The spectrum of charmonium and glueballs: adding the light hadrons

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FOR5269: Future methods for studying confined gluons in QCD

https://confluence.desy.de/display/for5269

Spokesperson: Francesco Knechtli

Main Goals:

- **Disconnected contributions in charmonium**
- String breaking in hybrid potentials
- **Glueballs in full dynamical QCD**
- **Multilevel algorithms for glueballs**
- Novel schemes for molecular dynamics
- **Connection of distillation and multi-grid**
- Multilevel Monte Carlo for trace estimation

Outline:

- Lattice Quantum Chromo Dynamics (LQCD)
- Hadron spectroscopy and Distillation
- New ensembles for glueball measurements
- Very preliminary results and outlook

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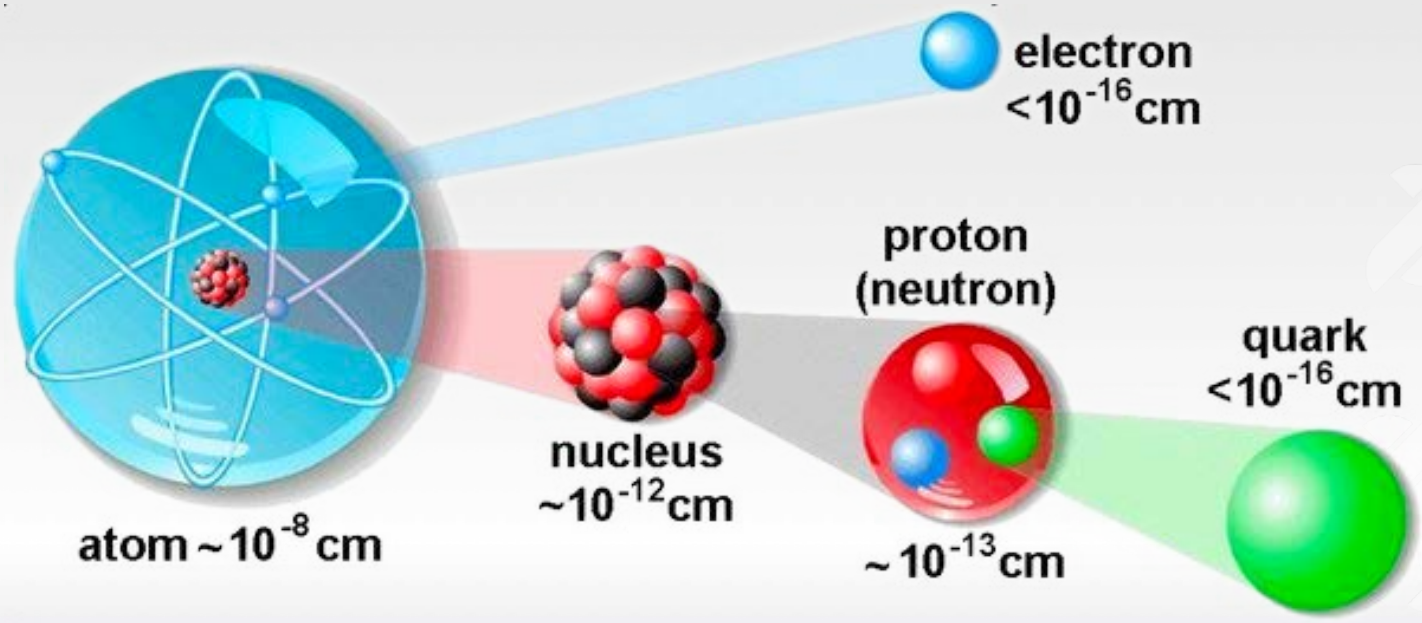
Dimensional Hierarchy



Strong force: responsible for interactions between quarks and gluons

- confines quarks into hadrons (pion, proton, neutron, etc)
- binds protons and neutrons to form nuclei of the atoms

Quantum Chromodynamics (QCD):

- fundamental theory that describes the strong interactions
- parameters: quark masses and coupling constant

The Standard Model, Elementary Particles

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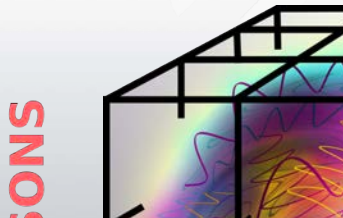
mass →	≈2.3 MeV/c²	≈1.275 GeV/c²	≈173.07 GeV/c²	0	≈126 GeV/c²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u	c	t	g	H
	up	charm	top	gluon	Higgs boson
QUARKS	≈4.8 MeV/c²	≈95 MeV/c²	≈4.18 GeV/c²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d	s	b	γ	
	down	strange	bottom	photon	
	0.511 MeV/c²	105.7 MeV/c²	1.777 GeV/c²	91.2 GeV/c²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e	μ	τ	Z	
	electron	muon	tau	Z boson	
LEPTONS	<2.2 eV/c²	<0.17 MeV/c²	<15.5 MeV/c²	80.4 GeV/c²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e	ν_μ	ν_τ	W	
	electron neutrino	muon neutrino	tau neutrino	W boson	

GAUGE BOSONS



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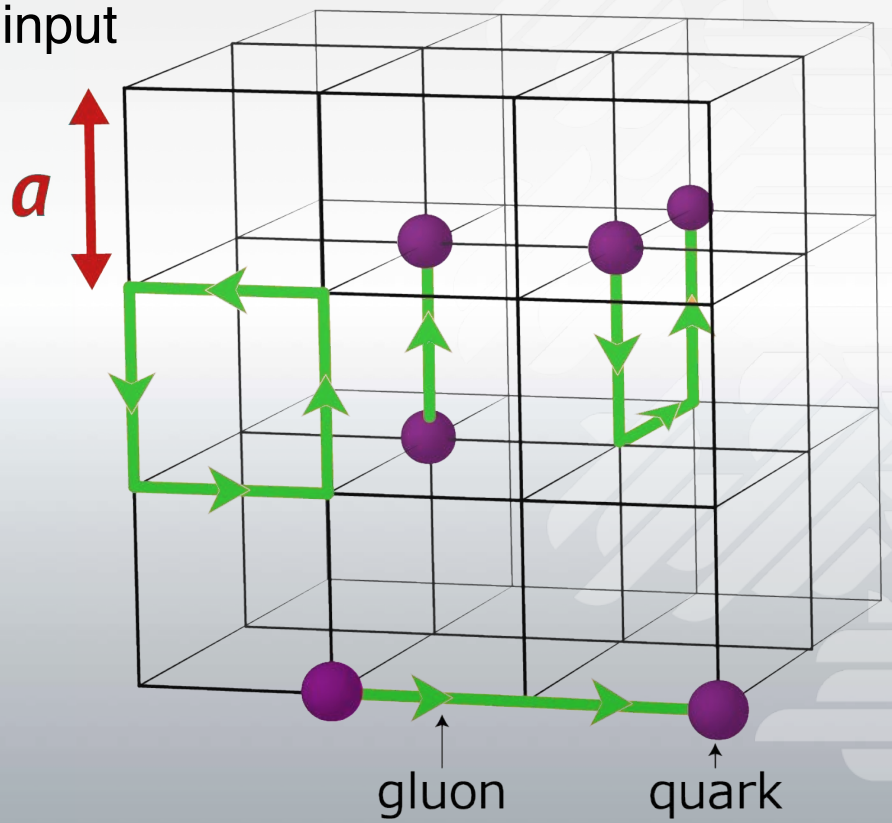
Numerical simulations of QCD using Monte Carlo methods

- well-established framework for non-perturbative QCD
- ab-initio calculations, action only input
- discretization of space-time,
- introduce lattice spacing a
- gluons, link variables, par. trans.
- quarks, covariant derivatives
- Dirac operator, quark propagator
- discretized forms must reduce

  to continuum forms in the limit

$$a \to 0 \quad (L \to \infty)$$



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Monte Carlo methods: statistical treatment of the theory

- create gluon configurations using QCD action
- average over configurations, error $\sim 1/\sqrt{N_{config}}$
- we need 1000s of (statistically independent) configurations
- observables: correlation functions in terms of 'quark propagators'
- building block of hadronic measurements on the lattice
- inversion of the Dirac operator, most intensive part of calculations
- very large ($\sim 10^8 \times 10^8$), but sparse matrix (most elements zero)
- highly optimized algorithms with good scaling behavior

Distillation: quark field smearing with $N_v \sim O(10^2)$ Laplacian eigenmodes

- we need $4 \times N_v \times N_T$ inversions to get 'quark perambulators'

$N_f = 3 + 1$ Lattice Ensembles

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3 degenerate light quarks (up, down, strange)
1 physical charm quark => η_c ~ 3 GeV

light : m_π ~ 420 MeV, heavy: m_π ~ 1 GeV, glueball ~ 2 GeV!

Coarse lattices: a = 0.054 fm @ β = 3.24

- A0 - light : $16^3 \times 72$
- A1 - light : $32^3 \times 96$
- A2 - light : $48^3 \times 128$

} light quark mass at physical average
=> many decay channels for glueballs!

- A0 - heavy : $24^3 \times 72$
- A1 - heavy : $32^3 \times 96$
- A2 - heavy : $48^3 \times 128$

} - 2000 configurations each (8000 MDUs)
- eigenmodes on every 4th configuration
=> 500 charm and light perambulators
=> glueball can only decay into two pions!

Fine lattice: a = 0.043 fm @ β = 3.43

- B - light : $48^3 \times 144$

R. Hoellwieser et al.. Eur. Phys. J. C **80** (2020) no.4. 349

New glueball ensembles, preliminary results

name	A10	A11	A12
volume	$24^3 \times 72$	$32^3 \times 96$	$48^3 \times 144$
P_{acc}	0.971(1)	0.947(1)	0.924(2)
configs	2000	2000	2000
MDUs	8000	8000	8000
#eigenvectors	100	200	600 / 300
perambulatorT	20-52	24-72	30-114
done	500	500	50
t_0/a^2	5.115(30)	5.074(16)	5.1093(79)
τ_{t_0}	34(12)	40(14)	54(22)
$\chi^{1/4}$ [MeV]	146(1)	148(1)	147(1)
m_π [MeV]	**1002(4)**	**1000(2)**	**998(2)**
m_{a_0} [MeV]	1786(41)	1795(25)	
m_{η_c} [MeV]	**2979(3)**	**2980(1)**	**2976(3)**
$m_{\chi_{c0}}$ [MeV]	3541.5(6.0)	3542.7(4.6)	
"glueball" 0^{++}	2090(310)	2120(140)	

preliminary, only gluonic observables, no decays!!!

New glueball ensembles, measurements, costs…

name	A10	A11	A12
volume	$24^3 \times 72$	$32^3 \times 96$	$48^3 \times 144$
cores	576	768(792)	2304
core-h / traj.	62	215	1460
core-h / rwf.	5	19	106
core-h / mass	2	9	74
core-h / eigen	12	79	879 / 439
core-h / perc	355	2932	- / 40k
core-h / perl	864	7681	- / 114k
core-h / cfg.	1362	11150	3100
core-h total	**1M**	**6M**	**7M + 3M**
size cfg. [GB]	0.54	1.7	8.6
size evs. [GB]	4.5	28	427 / 213
size per. [GB]	1.4	12	336 / 84
tot. / cfg. [GB]	8	54	1108 / 390

Light/Charm Correlators without disconnected contributions

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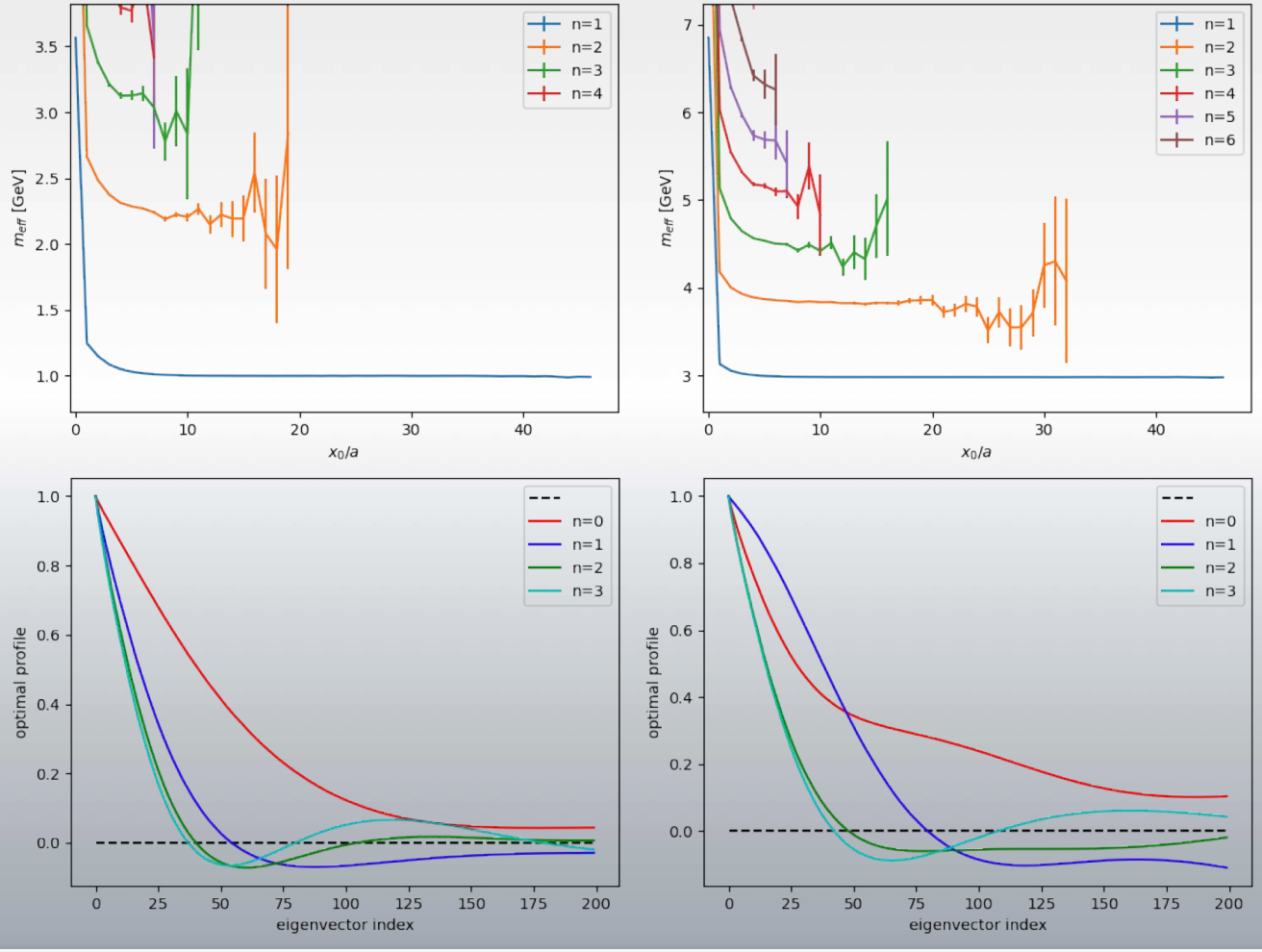
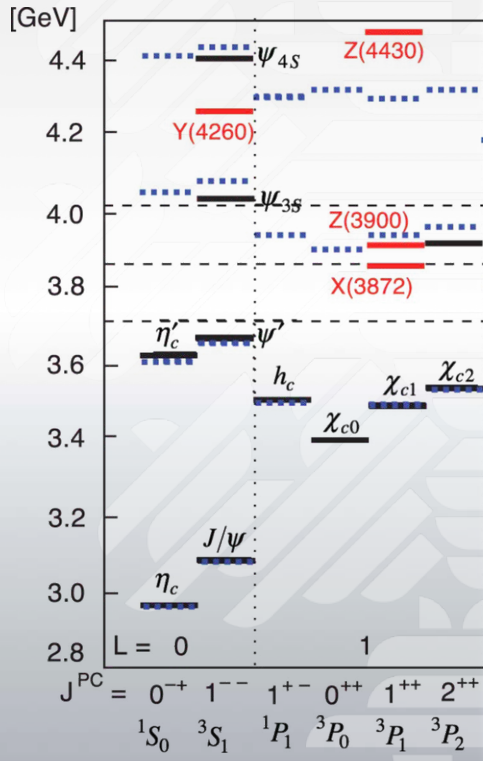
Solve generalized eigenvalue problem (GEVP) to access excited states on A1 - heavy (32^3 x 96) for, e.g., the pion ($\bar{q}q$, left) and η_c ($\bar{c}c$, right)





Hosaka et.al., 2016

Status of isoscalar 0++ with disconnected contributions

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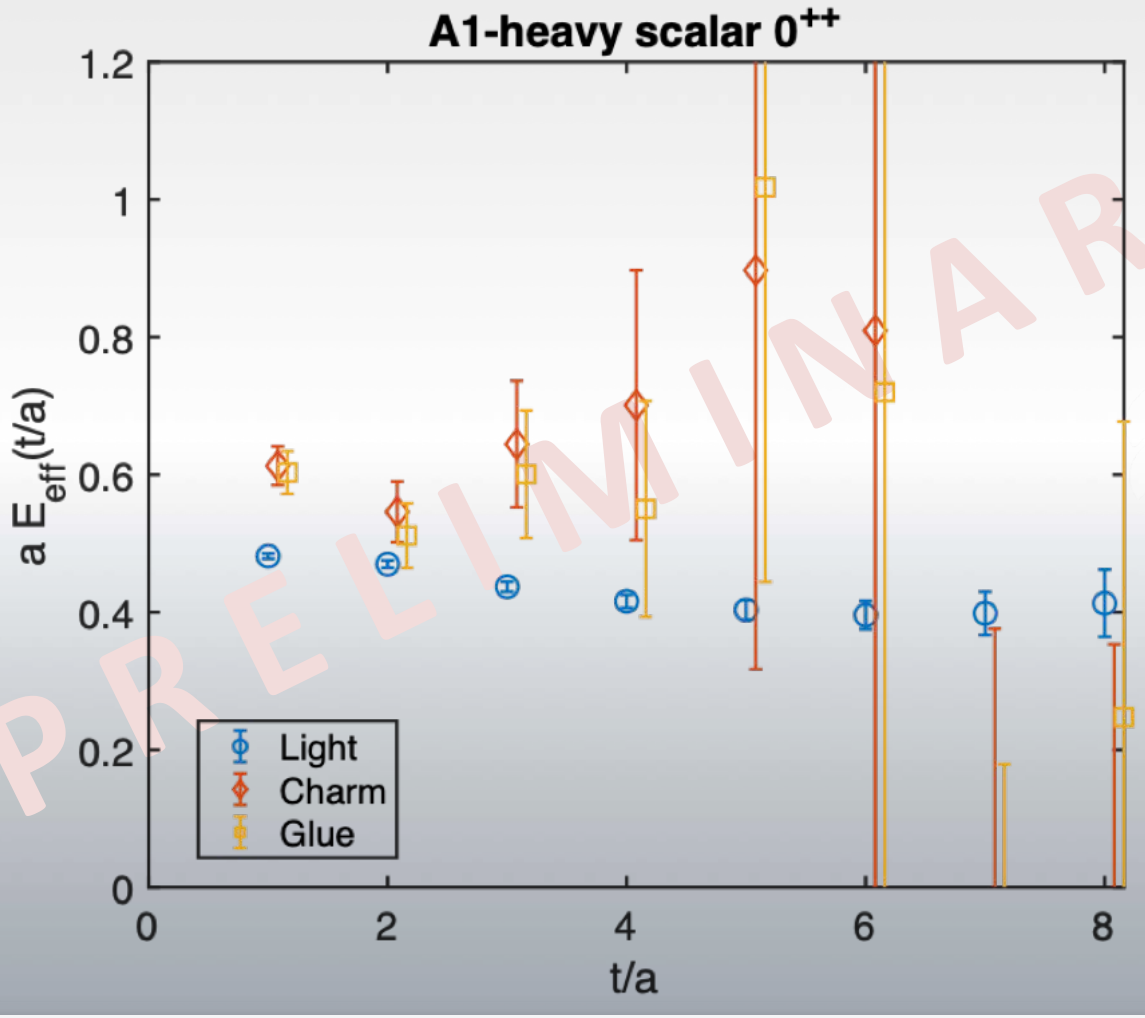
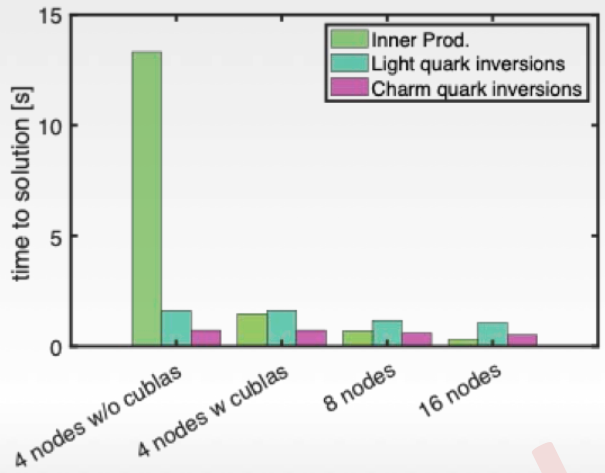
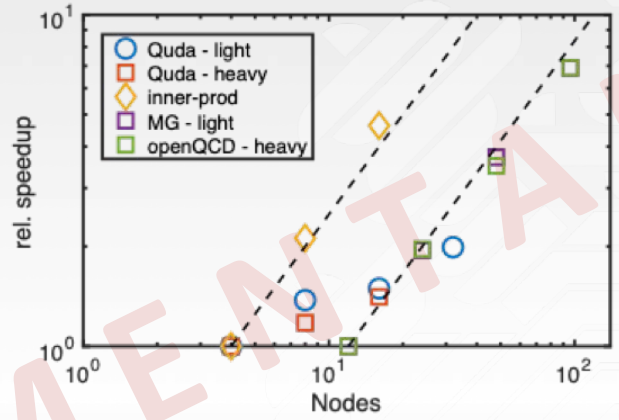
Glueballs from Laplacian eigenvalue correlators, work in progress…

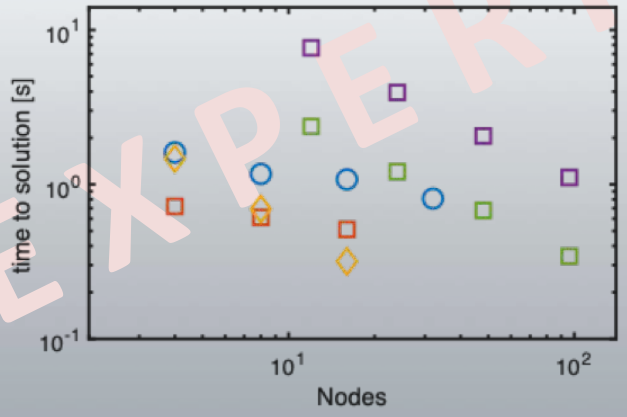


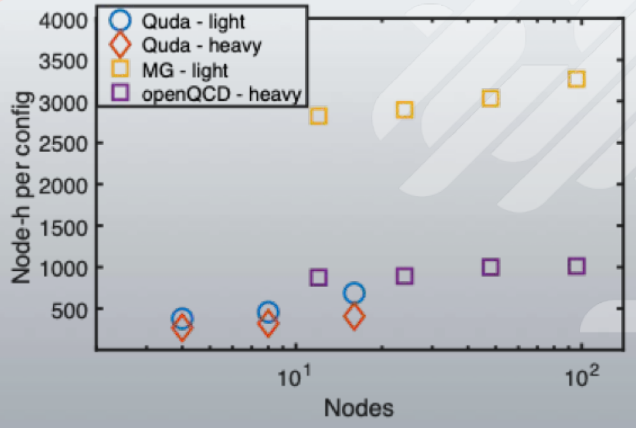
Development and tests of multi-grid and GPU codes

Test runs on **SuperMUC** and **Jureca** (GPU) using (light) ensemble B (48^3 x 144)









Conclusions

New $N_f = 3 + 1$ lattice ensembles

- a=0.054fm, 24^3 x 72, 32^3 x 96 and 48^3 x 128
- m_π ~ 1 GeV, physical charm $m_{\eta c}$ ~ 3 GeV
- 2000 configurations each (8000 MDUs)
- eigenmodes on every 4th configuration
- 500 charm and light perambulators
- glueball can only decay into two pions

Outlook

- mixing of charmonium with light hadrons and glueballs
- study glueballs via Lüscher analysis
- working on multilevel glueball operators in full QCD
- working on multi-grid and GPU codes

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Many Thanks from Wuppertal to NHR@FAU Erlangen!!!

Thank you for your attention!

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