



# *New View of Melting Nuclear Matter into Quark Matter*

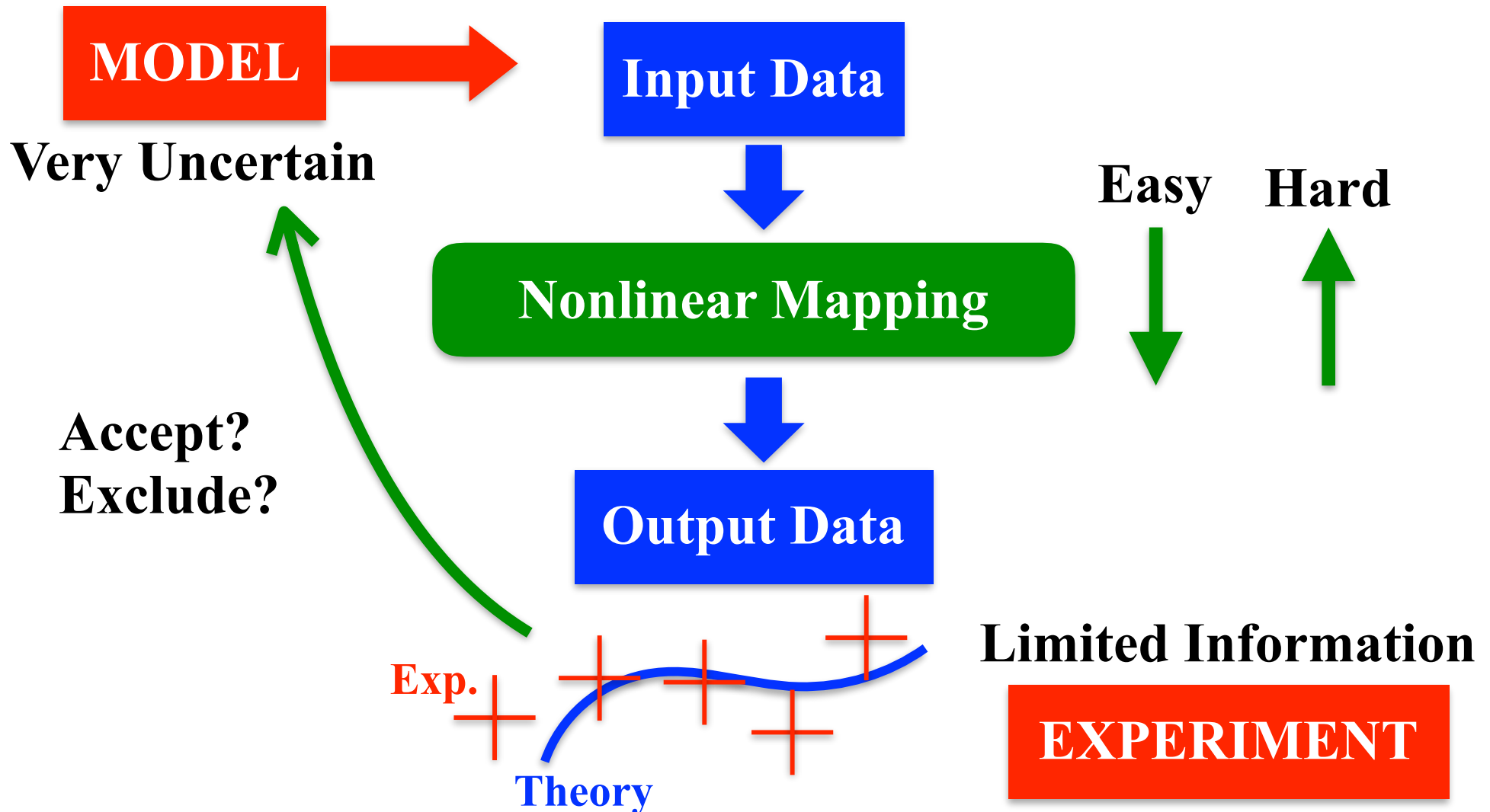


Kenji Fukushima

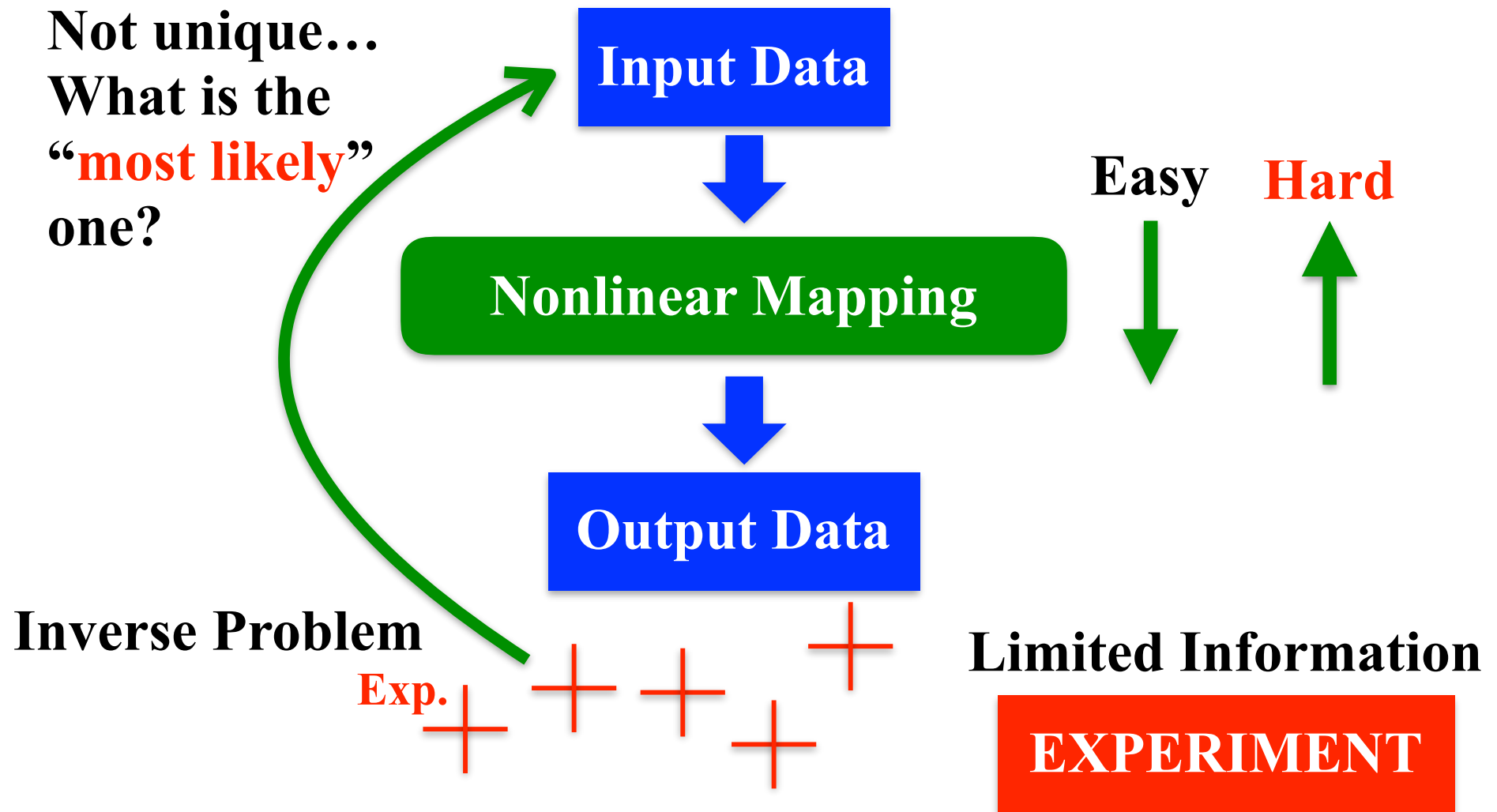
The University of Tokyo

— XIII Quark Confinement and the Hadron Spectrum —

# *QCD EoS from NS Observation*



# *QCD EoS from NS Observation*



# Model Independent Analysis



## Bayesian Analysis

$B$  :  $M$ - $R$  Observation

$A$  : EoS Parameters

(Bayes' theorem)      Normalization

$$\underline{P(A|B)} \cancel{P(B)} = \underline{P(B|A)} \underline{P(A)}$$

**Want to know**

**Likelihood**

**prior**

Calculable by TOV

**Model**

**Model must be assumed.**

**EoS parametrization must be introduced.**

**Integration in parameter space must be defined.**

# Model Independent Analysis

- Bayesian Analysis
- Supervised Learning



$$\{M_i, R_i\} \quad \{P_i\} = F(\{M_i, R_i\}) \quad \{P_i\}$$

~ **15 Points**

observation data hopefully  
available in the future

~ **5 Points**

corresponding to  
5 polytropes (your choice)

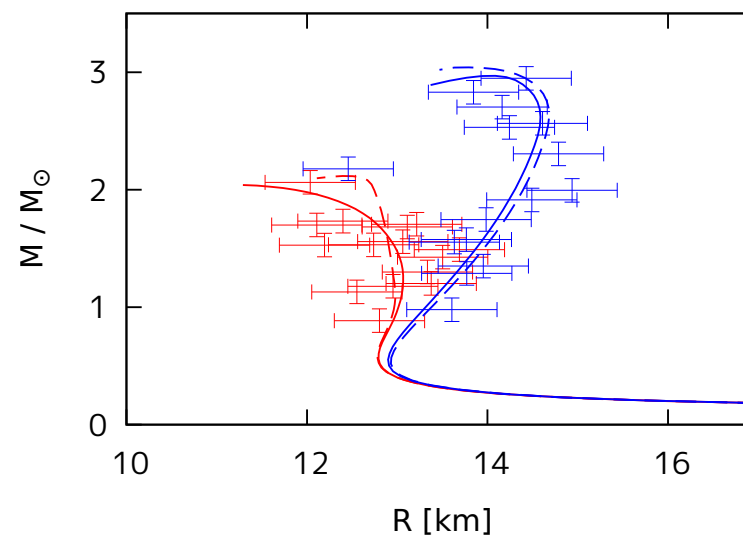
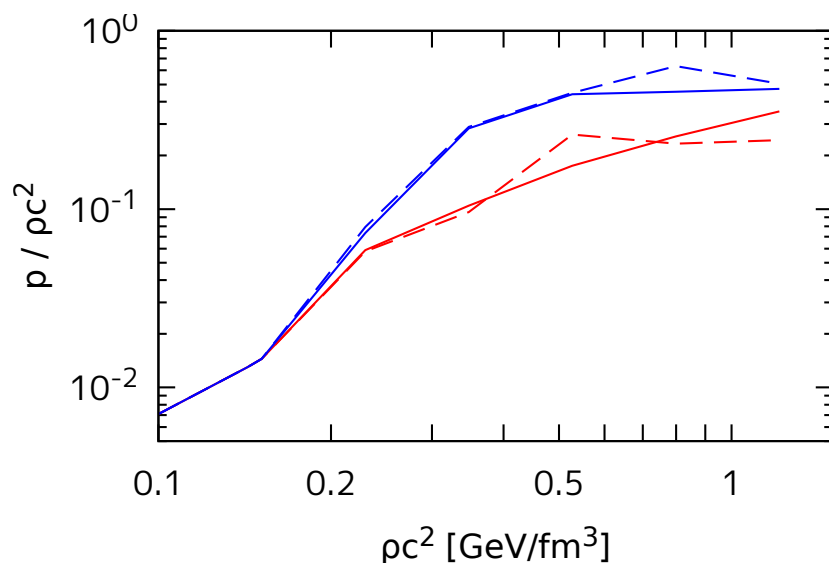
# Machine Learning



## Test with mock data

Fujimoto-Fukushima-Murase, PRD(2018)

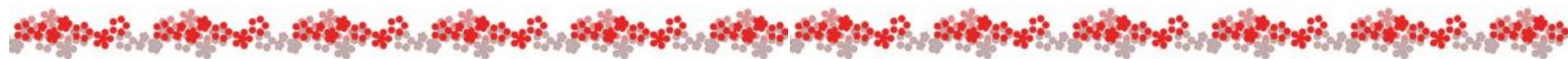
(not fitted results but reconstructed!)

### Two Typical Examples (not biased choice)



-  : randomly generated original EoS
-  : reconstructed EoS and guessed  $M$ - $R$

# Machine Learning



## Overall performance test

Fujimoto-Fukushima-Murase, PRD(2018)

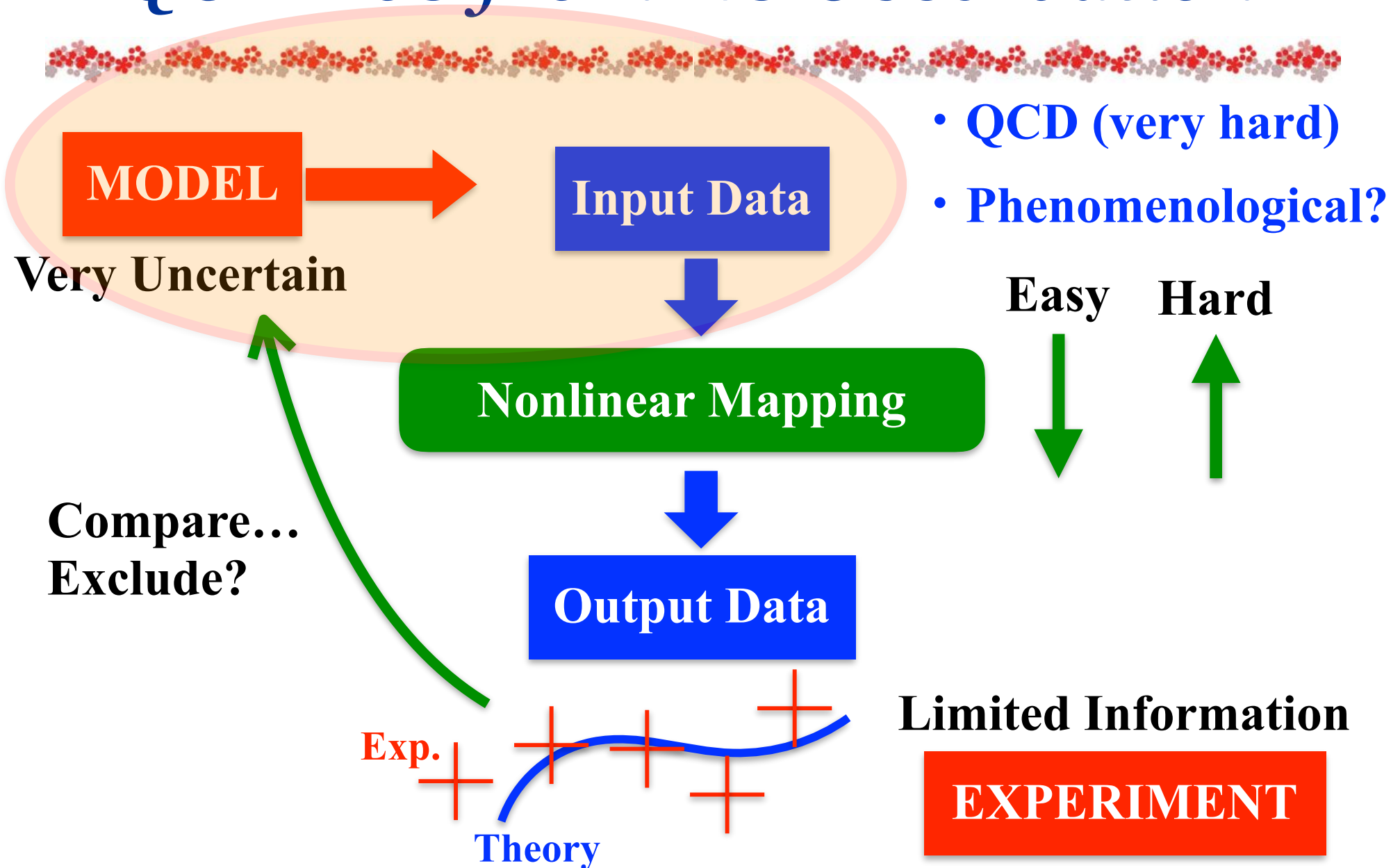
Mass ( $M_{\odot}$ )	0.6	0.8	1.0	1.2	1.4	1.6	1.8
RMS (km)	0.16	0.12	0.10	0.099	0.11	0.11	0.12

(with  $\Delta M = 0.1 M_{\odot}$ ,  $\Delta R = 0.5$  km)

$0.5\text{km}/\sqrt{15} \simeq 0.13\text{km}$       **Too good to be true?**

**Credibility estimate has not been done for simplicity, but it can be included in the learning process (in progress).**

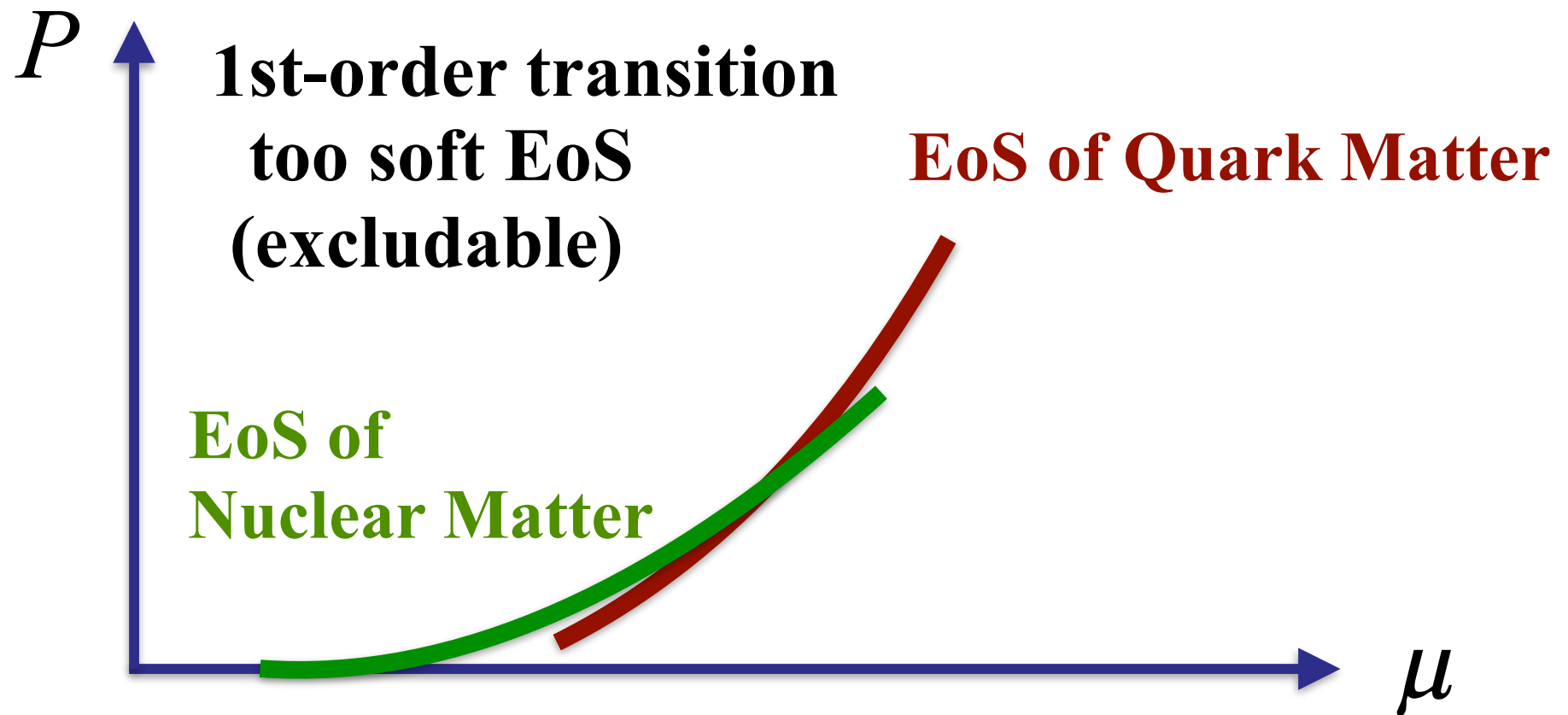
# *QCD EoS from NS Observation*



# Quark Matter ?



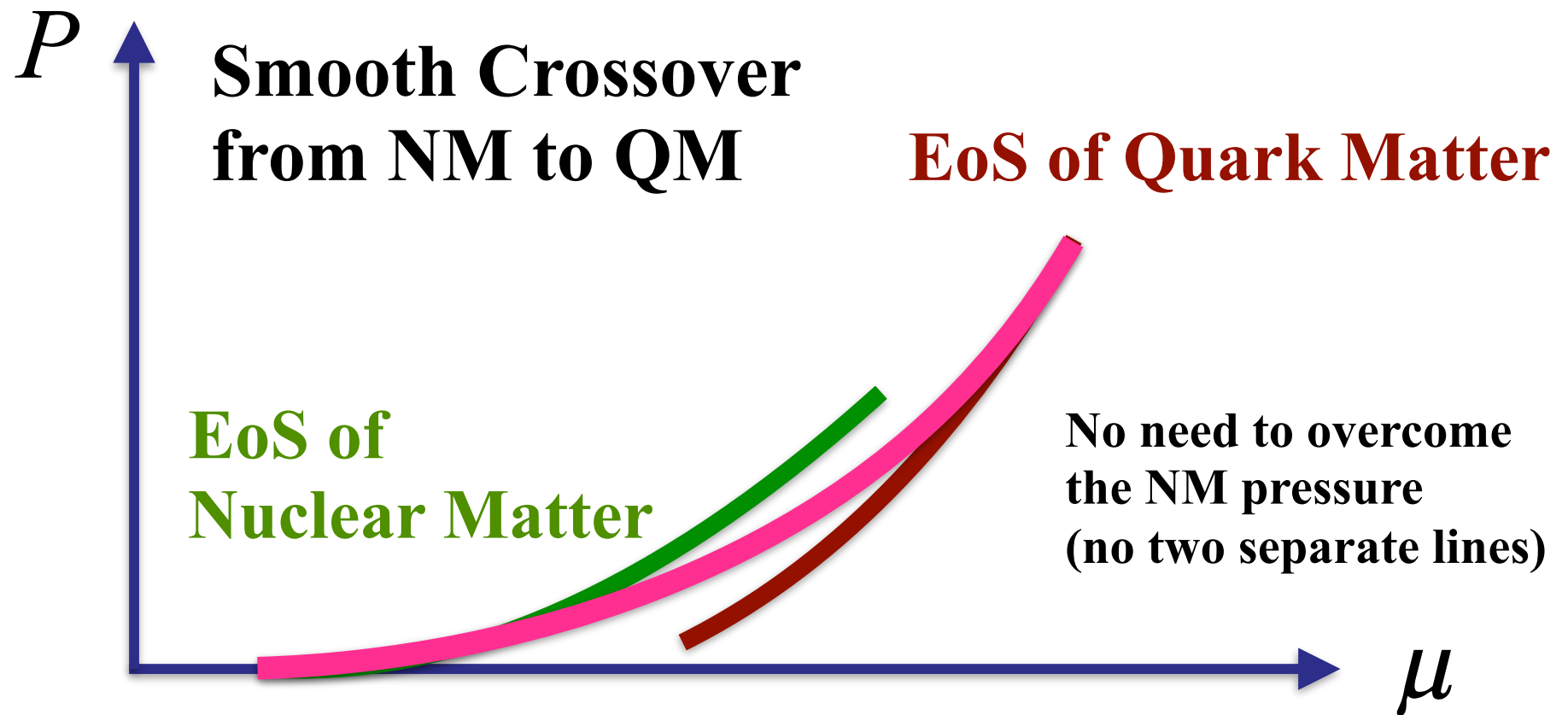
## Old View



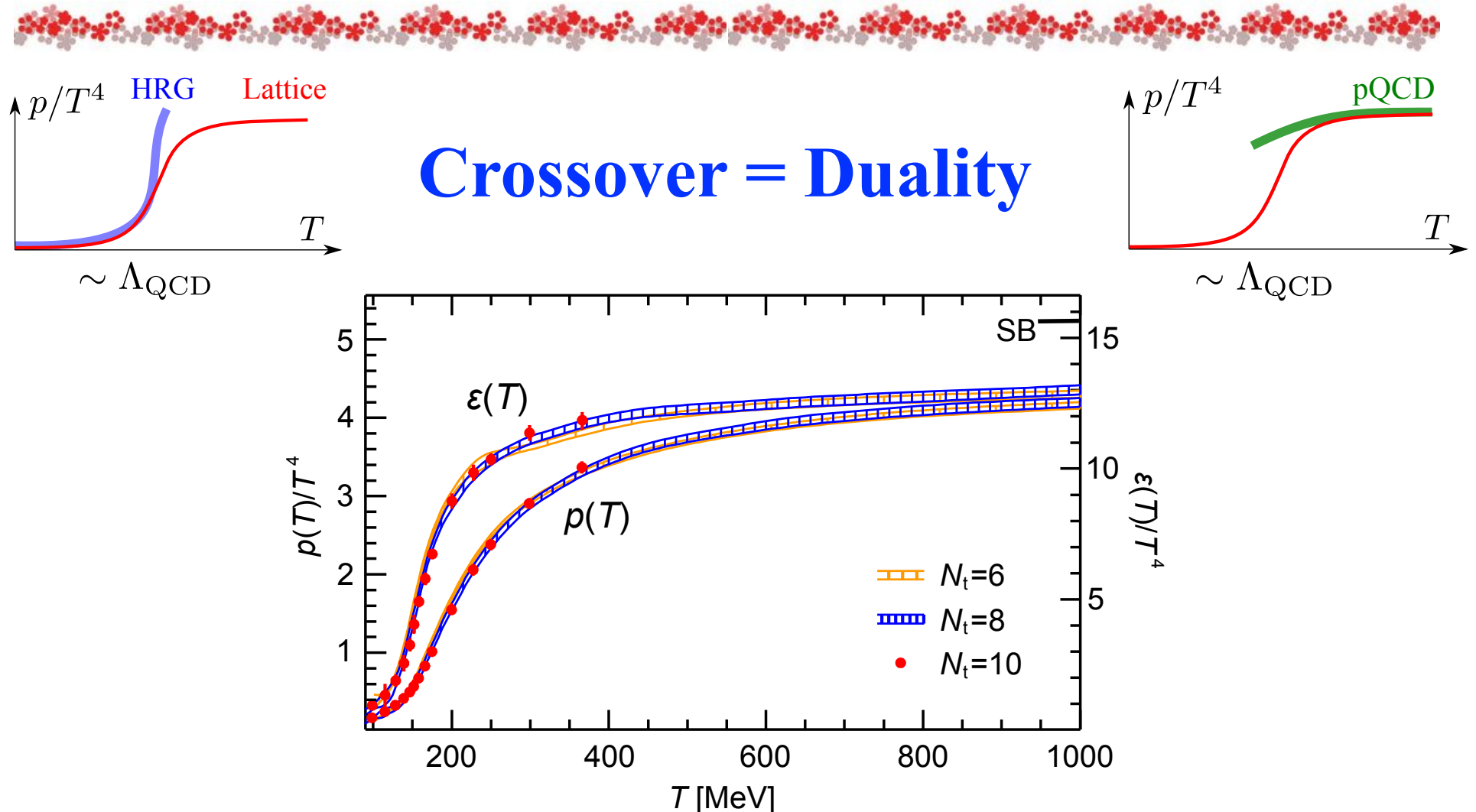
# Quark Matter ?



## Another Possible View



# Lesson from High- $T$ QCD Matter

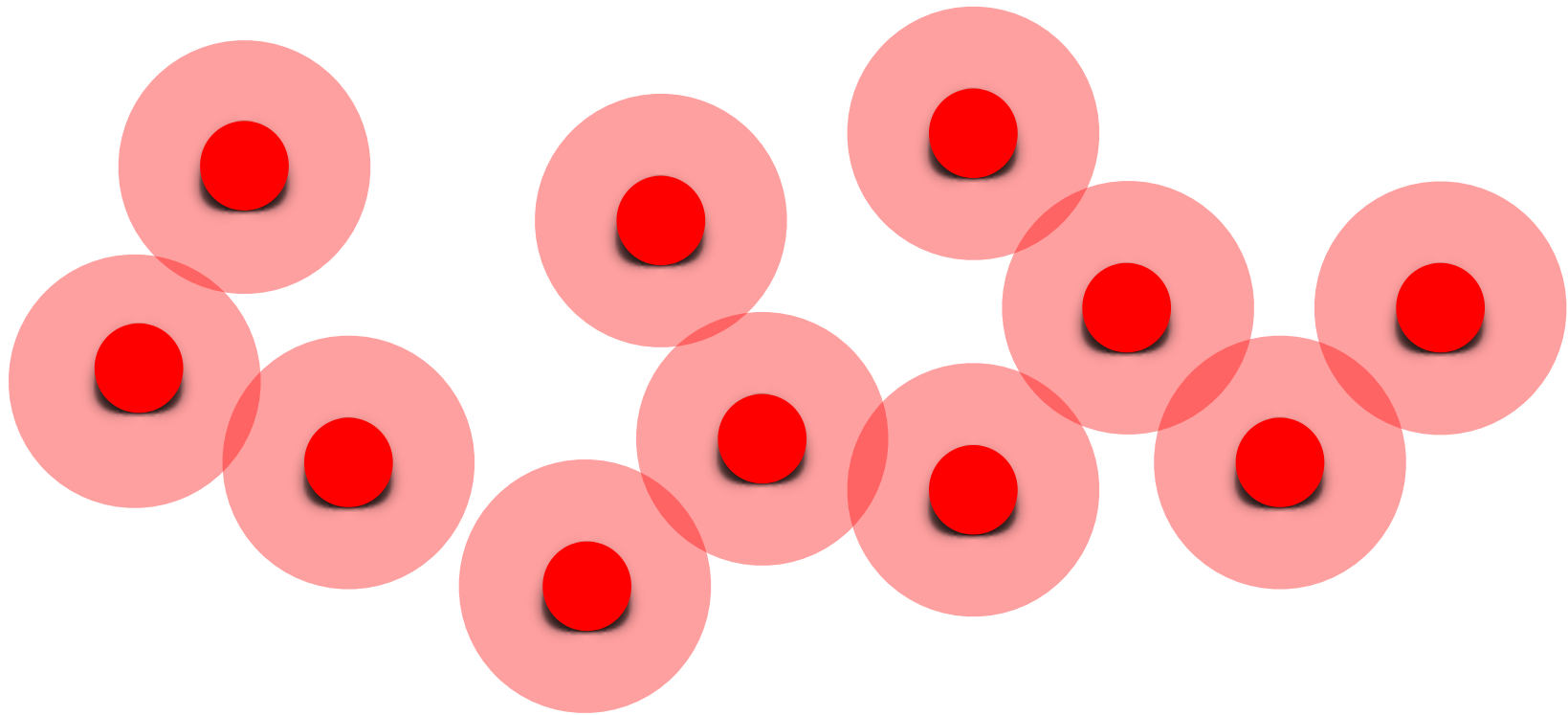


**Hadron gas has a larger pressure saturated by interaction**

# *Lesson from High-T QCD Matter*



**Dominated by (non-interacting) mesons**



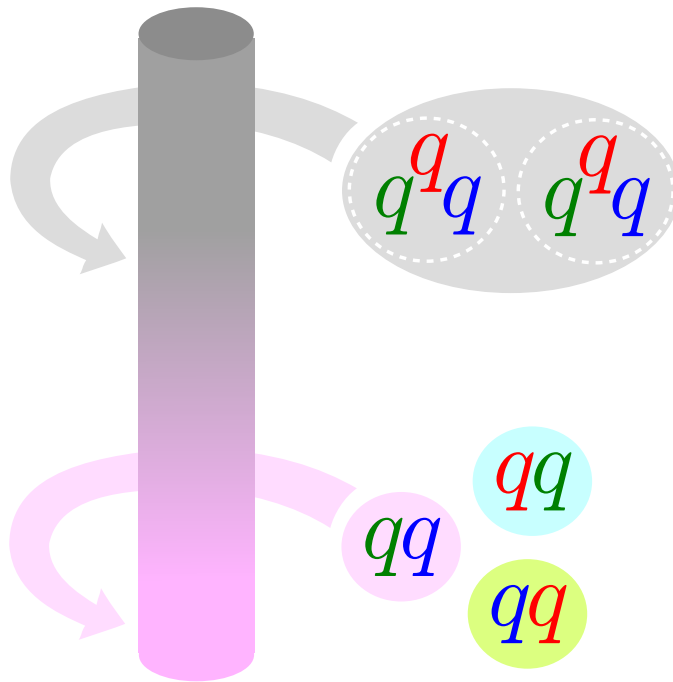
**Overlap of meson wave-functions → Quark mobility**

# *Lesson from Dense QM*



**Hadronic and color-superconducting matter indistinguishable**

**Continuity of superfluid vortices**

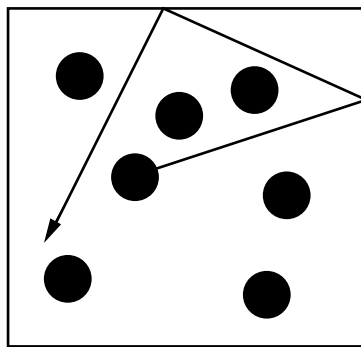


**Alford-Baym-Fukushima-  
-Hatsuda-Tachibana (2018)**

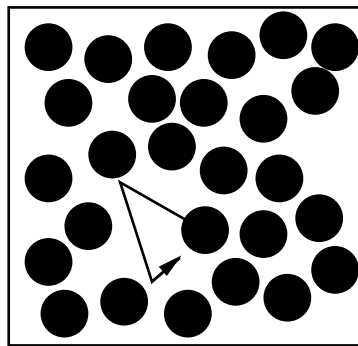
**Confinement / deconfinement  
very smooth change at high density  
(center symmetry badly broken)**

# Classical Percolation Scenario

## Percolation model by Helmut Satz

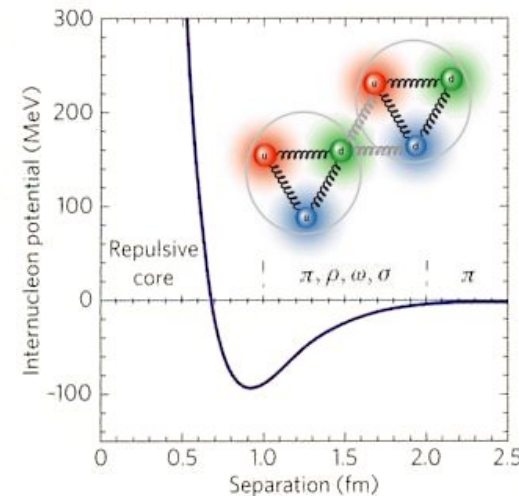


(a)



(b)

Fig. 7. States of hard core baryons: full mobility (a), “jammed” (b)



**Hard core radius:**  $R_{hc} = R_0/2 = 0.4 \text{ fm}$

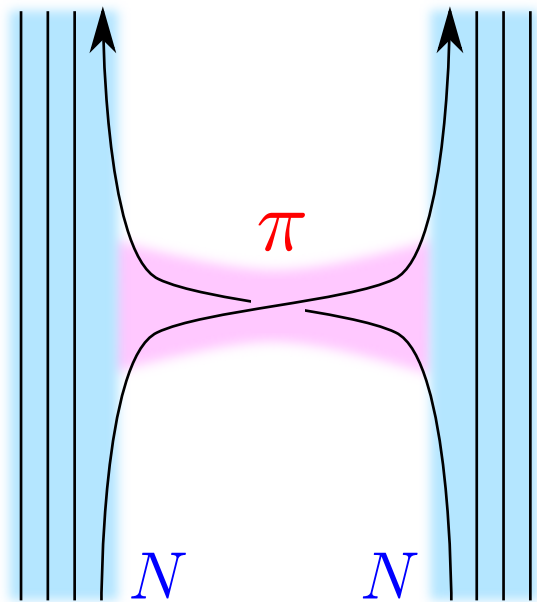
**Clustering density:**  $n_p^{hc} \simeq 2/V_0 \sim 5.5n_0$

**But, baryons are strongly interacting unlike mesons**

# Refined Percolation Scenario



## Baryon Interactions



**When baryons interact,  
quarks are inevitably exchanged**

**Nuclear matter knows  
quark d.o.f. via interactions**

$$P \sim \mathcal{O}(N_c)$$

**Confined NM and deconfined QM indistinguishable!**  
(cf. Quarkyonic Matter)

# Refined Percolation Scenario



## Duality implies:

**NM EoS extrapolated upward to approximate QM EoS**  
**(common strategy implicitly assumed)**  
**QM EoS extrapolated downward to approximate NM EoS**  
**(exotic strategy but works good! Fukushima-Kojo (2016))**

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## THE QUARKYONIC STAR

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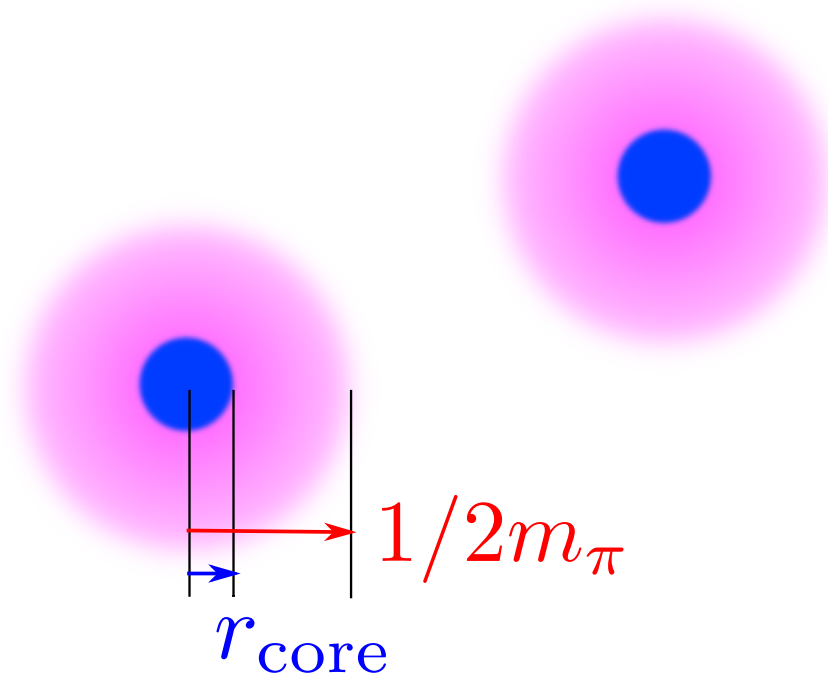
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# *Refined Percolation Scenario*



**Dilute baryonic gas**

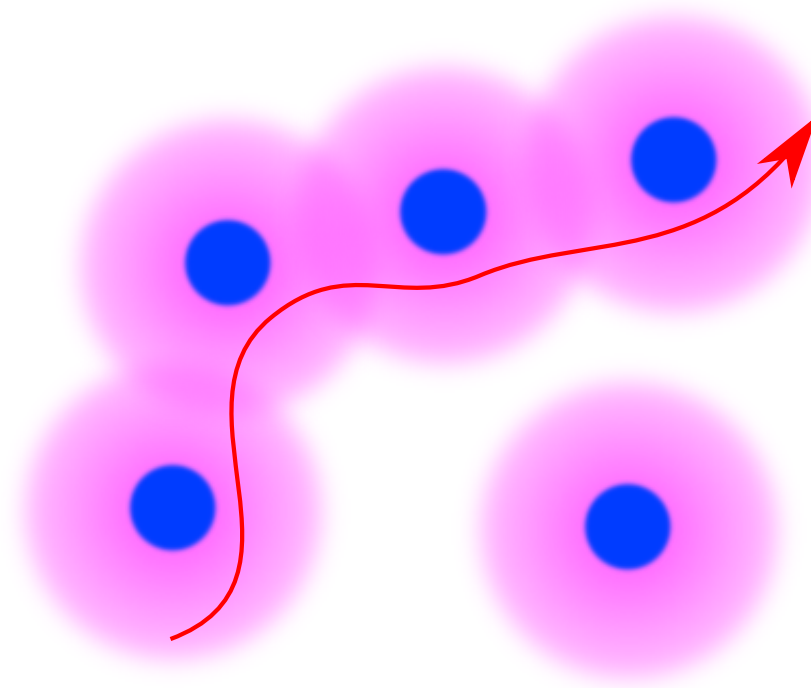


(as discussed by G. Baym)  
see: arXiv:0806.2706

# *Refined Percolation Scenario*



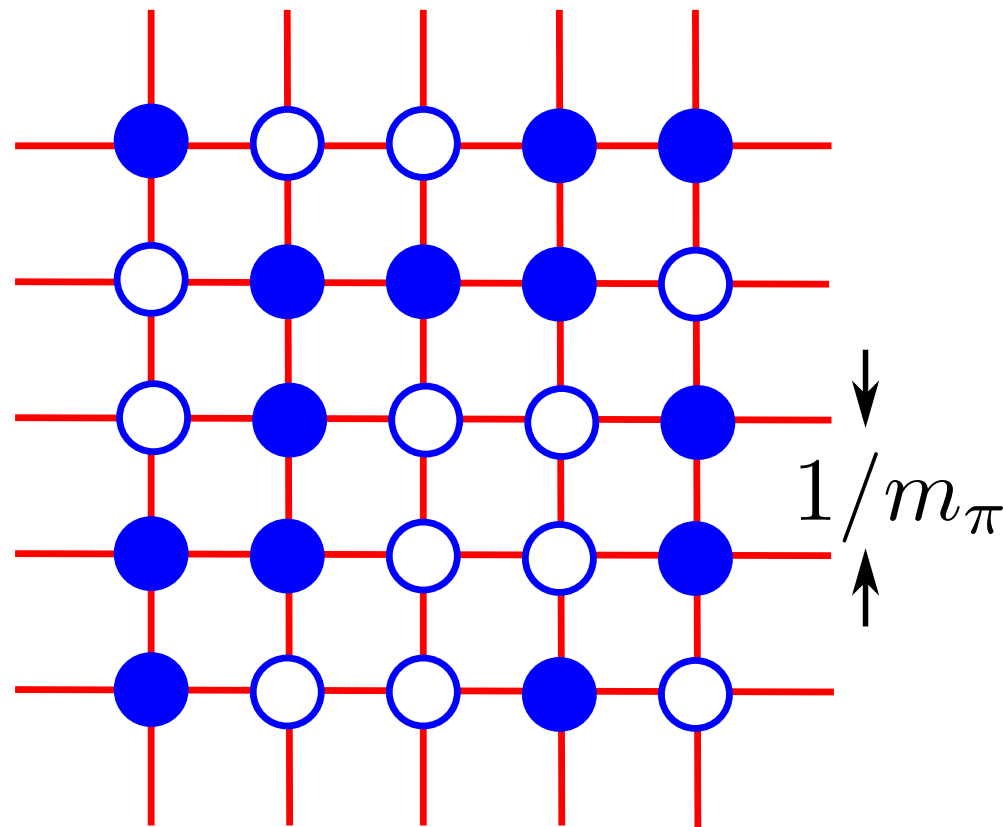
**Dense baryonic gas**



# Simple Toy Modeling



In the limit of “heavy” nucleons (as in the large  $N_c$ )  
the physics can be modeled in terms of the site percolation:



# Simple Toy Modeling



## Increasing Density ~ “Site Percolation” in $d = 3$

$p_c \simeq 0.31$       Classical critical probability  
of particles sitting on the site

(Gaunt-Ruskin 1978, Aharony-Binder 1980)

**Assume** (1) Interaction cloud size  $\sim 1/(2m_\pi) \sim 0.7\text{fm}$

(2)  $p = 1$  means complete saturation

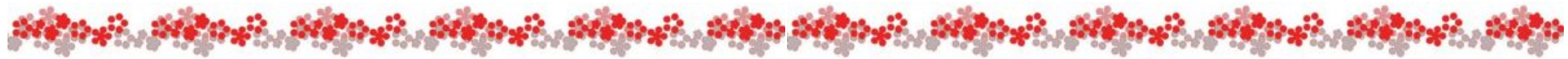


**Site-spacing  $\sim 1.1\text{fm}$**

$$n_c \simeq 0.23 \text{ fm}^{-3} \sim 1.4n_0$$

**Not an unphysical number but too small (?)**

# Simple Toy Modeling



## Quantum Percolation Model

$$H = \sum_n |n\rangle \varepsilon_n \langle n| + \sum_{n \neq m} |n\rangle V_{nm} \langle m|$$

Site-Percolation	$V = (\text{const.})$
------------------	-----------------------

$$P(\varepsilon_n) = p\delta(\varepsilon_n - \varepsilon_A) + (1 - p)\delta(\varepsilon_n - \varepsilon_B)$$

Bond-Percolation	$\varepsilon = (\text{const.})$
------------------	---------------------------------

$$P(V_{nm}) = p\delta(V_{nm} - V_A) + (1 - p)\delta(V_{nm} - V_B)$$

# Simple Toy Modeling



## Quantum Percolation Model

$$H = \sum_n |n\rangle \varepsilon_n \langle n| + \sum_{n \neq m} |n\rangle V_{nm} \langle m|$$

Site-Percolation
------------------

 $V = (\text{const.})$

$$P(\varepsilon_n) = p\delta(\varepsilon_n - \varepsilon_A) + (1 - p)\delta(\varepsilon_n - \varepsilon_B)$$

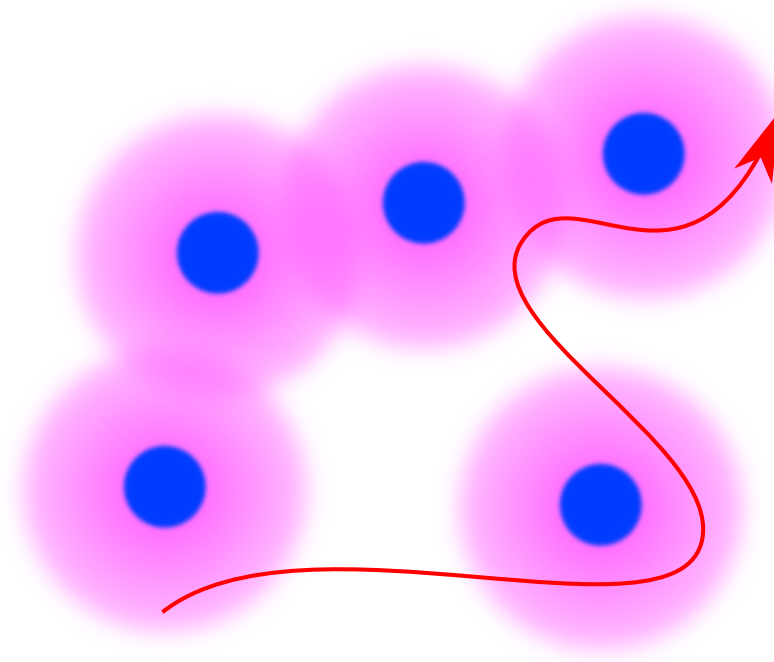
$$\varepsilon_A = -\varepsilon_B \rightarrow \infty \quad (\text{quarks tightly bound in } N)$$

## Classical Site-Percolation Limit

# *Simple Toy Modeling*



**Percolation eased by quantum tunneling?**



# *Simple Toy Modeling*



**Quantum Fluctuations**  $p_c \rightarrow p_q$

One might naively think that quantum tunneling makes:

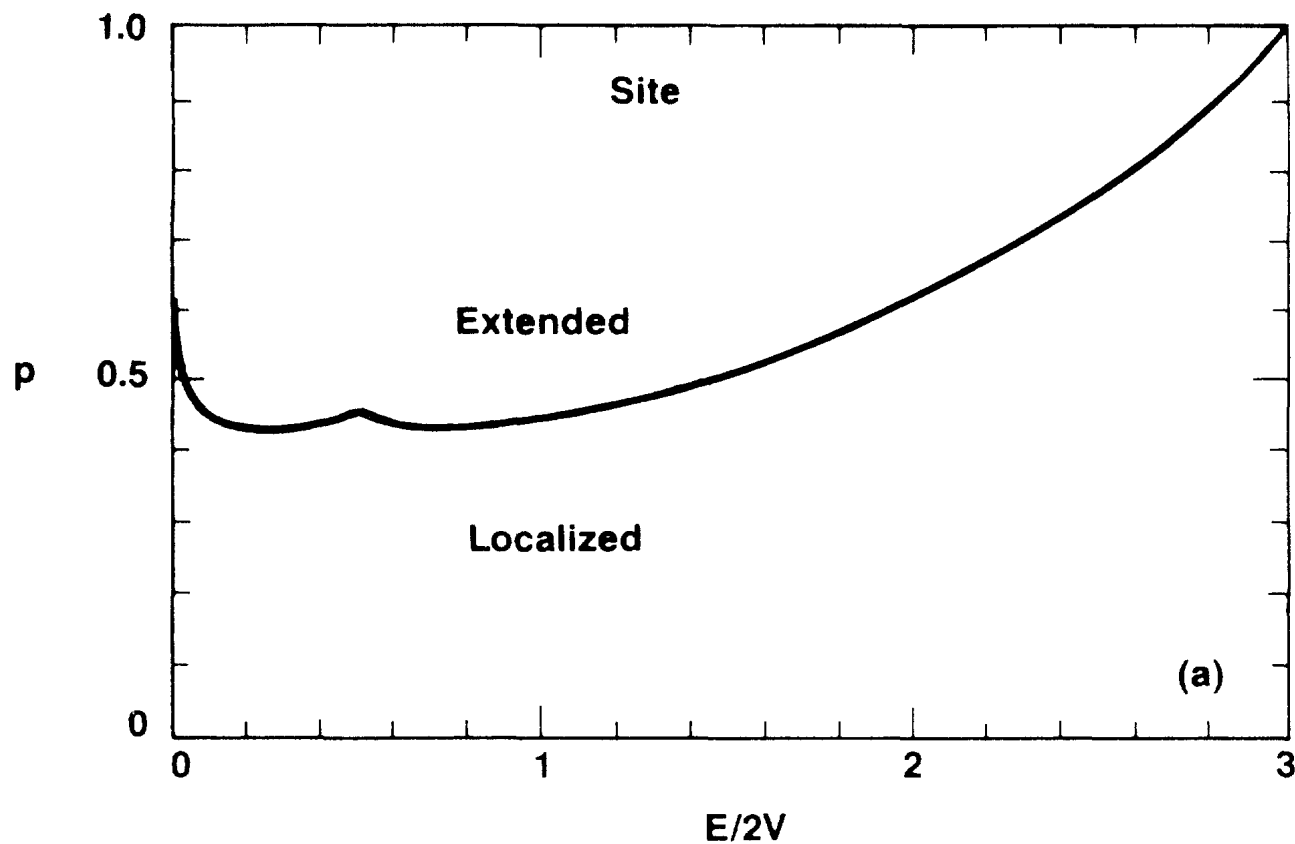
$$p_q < p_c \quad (?)$$

However, this is **NOT** true, and the answer should be:

$$p_q > p_c \quad (!)$$

**Quantum Fluct. ~ Impurities ~ Anderson Localization**

# $d=3$ Quantum Site-Percolation



**Minimum:**  $p_q \simeq 0.44$

(Soukoulis-Li-Grest 1992)

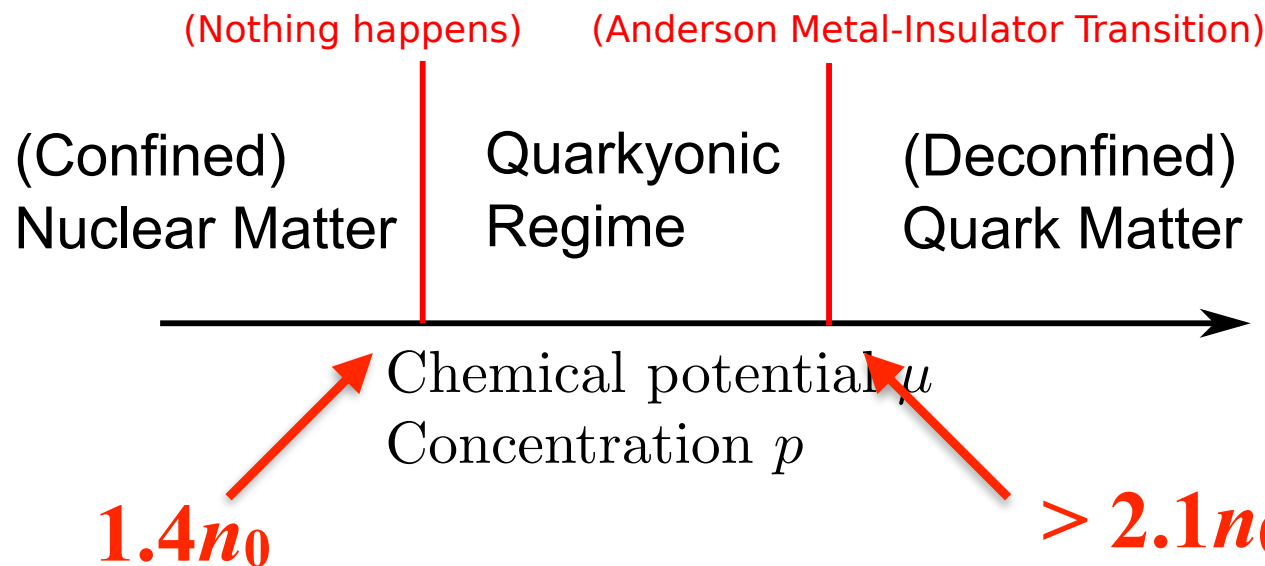
# $d=3$ Quantum Site-Percolation



$$p_q \simeq 0.44 \quad \longrightarrow \quad n_c \simeq 0.33 \text{ fm}^{-3} \sim 2.1n_0$$

Quantum percolation at  $p = p_q$

Classical percolation at  $p = p_c$



Precise value may depend on  $E/2V$  and crystal lattice (not square lattice but bcc/fcc)

# *Work in Progress*



## ■ **Realistic Model Building**

- Nuclear Matter + **Many-body Localization** of Quarks
- Pion Clouds in NM → Quasi-quarks in QM
- Quantifying the EoS ?

## ■ **Novel Implication**

- Scaling properties near the (pseudo) percolation point
- New (to QCD but not to cond-mat) mechanism of confinement — like **metal-insulator** transition

## ■ **Fundamental-level Question**

- No clear order parameter : similarity between quark confinement and the Anderson localization