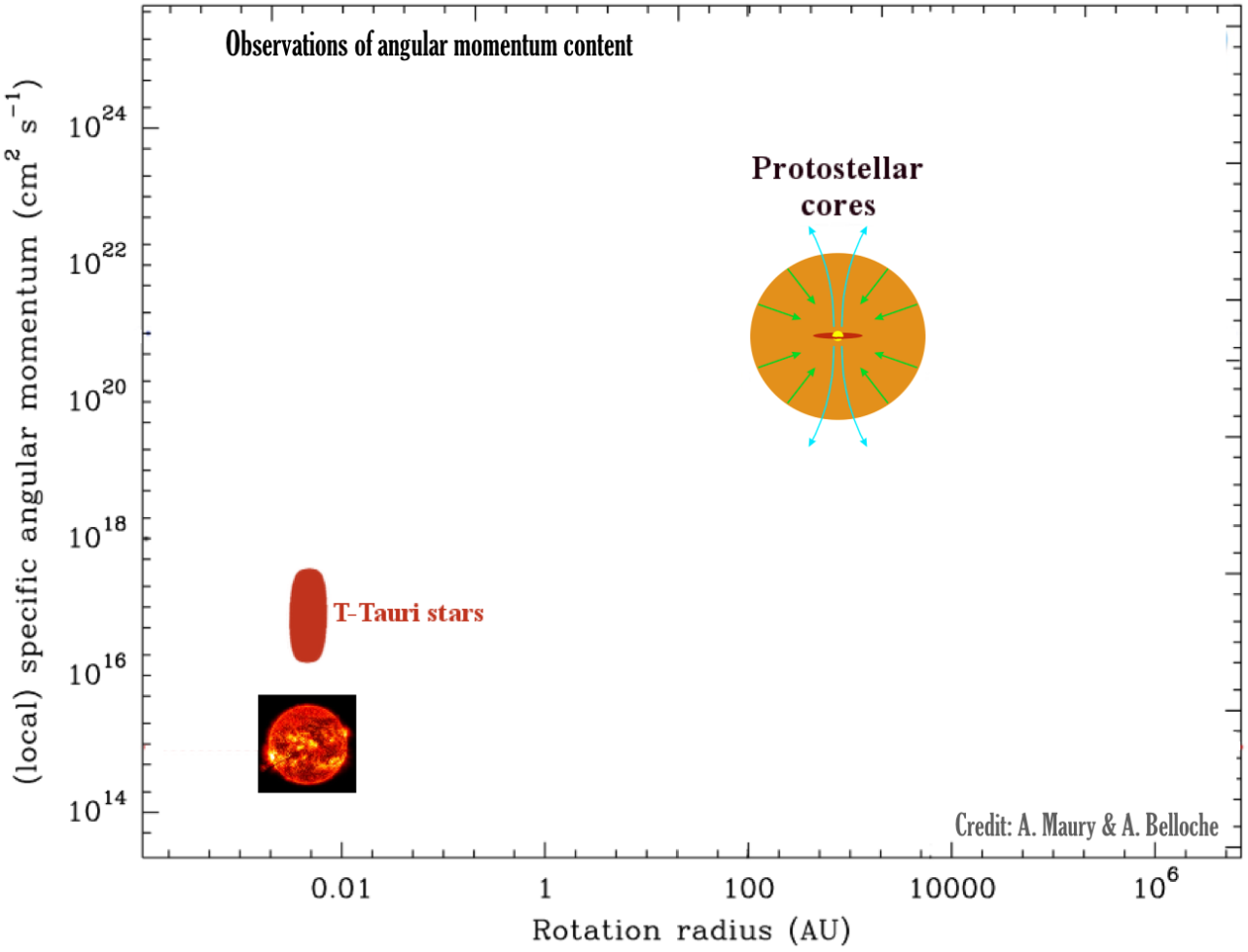


Can we solve the angular momentum problem ?



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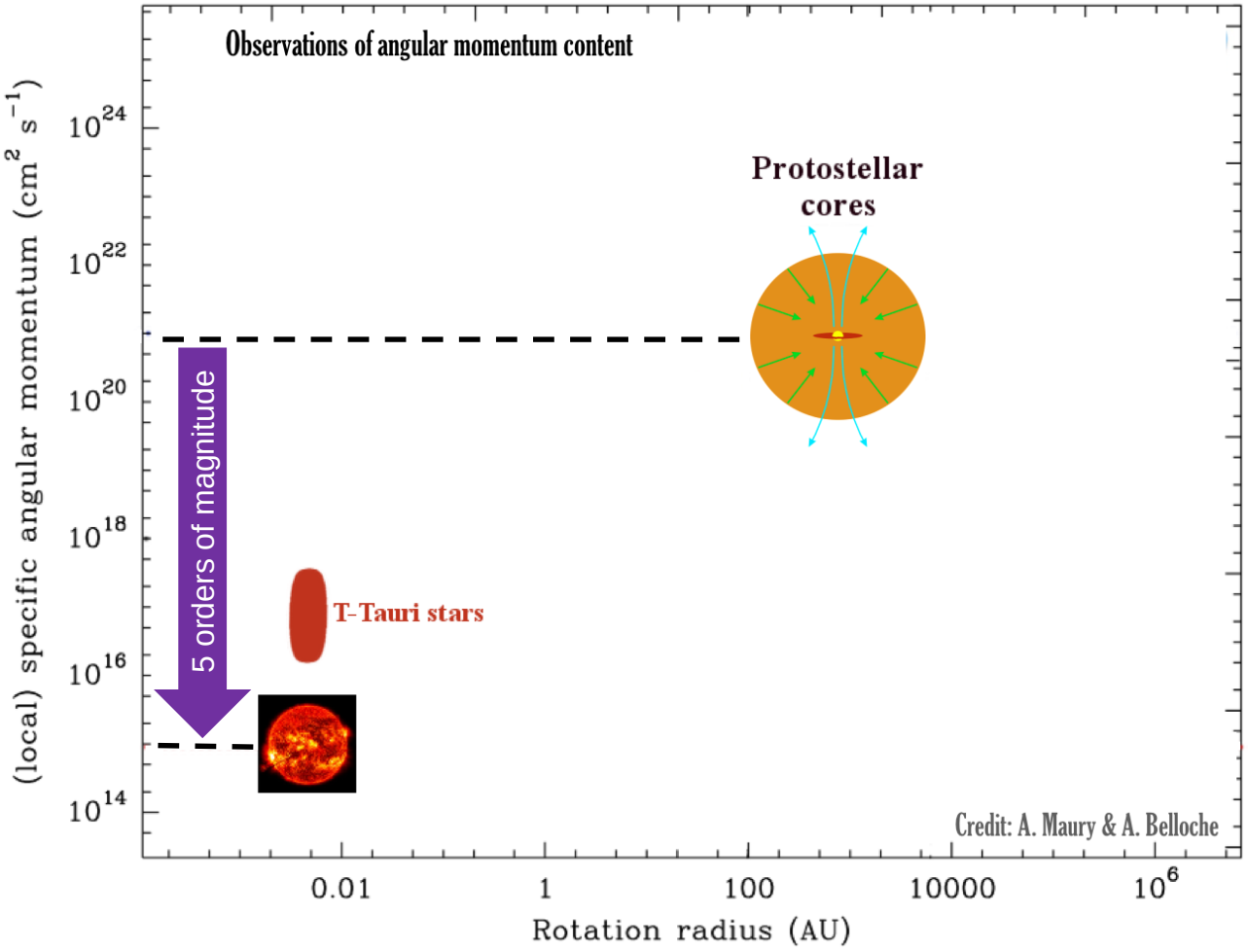
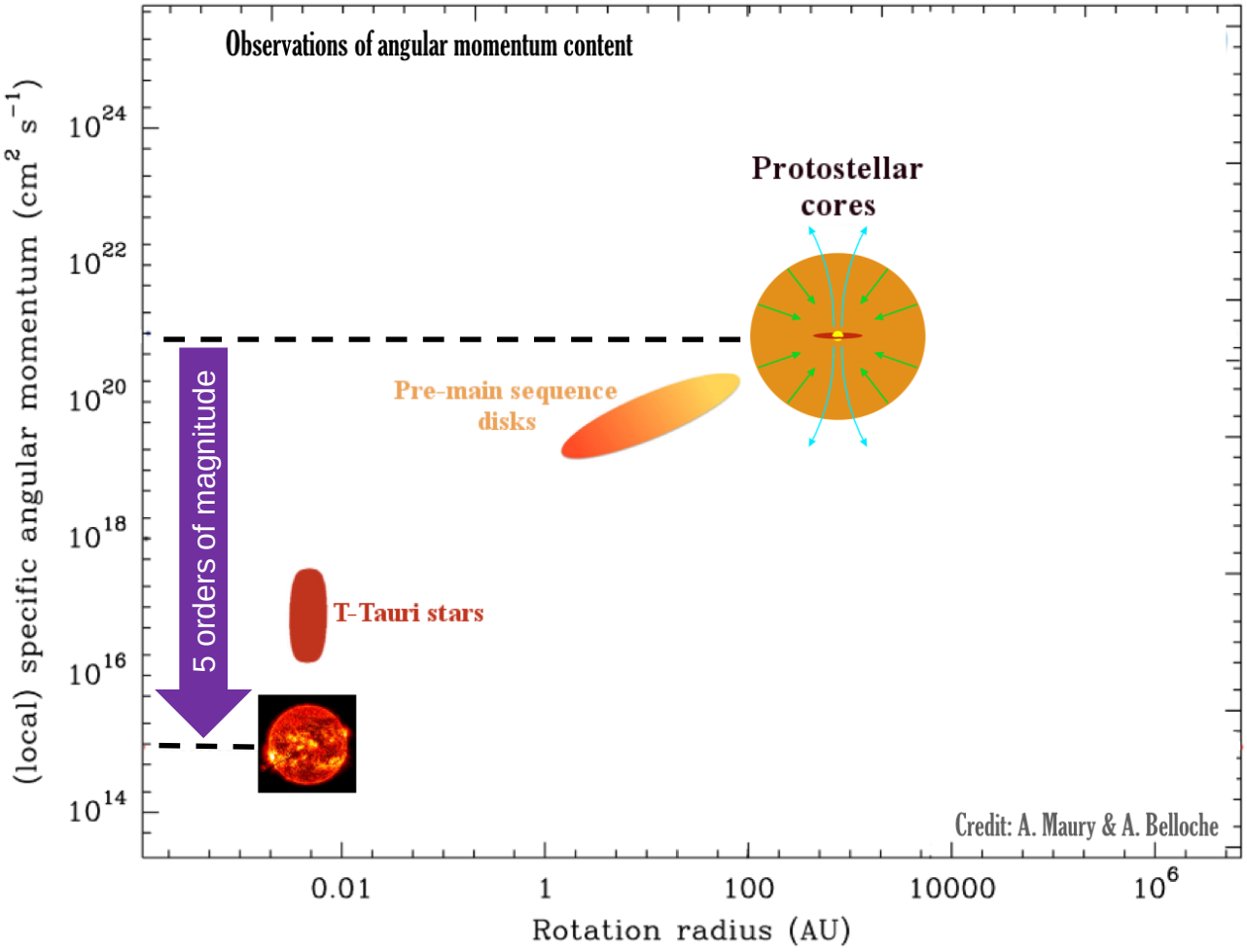


<u>Mechanisms of angular momentum dissipation</u>:

- Outflows and jets?
- Circumstellar disks?
- Magnetic braking?
- ?

Can we solve the angular momentum problem ?



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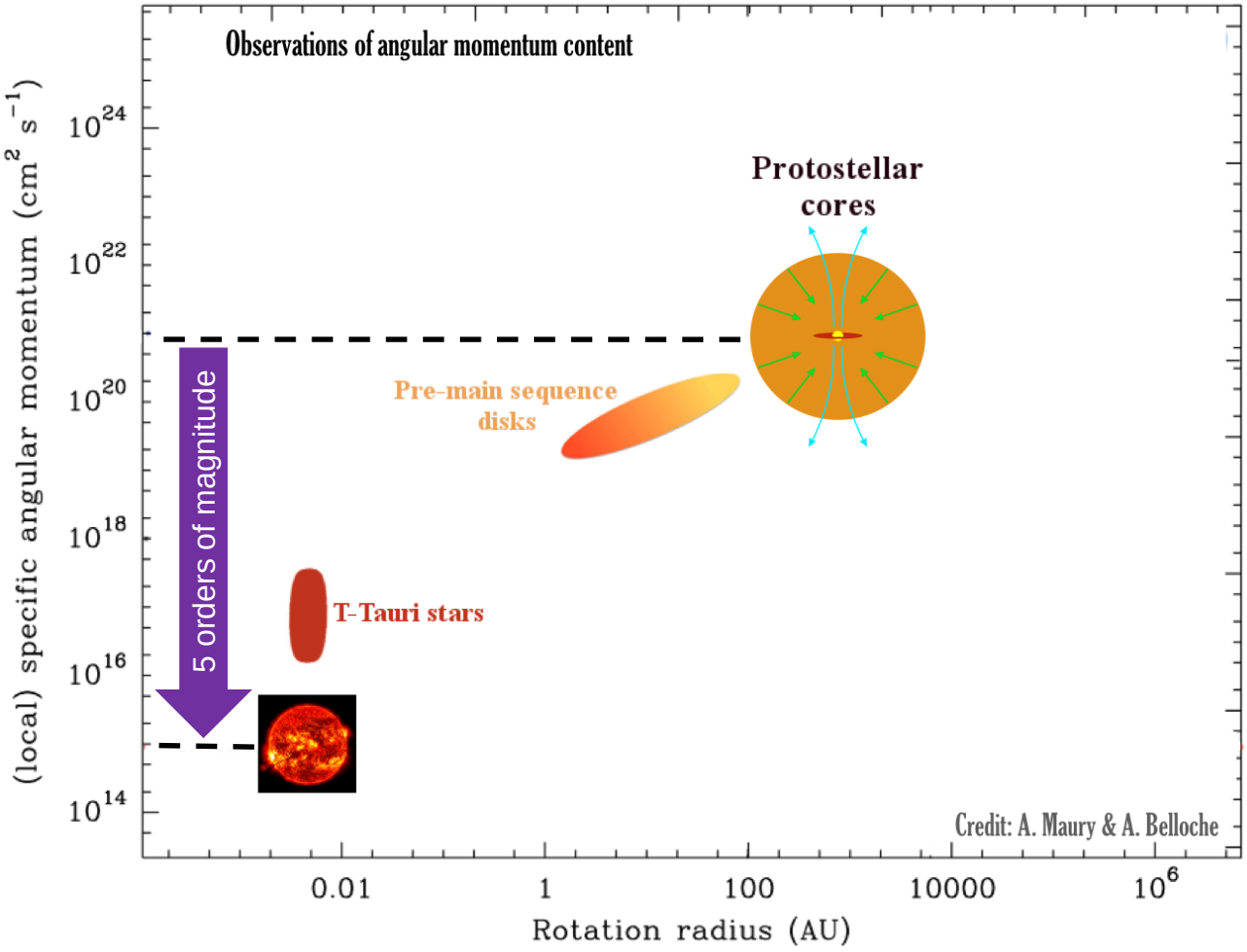

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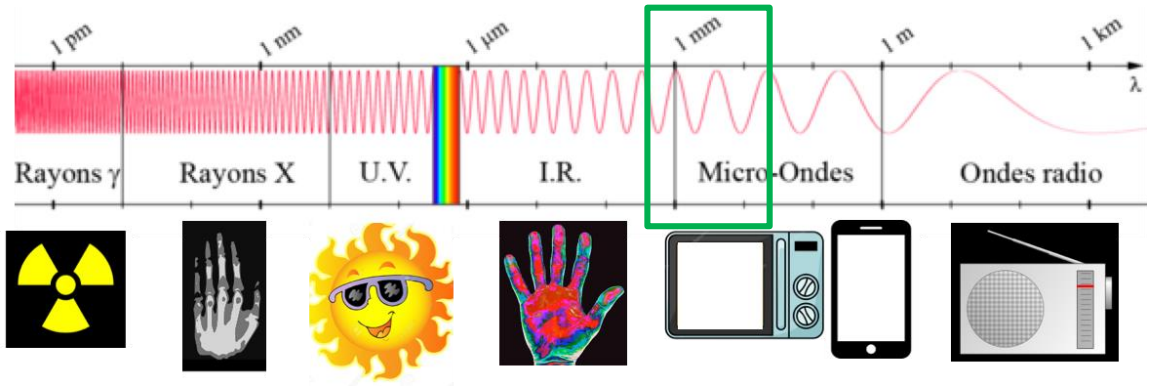
<u>Tools</u>: Distribution of angular momentum in young protostellar envelopes

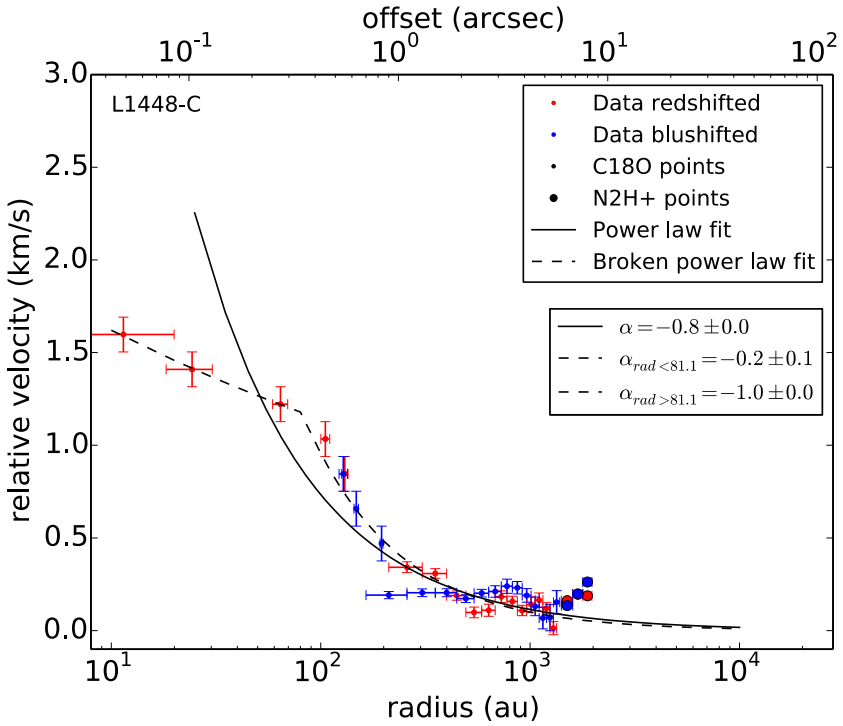
CALYPSO: an IRAM large program

- PI: Ph. André (DAp)
- CALYPSO: Continuum and Lines in Young Protostellar Objects (http://irfu.cea.fr/Projets/Calypso)
- Observations from IRAM instruments of dust continuum emission and molecular lines
- Sample: 16 young protostars

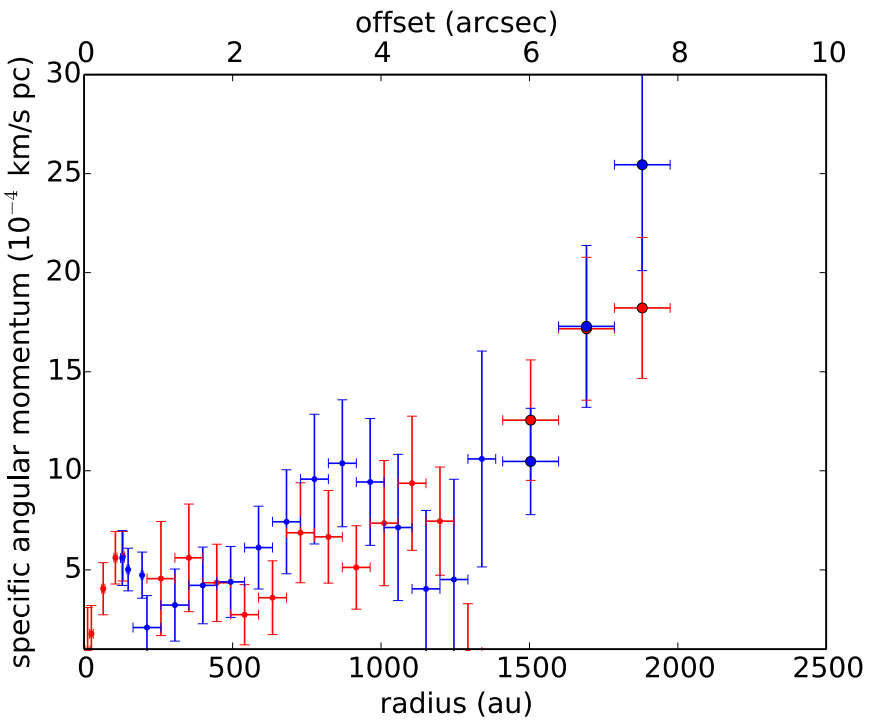


Preliminary results and on-going on studies

Rotation profile



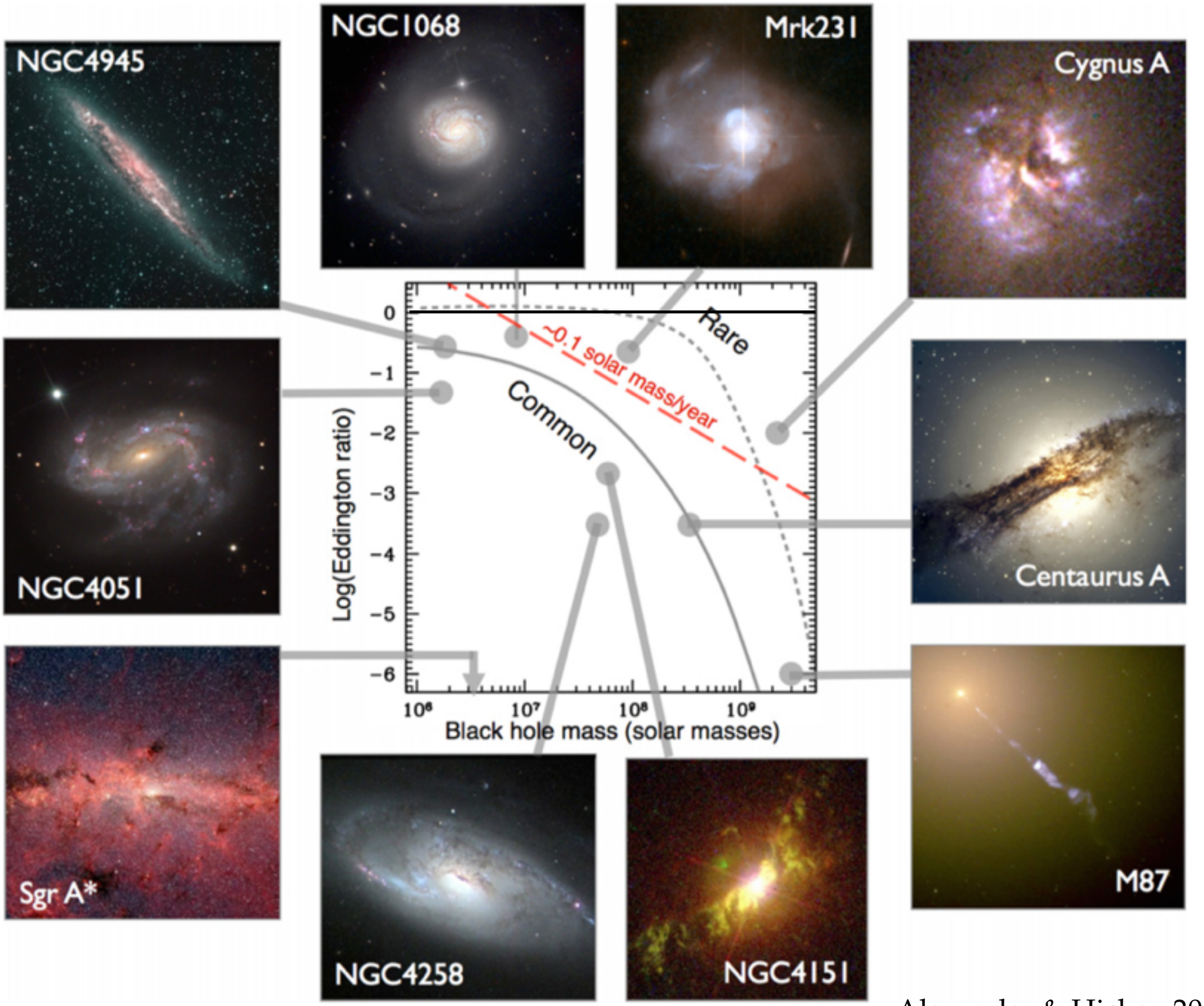
Angular momentum profile



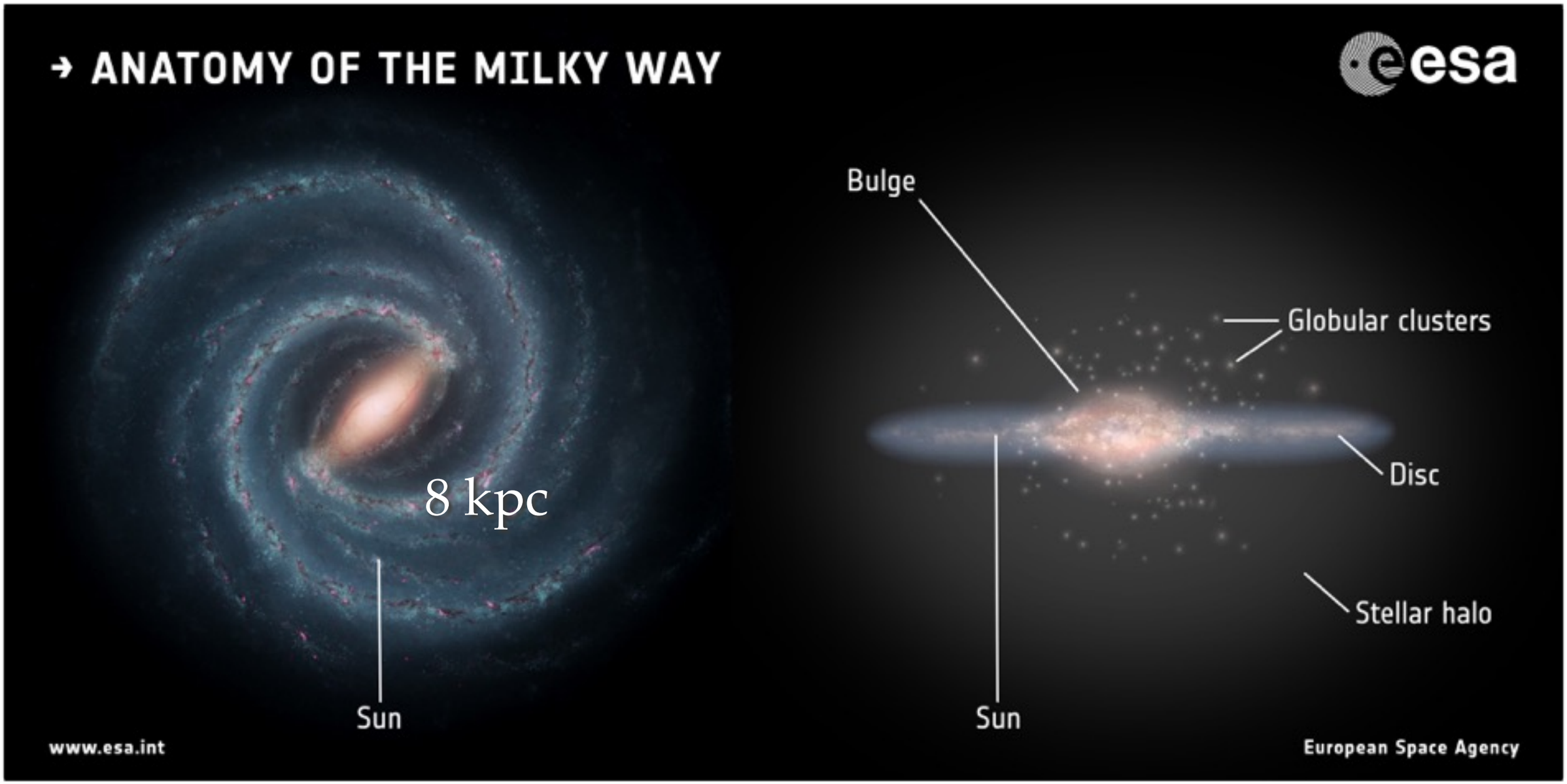
Gaudel+CALYPSO in prep

Need of models to properly read these profiles (RAMSES - P. Hennebelle)

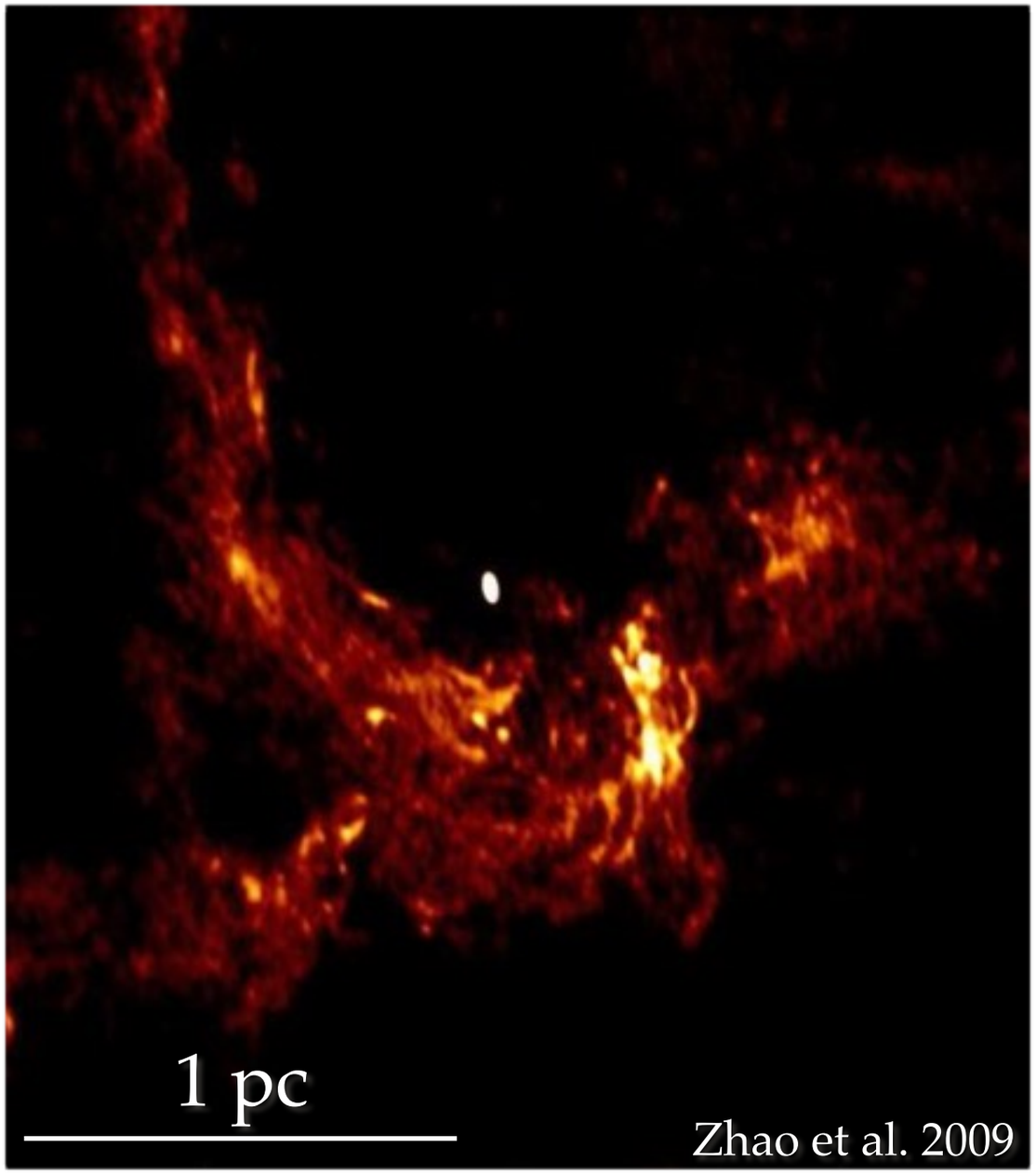
Seeing a black hole? Really?



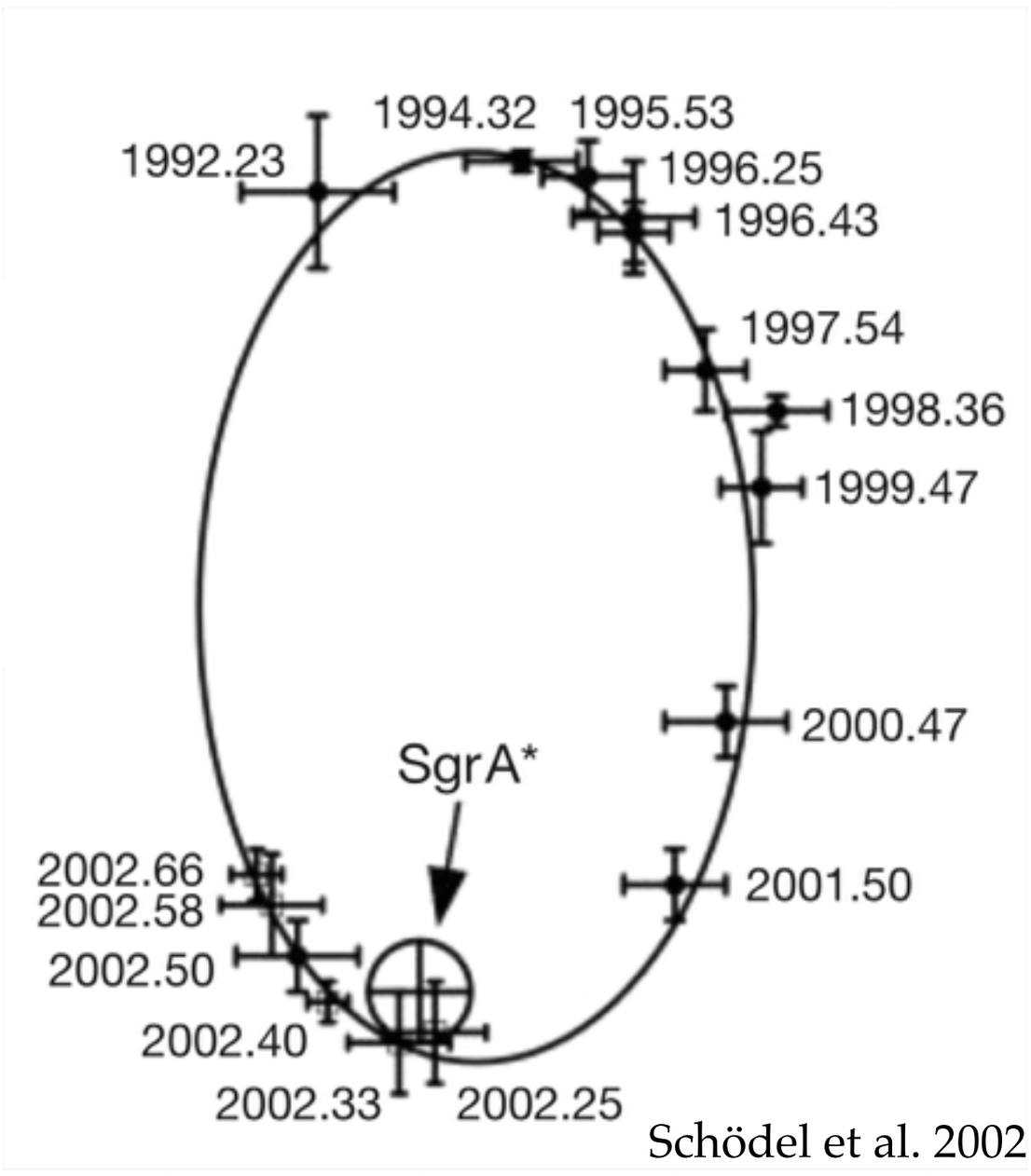
Alexander & Hickox 2012


→ ANATOMY OF THE MILKY WAY
esa
8 kpc
Sun
Bulge
Globular clusters
Disc
Stellar halo
Sun
www.esa.int
European Space Agency

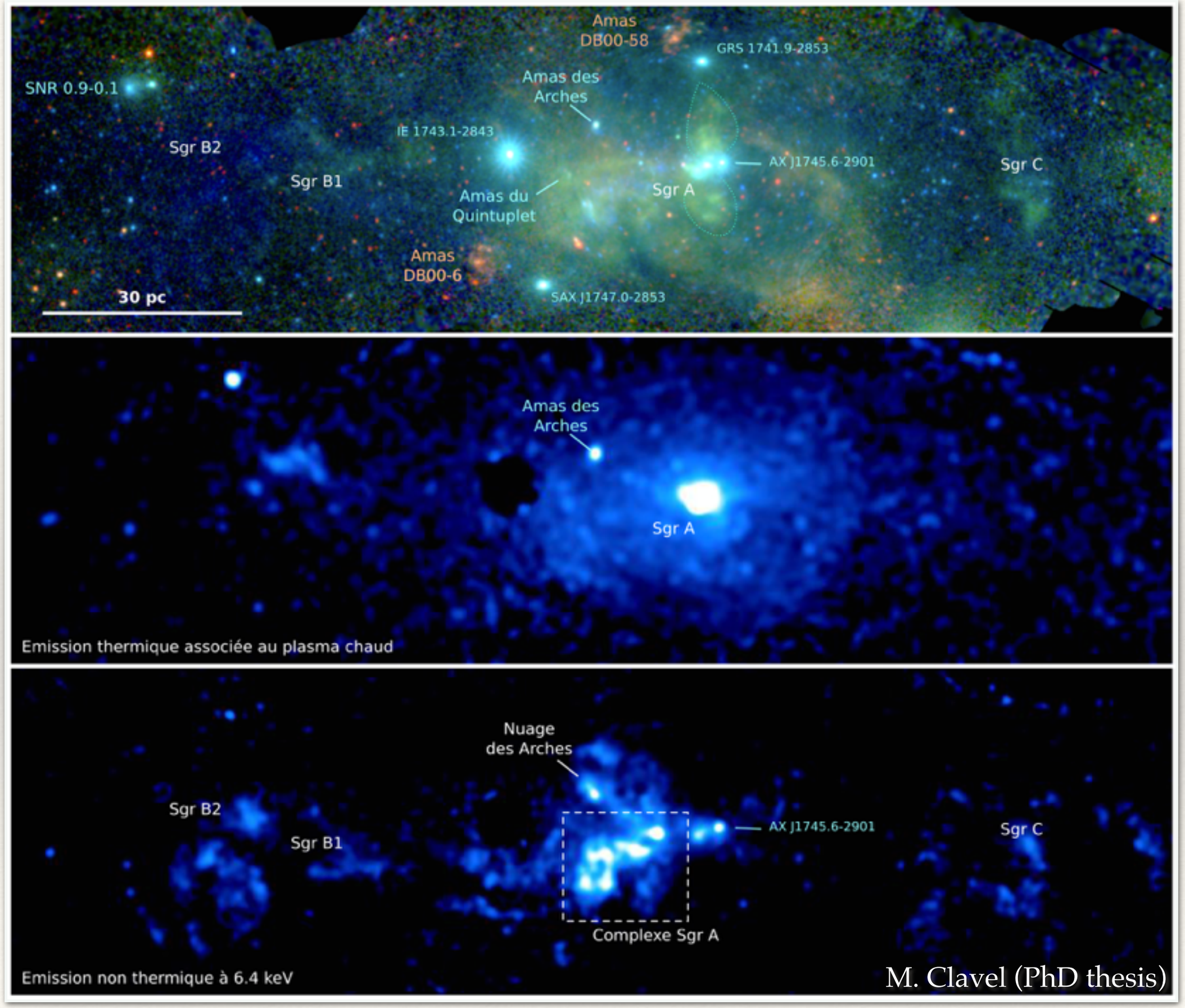
Sgr A* as a supermassive black hole



Zhao et al. 2009



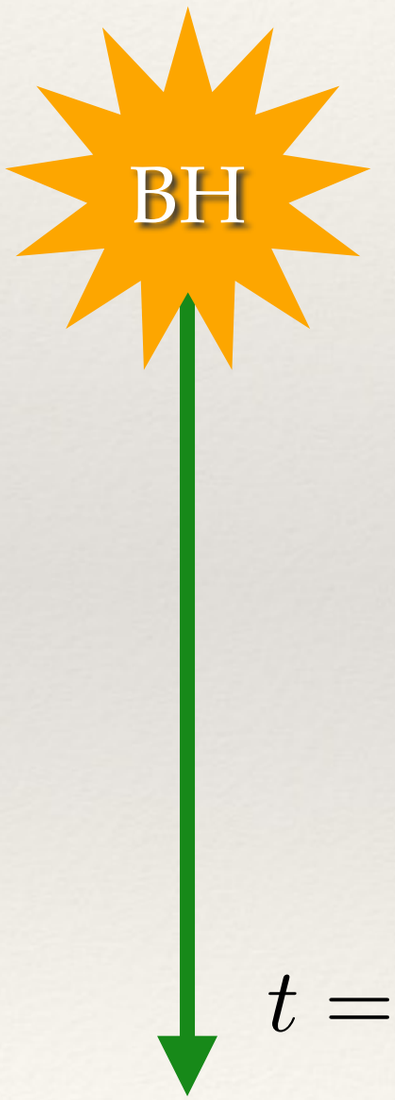
Schödel et al. 2002

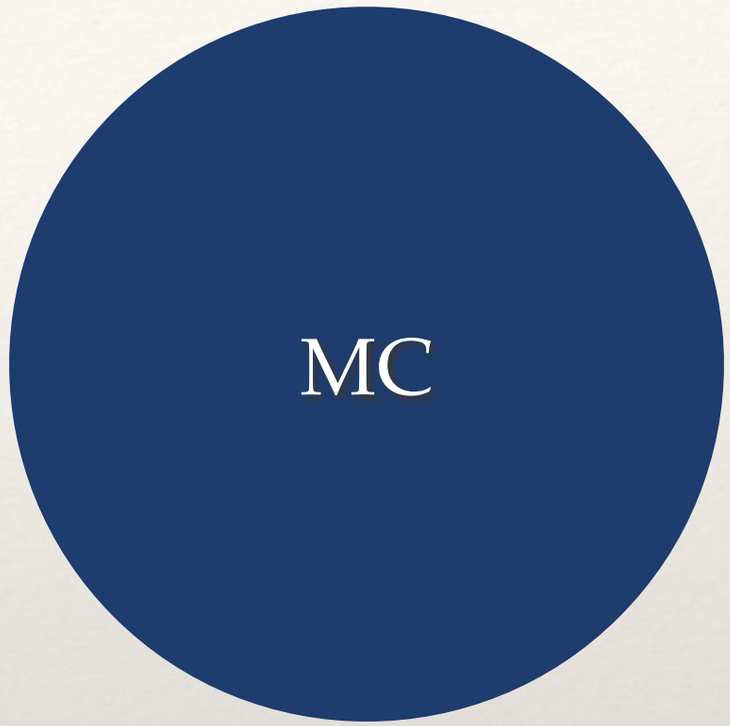


M. Clavel (PhD thesis)

X-ray reflection

View from above





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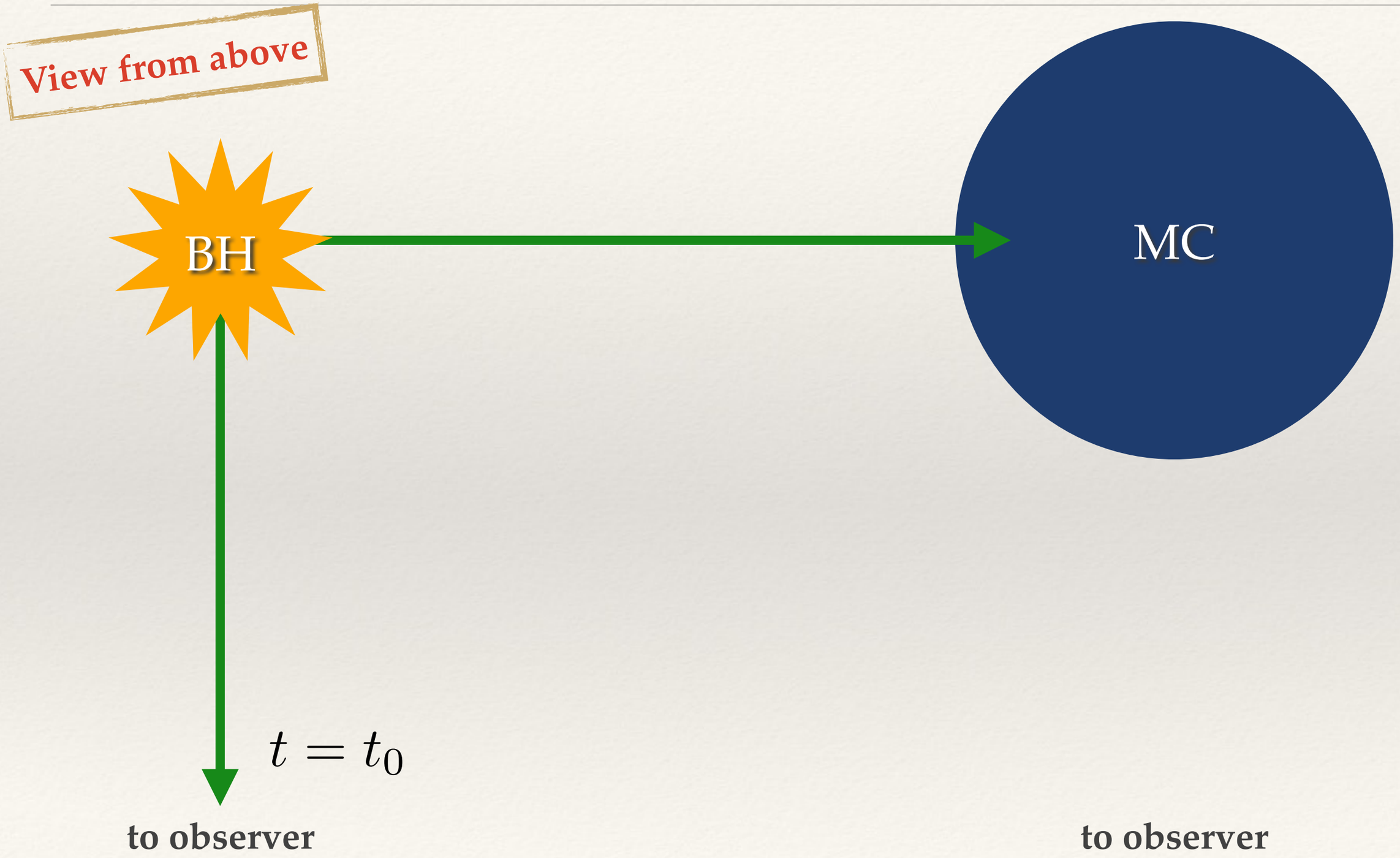
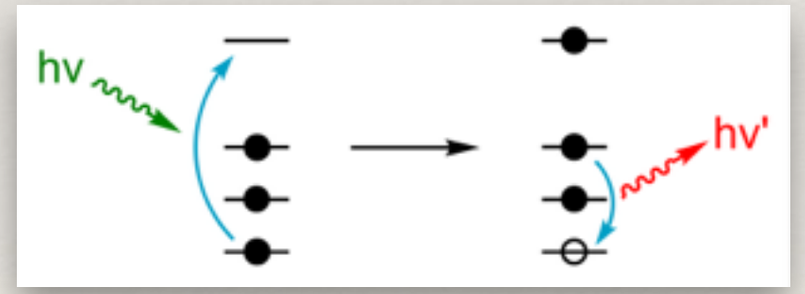


X-ray reflection

View from above

BH

MC



+ Compton scattering

$t = t_0$

to observer

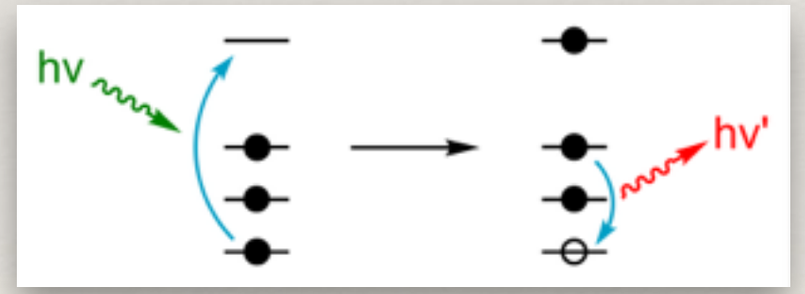
to observer

X-ray reflection

View from above

BH

MC



+ Compton scattering

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to observer

$t = t_0 + \Delta t$

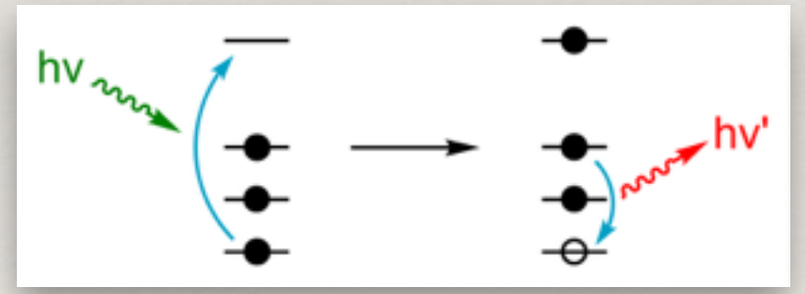
to observer

X-ray reflection

View from above

BH

MC



+ Compton scattering

$t = t_0 + \Delta t$

to observer

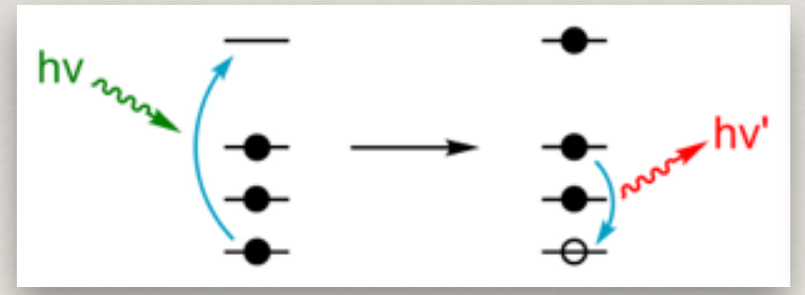
X-ray reflection

View from above

BH

$d = c\Delta t$

MC



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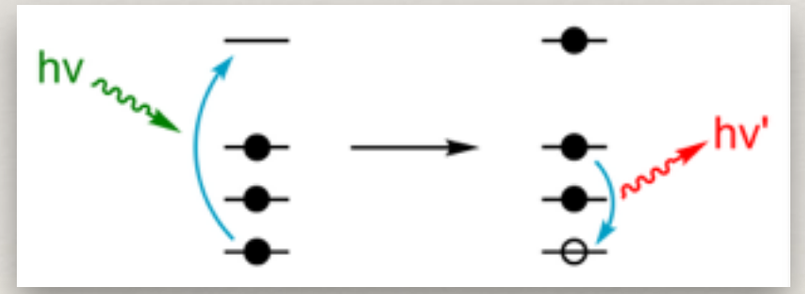

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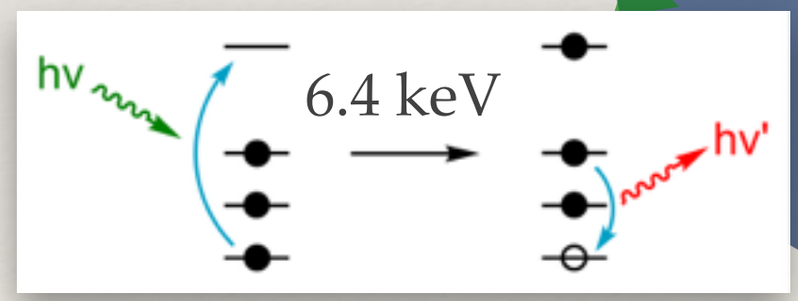
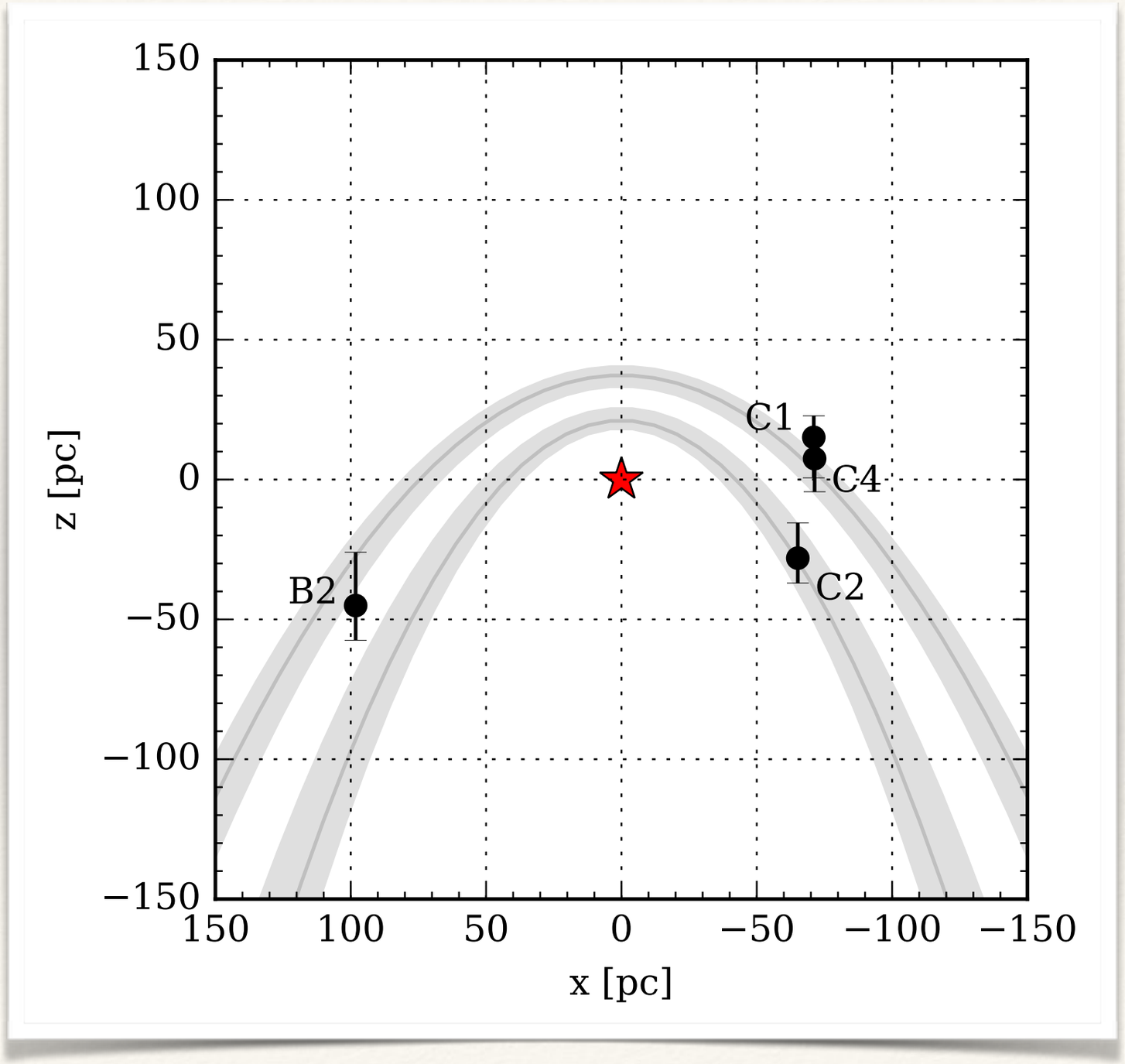


+ Compton scattering

$t = t_0 + \Delta t$

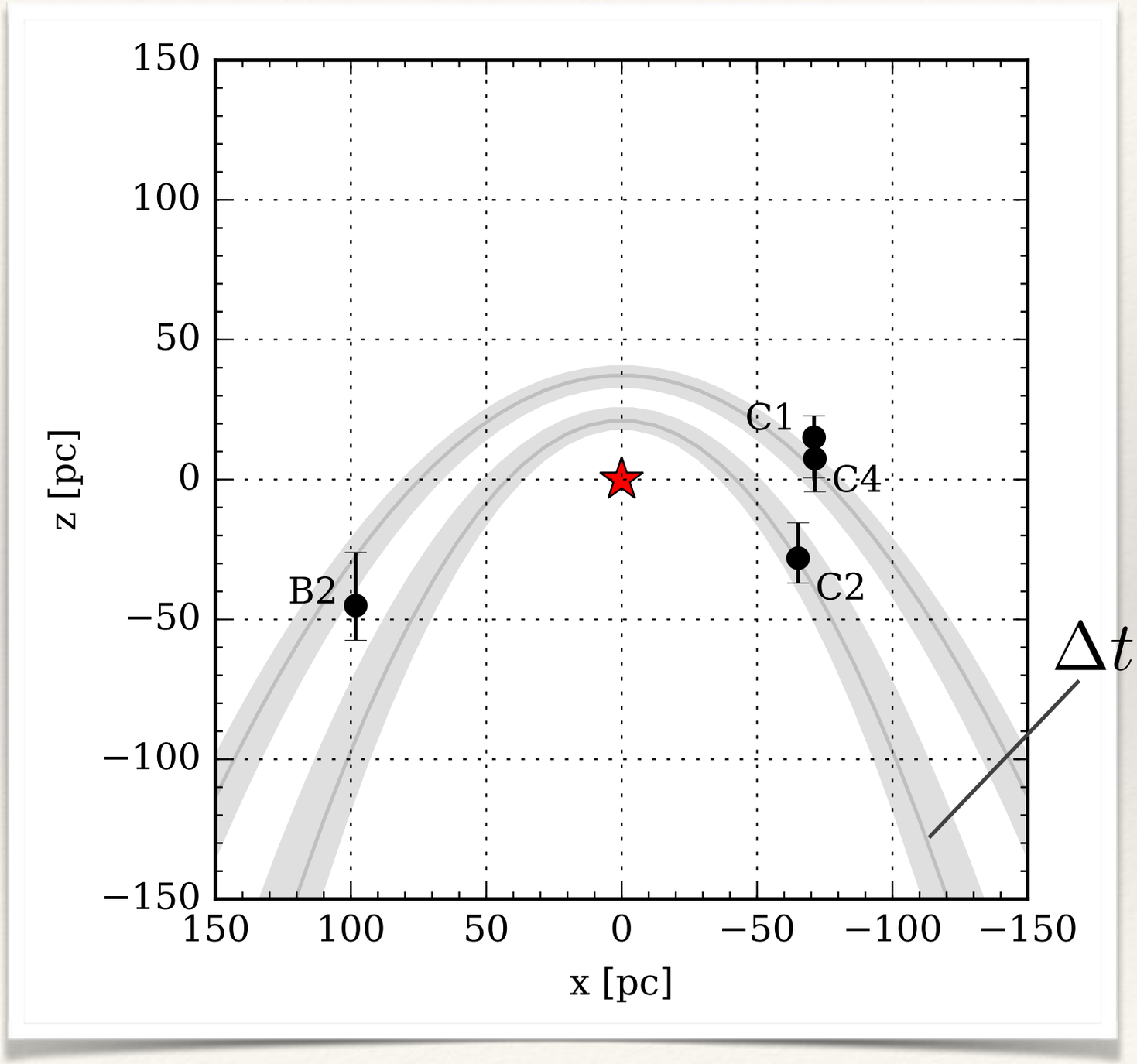
to observer

Reconstructing the past activity of Sgr A*



Chuard et al. (in prep.)

Reconstructing the past activity of Sgr A*



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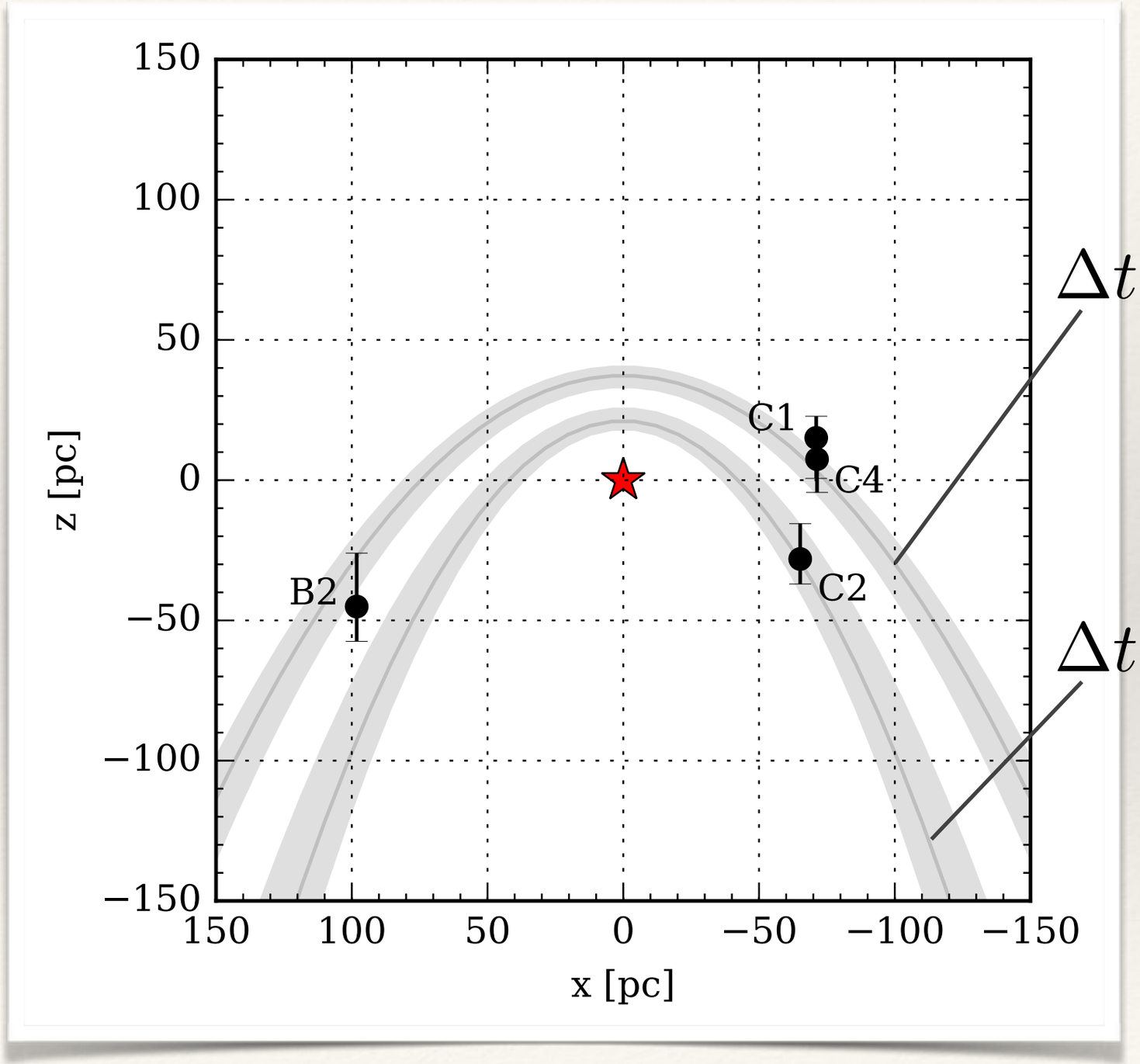

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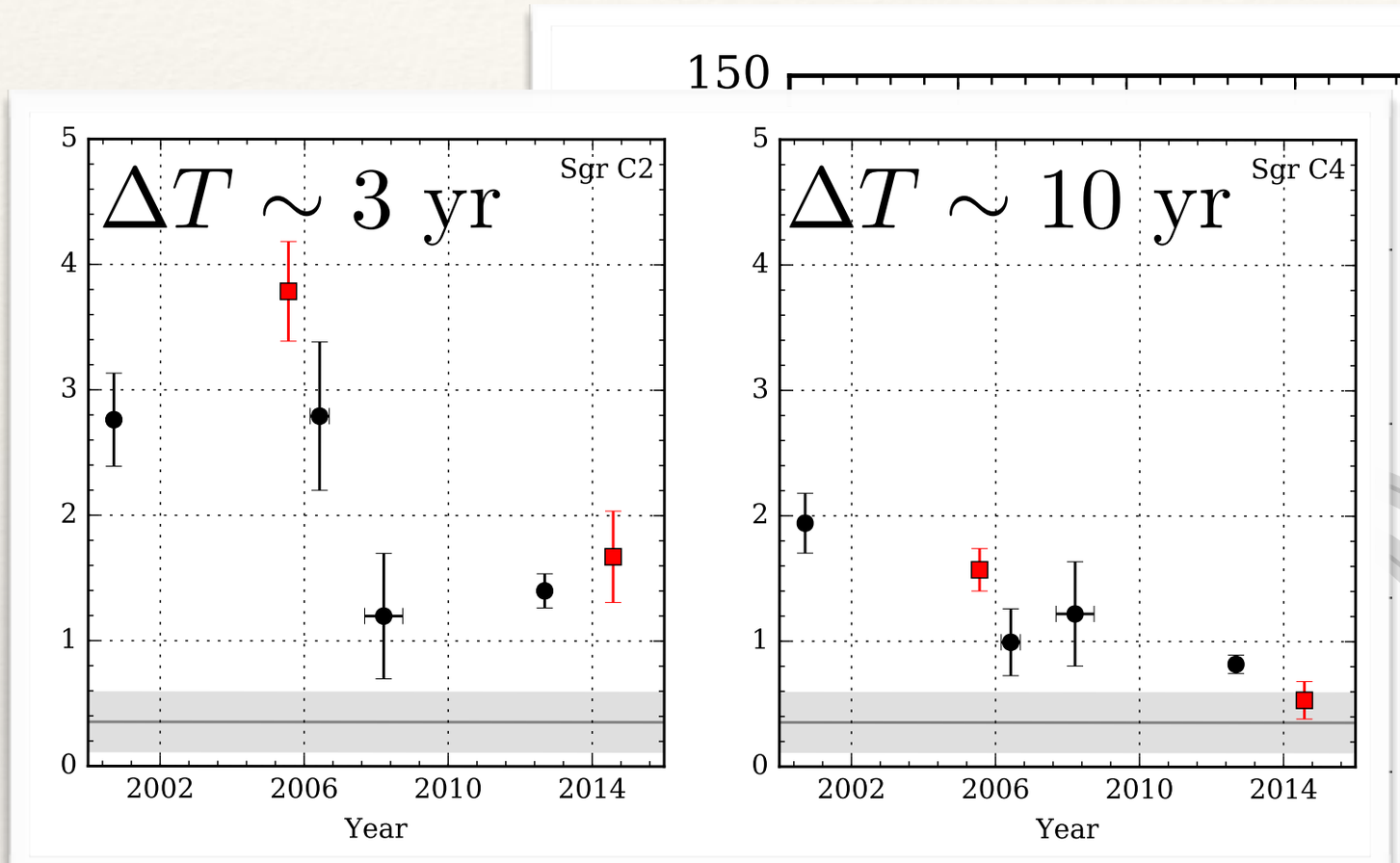

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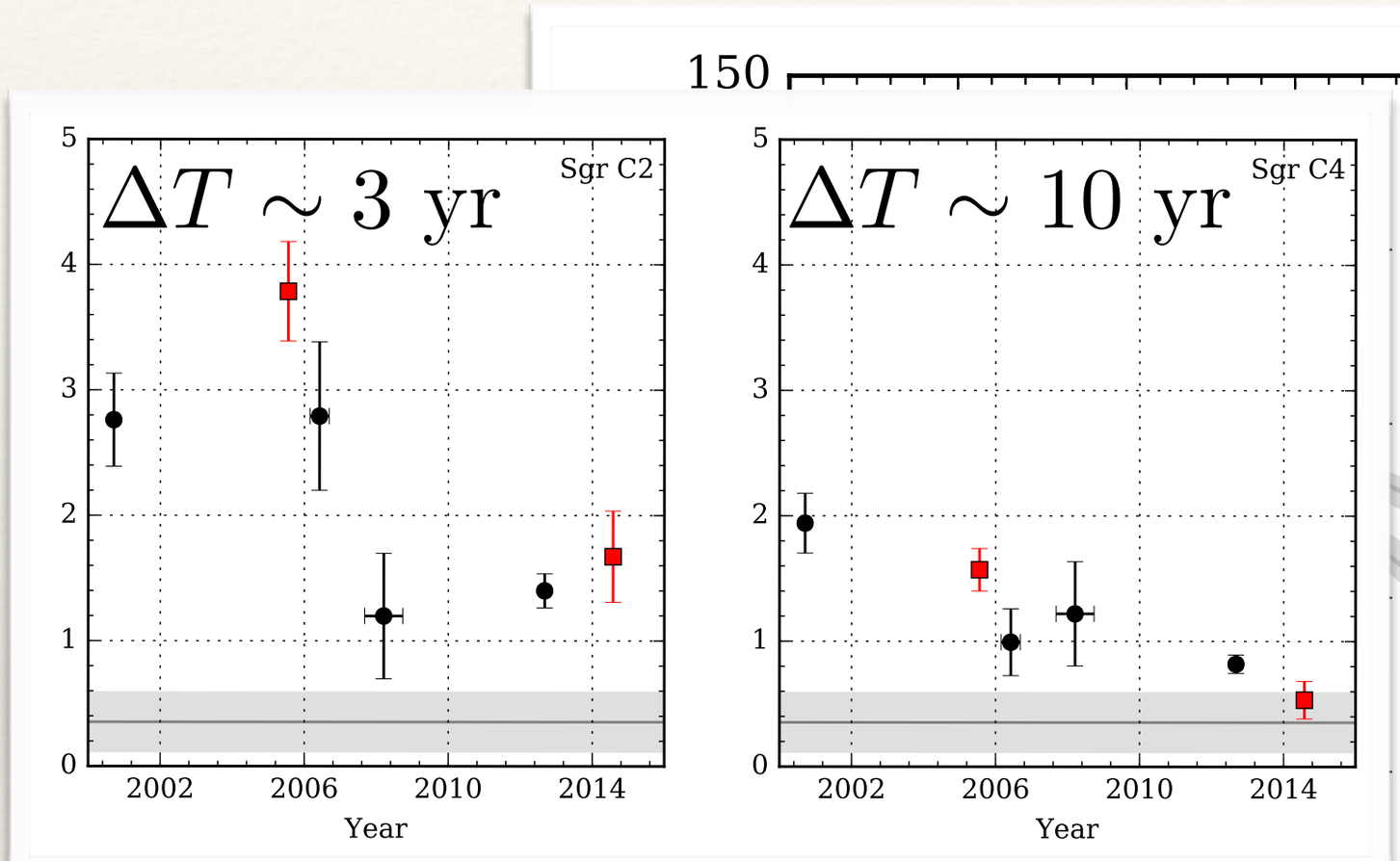


$\Delta t_2 = 243^{+20}_{-25}$ yr

$\Delta T \sim 10$ yr

1757

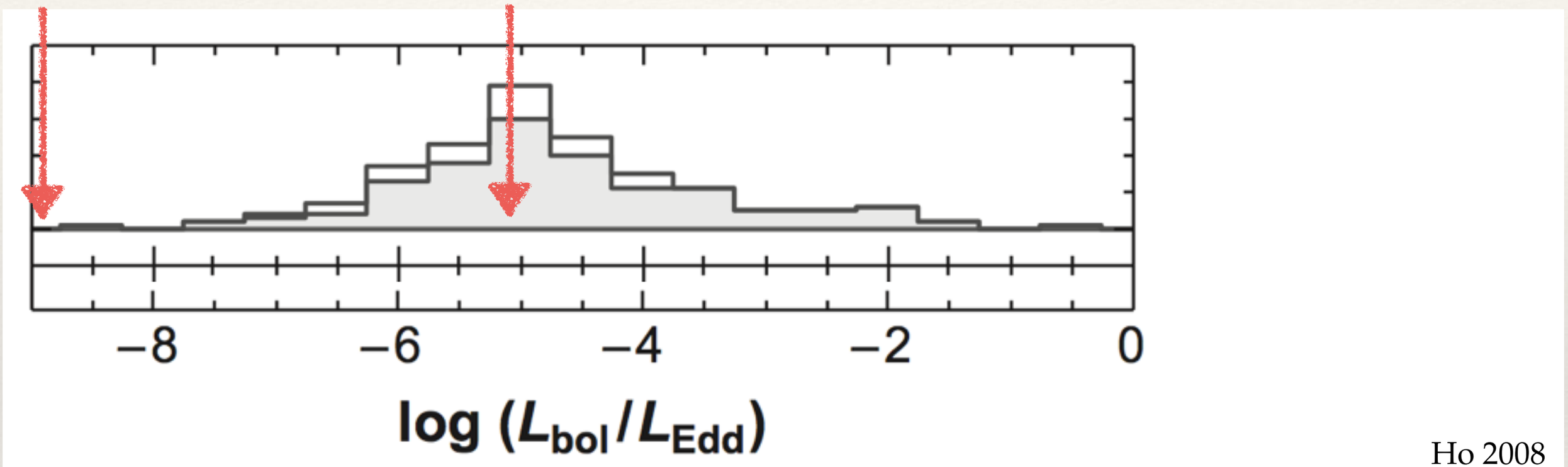
$\Delta t_1 = 138^{+27}_{-17}$ yr

$\Delta T \sim 3$ yr

1862

Chuard et al. (in prep.)

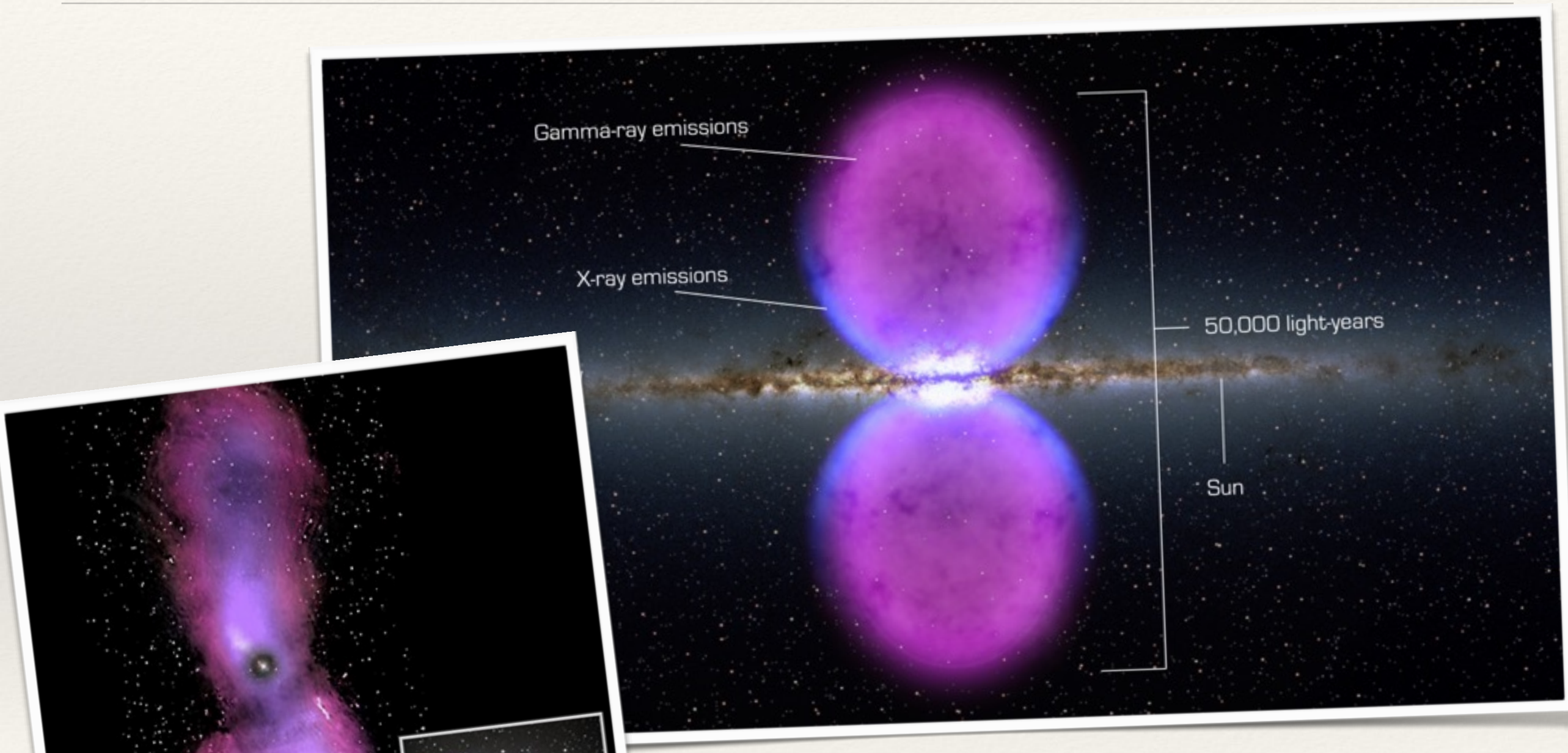
Now **~200 yr ago**

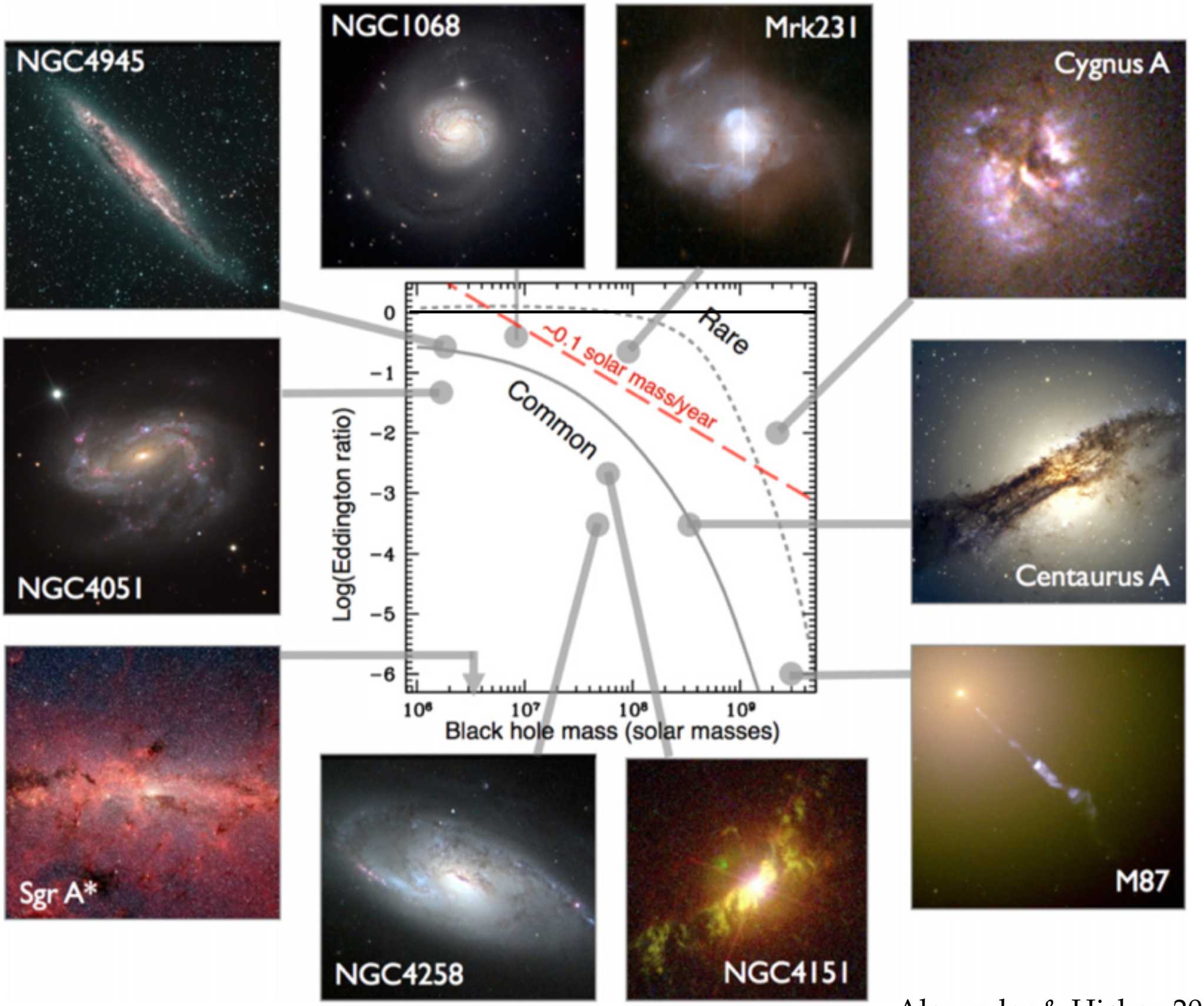


Ho 2008

Palomar survey of nearby galaxies

Traces of a past AGN episode?





Alexander & Hickox 2012

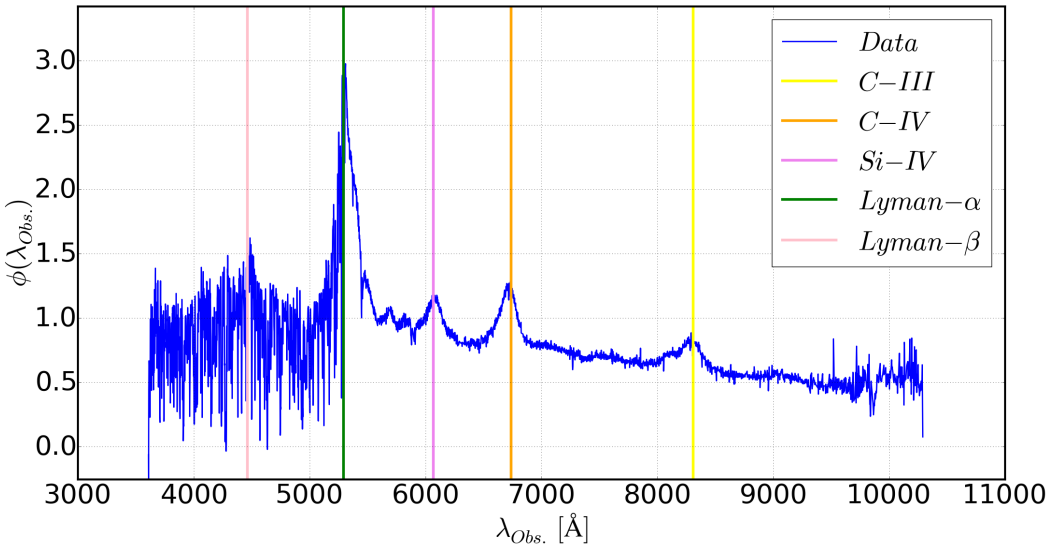
3. Testing the underlying theory of gravitation with large-scale structures

Pauline Zarrouk, Etienne Burtin

CEA/Irfu/DPhP

DATA: Quasars as tracers of the matter distribution in the sky

- Super-massive black hole at the center of some galaxies
- Very bright (~100 galaxies)
- Very massive (1 million times the Sun)
- Point-source (different from stars)



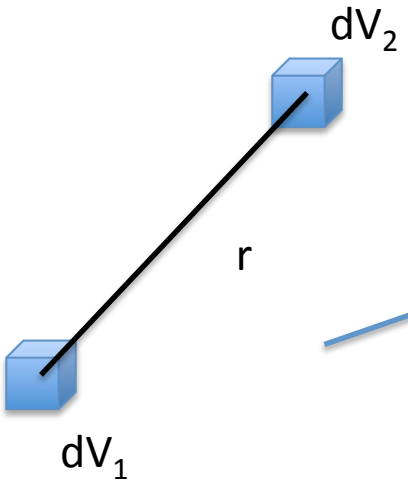
- Sample: more than 147, 000 quasars formed more than 6 billion years ago

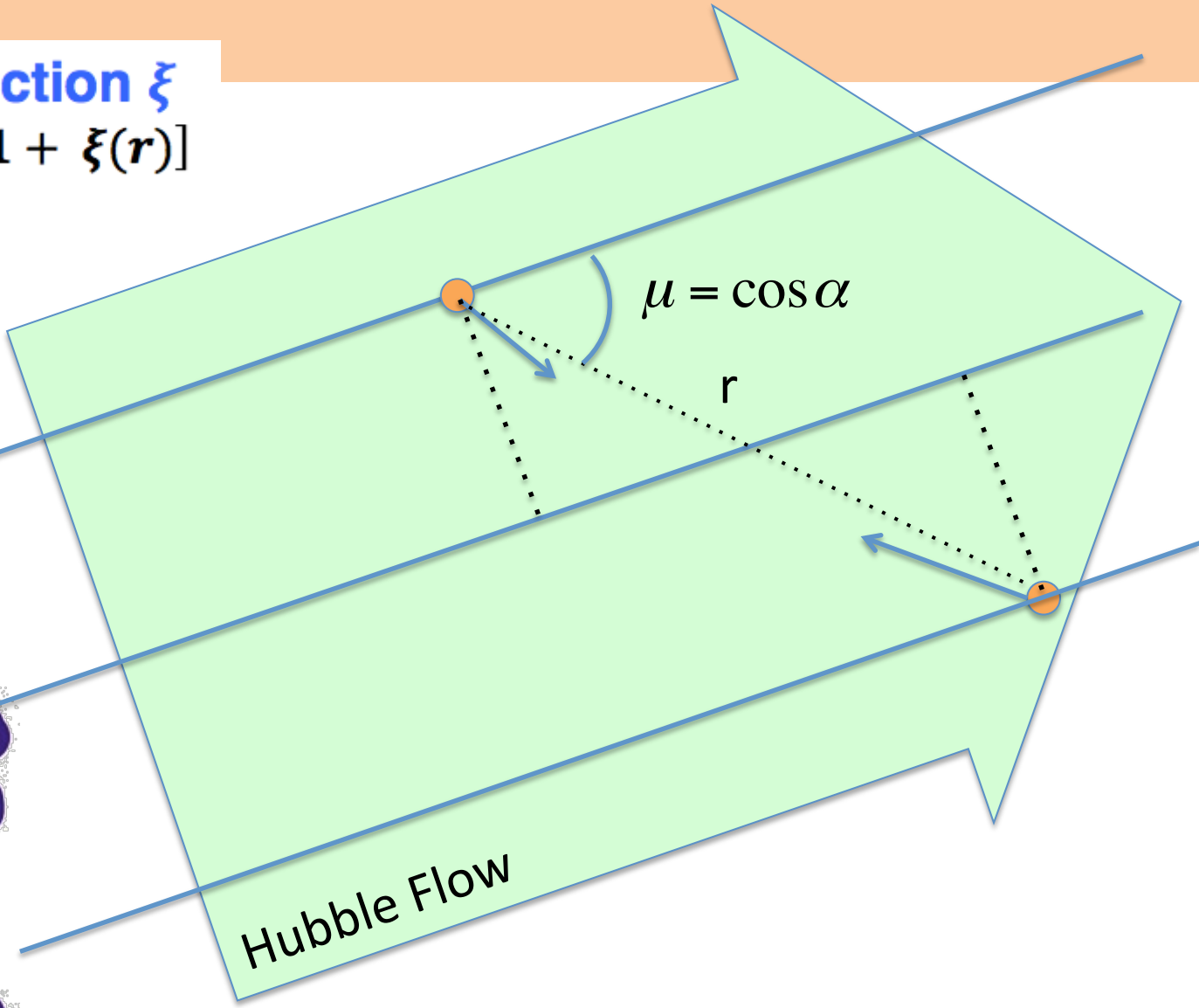
→ Map the large-scale structures in the universe with the positions of quasars, the brightest objects in the sky

THE TECHNIQUE: Spatial correlation of pairs of quasars

Correlation function ξ

$$dP = \bar{\rho}(r) dV_1 dV_2 [1 + \xi(r)]$$





THE TECHNIQUE: Spatial correlation of pairs of quasars

Correlation function ξ

$$dP = \bar{\rho}(r) dV_1 dV_2 [1 + \xi(r)]$$

dV_2

$s = r + v(r).u_{LOS}$

r

dV_1

r

s

Hubble Flow

MEASUREMENT: Growth rate of structures

→ The shape of the correlation function depends on cosmological parameters

1. General relativity predicts how many structures have been formed at a given epoch of the universe:

$$f(z) = \Omega_m(z)^{\gamma=0.55}$$

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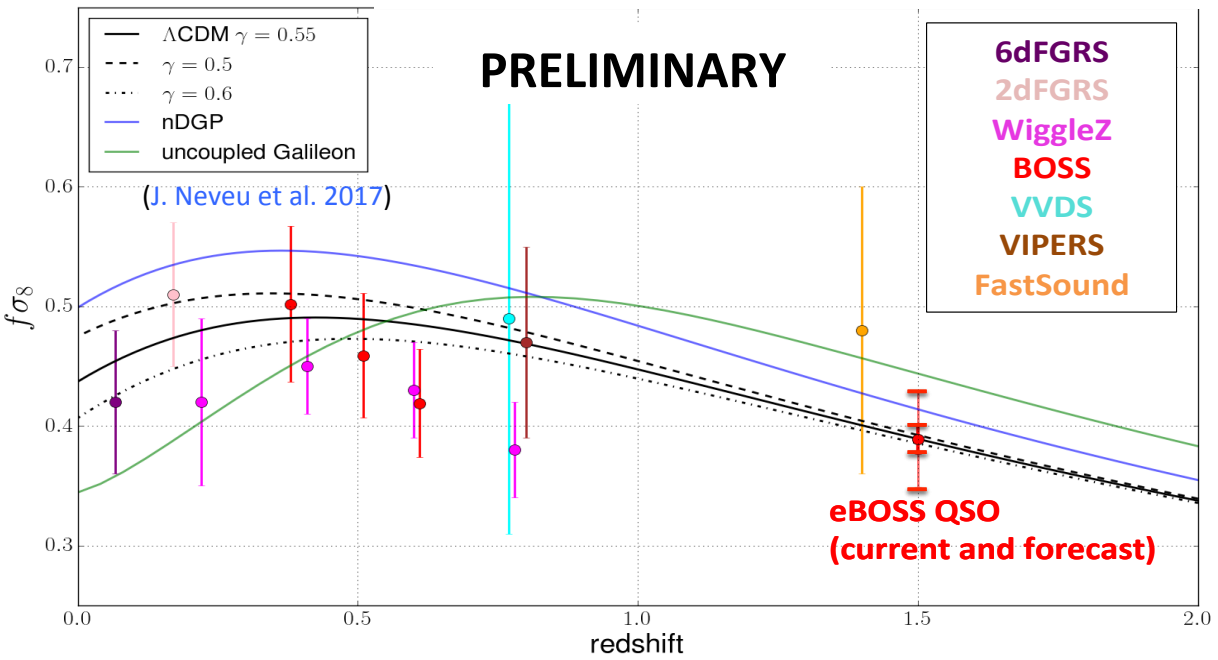
First measurement of the growth rate of structures at redshift ~1.5 using the eBOSS DR14 quasar sample

P. Zarrouk, E. Burtin et al. (2017a in prep)



MEASUREMENT: Growth rate of structures

→ The shape of the correlation function depends on cosmological parameters

- **eBOSS forecast for the quasar sample:** ~4% precision with 6 years data taking
- **DESI* (2018) and Euclid* (2021):** subpercent precision on cosmological parameters

* Irfu active in both projects

First measurement of the growth rate of structures at redshift ~1.5 using the eBOSS DR14 quasar sample

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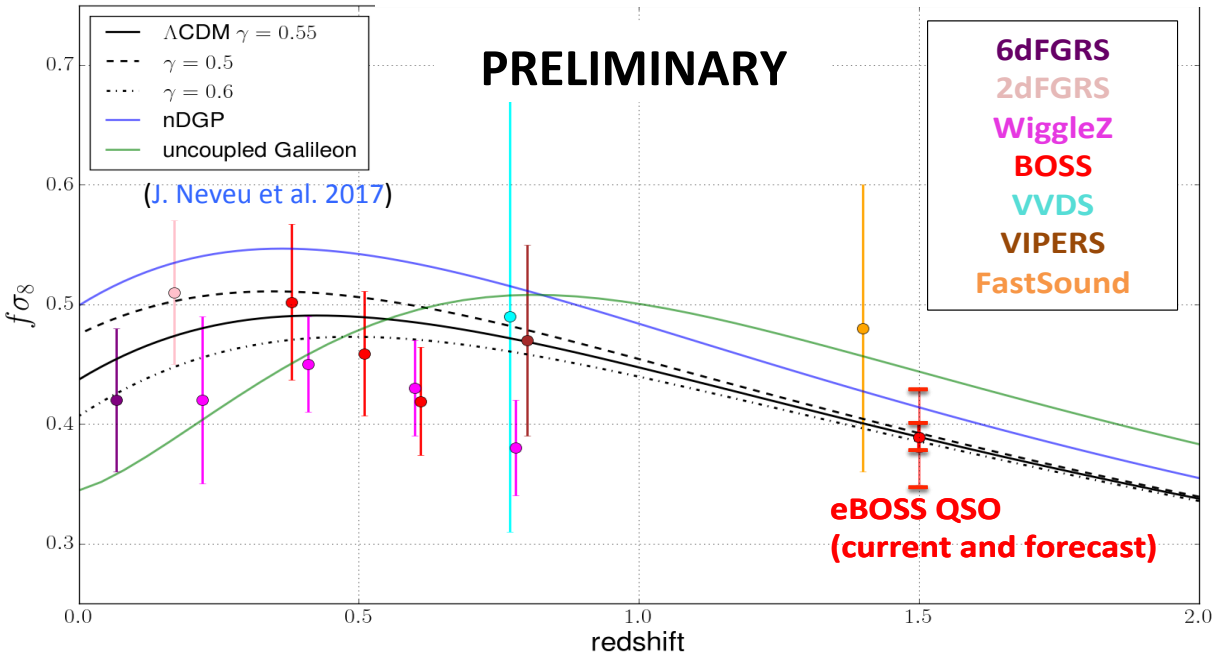


SUMMARY AND PERSPECTIVES

- **2 years data taking of eBOSS: more than 147,000 quasars spectra**

→ Biggest sample of the brightest objects in the sky used to map the largest structures of the universe

→ CEA/CNRS press release following the SDSS press release: Metin Ata *et. al.*, https://arxiv.org/abs/1705.06373

- **First measurement of the growth rate of structures in the eBOSS quasar sample** (P. Zarrouk, E. Burtin et al. 2017a in prep)

→ Unique and direct test of general relativity, the underlying theory of gravitation

→ Powerful discriminant between different dark energy scenarios

- **Ongoing analysis: Collaboration with IPhT to constrain different alternatives to the concordance model**

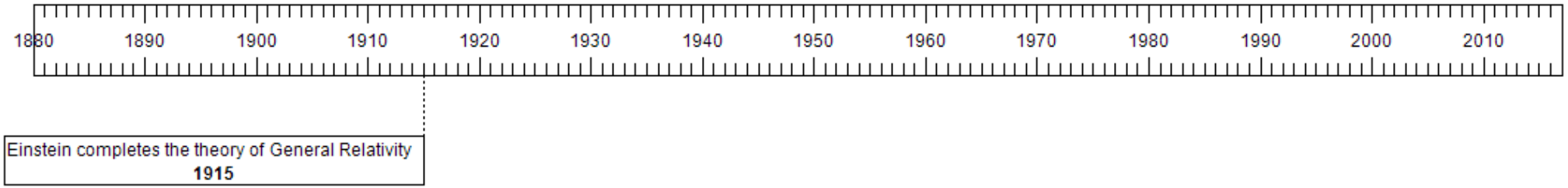
- **Ongoing analysis: Mock challenge**

4. Testing an alternative theory of gravitation with the very young universe

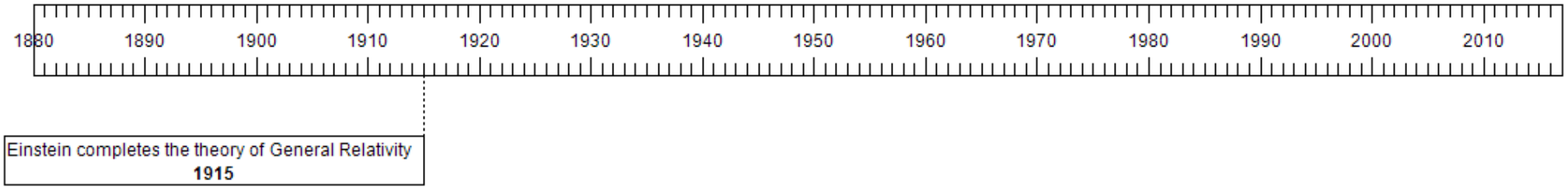
-DPhP-

Supervisors :
Vanina Ruhlmann-Kleider
Marc Besancon

The Universe expansion

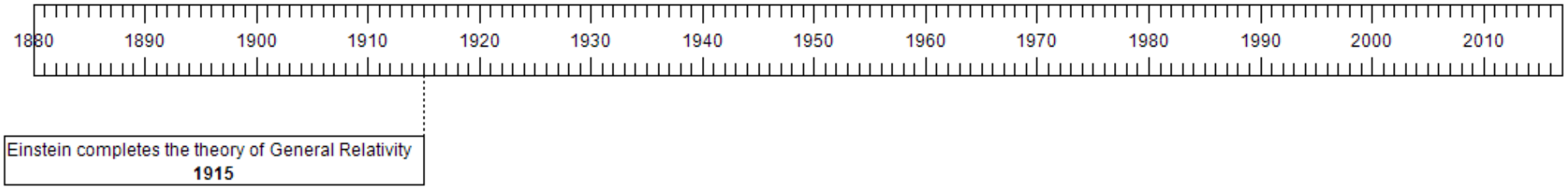


The Universe expansion



- Relativistic theory of gravitation

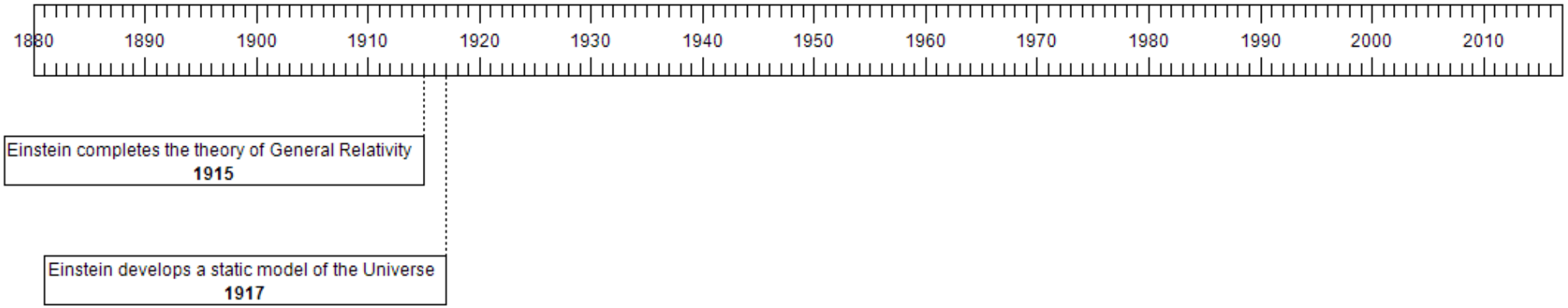
The Universe expansion



- Relativistic theory of gravitation
- Dynamics given by :

$$G_{\mu\nu} = \frac{T_{\mu\nu}}{M_P^2} \Leftrightarrow \mathcal{S} = \frac{M_P^2}{2} \int d^4x \sqrt{-g} R$$

The Universe expansion



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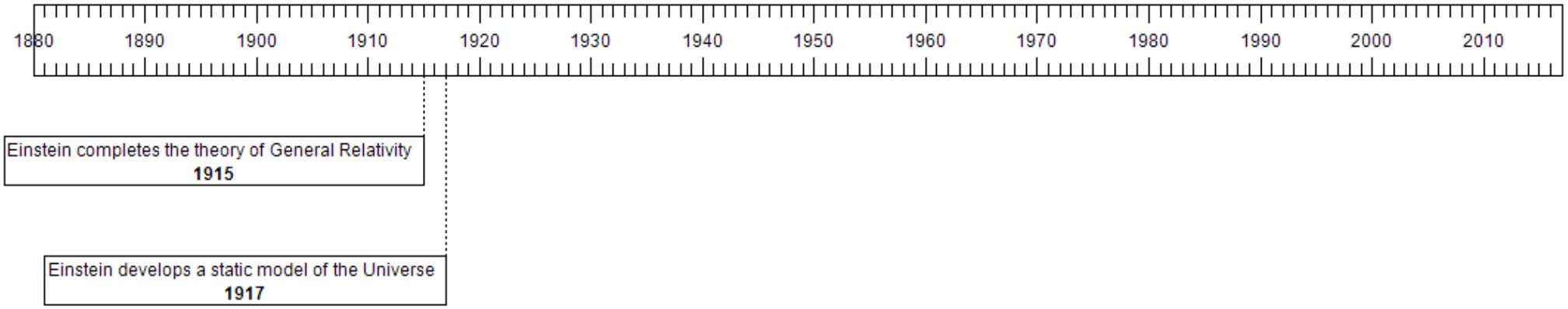
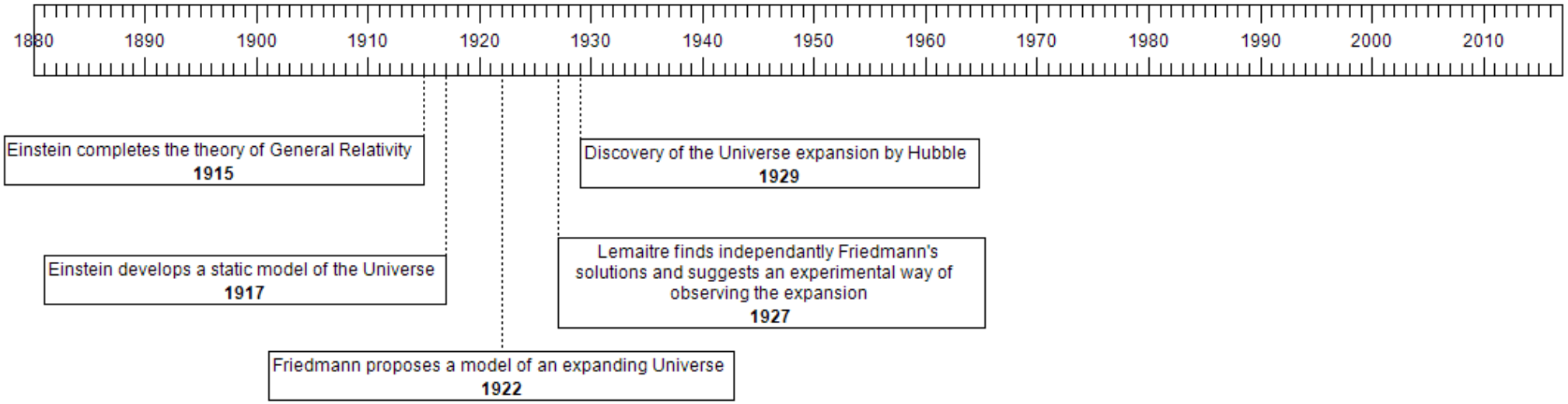


- Need to add a cosmological constant Λ to get a static Universe :

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{T_{\mu\nu}}{M_P^2} \Leftrightarrow \mathcal{S} = \frac{M_P^2}{2} \int d^4x \sqrt{-g} \left(R - 2\Lambda\right)$$

The Universe expansion



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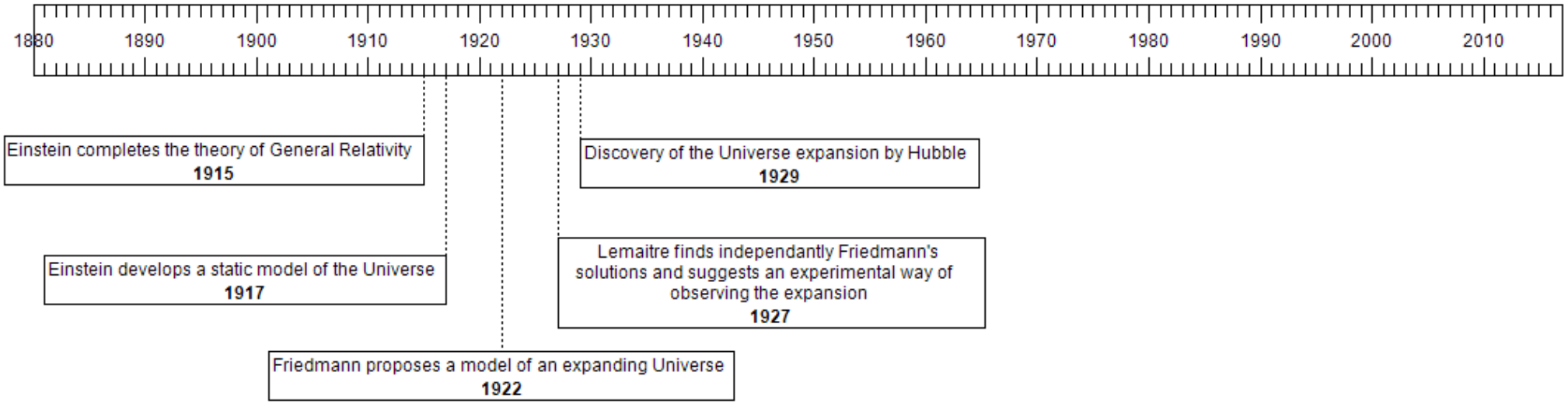
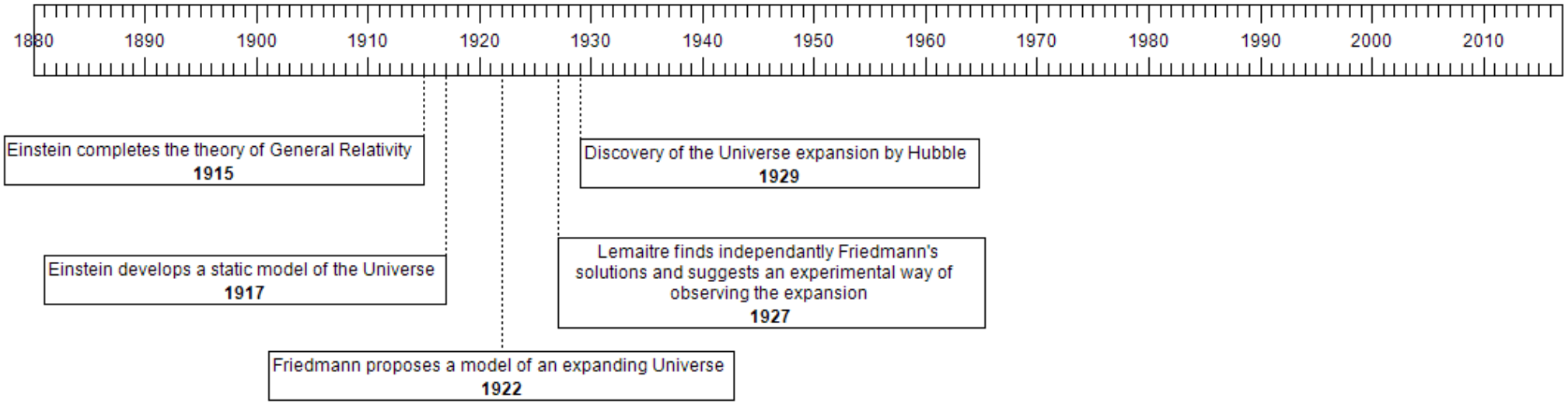


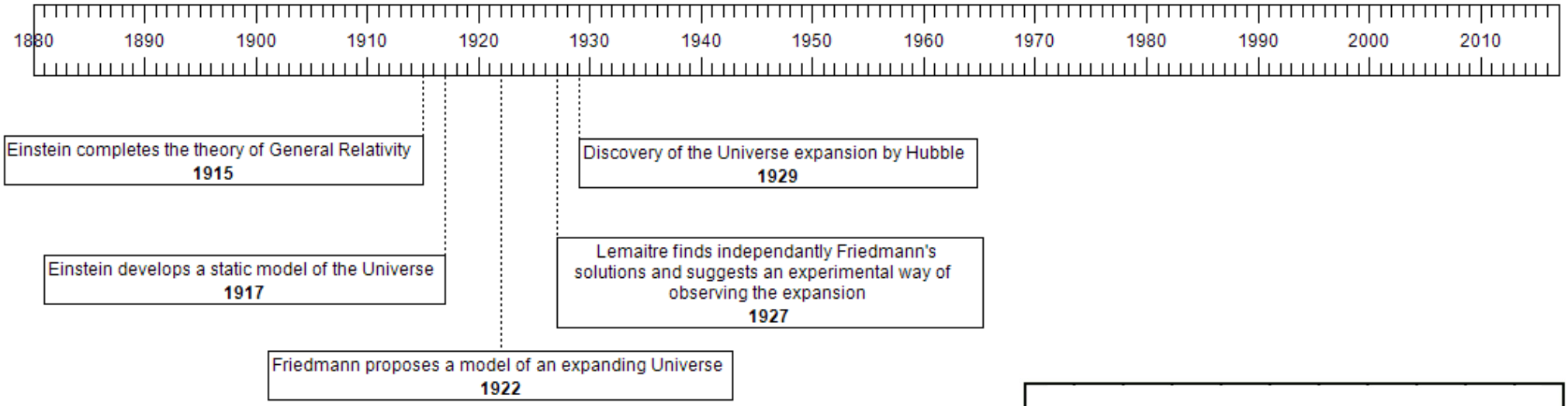
- Universe not static, no need for Λ

The Universe expansion



- Universe not static, no need for Λ
- The Universe expansion follows : $\left(\frac{da}{dt}\right)^2 = \frac{\kappa\rho_0}{3a(t)} - K$

The Universe expansion



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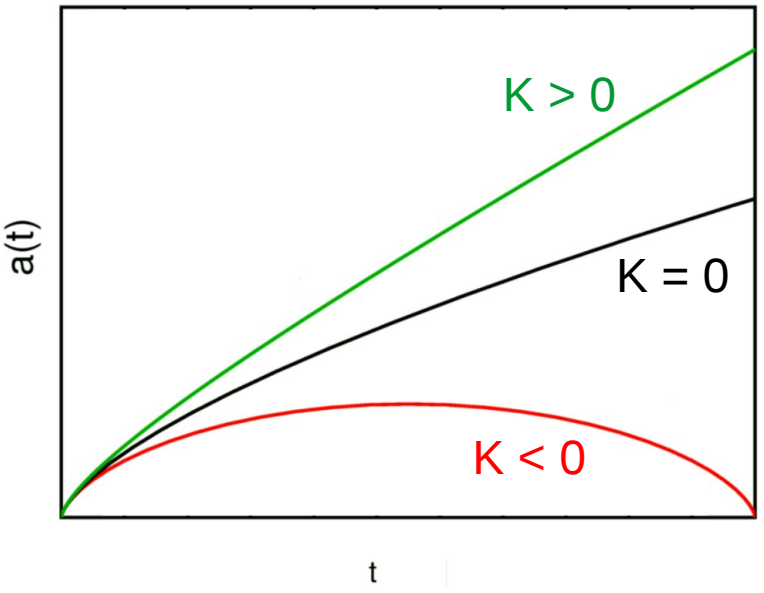

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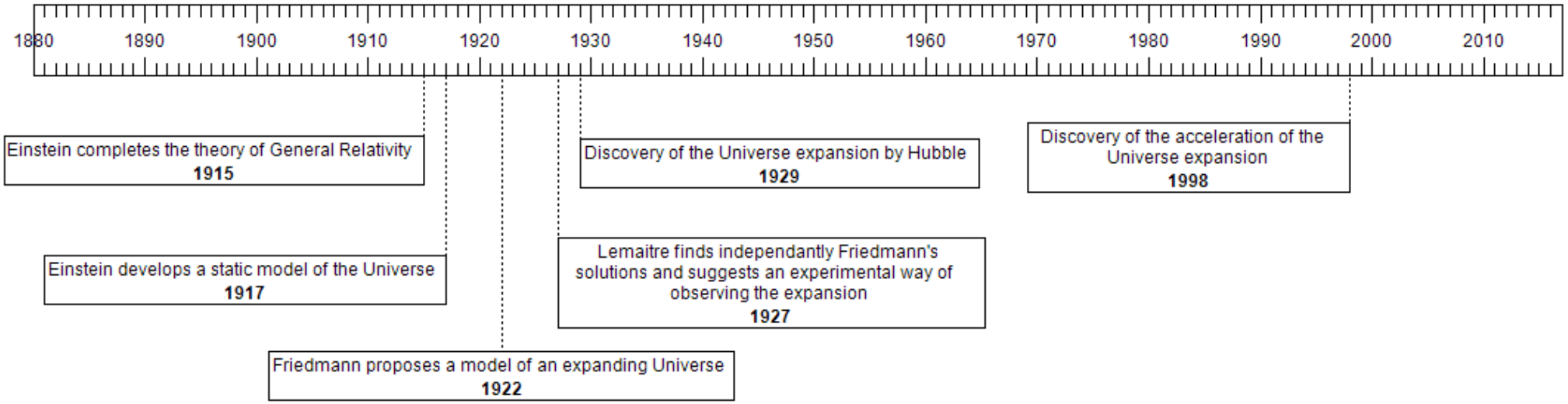

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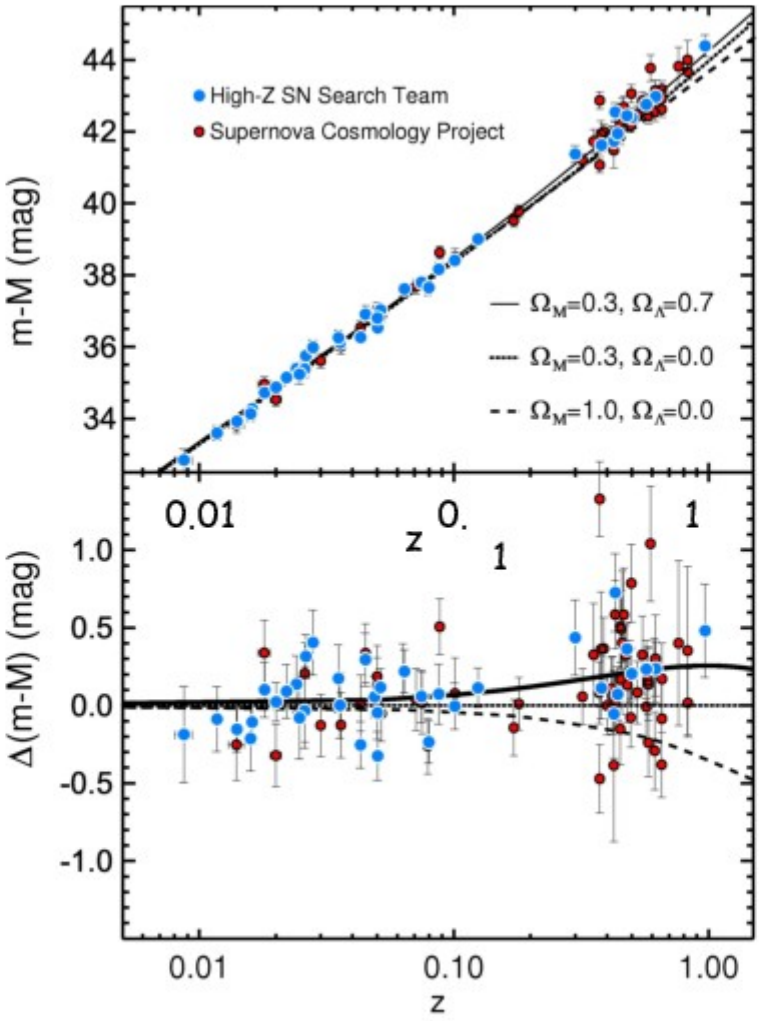
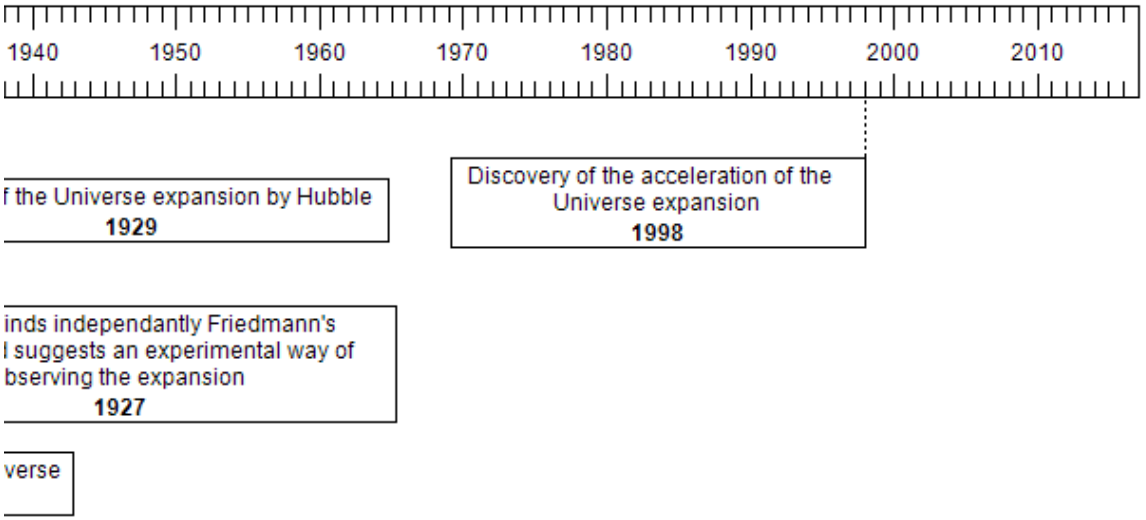


Riess et al. 1998



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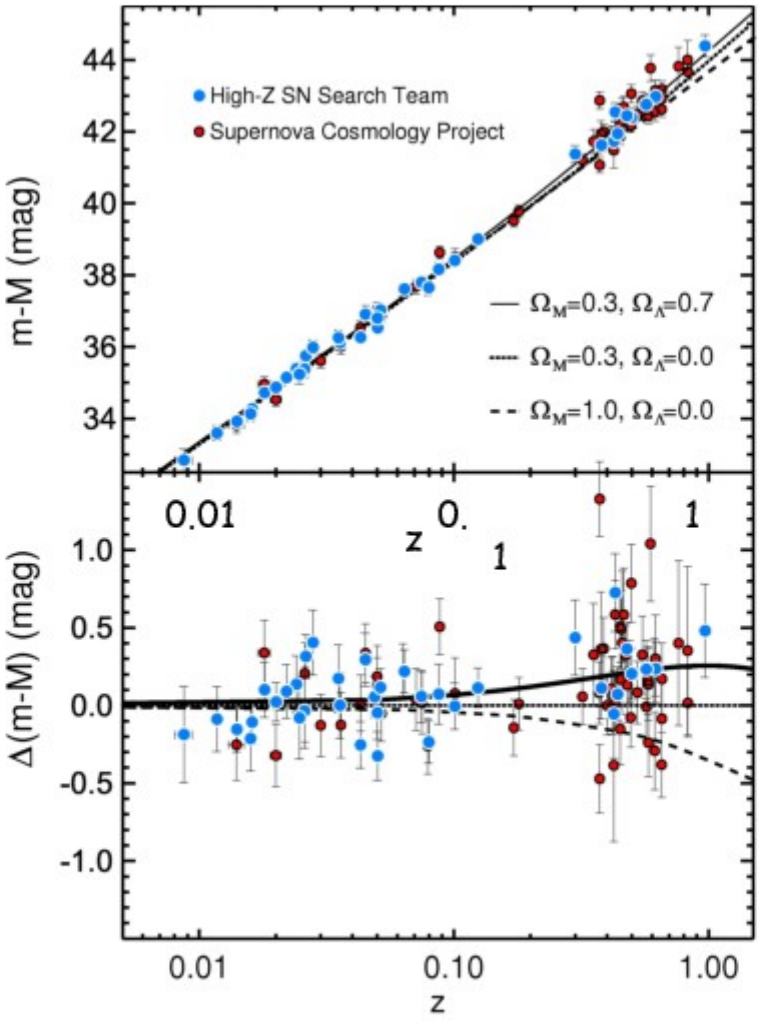

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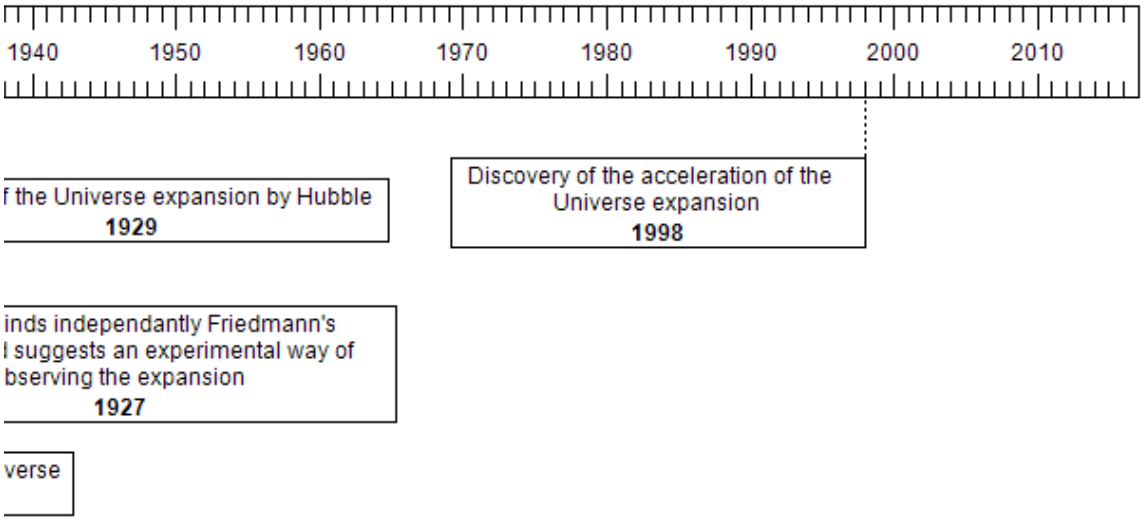
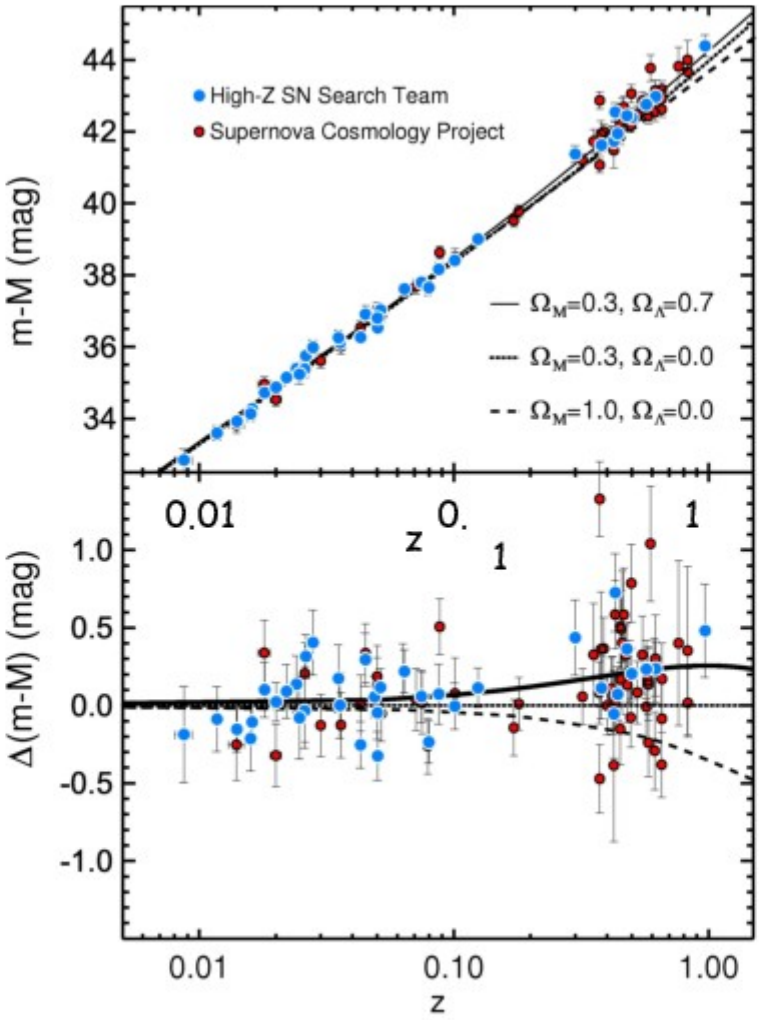


- Relation between luminosity of supernovae and their distance from us

The Universe expansion



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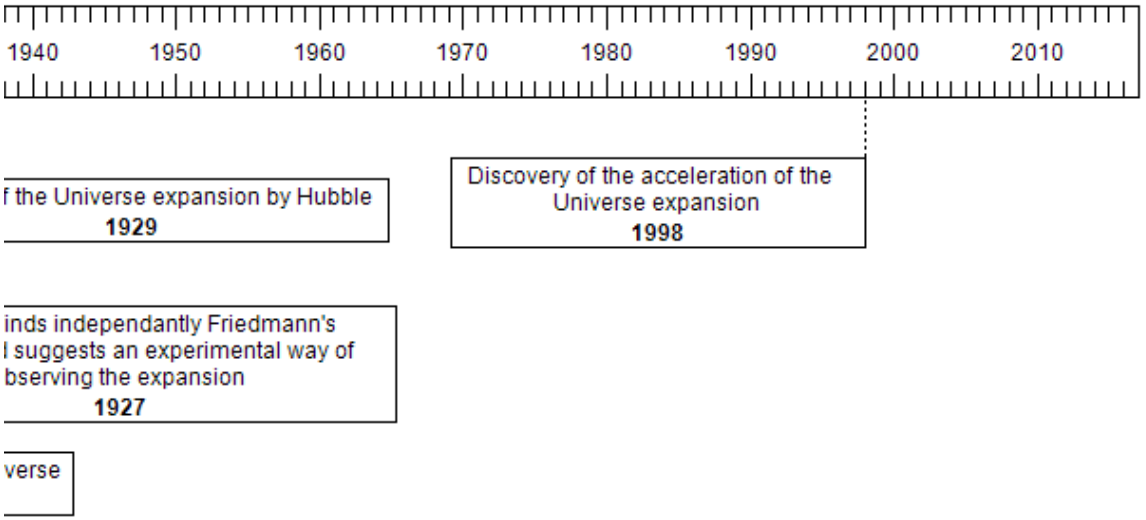
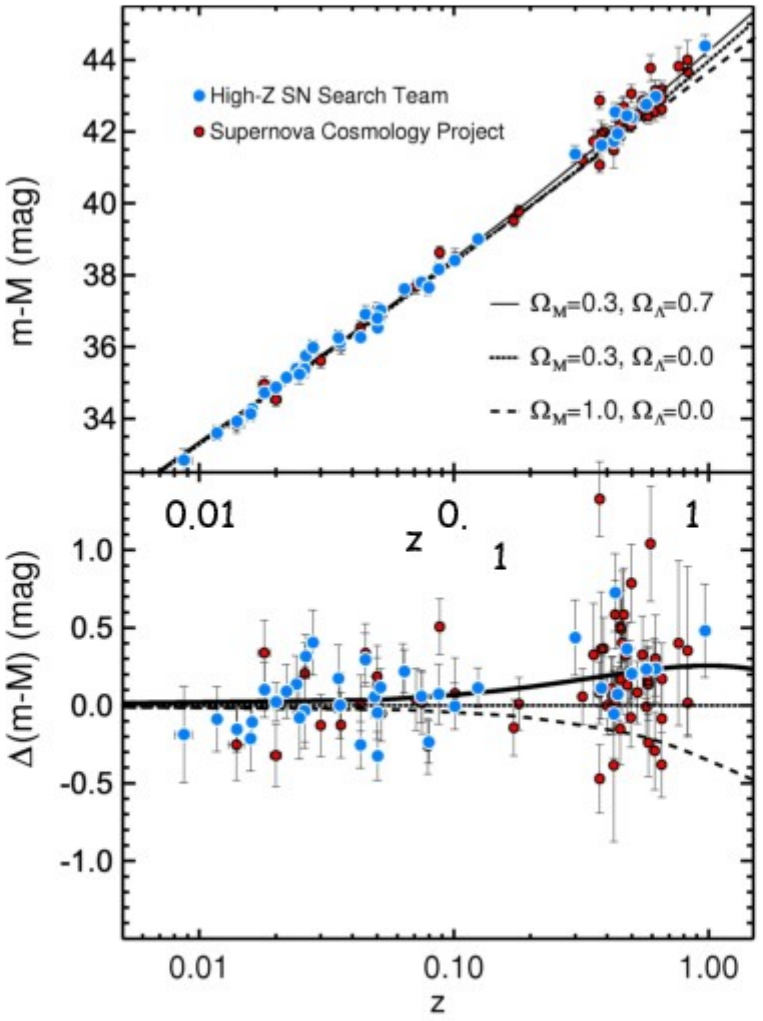


- Relation between luminosity of supernovae and their distance from us
- Possible to probe the expansion of the Universe

The Universe expansion



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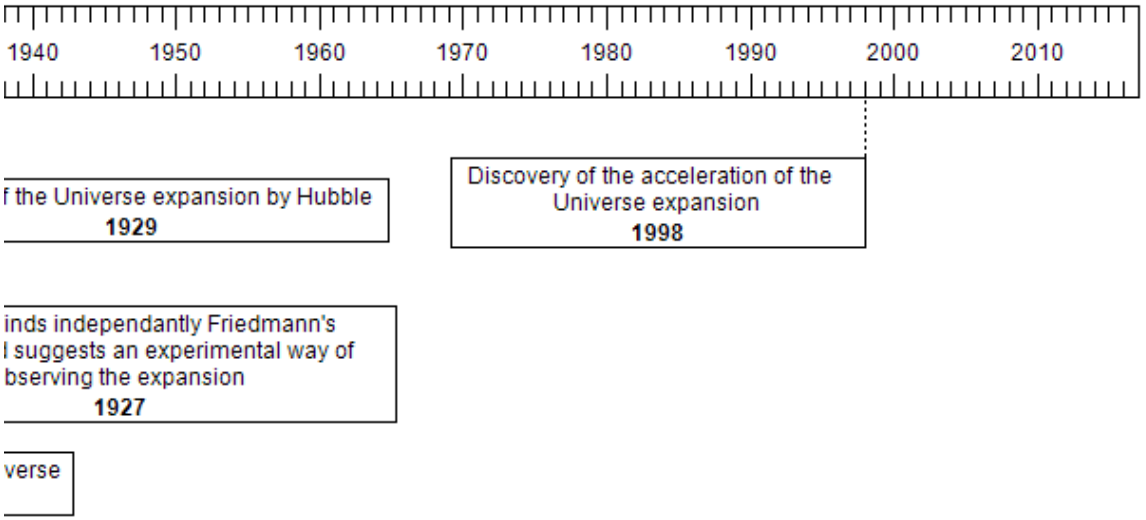
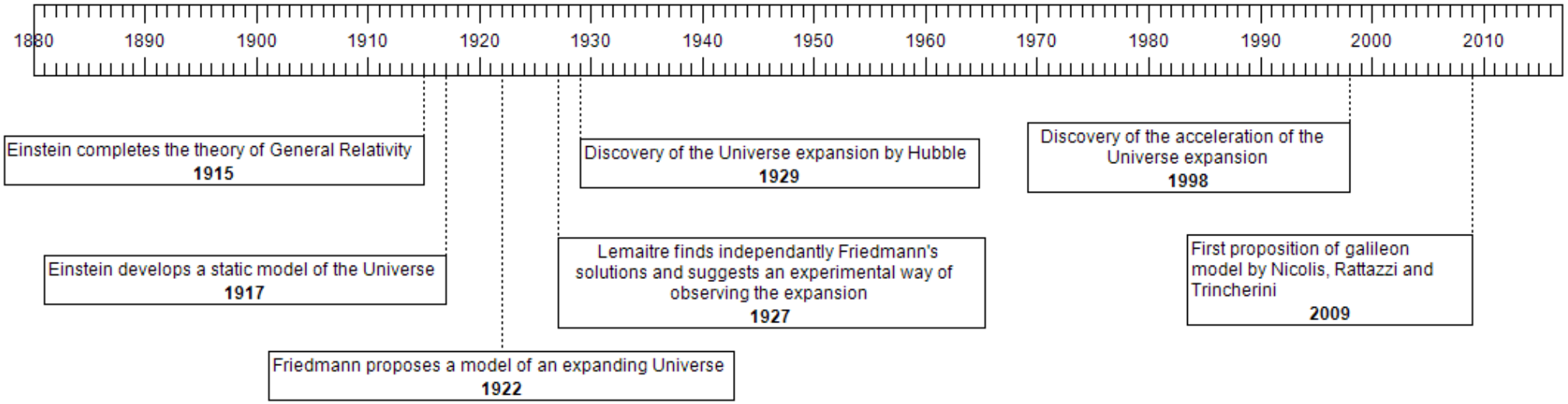


- Relation between luminosity of supernovae and their distance from us
- Possible to probe the expansion of the Universe
- Perlmutter, Schmidt and Riess won the Nobel Prize in 2011 for the discovery of its acceleration

The Universe expansion



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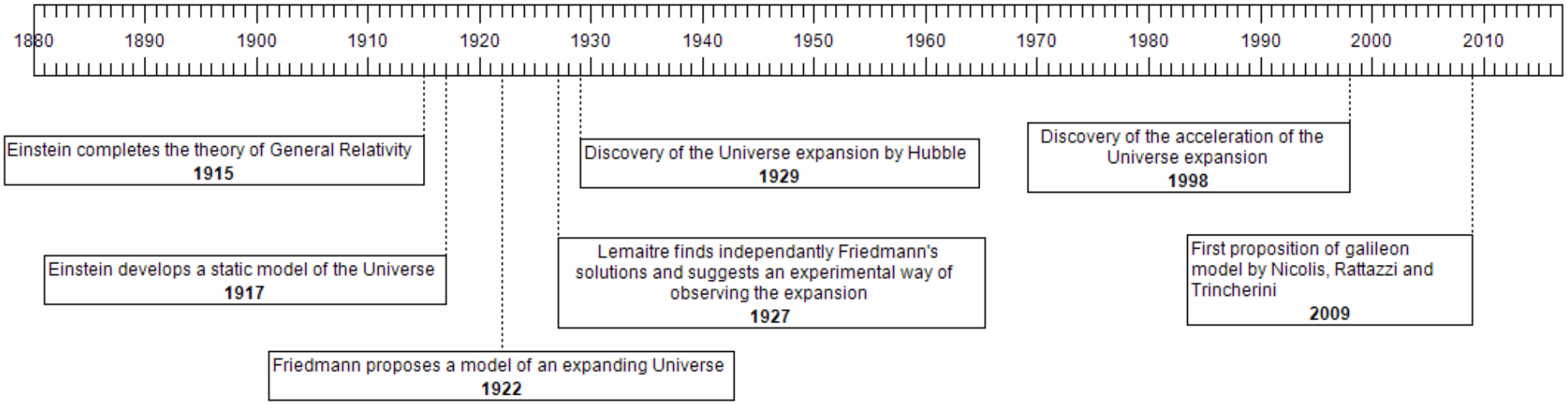
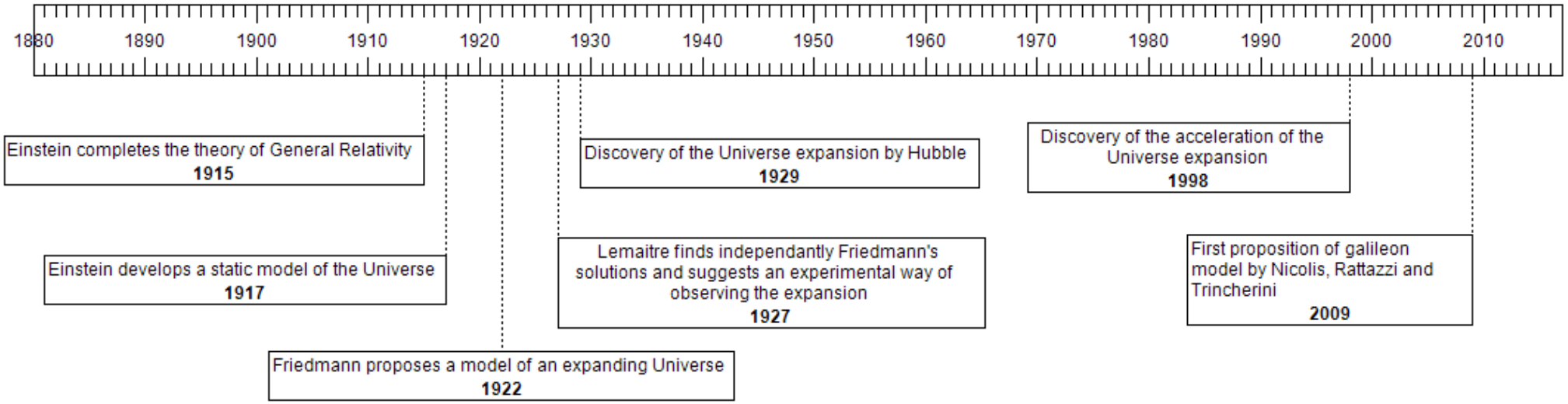


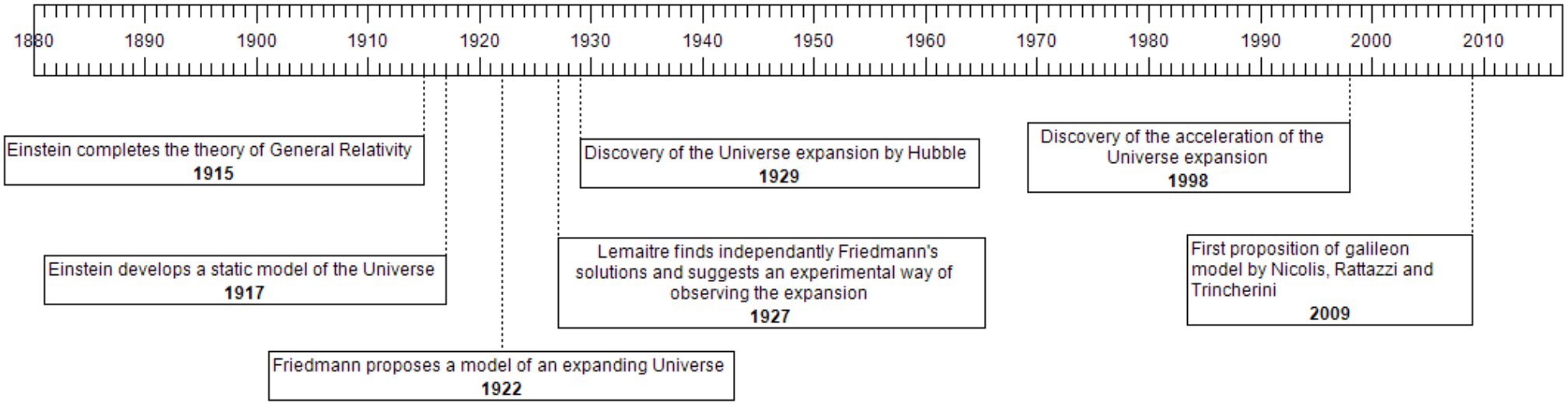
- Extension of General Relativity, adding a new component : the galileon

The Universe expansion



- Extension of General Relativity, adding a new component : the galileon
- No derivatives of order higher than two + invariance under galilean transformation

The galileon model



- Extension of General Relativity, adding a new component : the galileon
- No derivatives of order higher than two + invariance under galilean transformation

$$\mathcal{S}_G = \int d^4x\sqrt{-g}\left(\frac{M_P^2 R}{2} - \frac{1}{2}\sum_{i=1}^{5}\frac{c_i}{M_P H_0^{2(i-2)}}\mathcal{L}_i - \frac{c_0}{M_P}\varphi T^\mu_\mu - \frac{c_G}{M_P^2 H_0^2}\partial_\mu\varphi\partial_\nu\varphi T^{\mu\nu}\right)$$

Perturbations and CMB power spectrum

- Main goal : obtain the prediction of the CMB power spectrum in galileon cosmology.

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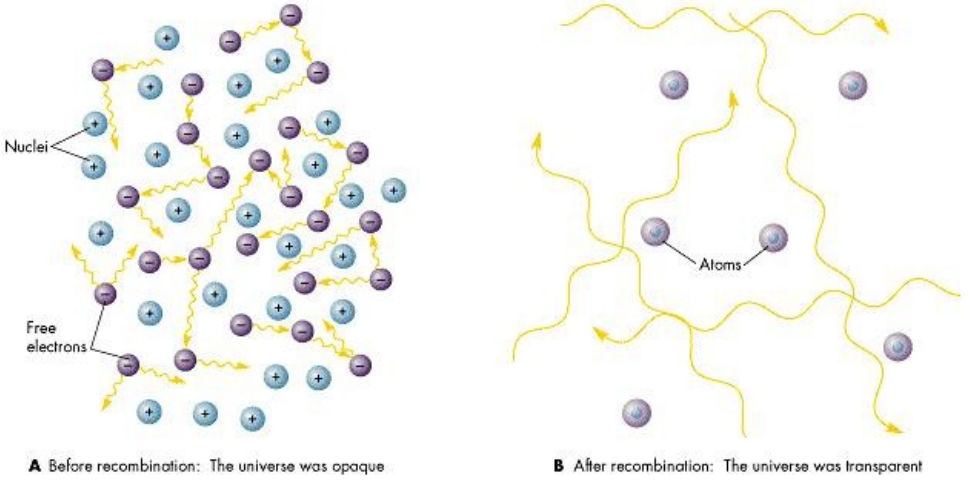

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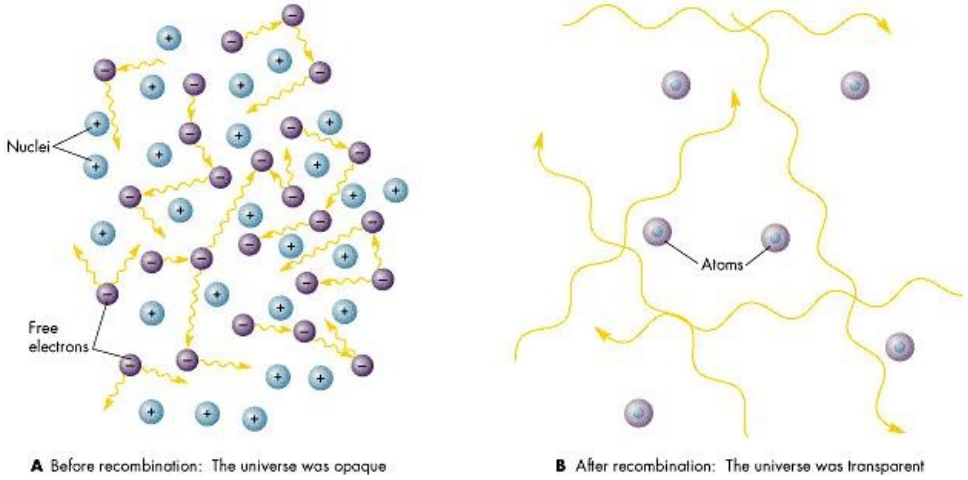

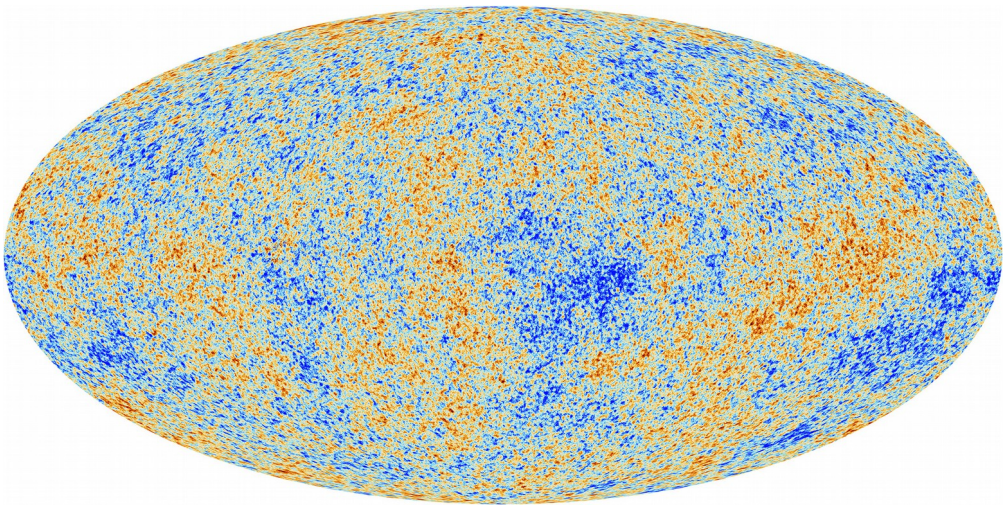

Planck CMB map

Perturbations and CMB power spectrum

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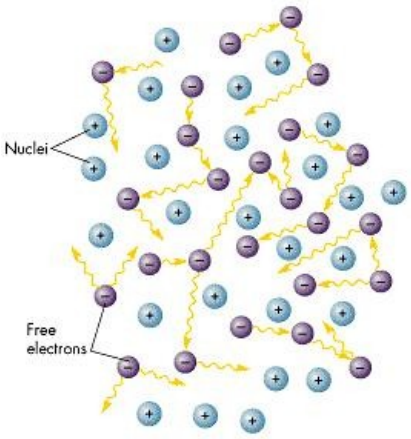
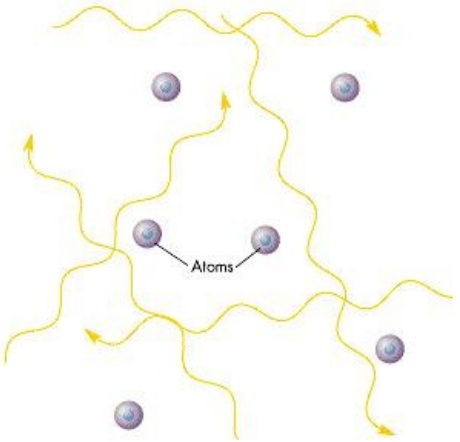
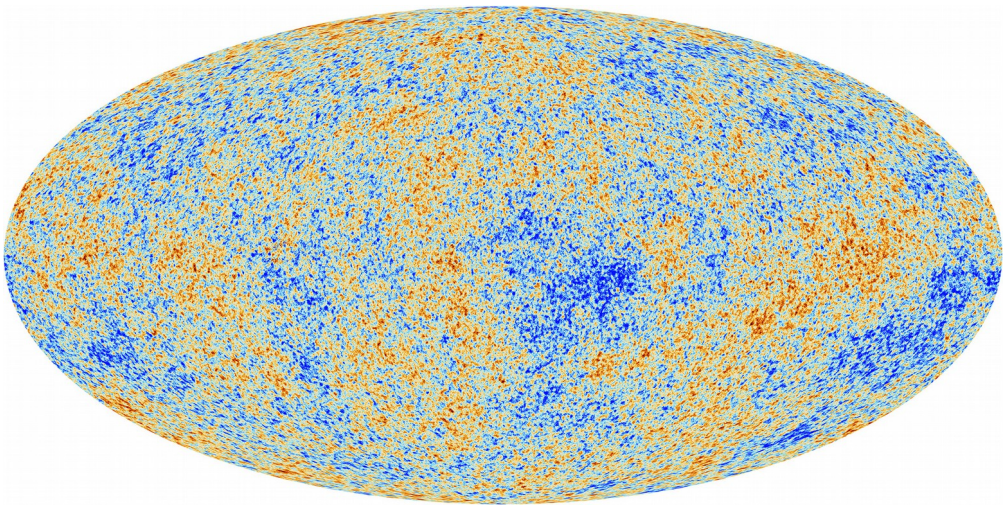


A Before recombination: The universe was opaque



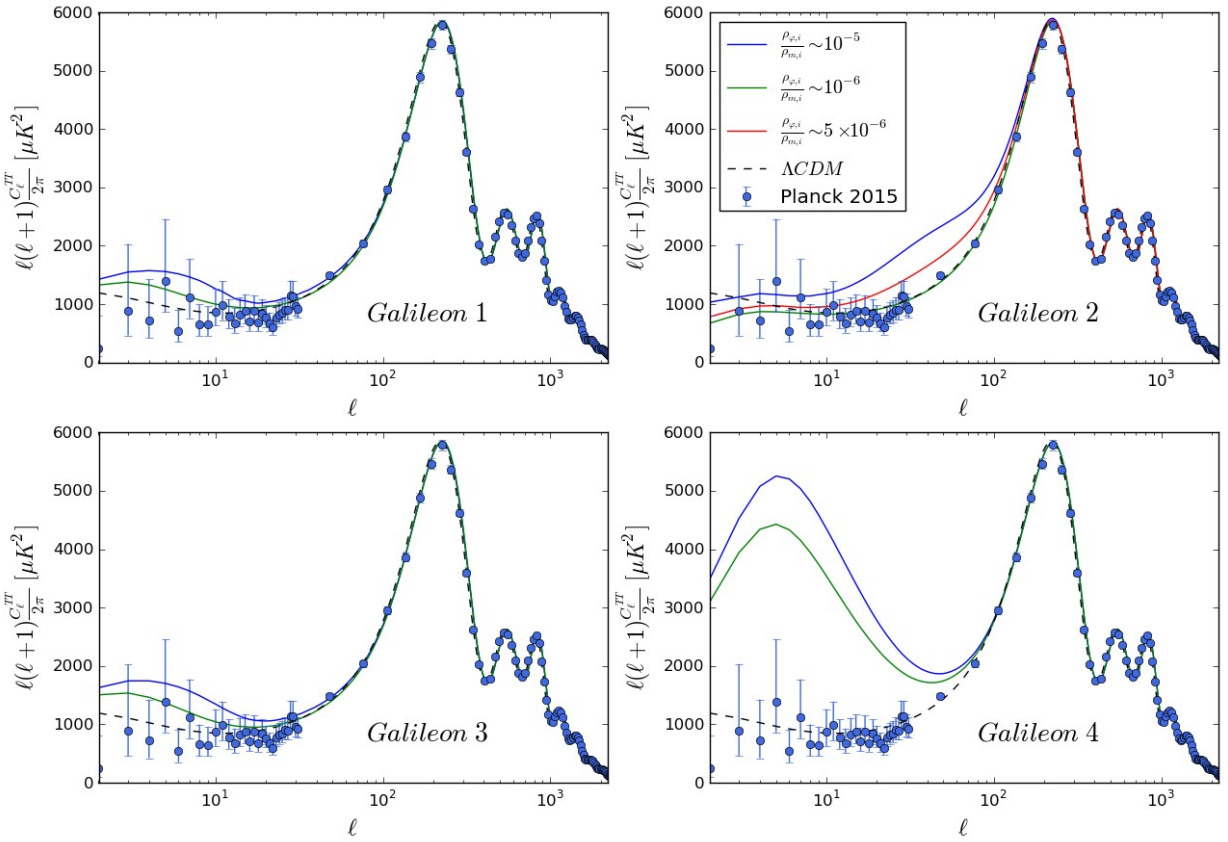
B After recombination: The universe was transparent



Planck CMB map

- Describe the dynamics of the constituants (e.g. the baryon-photon plasma) in galileon cosmology

Perturbations and CMB power spectrum



- Differences at large scales, coming from the gravitational behaviour
- Not a fit yet
- Seems possible to fit reasonably well the Planck data

Prospectives

- Fit galileon parameters to the CMB power spectrum

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- Fit to different observables simultaneously :

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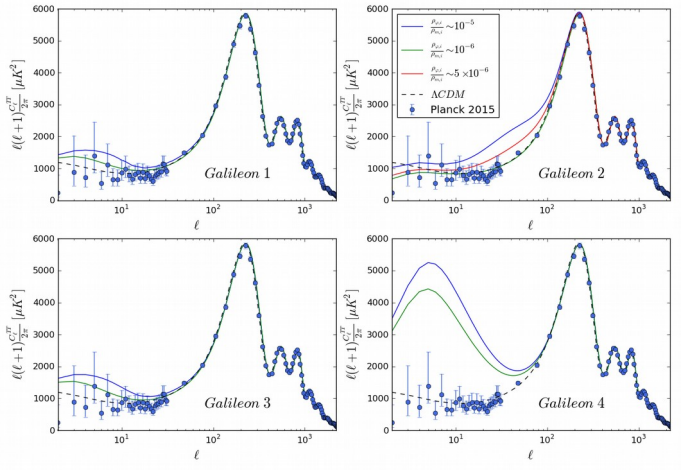
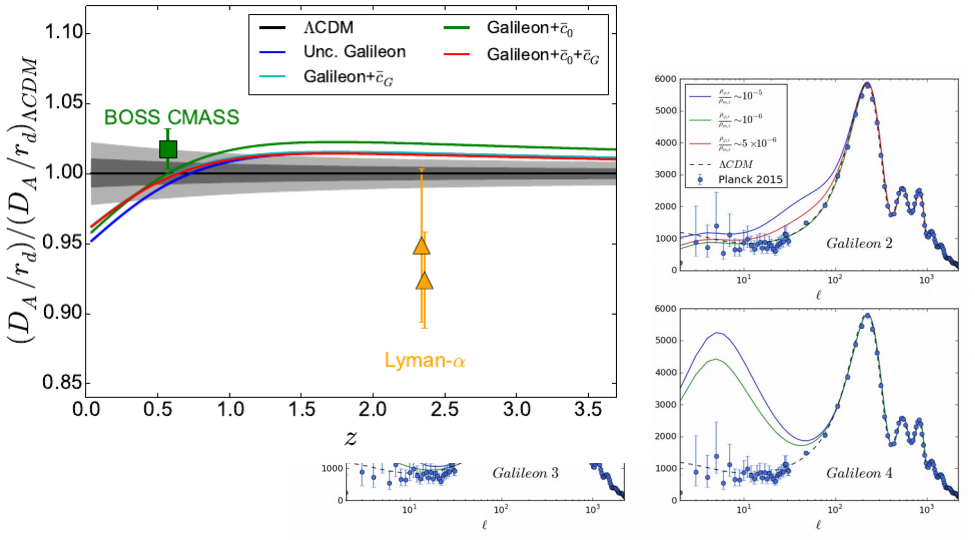


Prospectives

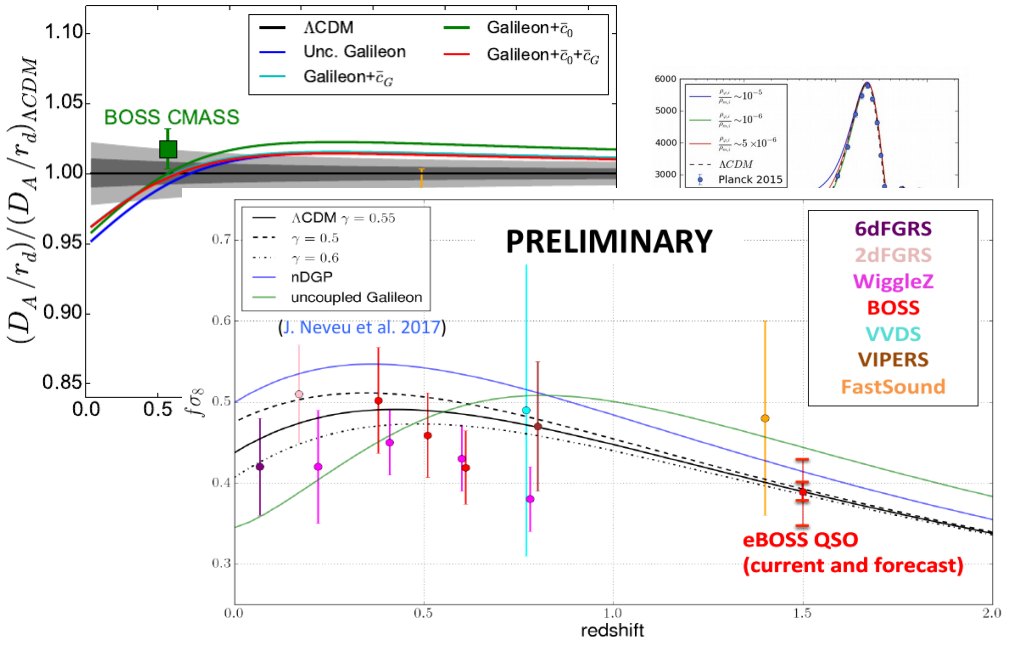
- Fit galileon parameters to the CMB power spectrum
- Fit to different observables simultaneously :
  - CMB
  - BAO



Prospectives

- Fit galileon parameters to the CMB power spectrum
- Fit to different observables simultaneously :

  - CMB
  - BAO
  - Growth of structures



Prospectives

- Fit galileon parameters to the CMB power spectrum
- Fit to different observables simultaneously :

  - CMB
  - BAO
  - Growth of structures
  - SNIa