Primordial Black Holes from Nontopological Solitons

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PRL 119 (2017) no. 3 031103 [arXiv:1612.02529] (EC, A. Kusenko)
PRD 96 (2017) no. 10 103002 [arXiv:1706.09003] (EC, A. Kusenko)
[arXiv:1801.03321] (EC, A. Kusenko, V. Takhistov)

Outline

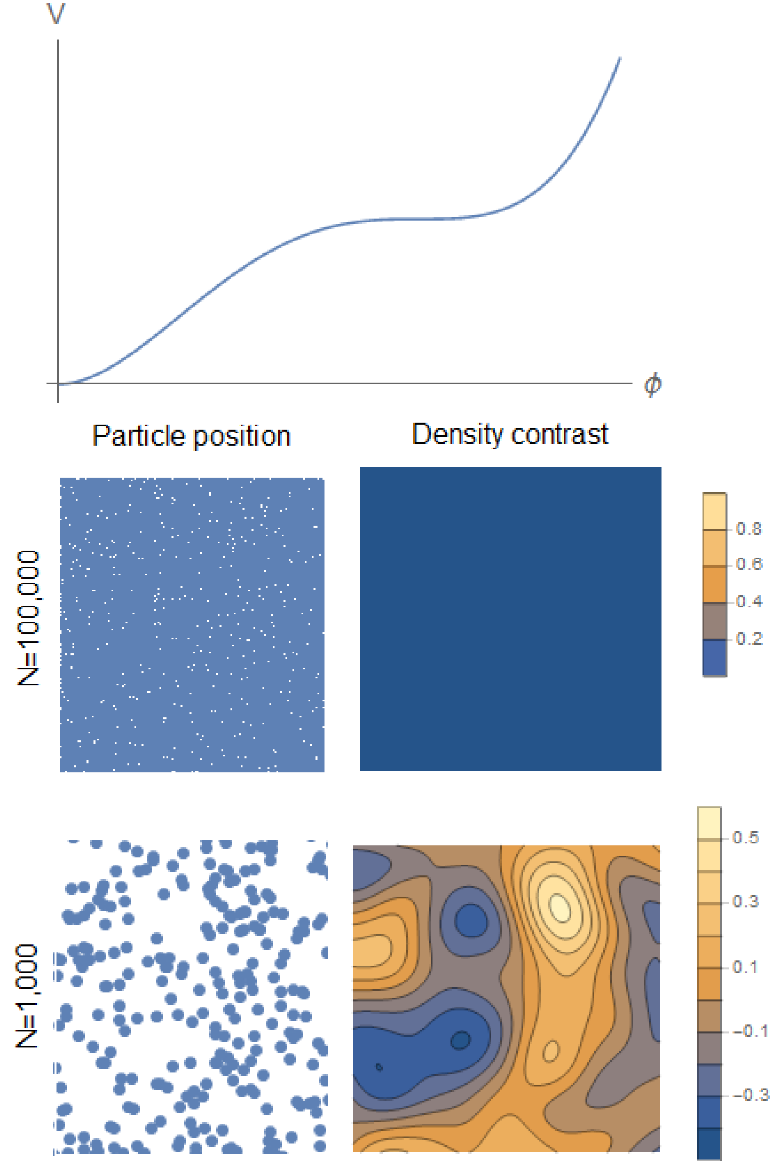
- History/motivation
- Some intuition – in pictures
- Condensate fragmentation/solitogenesis
- Soliton overdensities
- Black hole production
- Results for Q-balls and oscillons

History

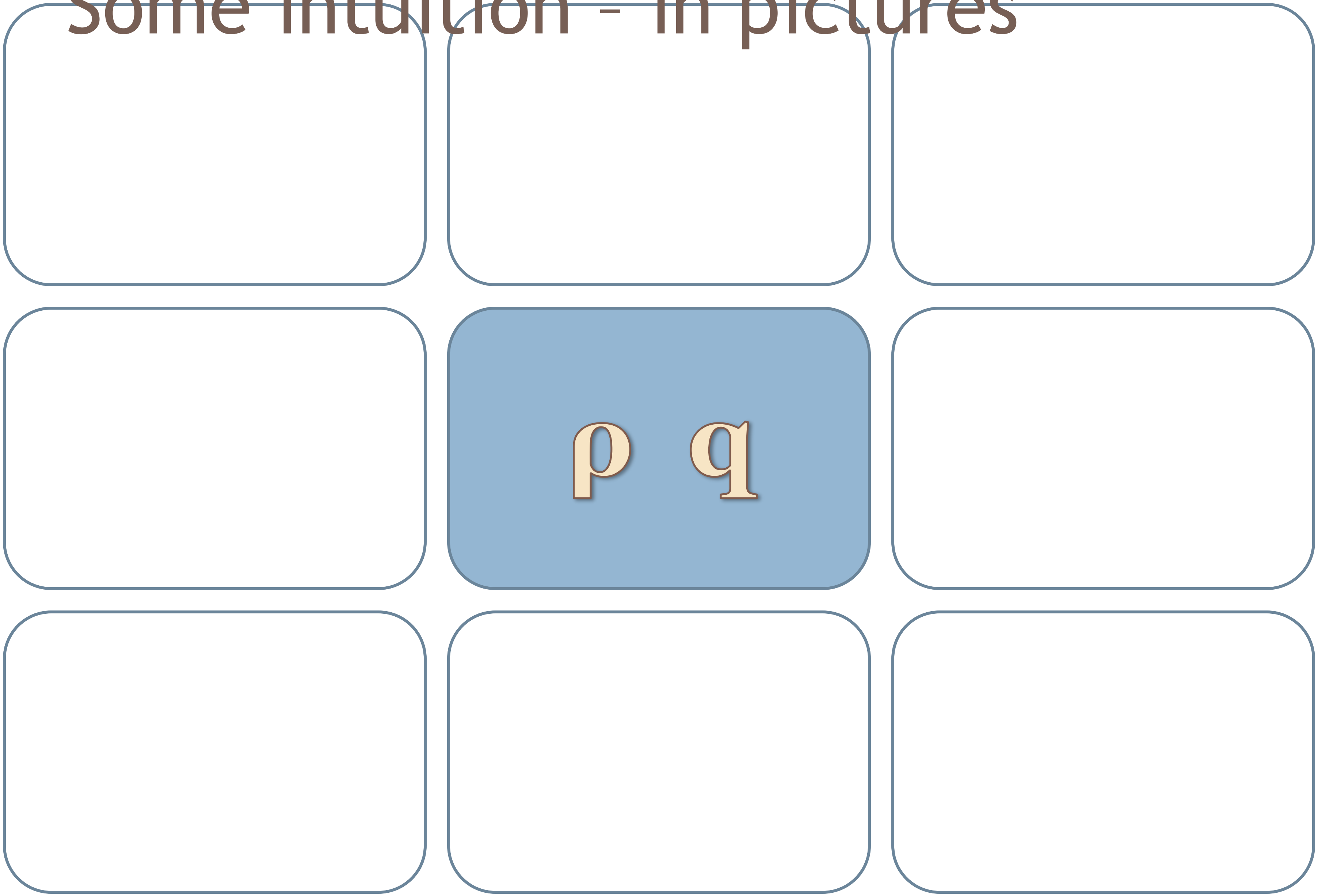
- Major early contributions to PBH due to Zel'dovich and Novikov (1967), Hawking (1971), Carr and Hawking (1974), Polnarev and Khlopov (1985)
- Original formulation: density perturbations decouple from Hubble expansion during RD era and collapse, forming PBH with mass on the order of the horizon mass
- Perturbations must be over critical density contrast ($\delta_c \sim 1$) to collapse
- Perturbations entering during MD era can be amplified: $\delta(t) = \delta_o a(t) = \delta_o (t/t_o)^{2/3}$, increasing probability of collapse

Motivation for this work

- Most PBH models assume source of density fluctuations are from inflation
  - Requires potential fine-tuned to produce perturbations on a specific scale
- PBH produced through solitogenesis gets density fluctuations from Poisson noise
  - Fluctuations scale as $\Delta\rho \sim 1/\sqrt{N}$
  - Particles in relativistic plasma have VERY large N per horizon => negligible fluctuations
  - Solitons have very few "particles" per horizon; leads to greater fluctuations
  - *No modifications to inflaton potential required*



Some intuition – in pictures



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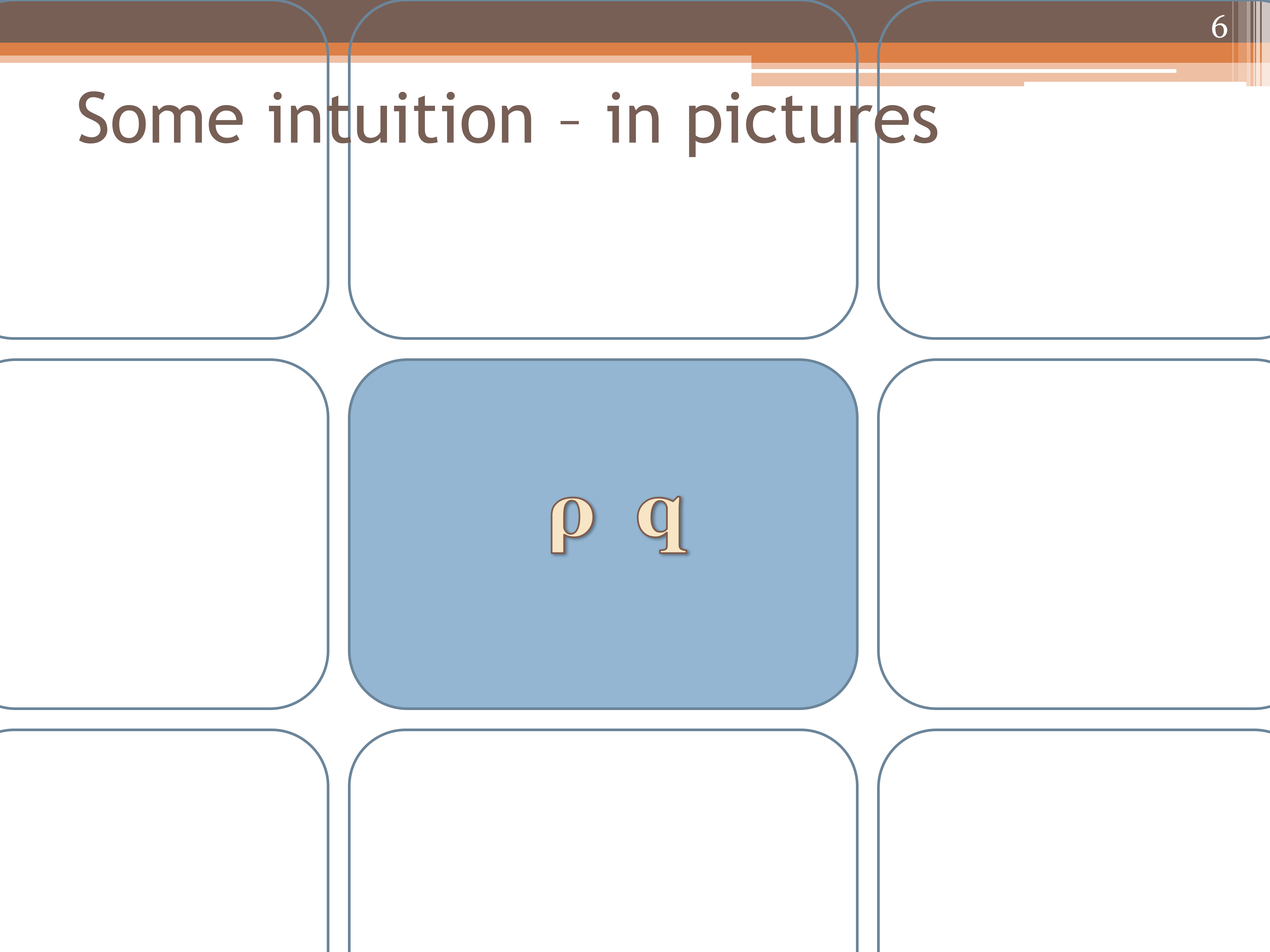

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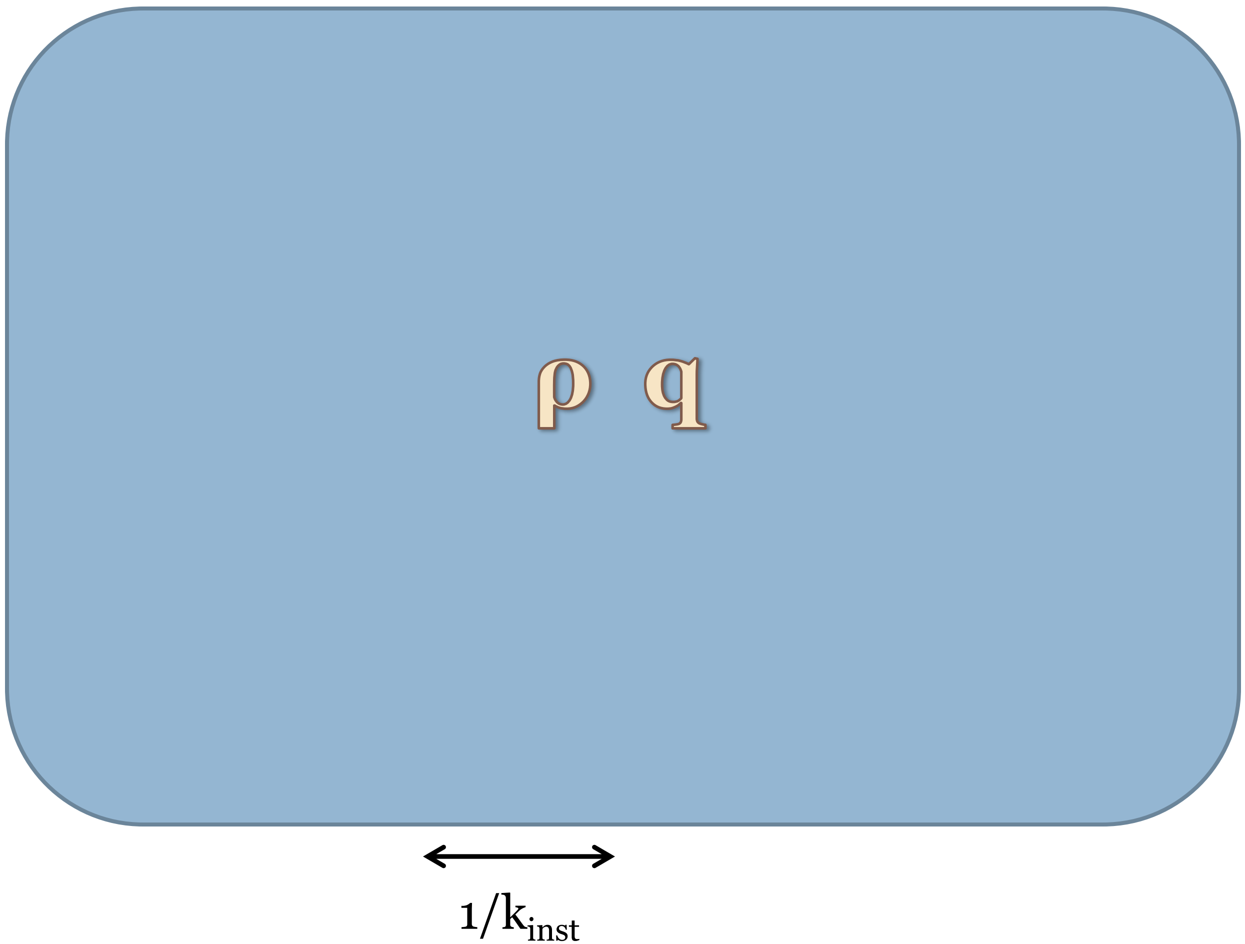

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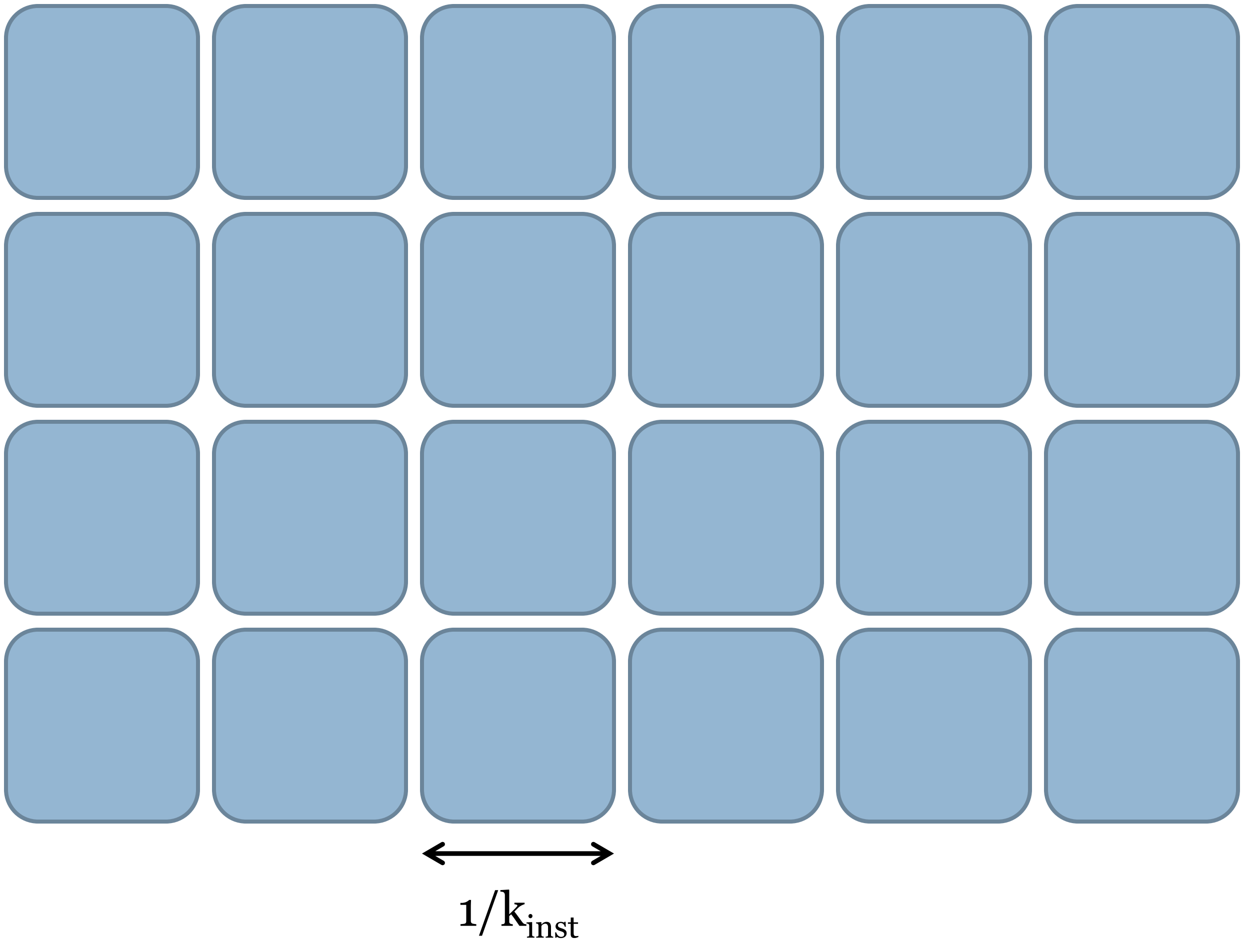

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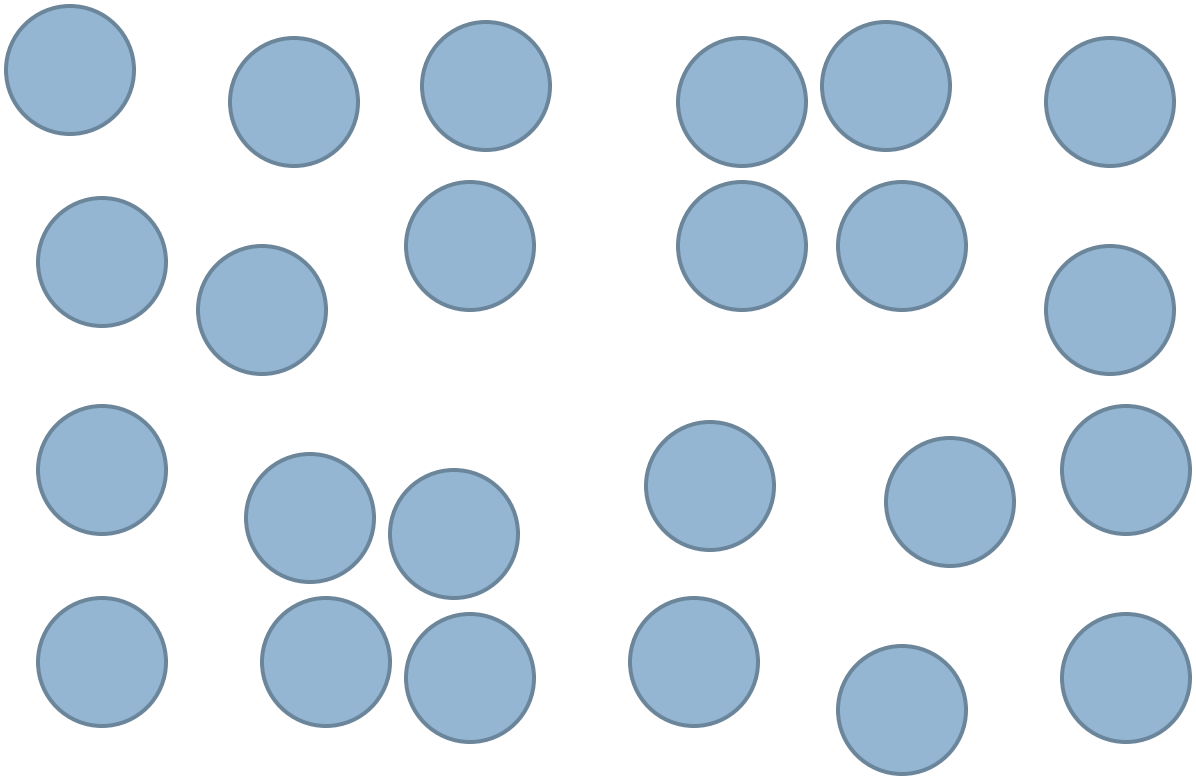

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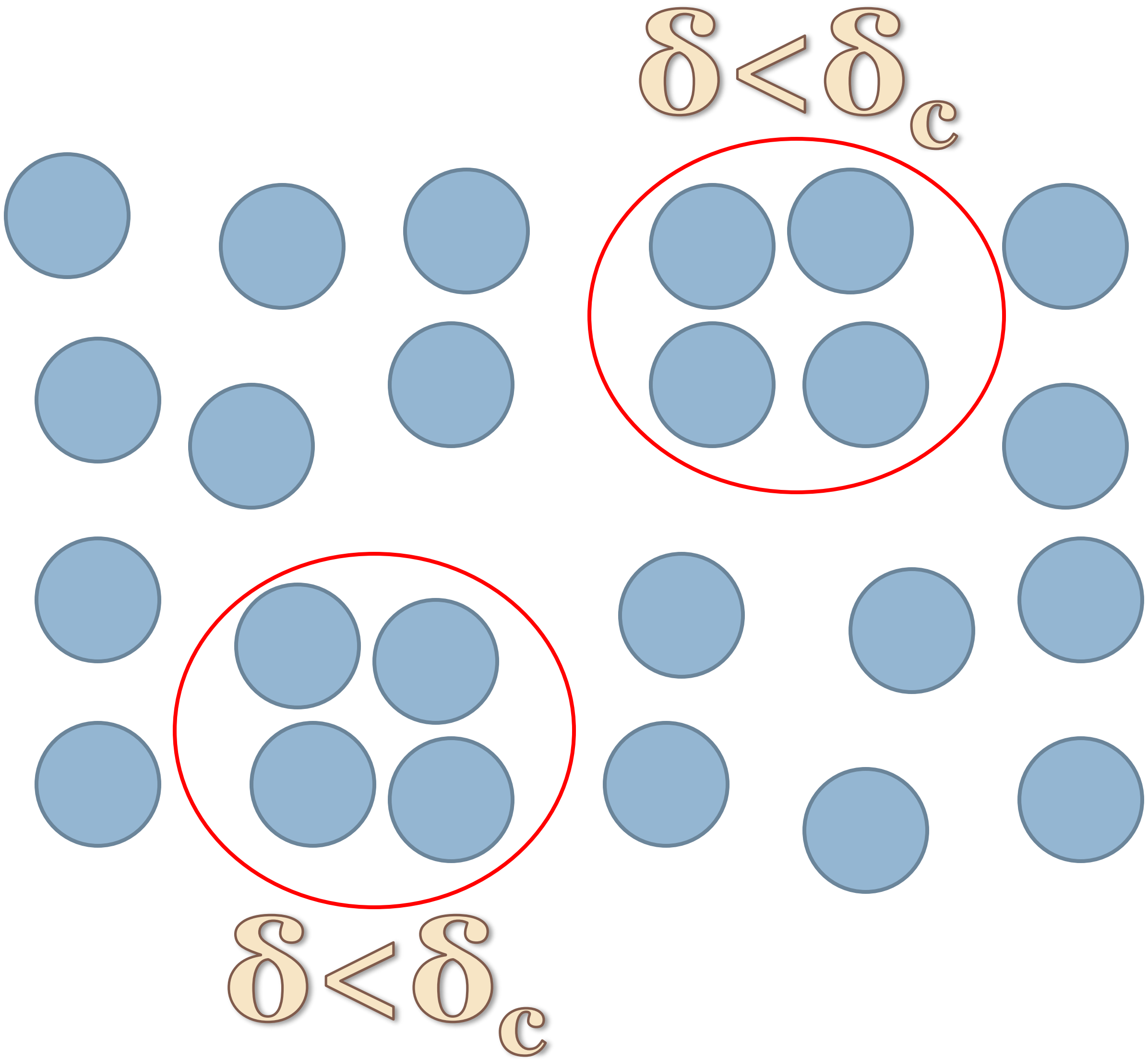

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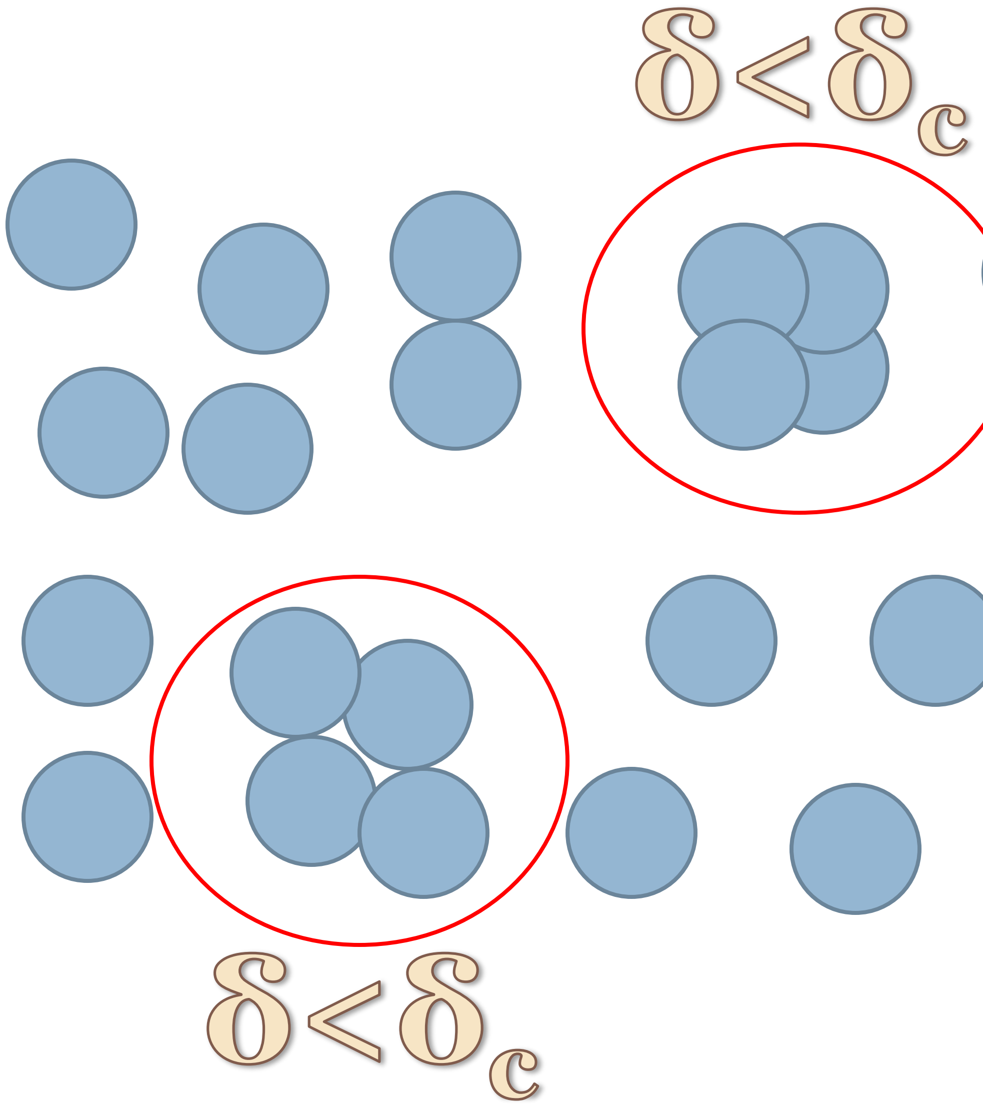

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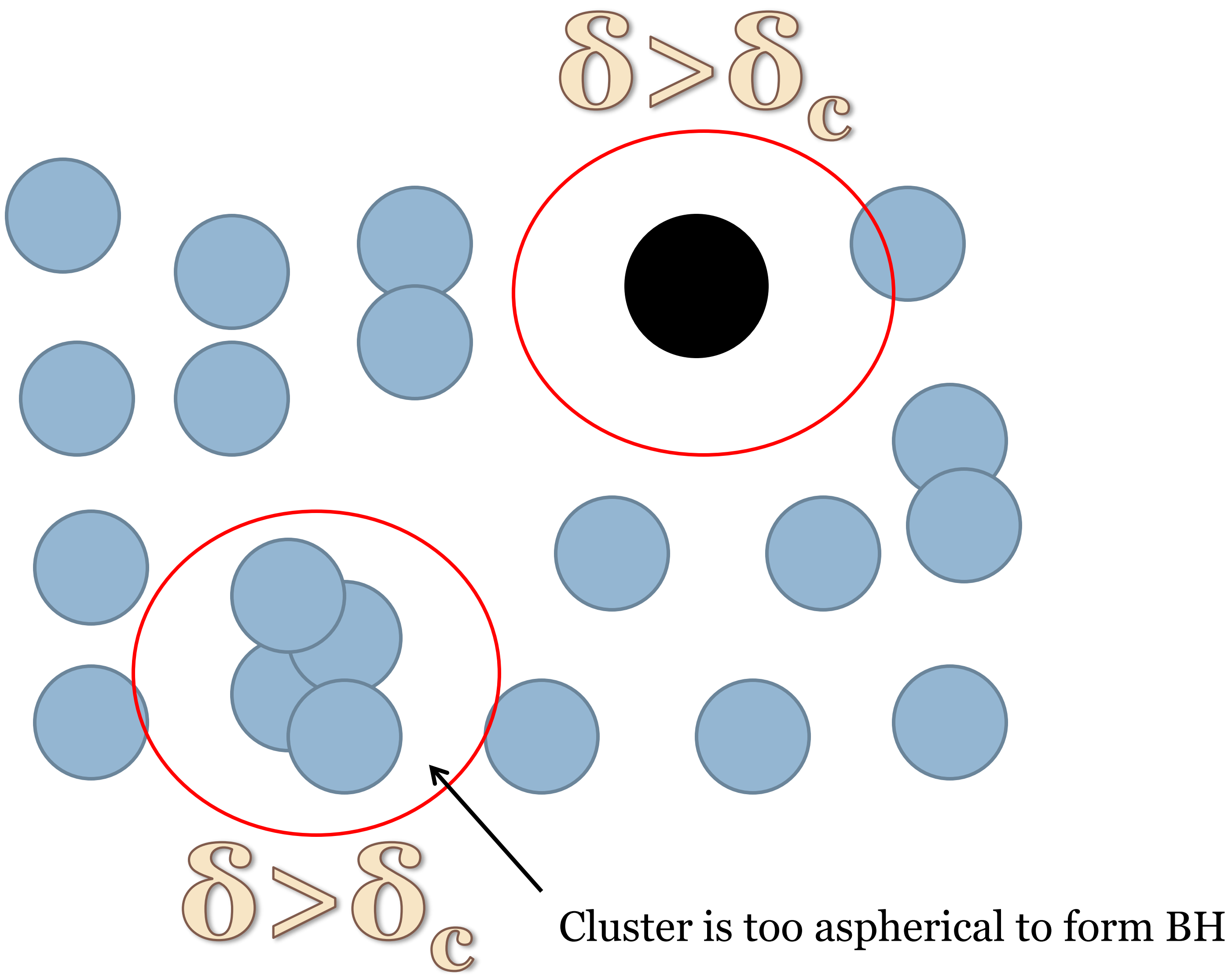

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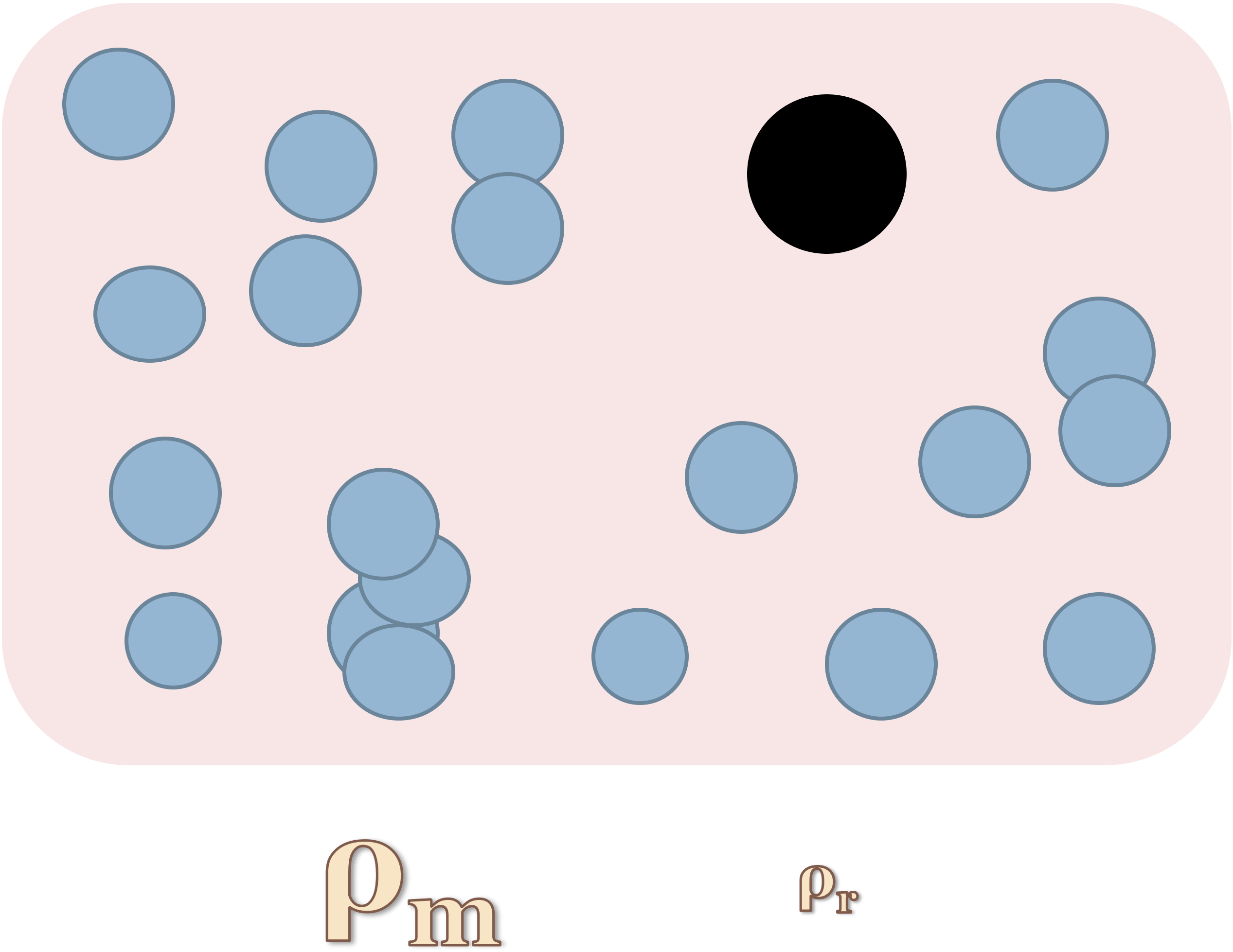

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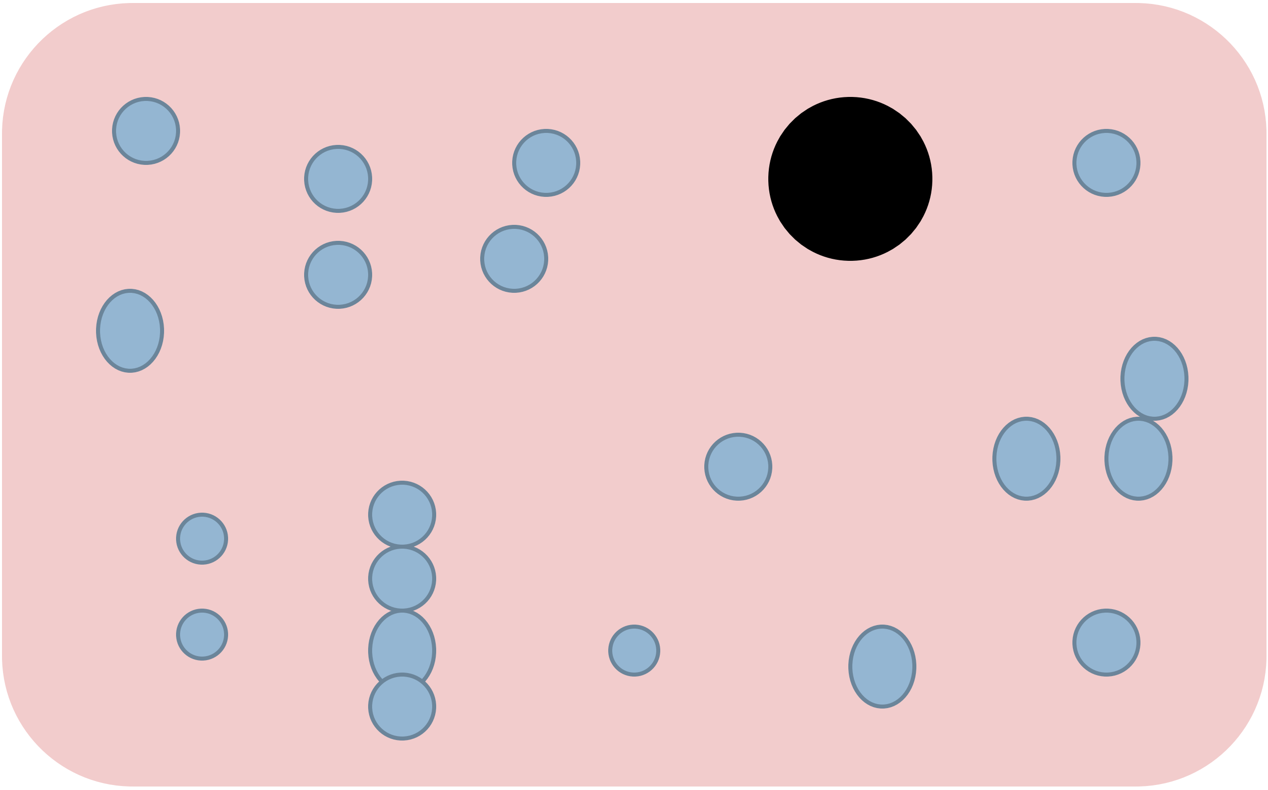
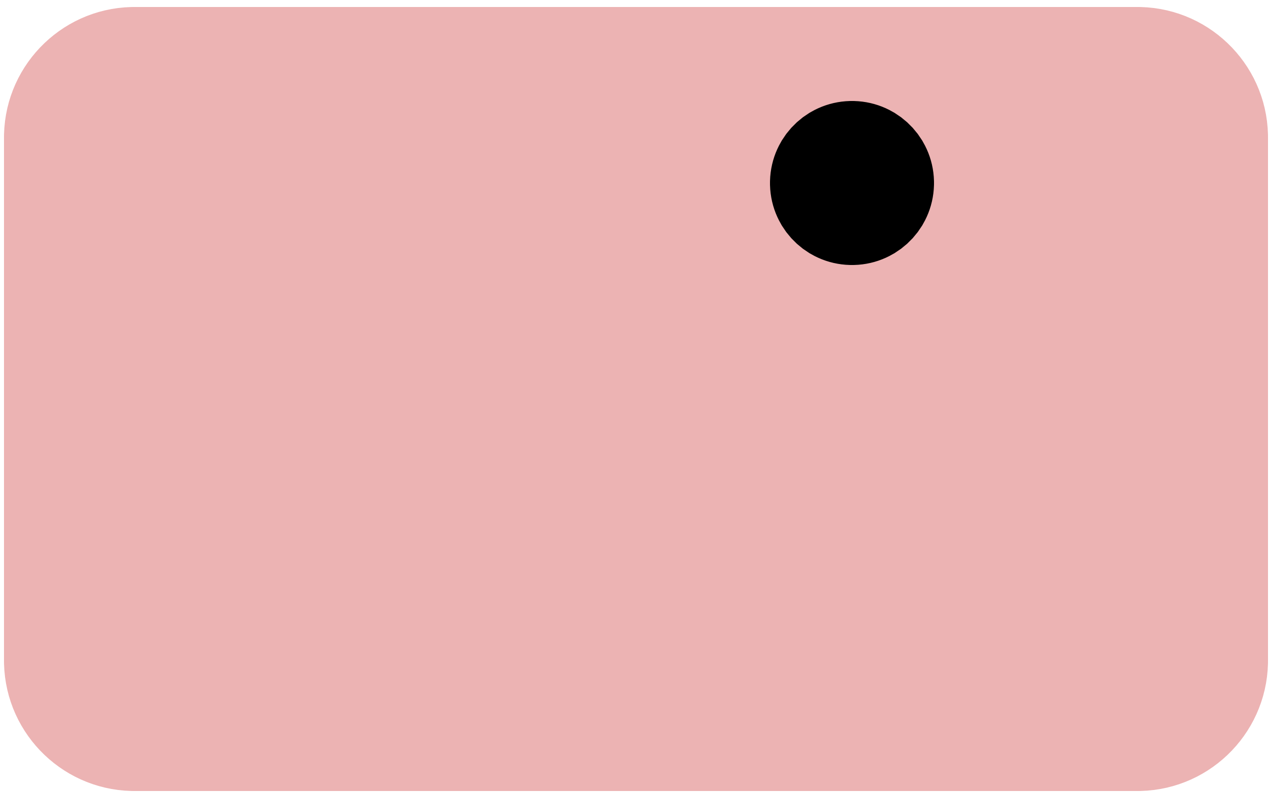


ρ_m ρ_r

Some intuition - in pictures



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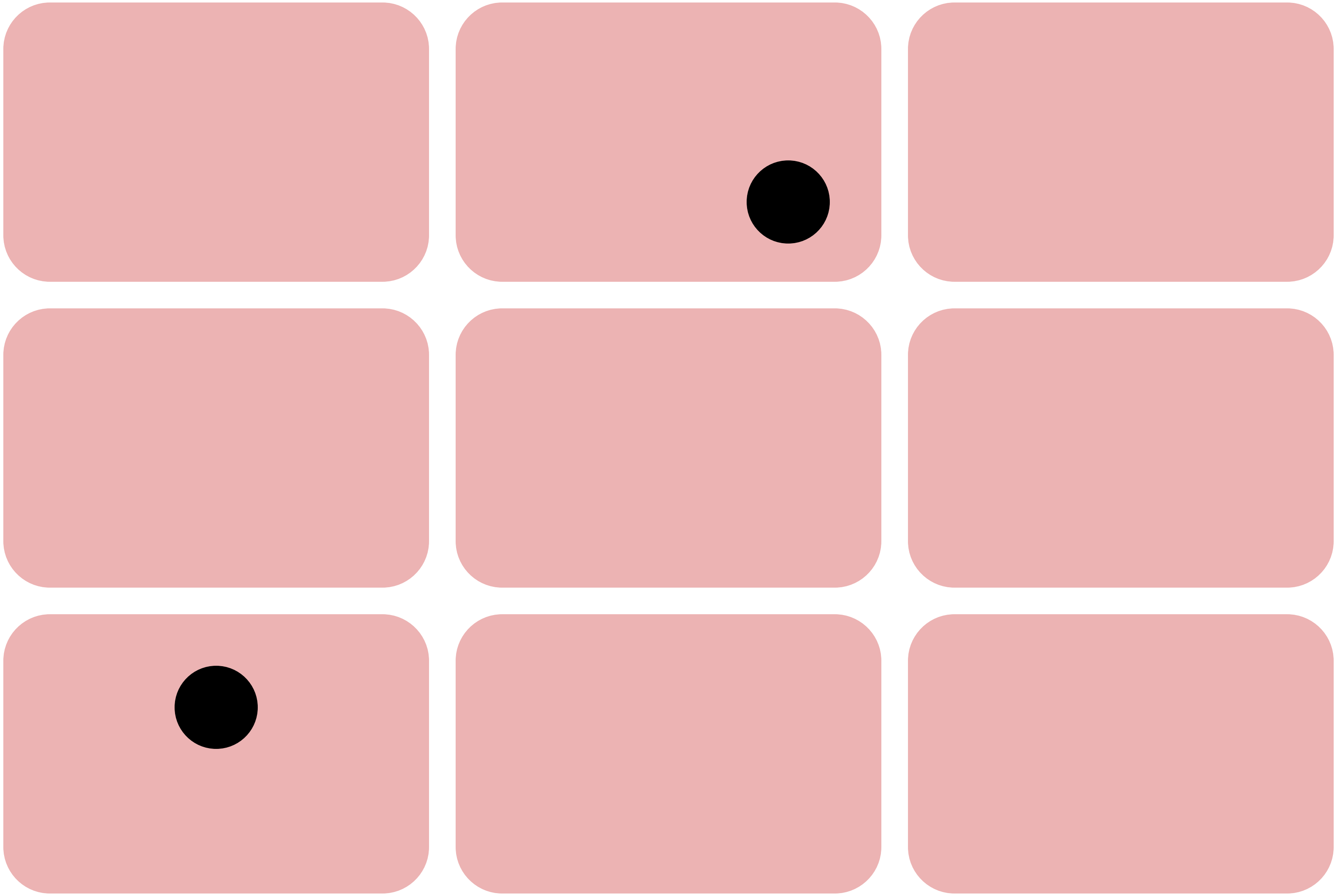
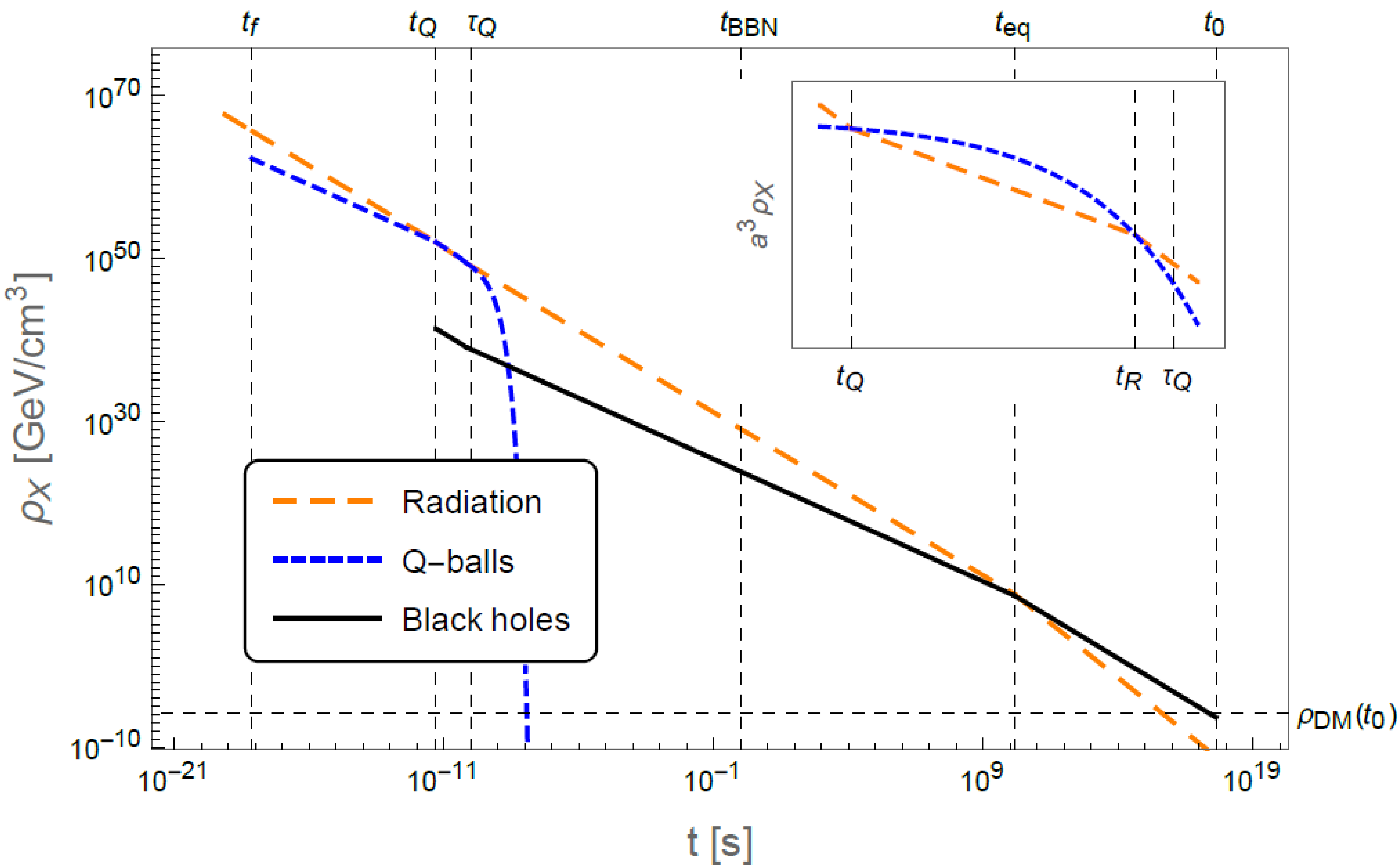


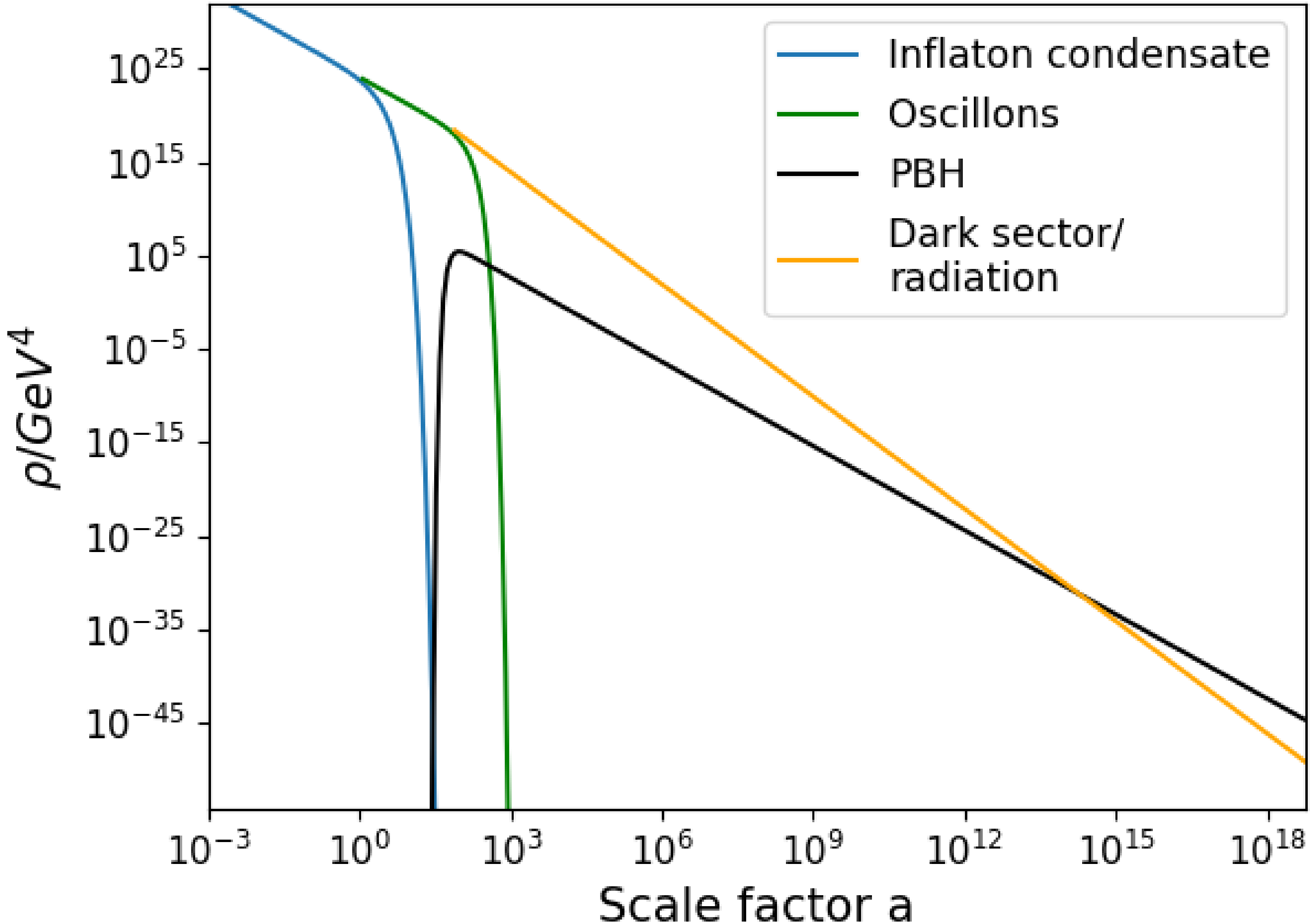
Mechanism summary

- Scalar field reaches large vev (Affleck-Dine mech. for charged scalars, coherent oscillations for inflaton, misalignment for axions…)
- Instability band in wavenumber forms, leading to fragmentation
- Solitons are formed, then cluster together under gravity during matter(soliton)-dominated era
- Some fraction of clusters will collapse into black holes
- All other clusters destabilize and radiate away, leaving the black holes behind
- Black holes survive to present day

Cosmological timeline – Q-balls

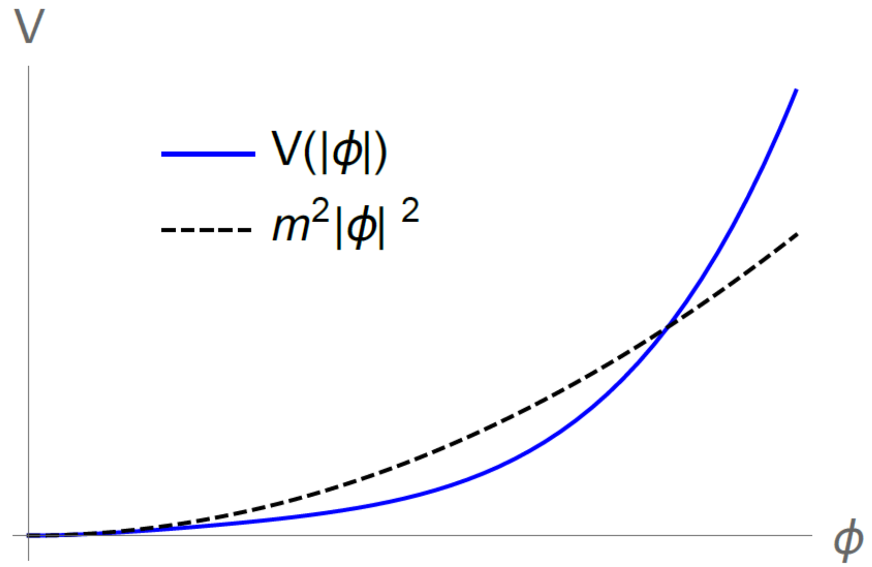


Cosmological timeline - oscillons



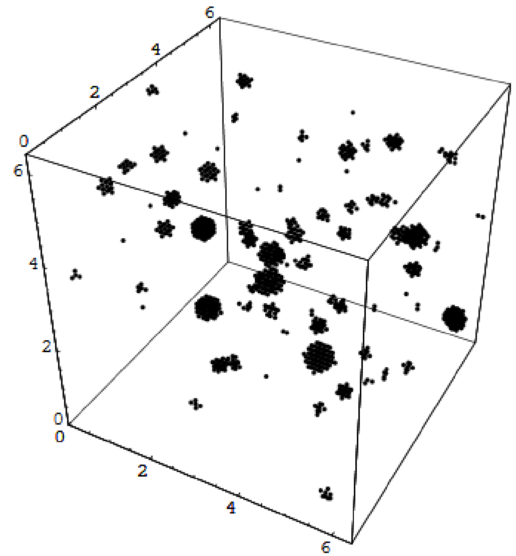
Scalar condensate fragmentation

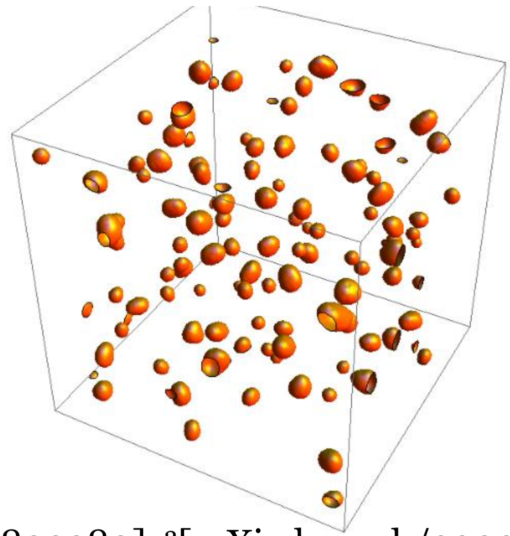
- Field in question could be scalar superpartner, inflaton, axion, etc.
- Uniform condensate fills early universe (nonzero vev or coherent oscillations)
- Only requirements are that:
  - (1) potential is relatively flat away from bottom of potential ($V(\varphi)<m^2\varphi^2$ for some value of φ)
  - (2) There exists some (pseudo)conserved charge
- Field develops instability band $0<k<k_{max}$
  - $k_{max} = \sqrt{[\omega^2 - V''(\varphi_o)]}$ $\omega=d\theta/dt$
- Fragmentation occurs, resulting in solitons with characteristic size of unstable wavelength



Scalar condensate fragmentation

- Q-ball fragmentation explored analytically (Kusenko and Shaposhnikov[1], Enqvist and McDonald[2]) and numerically (Kasuya and Kawasaki[3]).
- Inflaton fragmentation explored analytically (Amin[4]) and numerically (Amin, Easther, Finkel[5]).
- Findings indicate that typical numbers of solitons formed per horizon is $10^4 - 10^9$
- Distribution of solitons formed is well-localized in charge/mass/size, but show some variation.





[1][arXiv:hep-ph/9709492], [2][arXiv:hep-ph/9711514], [2][arXiv:hep-ph/9803380], [3][arXiv:hep-ph/9909509], [3][arXiv:hep-ph/0002285], [4][arXiv:1006.3075v2], [5][arXiv:1009.2505]

Calculating overdensities

1. Model the distribution of mass M of soliton clusters by assuming they are the sum of N individual solitons → $P(M|N)$
2. Assume Poisson distribution for N solitons within volume V to get joint distribution in mass/number → $P(M,N|V)=P(M|N)P(N|V)$
3. Black hole energy density operator $\rho_{BH}(M,N,V)$

(*) Take expectation values of BH density over $P(M,N|V)$ and sum over contributions from all length scales V → $(d\rho/dM)_{BH}$

1) Cluster mass distribution

- PDF for mass M composed of N Q-balls:

$$f_M(M|N) = \left(\prod_{i=1}^{N} \int dm_i \, f_m(m_i)\right) \delta\left(M - \sum_{i=1}^{N} m_i\right)$$

$$\tilde{f}_M(\mu|N) = \left[\int dm \, e^{i\mu m} f_m(m)\right]^N$$

- Will assume monochromatic soliton mass distribution for simplicity ($m_o = \Lambda|Q|^\alpha$ for Q-balls) $f_m(m) = \delta(m - m_0) \implies f_M(M) = \delta(M - N m_0)$
- Now need to find how N is distributed:
  - P(M,N) = P(M|N)P(N)

2) Number distribution

- Given $\mathcal{N}$ particles uniformly distributed in a box of volume L^3, what is probability to find $N \ll \mathcal{N}$ particles contained within subvolume $V \ll L^3$?

$$p(N|V) = \binom{\mathcal{N}}{N} \left(\frac{V}{L^3}\right)^N \left(1 - \frac{V}{L^3}\right)^{\mathcal{N}-N} \quad \text{(Binomial dist.)}$$

$$\xrightarrow{\mathcal{N},L\to\infty} \quad e^{-nV} \frac{(nV)^N}{N!}, \quad n = \mathcal{N}/L^3 \quad \text{(Poisson dist.)}$$

- This, together with $f_M(M|N)$ from previous slide, give us joint distribution:

$$F(M,N|V) = f_M(M|N)p(N|V)$$

3) BH density operator

- PBH density is soliton cluster density M/V weighted by fraction of clusters that collapse to black holes β(M):

$$\hat{\rho}_{\rm BH}(M,N,V) = \beta(M)\rho_{\rm S} = \beta(M)\frac{M}{V}$$

- Collapse fraction during MD era is given by (Polnarev, Khlopov 1985)[1] (Harada et. al. 2016)[2]:

$$\beta(M) = 0.05556\sigma^5 = 0.05556\delta_0^5\left(\frac{M}{\overline{M}(V_H)}\right)^{10/3}$$

- where

$$\delta_0(M,V) = \frac{\delta\rho}{\rho} = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle} = \frac{M/V}{\langle\rho\rangle} - 1$$

[1][1985 Sov. Phys. Usp. 28 213], [2][arXiv:1609.01588]

(*) Black hole production

- Expected PBH energy density at redshift $a(t)>a(t_{end})$ is the same as average soliton cluster energy density at $a(t_o)$ that **will eventually collapse** to PBH at the end of MD era:

$$\langle \rho_{\mathrm{BH}} \rangle\, a^3(t) = \langle \rho_{\mathrm{S}\to\mathrm{BH}} \rangle\, a^3(t_0)$$

- The soliton density that collapses into BH is the density $\rho=M/V$ weighted by the collapse fraction $\beta(M)$, then averaged/summed over M, N, V:

$$\langle \rho_{\mathrm{S}\to\mathrm{BH}} \rangle = \left(\frac{a(t_0)}{a(t)} \right)^3 \sum_{N=0}^{\infty} \int \frac{dV}{V} \int dM\, F(M, N|V)\, [\beta(M) M/V]$$

(*) Black hole production

- Differential density spectrum can be useful, and is found by not integrating over M:

$$\frac{d\langle\rho_{\mathrm{BH}}\rangle}{dM} = \frac{1}{a^3(t)}\sum_{N=0}^{\infty}\int\frac{dV}{V}F(M,N|V)[\beta(M)M/V]$$

- Can get rough idea of contribution to dark matter density within logarithmic mass scale*:

$$f_{\mathrm{BH}}(M) = \frac{M}{\rho_{\mathrm{DM}}}\left.\frac{d\langle\rho_{\mathrm{BH}}\rangle}{dM}\right|_{t=t_0}$$

*More rigorous comparison of constraints follows work by Carr et. al. [arXiv:1705.05567]

Radiation density, evolution to present day

- Need to ensure that thermal history is self-consistent
- Before MD era* – standard cosmology:

$$\rho_R(t < t_{0,\mathrm{MD}}) \approx \pi^2 M_p^2 / 327 t^2$$

- At beginning of MD era*:

$$\rho_R = \rho_S \implies \pi^2 M_p^2/327t^2 = \langle \rho_S \rangle \, e^{-\Gamma_\phi t_{0,\mathrm{MD}}} / a^3(t_{0,\mathrm{MD}})$$

- During MD:

$$\rho_R = \left[\rho_{R0} + \rho_{S0} \int_{x_0}^{x} dx' \, z(x') e^{-x'} \right] z^{-4}, \quad x = \Gamma t, \; z = (x/x_0)^{2/3}$$

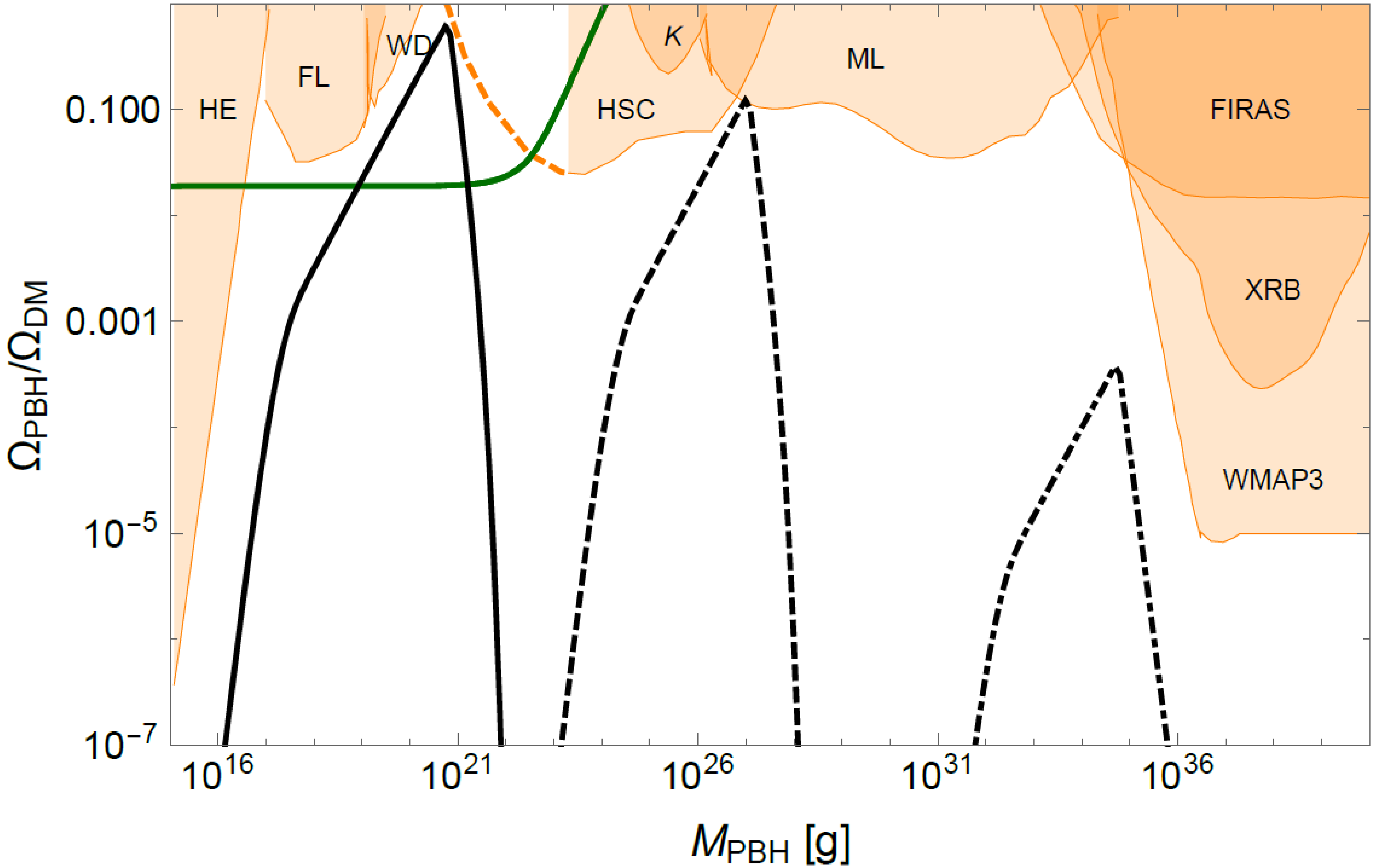
(Scherrer, Turner 1985)[1]

- Matching boundary conditions gives us

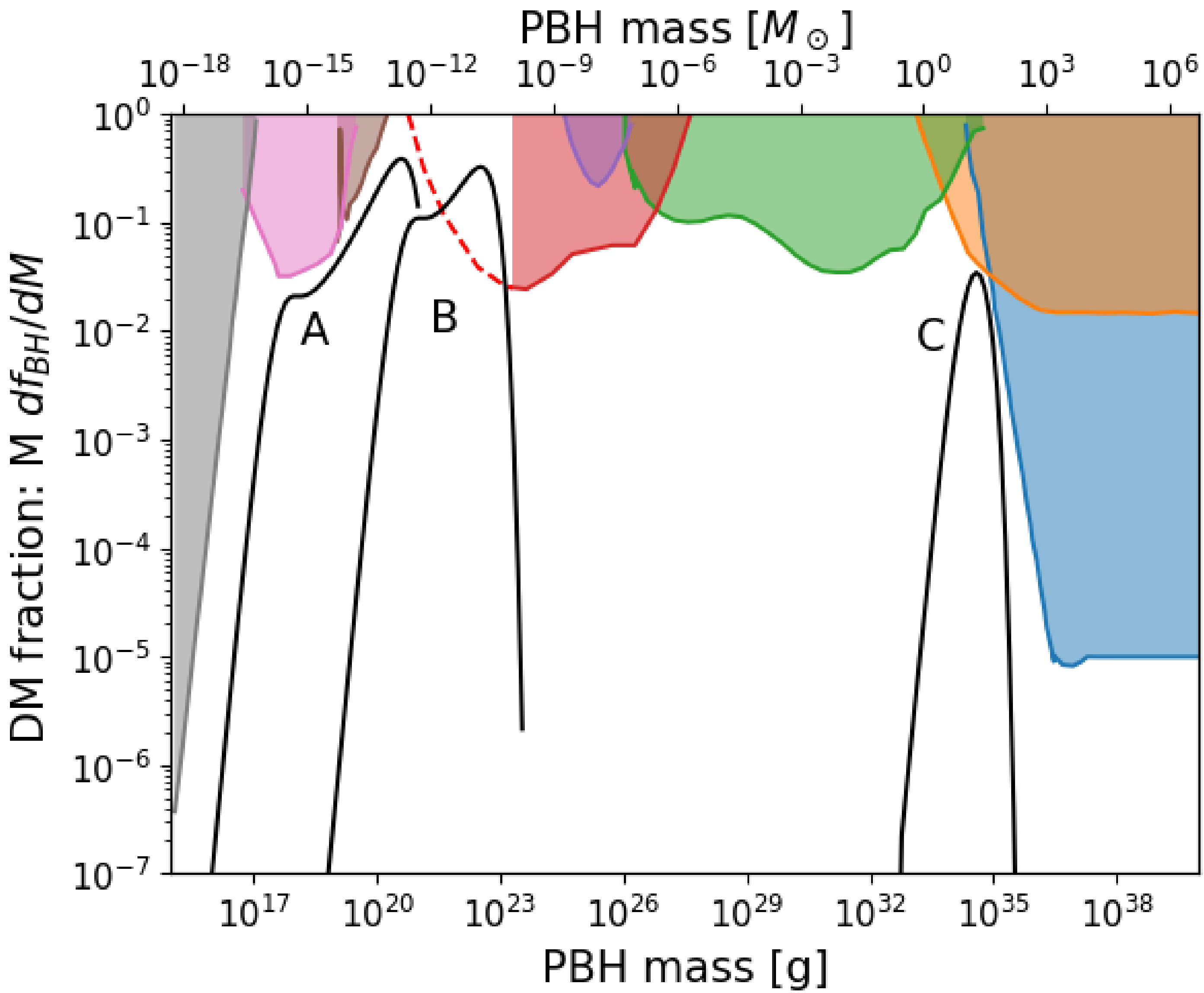
$$e^{x_{\mathrm{end,MD}} - x_{0,\mathrm{MD}}} \left(\frac{x_{0,\mathrm{MD}}}{x_{\mathrm{end,MD}}} \right)^{2/3} \left[1 + x_{\mathrm{end,MD}}^{-2/3} \Gamma\left(\frac{5}{3}, x_{0,\mathrm{MD}}, x_{\mathrm{end,MD}} \right) \right] = 1$$

*unless decay of solitons reheats the universe, [1][Phys. Rev. D **31**, 681]

Results – Q-balls



Results – oscillons from inflation



Summary

- Solitons form naturally in many BSM models (SUSY, axion, inflation, etc.)
- Does not require ad-hoc modifications to inflaton potentials
- PBH can be abundantly produced through clustering of solitons
- PBH generated in this way can make up 100% of dark matter (in low-mass regime), could potentially explain LIGO signals

Thank you!

Backup slides

Calculating overdensities (Q-ball case)

- Assume Q-ball charge Q is random variable with PDF $f_Q(Q)$ normalized such that $\int dQ\, f_Q(Q) = 1$
- Mass of a collection of Q-balls is given by

$$M = \sum_{i=1}^{N} \Lambda |Q_i|^{\alpha}$$

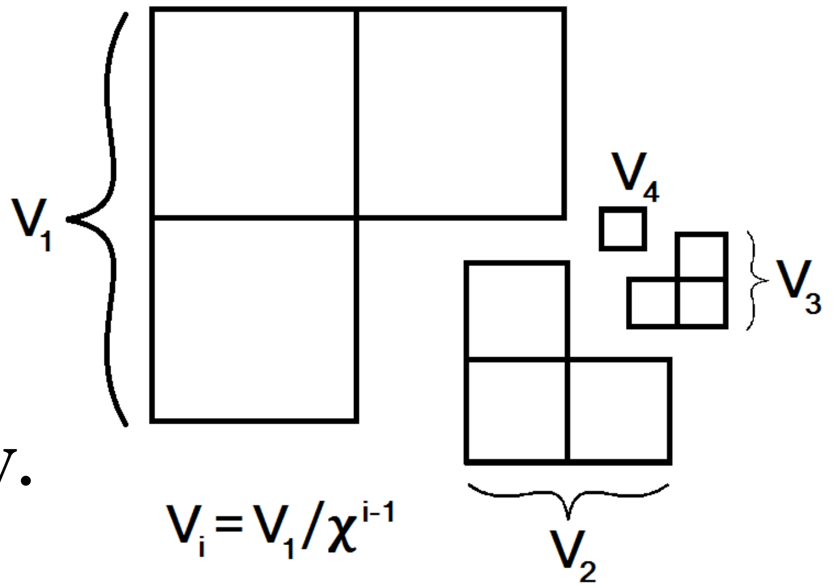
where $\Lambda^4 \sim V(\langle\varphi\rangle)$ and $\alpha=3/4$ for SUSY “flat direction” and $\alpha=2/3$ for “curved direction” Q-balls

Sum over length scales

- Consider arbitrary function of volume g(V):

$$\sum_{\{V\}} g(V) = g(V_1) + g(V_2) + \cdots = \sum_{i=1}^{i_{\max}} g(V_i) \approx \int_1^{i_{\max}} di\, g(V_1/\chi^{i-1})$$

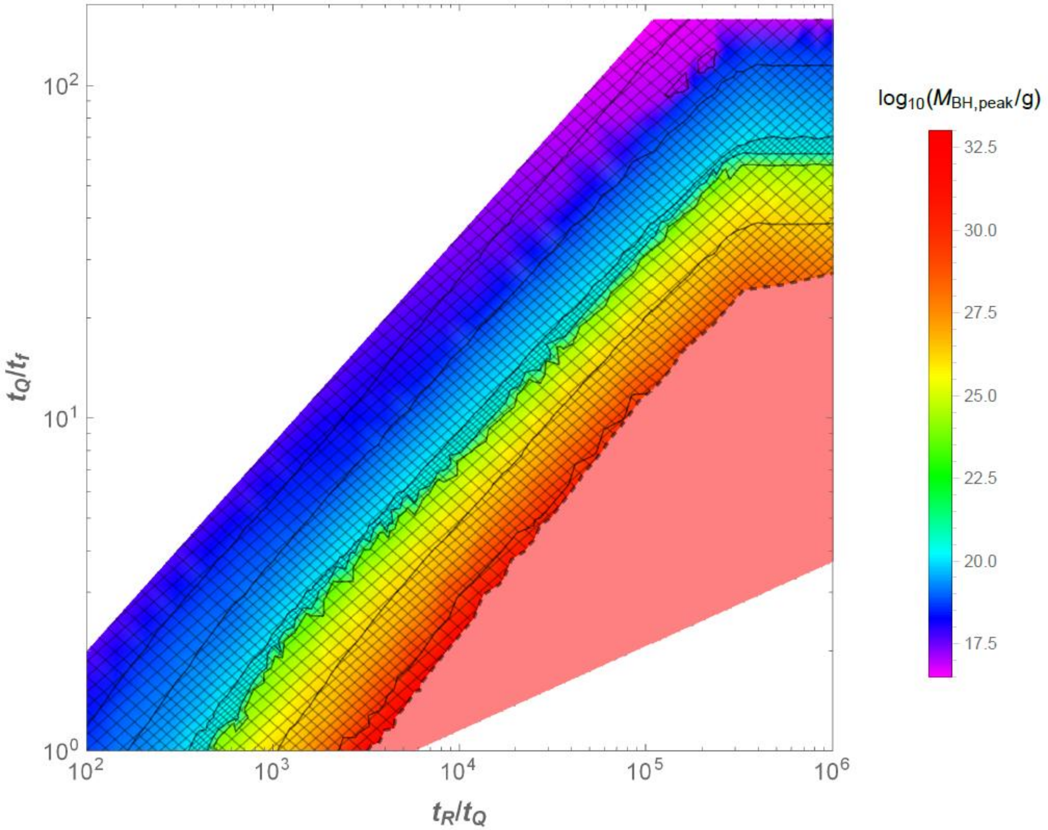
$$= \frac{1}{\ln\chi} \int_{V_{\min}}^{V_1} d(\ln V)\, g(V)$$



- χ determines degree of coarse-graining. Will assume χ=e for simplicity.

Results – Q-balls

- Long periods between fragmentation and MD era dilute Q-balls before clustering can begin and reduce PBH production
- Longer MD era amplifies perturbations and increases production
- Later fragmentation times result in heavier black holes due to larger horizon mass



Results – oscillons from inflation

- Avoids the "happy coincidence" of the Q-ball scenario where the solitons decay almost immediately after the universe becomes matter-dominated (oscillon decay reheats the universe)
- Requires fairly light scalar field– O(10 keV) for sub-lunar mass PBH, O(10^{-11} eV) for solar-mass PBH
- Stringent constraints on coupling of light scalars to SM from axion experiments – have inflaton decay through dark sector to SM to avoid this