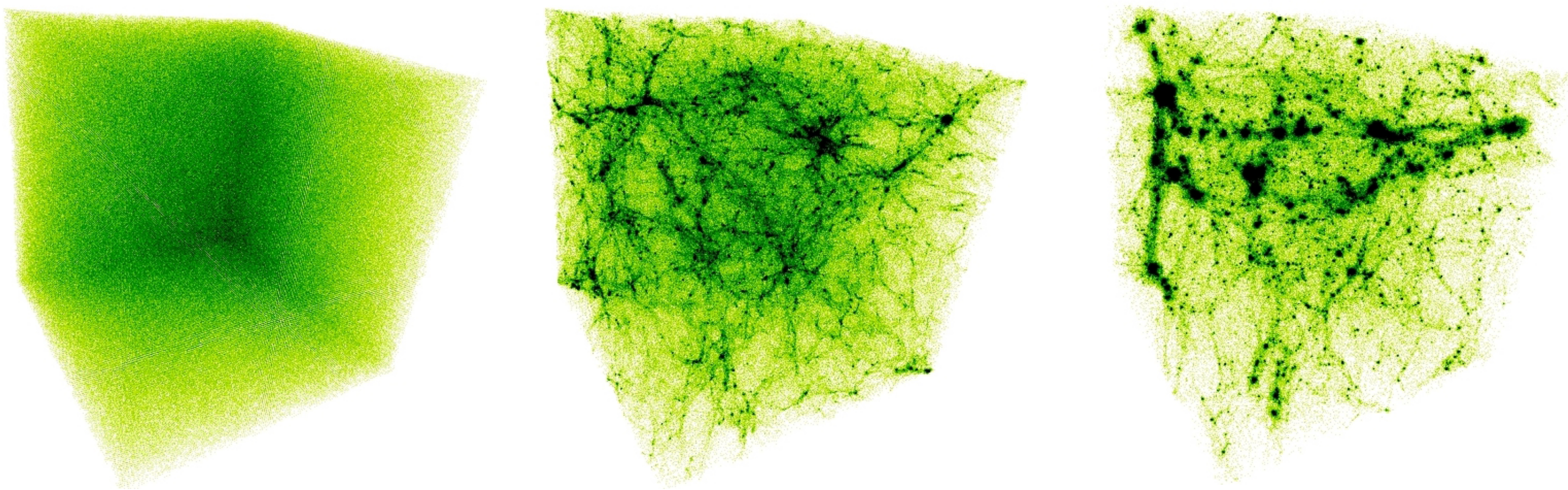
Alexander Knebe, *Universidad Autonoma de Madrid*



?

- The Situation
- The Methods
- Code Examples
- Code Comparison
- Tracking in Time Domain
- Summary

- **The Situation**
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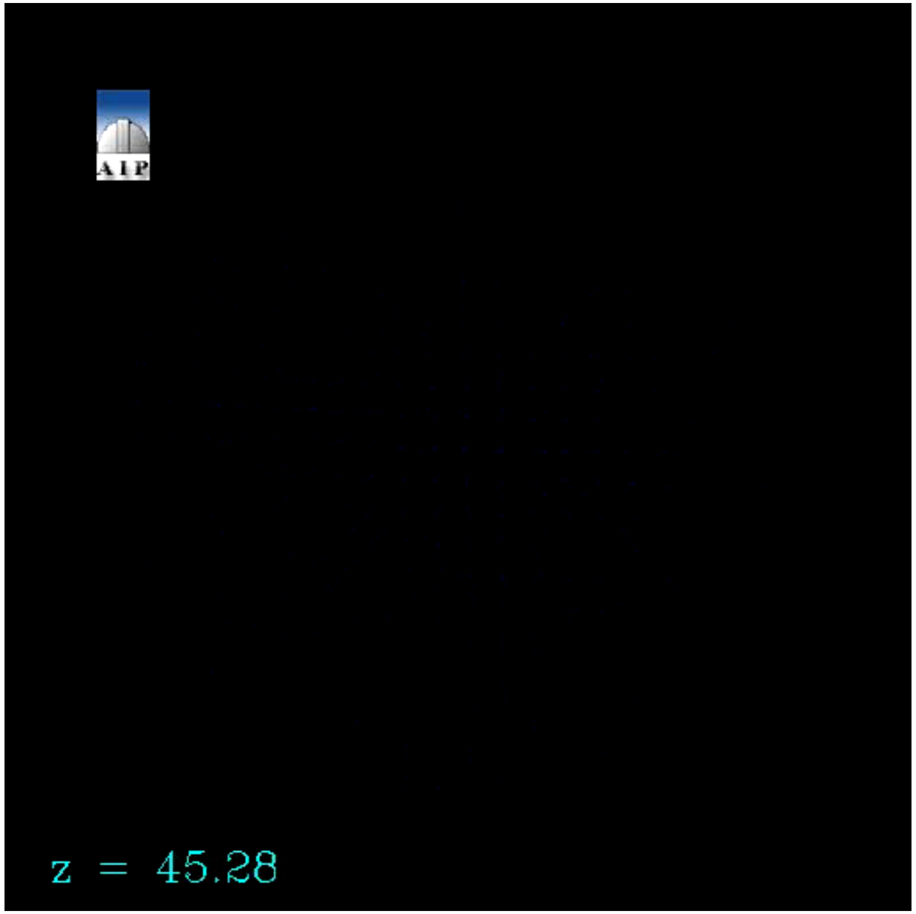
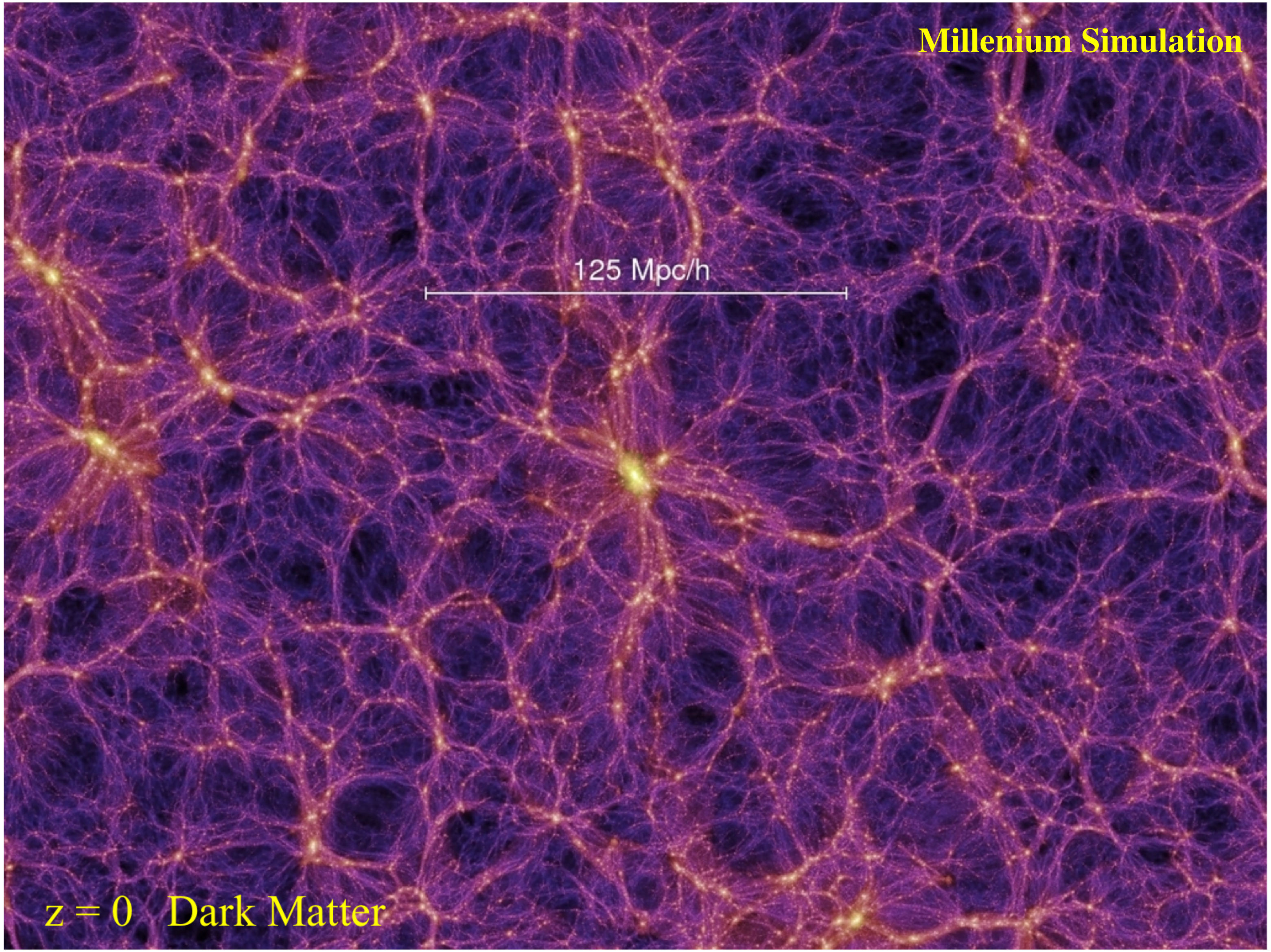
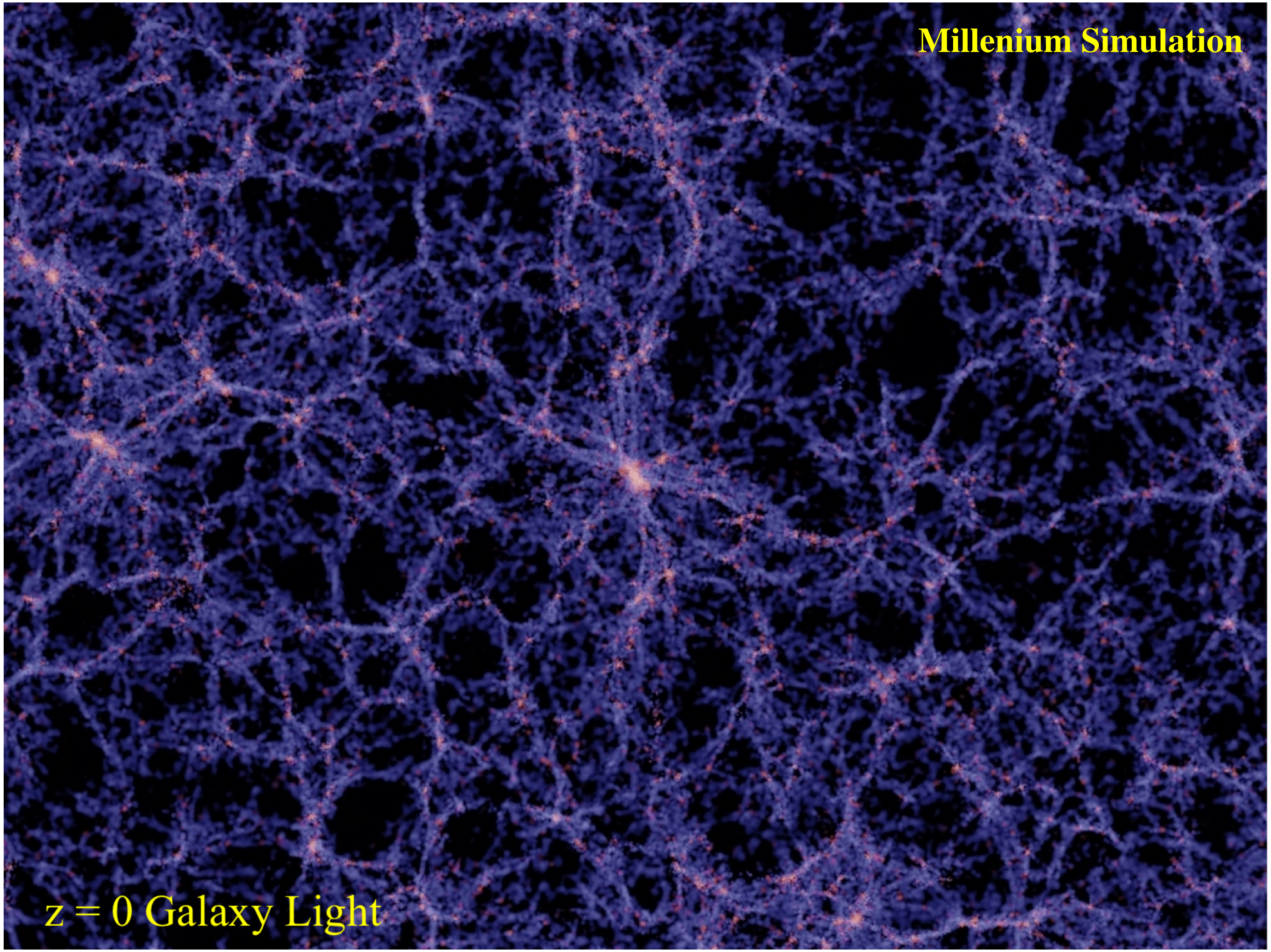
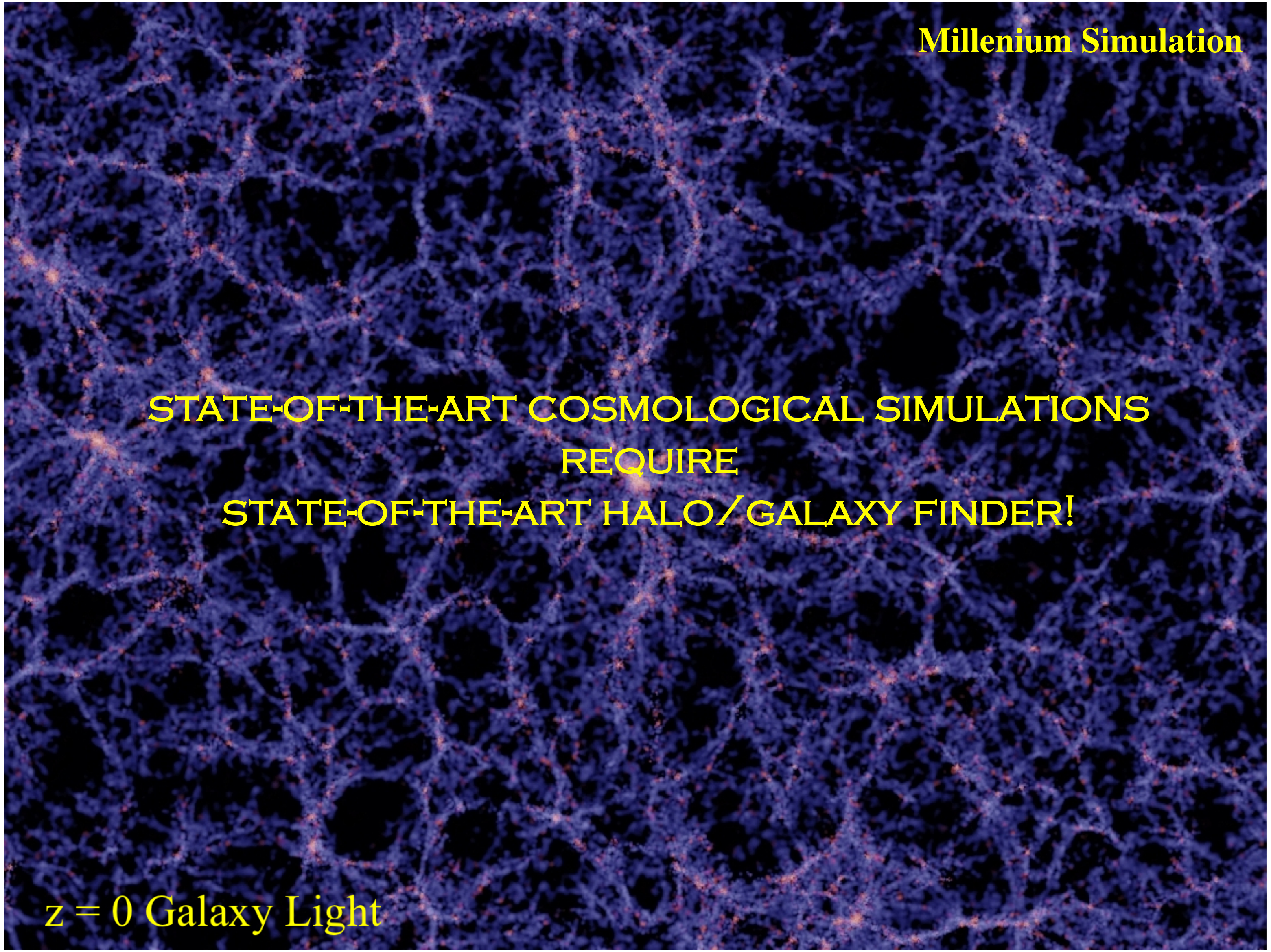
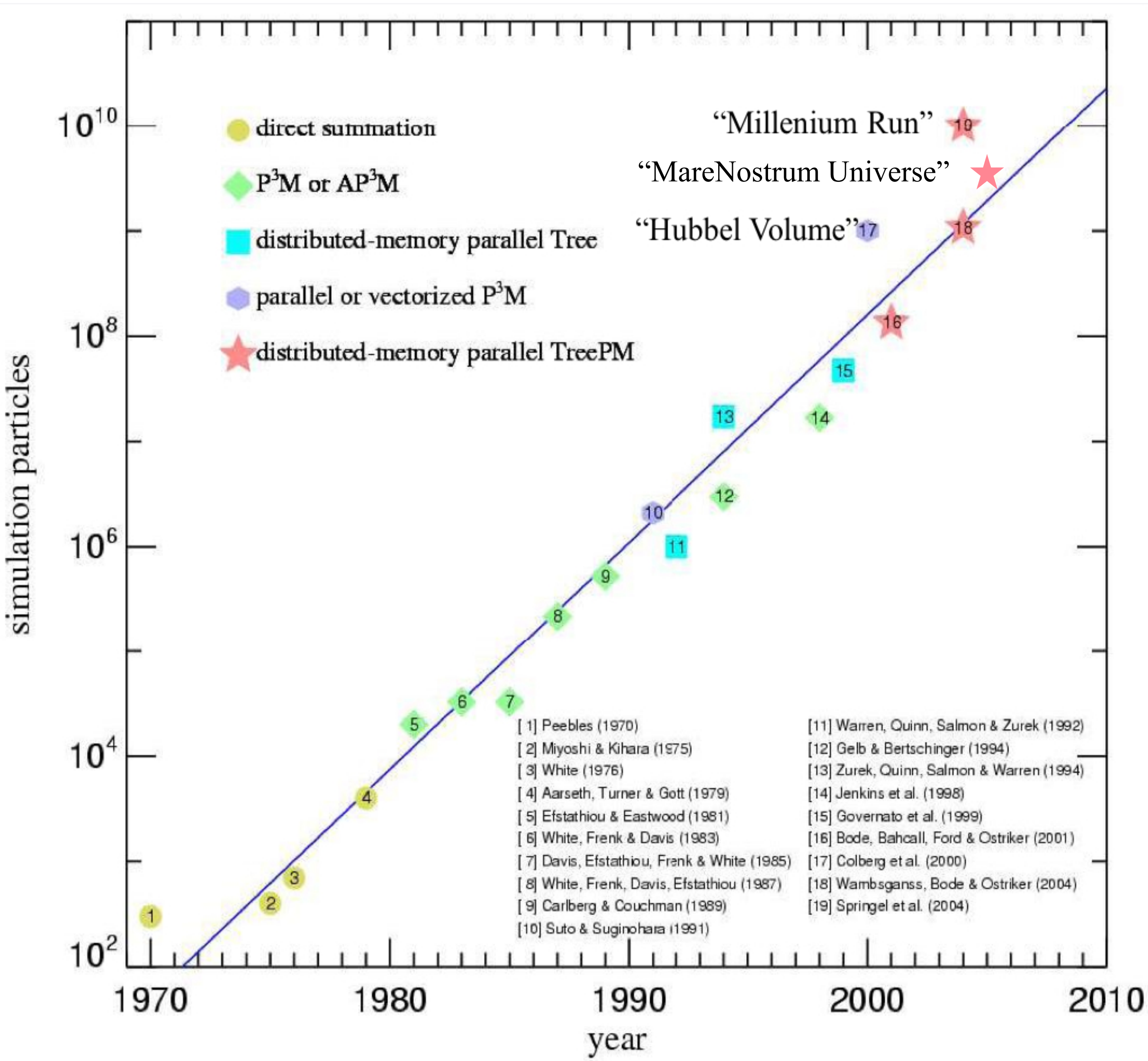
- hierarchical structure formation




Millenium Simulation
125 Mpc/h
z = 0 Dark Matter


Millenium Simulation
z = 0 Galaxy Light


Millenium Simulation
STATE-OF-THE-ART COSMOLOGICAL SIMULATIONS
REQUIRE
STATE-OF-THE-ART HALO/GALAXY FINDER!
z = 0 Galaxy Light


direct summation
P³M or AP³M
distributed-memory parallel Tree
parallel or vectorized P³M
distributed-memory parallel TreePM
"Millenium Run"
"MareNostrum Universe"
"Hubbel Volume"
simulation particles
year
[1] Peebles (1970)
[2] Miyoshi & Kihara (1975)
[3] White (1976)
[4] Aarseth, Turner & Gott (1979)
[5] Efstathiou & Eastwood (1981)
[6] White, Frenk & Davis (1983)
[7] Davis, Efstathiou, Frenk & White (1985)
[8] White, Frenk, Davis, Efstathiou (1987)
[9] Carlberg & Couchman (1989)
[10] Suto & Suginohara (1991)
[11] Warren, Quinn, Salmon & Zurek (1992)
[12] Gelb & Bertschinger (1994)
[13] Zurek, Quinn, Salmon & Warren (1994)
[14] Jenkins et al. (1998)
[15] Governato et al. (1999)
[16] Bode, Bahcall, Ford & Ostriker (2001)
[17] Colberg et al. (2000)
[18] Wambsganss, Bode & Ostriker (2004)
[19] Springel et al. (2004)

1974 SO
1985 FOF
1991 DENMAX
1994 SO
1995 adaptive FOF
1996 IsoDen
1997 BDM
1998 HOP
1999 hierarchical FOF

2001 SKID
2001 enhanced BDM
2001 SUBFIND
2004 MHF & MHT
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2004 DENMAX2
2004 SURV
2005 improved DENMAX
2005 VOBOZ
2006 PSB
2006 6DFOF
2007 further improved DENMAX
2009 HSF
2009 LANL finder
2009 AHF
2010 PHOP
2010 ASOHF
2010 PSO
2010 PFOF
2010 ORIGAMI
2010 HOT
2010 ROCKSTAR
2010 MENDIETA
2010 enhanced SURV
2011 HBT
2011 STF
2012 GRASSHOPPER
2012 JUMP-D

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millenium bug?!

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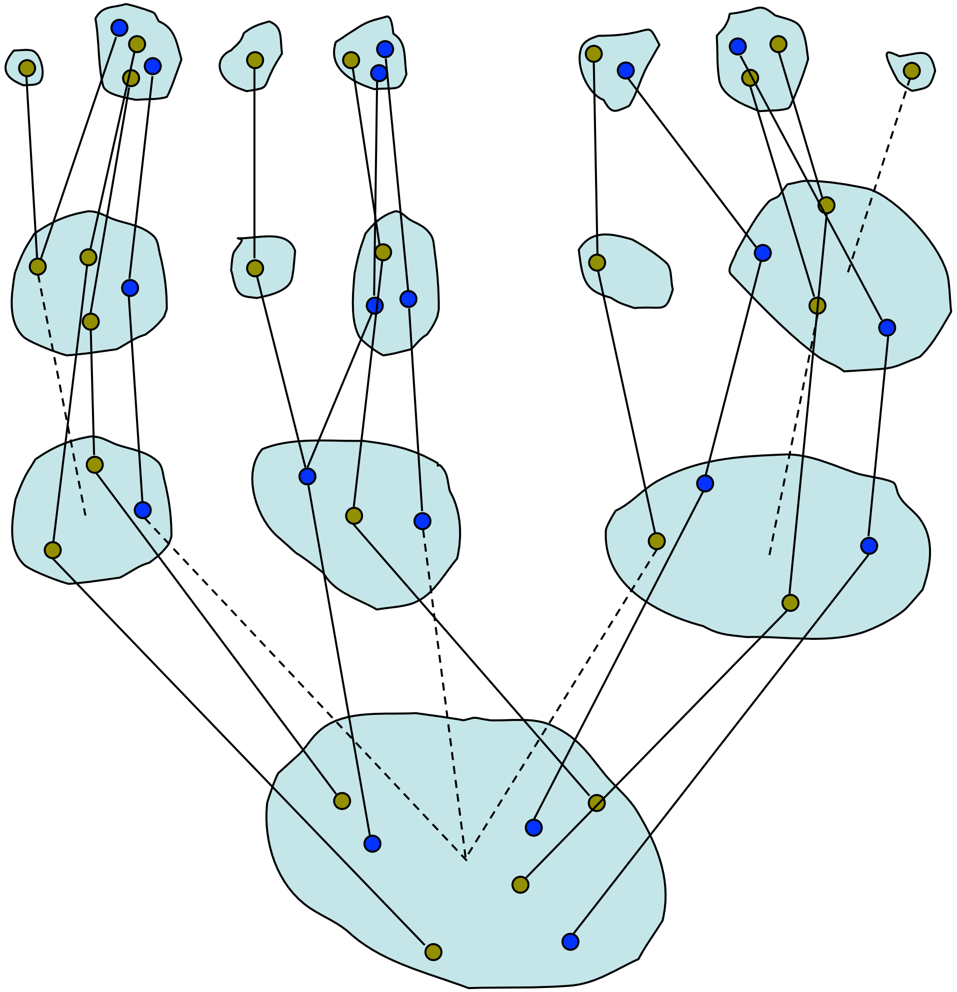
- our beloved CDM model induces hierarchical structure formation!



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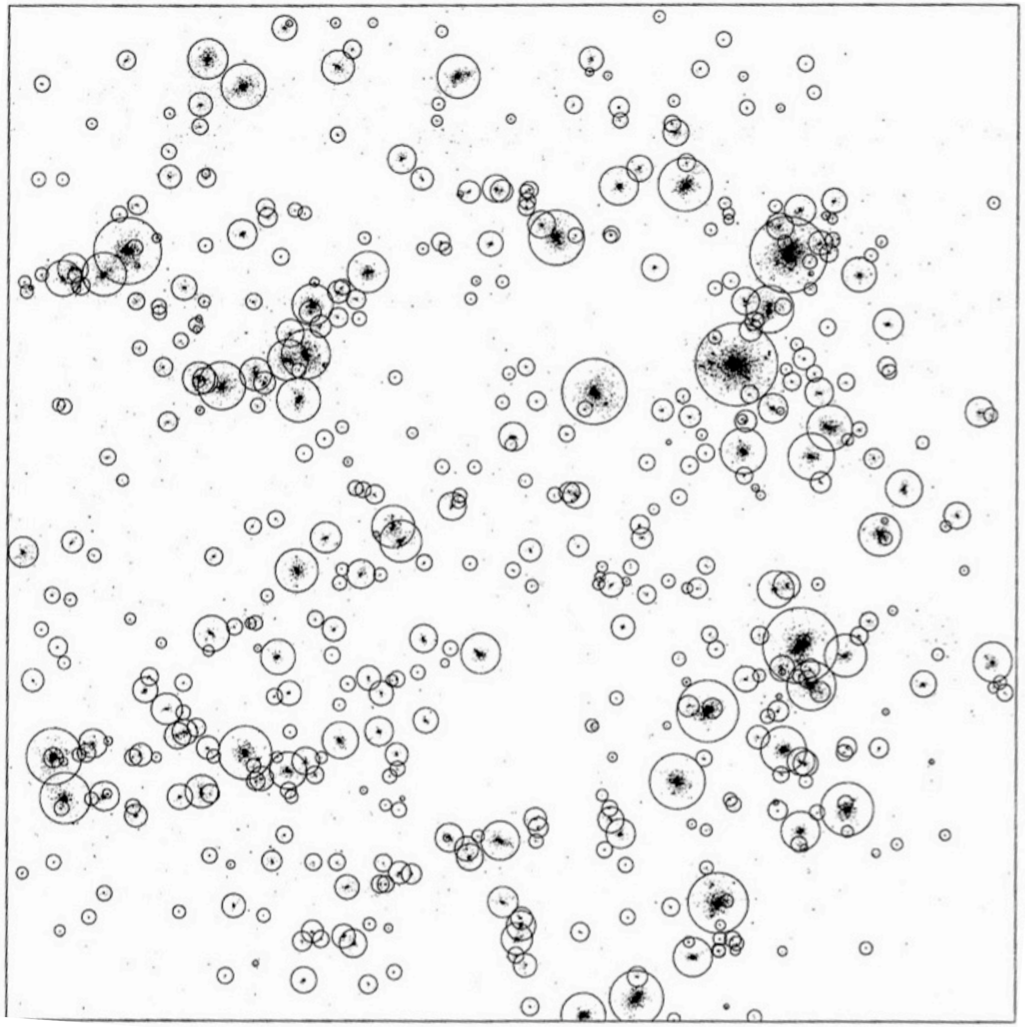
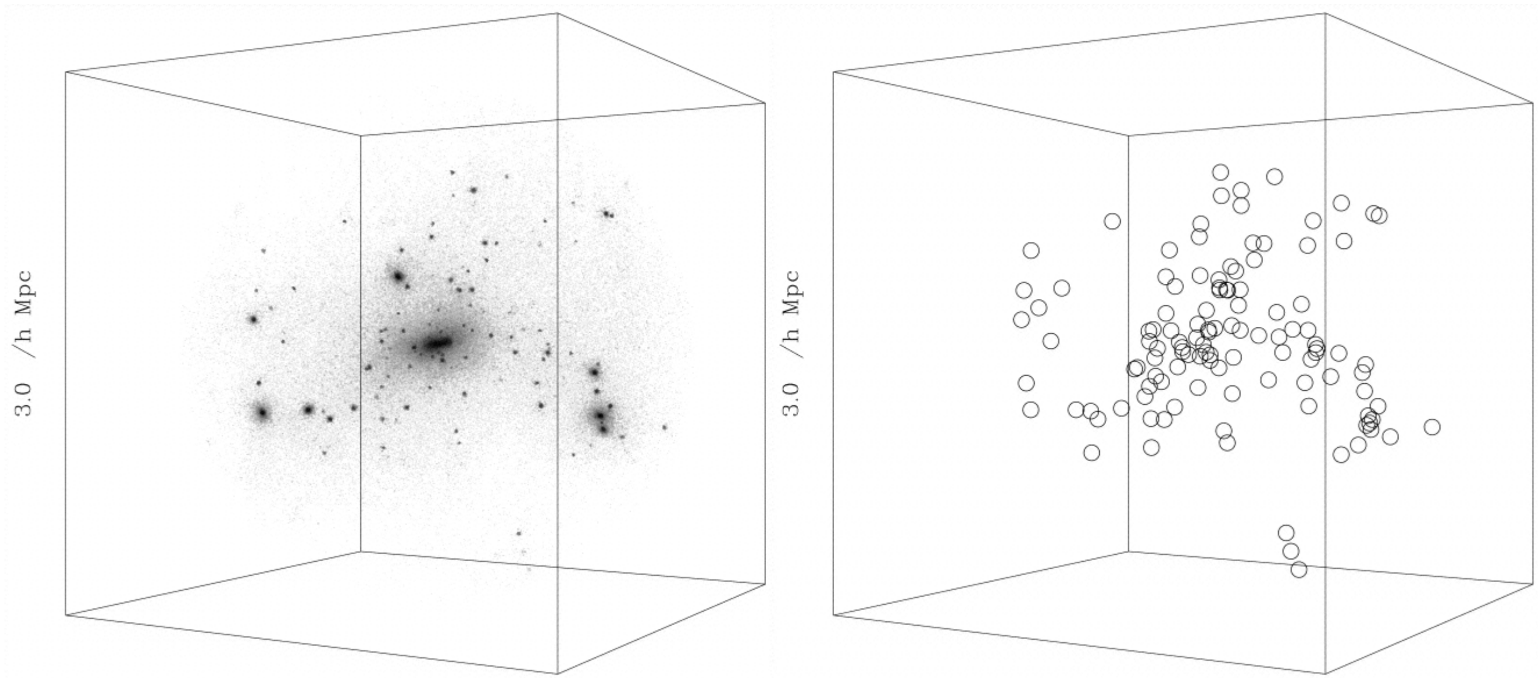


Warren et al. (1992)

- our beloved CDM model induces hierarchical structure formation!

overcoming the overmerging



Klypin et al. (1999)

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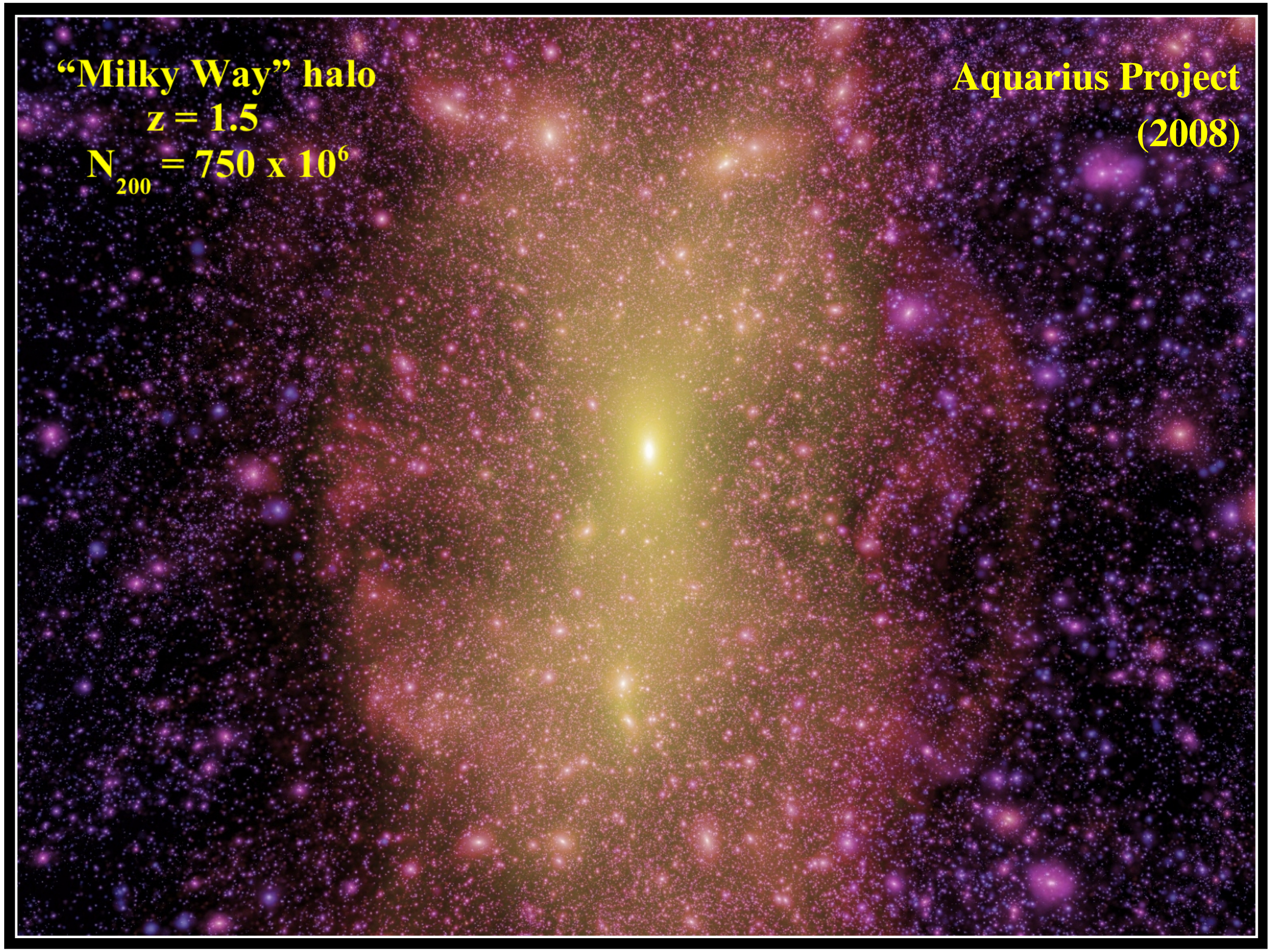

White et al. (2008)

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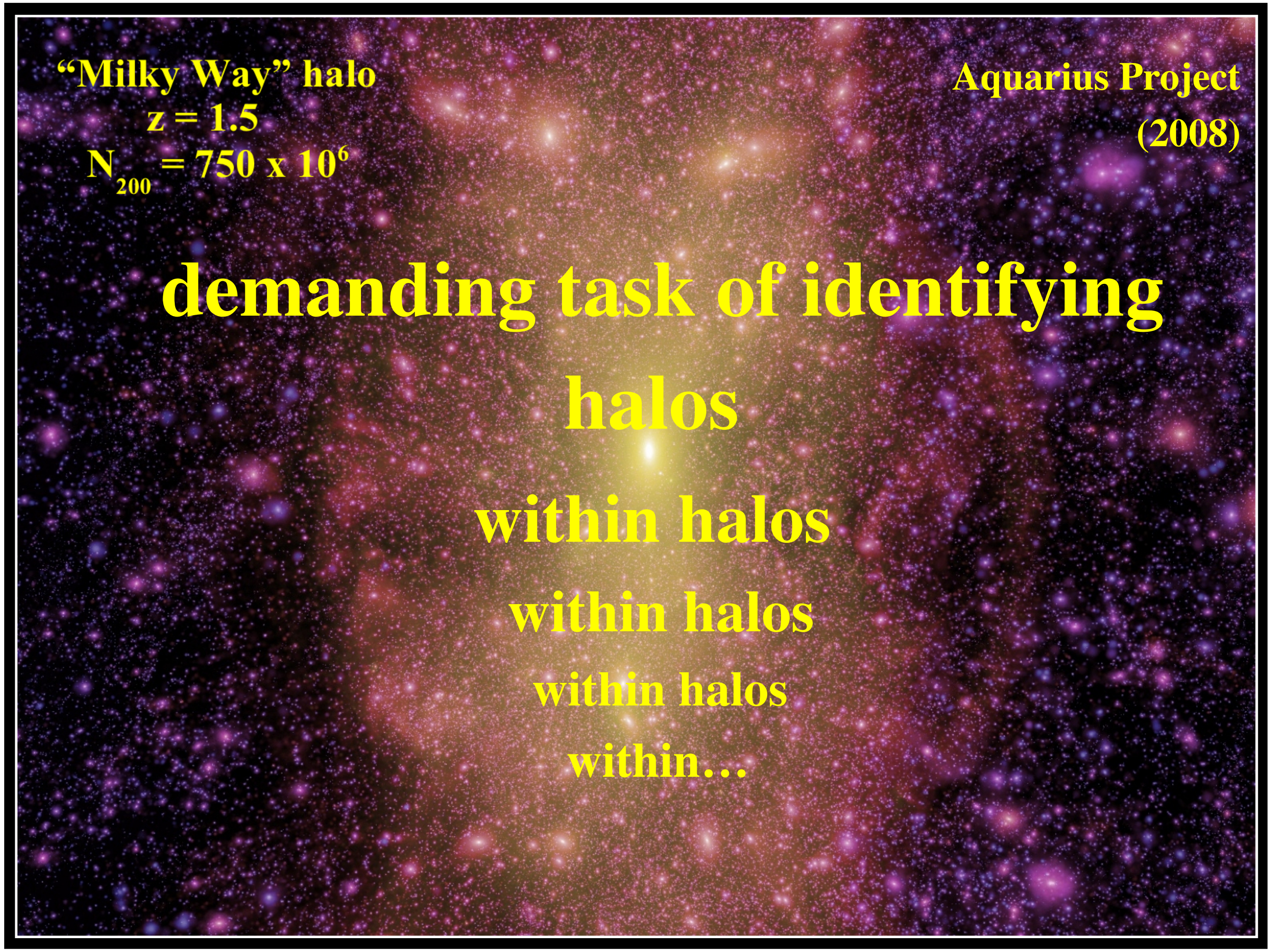
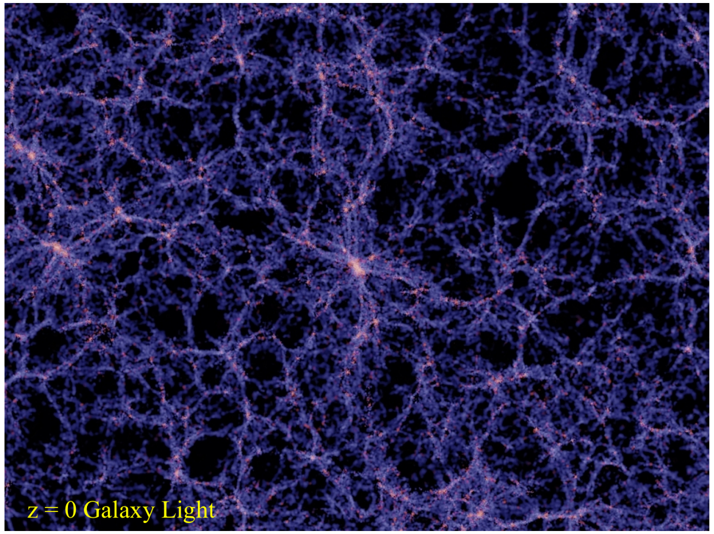


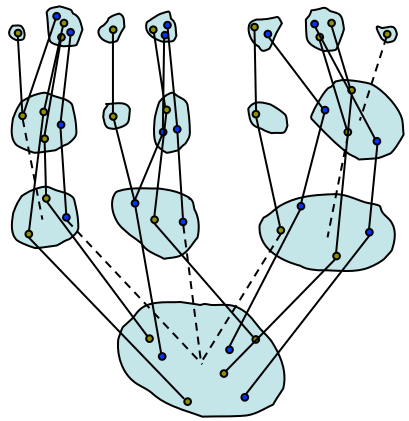
White et al. (2008)

- halo finders...

... map simulations onto observables:



... need to acknowledge hierarchical structure formation:



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- possibilities
  - configuration space 3D
  - configuration space + velocity space 2x 3D
  - phase space 6D

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  - configuration space 3D
  - configuration space + velocity space 2x 3D
  - phase space 6D

+ tracking in time domain!?

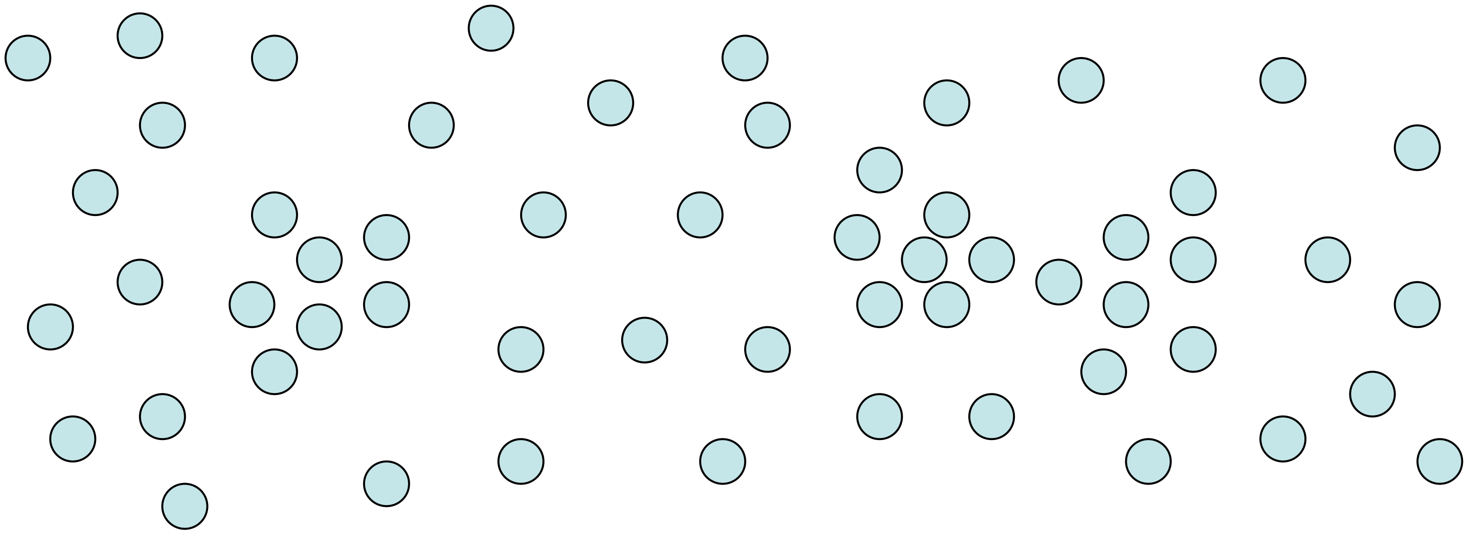
- possibilities
  - configuration space 3D

➢ **Friends-Of-Friends**

➢ **Density-Peak Collector**

- possibilities
  - configuration space 3D
    - » **group particles together that are spatially close**

$$|\vec{x}_i - \vec{x}_j| \leq b\,\Delta x \qquad \Delta x = \frac{B}{\sqrt[3]{N}}$$



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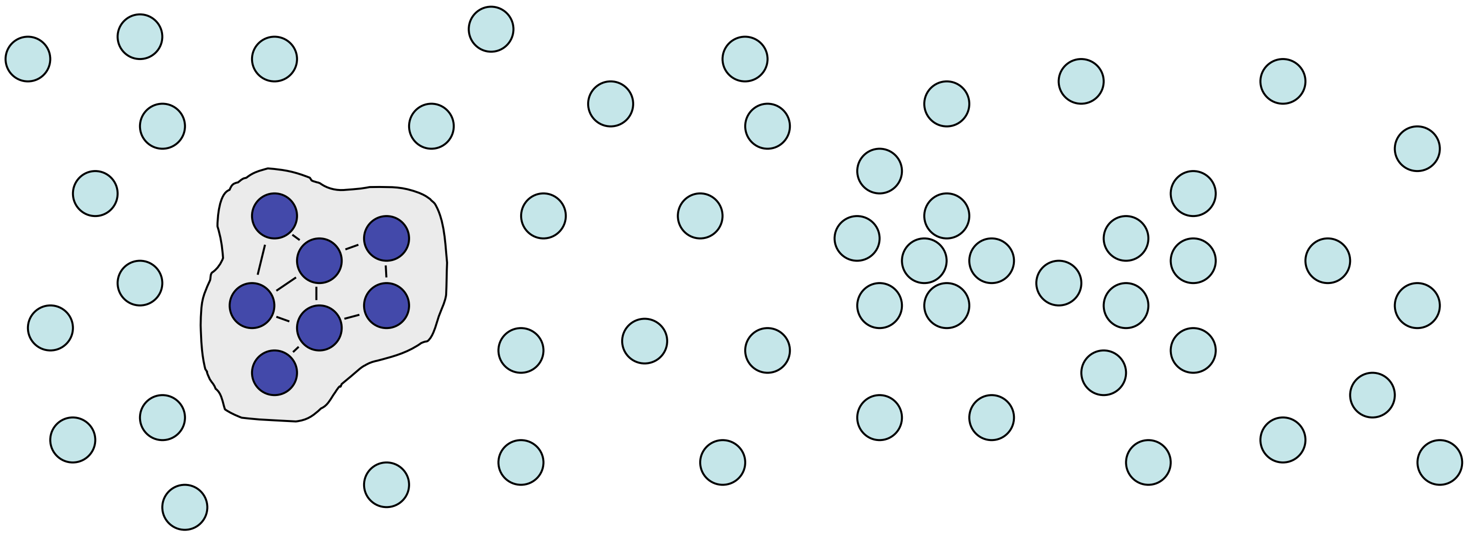

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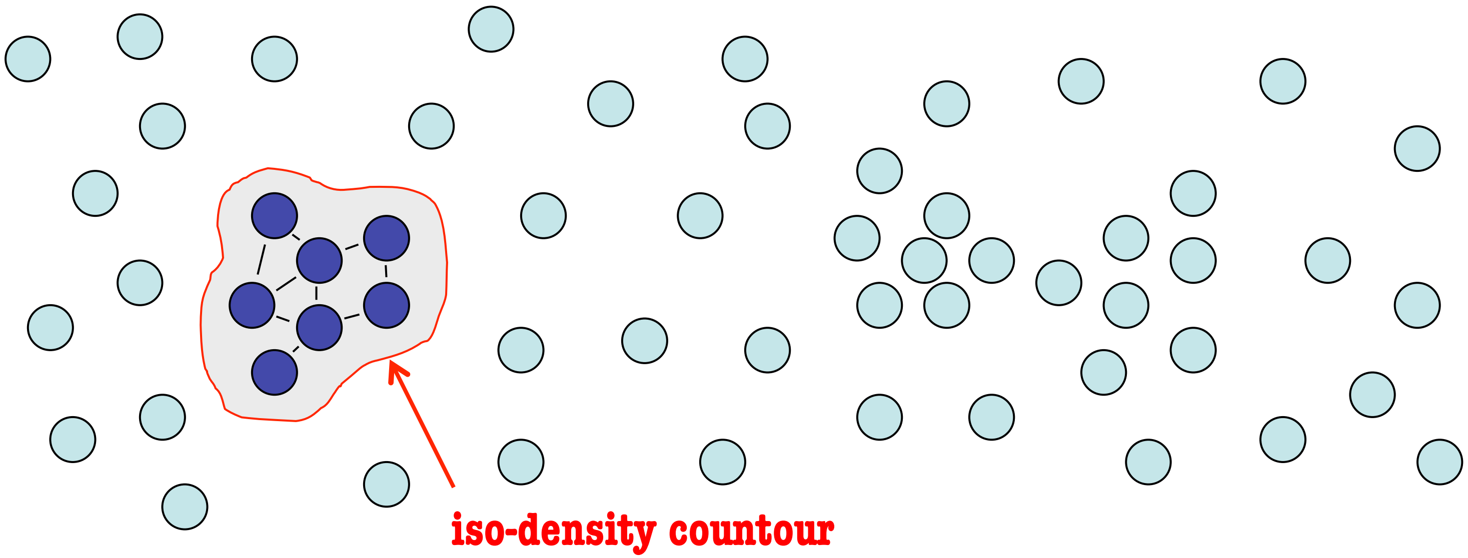

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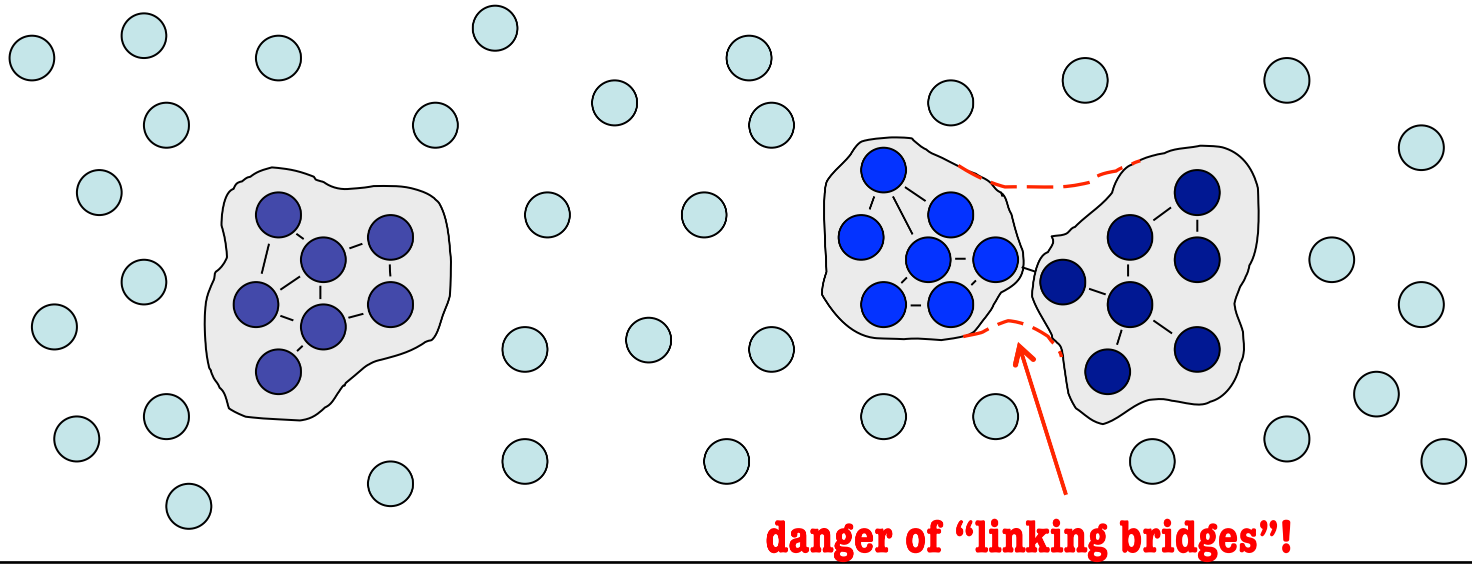
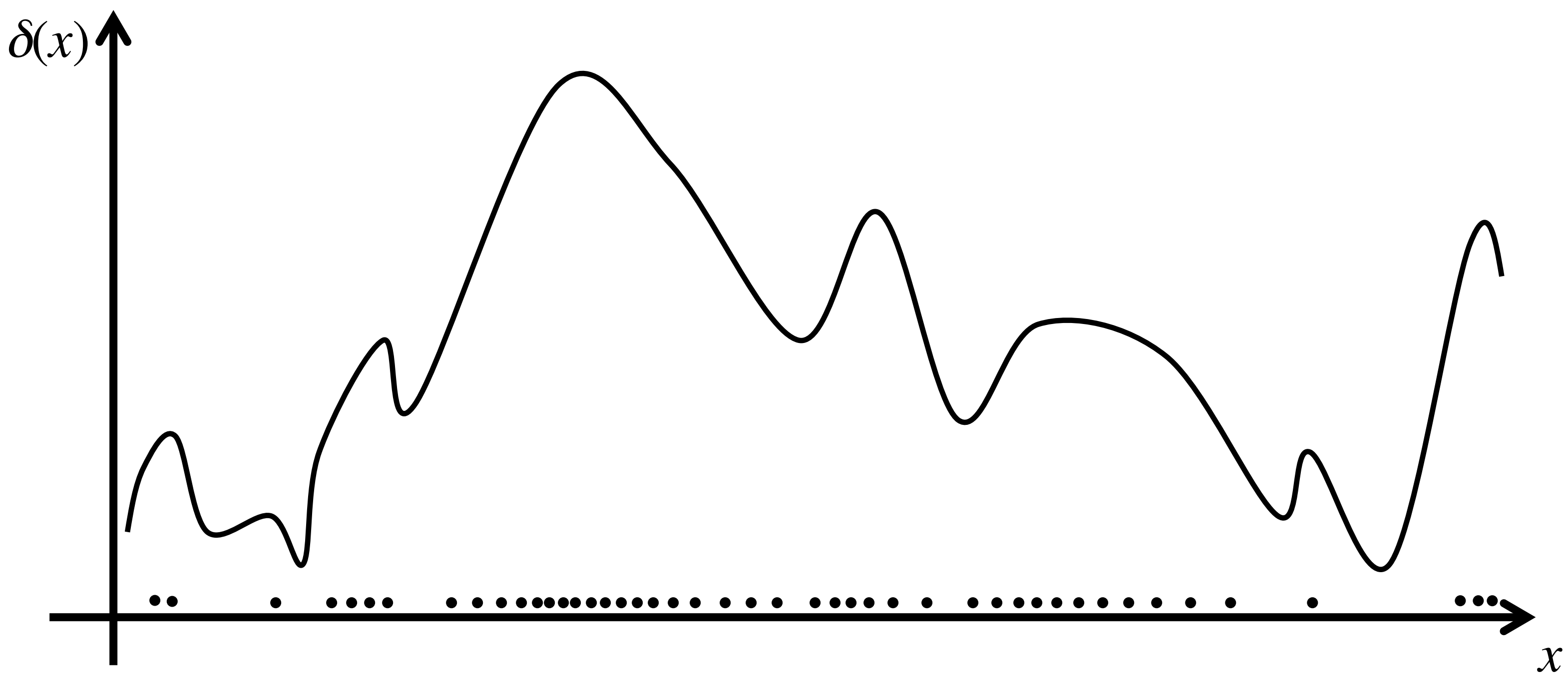
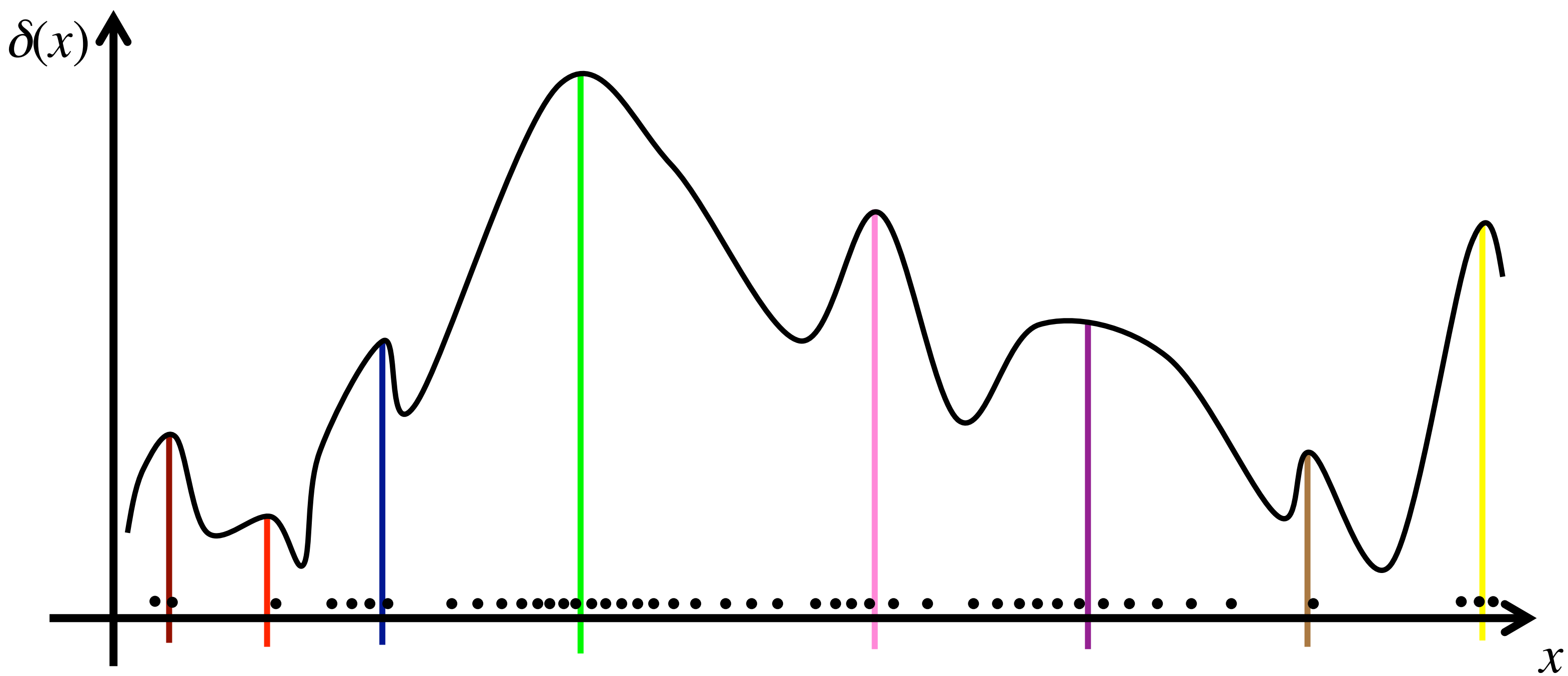


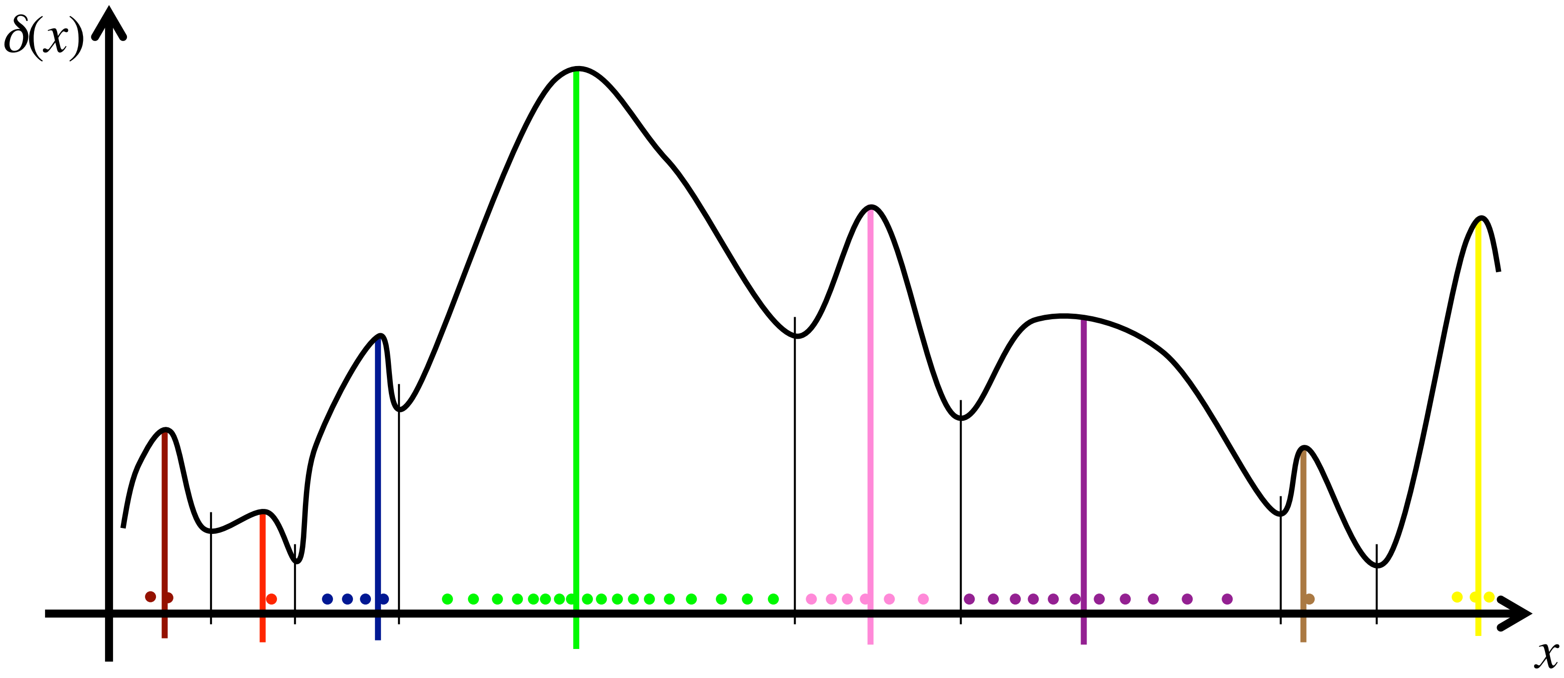
- possibilities
  - configuration space 3D



- possibilities
  - configuration space 3D
    - » **locate peaks in (smoothed) density field**



- possibilities
  - configuration space 3D
    - » **locate peaks in (smoothed) density field**
    - » **collect particles about peaks**



- possibilities
  - configuration space 3D

Friends-Of-Friends	Density-Peak Collector
» halos have arbitrary shape	» halos (can) have arbitrary shape
» *in-capable* of finding subhaloes	» *capable* of finding subhaloes
» danger of linking bridges	» requires density field

- possibilities
  - configuration space 3D
  - configuration space + **velocity space** 2x 3D

Friends-Of-Friends

» halos have arbitrary shape
» *in-capable* of finding subhaloes
» danger of linking bridges

Density-Peak Collector

» halos (can) have arbitrary shape
» *capable* of finding subhaloes
» requires density field

» **(iteratively) remove gravitationally unbound particles**

- possibilities
  - configuration space 3D
  - configuration space + velocity space 2x 3D

Friends-Of-Friends

» halos have arbitrary shape
» *in-capable* of finding subhaloes
» danger of linking bridges

- **adaptive FOF** (van Kampen 1995)
- **hierarchical FOF** (Gottloeber et al. 1999)
- ...

- possibilities
  - configuration space 3D
  - configuration space + velocity space 2x 3D

- **SO** (Press & Schechter 1974)
- **BDM** (Klypin et al. 1997)
- **IsoDen** (Pfitzner et al. 1997)
- **DENMAX** (Gelb & Bertschinger 1991)
- **SKID** (Stadel 2001)
- **HOP** (Eisenstein & Hut 1998)
- **SUBFIND** (Springel 2001)
- **MHF** (Gill, Knebe & Gibson 2004)
- **PSB** (Kim & Park 2005)
- **VOBOZ** (Neyrinck et al. 2005)
- **AHF** (Knollmann & Knebe 2009)
- …

Density-Peak Collector

» halos (can) have arbitrary shape

» *capable* of finding subhaloes

» requires density field

- possibilities
  - configuration space — 3D
  - configuration space + velocity space — 2x 3D

- **SO** (Press & Schechter 1974)
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- ...

Density-Peak Collector

» halos (can) have arbitrary shape

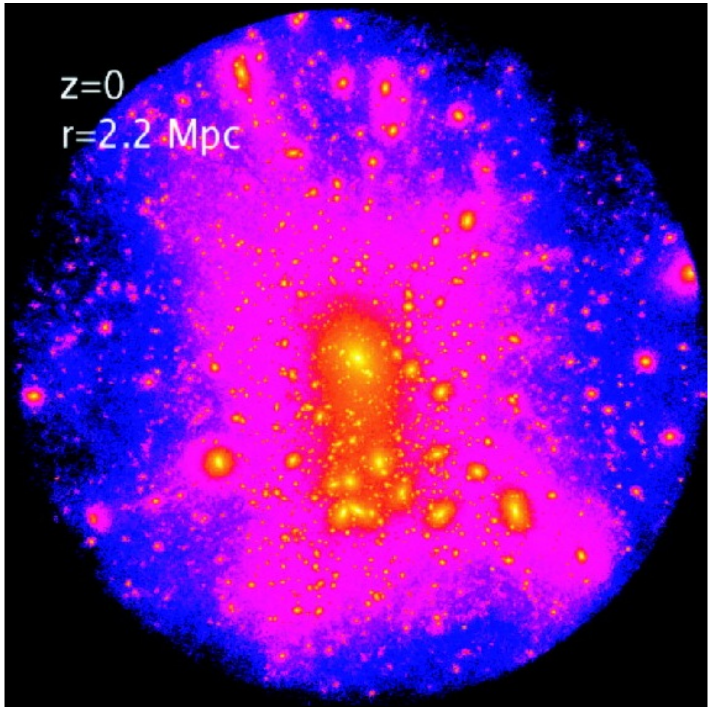
» *capable* of finding subhaloes

» requires density field

MPI-parallelized open-source (and essentially parameter free) halo finder

- possibilities
  - configuration space 3D
  - configuration space + velocity space 2x 3D
  - phase space 6D

➢ **6DFOF** (Diemand, Kuhlen & Madau 2006)

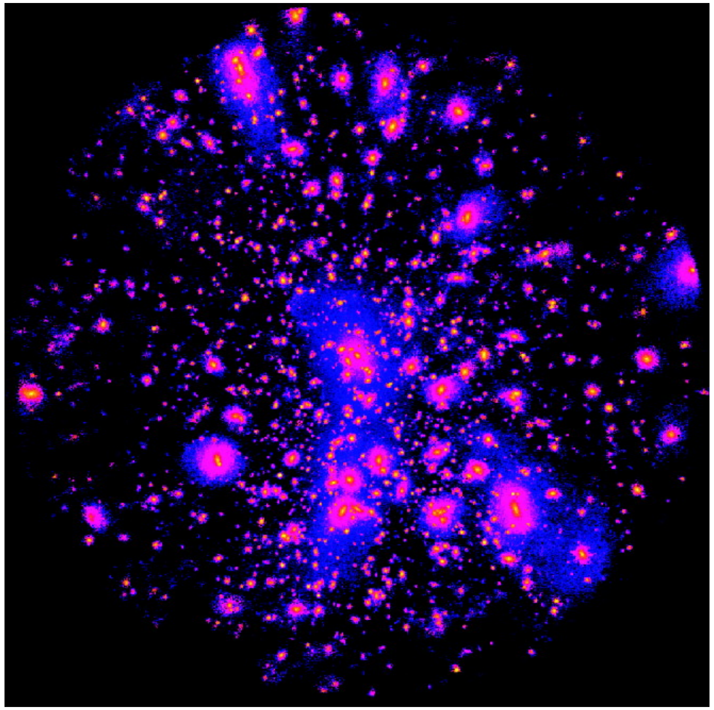


density field

- possibilities
  - configuration space 3D
  - configuration space + velocity space 2x 3D
  - phase space 6D

➢ **6DFOF** (Diemand, Kuhlen & Madau 2006)

$$\frac{\left(\vec{x}_i - \vec{x}_j\right)^2}{\left(b\Delta x\right)^2} + \frac{\left(\vec{v}_i - \vec{v}_j\right)^2}{\left(b_v \Delta v\right)^2} < 1$$



phase-space density field

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  - FOF
  - 6DFOF
  - AHF
  - BDM
  - SKID

- The Situation
- The Methods
- **Code Examples:**
    - **FOF**
    - 6DFOF
    - AHF
    - BDM
    - SKID

- FOF

$$\left|\vec{x}_i - \vec{x}_j\right| \leq b\,\Delta x \qquad \Delta x = \frac{B}{\sqrt[3]{N}}$$

- The Situation
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- **Code Examples:**
    - FOF
    - **6DFOF**
    - AHF
    - BDM
    - SKID

- 6DFOF

$$\frac{\left(\vec{x}_i - \vec{x}_j\right)^2}{\left(b_x \Delta x\right)^2} + \frac{\left(\vec{v}_i - \vec{v}_j\right)^2}{\left(b_v \Delta v\right)^2} < 1$$

$$\Delta x = \frac{B}{\sqrt[3]{N}}$$

$$\Delta v \approx \sigma_v$$

- The Situation
- The Methods
- **Code Examples:**
  - FOF
  - 6DFOF
  - **AHF**
  - BDM
  - SKID

- mode of operation for AHF, BDM & SKID (and practically all halo finders):
  - locate potential halo particles
  - iteratively remove gravitationally unbound particles
  - calculate integral properties of remaining objects
  - calculate radial profiles of (some) properties

- mode of operation for AHF:
    - locate potential halo particles using an adaptive mesh hierarchy
    - iteratively remove gravitationally unbound particles
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- mode of operation for AHF:
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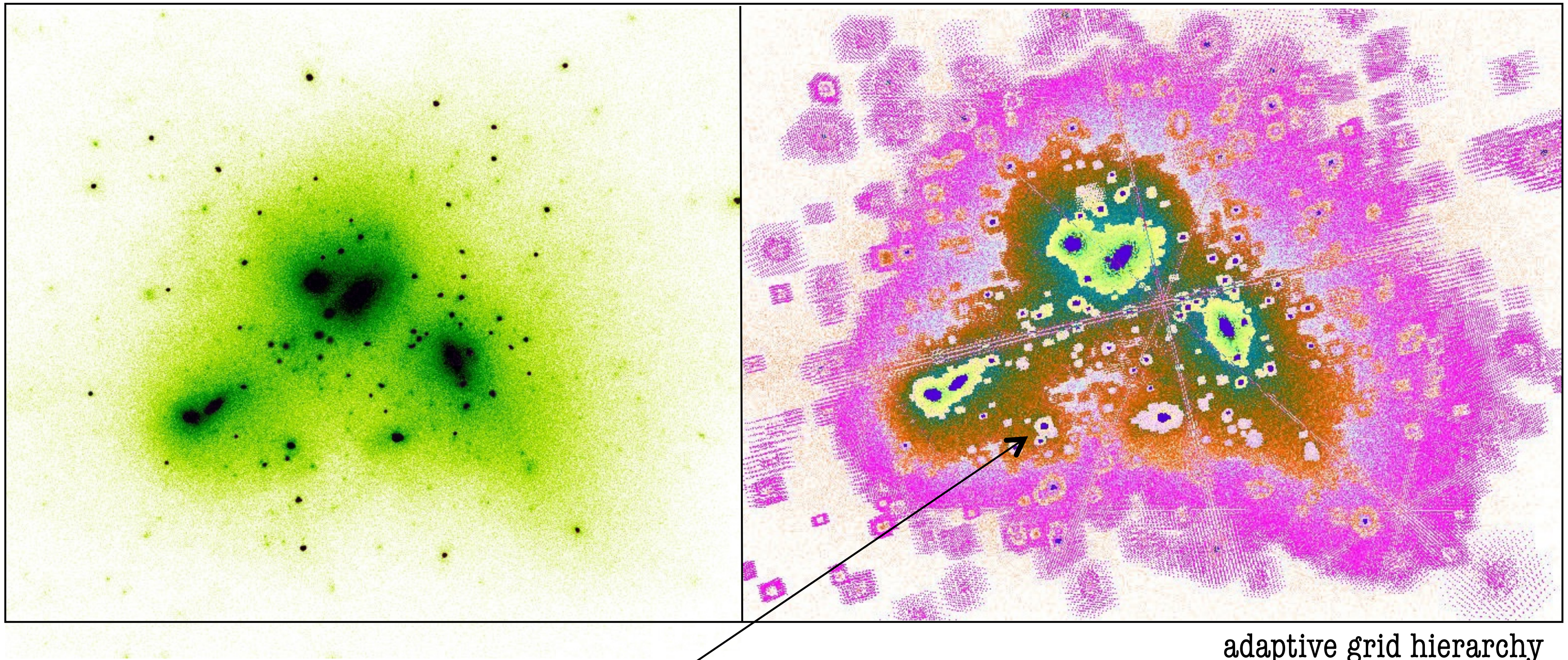
- ***AMIGA***'s ***H***alo ***F***inder

the AMR grids naturally locate prospective halo centres

- ***AMIGA***'s ***H***alo ***F***inder

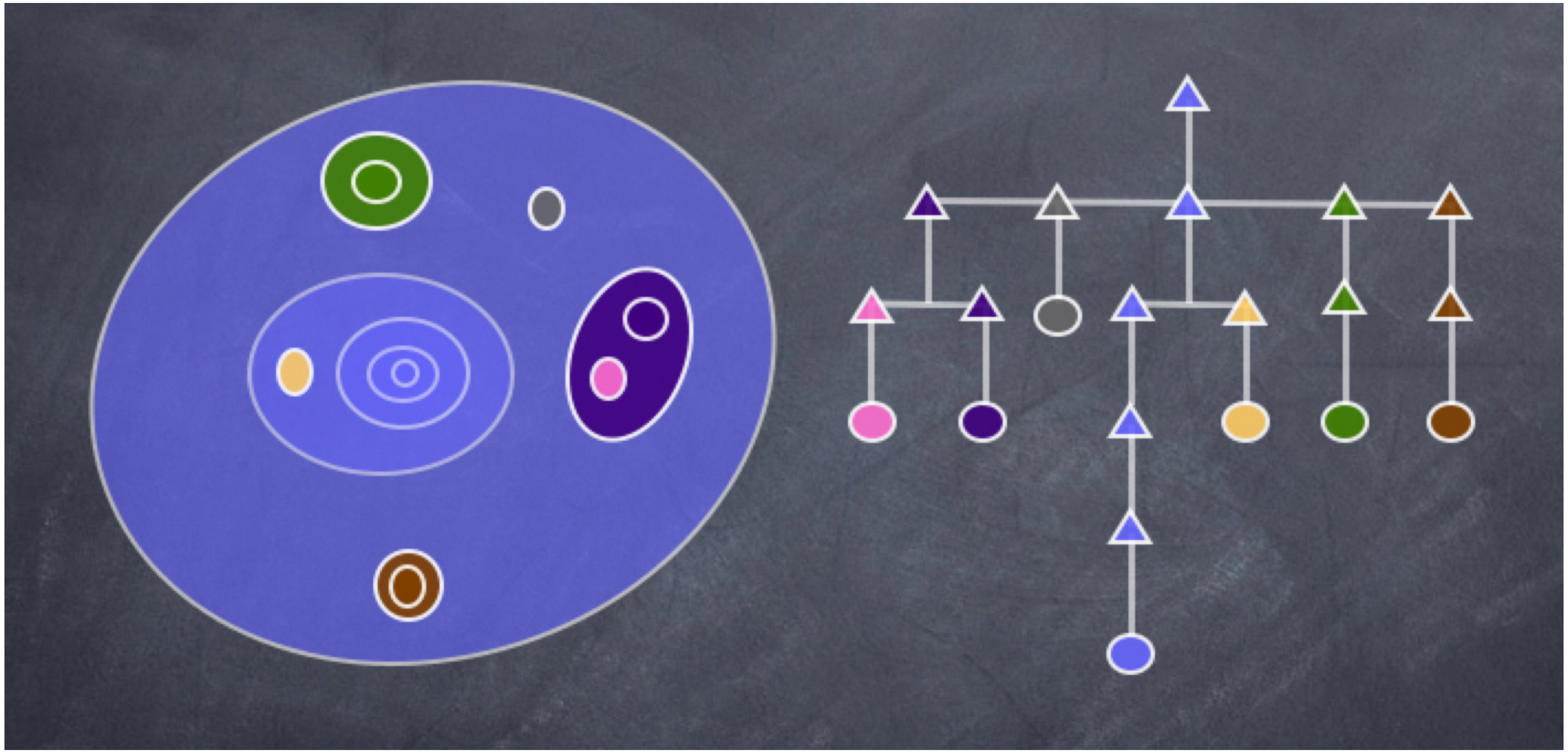
density field of simulated galaxy cluster



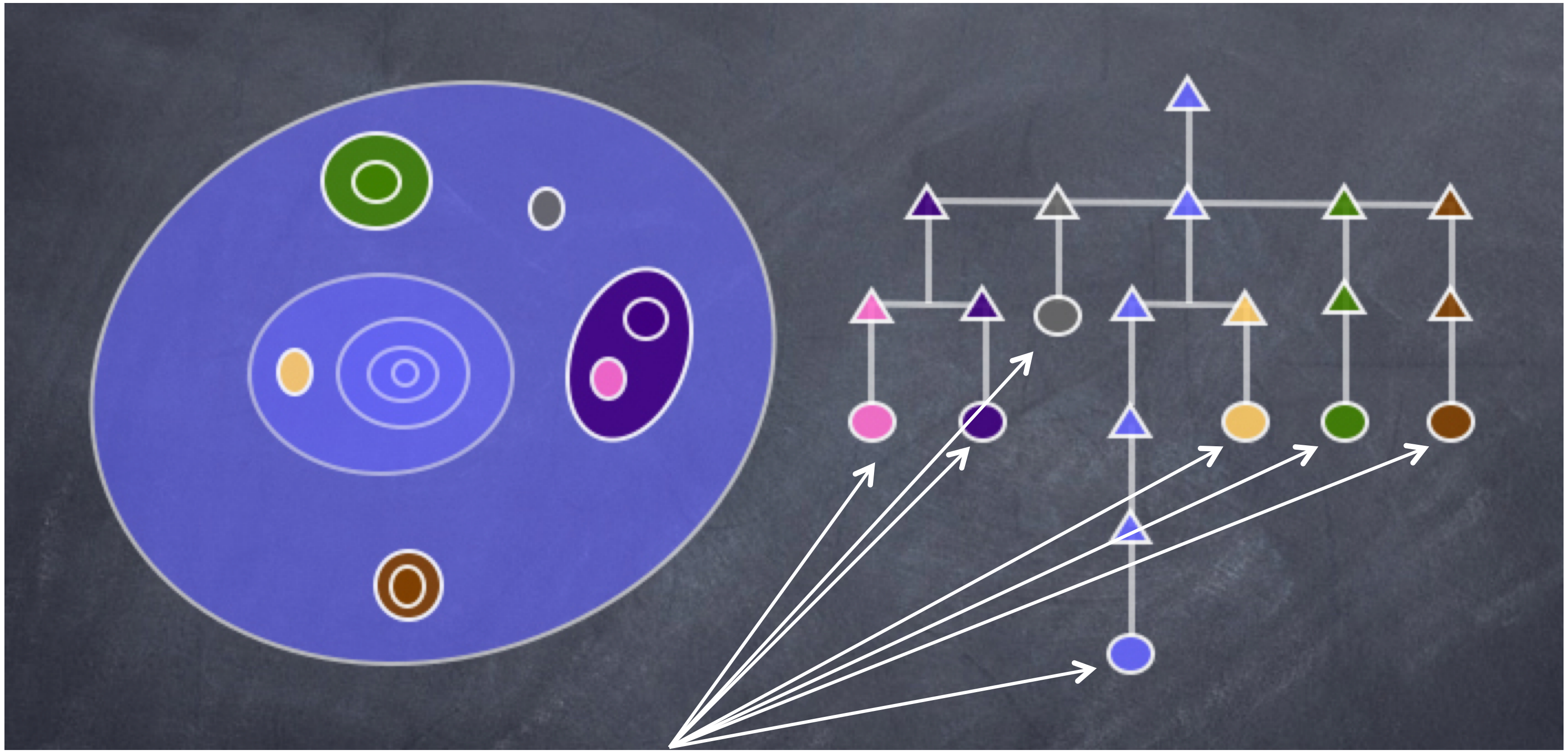
adaptive grid hierarchy

the AMR grids naturally locate centres

- ***AMIGA***'s ***H**alo **F**inder* – organize AMR hierarchy into tree structure

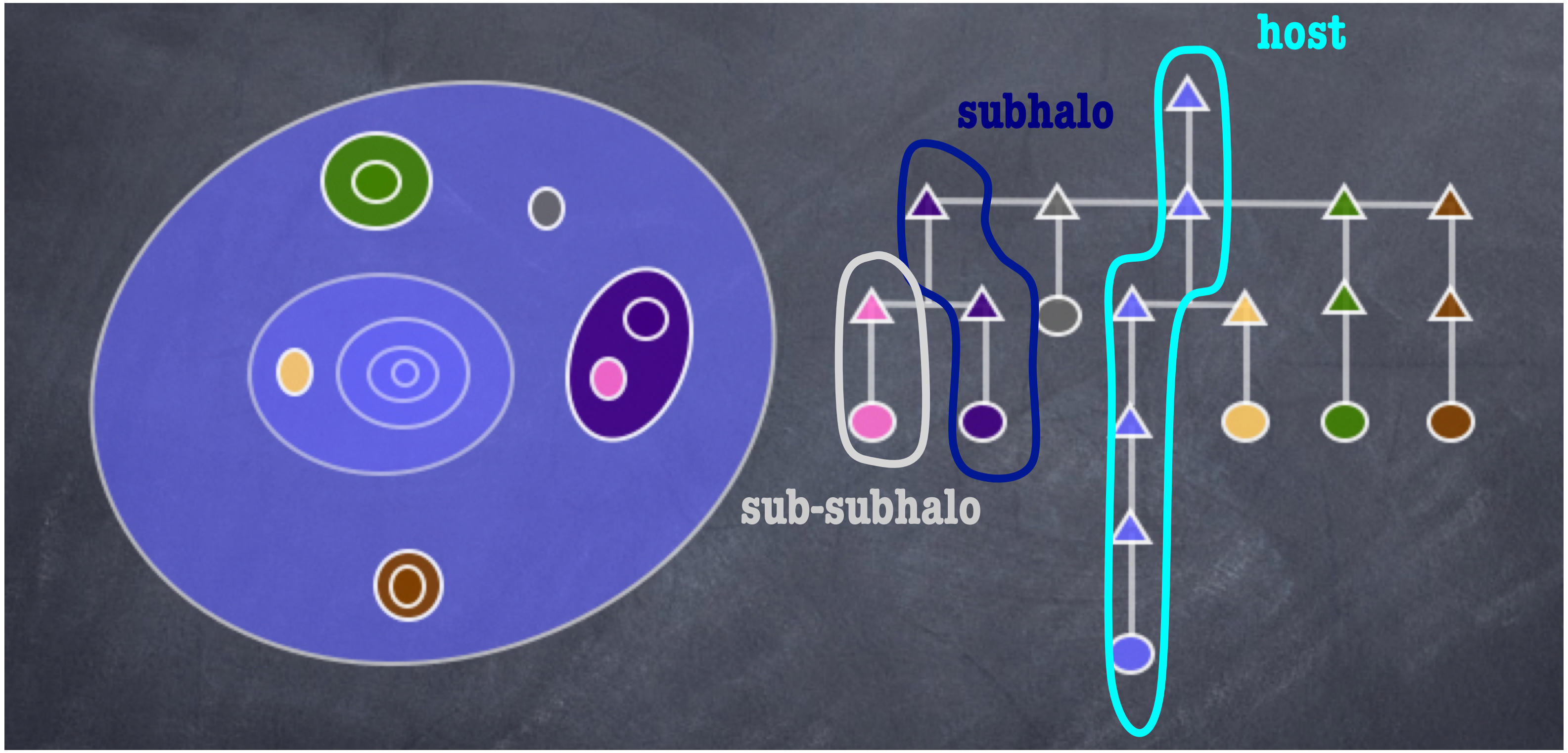


- ***AMIGA***'s ***H***alo ***F***inder – organize AMR hierarchy into tree structure



prospective halo centres...

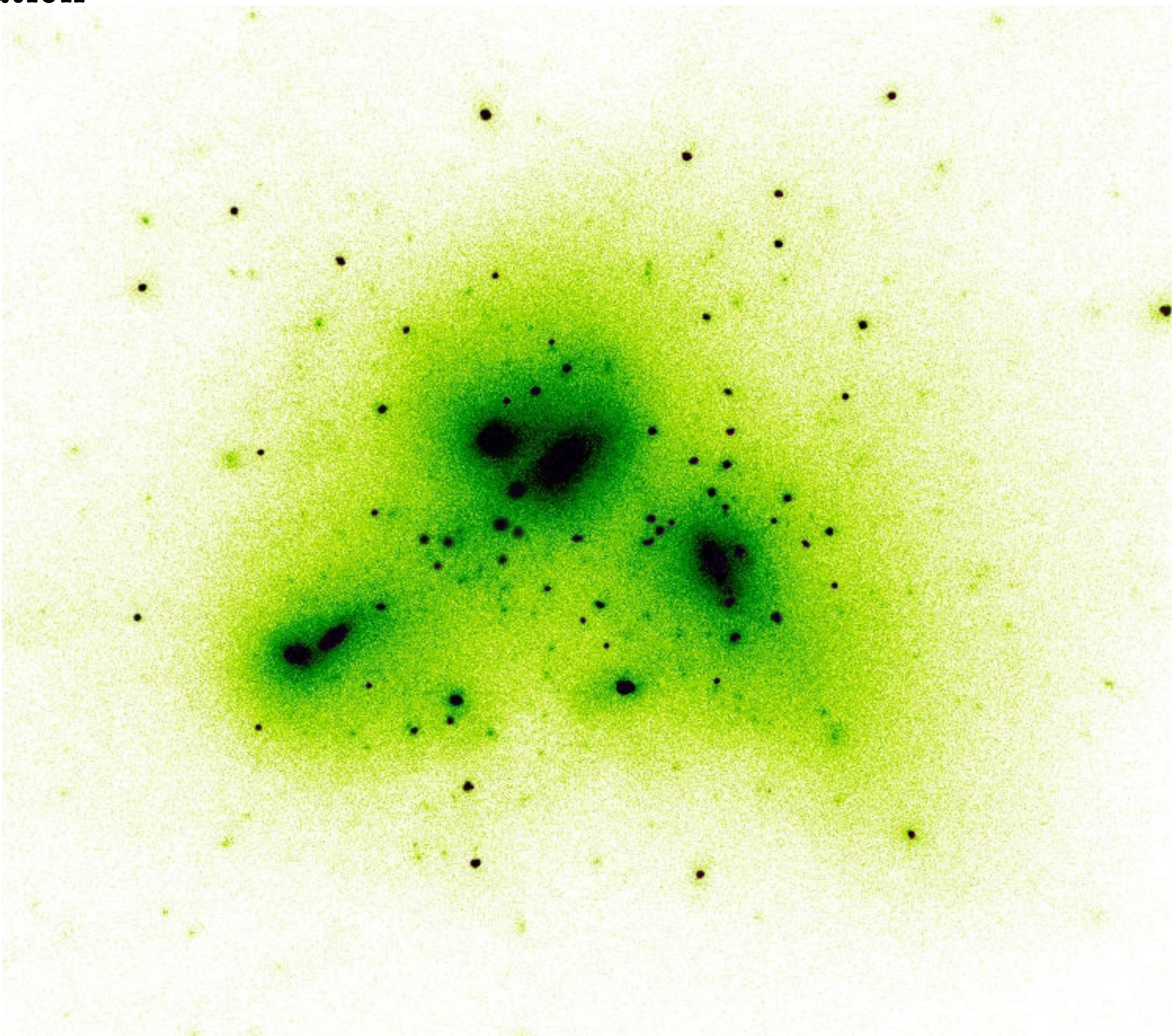
- ***AMIGA***'s ***H***alo ***F***inder – organize AMR hierarchy into tree structure



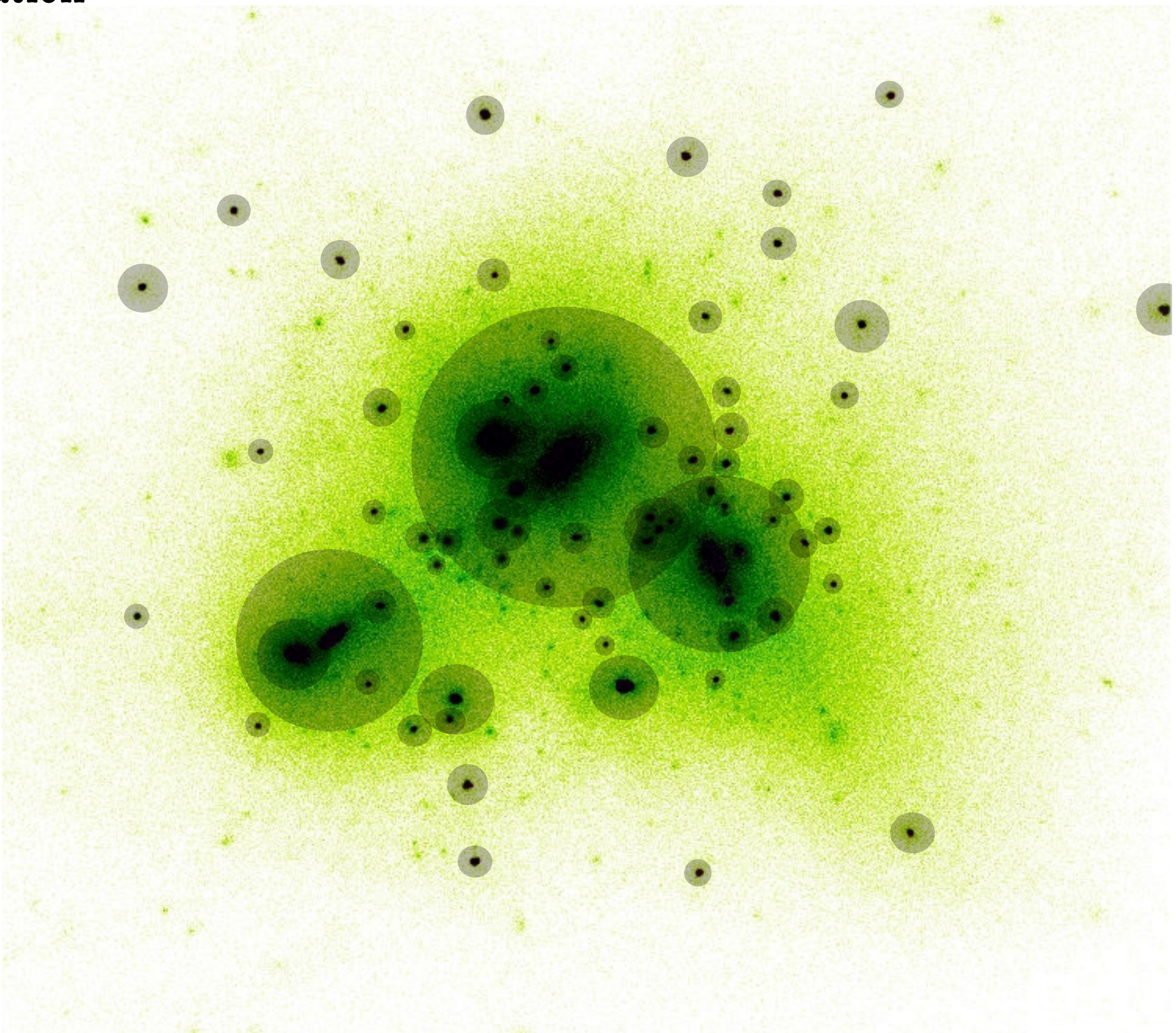
prospective halo centres...

...plus information about hosts, subhalos, sub-subhalos, etc.

- in operation



- in operation



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  - locate potential halo particles using an adaptive mesh hierarchy
  - **iteratively remove gravitationally unbound particles**
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- mode of operation
  - iteratively remove gravitationally unbound particles

$$\Delta\varphi = 4\pi G\rho$$

  - assume spherical symmetry, i.e. $\rho = \rho(r)$

- mode of operation
  - iteratively remove gravitationally unbound particles

$$\Delta\varphi = 4\pi G\rho$$

  - assume spherical symmetry, i.e. $\rho = \rho(r)$

first integration...

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\varphi}{dr}\right) = 4\pi G\rho$$

$$\psi = r^2\frac{d\varphi}{dr}$$

$$\frac{1}{r^2}\frac{d}{dr}(\psi) = 4\pi G\rho$$

$$\frac{d\psi}{dr} = 4\pi G\rho r^2$$

$$\psi(r) - \psi(0) = 4\pi G\int_0^r \rho r'^2 dr'$$

$$\psi(0) = \left[r^2\frac{d\varphi}{dr}\right]_{r=0} = 0$$

$$\psi(r) = GM(<r)$$

- mode of operation
  - iteratively remove gravitationally unbound particles

$$\frac{d\varphi}{dr} = \frac{GM(<r)}{r^2}$$ (Newton's force law)

- mode of operation

  - iteratively remove gravitationally unbound particles

$$\frac{d\varphi}{dr} = \frac{GM(<r)}{r^2}$$ (Newton's force law)

second integration...

$$\varphi(r) = G\int_0^r \frac{M(<r')}{r'^2}\,dr' + \varphi(0)$$

unbound particles...

$$v > v_{\text{esc}} = \sqrt{2|\varphi|}$$

- mode of operation

  - iteratively remove gravitationally unbound particles

$$\varphi(r) = G\int_0^r \frac{M(<r')}{r'^2}\,dr' + \varphi(0)$$

  - potential normalisation $\varphi(0)$?

- mode of operation

  - iteratively remove gravitationally unbound particles

$$\varphi(r) = G\int_0^r \frac{M(<r')}{r'^2}\,dr' + \varphi(0)$$

  - potential normalisation $\varphi(0)$

$$\begin{aligned}
\varphi(\infty) &= G\int_0^\infty \frac{M(<r')}{r'^2}\,dr' + \varphi(0) \\
&= G\int_0^{R_{vir}} \frac{M(<r')}{r'^2}\,dr' + G\int_{R_{vir}}^\infty \frac{M(<r')}{r'^2}\,dr' + \varphi(0) \\
&= G\int_0^{R_{vir}} \frac{M(<r')}{r'^2}\,dr' + GM_{vir}\int_{R_{vir}}^\infty \frac{1}{r'^2}\,dr' + \varphi(0) \\
&= G\int_0^{R_{vir}} \frac{M(<r')}{r'^2}\,dr' + GM_{vir}\left[-\frac{1}{r}\right]_{R_{vir}}^\infty + \varphi(0) \\
&= G\int_0^{R_{vir}} \frac{M(<r')}{r'^2}\,dr' + G\frac{M_{vir}}{R_{vir}} + \varphi(0)
\end{aligned}$$

$\xrightarrow{\varphi(\infty)=0}$

- mode of operation
  - iteratively remove gravitationally unbound particles

$$\varphi(r) = G\int_0^r \frac{M(<r')}{r'^2}\,dr' - \varphi_0$$

with: $$\varphi_0 = G\left(\frac{M_{vir}}{R_{vir}} + \int_0^{R_{vir}} \frac{M(<r')}{r'^2}\,dr'\right)$$

the integrals can be readily evaluated in cosmological simulations…

- mode of operation

  - iterately remove gravitationally unbound particles

$$\varphi(r) = G\int_0^r \frac{M(<r')}{r'^2}\,dr' - \varphi_0$$

  - order particles with respect to distance:

$$\int_0^r \frac{M(<r')}{r'^2}\,dr' = \int_0^{r_1} \frac{M(<r)}{r^2}\,dr + \int_{r_1}^{r_2} \frac{M(<r)}{r^2}\,dr + \ldots + \int_{r_{N-1}}^{r_N} \frac{M(<r)}{r^2}\,dr$$

$$= \frac{m_1}{r_1^2} r_1 + \frac{m_1+m_2}{r_2^2}\left|r_2 - r_1\right| + \frac{m_1+m_2+m_3}{r_3^2}\left|r_3 - r_2\right| + \ldots$$

- mode of operation

  - iteratively remove gravitationally unbound particles - ***in practice***

    1. guess initial set of particles and determine $M_{\rm vir}$ and $R_{\rm vir}$

    2. calculate φ_0 via...

$$\varphi_0 = G\left(\frac{M_{vir}}{R_{vir}} + \int_0^{R_{vir}} \frac{M(<r')}{r'^2}\, dr'\right)$$

...using ordered particles:

$$\int_0^{r_i} \frac{M(<r)}{r^2}\, dr = \frac{m_1}{r_1^2} r_1 + \frac{m_1 + m_2}{r_2^2}\left|r_2 - r_1\right| + \frac{m_1 + m_2 + m_3}{r_3^2}\left|r_3 - r_2\right| + \ldots + \frac{\sum_{j=1}^{i} m_j}{r_i^2}\left|r_i - r_{i-1}\right|$$

- mode of operation
  - iteratively remove gravitationally unbound particles - ***in practice***

3. while looping over all particles (again!) compare

$$v_i > v_{\text{esc}}(r_i) = \sqrt{2|\varphi(r_i)|}$$

4. calculating $\varphi(r_i)$ via...

$$\varphi(r_i) = G\int_0^{r_i} \frac{M(<r)}{r^2}\,dr - \varphi_0$$

...using ordered particles:

$$\int_0^{r_i} \frac{M(<r)}{r^2}\,dr = \frac{m_1}{r_1^2} r_1 + \frac{m_1 + m_2}{r_2^2}|r_2 - r_1| + \frac{m_1 + m_2 + m_3}{r_3^2}|r_3 - r_2| + \ldots + \frac{\sum_{j=1}^{i} m_j}{r_i^2}|r_i - r_{i-1}|$$

- mode of operation

  - iteratively remove gravitationally unbound particles - ***in practice***

    5. remove all unbound particles

$$v_i > v_{\text{esc}}(r_i) = \sqrt{2|\varphi(r_i)|}$$

    6. bound particles define a new set of initial particles for M_{vir} and R_{vir}

$\Rightarrow$ start from 2. again and repeat until no further unbound particles...

- The Situation
- The Methods
- **Code Examples:**
    - FOF
    - 6DFOF
    - AHF
    - **BDM**
    - SKID

- Bound-Density-Maxima

use maxima in smoothed density field as prospective halo centres

http://charon.nmsu.edu/~aklypin/PM/pmcode/pmcode.html

- Bound-Density-Maxima

use maxima in smoothed density field as prospective halo centres

=> nearly identical to ***AHF*** * ...

... major difference lies in determination of prospective centres

(and the removal of unbound particles)

http://charon.nmsu.edu/~aklypin/PM/pmcode/pmcode.html

* ***AHF*** can be understood as offspring of BDM

- mode of operation
  - locate potential halo centres via “sphere jittering”
  - iteratively remove gravitationally unbound particles
  - calculate integral properties of remaining objects
  - calculate radial profiles of (some) properties

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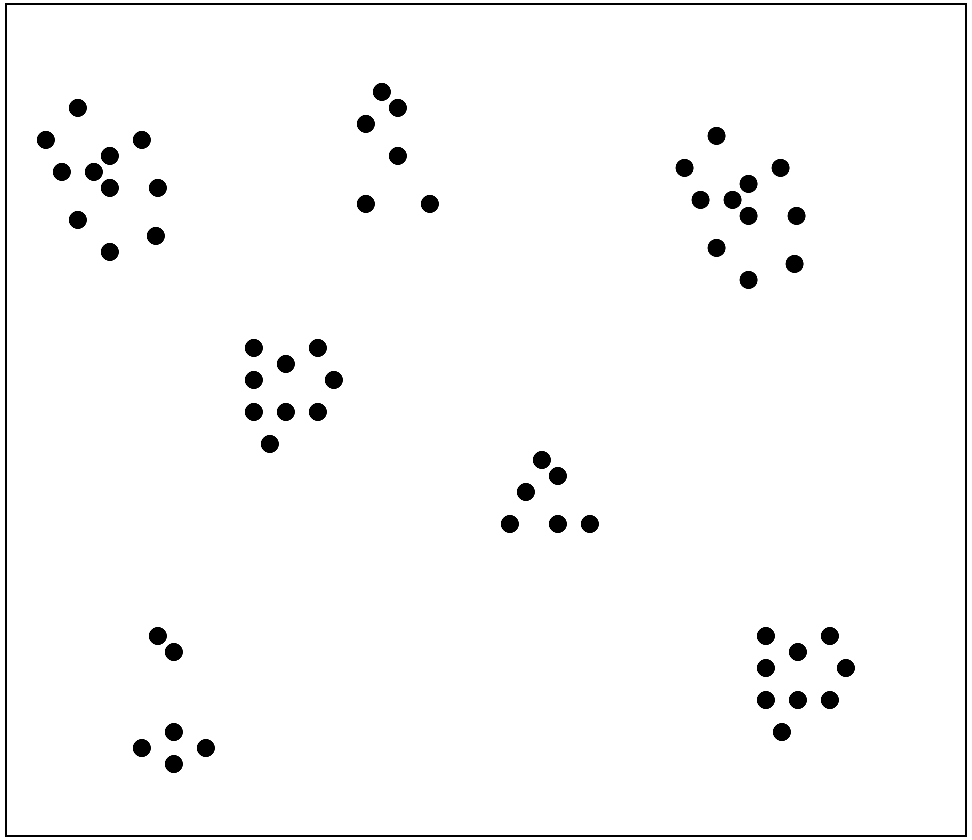

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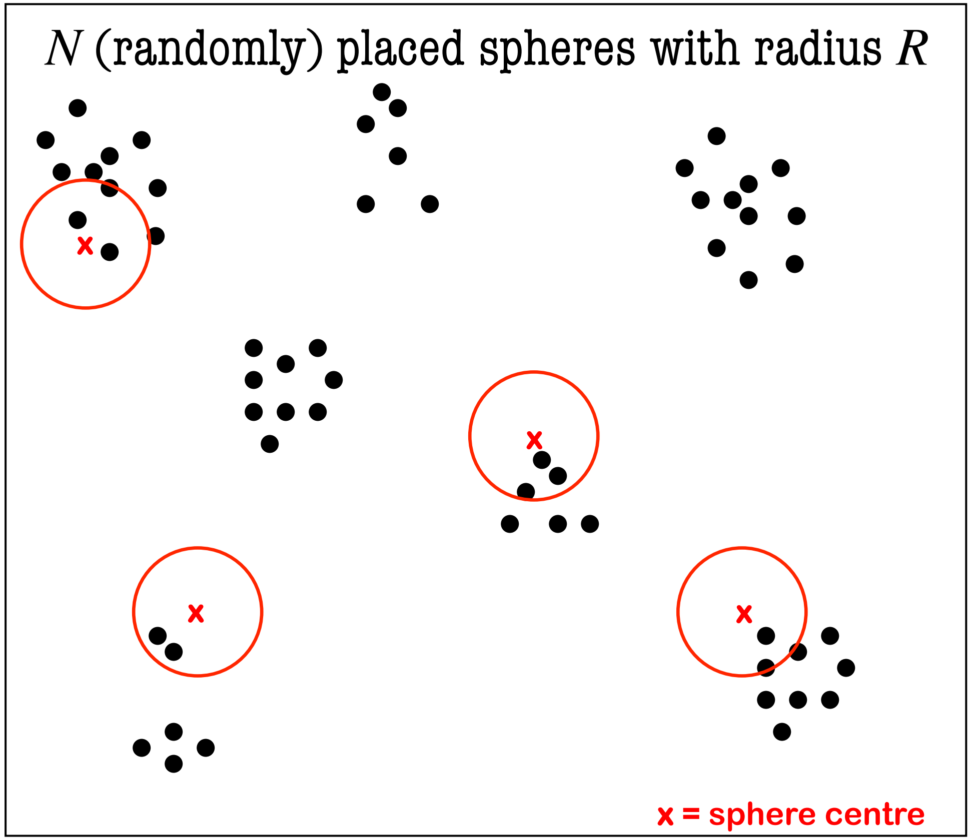

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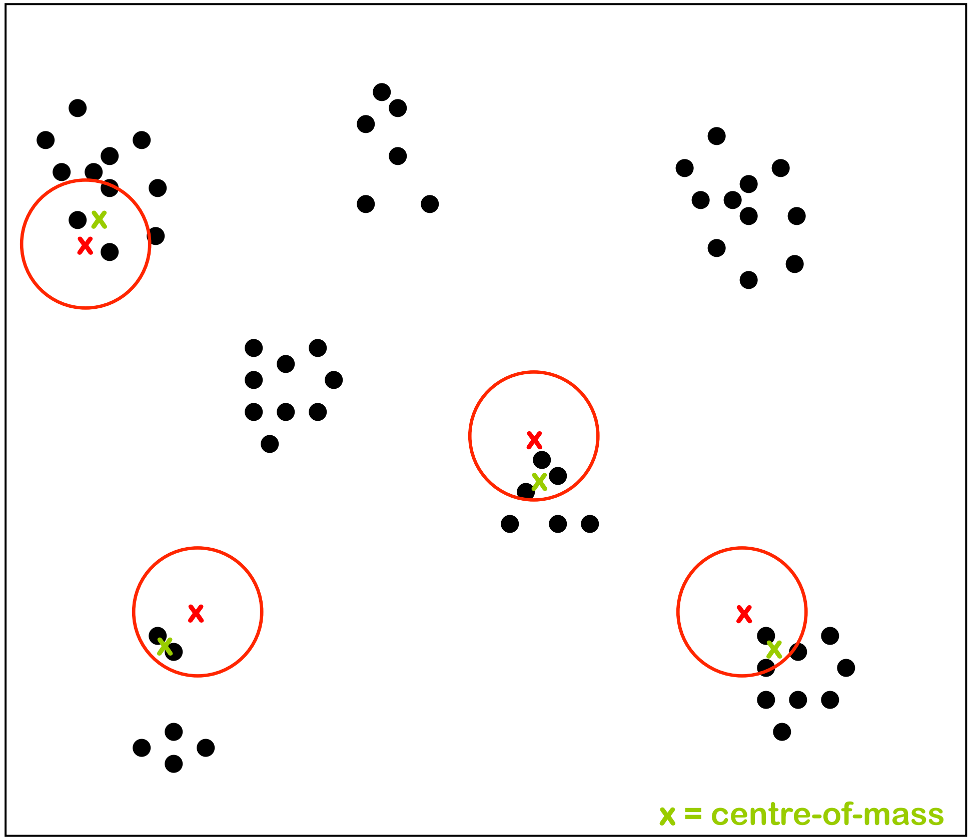

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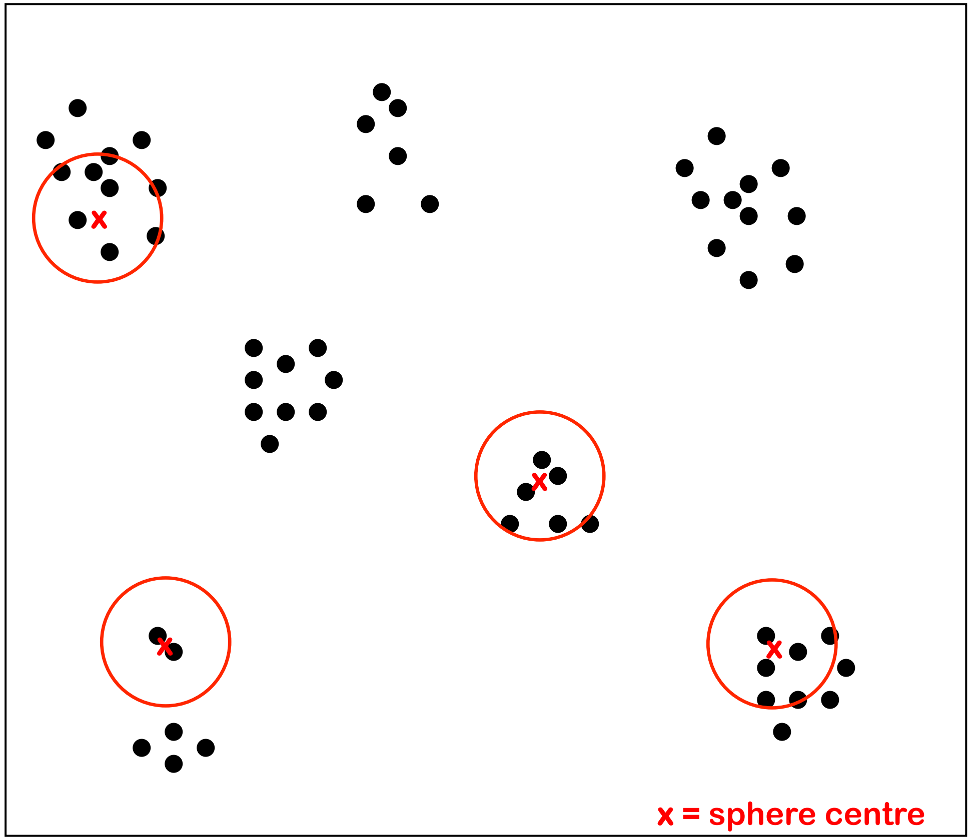

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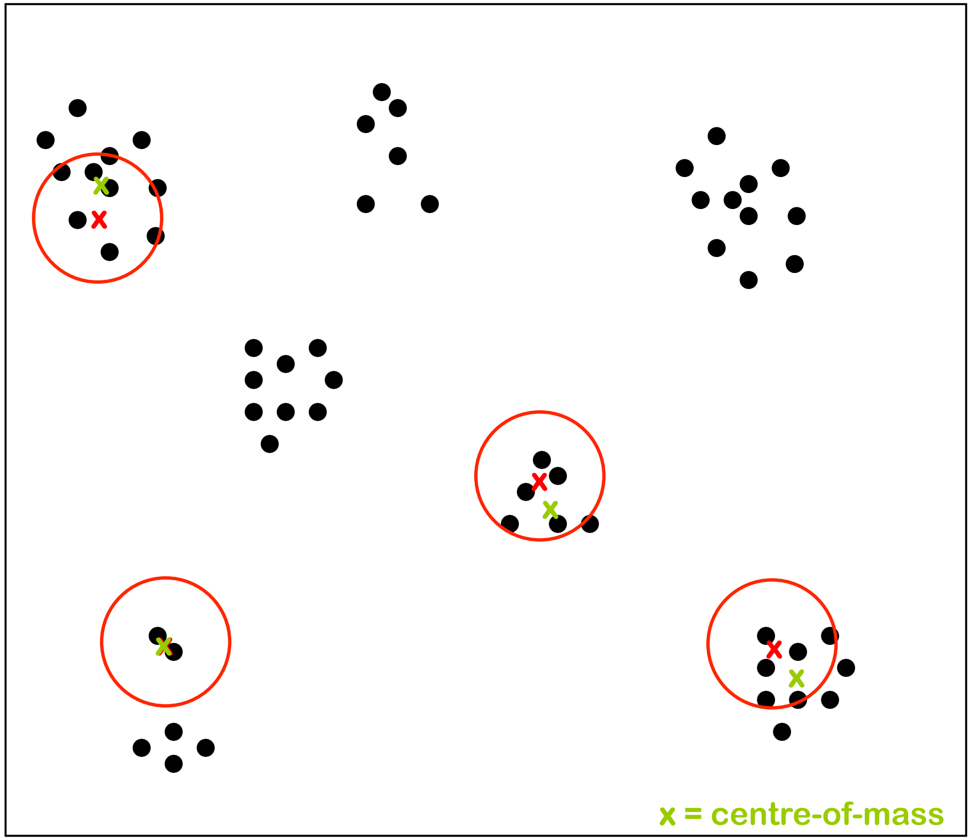

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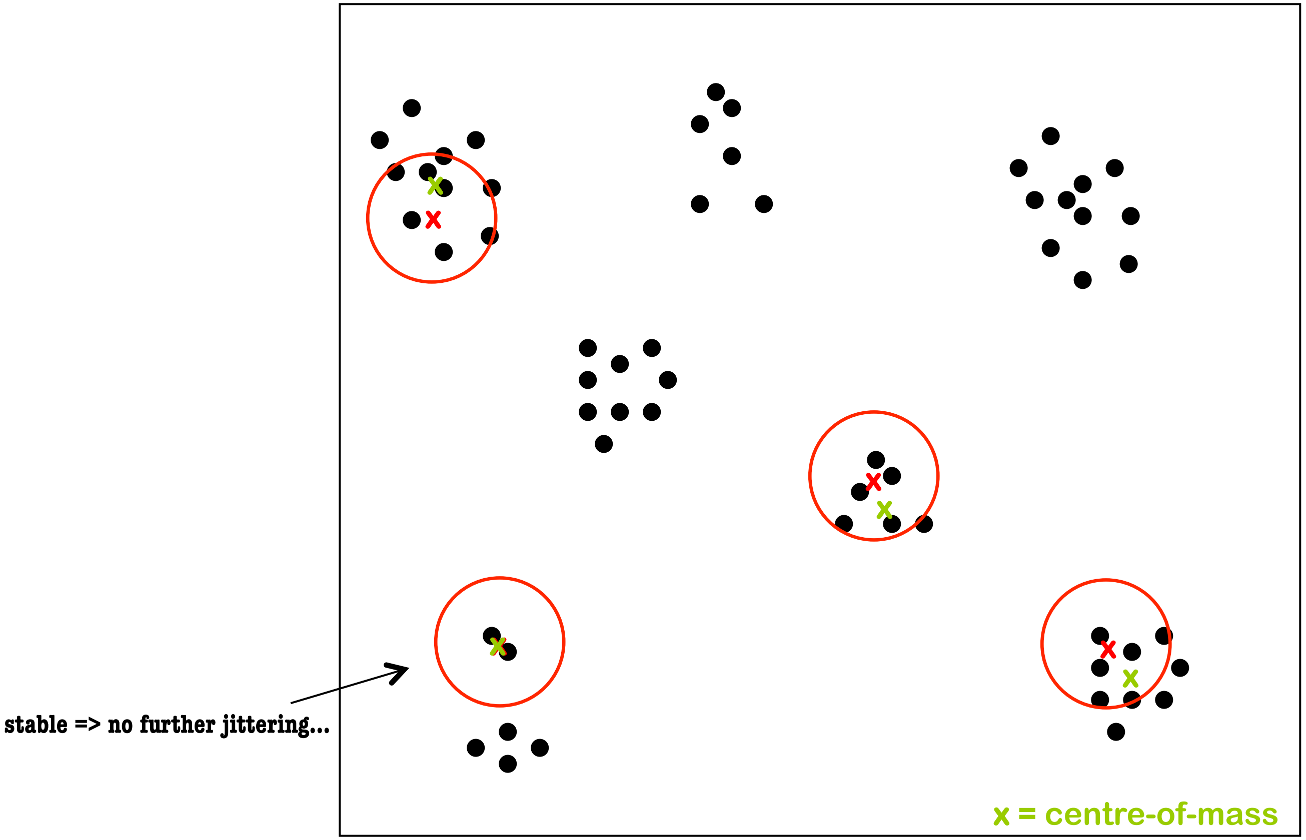

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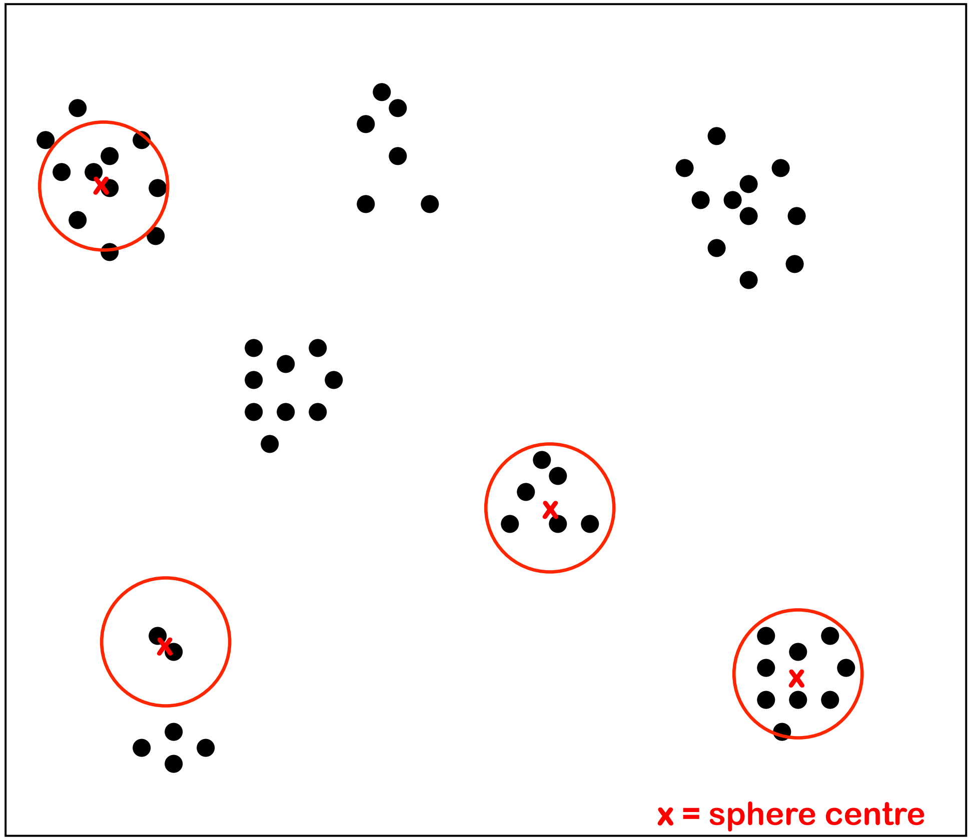

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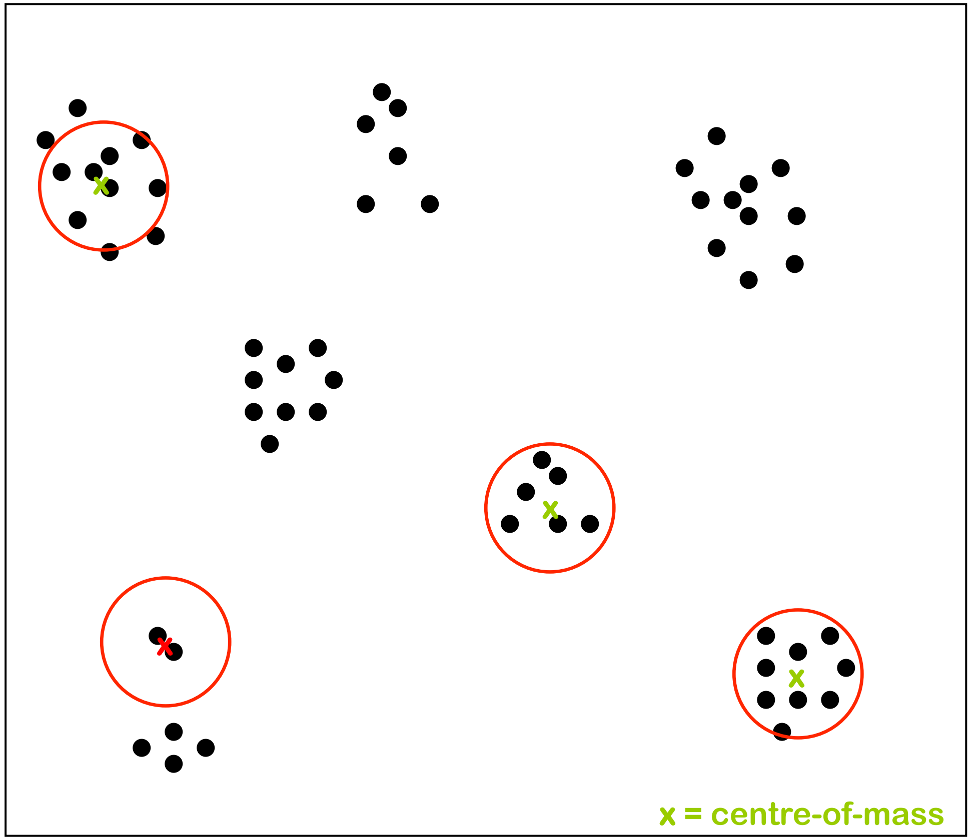

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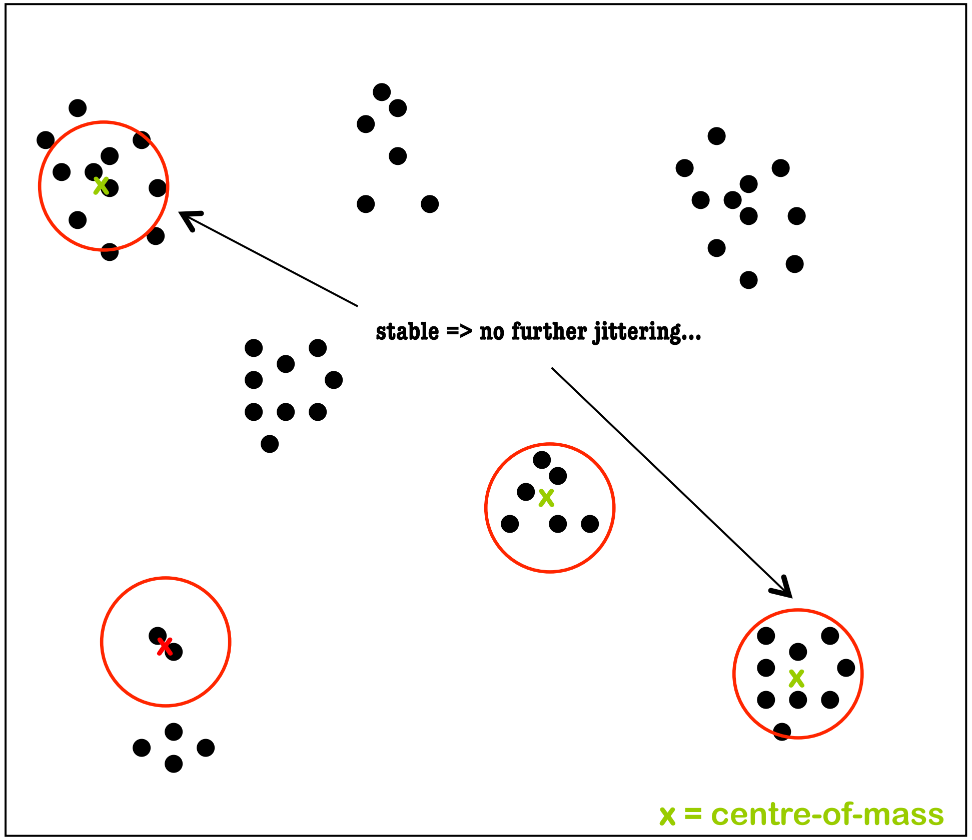

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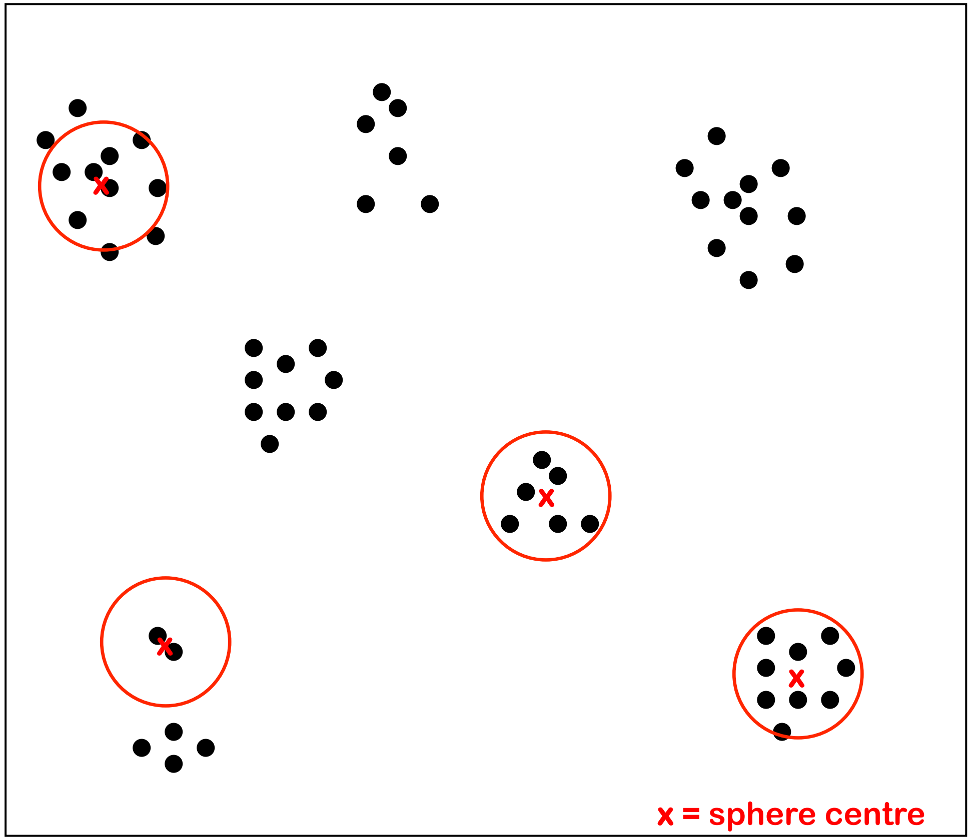

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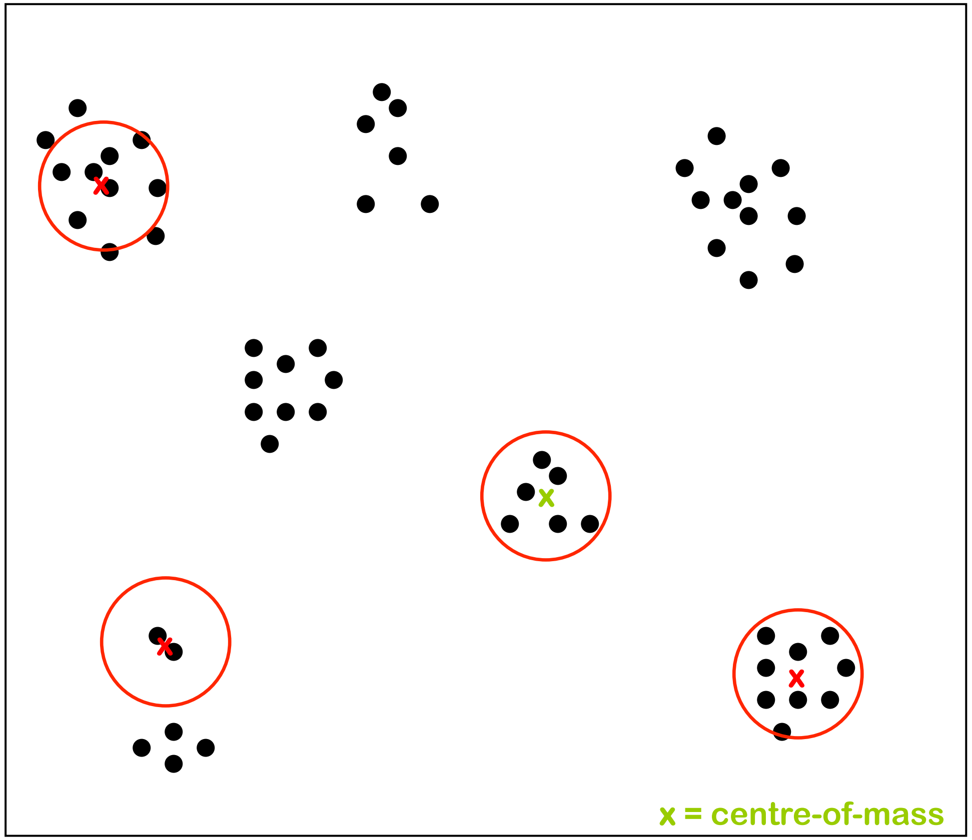

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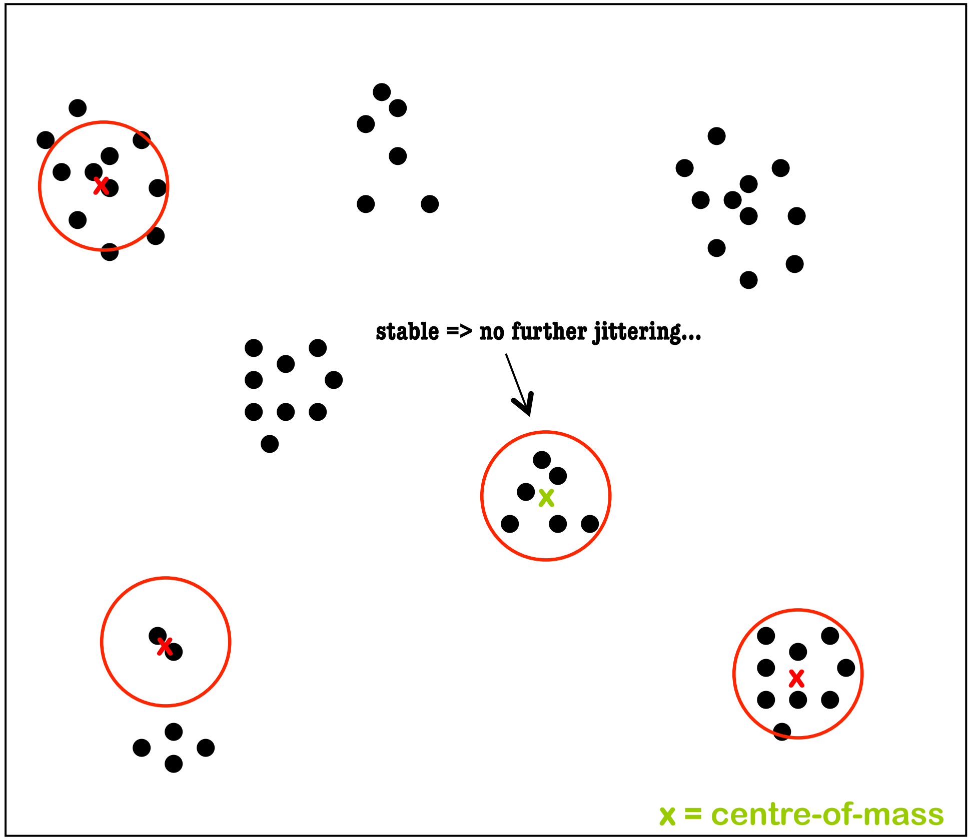


- mode of operation
  - locate potential halo centres via "sphere jittering"

<u>problems/parameter</u>:

– choice of initial sphere radius

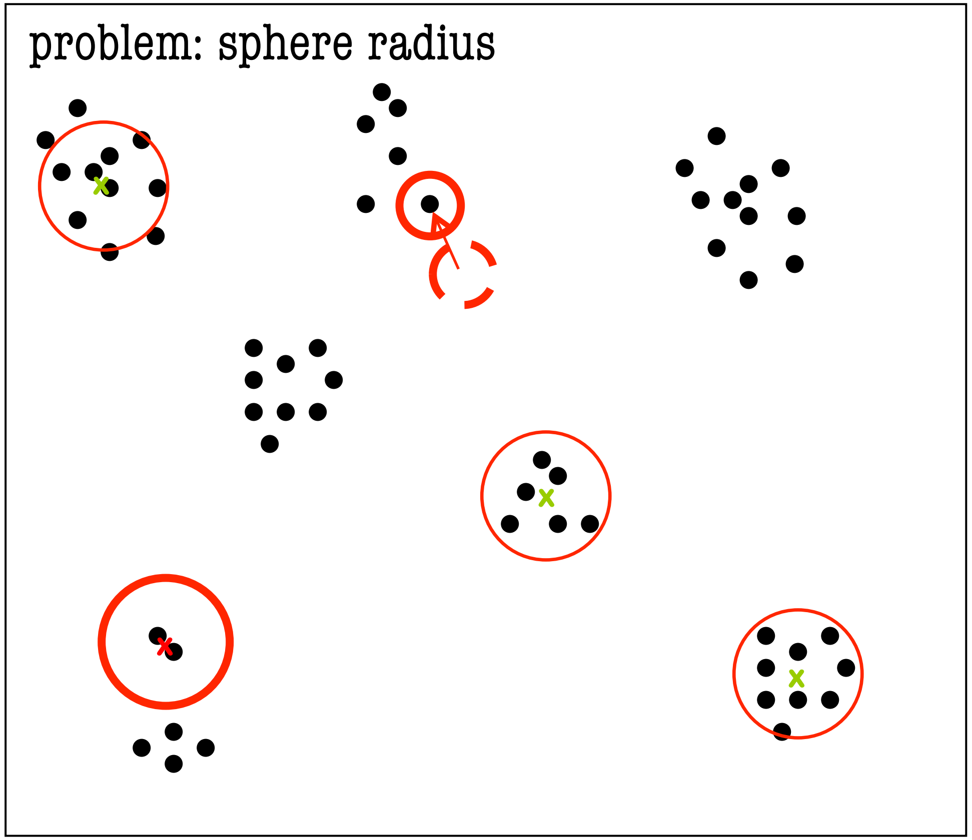
$\longrightarrow$smoothing scale

– number of spheres

$\longrightarrow$duplicates and/or missed objects

- mode of operation

  - locate potential halo centres via “sphere jittering”



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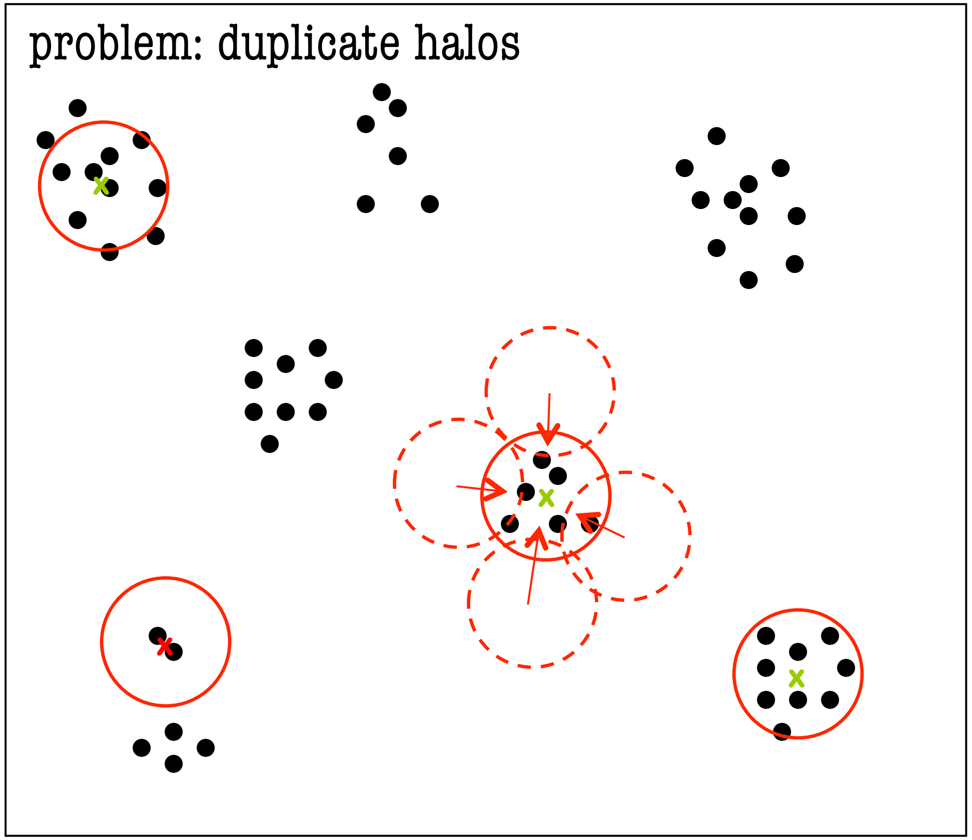

- mode of operation
  - iteratively remove gravitationally unbound particles

    1. gather all particles about centre out to pre-set distance
    2. fit analytical NFW function to density profile
    3. determine rotation curve $v_{\rm circ}(r)$ from NFW parameters
    4. remove particles faster than escape velocity $v_{\rm esc} = \sqrt{2}\, v_{\rm circ}$
    5. start at 2. again until no further particles are being removed...

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$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

<=>

$$\left(\frac{v_{circ}(r)}{v_{200}}\right)^2 = \frac{1}{x}\,\frac{\ln(1+cx) - \frac{cx}{1+cx}}{\ln(1+c) - \frac{c}{1+c}}$$

with $c = \frac{r_{200}}{r_s}$; $x = \frac{r}{r_{200}}$; $\frac{M(<r_{200})}{\frac{4\pi}{3} r_{200}^3} = 200 \times \rho_{crit}$; $v_{200}^2 = \frac{GM(<r_{200})}{r_{200}}$

- The Situation
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    - FOF
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    - BDM
    - **SKID**

- SKID

use density gradient to determine halo particles

http://www-hpcc.astro.washington.edu/tools/skid.html

- mode of operation
  - locate potential halo particles by "sliding along density gradients"
  - iteratively remove gravitationally unbound particles
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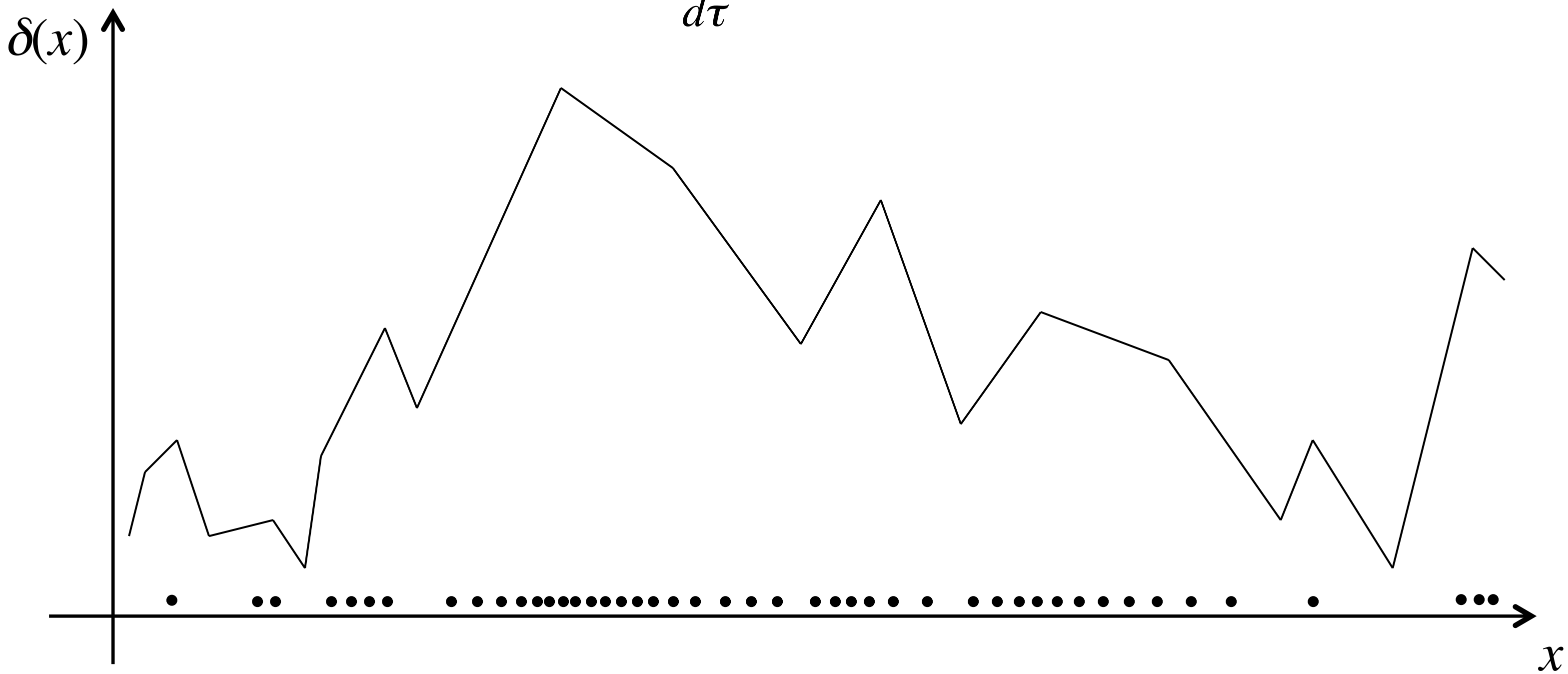
$$\frac{d\vec{x}}{d\tau} = \nabla\delta(\vec{x})$$



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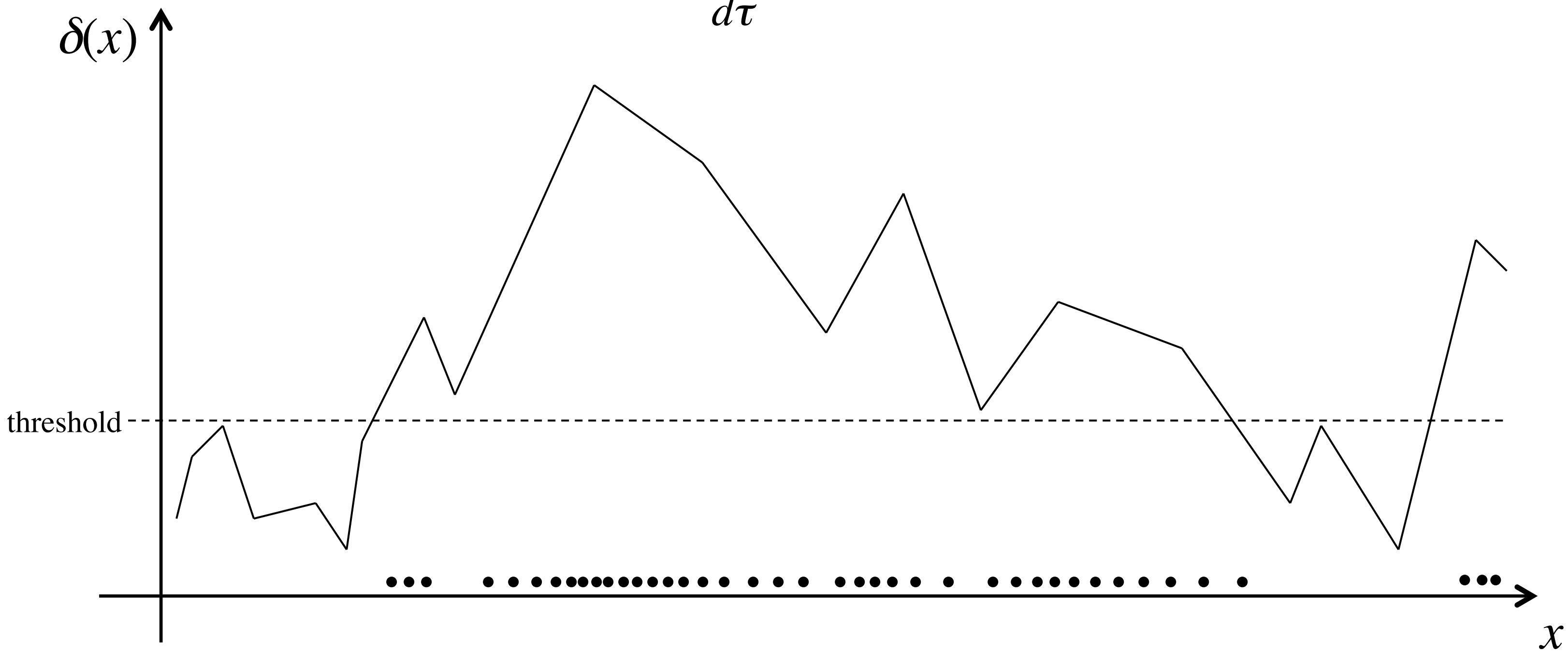

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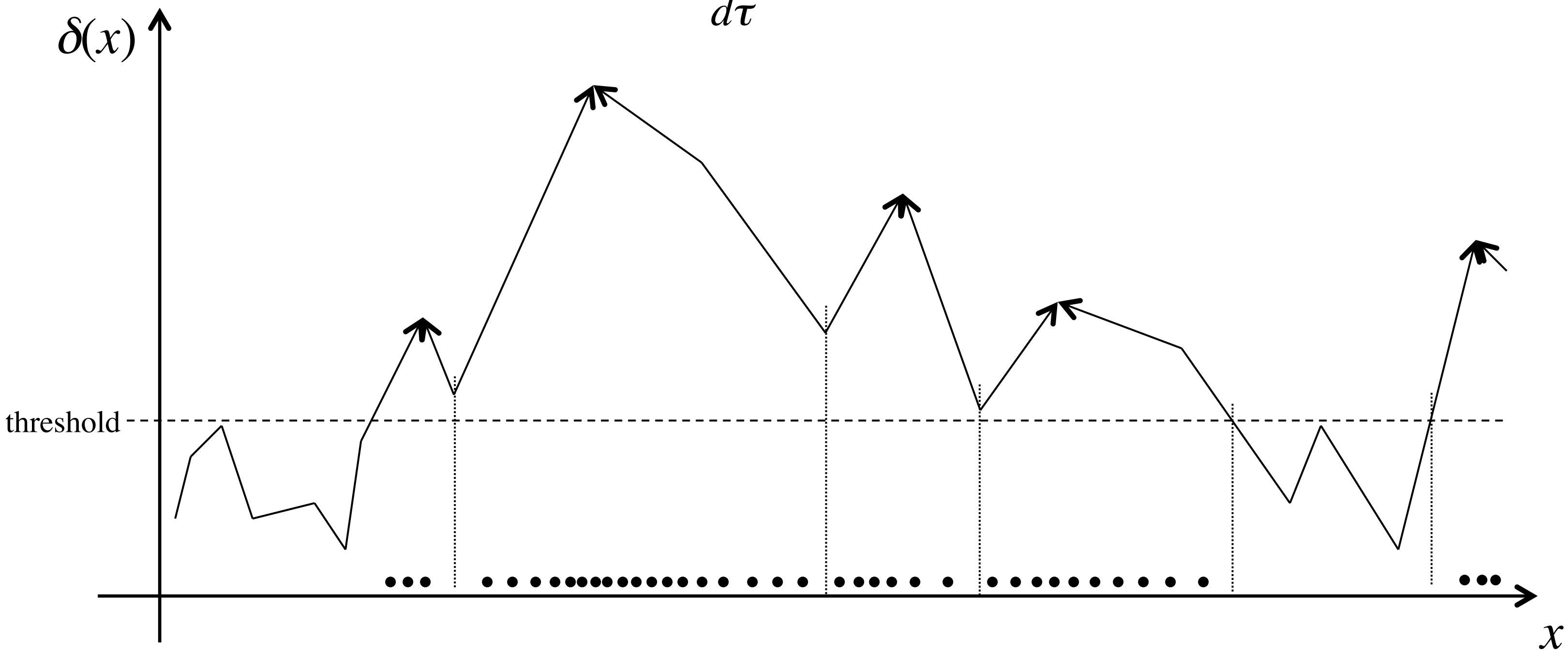

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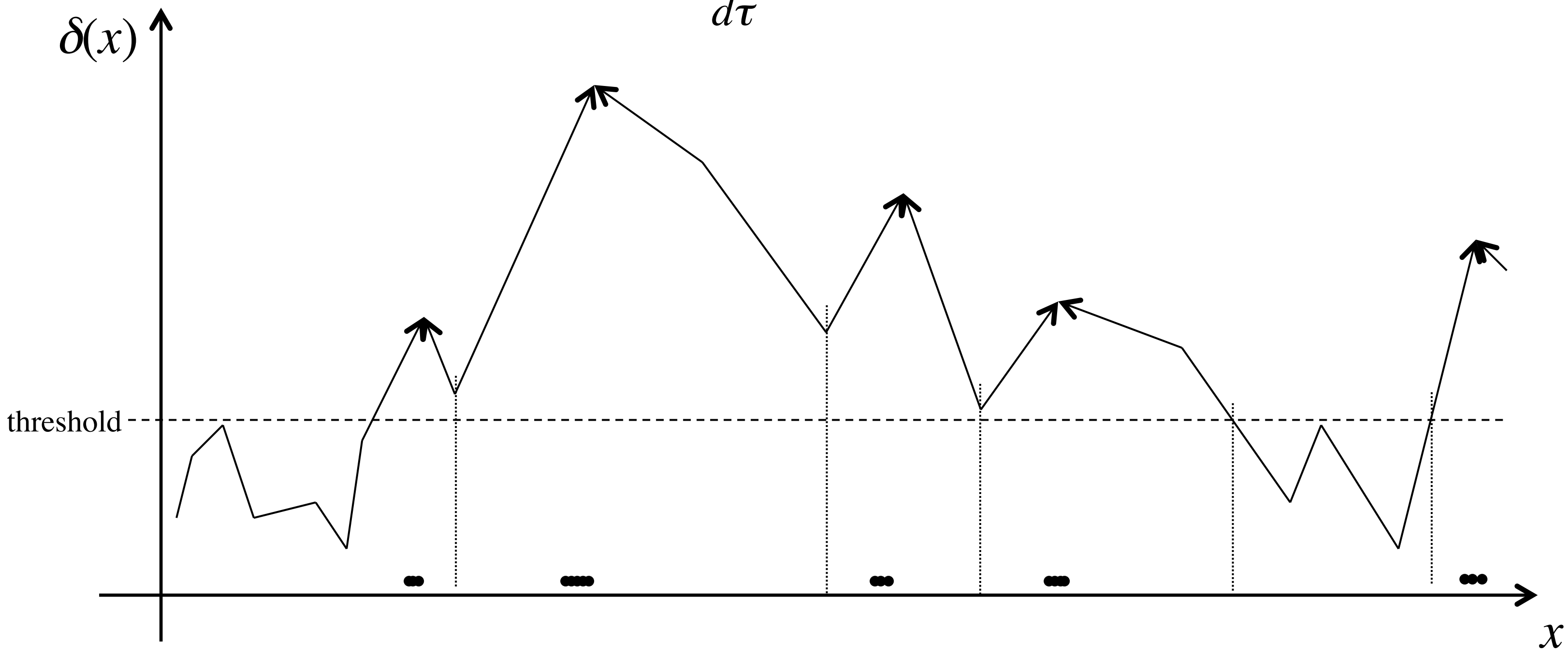

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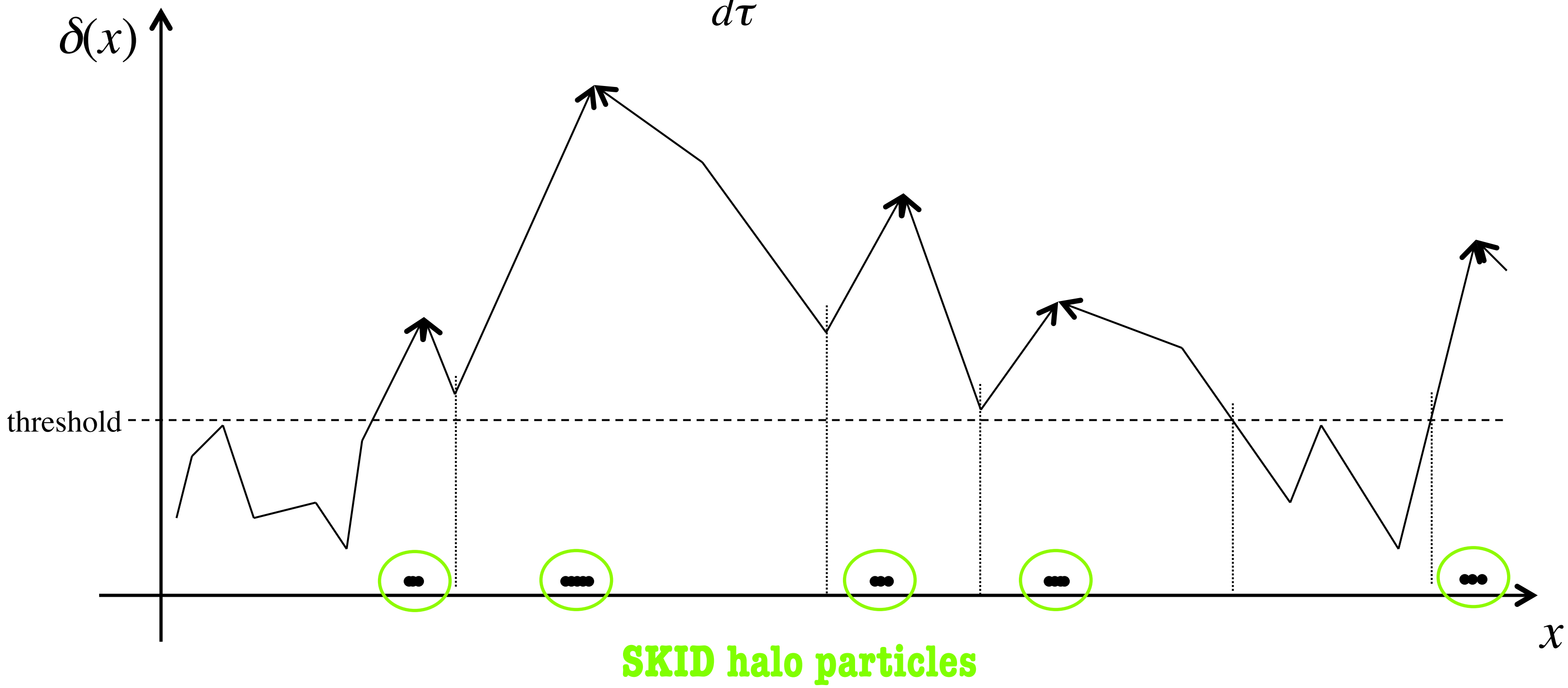

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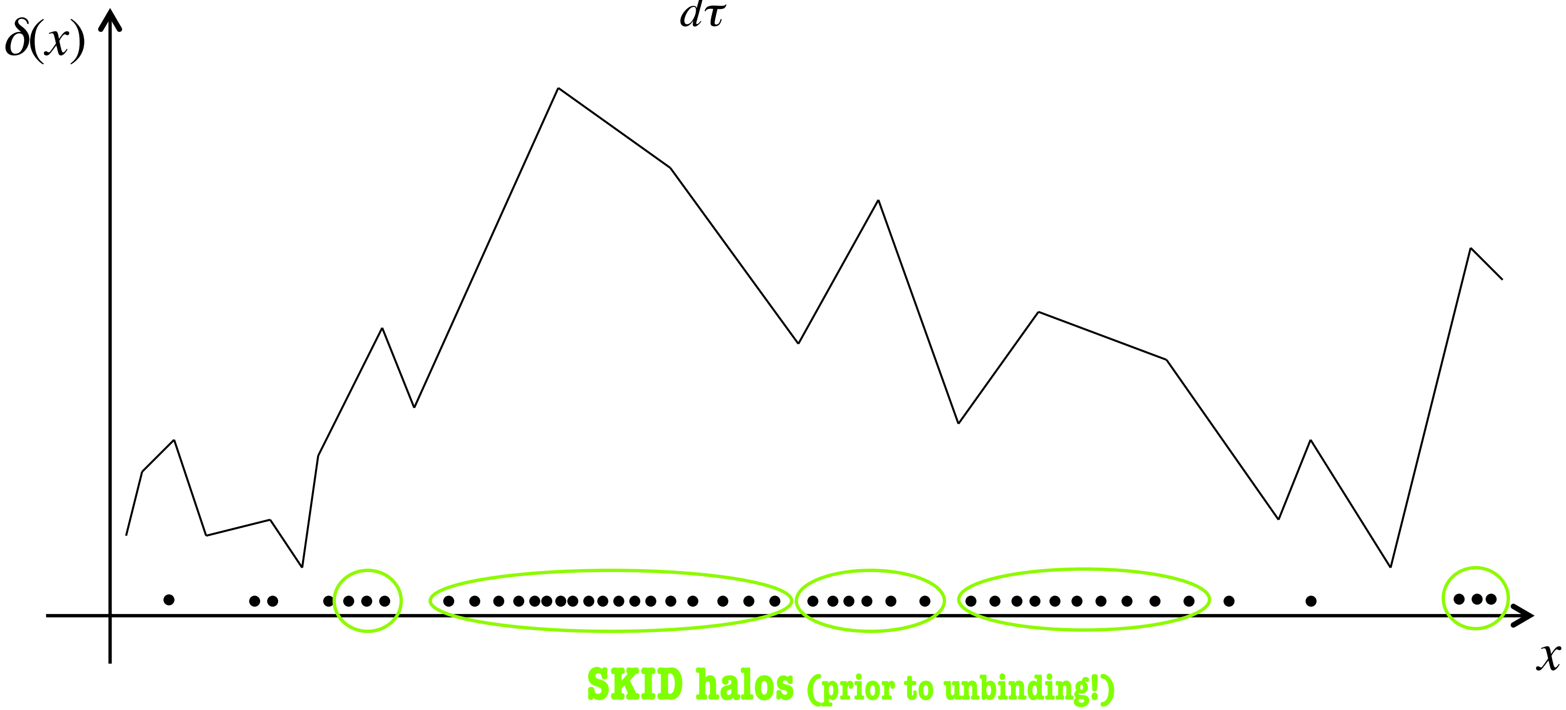

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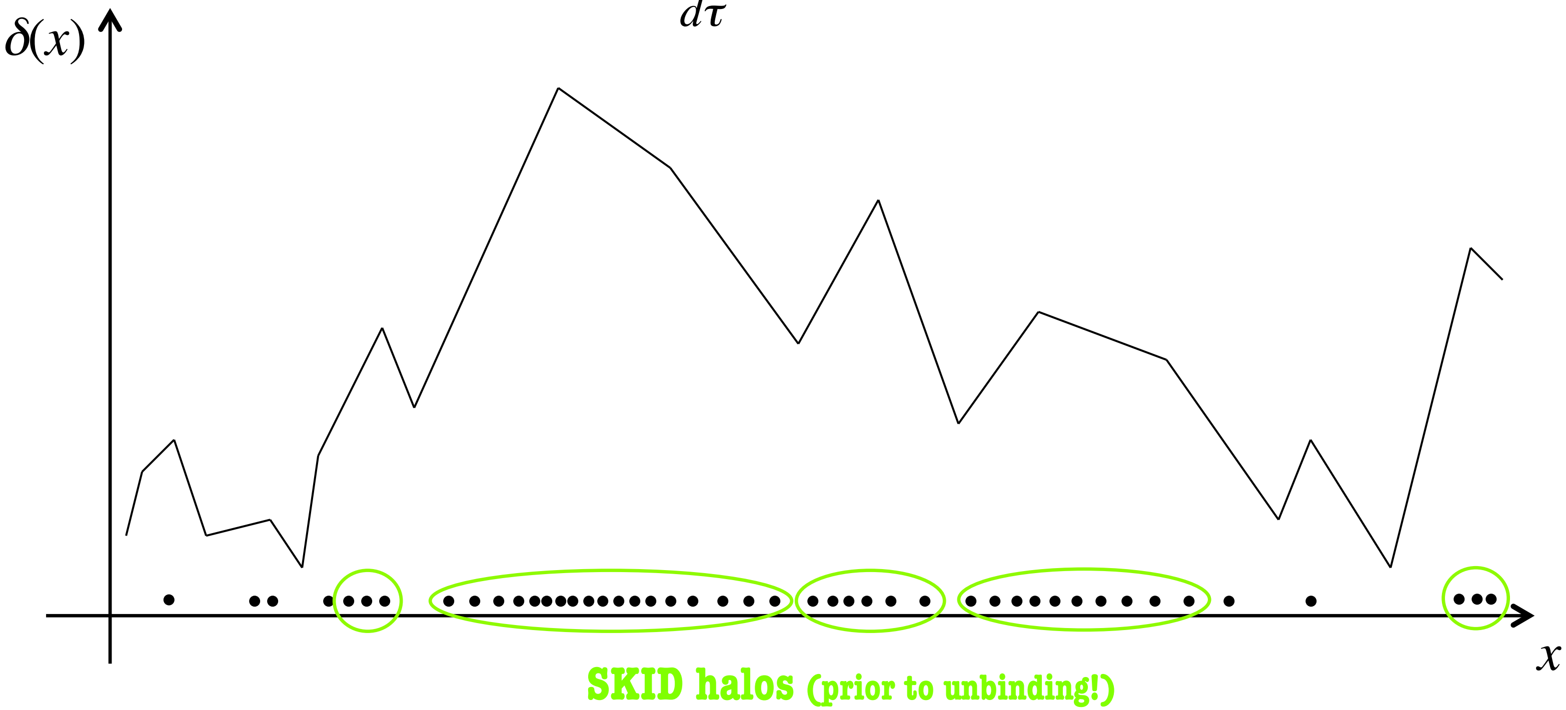

SKID finds halos of arbitrary shape!

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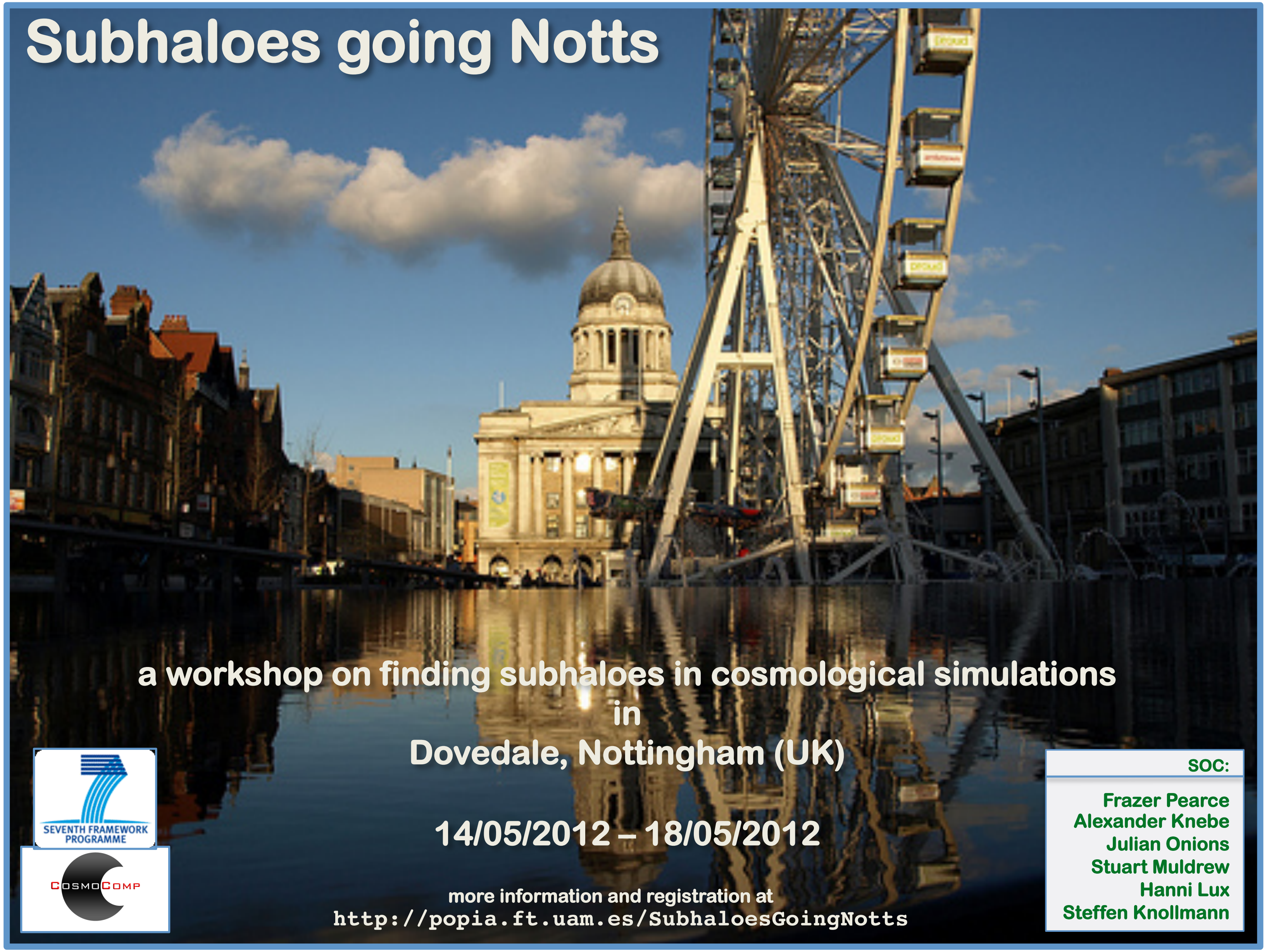
Haloes going MAD
a workshop on finding haloes in cosmological simulations
at
La Cristalera de la Universidad Autonoma de Madrid
ASTROSIM
European Network for Computational Astrophysics
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE
Madrid, 24/05/2010 – 28/05/2010
more information and registration at
http://popia.ft.uam.es/HaloesGoingMAD
SOC:
Alexander Knebe
Steffen Knollmann
Gustavo Yepes
Justin Read


Subhaloes going Notts
a workshop on finding subhaloes in cosmological simulations
in
Dovedale, Nottingham (UK)
14/05/2012 – 18/05/2012
more information and registration at
http://popia.ft.uam.es/SubhaloesGoingNotts
SEVENTH FRAMEWORK PROGRAMME
CosmoComp
SOC:
Frazer Pearce
Alexander Knebe
Julian Onions
Stuart Muldrew
Hanni Lux
Steffen Knollmann

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[16] *Vanderbilt University, Department of Physics & Astronomy, 6301 Stevenson Center, Nashville, TN 37235, USA*
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[18] *Institute of Cosmology and Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth, PO1 3FX, UK*
[19] *Departament d'Astronomia i Astrofísica, Universitat de València, 46100 - Burjassot (Valencia), Spain*
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[21] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801-3080, USA*
[22] *National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
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[24] *Zentrum für Astronomie der Universität Heidelberg, ARI, Mönchhofstr. 12-14, 69120 Heidelberg, Germany*
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[26] *Kavli Institute for Astronomy and Astrophysics, Peking University, Yi He Yuan Lu 5, Hai Dian Qu, Beijing 100871, P. R. China*
[27] *UPMC Univ Paris 06, UMR7095, Institut d'Astrophysique de Paris, F-75014, Paris, France*
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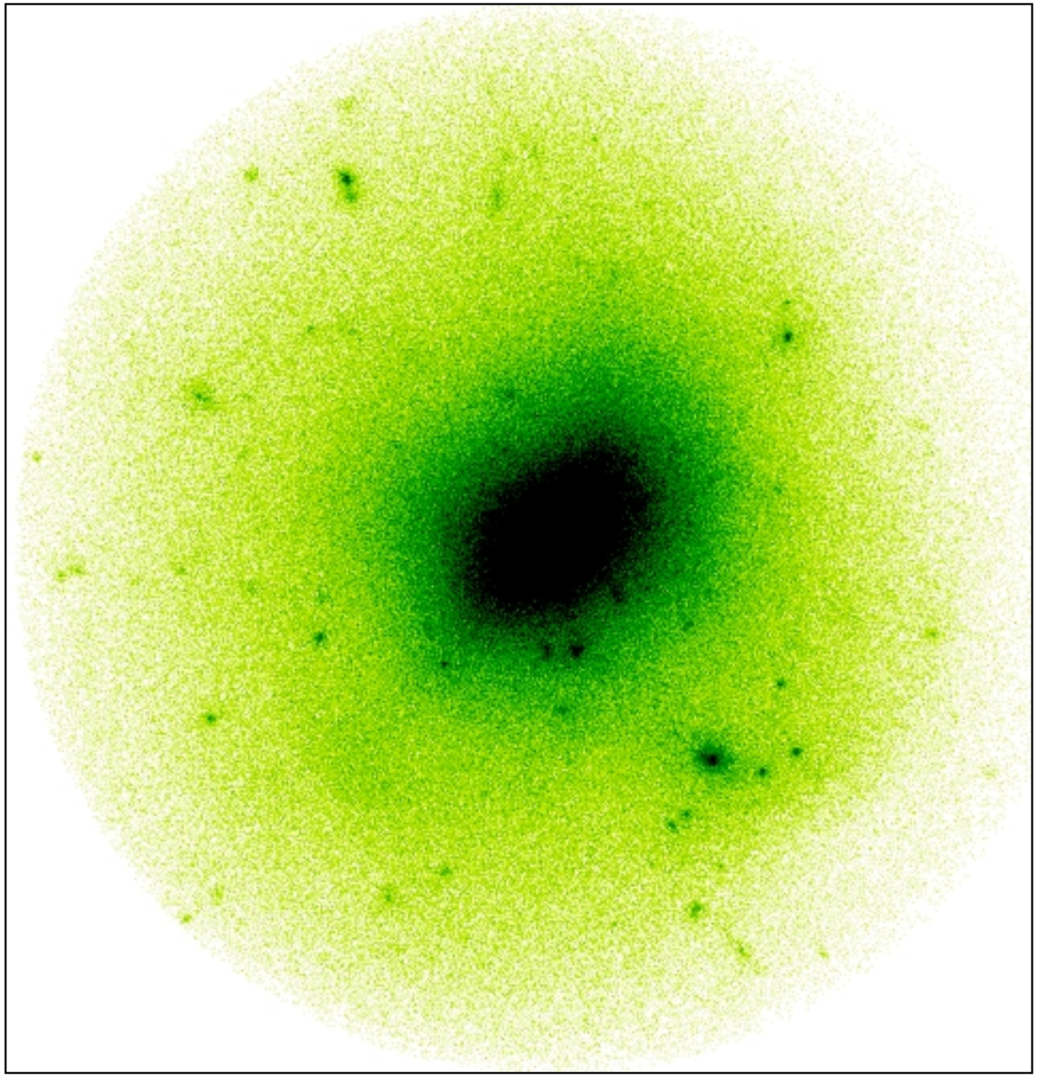
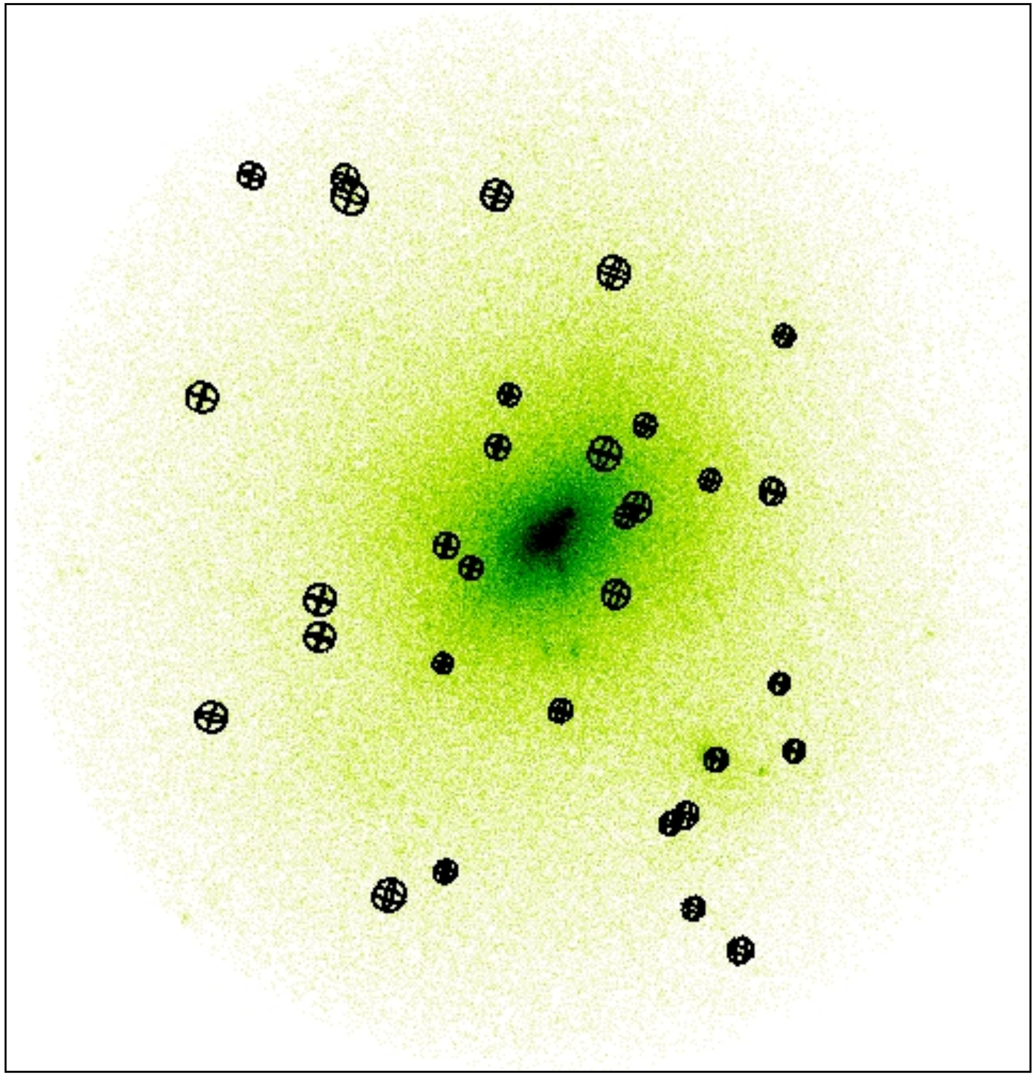
[29] *Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210*
[30] *Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK*
[31] *Astronomy Unit, Department of Physics, University of Trieste, via Tiepolo 11, I-34131 Trieste, Italy*
[32] *INAF, Osservatorio Astronomico di Trieste, via Tiepolo 11, I-34131 Trieste, Italy*
[33] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*
[34] *T-2, Theoretical Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87544, USA*

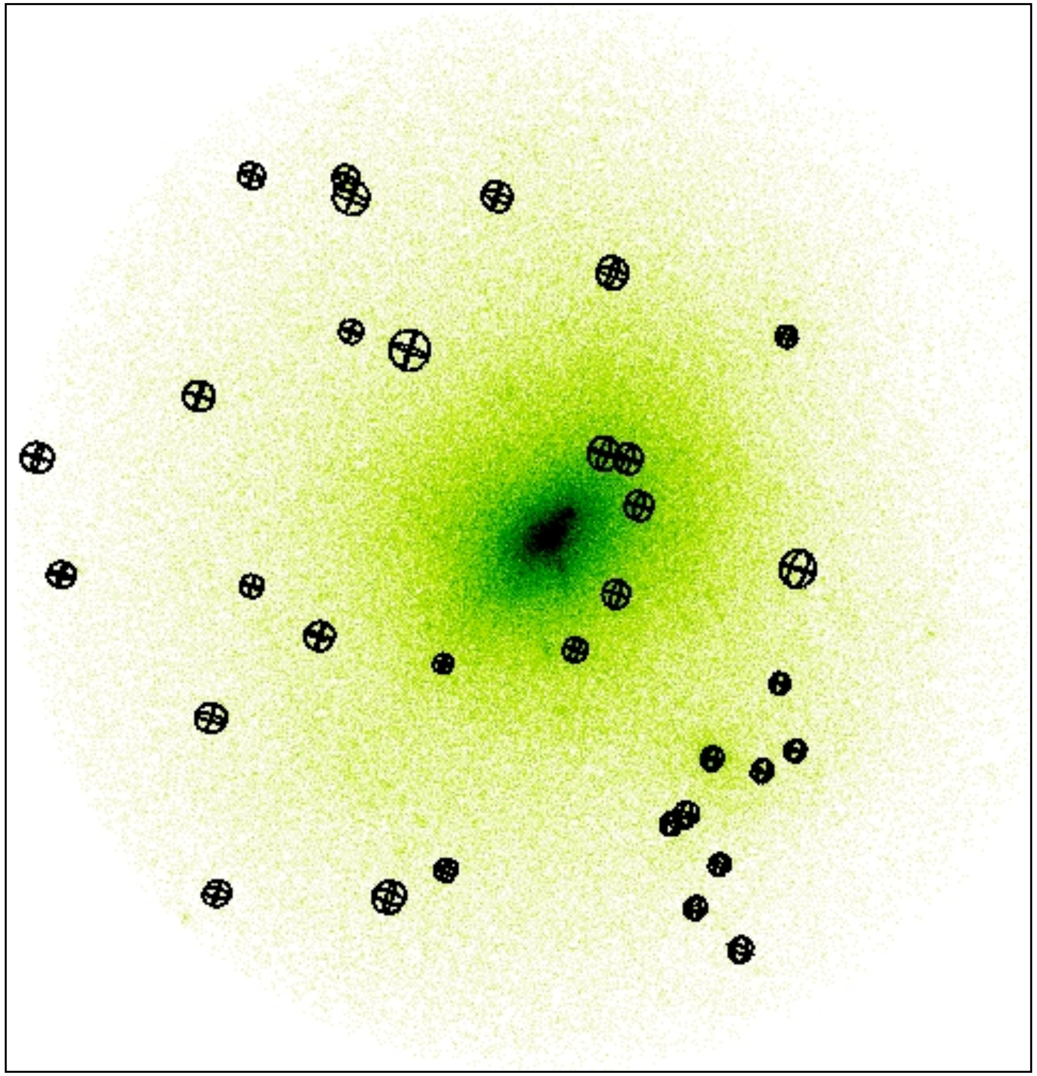
- the suspect



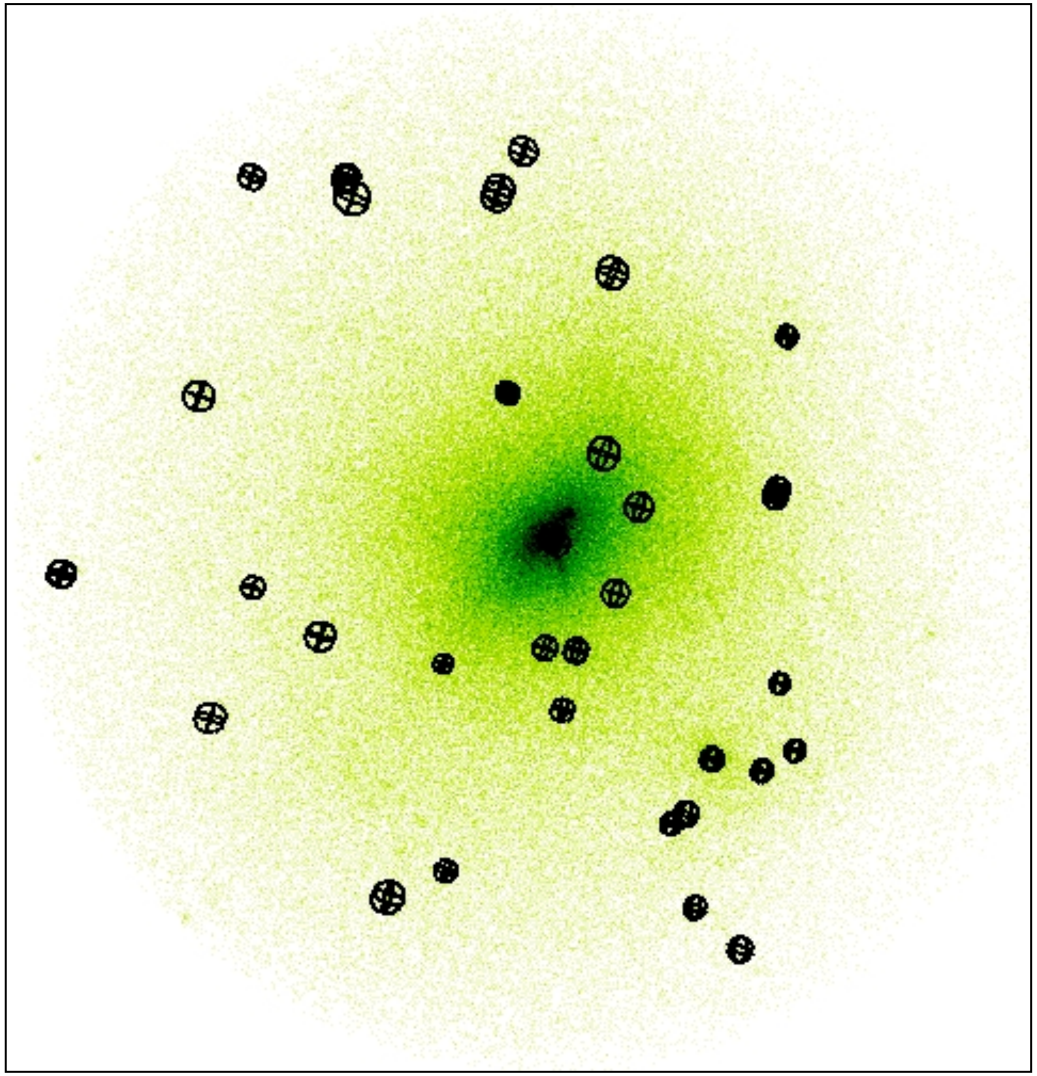
- FOF



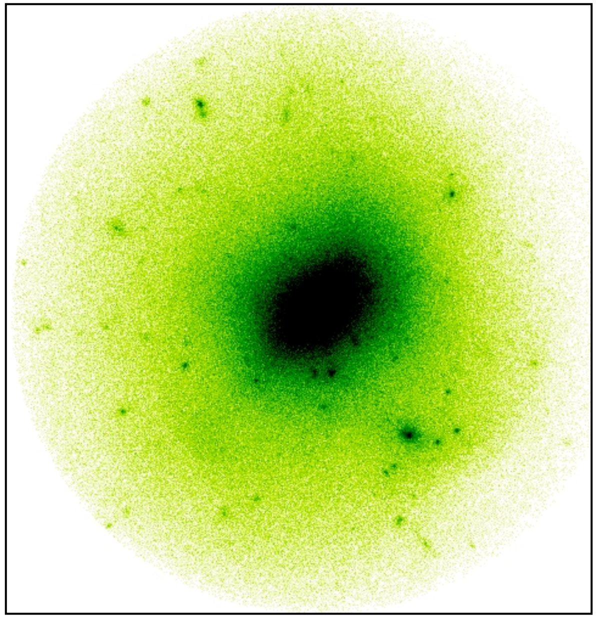
- AHF



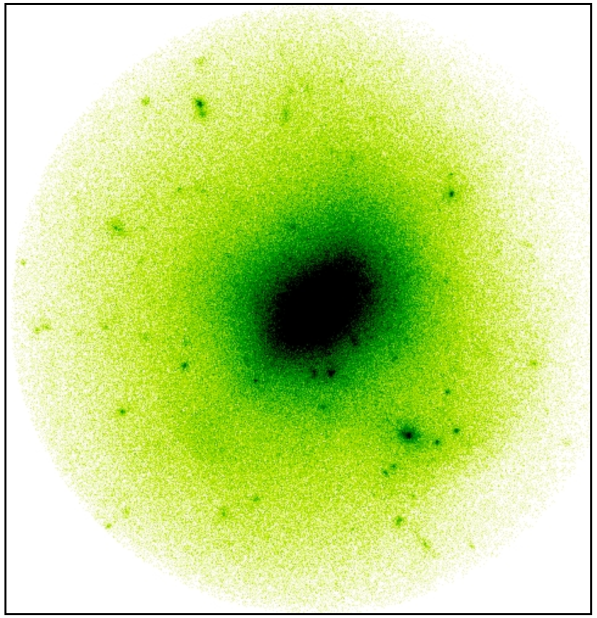
- SKID



FOF



AHF



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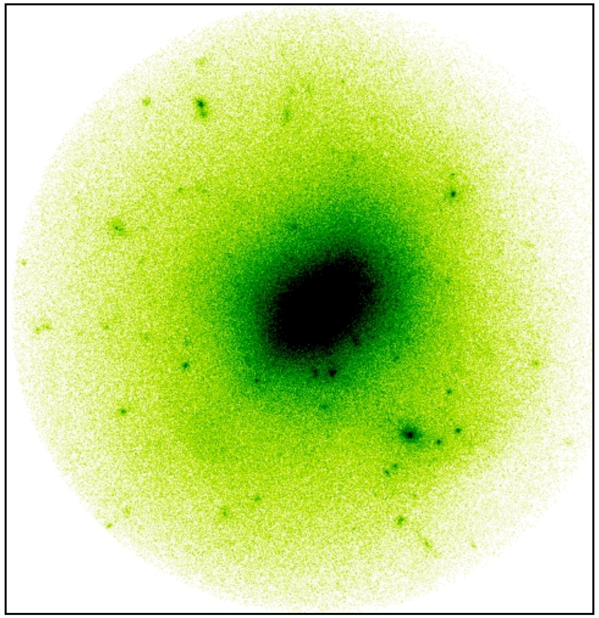

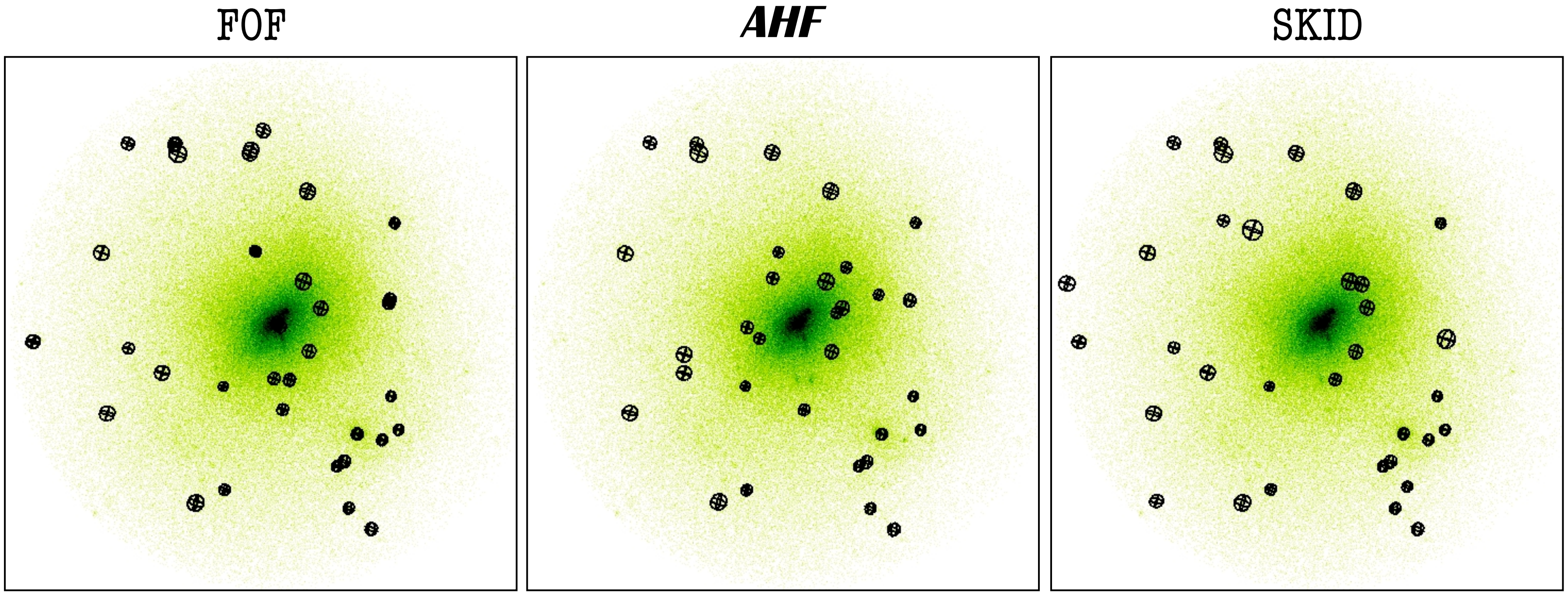
FOF
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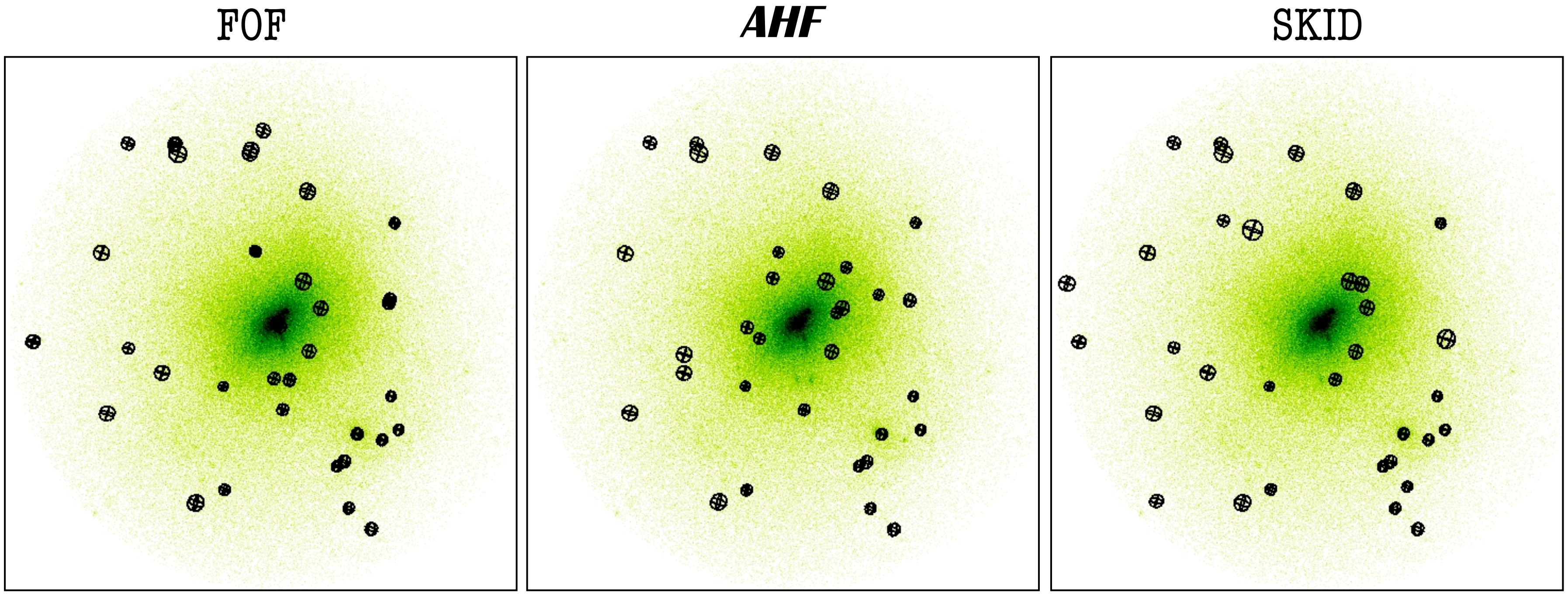

they do not all find the same objects!

- The Situation
- The Methods
- Code Examples
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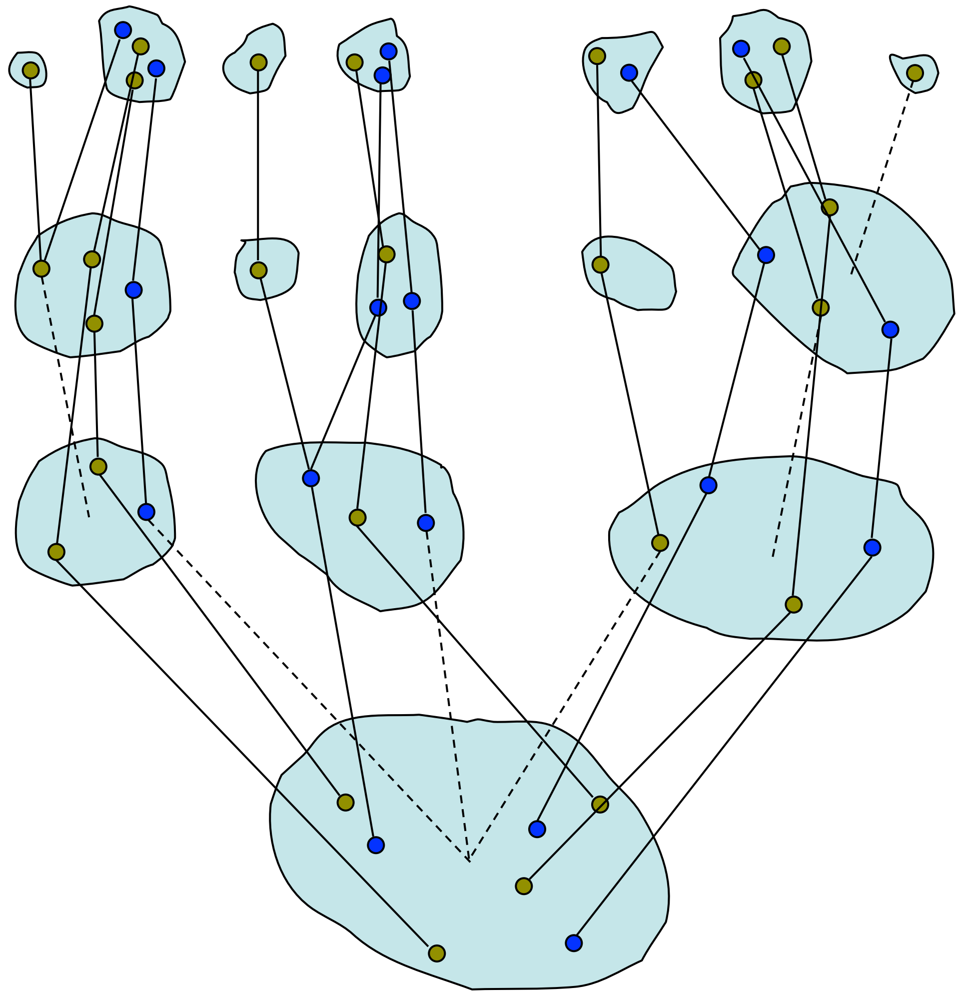
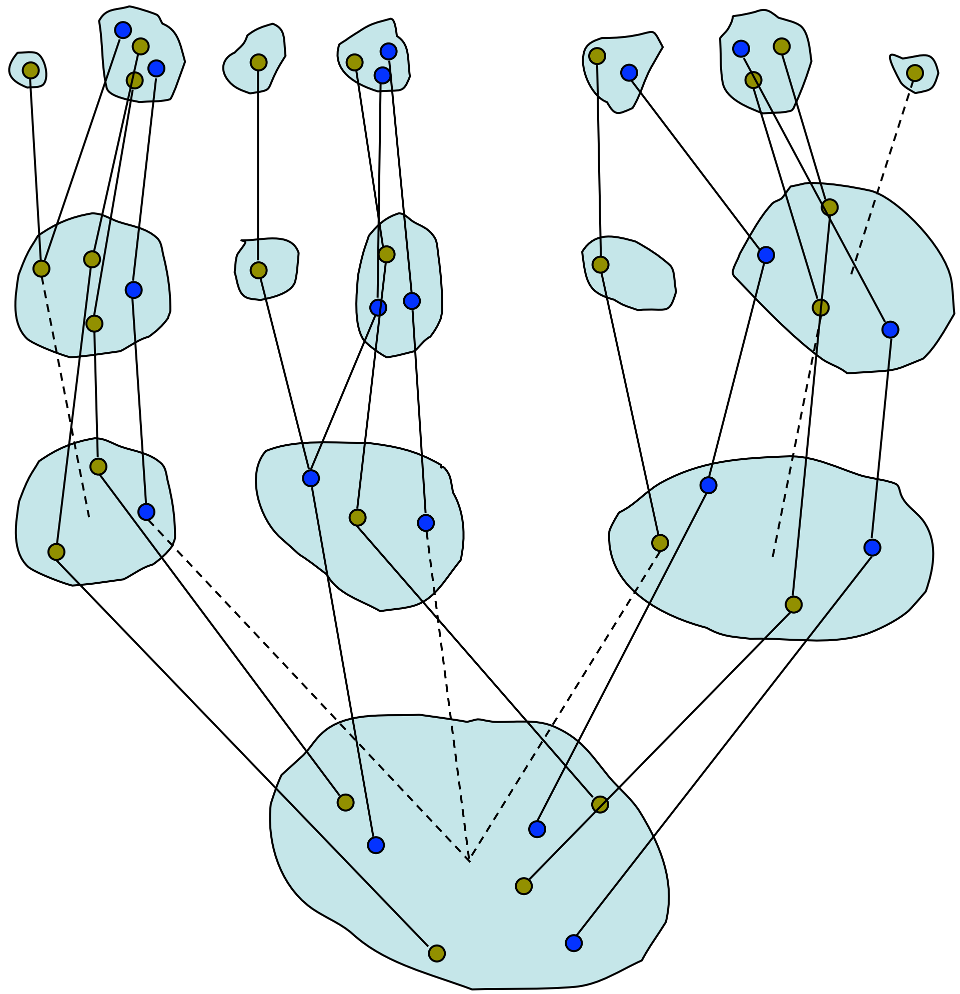
- **Tracking in Time Domain**
- Summary

for every object found at time t_1

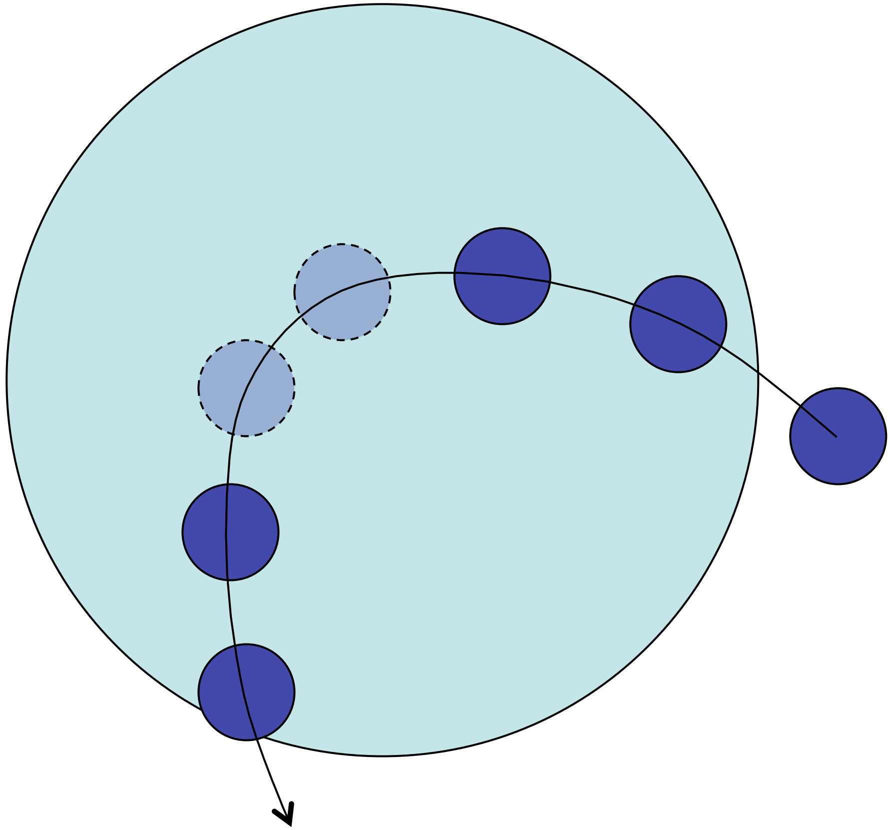


for every object found at time t_1

try to follow it to time t_2

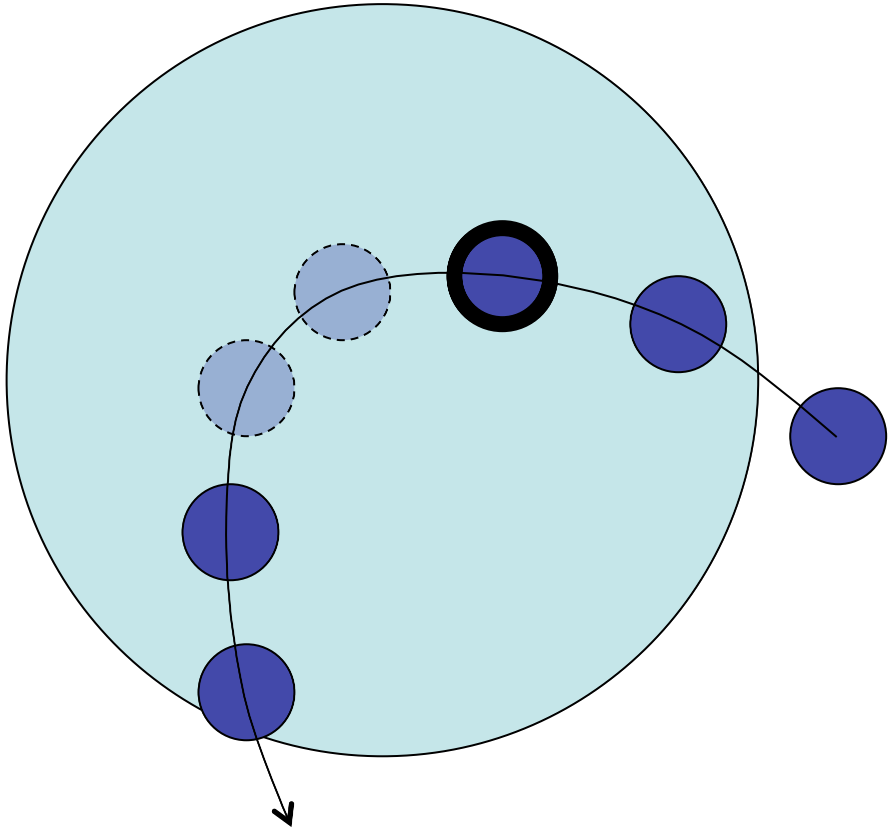


- limitations of halo finders



- limitations of halo finders

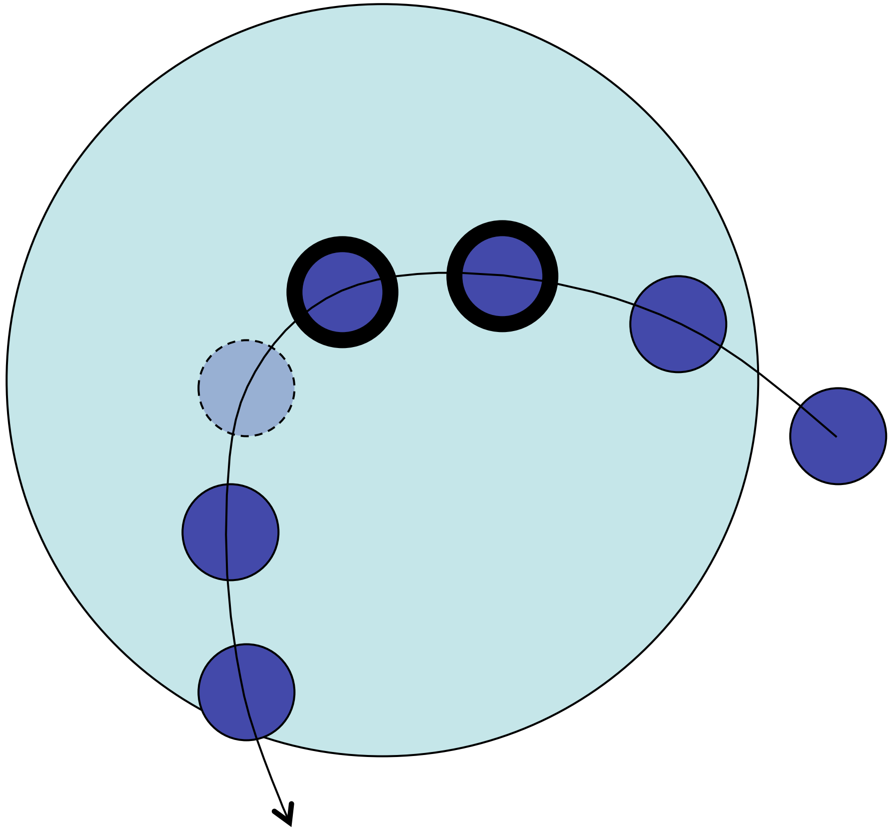
we know the object exits at time t_1...



- limitations of halo finders

we know the object exits at time t_1...

...so it should also be there at time t_2!



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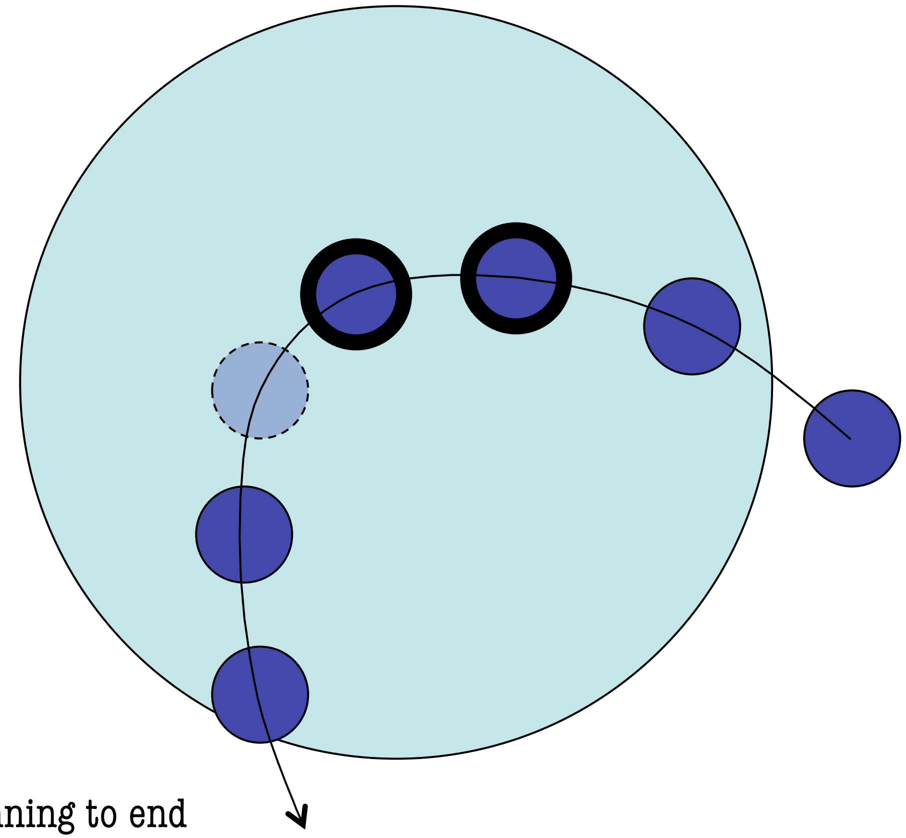

- HBT (Han 2012) is following objects from beginning to end
- some tree building codes (try to) capture this in post-processing

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Structure Finding in Cosmological Simulations: The State of Affairs

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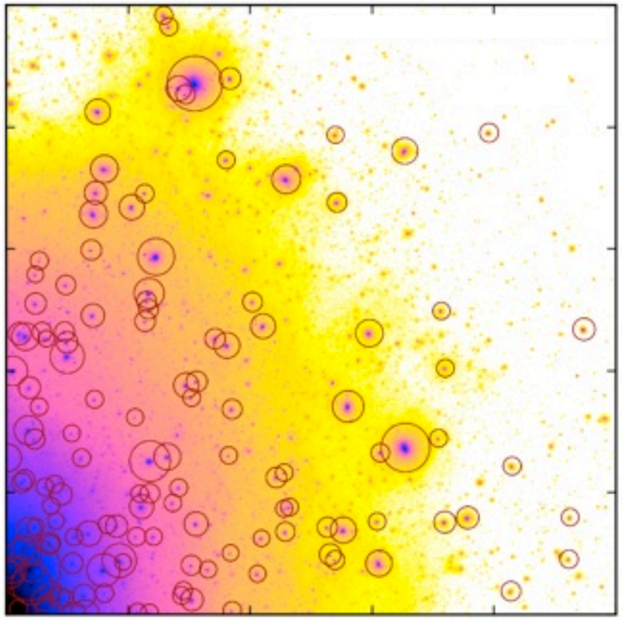

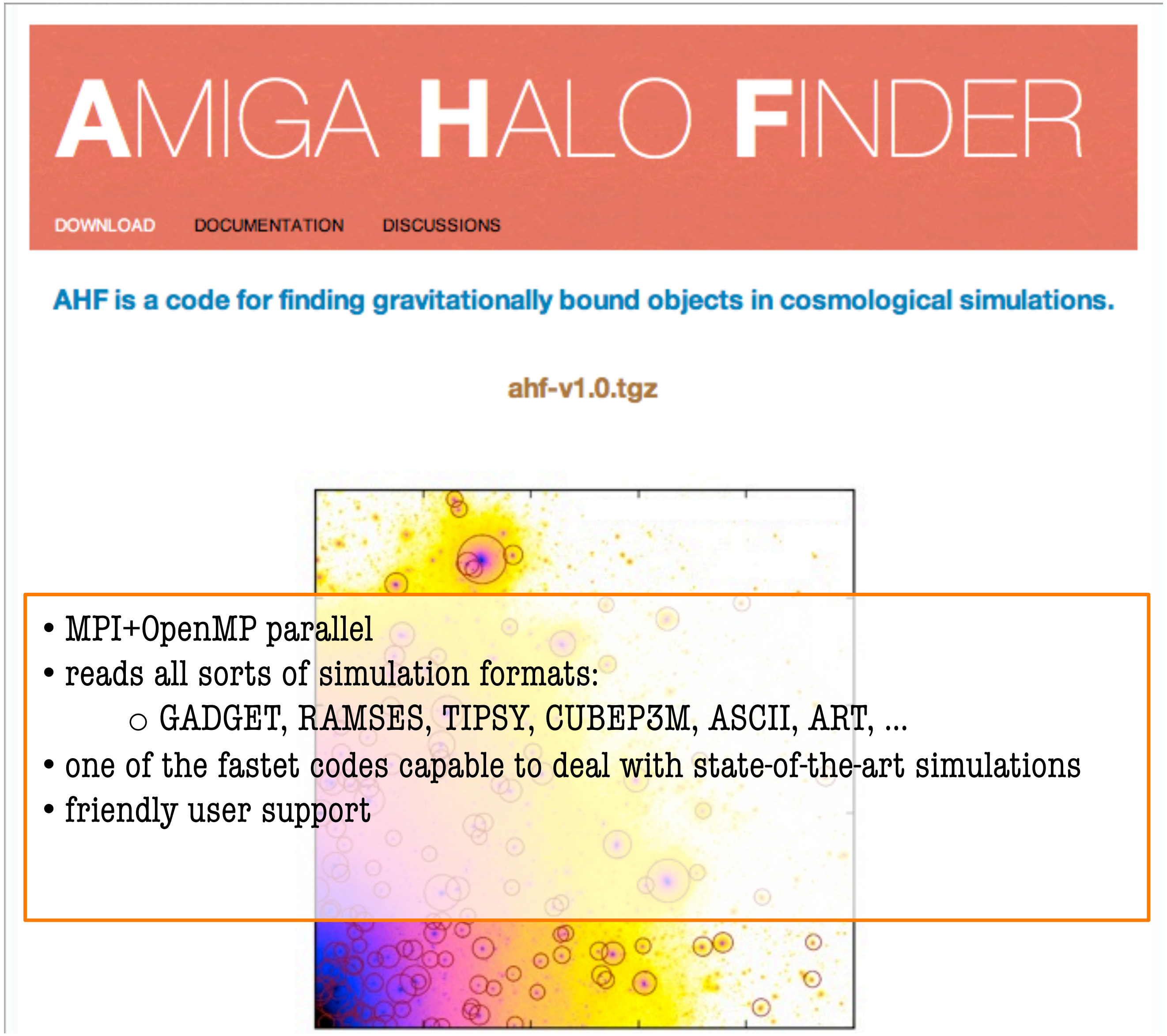

- MPI+OpenMP parallel
- reads all sorts of simulation formats:
  - GADGET, RAMSES, TIPSY, CUBEP3M, ASCII, ART, ...
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